# Development of GDT-based Fusion Neutron Source

## *On a path to fusion energy*

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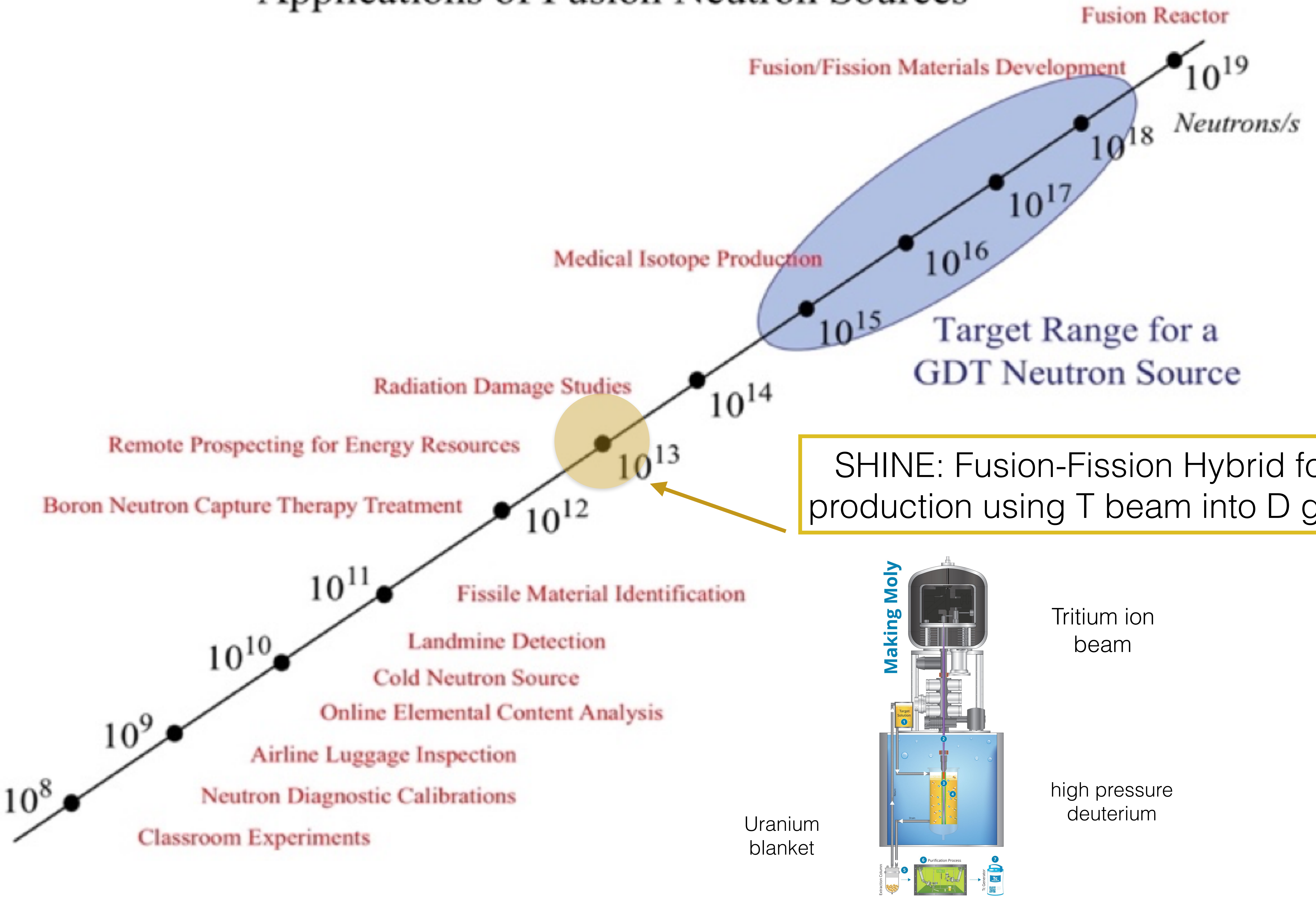
# Applications of Fusion Neutron Sources



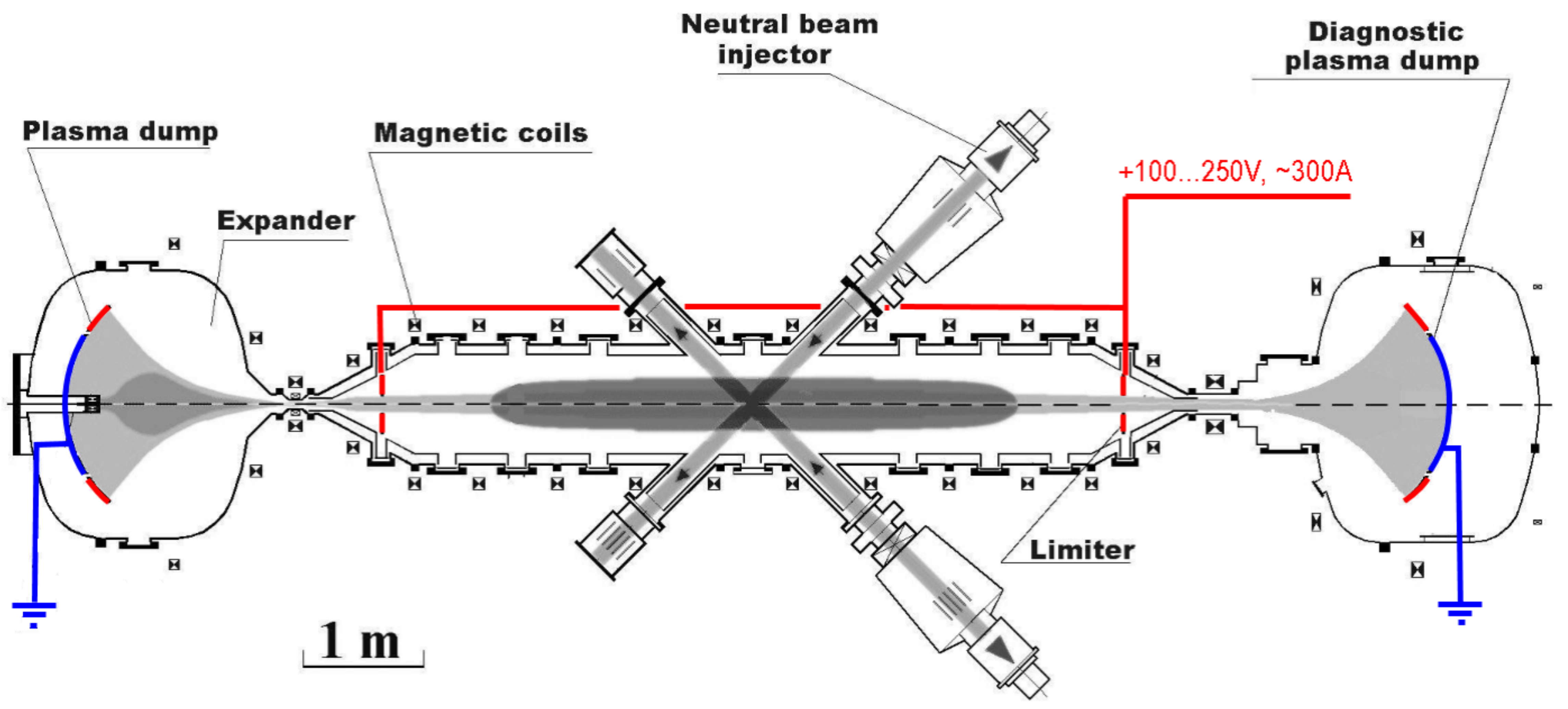

SHINE: Fusion-Fission Hybrid for Mo99 production using T beam into D gas target

# Outline

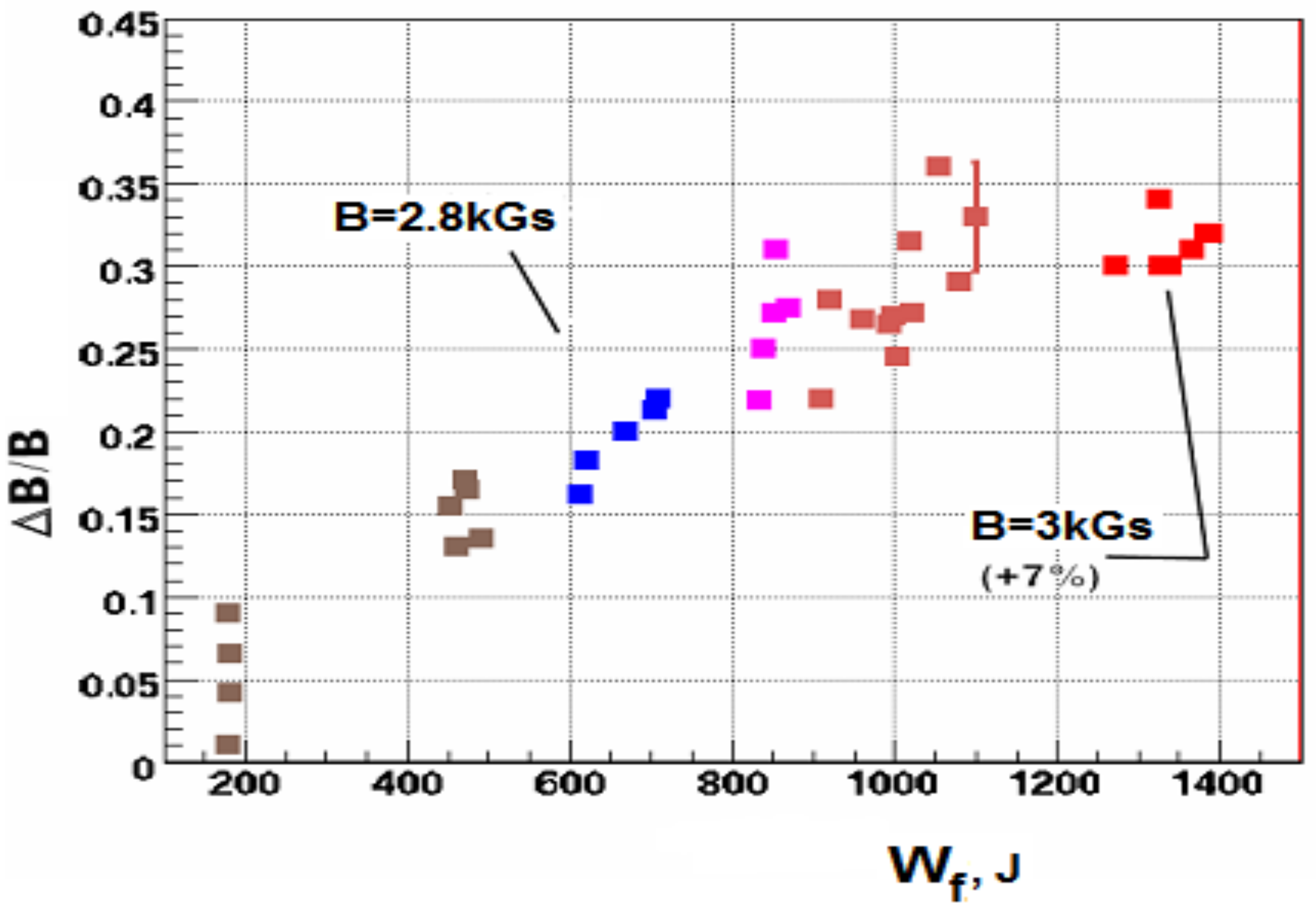
1. There have been recent game changing results in Gas Dynamic Trap mirror research
2. Fast ions confined in a steady-state GDT could be a very efficient neutron source for many applications (isotope production, radiography, neutron capture therapy)
   - ➡ offers a cost-effective short cut to fusion materials and sub-component testing
3. The mirror, like tokamaks, benefits from new high field magnet technology and other technological developments (eg. high frequency steady-state gyrotrons, lithium walls, negative neutral beams)
4. Near term experiments and theory effort could:
   - ➡ determine if GDT neutron source is feasible
   - ➡ be test bed for high field magnets and lithium walls
5. The fast development path of linear systems, may only require one or two miracles beyond the GDT to improve confinement for fusion energy: there are still good ideas

# 1. GDT Axisymmetric MHD Stability

## Limiter or End Wall Bias + Curvature

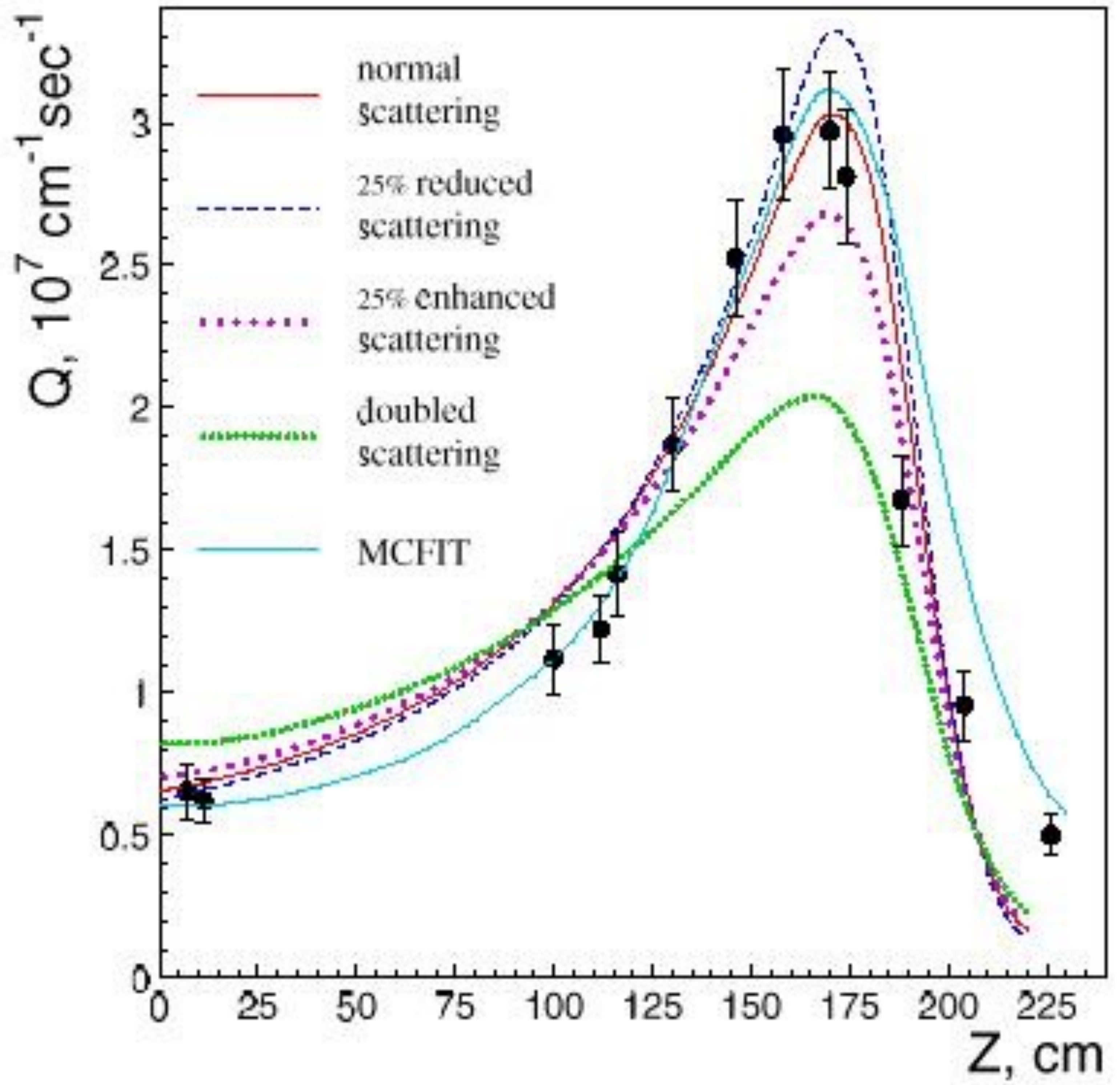



## Beta = 2 $\mu_0$ P/$B^2$=60% (MSE UW)

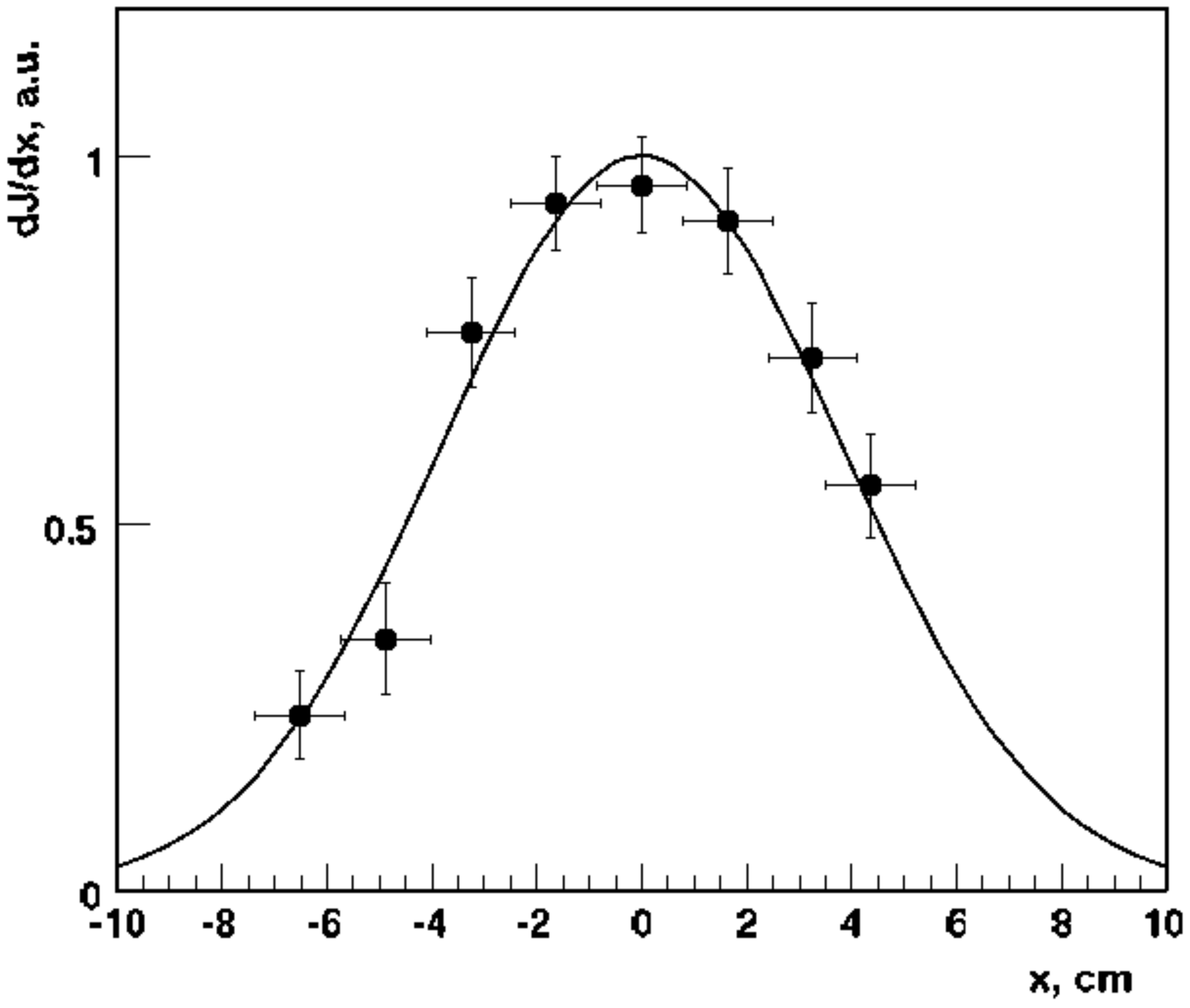


# 2. GDT D-D Neutron Production Illustrates Lack of Micro-Instabilities

**Axial Profile**



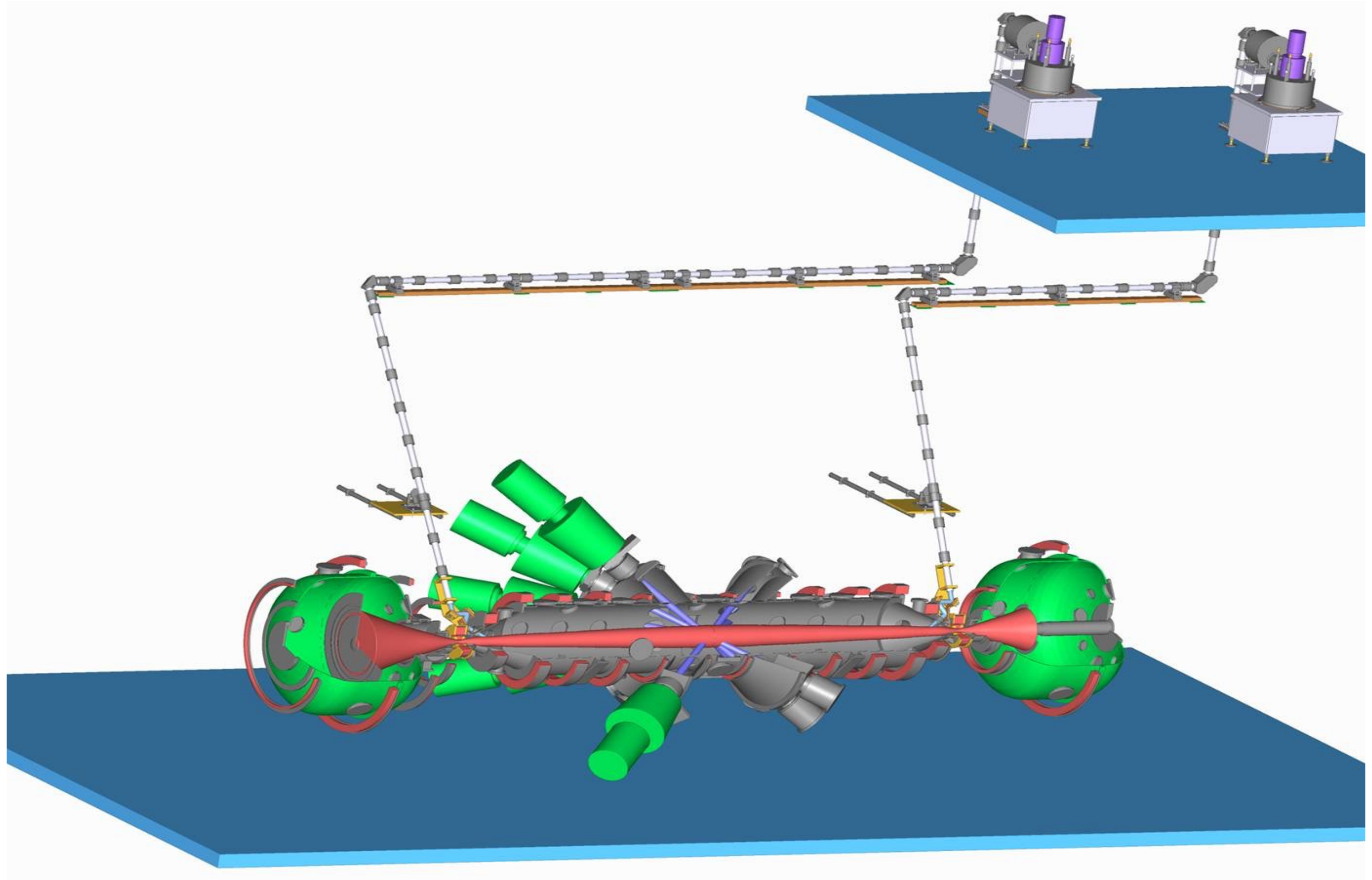

**Radial Profile**

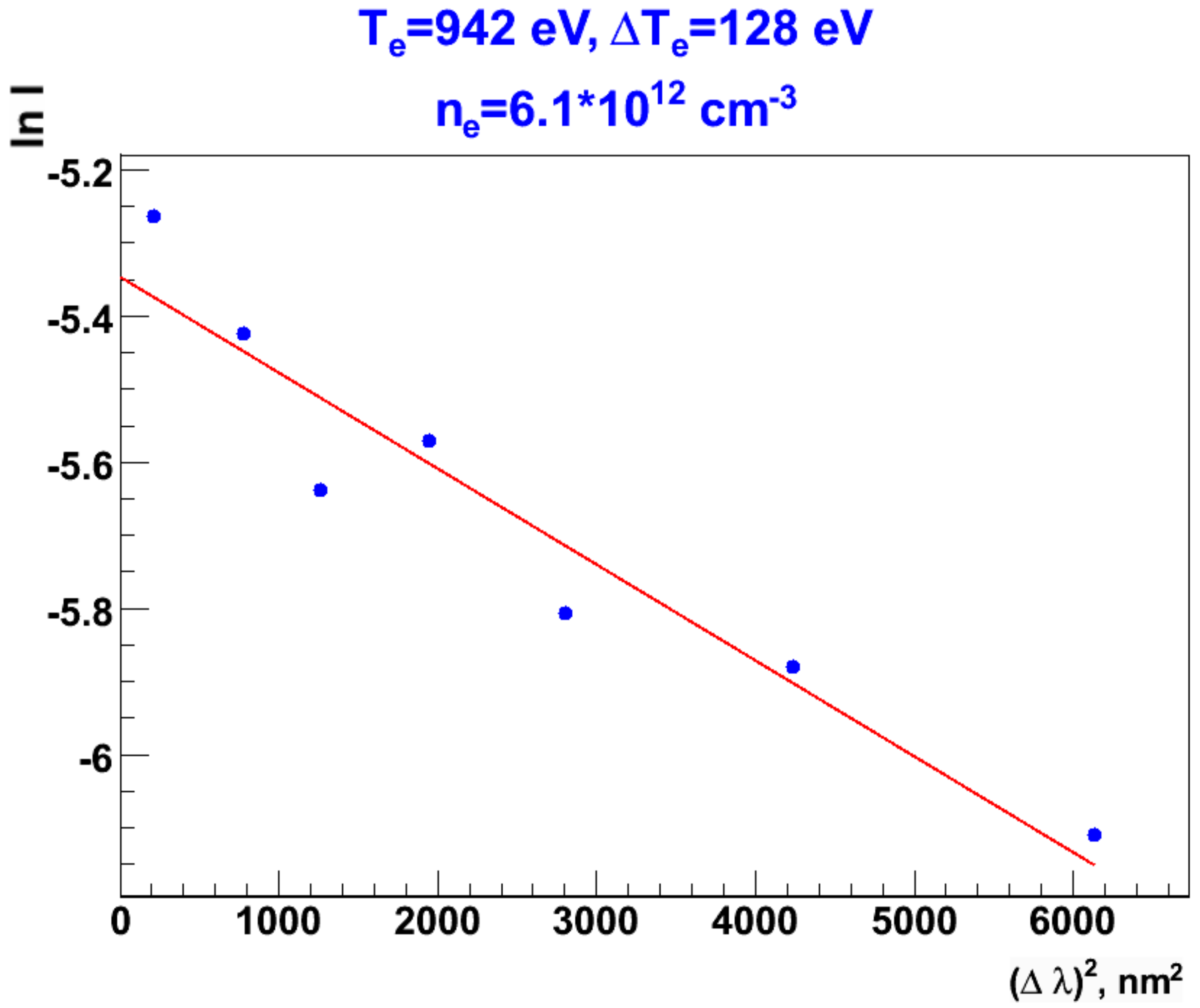



also demonstrated tandem mirror like plugging ($n_{fast}$>2 $n_e$(z=0) at turning points)

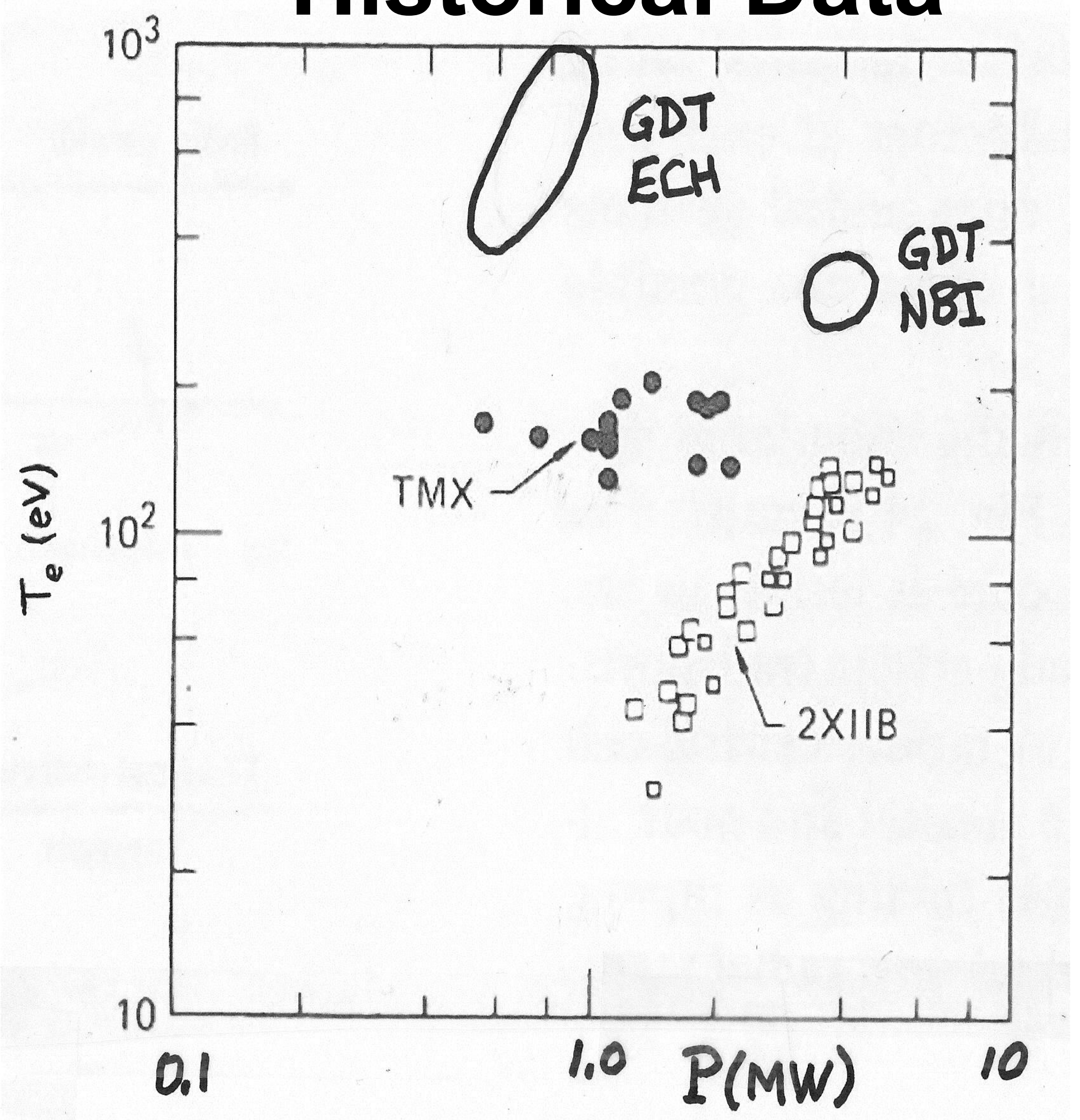
# 3. GDT Electron Temperature Reaches 1 keV with ECRH and Expanding Divertors

**Two 0.4 MW Gyrotrons at 54.5 GHz**






**Historical Data**



# Applications depend on achievable $T_e$

GDT Achieved

Diverter Test Facility (≤400 MW/$m^2$)

Neutron Source

Fusion-Fission Hybrid

Tandem Mirror Fusion Power Plant

0.1 1 10 100

$T_e$ (keV)

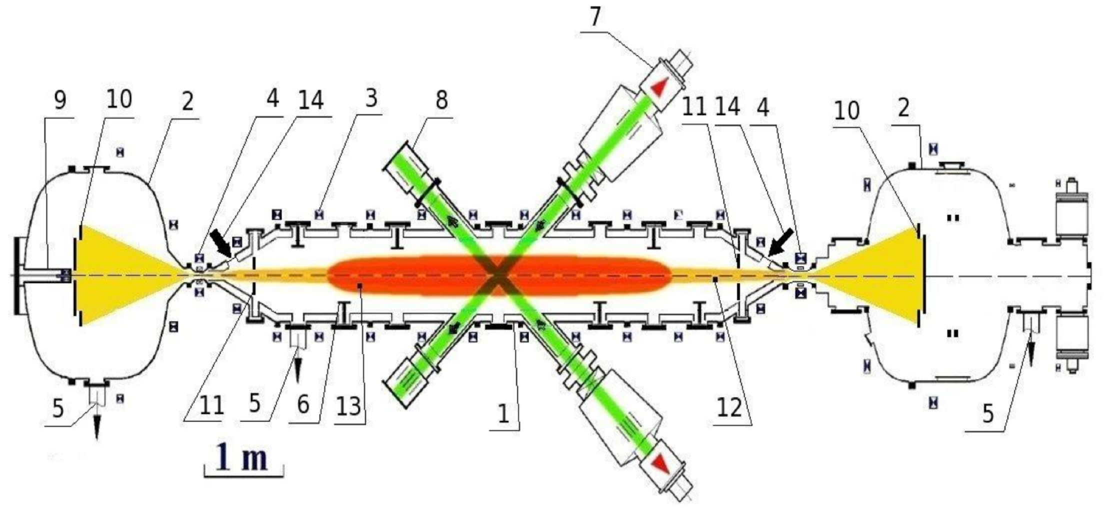
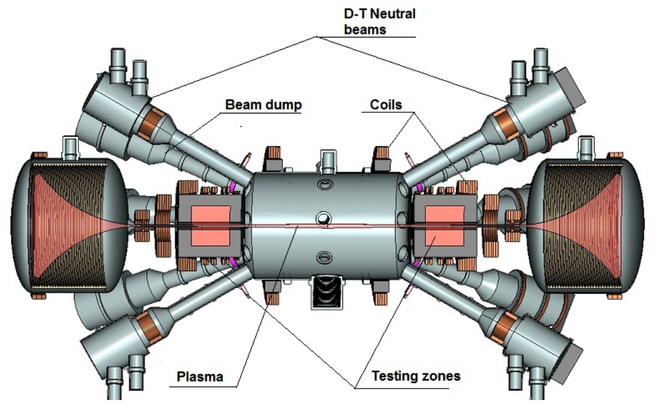
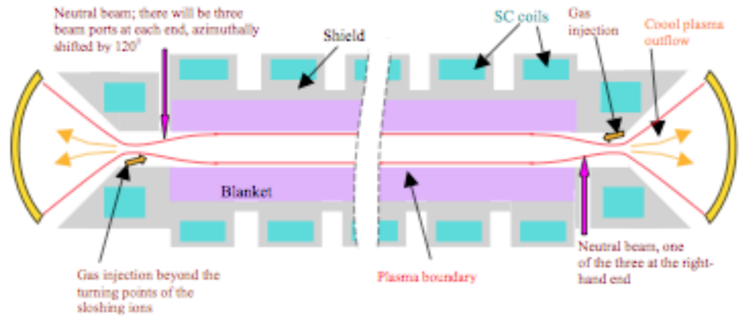
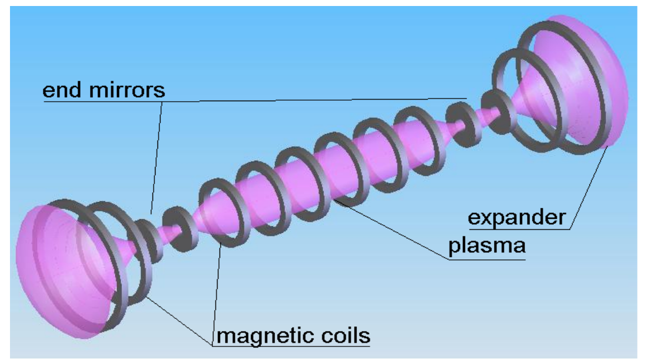



**Figure 1**. Schematic of the GDT device: 1 – central vacuum vessel; 2 – end tanks; 3 – central solenoid coils; 4 – mirror coils; 5 – vacuum pumping ports; 6 – titanium evaporators; 7 – neutral beam injectors; 8 – neutral beam dumps; 9 – initial plasma source; 10 – sectioned end-plates (central parts are grounded, external rings are biased with approximately +300 V); 11 - biasing limiters; 12 – warm plasma column; 13 – hot ion column; 14 – ports for launching of microwave radiation.



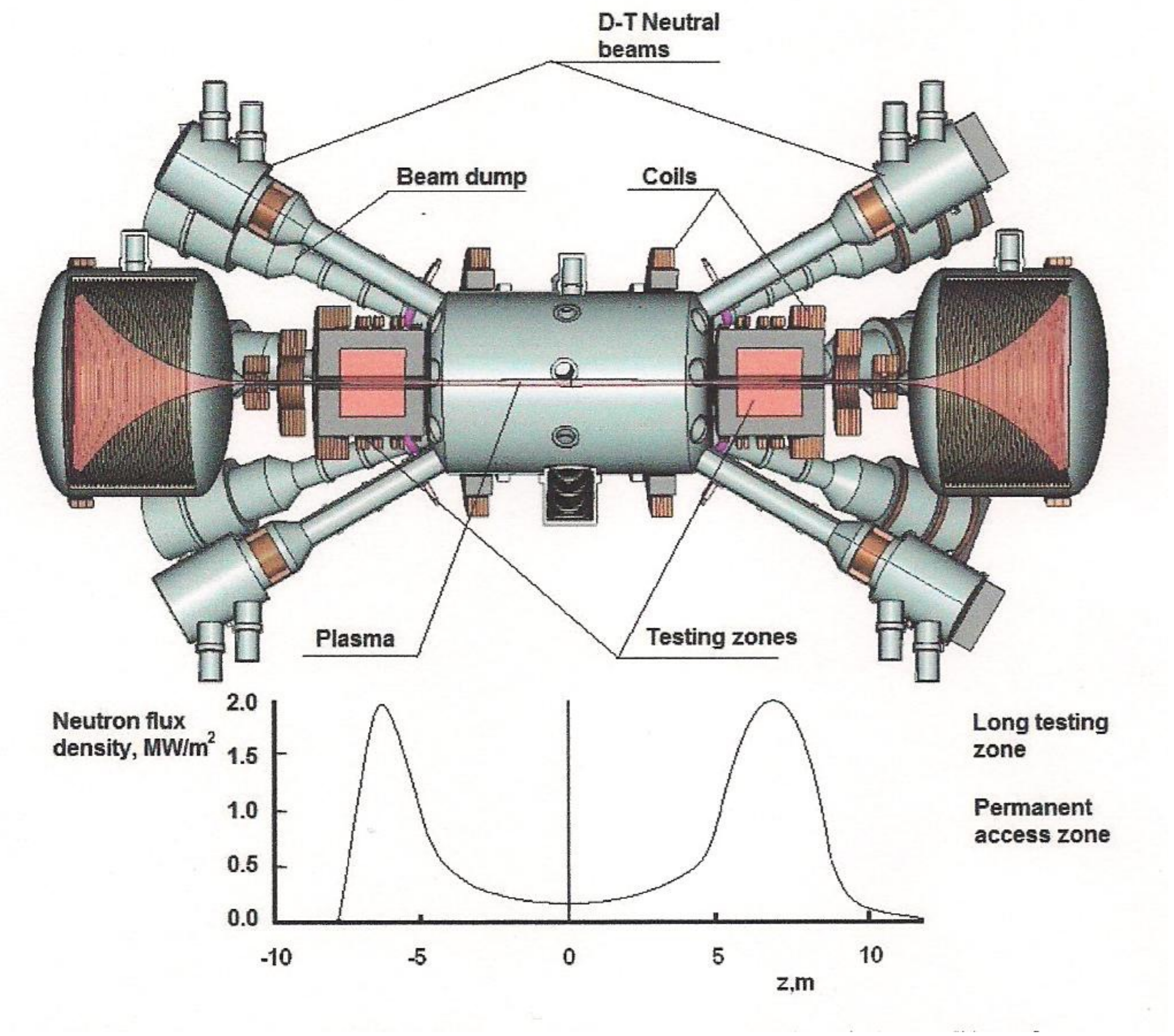



# DTNS: A Russian Design for a Neutron Source

**A MW of Fusion Power for Weeks**

**Neutron Flux ~ 2 $MW/m^2$ Test Area ~ 1 $m^2$**




Gas Dynamic Trap Accomplishments:

- axisymmetric MHD stability, β~60%
- Te ~ 0.9 keV
- $B_c$ ~ 0.3T, R < 40
- 25 kV beams, 5 ms with classical slowing down and sloshing ions

Scales to neutron source with higher B, higher NBI energy, higher ECH frequency

- Te = 0.65 keV
- $B_c$ = 1.3 T, R = 10
- 65 kV beams (DT for high flux)
- 2 $MW/m^2$ ( 4x ITER flux)

50 MW input! (low Q at 15m device)
A GDT reactor would be ~ 1km long

Tritium consumed 200g/fpy

- **No Tritium breeding needed**
- **10 dpa = 1 $MW/m^2$ fpy**

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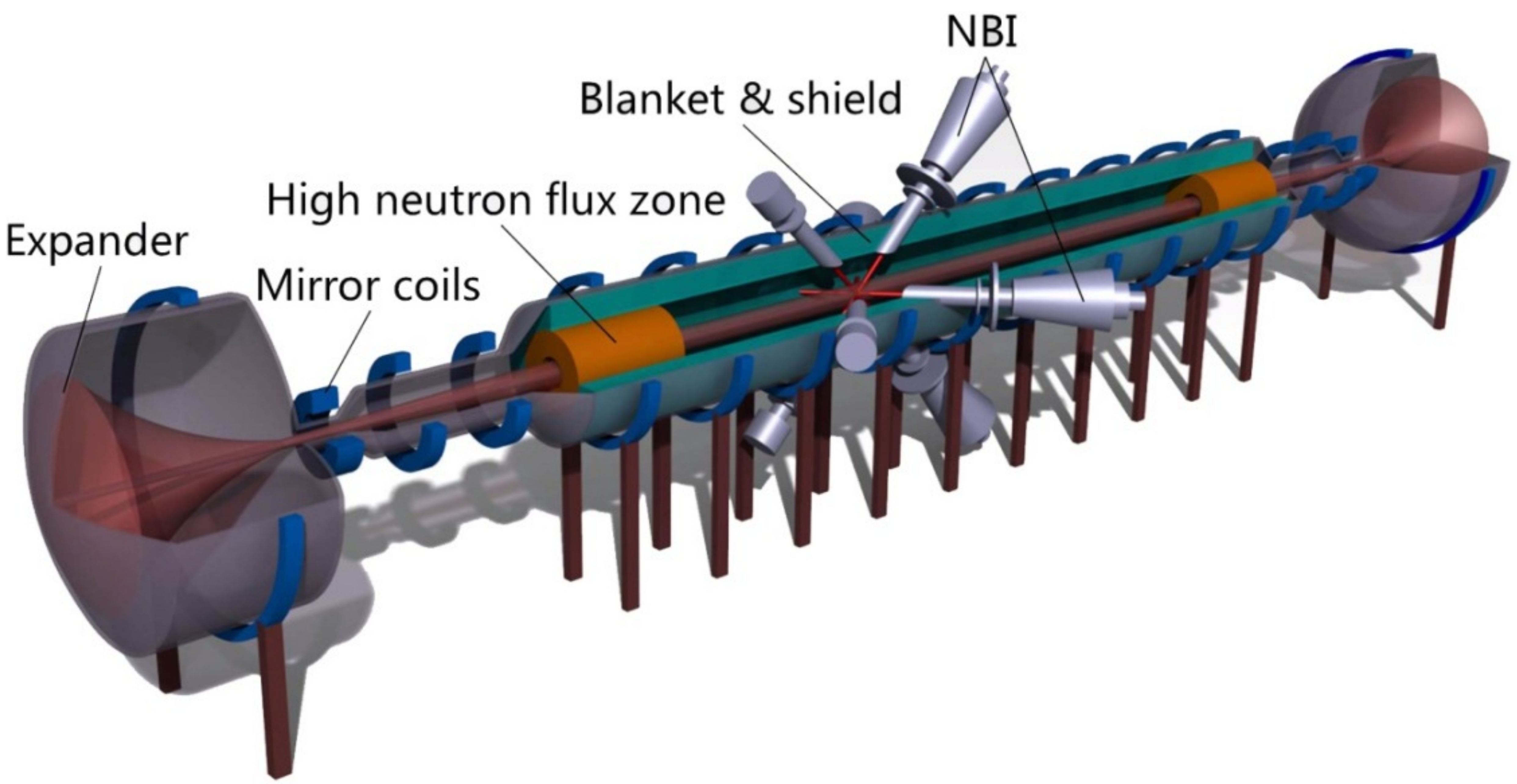
A.A. Ivanov, Fusion Science & Technology **55** 2010

A.A. Ivanov and V. V. Prikhodko, PPCF **55** 2013 and references therein.

# Initiate an International Mega-science Project

## International Fusion Volumetric Neutron Source (FVNS)




❖ **Design target for FVNS**

- **Neutron spectrum: fusion neutron**
- **Availability: > 70%**
- **Operation: quasi-continuous**
- **Tritium consumption rate: <200g/year**
- Neutron flux and test volume:

≥2MW/$m^2$ (~10L ); ≥ 1MW/$m^2$ (~100L); ≥ 0.5MW/$m^2$ (~1 $m^3$);

**International Cooperation:**

- Design and Licenses in ~5 years
- Construction in ~5 years
- Operation in ~20 years
- Construction Cost is ~1Billion $

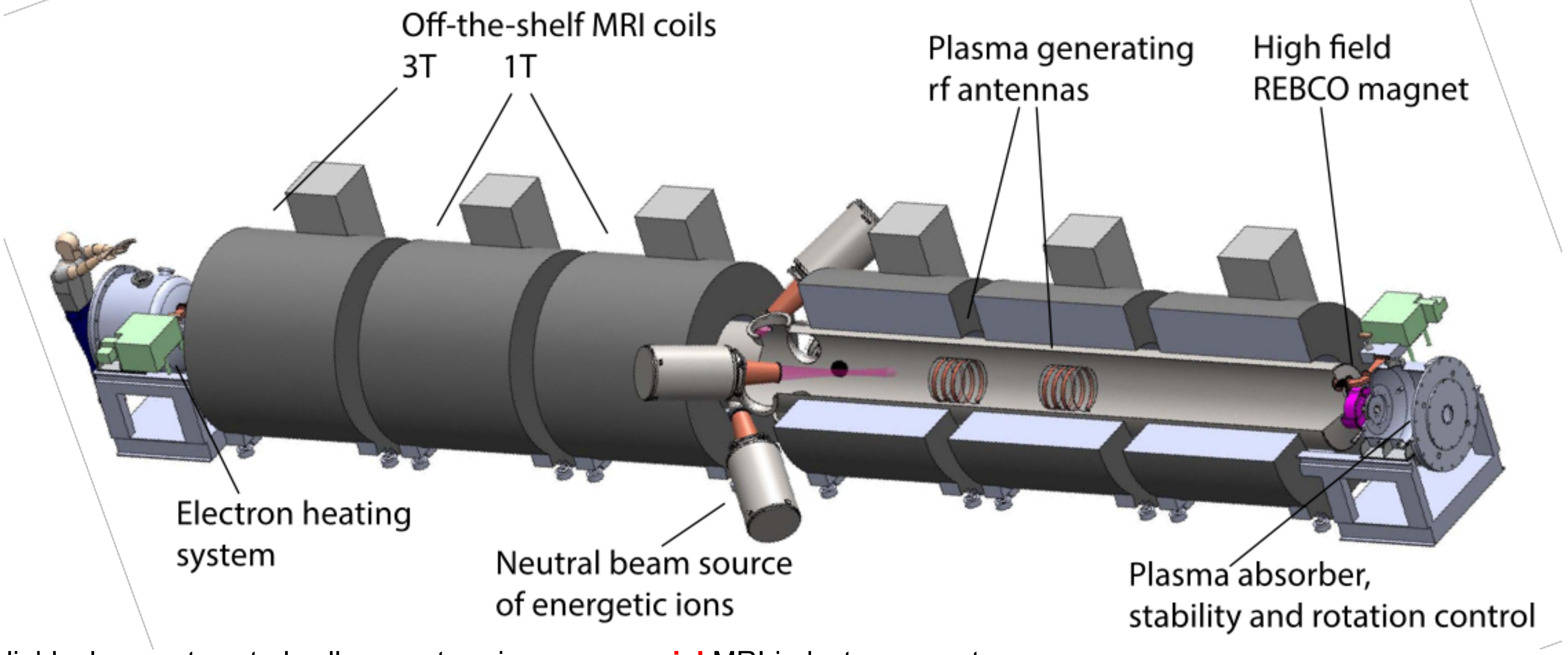
# Gaps (shortcomings) remaining from Budker GDT Experiment

- short plasma pulse (5 ms)
- low field (~2 kG)
- low energy neutral beams
- low frequency (and therefore low density) ECH
- less than optimized pumping and fueling (heavy use of Ti gettering)

**Advanced Concept Exploration at Mid-Scale is a necessary next step**

- longer pulse (>50 ms to reach steady-state fast ion distribution)
- higher field ($B_c$=0.5-1 T, $B_{plug}$>20 T for fast ion and high density)
- full energy neutral beams (80 keV)
- high frequency (and therefore high density) ECH
- Optimized pumping and fueling (Li walls)

# A cost-effective next step GDT would be a high-field, medium pulse (0.1-2 sec)




- Reliable, low-cost central cell magnets using **commercial** MRI-industry magnets (1-3T @$400k)
- Two compact, 20 T high-field mirror plug coils (simple planar REBCO coils)
- Novosibirsk-developed NBI injection for fast ions (2 MW, eg MST + TriAlpha beams )
- Expanding-field Li diverter for MHD stability and pumping
- HHFW for heating ions at turning points
- ECH for high density plasma formation and $T_e$ control (2 MW at 110 GHz)

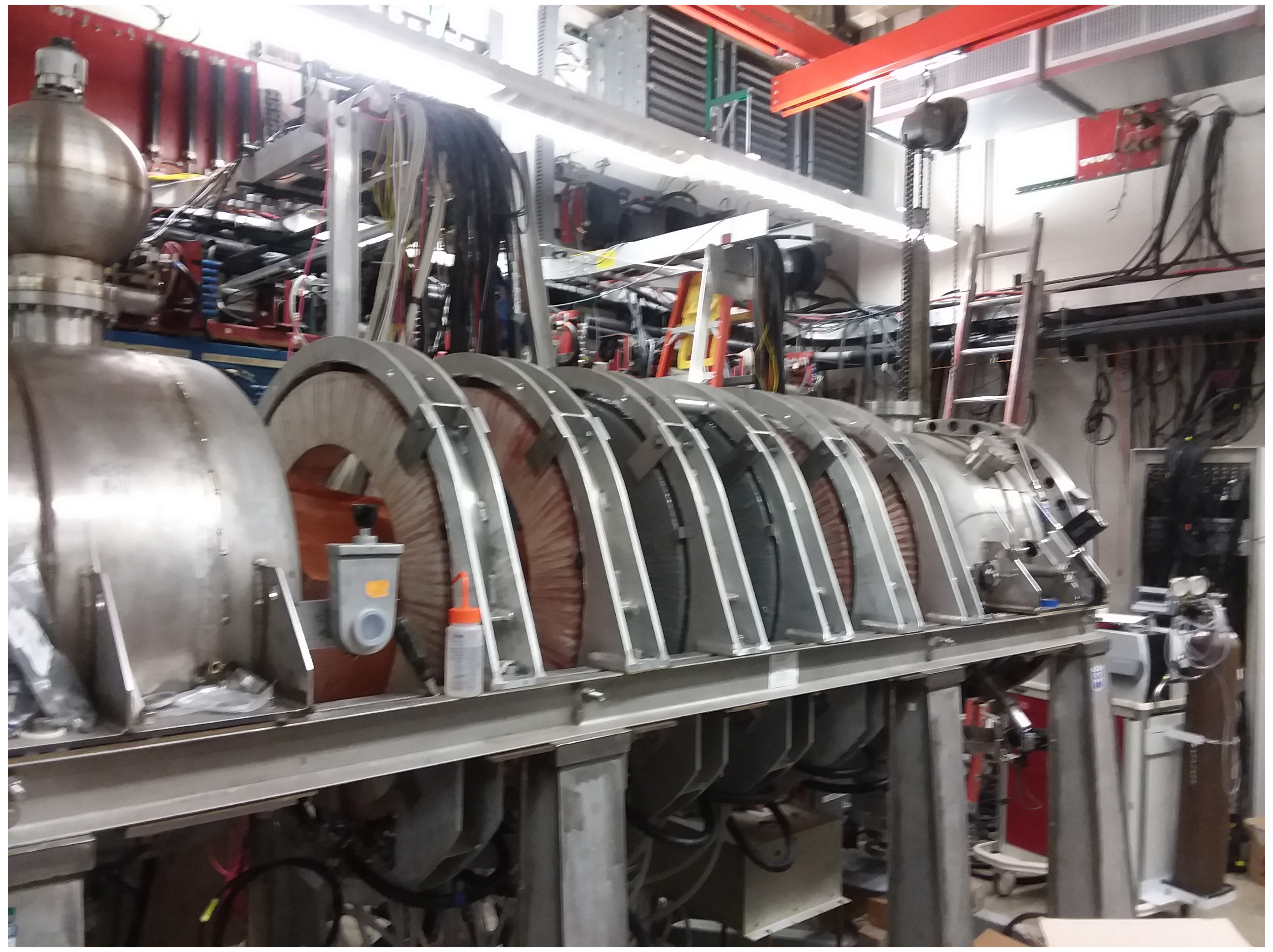
a= 10 cm
$P_{NBI}$ = several MW
$P_{ECH}$ = 1 MW
$f_{ECH}$ = 110 GHz

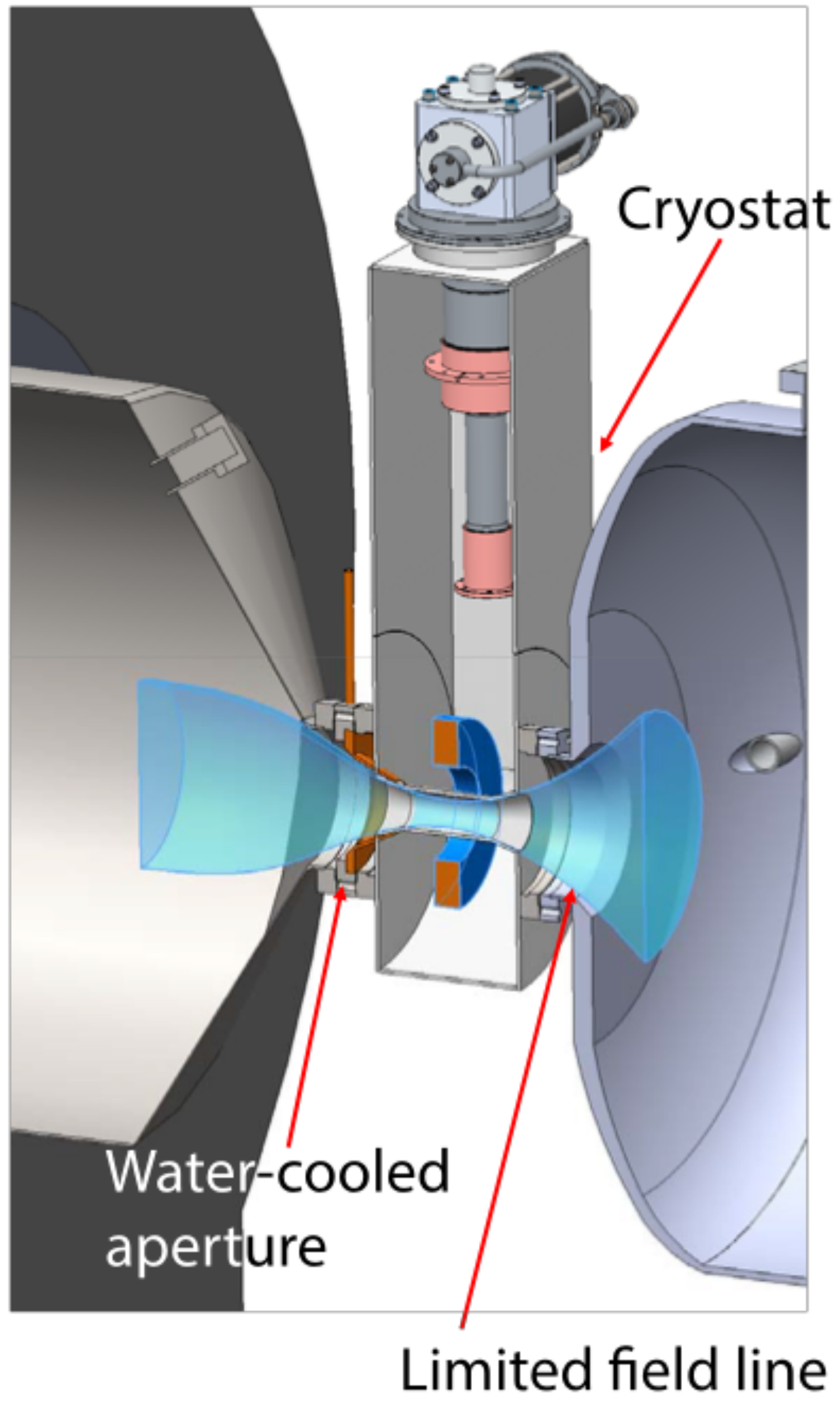
# Investment of internal funding by UW-Madison is being used to construct a GDT prototype device featuring HTS magnets

- **The Rotating Wall Machine is being repurposed as a prototype mirror device**
  - Will produce high density target plasma
  - Expander physics with Li end walls
  - Rotation/ biasing with $LaB_6$ cathodes
  - Adequate diagnostic set on hand

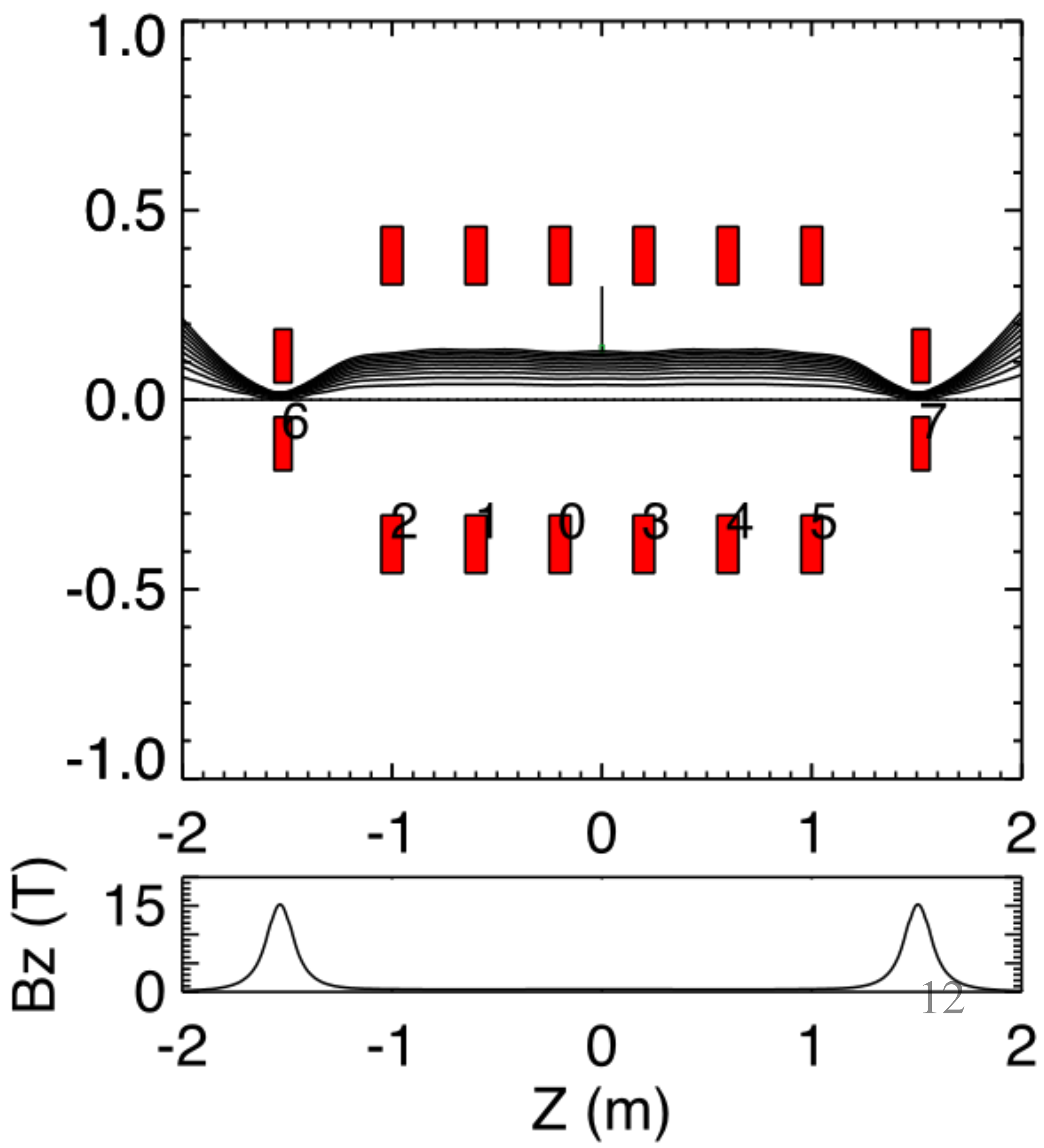
- **REBCO based coil under development**
  **(collaboration with both General Atomics and CFS)**
  - Will help drive use of HTS for plasma confinement

**Prototype device in UW Physics Dept.**






**GDT type magnetic field ($R_m$>15)**

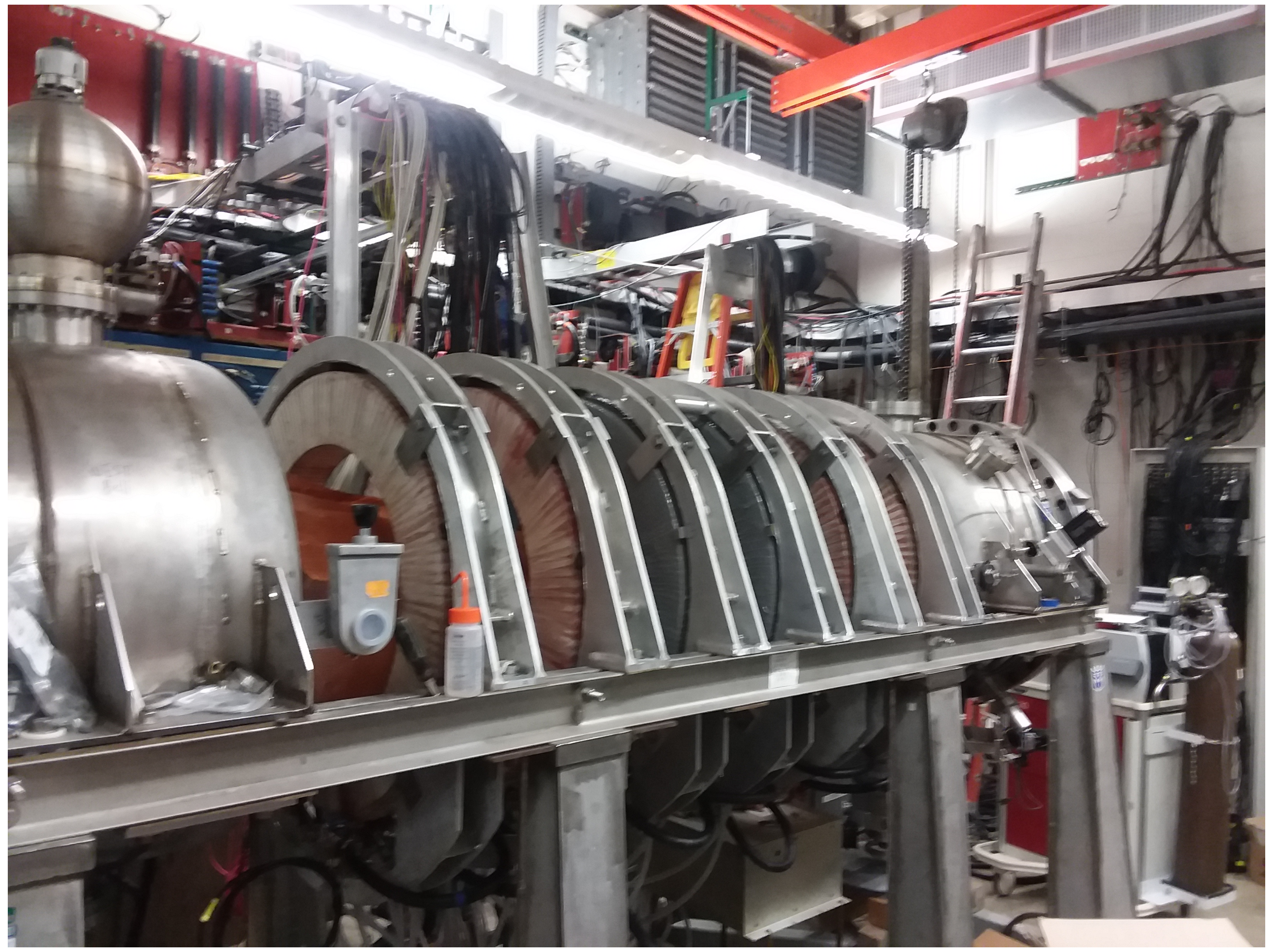


Investment of internal funding by UW-Madison is being used to construct a GDT prototype device featuring HTS magnets

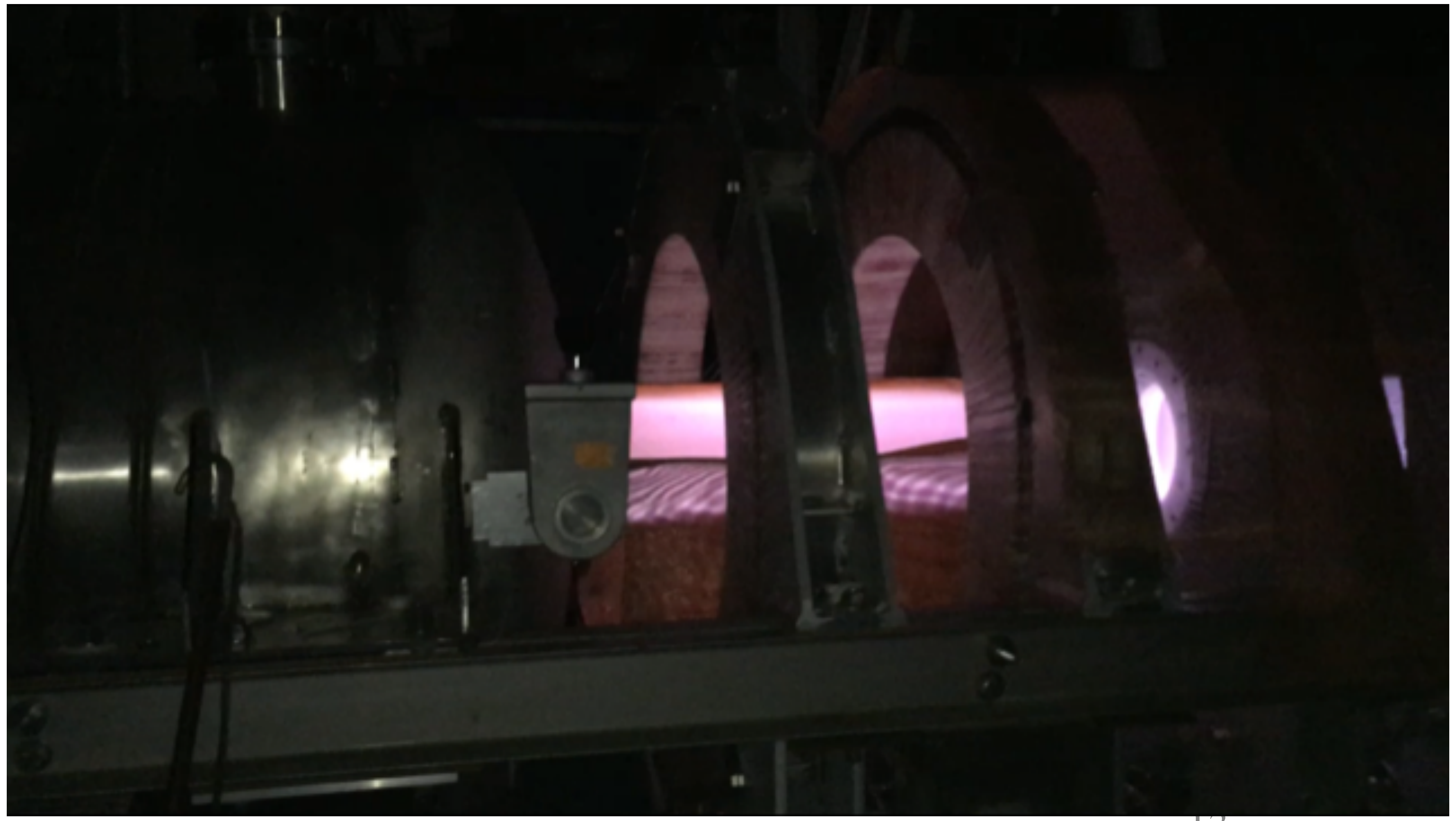
**Physics goals for proto-type experiment:**

- Demonstrate long pulse MHD stability in GDT geometry
- Understand and control Te
- begin sloshing ion studies
- Explore use of liquid Li in end-cells; compatibility with GDT plasma fueling and exhaust

**Proto-type device in UW Physics Dept.**



**First plasma 5/30/18, central solenoid only**



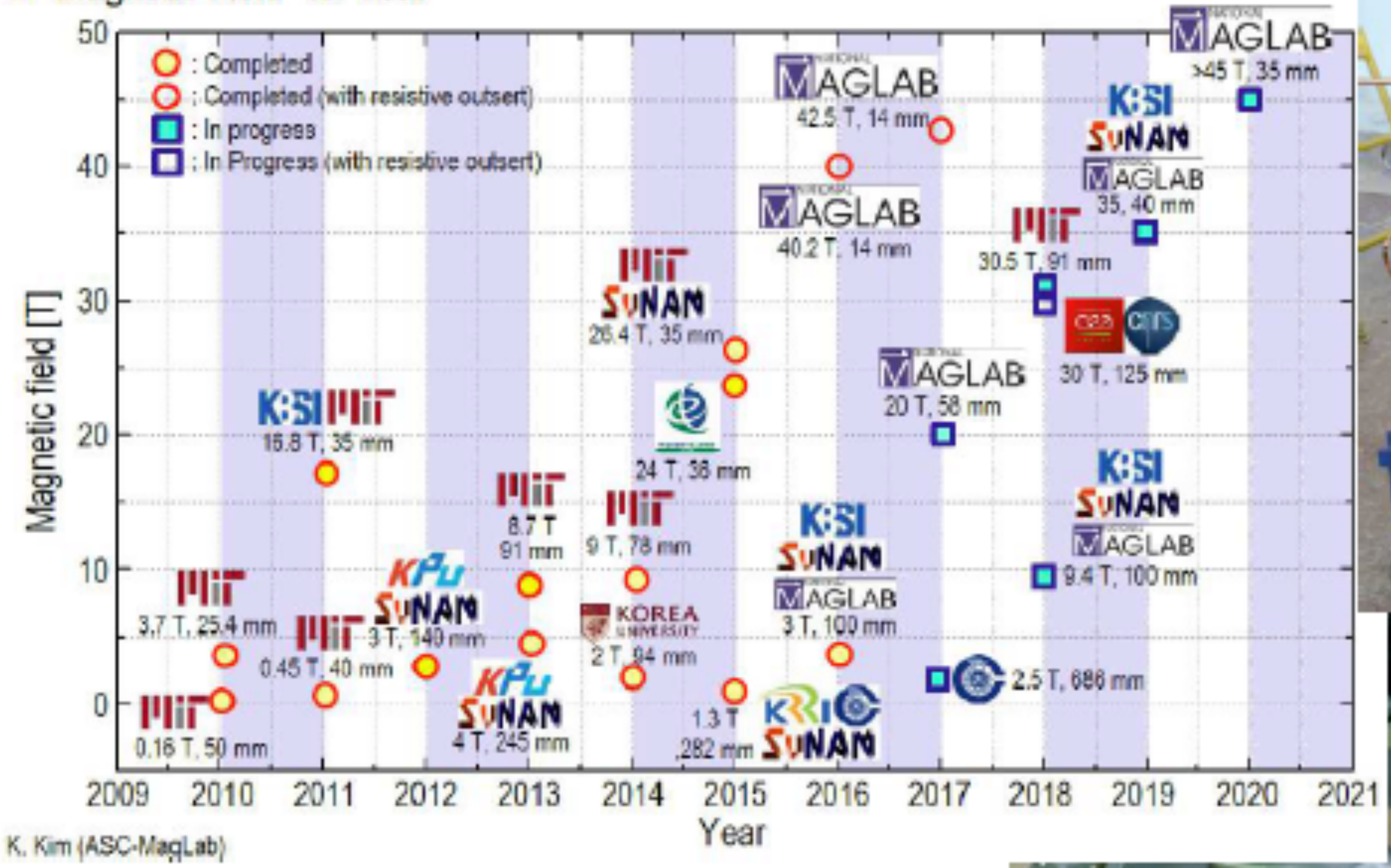
# HTS for Mirrors

1. Higher Field
2. Higher mirror ratios
3. magnet winding pack is can be different

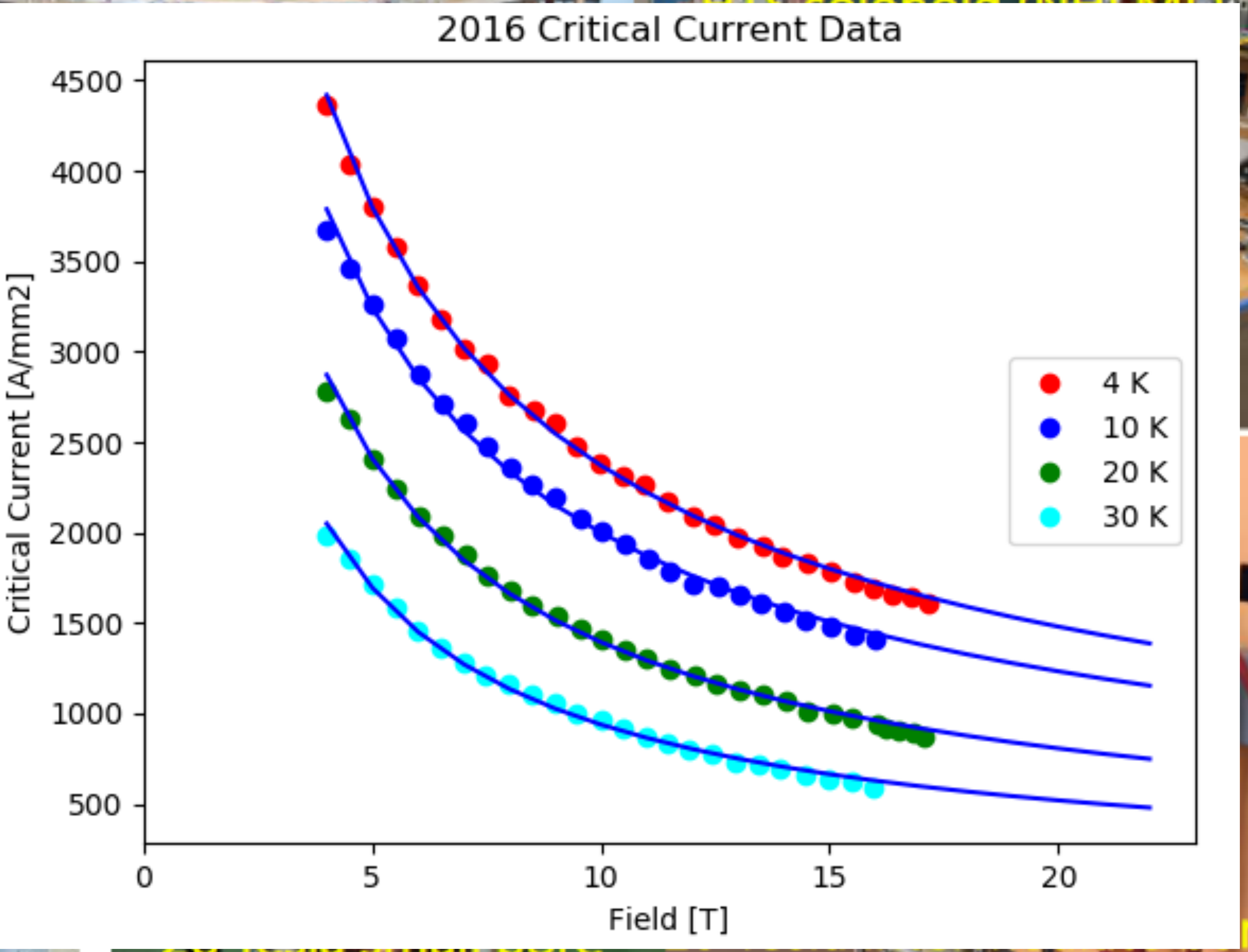
# HTS tape now being incorporated into cutting edge magnets across disciplines

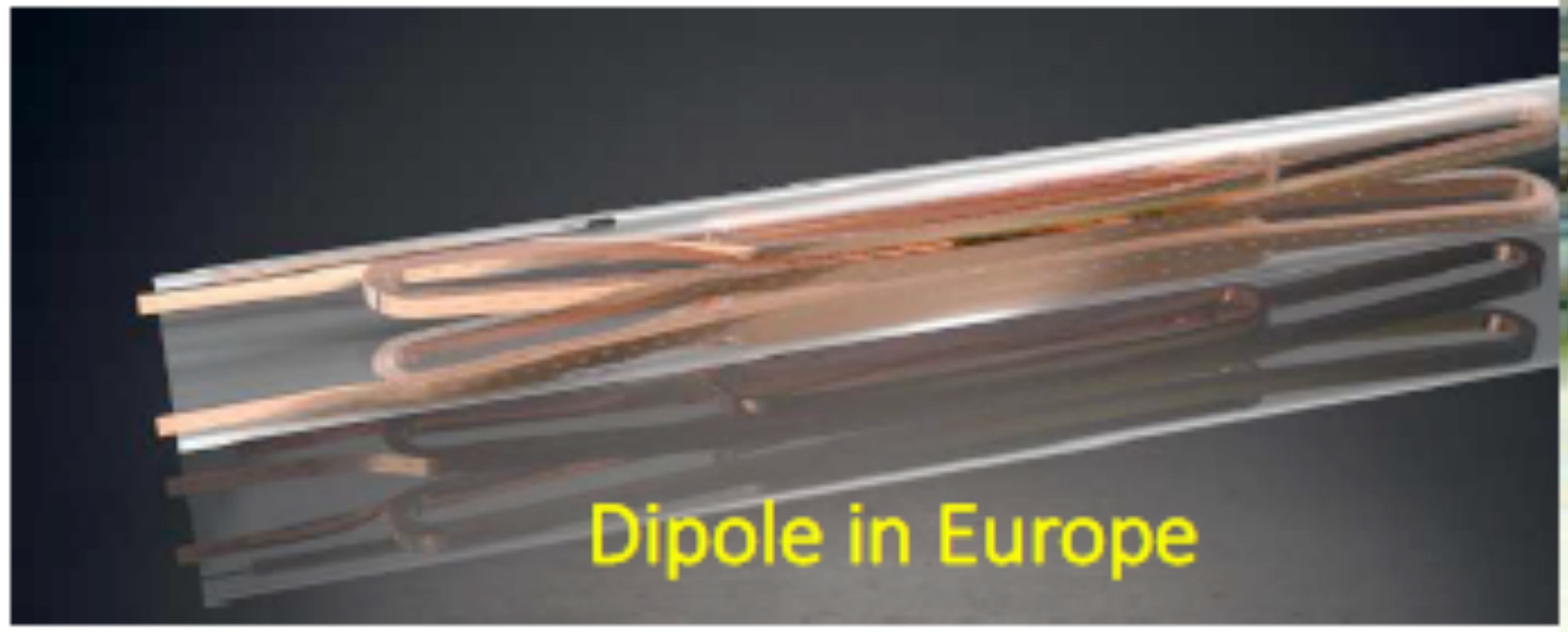
PSFC

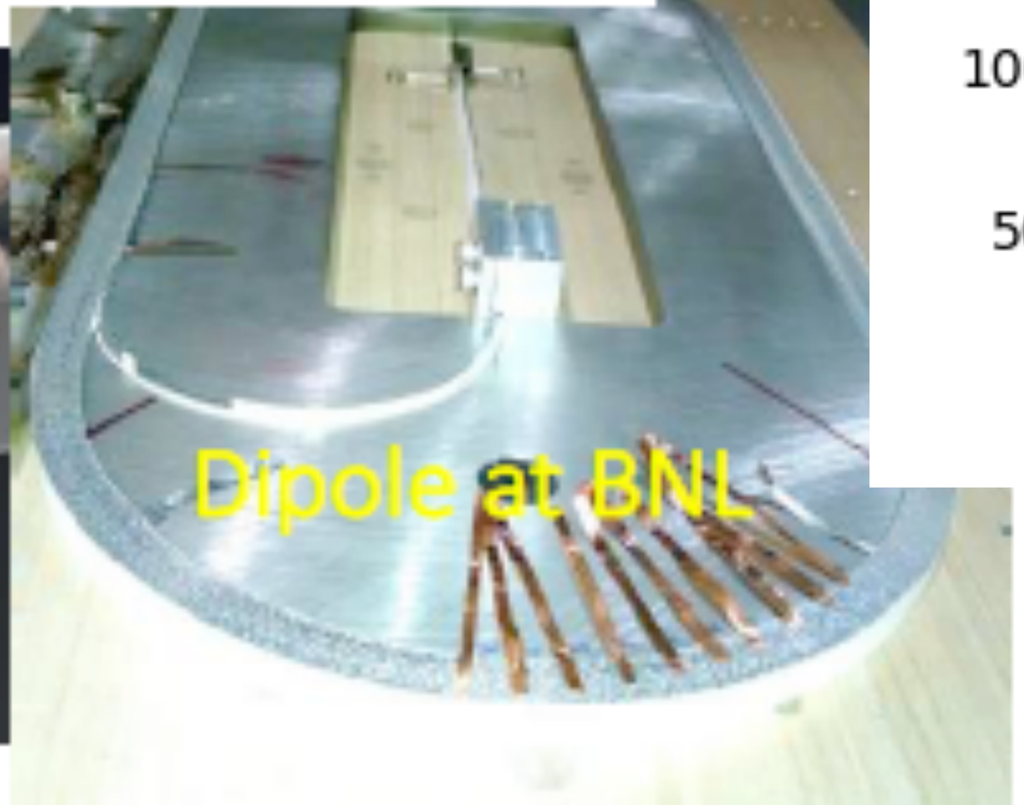
- Magnetic Field vs. Year

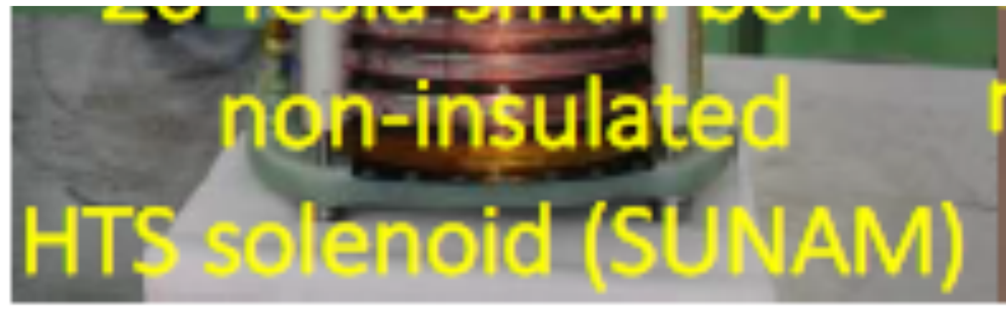




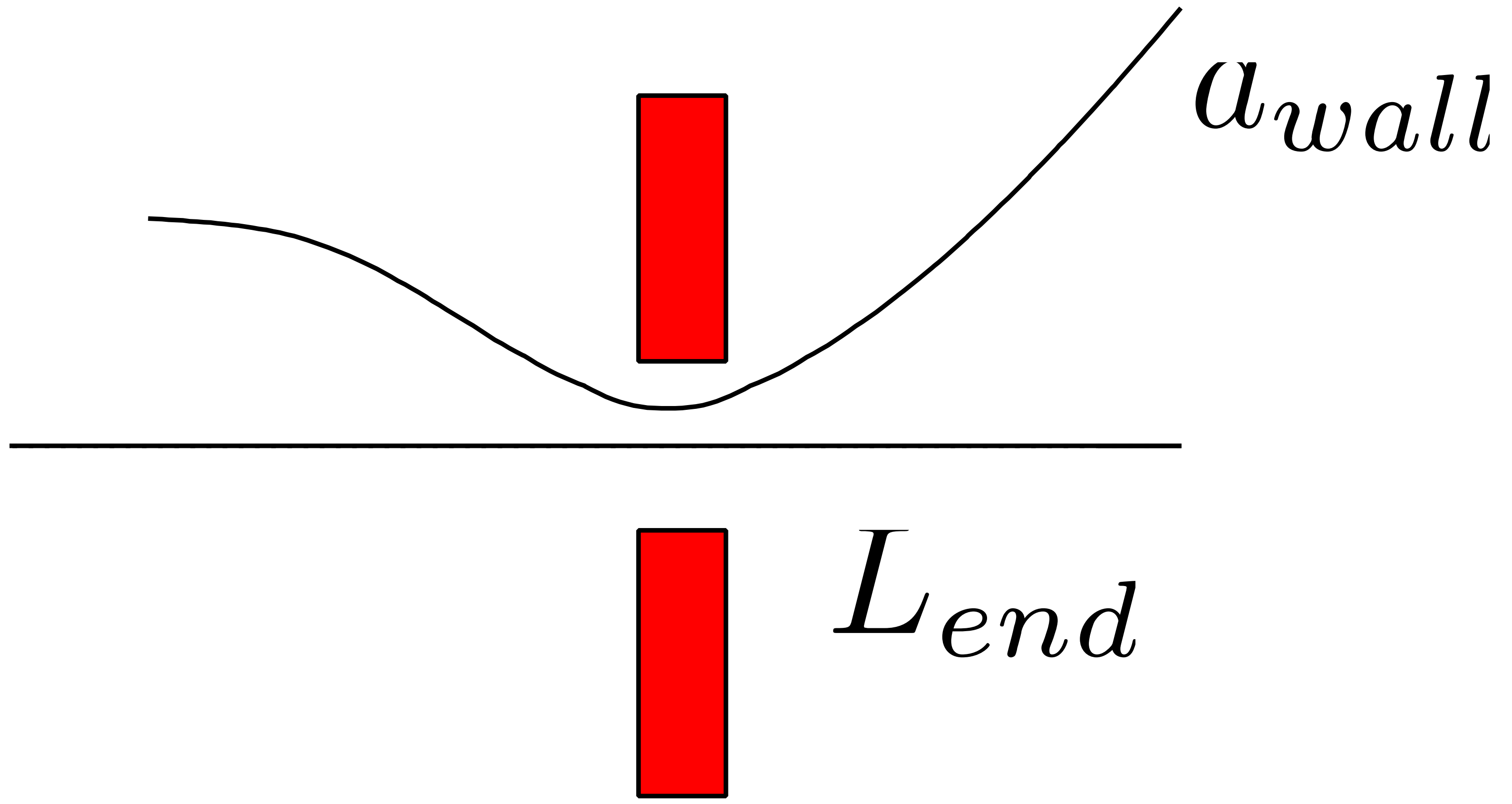




# Field fall-off in expander region key for MHD stability

- In the paraxial approximation ( a << L ), escaping plasma stability condition [Ryutov 2011]:

$$F_{end} \equiv \frac{4\alpha(\alpha-1)}{3(2\alpha-1)} \frac{L^2}{\tau_E L_{end} v_{ti}} \left(\frac{a_{wall}}{a}\right)^2 > 1$$

$$a = a_{wall} \left(\frac{z}{L_{end}}\right)^{\alpha}$$

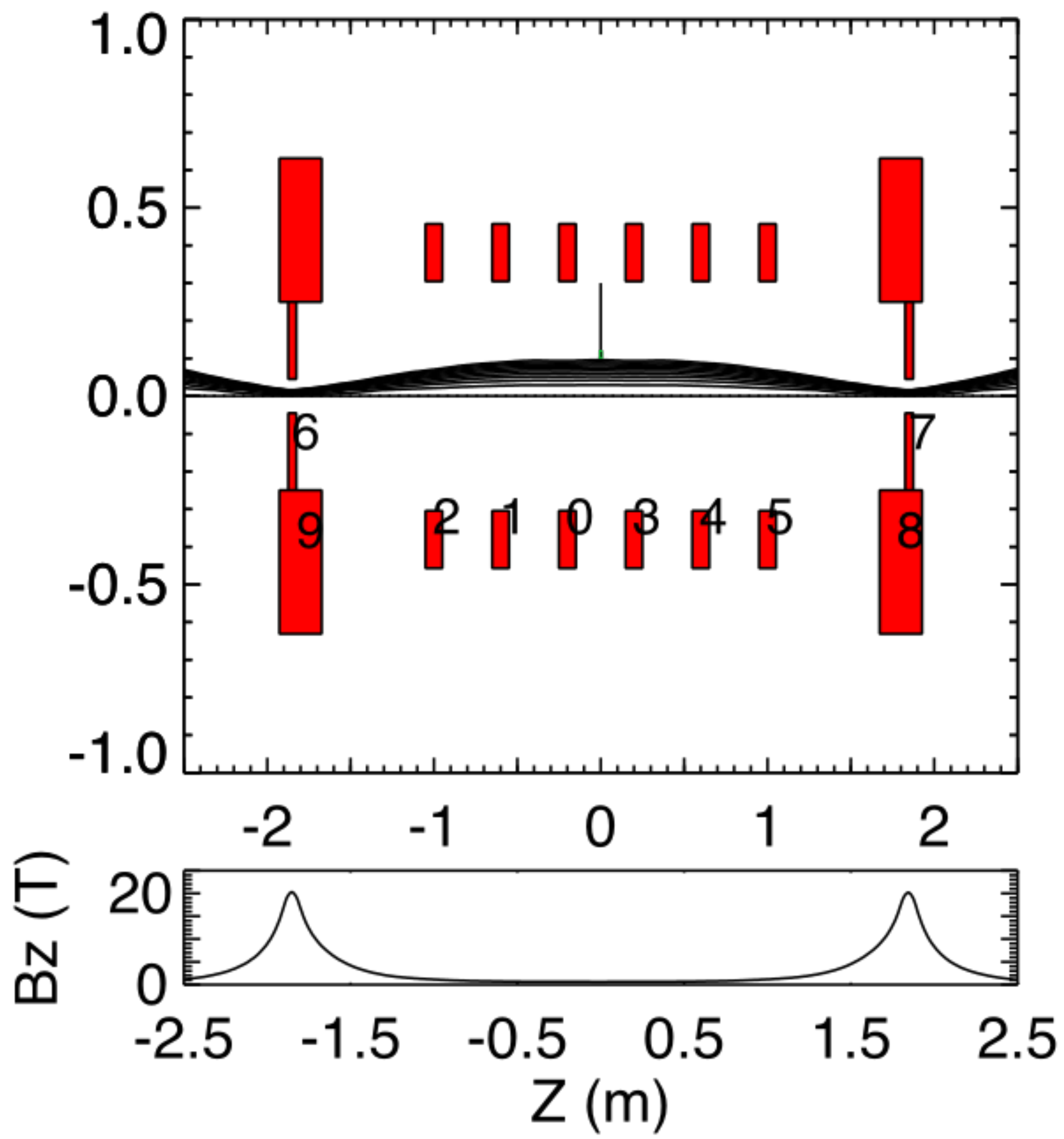



- Necessary condition on field reduction: $\alpha > 1$
- Full calculation, including fast pressure required. Some freedom in end cell design, length of device, etc, but $\alpha > 1$ necessary

# High Current Density Increases Geometric Capability

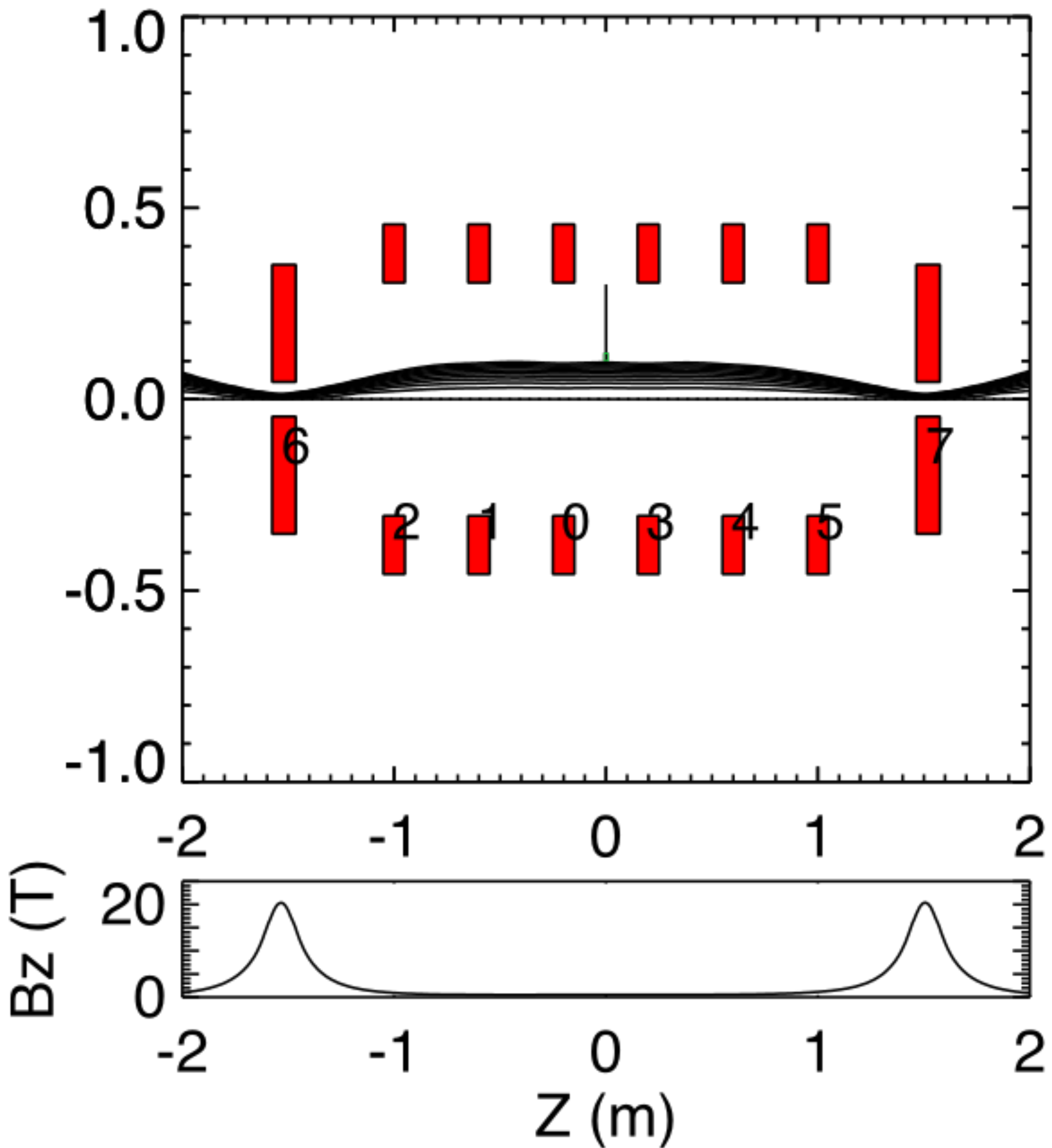
## HTS Insert

- <α> ~ 0.8



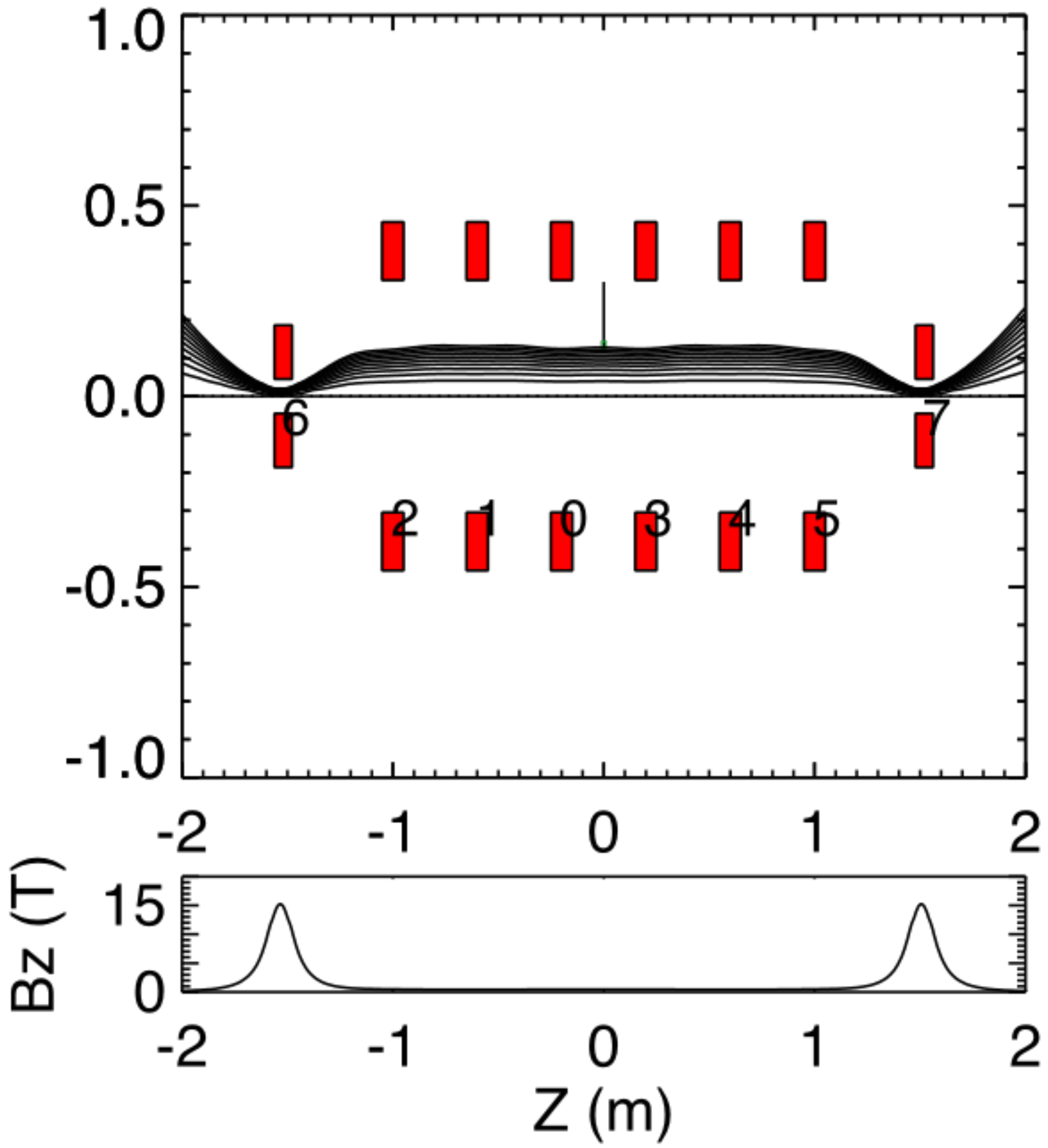

## Two Double Pancakes

- <α> ~ 1.15




## Quad Double Pancakes

- <α> ~ 1.35



# The Short-Fat Mirror as Alternative to GDT?

1. Simplest Mirror
   - Planar small bore REBCO coils
   - standalone or potential tandem mirror end cell
2. Axisymmetric MHD Stability
   - MHD stable to m=1 from flux expansion
   - FLR stable for m>=2 (?)
   - Rosenbluth-Hinton stability from sloshing ions (?)
3. Transport
   - high mirror ratio (~100) and high beta
   - self-plugging from sloshing ions (?)
4. Large diameter minimizes NBI shine through

Applications:

- $10^{15}$ DD neutrons/s for Mo99
- nuclear materials testing
- basic physics of collision less anisotropic MHD
- end cells for tandem

The Ryutov Non-Paraxial Mirror for Tandem End Cells
Theoretically MHD stable at β~1 for m=1 conjecture:
FLR stabilization for m=2,3,4.

# Flux expansion stabilizes m=1

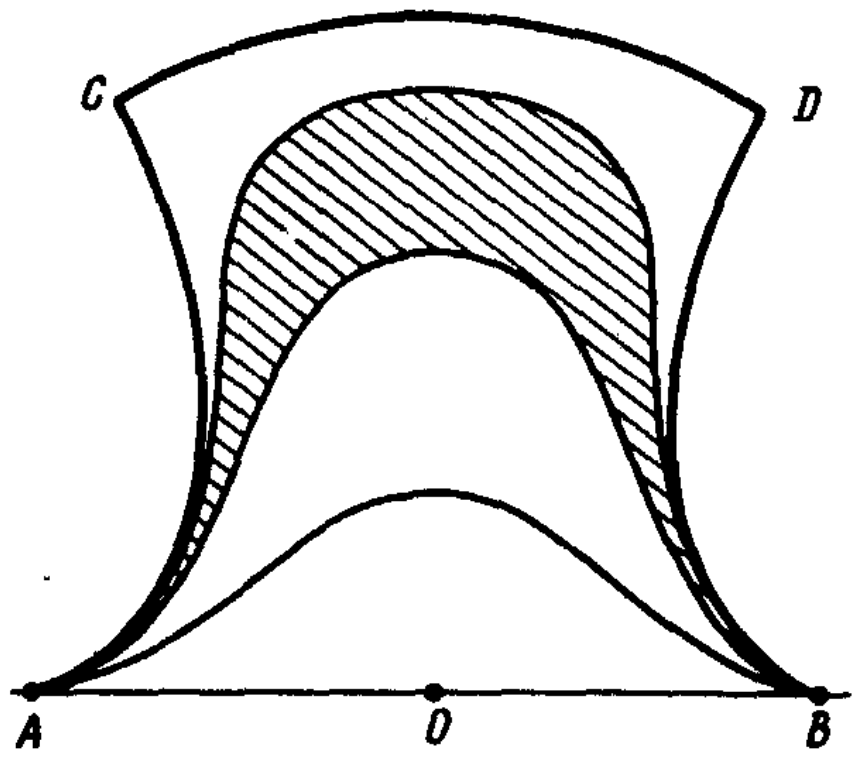
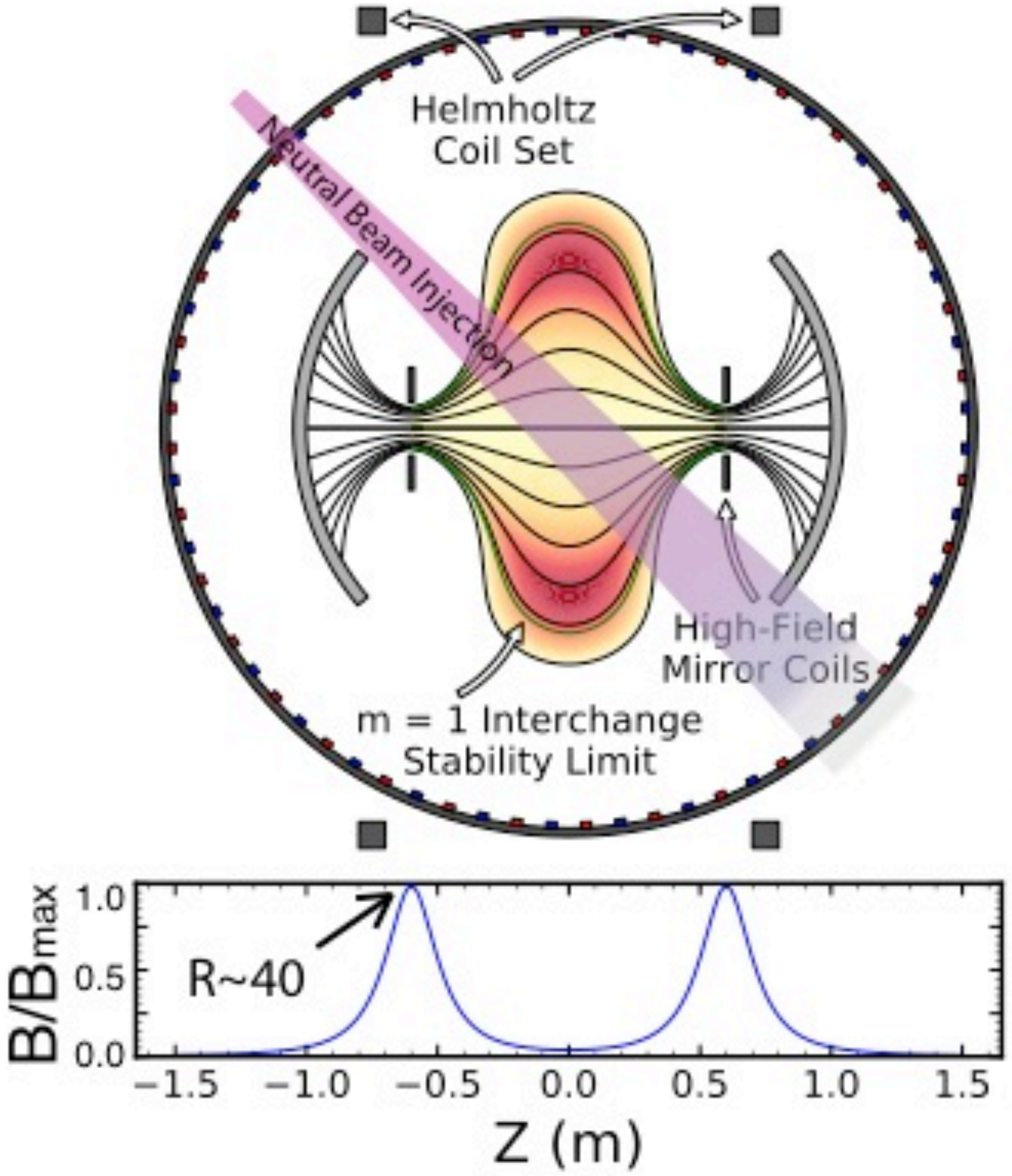


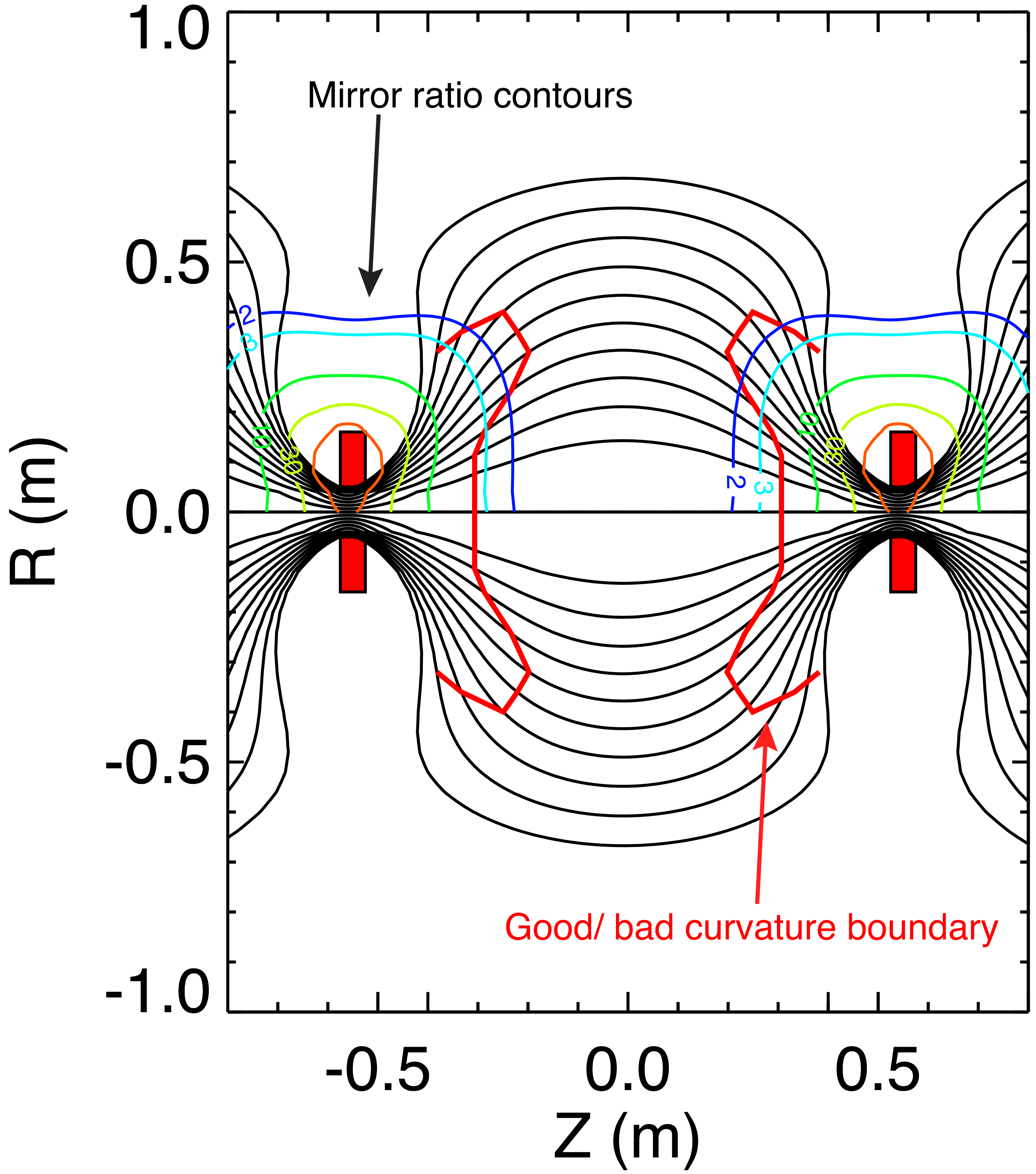

FIG. 1. Magnetic lines of force. The heavy line is the separatrix. The magnetic field vanishes at points *C* and *D*. The hatched region is the "stability ring."

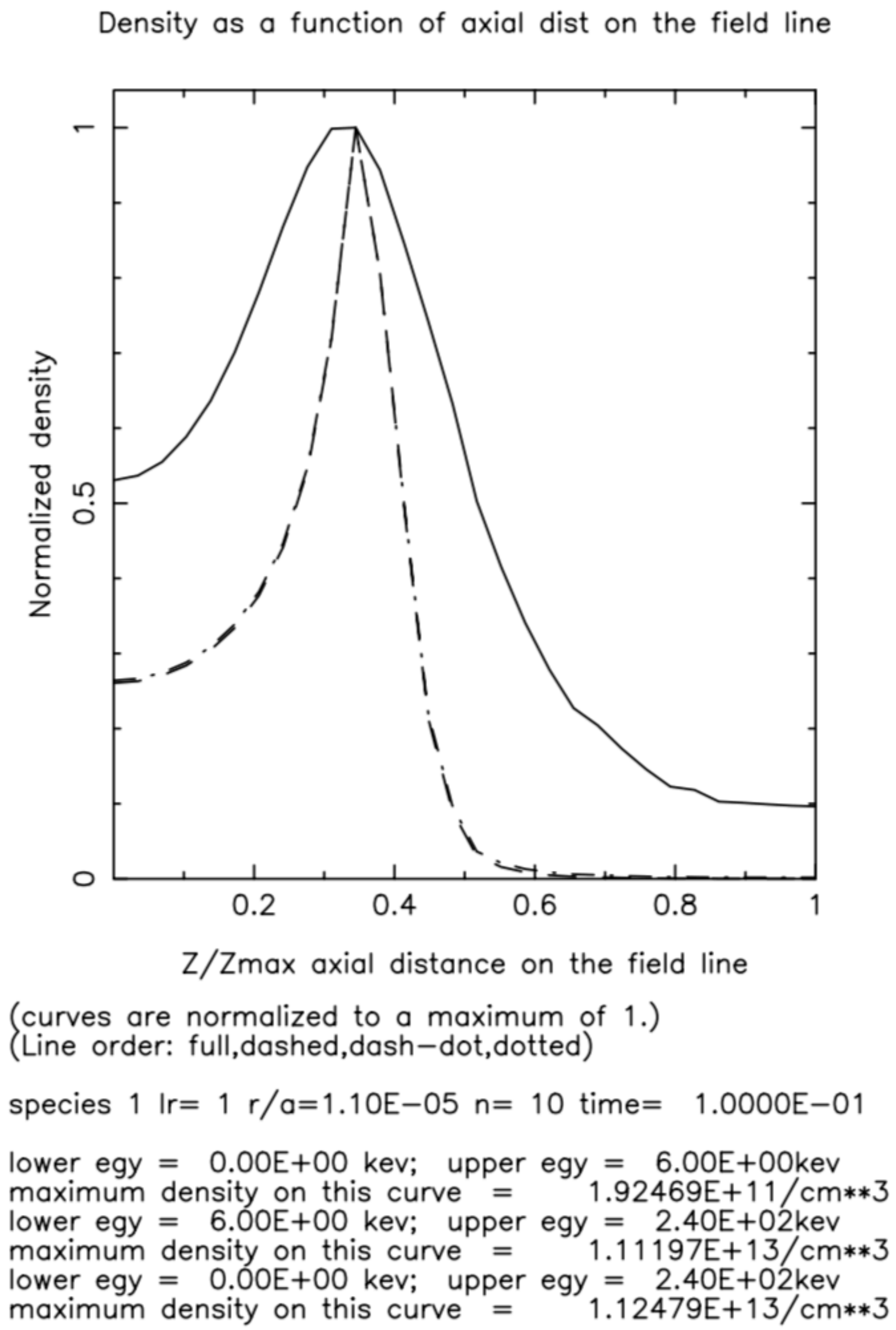
36 JETP Lett., Vol. 42, No. 1, 10 July 1985 D. D. Ryutov and G. V. Stupakov 36



# Can sloshing ions be used to stabilize plasma and self-plug short-fat mirror?

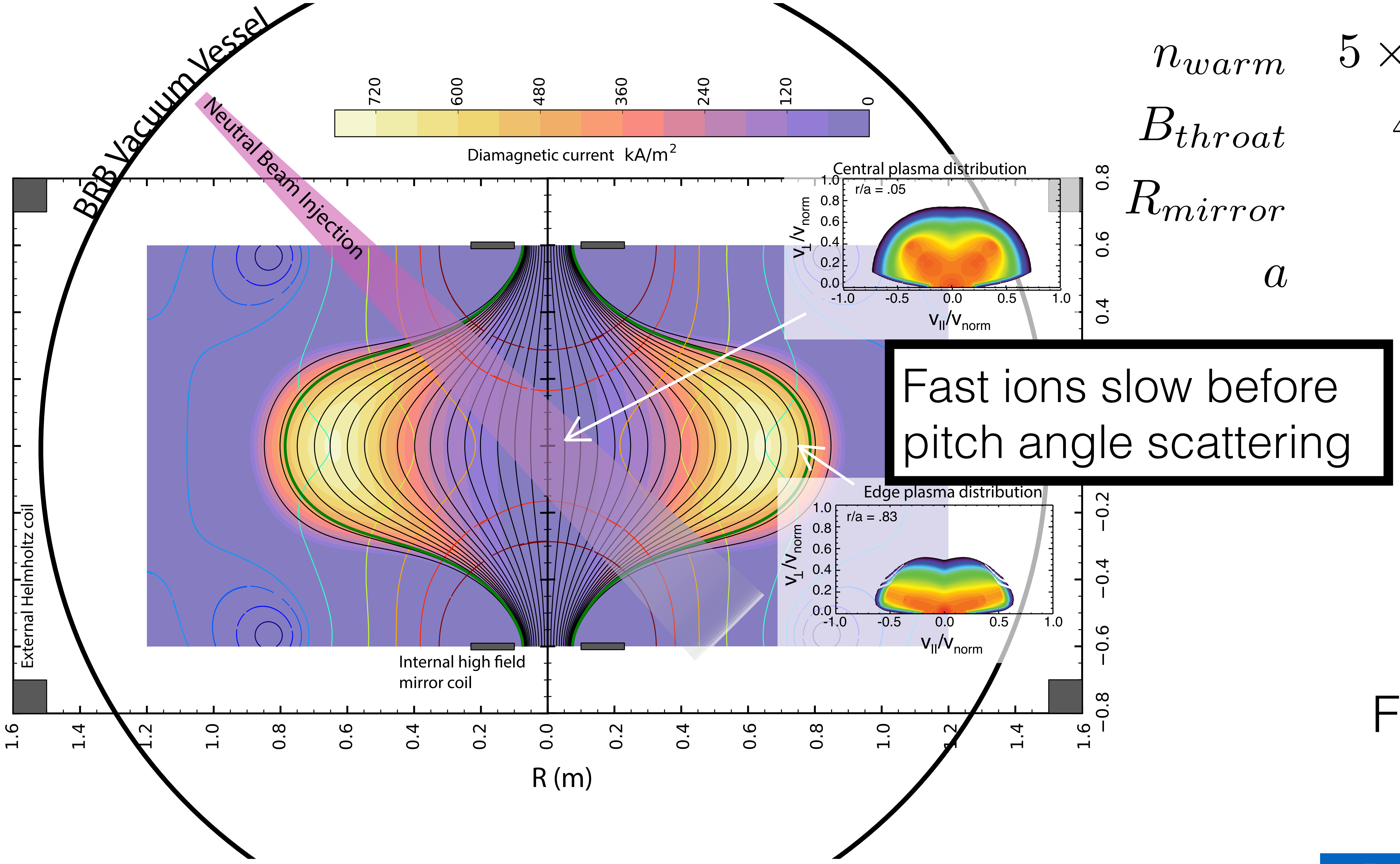
Following Rosenbluth/Hinton, pressure weighted stability when $$\int \frac{d\ell}{B^3 R^2} \vec{\kappa} \cdot \nabla\psi \left(p_\perp + p_\parallel\right) > 0$$




Turning points controlled by angle of injection: NBI injection at angles with turning points in good curvature (probably ~30 degrees)

# CQL3D Analysis of Neutron Yield



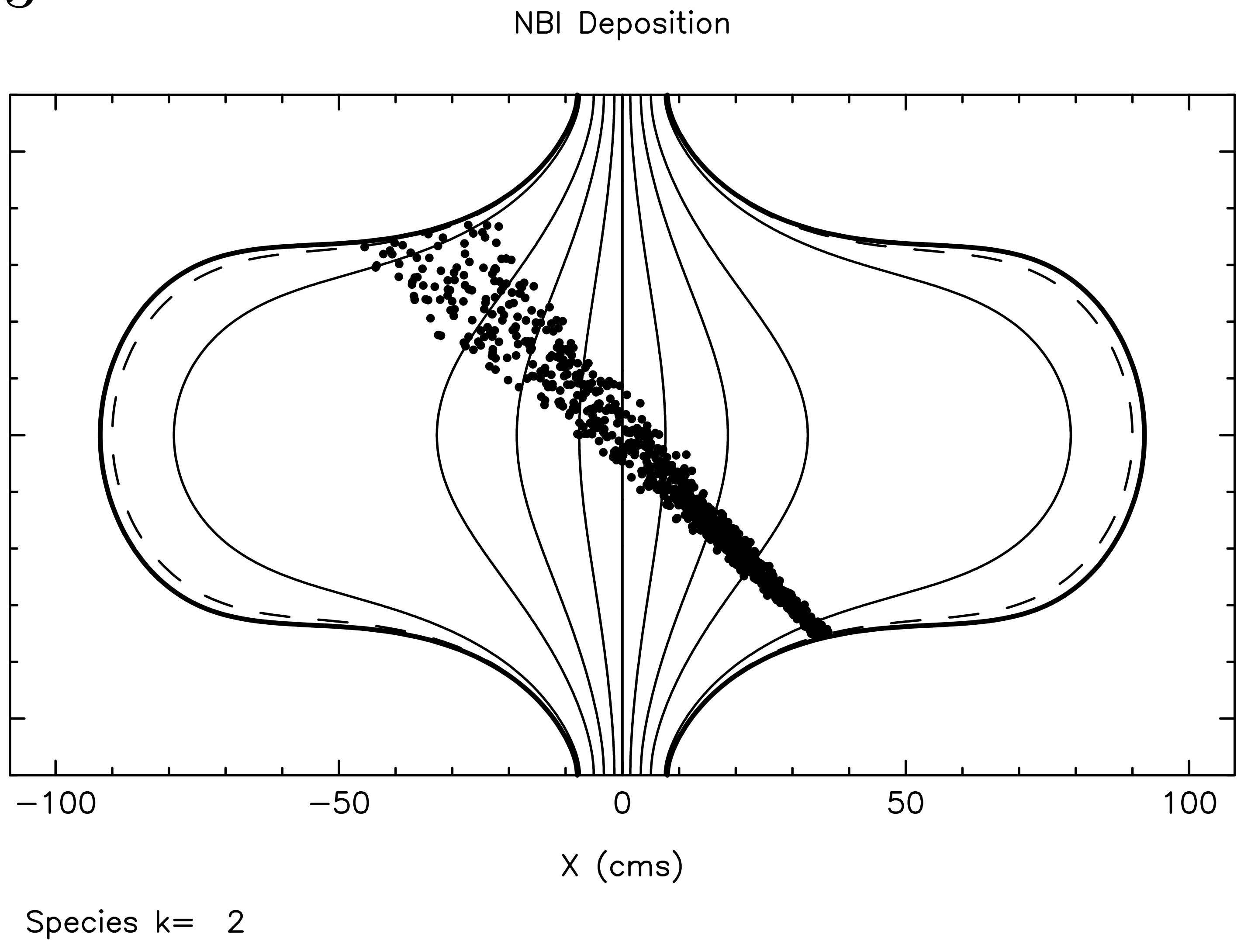

$n_{warm}$ $5 \times 10^{19}\ \mathrm{m}^{-3}$

$B_{throat}$ 40 Tesla

$R_{mirror}$ 100

$a$ 0.5 m

## MonteCarlo Beam Depostion




$$\text{Equilibrium Condition: } \frac{\partial P_\parallel}{\partial B} = \frac{P_\parallel - P_\perp}{B}$$

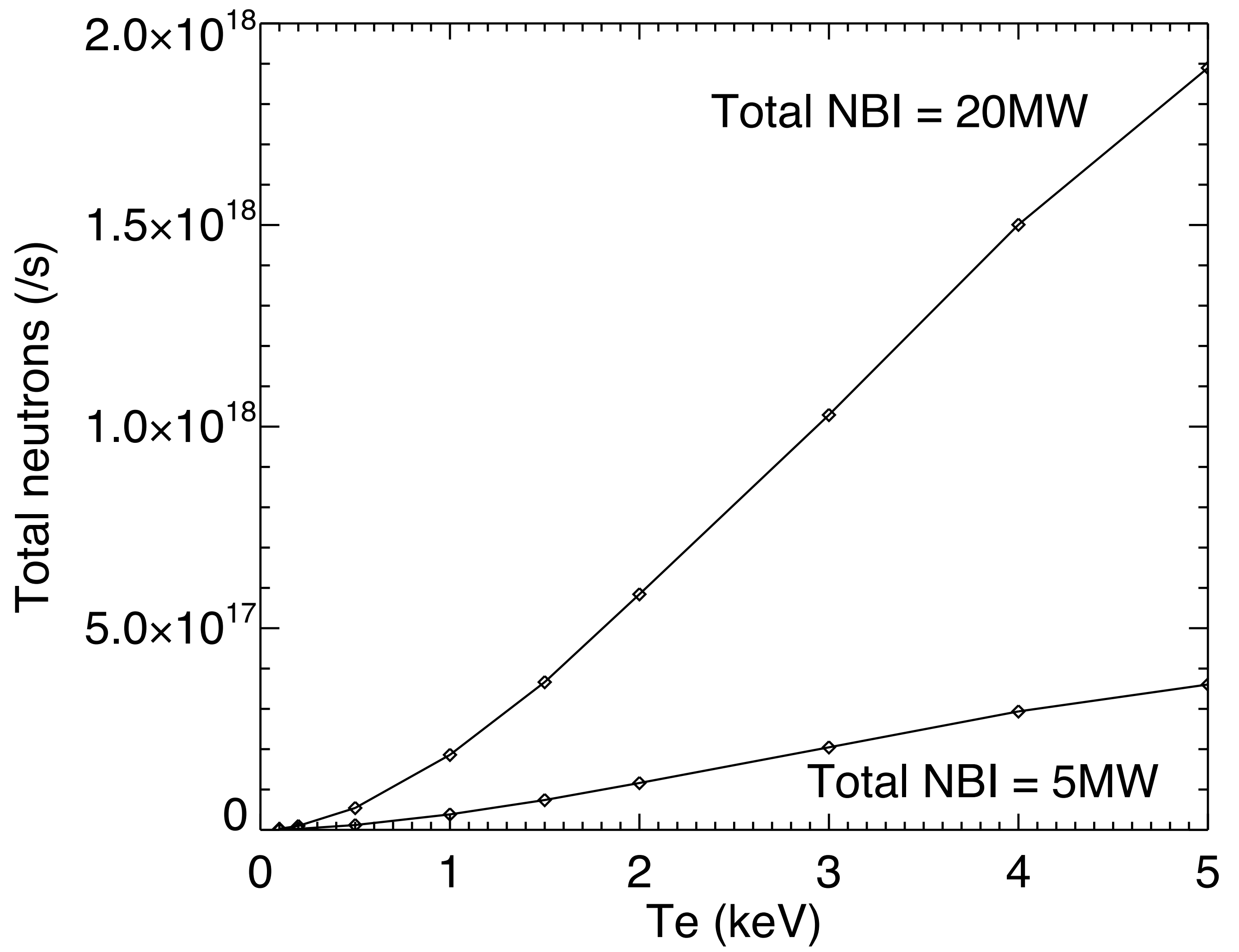
## Fast ion density depends on source and slowing down time

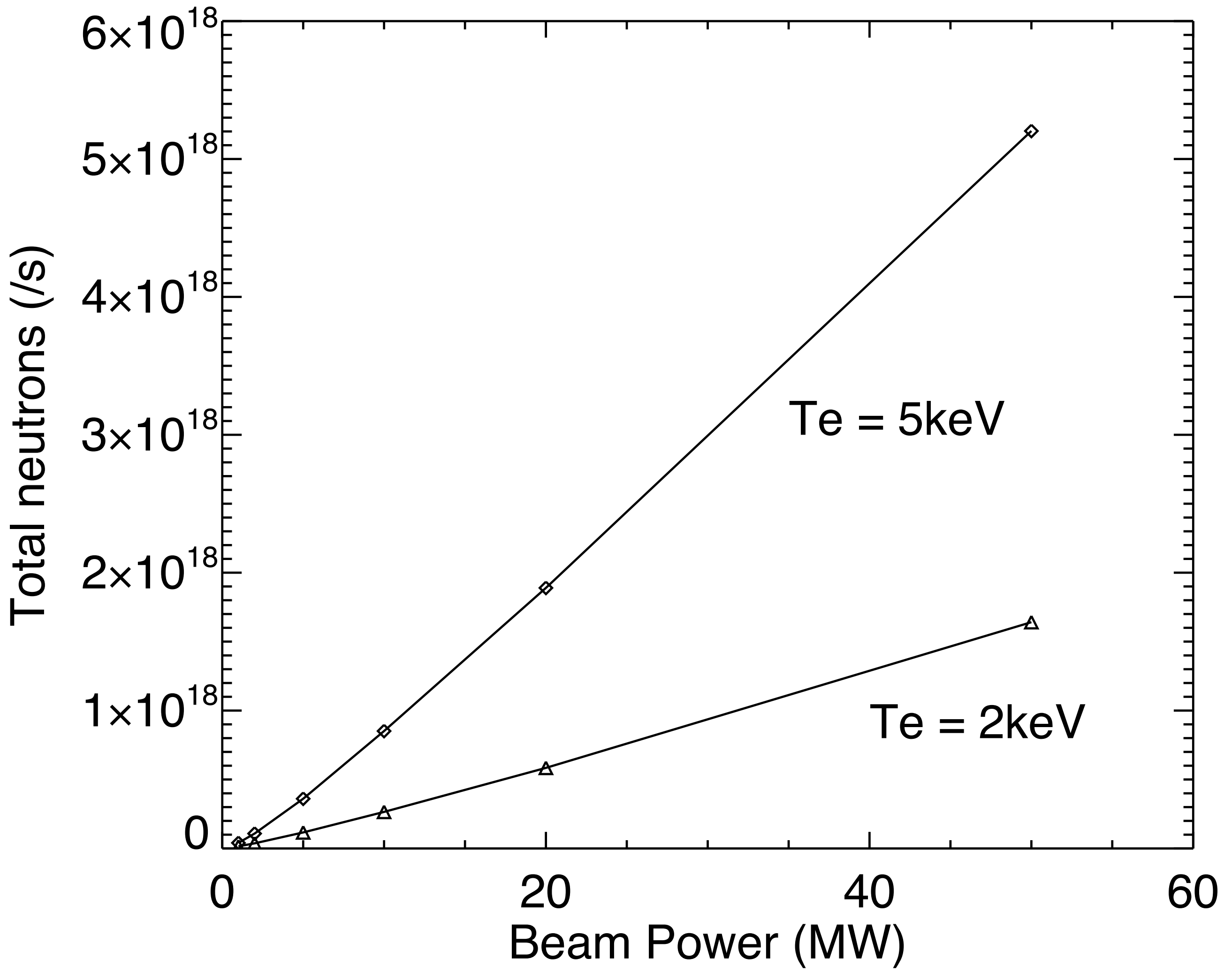
neutral beam power (MW)

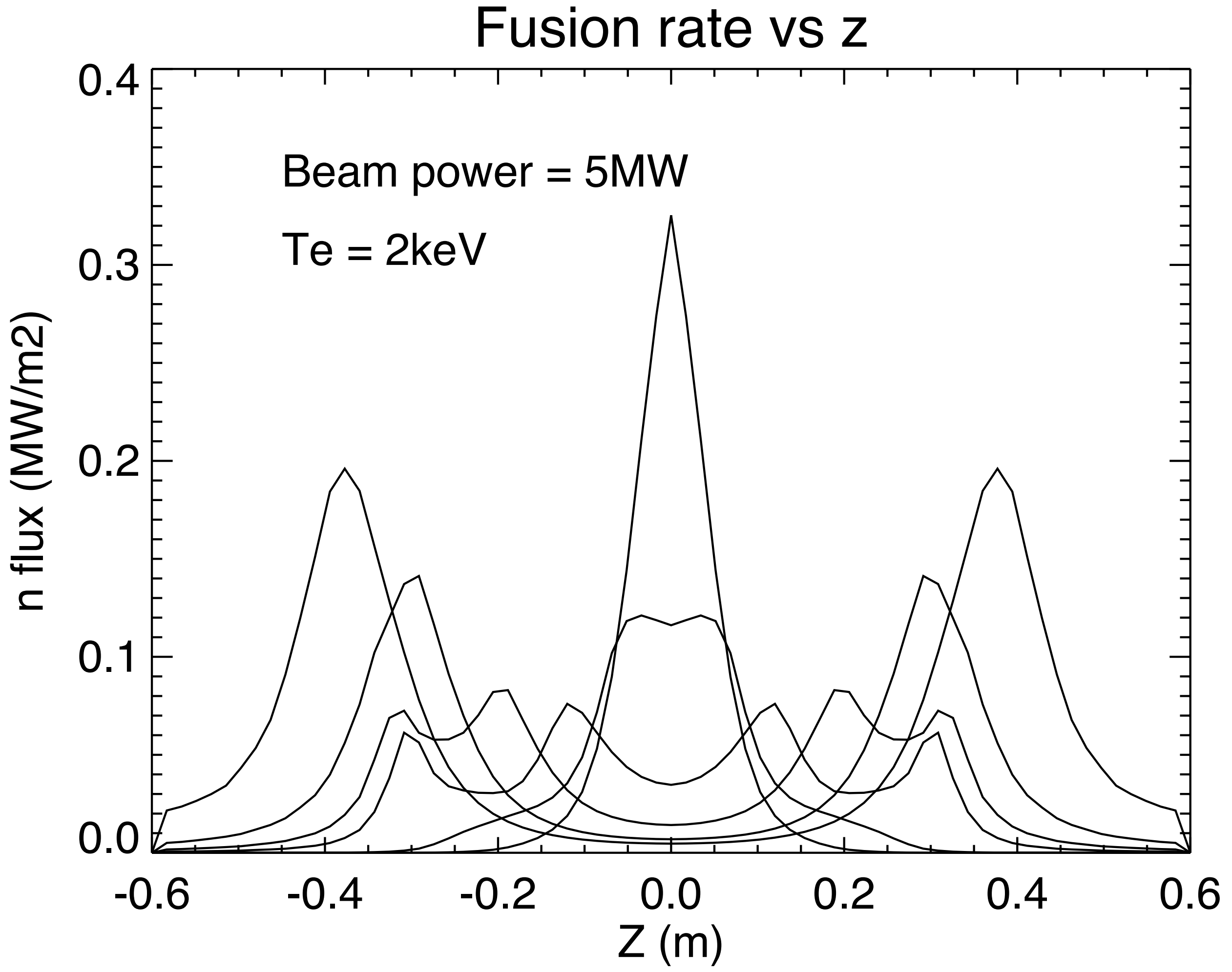
| Te (keV) | 1 | 2 | 5 | 10 | 20 | 50 |
|---|---|---|---|---|---|---|
| 0.1 | 0.1625 | 0.2 | 0.36875 | 0.575 | 0.8 | 1.25 |
| 0.2 | 0.35 | 0.36875 | 0.6125 | 0.8375 | 1.2125 | 1.93437 |
| 0.5 | 0.504687 | 0.725 | 1.175 | 1.625 | 2.30469 | 3.65937 |
| 1 | 0.8 | 1.1375 | 1.83125 | 2.6 | 3.67812 | 5.8625 |
| 1.5 | 1.025 | 1.49375 | 2.35625 | 3.36875 | 4.77969 | 7.5875 |
| 2 | 1.23125 | 1.75625 | 2.7875 | 4.025 | 5.675 | 9.03125 |
| 3 | 1.55 | 2.225 | 3.47187 | 4.925 | 6.95 | 11.1781 |
| 4 | 1.74688 | 2.525 | 3.96875 | 5.61875 | 8 | 12.7063 |
| 5 | 1.8875 | 2.70312 | 4.2875 | 6.125 | 8.675 | 13.8219 |

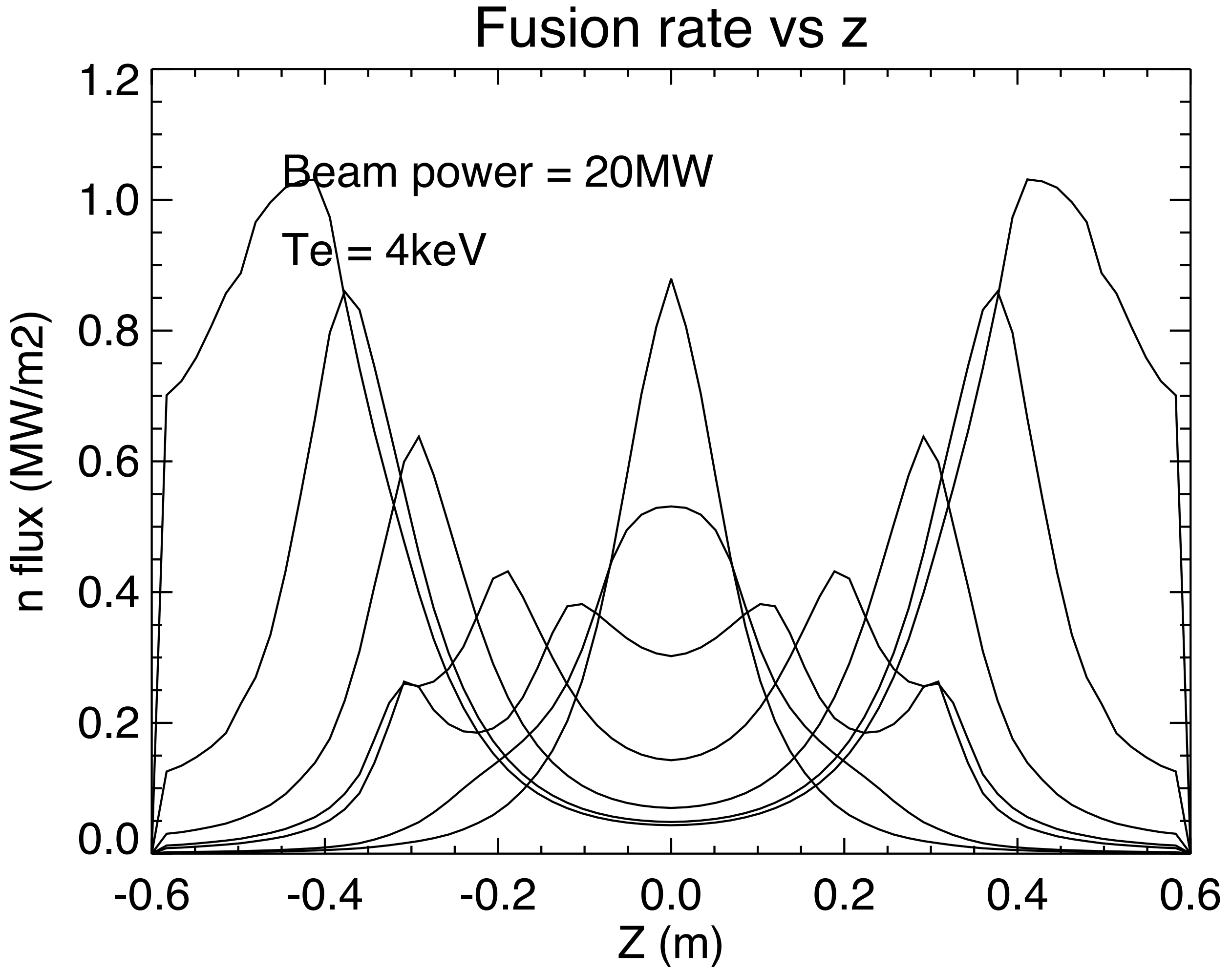
densities in $10^{19}\ \mathrm{m}^{-3}$

# Parametric dependence of DT neutron yield

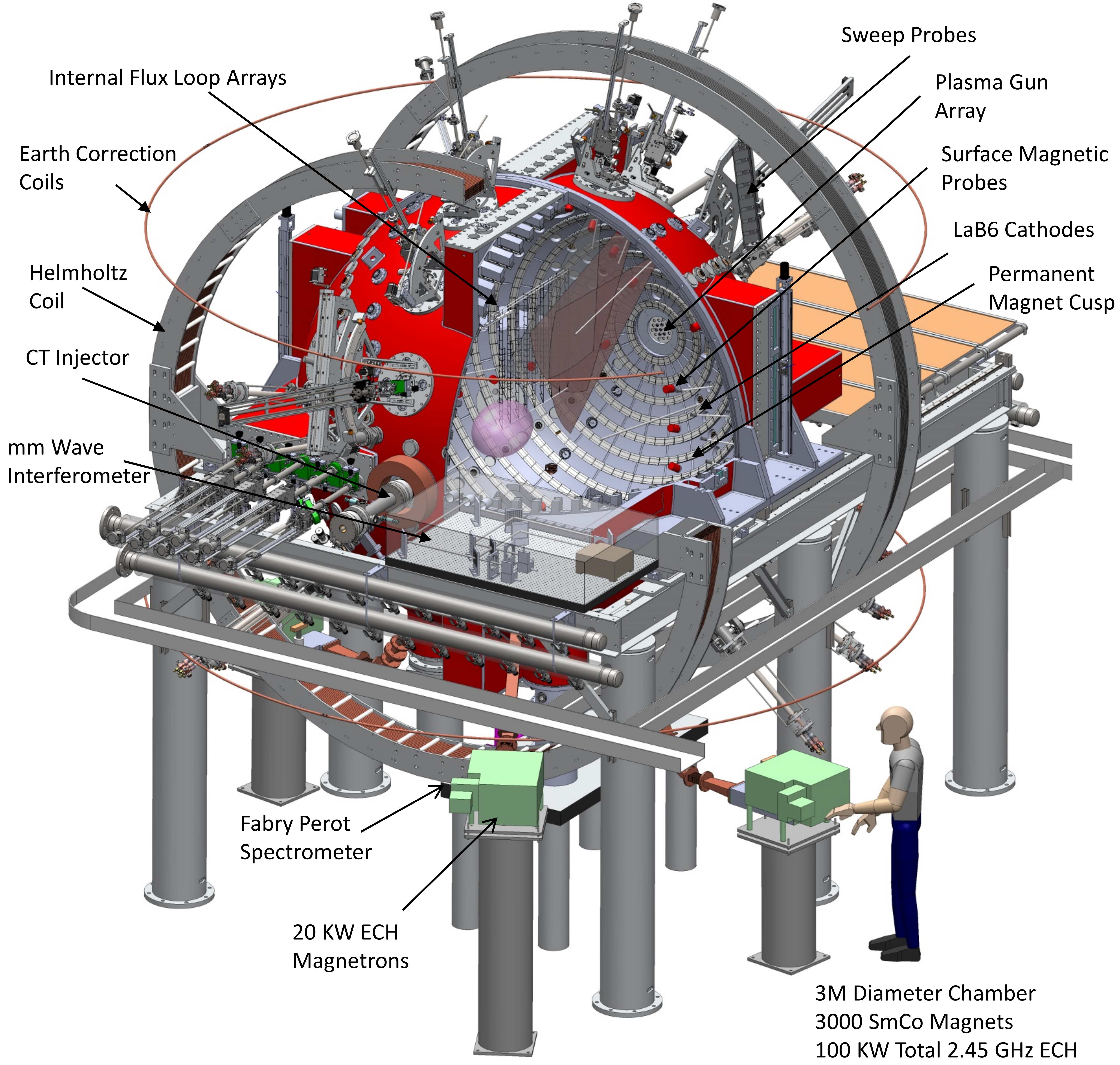



20,30,45,60,75,88 degrees from normal


Internal Flux Loop Arrays
Earth Correction Coils
Helmholtz Coil
CT Injector
mm Wave Interferometer
Sweep Probes
Plasma Gun Array
Surface Magnetic Probes
LaB6 Cathodes
Permanent Magnet Cusp
Fabry Perot Spectrometer
20 KW ECH Magnetrons
3M Diameter Chamber
3000 SmCo Magnets
100 KW Total 2.45 GHz ECH