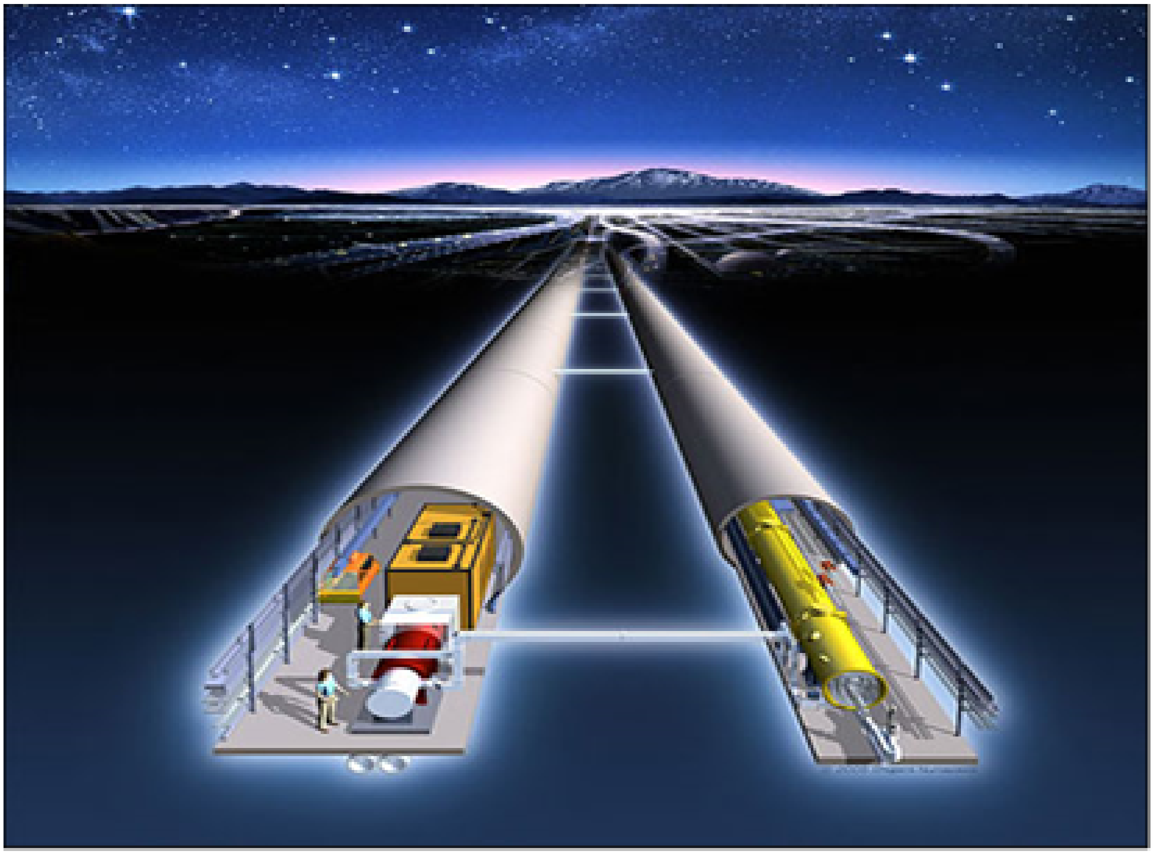
ORNL/TM-2024/3333

Considerations for Export Control of Accelerators and Accelerator Components



J. W. Roddy

March 2024

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Nuclear Nonproliferation Division

CONSIDERATIONS FOR EXPORT CONTROL OF ACCELERATORS AND ACCELERATOR COMPONENTS

J. W. Roddy

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ABBREVIATIONS

AEC	Atomic Energy Commission
AECL	Atomic Energy of Canada Limited
ADS	accelerator-driven system
AMS	accelerator mass spectrometry
ANL	Argonne National Laboratory
APT	accelerator production of tritium
AW	area
σ	cross section
b	Barn (1×10^{-24} cm^2)
BARC	Bhabha Atomic Research Centre
BNL	Brookhaven National Laboratory
CCDTL	Coupled-Cavity Drift Tüp Linac
CCL	Coupled-Cavity Linac
COCOM	Coordinating Committee for Multilatereral Export
CRF	Code of Federal Regulations
CSNS	China's Spallation Neutron Source
CW	Continuous wave
DC	direct current
DEMO	Demonstration Power Plant
DOE	US Department of Energy
DTL	Drift-tube linac
DUL	Dual Use List
ECR	electron cyclotron resonance
ECRIS	Electron Cyclotron Resonance Ion Source
ENSA	European Neutron Scattering Association
ESS	European Spallation Source
eV	Electron volt
ELiTe	EVEDA lithium test loop
EVEDA	engineering validation and engineering design activities
FEED	front-end engineering design
FOM	figure of merit
FRIB	Facility for Rare Isotope Beams
HEBT	High-energy beam transport
IAEA	International Atomic Energy Agency
IFMIF	International Fusion Materials Irradiation Facility
ING	intense neutron generator
IOT	inductive output tube
ITER	International Thermonuclear Experimental Reactor
J-PARC	Japan's Proton Accelerator Research Complex
KAERI	Korea Atomic Energy Research Institute
KOMAC	Korea Multipurpose Accelerator Complex
LAMPF	Los Alamos Meson Physics Facility
LANSCE	Los Alamos Neutron Science Center
LANL	Los Alamos National Laboratory
LBE	lead–bismuth eutectic
LEBT	low-energy beam transport
LEP	Large Electron Positron
LEU	low-enriched uranium

LHC	Large Hadron Collider
LIPAc	Linear IFMIF Prototype Accelerator
LRL	Lawrence Radiation Laboratory
linac	linac accelerator
LMFBR	liquid metal fast breeder reactor
LWR	light water reactor
M	multiplication coefficient
MEBT	medium energy beam transport
MEGAPIE	Megawatt Pilot Experiment
MSU	Michigan State University
MT	metric ton
MTA	Materials Testing Accelerator
MW	megawatts
MYRRHA	Multi-Purpose Hybrid Research Reactor for High-Tech Applications
NIST	National Institute of Standards and Technology
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory Ridge National Laboratory
P	electrical power
PET	positron emission tomography
PIE	post irradiation examination
pad	Proton Radiography Facility
PSI	Paul Scherrer Institut
PSR	proton storage ring
RCS	rapid cycling synchrotron
R&D	research and development
RF	radiofrequency
RFQ	radiofrequency quadrupole
RRCAT	Raja Ramanna Centre for Advanced Technology
SC	superconducting
SINQ	Swiss Spallation Neutron Source
SNM	special nuclear material
SNS	Spallation Neutron Source
SQ	significant quantity
S&T	science and technology
TAC	Turkic Accelerator Complex
TEF-P	Transmutation Physics Experimental Facility
UCN	Ultra-Cold Neutron
VHF	very high frequency
WNR	Weapons Neutron Research

PREFACE

This document represents a redacted version of the original document. Redactions to the text have not been marked.

SUMMARY

CONCLUSIONS

Although nuclear reactors have been the sole source for producing plutonium in all nuclear weapons states, accelerator-driven subcritical reactors are a tantalizing alternative. The United States pursued this option by constructing the Materials Testing Accelerator (MTA) in 1950 to alleviate the possible shortage of uranium-bearing ores.[S-1] Even though the project was eventually canceled; the technology still has many adherents, regardless of concerns that it has the potential for producing weapons-grade plutonium.[S-2]

During the 1990s, the Defense Programs Office within the US Department of Energy (DOE) explored several new sources for tritium production: (1) building a new reactor, (2) purchasing a commercial power reactor, (3) purchasing irradiation services from a commercial power reactor, and (4) building an accelerator. In 1995, DOE determined that using a reactor or an accelerator was the only practical method for producing a sufficient quantity of tritium to meet its stockpile requirements.[S-3] In December 1998, the Secretary of Energy selected the commercial reactor option as the primary source for tritium and designated the accelerator production of tritium (APT) option as the backup.[S-4] The major criticism of the APT was its prohibitive costs.[S-5]

The US DOE has recognized the potential utility of these systems for the production of special nuclear material (SNM) by including a definition of a production accelerator in Title 10, Chapter 810 of the Code of Federal Regulations (CFR): “a particle accelerator designed and/or intended to be used, with a subcritical assembly, for the production of special nuclear material or which a U.S. provider of assistance knows or has reason to know will be used for the production or processing of SNM.”[S-6] Assistance by US persons to any such foreign activity is controlled under 10 CFR 810 and would require a specific authorization from the Secretary of Energy. Although these systems are not commercially viable and are not energy efficient, they might be attractive for the covert production of weapons-grade plutonium.

In addition to the existing controls on “assistance” to foreign activities in 10 CFR 810, consideration of further, new dual-use export controls on particle accelerators and some of their key components with certain attributes may be warranted. The following recommendations are delineated in the appendix and summarized below:

- Particle accelerators having the following characteristics
  - Capable of accelerating singly charged particles to energies greater than 120 MeV, but less than 20 GeV
  - Having a figure of merit (*K*) of 160 or greater

[S-1] Livermore Research Laboratory, *Status of the MTA Process*, Livermore Research Laboratory, Report LRL-102 (Del) (1954).

[S-2] A. P. Armagnac, “The Most Fantastic Atom-Smasher,” *Popular Science*, **173**(5), 115–118, 252–256 (November 1958).

[S-3] “Nuclear Weapons: Challenges Remain for Successful Implementation of DOE’s Tritium Supply Decision,” GAO/RCED-00-24, United States General Accounting Office, January 2000.

[S-4] “Consolidated Record of Decision for Tritium Supply and Recycling,” *Federal Register*, **64**(93), May 14, 1999.

[S-5] P. W. Lisowski, “The Accelerator Production of Tritium Project,” Los Alamos National Laboratory, 1998. Source: http://accelconf.web.cern.ch/accelconf/pac97/papers/pdf/9B003.PDF.

[S-6] U.S. Government, “Title 10—Energy, Chapter III—Department of Energy, Subchapter I—Sales Regulation, Part 810—Assistance to Foreign Atomic Energy Activities,” September 12, 2012. Source: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title10/10cfr810_main_02.tpl.

- Pulsed or continuous duty particle sources producing H^+, H^-, D^+, or H_2^+ ions with an average ion current of 1 mA or greater and emittance of 3.0 pi-millimeter-milliradian (π-mm-mrad) or less

- Devices capable of providing radiofrequency (RF) power outputs greater than 100 kW continuous or 500 kW pulsed at frequencies between 25 MHz and 1.5 GHz and capable of an average power of 100 kW or greater

- Any linear accelerator structure designed to be driven by RF power and having a beam path operated at vacuum and capable of accelerating particle beams of protons or deuterons to multi-MeV energy or greater. These conditions include, but are not limited to:
  - Drift tube linear accelerator structures operating at frequencies in the range of 150 to 800 MHz
  - Coupled-cavity microwave linear accelerator structures operating in the frequency range of 500 MHz to 1.5 GHz and having 1 cm or larger beam bore diameter
  - Superconducting linear accelerator structures operating in the frequency range of 500 MHz to 1.5 GHz

- Cyclotron sector magnets and laminated particle synchrotron ring magnets designed for use in particle accelerators capable of 120-MeV or greater energy

- RF circulators capable of operating at a frequency between 300 and 1,200 MHz and at peak power levels >100 kW

- RF window systems with high-power handling capability

HISTORICAL

Following Chadwick's discovery of the neutron in 1932,[S-7] physicists have been designing, constructing, and operating devices to generate particles with ever-increasing energy to probe the nature of matter. Accelerators became the tool of choice with the first devices using direct voltage to accelerate ions to energies of a few hundred keV.[S-8] Resonant acceleration combined with the application of RF fields progressed from the linear accelerator to the cyclotron. The discovery of the principle of phase stability supplied the necessary technology for the invention of the synchrocyclotron and synchrotron. The concept of colliding beams in the 1960s provided a dramatic increase in energy production. Combining an accelerator with a subcritical code of fissionable material (depleted or natural uranium or thorium) to remove transuranic radioisotopes[S-9,S-10] from nuclear waste or for the production of energy (energy amplifiers)[S-11,S-12] have been a recurring interest with several designs having been proposed.

[S-7] J. Chadwick, "Possible Existence of a Neutron," *Nature*, p. 32 (February 1932). Source: http://web.mit.edu/22.54/resources/Chadwick.pdf.

[S-8] A. R. Steere, " A Timeline of Major Particle Accelerators," M.S. dissertation, Department of Physics and Astronomy, Michigan State University, 2005. Source: http://bt.pa.msu.edu/pub/papers/steeremsc/steeremsc.pdf.

[S-9] Y. Kadi and J. P. Revol, "Design of an Accelerator-Driven System for the Destruction of Nuclear Waste," *Workshop on Hybrid Nuclear Systems for Energy Production,* European Organization for Nuclear Research, CERN, Geneva, Switzerland, Trieste, 3–7 September 2001.

[S-10] International Atomic Energy Agency, *Implications of Partitioning and Transmutation in Radioactive Waste Management*, Technical Reports Series No. 435, Vienna, December 2004.

[S-11] P. Grand, et al., "The Accelerator-Breeder, An Application of High-Energy Accelerators to Solving our Energy Problems," *IEEE Transactions on Nuclear Science*, **24**(3), 1043–1044 (June 1977).

[S-12] C. M. Van Atta, J. D. Lee, and W. Heckrotte, "The Electronuclear Conversion of Fertile to Fissile Material, "UCRL-52144, Lawrence Livermore Laboratory, Livermore, California, October 1976.

Very few accelerators possess the capabilities to produce the beam current and power to be considered a realistic proliferation threat. The major hurdles for building such a system are the costs and the space required. Funding for the Spallation Neutron Source (SNS) in Oak Ridge, Tennessee, was $1.4 billion, and the space requirements approach 80 acres.[S-13] CERN's Large Hadron Collider cost $4.7 billion.[S-14] There is considerable worldwide activity and interest in larger, more powerful particle accelerators, but economic considerations are a major deterrent to development.

FURTHER CONSIDERATION

Largely in anticipation of a possible nuclear renaissance, there has been an enthusiastic renewal of interest in the fusion–fission hybrid concept, driven primarily by some members of the fusion community.[S-15,S-16] A fusion–fission hybrid is defined as a subcritical nuclear reactor consisting of a fusion core surrounded by a fission blanket. The fusion core provides an independent source of neutrons, which allows the fission blanket to operate in a subcritical mode. The idea is many decades old with both new and revisited ideas being considered.

The main applications of hybrids are (1) nuclear waste management by means of burning long-lived radioactive waste products, (2) simultaneous production of energy and management of new or existing nuclear waste by deep-burn fuel cycles, and (3) breeding of new fissile fuel by substantially increasing the utilization efficiency of ^{238}U, the dominant component of both natural uranium and spent nuclear fuel, or alternatively, converting to a ^{232}Th fuel cycle.

Although interest in this technology has been on a sinusoidal path for decades, present indications are that it is on an ascending portion of the curve.[S-17] The export control community should keep abreast of the progress and consider funding a small effort to determine the credibility of the process, identify current activities, identify interested parties, and investigate whether restrictions should be implemented for export control.

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[1] G. Edwards, "Use of Canadian Uranium in the World's First Atomic Bombs," 1998. Source: http://www.ccnr.org/uranium_in_bombs.html#el.

[S-13] "Spallation Neutron Source," Oak Ridge National Laboratory Neutron Sciences. Source: http://neutrons.ornl.gov/facilities/SNS/.

[S-14] A. Knapp, "How Much Does it Cost to find a Higgs Boson?," Forbes, July 5, 2012. Source: http://www.forbes.com/sites/alexknapp/2012/07/05/how-much-does-it-cost-to-find-a-higgs-boson/.

[S-15] "Research Needs for Fusion-Fission Hybrid Systems," Report of the Research Needs Workshop (ReNEW), U.S. Department of Energy, September 30–October 2, 2009. Source: http://fire.pppl.gov/Hybrid_Report_Final.pdf.

[S-16] L. Clippard, "Nuclear Fusion-Fission Hybrid Could Destroy Nuclear Waste and Contribute to Carbon-Free Energy Future," University of Texas, January 27, 2009. Source: http://www.utexas.edu/news/2009/01/27/nuclear_hybrid/.

[S-17] "Development of New Structural Material for Advanced Fission and Fusion Reactor Systems," Joint Research Centre of the European Commission, 2nd Joint IAEA – EC Topical Meeting, Ispra, Italy, April 16–20, 2012. Source: http://www.euronuclear.org/pdf/IAEA-EC-Ispra-2012.pdf.

1. BACKGROUND

The impetus for exploring alternative methods for producing fissile material was the perception that the United States could no longer rely on foreign sources for augmenting its limited supply of uranium-containing ores. During World War II, about half of the uranium used in the US nuclear weapons complex was imported from Canada, with additional supplies from Africa and other areas (e.g., Belgium).[1]

The Soviet Union detonated its first nuclear weapon in September 1949 was the motivation for the US government to expand its production of plutonium at Hanford, dramatically increasing the demand for uranium.[2] Between 1947 and 1955, the US Atomic Energy Commission (AEC) constructed five new reactors (C, H, DR, KE, KW) at the Hanford Site, while concurrently boosting the output of the existing three Manhattan Project reactors (B, D, F), further increasing the demand for uranium.

Ernest Lawrence at Livermore, one of the founders of the accelerator and inventor of the cyclotron, was quick to grasp the possibility that the readily available large quantities of depleted uranium stored at the gaseous diffusion plant near Oak Ridge, Tennessee, would be an excellent source for producing weapons-grade plutonium. His proposal was to combine the high-energy protons generated by an accelerator, like Luis Alvarez's newly completed linac (linear accelerator), with the discovery that a large number of neutrons are produced when these hadrons impact certain elements (preferably of high mass).[3] The same process could be used to produce tritium—used as a trigger in nuclear weapons—by the irradiation of lithium. Lawrence convinced the US government that this principle should be tested by building a prototype accelerator, creating the Materials Testing Accelerator (MTA).[4]

Authorized late in March 1950 with initial funding of $7 million (escalated to $21 million by 1951), the MTA was intended to test the possibility of producing 50 mA of 30 MeV deuterons and to use them to produce polonium-208 from bismuth. This prototype, Mark-I, consisted of a vacuum vessel (Figure 1.1) 60 ft in diameter and more than 60 ft long (other references provide values of 87 and 90 ft in length).[5] The total power, 18 megawatts (MW), was supplied by 18 oscillators (Figure 1.2). Each of the drift tubes had its own magnet focusing system and associated water-cooling system. A standard gauge railroad track down the middle of the accelerator was used to install the drift tubes. The last and largest drift tube weighed 40 tons.

Mark I ran ten times, once continuously for 13 hours with an average beam current of 50 mA. Operation was terminated in November 1953.The prototype proved that a very high vacuum, a potential gradient, and focusing magnets were possible in a very large vessel. In addition, an ion source emitting one ampere of deuterons or protons collimated to within 4° was possible.

Another, much larger system, Mark-II, was to produce 1 gram (6×10^{23}) of deuterons per day (at 500 mA and 350 MeV). Mark-I was to serve as the front end of Mark-II.[6] This accelerator was expected to cost $300 million and use a vacuum tank 1,500 ft long. The primary target was to be thorium encapsulated in stainless-steel canisters and cooled by liquid sodium. A magnetic field would sweep the tip of the beam across the canisters. Neutrons emerging from the thorium would penetrate a secondary target of uranium, producing plutonium.

The AEC, concerned about procuring sufficient uranium for weapons production, was impressed with the system that would make plutonium from nearly inexhaustible uranium tailings without consuming fissile material and without presenting undue safety hazards. In March 1951, the AEC found that Mark I was sufficiently promising to justify continued studies for Mark II. However, some of Lawrence's associates believed that proceeding simultaneously with several untried, experimental devices was courting disaster.

Figure 1.1. The MTA vacuum tank used a standard gauge railroad track to install the drift tubes.

Figure 1.2. An oscillator used for the MTA.

During this period, the AEC was astute enough to encourage the exploration and discovery of domestic sources of ore containing uranium by offering bonuses and price incentives. This effort was so successful—uncovering rich deposits on the Colorado plateau—that the Mark II project was terminated on August 7, 1951, and Mark I was relegated to a small program in AEC's Division of Research, thus ending a valiant effort by Lawrence.[7]

The development of new accelerators for probing particles in the subnuclear domain became a major interest in the United States, and recommendations for further study became the subject of several panels. A 1963 report by the General Advisory Committee and submitted to the AEC and the President's Science Advisory Committee listed 13 recommendations that included the construction of (1) a high-energy proton accelerator by Lawrence Radiation Laboratory (LRL) of approximately 200 gigaelectron volts (GeV, (2) storage rings at Brookhaven National Laboratory (BNL), and (3) a national accelerator with energy in the range of 600–1,000 GeV.[8] After much consternation and acrimonious discussions, the 200 GeV accelerator proposed for LRL was expanded to 500 GeV and built at the National Accelerator Laboratory (now Fermilab) near Weston (Batavia), Illinois.[9]

With continued interest in achieving higher neutron fluxes and the operational limits and difficulties in accessing the neutrons generated in research reactors, Canadian scientists proposed the construction of an accelerator called the Intense Neutron Generator (ING).[10] The results of a 2 year study were presented to the Atomic Energy of Canada Limited (AECL) in 1968. The original motivation for ING arose from the need for more intense continuous fluxes of thermal neutrons for research applications in neutron physics (including reactor physics), chemistry, and metallurgy. Another motivation was the ever-present requirement for irradiation facilities to meet the explosive demand for radioisotopes. In system planning for ING, research needs were given priority over radioisotope production, but every attempt was made to accommodate isotope production facilities when they were compatible and did not interfere with the routine operation of the research facilities. However, the ING was never built.[11]

In 1973, John Carpenter was granted a US patent that described a method for producing thermal neutrons using a fast neutron source and a novel arrangement of a moderator, a reflector, and a neutron energy-dependent decoupling reflector liner. The peak thermal neutron flux achievable at the maximum of each pulse was expected to be 1.6×10^{15} n/cm^2-s.[12] In a subsequent paper, Carpenter discussed the advantages and disadvantages of using pulsed spallation neutron sources for slow neutron scattering.[13]

The late 1970s saw a resurgence in interest in the accelerator breeder concept. The implementation of the once-through fuel cycle was expected to increase demand for uranium and deplete the more economically attractive sources of the element. In addition, there was a lingering concern about the viability of the liquid metal fast breeder reactor (LMFBR).

Several designs were proposed for producing plutonium and uranium-233, based on data generated during the MTA studies. Table 1.1 provides a summary of the results from three of these studies. Each used a linear accelerator, a spallation neutron source, and a subcritical assembly. The consensus was that the process was promising, but additional theoretical and experimental studies were needed, especially in the design of targets. Nevertheless, there was no recommendation to pursue further studies.

Table 1.1. Fissile material production as reported in several literature citations.

Accelerator beam			Primary target	Secondary target	Production (kg/year)[a]
Beam (Ref.)	Energy (MeV)	Current (A)			
^{1}H[14,15]	1,500	0.3	Pb–Bi	UO_2	1,000 Pu
^{1}H[14]	1,500	0.3	Pb–Bi	ThO_2	850 ^{233}U
^{2}H[16,17]	500	0.25	Li	Depl. U	675 Pu
^{2}H[16,17]	500	0.375	Li	Depl. U	1,015 Pu
^{1}H[18]	450	0.3	Pb–Bi	3% ^{235}U	1,700 Pu
^{1}H	450	0.3	Pb–Bi	6% ^{235}U	1,680 Pu

[a] Based on 80% plant factor.

Not to be deterred, accelerator proponents began promoting the capabilities of particle accelerators to remove the majority of long-lived radioisotopes in spent fuel from light water reactors (LWRs).[19,20,21] Their premise was based on fact that 99.995% of the long lasting (>500 years) radiotoxicity resides in a very few elements, representing only about 1% of the spent fuel mass. Although these radioisotopes are resistant to transmutation with thermal neutrons, they have favorable cross sections for fast neutrons and are amenable to destruction in a spallation neutron source and subcritical core. Experiments and system modeling indicated that such a system would also dramatically reduce the concentrations of ^{99}Tc and ^{129}I. The best results would be obtained by using a core containing thorium instead of uranium.

Two papers published in 2011 demonstrate the versatility and potential of particle accelerators. In the first citation, the authors discuss the feasibility of using a particle accelerator coupled with a subcritical reactor containing low enriched uranium (LEU) to produce ^{99m}Tc/^{99}Mo generators.[22] Protons from a 350 MeV accelerator would provide nucleons with energies greater than 10 MeV, resulting in fission in both ^{235}U and ^{238}U that have similar cross sections for nucleons in this energy range. Another interesting application of particle accelerators is in providing sufficient neutrons to drive a subcritical molten salt reactor.[23] The design uses a 5 to 10 mA negative hydrogen source (H^-) operating continuously at 3 GeV. One of the major advantages of the molten salt concept is in dissipating the heat generated by the beam. The heat from the target would be distributed in the salt and removed by the salt heat exchanger with the added possibility of partial recovery of the beam energy.

2. PARTICLE ACCELERATORS

2.1 INTRODUCTION

Ernest Rutherford's frustration in being restricted to the feeble energy for alpha (α) particles produced by naturally occurring radioisotopes (such as polonium-210) in his studies of the structure of the atom was the seed for the development of particle accelerators.[24] In a speech to the Royal Society of London in 1927, he challenged the audience to develop systems that would produce large quantities of particles more energetic than what was presently available from these naturally occurring radioactive sources.[24,25] Rutherford was the president of the society and well regarded by his peers, and he became a driving force in the development of new "machines." His associates accepted the challenge by developing many innovative designs.

Initially, electrostatic machines (voltage multiplying columns [Figure 2.1], Van de Graaff generators [Figure 2.2], and tandems) that mimicked the energies from natural radioactivity were developed. In the 1930s, cyclotrons were invented that would accelerate protons and deuterons to energies ten times greater than the electrostatic systems, but the large size of the systems was a serious detriment to increasing the transfer of energy to the particles. Linear accelerators were also developed for accelerating protons and electrons. Electrons posed a different challenge, requiring a special device—the betatron (uses magnetic induction to accelerate electrons [Figure 2.3]).

Figure 2.1. The Cockcroft–Walton preaccelerator at the National Accelerator Laboratory.

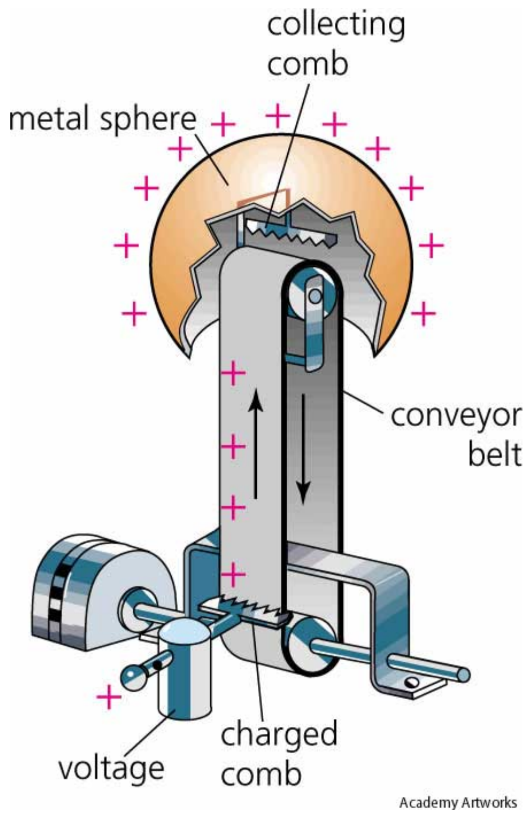

Figure 2.2. Schematic of a Van de Graaff accelerator.

Following World War II, the synchrotron and the collider, each producing particles with very high energies, were produced. It was soon realized that considerable energy was lost when a high-energy synchrotron particle impinged on a stationary target. To eliminate the lost energy that was transferred to the target and provided momentum to the products, the synchrotron was reconfigured to accelerate two particle beams in opposite directions. These head-on collisions transferred nearly all of the kinetic energy to the particles. The major problem was to produce a circulating beam of sufficient density to have a finite chance of particle–particle interaction. These accelerators became known as *colliders*.

Seeking ever-increasing energetic particles to answer the latest questions about the ultimate structure of matter, researchers conceived, designed, and constructed newer and larger accelerators. The advantages that accelerators can produce radiopharmaceuticals with high specific activities, while generating small quantities of radioactive waste, became an added incentive for their development. Accelerators have also been proposed for the transmutation of radioactive waste, production of tritium, and generation of energy.

Figure 2.3. The betatron was part of a 35,000,000 V electron accelerator used in nuclear research.

2.2 LINEAR ACCELERATOR

To overcome the problem of unwanted discharges inherent in electrostatic accelerators, Gustav Ising proposed accelerating charged particles in many small steps, using the fact that the particles would experience a change in energy when exposed to an electric field.[26] In 1928, Wideroe modified and utilized Ising's idea to produce the first linac by applying a varying voltage from a radiofrequency oscillator (Figure 2.4). The particles pass through a series of hollow cathodes, called *drift tubes*, which allow them to drift at constant velocity within the tube and then to be accelerated between the tubes (Figure 2.5). An electric field that is opposite in sign to the particle's charge accelerates the particle between the tubes. The phase of the electric field is changed to that of the particles as it exits each of the tubes. By setting the maximum potential just after the particles pass a specified point, the problem of particles arriving too early or too late at the next accelerating section is eliminated; consequently, they are in phase when entering the next section of the accelerator.

The late 1980s saw a burst of activity in the number of laboratories designing linear colliders, but it became clear that building one would not be easy. There were several major problems to overcome: (1) the large amount of electrical power needed; (2) the fundamental and inevitable consequence that the particles must be accelerated from rest; (3) that there is only one chance to collide (they do not circle around again); and (4) the excessive length that linacs need to be to produce particles possessing reasonable energies. The SLAC National Accelerator Laboratory is home to a 2 mile (3 km) linac, which is the longest in the world.[27] It can accelerate electrons and positrons to 50 GeV. A 250 GeV linac built, assuming the same specifications (15–20 MeV/m), would be 15 km long, or 30 km if the positron linac facing in the opposite direction is included.

2.3 CYCLOTRON

The idea of combining a magnetic field, while applying a small incremental voltage to charged particles, was being considered by several individuals during the late 1920s. Although Denis Gabor stated in 1924 that he recommended applying magnetic bending with radiofrequency acceleration, Leo Szilard was shrewd enough to patent the concept in 1929.[5] Max Steenbeck, a graduate student, proposed such a system in 1927, but his major professor concluded that it would be too costly, and another professor stated that it was not feasible.

Figure 2.4. One of the US's most powerful proton linear accelerator at Los Alamos.

Figure 2.5. A drift tube is a hollow cylindrical electrode to which a radiofrequency voltage is applied in a linear accelerator.

Lawrence rediscovered the idea in 1929, but he did not pursue it until two graduate students arrived at the University of California in the autumn of 1930, both seeking a subject for a doctoral thesis.[24] These two students, David Sloan and M. Stanley Livingston, followed a series of students who nurtured Lawrence's interest in accelerators. Sloan was assigned the task of building a linear accelerator using the ideas set forth in Rolf Wideroe's doctoral dissertation presented in October 1927. Wideroe was an electrical engineer and physicist and the builder of the first practical linac.[5] Sloan made excellent progress; his first linac used eight electrodes and a 75 W oscillator to produce 90 keV mercury ions with the oscillator operating at 11 kV.

Livingston's task proved more daunting: attempting to duplicate Niels Edlefsen's purported success in building and operating the first magnetic-resonance accelerator, the cyclotron (Figures 2.6 and 2.7).[28] Whether Edlefsen's cyclotron achieved resonance acceleration has been questioned by many.

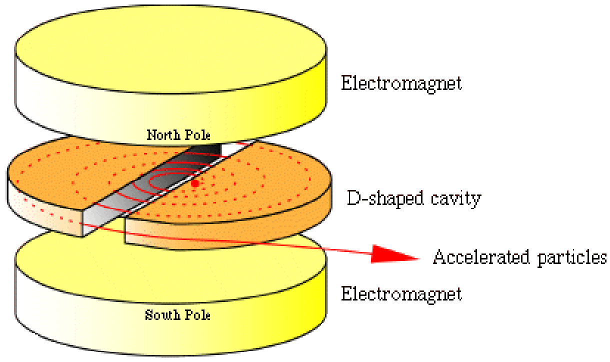

Figure 2.6. A cyclotron is a machine used to accelerate charged particles to high energies. Reproduced courtesy of Jefferson Laboratory.

Figure 2.7. A cyclotron provides protons for radiation therapy. Reproduced from Penn Medicine.

Livingston began with a 4 in. cylinder, a vacuum chamber, and a small magnet of 5,500 gauss. He became convinced that Edlefsen's system was not feasible as designed. Livingston continued to have problems with the ion source strength, system pressure, shielding grid, and electrostatic forces. After much improvement in the equipment, including a larger magnet, Livingston was somewhat successful, especially if data are selectively examined. Lawrence must have been persuaded because Livingston's thesis was accepted, and he received his doctorate and went to Cornell in 1934.[5]

The cyclotron operates on the principle that the rotational frequency of a charged particle traveling in a magnetic field is independent of the radius of its orbit; thus, the energy of the particle increases as its velocity increases. In a cyclotron, particles travel in a circular orbit when acted upon by a homogeneous magnetic field generated between the poles of a magnet. Located at the center of the magnet is an ion source whose ions are introduced and then accelerated by a high-frequency electric field through two or more hollow electrodes called *dees*. Ions are accelerated as they pass through a gap between the dees. The energy and path diameter of the particle increases because the rotational frequency remains constant. The high-energy particle is extracted at the perimeter of the cyclotron.

2.4 SYNCHROTRON

The major problem with cyclotrons is that increasing their energy output requires increasing their size. Their pole pieces become saturated, and the only way to double the maximum energy of particles is to make the circular path twice as large. Thus, the pole diameter must be doubled to double particle energy, increasing the volume by a factor of 8.

In 1943, Marcus Oliphant realized that only the outer rim of the magnet was needed to channel particles at the highest energy.[5] By restricting the particles to use the outer rim for all energies, it might be possible to replace the large cyclotron magnet with a slender annulus of magnets around the perimeter. In this scenario, particles would be injected into the machine in pulses; each pulse would then be accelerated and the magnetic field of the annulus increased to keep in step with the rising energy. The name of this accelerator, *synchrotron*, is derived from the need to synchronize the increase in field and the accelerating frequency to match the rising energy of the group of particles as they are accelerated.

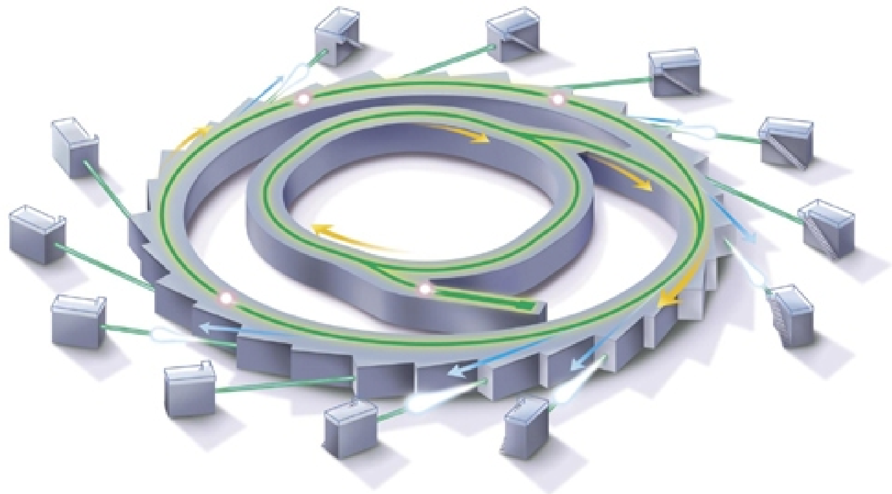

Figure 2.8. A linear accelerator injects particles into the inner synchrotron of the LHC, which are then injected into the outer synchrotron. Various experiments were run off the perimeter using the accelerated beam.

The synchrotron has become the premier system in the quest for higher energies. Two important discoveries, that of alternating gradient focusing and the use of colliding beams, have produced machines with energies of a few hundred MeV to several teraelectron volt (TeV). The largest synchrotron is the Large Hadron Collider (LHC) near Geneva, where it spans the border between Switzerland and France about 100 m underground.[29] CERN also operated the Large Electron Positron (LEP) collider from 1989 to 2000.[30] After 11 years of operation, LEP ceased operation in November 2000. A month later, dismantling began to make way for its successor—the LHC (Figure 2.8).

2.5 USES

Of the more than 30,000 particle accelerators that have been built worldwide over the past 60 years, more than half have been used for industrial purposes (Table 2.1).[31] The number of new systems installed annually by industry is almost twice that used for research and medical therapy.

Table 2.1. Accelerators in industry[32].

Application	Total (2012)	Systems Sold/year	Sales/year ($M)	System price ($M)
Ion implantation	~10,200	500	1,400	1.5–5.0
Electron beam modification	~7,000	100	150	0.5–2.5
Electron beam & X-ray irradiators	~2,600	75	130	0.2–8.0
Ion beam analysis (including AMS)[a]	~250	25	30	0.4–1.5
Radioisotope production (including PET)[b]	~1,000	50	70	1.0–30
High energy X-ray inspection	~1,500	100	70	0.3–2.0
Neutron generators (including sealed tubes)	~1,500	50	30	0.1–3.0
Total	24,500	900	1,780	

[a] AMS = accelerator mass spectrometry
[b] PET = positron emission tomography

Industrial accelerators include both electron-beam and ion-beam systems spanning essentially all of the acceleration methods developed for research: electrostatic systems, RF linacs, betatrons, cyclotrons, and synchrotrons.[33] The method of acceleration is often used for the classification of accelerators: direct voltage, linear accelerators with RF voltage, and cyclic accelerators using magnetic fields, with or without

RF voltage. Direct-voltage accelerators (also known as *DC accelerators*) are the most widely used in the industry for both electron and ion beams. Many use a relatively low DC voltage (300 kV or less) applied across a short gap with the external power supply connected to the accelerator through a high-voltage cable. Among these devices are ion-implementation accelerators to alter the surface properties of semiconductor materials, small deuteron-beam fusion-neutron generators for the oil industry, and electron-beam systems for materials processing.

Figure 2.9. Electron accelerator used in medical therapy.

Electron accelerators—The use of energetic electrons in industrial applications covers many modes of electron interactions with matter and electromagnetic fields: ionization, chemical changes, heating bremsstrahlung, and synchrotron radiation. The most widespread industrial use, electron-beam irradiation, relies on the ionizing interactions of electrons with atoms in the irradiated material to alter its chemical or physical properties. This change occurs when free radicals—molecular fragments with unpaired electrons—created by the electron beam causes secondary reactions in the bombarded material. Low-energy (75–300 keV) electron accelerators are used to cure (polymerize and crosslink) coatings, adhesives, and inks on paper, and plastic and metal substrates. High-energy (up to 10 MeV) accelerators are used to cure fiber-reinforced composite materials. Other uses of accelerator electrons include sterilizing medical products, preserving foods, treating municipal and industrial wastes, and medical therapy (Figure 2.9).

Ion beam accelerators—Industrial applications of ion beams make use of the full range of interactions of ions and materials. They exploit many types of nuclear interactions and the capturing of ions in materials. Ion implantation, primarily into semiconductors, is the largest application of industrial accelerators (Figure 2.10).[34] It is employed in the fabrication of virtually all integrated circuits and in the cleaving of thin silicon wafers for the production of photovoltaic cells. Almost 10,000 ion-implanter accelerators have been produced over the past half century. The commercial value of the semiconductor components they produce worldwide now exceeds $250 billion per year.

Figure 2.10. A 350 KeV ion implanter located at the Ångström Laboratory at Uppsala University, Sweden.

Nuclear reactions—Ion implantation is usually performed at energies below the Coulomb barrier for nuclear reactions. However, most of the other industrial ion-beam applications rely on nuclear reactions for ion-beam analysis, production of radionuclides for tracers, diagnostic imaging, and cancer therapy. Neutrons are also generated for a number of analytical applications.

The design of an accelerator for generating neutrons consists of a source to generate positively charged ions, one or more structures to accelerate the ions (~110 kV), a metal hydride target containing deuterium, tritium, or a mixture of both, and a gas-control reservoir, also made of a metal hydride (Figure 2.11).[35] Ion sources include a cold-cathode (Penning), hot cathode, magnetrons, and RF systems.

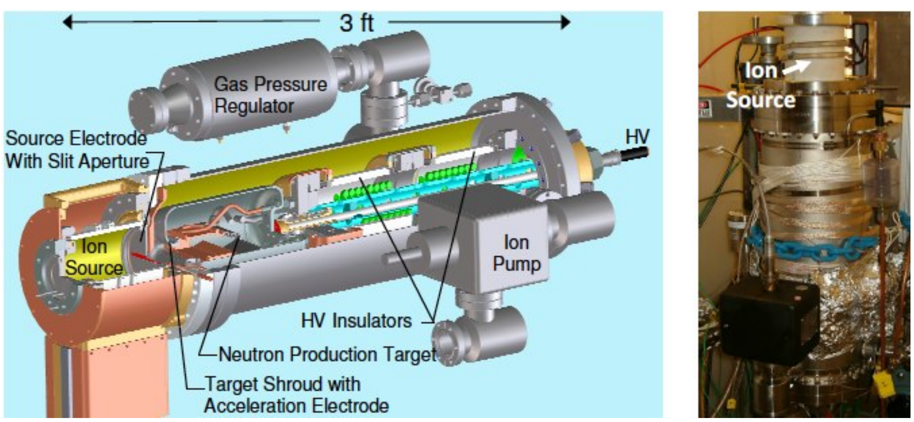

Figure 2.11. This compact and simple device can generate 5×10^{11} neutrons per second by accelerating deuterium or tritium (depending on the desired neutron spectrum) into a deuterated or tritiated neutron production target.

3. NEUTRON PRODUCTION

3.1 INTRODUCTION

The unique properties of neutrons, being neutral and having a magnetic moment and a spin, make them a very desirable tool in solid-state physics. Neutrons are able to pass through layers of materials with thicknesses of several centimeters. They can induce nuclear reactions, which can be used for activation analysis. The reaction of neutrons with many substances may lead to a radioactive nucleus, whose presence can easily be detected by its characteristic radiation. When a neutron beam passes through a solid, the scattered beam transports information on the microstructure inside the solid body. Thus, the microscopic structure of crystals or the inner mechanical strain of big mechanical parts, like the valve of a ship diesel motor, may be determined. Neutrons are also useful in studying the structure of magnetic layer systems, like those used in magnetic storage media (hard discs in computers). Finally, neutrons can produce fission in certain radioisotopes.

There are two mechanisms for producing neutrons: (1) nuclear chain reactions (fission) and (2) energetic particle beams interacting with target nuclei. Fission reactors were first used to produce plutonium in weapons programs. Following World War II, the energy produced from fission was used to generate electricity in commercial nuclear power plants. In addition, neutrons generated in small-scale, research reactors have seen wide application.

Neutrons from either one of the production methods may and have been used to produce weapons-grade ^{239}Pu (Equation 1). In a sufficient neutron flux, ^{238}U will capture a neutron, producing ^{239}U. Through a series of decays, the relative stable plutonium isotope, ^{239}Pu, results. A chemical process is required to separate the plutonium from residual uranium and highly radioactive fission products.

$$^{238}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{239}_{92}\text{U} \xrightarrow{\beta -} ^{239}_{93}\text{Np} \xrightarrow{\beta -} ^{239}_{94}\text{Pu}. \quad (1)$$

3.2 FISSION (NUCLEAR CHAIN REACTIONS)

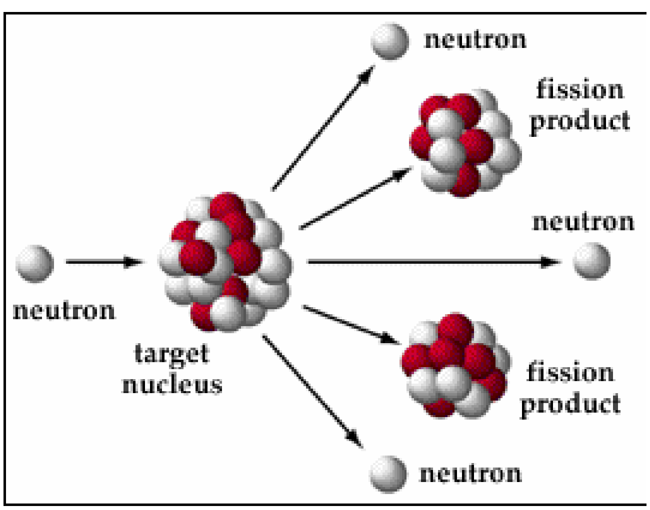

Figure 3.1. The nuclear fission process. Reproduced from http://www.indiana.edu/~neutron/notes/20060927_Pynn.pdf

Nuclear fission occurs when a particle, usually a neutron, interacts with a fissile nucleus, resulting in two different nuclei whose total mass is somewhat less than the original nucleus plus the interacting neutron (Figure 3.1). This neutron capture occurs only with the heaviest elements, those of special interest being thorium, uranium, and plutonium. The most probable fission masses for ^{235}U lie between 70 and 160. The most probable mass numbers, which occur in about 6.5% of fissions, are about 96 and 135. Symmetrical fission with two products of mass of 117 occurs only about once in 20,000 fissions.[36]

The number of neutrons produced during fission ranges from zero to seven. Most (more than 99%) of the neutrons produced in fission are emitted almost immediately (~10^{-13} s) after the fission event occurs.[37] These are called *prompt neutrons*. A small portion of fission neutrons are *delayed neutrons*, which are produced some time after the fission process has taken place. The delayed neutrons are emitted immediately following the first ß decay of a fission fragment known as a delayed neutron precursor.

In thermal reactors, the neutrons that cause fission are at a much lower energy than the energy level at which they were born from fission. In this type of reactor, specific materials must be included in the reactor design to reduce the energy level of the neutrons in an efficient manner.

Fission neutrons are produced at an average energy level of ~2 MeV and begin to decelerate immediately as the result of numerous scattering reactions with a variety of target nuclei. After a number of these collisions with nuclei, the speed of a neutron is reduced to such an extent that it has approximately the same average kinetic energy as the atoms (or molecules) of the medium in which the neutron is undergoing elastic scattering. This energy, which is only a small fraction of an electron volt at ordinary temperatures (0.025 eV at 20°C), is frequently referred to as *thermal energy* because it depends upon the temperature. Neutrons whose energies have been reduced to values in this region (<1 eV) are designated thermal neutrons.

The process of reducing the energy of a neutron to the thermal region by elastic scattering is referred to as *thermalization*, slowing down, or moderation. The material used for the purpose of thermalizing neutrons is called a *moderator*. A good moderator reduces the speed of neutrons in a small number of collisions, but does not absorb them to any great extent. Slowing the neutrons in as few collisions as possible is desirable to reduce the amount of neutron leakage from the core and to reduce the number of resonance absorptions in nonfuel materials.

3.3 SPALLATION

Spallation refers to a nonelastic nuclear interaction induced by a high-energy particle. One important feature of spallation is the production of a large number of secondary particles. Although spallation occurs at an energy of about 12 MeV, it only becomes attractive when the energy of the charged particles is >120 MeV.[38]

When a highly energetic charged particle, proton, neutron, or light ion, impacts matter, various nuclear and atomic interactions take place. Ionization and excitation are the most important atomic interactions. The important nuclear interaction is the nonelastic collision with target nuclei. It is a multiple collision process and proceeds in several stages (Figure 3.2).

Intranuclear or hadronic cascade—The incident proton collides with one of several nucleons, inducing a cascade of quasifree nucleon–nucleon collisions that result in a forward-directed component of high-energy (>15 MeV) hadron-like protons, neutrons, and pions. For sufficiently thick targets, these hadrons proceed to produce additional collisions, inducing an internuclear cascade, or “hadronic” cascade. This process continues until the particle energy is reduced to less than the probable threshold energy for initiating a spallation reaction.[39]

Evaporation stage—The second process of the spallation reaction is the evaporation of low-energy (about 0.1–10 MeV) particles from these excited nuclei; the emission of neutrons, protons, deuterons (*d*), tritons (^3H), ^3He, α, and heavier particles. If the target nuclei are very heavy, such as uranium, high-energy fission can compete with evaporation during nuclear de-excitation. Among these emitted particles, neutrons are the most common. They also may be a source of thermal neutrons with the use of a moderator.

The number of neutrons generated via spallation varies with the energy of the beam, dimension of the target, and the composition of the target. Carpenter and Manner performed a series of experiments to determine the number of neutrons released for proton energies between 0.47 and 1.47 GeV for a 10.2 cm diameter by 60 cm long depleted uranium target.[39] Their data for the number of neutrons (Y_{spl}) released per proton energy delivered on the target can be represented by the following equation:

$$Y_{spl} = 0.05 \times (E_{MeV} - 120), \tag{2}$$

where E_{MeV} is the proton energy in MeV. An earlier set of measurements on targets of 10 cm in diameter and 60 cm in length with proton energies between 200 MeV and 1.5 GeV produced yields represented by equation 3.

$$Yield = a \times (A + 20) \times (E_{MeV} - b), \tag{3}$$

where A is the atomic mass of the nucleus and $b \approx 120$ MeV.[39] The value of a is 1×10^{-4} for all heavy elements, except for ^{238}U where it is 1.9×10^{-4}. Thus, spallation in ^{238}U yields nearly twice as many neutrons per proton than other heavy elements. These equations are consistent with the calculations obtained by Barashenkov, Toneev, and Chigrinov.[40]

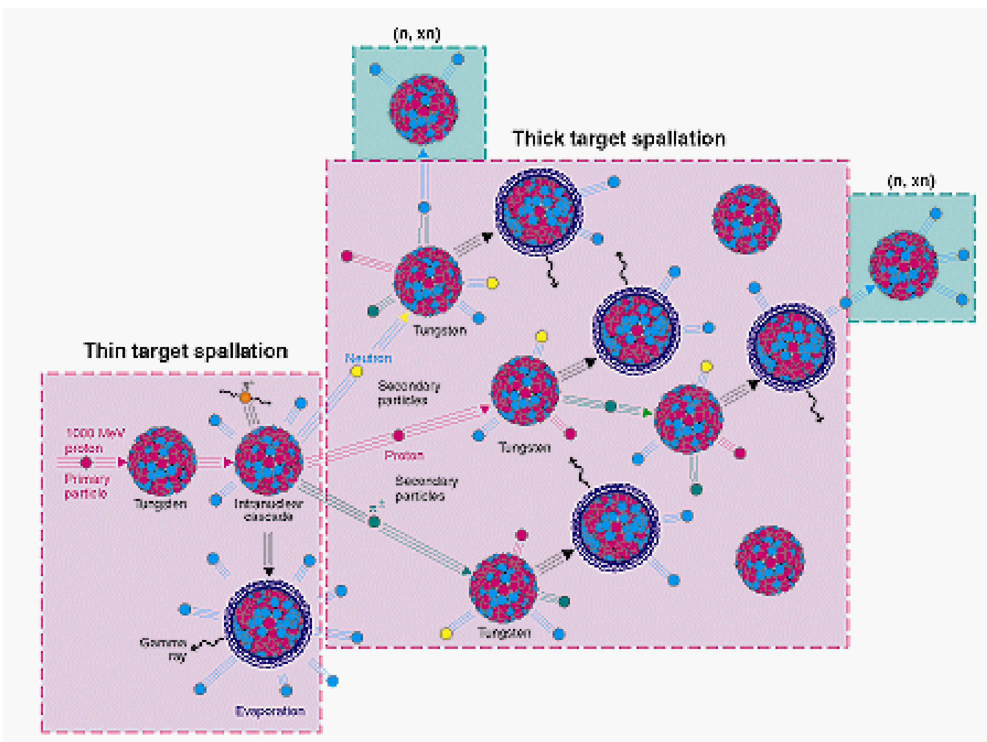

Figure 3.2. The course of a spallation reaction.

3.4 SUBCRITICAL CORE

Accelerator-driven systems (ADS)—Systems driven by a high-power proton accelerator, which provide protons to a spallation target and generate neutrons for a subcritical core—have been proposed for addressing certain missions in advanced nuclear fuel cycles.[41] Their application to transmutation of nuclear waste and to the production of energy has been evaluated by many government organizations over the years. Impetus was provided by the National Research Council in a report published nearly 30 years ago that included an evaluation of a large-scale system using a ~100 MW accelerator to drive a molten salt subcritical core.[42]

An assembly of fissionable material is subcritical if the quantity of material present, coupled with its physical arrangement and complement of supplementary materials, such as those that comprise the fuel lattice structure, moderator, reflector, fuel rod cladding, etc., is insufficient to achieve a sustained fission chain reaction ($k_{eff} < 1$). The parameter k is defined as the ratio of the number of neutrons available in the present generation to that in the preceding generation. When $k_{eff} = 1$, the number of neutrons produced by fission is equal to the number of neutrons removed by nuclear reactions in the core in addition to those that escape the system. If an external neutron is introduced (e.g., an accelerator or a spontaneous fission neutron source), then fissions will occur in the subcritical assembly at some sustainable and determinable rate. However, once the external source is removed, the neutron inventory from fission in the core will decrease rapidly.

By contrast, a critical reactor does not rely on an external neutron source other than to serve as an initiator of the chain reaction. Critical reactor cores are designed to have a small amount of excess reactivity ($k_{eff} > 1$) that can be controlled and maintained at criticality during operation by the insertion of rods containing material, such as cadmium or a boron compound that is capable of removing neutrons by capture because they possess large neutron capture cross sections in certain energy regions (e.g., at specific resonances or thermal energy). Thus, a delicate balance is maintained during the operation of critical reactors by the position and number of control rods introduced into the core in such a way that $k_{eff} \approx 1$. Delayed neutrons (i.e., those neutrons emitted from highly neutron-unstable states of fission products and not from fission itself) play an important role in assuring reactor controllability because the time scale for prompt fission is so short that it is virtually impossible to control criticality effectively by any physical means (e.g., inserting or withdrawing control rods). However, the time scale for delayed neutron emission is sufficiently long, on average, that control by physical means is feasible.

Considerable information is available about the properties of critical reactors because of research spanning more than 60 years, as well as from the operation of many research and power-generating reactors throughout the world. However, less is known from experimental results about the properties of subcritical reactors driven by external neutron sources.

4. ADS FOR PLUTONIUM PRODUCTION

4.1 INTRODUCTION

Nearly all of the accelerators used in industry, medicine, and research do not possess the attributes necessary for producing sufficient quantities of plutonium to warrant consideration as a proliferation risk. However, the continuing progress in accelerator development and the minimal export controls on ADS components may prove attractive to a rogue state. To capture such systems and components, an appropriate set of guidelines would be of use in evaluating ADS for export control. The ultimate benchmark is the plutonium production rate and criteria published by the International Atomic Energy Agency (IAEA), US Department of Energy (DOE), and the US Nuclear Regulatory Commission (NRC) have been used as a guide. Because both US government agencies consider 2 kg of plutonium as the "threshold" value this quantity of material was chosen for this study.

4.2 SELECTION CRITERIA

From a series of meetings and recommendations from various committees on safeguards, the IAEA has published multiple documents in which it describes processes that could be used to verify a state's compliance with its undertaking to (1) accept safeguards in all of its peaceful nuclear activities and (2) confirm that nuclear material is not diverted to nuclear weapons or other nuclear explosive devices.[43] One area of concern has been in authenticating inventories of nuclear material as provided by states—whether fissile material has been diverted. From these efforts, the IAEA has defined what it considers as a *significant quantity* (SQ) of nuclear material (Table 4.1), quantities of which it considers as the "approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded."[44]

The IAEA also defines the *rate of diversion* as the amount of nuclear material that could be diverted in a specified unit of time. If the amount diverted is 1 SQ or more of nuclear material in a short time (i.e., within a period that is less than the material balance period), it is referred to as an *abrupt diversion*. If the diversion of 1 SQ or more occurs gradually over a material balance period, with only small amounts removed at any one time, it is referred to as a *protracted diversion*.

Table 4.1. Significant quantities (SQ) of nuclear material as defined by the IAEA[44].

Material	Quantity
Direct use[a]	
Plutonium[b]	8 kg
^{233}U	8 kg
Highly enriched uranium (^{235}U ≥20%)	25 kg ^{235}U
Indirect use[c]	
Uranium (^{235}U <20%)[d]	75 kg ^{235}U
Natural uranium (^{235}U ~0.7%)	10 MT
Depleted uranium (^{235}U <0.7%)	20 MT
Thorium (Th)	20 MT

[a] Nuclear material that can be used for the manufacture of nuclear explosive devices without transmutation or further enrichment.
[b] For Pu containing ^{238}Pu <80%.
[c] All nuclear material, except direct use material.
[d] Including low-enriched, natural, and depleted uranium.

US government agencies have developed a set of criteria for controlling special nuclear material (SNM) under their jurisdiction. The NRC uses the following three-tiered system (categories) as to its safeguards approach to SNM: (a) according to risk, (b) the potential for its direct use in a clandestine fissile explosive, or (c) its use in the production of nuclear material for use in a fissile explosive device. Category I applies to strategic SNM, Category II considers SNM of moderate strategic significance, and Category III pertains to SNM of low strategic significance.[45] Any quantity of plutonium >2 kg is classified as Category I.

DOE has its own requirements and procedures for control and accountability of nuclear material at its owned and leased facilities, and for DOE-owned nuclear materials at other facilities that are exempt from licensing by the NRC. DOE uses five attractiveness levels and four safeguards categories for its safeguards considerations.[46] Attractiveness Level B includes pure products that are defined as weapon pits, major components, buttons, ingots, recastable metal, and directly convertible materials containing ≥2 kg of plutonium, ≥2 kg of ^{233}U, or ≥5 kg of ^{235}U.

4.3 ADS REQUIREMENTS

4.3.1 Introduction

An ADS used to produce plutonium requires coupling two systems: a high-neutron yield material and a supply of source material. Several nuclear reactions are capable of producing neutrons (i.e., protons, deuterons, and tritons) in the spallation process. Deuterons and tritons produce more neutrons than protons in the energy range below 1–2 GeV. However, the high yield of neutrons among the low-energy deuterons and tritons can easily contaminate the low-energy part of the accelerator with radioactivity from the stray charged particles. In addition, the use of protons would be expected to minimize the energy cost.

Many materials have been used for spallation target material—tungsten, lead–bismuth, and mercury—but uranium is the one of the more efficient elements for producing neutrons from a proton beam (Section 3.3). In an ADS for plutonium production, a subcritical blanket of natural or depleted uranium would surround the spallation target, multiplying the number of neutrons.

4.3.2 Accelerator

Assuming ideal conditions with no losses of ^{239}Pu resulting from nuclear absorption during production or because of chemical losses during reprocessing and separation, the required neutron capture rate in ^{238}U will equal the production rate of ^{239}Pu (Equation 1). Hence, assuming that there are no neutrons produced from fission, an accelerator/target must be capable of producing 1.6×10^{17} neutrons/s—the number of atoms in 2 kg of ^{239}Pu. If each neutron is the result of one proton striking the target, then an identical number of protons will be required from the accelerator. As noted in Section 3.3, spallation requires minimum proton beam energy before any substantial number of neutrons is produced, >120 MeV for uranium (Equation 2).

4.3.3 Subcritical core

The important issues in designing an ADS are its inherent subcriticality and reactor stability. These features can significantly improve the safety of a subcritical core in an ADS. Unlike a critical reactor, an ADS operates in a non-self-sustained chain reaction mode, which minimizes criticality and power excursions (Figure 4.1). The ADS is operated in a subcritical mode and remains subcritical whether the accelerator is operating or not, providing an extra level of safety against criticality accidents. The accelerator furnishes a control mechanism for subcritical systems, which many consider far more convenient than control rods in critical reactors. The ADS provides a decoupling of the neutron source (spallation source) from the fissile fuel.

The main parameter characterizing the neutron economy of an accelerator-driven subcritical fission device is the factor M by which the source spallation neutrons are multiplied by the fission-dominated cascade. A related quantity is the multiplication coefficient k_{scc},

$$k_{scc} = (M - 1)/M, \tag{4}$$

where k_{scc} is defined as the average ratio of the neutron population in two subsequent generations of the source-initiated cascade.

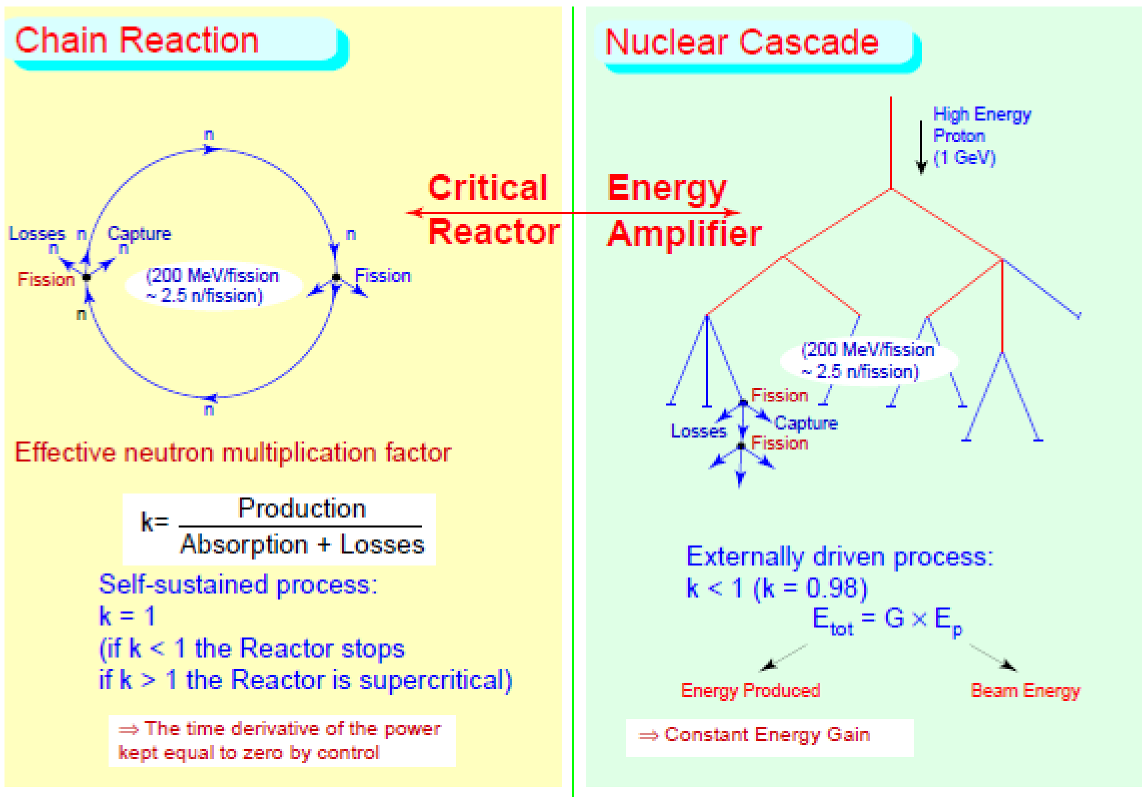

Figure 4.1. Illustration of the self-sustained chain reaction that drives a critical fission reactor (*left*) as opposed to the nuclear cascade that drives an ADS (*right*).[19]

Depending on the properties of the source and of the medium, k_{scc} is in general conceptually and numerically different from the effective criticality factor k_{eff}, commonly used in reactor theory. The effective criticality factor is, in fact, only relevant to the fundamental mode of the neutron flux distribution and is independent of the source. However, the effective criticality factor k_{eff} is a meaningful measure of the actual safety characteristics of the device, that is $1 - k_{eff}$ is a proper gauge of the "distance" from criticality.

Although the neutron distribution inside a reactor is determined primarily by the boundary conditions, the geometry of the initial high-energy cascade in an ADS is dominant. The two spatial distributions are expected to differ substantially (Figure 4.2). The flux distribution is of fundamental importance for determining the generated power distribution and the uniformity of the irradiation of the fuel, both of major relevance when designing a practical device. Thus, the fuel in a subcritical core would be expected to be contained in a moderator to soften the energy spectrum by (*n*, *n*') reactions.

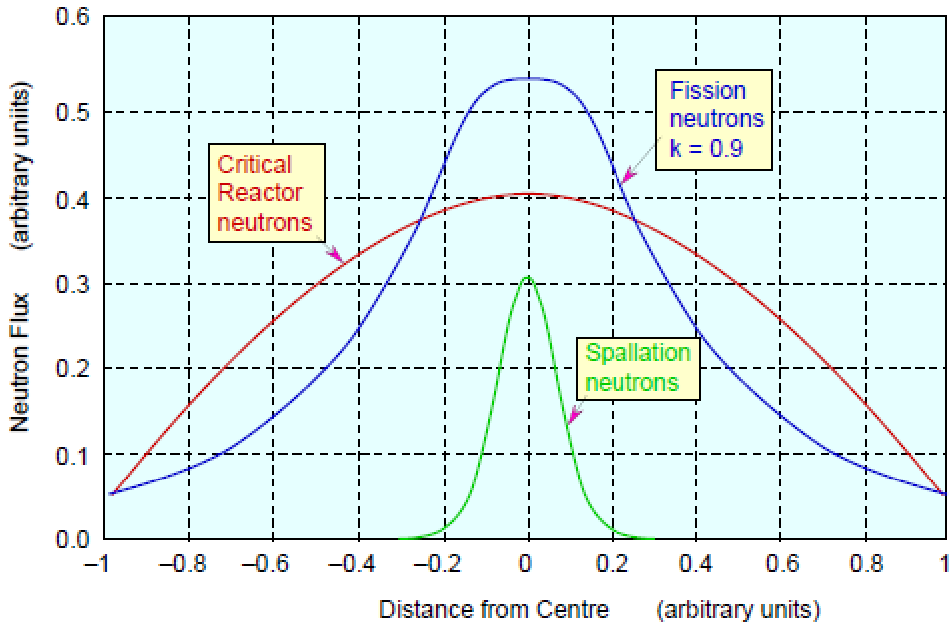

Figure 4.2. Spatial distribution for spallation and reactor generated neutrons.[19]

There are two principal mechanisms of interaction between neutrons and nuclei, potential scattering and compound nucleus formation in the core. The latter process may result in the neutron being captured in the nucleus, being scattered, or causing fission. The probability of one of these events occurring between a neutron and a nucleus is expressed through the concept of the cross section. If a large number of neutrons of the same energy are directed into a thin layer of material, some may pass through with no interaction, others may have interactions that change their directions and energies, and still others may fail to emerge from the sample. There is a probability for each of these events. For example, the probability of a neutron not emerging from a sample (e.g., being absorbed or captured) is the ratio of the number of neutrons that do not emerge to the number of originally incident on the surface. The cross section for being absorbed is the probability of neutrons being absorbed divided by the areal atom density (the number of target atoms per unit area of the layer). Thus, the cross section has the dimensions of the area and is a small fraction of a square centimeter because of the large number of atoms involved. Because this type of cross section describes the probability of neutron interaction with a single nucleus, it is called the microscopic cross section and is represented by the symbol σ.

The physical cross-sectional area of a heavy nucleus is about 2.0×10^{-24} cm^2. Interaction cross sections for most nuclei are typically between 10^{-27} and 10^{-21} cm^2. To avoid the inconvenience of working with small numbers, a different unit of area is used; the barn, denote by the symbol *b*. It is defined to be 10^{-24} cm^2, so that the physical cross-sectional area of a heavy nucleus is about 2 *b*. Many neutron interaction cross sections range from 0.001 to 1,000 *b*.

Each type of event has its own probability and cross section. The probability of each type of event is independent of the probabilities of the others, so the total probability of any event occurring is the sum of the individual probabilities. Similarly, the sum of all the individual cross sections is the total cross section.

A neutron can have many types of interactions with a nucleus (Figure 4.3). Each category of interaction in the figure consists of all those linked below it. The total cross section, σ_f, expresses the probability of any interaction taking place.

A neutron interaction may be one of two major types, scattering or absorption. When a neutron is scattered by a nucleus, its speed and direction change, but the nucleus retains the same number of protons and neutrons it had before the interaction. The nucleus will have some recoil velocity and it may be left in an excited state that will lead to the eventual release of radiation. When a neutron is absorbed by a nucleus, a wide range of radiations can be emitted, or fission can be induced.

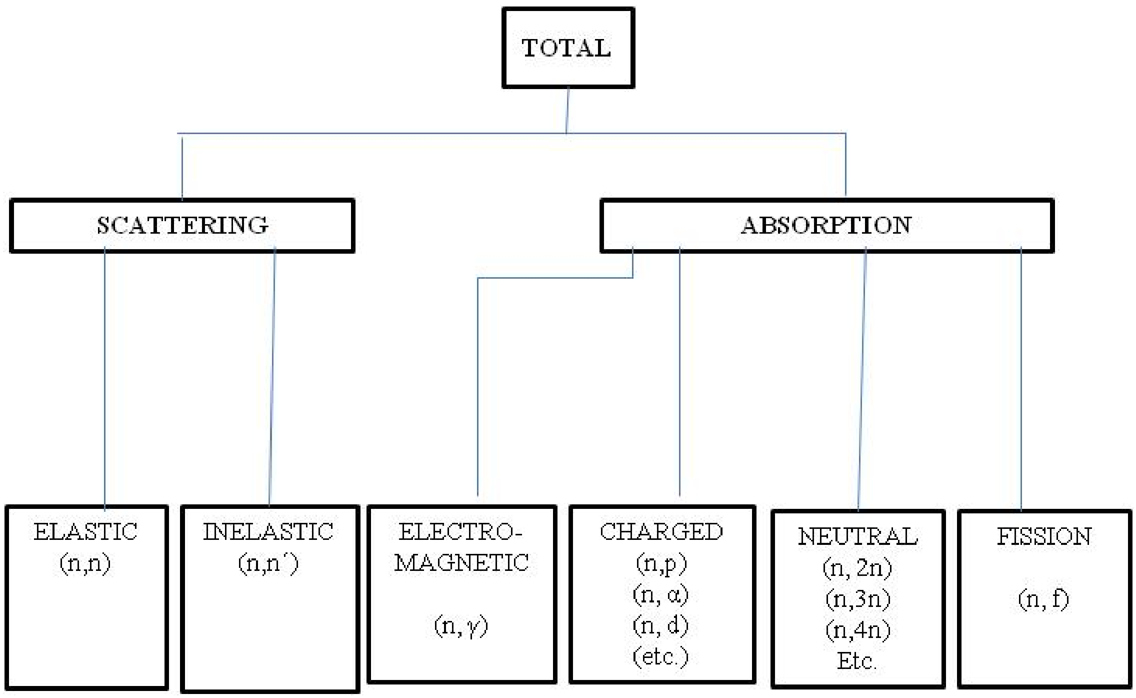

Figure 4.3. Various categories of neutron interactions. The letters separated by commas in the parentheses show the incoming and outgoing particles.[47]

Scattering events can be subdivided into elastic and inelastic scattering. In elastic scattering, the total kinetic energy of the neutron and nucleus is unchanged by the interaction. During the interaction, a fraction of the neutron's kinetic energy is transferred to the nucleus. For a neutron of kinetic energy *E* encountering a nucleus of atomic weight, *AW*, the average energy loss is

$$\textit{Energy loss} = [2 \times E \times (AW)]/(AW + 1)^2. \tag{5}$$

On average, a neutron with 2 MeV of kinetic energy will have 1 MeV left after one elastic collision with a hydrogen nucleus, 0.5 MeV after a second such collision, and so on. To achieve a kinetic energy of 0.025 eV, an energy that is approximately in thermal equilibrium with its surrounding medium and is considered a thermal neutron, the neutron would experience about 27 such collisions.

Inelastic scattering is similar to elastic scattering except the nucleus undergoes an internal arrangement into an excited state from which it eventually releases radiation. The total kinetic energy of the outgoing neutron and nucleus is less than the kinetic energy of the incoming neutron—part of the original kinetic energy is used to place the nucleus into the excited state. It is difficult to write an expression for the average loss because it depends on the energy levels within the nucleus, but the net effect on the neutron is again to reduce its speed and direction. Inelastic scattering is impossible if the energy available from the incoming neutron is too low to exceed any of the excited states of the target nucleus. In particular, the hydrogen nucleus does not have an excited state, so only elastic scattering can occur. In general, scattering moderates or reduces the energy of neutrons.

Instead of being scattered by a nucleus, the neutron may be absorbed or captured. A variety of emissions may follow (Figure 4.3). The nucleus may rearrange its internal structure and release one or more gamma rays (γ). Charged particles may also be emitted; the more common ones are protons (*p*), deuterons (*d*), and alpha particles (α). The nucleus may also rid itself of excess neutrons. The emission of only one neutron is indistinguishable from a scattering event. If more than one neutron is emitted, the number of neutrons now moving through the material is larger than the number present before the interaction—the number is said to have been multiplied. Finally, there may be a fission event, leading to two or more fission fragments and more neutrons.

When moderation alone is desired, absorption should be avoided. For example, hydrogen is a better moderator than deuterium (i.e., it requires fewer collisions to achieve a lower speed), but it also has a much larger absorption cross section for neutrons (0.33 vs. 0.005.)[48] The net effect is that deuterium will yield more thermal neutrons than hydrogen and may be the preferred moderating material.

All of the cross sections vary with neutron energy and target nucleus, sometimes in a dramatic way. As an example, the cross sections for various neutron interactions with ^{238}U are presented in Figures 4.4–4.6.

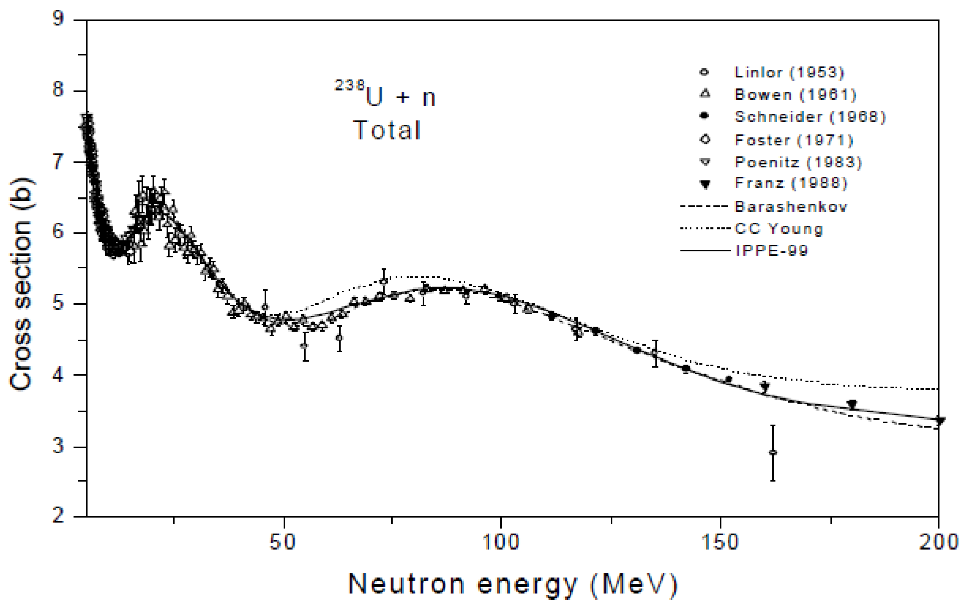

Figure 4.4. Comparison of different calculations with experimental data for the total neutron cross section for ^{238}U.[49]

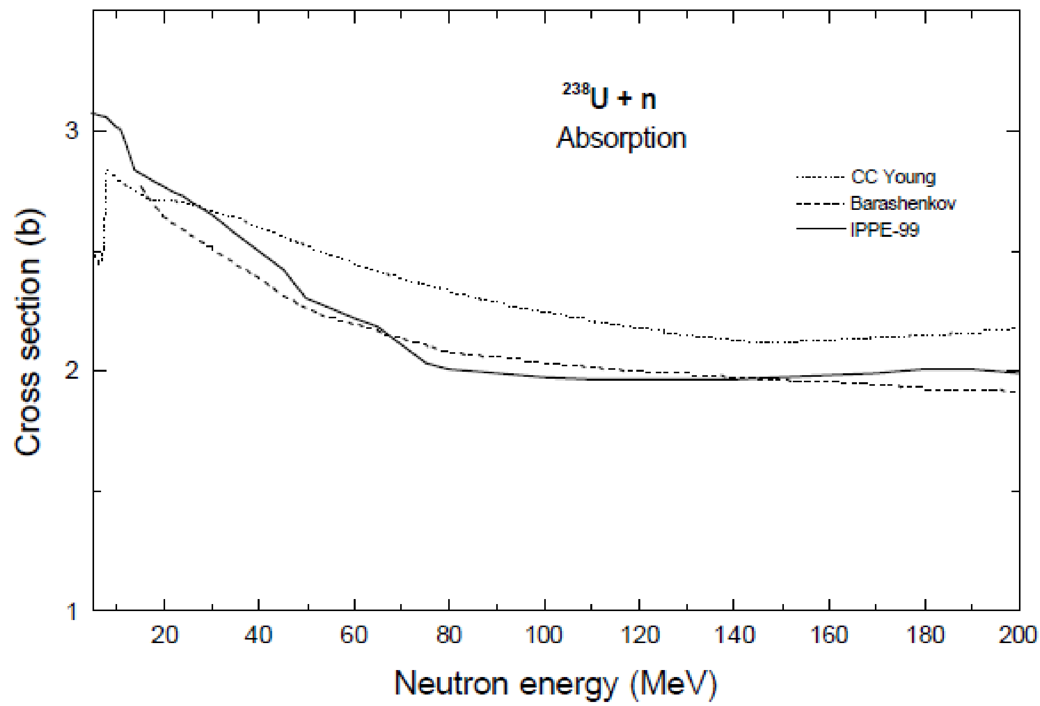

Figure 4.5. Comparison of calculated neutron absorption cross sections for ^{238}U.[49]

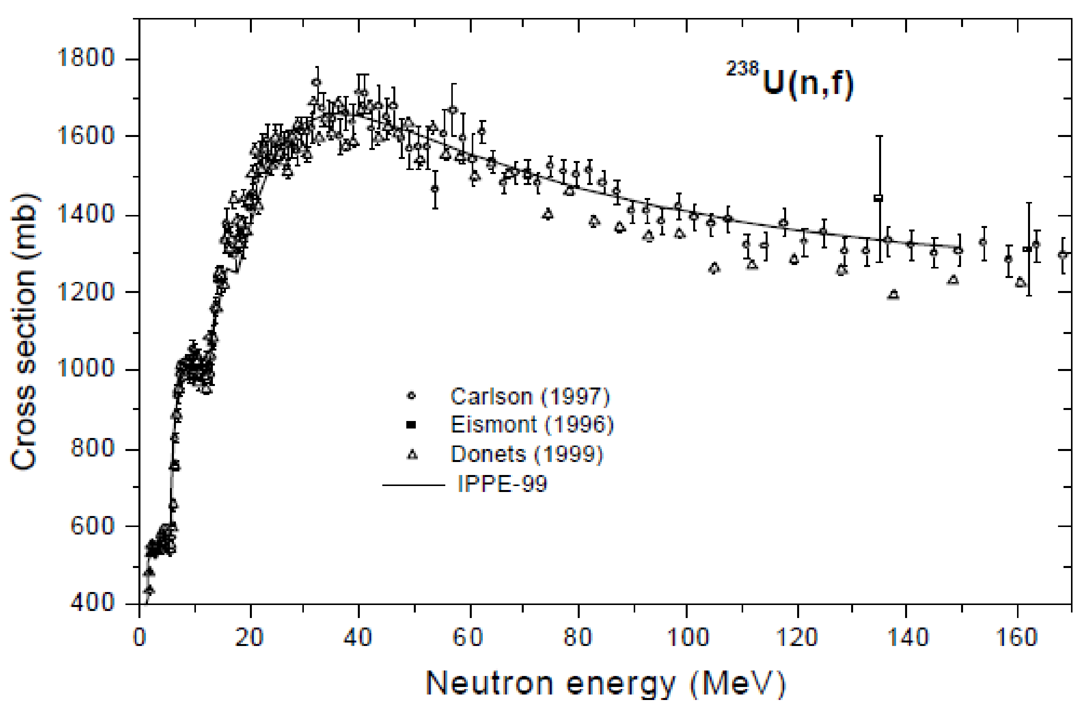

Figure 4.6. Comparison of calculated fission cross sections for ^{238}U with experimental data.[49]

4.4 POSSIBLE EXPORT CONTROLS

Because neutrons are produced by two individual systems in an ADS, an accelerator and a subcritical core, both of these may possess unique characteristics that might be used to develop regulations for export control. Accelerators have a number of measurable attributes that may be applicable: injection energy, beam power, pulse duration, and repetition rate. Although the flow-rate characteristics of the proton beam are important for some applications, whether continuous or pulsed, and repetition rate, the production rate of plutonium in an ADS is affected solely by the average proton beam current and power—producing neutrons via spallation. These neutrons are generated in a local target zone, where no fission source is generated. However, the energy spectrum of spallation neutrons is far from that of the fission neutrons.

The major variables for a subcritical core are its size and configuration (i.e., spherical, cubical, cylindrical), moderator (graphite, heavy, or light water), operating temperature, heat dissipation system, composition (depleted, natural, or slightly enriched uranium or thorium), and quantity. Although these attributes are critical to a successful operating ADS, they are beyond the scope of this analysis and will not be considered as they relate to export control.

In the following sections, various components of an accelerator that may be considered for export control are discussed. From this analysis, suggested export controls have been developed and are presented in Appendix A, including a figure of merit (FOM) that is a measure of the capability of the ADS to produce plutonium. Its derivation is discussed in Section 4.4.1. The spallation neutron source (target) and the subcritical core will produce significant heat, both of which must be dissipated. Each of these sources will be examined.

4.4.1 Accelerator figure of merit

The contribution of neutrons from the subcritical core and those generated by the accelerator through the spallation target are pertinent in determining a value for the figure of merit (FOM). Additional factors that should be considered in determining a FOM are the operational characteristics (i.e., k_{scc}) of the subcritical core, the beam availability of the accelerator, and the efficiency of the spallation source. Besides the configuration (e.g., linear or circular) of an accelerator used in an ADS, the defining characteristics are its electrical power input and beam characteristics. These two measurable quantities were used to evaluate a FOM in the earlier document to assist in identifying those accelerators that would be useful in producing sufficient plutonium to be of concern.**Error! Bookmark not defined.** The process used to determine whether the present FOM (K = 82) is still valid is discussed in the following sections.

Subcritical core—Of the variables that determine the neutron production rate of a subcritical core, the two that must be quantified are the source neutron multiplication factor and the ^{238}U capture rate.

Accelerator contribution—In accelerator-driven spallation, high-energy particles from the accelerator impinge on a thick target of a dense, high-mass-number material (e.g., uranium, tungsten, tantalum, or mercury) (Section 3.3). Neutrons, protons, and pions that emerge from collisions with sufficient energy proceed to collide again and leave further excited nuclei. The excited nuclei shed their energy by promptly evaporating particles (nearly all are neutrons). The excited particles decay by emitting ß particles and γ radiation. Thus, these neutrons from the spallation target will further reduce the total number of protons generated by the accelerator and the current.

Previous assumptions—FOM, K, has been defined as

$$K = I \times (E_{\text{MeV}} - 120), \quad (6)$$

where I is the average accelerator beam current in milliampere, and E_{MeV} is the final particle energy in megaelectron volts. The following assumptions and calculations are provided either to validate the present value or to justify a new one.

Current assumptions—The production of 2 kg of ^{239}Pu in the subcritical core is equivalent to

$$2 \text{ kg } ^{239}Pu = 2000 \text{ g } ^{239}Pu = (2000 \text{ g})/(239 \text{ g/mole}) = 8.37 \text{ moles } ^{239}Pu. \quad (7)$$

Using Avogadro's number, 6.022×10^{23} atoms per mole and the number of seconds in a year (60 sec/min × 60 min/hr × 24 hr/day × 365 days/year = 3.154×10^7 sec/year), the number of atoms of ^{239}Pu that will be produced per second will be

$$[(8.37 \text{ moles} \times 6.022 \times 10^{23} \text{ atoms/mole})]/(3.154 \text{ x } 10^7 \text{ sec/year}) = 1.6 \times 10^{17} \text{ atoms } ^{239}Pu/\text{sec}. \quad (8)$$

Subcritical core—The production of an atom of ^{239}Pu entails the capture of a neutron by a ^{238}U nucleus (Equation 1). Thus, 1.6×10^{17} neutrons/s must be captured by an equal number of ^{238}U atoms in the core.

Accelerator—A second contributor to the production of neutrons is that from the spallation target. The consensus from several studies is that the yield (Y)[39,40] for uranium is

$$Y_{spl} = 0.05 \times (E_{MeV} - 120), \quad (9)$$

where E_{MeV} is the proton energy in megaelectron volts.

The current, I, necessary for the production of this number of neutrons per second may be calculated, assuming one proton produces one neutron and that for a singly charged particle, 1 proton/s is equivalent to 1.6×10^{-19} Coulombs ($A \cdot s$). So

$$I\,(A) = [(1.0 \times 10^{18}) \times (1.6 \times 10^{-19})]/(E_{MeV} - 120) = (1.60 \times 10^{-1})/(E_{MeV} - 120), \quad (10)$$

or

$$I(mA) = 160/(E_{MeV} - 120). \quad (11)$$

Inserting this value for I into equation 5 gives

$$K = I \times (E - 120) = [(160 \times (E_{MeV} - 120)]/(E_{MeV} - 120) = 160. \quad (12)$$

where E_{MeV} is the accelerator power. A minimum accelerator voltage, 120 MeV, is required to obtain spallation.

Both the spallation target and the subcritical core will generate significant quantities of heat that must be dissipated. ORNL's Spallation Neutron Source uses liquid mercury as its target for spallation production. About 60% of the proton beam power is deposited in the target. Because the pulse frequency is 60 Hz, the amount of energy deposited in the target during a single pulse has been estimated to be 10–20 kJ.[50,51] This is generated by a proton beam power of 1–2 MW. Thus, the cooling system for the target must dissipate a time-averaged power of 0.6–1.2 MW.

4.4.2 Ion sources

For high-power particle accelerators, it is essential that the beam produced by the ion source has a low divergence angle (Figure 4.7).[52] This allows the beam to be transported and accelerated easily by the following components of the accelerator without losing any intensity.

Emittance is a term used to specify the divergence of a beam in particle accelerators. It is a measure of how large a beam is and how much it is diverging. It is measured in millimeter·milliradian and is the product of beam size and divergence angle. Often emittance is normalized to beam energy because a beam that has had its longitudinal velocity increased by acceleration will still have the same transverse velocity, thus its divergence angle will be reduced. Emittance is normalized to allow emittances to be compared at different energies in different accelerators.

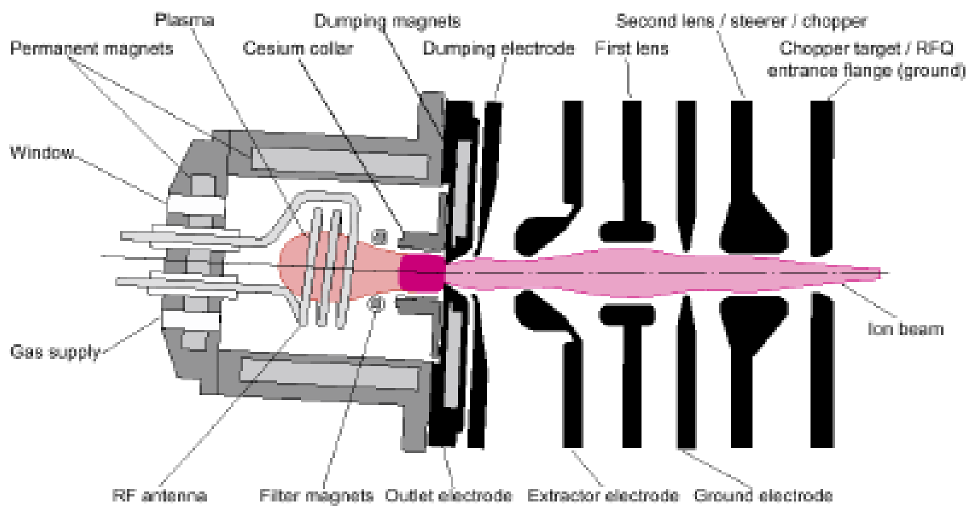

Figure 4.7. Spallation Neutron Source ion source and low-energy beam transport representation, seen from the top.[53]

Distance is used as the unit of emittance because the dimensions of phase space are millimeters and a dimensionless angle; hence areas in phase space have units of millimeters. However, ion source emittances are very often expressed in units of π·millimeter·milliradian. This is because the particle distributions in phase space plots often have an ellipse drawn round them to define the beam boundary. The area of an ellipse is π multiplied by the product of the length of its two semiaxes. Later in the rest of the accelerator, higher energy beams usually do tend to have elliptical phase space distributions. Close to the ion source, large aberrations still exist and the beam shape in phase space is often far from elliptical, so a root mean square integration is the best method to calculate the emittance. It is counterintuitive that the root mean square of ion source emittances are expressed in π·millimeter·milliradian (which is indicative of an ellipse calculation). Units of millimeters or π·millimeter·milliradian do not change the emittance value quoted and can be used interchangeably.

4.4.3 High-power RF power amplifiers

All particle accelerators with energies greater than 20 MeV require high-power RF sources (Figure 4.8).[54] Normally, these sources are amplifiers, which is required to achieve sufficient frequency and phase stability. The frequencies employed range from about 50 MHz to 30 GHz or higher. Power requirements range from 10 kW to 2 MW or more for continuous sources and up to 150 MW for pulsed sources.

The function of the power amplifier is to convert DC input power into RF output power whose amplitude and phase is determined by the low-level RF input power. The RF amplifier extracts power from high-charge, low-energy electron bunches. The transmission components (couplers, windows, circulators, etc.) convey the RF power from the source to the accelerator, and the accelerating structures use the RF power to accelerate low-charge bunches into high energies. Thus, the complete RF system can be seen as an energy transformer, which takes energy from high-charge, low-energy electron bunches and conveys it to low-charge, high-energy bunches of charged particles. When sufficient power cannot be obtained from a single amplifier, the output from several amplifiers may be combined. In some cases, power is supplied to multiple accelerating cavities from one amplifier.

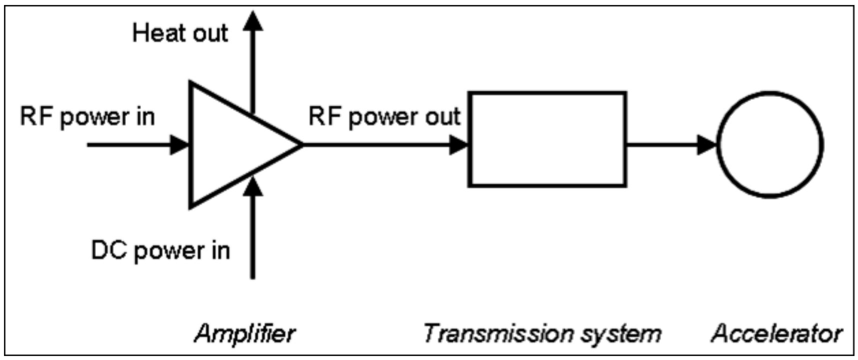

Figure 4.8. Block diagram of the high-power RF system of an accelerator.

All RF power amplifiers employ either vacuum tube or solid-state technology. Vacuum tubes use either direct current (DC) or pulsed voltages from several kilovolts to hundreds of megavolts, depending upon the type of tube, the power level, and the frequency. The electron velocities can be comparable with the velocity of light and the critical tube dimensions are therefore comparable with the free-space wavelength at the working frequency. Vacuum tubes can therefore generate RF power outputs up to 1 MW continuous wave and 150 MW pulsed. The main tube types employed in accelerators are gridded tubes (tetrodes), inductive output tubes (IOTs), klystrons, and magnetrons. The magnetron is an oscillator rather than an amplifier and its use is currently restricted to medical linacs. The gyrotron, which is widely used as a power source in fusion reactors, has the potential to be used for high-frequency accelerators. Solid-state RF power transistors operate at voltages from tens to hundreds of volts. The electron mobility is much less in semiconductor materials than in vacuum, and the size of the devices is therefore small and the power, which can be generated by a single transistor, is of the order of hundreds of watts continuous and up to 1 kW pulsed. Large numbers of transistors must be operated in parallel to reach even the lowest power levels required for accelerators.

Tetrode vacuum tubes are well established as high-power RF sources in the very high frequency (VHF) (30–300 MHz) band (Figure 4.9). Normal construction is coaxial with the cathode inside and the anode outside. The output power available from such a tube is limited by the maximum current density available from the cathode and by the maximum power density, which can be dissipated by the anode.

Solid-state power amplifiers for use at high frequencies employ transistors fabricated from wide band-gap semiconductor materials (Si, GaAs, GaN, SiC, diamond). It is sometimes claimed that solid-state amplifiers are more reliable than their vacuum-tube counterparts are. Because many transistors are operated in parallel, the failure of one produces a negligible drop in power output. However, the transistors are operated close to their design limits and are vulnerable to accidental overloads. Appreciable power is dissipated in the combining circuits and provision may have to be made to isolate a device, which fails so that it does not adversely affect the performance of others nearby. Other advantages claimed for solid-state amplifiers are their high stability, low-maintenance requirements, absence of warm-up time, and low-voltage operation. The supply voltage is low enough to avoid the high-voltage and X-ray safety issues arising with tube amplifiers. The disadvantage is the need to supply and manipulate very large DC currents using large bus bars in which there are appreciable resistance losses.

A klystron is a specialized linear-beam vacuum tube (evacuated electron tube) that is used as an amplifier at microwave and radiofrequencies to produce both low-power reference signals for superheterodyne radar receivers and to produce high-power carrier waves for communications and the driving force for modern particle accelerators. At a frequency of 1.3 GHz, the continuous output power of an IOT is limited to around 30 kW by the need to use a control grid to modulate the electron beam. At higher frequencies and high powers, it is necessary to modulate the beam in some other way. In the klystron, this is achieved by passing an unmodulated electron beam through a cavity resonator, which is excited by an external RF source. The electrons are accelerated or retarded according to the phase at which they cross the resonator, and the beam is then said to be velocity modulated. The beam leaving the gap has no current modulation, but downstream from the cavity the faster electrons catch up to the slower ones so that bunches of charge are formed. Eighty-one 550 kW 805 MHz klystrons, each drive a single cavity in the superconducting (SC) section of the Spallation Neutron Source (SNS) linac (Figure 4.10).

Figure 4.9. A ceramic-metal tetrode suitable for use as an RF amplifier in particle accelerators.[55]

Figure 4.10. A recent generation of long-pulse klystrons specially designed for the linac of the SNS.[56]

A *gyrotron* is an alternative type of tube for producing very high-pulsed RF power at high frequencies. This type of tube has been the subject of intensive developmental work mainly with a view of providing RF power for plasma heating experiments. The gyrotron employs the interaction between an annular electron beam and the azimuthal electric field of a circular waveguide mode. There is a strong axial magnetic field so that the electrons move in small orbits at the cyclotron frequency within the beam. The cyclotron frequency is made equal to the signal frequency. At frequencies above 60 GHz, this means that a superconducting solenoid is needed to produce the magnetic field. It is essential to the working of the gyrotron that the electrons have relativistic velocities. The gyrotron is a so-called fast-wave device because the dimensions of its interaction structure is much larger compared to the wavelength of the radiation. This is in contrast to slow-wave devices, which have interaction structures that are of the order of the wavelength of the generated radiation. However, especially at high frequencies, these interaction structures can be very small (submillimeter) and therefore can easily burn out at the high power densities required to generate sufficient output power, significantly limiting the lifetime of the tube.

Since gyrotrons are typically operated in a higher mode, the interaction structure (cavity) can be much larger compared to the wavelength of the radiation. Furthermore, the cavity is typically a metal tube (copper), which can be effectively cooled because of its simple structure. Therefore, the gyrotron can provide high-output power at high frequencies and guarantees a long lifetime.

4.4.4 RF window systems with high-power handling capability

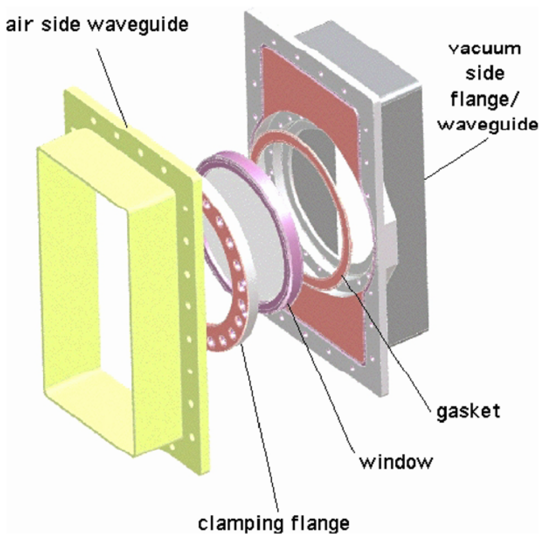

Figure 4.11. RF window assembly.

The RF power windows, when incorporated in waveguide couplers, are important devices operating under ultrahigh vacuum, which allow the transfer of the RF power to the superconducting accelerating cavities (Figure 4.11). High reliability of windows is essential for the smooth and efficient operation of facilities, especially for machines with a large number of RF structures and/or high power requirements.

As RF accelerator technology has advanced over the past several decades, the accelerating structures have improved to allow for higher accelerating field and beam current. These advances have occurred in both normal and superconducting structures. As these barriers have been broken, the fundamental limiting technology has become the RF transmission system, specifically the RF vacuum window. Next generation accelerator systems will place high demand on the RF window.

RF windows, used in input power couplers for linear particle accelerators, are one of the components limiting the amount of power that can be coupled into an accelerator. The window failures are thought to be due to a nonlinear surface heating caused by multipacting and material imperfections. For continuous wave and superconducting accelerator applications, reliable windows are critical because window failures are devastating to the system. The most common material used for RF windows is high-purity polycrystalline alumina.

4.4.5 High-power RF circulators made with ferrite

Ferrite isolators and circulators play a fundamental and valuable role in RF systems. They are passive, magnetic ferrite material devices that are used to control the propagation of RF signals. RF isolators are two-port units that allow signals to pass in one direction while providing high isolation for reflected energy in the reverse direction. RF circulators have three or more ports and are used to control the direction of signal flow in a circuit. They allow the signal entering one port to pass to an adjacent port in either a clockwise or a counter-clockwise direction, but not to any other port. Three-port or Y-junction circulators are commonly available. In these devices, the signal flow is normally expressed as 1 to 2, 2 to 3, and 3 to 1. For example, when the input is Port 1, the RF signal exits Port 2. Ideally, Port 3 remains isolated and does not receive or pass the signal. Some RF isolators and RF circulators are designed for use with a coaxial cable. Others are designed for use with a waveguide. RF isolators and RF circulators that contain magnets are not designed for mounting near ferrous materials because the close proximity of metals such as iron can change the frequency response.

5. ACCELERATOR COMMUNITY

5.1 INTRODUCTION

The IAEA has developed a database using information compiled from publicly available sources, research institutes, and accelerator manufacturers that includes technical data on accelerator-based radiation facilities used for applied research and analytical services in IAEA member states.[57] The Agency uses three categories for accelerator-based radiation facilities; low-energy electrostatic (low-beam) accelerators, spallation neutron sources, and synchrotron light sources. There are approximately 160 entries in the first category, which are further divided into four groups (number in each); EN-FN-MP-UD (41), Pelletron® (53), single-ended (31), and Tandetron© (35), representing both old and modern technology. There are nine entries for spallation neutron sources located in five countries, and 38 synchrotron light sources found in 20 countries.

ANL has developed a web site devoted to accelerators that lists facilities, reference sources for information (e.g., associations, projects and collaborations, and scattering data), software as applied to accelerators (data analysis and visualization, Monte Carlo simulation, and format systems), conferences, and announcements (deadline schedule for proposals, employment needs, etc.).[58] The listing of neutron-scattering facilities is divided into three groups, operational, planned, and closed.

The National Institute of Standards and Technology's (NIST) Center for Neutron Research has a similar list that identifies facilities that generate and provide a source for neutrons for research purposes.[59] Its web site organizes the facilities by location—North America, Europe, Asia, and Australia.

Another source of information for neutron-generating facilities is found on a web site produced by Del Mar Ventures, a venture capital company that provides funding for early stage teams in the photonics market and is involved in the development of femtosecond lasers, sensors, and ultrafast optic products.[60] Their listing presents the data by the process used for neutron generation (spallation, research reactors, and synchrotron radiation) and by location.

A listing by the American Physical Society identifies major international X-ray and neutron facilities on one of its web sites.[61] Both current and future facilities are included and categorized by location and method of neutron production.

The University of Bonn in Nordrhein-Westfalen, Germany has compiled a listing of particle accelerators that is available on its web site.[62] The facilities are arranged by location and type.

Using the information collected from the above references, the author has attempted to identify the major accelerators that may be applicable to drive a subcritical reactor core. There are a number of accelerators that have been proposed. These have been included in the following discussion.

5.2 CURRENT SYSTEMS

5.2.1 Introduction

Since the days of cathode ray tubes in the 1890s, particle accelerators have made an extraordinary evolution as tools of basic science. Between Ernest Lawrence's first 4-in. diameter cyclotron and today's most powerful particle accelerator, the 17-mile-circumference Large Hadron Collider, have come many of progressively more powerful and precise machines, each incorporating innovations and breakthroughs to advance scientific progress. Each generation of particle accelerators builds on the accomplishments of the previous ones, raising the level of technology ever higher, a thrust that continues today.

An attempt has been made to review the preeminent particle accelerators in the world. These include accelerators located in Japan, Canada, the United Kingdom, the United States, and Switzerland. A synopsis of each machine is presented in the following sections.

5.2.2 Japan's Proton Accelerator Research Complex (J-PARC)

The Japan Proton Accelerator Research Complex (J-PARC) consists of a series of proton accelerators and the experimental facilities that make use of the high-intensity proton beams (Figures 5.1 and 5.2).[63] A proton beam is accelerated by the following three types of accelerators (Table 5.1):

- A 400 MeV (currently operating at 180 MeV) linear accelerator (LINAC),
- A 3 GeV rapid cycling synchrotron (RCS), and
- A 50 GeV (currently 30 GeV) main ring (MR) synchrotron.

Figure 5.1. Aerial view of J-PARC.

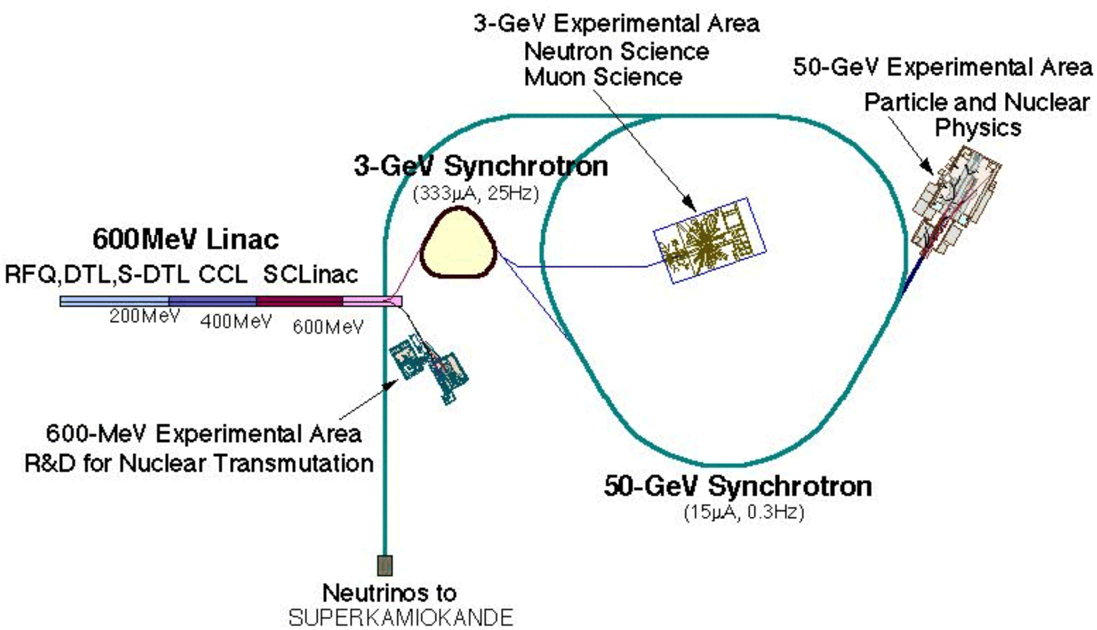

Figure 5.2. A schematic of the series of proton accelerators at J-PARC.

The high-energy beam is diverted to one of three different experimental facilities for conducting research in the fields of materials and life science, and particle and nuclear physics. The majority of the protons (90%) are used for studies in the Materials and Life Science Experimental Facility. The accelerators were shut down following the earthquake of March 11, 2011. After a series of thorough inspections, the accelerators began producing proton beams toward the end of 2011 and achieved full power in early 2012.[64,65,66]

Table 5.1. Basic parameters for the accelerators at the J-PARC complex.

Specification	Linac	RCS	MR
Extraction beam energy	180 MeV	3 GeV	30 GeV
Average beam current	15 mA × 500 μs	60 μA	5 μA
Average beam power	Maximum 30 kW	200 kW	150 kW

J-PARC has an active program in the study of transmutation of radioactive wastes in two separate facilities (Figure 5.3).[67] The Transmutation Physics Experimental Facility (TEF-P) will utilize a low-power (10 W) proton beam impinging on a critical assembly to investigate the physical and dynamic properties of an ADS. Uranium, plutonium, and minor actinide fuels are to be included into the plate-type fuel assembly. The ADS Target Test Facility (TEF-T) contains a liquid lead-bismuth spallation target, which is irradiated by a 600 MeV, 200 kW proton beam. Maximum k_{eff} is to be 0.97 and maximum beam current will be 20 mA.

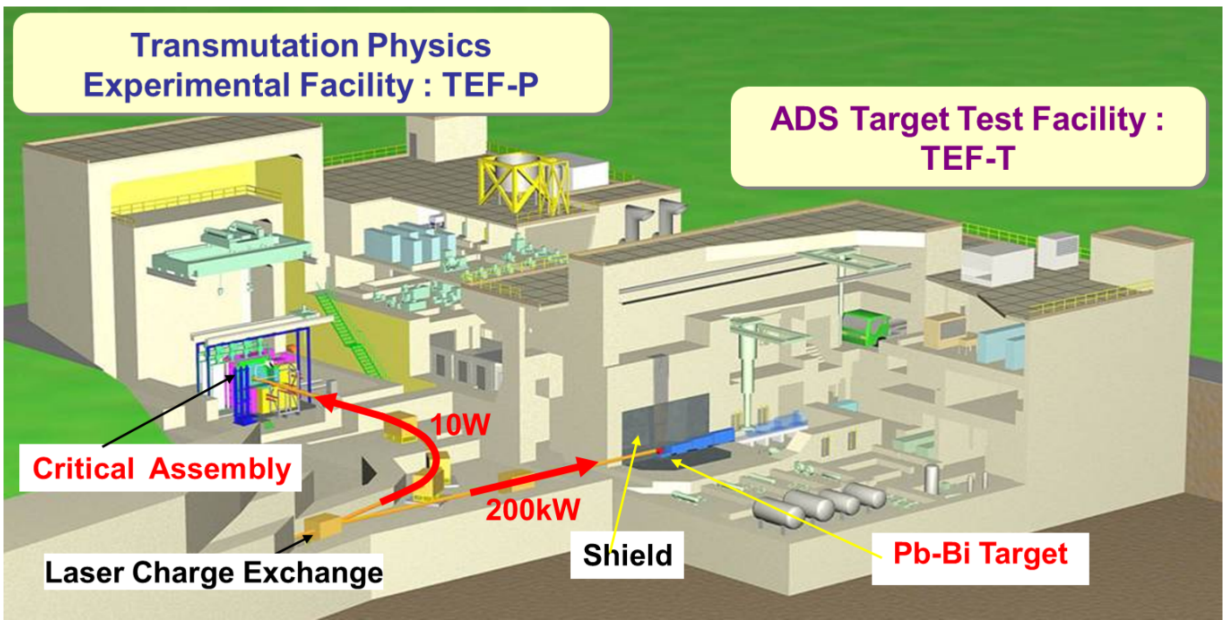

Figure 5.3. J-PARC's two facilities for transmutation and ADS studies.

5.2.3 TRIUMF

TRIUMF is Canada's national laboratory for nuclear and particle physics research and related sciences.[68] It is owned and operated as a joint venture by a consortium of universities. Operations are supported by the Government of Canada via a contribution through the National Research Council. The Government of British Columbia provides additional support for building infrastructure.

At the heart of TRIUMF is a 500 MeV cyclotron that produces the primary proton beams. (Figures 5.4 and 5.5).[69] TRIUMF produces negatively charged hydrogen ions from an ion source. The ions are transported through an evacuated electrostatic beam line containing elements to focus and steer the beam over its 60-m length to the cyclotron. The variable energy cyclotron accelerates these ions with a high-frequency alternating electric field and uses a massive six-sector magnet to confine the beam in an outward spiral trajectory. Electrons are removed from the H^- ions by inserting very thin graphite extraction foil strips in the beam's path, allowing the protons to pass through. The protons, because they are positively charged particles, are deflected in the outward direction due to the magnetic field and are directed to a proton beam line.

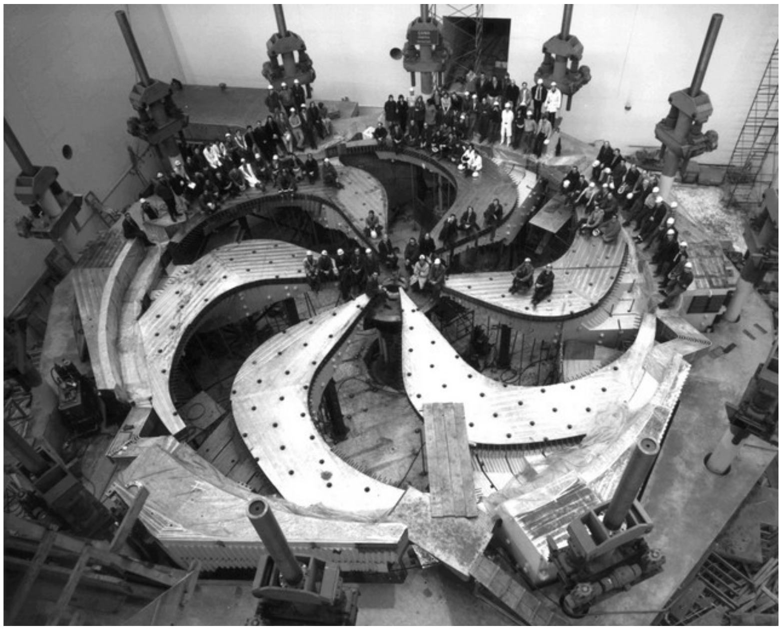

Figure 5.4. TRIUMF staff gather on the lower six sectors of the cyclotron magnet.

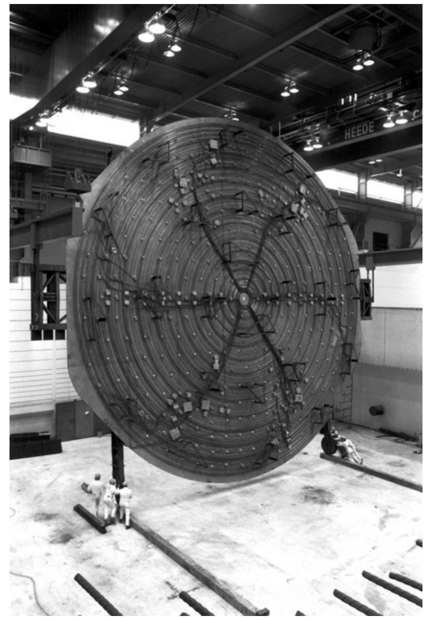

Figure 5.5. The vacuum tank for TRIUMF's main cyclotron.

5.2.4 ISIS

Located at the Rutherford Appleton Laboratory near Oxford in the United Kingdom, ISIS is a center for research in the physical and life sciences utilizing neutrons and muons generated by a linear accelerator (linac) that feeds a synchrotron.[70] The system contains the following four components:[71]

- The ion source produces H^- from hydrogen gas and cesium generated in a plasma. The H^- ions are extracted from the ion source in 200-μs long pulses to form a beam, which is then passed through a 90° magnet to remove any electrons. The H^- ions acquire an energy of 35 keV across a DC acceleration gap, are focused and monitored in the Low Energy Beam Transport, and then passed into the RF Quadrupole (RFQ) accelerator.

- The ISIS RFQ operates at 665 keV, 202.5 MHz. Four specially shaped electrodes in the RFQ produce an alternating-gradient, quadrupole electric field for focusing and acceleration. Discrete bunches of H^- ions, 4.94 ns apart, are passed into the linac.

- The linac consists of four accelerating tanks in which high-intensity RF fields accelerate the beam to 70 MeV. RF power at 202.5 MHz is fed to the tanks through a coaxial line from high-power amplifiers. The H^- beam enters the tank and travels along the axis where it passes through a series of drift tubes. The bunches of ions keep in step with the alternating RF electric field, crossing the gaps between the drift tubes when the field is in the correct direction for acceleration, but being shielded inside the drift tubes when the field is in the wrong direction. The linac provides 200-μs-long, 22-mA

H^{-} pulses, which are transported to the synchrotron. Final acceleration of the beam occurs in the synchrotron.

- In the synchrotron, ten dipole-bending magnets are used to keep the beam travelling in a circular orbit of 26-m radius, while quadrupole magnets keep the beam tightly focused. On entry, the H^{-} beam is stripped of its electrons by a 0.3-µm thick aluminium oxide stripping foil. Once injection is complete, the RF system traps the beam into two bunches and accelerates them to 800 MeV, delivering protons in two 100-ns-long pulses to the neutron and muon targets. The entire acceleration process is repeated at 50 Hz, so a mean current of 200 µA is delivered to the targets (Figures 5.6 and 5.7).

Figure 5.6. Interior view of the ISIS Target 1 experimental hall.

Figure 5.7. ISIS's Target 2 experimental hall serves seven instrument stations.

The ISIS target station uses the high-energy protons produced by the ISIS accelerator to generate neutrons by the spallation process and to modify their characteristics to make them useful for neutron scattering experiments. Muons are also produced at ISIS using a thin carbon target in the proton beam before the neutron target. The ISIS target station uses the high-energy protons produced by the ISIS accelerator to generate neutrons by the spallation process and to modify their characteristics to make them useful for neutron scattering experiments.

- In the Target Station 1, neutrons are produced when the 160-kW proton beam from the accelerator hits a metal target. The target is made from a series of thick tungsten plates (clad with tantalum to prevent corrosion), housed in a pressure vessel. Water cooling channels remove about 90 kW of heat generated in the target.

- The ISIS Target Station 2 is at a low-power, low-repetition-rate neutron source optimized to maximise the production of long wavelength neutrons.

5.2.5 Spallation Neutron Source (SNS)

The SNS, a user facility operated for the US DOE Office of Science by Oak Ridge National Laboratory (ORNL), provides the most intense pulsed neutron beams in the world and is used for scientific research and industrial development (Figure 5.8).[72] SNS produces neutrons with an accelerator-based system that delivers short (µs) proton pulses to a target/moderator system, where the spallation process produces neutrons. At full power, SNS will deliver 1.5×10^{14} protons at a pulse rate of 60 Hz (1.44-mA current and

1.4 MW of beam power) onto the target.[73] SNS was designed from the start with the flexibility to provide additional scientific output in the future by increasing the power output to 3 MW and by adding a second target station. The components of the system are:

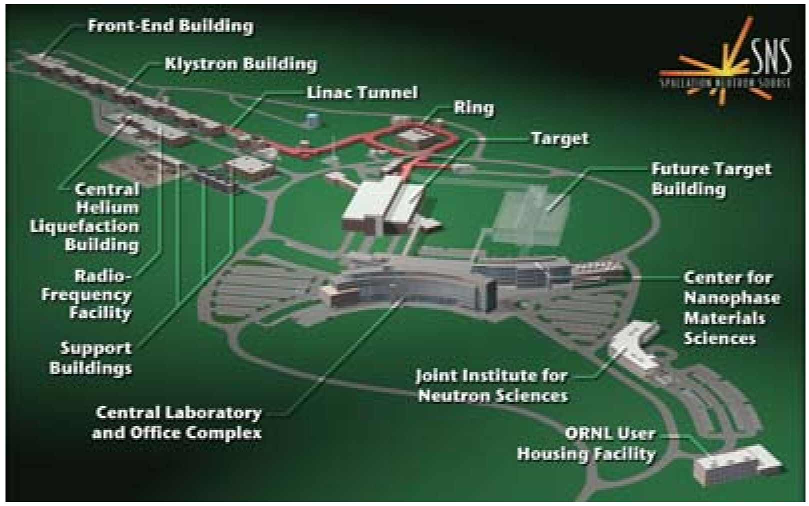

Figure 5.8. SNS is located near ORN L and produces neutrons via the spallation process.

- The SNS's ion source produces negative hydrogen (H^{-}) ions that are formed into a pulsed beam and accelerated to an energy of 2.5 MeV. This beam is delivered to a large linac.

- The linac accelerates the H^{-} beam from 2.5 to 1000 MeV (1 GeV) (Figure 5.9). The linac is a superposition of normal conducting and superconducting RF cavities that accelerate the beam and a magnetic lattice that provides focusing and steering. Three different types of accelerators are used. The first two, the drift-tube linac and the coupled-cavity linac, are made of copper, operate at room temperature, and accelerate the beam to about 200 MeV. The remainder of the acceleration is accomplished by superconducting niobium cavities. These cavities are cooled with liquid helium to an operating temperature of 2 K.

- The accumulator ring structure bunches and intensifies the ion beam for delivery onto the mercury target to produce the pulsed neutron beams (Figure 5.10). The H^{-} pulse from the linac is sent to a stripper foil that removes the electrons from the negatively charged hydrogen ions to produce the protons (H^{+}) that circulate in the ring. The short, intense proton pulses are extracted from the ring at a rate of 60 Hz to bombard the target.

- The proton beam interacts with mercury, contained in the target vessel, producing 20 to 30 neutrons (Figure 5.11). Those neutrons are guided out of the target vessel into beam guides that lead directly to instrumented stations.

5.2.6 Swiss Spallation Neutron Source (SINQ)

SINQ is designed as a neutron source mainly for research with extracted beams of thermal and cold neutrons, but also hosts facilities for isotope production and neutron activation analysis (Figure 5.12).[74] Except for the different process of releasing neutrons from matter, it resembles closely a medium flux research reactor for most of its users. Four components constitute SINQ:

- Three accelerators located at the end of a cascade deliver a continuous proton beam of 590 MeV at a current up to 2.3 mA. The proton beam is accelerated to 870 keV in a Cockcroft-Walton column. A 4-sector injector cyclotron, providing a 73 MeV proton beam, provides further acceleration.[75] An 8-sector main ring cyclotron is used to generate a 590 MeV proton beam (Figure 5.13).

Figure 5.10. The 1,000-foot SNS linear accelerator utilizes three different types of accelerators.

Figure 5.9. The SNS ring intensifies the high-speed ion beam, which then impacts the mercury target 60 times a second (60 Hz).

Figure 5.11. The curved, rectangular object is the SNS target. Inside is liquid mercury, where spallation takes place.

- The SINQ target station contains the heavy-metal target, which receives the proton beam from below the tank (Figure 5.14).[76] Magnets are used to divert the beam.

- The spallation target, about 50-cm long and located in the center of the moderator tank, is an array of lead rods, enclosed in zircaloy tubes and cooled in cross flow by heavy-water (Figure 5.15). In 2006, a liquid metal target with eutectic lead-bismuth target material was tested successfully in the framework of the MEGAPIE-Project.

- A light-water reflector jacket (Figure 5.16) surrounds the cylindrical moderator tank of about 2 m in diameter. A proton beam of 1 mA (6.25×10^{15} protons/s) produces about 3.6×10^{16} high-energy spallation neutrons per second, which are slowed down to thermal energy in the moderator.

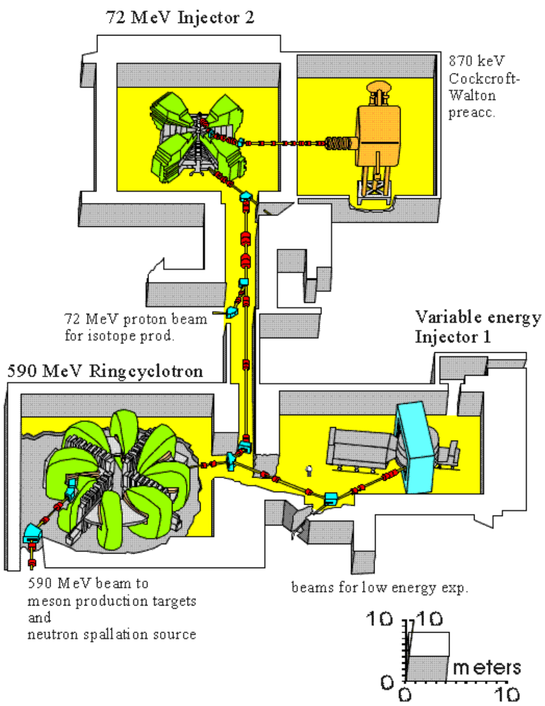

Figure 5.12. Schematic representation of the SINQ.

Figure 5.13. The 8-sector main ring cyclotron

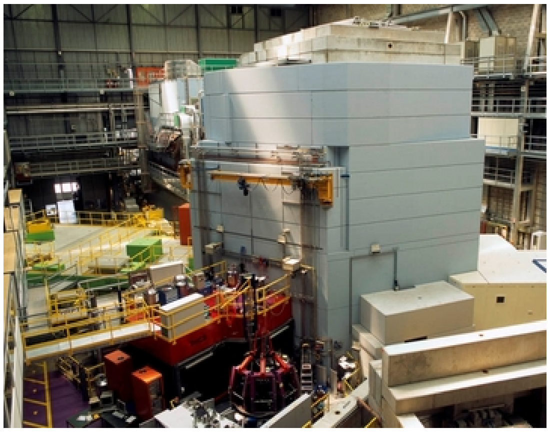

Figure 5.14. SINQ target station.

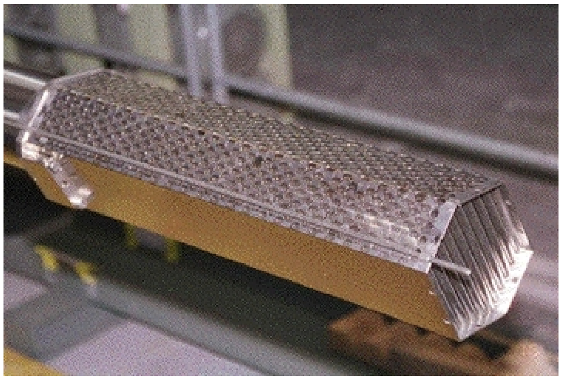

Figure 5.15. The spallation target is composed of lead rods.

Figure 5.16. Open moderator tank with visible inserts for cold source and beam tubes

The MEGAPIE (Megawatt Pilot Experiment) was a joint international project started in 2000 to design, build, operate, dismantle, and dispose of a liquid lead-bismuth eutectic (LBE) spallation target.[77] The MEGAPIE target was the first liquid metal target ever operated in the Megawatt regime, at a power level of 0.8 MW, as an alternate to the lead-rod, spallation neutron source. The target was successfully irradiated from August until December 2006, receiving a total beam charge of 2.8-ampere hours (Ah) of

590 MeV protons. After successful operation, the target was stored in the target storage facility at SINQ, awaiting a post irradiation examination (PIE), which was performed over the next few years. The dismantling of the MEGAPIE target was initiated in June 2009. The target was successfully cut into 21 pieces; ten of these pieces have been shipped back to the Hot Laboratory of Paul Scherrer Institut (PSI) to produce samples of the structural materials, as well as the LBE, while the remaining parts of the MEGAPIE target were conditioned to become nuclear waste.

5.2.7 Los Alamos Neutron Science Center (LANSCE)

LANSCE began as the Los Alamos Meson Physics Facility (LAMPF), which was conceived in 1962 by a small group of Los Alamos Scientific Laboratory scientists.[78]The core of LACSCE is an 800 MeV linear accelerator and its attendant facilities—the first 800 MeV proton beam was obtained in June 1972 (Figure 5.17). During the mid-1980s, significant improvements were made with the addition of a pulsed spallation neutron source[79] and a proton storage ring (PSR).

With the termination of the nuclear physics user program in October 1995, LANL refocused the mission of its linear accelerator complex, including changing its name to the Los Alamos Neutron Science Center.[80] It is now considered a multidisciplinary facility with the accelerator providing particles to five experimental areas (Figure 5.18).[81] H^- beams are utilized by four areas as follows:

- Manual Lujan Jr. Neutron Scattering Center (Lujan Center), producing neutrons from a tungsten spallation target (moderated with water or liquid hydrogen);
- Weapons Neutron Research Facility (WNR);
- Proton Radiography Facility (pRAD), and
- Ultra-Cold Neutron (UCN) facility, which uses a moderated solid deuterium target to generate intense pulses of ultra-cold neutrons.

Figure 5.17. LANSCE provides the scientific community with intense sources of neutrons.

Radioisotopes are produced at the Isotope Production Facility (IPF) for medical imaging diagnostics and fundamental research by employing a 100 MeV proton beam producing 275 µA. Beam current to the Lujan target is nominally 100 µA, but may be as high as 125 µA depending on ion source and accelerator optimization.

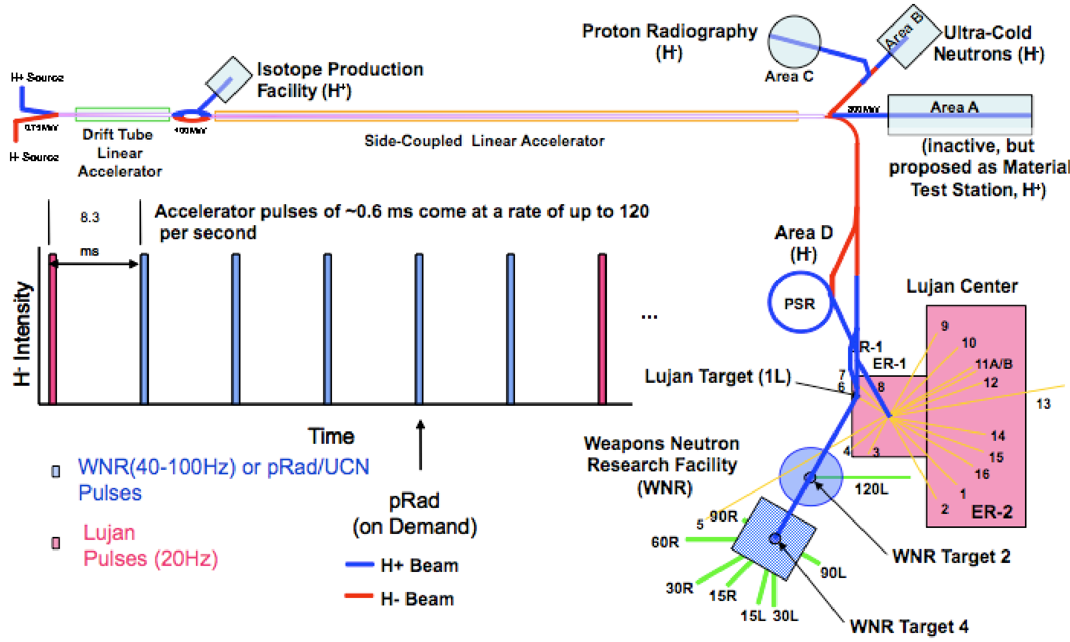

Figure 5.18. Schematic representation of the LANSCE user facility.

The three-stage linac is half-a-mile long and provides beams of H^+ with an average current of up to 1 mA at 100 Hz with a peak of 17 mA, and H^- with an average current of 100 µA at 20 Hz with a peak of 20 mA.[80] The first stage of the accelerator contains injector systems consisting of a 750-keV Cockroft-Walton generator and an ion source for each type of particle (H^+ and H^-). The two ion beams from the injectors are merged, bunched, and matched into a 201.25-MHz drift-tube linac for acceleration to 100 MeV. The third and longest stage of the accelerator is a side-coupled-cavity linac, where the particles are accelerated to their final energy (800 MeV). Operators can control each of the beams separately, permitting most experiments to run simultaneously. The PSR converts ~70-ms-long H^- linac macropulses into short (0.27-µs) intense proton (H^+) bursts that provide the capability for precise neutron time-of-flight measurements for a variety of experimental programs.

The tungsten used as the spallation target produces about 20 neutrons per proton ejected. These short, highly intense bursts are used in neutron scattering and other nuclear science experiments. For some studies at WNR and the Lujan Center, these high-energy neutrons are appropriate, while they are too energetic for studies on condensed matter at the Lujan Center. Several combinations of moderators are used to feed 16 flight paths at the Center: (1) water, (2) partially coupled liquid hydrogen, (3) coupled-water, and (4) coupled liquid-hydrogen.

5.2.8 Large Hadron Collider (LHC)

The LHC is a two-ring superconducting-hadron accelerator and collider installed in the existing 17-mile tunnel, which was constructed between 1984 and 1989 for the CERN LEP.[82] The LEP tunnel has eight straight sections and eight arcs and lies between 45 and 170-m below ground surface. Approval for the LHC project was granted by the CERN Council in December 1994. At that time, the plan was to build a machine in two stages, starting with a center-of-mass energy of 10 tera electron volts (TeV), to be upgraded later to 14 TeV. However, during 1995 and 1996, intense negotiations secured substantial contributions to the project from non-member states, and in December 1996, the CERN Council approved construction of the 14 TeV machine in a single stage.

The LHC is designed to collide two counter-rotating beams of protons or heavy ions (Table 5.2).[83] Proton-proton collisions are foreseen at an energy of 7 TeV per beam (Figure 5.19). The beams move around the LHC ring inside a continuous vacuum guided by magnets (Figure 5.20). The magnets are superconducting and are cooled by a huge cryogenics system. The cables conduct current without resistance in their superconducting state. The beams are stored at high energy for hours. During this time, collisions take place inside the four main LHC experiments.

Table 5.2. Beam parameters for the LHC[84].

Beam data	Injection	Collision
Proton energy (GeV)	450	7,000
Relativistic gamma	480	7,460
Number of particles/bunch	1.15×10^{11}	
Number of bunches	2810	
Circulating beam current (A)	0.58	
Stored energy/beam (MJ)	23	360

The first beams were circulated successfully on September 10, 2010. Nine days later, a serious fault developed that damaged a number of superconducting magnets. The beam was restored in November 2009 with the first collisions occurring on March 30, 2010. The rest of the year was devoted to commissioning. The first production was in 2011 with over five inverse femtobarns delivered to two of the workstations (ATLAS and CMS). Over six inverse femtobarns were produced in 2012, which paved the way for the announcement of discovery of the Higgs boson on July 4, 2012.

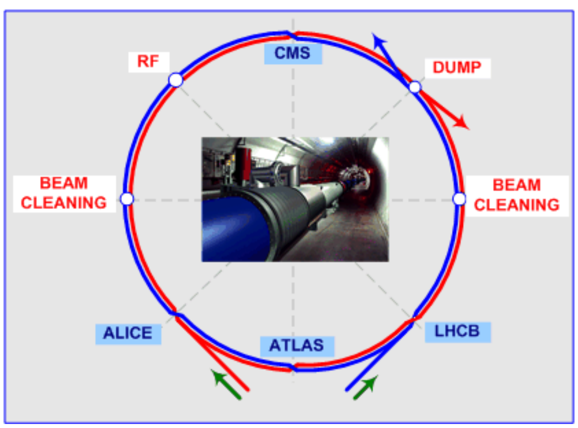

Figure 5.19. Schematic representation of the LHC.

Figure 5.20. View of the LHC's Tevatron.

5.3 PROPOSED SYSTEMS

5.3.1 Introduction

Although there is a continuing interest in high-energy accelerator-driven spallation neutron sources, their costs have been a serious barrier to any substantial construction of new systems—funding for the US SNS was \$1.4 billion.[85] Never-the-less, there are still literature citations and presentations demonstrating that avenues are still being pursued by several countries and research organizations in an effort to justify the construction of these systems, but adequate funding is scarce.[86, 87] Information for some of these proposed designs is given in the following sections.

5.3.2 Indian Spallation Neutron Source (ISNS)

The ISNS will be the first spallation neutron source in India and will be used to perform research in the fields of condensed material physics, material sciences, chemistry, biology, and engineering. It will complement the existing reactor-based neutron research facility at the Bhabha Atomic Research Centre (BARC), and the Indus synchrotron facilities at the Raja Ramanna Centre for Advanced Technology (RRCAT).[86] The system will be based on a 1-GeV H^- superconducting linac feeding into an accumulator ring (Table 5.3). The Indians are projecting a beam current of 1 mA. The project has been divided into two phases: (1) R&D design of the linac, accumulator, target, moderator, and neutron beam transport lines and (2) construction of the ISNS and user facility (expected to take 10–12 years).[88] International collaborators include Fermilab (Project X), CERN (Linac 4), J. Lab (Proton Linac at SNS), and ESS.

Table 5.3. Basic parameters for the ISNS.

Component	Value	Component	Value
RFQ injection energy	50 KeV	DTL injection	4.5 MeV
RCS injection energy	100 Mev	Beam energy on target	1.0 GeV
RCS repetition rate	25 Hz	Average beam current	100 µA

5.3.3 China's Spallation Neutron Source CSNS)

Figure 5.21. Plan of the CSNS.

Following a conceptual and feasibility study, China is expected to build the CSNS in two phases (Figure 5.21, Table 5.4).[89] The CSNS-I accelerator train is to consist of (a) a H^- Penning ion source that will produce a beam of 20 mA and exhibit low emittance, (b) a low-energy beam transfer line (LEBT) using magnetic focusing and electric beam chopping, (c) a four-vane RFQ linac of 3 MeV, (d) a medium energy beam transfer line (MEBT), (e) four Drip tube line (DTL) tanks of 80 MeV at exit, (f) a linac to RCS beam transfer line of 197 m in length (including a reserved space for linac upgrading), (g) an RCS of 1.6 GeV as the extraction energy device, and (h) an RCS to target beam transfer line of 144 m in length (Figure 5.22). Whereas the linac and the RCS are cycling at 25 Hz, the two main beam transfer lines (LRBT and RTBT) work in the DC mode. The H^- beam is converted to a proton beam by a stripping foil at the RCS injection—necessary to accumulate the required large number of protons in the RCS and to transfer the linac beam of small emittance into large acceptance in the RCS with good uniformity in both the transverse and the longitudinal phase planes.

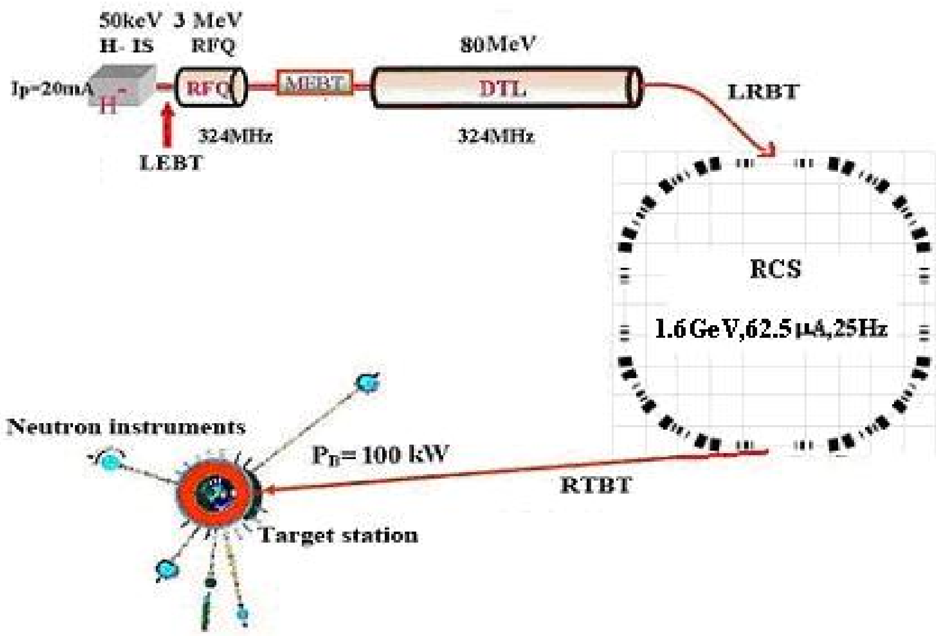

Figure 5.22. Schematic representation of China's CSNS.

Table 5.4. Basic parameters for the CSNS.

Specification	CSNS-I	CSNS-II
Beam power (kW)	100	200
Repetition rate (Hz)	25	25
Average Current (μA)	62.5	125
Proton energy (GeV)	1.6	1.6
Linac energy (MeV)	80	132
Target material	Tungsten	Tungsten

Initial construction began in Dongguan in Guangdong Province in October 2011.[90] The ¥1.67 billion CSNS Project was approved by the central government in 2005 and has been listed in the National Long- and Medium-Term Plan for S&T Development. According to the blueprint of the CAS-Guangdong cooperation, the facility will take 7 years to complete with financial support from both the central and local governments. Commissioning is to be in 2016 with operation in 2018.

5.3.4 South Korea's Multipurpose Accelerator Complex (KOMAC)

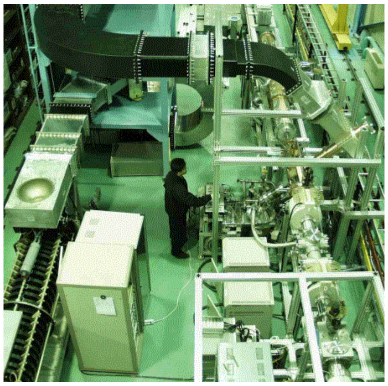

Figure 5.23. KOMAC test facility.

One of the activities of the Korea Atomic Energy Research Institute (KAERI) is to construct a proton linear accelerator, which to be a part of the Korea Multipurpose Accelerator Complex (KOMAC).).[91] The proton energy and the average current are projected to be 20 MeV and 4.8 mA, respectively. This will produce a beam power of 96 kW. The first stage, a low-energy accelerator (20 MeV) consisting of an injector, RFQ, CCDTL, and RF systems has been tested successfully in the KOMAC Test Facility (Figure 5.23). For proton beam applications, a second phase accelerator will supply beams with 20 MeV and 100 MeV (Figure 5.24).[92] The 50-keV beam from the injector will be chopped with time-structure suitable for applications, and supplied via switching magnets at each of the energy stages. The 20 MeV front-end accelerator has been installed and operated at Daejeon for user service.[93]

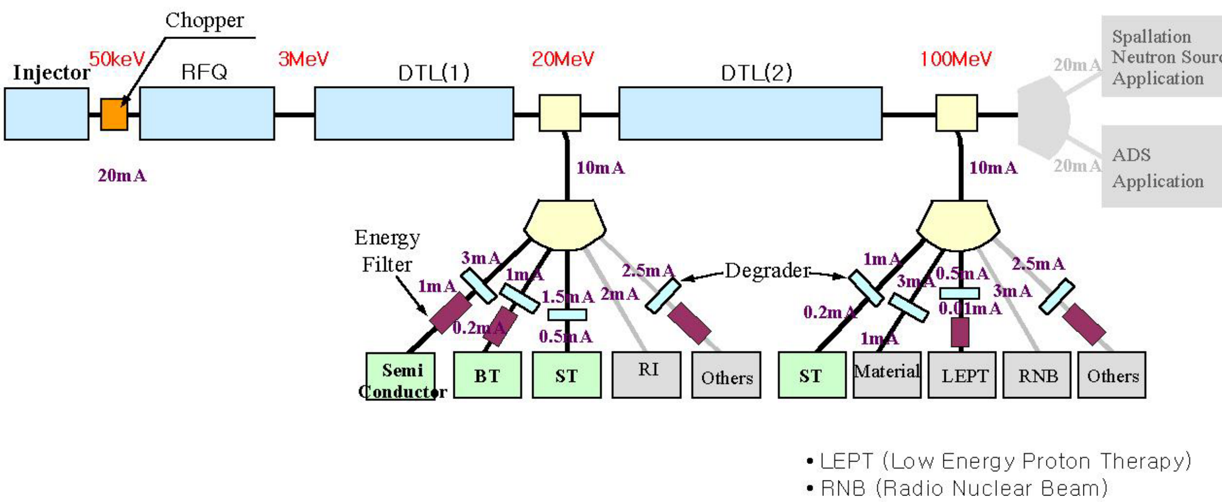

Figure 5.24. Proton beam line for 2nd Phase KOMAC accelerator.

5.3.5 Project X

Fermilab is proposing locating a proton accelerator at its current site, which will support neutrino physics and studies of rare processes.[94] The tentative schedule is to begin construction in 2016 with a completion date of 2021 (Figure 5.25). Criteria for the basic design were provided by an advisory panel and include:[95]

- A long baseline neutrino beam facility based on a proton source capable of delivering at least 2 MW of beam power at any energy over the range 60-120 GeV,
- High-intensity protons supporting muon and kaon precision experiments, simultaneous with the neutrino program, and
- A path toward a muon source for a possible future neutrino generator or muon collider.

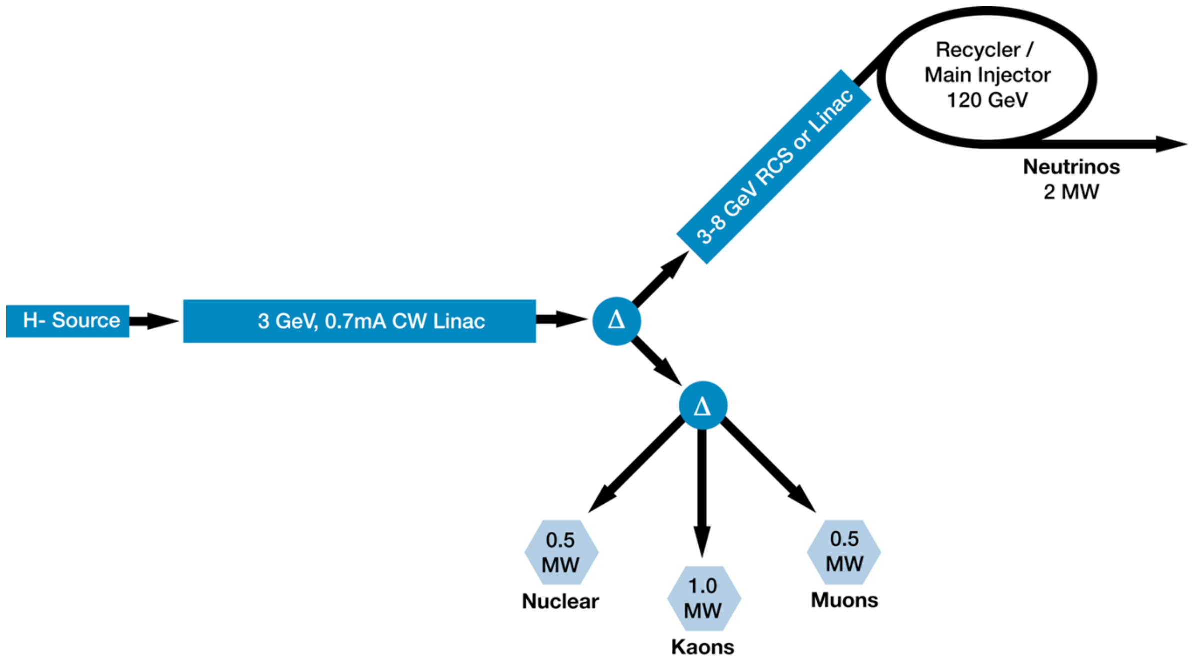

Figure 5.25. Project X is based on a 3 GeV CW superconducting H^- linac.

Physicists have developed two configurations that meet these requirements. The first uses an 8 GeV pulsed linac; the second incorporates a ~3 GeV CW linac followed by an 8 GeV rapid cycling synchrotron (RCS) or superconducting pulsed linac. Both configurations use Fermilab's existing recycler and main injector rings for beam accumulation and acceleration to 60 –120 GeV. Both configurations meet the requirements of a very-high-energy neutrino beam to support experiments in detectors located more than 1000 km away. However, the second (CW-linac based) configuration not only offers performance vastly superior to the first for a precision measurements program, but also provides a capability that is unique among facilities being commissioned, constructed, or designed worldwide.

A national collaboration with international partners has been formed to develop Project X. The national collaboration comprises Argonne National Laboratory, Brookhaven National Laboratory, Cornell University, Fermilab, Lawrence Berkeley National Laboratory, Michigan State University, Oak Ridge National Laboratory, Thomas Jefferson National Accelerator Facility, SLAC National Accelerator Laboratory, and the Americas Regional Team of the ILC Global Design Effort. Currently, the most significant international collaboration is with India, although the collaboration is also forming ties with other European and Asian institutions.

5.3.6 Multipurpose Hybrid Research Reactor for High-Tech Applications (MYRRHA)

The Belgian Nuclear Research Center in Mol envisions replacing its 100-MW BR2 research reactor with an ADS fast spectrum research reactor of 50–100 MW(t).[96] The reactor, operating in both subcritical and critical modes, would use a 600 MeV proton accelerator, a spallation target, and a multiplying core of mixed oxide fuel (Figure 5.26). A liquid lead-bismuth mixture would provide cooling. The beam, entering the reactor from the top, will be CW with an average beam current of 4 mA.

An electron cyclotron resonance (ECR) ion source is expected to provide significantly higher beam currents (100 mA) than needed, thereby providing ample margin for reliability improvements. The DC beam from the source will be injected into a RFQ, which is used for bunching and initial acceleration of the beam. Crossbar H-type (CH) cavities will accelerate the beam up to 5 MeV. Acceleration to 17 MeV will be obtained through four superconducting CH cavities, which will be combined into one single cryomodule together with the necessary focusing elements. With this configuration, the total length of the front-end section will be less than 16 m. A frequency of 176 MHz will be use for 4-rod type RFQ, while 352 MHz will be used for a 4-vane RFQ.

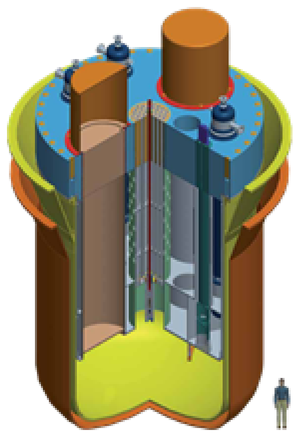

Figure 5.26. Schematic representation of the MYRRHA research reactor.

The independently phased superconducting section is further subdivided according to the increasing beam velocity. Acceleration from 17 MeV up to 90 MeV is obtained by a series of spoke cavities. The frequency is 352 MHz. The RF frequency is increased to 704 MHz, and the main section of the linac is made of two families of elliptical cavities. The focusing quadrupoles in the linac section are normal conducting magnets, organized in doublets and installed in between the cryomodules that carry the cavities. According to the requirements of the transverse beam optics, each cryomodule houses two or three independent cavities. The total length of the independently phased superconducting section is estimated at 232 m.

The current plans are to complete the initial front-end engineering design (FEED) and associated R&D programs, licensing process, and develop an international consortium by 2014. Construction is projected to take five years, being completed by 2019. Full commissioning will follow over a three-year period with routine operation beginning by 2023. Total investment is €960 million (2009 €).

5.3.7 European Spallation Source Accelerator (ESS)

In March 1998, a large number of members of the European Neutron Scattering Association (ENSA) expressed their support for the building of a spallation source accelerator as being the best option, both to satisfy their research needs in the future and to maintain their leading position in neutron utilization.[97] By 2003, a set of detailed design reports were produced. A site in Sweden, Lund, was selected and a company, ESS AB, was created to design, construct, and operate the ESS.[98] ESS AB is a Swedish public limited company (rather than a research laboratory). Sweden, Denmark, and Norway are to provide 50% of the funding with the other 14 member states providing the rest through the European Investment Bank.

By the end of 2011, the baseline requirements for the ESS accelerator were as follows:

- Provide 50 mA of protons,
- Beam power of 2.5 GeV,
- Pulse length of 2.86 ms, and
- Repetition rate of 14 Hz.[99]

This results in an average beam power on the target of 5 MW with a peak power of 125 MW. The linac will have a normal conducting front-end with an ion source, a RFQ, and a DTL. Spoke cavities will be used for the superconducting section, which will be followed by two families of elliptical cavities. A tungsten disk, 1.5-m in diameter, 8-cm thick and rotating at 0.5 Hz is to be used as the spallation target (Figure 5.27).[100] Target lifetime is expected to depend critically on maximum peak current density, intensity gradient, and extent of tails.

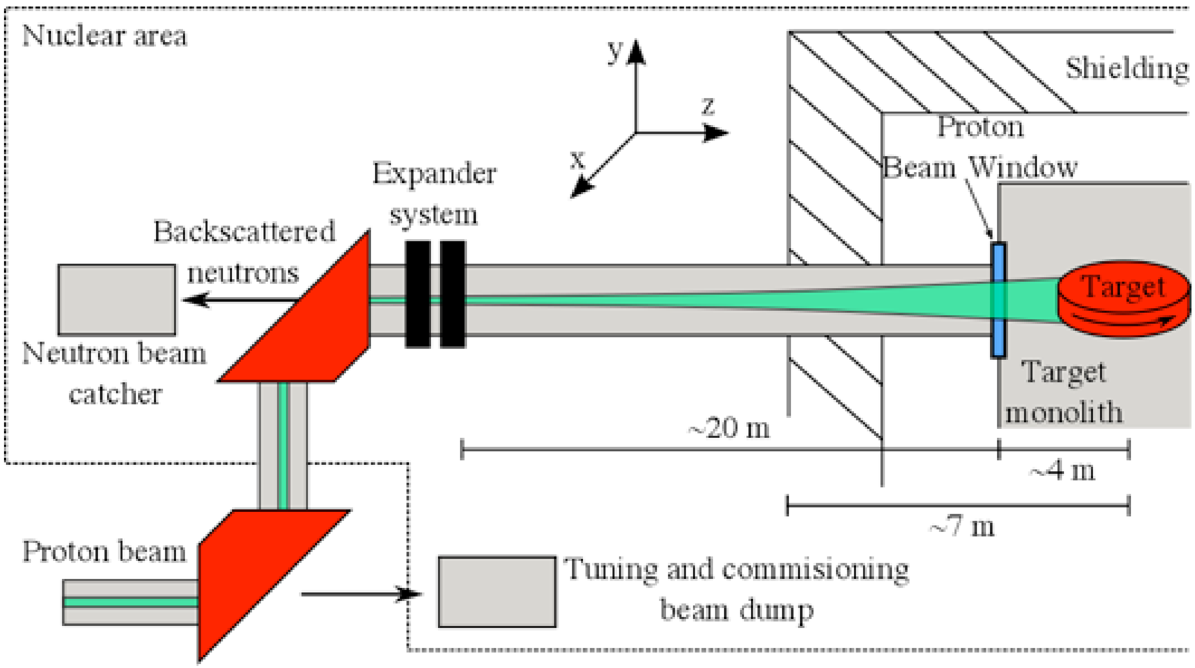

Figure 5.27. Tungsten disk to be used as the spallation target.

Because there is no need for a charge injection system into an accumulator ring for a long pulse source, the ion source for the ESS will produce a proton beam (Figure 5.28). An electron cyclotron resonance source (ECR) is under consideration. The beam will be transported through a low energy beam transport (LEBT) section to the RFQ for bunching and accelerating to 3 MeV. The RFQ will be of the four-vane type.

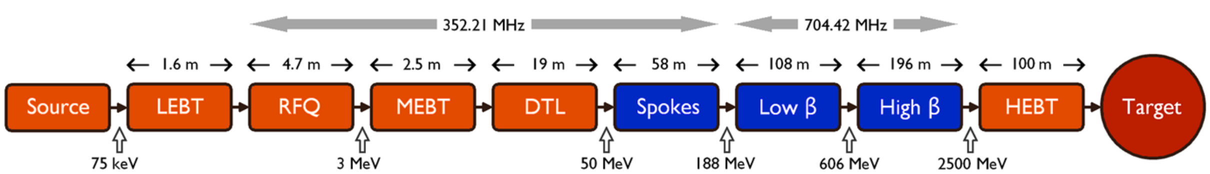

Figure 5.28. General representation of the ESS accelerator.

From the RFQ, the beam will be transported to the medium energy beam transport (MEBT) section and matched to the first normal conducting drift-tube linac (DTL) structure. Cryomodules of the superconducting linac are to be fully segmented. The current baseline has spoke cryomodules with two double-spoke cavities per module, medium-beta modules with four five-cell elliptical cavities, and high-beta modules with four five-cell cavities that feed into high-energy beam transport (HEBT) section.

5.3.8 International Fusion Materials Irradiation Facility (IFMIF)

In support of fusion energy development, a high deuteron beam intensity (125 mA–9 MeV) prototype accelerator is to be built and tested at Rokkasho (Japan) in order to characterize materials envisaged for fusion reactors (Figure 5.29).[101] The facility is based on two high-power CW accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV to a common lithium target (Figure 5.30). The interaction of the accelerated deuterons with the liquid lithium in the loop will generate neutrons similar to those produced in the DT fusion reactions. These neutrons will in turn irradiate reduced-scale samples of material to be tested and other experiments in specific modules.

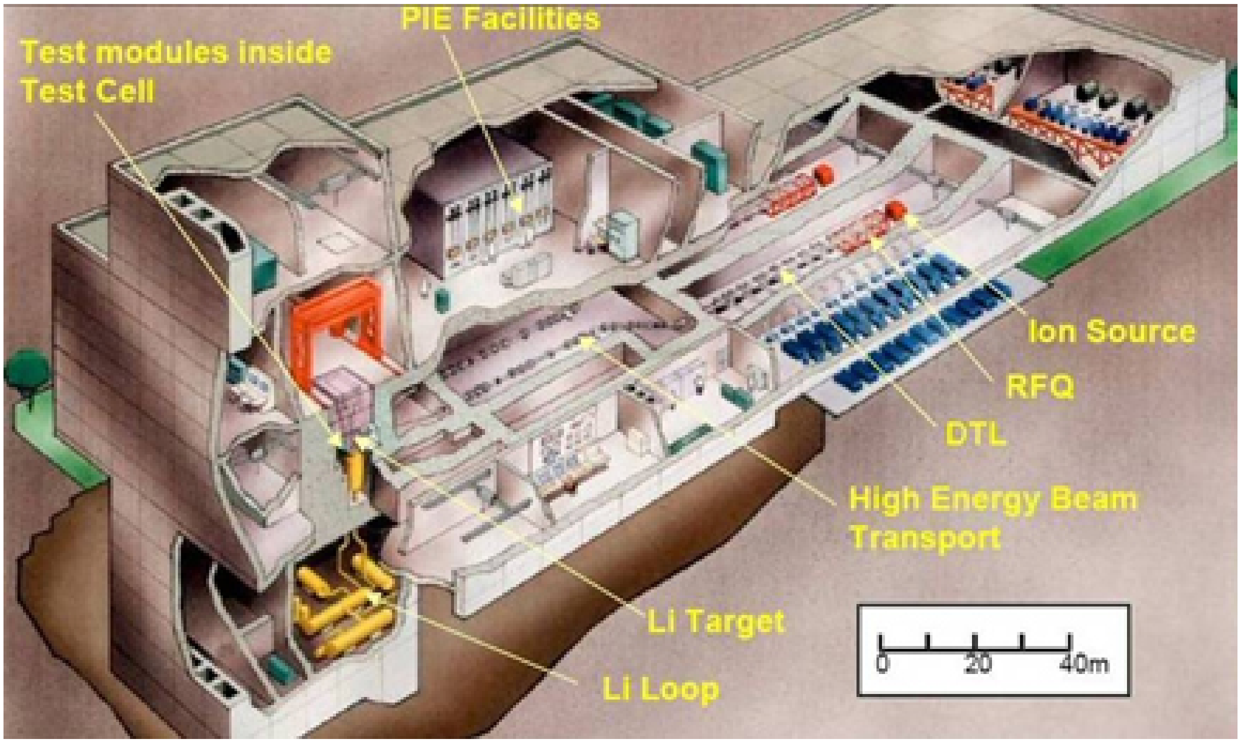

Figure 5.29. Schematic representation of the IFMIF device.

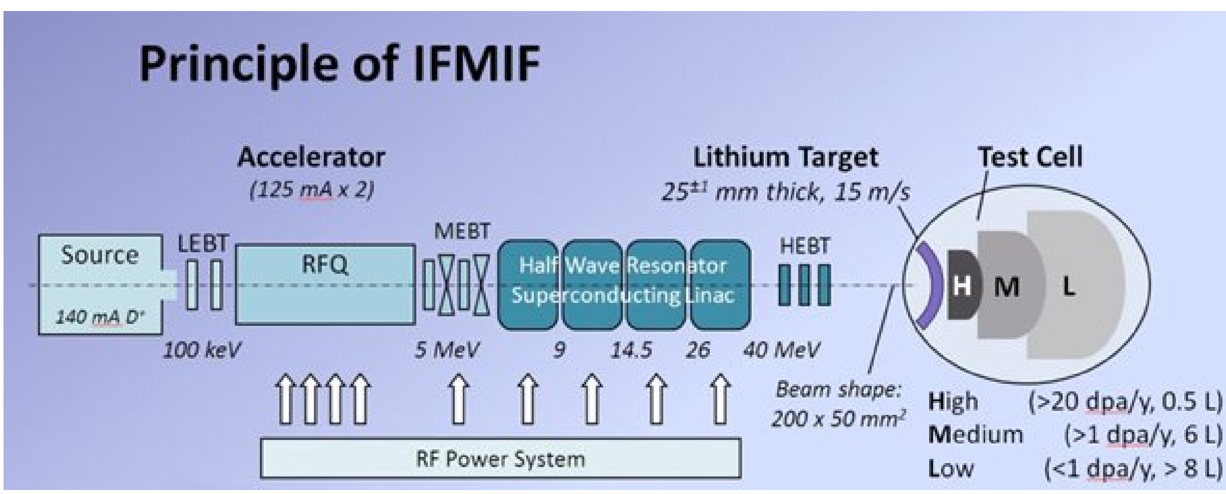

Figure 5.30. Principle of the IFMIF.

The engineering validation and engineering design activities (EVEDA) phase of the IFMIR was initiated in mid-2007 with the goal of building and testing a number of prototypes. The major components were designed and developed in Europe and will be assembled and operated at Rokkasho. The individual components are being developed in Spain (CIEMAT), Italy (INFN), Belgian (SCK-CEN), and France (CEA). A European team was selected for the coordination of the accelerator activities. Construction of the EVEDA lithium test loop (ELiTe) was completed in December 2010 at the JAEA Oarai Centre, and the first beam was observed on May 4, 2011.[102] This first beam was in pulsed regime whereas the final one will be continuous. Once tested in Saclay, the injector will be shipped to Rokkasho within 1 year.

The other systems will then be installed and the entire Linear IFMIF Prototype Accelerator (LIPAc) assembled by mid-2015. Two years of experiments are planned in order to reach a stable and continuous beam at full energy—expected to be accomplished in mid-2017. In the actual IFMIF installation, the 40 MeV deuterium ions will generate an accumulated neutron flux (the "fluence") a hundred times that of International Thermonuclear Experimental Reactor (ITER), and slightly above that of the future DEMOnstration Power Plant (DEMO). The target samples will hence "age" some 20 to 40 % faster than in an actual steady-state fusion reactor ―a unique case of a particle accelerator that also accelerates time.

5.3.9 Facility for Rare Isotope Beams (FRIB)

In 2008, DOE selected Michigan State University (MSU) as the site for the Facility for Rare Isotope Beams (FRIB), a national user facility, which is to provide intense beams of rare isotopes for nuclear science researchers.[103] A superconducting driver linac will deliver CW beams of stable isotopes with an energy of >200 MeV per mass unit (u) at a beam power of 400 kW (Figure 5.31). Highly charged ions will be produced from an electron cyclotron resonance ion source (ECRIS) with a total extraction current of several mA. Multiple charge states of heavier ions will be accelerated simultaneously to meet the final beam power requirement. The FRIB driver linac lattice design has been developed and end-to-end beam simulations have been performed to evaluate the machine performance. Although construction has been initiated, adequate funding has become a contentious issue.[104,105]

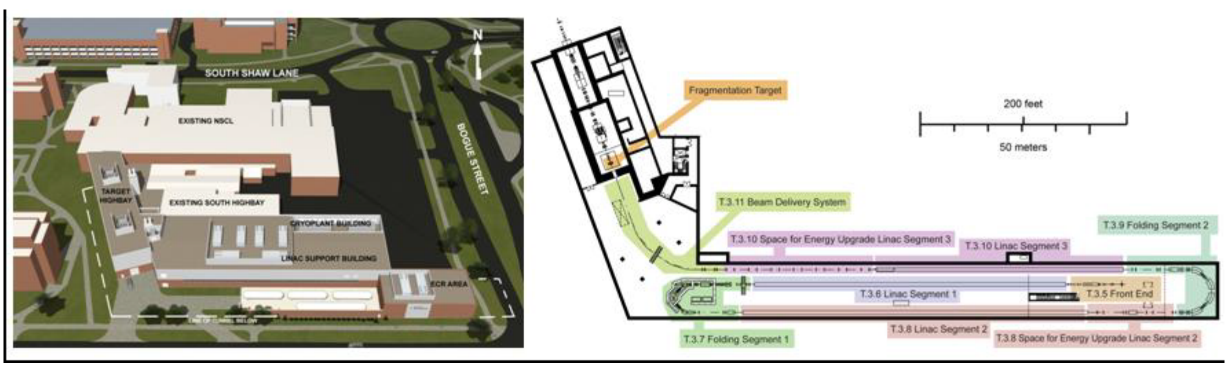

Figure 5.31. The planned FRIB surface buildings (left) and the representation of the double-folded superconducting driver linac in tunnel (right).

To meet the beam intensity requirements, the FRIB linac will utilize simultaneous multi-charge-state acceleration for heavier ions. The driver linac will consist of a front end to bring the beam energy to 0.3 MeV/u, three superconducting acceleration segments connected by two 180° bending systems to achieve a final beam energy of >200 MeV/u, and a beam delivery system to transport the multicharge-state beams to a fragmentation target. The superconducting linac has an 80.5-MHz base frequency and utilizes four types of resonators with only one frequency transition to 322 MHz after the linac.

5.3.10 Turkic Accelerator Complex (TAC)

The Turkish State Planning Organization with the collaboration of 10 Turkish universities is proposing the development of an accelerator complex, one of which is to be a proton accelerator for ADS applications (Figure 5.32).[106,107] Their interest is two-fold; (a) transmutation of long-lived actinides and (b) energy production from thorium fuel. The current linear accelerator design is based on 1-GeV energy and 2.5-mA proton beam current, producing medium power (250 MW). Their goal is to start producing energy from ADS in the 2020s.

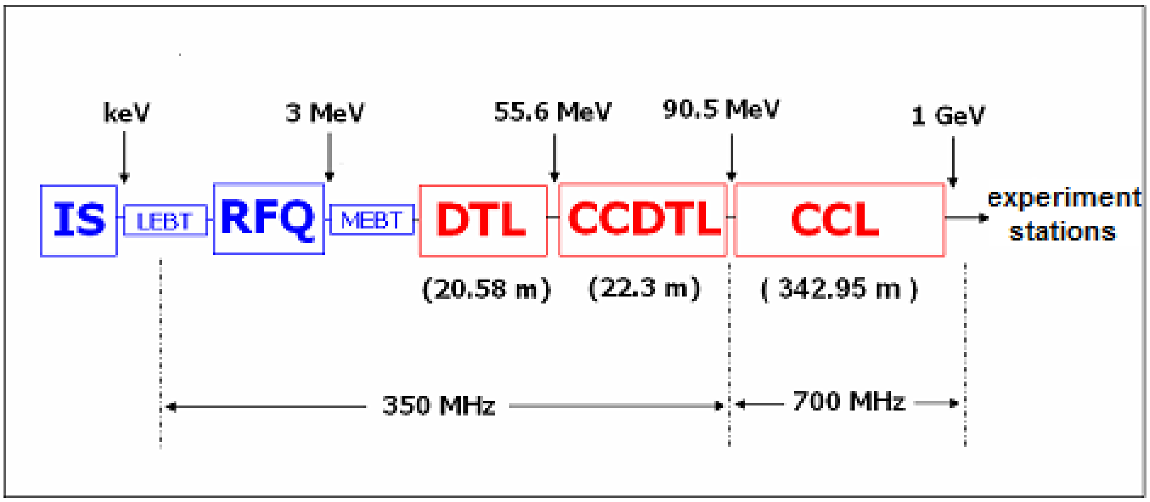

Figure 5.32. Block diagram of the TAC proton accelerator.

The low and medium energy part of the proposed proton accelerator will consist of normal conducting cavity structures. After an ion source, RFQ, DTL, and Coupled-Cavity Drift Tüp Linac (CCDTL) accelerator structures will be used, respectively. There is a low-energy beam transport channel (LEBT) between the ion source and the RFQ. Its task is to match the ion beam to the RFQ by using the solenoid and steering magnets. While the beam obtained from the ion source is in the un-bunched structure, the conversion of the ion beam to the bunched structure is realized in the RFQ structure. The acceleration, the focusing, and the bunching of the ion beam are simultaneously performed in the RFQ. Only transverse electric fields are used in the RFQ for these three processes. Axial longitudinal electric fields needed for the beam acceleration process are produced by internal surface modulation for each of the electrodes inside the RFQ. There is no acceleration in the first section of the RFQ structure called the radial matching section. After the beam is converted into the bunched structure, acceleration to an energy of 3 MeV is initiated. The second transport section of the proton accelerator is between the RFQ and the DTL. In this channel, called medium energy beam transport (MEBT), matching to the DTL is performed by using the quadrupole magnets. In both transport channels, beam diagnostic elements use Faraday cups. Normal conducting Coupled-Cavity Linac (CCL) cavities are planned for the high-energy section. Beam simulations for the entire line demonstrated that the beam would be stable up to 60-mA beam current.

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APPENDIX A.

1. Ion accelerators

Proposed action: New DUL control entry.

Proposed control language: Ion accelerators having both of the following characteristics:

(a) Capable of accelerating singly-charged ions to energies greater than 120 MeV, but less than 20 GeV; and

(b) Having a figure of merit (K) of 160 or greater.

Technical Note*: *The figure of merit K is defined as K = 1(E −120), where I is the average accelerator beam current in milliamperes (mA) and E is the final particle energy in million electron volts (MeV). The figure of merit is an arbitrary parameter, for export control purposed only. It is proportional to the accelerator's potential plutonium production rate. The control point of 160 corresponds to producing 2 kg of plutonium per year, assuming 100% beam availability, optimal design of a spallation target, and use of a neutron multiplying assembly dissipating approximately 5.2-MW thermal and with a multiplication factor of 8 (k_{eff} = 0.875) and a capture ratio for ^{238}U of 0.4.

Reasons for control: High-power accelerators, in conjunction with neutron-producing targets and subcritical multiplying assemblies, can be used to produce significant quantities of plutonium.

Major research programs under way worldwide are exploring the use of high-power accelerator-driven systems for radioactive waste transmutation, energy production, and plutonium disposition. Recent calculations have demonstrated the feasibility of producing significant quantities of plutonium using subcritical lattices of natural uranium moderated by light water, driven by spallation neutron sources.

Non-nuclear uses: High- and medium-energy accelerators have predominantly been used for research in basic nuclear and particle physics and materials science research.

Notes: Spallation reactions have an incident particle energy threshold of around 120 MeV. For incident particle energies greater than 20 GeV, the particle stopping range becomes excessive, making the required target sizes unreasonably large. In addition, above this energy, other reactions dominate the spallation process. Sweden currently controls proton accelerators with average beam power greater than 5 MW, and electron accelerators with average beam power greater than 0.5 MW. When active, COCOM had general controls in place covering directed energy weapon systems, including "particle accelerators which project a charged or neutral beam with destructive power."

2. Low-emittance ion sources, either pulsed or continuous duty (i.e., d.c. or cw)

Proposed action: New DUL entry.

Proposed control language: Pulsed or continuous duty (i.e., d.c. or cw) ion sources producing H^+, H^-, D^+, or H_2^+ ions with average ion current of 1 mA or greater and emittance 3.0 π-mm-mrad or less (pi-millimeter-milliradian).

Reasons for control: These provide the necessary source of ions to be injected into a particle accelerator (usually some form of linear accelerator or a cyclotron). High-power particle accelerators, in conjunction with neutron-producing targets and subcritical multiplying assemblies, can be used to produce significant quantities of plutonium.

Non-nuclear uses: Research applications and ion implantation systems.

3. High-power radiofrequency (RF) power amplifiers {including certain klystrons, klystrodes [inductive output tubes (IOTs)], power tetrodes and triodes, gyrotrons, and crossed-field amplifiers}

Proposed action: New DUL entry.

Proposed control language: Devices capable of providing RF power outputs greater than 100 kW cw or 500 Kw pulsed at frequencies between 25 MHz and 1.5 GHz and capable of average power of 100 kW or greater.

Reasons for control: High-power RF amplifiers provide RF power to the accelerating cavities in particle accelerators. High-power particle accelerators, in conjunction with neutron-producing targets and subcritical multiplying assemblies, can be used to produce significant quantities of plutonium.

Non-nuclear uses: Primarily used in specialized research applications. Lower-power amplifiers are used in radars, television and radio broadcast transmitters, and satellite and microwave communications links. Low-power triodes and tetrodes are common to most vacuum tube electronic systems.

4. Linear accelerator structures designed for protons or deuterons

Proposed action: New DUL entry.

Proposed control language: Any linear accelerator structure designed to be driven by radiofrequency power and having a beam path operated at vacuum and capable of accelerating particle beams of protons or deuterons to multi-MeV energy or greater. This includes but is not limited to:

(1) Drift tube linear accelerator structures operating at frequencies in the range of 150 MHz to 800 MHz,

(2) Coupled-cavity microwave linear accelerator structures, operating in the frequency range 500 MHz to 1.5 GHz and having a 1 cm or larger beam bore diameter, and

(3) Superconducting linear accelerator structures operating in the frequency range 500 MHz to 1.5 GHz.

***Technical Note*: Linear accelerating structures designed for electrons are not of concern.**

Reasons for control: Accelerator structures are the basic building block for particle accelerators. They couple radiofrequency energy into the particle beam, thereby accelerating the particles. High- power particle accelerators, in conjunction with neutron-producing targets and subcritical multiplying assemblies, can be used to produce significant quantities of plutonium.

Non-nuclear uses: No uses outside of particle accelerators are known. Many accelerators are used for basic and applied research applications, including medical applications.

5. **Cyclotron sector magnets and laminated ion synchrotron ring magnets**

Proposed action: New DUL entry.

Proposed control language: Cyclotron sector magnets and laminated ion synchrotron ring magnets designed for use in particle accelerators capable of 120 MeV or greater energy.

Technical Note**: *These magnets are very difficult to describe in a way by which a non-accelerator expert could recognize them. Cyclotron magnets will be made primarily of iron, will be larger than synchrotron magnets and will weigh at least 75 metric tons. Synchrotron magnets will be made of laminated (sheets) or iron.***

Reasons for control: These magnets are used to provide magnetic guide fields for the particles being accelerated in a cyclotron or synchrotron type particle accelerator. High-power particle accelerators, in conjunction with neutron-producing targets and subcritical multiplying assemblies, can be used to produce significant quantities of plutonium.

Non-nuclear uses: No uses outside of particle accelerators are known. Many accelerators are used for basic and applied research applications, including medical applications.

6. **High-power radiofrequency (RF) circulators made with ferrite**

Proposed action: New DUL entry.

Proposed control language: Radiofrequency circulators capable of operating at a frequency in the range from 300 to 1200 MHz and at a peak power level greater than 100 kW.

Reasons for control: RF circulators prevent damaging amounts of RF power from being reflected back into RF amplifiers in case of mismatch with load (i.e., mismatch with accelerator). Basically, they allow full power transfer from RF amplifier to the accelerator structure and beam but direct any power reflected back to a dummy load. They are used in the high-power RF systems of particle accelerators to protect the expensive RF amplifiers. High-power particle accelerators, in conjunction with neutron-producing targets and subcritical multiplying assemblies, can be used to produce significant quantities of plutonium.

Non-nuclear uses: There are rare research applications.

7. **Radiofrequency (RF) window systems with high power-handling capability**

Proposed action: New DUL entry.

Proposed control language: Radiofrequency (RF) windows that are capable of continuously coupling kW or greater average power at a frequency between 400 MHz and 1.5 GHz and operating with vacuum on one side and atmospheric or greater gas pressure on the other side.

Technical Note**: *It is not the intent of this entry to control the raw material the RF windows are made from. The control applies to material pre-cut to mount in an RF window frame and to windows mounted in frames, sized for waveguide connection, and equipped for vacuum sealing. Most such frames will include connections for liquid cooling.***

Reasons for control: RF windows allow coupling high levels of RF power from power amplifiers into waveguides and from waveguides into accelerator structures while providing vacuum isolation. They are an essential component in many types of particle accelerators. High-power particle accelerators, in conjunction with neutron-producing targets and subcritical multiplying assemblies, can be used to produce significant quantities of plutonium.

Non-nuclear uses: There are some specialized research applications.