Development of Pellet Fueling Systems and Associated Technologies at ORNL – Past And Present

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March 15, 2010

Many ORNL Technical Staff Has Contributed to this Specialized Field of Research over the Last 35 Years

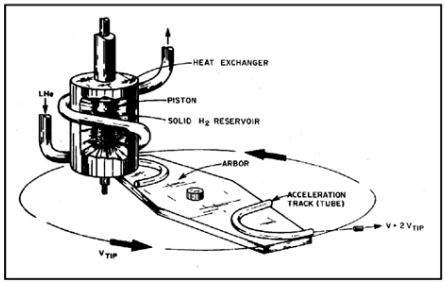
- **Stan Milora and Chris Foster pioneered the pellet fueling work**

- **Present team**
  - **L.R. Baylor, S.K. Combs, J.B.O. Caughman, M. Cole, N. Commaux, D.T. Fehling, C.R. Foust, T.J. Jernigan, J.M. McGill, S.J. Meitner, and D.A. Rasmussen**

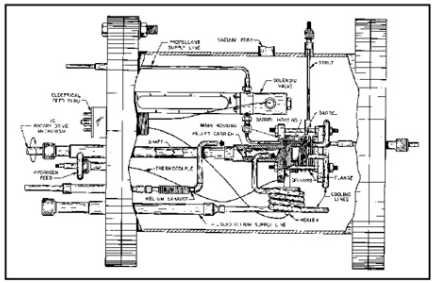
- **Previous key contributors**
  - **P.W. Fisher, M.J. Gouge, A.L. Qualls, D.D. Schuresko, C.E. Thomas, J.B. Wilgen, and many others**

Main Objective of Pellet Fueling R&D Has Always Been to Develop Systems for Fusion Experiments

First Experimental Centrifuge

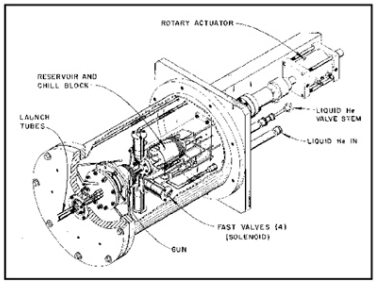


Single-Pellet Gas Gun



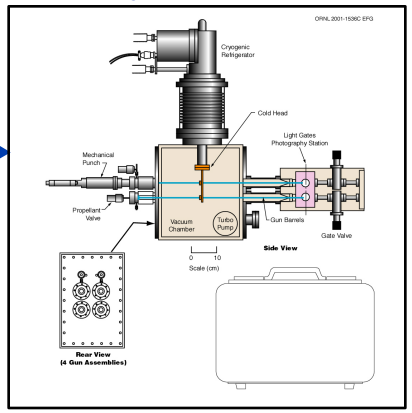
• ISX-A

4-Pellet Gas Gun



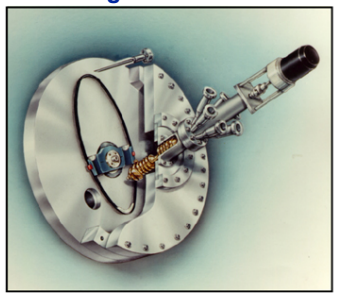
• PDX • ISX-B • Alcator-C • TEXT

Pellet Injector in a Suitcase



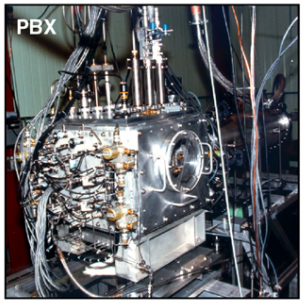
• MST • TJ-II (in progress)

Centrifuge



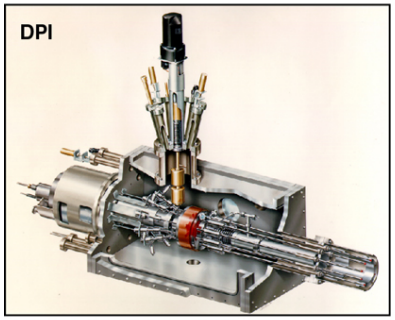
• D-III

Since First-Generation Injectors, Significant Developments Have Been Made in Performance Parameters and Reliability



8-Pellet Gas Gun

• ATF • PBX • GAMMA-10



• TFTR (RPI, DPI, and TPI)

Centrifuge

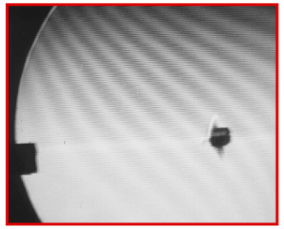
• Tore Supra

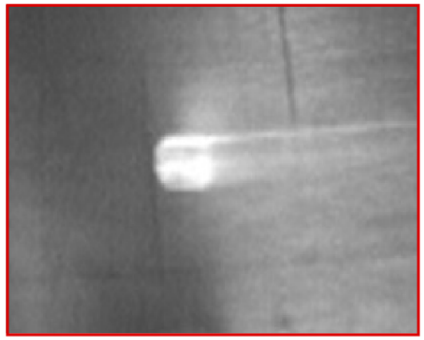
• JET • DIII-D

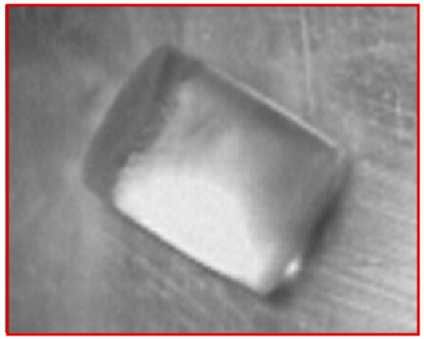
Pellet Sizes Are Relevant for Fueling Applications on Any Present Experimental Fusion Device and Future Fusion Reactors

ORNL 2000-1170C EFG

Small Innovative Confinement Experiments	**1-mm-diam ~5 x 10^{19} D^o**
DIII-D	**2.7-mm-diam ~10^{21} D^o**
Reactor	**10-mm-diam ~5 x 10^{22} D^o**



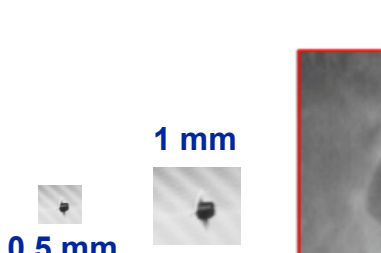


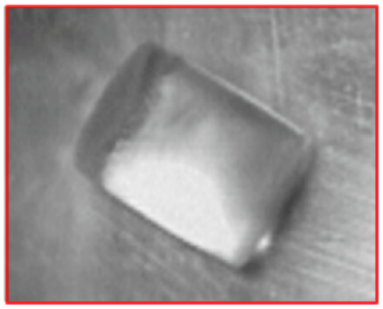


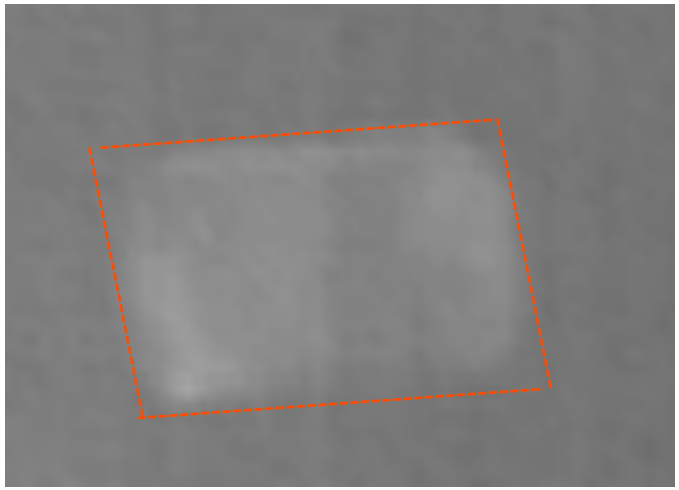
Damage from 6-mm pellet

(Photographs of In-flight D_2 Pellets; Nominal Sizes Are Listed)

Two Recent Applications Require Extensive of Pellet Sizes – Smallest and Largest D2 Pellets Ever Produced in Program







Small pellets for plasma fueling experiments on TJ-II

Large pellets for disruption mitigation experiments on DIII-D

Outline

- Background and basic pellet injector technology
  - Hydrogen properties
  - Ice/pellet formation techniques
  - Selected Acceleration techniques

- R&D topics covered here
  - Three-barrel repeating pneumatic injector – multiple machine guns
  - Compact four-barrel pipe gun injector – pellets in a suitcase
  - High-speed pellet injectors – two-stage light gas guns
  - HFS/inside launch pellet injection technology – pellets via roller coasters
  - New high-speed camera

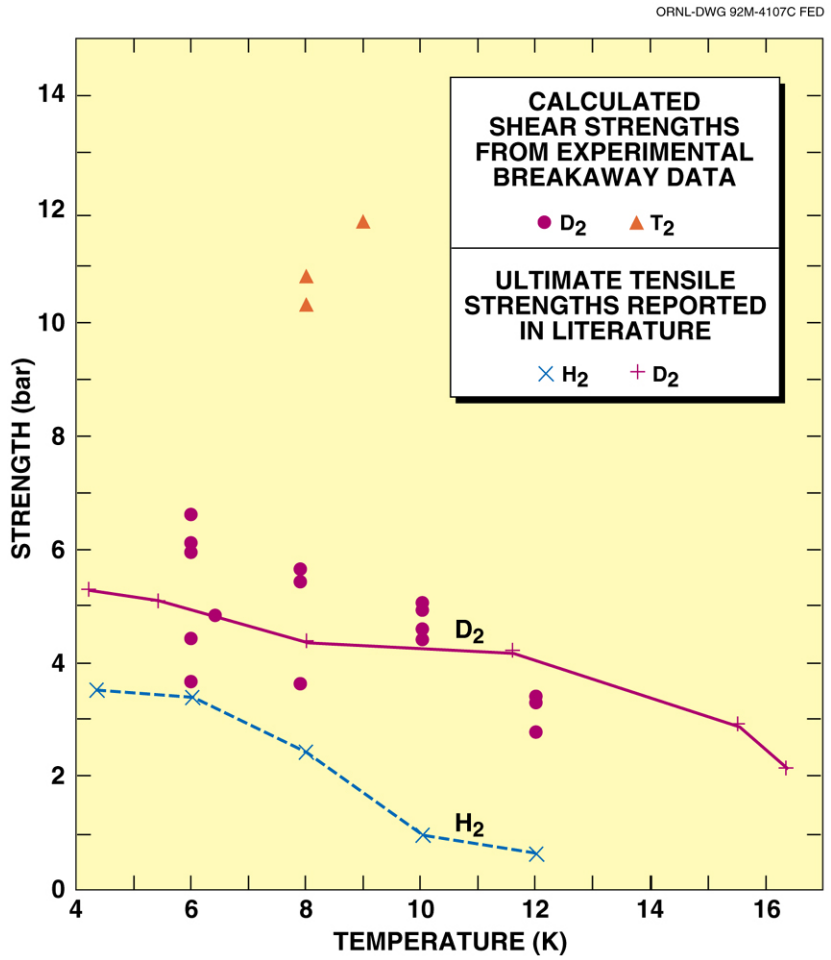
- Other Pellet Related R&D topics
  - ELM pacing pellets – previously covered by L.R. Baylor
  - ITER Pellet Injector – previously covered by D.A. Rasmussen
  - Long-pulse/steady-state pellet feed systems – future talk by S. J. Meitner?
  - Disruption Mitigation Support for DIII-D and ITER – future talk by T.J. Jernigan?
  - Tritium and DT pellet studies – future talk by P.W. Fisher or M.J. Gouge?

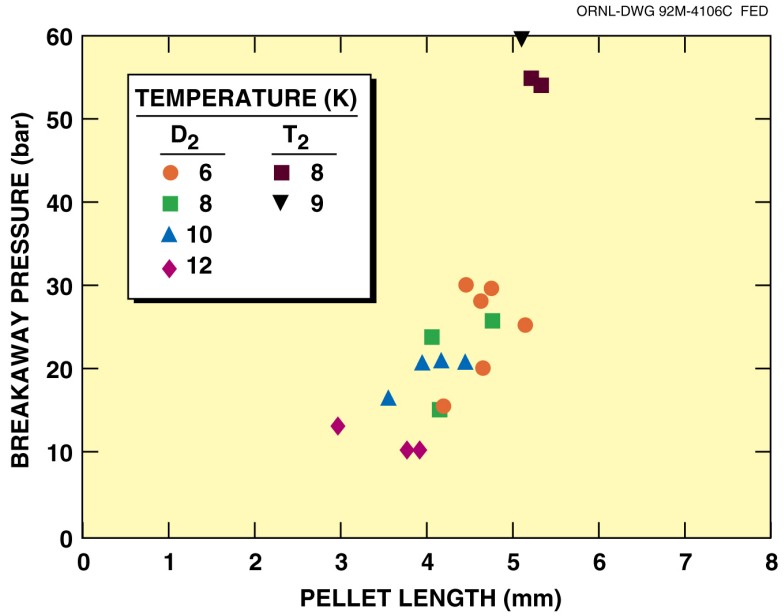
Properties of Hydrogen Isotopes

Isotope	Molecular weight (g/mol)	Critical-point temperature (K)	Triple-point temperature (K)	Triple-point pressure (bar)	Solid parameters	
					Density (g/cm^3)	Ultimate yield strength (bar)
H_2	2.016	33.2	13.9	0.072	0.087	0.7–3.5 (12.0 to 4.2 K)
D_2	4.028	38.3	18.7	0.172	0.20	2.1–5.3 (16.4 to 4.2 K)
T_2	6.032	40.4	20.6	0.216	0.32	10.3 (8.0 K) 11.7 (9.0 K)

- Reported strengths for hydrogen and deuterium at 8 K are 2.4 and 4.4 bar, respectively
- Tritium strength is estimated from breakaway pressures for tritium pellets in pipe-gun experiments (Fisher et al.)

Strength Data for Hydrogen Ice

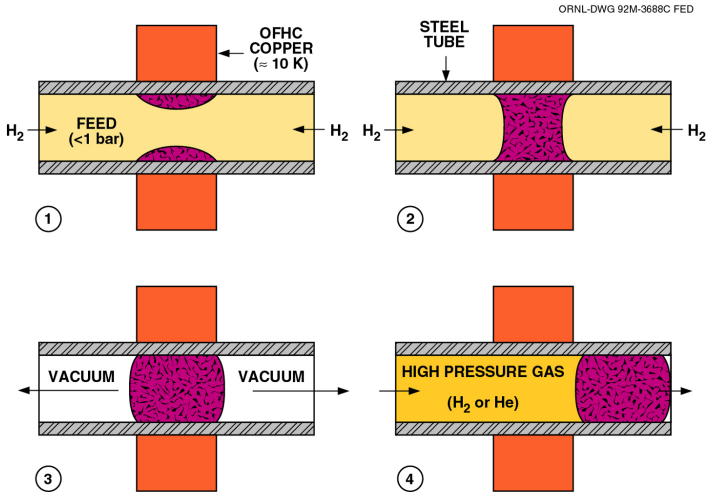




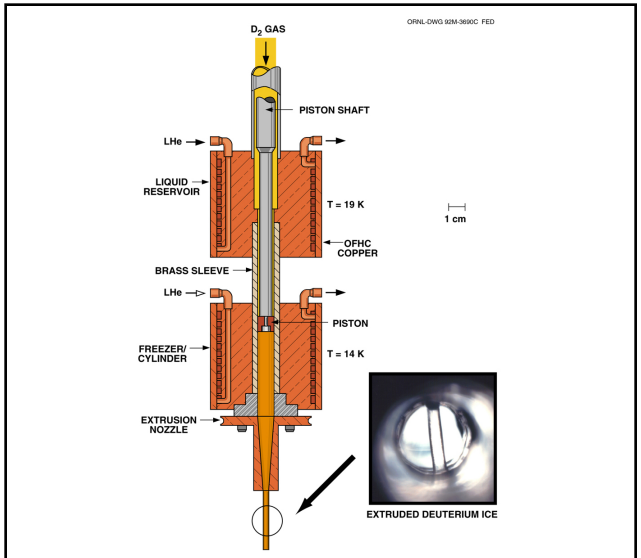
$$\sigma = \frac{P_b D_p}{4 L_p}$$

σ = Pellet shear strength
P_b = Breakaway pressure
D_p = Pellet diameter
L_p = Pellet length

Ice/Pellet Formation Techniques

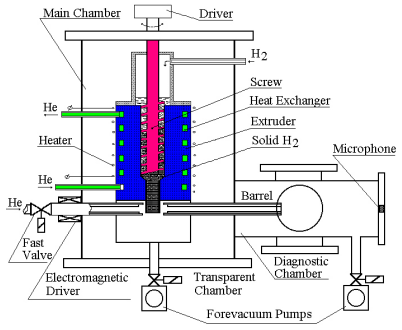


Pipe Gun – Simplest Pellet Injector
(Limited Number of Pellets)

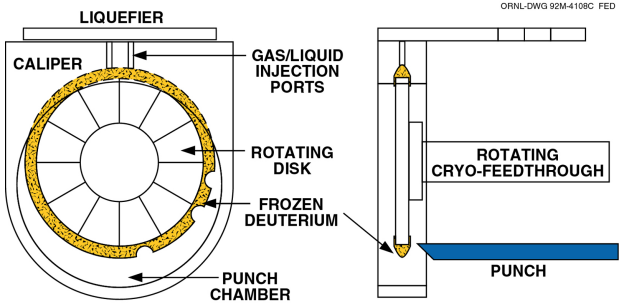


Basic Extruder – Long-Pulse Applications
(Multiple Units – Steady-State Applications)

Russian Company: (I. Viniar)



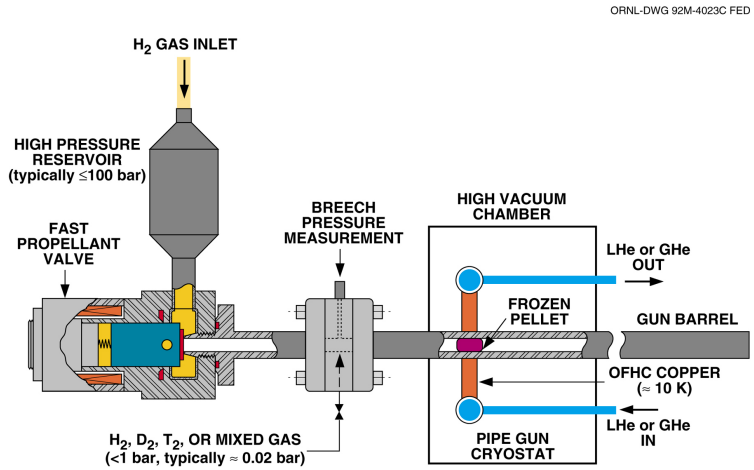
Screw Extruder – Steady-State Applications
(ORNL is working on Twin-Screw Extruder)



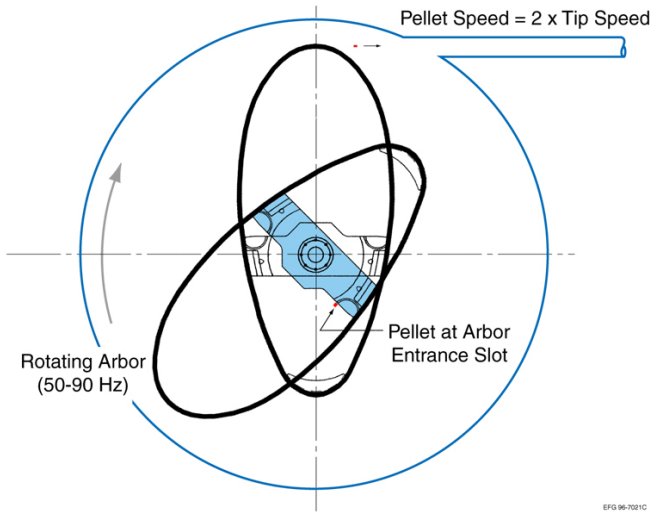
Zamboni Machine – Long-Pulse Applications

Acceleration Techniques

- **Standard injectors**
  - **Light gas gun (single-stage pneumatic device); speeds up to 2 km/s**



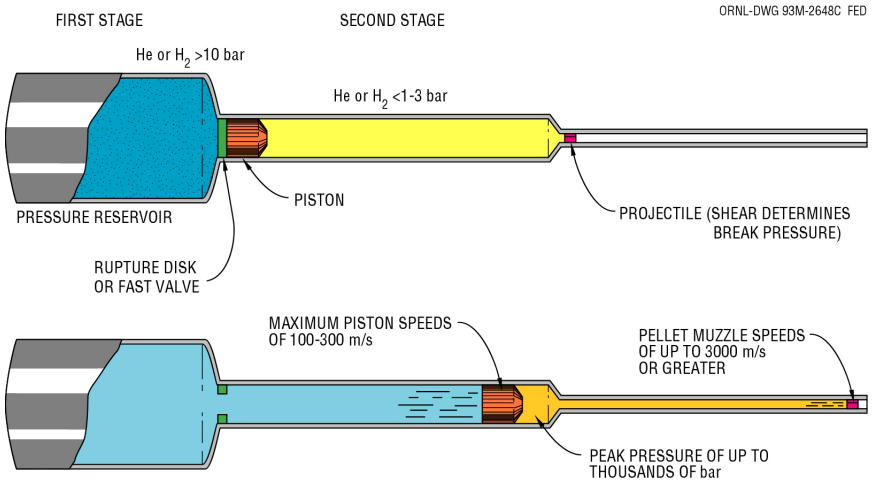
  - **Centrifuge (mechanical device); speeds up to 1.2 km/s**



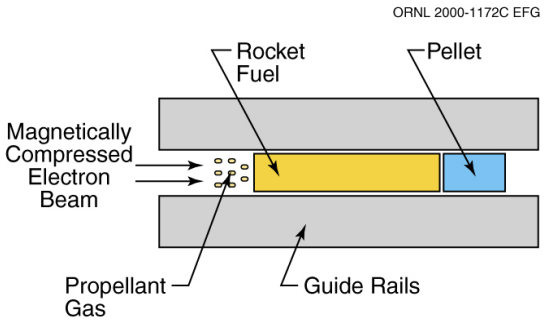
In the original ITER baseline design, the centrifuge was the pellet acceleration technique of choice. However, such devices have not been able to demonstrate the required reliability level (~100%) of delivering intact pellets to plasmas in fusion experiments to date. Thus, the light gas gun is now part of the ITER baseline pellet injector design, with the U.S. and ORNL having responsibility for this task.

Acceleration Techniques (continued)

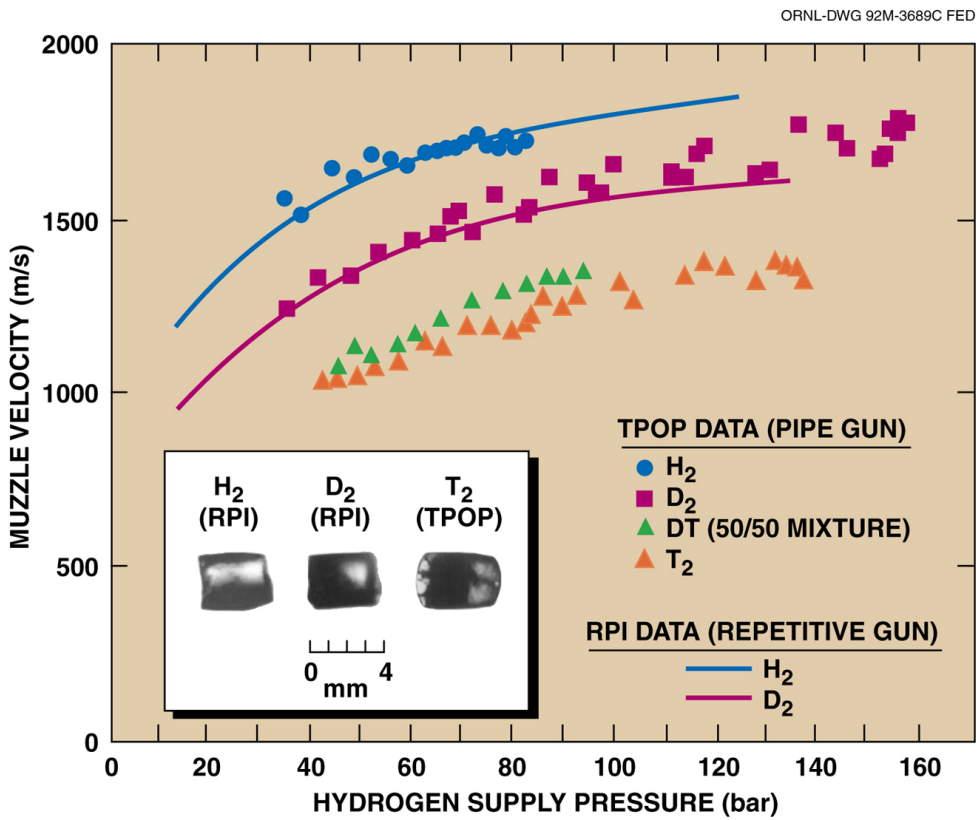
- **High-speed injectors**
  - **Two-stage light gas gun (two-stage pneumatic device); speeds >4 km/s routinely achieved at Tore Supra**



  - **Electrothermal (CRADA with UTRON, Inc.)**
  - **Rail gun (University of Illinois, K. Kim)**
  - **Electron-beam heated rocket pioneered at ORNL (no activity since 1992)**



Pellet Speed Data for Hydrogen Ice Accelerated with Light Gas Guns

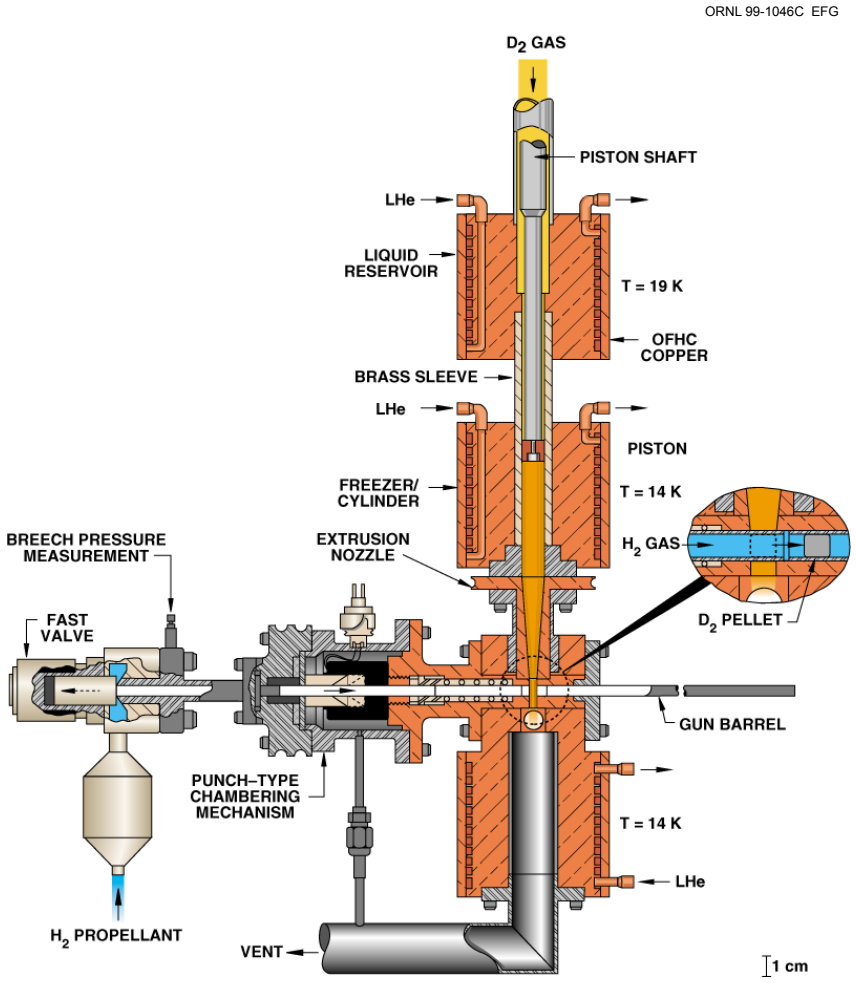


$$U(t) = \frac{2C_0}{\gamma - 1}\left\{1 - \left[1 + \frac{(\gamma+1)A_p}{2MC_0} P_0 t\right]^{-(\gamma-1)/(\gamma+1)}\right\}$$

- Tritium work was carried at TSTA in Los Alamos (facility has since been shut down); principal investigators were Paul Fisher and Mike Gouge
- Ideal gun equation
  - Assuming pellet accelerates in infinite tube of constant cross section, motion of pellet governed by propagation of simple rarefaction waves into high-pressure medium
  - Good performance is possible with relatively low forces because the projectile mass is low
  - High sound speed is required for high-speed operation; this favors low -molecular-weight gases and high temperatures
  - Measured speeds are about 80% of calculated values from model

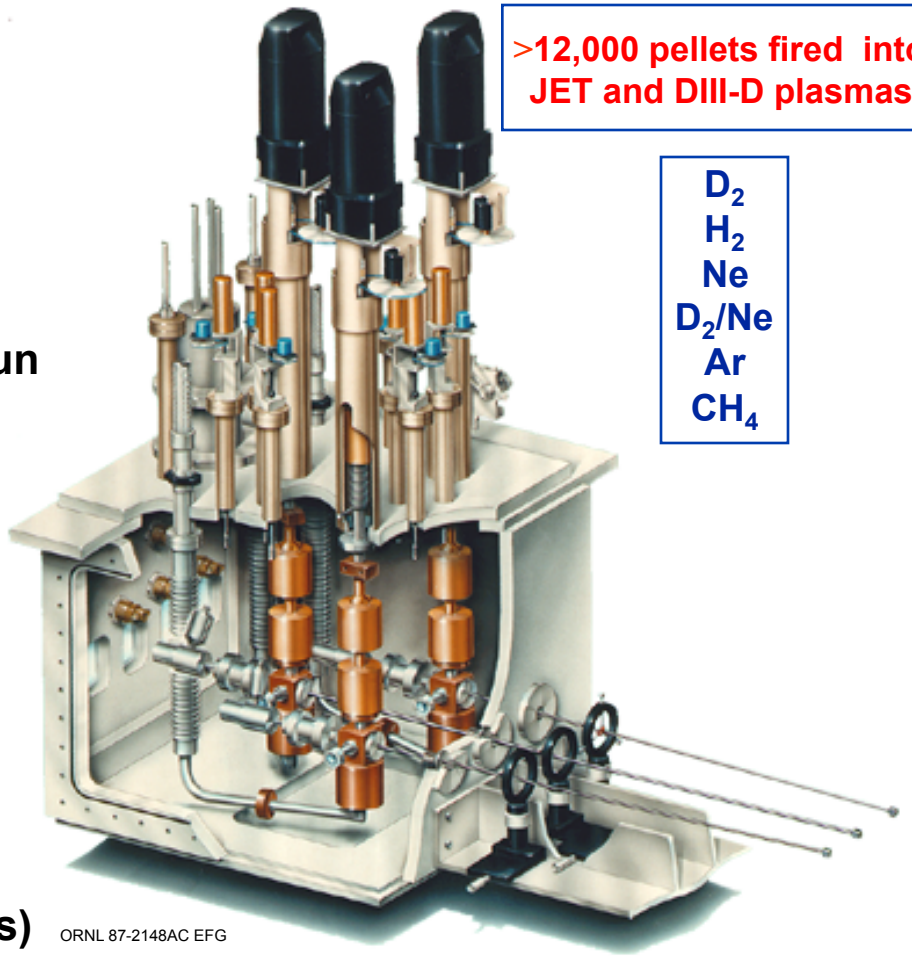
Repeating Pneumatic Injector – Operations

- Injector comprised of cryogenic extruder and gun assembly
- Normal sequence (up to 10 Hz)
  - Extruder provides filament of D_2 ice to gun assembly (≈14 K)
  - Activation of punch-type cutter mechanism chambers pellet
  - Firing of propellant valve admits He/H_2 gas (≈70 bar) for acceleration of pellet in barrel (up to ≈1500 m/s)
  - Reliability of delivering intact pellets to the plasma during fueling experiments has been ≈100% for standard mode of operation



Three-Barrel Repeating Pneumatic Injector

- Fabricated 1986-1987
- Three independent single-stage guns/ extruders
  - Standard speed: 1-1.5 km/s
  - Nominal pellet sizes: 2.7, 4.0 and 6.0 mm
  - Repetition rates: 1 to 10 Hz for each gun
  - Total pellets: 10 to 100 per gun
- Installed on JET in 1987 and used for experiments until 1991
- Returned to ORNL in 1992 and modified/ reconfigured for DIII-D (1.8-mm size added); installed on DIII-D in 1994 and used in experiments since
- Improvements include higher repetition rates (up to ≈20 Hz) and capability to operate at slower speeds (≈100 to 300 m/s)



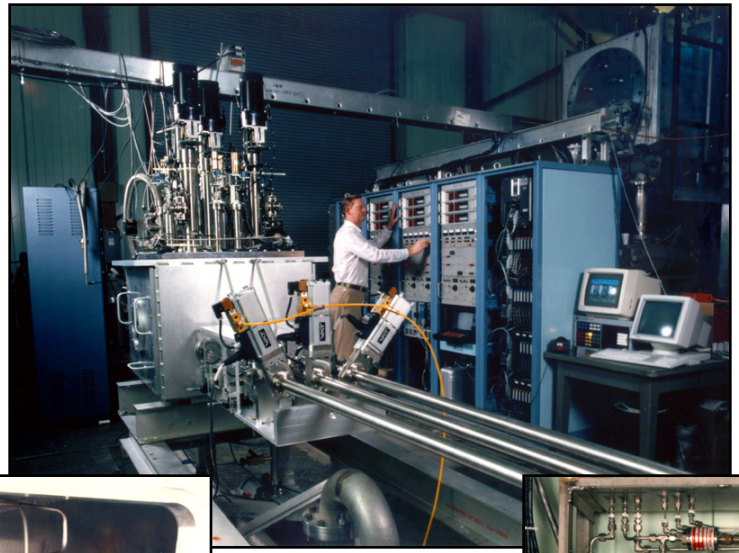
ORNL 87-2148AC EFG

>12,000 pellets fired into JET and DIII-D plasmas

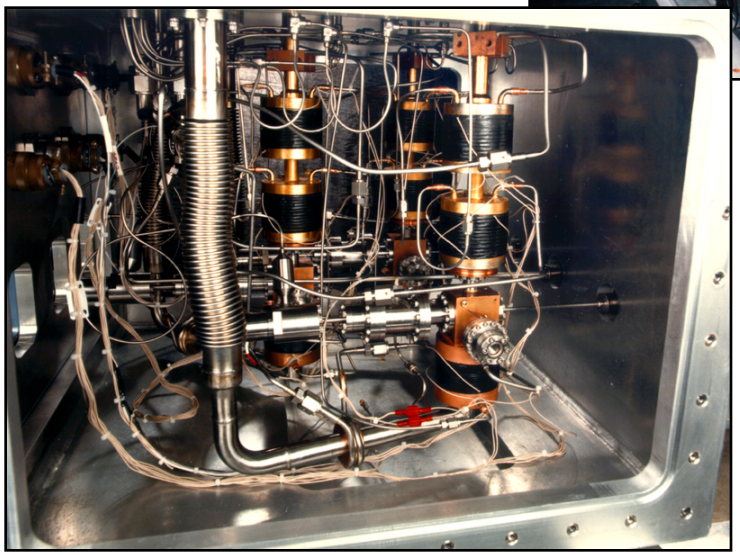
D_2
H_2
Ne
D_2/Ne
Ar
CH_4

Three-Barrel Repeating Pneumatic Injector – Major Components/Systems

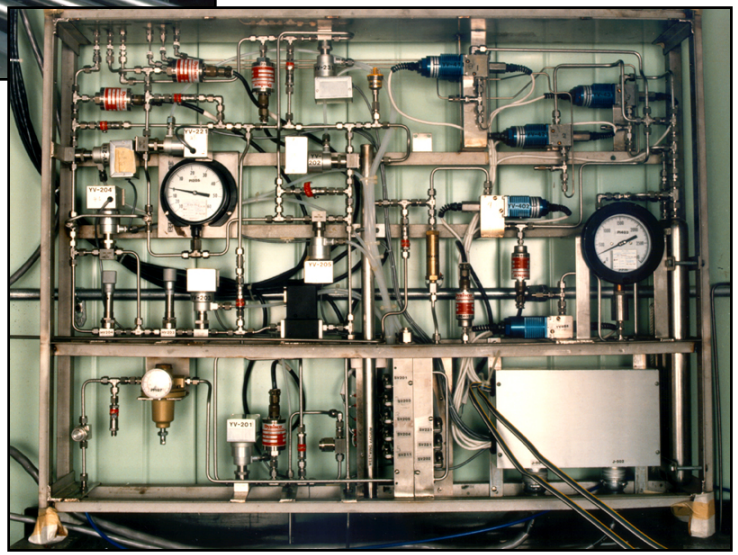
Injector and Control/Data Acquisition Systems



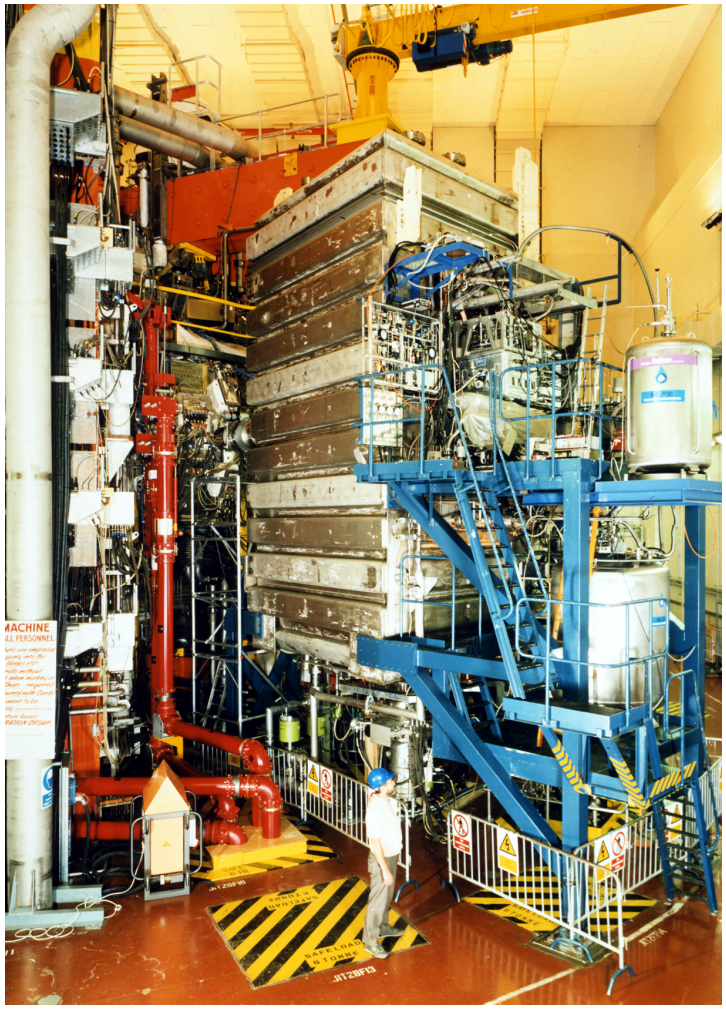
Cryogenic Extruders/ Gun Assemblies



Gas Manifold System

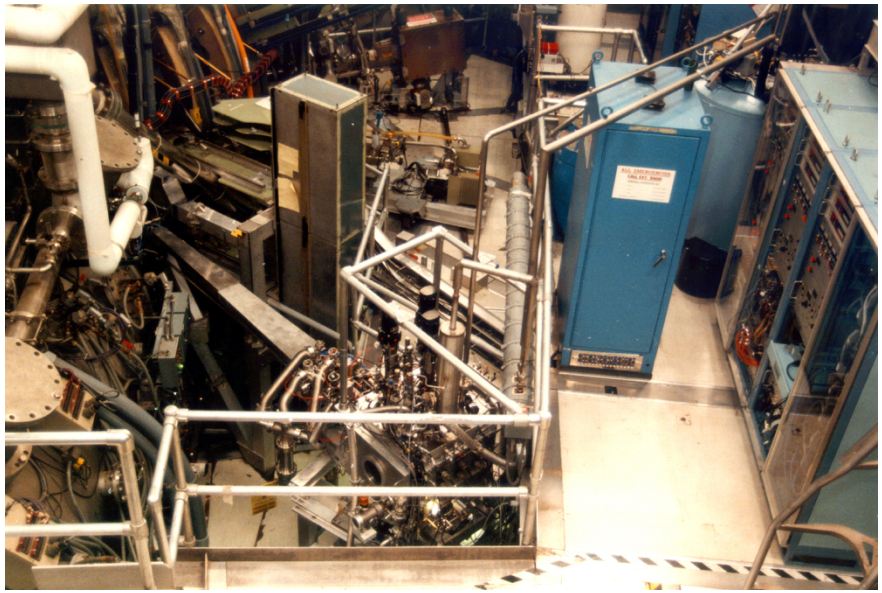


Three-Barrel Repeating Pneumatic Injector – Installations on JET and DIII-D

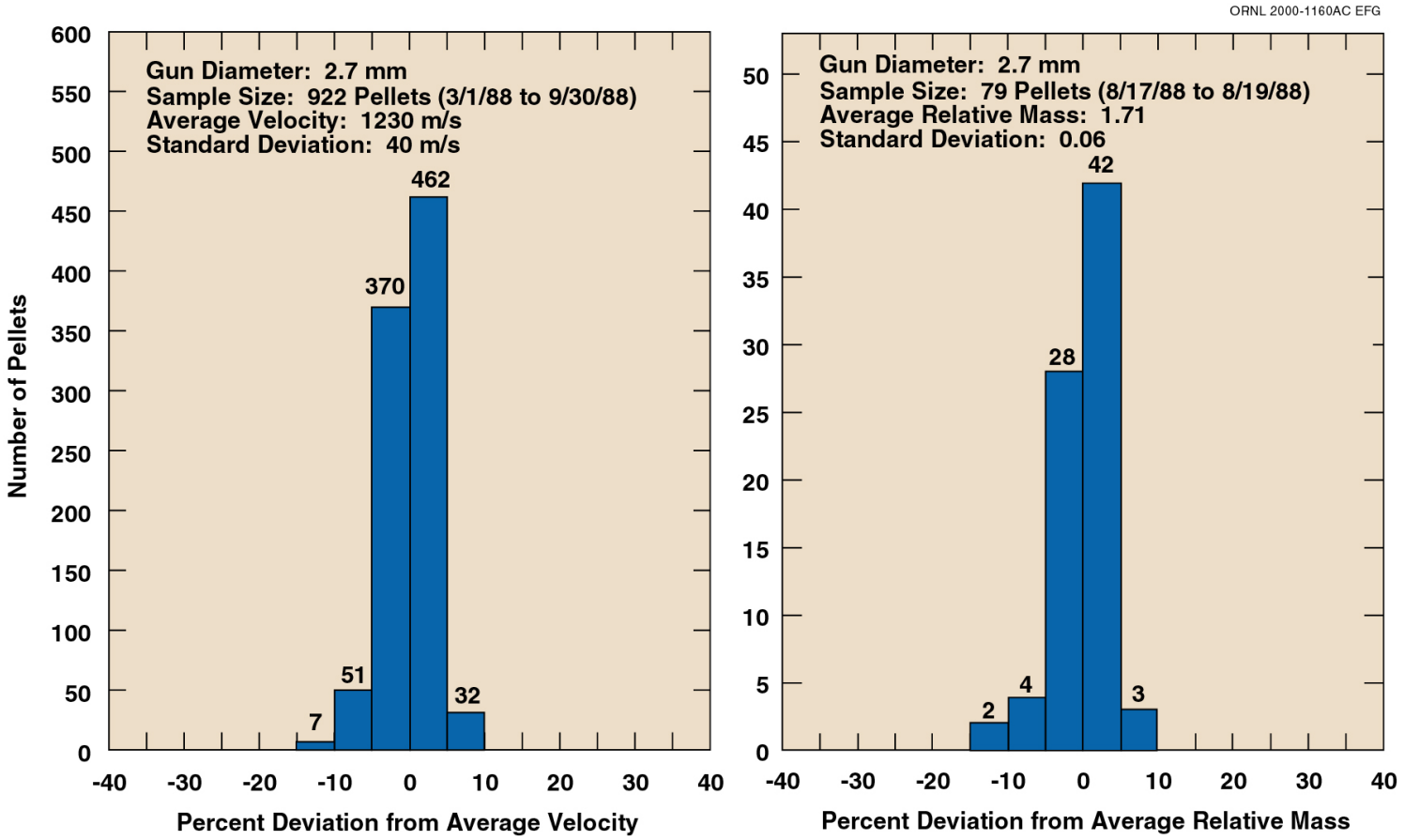


JET

DIII-D

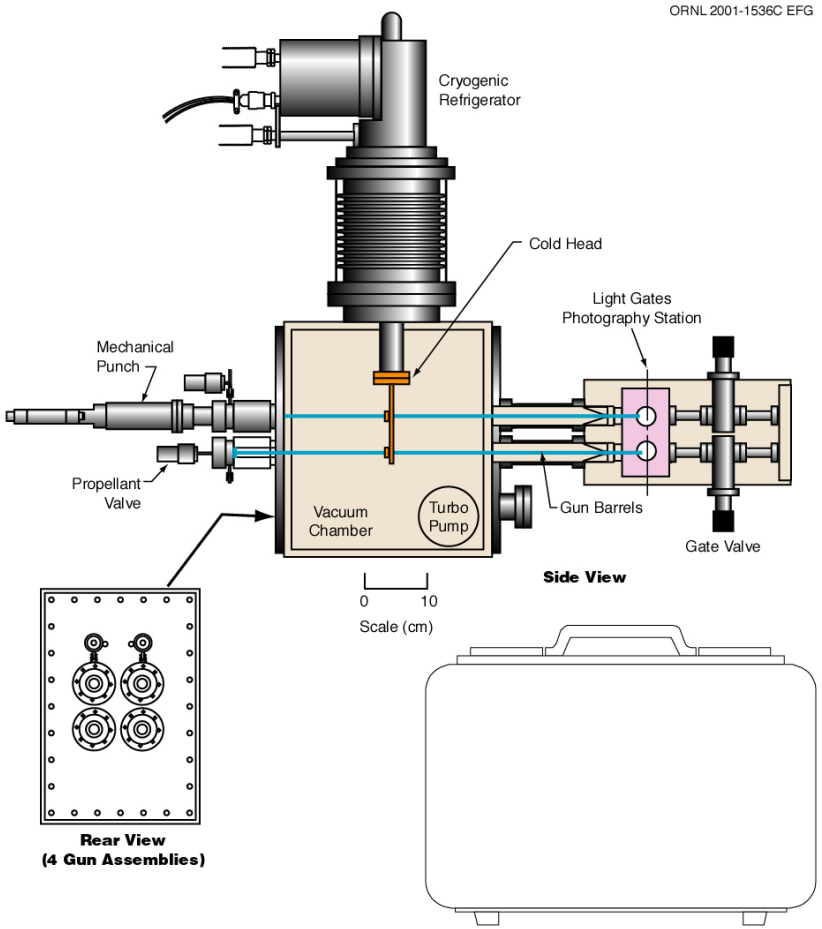


Three-Barrel Injector Delivered Pellets with Consistent Speed and Mass in Fueling Experiments on JET



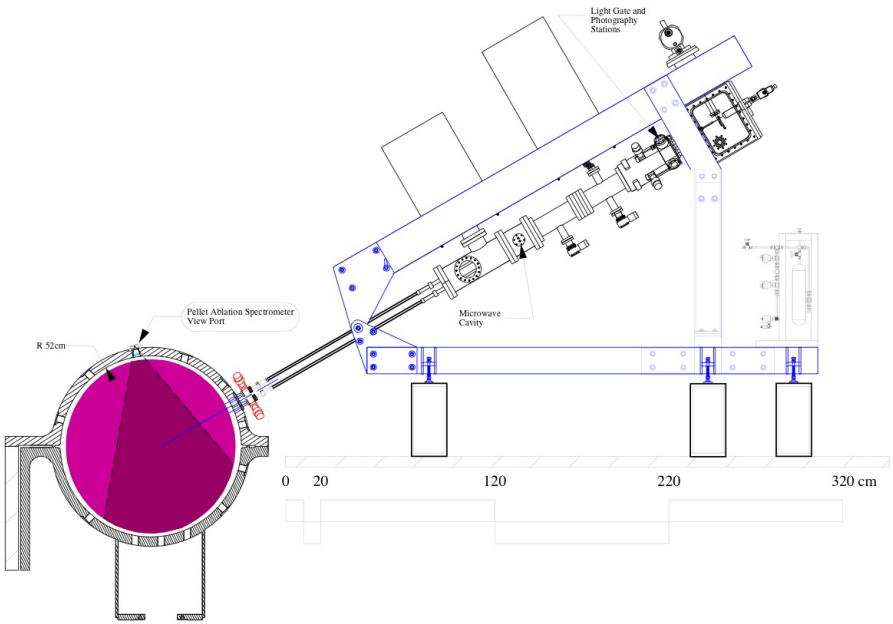
- 90.2% of Pellets with Velocities within ±5% of Average and 99.2% within ±10%
- 88.6% of Pellets with Masses within ±5% of Average and 97.5% within ±10%

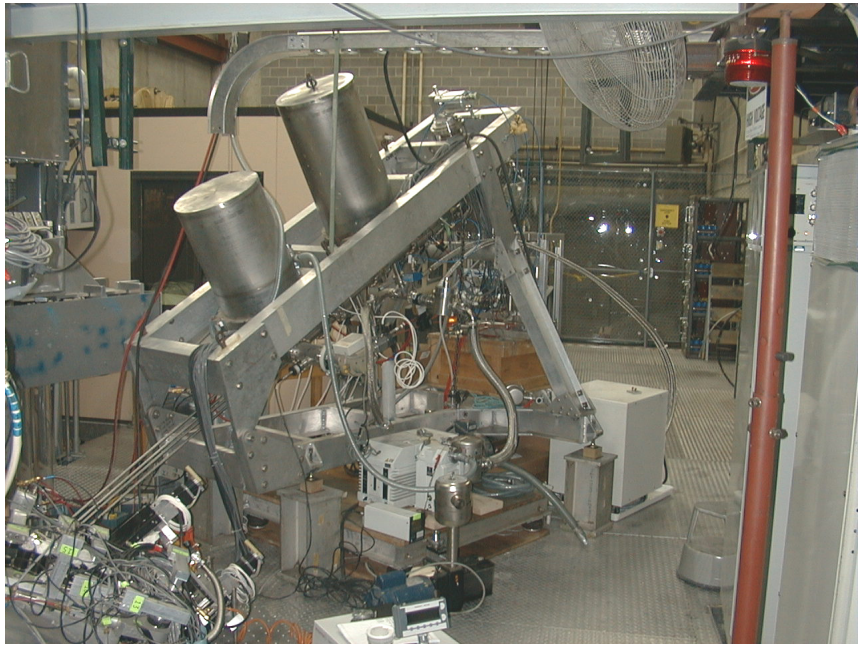
"Pellet Injector in a Suitcase"



- **Features**
  - Compact size and portable
  - Low construction/operating costs
  - Cooled with cryogenic refrigerator for simple operations
  - 4-barrel capability (1 to 6 mm diam)
  - Design facilitates barrel change-outs (explore different pellet sizes)
  - Fast (>1000 m/s) pellets with closed-coupled propellant valve
  - Slow (≈100 m/s) pellets with mechanical punch
  - Intermediate pellet speeds with punch/valve combination
  - Light gate diagnostics included on barrel exhausts
  - Downstream microwave cavity mass detector (via John Caughman and John Wilgen)

Prototype Used Routinely in Experiments on MST

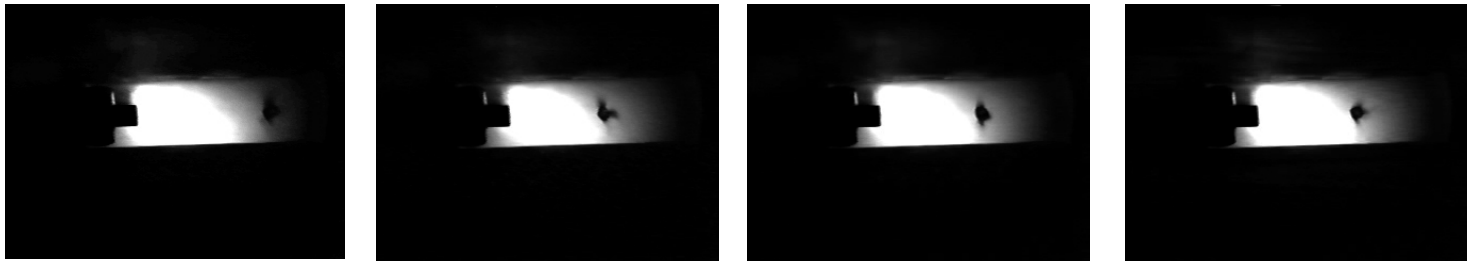




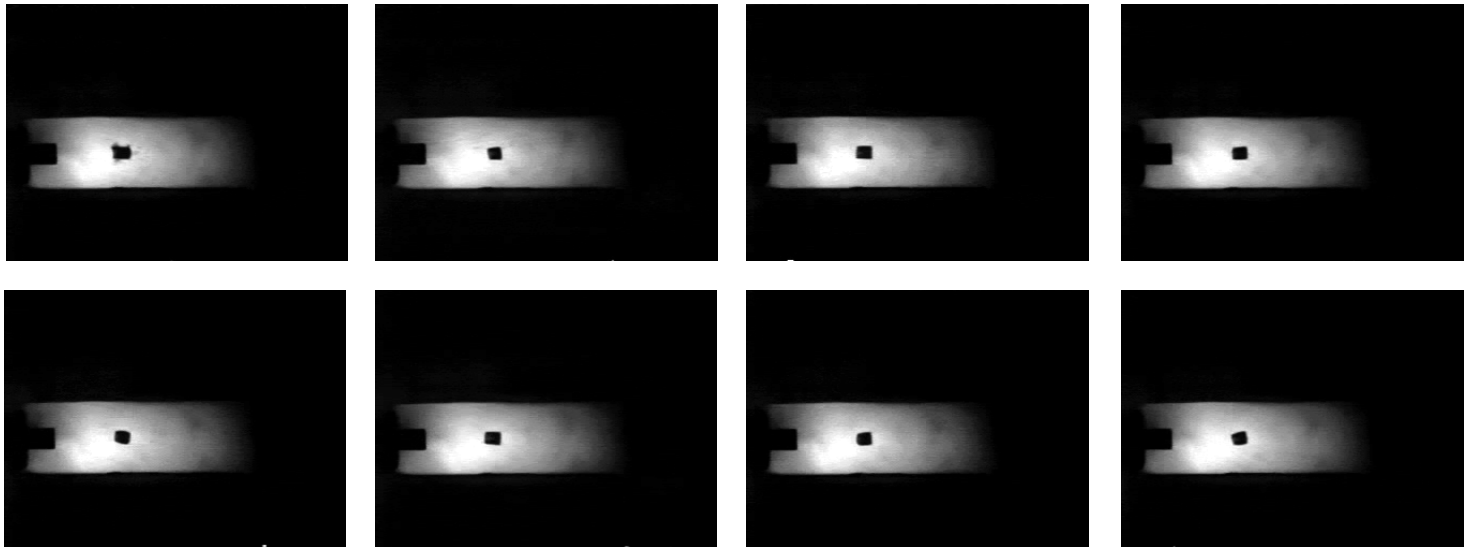
- Injection system installed on MST in 2002
- Full complement of four pellets (available barrel sizes: 1.0, 1.3, 1.6, 1.8. 2.0 mm)
- Special vented gun barrel was developed at ORNL and is now used on the MST injector; this limits pellet acceleration to speeds of ≈500 m/s (with precise delivery times)
- ORNL continues to provide support, including additional pellet and acceleration hardware, that allows maximum flexibility of pellet sizes and speeds for MST experiments

MST Pellet Photos Taken at Gun Muzzle (Bore = 1 mm)

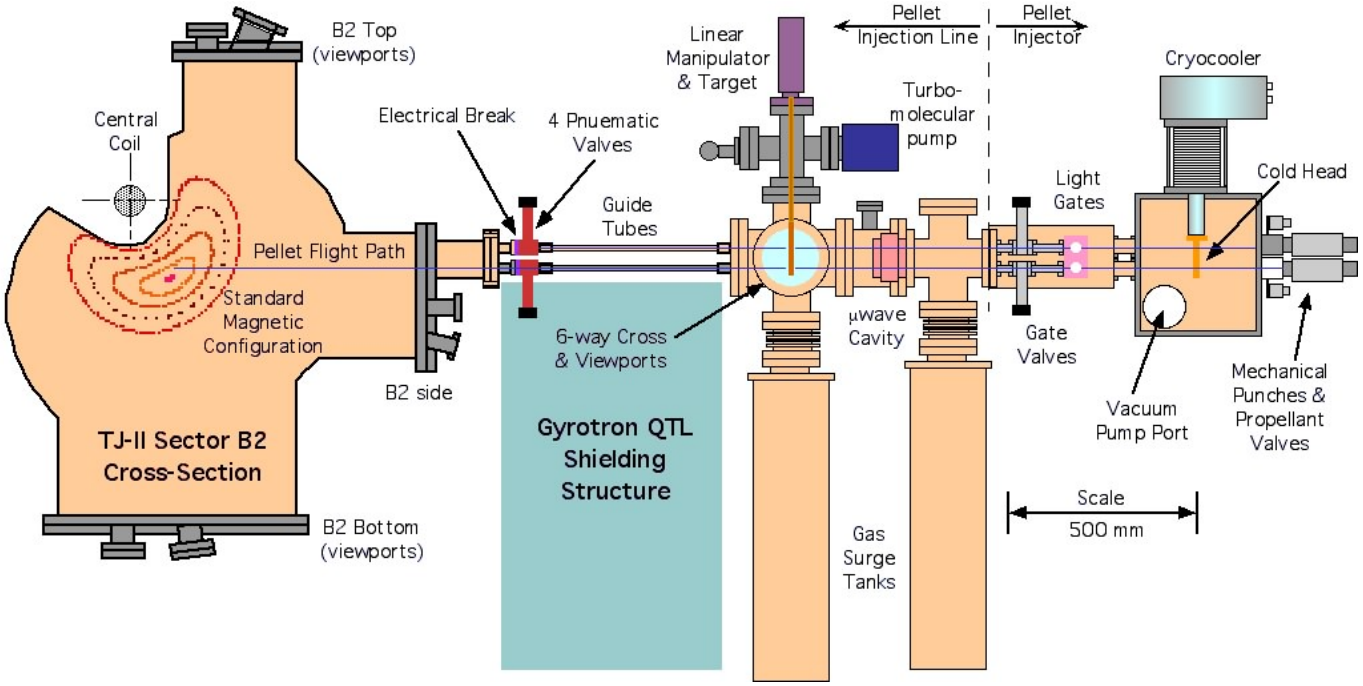
- Gun 1: close-coupled propellant valve (1000 psig hydrogen & pellet speed ≈1000 m/s)



- Gun 4: mechanical punch (pellet speed ≈100 m/s)



ORNL Is Producing a Second Version of the "Pellet Injector in a Suitcase" for TJ-II

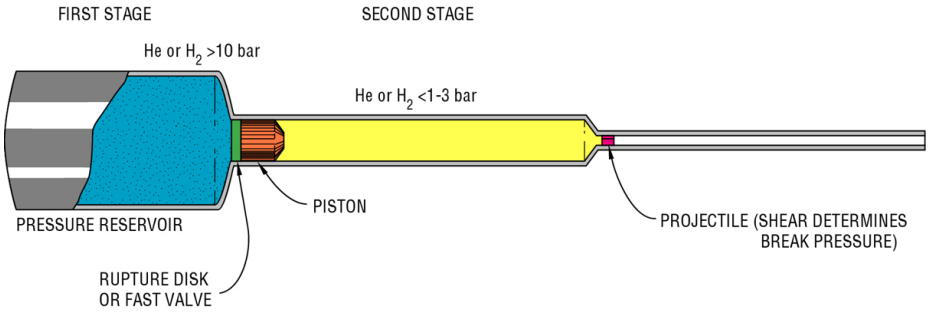


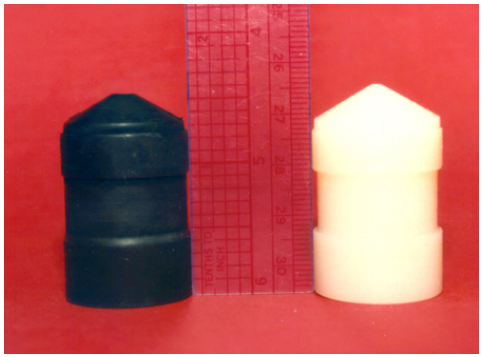
- **System will be equipped with four barrels, and TJ-II will provide most of the support systems (stand, vacuum and ballast tanks, cryo-cooler, computer control, and some I&C)**
- **Reliable operation with pellet size <0.5 mm will be technically challenging**
- **ORNL will test injector thoroughly in the lab and assist in installation and check-out at TJ-II; in addition, ORNL will collaborate on the plasma experiments that utilize the injector**

Two-Stage Light Gas Gun Development – ORNL Highlights

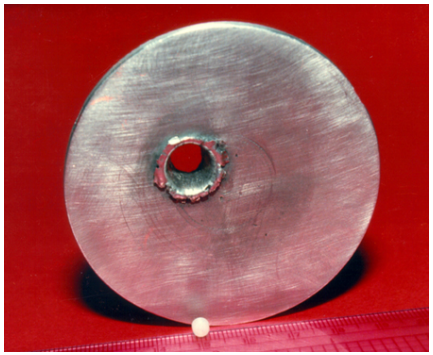
- **Accelerated plastic projectiles (4 and 6 mm) up to 5 km/s (single pellets)**
- **QUICKGUN Algorithm for estimating the performance of two-stage guns developed by Milora et. al**
- **Accelerated D_2 pellets (4 mm) up to 3 km/s (single pellets)**
- **Operation of repetitive two-stage gun demonstrated at 1 Hz and 3 km/s with plastic projectiles (4 mm)**
- **Two-stage light gas gun developed for TPI and installed/operated on TFTR in 1992**
- **Sabot separation technique demonstrated with plastic pusher/pellet arrangement (6 mm) at speeds of >3 km/s**
- **In an ORNL/ENEA Frascati collaboration (1991-1994), operation of repetitive two-stage gun demonstrated at 1 Hz and up to 2.5 km/s with D_2 pellets (2.7 mm)**
- **ORNL/ENEA collaboration on high-speed pellet injection systems has resumed with development of a compact 4-pellet system for IGNITOR (2005 – present)**

Two-Stage Light Gas Gun Development – Test Results

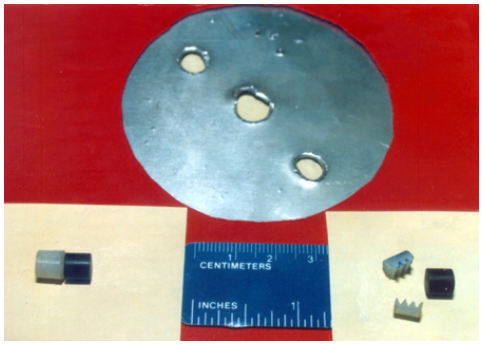




Condition of Nylon Piston Before (Right) and After Shot (Left)

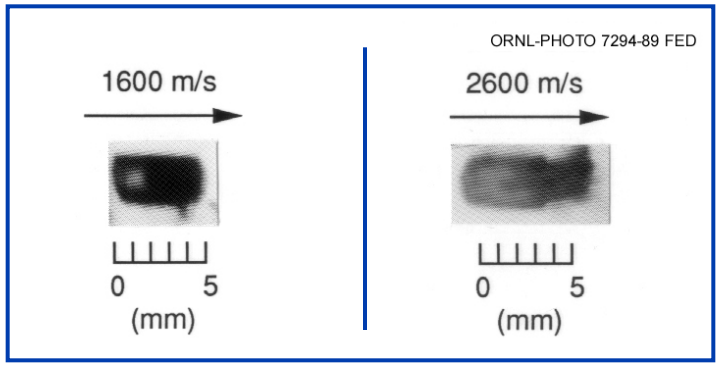


Al Target Plate (4.5-mm Thick) After Impact of 35 mg Nylon Projectile at 4.5 km/s

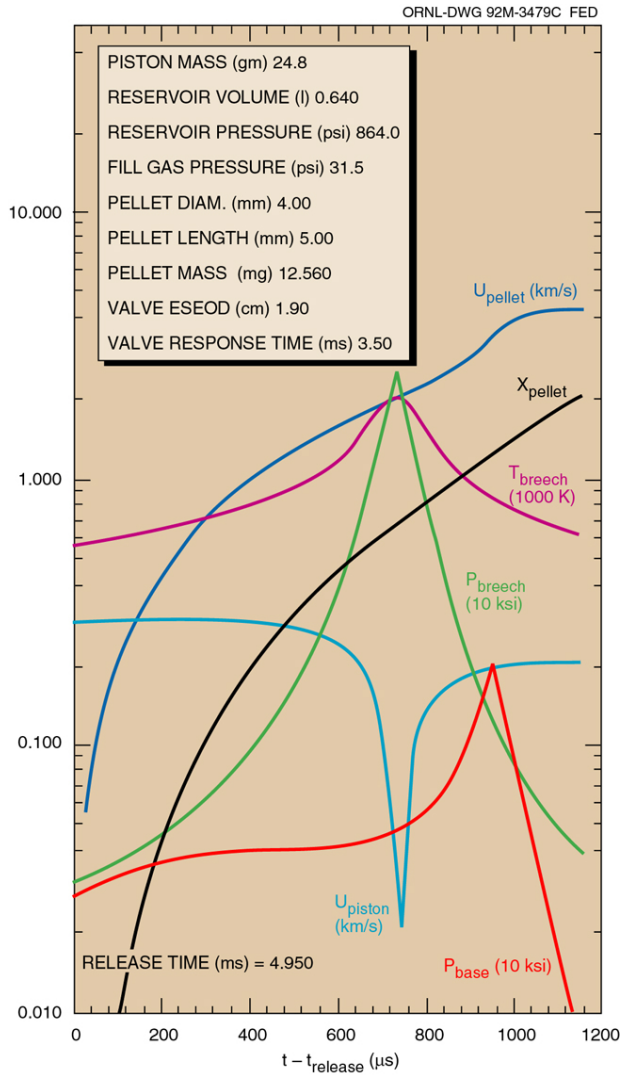


Sabot Separation with 6-mm-Bore Rifled Gun Barrel and Pusher/ Pellet Arrangement

D_2 Pellets



Two-Stage Light Gas Gun Development – QUICKGUN Calculations for 4-mm D_2 Pellet



- **Code was developed by Stan Milora and runs on PCs and used by researchers around the world**
- **Brief description given on next page which shows the abstract from technical memo on code**
- **Modeling efforts like this are crucial to help guide the R&D**

QUICKGUN Abstract (S.L. Milora et al.)

An approximate method is described for solving the equation of motion of a projectile accelerated by a two-stage light gas gun that uses high-pressure (<100-bar) gas from a storage reservoir to drive a piston to moderate speed (<400 m/s) *for* the purpose of compressing the low molecular weight propellant gas (hydrogen or helium) to high pressure (1000 to 10,000 bar) and temperature (1000 to 10,000 K). Zero-dimensional, adiabatic (isentropic) processes are used to describe the time dependence of the ideal gas thermodynamic properties of the storage reservoir and the first and second stages of the system. A one-dimensional model based on an approximate method of characteristics, or wave diagram analysis, for flow with friction (nonisentropic) is used to describe the nonsteady compressible flow processes in the launch tube. Linear approximations are used for the characteristic and fluid particle trajectories by averaging the values of the flow parameters at the breech and at the base of the projectile. An assumed functional form for the Mach number at the breech provides the necessary boundary condition. Results of the Calculation are compared with data obtained from two-stage light gas gun experiments at Oak Ridge National Laboratory for solid deuterium and nylon projectiles with masses ranging from 10 to 35 mg and for projectile speeds between 1.6 and 4.5 km/s. *The* predicted and measured velocities generally agree to within 15%.

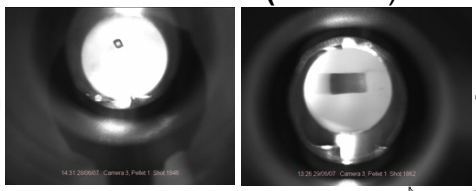
S. L. Milora, S. K. Combs, M. J. Gouge, and R. W. Kincaid, "QUICKGUN: "An Algorithm for Estimating the Performance of Two-Stage Light Gas Guns," Oak Ridge National Laboratory Report, ORNL/TM-11561 (September 1990).

ENEA-Frascati/ORNL Collaboration on Compact, Multiple-Barrel High-Speed Pellet Injector for IGNITOR Experiment

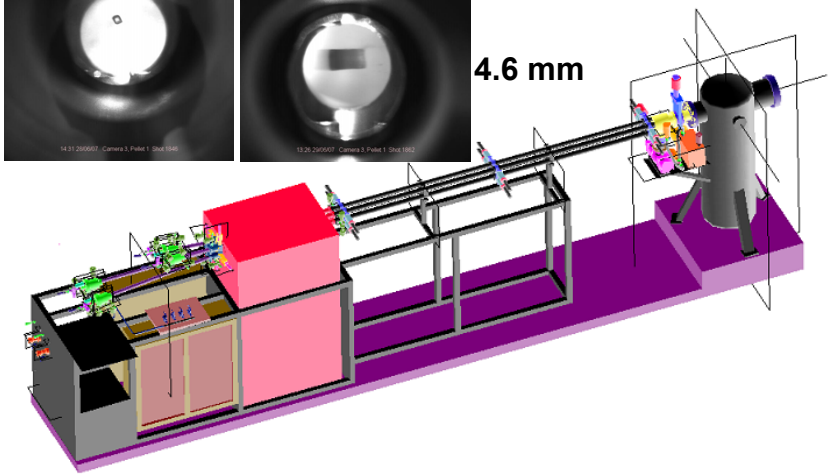
- **No. of pellets: 4**
- **Pellet material/sizes: D_2 / 2 – 5 mm**
- **Pellet speed: 3.5 – 4 km/s (or higher)**
- **Type of cryostat: pipe gun with cryocooler (option for LHe supplement)**
- **Propulsion: two-stage pneumatic guns (special feature of gas pulse shaping)**
- **Diagnostics:piezoelectric ballistic transducers, light gates, in-flight pellet photography, microwave cavity mass detector, and accelerometer impact target**
- **Gas removal system: special design with fast-closing valves (reduces overall size and avoids use of large ballast tanks)**
- **Each party prepared and tested their hardware independently, and the systems have been combined for joint testing at ORNL (three joint experimental campaigns carried out at ORNL to date)**

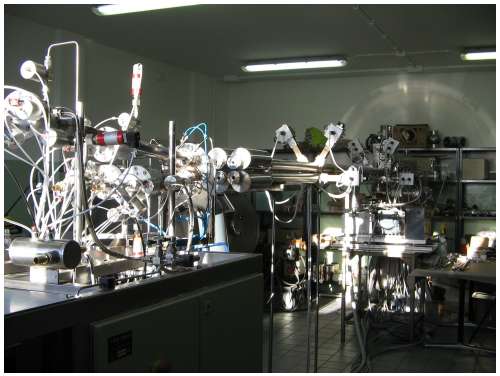
Pellet Photos (≈1 km/s)

2.1 mm

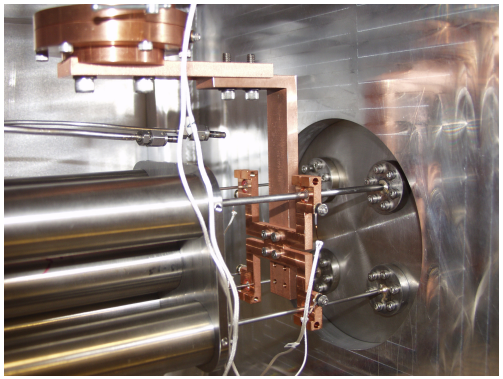


4.6 mm



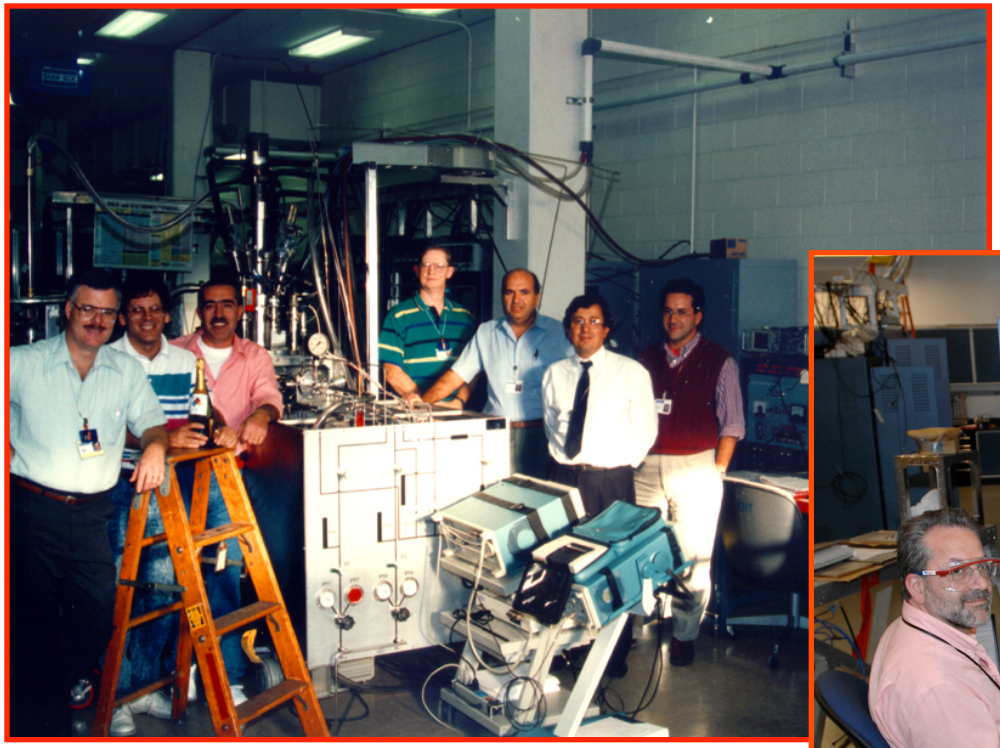


ENEA provides Two-Stage Gun and Gas Removal Components



ORNL provides cryostat/gun barrels and pellet diagnostics

ORNL/ENEA-Frascati Collaboration on High-Speed Pellet Injectors Has Spanned Almost 20 Years



1992 (Y-12)

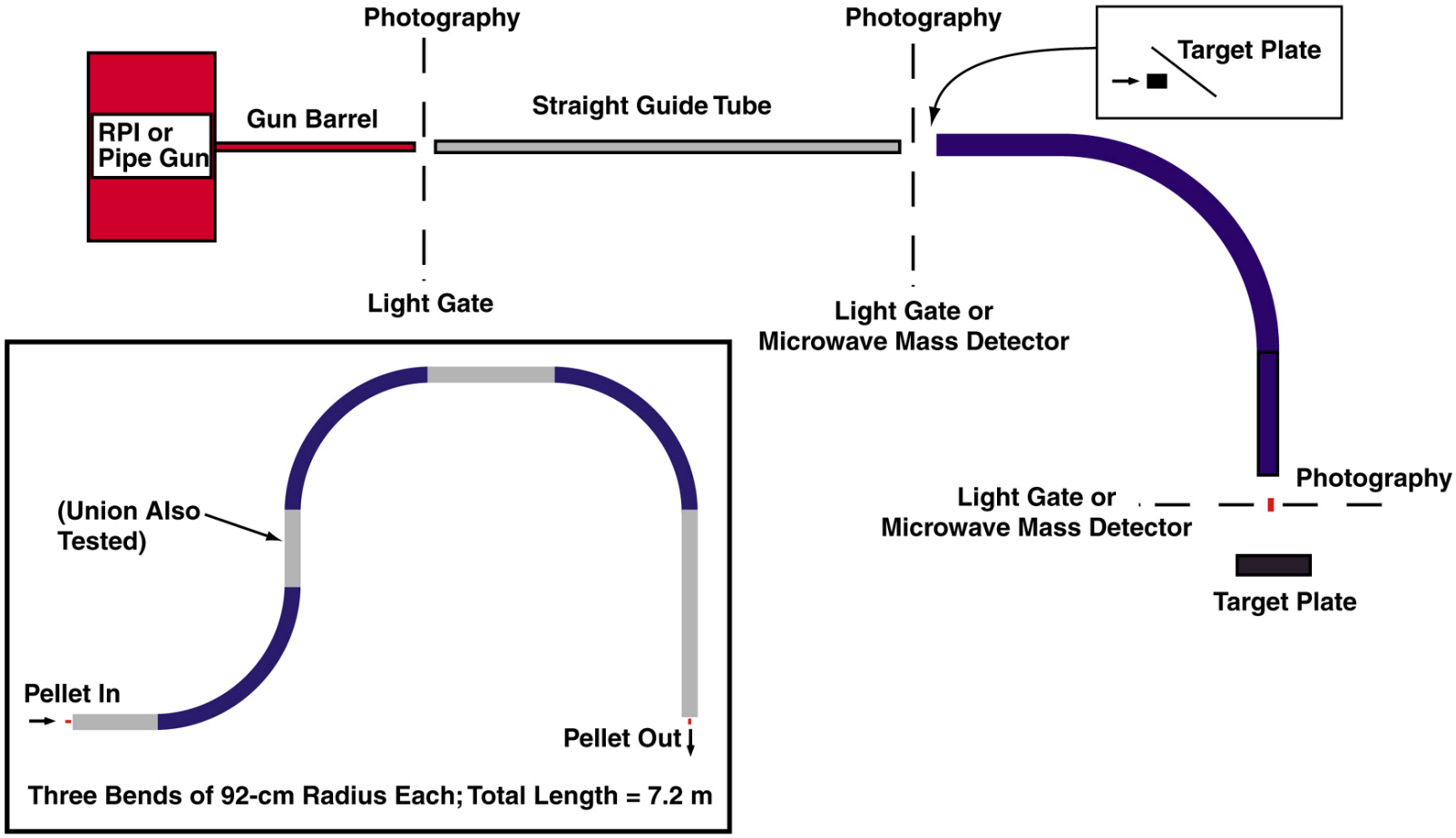
2009 (ORNL)

HFS/Inside Launch Pellet Injection Technology

- Basic impact studies to determine speed limits for pellet collisions with hard surfaces
- Curved guide tube experiments to determine the pellet speed limit for different pellet/tube parameters
- Mock-up of alternative injection schemes for large fusion experiments (supportive data required before proceeding with installations); a few examples will be shown here
  - DIII-D (inside launch and vertical injection)
  - JET (inside launch)
  - ITER (inside launch)

Test Configurations for Experiments with RPI and Pipe Gun; Insets Show Special Setups for Multiple Bends and Impact Tests

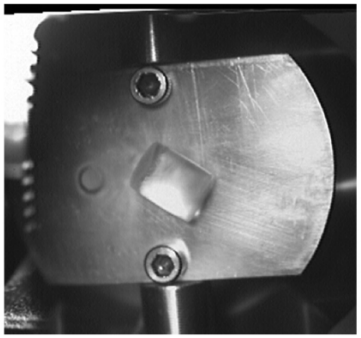
ORNL 98-2256C EFG



Photographs of 10-mm D_2 Pellets after Impact on Inclined Flat Plate

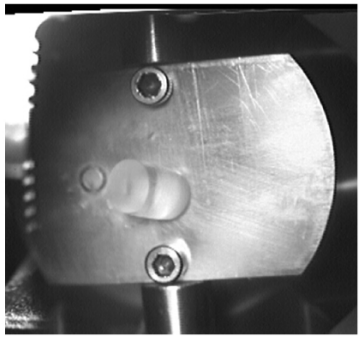
ORNL 98-2265A2C EFG

Shot 1067



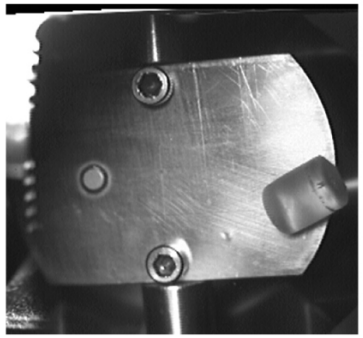
Pellet Speed = 82.1 m/s
Impact Angle = 15°
Normal Velocity = 21.2 m/s

Shot 1069



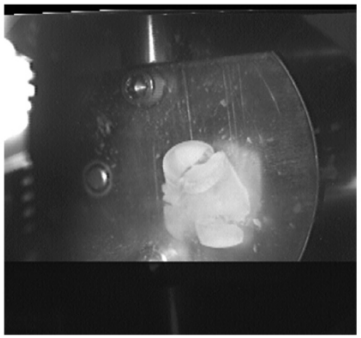
Pellet Speed = 77 m/s
Impact Angle = 15°
Normal Velocity = 20 m/s

Shot 1070 10 mm



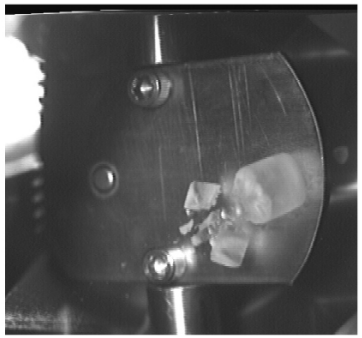
Pellet Speed = 47.8 m/s
Impact Angle = 15°
Normal Velocity = 12.4 m/s

Shot 1072



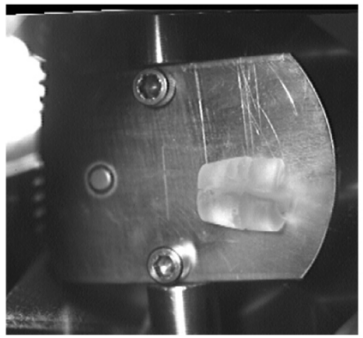
Pellet Speed = 81.1 m/s
Impact Angle = 30°
Normal Velocity = 40.6 m/s

Shot 1074



Pellet Speed = 61.5 m/s
Impact Angle = 30°
Normal Velocity = 30.8 m/s

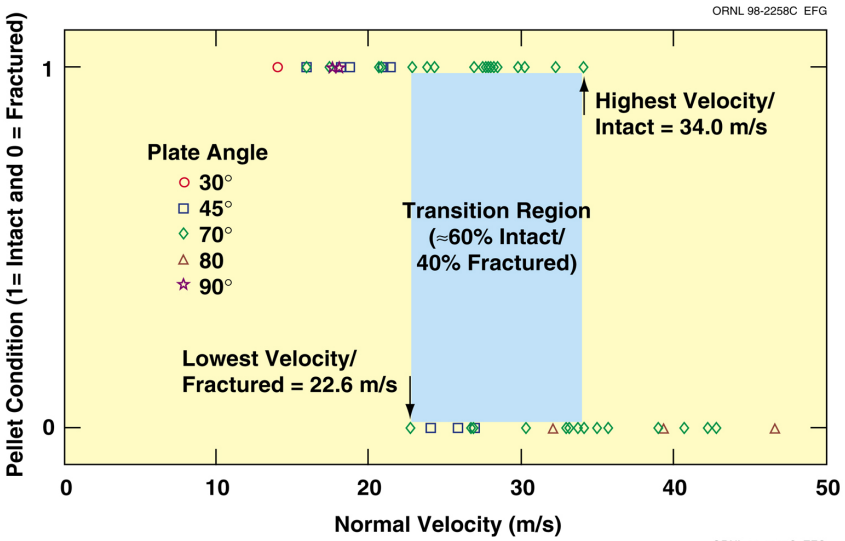
Shot 1076



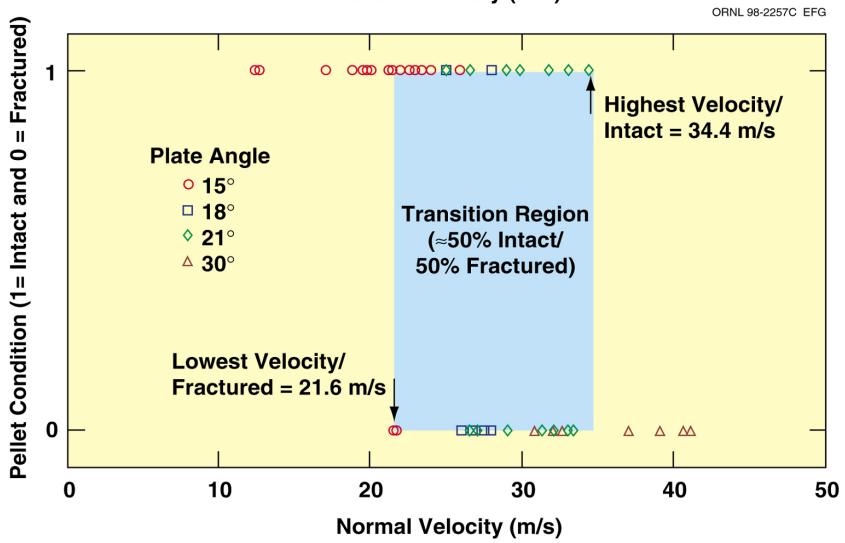
Pellet Speed = 74 m/s
Impact Angle = 21°
Normal Velocity = 26.5 m/s

Impact Test Results for D_2 Pellets on Inclined Stainless Steel Plate

2.7 mm



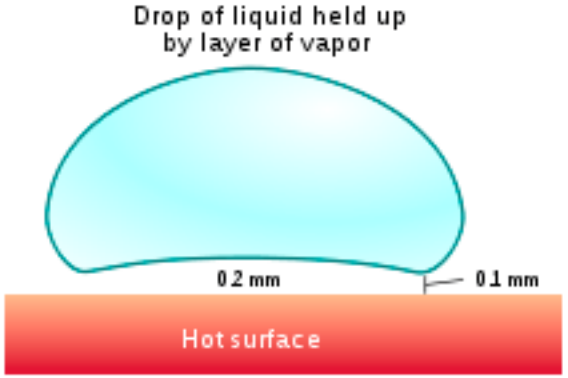
10 mm



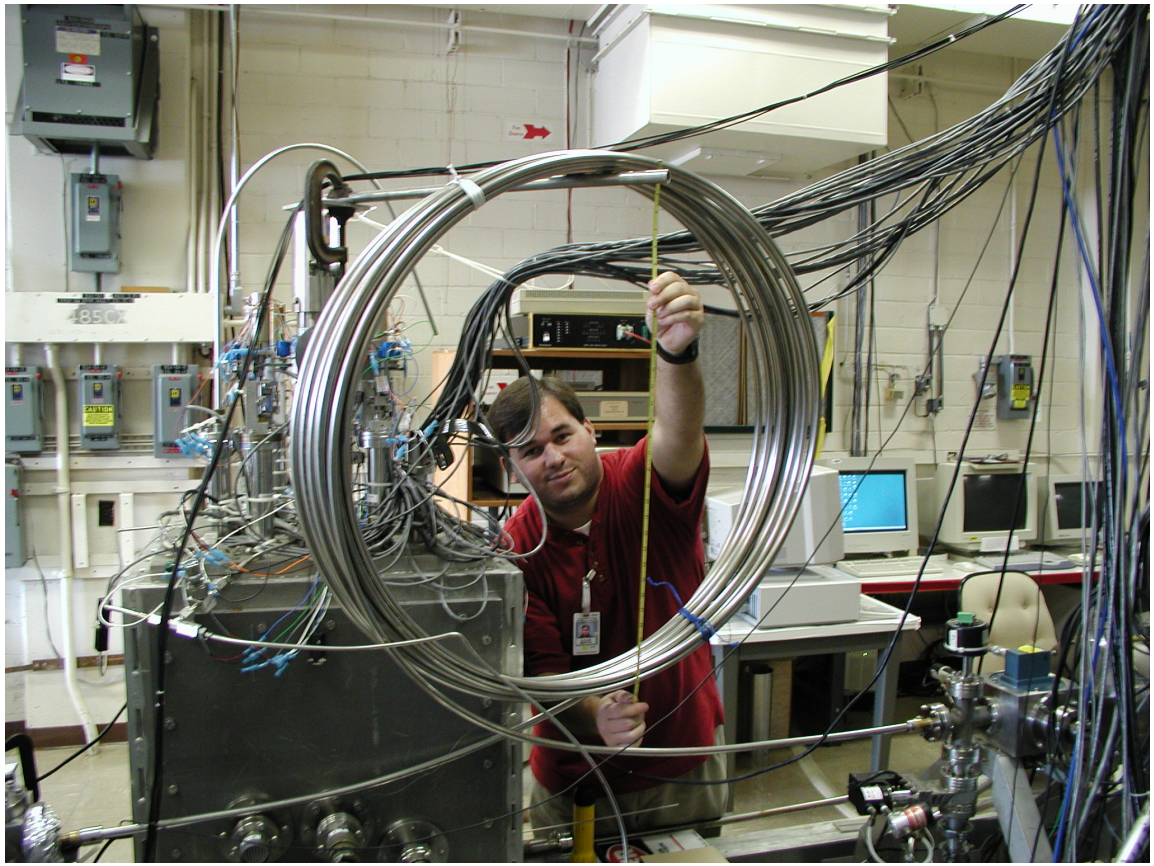
- Almost no difference observed in the speed limit for the two pellet sizes
- Pellets with speeds <22 m/s were intact; pellets with speeds >34 m/s were fractured
- In the transition region, about half of the pellets were fractured

Pellets Can Survive Complex Runs of Transport Tubes with Many Twists and Turns to Arrive Intact at Plasma Boundaries

The Leidenfrost effect is a phenomenon in which a liquid (or a cryogenic frozen "gas"), in near contact with a mass significantly hotter than the liquid's boiling point, produces an insulating vapor layer which keeps that liquid (or solid) from boiling rapidly. Thus, cryogenic hydrogen pellets will float or glide (almost without any friction) through room temperature curved guide tubes for transport over long distances, with very little mass or speed loss.



The Extreme Guide Tube Test

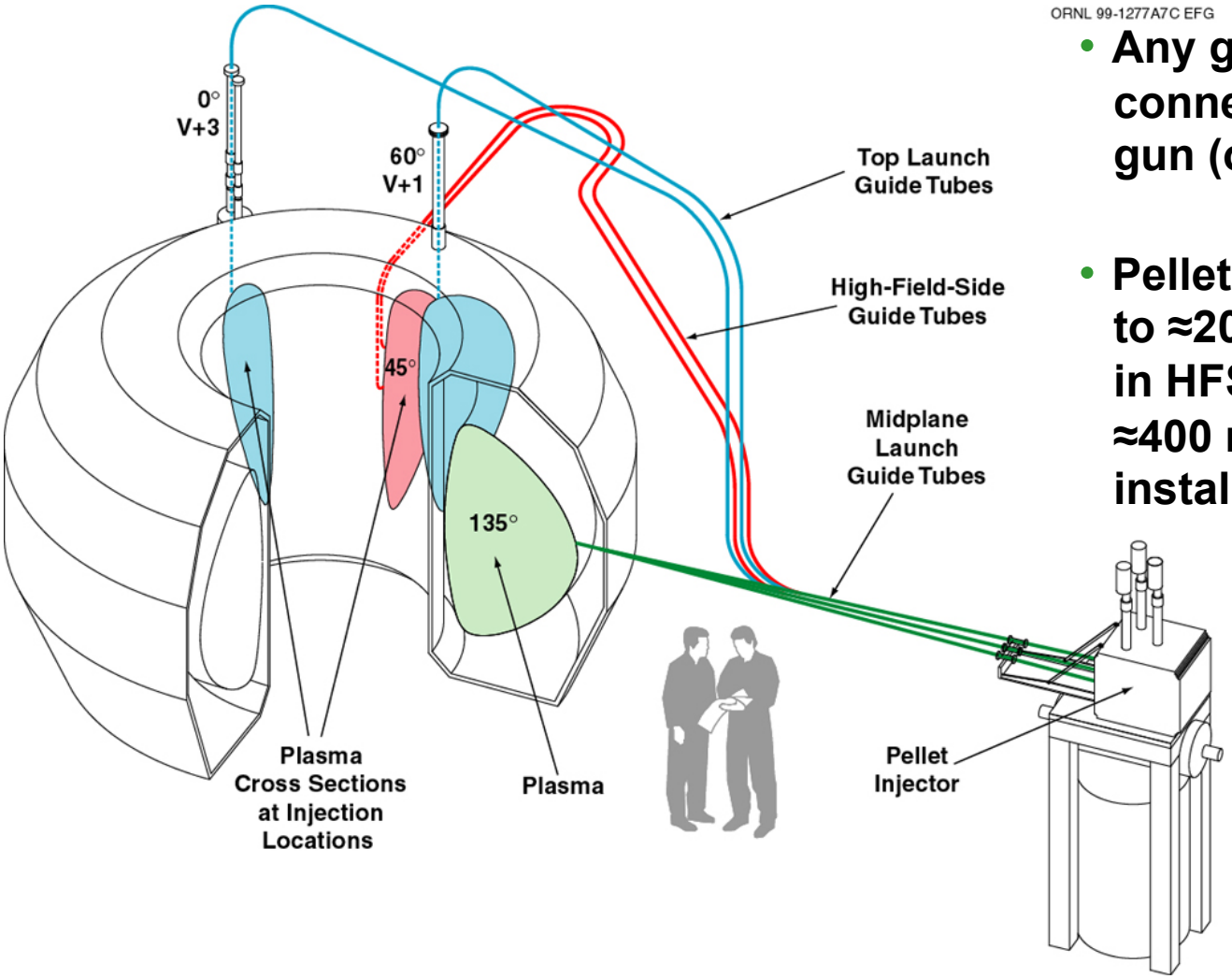


Stainless Steel Tube
Overall tube Length ≈ 30 m
Number of Loops = 11
Bend Radius = 800 mm
ID = 10.9 mm

2.7-mm D_2 Pellets

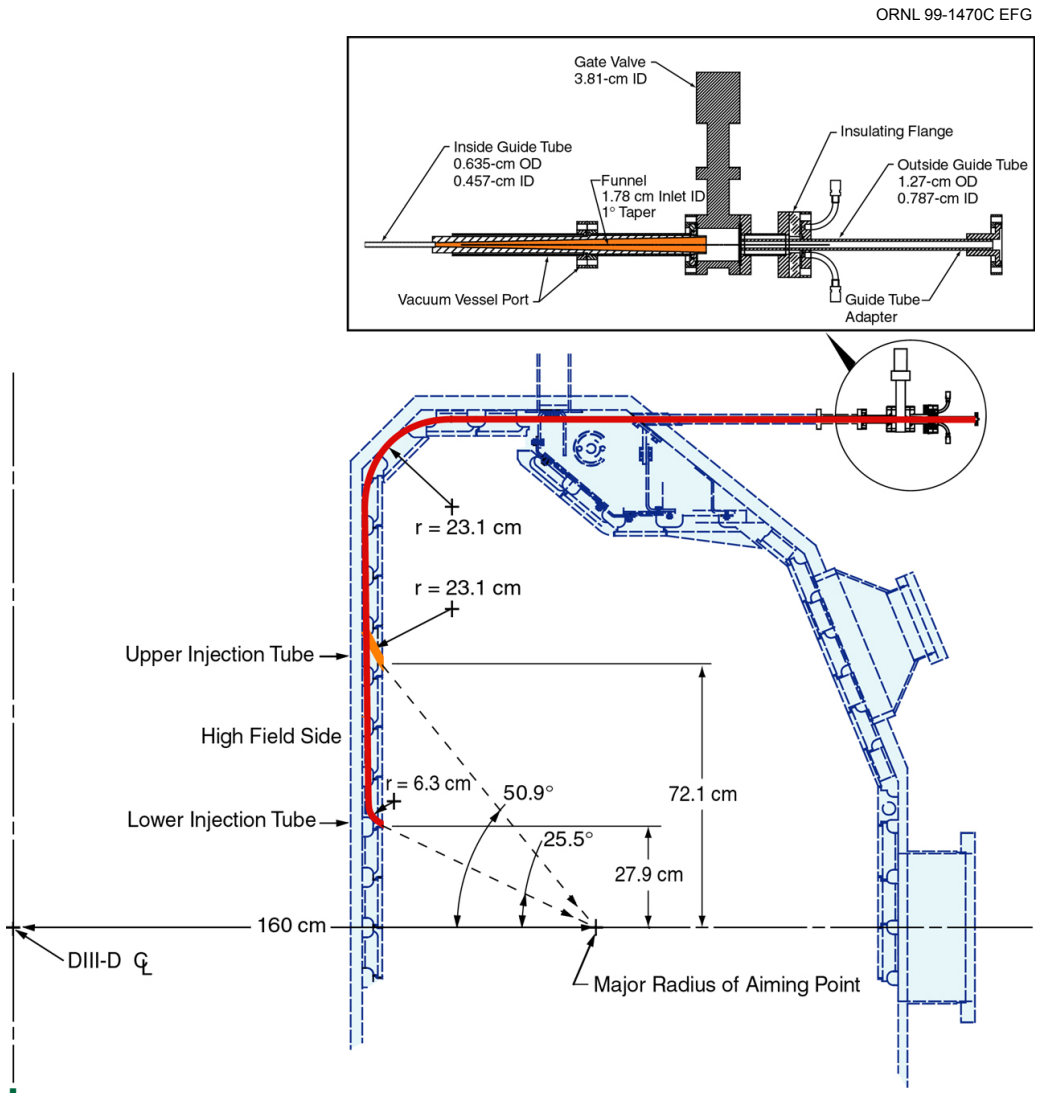
Pellets with speeds <100 m/s typically survive in good shape

Some of the More Complex Guide Tube Runs Are Found On the DIII-D Pellet Injection System



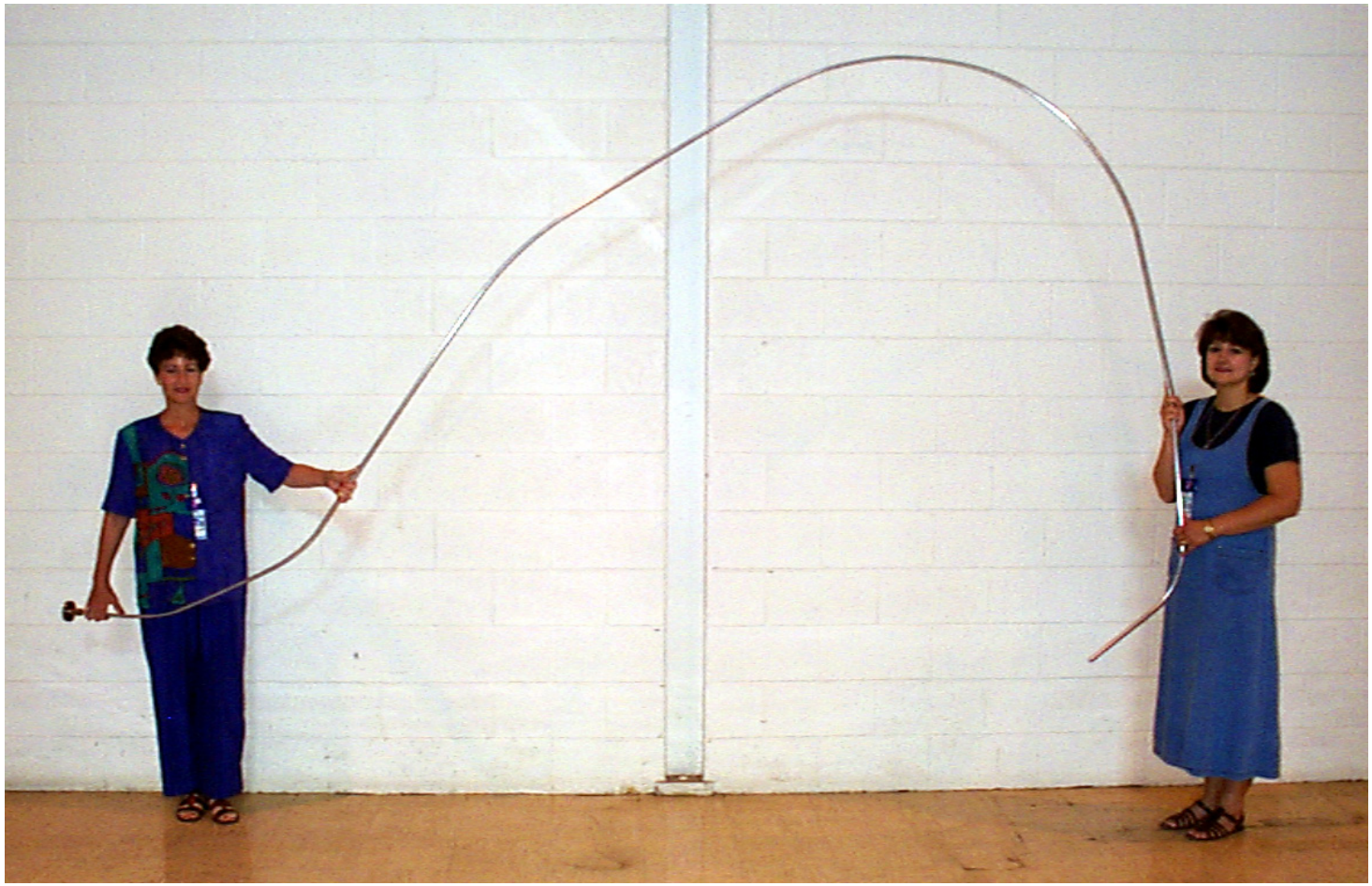
- **Any guide tube can be connected to any pellet gun (or a gas valve)**
- **Pellet speeds are limited to ≈200 m/s for survival in HFS tube runs and ≈400 m/s for vertical installations**

HFS Pellet Injection Tubes on DIII-D



Guide Tube for ORNL Simulation of JET High-Field-Side Pellet Launch

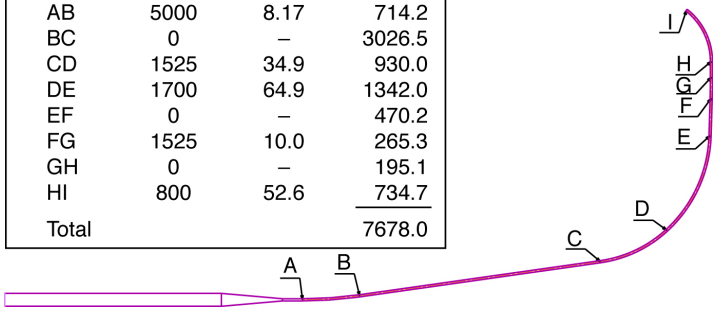
ORNL 99-1068C EFG



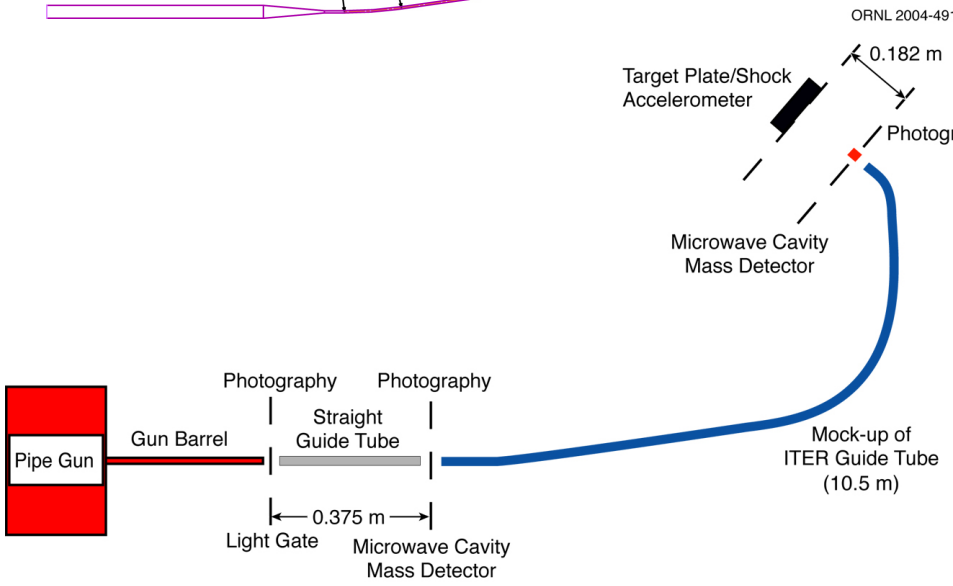
ITER Guide Tube and Set-Up for Testing in Lab

ORNL 2004-492C EFG

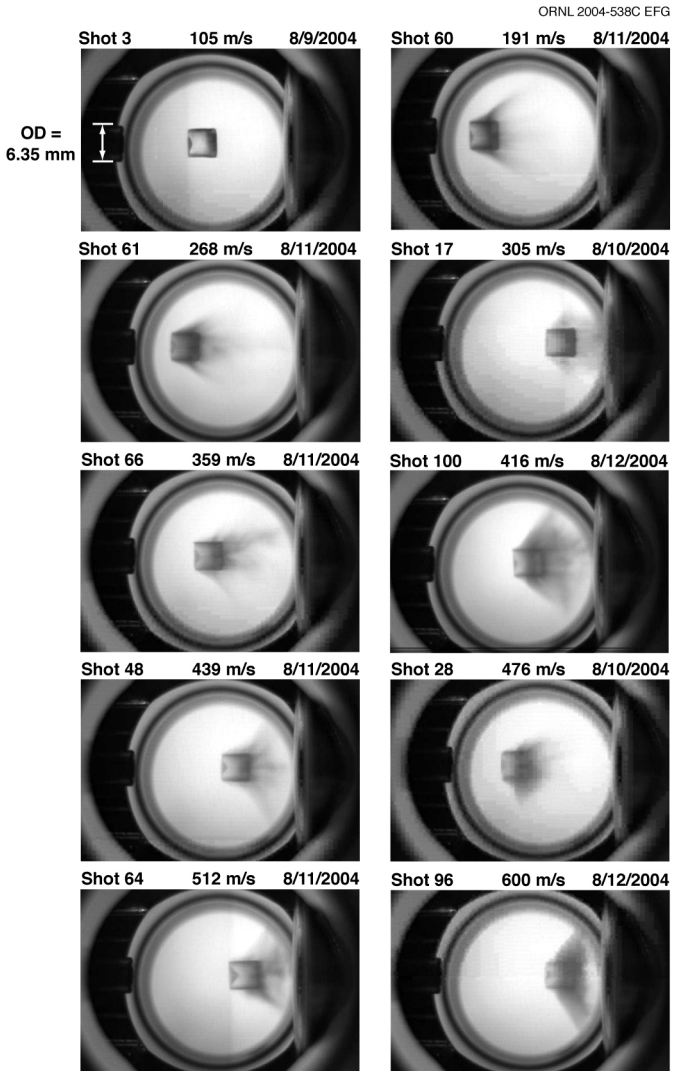
Segment	Bend Radius (mm)	Included Angle (deg)	Length (mm)
AB	5000	8.17	714.2
BC	0	–	3026.5
CD	1525	34.9	930.0
DE	1700	64.9	1342.0
EF	0	–	470.2
FG	1525	10.0	265.3
GH	0	–	195.1
HI	800	52.6	734.7
Total			7678.0



ORNL 2004-491C EFG

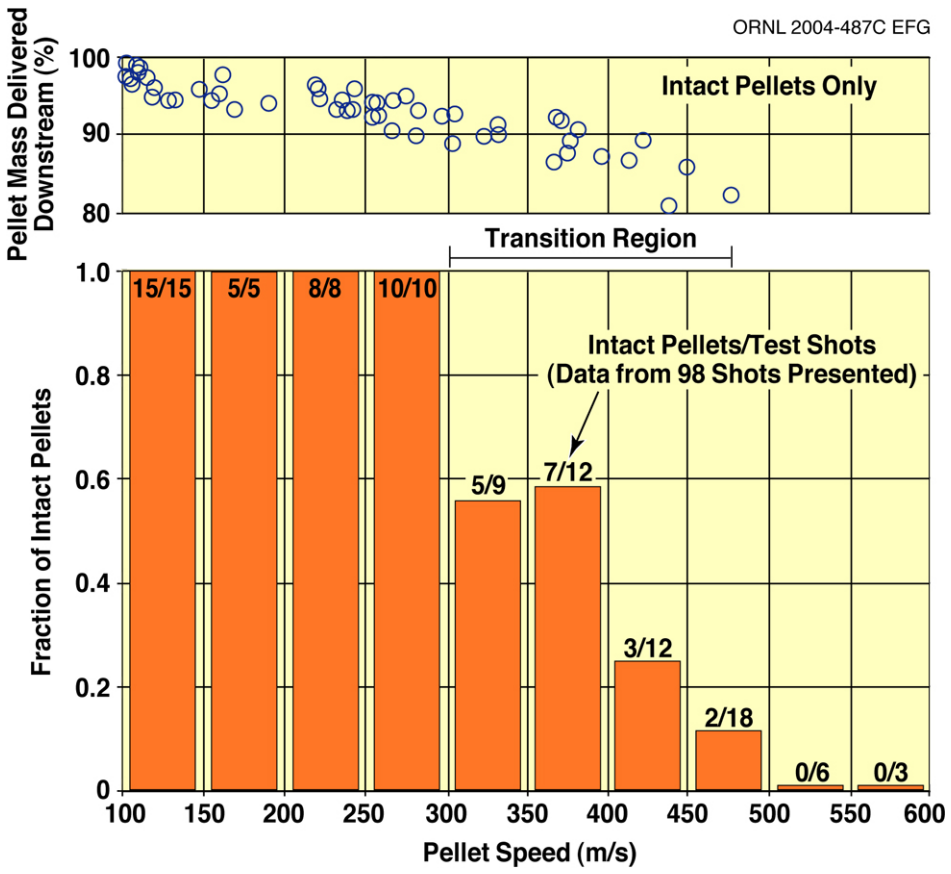


D_2 Pellets Sized for Fueling ITER Plasmas



- Pellet size of 5.3 mm (nominal diameter); corresponds to largest size in the present ITER physics design specifications
- Pellet speeds ranged from ≈100 to 600 m/s
- Photographs at the gun muzzle provided information on pellet condition and size
- Calibrated microwave cavity mass detectors located near the muzzle and end of the curved guide tube provided more precise mass measurements (particularly for mass loss)

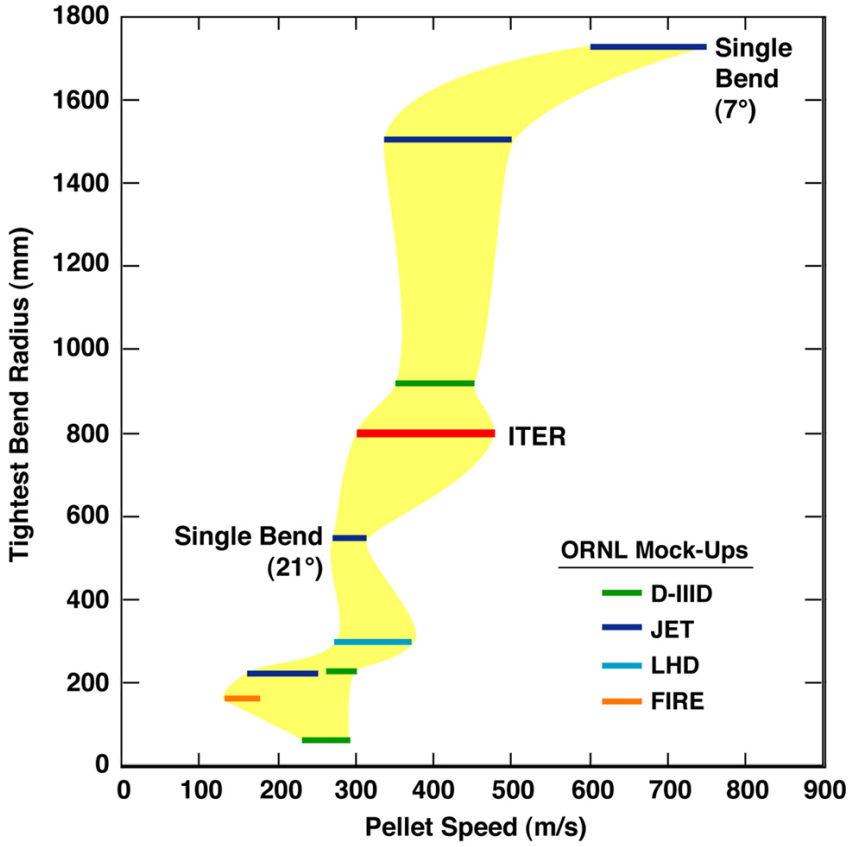
Pellet Survivability and Mass Loss - ITER Inner Wall Simulation



- Pellet size of 5.3 mm (nominal diameter); corresponds to largest size in the present ITER physics documents
- Fully evacuated test tube (≈10^{-4} torr)
- Speed transition range: ≈300 to 480 m/s
- Mass loss of ≈10% at speed limit of 300 m/s
- Test were also carried out with a tube test pressure of 10 torr which is representative of that estimated for steady-state (or long-pulse) pellet fueling sequences; no appreciable differences in the test results were observed

Summary of ORNL Mock-up Data for Pellet Delivery Systems and Implications for ITER Inside Launch Pellet Survivability

ORNL 2004-196RC EFG

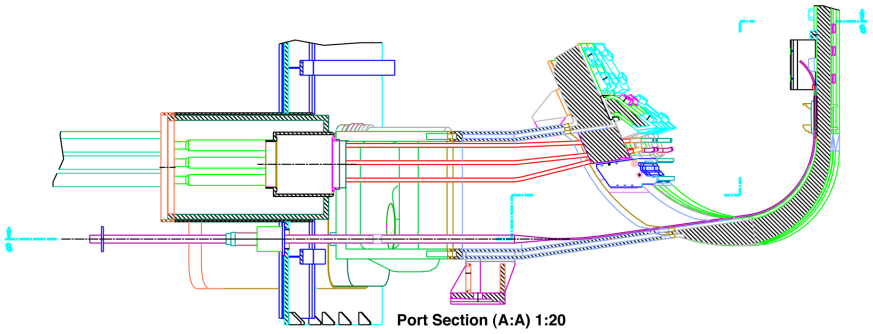


ORNL 2004-534C EFG

Mock-Up	Injection Scheme	Tightest Bend Radius (mm)	Speed Transition Range (m/s)
DIII-D	Inside launch I	63	230–290
	Inside launch II	231	260–300
	Vertical launch	920	350–450
JET	Inside launch	220	160–250
	Vertical launch I	1500	340–500
	Vertical launch II[a]	1725	600–750
	Vertical launch III[a]	545	270–310
LHD[b]	Inside launch	300	270–370
FIRE[c]	Inside launch	165	130–175
ITER[c]	Inside launch	800	300–480

[a]Tube was tested with single bend, which would correspond to an injector mounted and operating vertically.
[b]H_2 pellets are used on LHD; however, data from tests with D_2 pellets are shown for this comparison.
[c]Tube layouts from the present designs of these proposed experiments were tested.

ORNL 2004-539C EFG



For all cases in which the mock-up was for an existing or planned experiment, it was found that the actual performance in the field matched the experimental mock-up data remarkably well.

New High-Speed Camera Should Prove Very Useful in Pellet Injector R&D and Related Research

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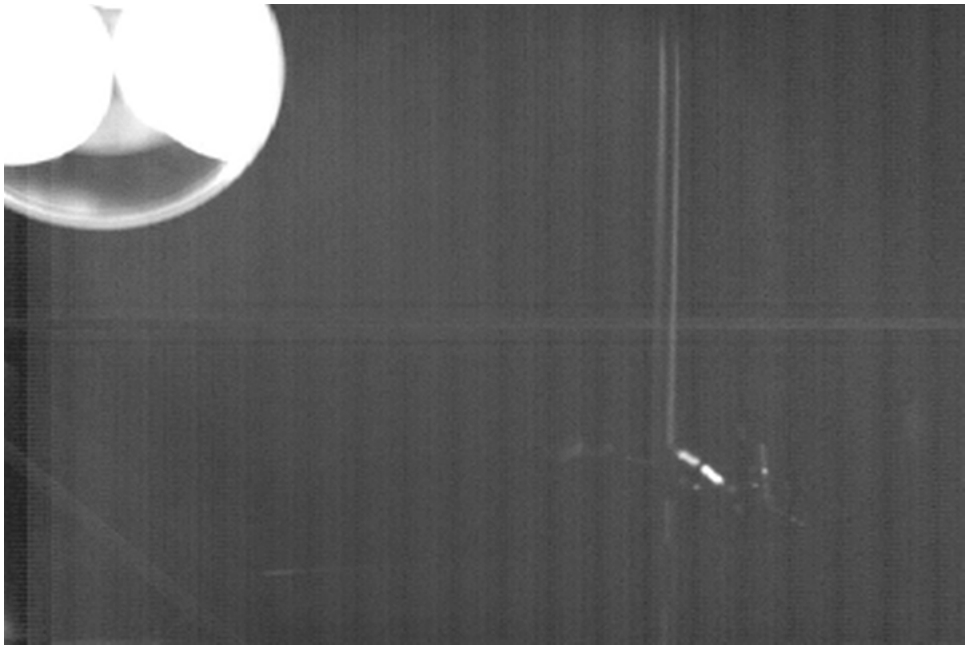
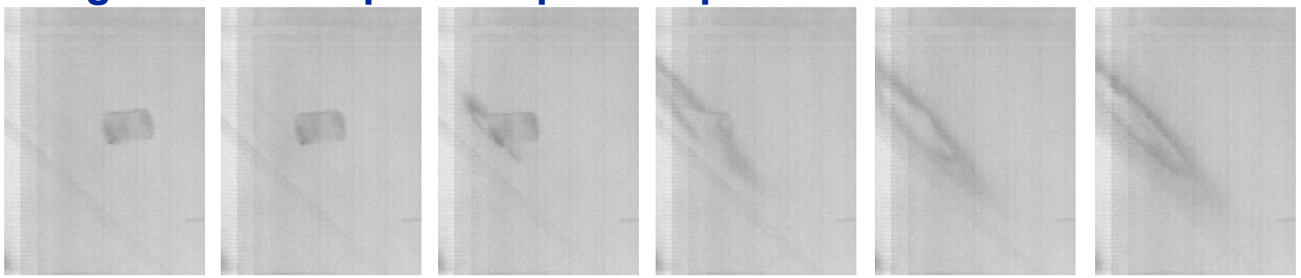
Virtual Laboratory for Technology
For Fusion Energy Science

Movie from Phantom v710



- Movies of large wine-cork-size pellets were recorded in lab in support of disruption mitigation studies on DIII-D
- Size = 16.5 mm diameter
- Speed = 340 m/s (right to left)
- Composed of 0.1 mm D2 outer shell and Ne core
- Framing rate = 22,400/s
- Exposure time = 2 microsec

Single frames of pellet impact on plate



Camera is capable of 1.4 million frames/s with exposure time as low as of 300 nsec

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Present and Future R&D Activities

- Continue to support DIII-D
  - Upgrade three-barrel injection system for ELM pacing experiments
  - Improvements to massive-pellet injector (used for disruption mitigation studies)
- Four-shot pellet injector in a "suitcase"
  - Continue to support MST system
  - Complete and test new system for TJ-II
- Continue collaboration with ENEA-Frascati on high-speed pellet injector
- Continue studies of HFS/inside launch pellet injection technology
  - ITER (new optimized microwave cavities)
  - KSTAR (new test configuration)
- ITER Pellet Injection System
  - Continue development of double-screw extruder
  - Propellant gas minimization and recycling for repetitive gas guns
  - Start evaluating/designing all components for tritium compatibility and long "life"