The Wisconsin **H**TS **A**xisymmetric **M**irror **(WHAM)**
on a Faster Path to Lower Cost Fusion Energy

BETHE Kickoff Virtual Workshop
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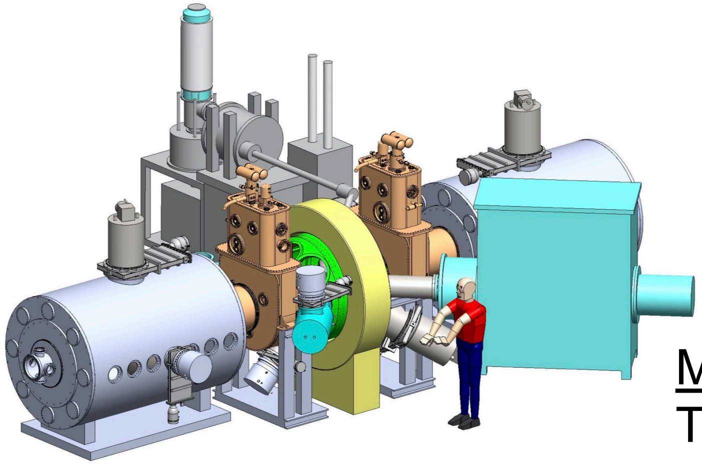
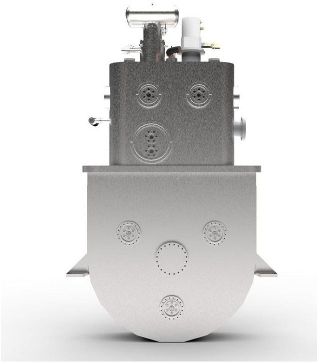
A public-private partnership will build and operate WHAM, a prototype end plug for an Axisymmetric Tandem Mirror

- University of Wisconsin
  - Construction of the WHAM toolkit: vacuum vessel, ECH, NBI and RF heating systems
  - Scientific team for mirror physics
  - Sited at the Physical Sciences Laboratory of the UW
- Commonwealth Fusion Systems
  - Design and construction of HTS high field mirror coils
  - Design of next step magnets needed for BEAT
- MIT
  - RF transmitter and expertise
  - Neutron shielding and blanket design for BEAT/HAMMER
- Three ARPA-E Capabilities Teams
  - RF and ECH modeling/antenna design
  - Gyrokinetics/PIC modeling of stability/transport
  - ORNL led Thomson Scattering measurement

The REBCO high field magnet revolution (and other recent breakthroughs) radically improves the Axisymmetric Tandem Mirror path to fusion energy

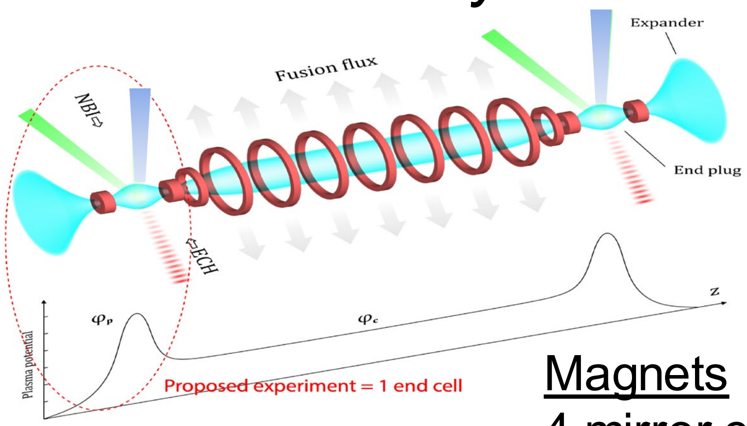
W*isconsin* **H***TS* **A***xisymmetric* **M***irror*





Magnets
Two CFS mirror coils:
5 cm bore 17 T

Break*-*E*ven* **A***xisymmetric* **T***andem*



Magnets
4 mirror coils: 30 cm 25 T
Central solenoid: 1 m 2 T

High Field Benefits

- Compact end cells at pressure limit imposed by magnetic field can be physically small and still confine large thermonuclear core (central cell)
  - Eliminate need for complex thermal barriers
  - Reduce power (cost) of end cell heating systems
- Higher mirror ratio increases fusion output of central cell
- Numerous physics advantages: e.g. micro-stability, ech heating accessibility

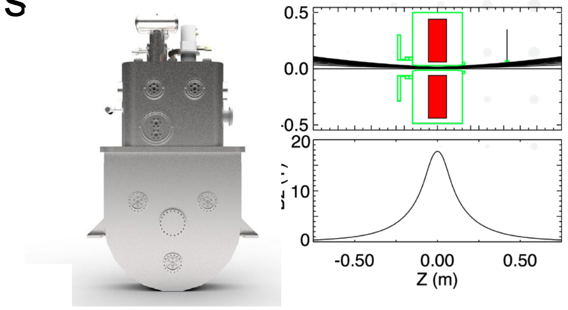
Modern Axisymmetric Tandem

- vastly simpler geometry than tokamak, stellarator, or min B mirrors from the ‘80s—much less expensive to advance
- Stability and electron confinement solutions have recently been experimentally demonstrated in Russia and Japan (including electron temperature = 1 keV)

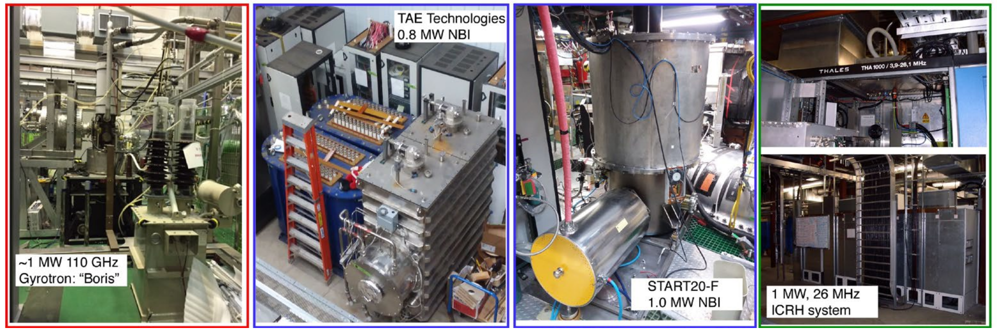
Major Project Outcomes

1. Build and operate high field HTS magnets in mirror configuration
2. Demonstrate long pulse vortex control of instabilities in compact axisymmetric mirrors
3. Confine and accelerate high energy ions using RF (eliminate need for MeV beams)
4. Confine and heat electrons at high density using microwaves (ECH)

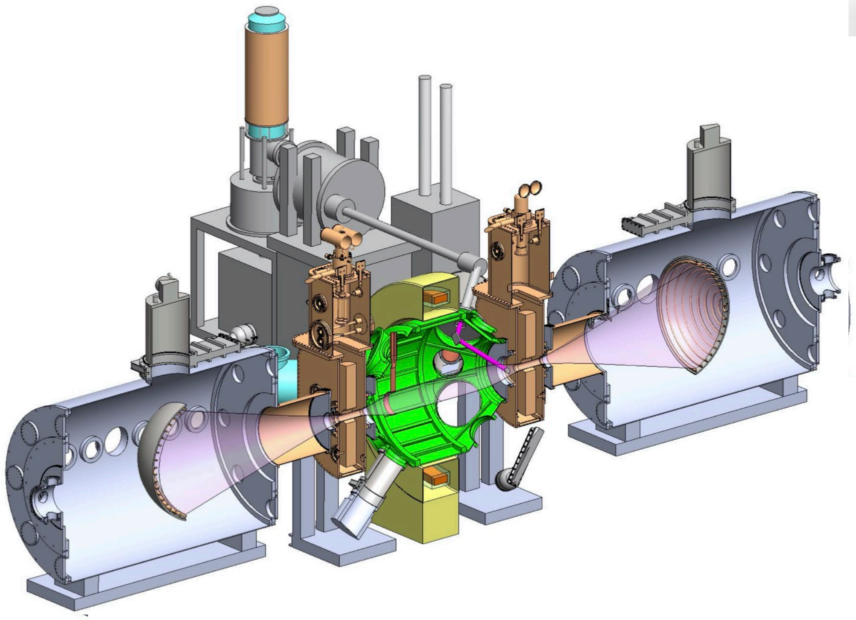
High field HTS Magnet

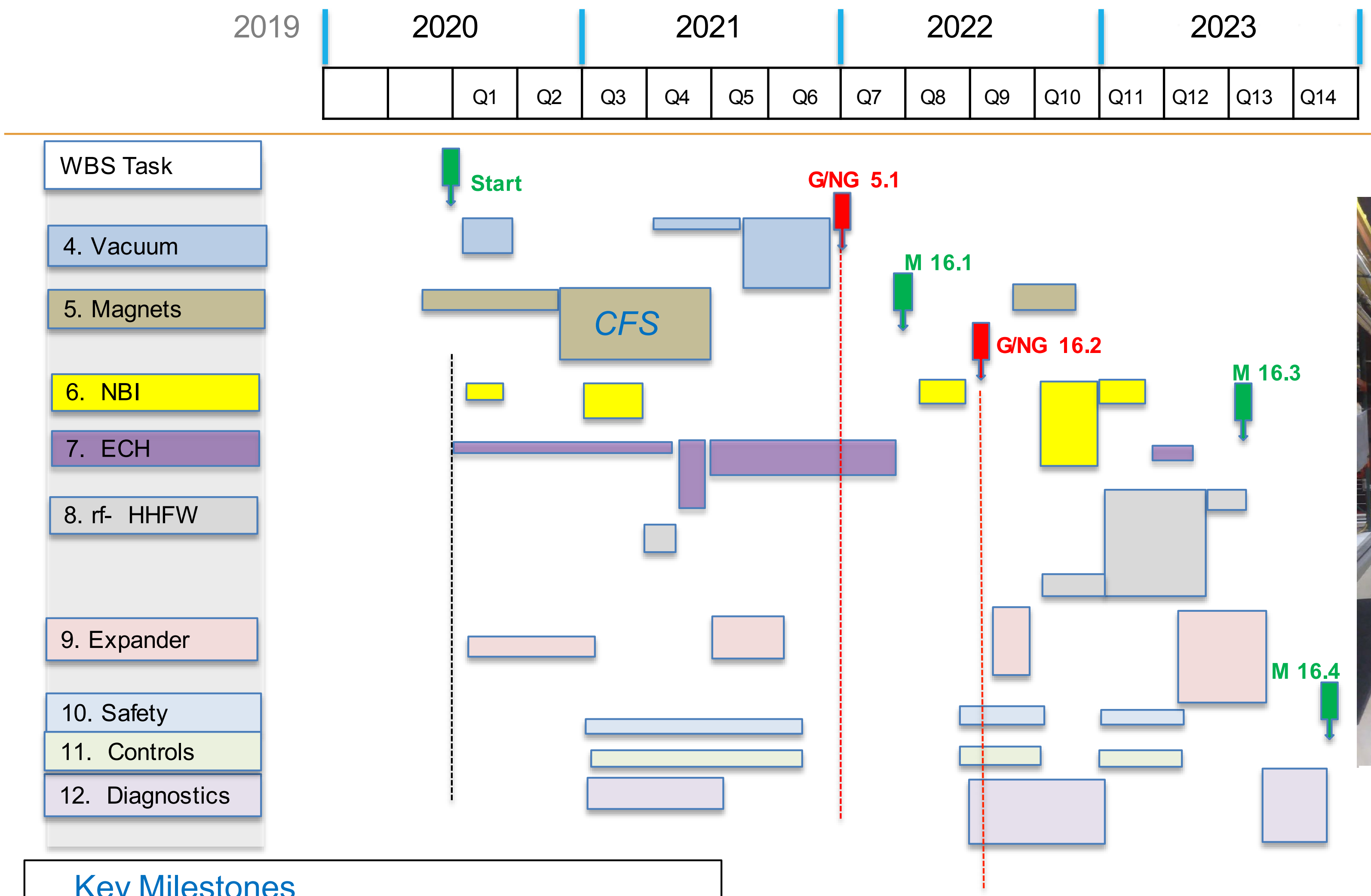


ECH (1 MW) Neutral Beams (2 MW) RF (1 MW)



design, build, repeat ⟹
Integrate lessons-learned into
5. design of BEAT end plug





Key Milestones

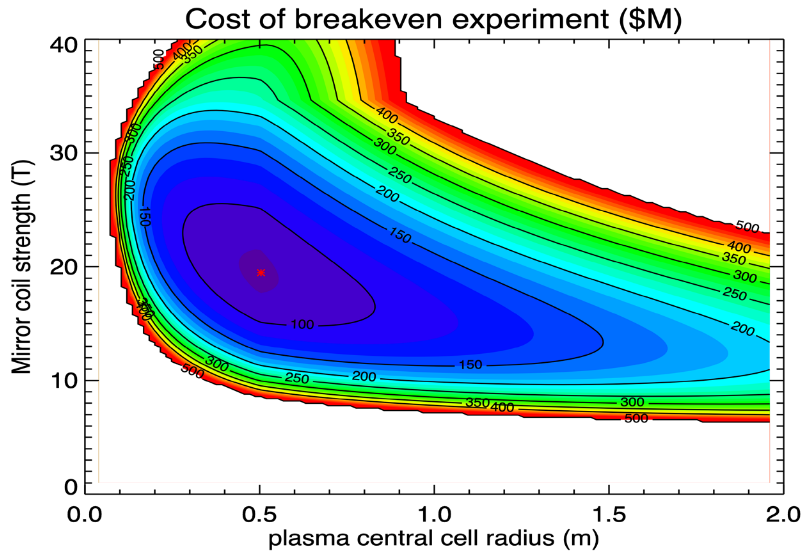
G/NG 5.1: Mirror coils energized; high vacuum: 31 Dec 2021
M16.1 NBI-ready target plasma: 30 Mar 2022
G/NG 16.2 NBI + ECH stable plasma: 31 Jul 2022
M16.3 NBI + HHFW synergy proof: 15 July 2023
M16.4 Triple product measurements: 15 Dec 2023

WHAM experimental Hall at the UW Physical Sciences Laboratory (Gyrotron shipment from GA/KSTAR, June 2020)

A mirror-based fusion development path has bite size steps:

WHAM ($10M,3yrs) ⟹ BEAT- End Plug (+$25M, 3yrs) ⟹ BEAT (+$75M,4 yrs) ⟹ HAMMER (~$500M)

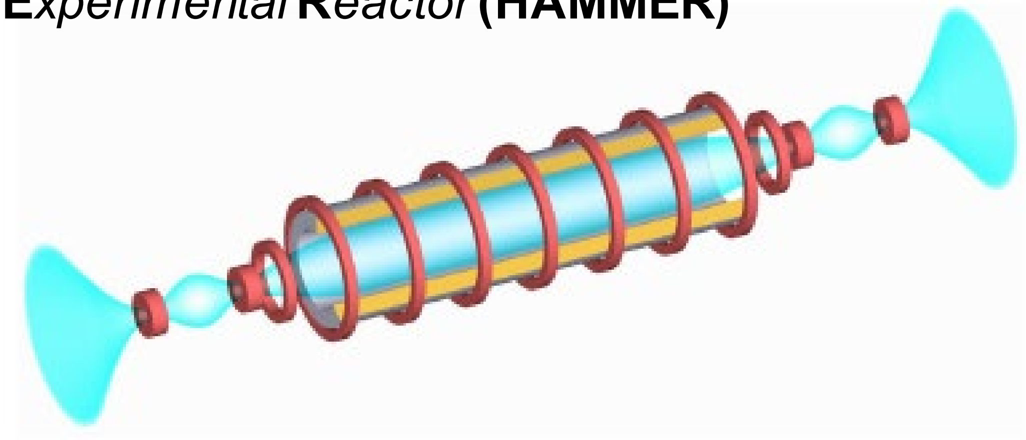
BEAT



Using ARPA-E costing rules, a low cost break-even experiment is possible without blanket

End plug magnets: 2 x $15M = $30M
heating: $5 / watt x 10 MW = $50M
central cell: $0.5M/m x 40 m = $20M
= $100M

H*TS* **A***xisymmetric* **M***agnetic* **M***irror* **E***xperimental* **R***eactor* **(HAMMER)**

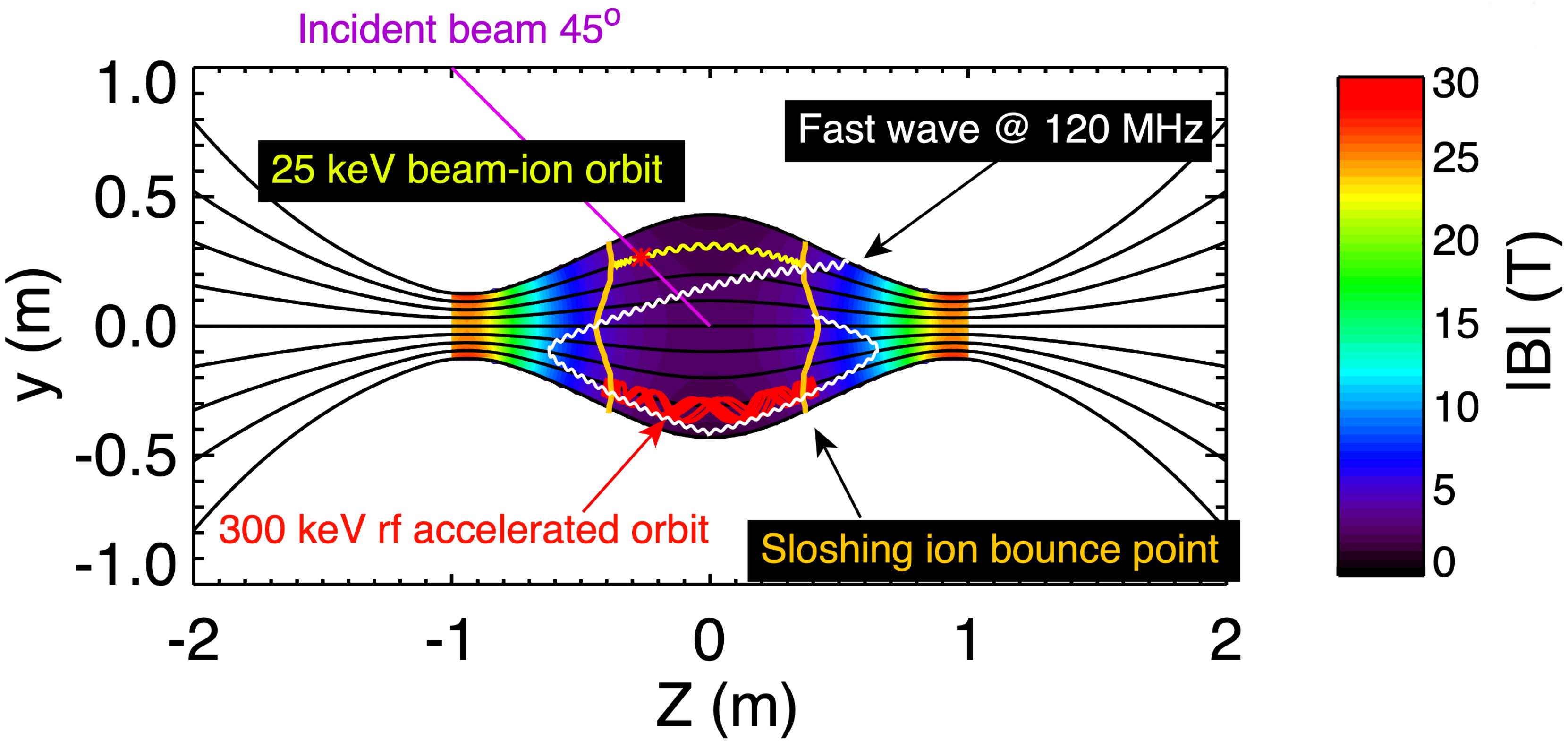


Advanced Tandem Mirrors promise

- *High beta*
- *low cost/length molten salt blanket and magnets built from cylindrical segments*
- *long lifetime PFCs and Blanket*
- *economical low power (50-100 MW) entry point*
- ***R**eliability, **A**vailability, **M**aintainability, **I**nspectability*
- *Small enough to overcome the valley of death in the fusion innovation cycle??*

Backup Slides

BEAT will need 30 cm bore, 25 T magnets and use higher frequency RF to accelerate ions to high ion energies ($25M)



- Higher frequency rf scheme again shows in-situ acceleration
- Ion energies to 300 keV without high energy NBI
  - uses instead ***much***-simpler 25 keV NBI to fuel and seed fast ions

Axisymmetric Tandem Mirror (Ambipolar Trap)

Four species to consider:

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

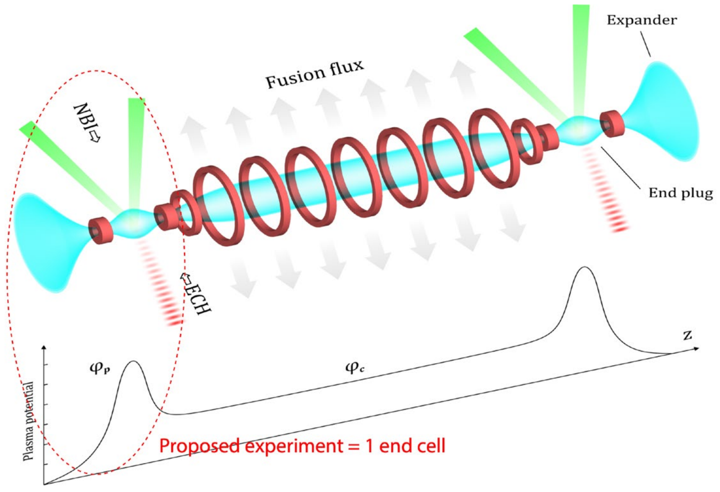
Confined by:

Sloshing fast ions mirror confined for $\sim \tau_{ii} log_{10} R_M$

ambipolar potential associated with fast plug ions

Confined by potential in expander (and well in plug due to $T_{ep} > T_{ec}$)

Electrostatically confined Maxwellian ions (with $T_{ic} < T_{ep}$)



$$\tau_i \approx \tau_{ii} ln(2R_m + 2)\Phi_i/T_{ic} e^{\Phi_i/T_{ic}}$$ Pastukhov factor

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

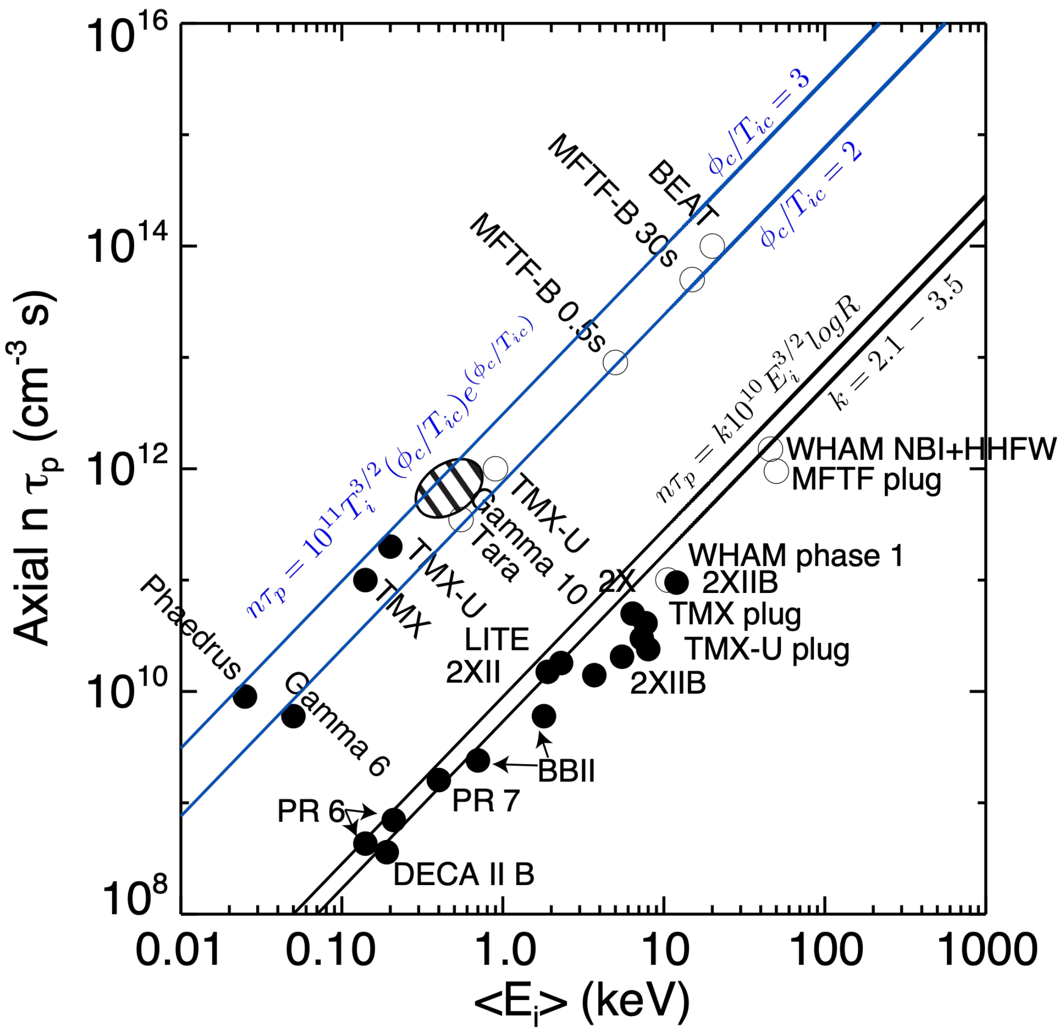
For the standard tandem mirror high B is needed in plugs to contain high pressure plasma
-Impossible in ‘80s—> thermal barriers invented

$$nT_i\tau = 0.06\, T_{i,10\,keV}^{5/2} \ln(2R_M+1) \ln(n_p/n_c)\, (n_p/n_c)^{T_{ep}/T_{ic}}\, 10^{20}\ \mathrm{m^{-3}\ keV\ sec}$$

Anticipating $n_p/n_c \sim 5$ and $T_{ep}/T_{ic} \sim 2$ gives $\approx 10^{21}$ at $T_{ic} \sim 20$ keV.

arpa·e
CHANGING WHAT'S POSSIBLE

Electrostatic confinement in tandem over simple has been validated

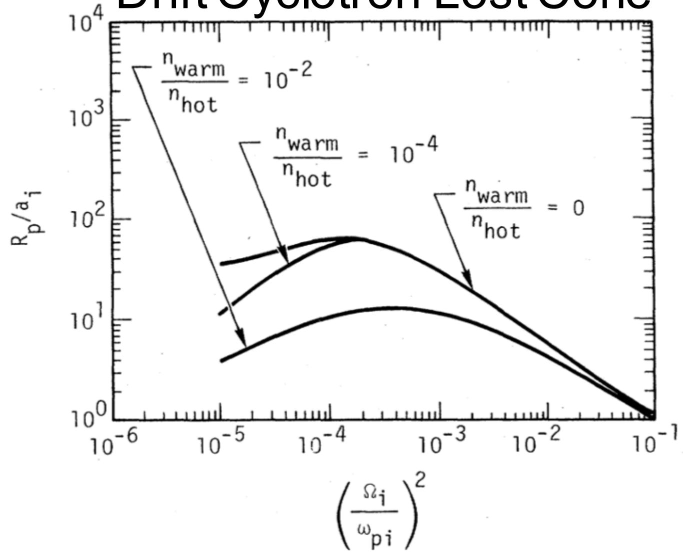


Limited experimental database confirms 10x confinement enhancement over simple mirror

Instability Concerns

1. MHD
   - Er control via end biasing and Te(r) control in big plasmas
   - line-tying improvement using reduced sheath potential afforded by large expansion.
   - FLR
   - Straight field line mirrors?
   - LAMEX-like configuration using permanent magnets?
   - modulated ECH (Kapitza Pendulum idea of Post)?
2. Alfvén Ion Cyclotron instability (solved)
   - sloshing ions injected at 45 degrees
3. Drift Cyclotron Loss Cone Instability (to be demonstrated)
   - mitigate with large size, (low density / high field helps)
4. Trapped Electron Modes (observed on TARA/mitigated on GAMMA-10
   - Er using end biasing and Te(r) control

Drift Cyclotron Lost Cone



That increasing the plasma radius does require less filling of the hole has already been demonstrated, in the range $R_p/\rho = 1.6$ to 6 [43]. Stability with an empty ambipolar hole is predicted for a plug radius $R_p > A_1$ (50ρ) and an adjustable parameter A_1. We obtain [42]:

$$R_p = A_1(50\rho) = 0.22A_1(E_o^{1/2}/B_p) \quad (16a)$$

$(\omega_{pi}/\omega_{ci})^2$	10^2	10^3	10^4	10^5	
A_1	0.12	0.2	1.2	0.8	(16b)