The High Field Compact Mirror Path to Fusion Energy

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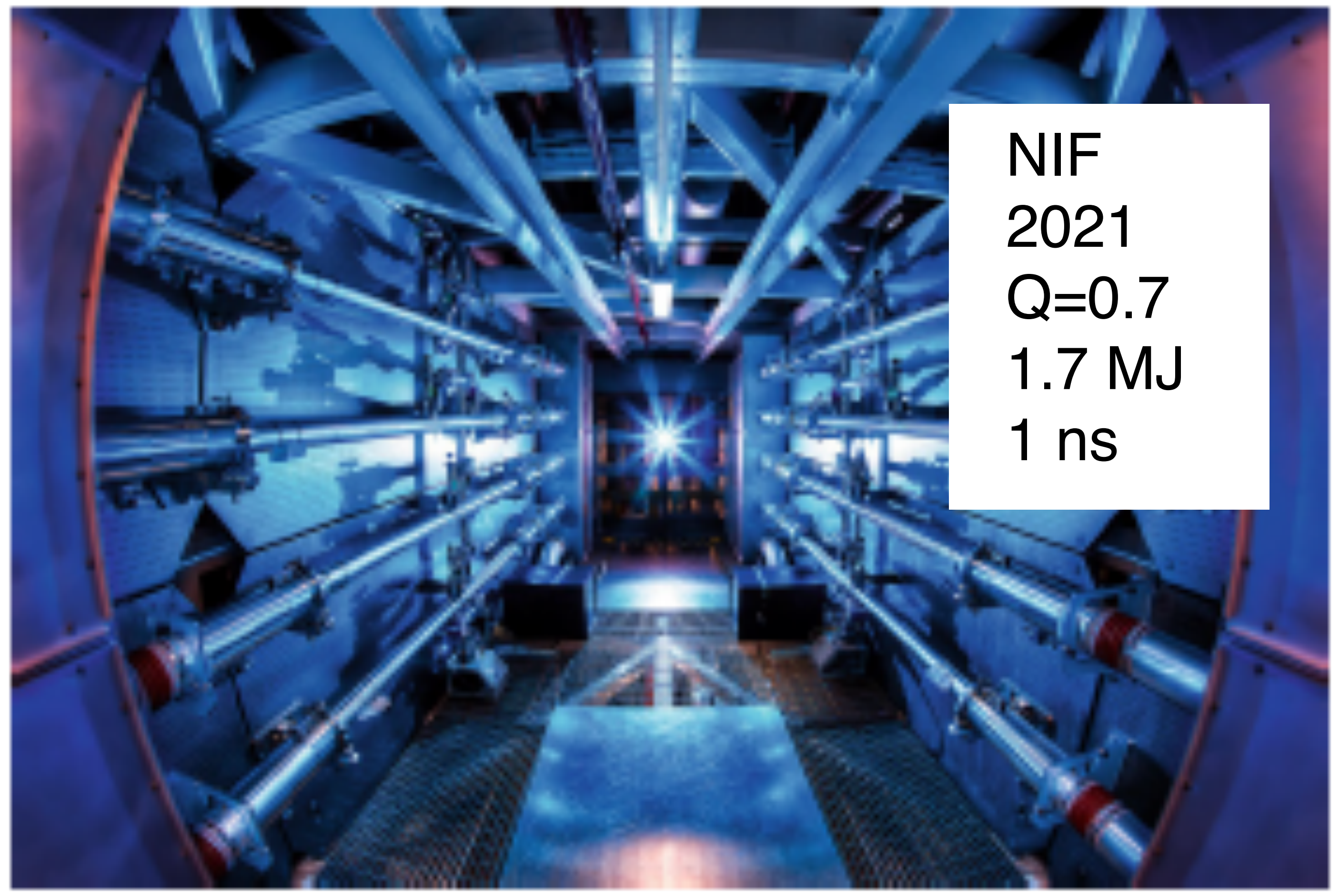
50+ years of research has us at the cusp of using fusion energy from deuterium and tritium

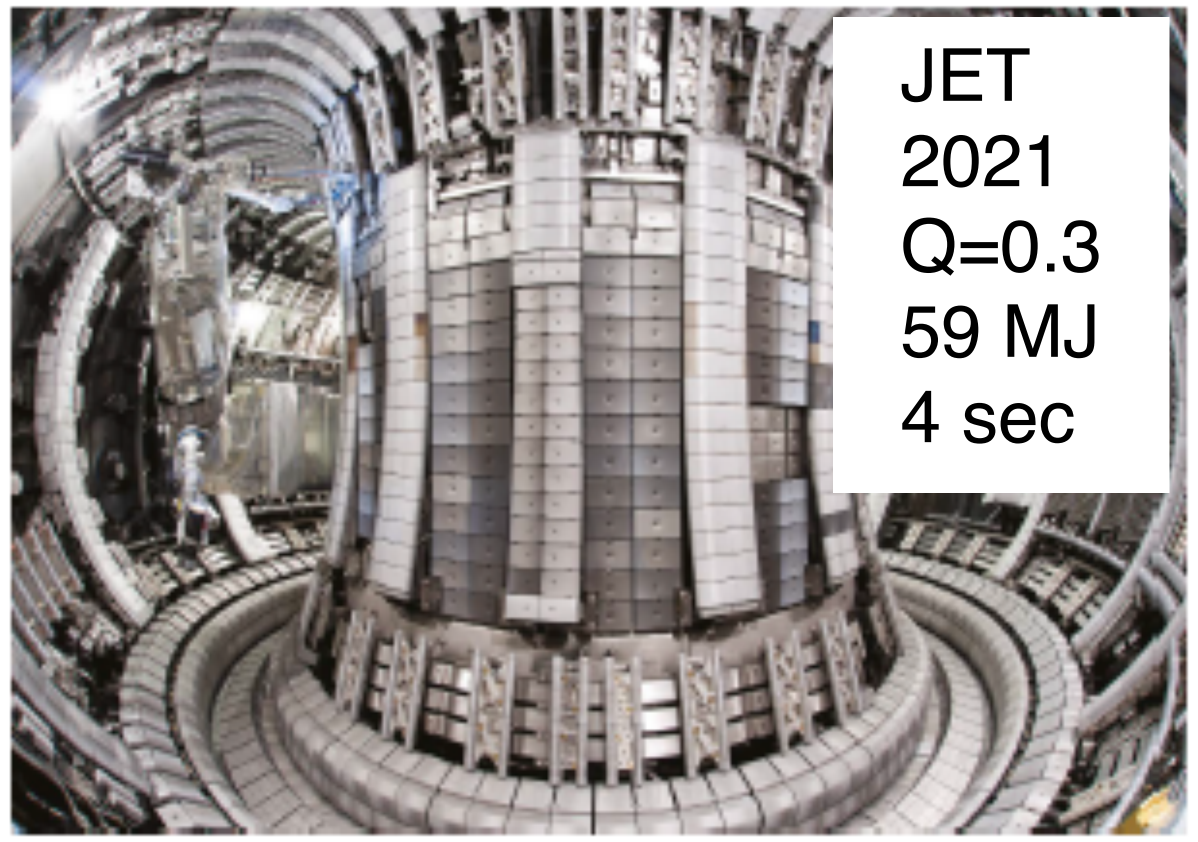
Fusion news ignites optimism

News of a 1.3-MJ-output-energy experiment at the National Ignition Facility in the United States in August has
raised hopes that laser-based fusion is back on track.



Credit: Damien Jemison / Lawrence Livermore National Laboratory

Nature PhotoNics | VOL 15 | OCtOber 2021 | 713 |
www.nature.com/naturephotonics



The Joint European Torus tokamak reactor near Oxford, UK, hosted experiments with tritium.

NUCLEAR-FUSION REACTOR SMASHES ENERGY RECORD

The Joint European Torus has doubled the record for the amount of energy made from fusing atoms.

Phoenix and SHINE Achieve New World Record for Strongest Nuclear Fusion Reaction in a Steady-State System

October 02, 2019 08:00 ET | Source: Phoenix; SHINE Medical Technologies LLC

- During the next decade we will see at least two experiments demonstrate viability of the tokamak
  - Iter, dt planned for 2035, 500 MW_t for 1000 sec, Q~10
  - SPARC, DT planned for 2027, Q~10

- Appetite in the private sector is growing
  - > $4B investement by venture capital in past few years
  - CFS likely leading the US Pilot Plant Race with ARC

The Problem

The vision for fusion power plants based on stellarators and tokamaks are enormous, capital intensive, and complex

- ➡ difficult to fund
- ➡ long and risky construction projects
- ➡ unreliable

© 2021, ITER Organization

$22B, first conceived 1992, dt operation 2035

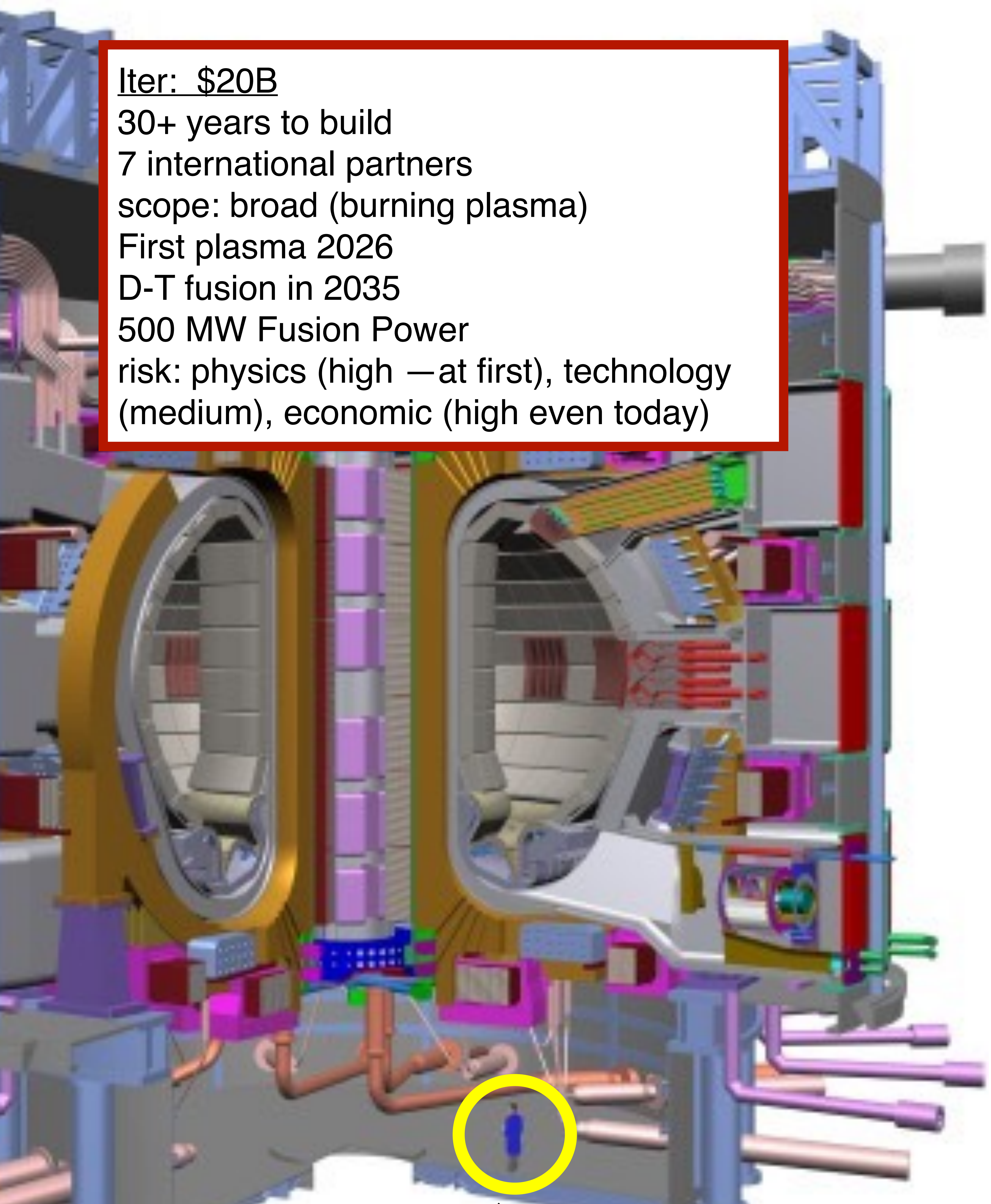
Wendelstein 7X
conceived 1992
First plasma 2015
cost > 1B Euros

Its not just Iter:
also W7-X, NCSX, NSTX-U…

The Solution (one person's opinion)

Simplify and innovate, embrace risk as a necessity, to make fusion more compact and dependable

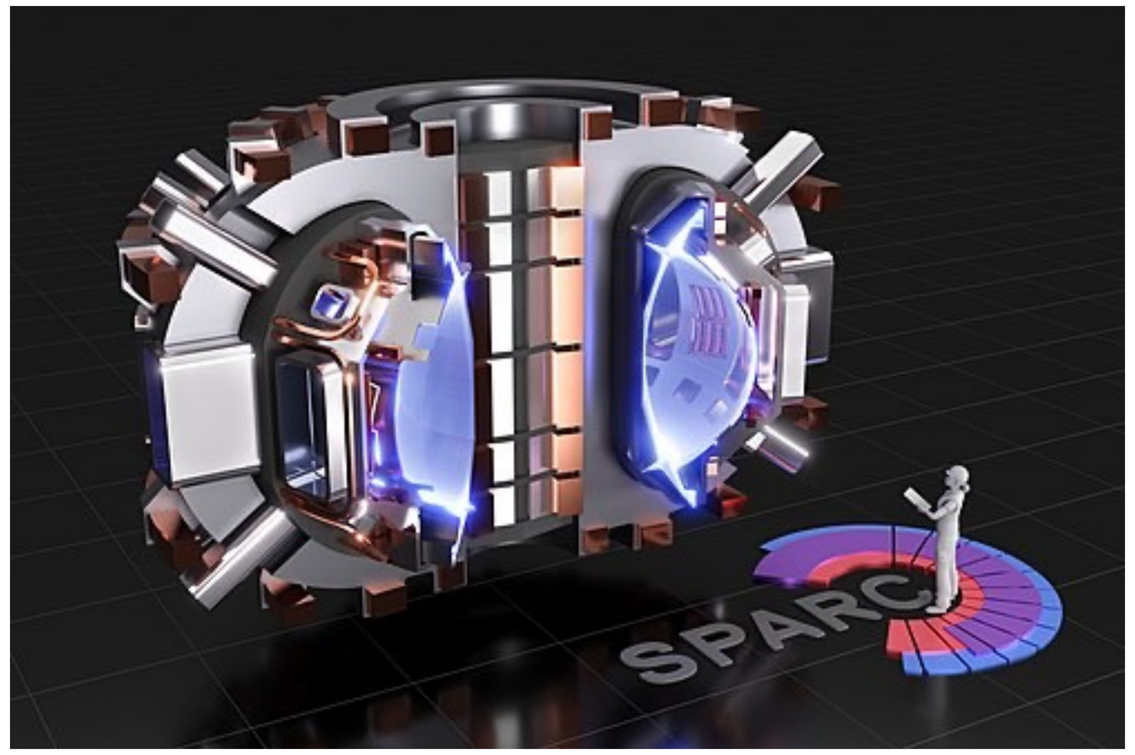
Reducing size and simplifying will make fusion more viable



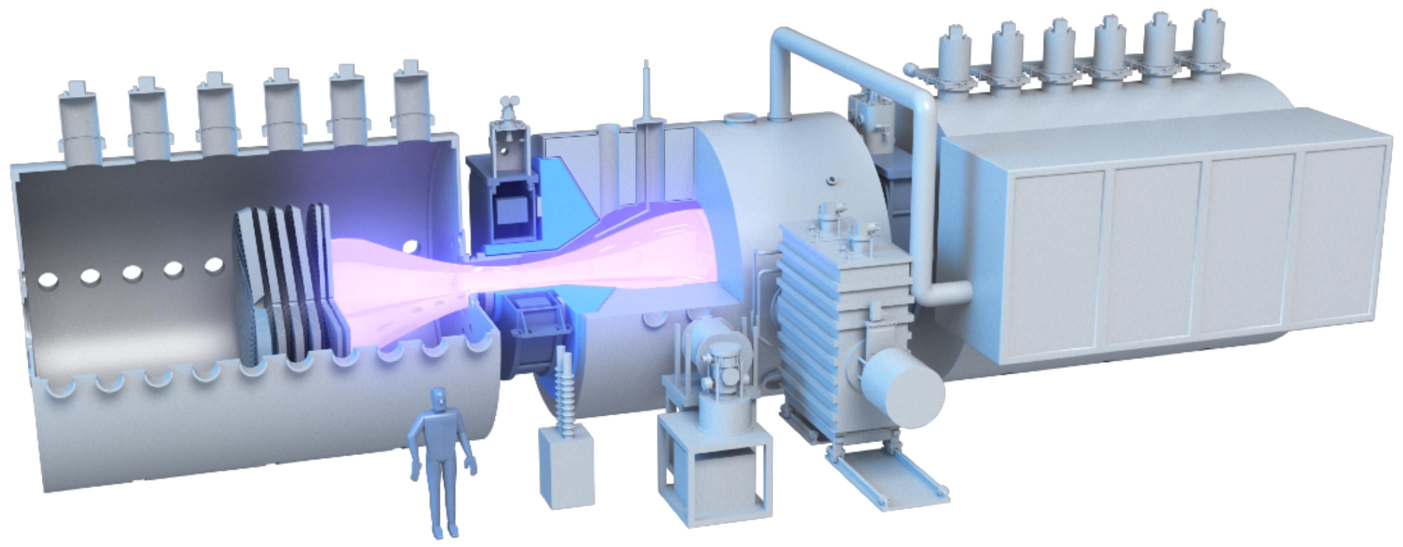
Iter: $20B
30+ years to build
7 international partners
scope: broad (burning plasma)
First plasma 2026
D-T fusion in 2035
500 MW Fusion Power
risk: physics (high —at first), technology (medium), economic (high even today)

↑
Person!

Sparc: $2B
5 years to build
one company
$Q_{scientific}>1$ limited scope
First plasma 2025
140 MW fusion power
risk: physics (low), technology (high), economic (medium)



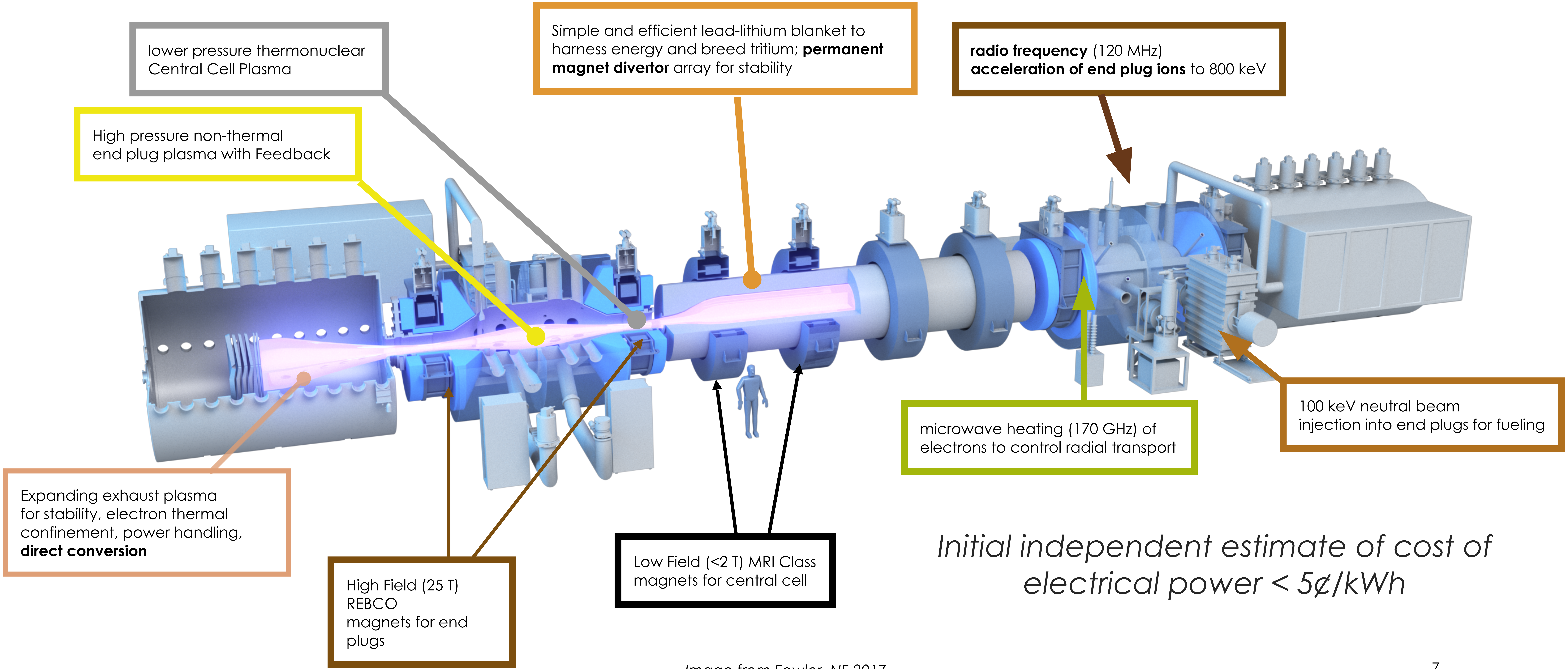
WHAM++: $200M
5 years to build
one company
$Q_{electric}>1$ limited scope
First plasma 2027
5 MW fusion power
risk: physics (high for integration), technology (medium), economic (low—by fusion standards)



conjecture: simpler and less costly Q>1 demonstration will translate to a more economical and reliable pilot plant

High-Field Axisymmetric Magnetic Mirror (HAMMiR)

*The **lowest capital** and **least complex** fusion reactor suitably scaled for industrial use*



Initial independent estimate of cost of electrical power < 5¢/kWh

Image from Fowler, NF 2017

Attractive Features of Mirror

1. Simple cylindrical geometry for construction
   - ➡ high-field, insulator free planar coils, lower tech central cell magnets
   - ➡ Linear geometry attractive for R*eliability*, A*vailability*, M*aintainability*, I*nspectability*
2. Simple high temperature blanket geometry
3. no minimum power
   - ➡ extensible in length to control output power output
   - ➡ Q~1 milestone can be met with a bitesize chunk
4. Intrinsically steady-state, no plasma current and no disruptions
5. The obvious geometry for a fusion powered rocket engine…
6. Development path provides low-tritium-use materials testing, component testing, fuel cycle demonstration platform

conjecture: simpler and less costly Q>1 demonstration will translate to a more economical and reliable pilot plant

2020 2024 2028 2032 2036

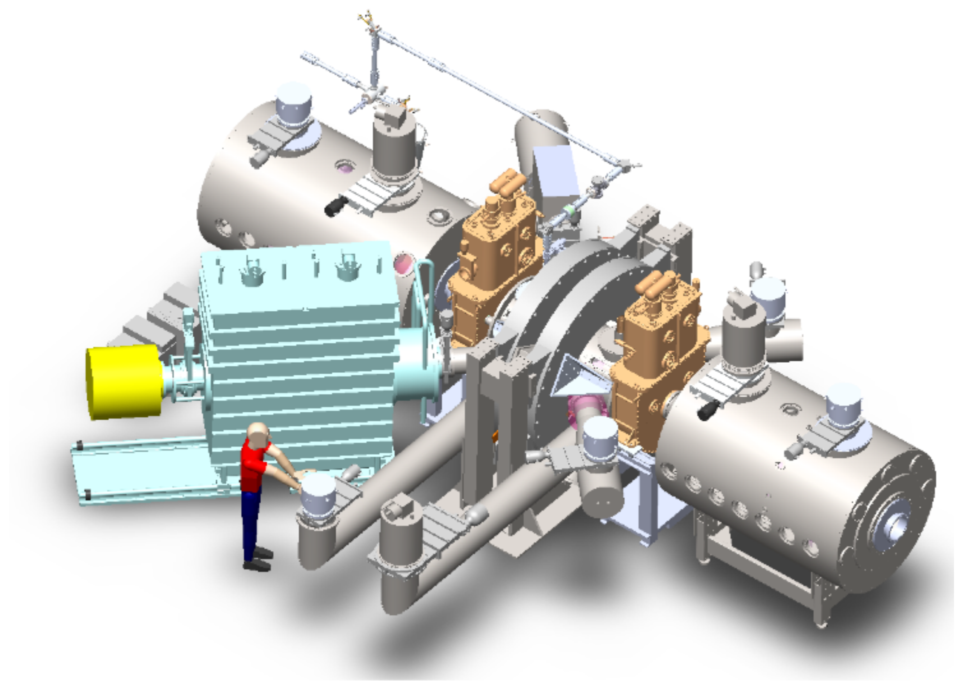
WHAM 1.0

WHAM++ Q_{equiv}~1 (dd) short pulse

WHAM++ Q~1 (dt) steady-state

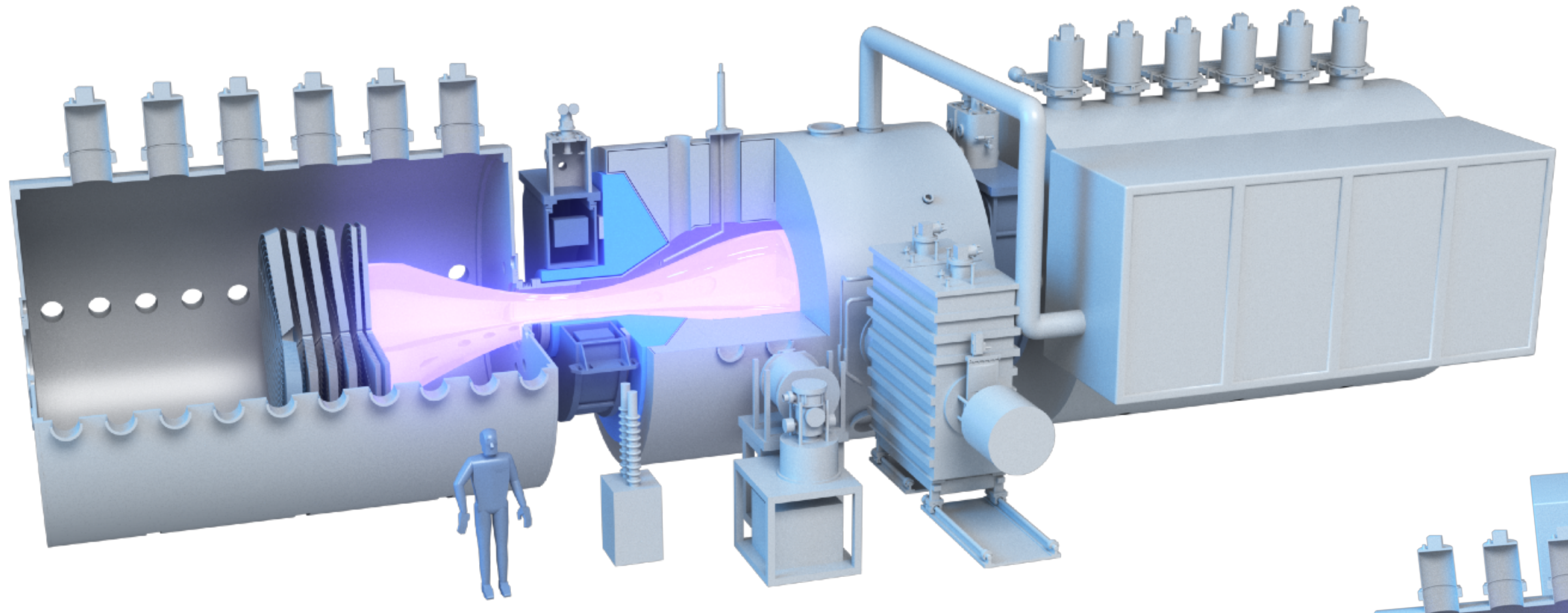
WHAM++ high B_p (go/no go)

HAMMir (2 x WHAM++, central cell)

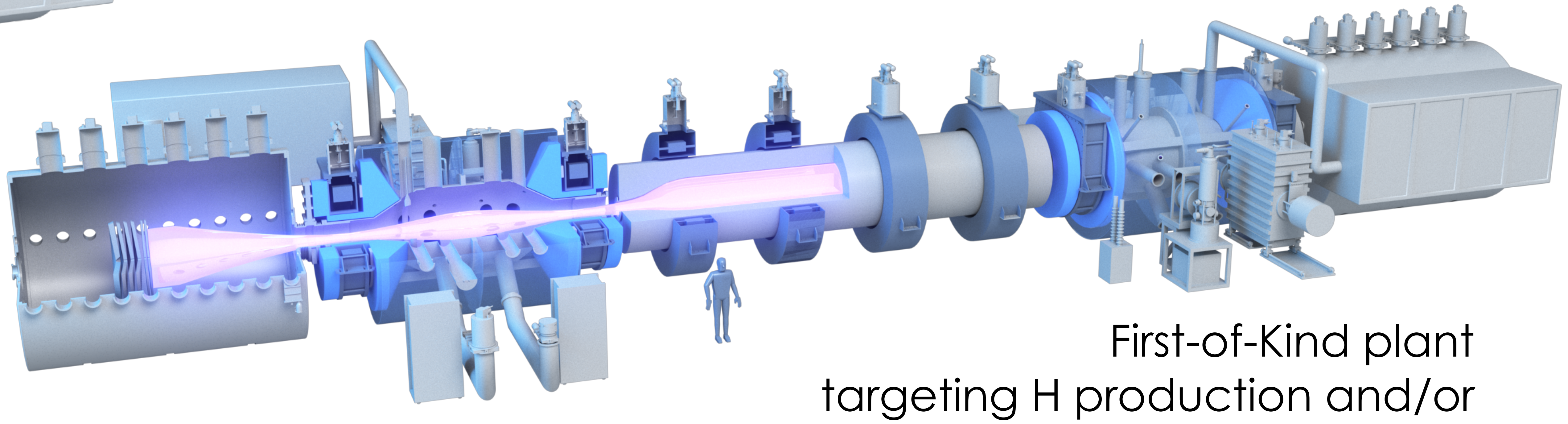


- HTS
- MHD, Confinement
- rf ion acceleration

Initial independent estimated cost of thermal energy <$7/mmBtu



- Integrated physics
- component and materials testing
- dt fuel cycle demonstration
- Q_{elec}~1 in steady-state



First-of-Kind plant
targeting H production and/or
process heat with industrial partner
Q>10 ca. 300 MW_t

Path to Commercial Scale

Outline

1. Weakly collisional axisymmetric mirror (review)

   ➡high mirror ratio leads to lowest capital cost Q~1 device (component testing)

   ➡directly on path to an axisymmetric tandem mirror for power

   ➡enormous progress in short time was made on tandem—technology wasn't ready

2. What has changed?

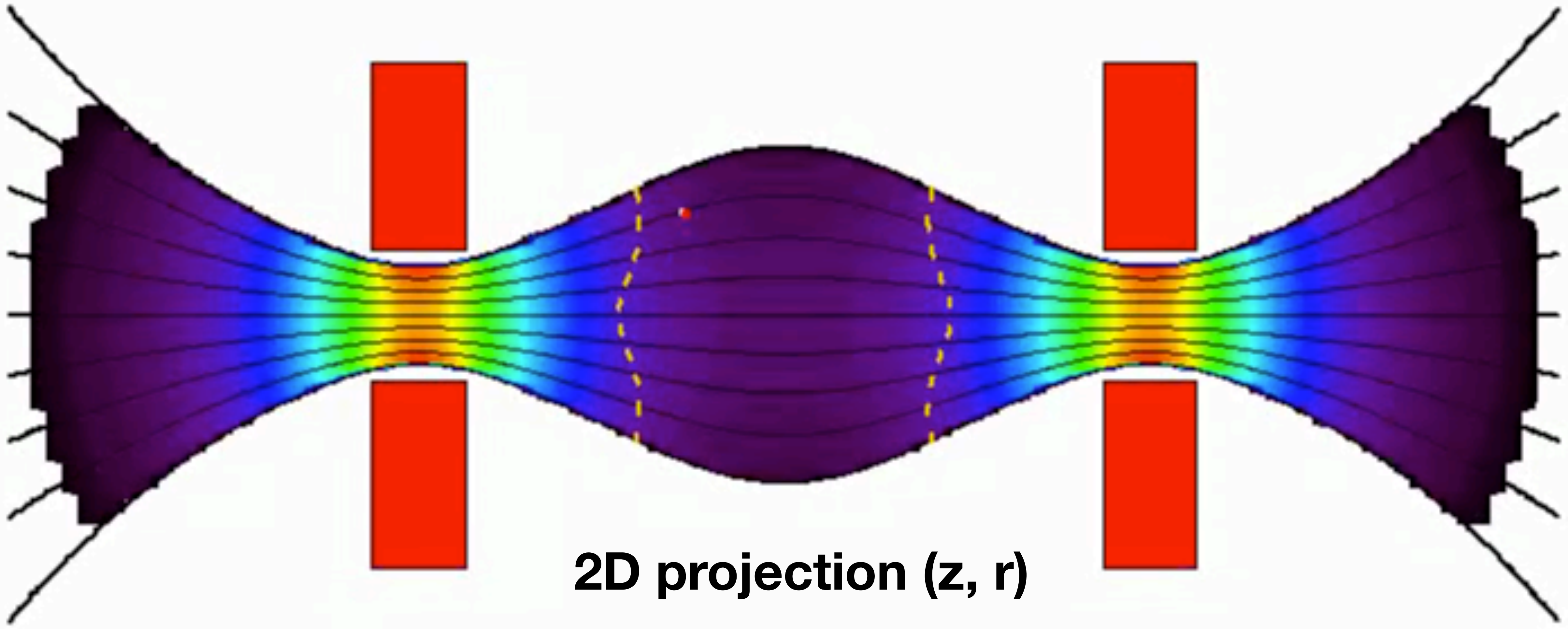
   ➡ axisymmetric mirrors can be made to work

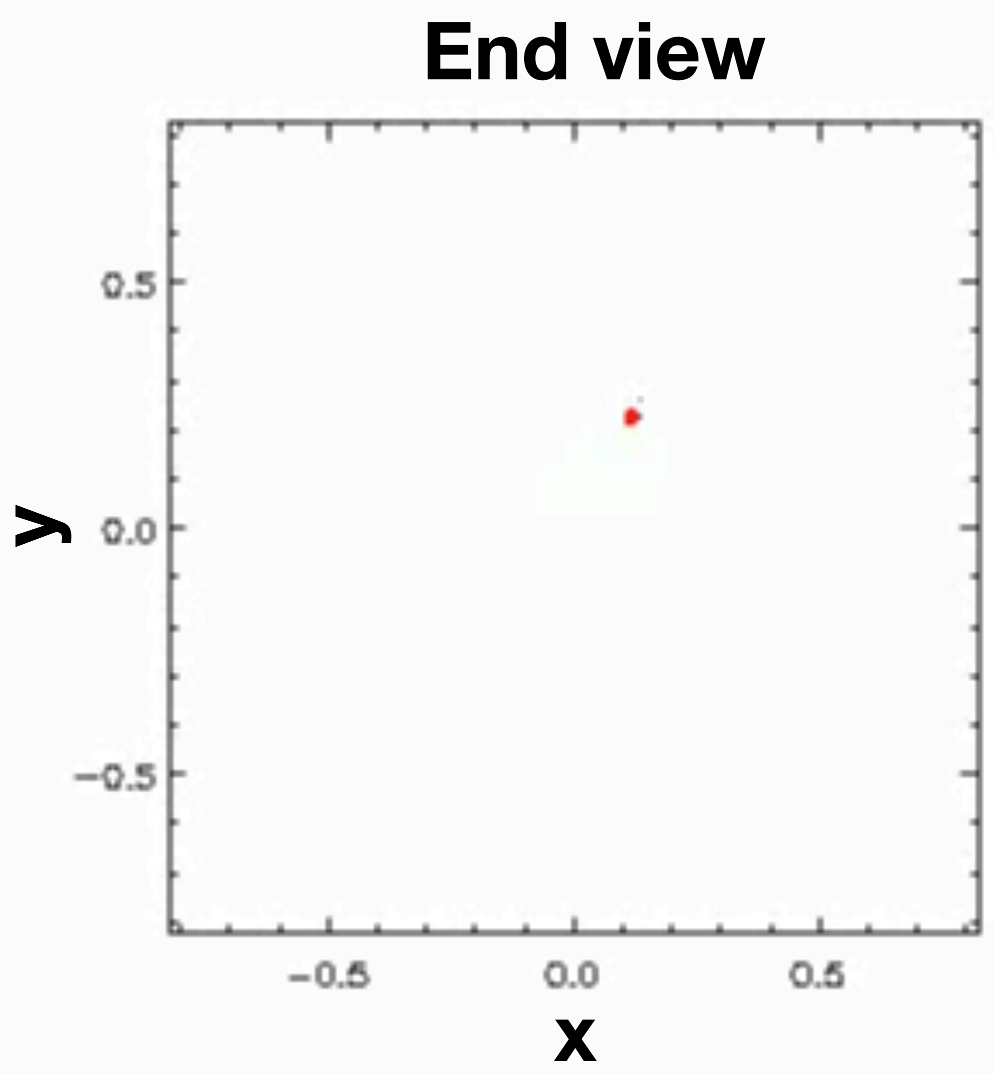
   ➡ Rebco magnets and other technological advances

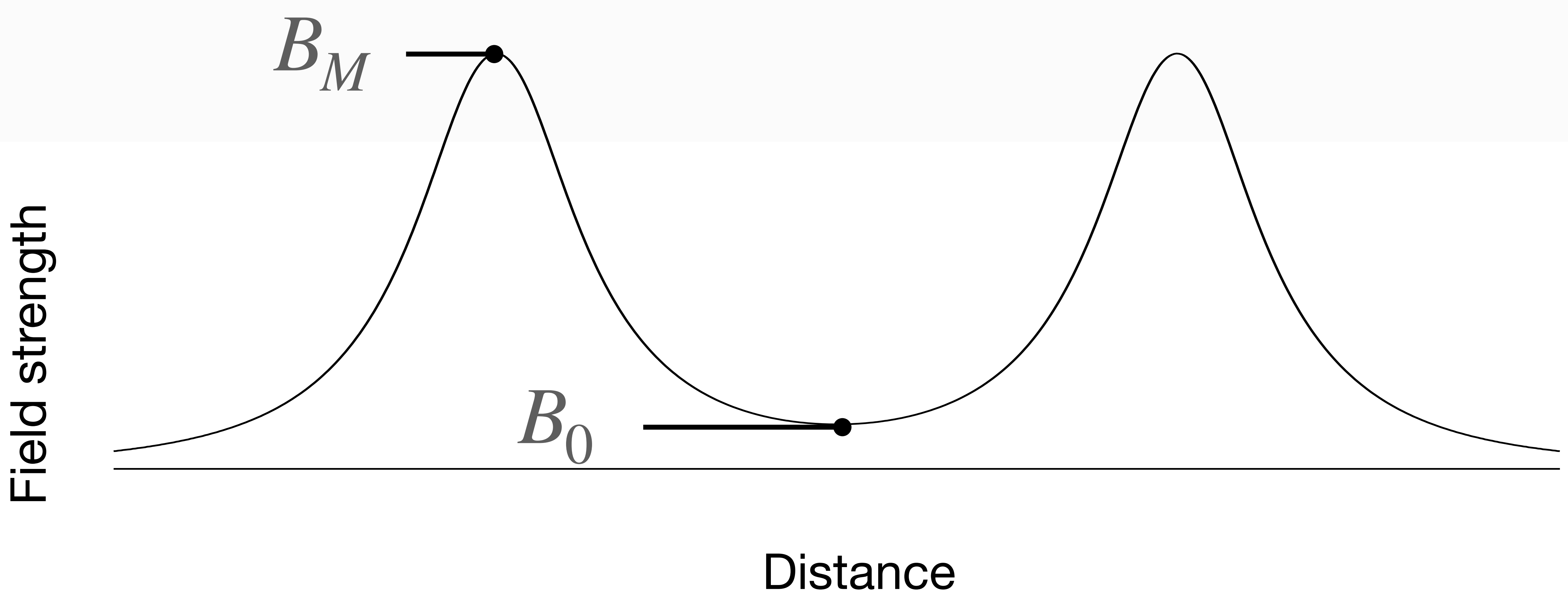
3. WHAM Prototype Status

   ➡ on schedule for first plasma later this summer

Probkotron (simple mirror): conservation of magnetic moment provides parallel confinement



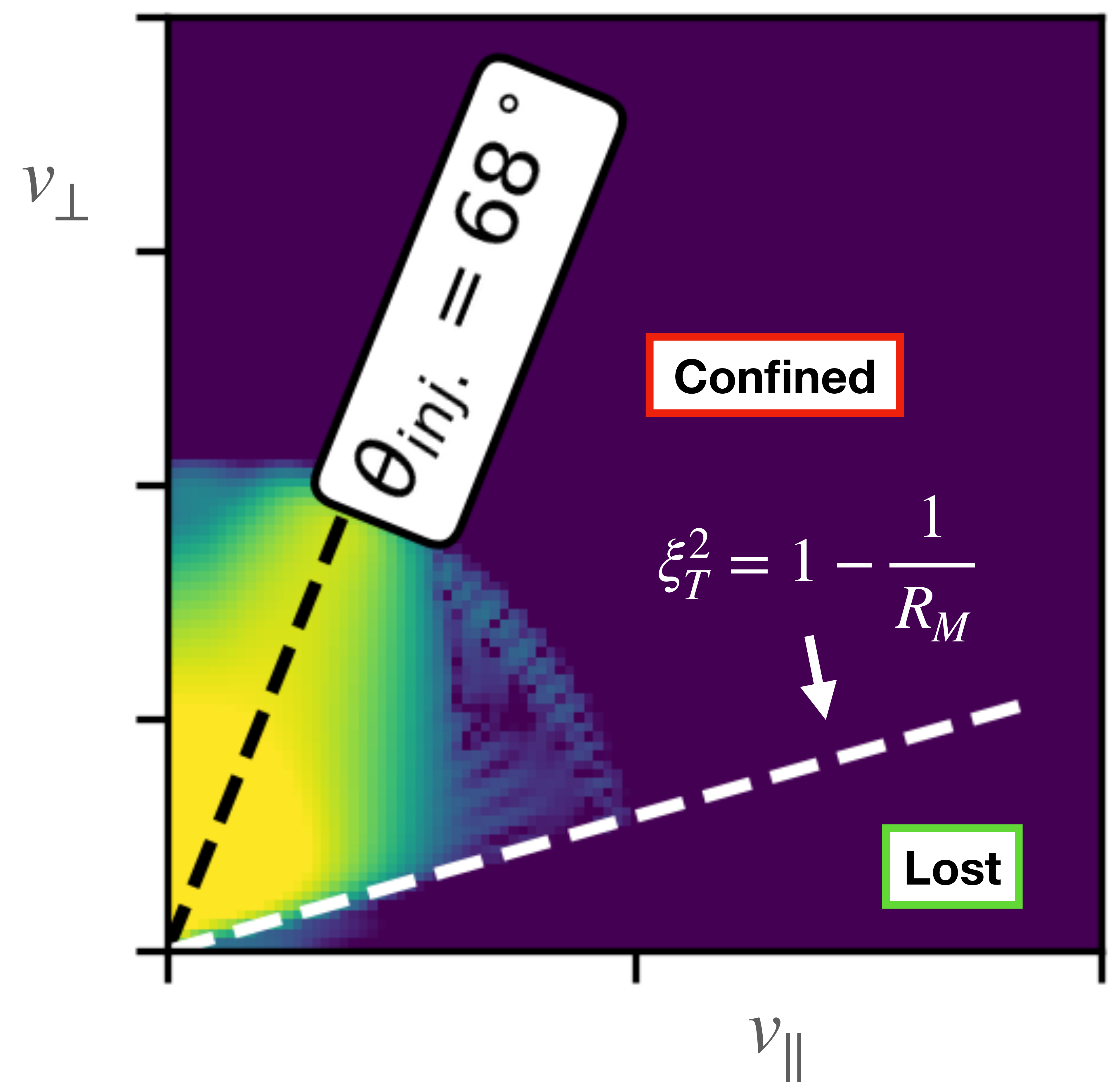


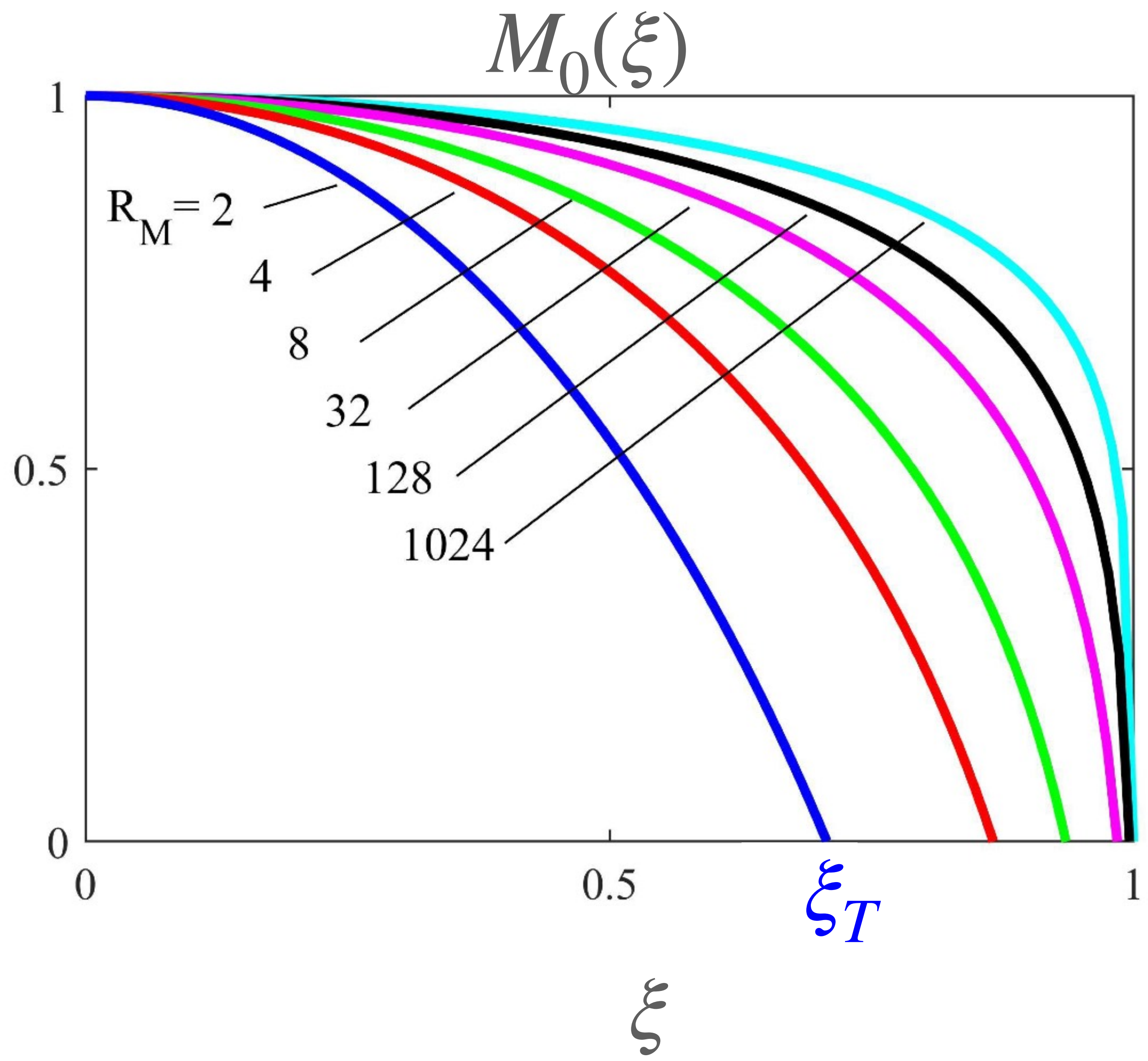


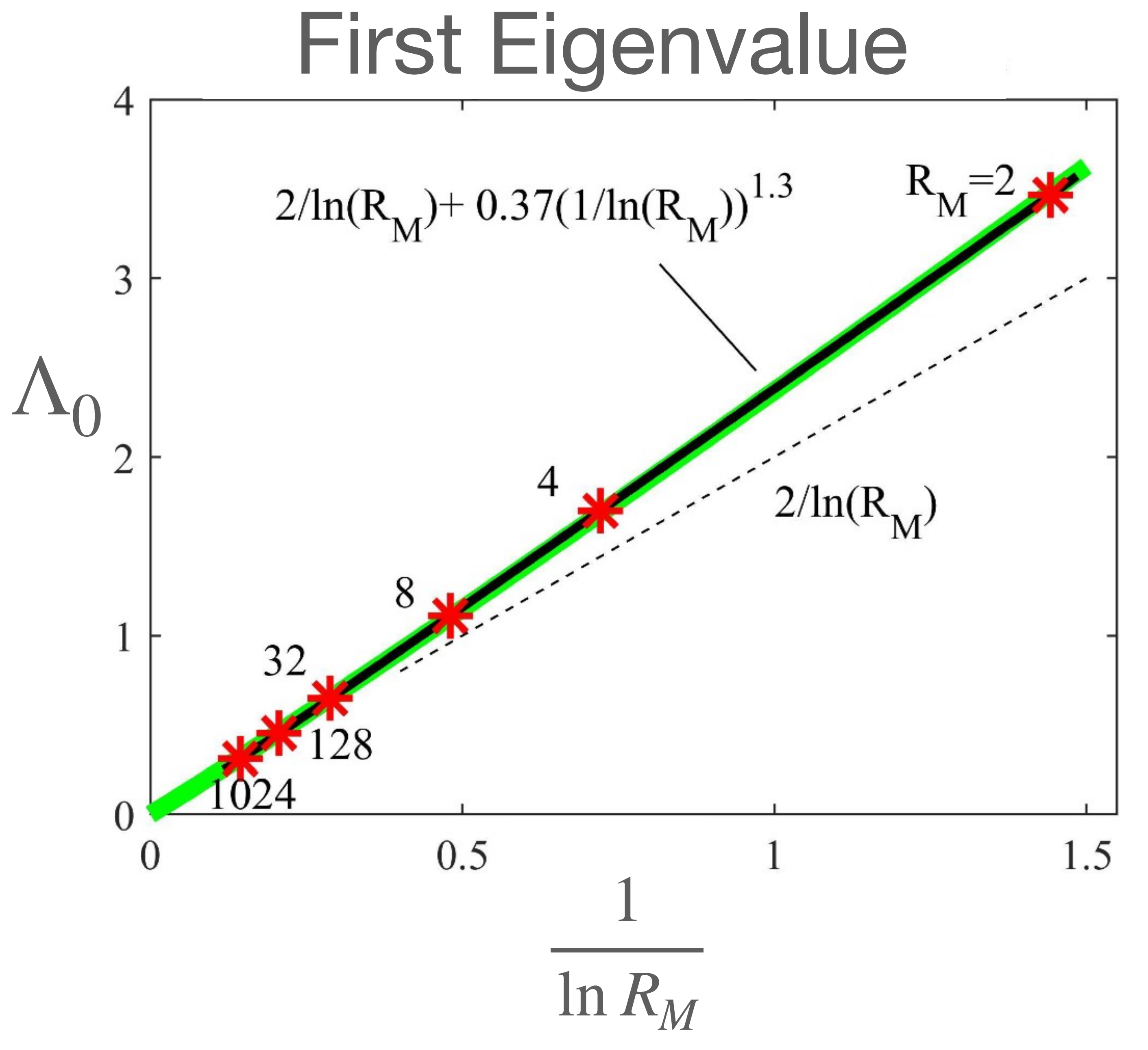
- Conservation of
$$\mu = \frac{mv_\perp^2}{2B} \text{ and } E = \frac{1}{2}mv_{||}^2 + \mu B$$
confines particles of $v_\perp^2 \geq v_{||}^2\ (R_M - 1)$.

- Confinement limited by angular scattering: $\tau \approx 0.4\tau_{ii}\ \ln R_M$ (When non-adiabaticity and scattering by waves are in check)

Ion confinement is set by collisional slowing on electrons and pitch angle scattering off each other into the loss cone







$$\frac{\partial f}{\partial t} = \frac{1}{\tau_s v^2}\frac{\partial}{\partial v}[(v^3 + v_c^3)f] + \frac{1}{2\tau_s}\frac{v_c^3}{v^3}\mathscr{L}f + S(v,\xi)$$

$$\mathscr{L} = \frac{\partial}{\partial \xi}(1-\xi^2)\frac{\partial}{\partial \xi}, \quad \xi = \frac{v_\parallel}{v}$$

$$\tau_s = 0.005\,\frac{T_{e,keV}^{3/2}\mu}{n_{20}Z^2}\ \text{sec}$$

$$\frac{1}{2}m_i v_c^2 \approx 20kT_e$$

$$\mathscr{L}M(\xi) = \Lambda M(\xi),\ M(\xi_T) = 0$$

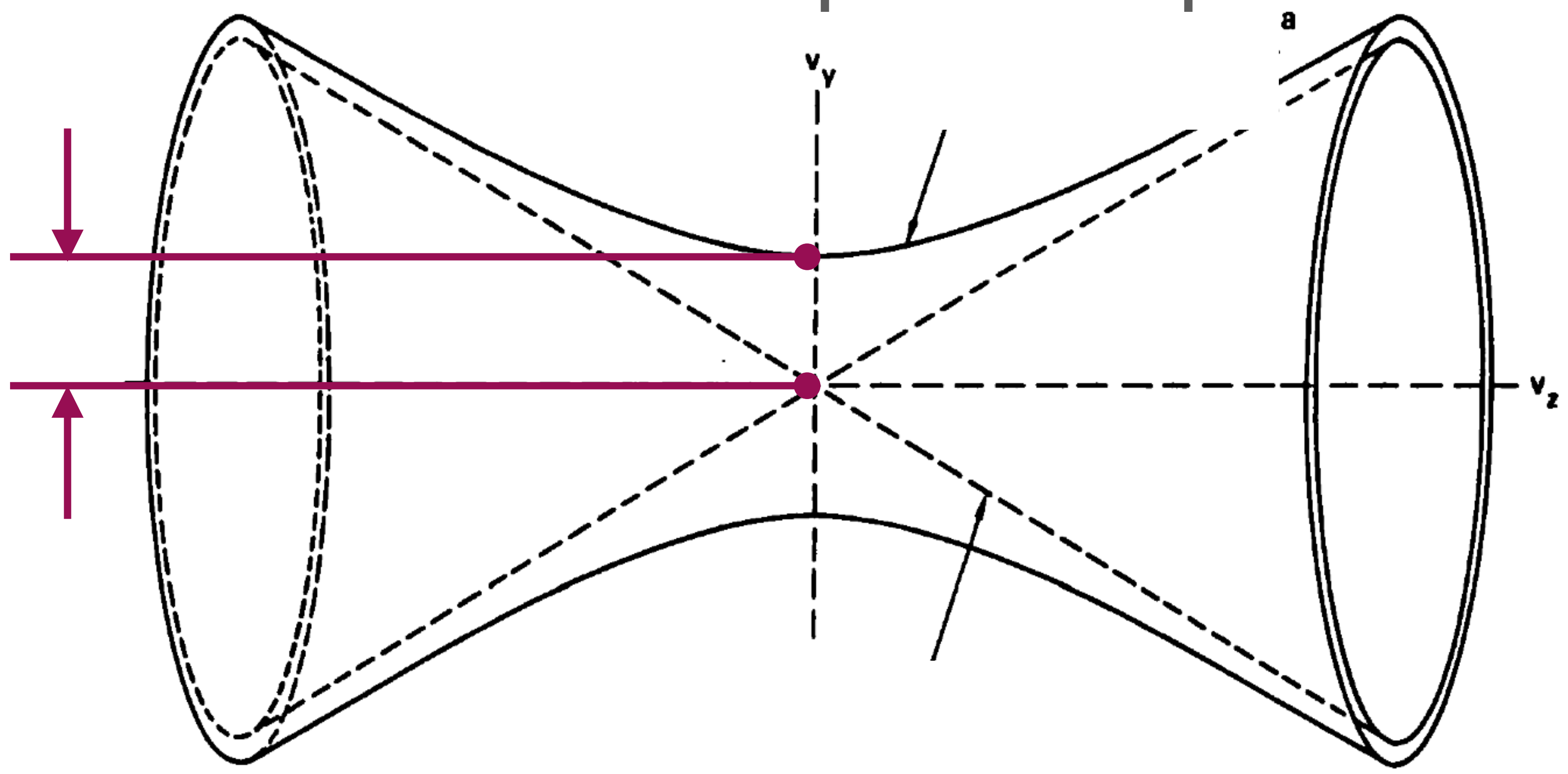
$$\Lambda \approx -1/\ln R_M$$

D. E. Baldwin "*End loss processes from mirror machines*"
Reviews of Modern Physics **49**, 2 (1977).

An ambipolar potential is established to equilibrate ion and electron losses

Ion loss cone for positive potential

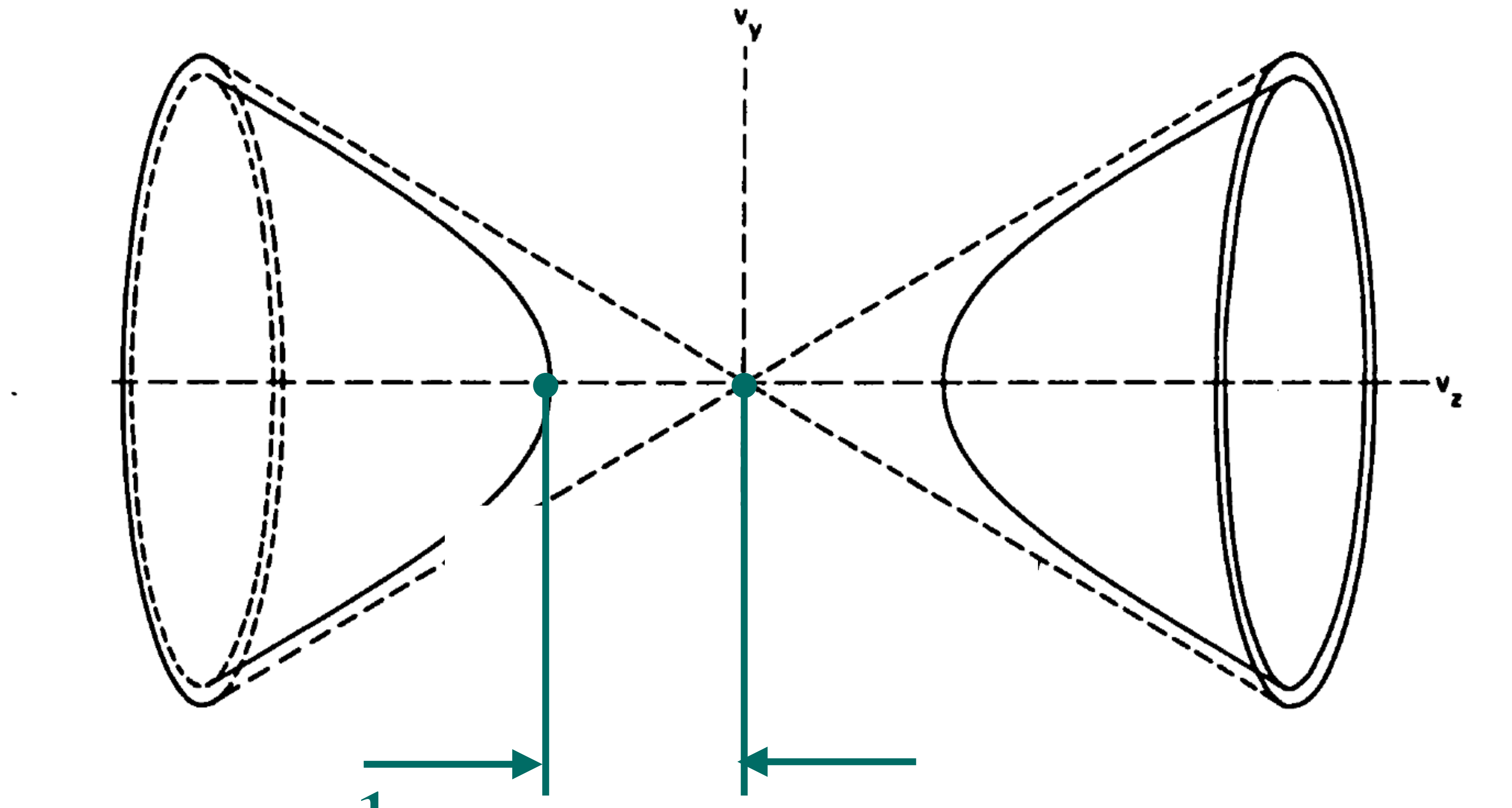
$$\frac{1}{2}m_i v_{\perp,crit}^2 < \frac{6kT_e}{R_M - 1}$$



electron loss cone for positive potential

Electron Energy Losses

$$P_e \approx 7\, I_{inj} kT_e$$



$$\frac{1}{2}m_e v_{\parallel,crit}^2 > 6kT_e$$

1. Ambipolar hole formed at low ion energy—extra losses and source of instability

2. electrons confined electrostatically for many scattering times->nearly thermal

3. confinement improved by Pastukhov Factor

$$\tau_{ii} \ln R_M = \tau_{ee} \ln R_M \frac{e\phi}{kT_e} \exp - \frac{e\phi}{kT_e}$$

$$\frac{\tau_{ii}}{\tau_{ee}} = \sqrt{m_i/m_e} = \frac{e\phi}{kT_e} \exp - \frac{e\phi}{kT_e}$$

$$e\phi \sim 5 - 7kT_e$$

Breakeven in beam heated weakly collisional mirror

- Fokker Planck calculations for coupled ion and electron losses showed

$$\tau_p = 0.00028\frac{E_{b,keV}^{3/2}}{n_{20}}\log_{10} R_M \text{ sec}$$

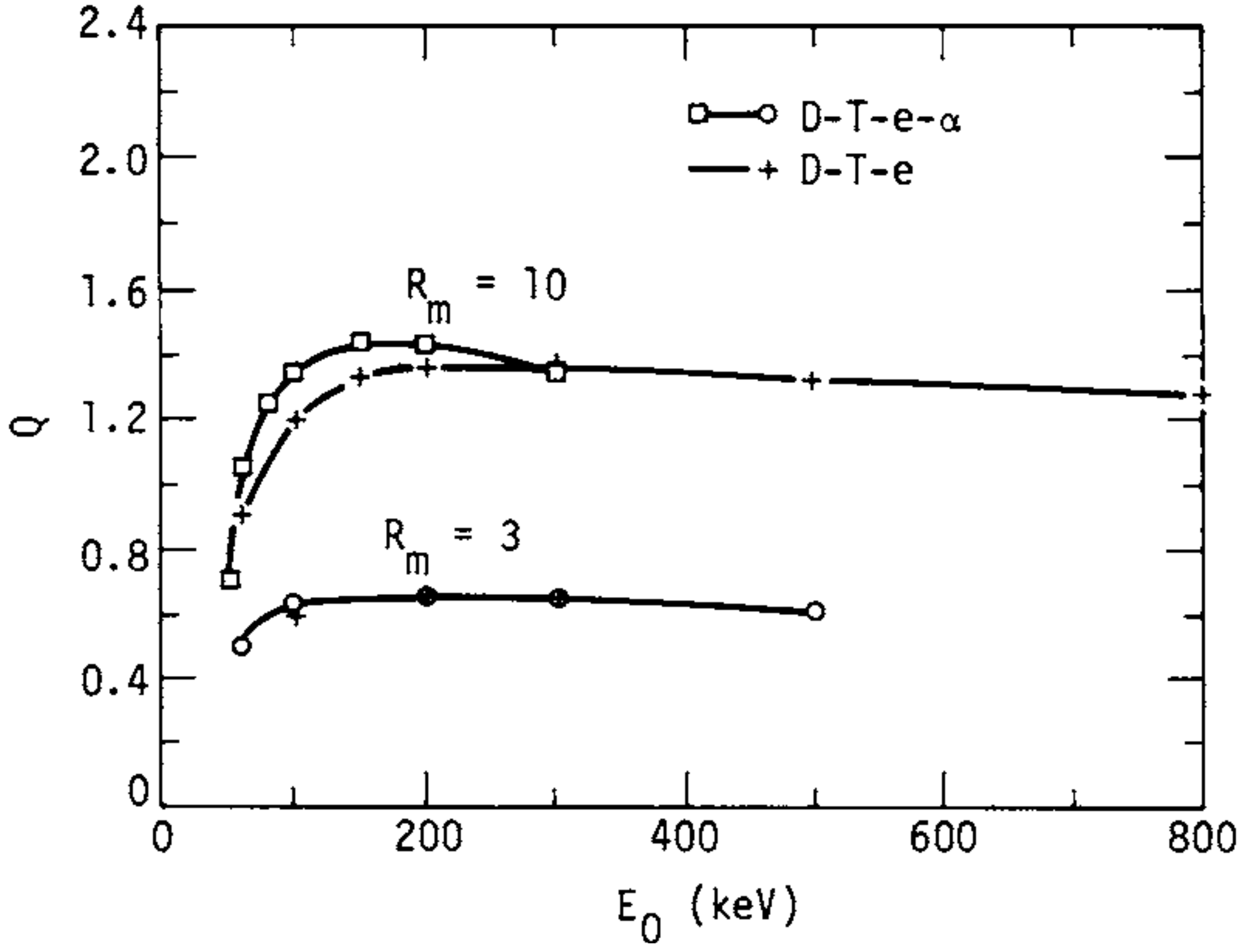
- Optimizes around $E_b \sim$ 100 keV

$$P_{nbi} = I_b E_b = \frac{enV}{\tau_P}E_b \sim \frac{10^{20}}{3}\frac{n_{20}^2}{E_{b,100keV}^{1/2}\log_{10} R_M}V\frac{MeV}{sec}$$

$$P_{fus} = \frac{1}{4}\langle\sigma v\rangle n^2 \mathscr{E}_{fusion} V \sim 5\times10^{19} n_{20}^2 V\frac{MeV}{sec}$$ for $\mathscr{E}_{fusion}$=22.4 MeV and $T_i \sim$ 100 keV

- Independent of plasma parameters, size or B

$$Q \equiv \frac{P_{fusion}}{P_{nbi}} \propto \langle\sigma v\rangle E_b^{1/2}\log_{10} R_M \sim 1.5\ E_{b,100keV}^{1/2}\log_{10} R_M$$

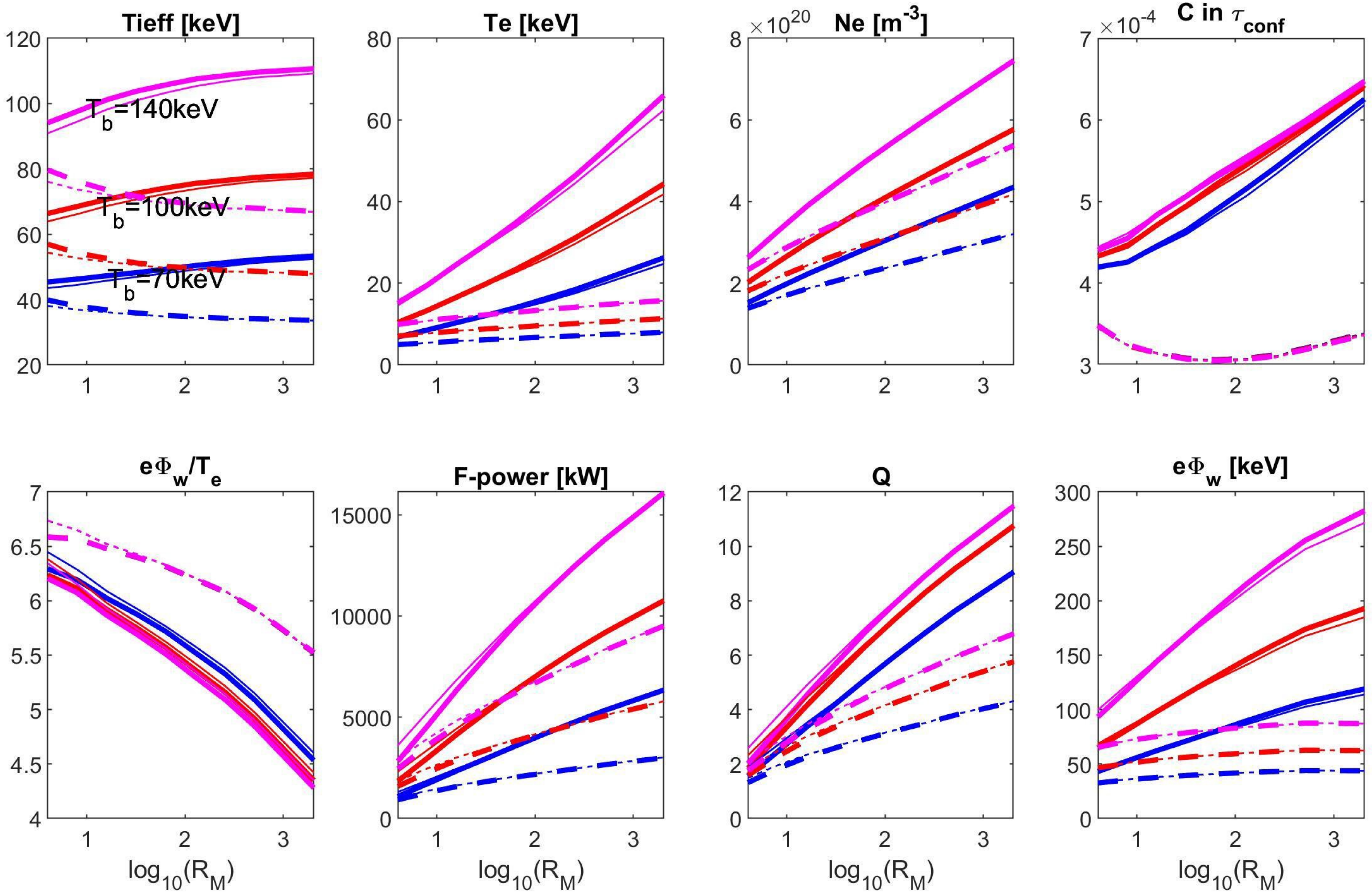


Comparison of Q Values ($R_m = 10$)

Code description	Plasma species D-e-T	D-e-T-α	D-e-³He	D-e-³He-α-p
One-dimensional code; P_0 only	1.22	1.39	0.244	0.264
One-dimensional code; P_0 and P_2	1.44	1.68	0.289	0.312
Two-dimensional code; normal mode source	1.38	1.61	0.278	0.301
Two-dimensional code; narrow source	1.71	1.99	0.337	0.365

KILLEEN, J., MIRIN, A. A. & RENSINK, M. E. The Solution of the Kinetic Equations for a Multispecies Plasma *Methods Comput Phys Adv Res Appl* **16**, 389–431 (1976).

Confirmed by modern bounce-averaged Fokker Plank/DKE solver valid for arbitrary Rm and real equilibria (Egedal)



What could possibly go wrong?

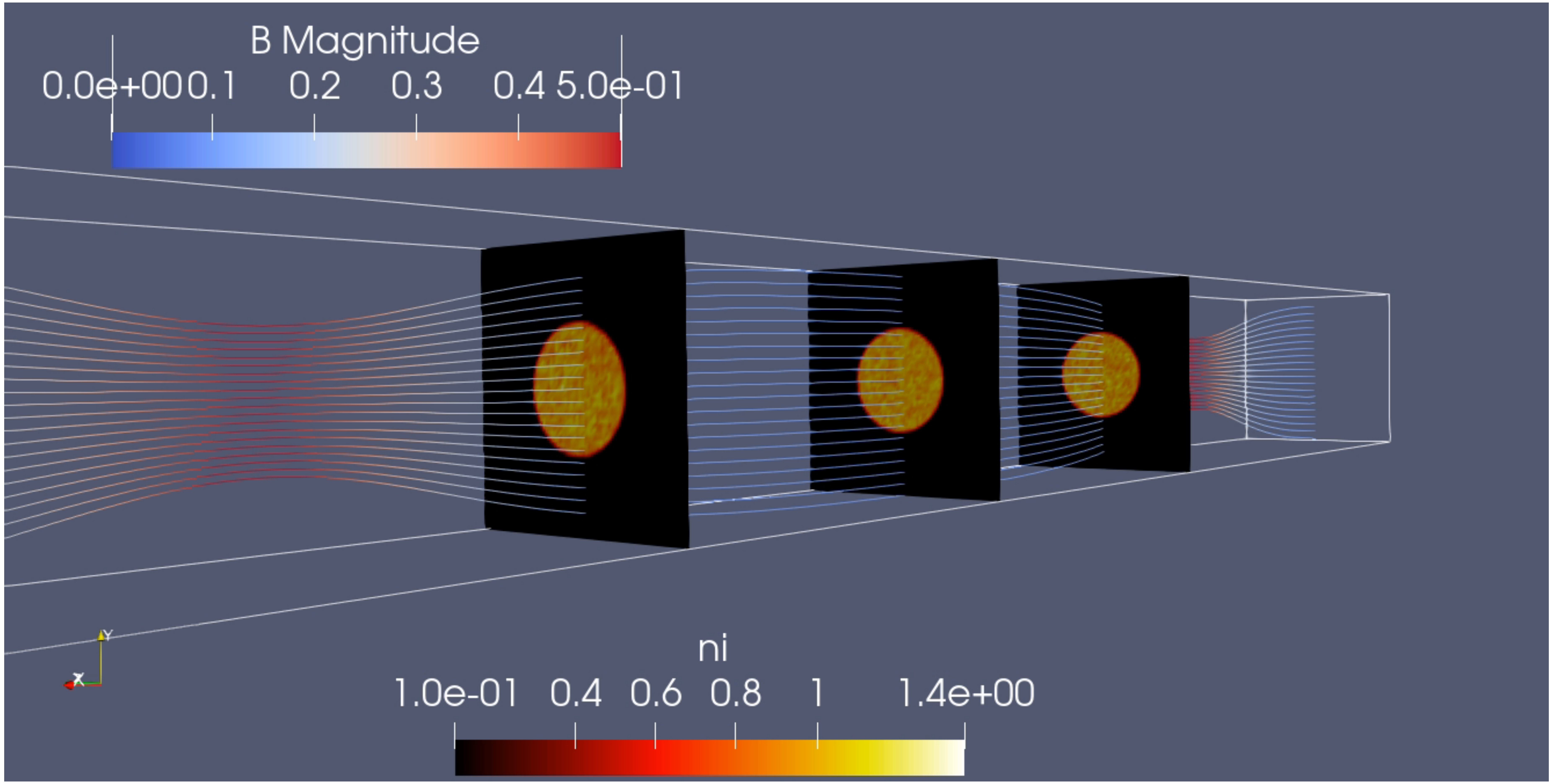
and

Hasn't this been tried before?

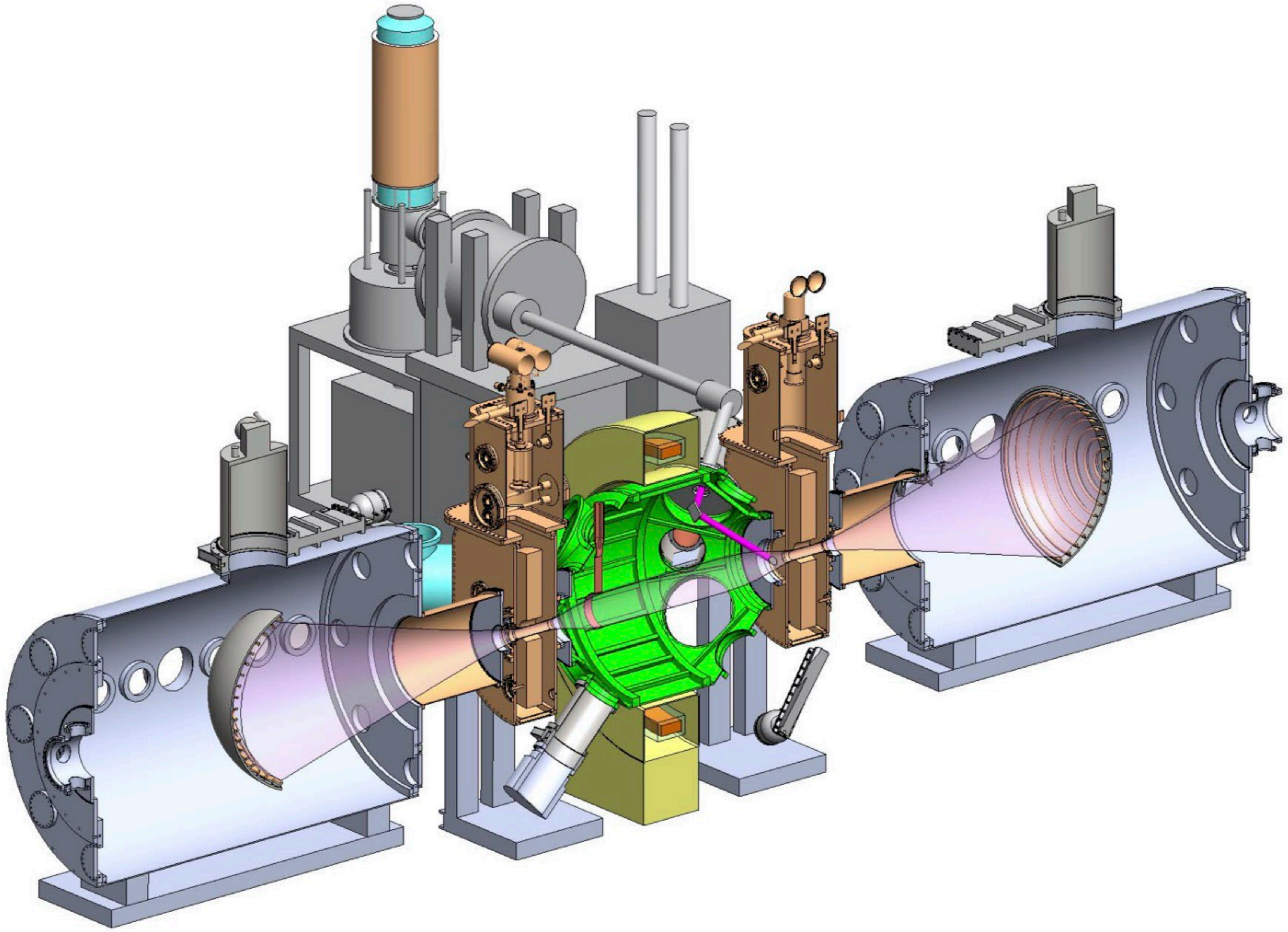
Hint: MHD and Kinetic Instability

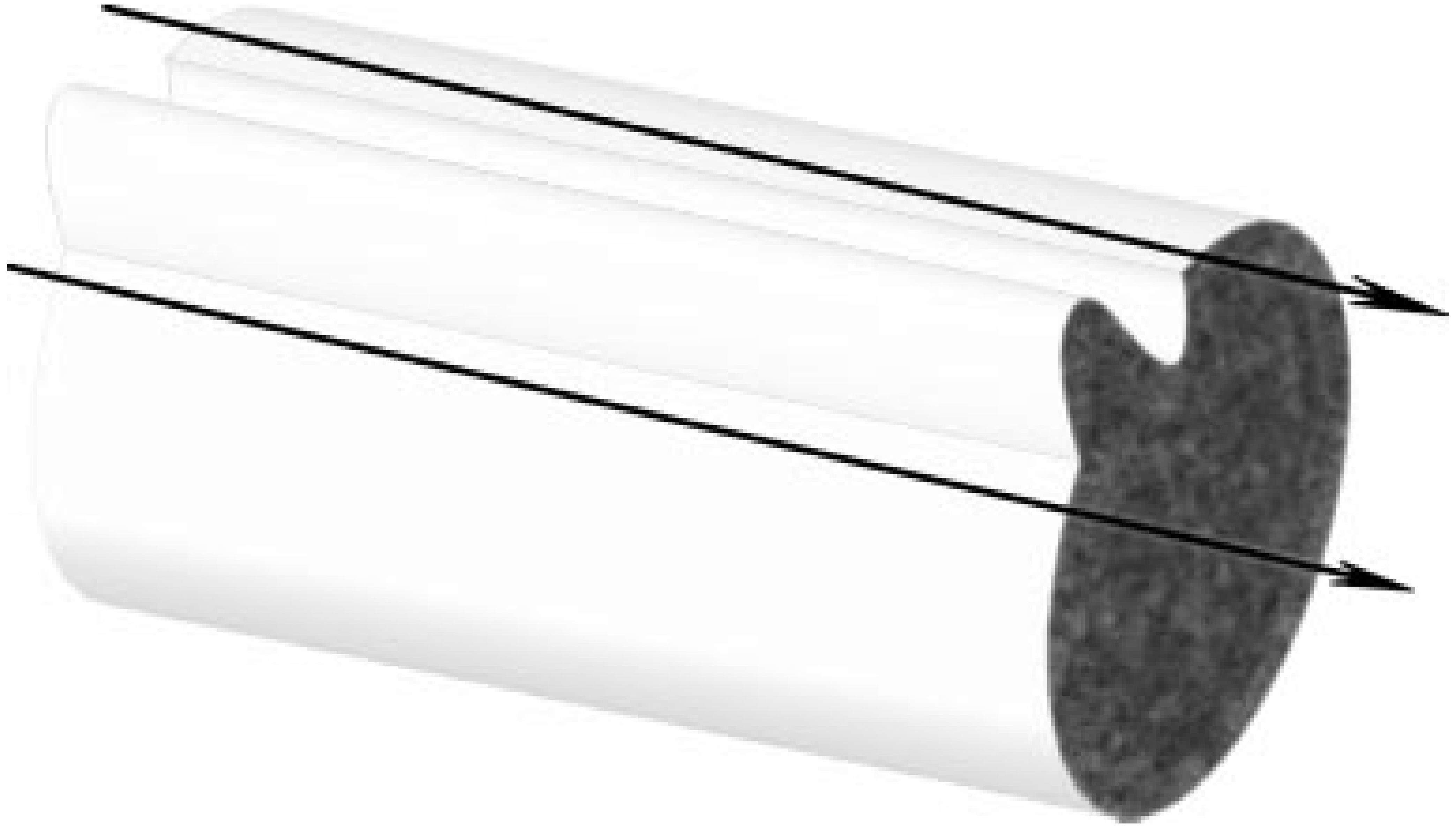
So what could go wrong?

Instability in a 3D Hybrid simulation using VPIC: Plasma science and computation has now advanced so far that we can simulate almost anything before building it



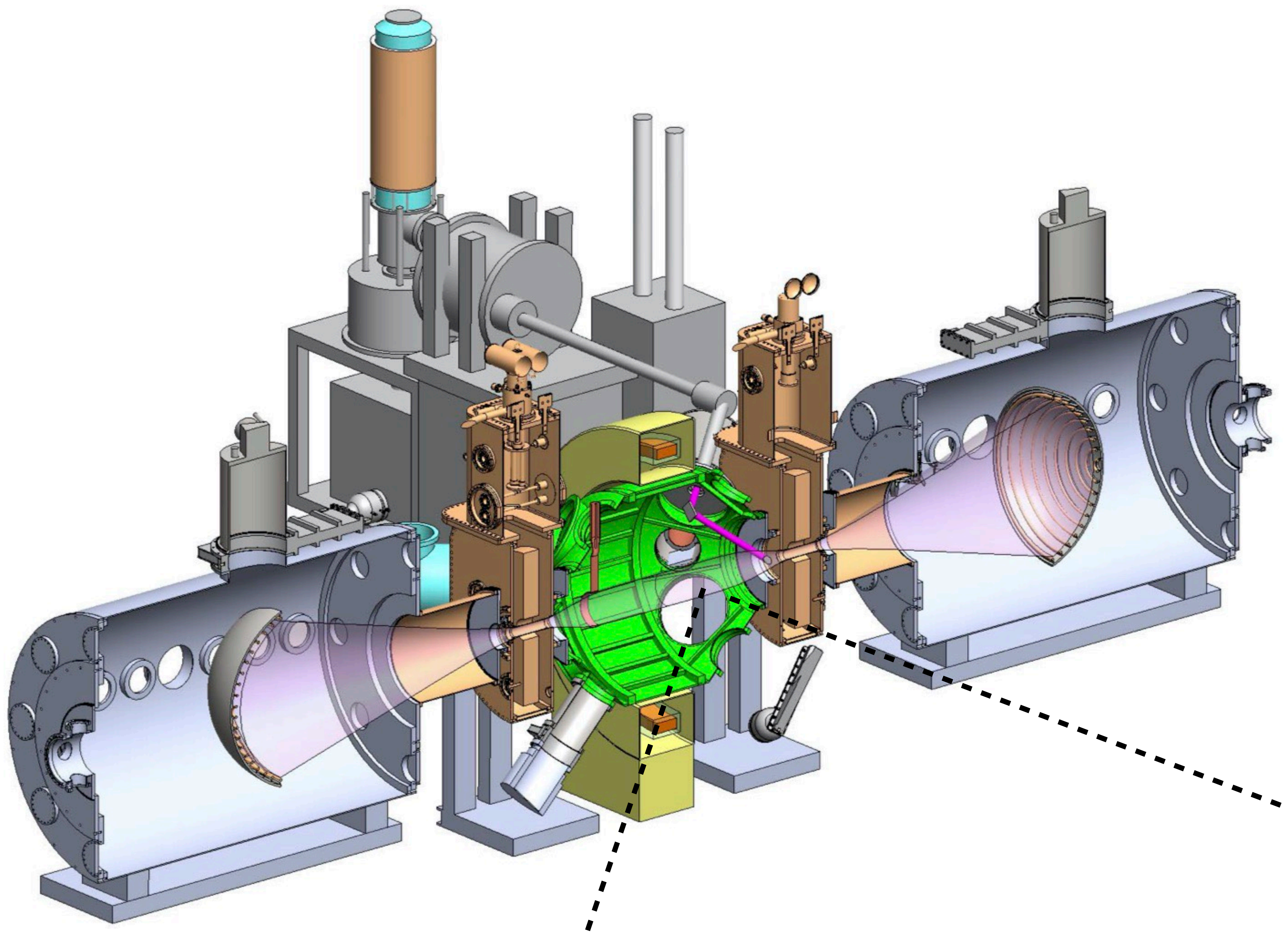
Axisymmetric mirror prone to Interchange

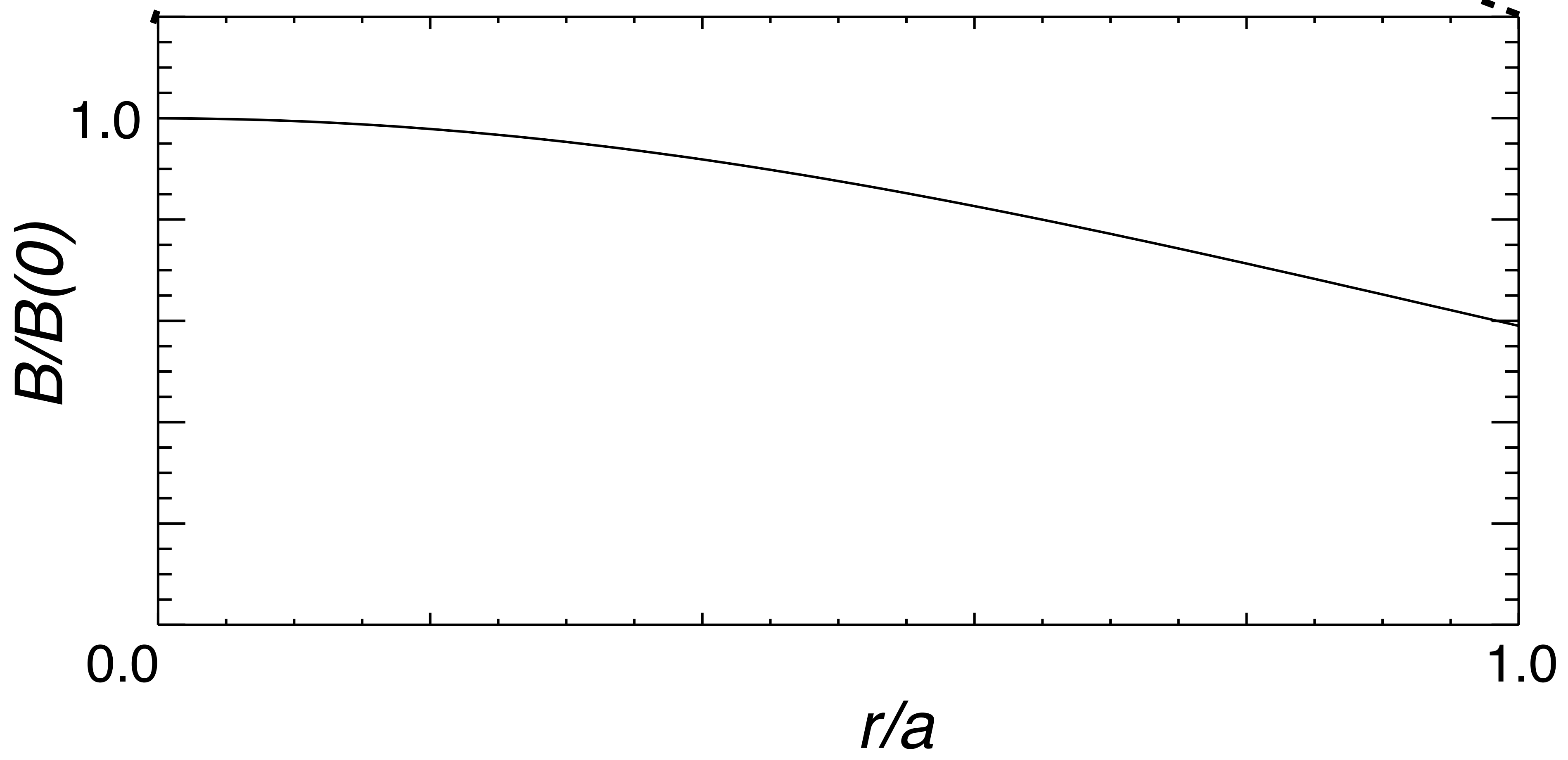


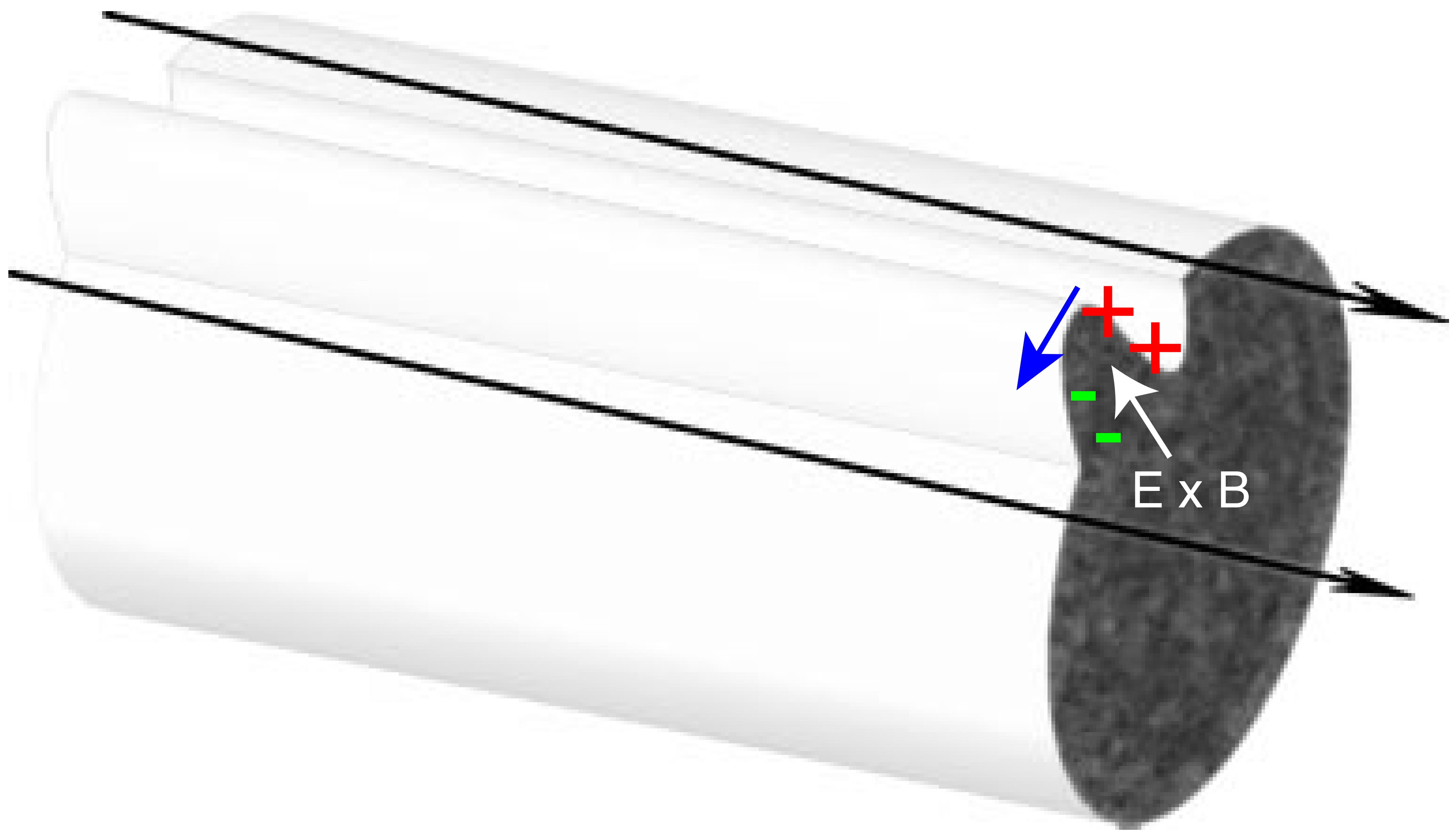


The "flute" mode; m=1 is expected to be most unstable.

Axisymmetric mirror prone to Interchange





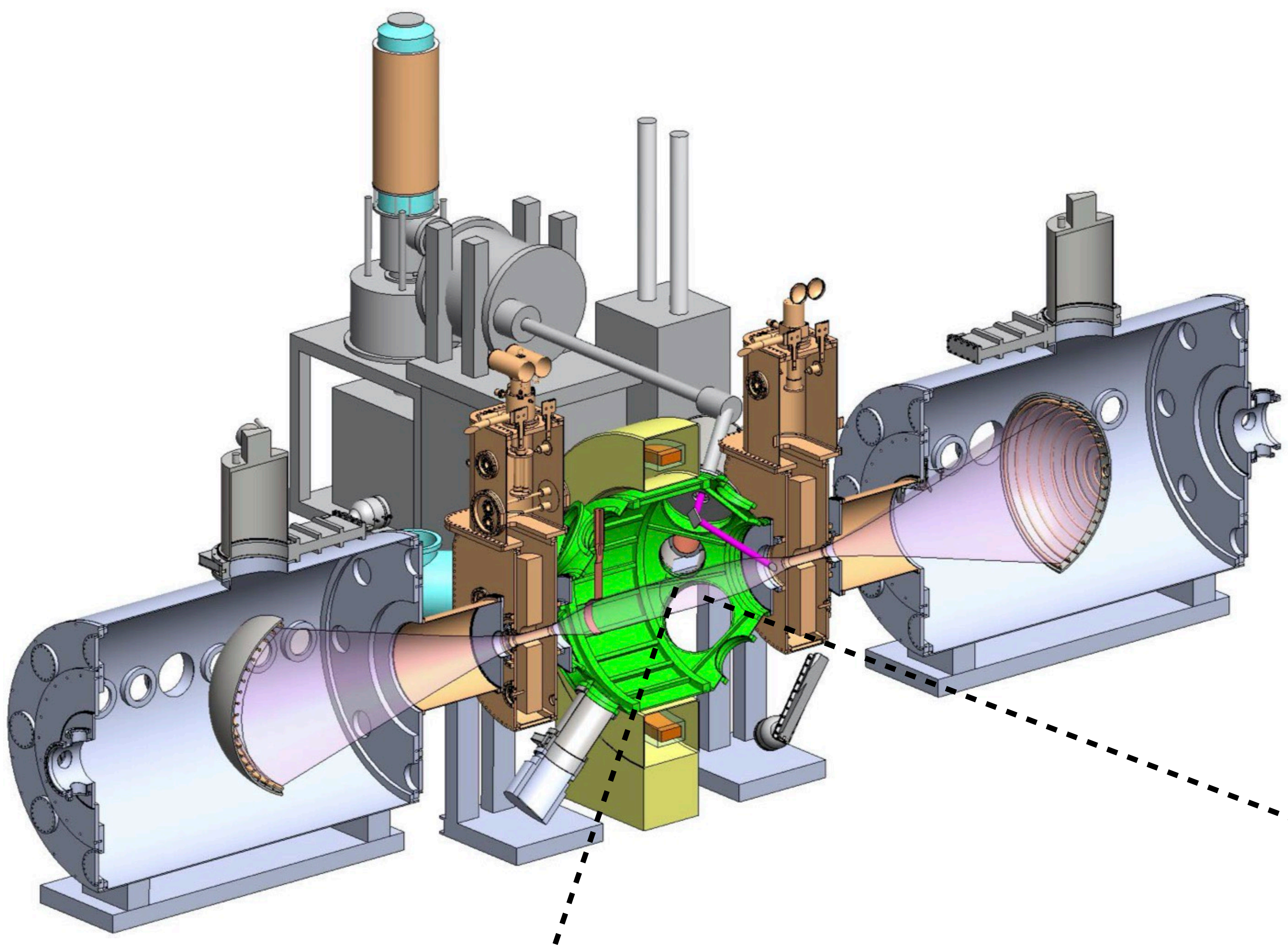


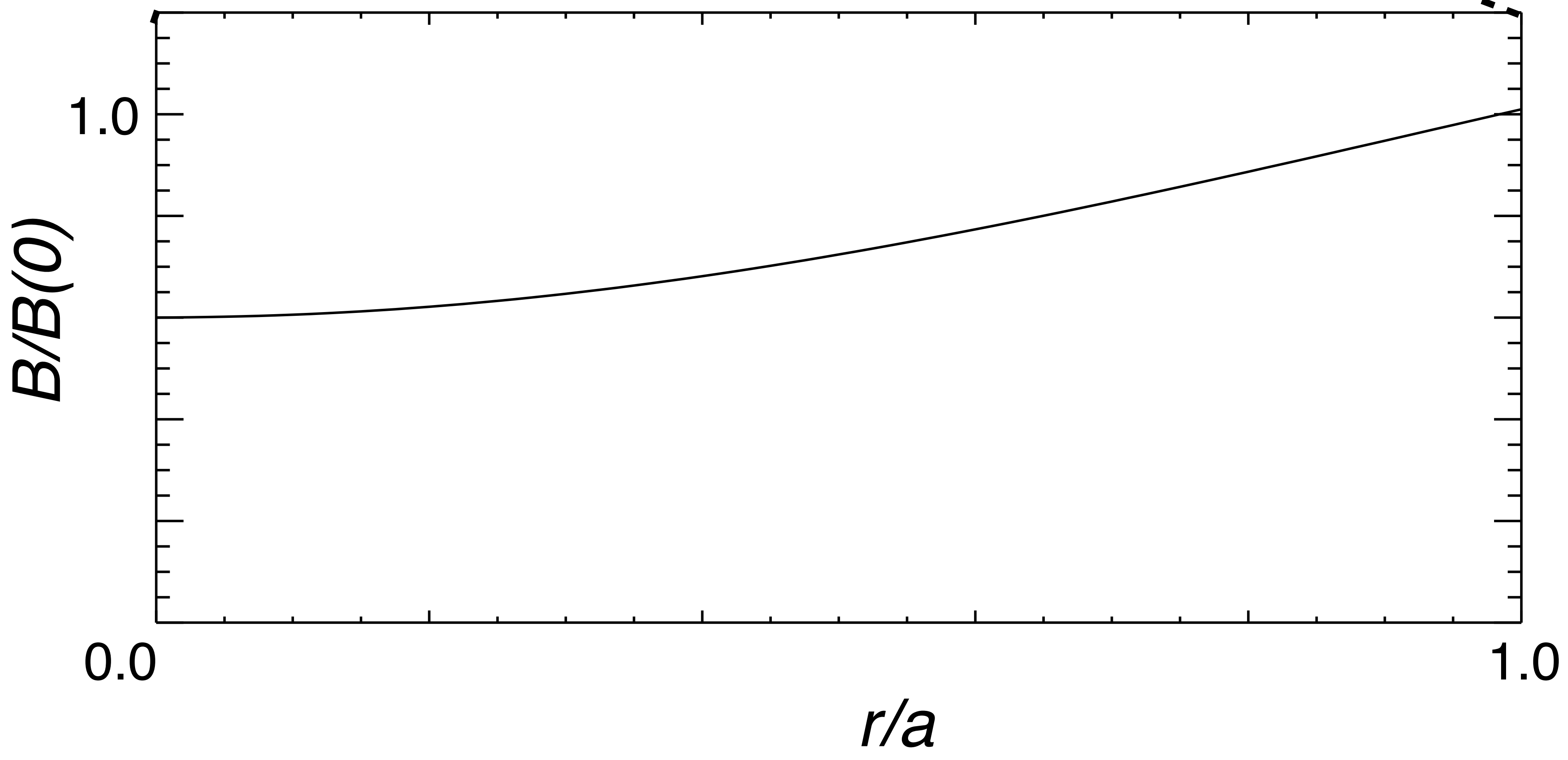
Curvature and ∇B lead to charge separation in perturbed region creatin electric field.

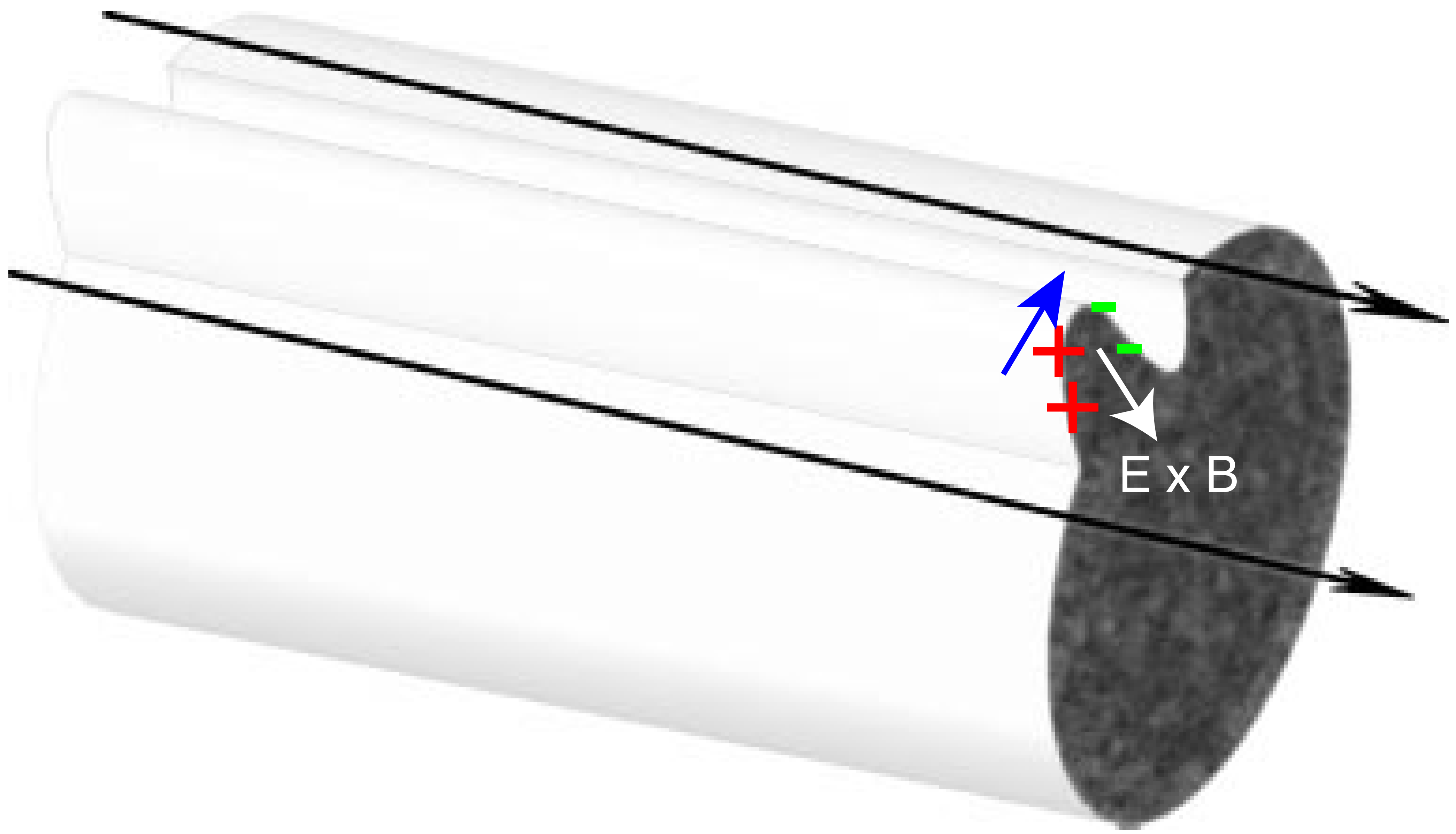
For "bad curvature", resulting ExB reinforces perturbation $\Longrightarrow$ instability.

Growth rate $\gamma \propto v_i/L$ (fast!).

Create instead a radially increasing magnetic field



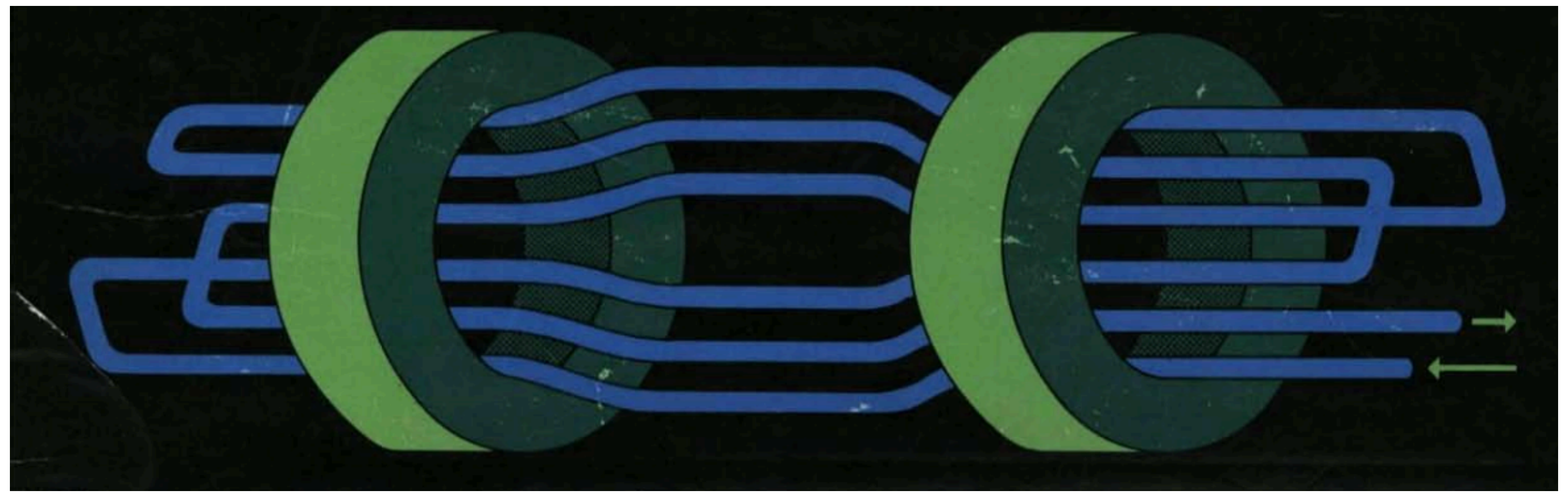




Opposite signs on drift velocities;
$E \times B$ returns boundary to equilibrium.

"Min B stabilization"

Minimum-B MHD stable configurations



- Ioffe bars. (Kurchatov Institute)

- Baseball coil. (Culham, LLNL)

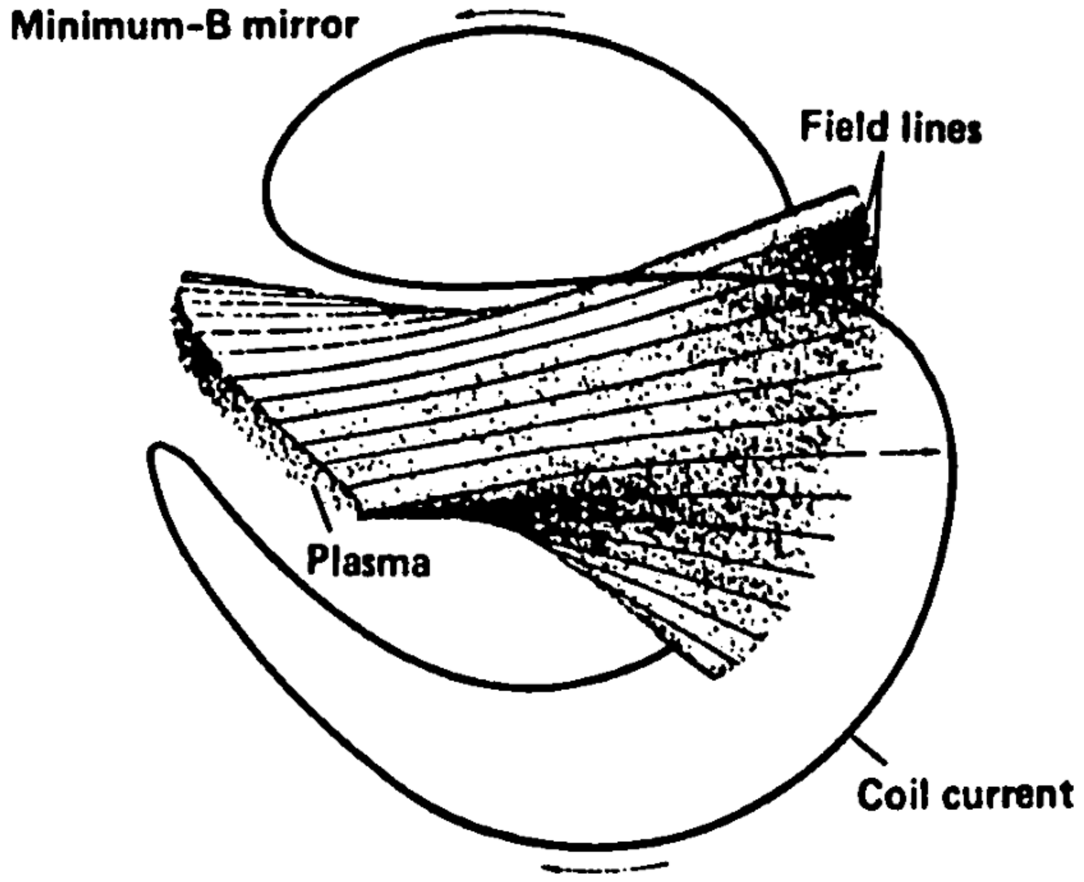
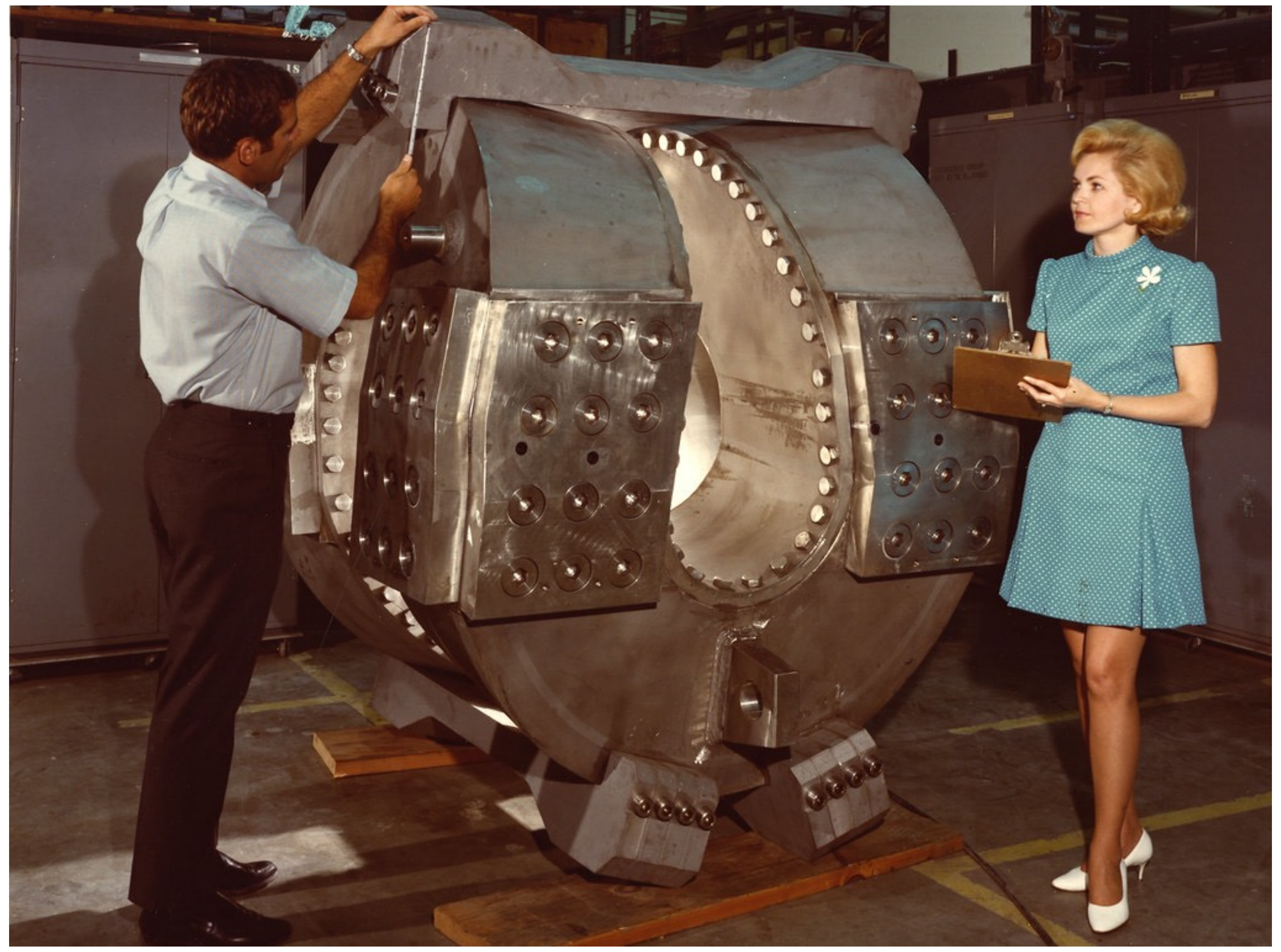


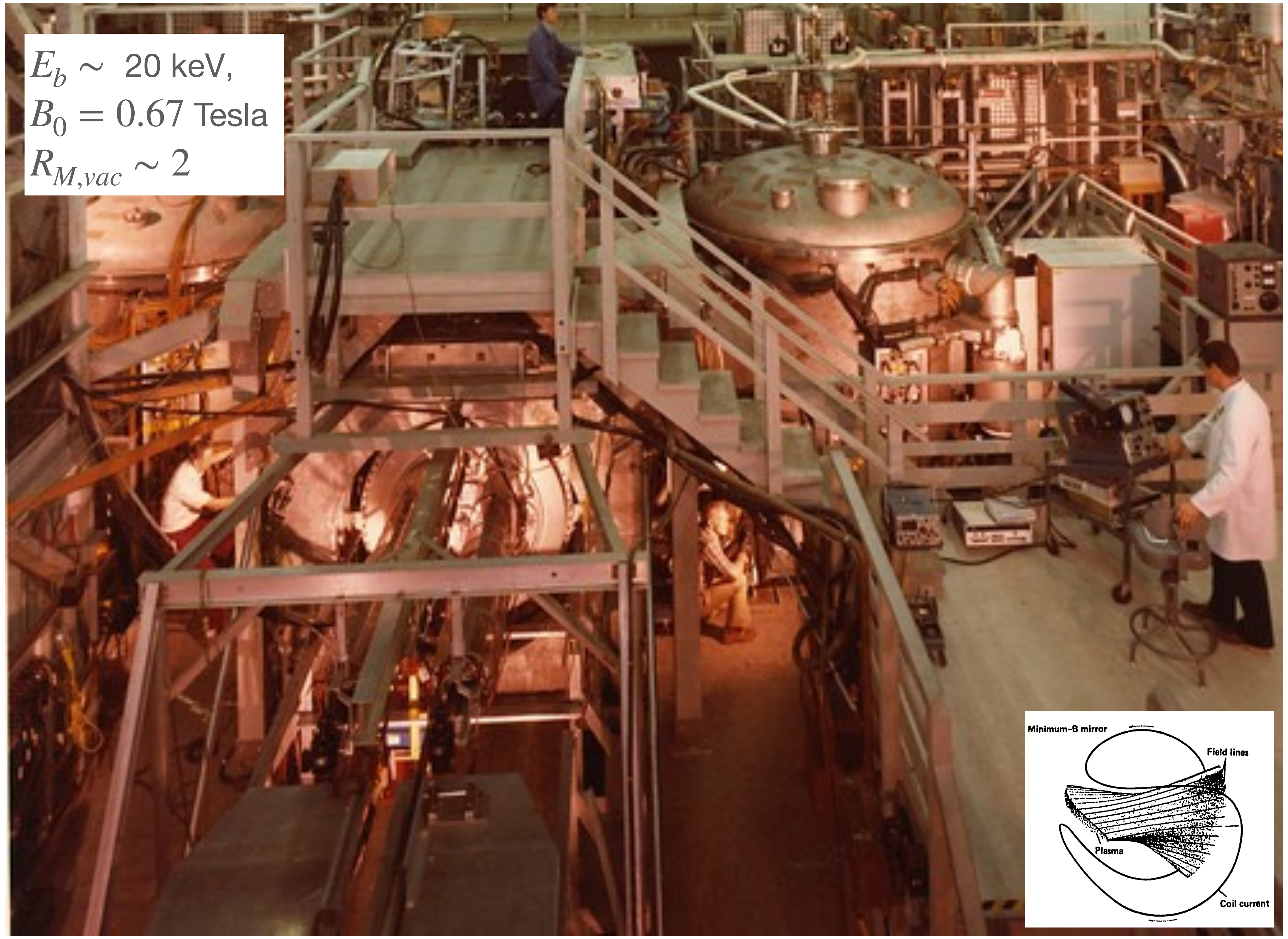
FIG. 1. Schematic representation of the coil and field lines in a magnetic-well field as produced by a "Baseball" coil.



- Ying-Yang coils. (LLNL)

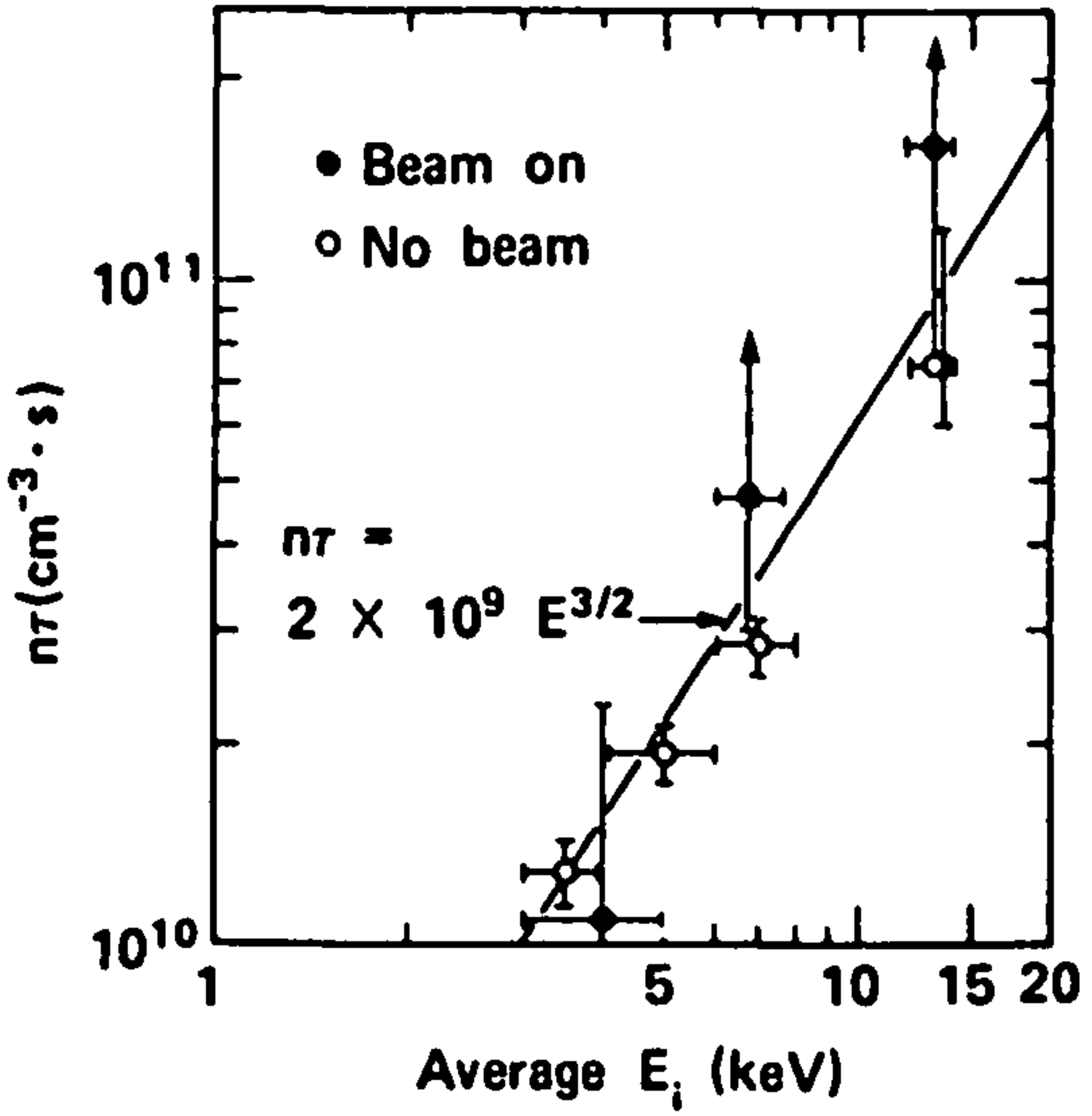
Non-circular coils successful in stabilizing the plasma;
Major downsides are decreased particle confinement, simplicity and field strength/ mirror ratio.

2XIIB showed near classical scaling of confinement and $\beta \sim 1$



$E_b \sim$ 20 keV,
$B_0 = 0.67$ Tesla
$R_{M,vac} \sim 2$

- Mirrors want to run at high ion energy
  $\tau \sim E_b^{3/2} \ln R_M / n$
- Kinetic Instability stabilized by plasma guns at ends filling ambipolar hole
  - later on TMX with skewed NBI injection to trap warm plasma



In retrospect: skewed injection, E_b=100 keV, and high beta $R_M = R_{M,vac}/\sqrt{1-\beta}$ would have been close to Q~1 with optimistic assumptions

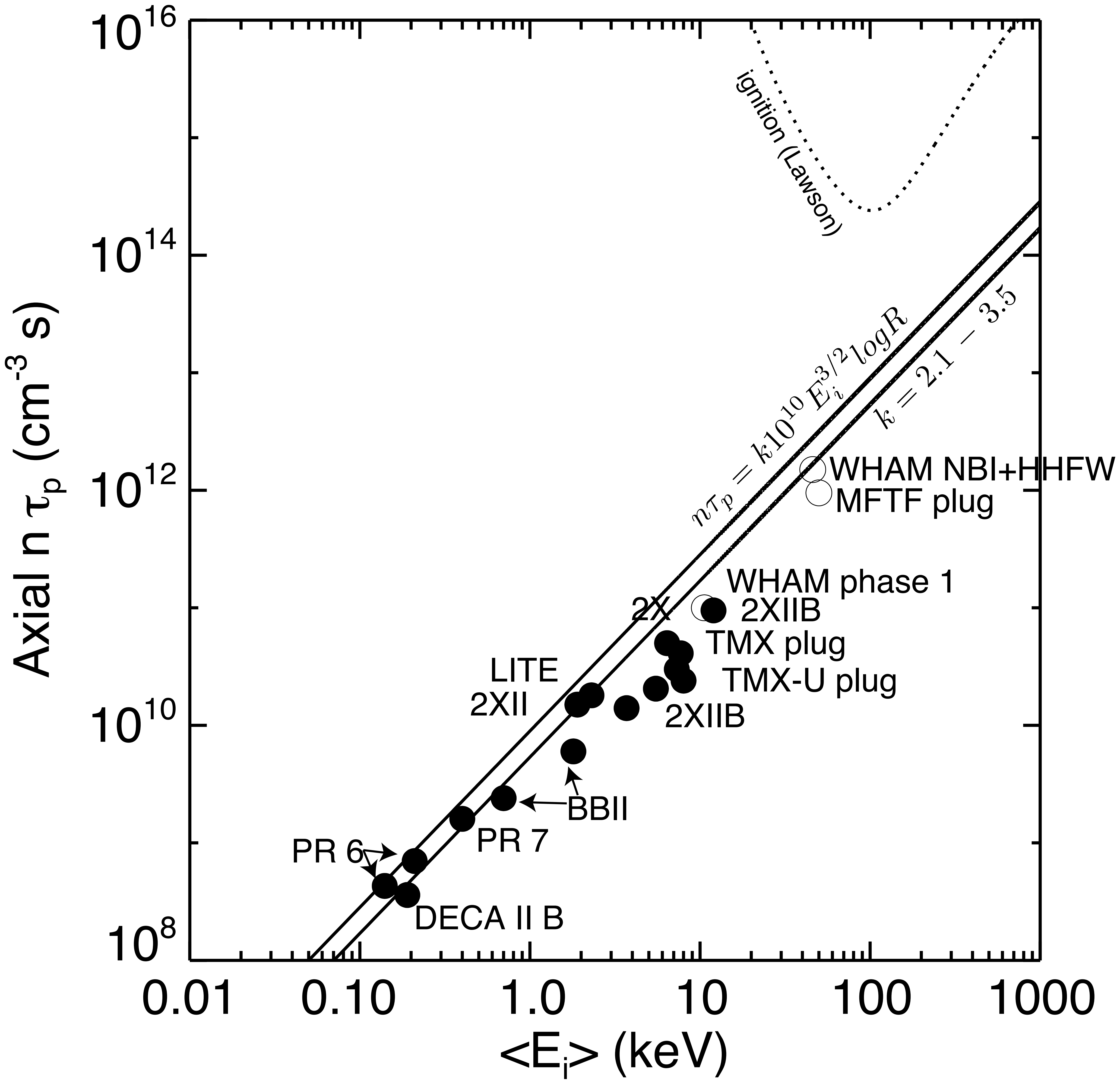
F. H. Coensgen, W. F. Cummins, B. G. Logan, A. W. Molvik, W. E. Nexsen, T. C. Simonen, B. W. Stallard, and W. C. Turner, *Stabilization of a Neutral-Beam—Sustained, Mirror-Confined Plasma*, Phys Rev Lett **35**, 1501 (1975).

ca. 1980 simple mirror is abandoned due to low projected Q — Imagine if we had achieved Q~1 in 1980!

- High energy NBI not yet available
- Ignition out of reach in minB simple mirror at modest R_M (~2-3 because of geometry and magnet technology)

"Disappointing from a fusion context, but important and valuable in context of a tandem mirror endplug, where the ability to maintain non-equilibrium angular distribution of ions is highly advantageous." R.F. Post 1987

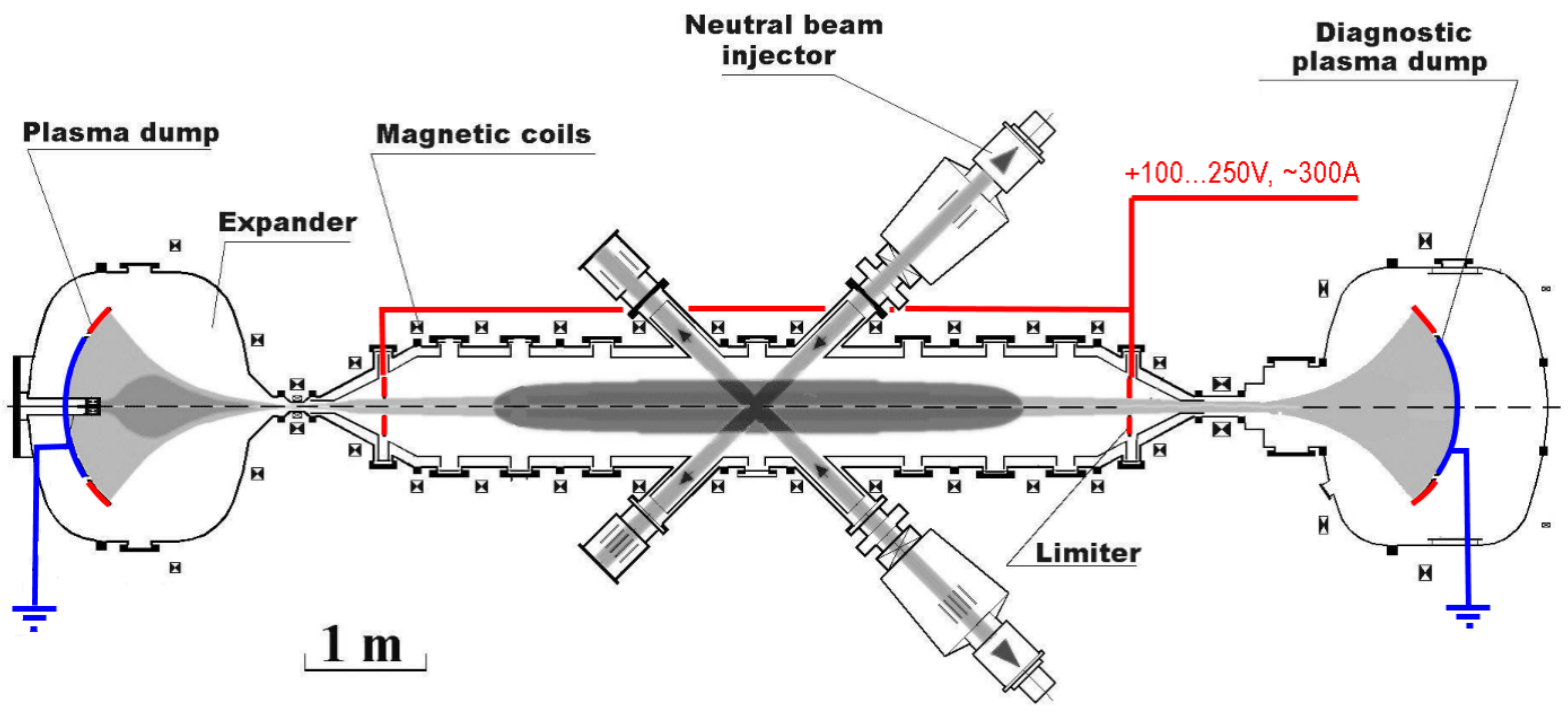
R.F. Post *"The magnetic mirror approach to fusion"* Nuc. Fusion 1987



So what has changed?

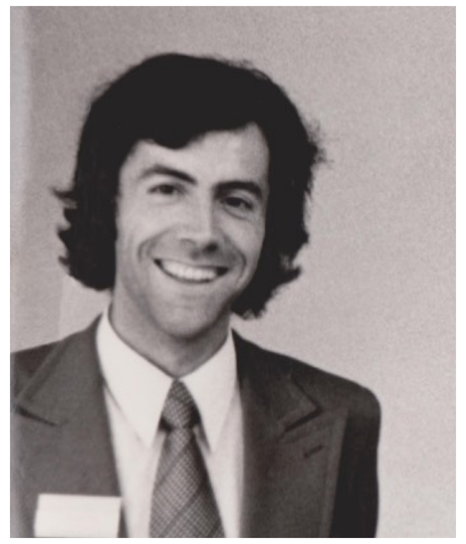
Hint: axisymmetric physics breakthroughs, HTS Magnets, computation, and 40 years of advancement of fusion technology

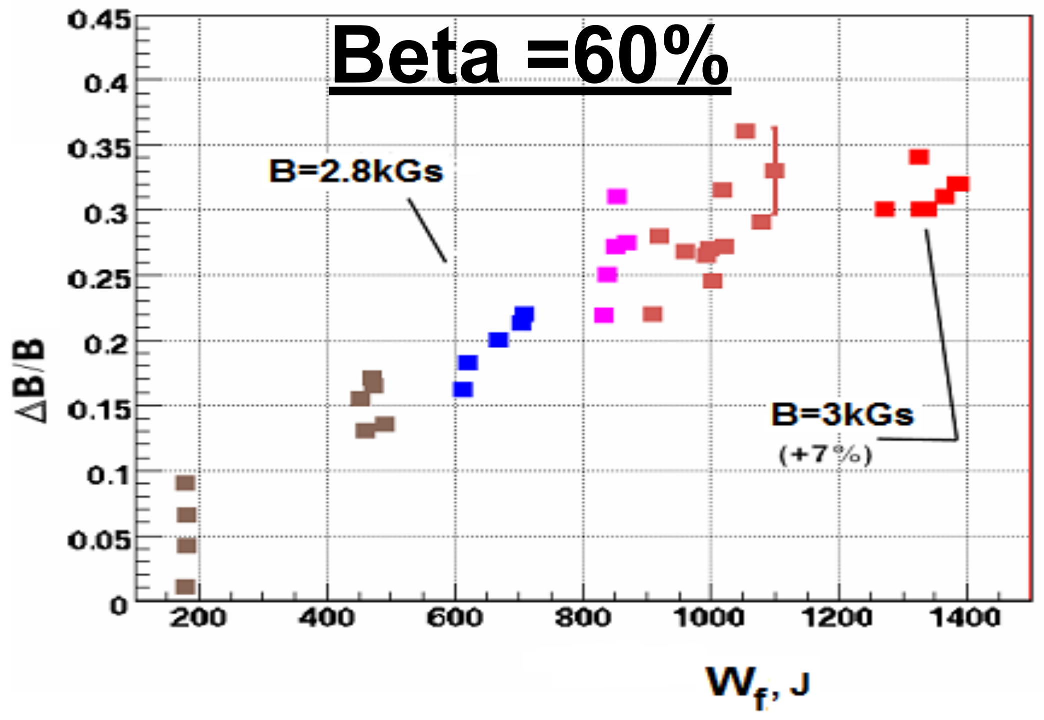
Three (*four!*) myths about axisymmetric mirror performance have been shattered by the GDT device in the past decade

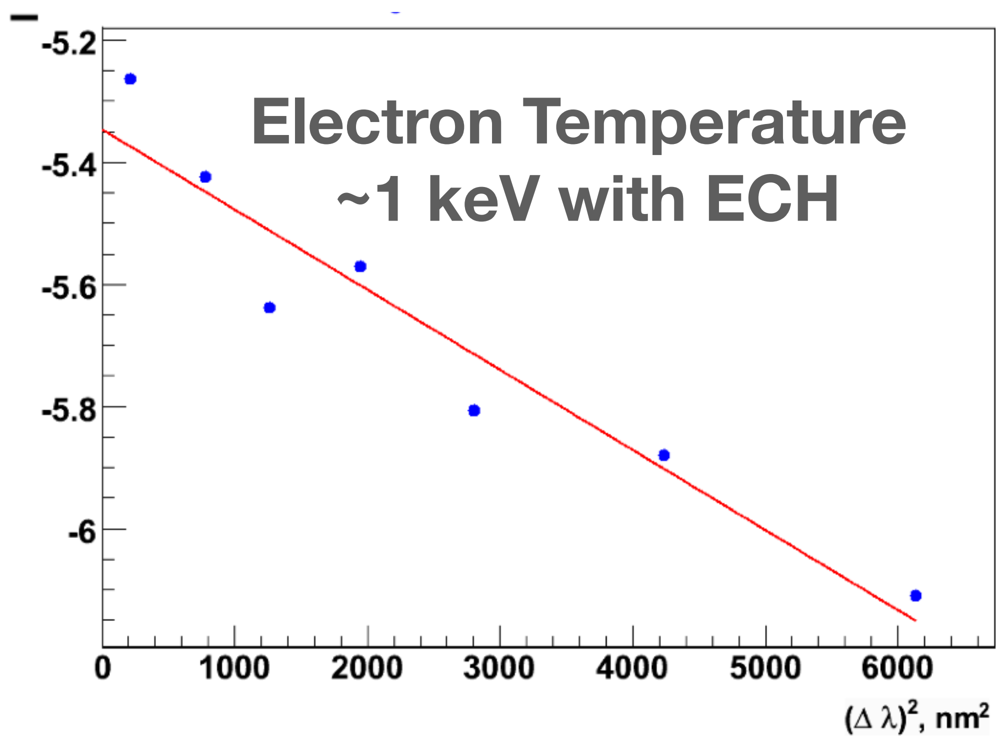


Ryutov

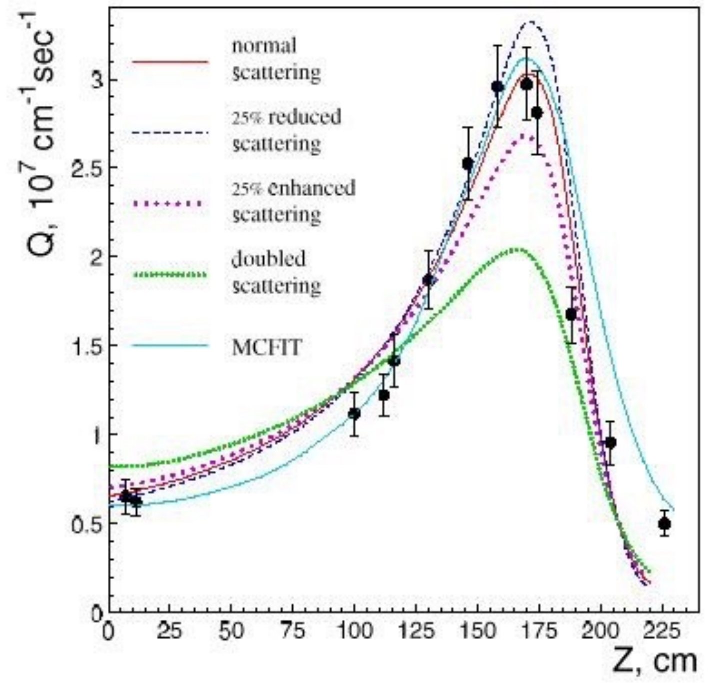
Mirnov





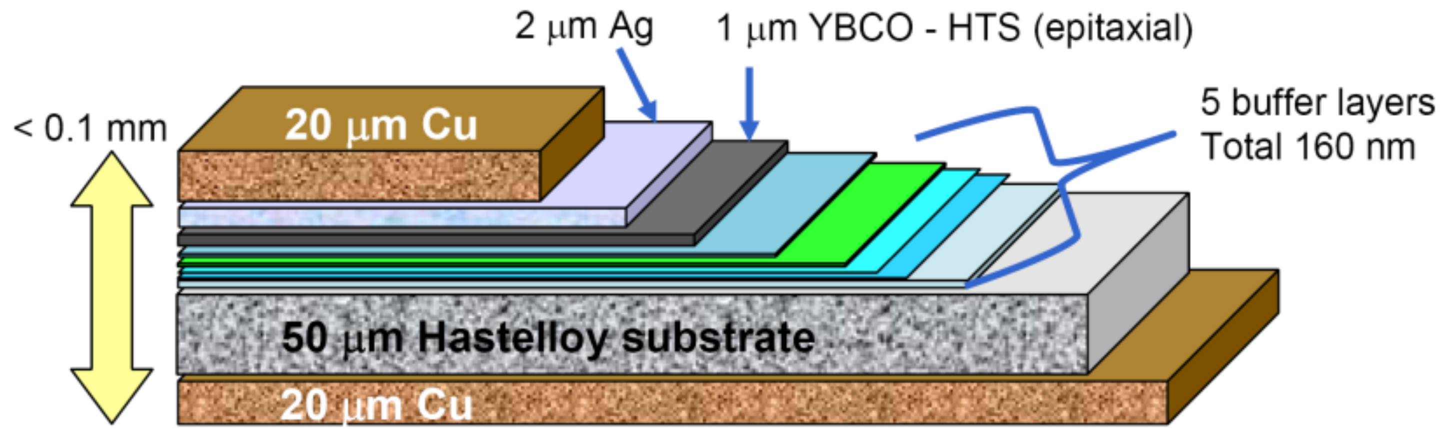


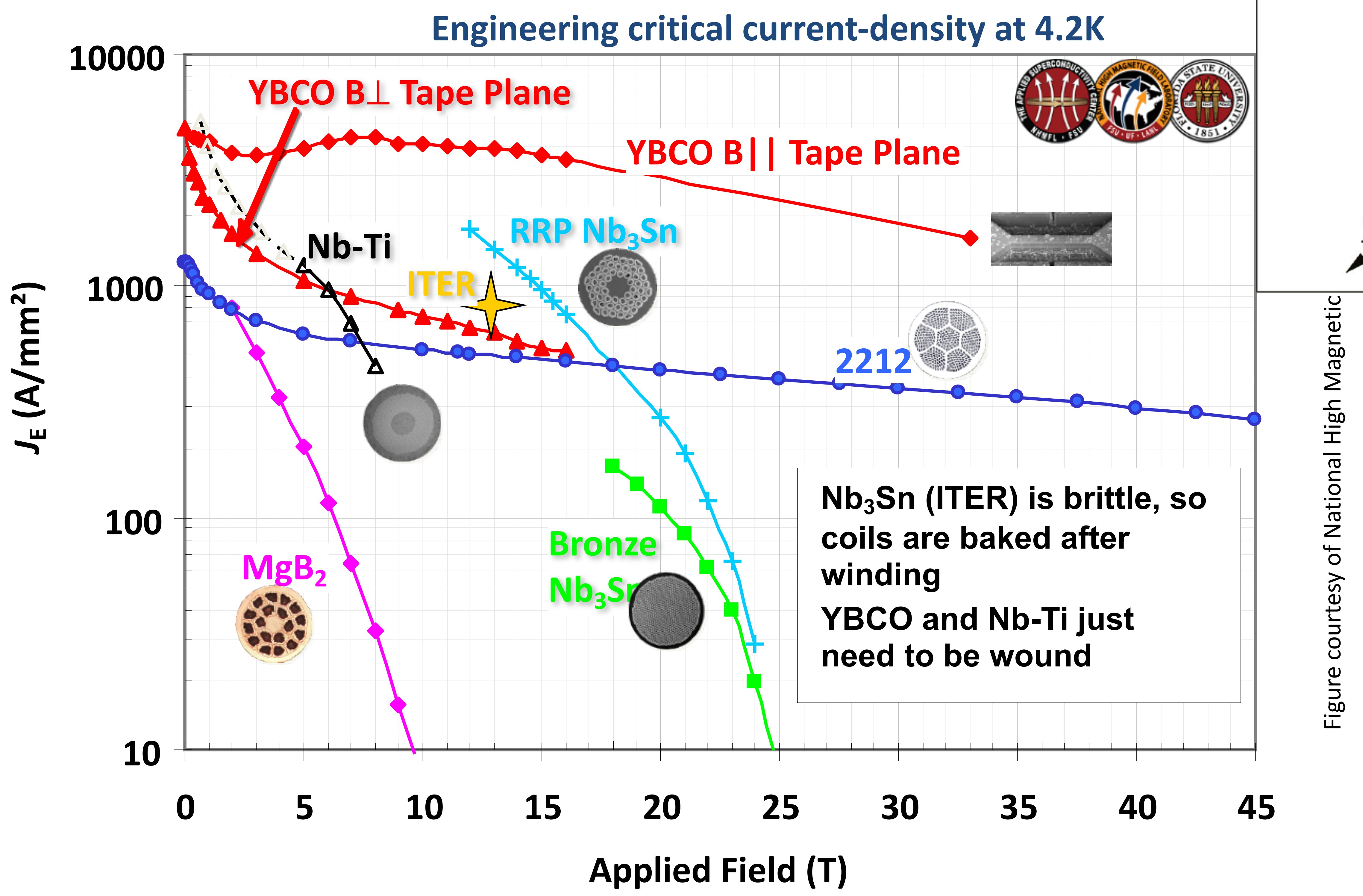
neutron yield profile

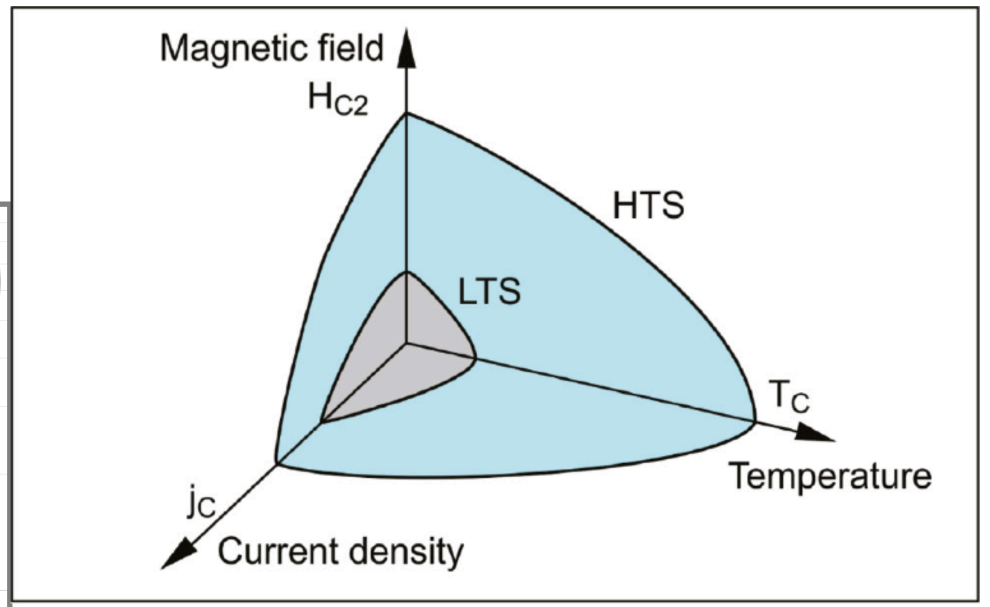


1. Axisymmetric mirrors can't overcome interchange: high pressure observe $(\beta \sim 0.4)$
2. Electrons in mirrors are always cold: high electron temperatures $T_e \sim 1$ keV generated with ECH and ambipolar confinement
3. Non-thermal plasmas are always unstable to micro instabilities: classical fast ion confinement and fusion products observed
4. *mirror reactors must be complicated: ATM reactor is possible!*

High Temperature Superconductors are a game-changing technology for fusion







New developments in superconductor technology mean a smaller, more maintainable fusion reactor than the ITER-like reactor that was previously envisioned.

ARC = 1/10 Iter using twice the field

0D Design of a Simple Mirror

$nT_i\tau = 33.5 \times 10^{20}$ m^{-3} · keV · sec
$Q = 1.33$

1.Choose B_M, R_M, magnet bore a_M — $B_M = 25$, $a_M =$ 15 cm

2. $B_0 = B_M/R_M$, $a = \sqrt{R_M}a_M \rightarrow V = \pi a^2 L$ — $R_M = 10$, $B_0 = 2.5$, $a =$ *0.47 m*, $L =$ *1 m*, $V =$ *1.4 m*$^{-3}$

3. Choose $\langle E_i \rangle$ — $\langle E_i \rangle =$ 120 keV, $kT_e = 0.9 \langle E_i \rangle$ for classical energy transfer

4. check $N_{gyro} = a/\rho_i$ — $N_{gyro} \approx 30$ (maybe not big enough to stabilize DCLC, need sloshing)

5. Choose β $\rightarrow n = \dfrac{\beta B_0^2}{\mu_0 \left(kT_e + \langle E_i \rangle\right)}$ — $T_e =$ 11 keV, $\beta = 0.5$, $n = 0.9 \times 10^{20}$ m^{-3}

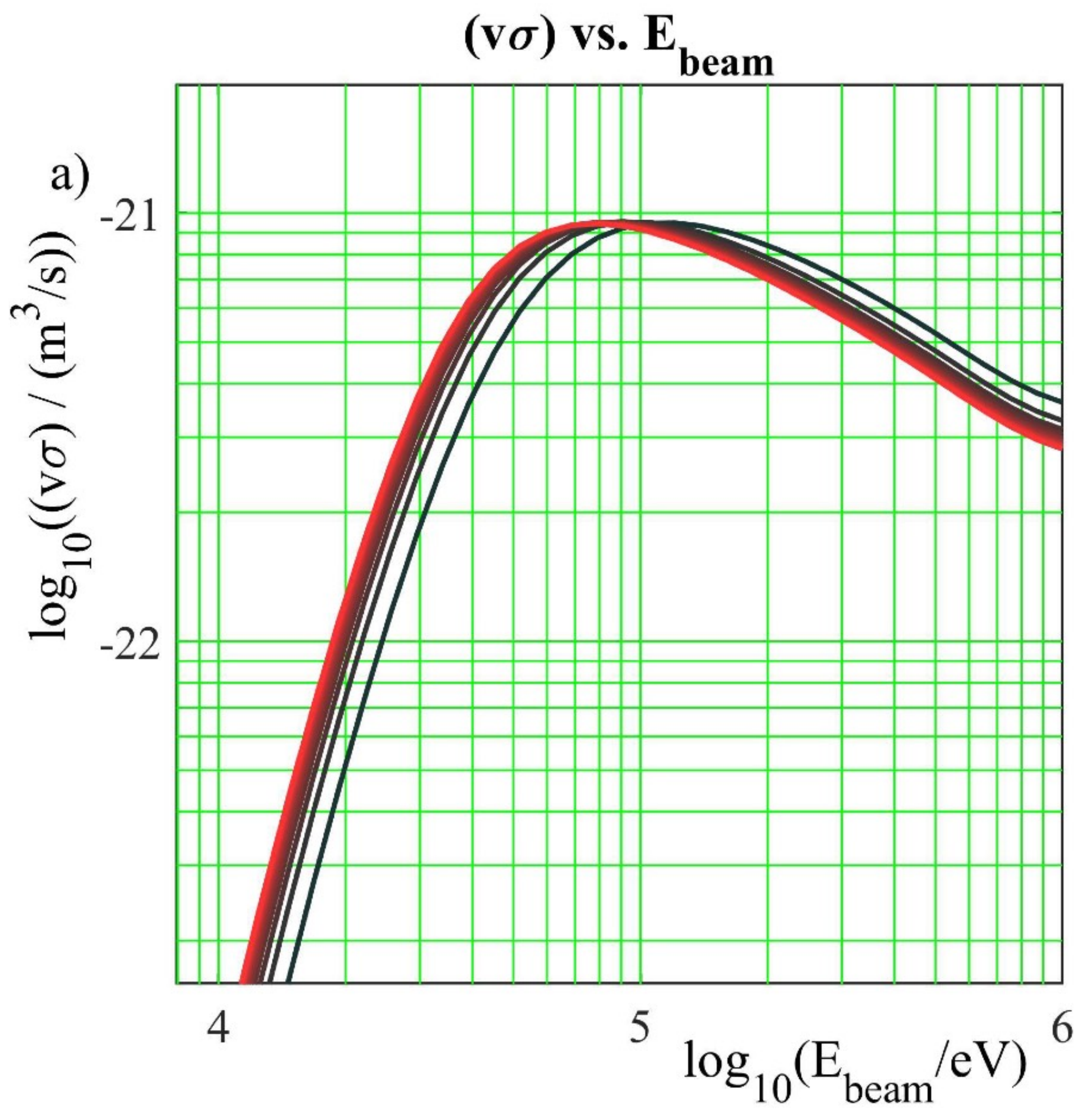
6. $\tau_P = 2.8 \times 10^{-4} \dfrac{\langle E_{b,keV} \rangle^{3/2}}{n_{20}} \log_{10} R_M$ sec — $\tau_P = 0.49$ sec $\tau_s = 0.005 \dfrac{T_{e,keV}^{3/2}\mu}{n_{20}Z^2}$ sec $= 0.583$ sec

7. Calculate $I_{inj} = \dfrac{enV}{\tau_P}$, — 40 amps

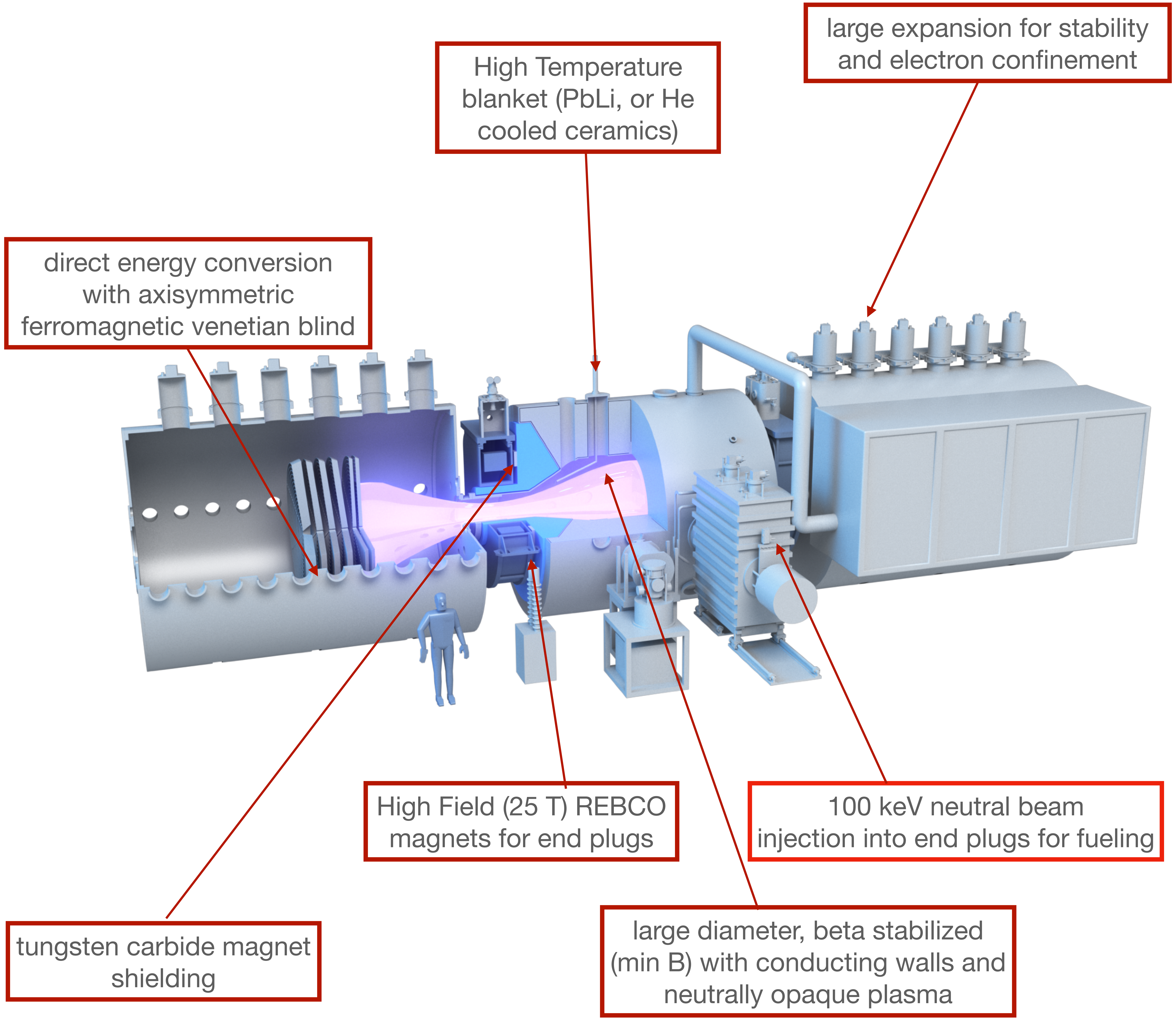
8. $P_{nbi} = E_b I_{inj}$, $P_{rf} = \left(\langle E_i \rangle - E_b\right) I_{inj}$, — E_b=120 keV, P_{nbi} = 4.8 MW, P_{rf} = 0

9. $P_{ech} = (2 + A)\dfrac{kT_e}{e}\left(I_{inj} + I_{cool}\right) - \left(P_{nbi} + P_{rf}\right)\dfrac{\tau_P}{\tau_s}$ — A= 5, P_{ech} = 0 MW

10. Compute neutron yield: — 2.3 x 0[18] n/s (DT) , $P_{DT} = 6.45$ MW, neutron



Aspirational WHAM++



WHAM ++

B_M=25 T, B_0=2.5 (5) T, a = 0.5 m
P=2-5 MW (100 keV NBI) CW and DT
Q ~ 3 (6-15 MW of fusion power)
R_M=15 at β=0.5

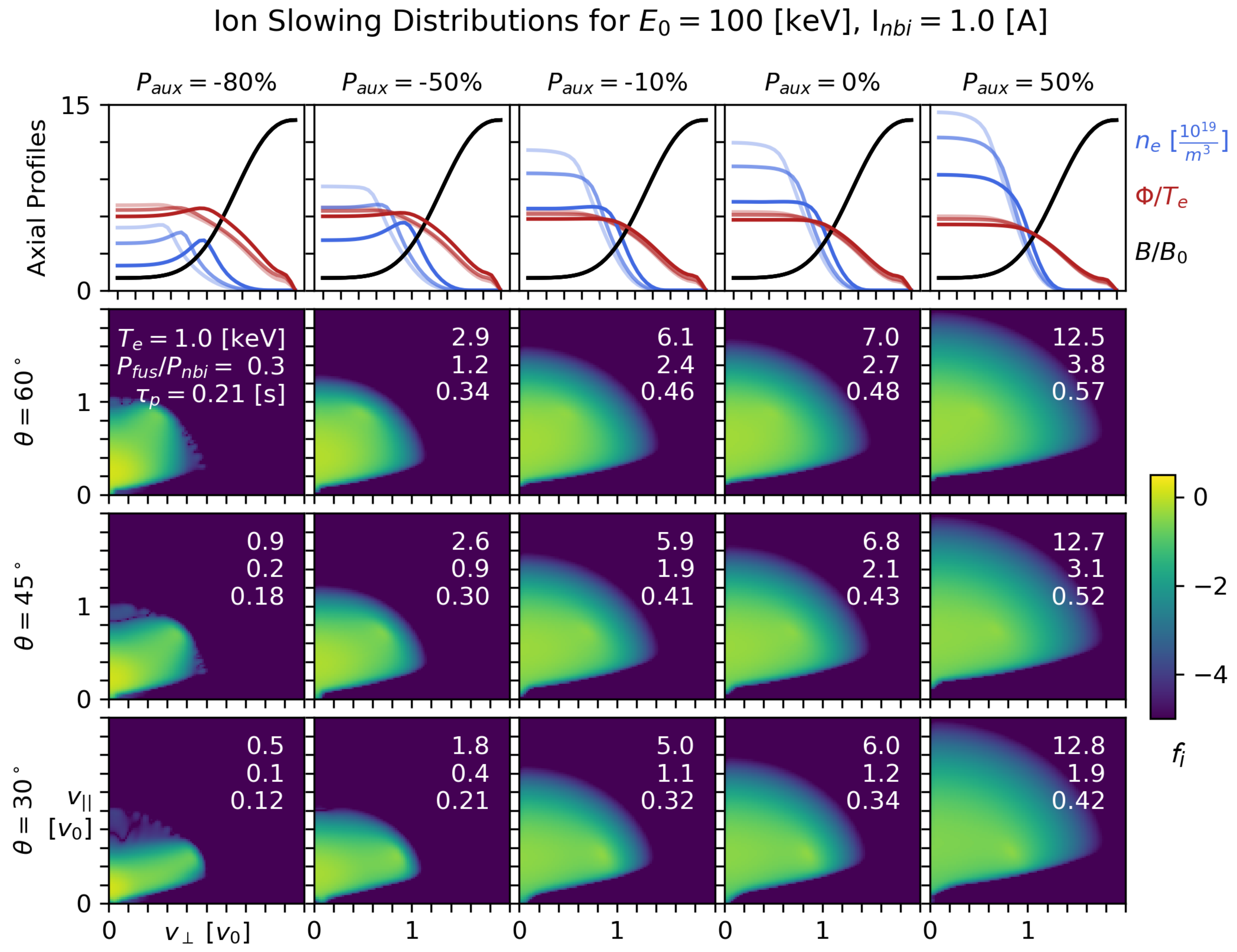
WHAM+
-full power performance verification of end plug
-test direct energy conversion boost to Q~6-10

WHAM++
steady-state operation with dt
High temperature blanket testing (PbLi ?)

Cost (driven by magnets)
ca. $50M of Rebco tape

High β, $p_\perp \neq p_\parallel$ solution to Grad-Shafranov equilibrium model shows enhancement allows shape optimization for confinement and stability

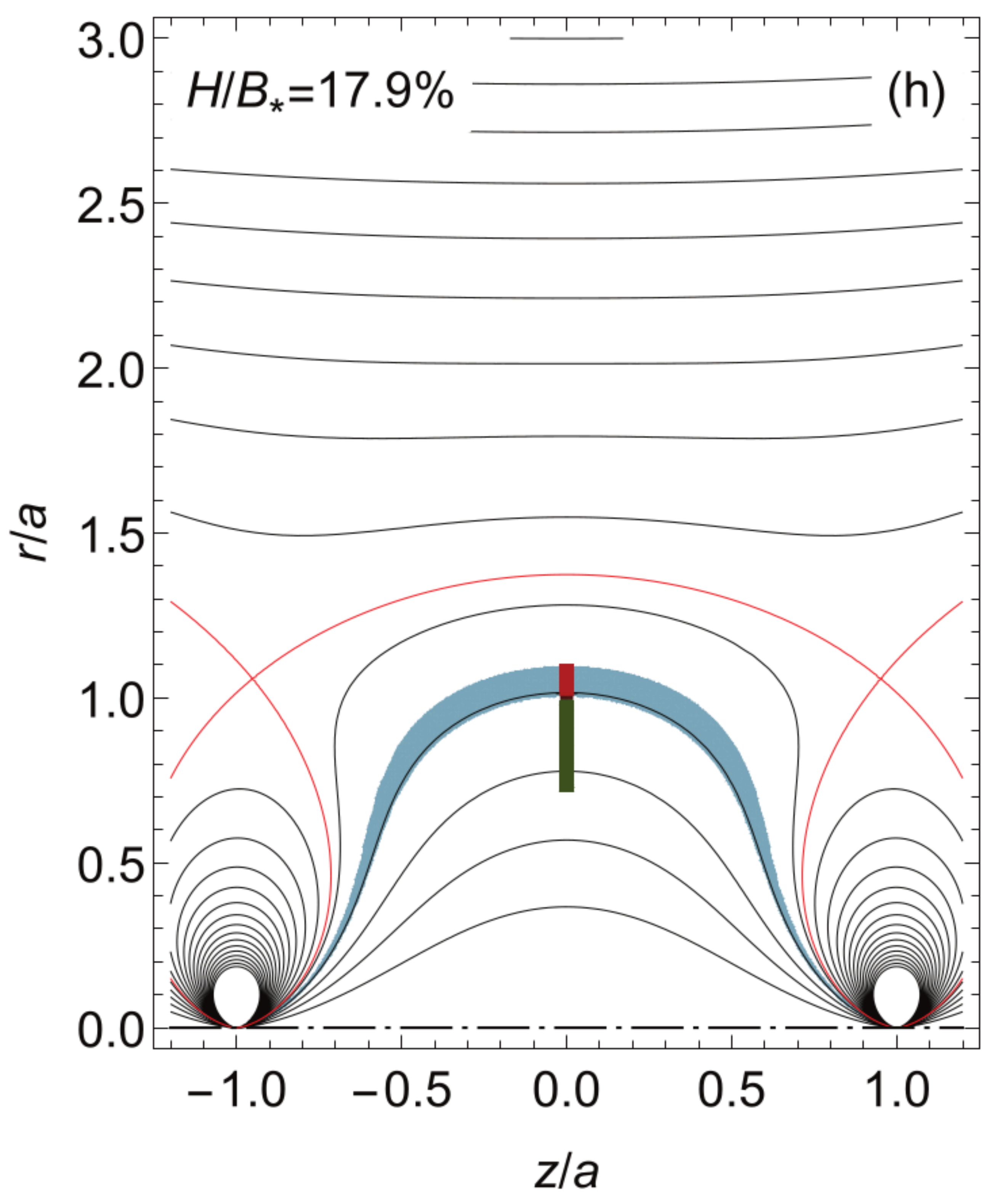
Bounce-averaged Fokker Plank solution show tradeoffs with beam injection angle and role of extra electron cooling (or heating)



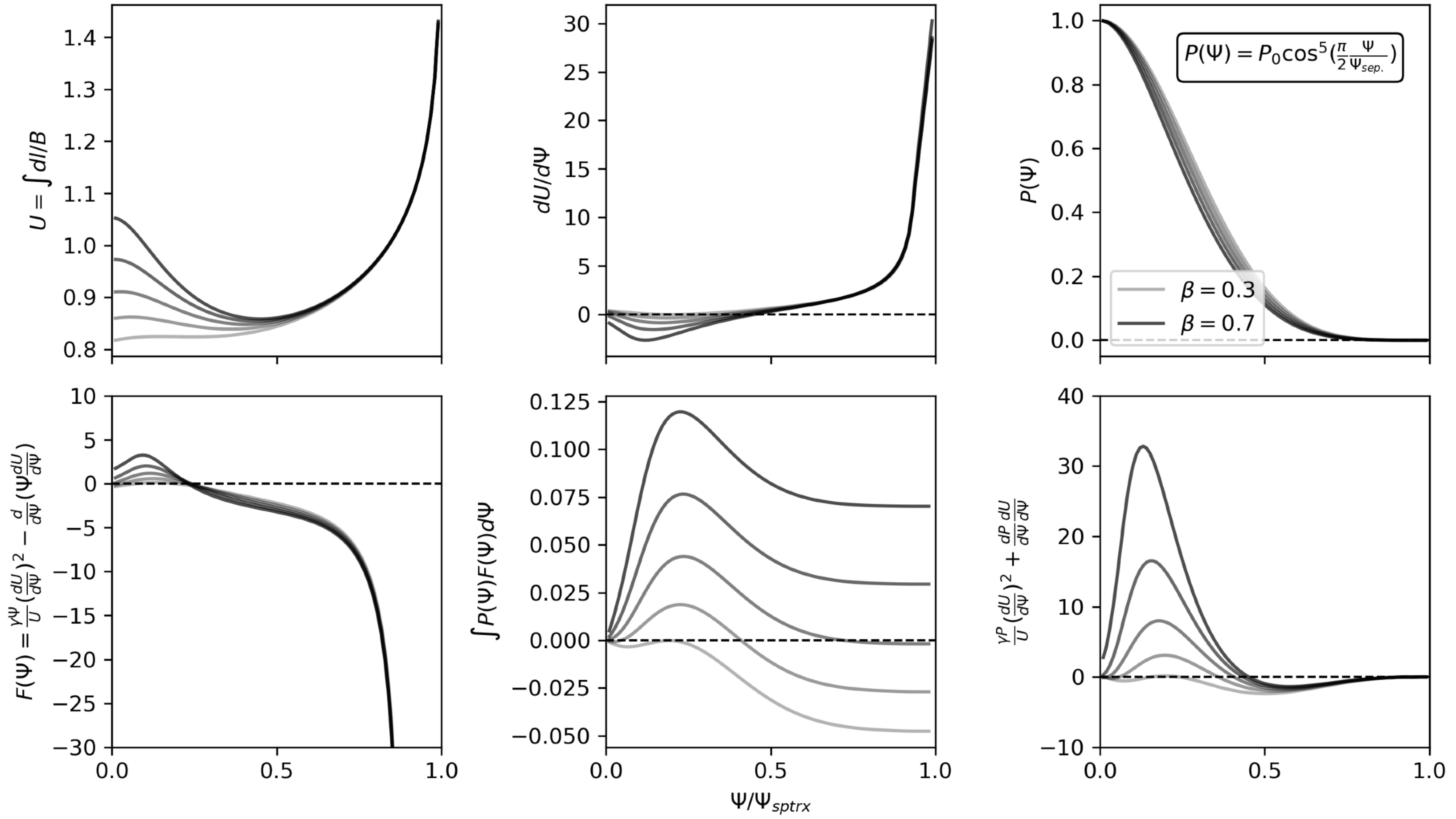
Diverters and non-paraxial (short-fat) effects may help solve MHD stability

I.A. Kotelnikov *et al* 2020 *Nucl. Fusion* **60** 016008

$$\delta W = \textbf{const.} \int d\Psi (r_0 \xi_r B_0)^2 \left[U' p' + \gamma \frac{p}{U} U'^2 \right]$$



- High-beta configuration may be stable (δW>0) to rigid shift m=1 interchange mode.
- Remains marginally unstable to higher order ballooning modes (to be FLR stabilized)



Axisymmetric Tandem uses high pressure end plugs to confine thermal central cell plasma

Four species to consider:

1. High density plug
2. High Te plug electrons
3. Central cell electrons
4. Central cell thermal ions

Confined by:

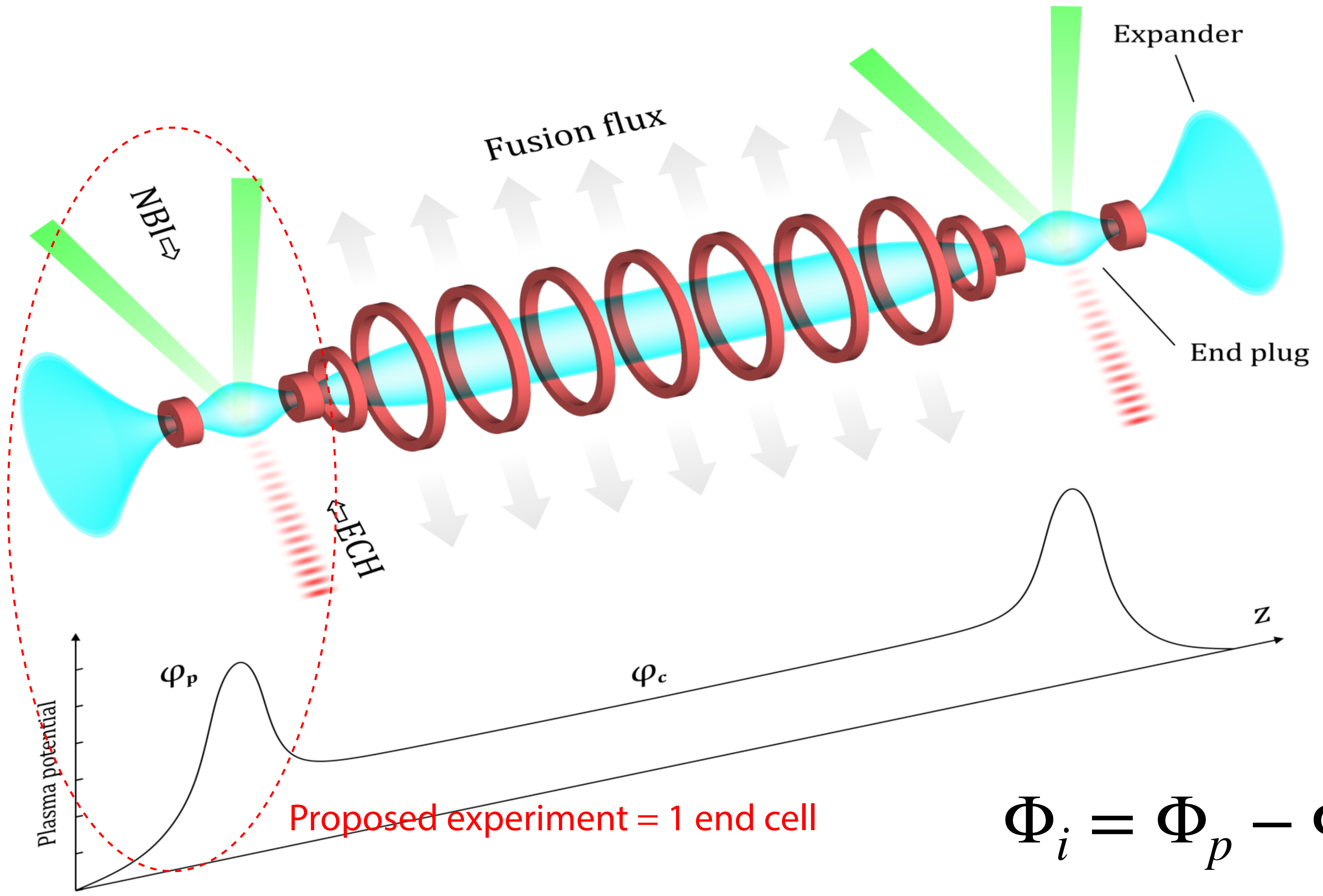
high energy ions

ambipolar potential associated with fast plug ions

Confined by potential of expander

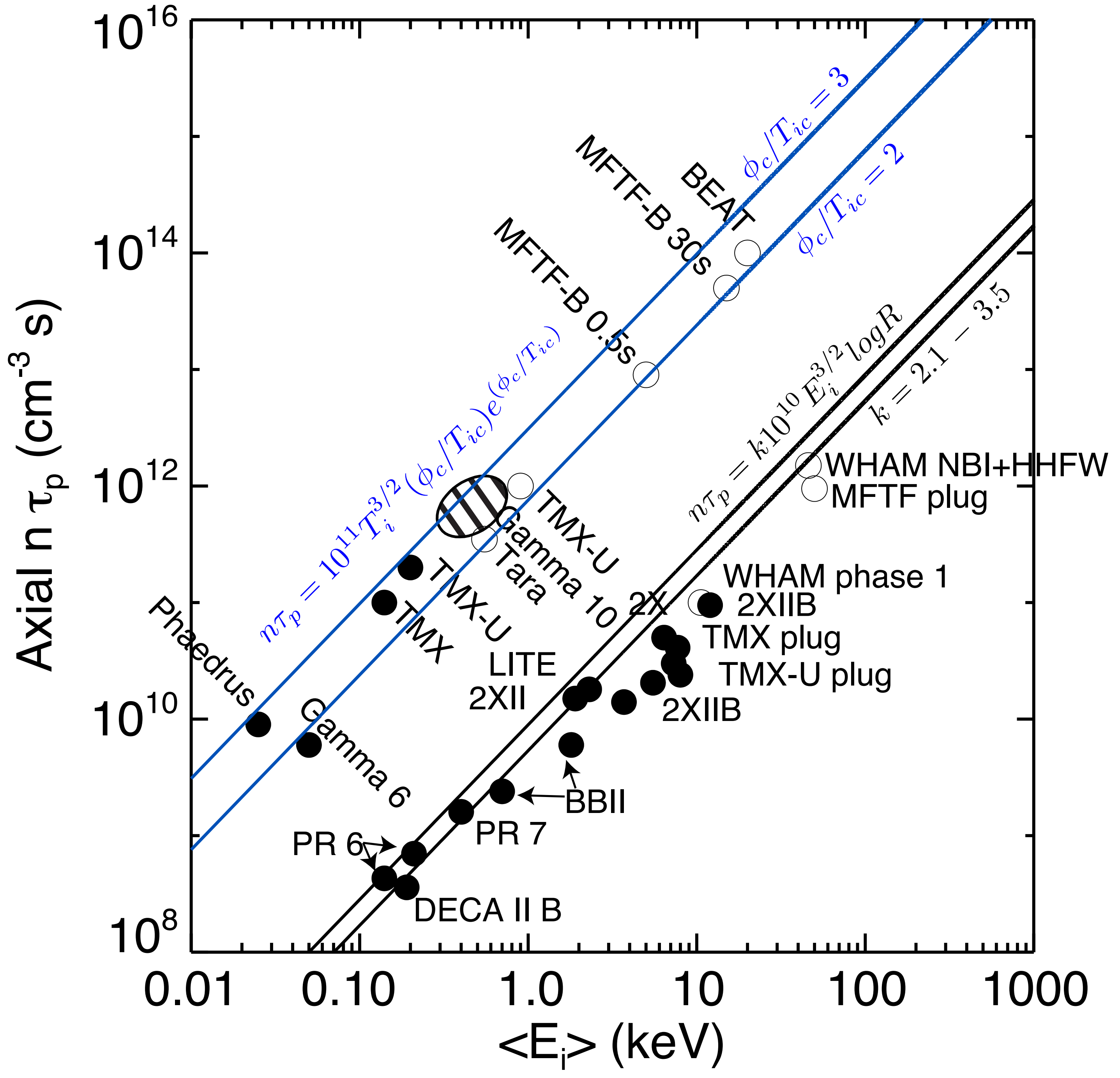
Electrostatically confined by end plug potential $\tau_i \sim \tau_{ii} \ln R_M \; \Phi_i/T_{ic} \; e^{\Phi_i/T_{ic}}$

Pastukhov factor



$$\Phi_i = \Phi_p - \Phi_c = T_{ep} \, ln(n_p/n_c)$$

T. K. Fowler, R. W. Moir, and T. C. Simonen, *A New Simpler Way to Obtain High Fusion Power Gain in Tandem Mirrors*, Nucl Fusion **57**, 056014 (2017).



What’s New (Summary)

1986: US cuts mirror research budget by ~95%

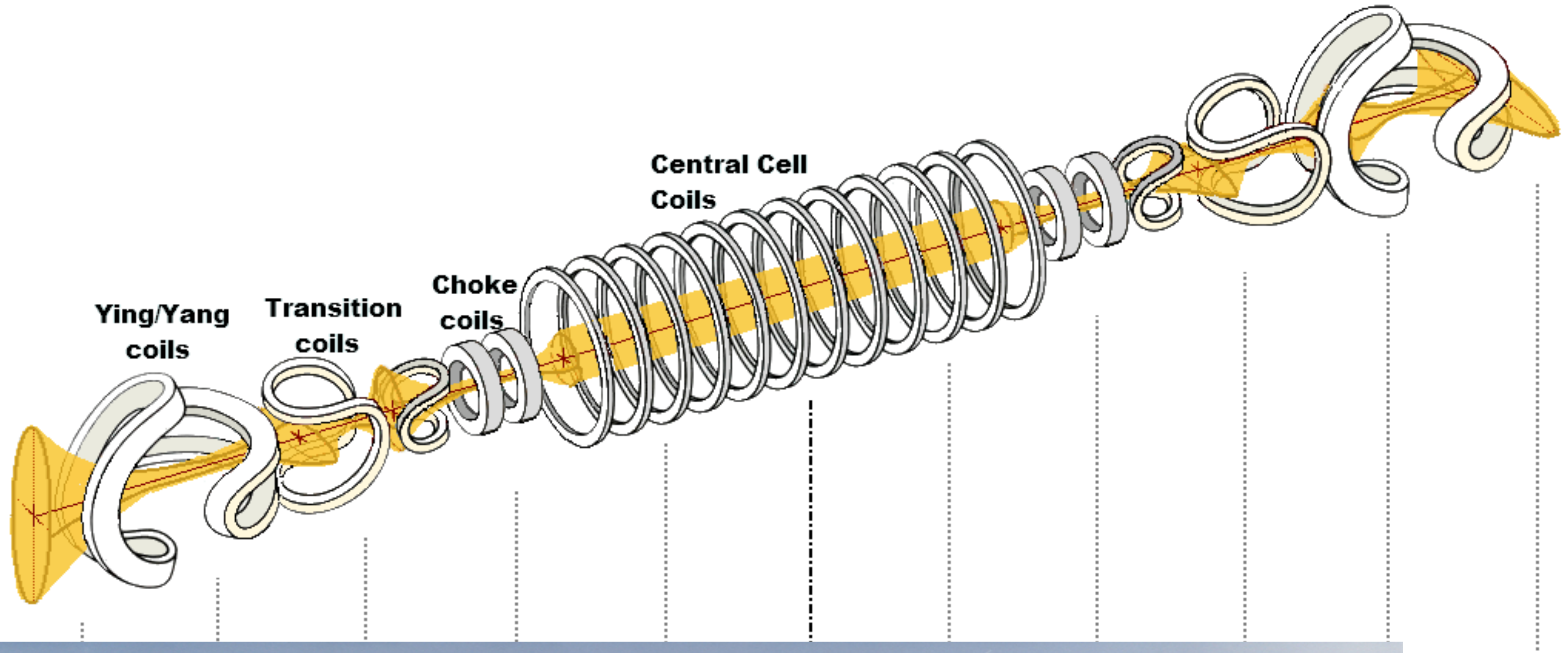
Perceived physics flaws

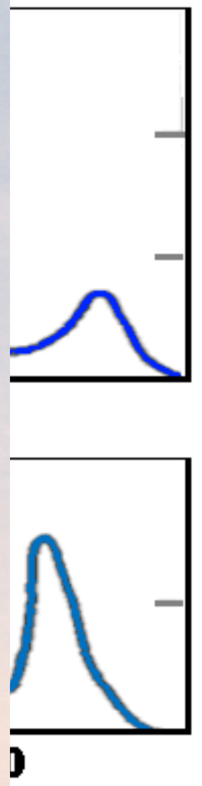
- required 3D coils
- mirror ratio limited by superconductors
- Complicated thermal barrier
- Low Te, poor electron confinement
- micro instabilities
- major technology gaps
  - superconducting magnets limited to < 12 T
  - >100 ghz cw gyrotrons nonexistant
  - MeV beams not available

Today:

Remarkable physics achievements

- Axisymmetric high β MHD stability
- High field enables simpler path to high Q (without thermal barrier)
- Axial electron thermal confinement from electric fields: Te~1 keV
- Major micro instabilities stabilized
- high mirror ratios now possible

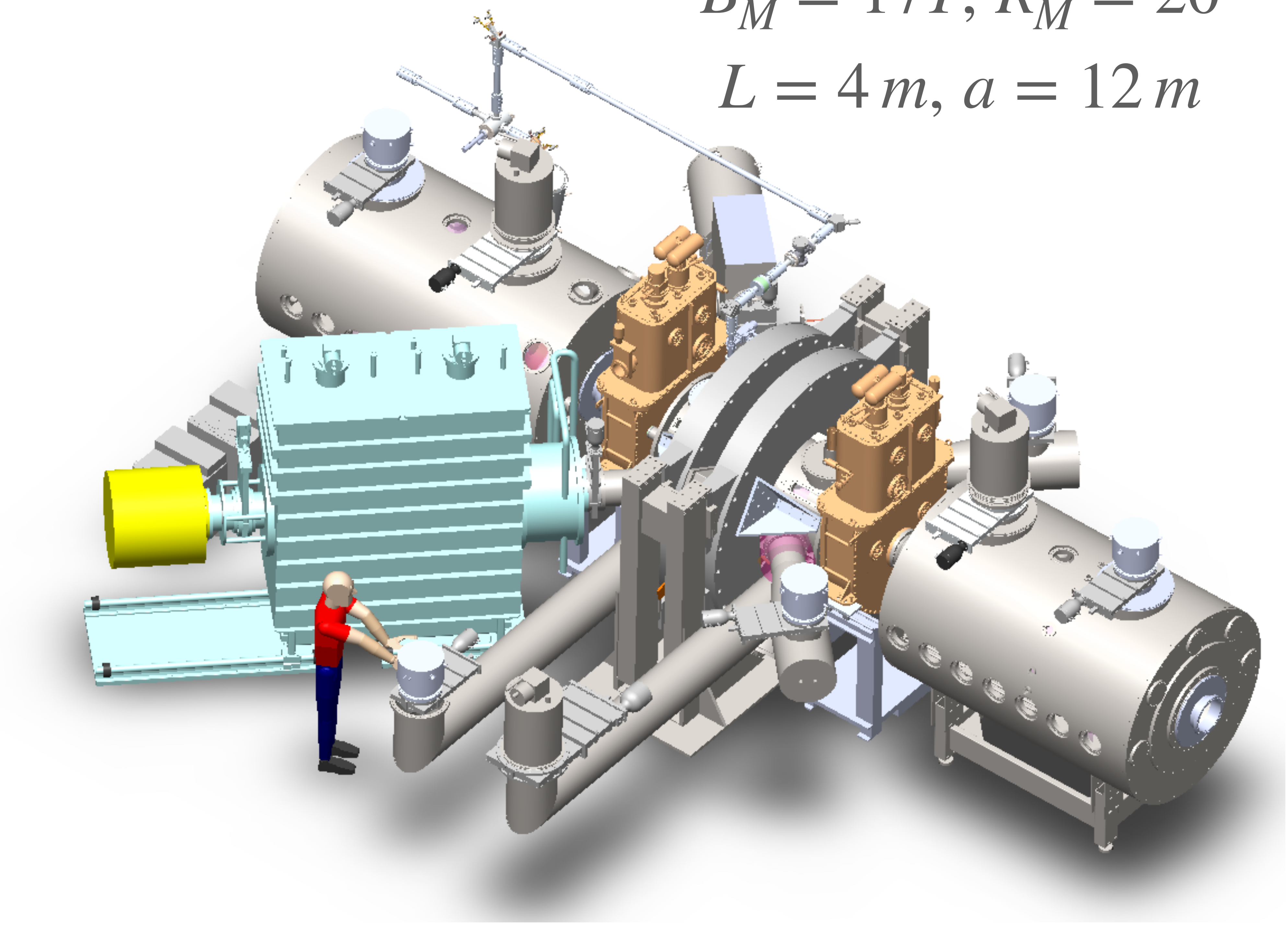




WHAM is a ARPA-E funded and aims to prototype the ATM end plug

$B_M = 17T,\ R_M = 20$

$L = 4\,m,\ a = 12\,m$



Physics Missions:

1. ***Confine MHD stable, high Te plasma in axisymmetric mirror***
   - demonstrate vortex stabilization combined with electron heating and expander confinement
   - create high plasma pressure allowed by strong magnetic field
2. ***Demonstrate novel in-situ ion acceleration***
   - combine radio-frequency heating with neutral beam fueling
   - show confinement benefit of high energy ions

Technology Missions: (intertwined with physics goals)

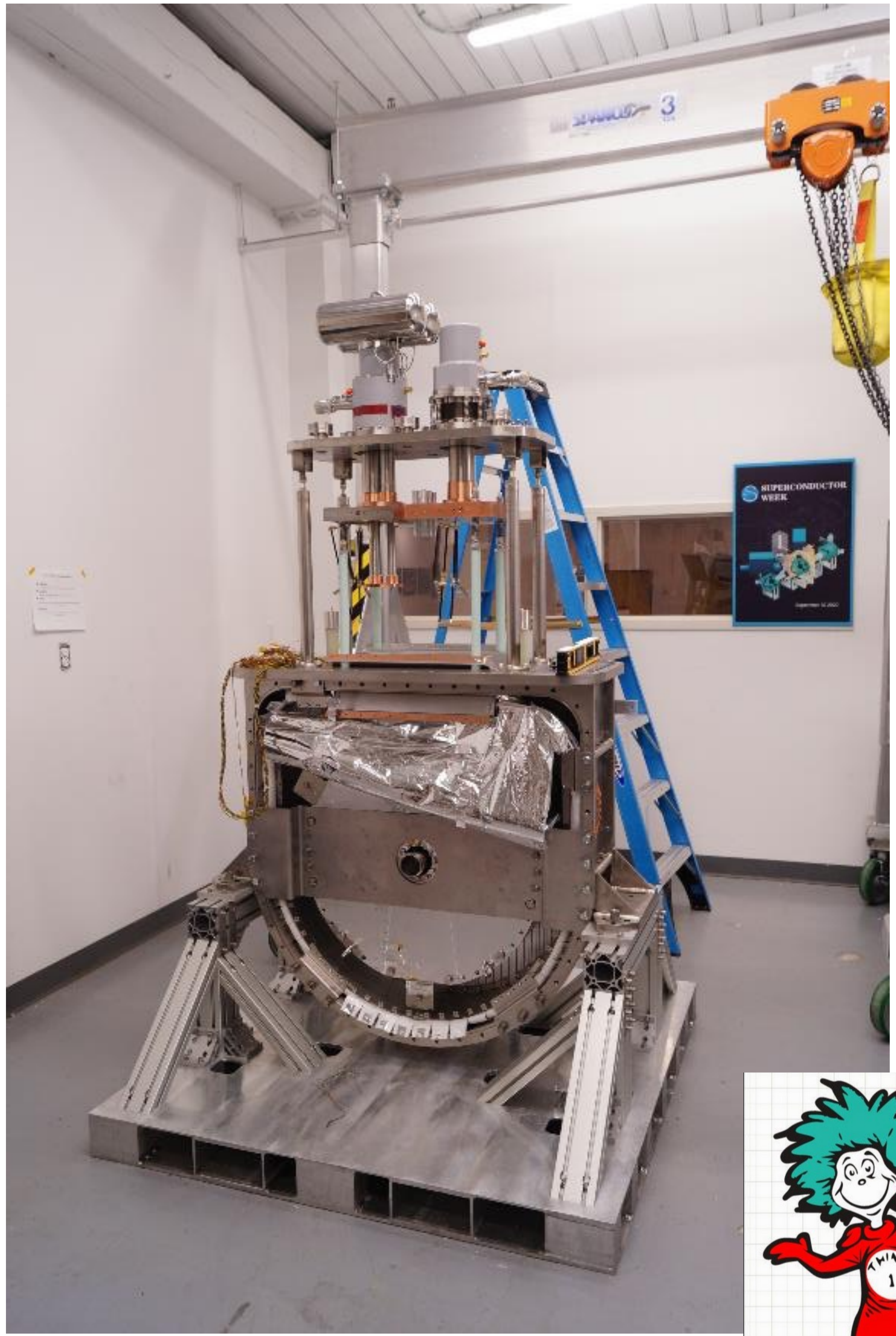
1. ***Build REBCO HTS mirror reactor magnets***
   - build and operate 17 T, 5.5 cm bore HTS coils
   - design 25 T, 50 cm integrated end plug for WHAM++, Hammir
2. ***Demonstrate advanced particle handling techniques***
   - Novel non-evaporable tantalum getters
   - test advanced plasma facing components

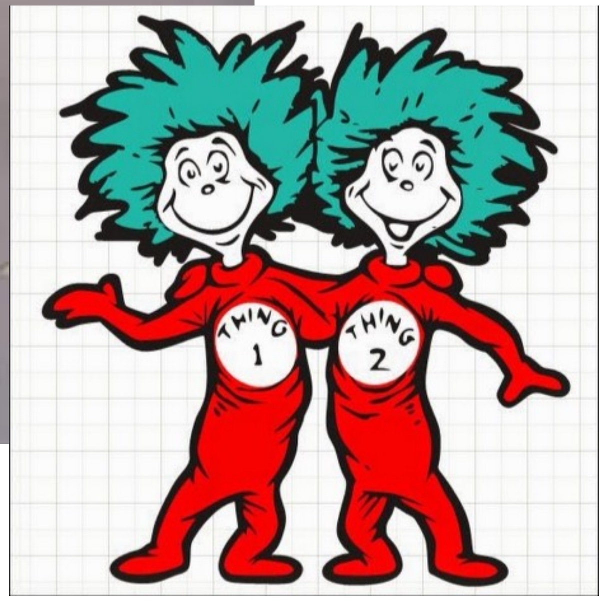
Additional ARPA-E directives:

1. ***Refine reactor concept***
   - low cost/length central cell solution
   - neutronics analysis for shielding
2. ***Develop commercialization plan***

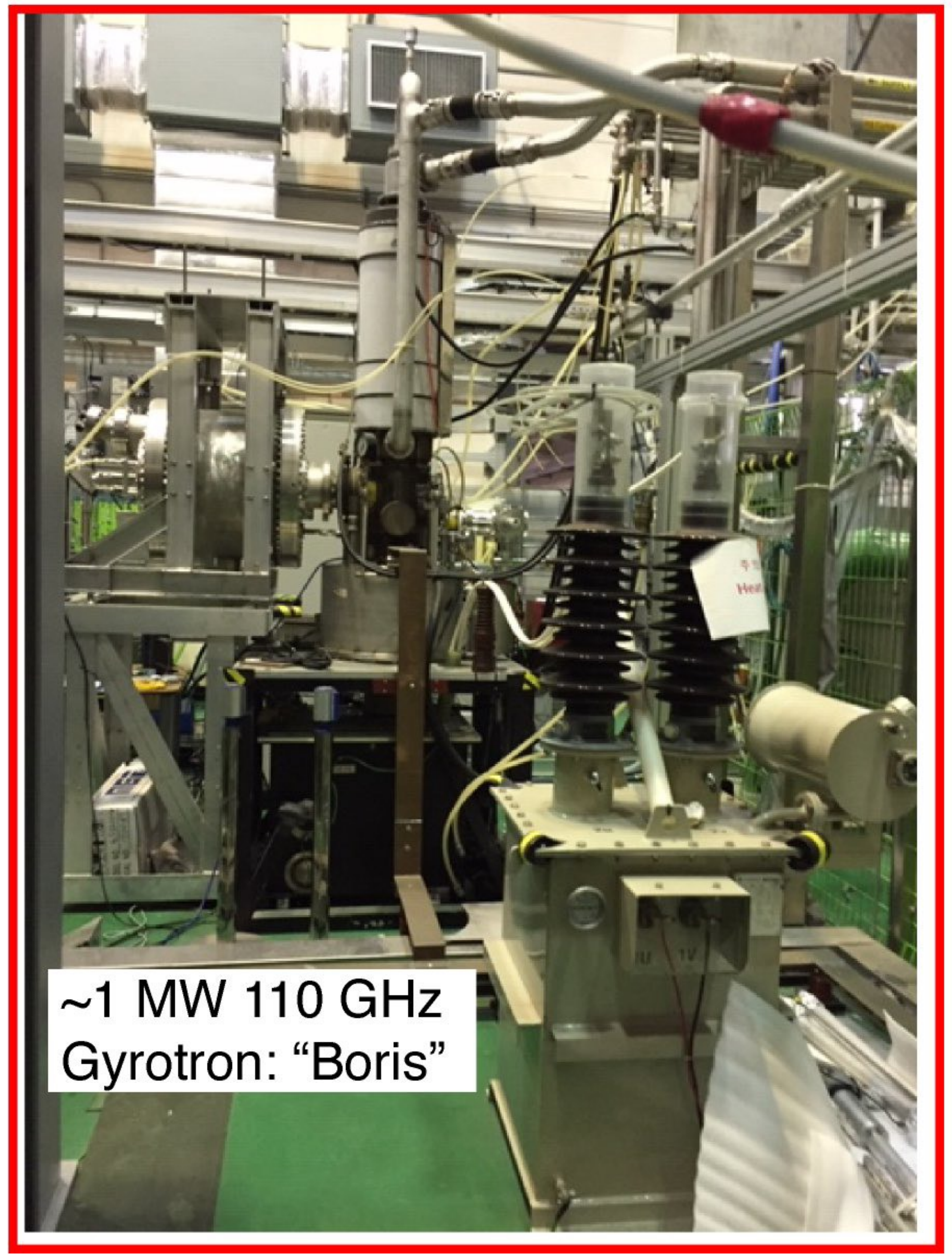
WHAM magnet specifications (Thing 1 is testing next week)

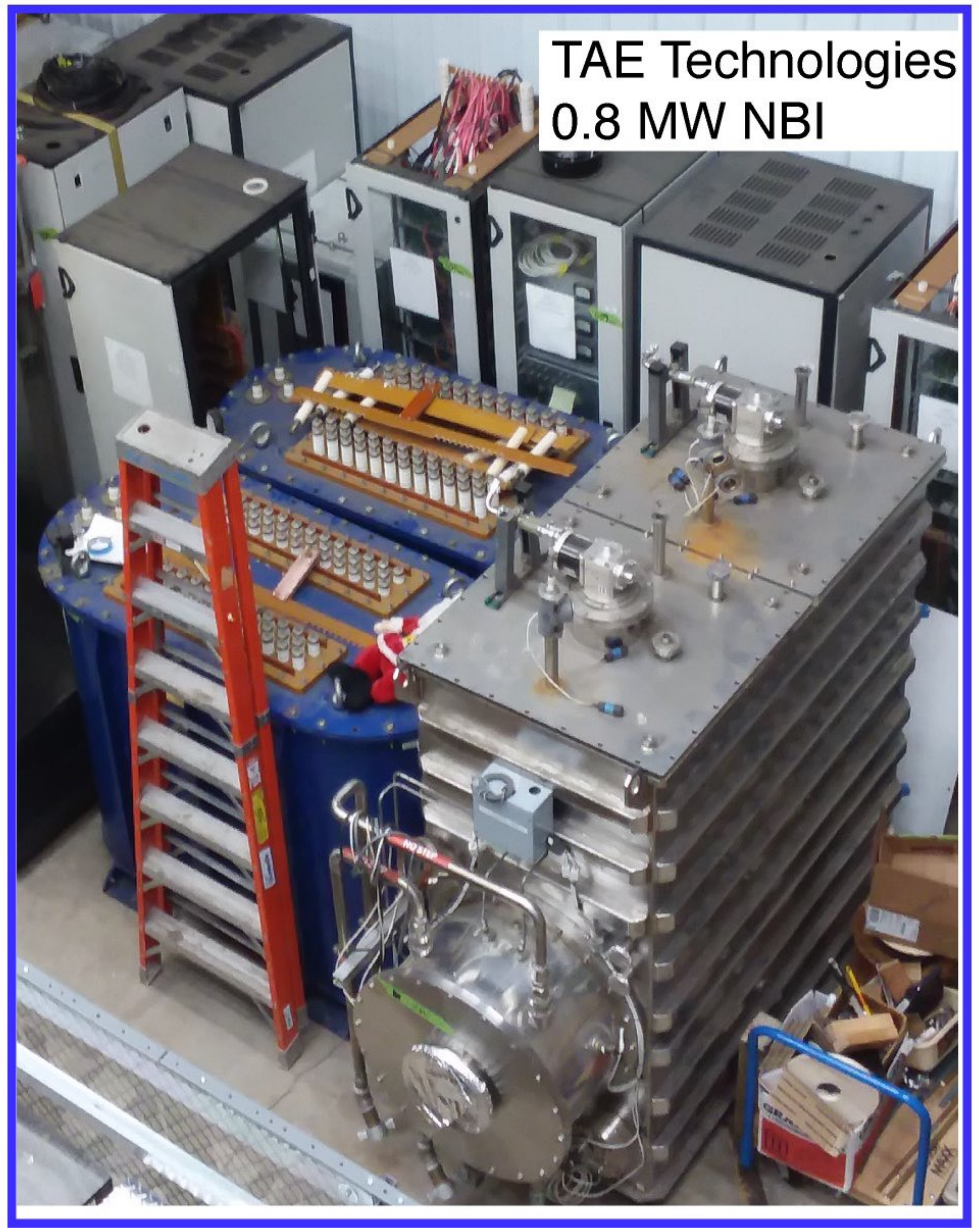
Stored energy	3.2	MJ
Magnetic field at center	17	T
Maximum magnetic field	20	T
Operating current	2000	A
Inner diameter	0.05	m
Outer diameter, WP	0.7	m
Thickness	0.15	m
Height	2.1	m
Winding pack mass	500	kg
Magnet mass	1500	kg
Operating temperature	20	K

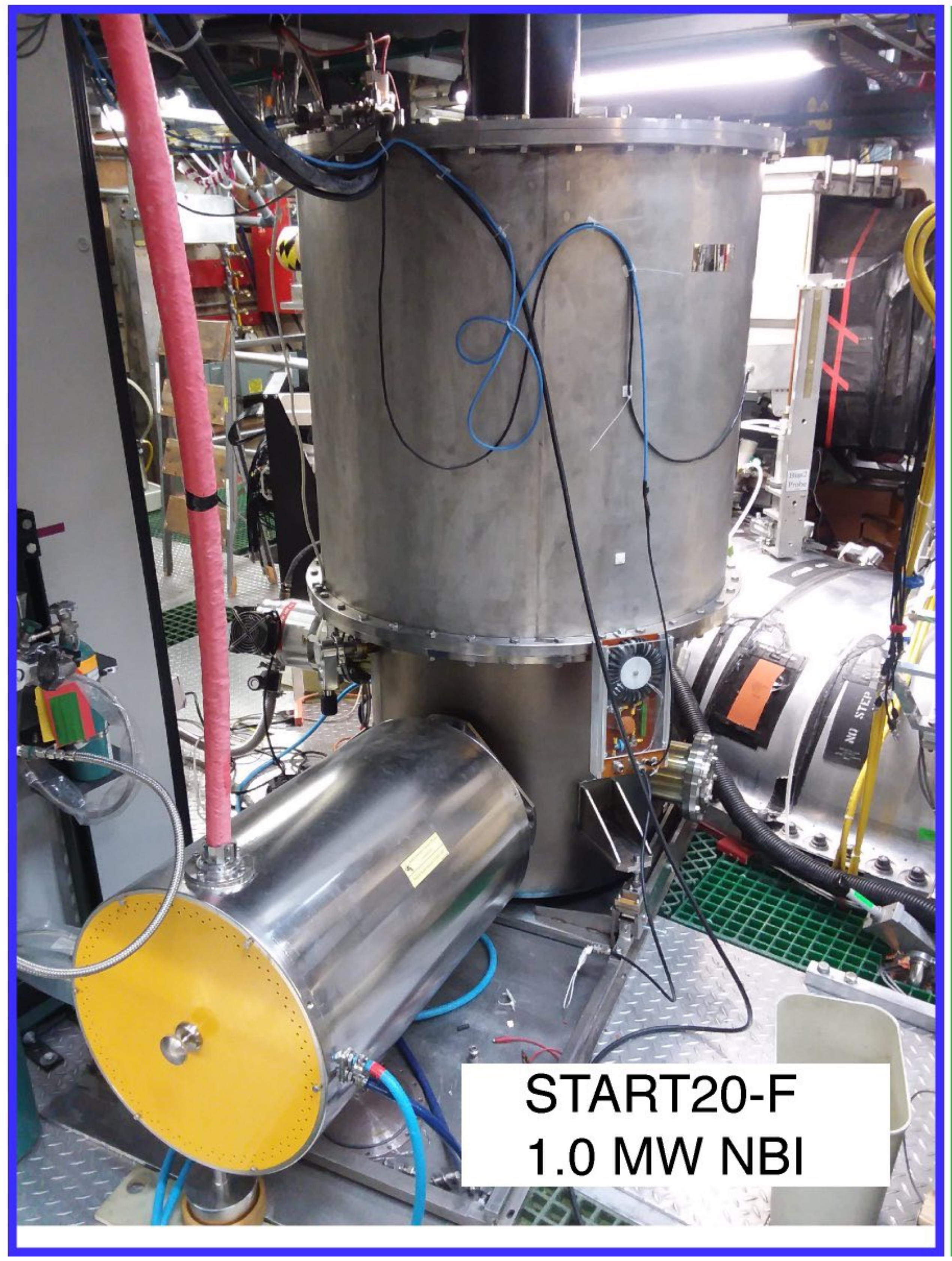




WHAM will use existing heating systems to create high Te, <Ei> plasmas





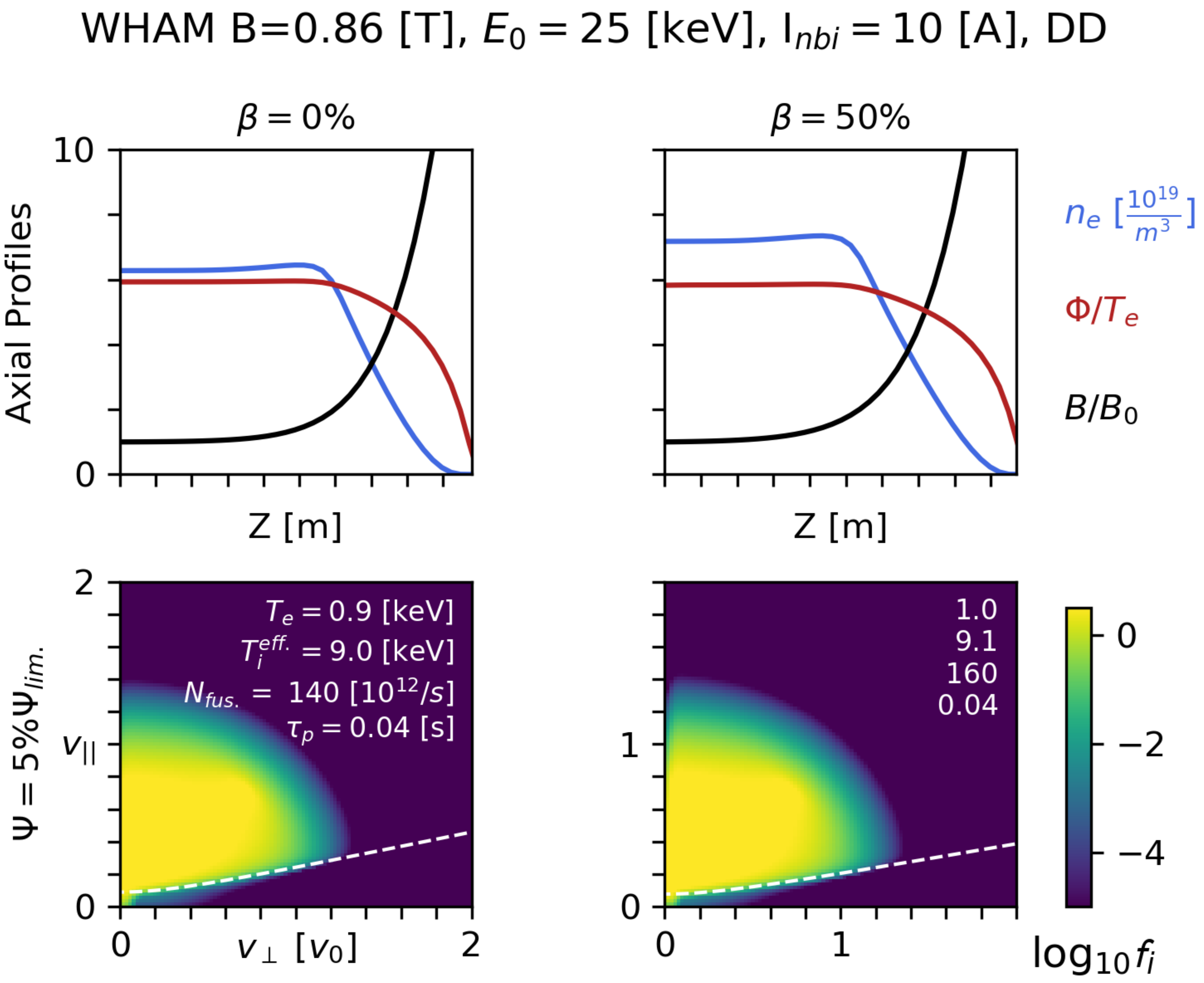


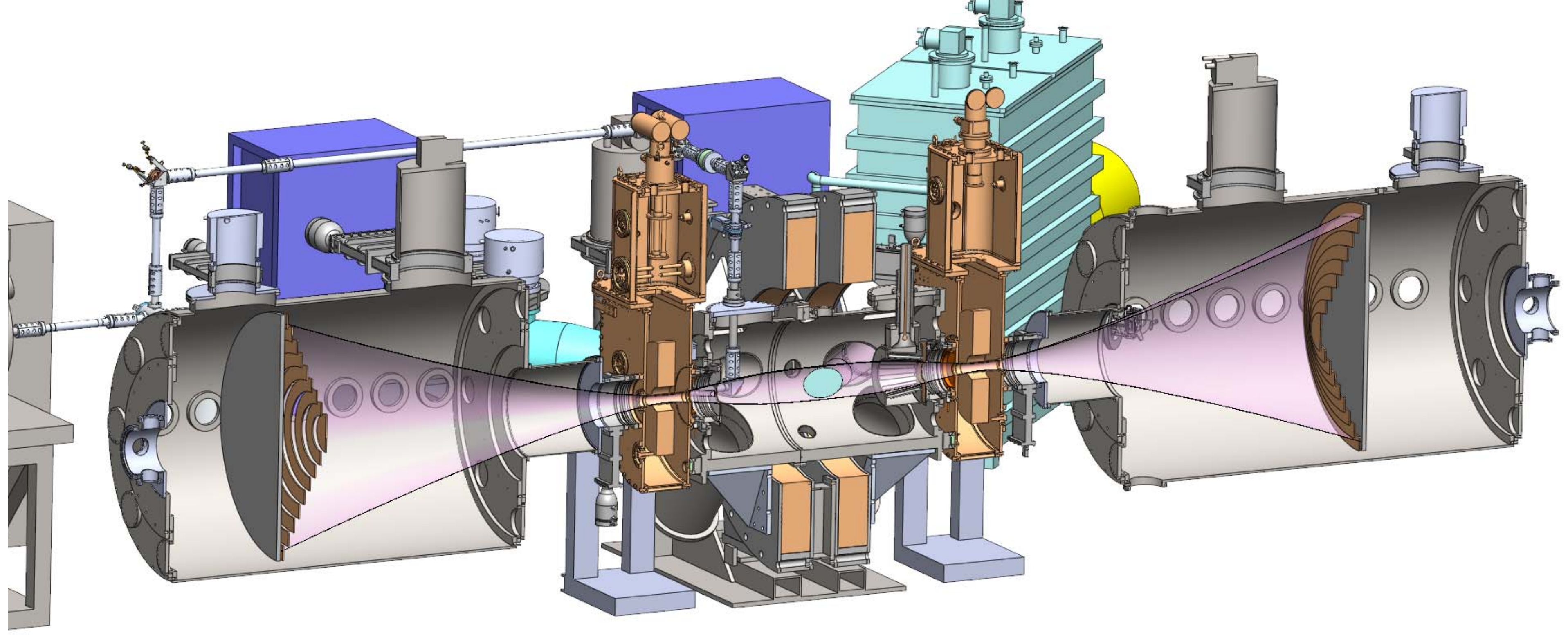
High $\beta, p_\perp \neq p_\parallel$ solution to Grad-Shafranov Equation shows enhancement of $R_M : 20 \rightarrow 28$ (even more maybe possible)

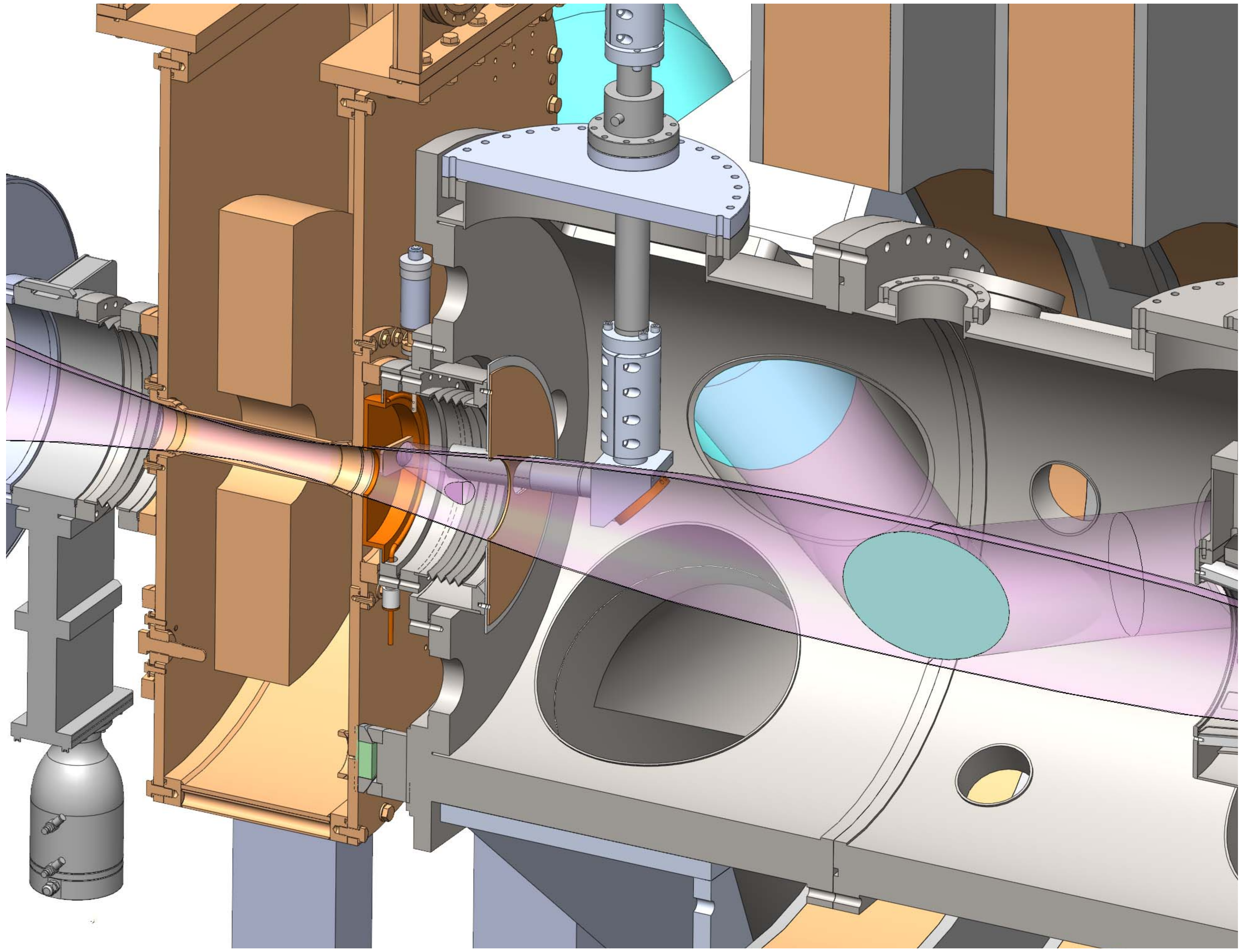
$$P_{NBI} = 250kW$$

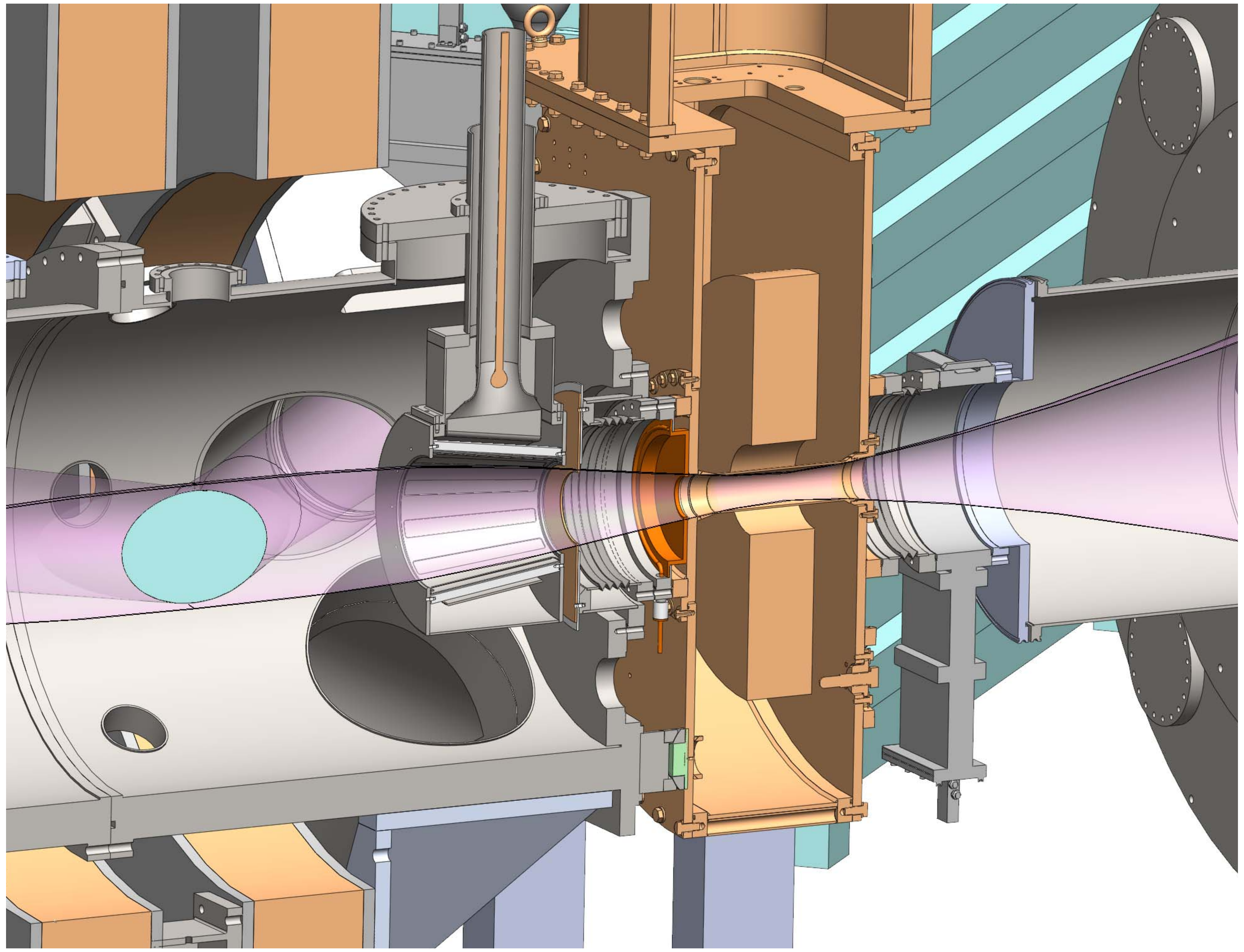
Mild sloshing ions help fill ambipolar hole (solve DCLC)

T_e=1 keV, T_i=10 keV, n=6x10^{19} m^{-3}, τ_P=40 ms, S_{dd}=10^{14} n/s

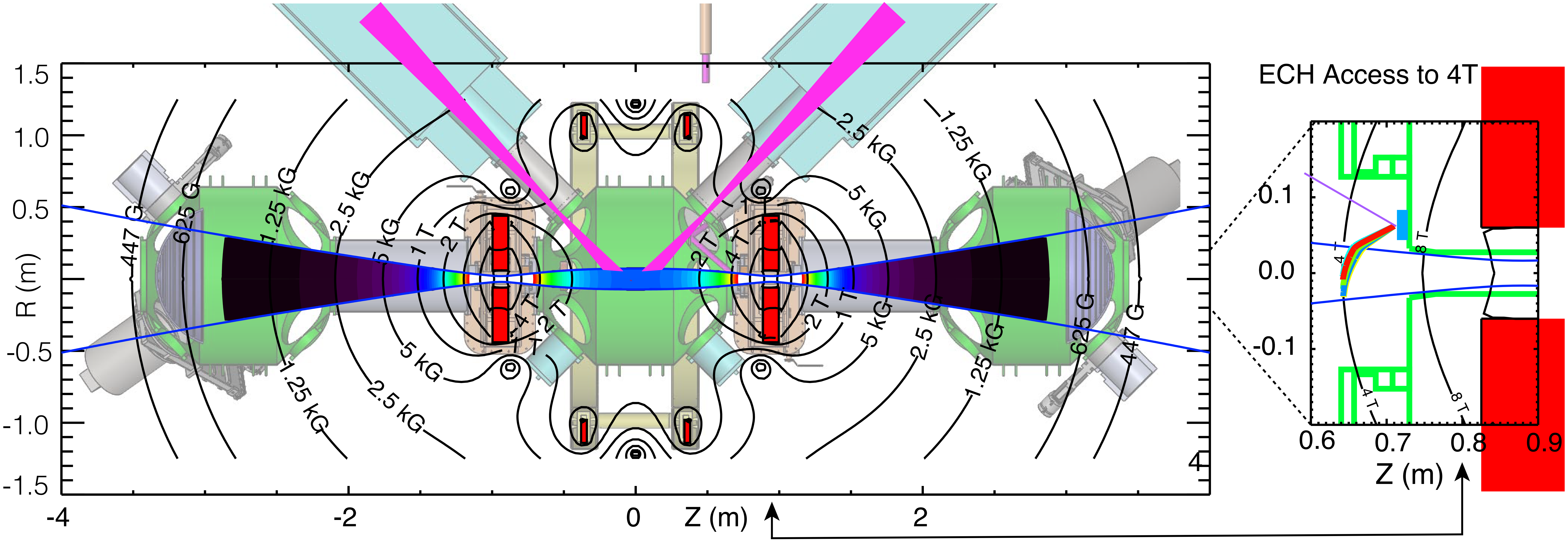






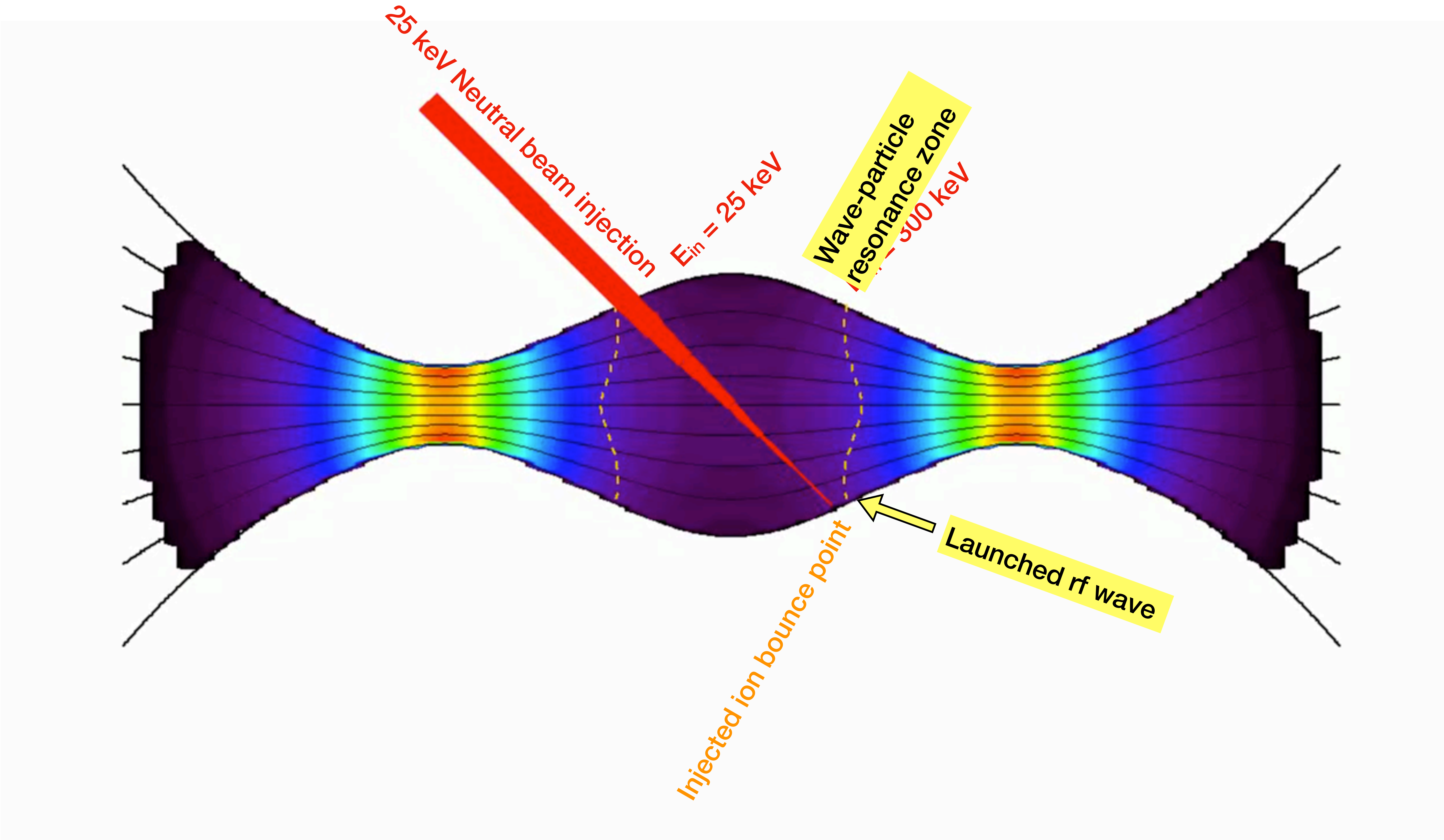


The heating cocktail for WHAM has been modeled using the CQL3D-genray suite of codes

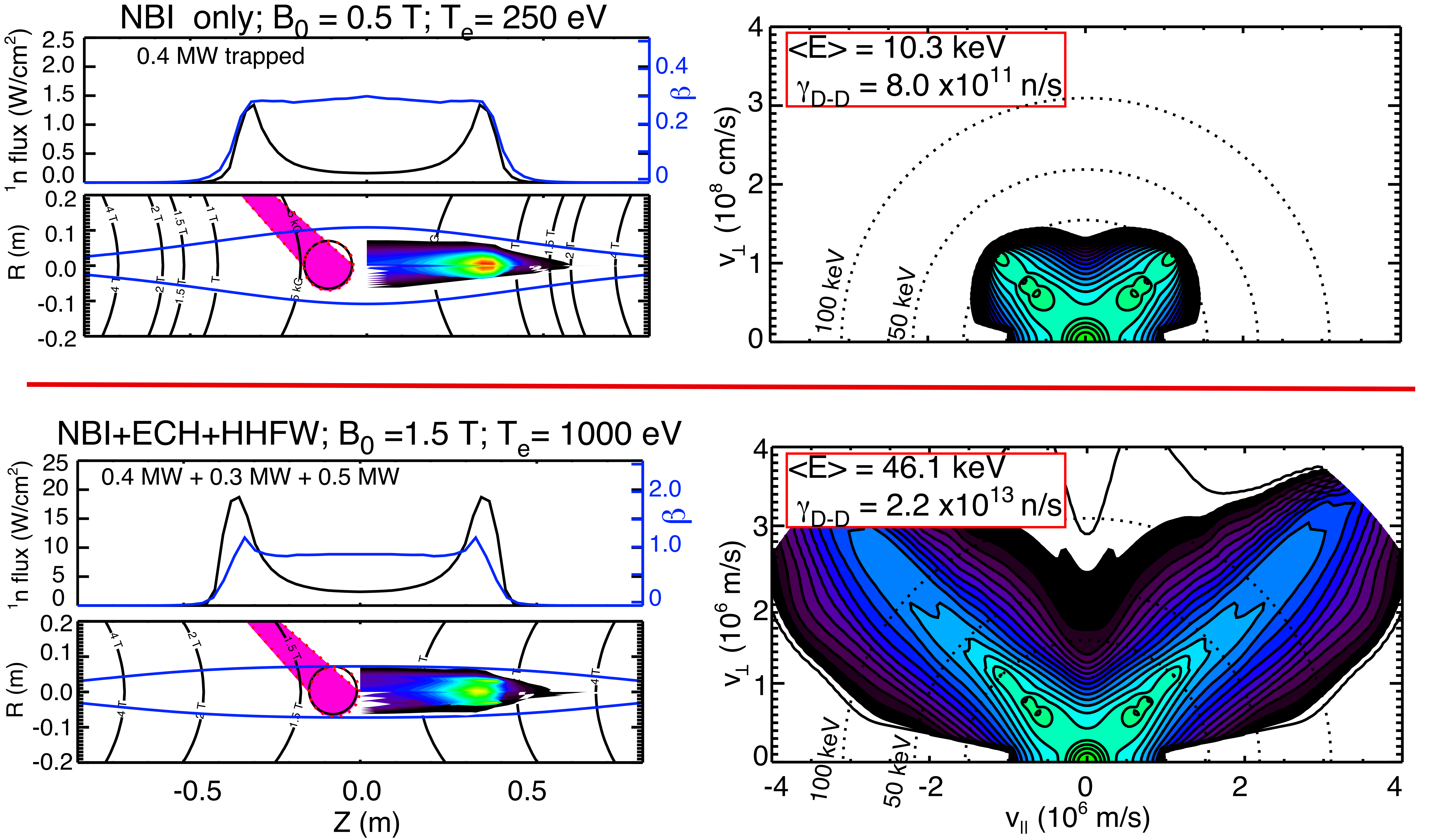


4

Wave/ ion resonance leads to in-situ energization

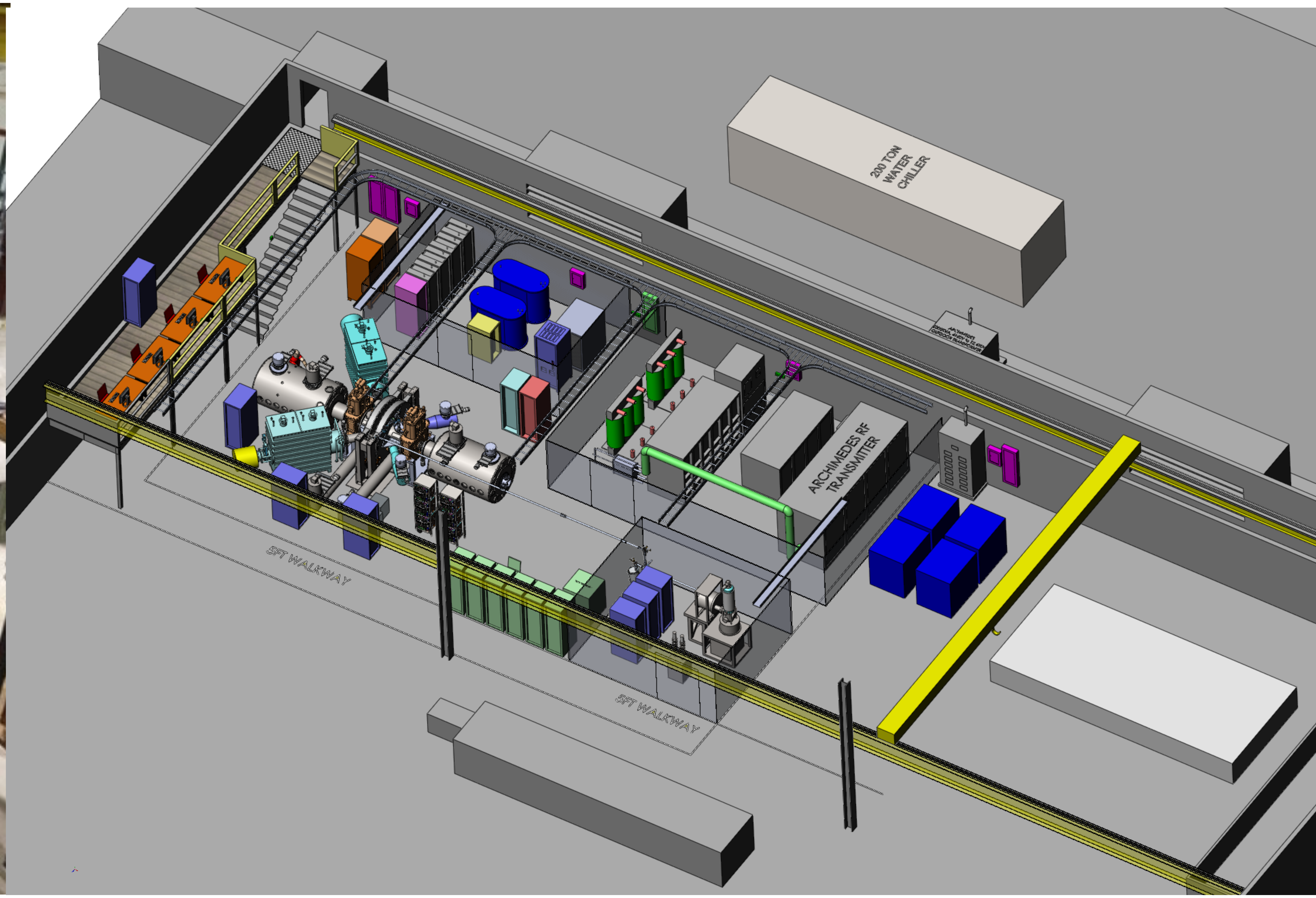


Fokker-Planck modeling of synergistic heating scheme shows in-situ ion acceleration; improved confinement



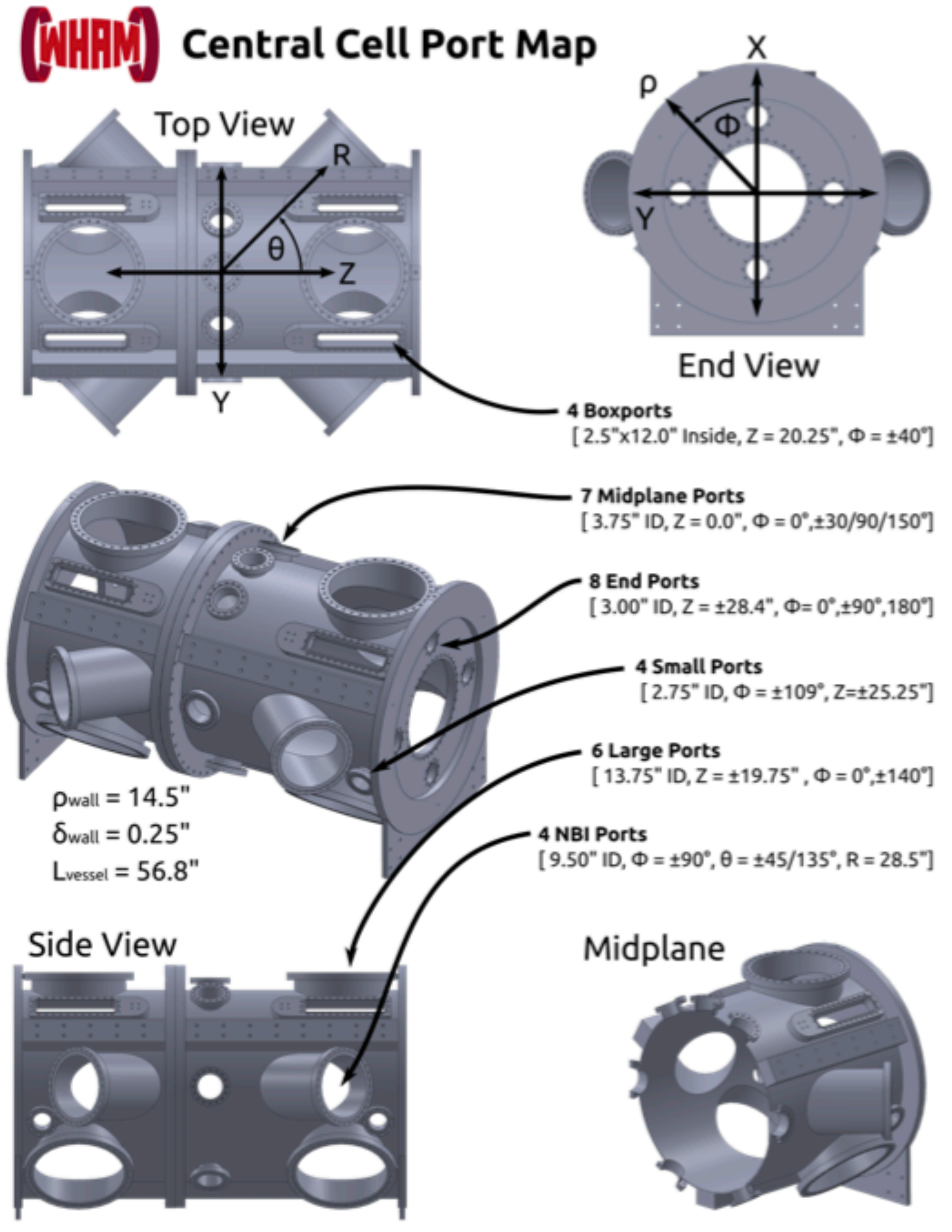
R. W. Harvey, Y. V. Petrov, and C. B. Forest, *"3D distributions resulting from neutral beam, ICRF and EC heating in an axisymmetric mirror,"* AIP Conference Proceedings 1771 , 040002 (2016).

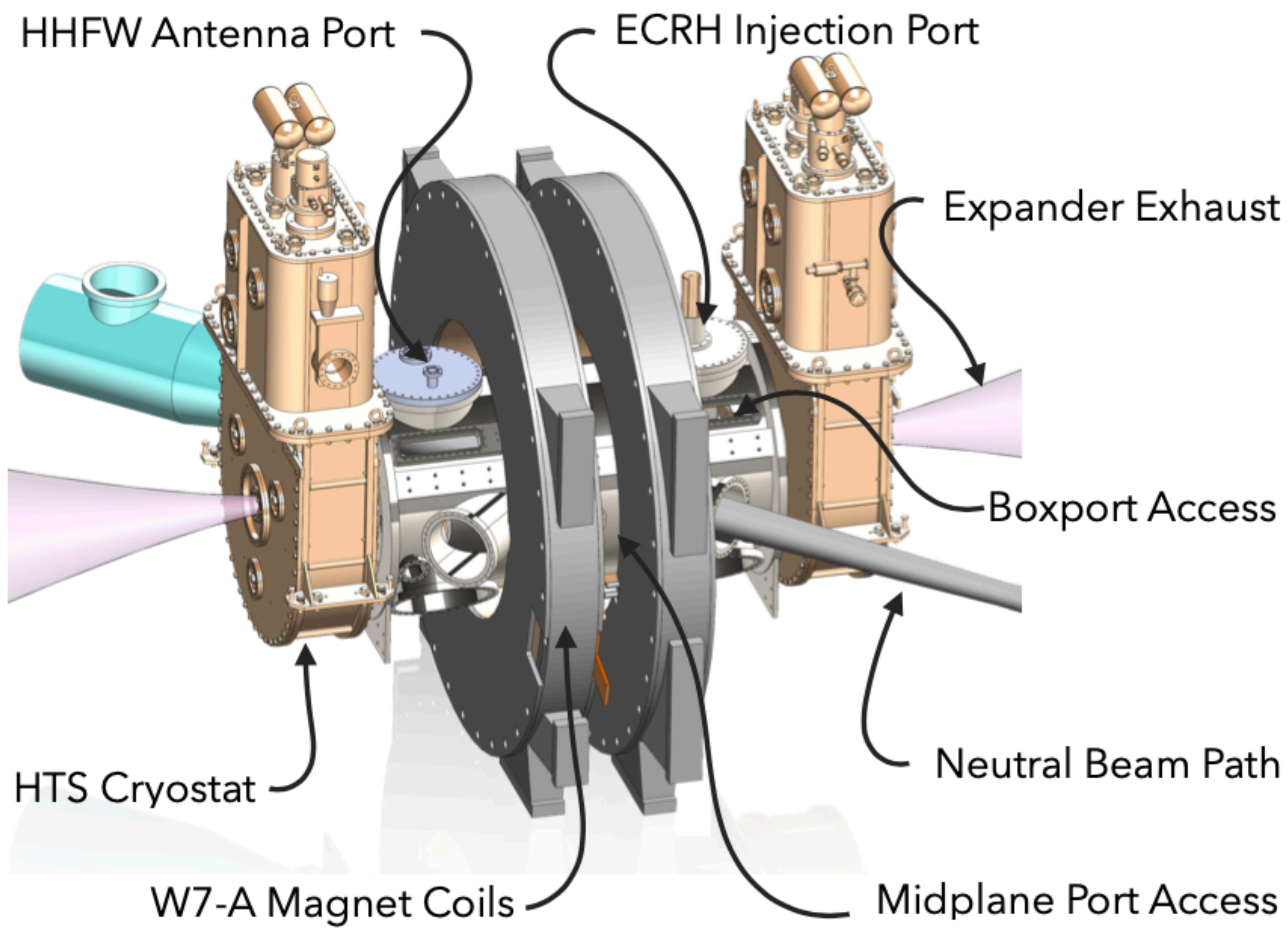
WHAM is now under construction at the Physical Sciences Lab of the University of Wisconsin: First plasma expected summer 2022




WEST
FRAGILE
fragile
TOP LOAD ONLY

WHAM Central Cell Diagnostic Access






WHAM
Wisconsin HTS Axisymmetric Mirror
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Oliver Schmitz
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Mary Severson
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Kunal Sanwalka
Danah Velez
Douglass Endrizzi
Oscar Anderson
Jake Murawski
Jon Pizzo
Post Docs
Mykola Ialovega
MIT and CFS
Sergey Kuznetsov
Alexey Radovinsky
David Meichle
Alex Zhukovsky
Dennis Whyte
Mark Stowell
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Blake Mitchell
Dan Nash
Nick Kelton
Bob Mumgaard
Abhay K Ram
Cornwall Lau
MIT rf C
John C Wright
Atul Kumar
Bob Harvey
GA ECH hardware
Ethan Peterson
Dylan Copeland
Yuri Petrov
Charles Moller
Juan Francisco Caneses Marin
David Green ORNL
John Lohr

End of talk

Thank you for your attention and please help us !