Mirror Research: New Directions

Axi-symmetry
Results from Japan and Russia
A Strategy to a Fusion-Fission Hybrid

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September 2, 2009

ORNL

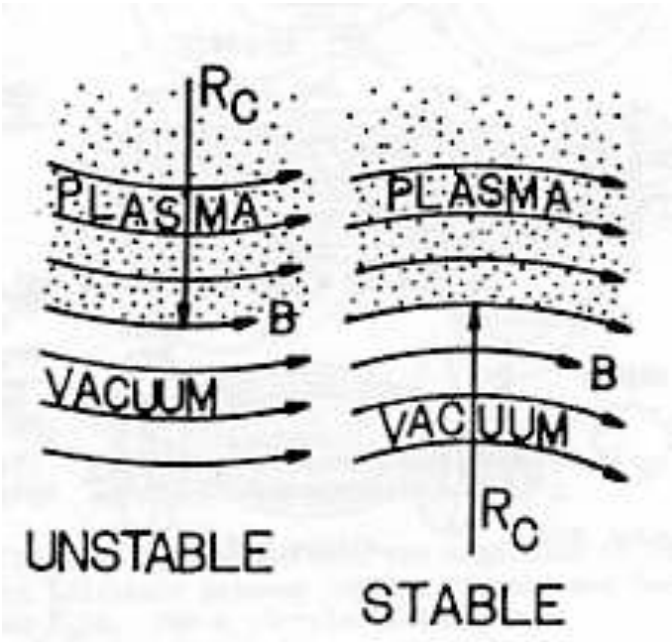
Mirror Study Group

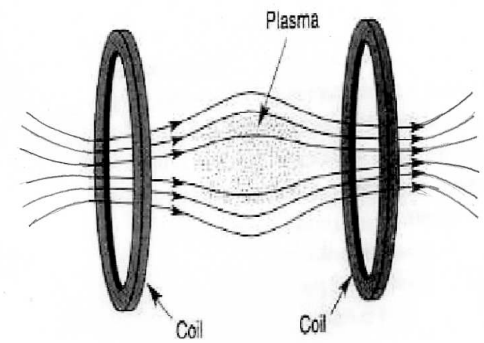
- Triggered by Japan/Russia Results
  - Gamma-10 and GDT
- A Mirror Study Group was Convened
  - 25 Participants from 10 institutions
  - Physics Workshop --September 2008
  - Technology Workshop -- March 2009
- The Assessment was positive
  - Potential Applications - Attractive
  - Physics and Technology - Credible

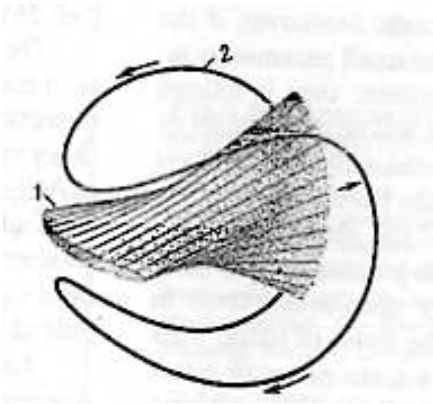
What's New in Mirror Research?

- What was the old mirror program?
  - Thermal-barrier Tandem-mirror
- What's new from Japan and Russia?
  - Axi-symmetry, Te, micro-stability, radial conf.
- Why is new data a game changer?
  - Neutron source, hybrid
- What is strategy to fusion-fission hybrid?
  - GDT > Hydrogen prototype > DTNS > Hybrid

Magnetic Mirror MHD Physics



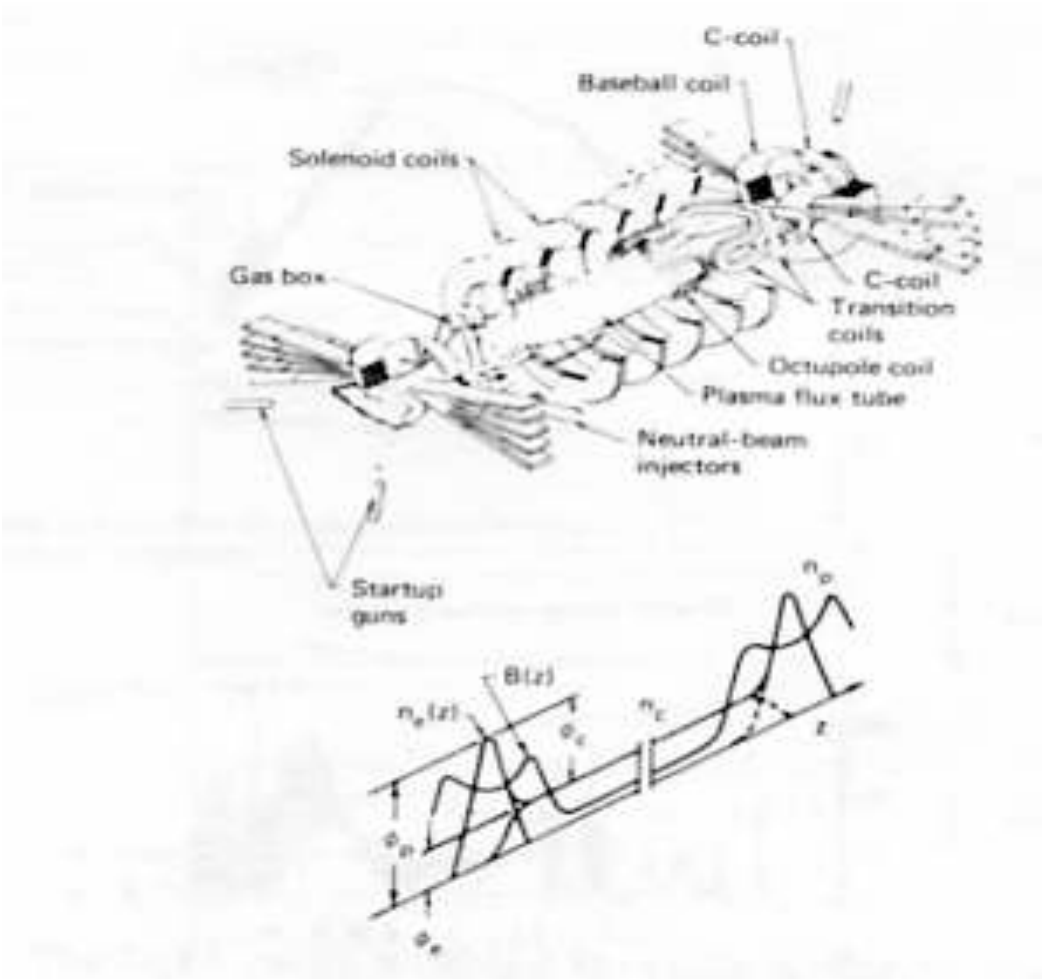




Magnetic Mirror Confinement

- Particles with enough perpendicular energy are confined by mirror: R=Bm/Bo
- Electrons scatter faster into loss cone.
- Plasma charges up positive ~4Te
- Impurity ions expelled – good
- Low energy ions expelled – bad
  - Drift-Cyclotron-Loss-Cone modes stimulated

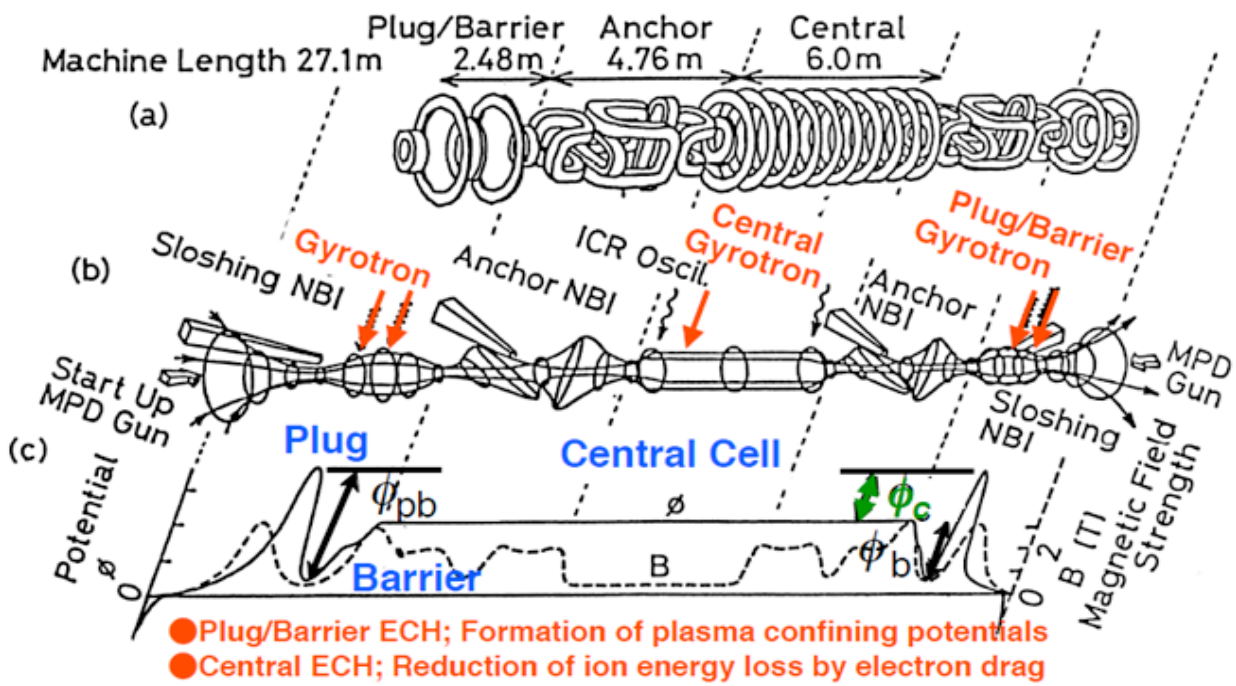
Tandem Mirror End-Plugs Confine Center-Cell Ions



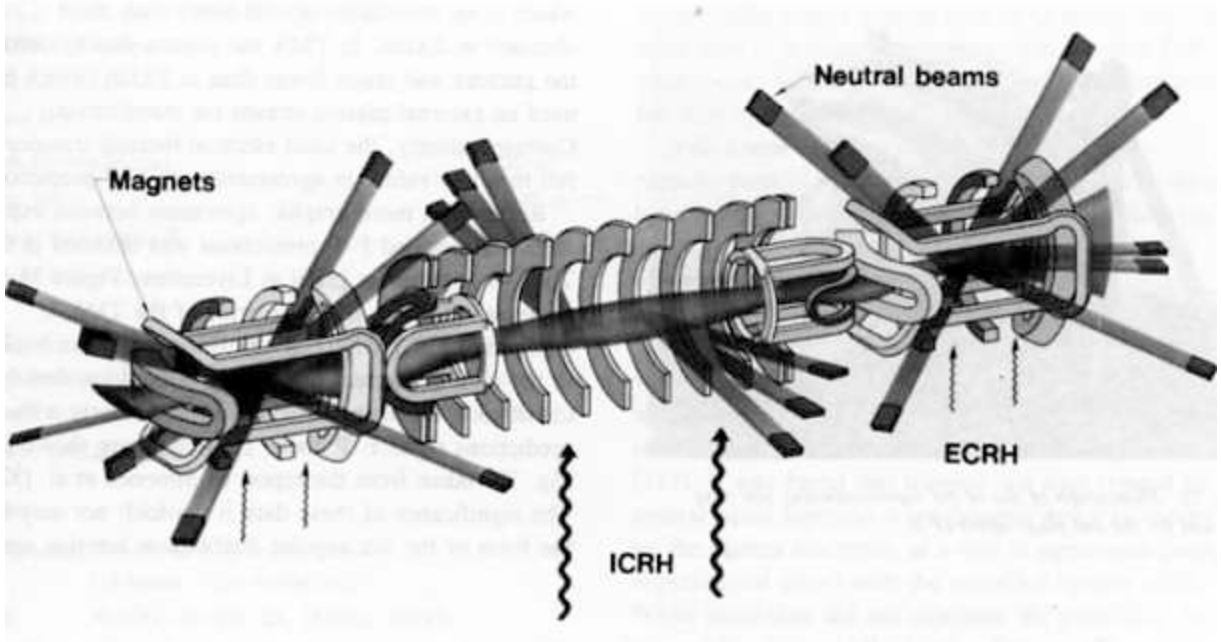
Thermal Barriers Confine Center-Cell Electrons

- Plug Skew Injection Creates Sloshing Ions
- Plug ECH Forms Mirror Electrons and Potential Dip isolating Center Electrons
- Pump Beams deplete warm ions trapped in potential Dip
- ECH Heats Plug Electrons to Increase Positive End-Plug Ion Confining Potential
- Increases System Q

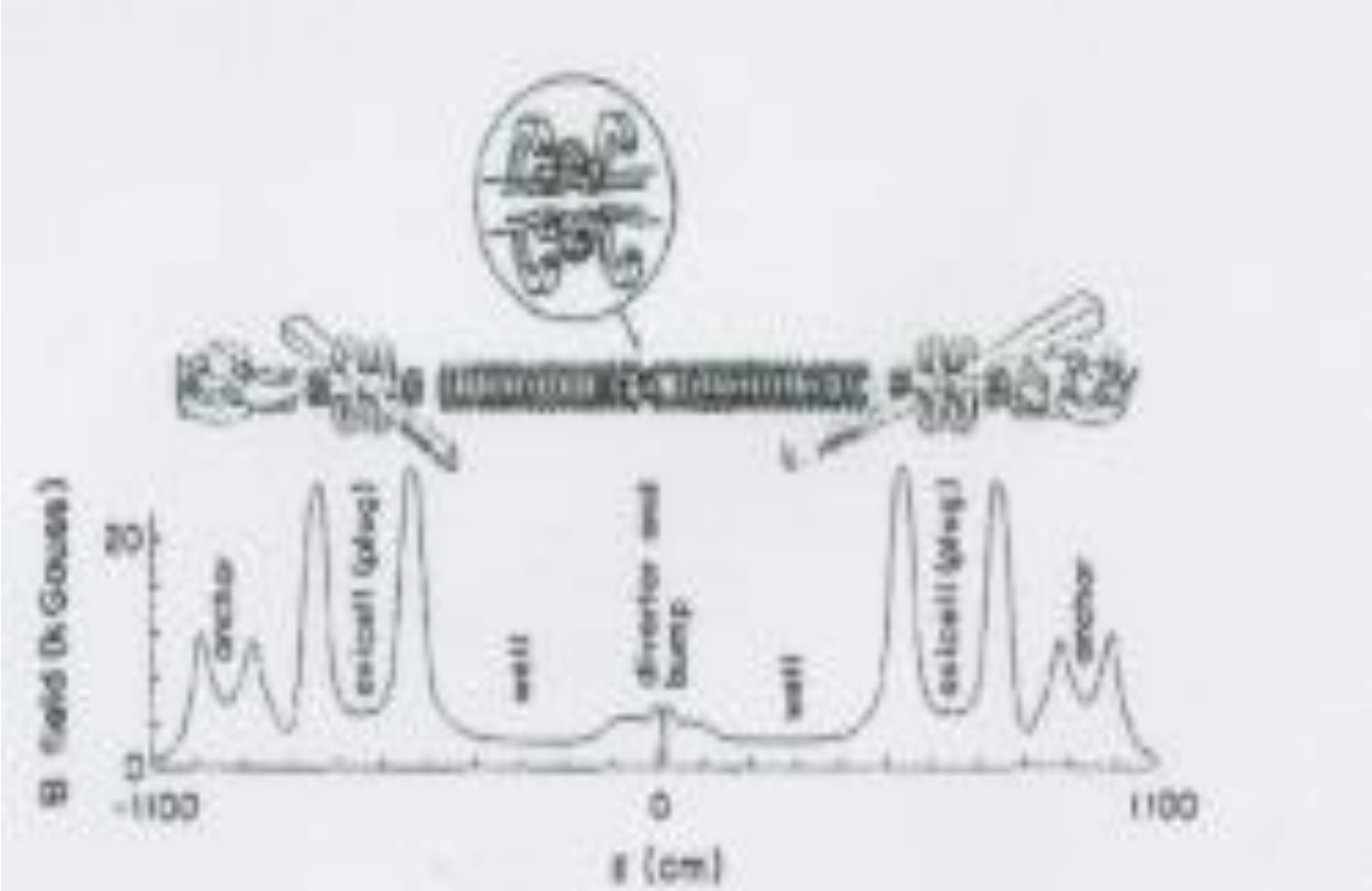
Gamma 10 Magnet Geometry
Powered by ICRF and ECH



TMX-Upgrade



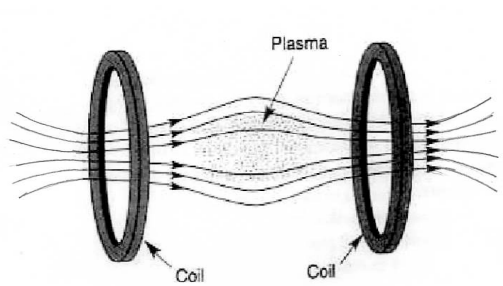
TARA (MIT)



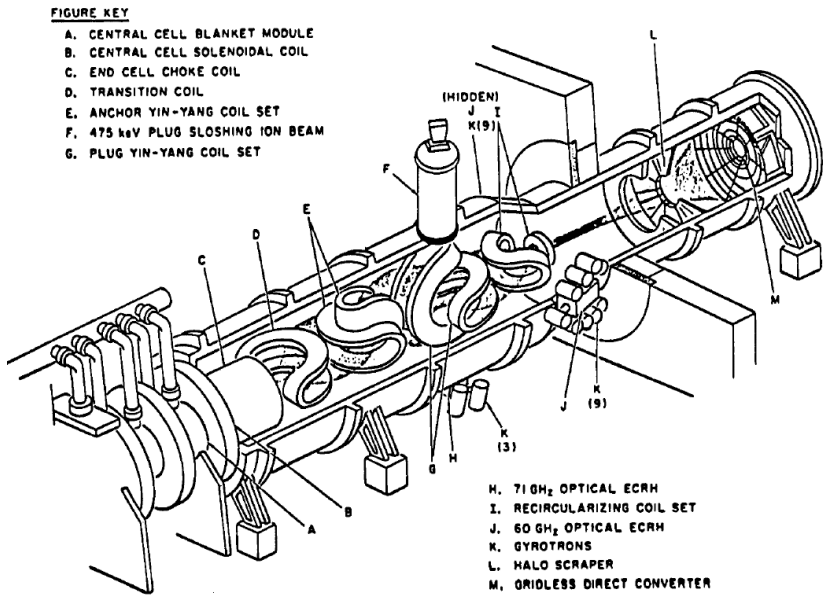
B field (kGauss)
20
0
anchor
axicell (plug)
well
divertor and bump
well
axicell (plug)
anchor
-1100
0
1100
z (cm)

From Simple to Complex

Simple Mirror



MARS Reactor End-Plug

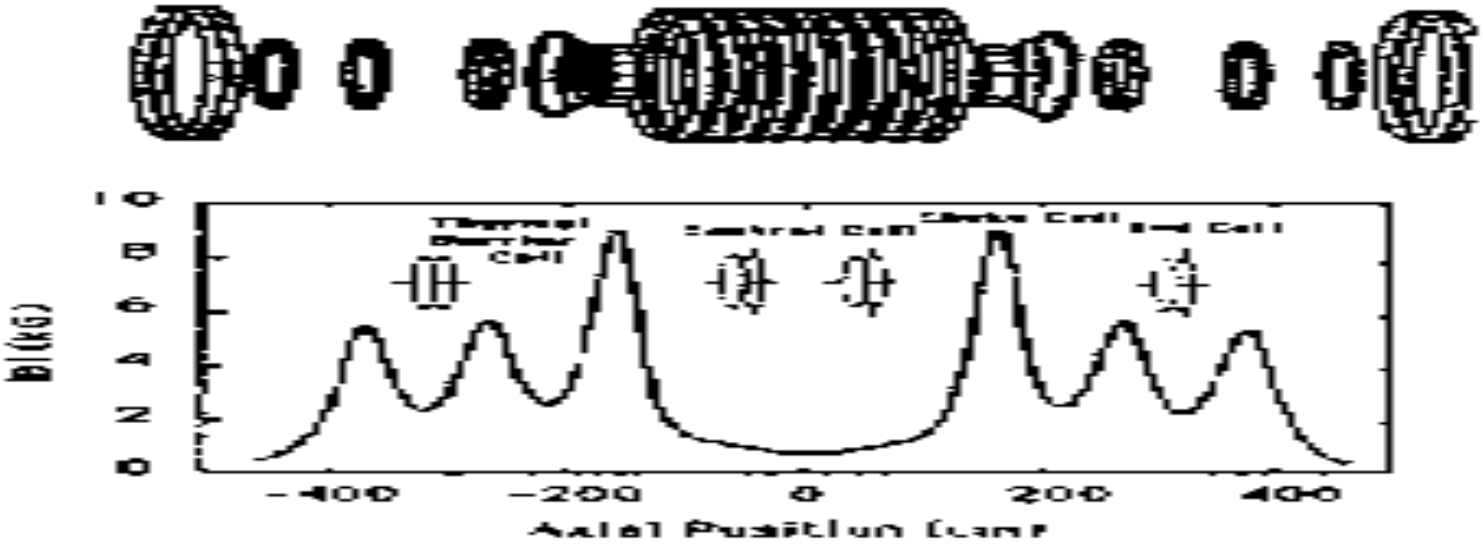


Why Mirrors Became Complex

- Simple Mirror was MHD Unstable
- Minimum-B Mirror was Low Q ~ 1
- Tandem Mirror System increased Q ~ 5
- Complex Thermal Barrier TM increases Q ~ 10 but:
  - Large Minimum-B end plugs requires lots of auxiliary heating power
  - Thermal Barrier TM requires two ECH systems and barrier pump beams

Phaedrus (U. Wisconsin)

- Axi-symmetric Magnetic Mirror



GDT Schematic

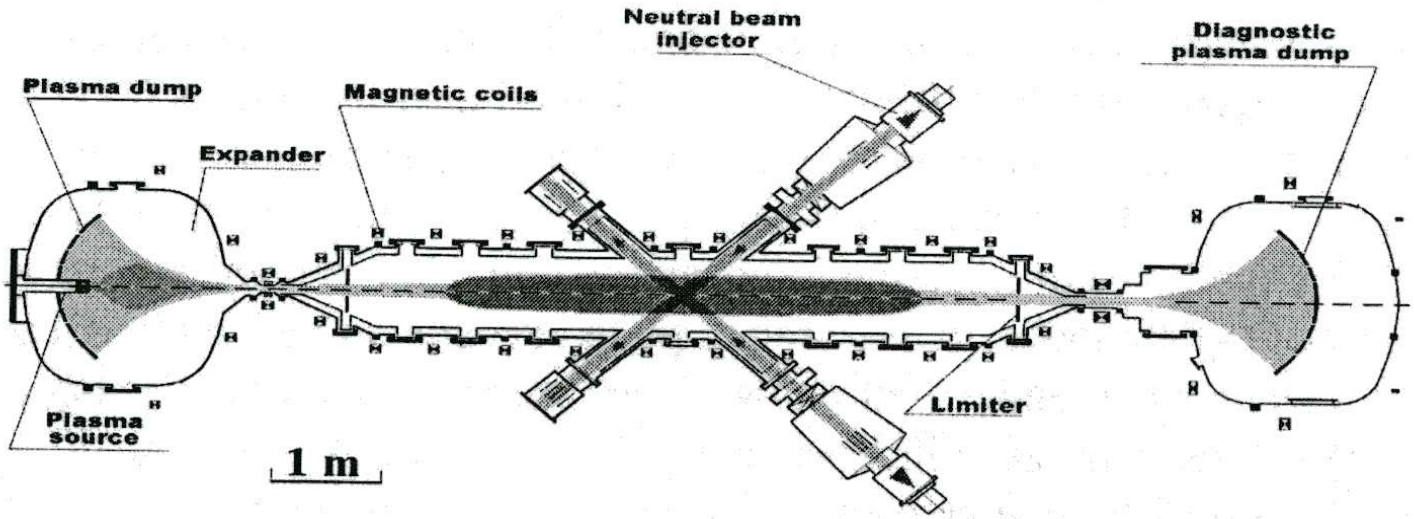
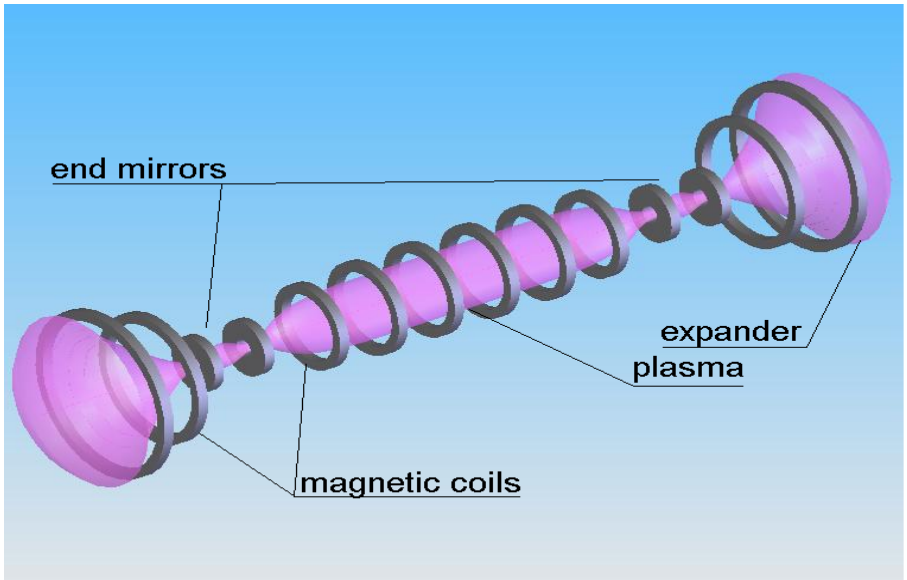


FIGURE 1. The gas dynamic trap (GDT) scheme. Plasma parameters: $L \sim 7/12m$, $r \sim 15cm$, $k = B_{max}/B_{min} = 30$, $T_w \sim 180eV$, $T_{hi} \sim 15keV$, $n \sim 2 \cdot 10^{13} cm^{-3}$, $\beta \sim 60\%$. Since 2003 routinely operates with an average magnetic hill.

Back to Simplicity: Axisymmetry



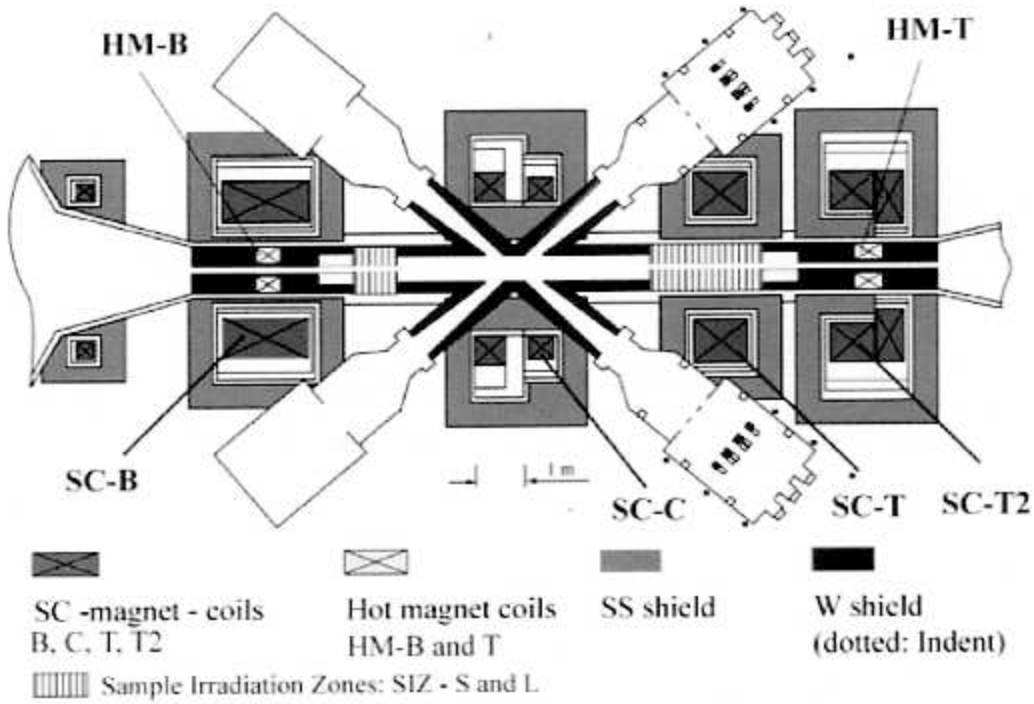
- A simple magnetic mirror geometry without Thermal Barriers
  - Simplified Engineering, Physics and Technologies
  - For material testing and fusion-fission hybrid systems

The Axi-symmetric Mirror is Suited for Many Applications

- Q ~ 0 for Plasma-Wall Interaction Studies
- Q < 1 for materials and subcomponent nuclear testing with low tritium consumption
- Q ~ 2 to 5 for Fusion-Fission Applications
- Q ~ 10 for electric power with ignited central cell

Further evaluation is warranted

DTNS Scale Size



Strategy to a Mirror Hybrid

- Physics Studies on GDT and Gamma-10
  - Te, MHD, DCLC, rotation shear, limiter pwi, fueling
- Hydrogen Prototype (2x GDT scale)
  - Confirm physics scaling, PMI Studies
- DT Neutron Source (2x HP scale)
  - Material and subcomponent testing/valedation
- Mirror Fusion-Fission Hybrid
  - Waste Burner

Potential Near-Term US-GDT Collaboration Topics

- GDT Stability and Power Balance Studies
  - MSE Upgrade for high beta physics
  - Thomson Upgrade for electron physics
  - High resolution physics diagnostics
  - Theory and Computation
- Hydrogen Prototype (2x scale up)
- DTS Neutron Source and Hybrid Burner Studies

How Can a Simple Mirror be MHD Stable?

- **Seven Demonstrated Methods**
  1. Expander plasma Outflow (GDT)
  2. Plasma Rotation (MCX, PSP-2. GDT
  3. Divertor (Tara)
  4. Pondermotive (Phaedrus & Tara)
  5. End Wall Funnel Shape (Nizhni Novgorod)
  6. Line-Tying (UC Berkeley)
  7. Cusp End Plugs (GDT)

- **Four Other Methods**
  1. Kinetic Stabilized Tandem Mirror (Post)
  2. Pulsed ECH Dynamic Stabilization (Post)
  3. Wall Stabilization & Feedback (Berk)
  4. Non-paraxial End Plugs (Ryutov)

Attractive Features of Axisymmetric Mirrors

- No Resonant Transport as in Min-B Mirrors and Stellarators
- No Banana Orbits thus No Neoclassical Transport as is min-B Mirrors, Tokamaks, & Stellarators
- No Toroidal Curvature so Drift Wave Drive is Weak
- No Plasma Current so No Disruptions
- Circular Magnets enable Higher Fields and Mirror Ratios
- Plasma Exhaust at Low Power Density Outside the Magnet System.
- Potential Direct Energy Conversion and Liquid Molten Salt Blanket

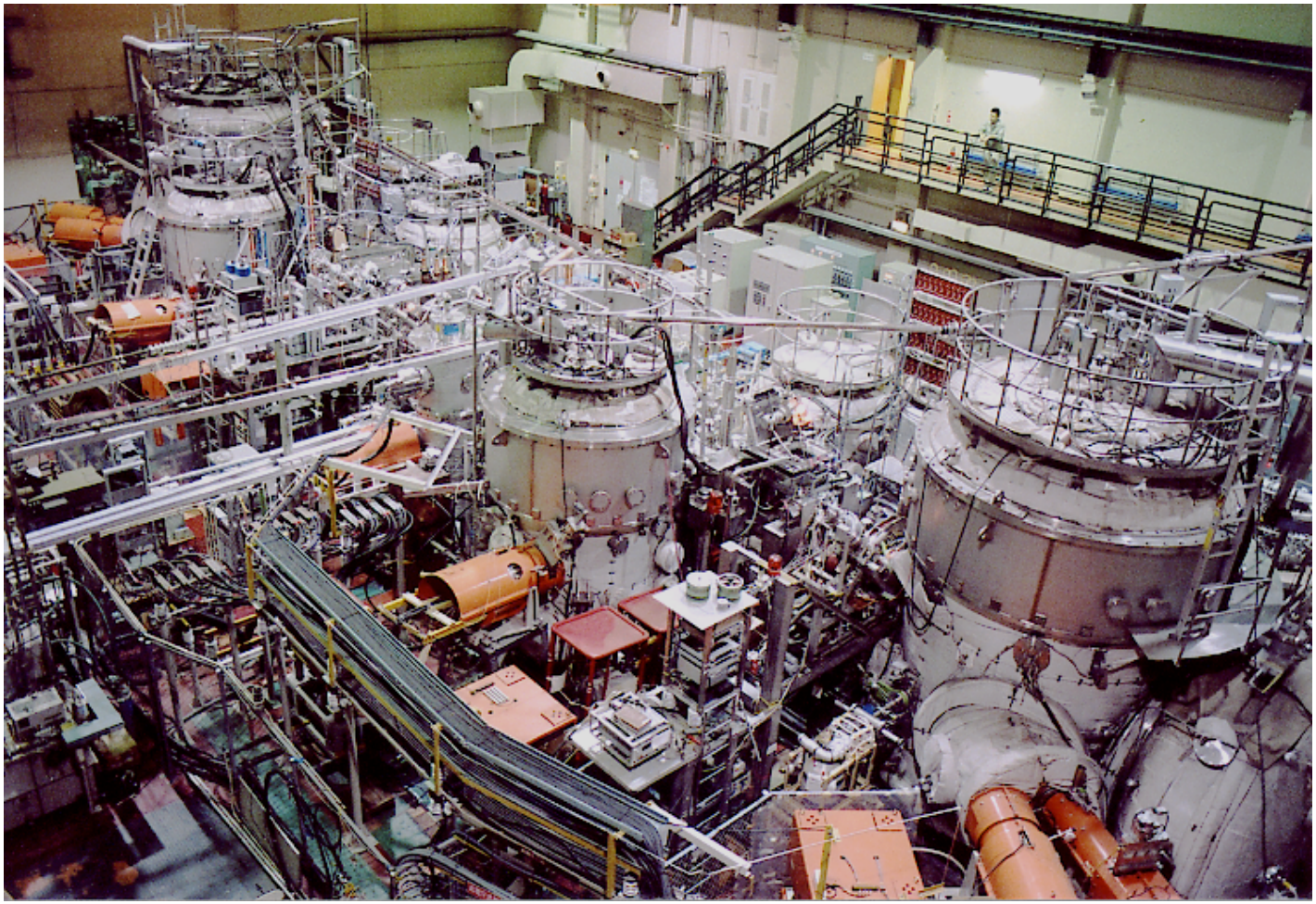
Most Conventional Mirror Wisdom is Wrong

- Complex minimum-B magnets are required
  - No, simple circular coils are an option
- Complex thermal barriers are required to obtain adequate Q
  - Not with small Axisymmetric end plugs
- Particles leak too rapidly out the ends
  - Not with high mirror ratio with Axisymmetric coils and tandem end plugs
- Electron temperature is intrinsically low
  - Not when end loss is expanded with high mirror ratio from end wall
- Micro instabilities cause excessive energetic ion loss
  - No: Warm plasma suppresses DCLC, Skew injection suppresses AIC
- Drift waves cause excessive radial transport
  - Not with sheared ExB rotation
- Plasma-wall interactions are unmanageable
  - Not with pumped large end tanks
- Mirrors necessarily suffer from RF pump-out
  - Not when waves are properly controlled
- Mirror reactors require exotic undeveloped technologies
  - No, ITER Magnet, NNBI & ECH Technologies are adequate

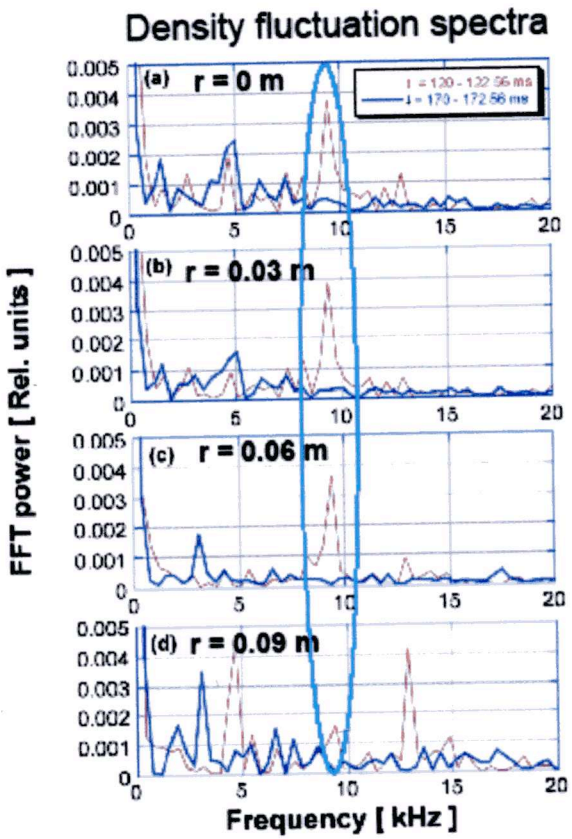
Conventional Wisdom, Short Funding, and Slow Thermal Barrier Progress killed the US Mirror Program in the mid 1980's

Gamma 10 Tandem Mirror at Tsukuba U. Japan

27 m Long with Large End Tanks



Suppression of Gamma 10 Turbulence with ECH



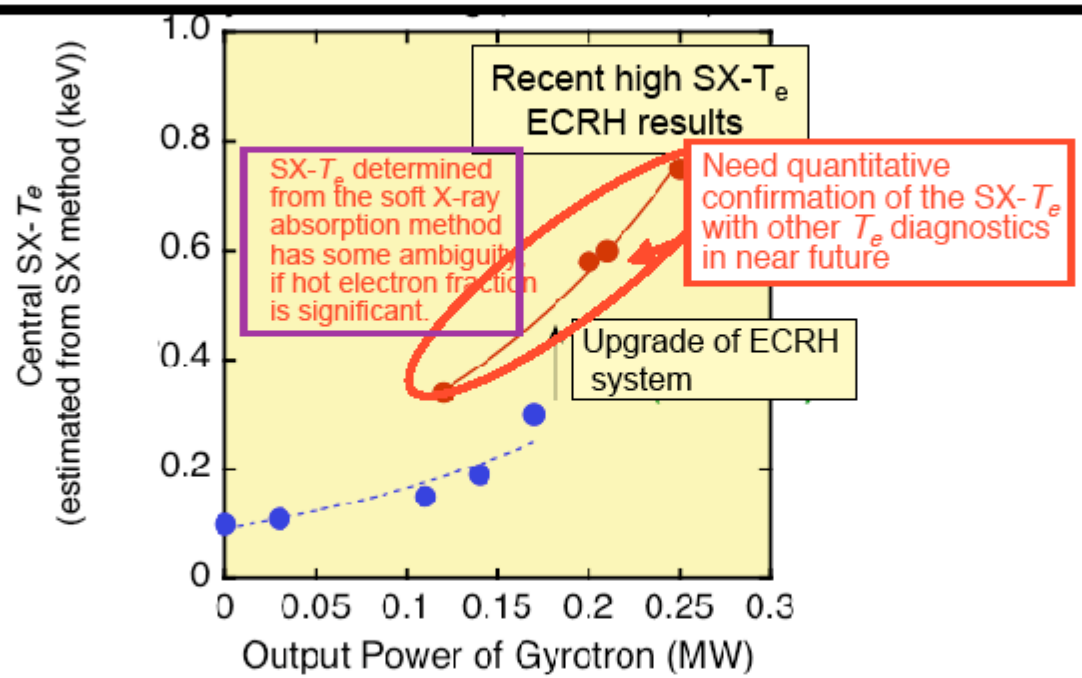
- Red without ECH
- Blue with ECH

- ExB Rotation Shear
- Like H-mode & ITB
- Possible ITER Application?

5. Efficiency Enhancement of ECRH System

Power Scalings of Soft X-ray estimated T_e (SX-T_e)with ECH Power (Tentative)

PRC

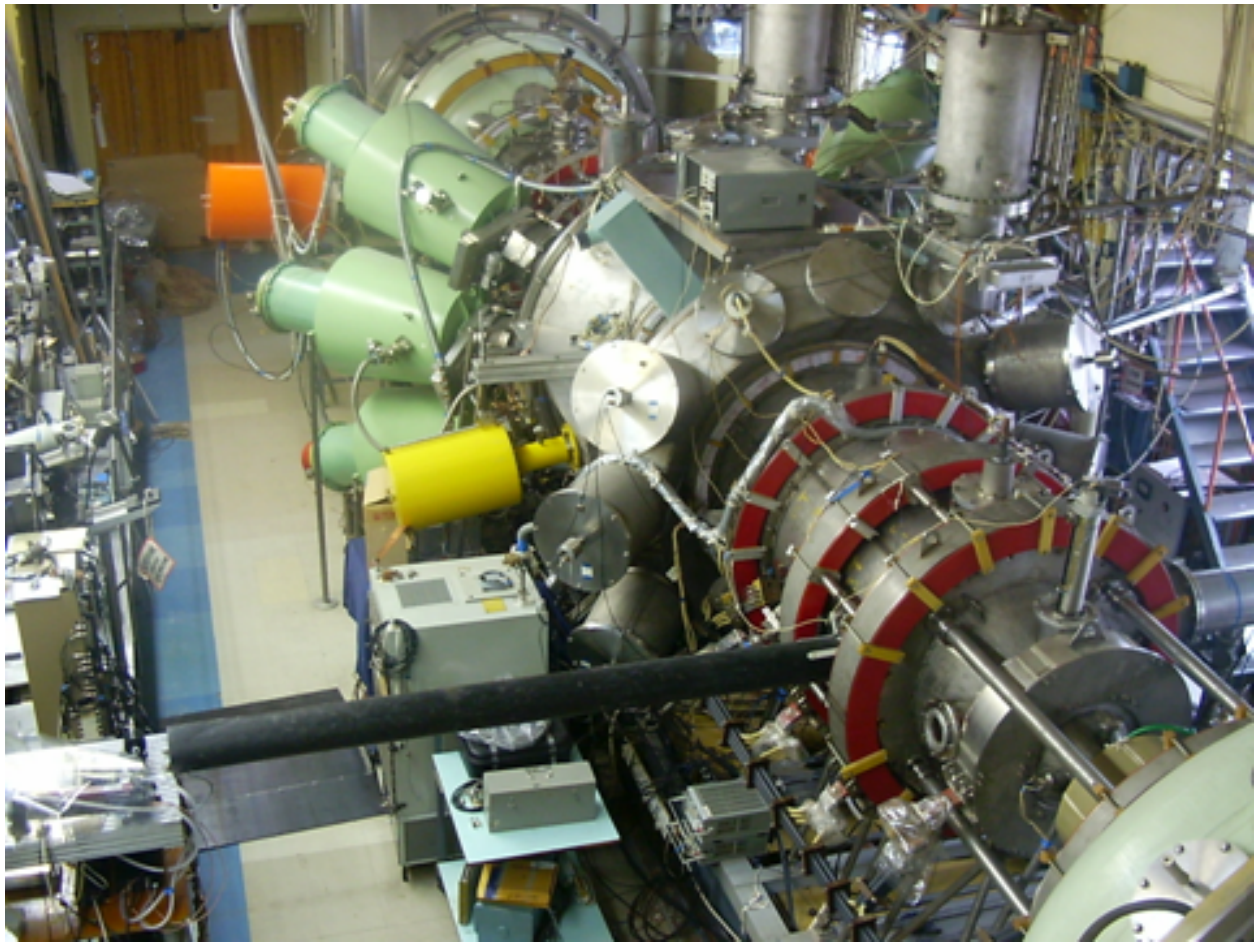


No saturation of power scaling of SX-T_e

Highest SX-T_e estimated from Soft X-ray seems to be 0.5 ~ 0.75 keV,
but its confirmation must be done by other diagnostics like Thomson Scattering.

GDT General View

18 meters Long



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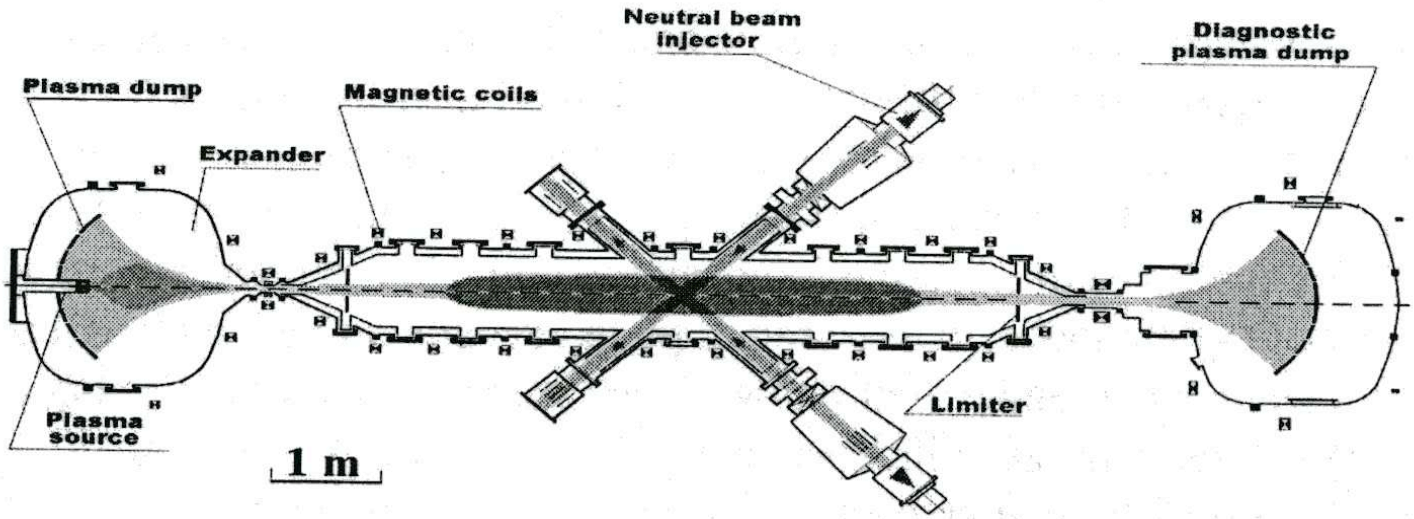

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GDT MHD Stabilization Methods

- Plasma pressure in expander (beta ~10%)
- Cusp Anchor (beta ~ 20%)
- Vortex Stabilization (beta ~ 60%)

GDT DD Neutron Axial Profile

Ivanov et. al. PRL, v90, 2003, p105002

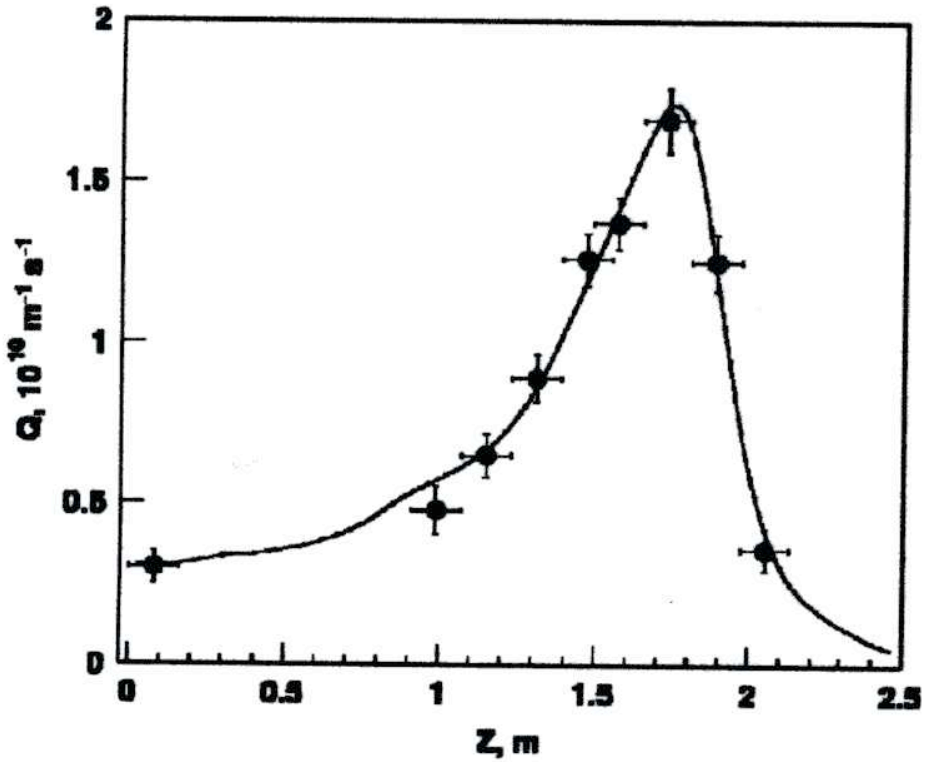
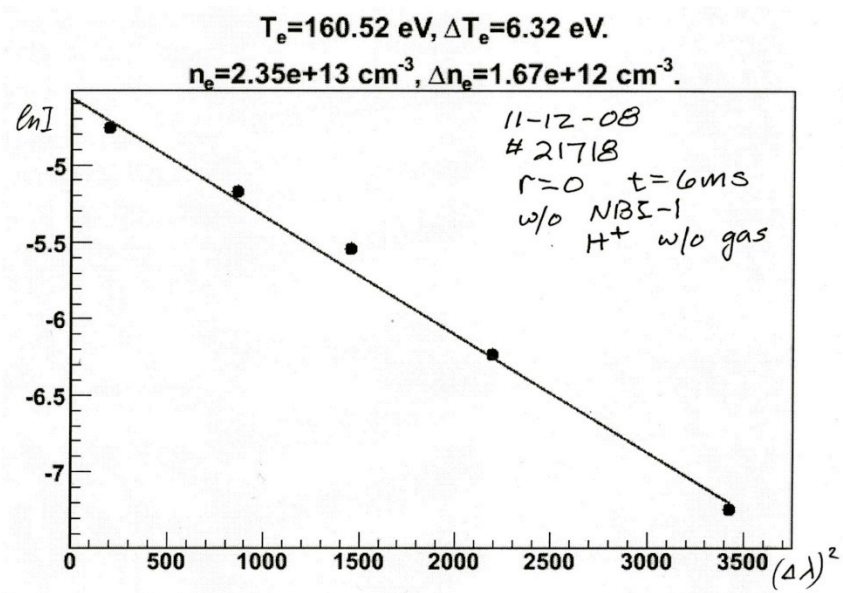
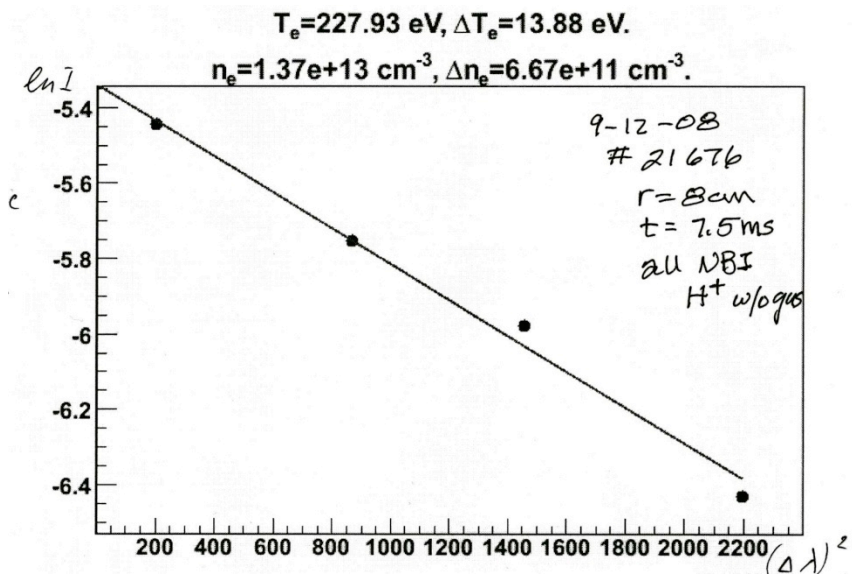


FIG. 3. Axial profile of DD reaction yield as measured from the midplane ($z = 0$).

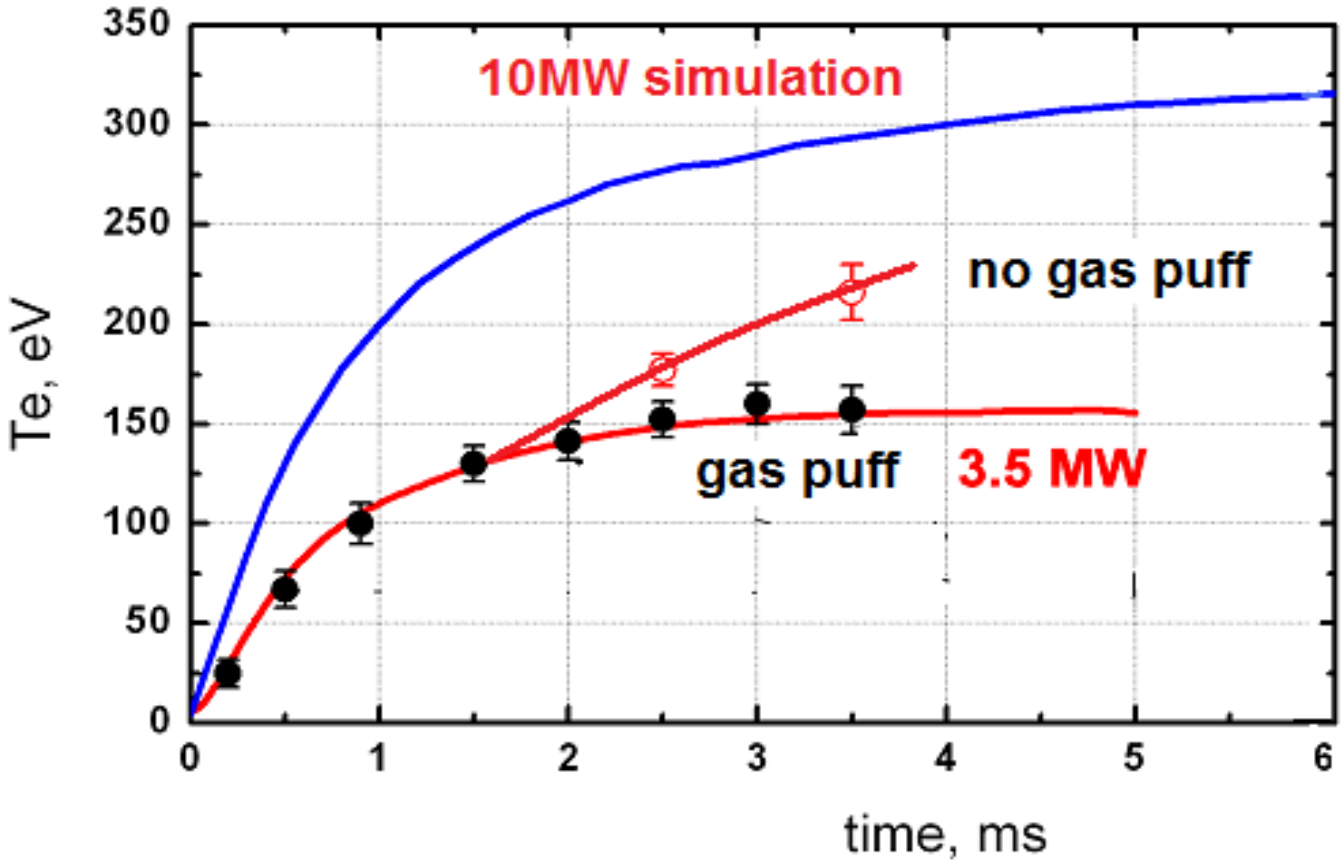
GDT Thomson Scattering Data





GDT Electron Temperature

(Thomson Scattering)



GDT Experiments – May 19-26, 2009

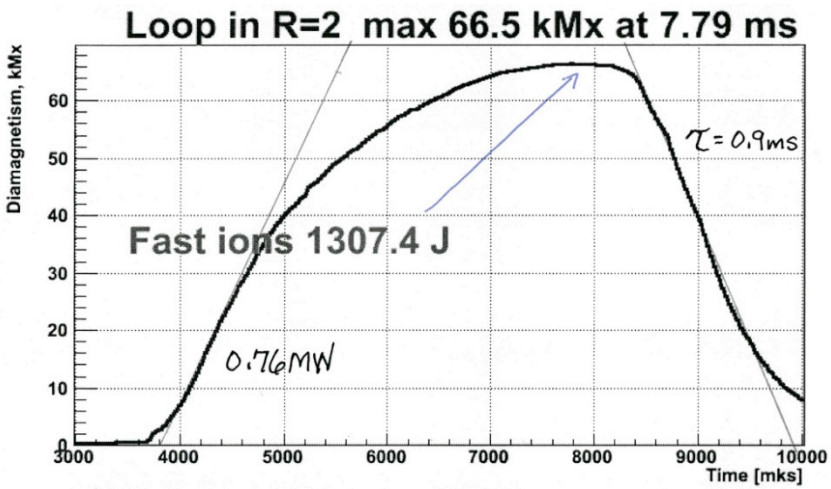
- Investigation of high beta experiments with 6 neutral beam injectors (~4 MW injected)
- Trapped beam power ~2 MW (~20 keV)
- Measure Delta-B with MSE (~30%)
- Plasma beta 50% or 100% (normalized to vacuum or depressed magnetic field)

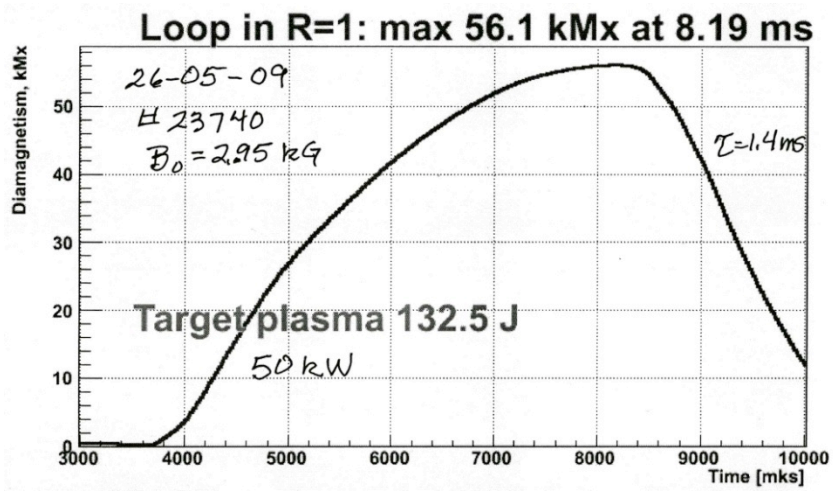
Key GDT Diagnostics

- Thomson Scattering
- Motional Stark Effect
- Charge Exchange Energy Analysis (2)
- End Loss Analyzer
- Microwave Interferometer
- Dispersion Interferometer
- Diamagnetic Loops
- Langmuir Probes
- Pyroelectric Detectors
- Neutron Detectors
- Thermonuclear Proton Detectors
- RF Probes
- Beam Dump Calorimeters
- NBI Secondary Electron Detectors

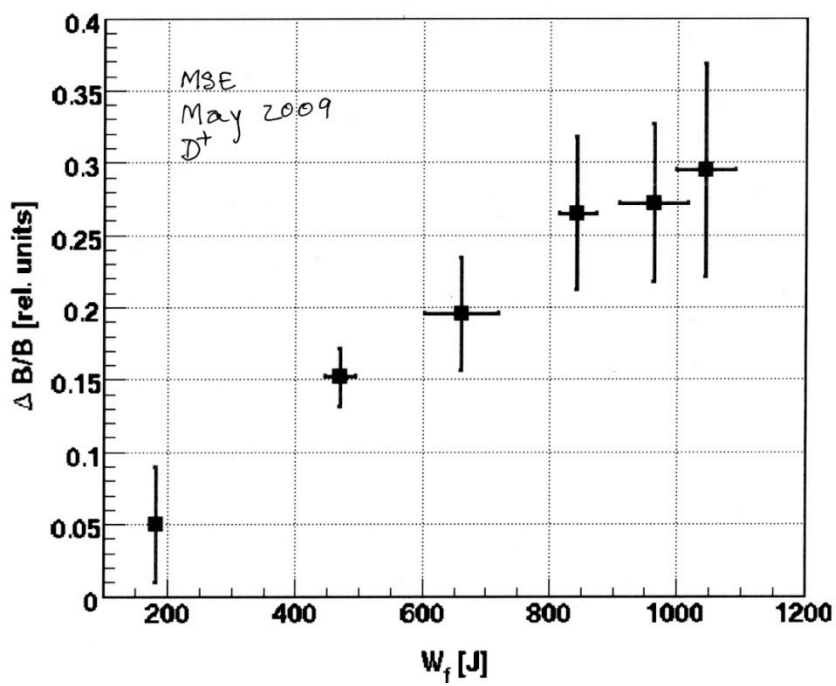
- d

Dimagnetic Loop Data





MSE Data



$$8\pi p_\perp + B^2 = B_v^2$$

$$\beta_v = 2\frac{\Delta B}{B_v} - \left(\frac{\Delta B}{B_v}\right)^2$$

$$= 2 \times 0.3 - (0.3)^2$$

$$= 0.5$$

$$\beta = \left(\frac{1}{1-\Delta B/B}\right)^2 - 1$$

$$= \frac{1}{0.7^2} - 1$$

$$= 1.0$$

Interesting High-beta-Plasma Self-Organizing GDT Physics

- Vortex Shear Flow MHD “Stabilization”
  - Alexei Beklemishev, Varenna 2008
  - Peter Bagryansky, Open Systems 2006
  - Alexei Beklemishev, Open Systems 2006
- Fast Ion Radial Compaction (a to ~ a/2)
  - Yuri Tsidulko, Phys. Plasma, 11 (2004), 4420
  - Vadim Prikhodko, Plasma Phys Reports, 31 (2005), 899

Vortex Shear Flow MHD "Stabilization"

A.D. Beklemishev, Varenna 2008

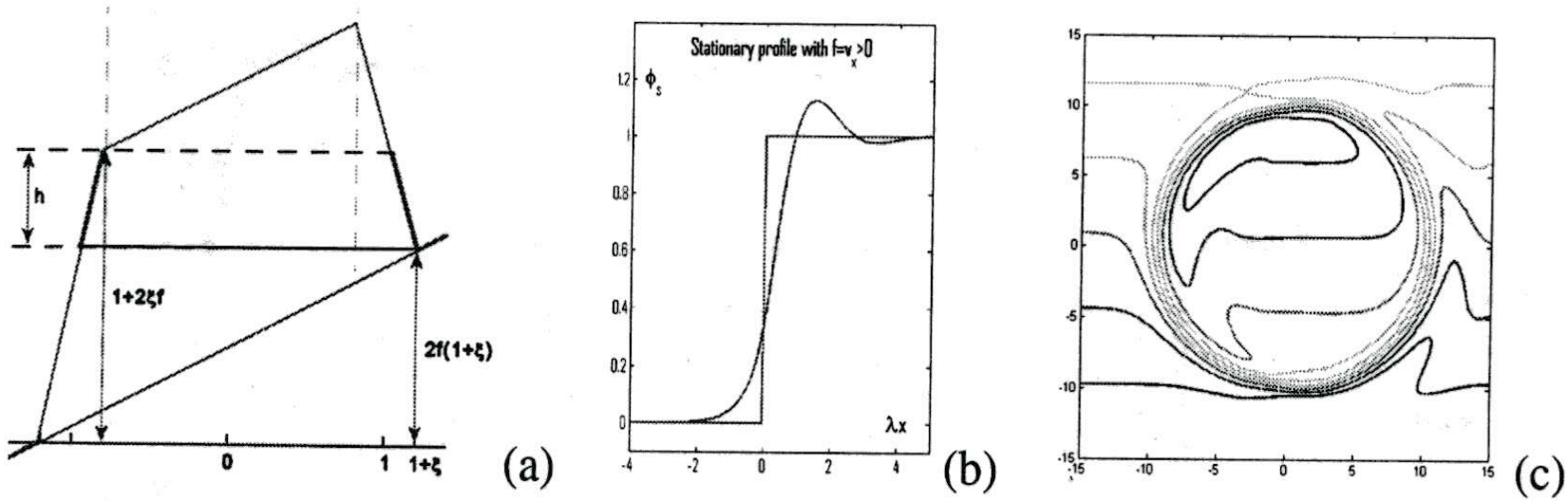


FIGURE 6. (a) Scheme of the vortex potential profile perturbed by the "rigid" $m = 1$ mode, which generates a quasi-uniform transverse "wind-field", $f = f_0 \cdot r cos\theta$. The flow-lines in the region $h > 0$ remain closed, if the perturbation amplitude is lower than the vortex amplitude, $2f_0 < 1$. (b) Potential profile in the perturbed flow-layer (slab). (c) Flow-lines in cylindrical geometry.

Hot-Ion Pinch

- Measured Hot Ion radius half that expected
- Liouville Thm: Integral (d3x)(d3v)=const.
- If r decreases the z or v increase
- Resonce: azimuthal drift & axial bounce
- Chirikov Criterion for overlap
  - Sqrt[(beta)(beta1)] = (a2/Lai)
  - (a2/Lai) ~ 0.04
  - Beta1 is MHD fluctuation
  - If beta = 0.1, then beta1~0.01 triggers pinch

Ambipolar End Plug (SHIP)

End Loss Current Density Referenced to Center (plug radius=7 cm)

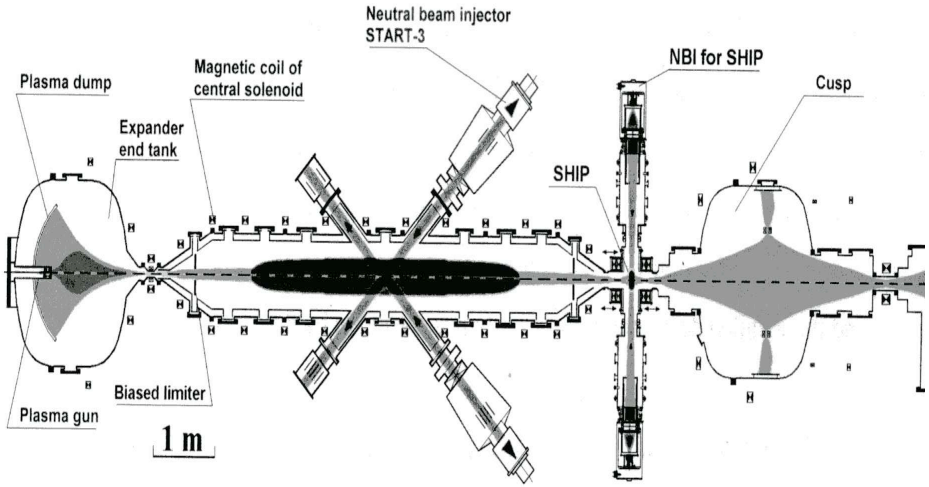
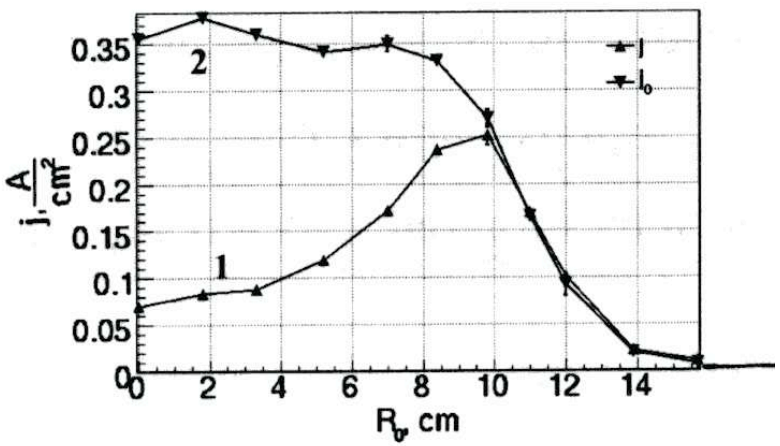


Fig.1. GDT experimental layout



Integrated Transport Code System (ITCS)

- Time dependent 3-D space & velocity
- Fast ions: Monte-Carlo Fokker Planck
  - Beam geometry, electron drag, ion scatter, B-variation (finite beta), charge exchange loss, target plasma, electrostatic potentials, etc…
- Warm plasma collisional physics
- Neutral gas transport (NEUFIT)

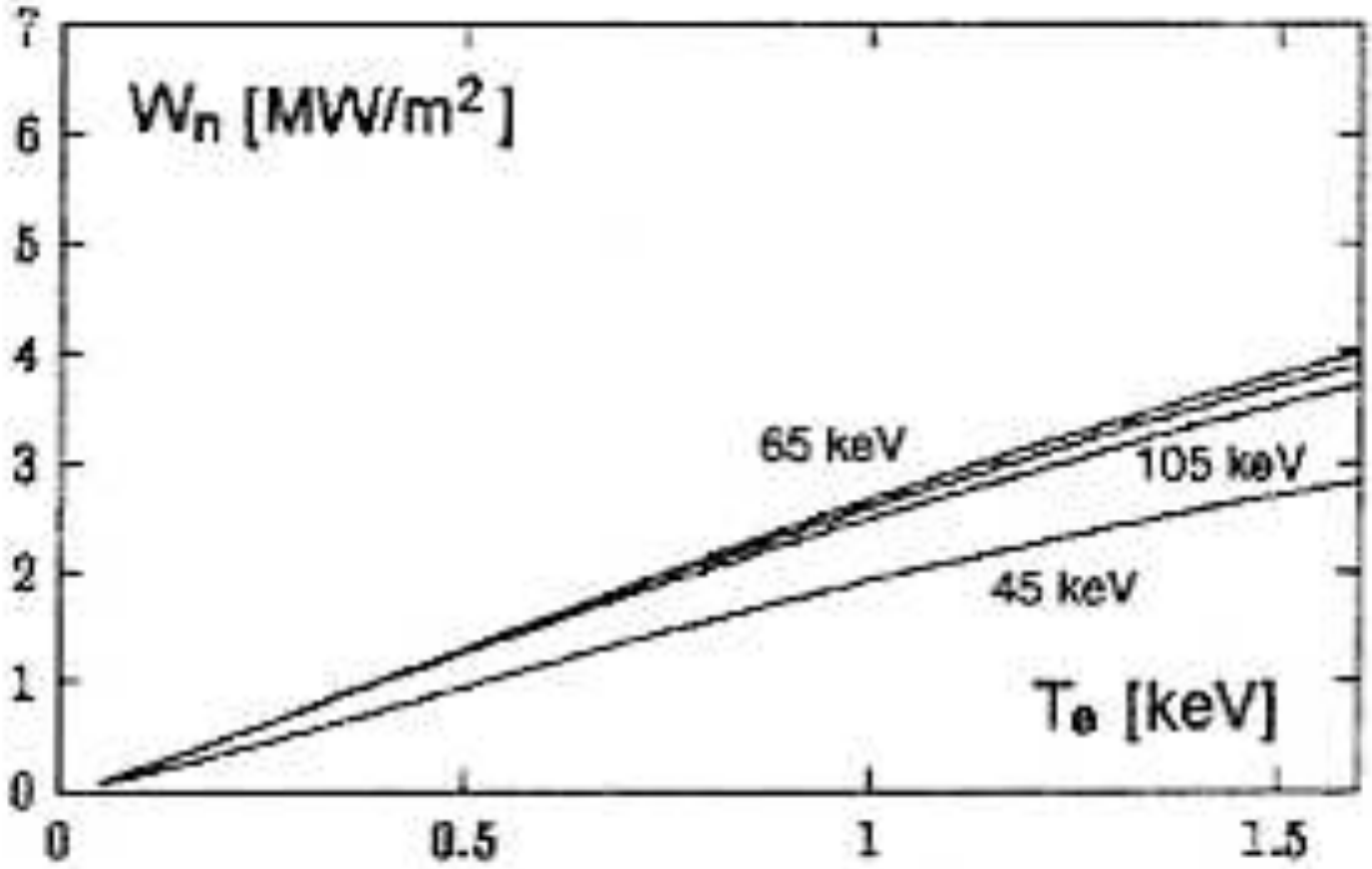
GDT Facility Plan

- 2009
  - Install 8 low divergence Beams (6 MW)
  - Increase mirror field by 25% (R=50)
  - Increase Limiter Bias (from 300 V to 450V)
- 2010
  - Tandem Mirror (2 SHIP cells)
- 2011
  - Add ECH to SHIP cells (450 kW 75 GHz & 45 GHz)

Construction Status of the Hydrogen Prototype

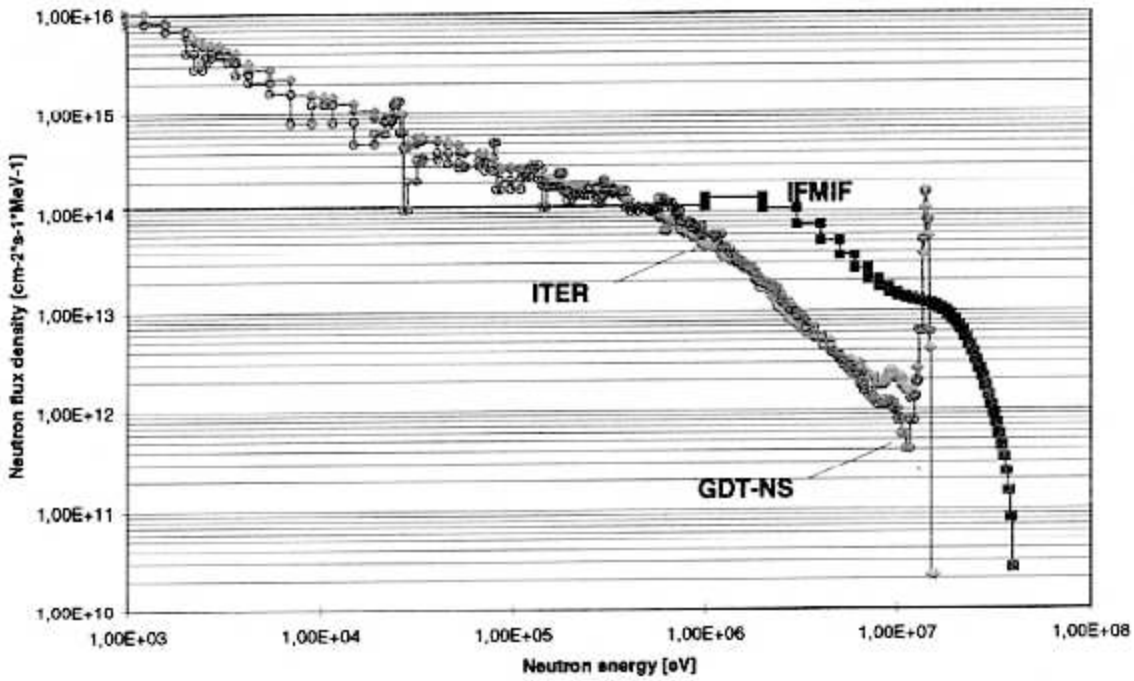
- 2x scale up of GDT: B-field, NB energy & power but similar size
- Vacuum Vessels & Magnets Fabricated
- Motor Generators & Building available
- Diagnostics from GDT
- Vacuum pumps and NB not fabricated
- Work halted due to lack of funds

Neutron Flux Scales With Te to 4 MW/m2 (for various NBI energies)



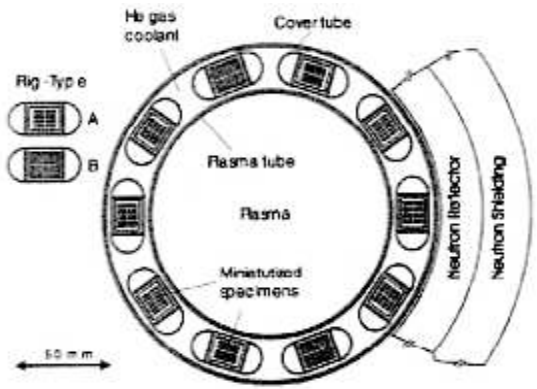
DTNS Could Produce ITER-Like Neutron Energy Spectra

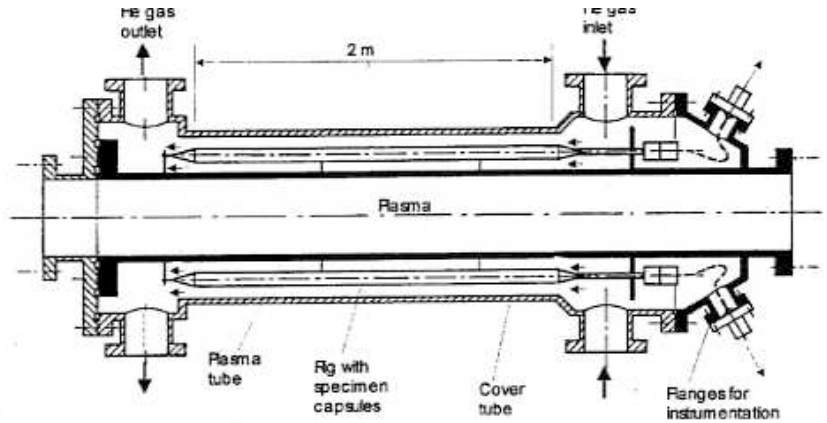
(Fischer, A.Moslang, A.Ivanov, FE&D 48 (2000) p.307)

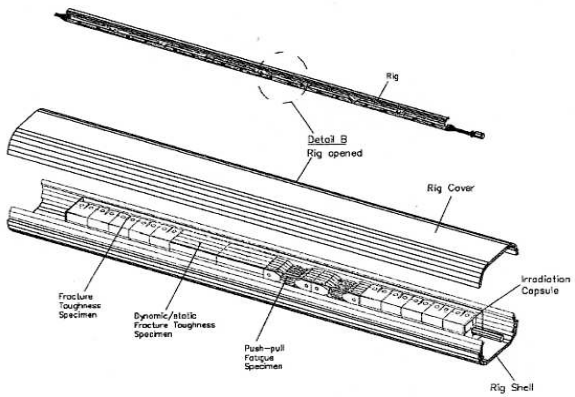


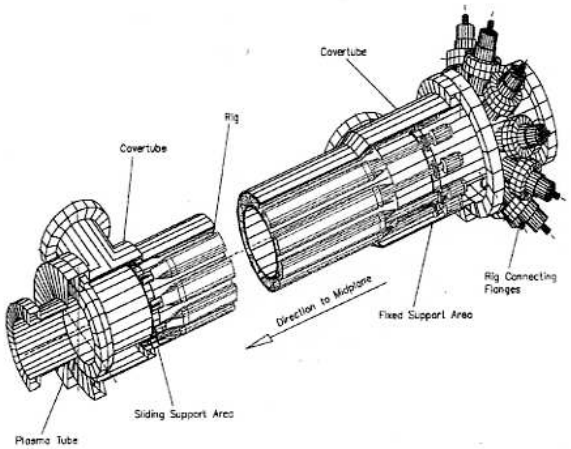
Small Material Sample Test Assembly
(Holds ~8,000 Temp. Controlled Specimens)

ref: U. Fisher, A. Moslang, A.A. Ivanov, FE&D 48 (2000) p307



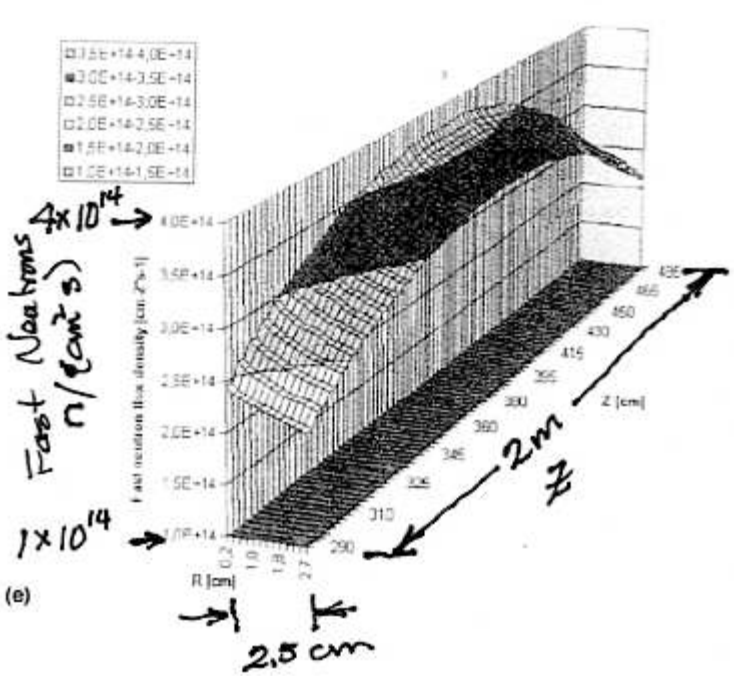






Monte Carlo Calculation Indicates Uniform Radial-Axial Neutron Flux

(r-uniformity < 5%/cm, z-uniformity < 0.1%/cm)



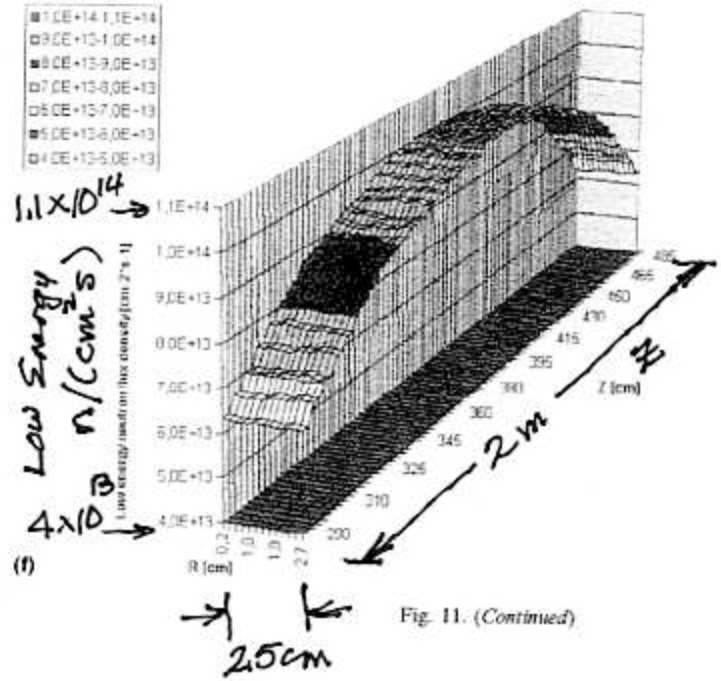


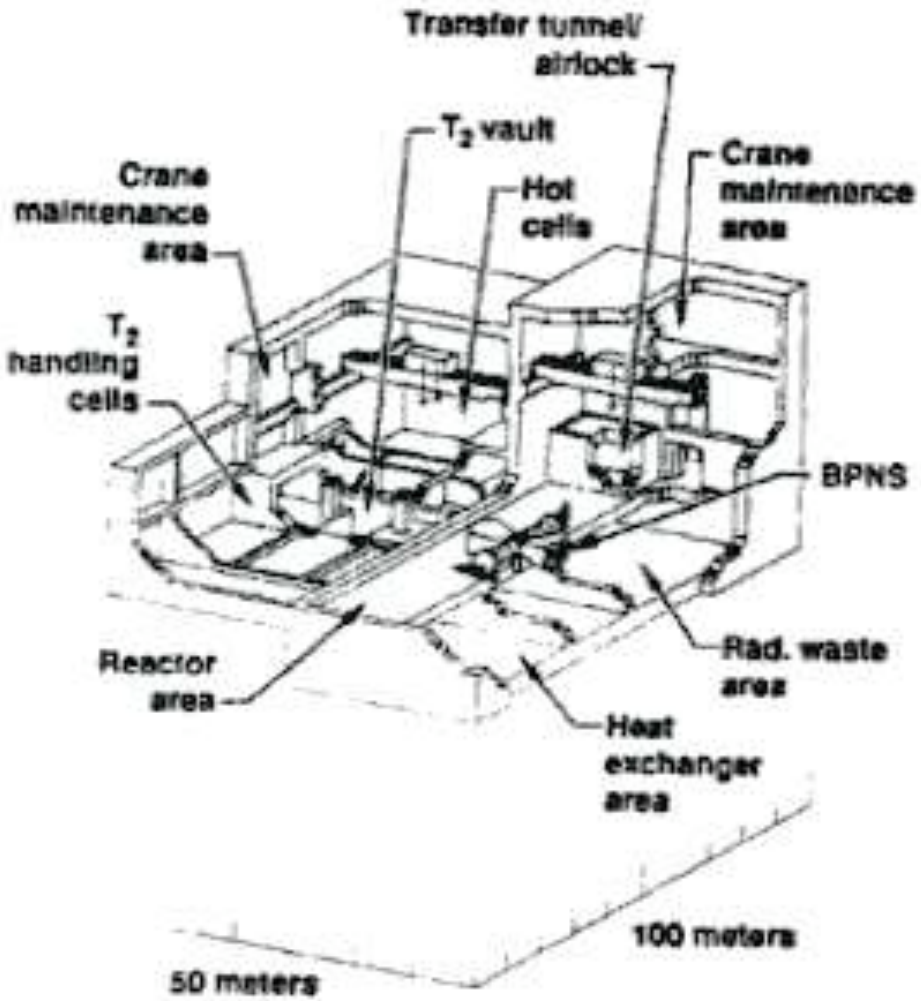
Fig. 11. (*Continued*)

Materials Testing Neutron Sources

	RTNS D-T 82-87	IFMIF D+Li	DTNS D-T	FDF/CTF D-T
Neutron Power (MW)	20 W	?	2+	100-300 30-160
Flux (MW/m2)	0.2	1.5	2+	2 - 3 1 - 3
Area (m2)	.0001	0.01	2	70 15
Tritium (kg/FPY)	~0	0	0.15	~2 to 20 without breeding
Cost ($M) FY08		1000	750?	? 1500?

Rough Scale of DTNS Facility

Based on BPNS, Coensgen et. al.



ATM System Studies Summary

		Neutron Source[1]	Hybrid Reactor [2]	Power Plant[3]	Advanced Power Plant [4]
L	m	10	30	30	95
a	m	0.08	1.5	1.5	0.42
B-min	T	1.3	3.0	3.0	3.0
B-max	T	20	18	-	26
NBI	keV	70	70	1000	
NBI	MW	30	70		30
Ne	1e20 m-3	2.0	1.0		2.2
Ti	keV	-	30-60	22	30
Te	keV	0.75	50-150	66	
Beta	%		30	40	60
P-neut	MW	2	100-500	-	960
Flux	MW/m2	2	2.7		
Area	m2	1.5x0.6			
Q		0.07	1.5 to 5	10	40

- [1] D.D. Ryutov, et.al., J. Fusion Energy, 17, p253 (1998)
- [2] J. Pratt & W. Horton, Phys. Plasmas, 13,042513 (2006)
- [3] D.D. Hua & T.K. Fowler, LLNL Report UCRL-ID-204783 (June 14, 2004)
- [4] R.W. Moir & T.D. Rognlien, Fusion Sci. & Tech 52, p408 (2007)

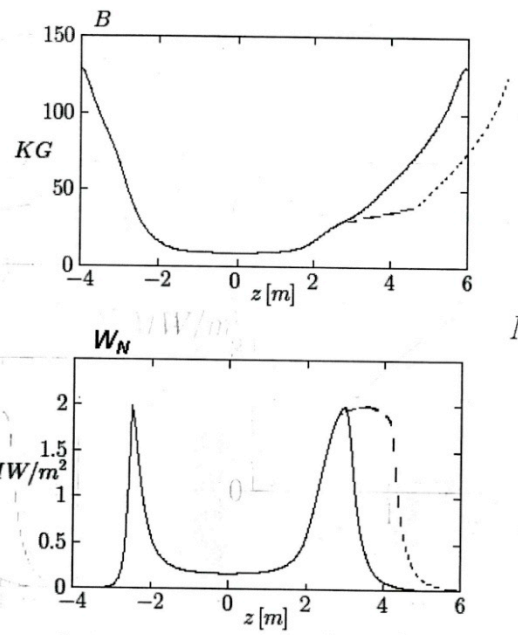
BINP Fusion-Fission Hybrid Design GDT-long (vertical)

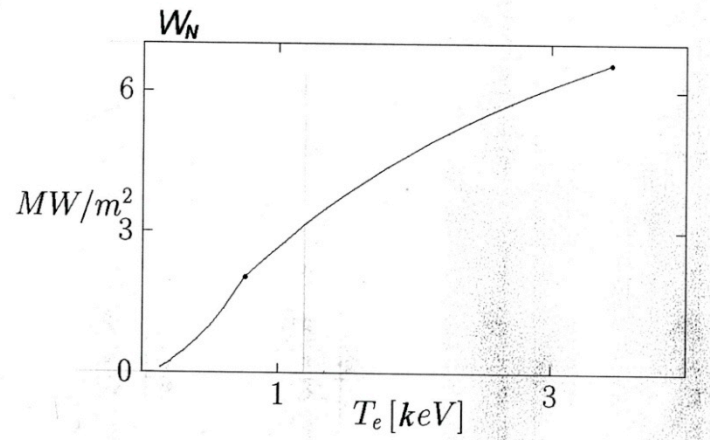
- 5 m long turning regions & Te~2keV
- 16 MW NBI needed per meter of elongation
- Te ~ 3.5 keV, Q ~ 2.8
- Incinerates waste of 5 LWRs
- Electrical Power ~250 MW for sale
- 150 MW electrical to produce 4 MW neutrons
- Design not yet optimized (0.75 keV version?)
- Superior to ADS

Neutron Source costs 16 MW per meter length of neutron flux

Extrapolation to larger length and temperatures

Экстраполяция на большие длины и температуры





of test zone costs

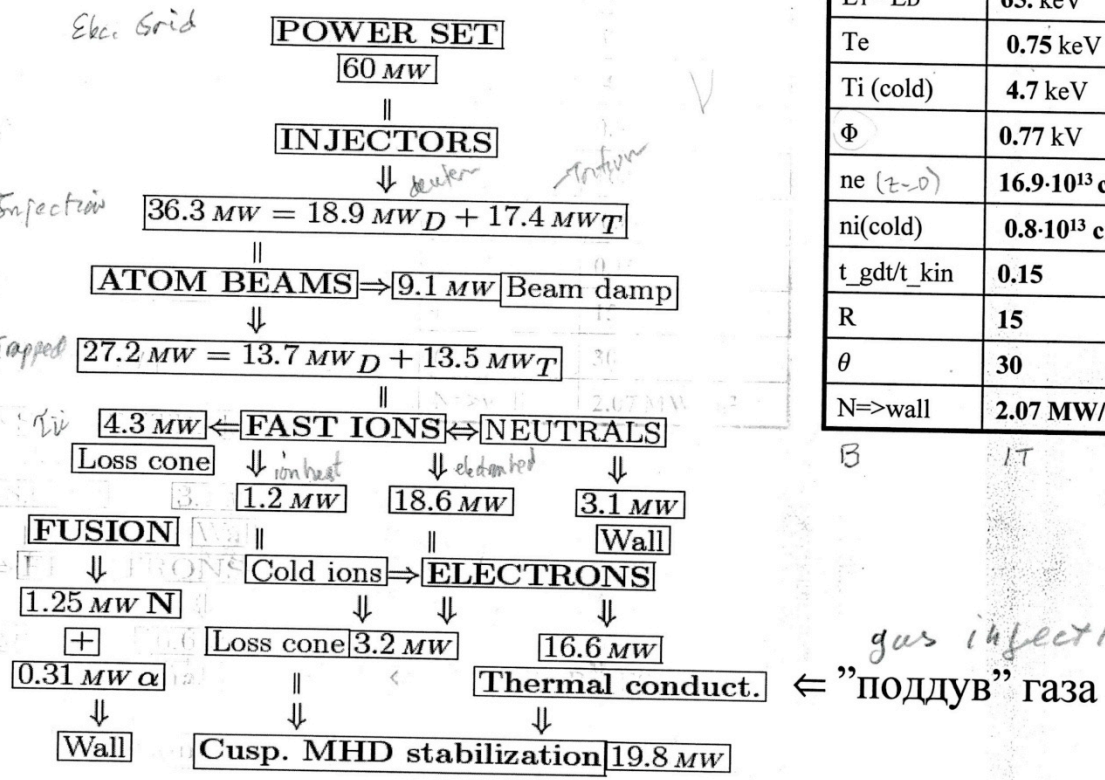
1м “тестовой” зоны стоит 16 MW от сети
и дает 0.5 MW нейтронов

and gives neutrons

Neutron Source Power Balance

Energy balance

Баланс энергии в базовой версии нейтронного генератора



$E_T = E_D$	**65.** keV
Te	**0.75** keV
Ti (cold)	**4.7** keV
Φ	**0.77** kV
ne (z=0)	**16.9·10^{13} cm^{-3}**
ni(cold)	**0.8·10^{13} cm^{-3}**
t_gdt/t_kin	**0.15**
R	**15**
θ	**30**
N=>wall	**2.07 MW/ m^2**

B 1T

gas injection

⇐ "поддув" газа