

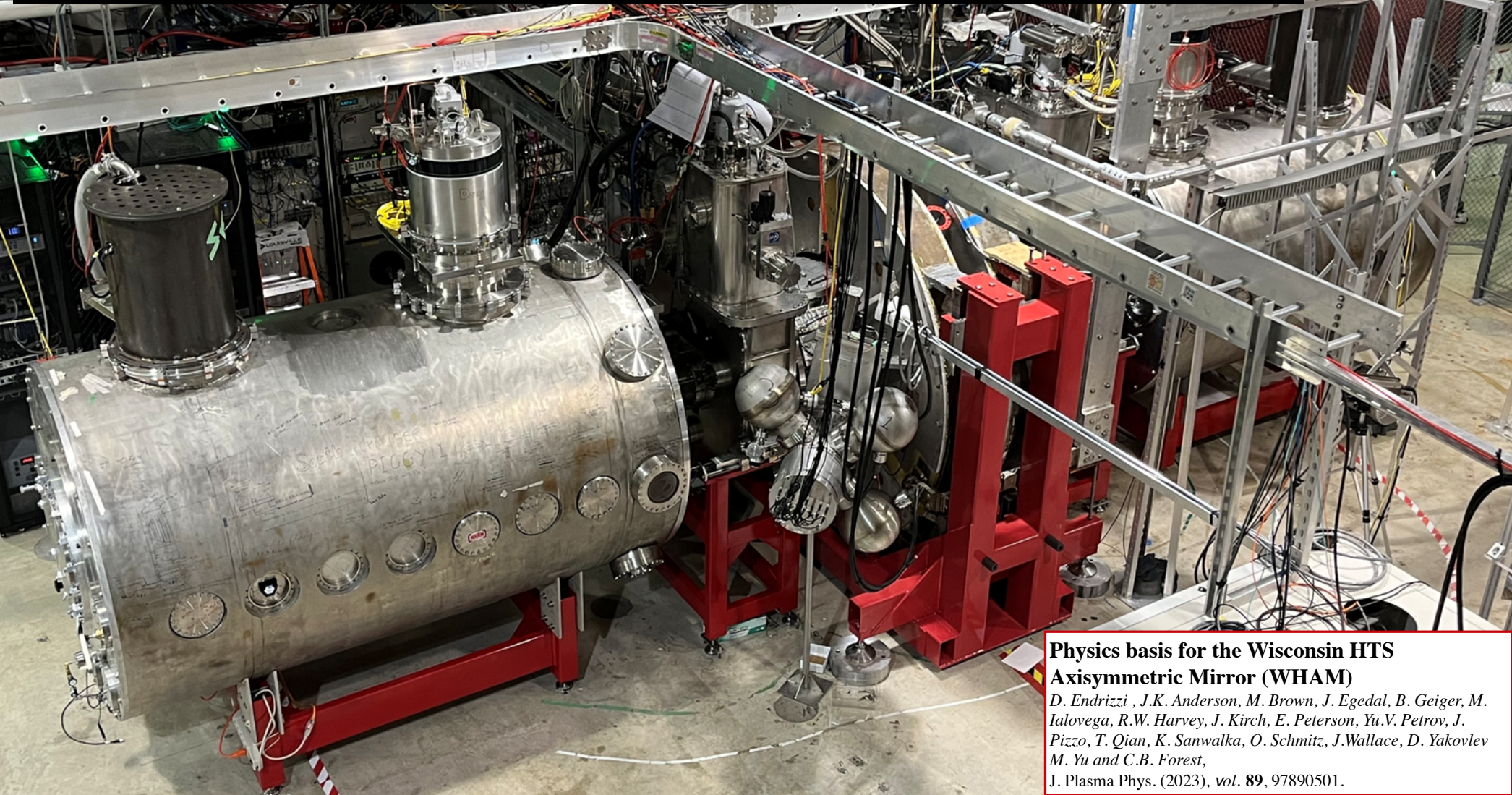


Magnetic Mirrors: a brief history and tutorial + modern experiments

Cary Forest - 3 Aug 2026

WPI Vienna, Austria

The Wisconsin HTS Axisymmetric Mirror is operational!



Physics basis for the Wisconsin HTS Axisymmetric Mirror (WHAM)

D. Endrizzi, J.K. Anderson, M. Brown, J. Egedal, B. Geiger, M. Ialovega, R.W. Harvey, J. Kirch, E. Peterson, Yu.V. Petrov, J. Pizzo, T. Qian, K. Sanwalka, O. Schmitz, J. Wallace, D. Yakovlev M. Yu and C.B. Forest, J. Plasma Phys. (2023), vol. 89, 97890501.

Plan for talk

1. Mirror Basics

2. MHD Equilibrium

3. Improved Mirrors

4. WHAM

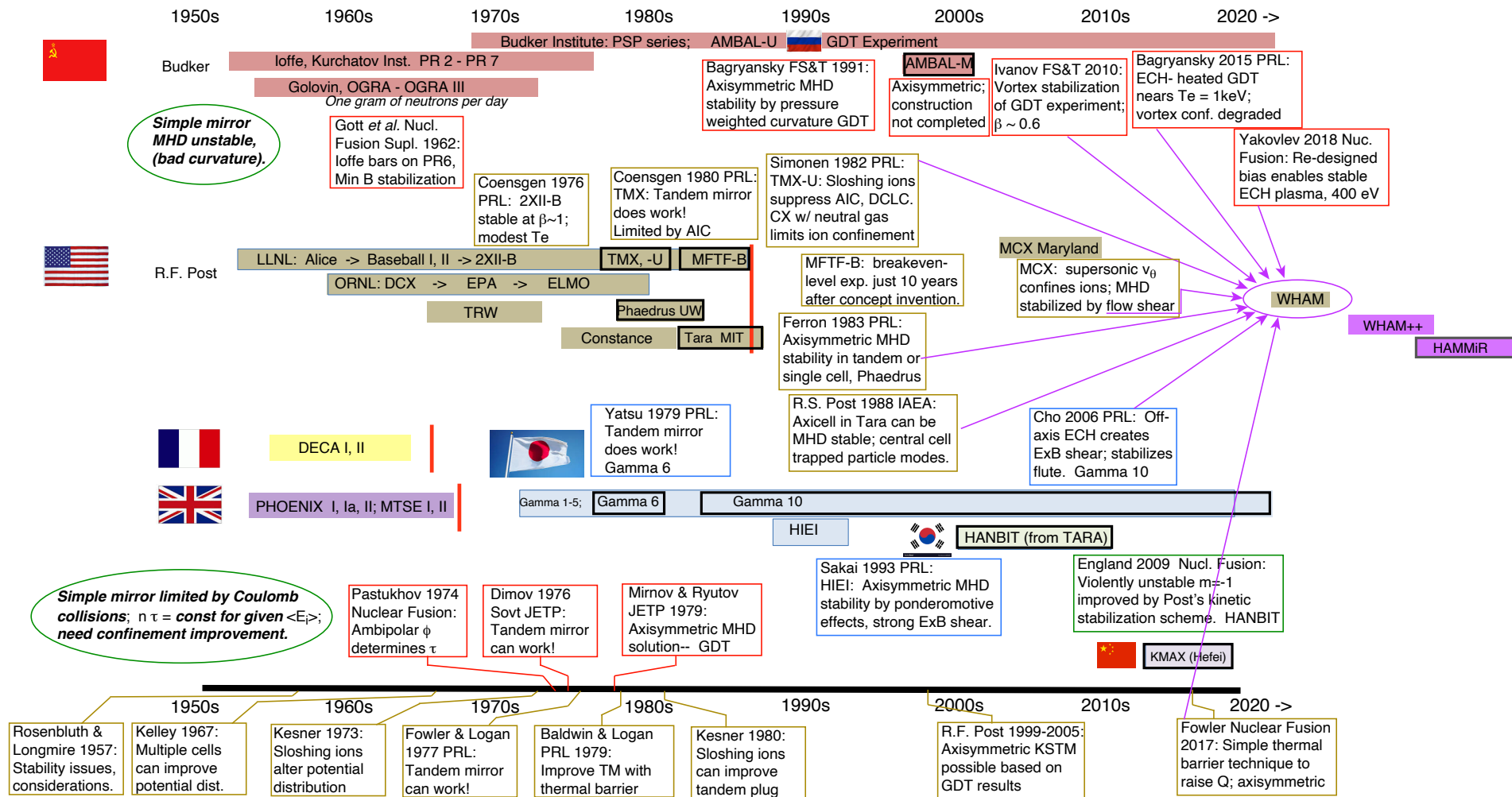
5. Observation of Classical Mirror Confinement of Electrons and

- (a 500 keV Maxwell Demon)

6. Direct Energy Conversion Demonstration

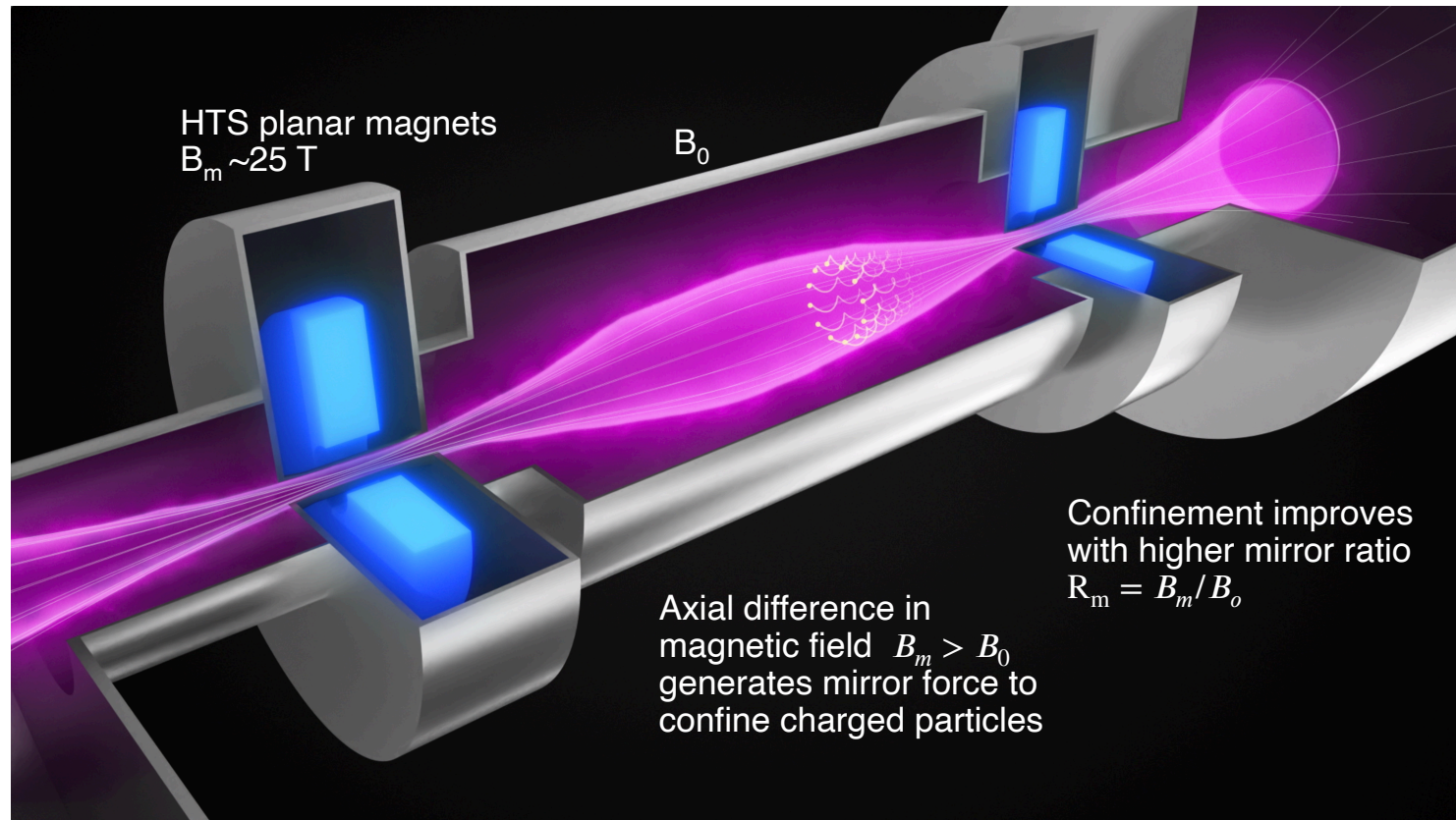
7. Realta Fusion

- Mirror-based volumetric neutron sources
- Recent announcement of new laboratory to be located in Madison

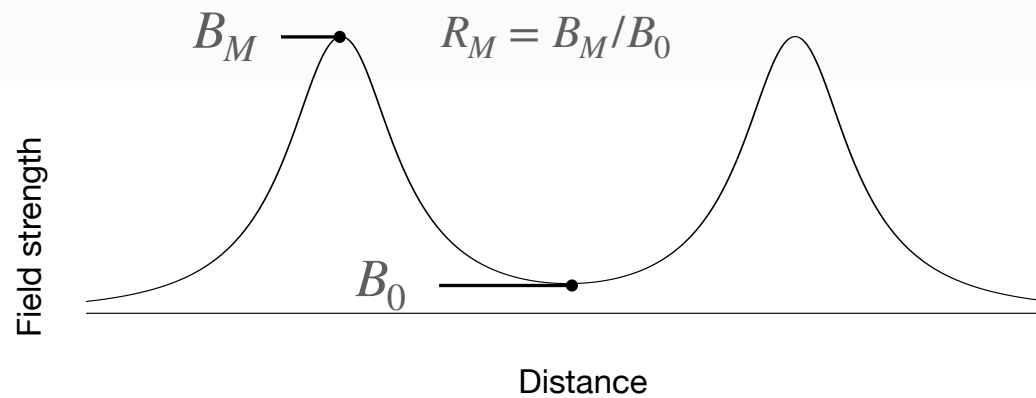
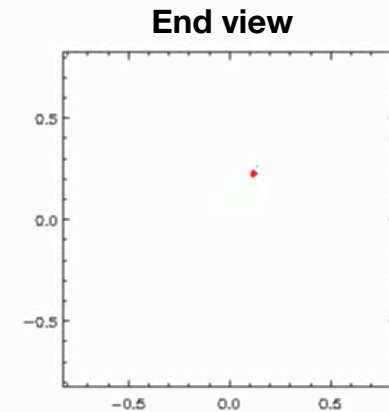
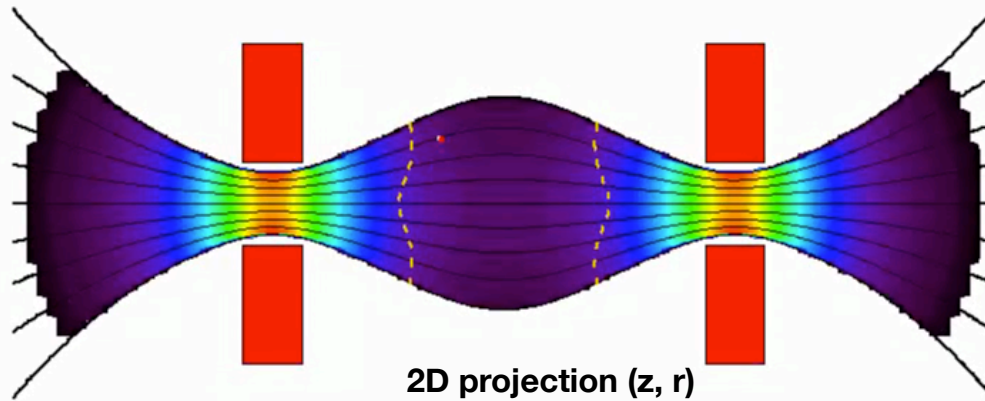


1. Mirror Basics

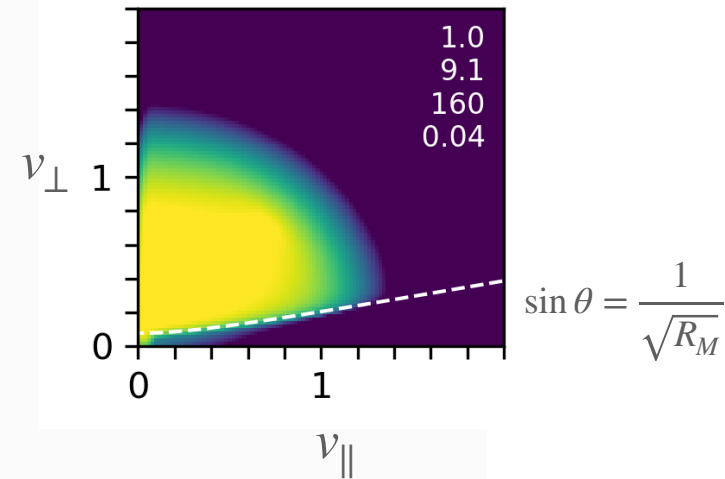
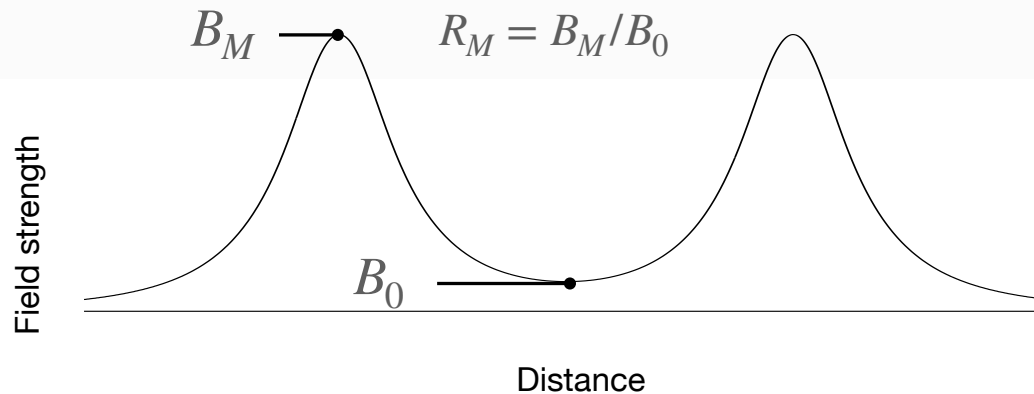
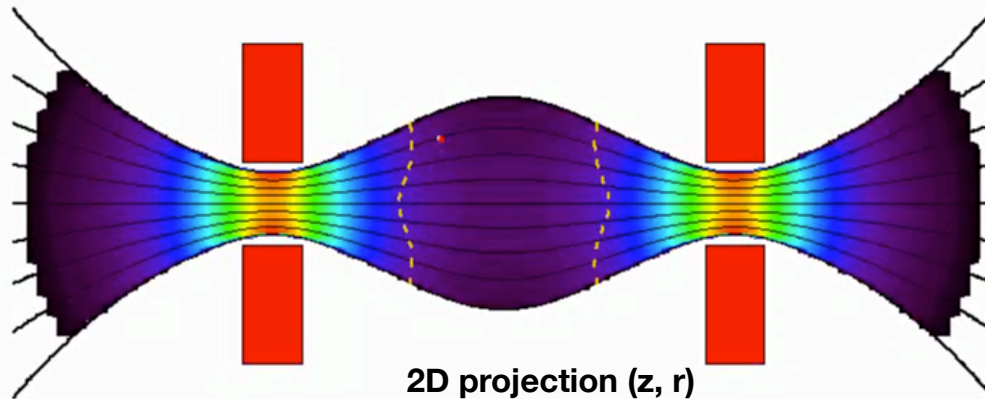
Compact axisymmetric magnetic mirrors for fusion



Simplest confinement geometry is the magnetic mirror



Simplest confinement geometry is the magnetic mirror



$$E = \text{const} = \frac{1}{2}mv_{\parallel}^2 + \mu B(\ell) + q\Phi(\ell)$$

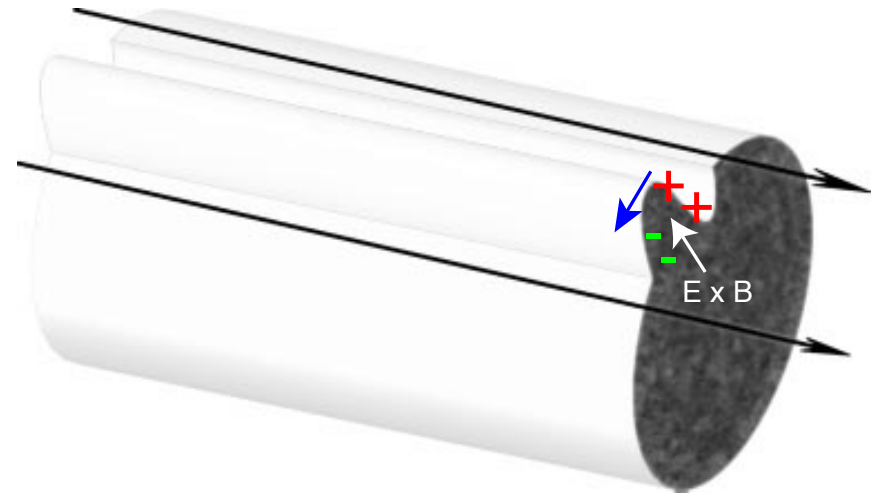
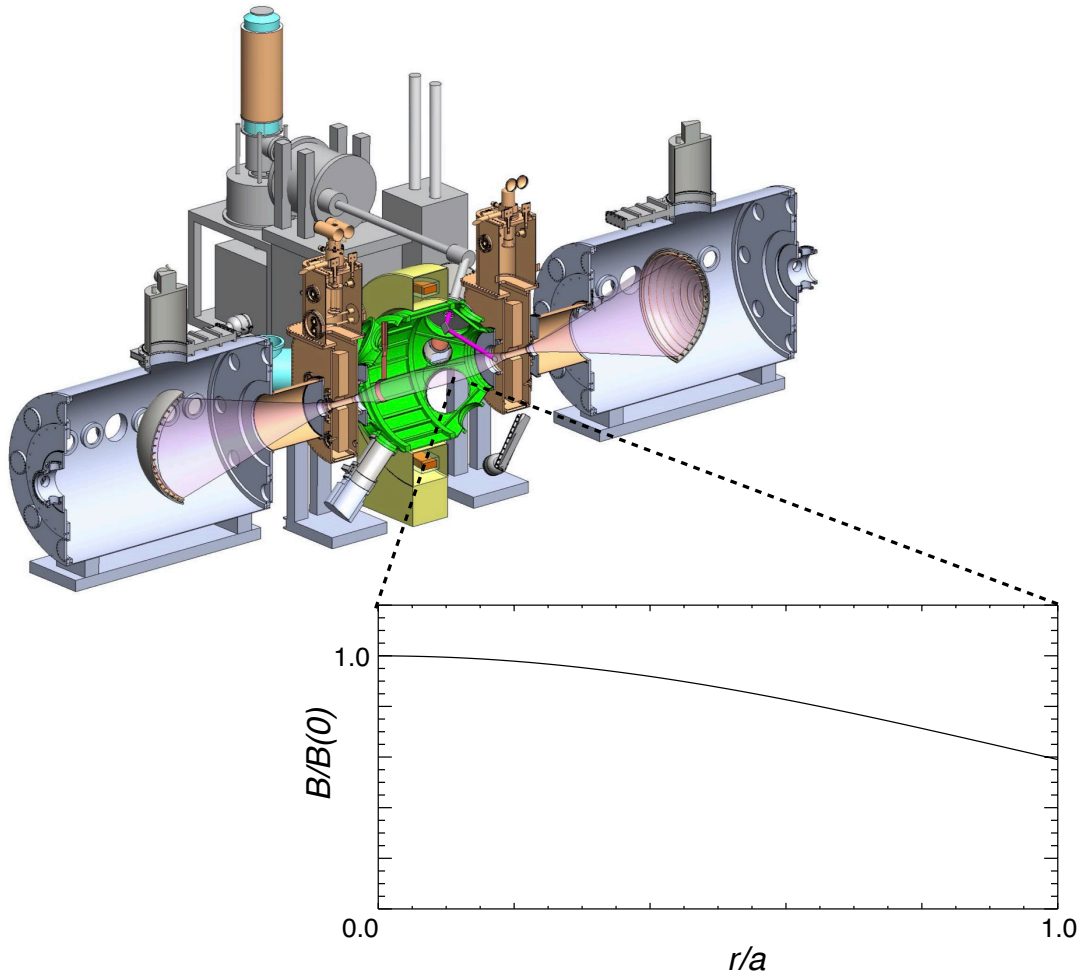
- Consider $\Phi = \text{const}$ to begin. If $E < \mu B_M$ particles are confined

$$v_{\parallel}(\ell) = \sqrt{\frac{2}{m}(\mu B_T - \mu B(\ell))}; E = \frac{1}{2}mv^2 = \mu B_T$$

- At minimum B_0 we can see that confined particles have

$$v_{\parallel}^2 < v^2 \left(1 - \frac{B_0}{B_M}\right) \text{ or } v_{\perp}^2 > v^2 \frac{B_0}{B_M} \text{ giving so-called "loss cone"}$$

Axisymmetric mirror prone to Interchange

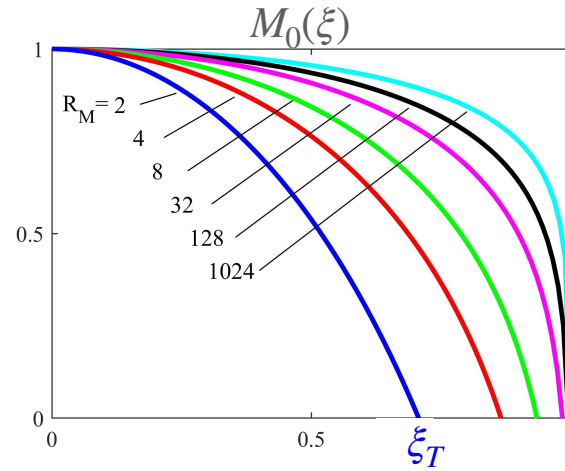
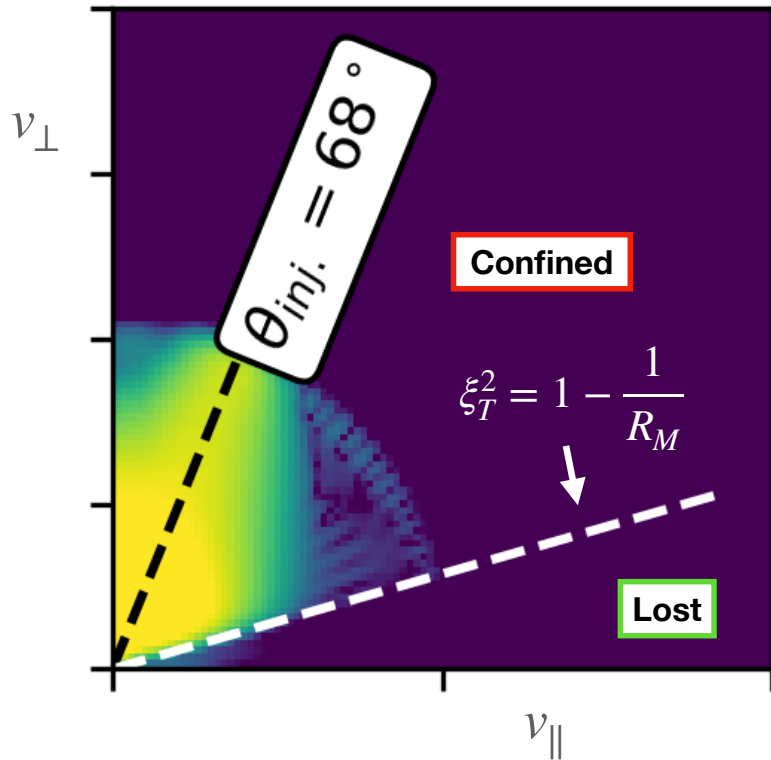


Curvature and ∇B lead to charge separation in perturbed region creating electric field.

For “bad curvature”, resulting $\mathbf{E} \times \mathbf{B}$ reinforces perturbation $\Rightarrow$ instability.

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

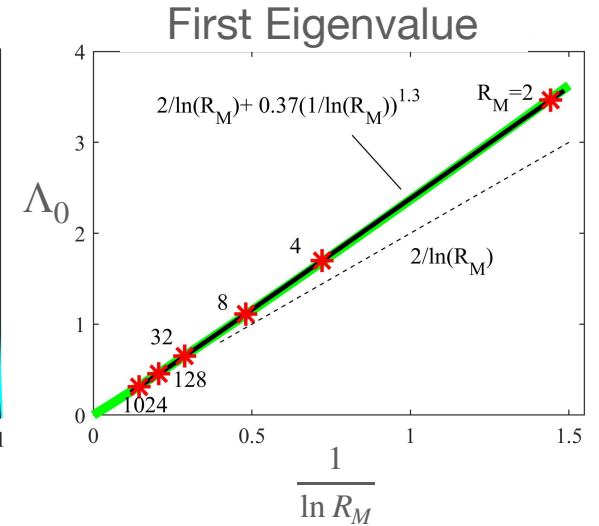
In the “collisionless mirror” regime, particle confinement is set by collisional slowing on electrons and ion-ion pitch angle scattering into the loss cone



$$\xi = \frac{v_{\parallel}}{v}$$

$$n_{20}\tau_s = 5 \frac{T_{e,keV}^{3/2} \mu}{Z^2} \text{ msec}$$

$$n_{20}\tau_{ii} = 0.125 \frac{\langle E_{i,keV} \rangle^{3/2} \mu}{Z^2} \text{ msec}$$



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

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

$$n_{20}\tau_P = 0.05 \frac{\langle E_{i,keV} \rangle^{3/2} \mu}{Z^2} \ln R_M \text{ msec}$$

Confinement of Ions in Mirror calculated from the Lorentz Collision Operator in square well

We can get very close to estimating the confinement time in a mirror using the Lorentz

Collision operator that only considers pitch angle scattering

$$C(f) = \nu(v) \mathcal{L}f \text{ where } \nu(v) = \frac{4\pi n_e Z e^4}{(4\pi\epsilon_0)^2 m^2 v^3} \ln \Lambda \text{ and } \mathcal{L} = \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \sin \theta \frac{\partial f}{\partial \theta}$$

$$\text{Convenient to use } \xi = \frac{v_{\parallel}}{v} = \cos \theta \text{ and easy to show that } \mathcal{L} = \frac{1}{2} \frac{\partial}{\partial \xi} (1 - \xi^2) \frac{\partial}{\partial \xi}$$

Now consider the problem $\frac{df}{dt} = C(f) + S = 0$ with boundary conditions of

$$f\left(v, \xi_c = \sqrt{1 - \frac{1}{R_M^2}}\right) = 0 \text{ and } \frac{\partial f}{\partial \xi} \Big|_{\xi=0} = 0 \text{ by symmetry. Assume } S \text{ is uniform in pitch angle and for}$$

now can assume constant ν . So $\frac{\nu}{2} \frac{\partial}{\partial \xi} (1 - \xi^2) \frac{\partial f}{\partial \xi} + S = 0$.

$$\text{Integrate once } (1 - \xi^2) \frac{\partial f}{\partial \xi} = -\frac{2S}{\nu(v)} \xi + C \text{ and B.C. at } \xi = 0 \text{ sets } C = 0$$

$$\text{Next see that } \frac{\partial f}{\partial \xi} = \frac{S}{\nu(v)} \frac{-2\xi}{(1 - \xi^2)} \rightarrow f = \frac{S}{\nu(v)} \ln(1 - \xi^2) + C$$

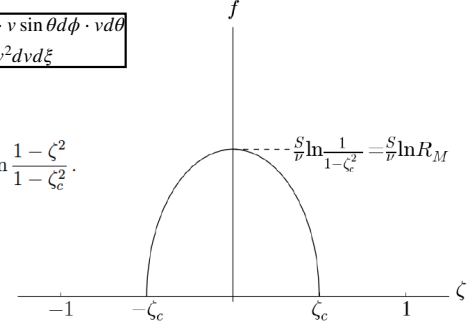
$$\text{Using BC at } \xi_{LC}: f = \frac{S}{\nu(v)} \ln \frac{1 - \xi^2}{1 - \xi_c^2} = \frac{S}{\nu(v)} \ln \frac{1 - \xi^2}{R_M}$$

$$0 = \int d^3v \left[\frac{\partial f}{\partial t} - C(f) - S \right] = \frac{\partial n}{\partial t} - \int d^3v C(f) - \int d^3v S$$

$$\boxed{d^3v = dv \cdot v \sin \theta d\phi \cdot v d\theta} \\ = 2\pi v^2 dv d\xi$$

$$\tau_p \equiv \frac{\int d^3v f}{-\int d^3v C_L(f)} = \frac{\int d^3v f}{\int d^3v S} = \frac{\int_0^\infty 2\pi v^2 dv \int_{-\xi_c}^{\xi_c} d\xi \underbrace{\frac{S}{\nu} \ln \frac{1 - \xi^2}{1 - \xi_c^2}}_{S=S_0 \delta(v-v_0) \text{ for simplicity}}}{\int_0^\infty 2\pi v^2 dv \int_{-\xi_c}^{\xi_c} d\xi \underbrace{S}_{2\xi_c}} = \frac{1}{\nu \xi_c} \int_0^{\xi_c} d\xi \ln \frac{1 - \xi^2}{1 - \xi_c^2}.$$

In equilibrium - calculating $\int d^3v C_L(f)$ gives same answer



Now, using $\ln(1 - \xi^2) = \ln(1 - \xi) + \ln(1 + \xi)$ and $\int d\xi \ln \xi = \xi \ln \xi - \xi$, we find

$$\begin{aligned} I &\equiv \int_0^{\xi_c} d\xi \ln \frac{1 - \xi^2}{1 - \xi_c^2} = \int_0^{\xi_c} d\xi [\ln(1 - \xi^2) - \ln(1 - \xi_c^2)] \\ &= \left\{ \left[\xi \ln(1 - \xi^2) - 2\xi + \ln \frac{1 + \xi}{1 - \xi} \right]_0^{\xi_c} - \xi_c \ln(1 - \xi_c^2) \right\} \\ &= \cancel{\xi_c \ln(1 - \xi_c^2)} - 2\xi_c + \ln \frac{1 + \xi_c}{1 - \xi_c} - 0 - 0 + 0 - \cancel{\xi_c \ln(1 - \xi_c^2)} \\ &= \ln \frac{1 + \xi_c}{1 - \xi_c} - 2\xi_c. \end{aligned}$$

$$\tau_p = \frac{1}{\nu} \frac{1}{\xi_c} \left[\ln \frac{1 + \xi_c}{1 - \xi_c} - 2\xi_c \right]$$

$$\xi_c \rightarrow 1 - \frac{1}{2R_M}, R_M \gg 1$$

$$\tau_p = \frac{1}{\nu_{\perp}} \left[\frac{\ln 4R_M}{1 - \frac{1}{2R_M}} - 2 \right]$$

$$\tau_p \approx \frac{1}{\nu_{\perp}} (\ln R_M - 0.62)$$

Classical simple mirror scales to $Q \sim 1$ conditions at $R_M \sim 10$

- Classical Mirror confinement

$$\tau_p = 0.25 \frac{E_{b,100keV}^{3/2}}{n_{20}} \log_{10} R_M \text{ sec}$$

- For NBI fueled plasma

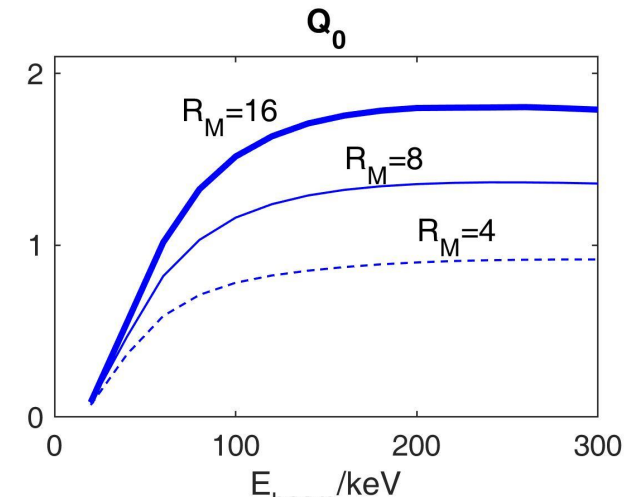
$$P_{nbi} = I_b E_b = \frac{enV}{\tau_p} E_b \sim \frac{10^{20}}{3} \frac{n_{20}^2}{E_{b,100keV}^{1/2} \log_{10} R_M} V \frac{MeV}{sec}$$

- For DT Fusion

$$P_{fus} = \frac{1}{4} \langle \sigma v \rangle n^2 \mathcal{E}_{fusion} V \sim 5 \times 10^{19} n_{20}^2 V \frac{MeV}{sec} \text{ for } \mathcal{E}_{fusion} = 22.4 \text{ MeV and } T_i \sim 100 \text{ keV}$$

- In this classical limit, fusion gain *seems* independent of size or B

$$Q \equiv \frac{P_{fusion}}{P_{nbi}} \propto \langle \sigma v \rangle E_b^{1/2} \log_{10} R_M \sim 1.3 E_{b,100keV}^{1/2} \log_{10} R_M$$



J. Egedal, D. Endrizzi, C.B. Forest, and T.K. Fowler
Fusion by beam ions in a low collisionality, high mirror ratio magnetic mirror.
Nucl Fusion **62**, 126053 (2022).

What *actually* sets minimum size for a beam-heated breakeven-class experiment at $R_M \sim 10$?

1. Interchange/ballooning beta limit sets density:

$$n_{20} = \beta_c B_0^2 / 3 E_{b,100\text{keV}}, \quad \beta_c \sim 0.3$$

2. neutral beam shine through sets plasma radius:

$$n_{20} a_0 \geq 0.42 E_{b,100\text{keV}}^{1/2}$$

3. Kinetic Stability (DCLC) and fast on adiabaticity sets normalized plasma size:

$$\frac{a_0}{\rho_i} \equiv N_\rho \approx 25 \frac{a_0 B_0}{\sqrt{E_{b,100\text{keV}}}} > 25$$

4. FLR stabilization sets plasma length:

$$L > 12.5 a_0^2 B_0 \approx 10 \frac{E_{b,100\text{keV}}^3}{\beta_c^2 B_0^3} \text{ m}$$

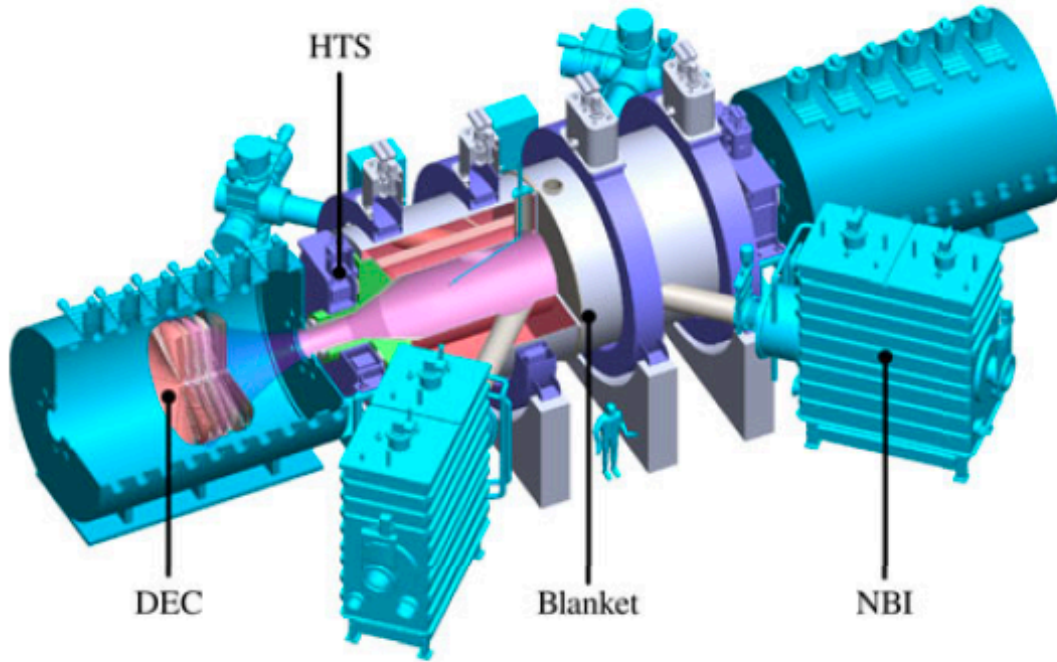
5. Unique solution from 1-3:

$$B_0 \gtrsim \frac{E_{i,100\text{keV}}}{N_{25} \beta_c} \text{ Tesla}, \quad a_0 = 1.4 \frac{\beta_c N_{25}^2}{\sqrt{E_{b,100\text{keV}}}} \text{ meters}$$

E_b	100 keV
beta	0.3
B_0	3 T
B_M	30 T
a_0	0.4 m
n_{20}	0.9
L	4 m
N_{rho}	25
P_{nbi}	7 MW

Prospects for a high-field, compact break-even axisymmetric mirror (BEAM) and applications

C.B. Forest, J.K. Anderson, D. Endrizzi, J. Egedal, S. Frank, K. Furlong, M. Ialovega, J. Kirch, R.W. Harvey, B. Lindley, Yu.V. Petrov, J. Pizzo, T. Qian, K. Sanwalka, O. Schmitz, J. Wallace, D. Yakovlev and M. Yu
J. Plasma Phys. (2024), vol. 90, 975900101, 2024.



	WHAM	BEAM
Q_{DT}	~ 0.05	~ 1
β	0.3	0.3
L_p (m)	2.0	8
a_0 (m)	0.12	0.30
a_M (m)	0.025	0.10
R_M	20	10
B_0 (Tesla)	0.85	2.5
B_M (Tesla)	17	25
E_{NBI} (keV)	30	100
P_{NBI} (MW)	< 1	10
T_i (keV)	17	80
T_e (keV)	2.5	10
n_{20} (m^{-3})	0.3	1
τ_p (sec) [†]	0.15	0.25
$nT\tau$ ($10^{20} m^{-3} \cdot keV \cdot sec$)	0.7	20
pulse length (sec)	< 2	> 5
kA·m of HTS tape	$\sim 10^4$	4.3×10^5
Cost of tape (\$M)	~ 1	40

Drift waves stabilized in Gamma 10 by sheared rotation from ambipolar potential control

1. A major lesson from past 25 years is that plasma flow and flow shear (especially in toroidal systems) plays a very strong role in regulating low frequency turbulence (not just MHD)
2. The mirror affords much more direct control of plasma potential (and ExB flow) through end-plate biasing AND ambipolar potential control via $\text{Te}(r)$
3. Turbulence suppression by flow shear demonstrated in Gamma-10 tandem mirror and radial losses eliminated

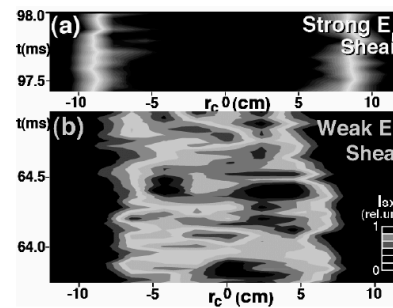
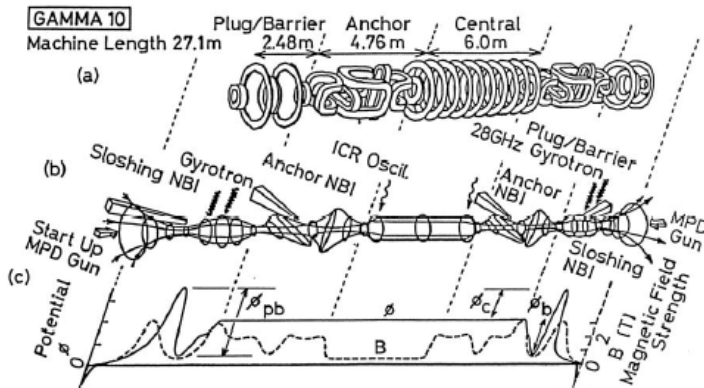
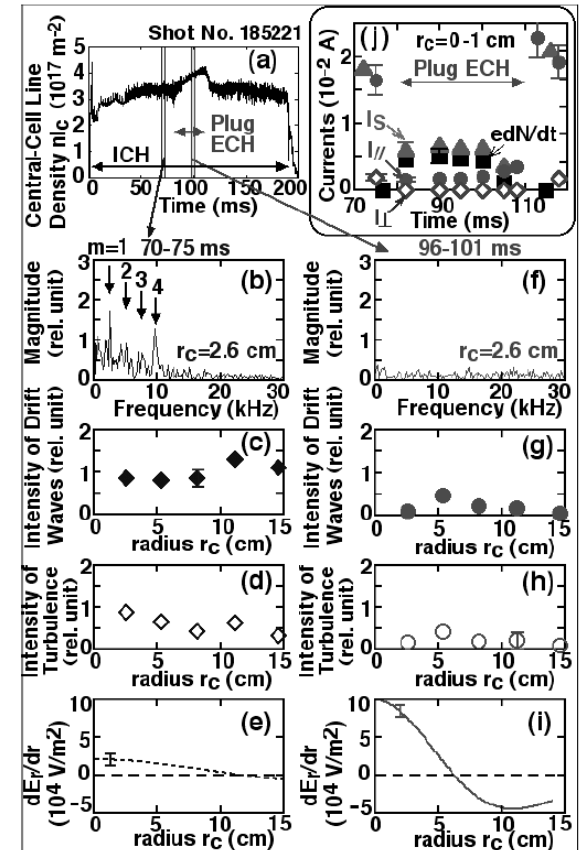


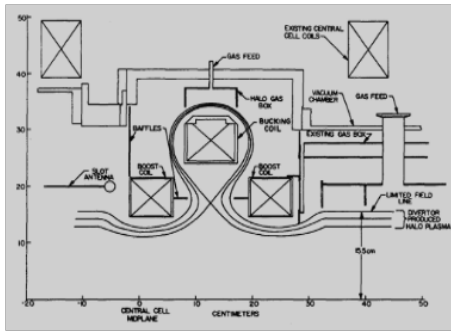
Fig.6. Contours of central-cell x-ray intensities in (a) strong and (b) weak E_r shear cases. "Hot-colored areas" illustrate higher plasma-pressure locations. Vortex-like structures are found in (b).



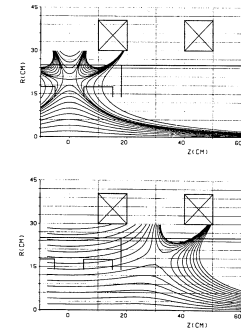
PRL **94**, 085002 (2005) Observation of the Effects of Radially Sheared Electric Fields on the Suppression of Turbulent Vortex Structures and the Associated Transverse Loss in GAMMA 10



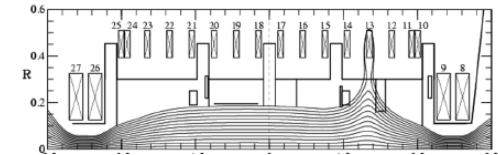
Divertor Stabilization (electrical short-circuit for $m=1$ mode)



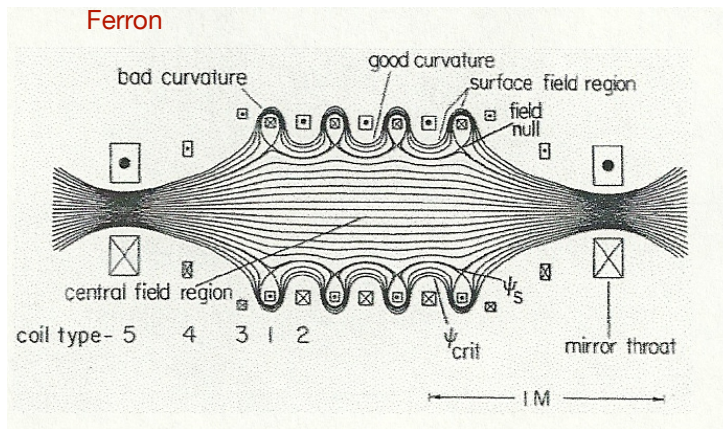
Tara



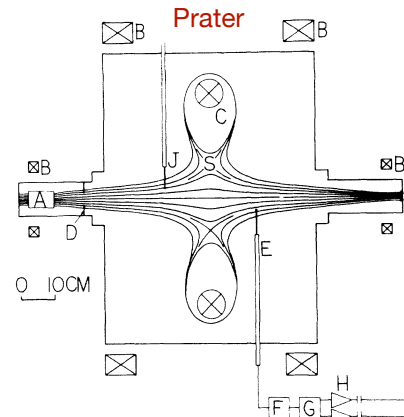
HIEI



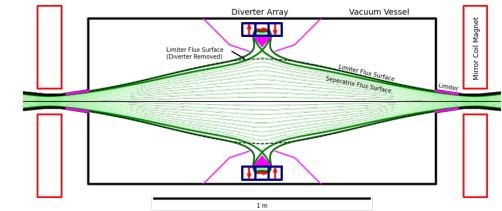
Hanbit



LAMEX



Stable with separatrix; unstable with limiter

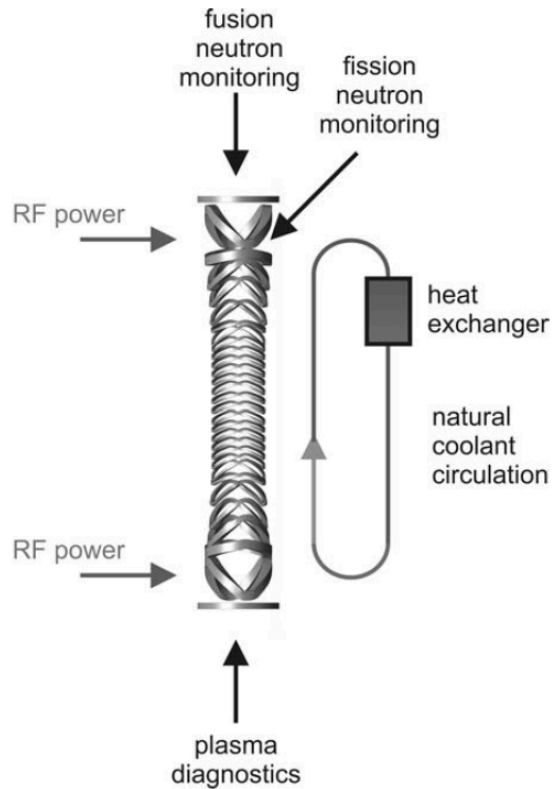


Permanent magnet configuration

Prater, R. Feedback Suppression of a Large-Growth-Rate Flute Mode. *Phys Rev Lett* **27**, 132-135 (1971).

HYBRID REACTOR STUDIES BASED ON THE STRAIGHT FIELD LINE MIRROR

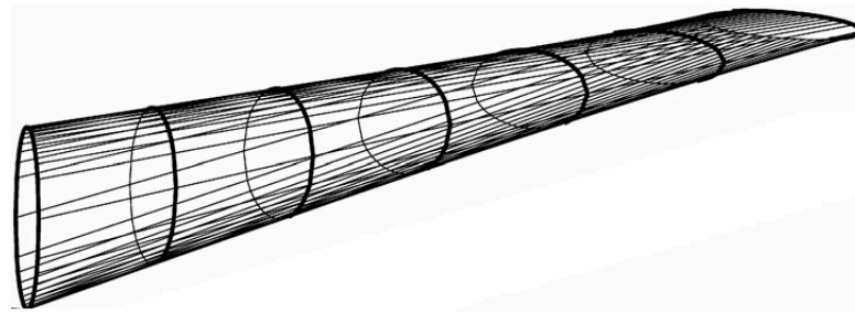
O. Ågren¹, V.E. Moiseenko², K. Noack¹, A. Hagnestål¹, J. Källne¹, H. Anglart³



Theory Challenge

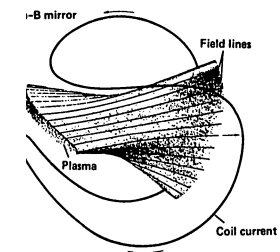
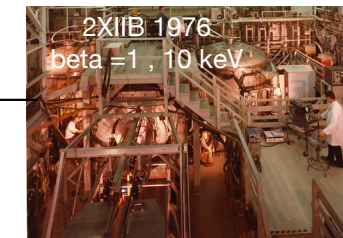
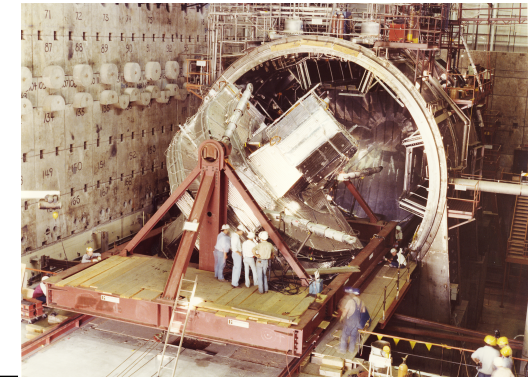
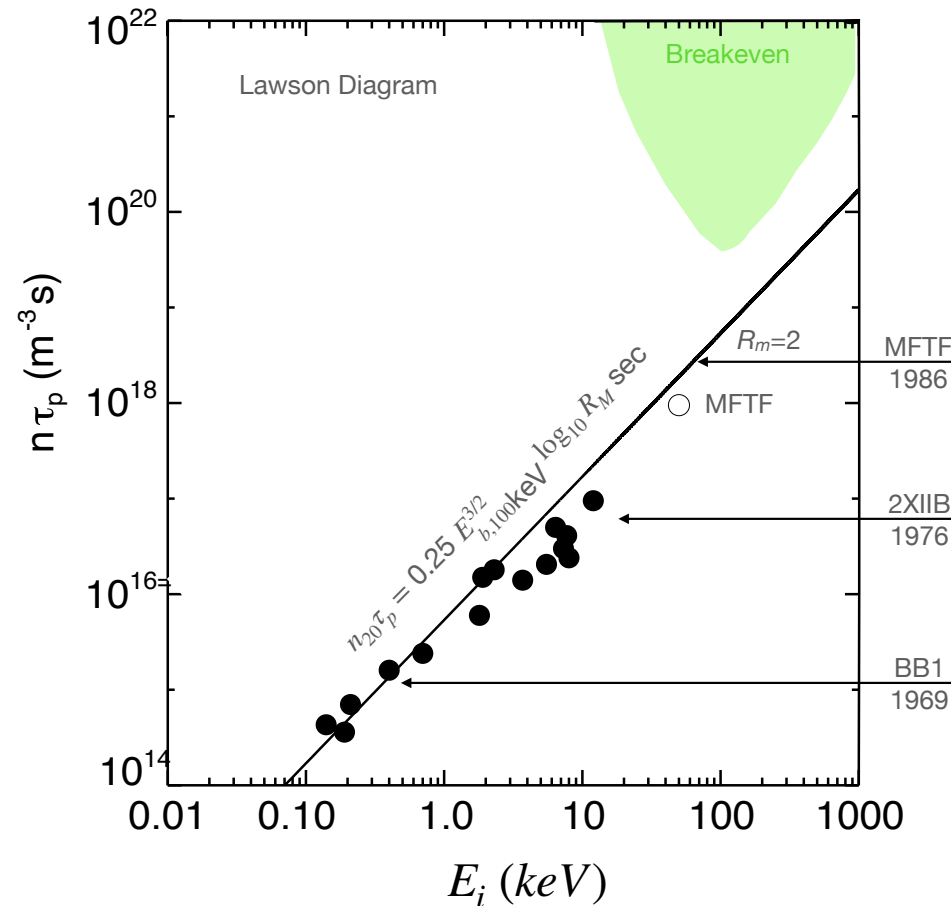
3D Optimization of an open geometry to

1. for magnetic well
2. high mirror ratio
3. omnigenous particle orbits
4. buildable coils
5. robust to high beta



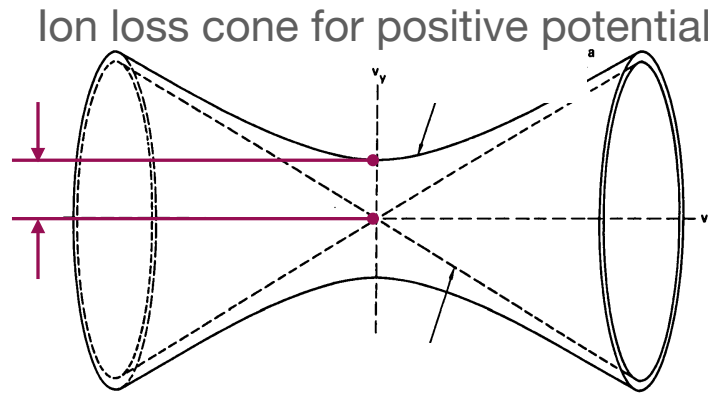
Still limited to $Rm \sim 4$

US Mirror Confinement up to 1986 showed classical mirror confinement works at low mirror ratio, if stabilized by non-axisymmetric coils

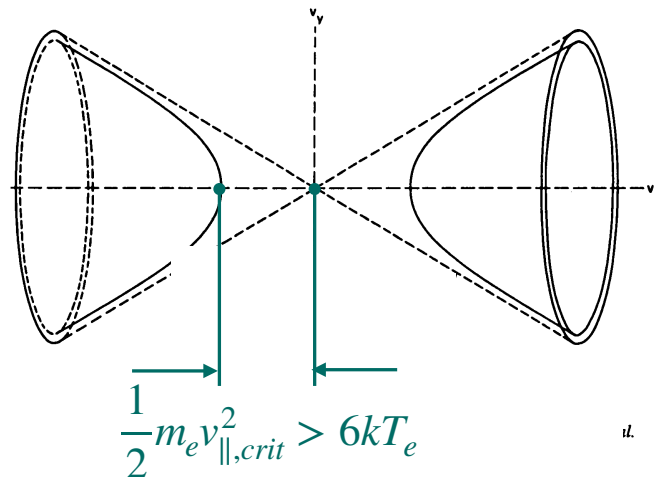


Including electrostatic potential changes things: An ambipolar potential is established to equilibrate ion and electron losses thus creating an “ambipolar hole” in $f_i(v_\perp, v_\parallel)$

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



electron loss cone for positive potential



Electron Energy Losses

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

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

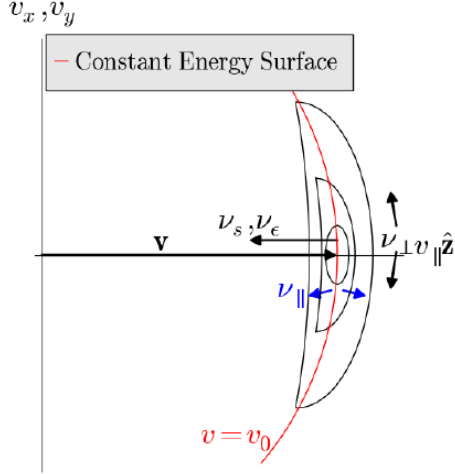
2. electrons confined electrostatically for many scattering times → nearly thermal

3. electron confinement improved by Pastukhov Factor

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

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

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



$$\begin{aligned} \frac{d}{dt} m_\alpha \mathbf{v} &= -\nu_s^{\alpha\beta} m_\alpha \mathbf{v} && \equiv m_\alpha \frac{\langle \Delta \mathbf{v} \rangle^{\alpha\beta}}{\Delta t} \text{ where } \nu_s^{\alpha\beta} = \left[\left(1 + \frac{m_\alpha}{m_\beta} \right) \Psi(x) \right] \nu_0^{\alpha\beta} \\ \frac{d}{dt} (\mathbf{v} - \bar{\mathbf{v}})_\perp^2 &= -\nu_\perp^{\alpha\beta} v^2 && \equiv \frac{\langle \Delta \mathbf{v}_\perp^2 \rangle^{\alpha\beta}}{\Delta t} \text{ where } \nu_\perp^{\alpha\beta} = 2 \left[\Psi + \Psi' - \frac{\Psi}{2x} \right] \nu_0^{\alpha\beta} \\ \frac{d}{dt} (\mathbf{v} - \bar{\mathbf{v}})_\parallel^2 &= -\nu_\parallel^{\alpha\beta} v^2 && \equiv \frac{\langle \Delta v_\parallel^2 \rangle^{\alpha\beta}}{\Delta t} \text{ where } \nu_\parallel^{\alpha\beta} = 2 \left[\frac{\Psi}{2x} \right] \nu_0^{\alpha\beta} \\ \frac{d}{dt} \left(\frac{1}{2} m v^2 \right) &= -\nu_\epsilon^{\alpha\beta} \frac{1}{2} m v^2 && \text{ where } \nu_\epsilon^{\alpha\beta} = 2 \left[\frac{m_\alpha}{m_\beta} \Psi - \Psi' \right] \nu_0^{\alpha\beta} \\ \frac{d}{dt} \left(\frac{1}{2} m v^2 \right) &\equiv -\mathbf{v} \cdot \frac{m \langle \Delta \mathbf{v} \rangle^{\alpha\beta}}{\Delta t} + \frac{\langle \Delta \mathbf{v}_\perp^2 \rangle^{\alpha\beta}}{\Delta t} + \frac{\langle \Delta v_\parallel^2 \rangle^{\alpha\beta}}{\Delta t} \text{ so that } \nu_\epsilon^{\alpha\beta} = -2\nu_s + \nu_\perp + \nu_\parallel \end{aligned}$$

$$\begin{aligned} \nu_0^{\alpha\beta} &= \frac{q_\alpha^2 q_\beta^2 n_\beta \ln \Lambda}{4\pi \epsilon_0^2 m_\alpha^2 v_\alpha^3} = \frac{\Gamma_{\alpha\beta}}{v_\alpha^3} \\ \Psi(x) &= \frac{2}{\pi^{1/2}} \int_0^x \sqrt{x'} e^{-x'} dx' \text{ and } \Psi'(x) = \frac{2}{\pi^{1/2}} \sqrt{x} e^{-x} \\ \text{For } x \ll 1 \quad \Psi(x) &\approx \frac{4}{3\pi^{1/2}} x^{3/2} \text{ and } \Psi'(x) \approx \frac{2}{\pi^{1/2}} \sqrt{x} \\ \text{For } x \rightarrow \infty \quad \Psi(x) &\approx 1 \text{ and } \Psi'(x) \approx 0 \end{aligned}$$

$x \ll 1$	$x \gg 1$
$\Psi(x) \approx \frac{4}{3\pi^{1/2}} \left(1 - \frac{3x}{2} + \frac{3x^2}{2} - \dots \right)$	$\Psi(x) \approx 1 - \frac{2\sqrt{x}}{\sqrt{\pi}} e^{-x} \left(1 + \frac{1}{2x} - \frac{1}{4x^2} + \dots \right)$
$\Psi'(x) \approx \frac{2\pi^{1/2}}{\sqrt{x}} \left(1 - x + \frac{x^2}{2} - \dots \right)$	$\Psi'(x) = \frac{2\sqrt{x}}{\sqrt{\pi}} e^{-x}$
$\Psi + \Psi' - \frac{\Psi}{2x} \approx \frac{4}{3\pi^{1/2}} \left(1 - \frac{3x}{2} + \frac{3x^2}{2} - \dots \right)$	$\Psi + \Psi' - \frac{\Psi}{2x} \approx 1 - \frac{1}{2x} + \frac{e^{-x}}{\sqrt{\pi x}} \left(1 - \frac{1}{2} + \dots \right)$
$\frac{\Psi}{x} \approx \frac{4}{3\pi^{1/2}} \left(1 - \frac{3x}{2} + \frac{3x^2}{2} - \dots \right)$	$\frac{\Psi}{x} \approx \frac{1}{x} - \frac{2\sqrt{x}}{\sqrt{\pi}} e^{-x} \left(1 + \frac{1}{2x} - \frac{1}{4x^2} + \dots \right)$

Example: fast ions slowing on background plasma (α particles or neutral beam injected ions)

consider slowing on electrons and ions, $n_e \sim n_i, Z_i = 1$ with $v_{Ti} \ll v_f \ll v_{Te}$ so that $x^{fle} = \frac{m_e v_f^2}{2T_e} \ll 1, x^{fli} = \frac{m_i v_f^2}{2T_i} \gg 1$

$$\frac{\nu_s^{fle}}{\nu_s^{fli}} \sim \frac{\left(1 + \frac{m_b}{m_e} \right) \frac{4}{3\pi^{1/2}} x^{3/2}}{1 + \frac{m_b}{m_i}} \sim \frac{\frac{4}{3\pi^{1/2}} \left(\frac{m_e}{m_b} \right)^{1/2} \left(\frac{E_b}{T_e} \right)^{3/2}}{1 + \frac{m_b}{m_i}}, \text{ using } x = \frac{m_e}{m_b} \frac{E_b}{T_e}. \text{ These are approximately equal when } \frac{E_c}{T_e} \sim \left(\frac{3}{4} \pi^{1/2} \left(1 + \frac{m_f}{m_i} \right) \right)^{2/3} \left(\frac{m_f}{m_e} \right)^{1/3}.$$

For 3.5 MeV α , $E_c \sim 44T_e$
For H NBI in $E_c \sim 15T_e$

$$\frac{\nu_\perp^{fle}}{\nu_\perp^{fli}} \sim \frac{\left(1 + \frac{m_b}{m_e} \right)}{2} \sim \frac{m_b}{2m_e} \gg 1 \text{ and } \frac{\nu_\parallel^{fli}}{\nu_\parallel^{fle}} \sim \frac{\left(1 + \frac{m_f}{m_i} \right)}{2} \sim \frac{m_f}{2m_i} \sim 1$$

If $E_f > E_c$ Fast ions slow on electrons before pitch angle scattering on background ions

Fast ion slowing down

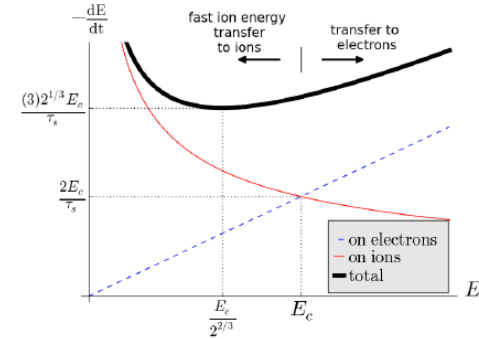
$$\begin{aligned}
 \frac{dv_f}{dt} &\approx - \left(\nu_0^{fli} \left(1 + \frac{m_f}{m_i} \right) + \nu_0^{fle} \left(1 + \frac{m_f}{m_e} \right) \frac{4}{3\pi^{1/2}} x^{3/2} \right) v_f \\
 &\approx - \Gamma_0^{fle} \left(\frac{\Gamma^{fli}}{\Gamma^{fle}} \frac{\left(1 + \frac{m_f}{m_i} \right)}{v^3} + \frac{m_f}{m_e} \frac{4}{3\pi^{1/2}} \frac{x^{3/2}}{v^3} \right) v_f \\
 &\approx - \Gamma_0^{fle} \frac{m_f}{m_e} \frac{4}{3\pi^{1/2}} \frac{1}{v_{Te}^3} \left(\frac{\Gamma^{fli}}{\Gamma^{fle}} \frac{m_e}{m_f} \frac{3\pi^{1/2}}{4} \left(1 + \frac{m_f}{m_i} \right) \frac{v_{Te}^3}{v^3} + 1 \right) v_f \\
 &= \nu_s^{fle} \left(1 + \frac{v_c^3}{v^3} \right) v_f \text{ with } \frac{1}{2} m_f v_c^2 = E_c
 \end{aligned}$$

$$v^2 \frac{dv}{dt} = -\frac{v^3}{\tau_s} \left[1 + \frac{v_c^3}{v^3} \right] \rightarrow \frac{1}{3} d(v^3) = -\frac{dt}{\tau_s} [v^3 + v_c^3]$$

$$dt = -\frac{\tau_s}{3} \frac{d(v^3)}{v^3 + v_c^3} \Rightarrow \int_{t=0}^t dt' = -\frac{\tau_s}{3} \ln(v^3 + v_c^3) \Big|_{v'=v_0}^{v'=v},$$

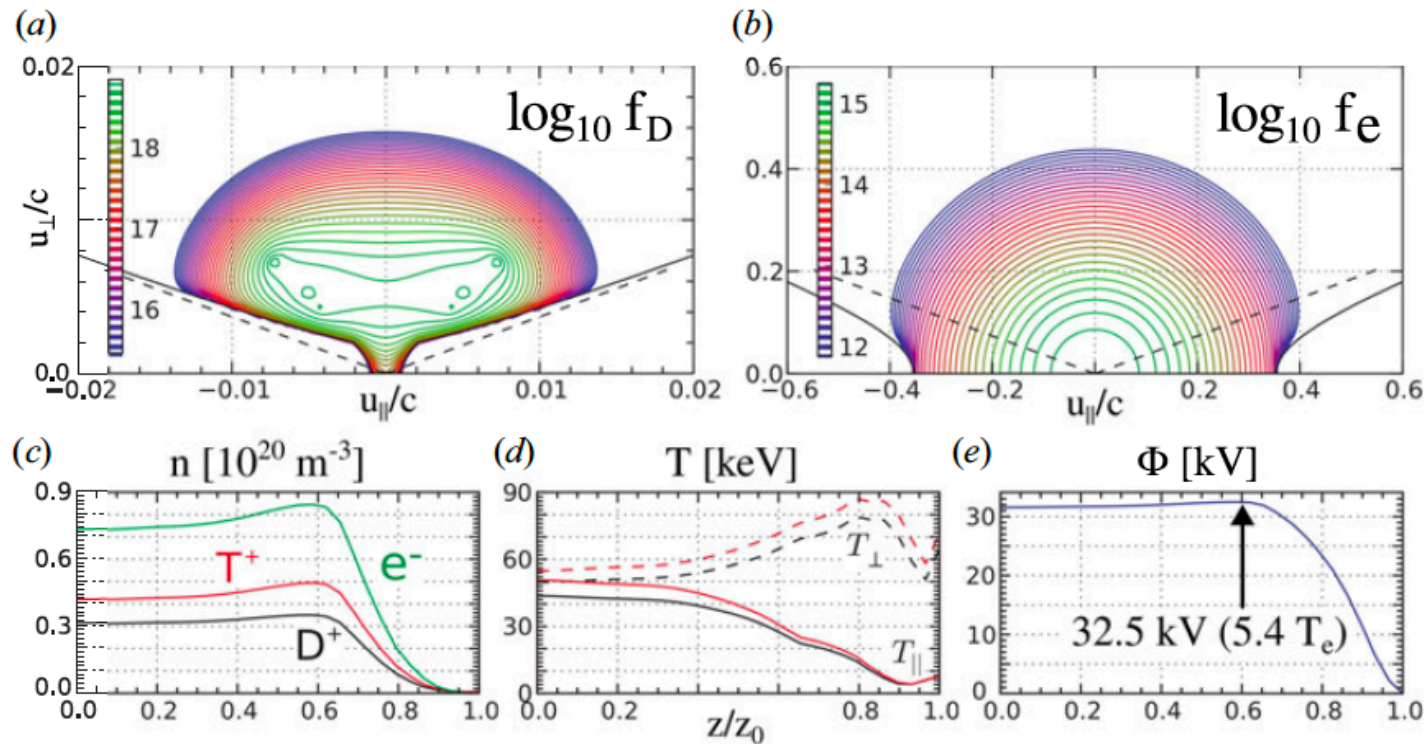
$$t = \frac{\tau_s}{3} \ln \left(\frac{v_0^3 + v_c^3}{v^3 + v_c^3} \right),$$

$$v^3 = (v_0^3 + v_c^3) e^{-3t/\tau_s} - v_c^3.$$



For the mirror we can generalize this to assume that if $E_b > E_{crit}$ equivalent to $T_e \gtrsim E_{nbi}/15$ for pitch angle scattering dominated mirror distribution function, and that $\frac{\nu_{\perp}^{ii}}{\nu_{\perp}^{ie}} \sim \frac{m_i}{m_e}$ so that confinement is dominated by ion-ion collisions

Illustrative Example midplane distribution functions of self-consistent bounce-averaged Fokker-Planck Solution (CQL3D) for with Sloshing ions



MHD Equilibrium

The MHD of motion with anisotropic pressure is

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \mathbf{J} \times \mathbf{B} - \nabla \cdot \bar{\mathbf{P}}. \quad \mathbf{J} \times \mathbf{B} = \nabla \cdot \bar{\mathbf{T}}, \text{ with Now assume equilibrium is time independent and not flowing so } \mathbf{u} = 0, \text{ although interesting to include } \mathbf{u} = U\mathbf{b}$$

$$\bar{\mathbf{P}} = \begin{pmatrix} p_{\perp} & 0 & 0 \\ 0 & p_{\perp} & 0 \\ 0 & 0 & p_{\parallel} \end{pmatrix} = p_{\perp} \bar{\mathbf{I}} + (p_{\parallel} - p_{\perp}) \hat{\mathbf{b}}\hat{\mathbf{b}}, \text{ and } \bar{\mathbf{T}} = \begin{pmatrix} -\frac{B^2}{2\mu_0} & 0 & 0 \\ 0 & -\frac{B^2}{2\mu_0} & 0 \\ 0 & 0 & \frac{B^2}{2\mu_0} \end{pmatrix} = -\frac{B^2}{2\mu_0} \bar{\mathbf{I}} + \frac{B^2}{\mu_0} \hat{\mathbf{b}}\hat{\mathbf{b}}$$

$$\mathbf{u} \cdot \nabla \mathbf{u} = u_{\parallel}^2 \mathbf{b} \cdot \nabla \mathbf{b} + \mathbf{b}(\mathbf{b} \cdot \nabla) \frac{u_{\parallel}^2}{2} - \frac{u_{\theta}^2}{r} \hat{\mathbf{r}} = u_{\parallel}^2 \mathbf{b} \cdot \nabla \mathbf{b} + \mathbf{b}(\mathbf{b} \cdot \nabla) \frac{u_{\parallel}^2}{2} - \nabla \frac{r^2 \Omega^2}{2}$$

$$-\nabla \cdot \bar{\mathbf{P}} = -\frac{\partial}{\partial x_j} P_{ji} = -\nabla p_{\perp} - \nabla \cdot (p_{\parallel} - p_{\perp}) \hat{\mathbf{b}}\hat{\mathbf{b}}$$

Use tensor identities with $f = p_{\parallel} - p_{\perp}$, noting that $\hat{\mathbf{b}}\hat{\mathbf{b}} = \mathbf{B} \frac{\hat{\mathbf{b}}}{B}$, and choosing $\mathbf{C} = \mathbf{B}$ and $\mathbf{D} = \frac{\hat{\mathbf{b}}}{B}$

Useful Tensor Identities

$$\nabla \cdot (f \bar{\mathbf{T}}) = \nabla f \cdot \bar{\mathbf{T}} + f \nabla \cdot \bar{\mathbf{T}} \text{ and } \nabla \cdot (\mathbf{CD}) = (\nabla \cdot \mathbf{C})\mathbf{D} + (\mathbf{C} \cdot \nabla)\mathbf{D}$$

$$\begin{aligned} -\nabla \cdot \bar{\mathbf{P}} &= -\nabla p_{\perp} - \nabla (p_{\parallel} - p_{\perp}) \cdot \hat{\mathbf{b}}\hat{\mathbf{b}} - (p_{\parallel} - p_{\perp}) \nabla \cdot \hat{\mathbf{b}}\hat{\mathbf{b}} & \nabla \cdot \bar{\mathbf{T}} &= -\nabla \frac{B^2}{2\mu_0} + \nabla \frac{B^2}{\mu_0} \cdot \hat{\mathbf{b}}\hat{\mathbf{b}} + \frac{B^2}{\mu_0} \nabla \cdot \hat{\mathbf{b}}\hat{\mathbf{b}} \\ \nabla \cdot \hat{\mathbf{b}}\hat{\mathbf{b}} &= (\nabla \cdot \mathbf{B}) \frac{\hat{\mathbf{b}}}{B} + B (\hat{\mathbf{b}} \cdot \nabla) \frac{\hat{\mathbf{b}}}{B} = (\hat{\mathbf{b}} \cdot \nabla) \hat{\mathbf{b}} + \frac{\hat{\mathbf{b}}}{B} (\hat{\mathbf{b}} \cdot \nabla) B & \nabla \cdot \hat{\mathbf{b}}\hat{\mathbf{b}} &= (\nabla \cdot \mathbf{B}) \frac{\hat{\mathbf{b}}}{B} + B (\hat{\mathbf{b}} \cdot \nabla) \frac{\hat{\mathbf{b}}}{B} = (\hat{\mathbf{b}} \cdot \nabla) \hat{\mathbf{b}} + \frac{\hat{\mathbf{b}}}{B} (\hat{\mathbf{b}} \cdot \nabla) B \end{aligned}$$

So that

$$-\nabla \cdot \bar{\mathbf{P}} = -\nabla_{\perp} p_{\perp} - (p_{\parallel} - p_{\perp}) \hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}} - \hat{\mathbf{b}} \left(\frac{\partial p_{\parallel}}{\partial \ell} - \frac{p_{\parallel} - p_{\perp}}{B} \frac{\partial B}{\partial \ell} \right). \text{ Now recall that } \mathbf{J} \times \mathbf{B} = \nabla \cdot \bar{\mathbf{T}} = -\nabla_{\perp} \frac{B^2}{2\mu_0} - \frac{B^2}{\mu_0} \boldsymbol{\kappa} \text{ so}$$

$$\nabla \cdot \bar{\mathbf{T}} - \nabla \cdot \bar{\mathbf{P}} = -\nabla_{\perp} \left(\frac{B^2}{2\mu_0} + p_{\perp} \right) + \rho \frac{v_{\theta}^2}{r} \hat{\mathbf{r}} - \left(\frac{B^2}{\mu_0} + p_{\parallel} + \rho v_{\parallel}^2 - p_{\perp} \right) \boldsymbol{\kappa} - \hat{\mathbf{b}} \left(\frac{\partial}{\partial \ell} (p_{\parallel} + \rho u_{\parallel}^2) - \frac{p_{\parallel} - p_{\perp}}{B} \frac{\partial B}{\partial \ell} \right)$$

Parallel Force Balance Equilibrium

For the case of anisotropic pressure, the equilibrium conditions must be satisfied both parallel to and perpendicular to the magnetic field.

For parallel force balance
$$\frac{\partial p_{\parallel}}{\partial \ell} + \frac{p_{\perp} - p_{\parallel}}{B} \frac{\partial B}{\partial \ell} = 0$$

Very convenient and also sufficiently general to assume $p_{\perp} \equiv p_{\perp}(\psi, B)$ and $p_{\parallel} \equiv p_{\parallel}(\psi, B)$ in which case parallel force balance can also be written as

$$\frac{\partial p_{\parallel}}{\partial B} + \frac{p_{\perp} - p_{\parallel}}{B} = 0. \quad \text{Pressure can be balance with increasing magnetic field strength (the mirror force).}$$

If $p_{\parallel}$ is known, there is a unique $p_{\perp}(B) = -B^2 \frac{\partial}{\partial B} \frac{p_{\parallel}}{B}$ in equilibrium.

Perpendicular Force Balance

Recalling that $\mathbf{J} \times \mathbf{B} = \nabla \cdot \bar{\bar{\mathbf{T}}} = -\nabla_{\perp} \frac{B^2}{2\mu_0} + \frac{B^2}{\mu_0} \boldsymbol{\kappa}$

As spelled out neatly by Grad, the equilibrium condition is

$$\nabla_{\perp} \left(p_{\perp} + \frac{B^2}{2\mu_0} \right) = \sigma B^2 \boldsymbol{\kappa} \text{ where } \sigma = \left(\frac{1}{\mu_0} + \frac{p_{\perp} - p_{\parallel}}{B^2} \right)$$

“pressure”

“tension”

$$\begin{aligned} \mathbf{J}_{\perp} &= \frac{\mathbf{B} \times \nabla \cdot \bar{\bar{\mathbf{T}}}}{B^2} \\ &= \frac{\mathbf{B} \times \left(\nabla_{\perp} p_{\perp} + (p_{\parallel} - p_{\perp}) \hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}} \right)}{B^2} \\ &= R \frac{\partial p_{\perp}}{\partial \psi} \hat{\boldsymbol{\phi}} + \frac{\mathbf{B} \times \left((p_{\parallel} - p_{\perp}) \hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}} \right)}{B^2} \\ J_{\phi} &= R \frac{\partial p_{\perp}}{\partial \psi} + \frac{\partial p_{\parallel}}{\partial B} |\boldsymbol{\kappa}| \end{aligned}$$

and when pressure is isotropic, gives just magnetic tension force on RHS. Note that this equilibrium will be unstable when $\sigma < 0$. Easy to see if that if the plasma bulges outward from equilibrium and kappa gets larger, the equilibrium will be lost. This instability, largely arising from the flacidity introduced by $p_{\parallel}$ reducing the restoring force of magnetic tension, is known as the **Firehose Instability**.

Perpendicular Force Balance with parallel flow

Recalling that $\mathbf{J} \times \mathbf{B} = \nabla \cdot \bar{\bar{\mathbf{T}}} = -\nabla_{\perp} \frac{B^2}{2\mu_0} + \frac{B^2}{\mu_0} \boldsymbol{\kappa}$

As spelled out neatly by Grad, the equilibrium condition is

$$\nabla_{\perp} \left(p_{\perp} + \frac{B^2}{2\mu_0} \right) = \sigma B^2 \boldsymbol{\kappa} \text{ where } \sigma = \left(\frac{1}{\mu_0} + \frac{p_{\perp} - p_{\parallel} - \rho u_{\parallel}^2}{B^2} \right)$$

“pressure”

“tension”

and when pressure is isotropic, gives just magnetic tension force on RHS. Note that this equilibrium will be unstable when $\sigma < 0$. Easy to see if that if the plasma bulges outward from equilibrium and kappa gets larger, the equilibrium will be lost. This instability, largely arising from the flacidity introduced by $p_{\parallel}$ anisotropy reducing the restoring force of magnetic tension, is known as the **Firehose Instability**.

Mirror Instability

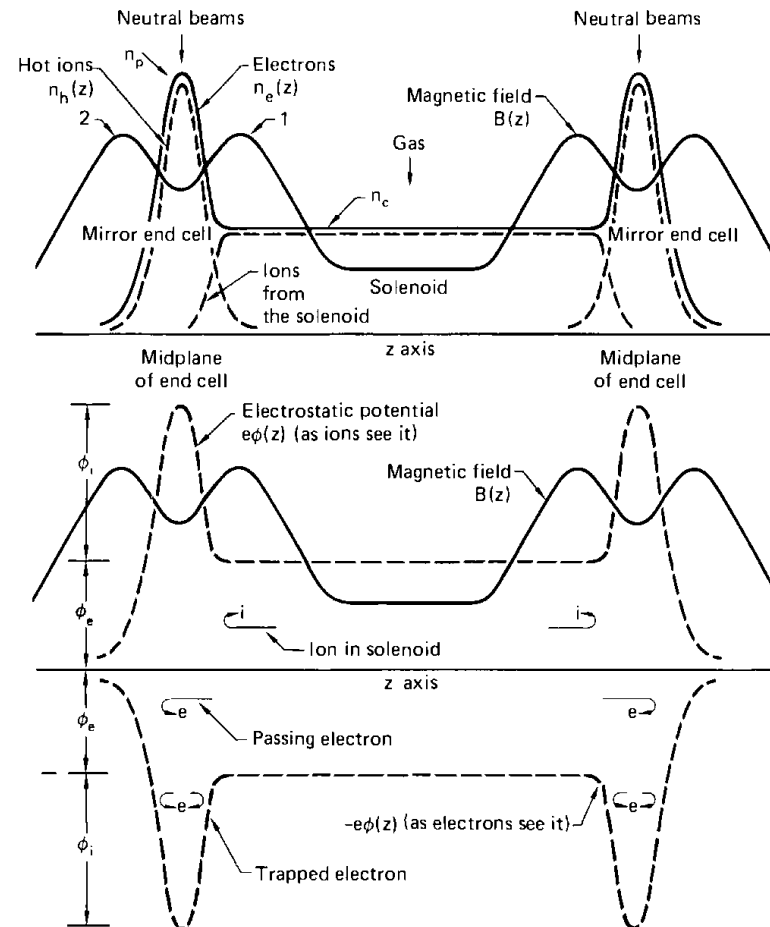
There is a second criteria on equilibrium, which is that $p^* = p_{\perp} + \frac{B^2}{2\mu_0}$ must be increasing as a function of B: $\frac{dp^*}{dB} > 0$. Newcomb refers to this as a positive compressibility condition. Imaging a small constriction in the cross section which in turn requires $\Delta B > 0$ since flux is conserved. When $\frac{dp^*}{dB} < 0$ there would be a decrease in total perpendicular pressure and the plasma would continue to contract in a Mirror Instability.

Physics Challenges

- Axial confinement
- MHD Stability
- Kinetic Stability and Fast Ion Confinement
- Electron Thermal Confinement
- Radial Transport

2. Mirror Variants

the Classical Tandem



Tandem Mirror uses very high energy (well confined) hydrogen ions in 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:

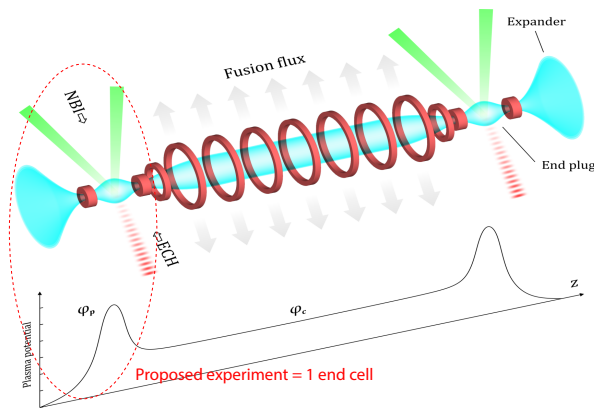
high energy ions

ambipolar potential associated with fast plug ions

Confined by potential of expander

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

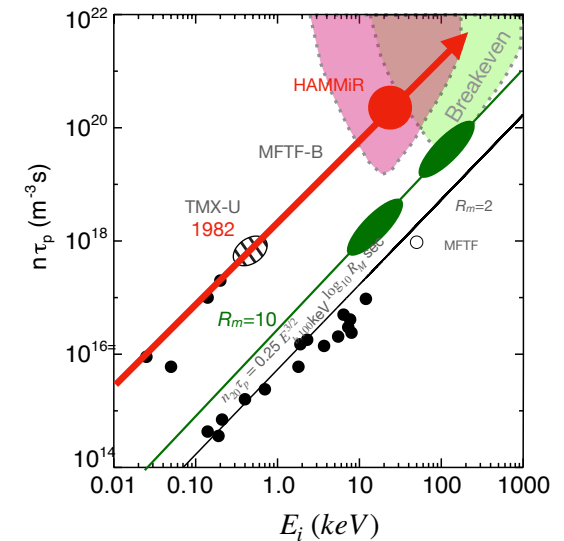
$$\Phi_i = \Phi_p - \Phi_c = T_{ep} \ln(n_p/n_c)$$



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

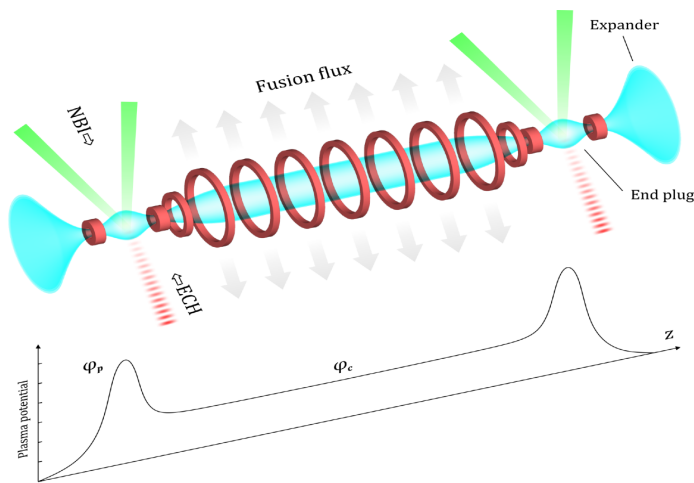
T. K. Fowler, R. W. Moir, and T. C. Simonen, *A New Simpler Way to Obtain High Fusion Power Gain in Tandem Mirrors*, Nucl Fusion **57**, 056014 (2017).

Pastukhov factor



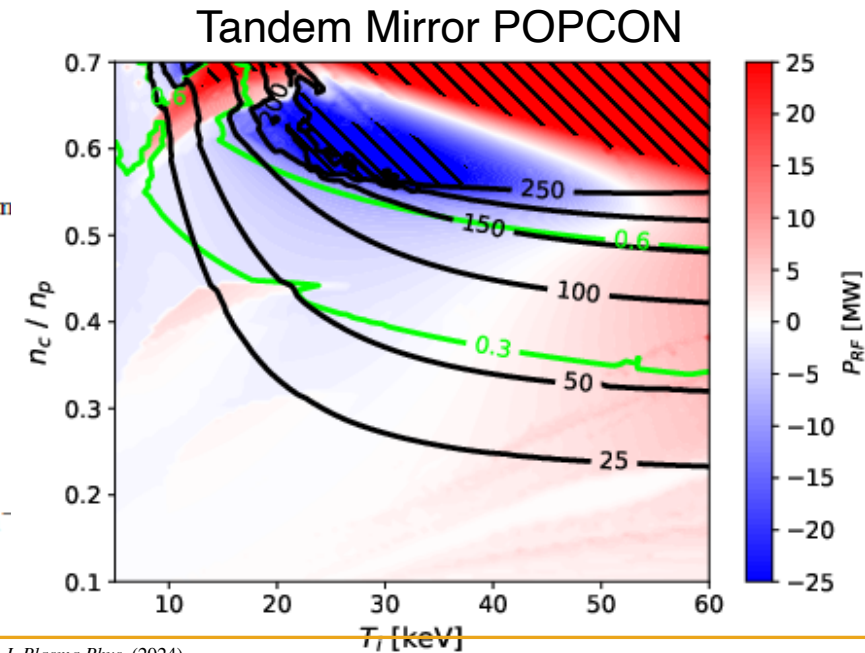
Compact, high field mirror also leads to attractive Tandem Mirror Designs

axisymmetric classical tandem mirror
(no thermal barriers)



A new simpler way to obtain high fusion power gain in tandem mirrors, Fowler, T. K., Moir, R. W. & Simonen, T. C.. *Nucl Fusion* 57, 056014 (2017).

End plug	
a_m	0.15 m
ℓ_p	4.5 m
B_m	25 T
B_0	4.0 T
$\langle n_{p0} \rangle$	$1.66 \times 10^{20} \text{ m}^{-3}$
$\langle \beta_{p0} \rangle$	0.58
E_{NBI}	240 keV
P_{NBI}	15 MW
Central cell	
a_c	0.54 m
ℓ_c	50 m
B_{0c}	3.0 T
β_c	0.6
n_c	$7.5 \times 10^{19} \text{ m}^{-3}$
T_{ic}	50 keV
T_{ec}	100 keV
P_{fus}	175 MW
Q	5.8



J. Plasma Phys. (2024)
Published by Cambridge University Press

Integrated modelling of equilibrium and transport in axisymmetric magnetic mirror fusion devices

S. J. Frank, J. Viola, Yu. V. Petrov, J. K. Anderson, D. Bindl, B. Biswas, J. Caneses, D. Endrizzi, K. Furlong, R. W. Harvey, C. M. Jacobson, B. Lindley, E. Marriott, O. Schmitz, K. Shih, C. B. Forest

the Gas Dynamic Trap

If gas is magwellian the losses out the ends can be estimated from

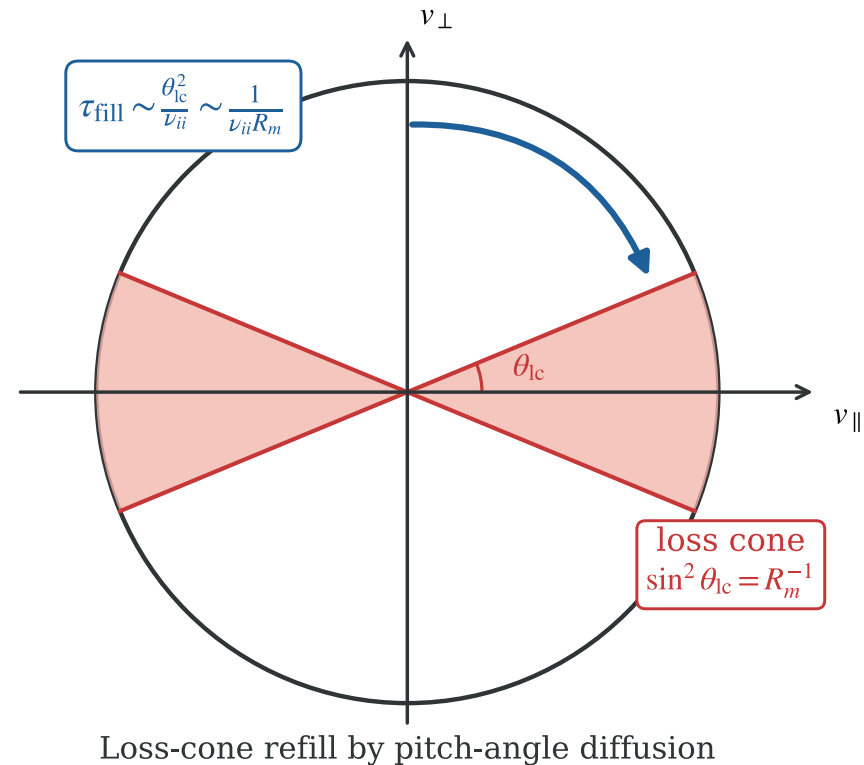
$$\frac{N}{\tau_{gdt}} = \frac{n\pi a^2 L}{\tau_{gdt}} = nc_s \pi a_T^2 \text{ or } \tau_{gdt} = \frac{LR_m}{c_s}$$

This can exceed the classical mirror predictions

$\tau \propto \tau_{ii} \ln R_M$ when

$$L > \lambda_{ii} \frac{\ln R_m}{R_m}$$

(using $\lambda_{ii} \approx c_s \tau_{ii}$)



the Gas Dynamic Trap

Bulk plasma:

$$L \gg \lambda_{ii} \frac{\ln R}{R}, \quad R = \frac{B_m}{B_0} - \text{mirror ratio}$$

$$\tau_{GDT} \sim \frac{nLS_0}{2nv_i S_m} = \frac{LR}{2v_i}$$

Fast ions:

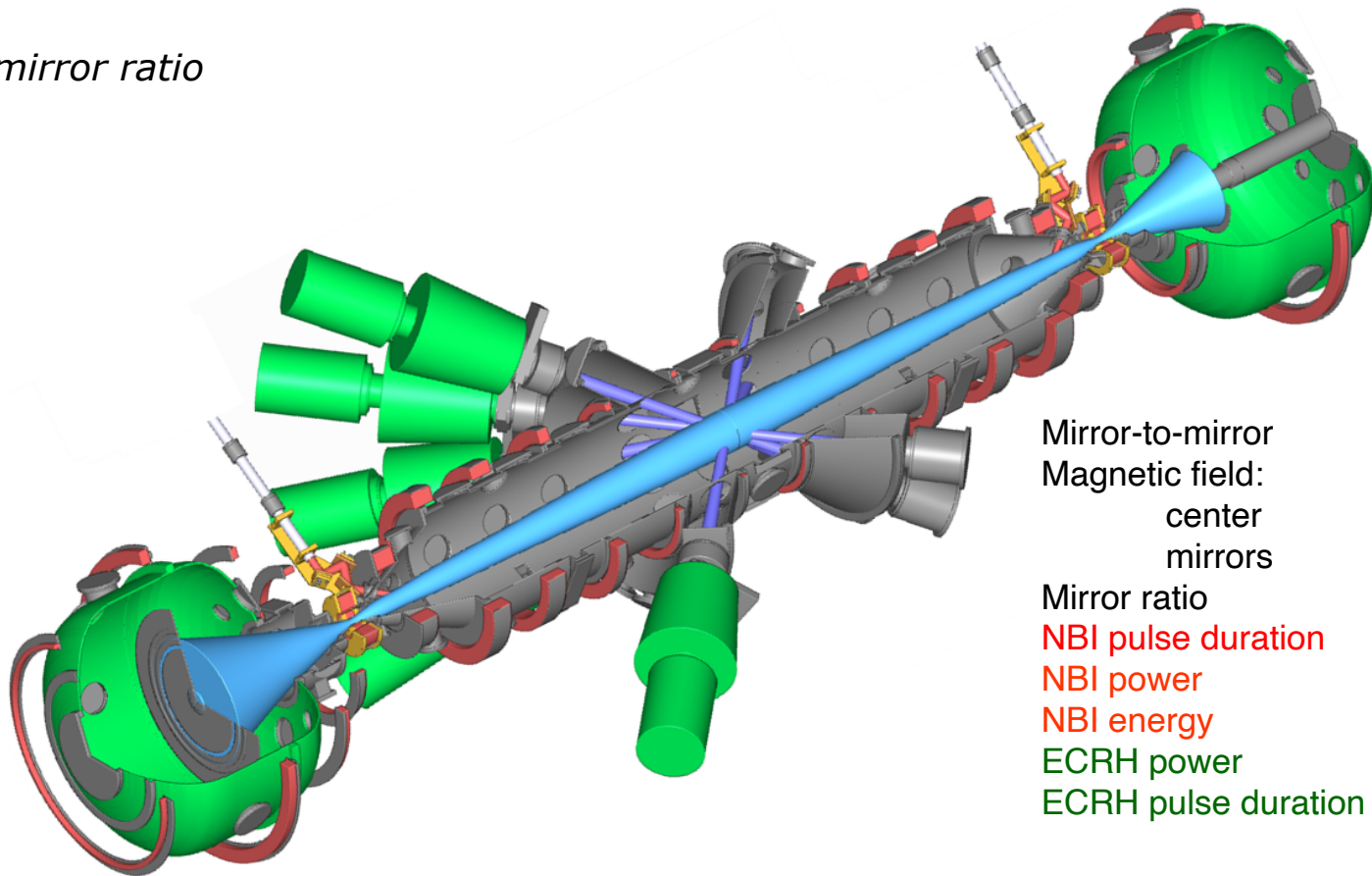
$$\tau_{adiab} \sim \tau_{ii} \ln R \gg \tau_{drag}$$

Bulk plasma:

Electrons: $\approx 2 \cdot 10^{19} \text{ m}^{-3}$, 250 – 900 eV;

Fast ions (H^+, D^+):

Up to $5 \cdot 10^{19} \text{ m}^{-3}$,
 $\langle E \rangle \approx 10 \text{ keV}$, $\beta \approx 0.5$



Mirror-to-mirror	7 m
Magnetic field:	
center	0.35 T
mirrors	12 T
Mirror ratio	35
NBI pulse duration	5 ms
NBI power	5 MW
NBI energy	23 keV
ECRH power	1.2 MW
ECRH pulse duration	8 ms

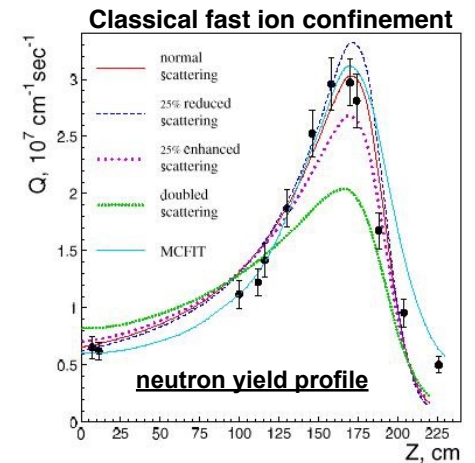
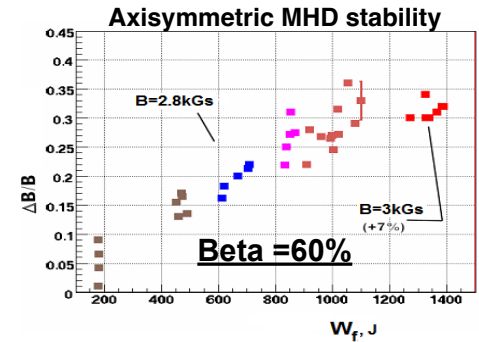
The Budker GDT

Three Game Changing Discoveries: A Simpler Fusion Concept?

Thomas C. Simonen¹

J Fusion Energ (2016) 35:63–68
DOI 10.1007/s10894-015-0017-2

1. **MHD stability in axisymmetric plasma with plasma beta of 60 %** has using vortex stabilization and good magnetic curvature expanders
2. **Micro-stability of energetic mirror trapped ions** has been achieved with densities reaching 10^{20} m^{-3} by skew injected neutral beams
3. **Electron temperatures up to 1 keV** have been achieved with Electron Cyclotron Heating (ECH) and large plasma expansion



Centrifugal Mirror

Guiding Center Hamiltonian for $\rho/L \ll 1$ are beads on a wire ($\psi = \text{const}$) with canonical variables ψ, B

$$H = \frac{1}{2}mv_{\parallel}^2 + \mu B + q\Phi + \frac{1}{2}mv_{\theta}^2$$

$$\text{Assume: } \Phi = \Phi(\psi, B), \mathbf{E} = -\frac{\partial\Phi}{\partial\psi}\bigg|_B \nabla\psi - \frac{\partial\Phi}{\partial B}\bigg|_{\psi} \nabla B \text{ so that } \mathbf{V}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2} = -r \frac{\partial\Phi}{\partial\psi}\bigg|_B \hat{\phi} \equiv r\omega(\psi, B)\hat{\phi} \text{ where } \omega(\psi, B) = \frac{\partial\Phi}{\partial\psi}\bigg|_B$$

$$H = \frac{1}{2}mv_{\parallel}^2 + \mu B + q\Phi - \frac{1}{2}mr^2\omega^2 \text{ or equivalently } H = \frac{1}{2}mv_{\parallel}^2 + \mu B + q\Phi - \frac{1}{2}mV_E^2(\psi, B)$$

$$\text{so that } \frac{1}{2}mv_{\parallel}^2 = \frac{1}{2}mv_{\parallel 0}^2 + \mu(B_0 - B) + q(\Phi_0 - \Phi) + \frac{1}{2}m(r^2\omega^2 - r_0^2\omega_0^2)$$

Gives a loss cone boundary at

$$\frac{1}{2}mv_{\perp 0}^2(R_M - 1) = \frac{1}{2}mv_{\parallel 0}^2 + q\Delta\Phi - \frac{1}{2}mr_0^2\omega_0^2 \left(1 - \frac{\omega_M^2}{\omega_0^2} \frac{1}{R_M}\right) \text{ with } \Delta\Phi = \Phi_0 - \Phi_M$$

For ions, with Ambipolar hole set by

$$0 = \frac{1}{2}mv_{\parallel 0}^2 + \frac{1}{2}mv_{\perp 0}^2(R_M - 1) + q\Delta\Phi - \frac{1}{2}mr_0^2\omega_0^2 \left(1 - \frac{\omega_M^2}{\omega_0^2} \frac{1}{R_M}\right)$$

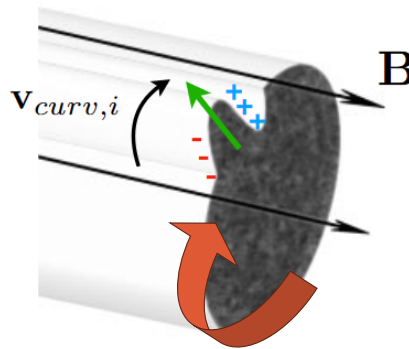
New advances in technology, computational capability and physics understanding are reinvigorating the magnetic mirror fusion concept



Commonwealth
Fusion Systems

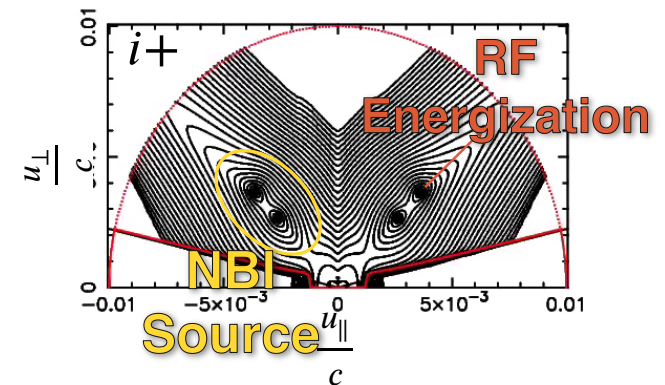
HTS

~ 2x field possible
from previous
technology



Advanced Stabilization

Axisymmetric mirrors
 $R_m \sim 10$ possible



Advanced heating systems

Modern NBI, ECH, and
ICRH systems.

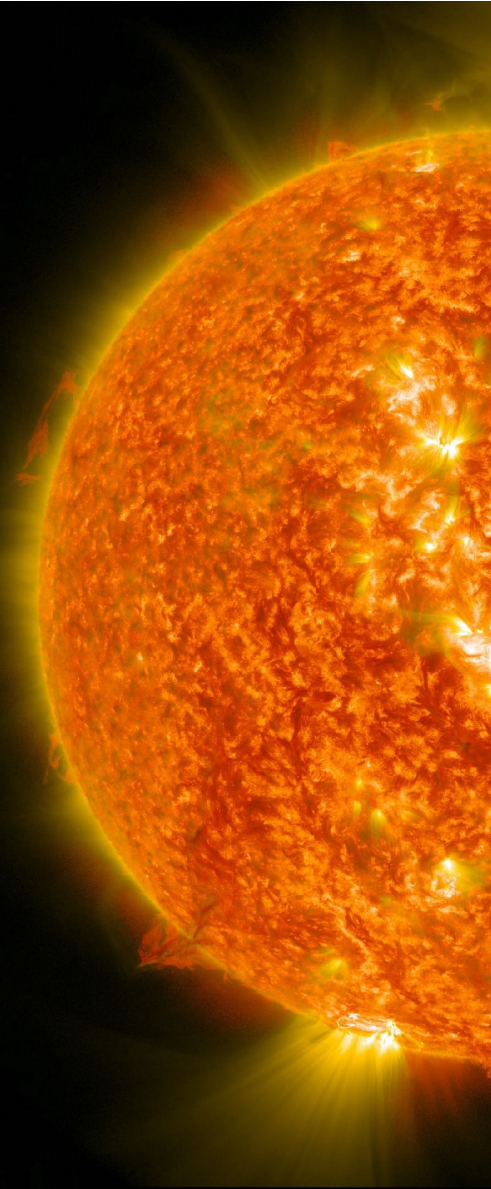


INDUSTRIAL HEAT & POWER FROM FUSION

is currently

- supporting WHAM operations through sponsored research
- in an ongoing unique public-private partnership with the University of Wisconsin and Realta

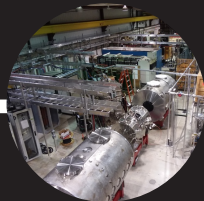
WHAM operates as one-team with UW staff, students, and Realta Fusion scientists planning and carrying out experiments



\$60M
investment to
date
Latest equity
financing -
\$36M Series A
in May 2025



**Powering data
centers & heavy
industry**



October 2020

Start of ARPA-E funded
project, WHAM

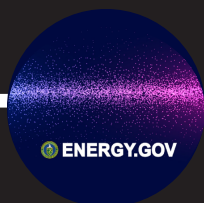
**REALTA
FUSION**

September 2022

Spin-out
established

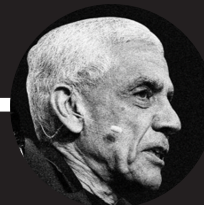
June 2024

U.S. Dept. of Energy
Milestone contract



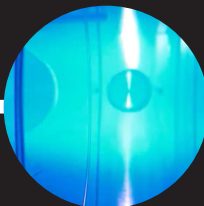
May 2023

Seed round led by
Khosla Ventures



July 2024

World-record breaking
first plasma: 17 Tesla



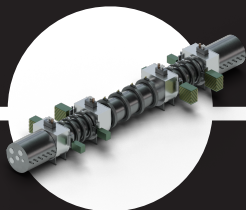
May 2025

Series A led
by Future Ventures



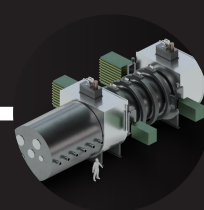
2030s

Hammir Fusion Power
Plant Deployment



2028

Anvil
Scale-Up



Realta Roadmap



(WHAM)

Demonstrate tech



Advance performance

Consolidate Physics Basis

REALTA
FORGE

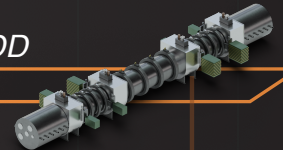
ANVIL^{*}-EP

+ Components

build

HAMMIR^{*}-DD

operate



Demonstrate Physics At Scale

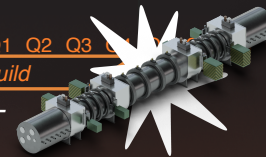
TRITIUM
FACILITY

Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4

Demonstrate Technology Integration

HAMMIR^{*}-DT

build



2024

2025

2026

2027

2028

2029

2030

2031

2032

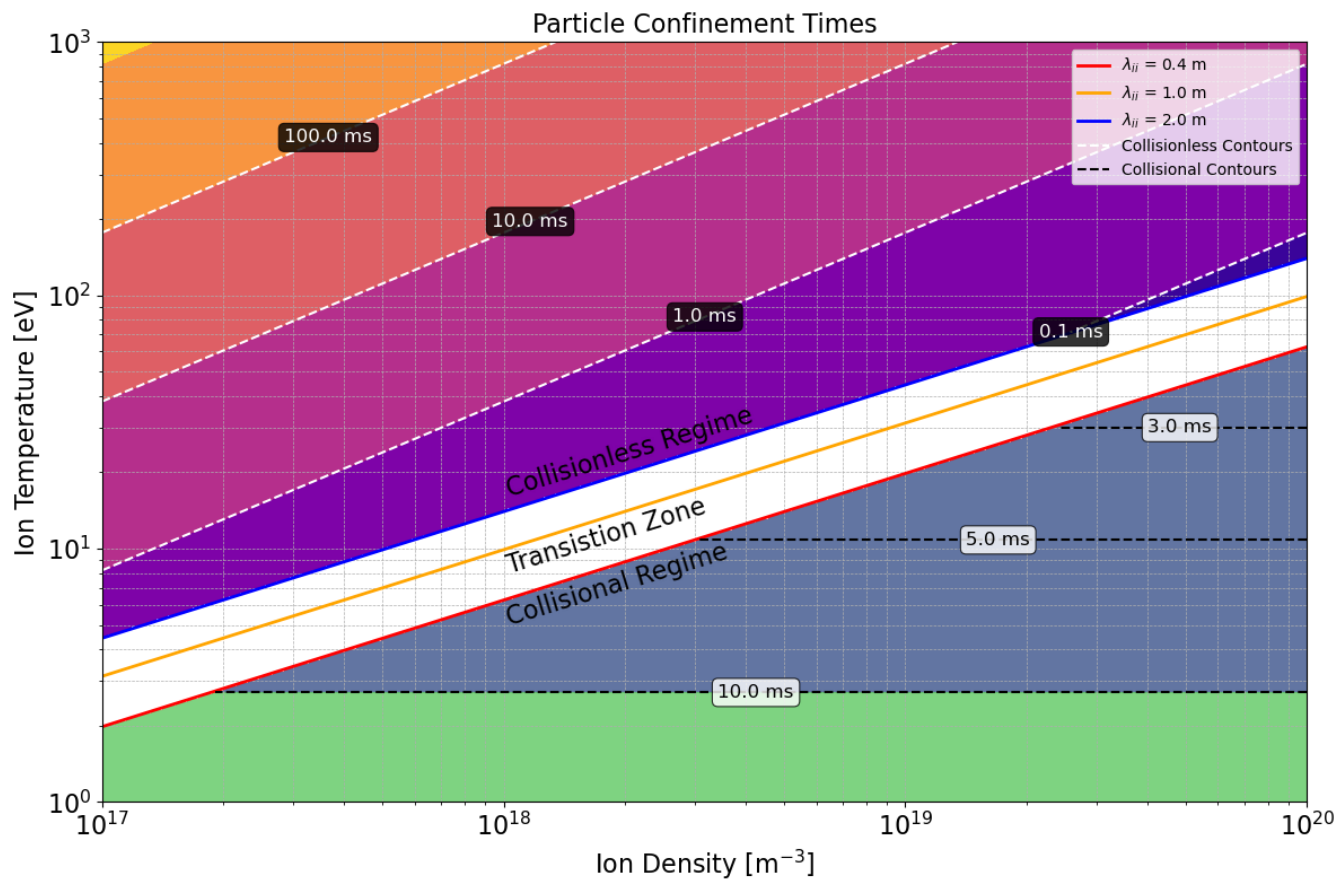
2033

2034

WHAM aspires to bridge the gap from gas dynamic to classical mirror in a compact axisymmetric geometry

classical “weakly collisional” mirror

$$\tau_p \sim \frac{\langle E_i \rangle^{3/2}}{n} \ln R_M$$



$$\lambda_{ij} \sim 2m$$

$$5\lambda_{ij} \sim 2m$$

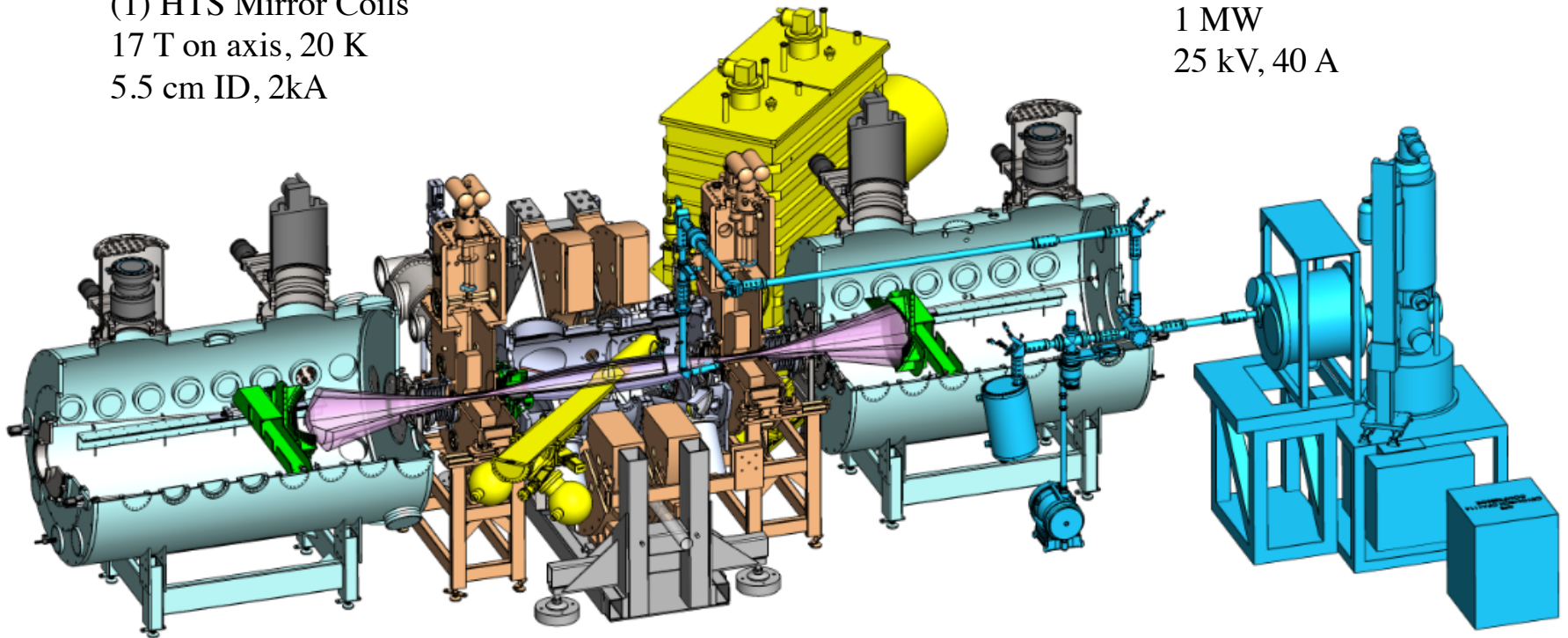
collisional “gas dynamic” mirror

$$\tau_p \sim \frac{R_M L}{c_s}$$

WHAM Overview

(1) HTS Mirror Coils
17 T on axis, 20 K
5.5 cm ID, 2kA

(3) Neutral Beam Injection
1 MW
25 kV, 40 A



(4) Biased Ring and Limiter
Up to 2.7 kV, 1.7 kA
10 kHz switching

(2) Electron Cyclotron Resonance Heating
1 MW, 110 GHz (4T)
70 kV, 30 A (at source)

Recycled components on WHAM kept costs down



Archimedes transmitter via **MIT PSFC**



MAX PLANCK INSTITUTE
FOR PLASMA PHYSICS



System	Phase 1 2024	Phase 2 2025
Mirror coils	17.05 T	17.05 T
End-ring biasing (stability)	2 MW bipolar waveforms	
NBI	~24 kV, <800 kW, 20 msec	
RF: fast wave		4 – 30 MHz, < 1 MW
ECH	110 GHz, <600 kW, 20 msec	
Vacuum	<2,000 L/s turbos / cryos	>100,000 L/s Ti, Ta gettering
Central field	< 0.3 T, R ~ 50 – 70	0.3 – 0.9 T, R = 20-50

HTS Magnets

24/7 operation. Multi-day charging time.

5.5 cm ID

Partially Insulated Co-winding

16 HTS, 1 SS stack

100 km tape per coil, 4mm width

Bmax: 17 T

Bmin: 0.25 T

Mirror Ratio: 68

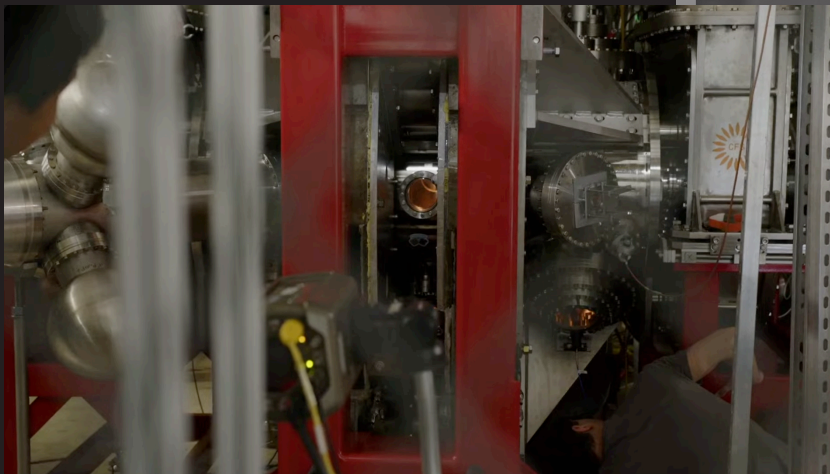


Kristofek IEEE (2025), Radovinsky IEEE (2023)

Parameter [unit]	Design target	Measured performance
Field on axis [T]	17	17.05
Peak field on winding pack [T]	20	*
Stored Energy (per magnet) [MJ]	3.2	*
Engineering current density [A/mm ²]	178	*
Operating temperature (1st stage) [K]	60	47.7
Operating temperature (2nd stage) [K]	20	11
Operating current [A]	2000	1727
Winding pack power (at full current) [W]	*	1.1
Estimated heat load to 1st stage [W]	180	167



From magnet delivery to plasma in 14 days



Climate

WHAM! Nuclear fusion experiment hits new record for magnet strength

Tim De Chant / 6:00 AM PDT • July 18, 2024

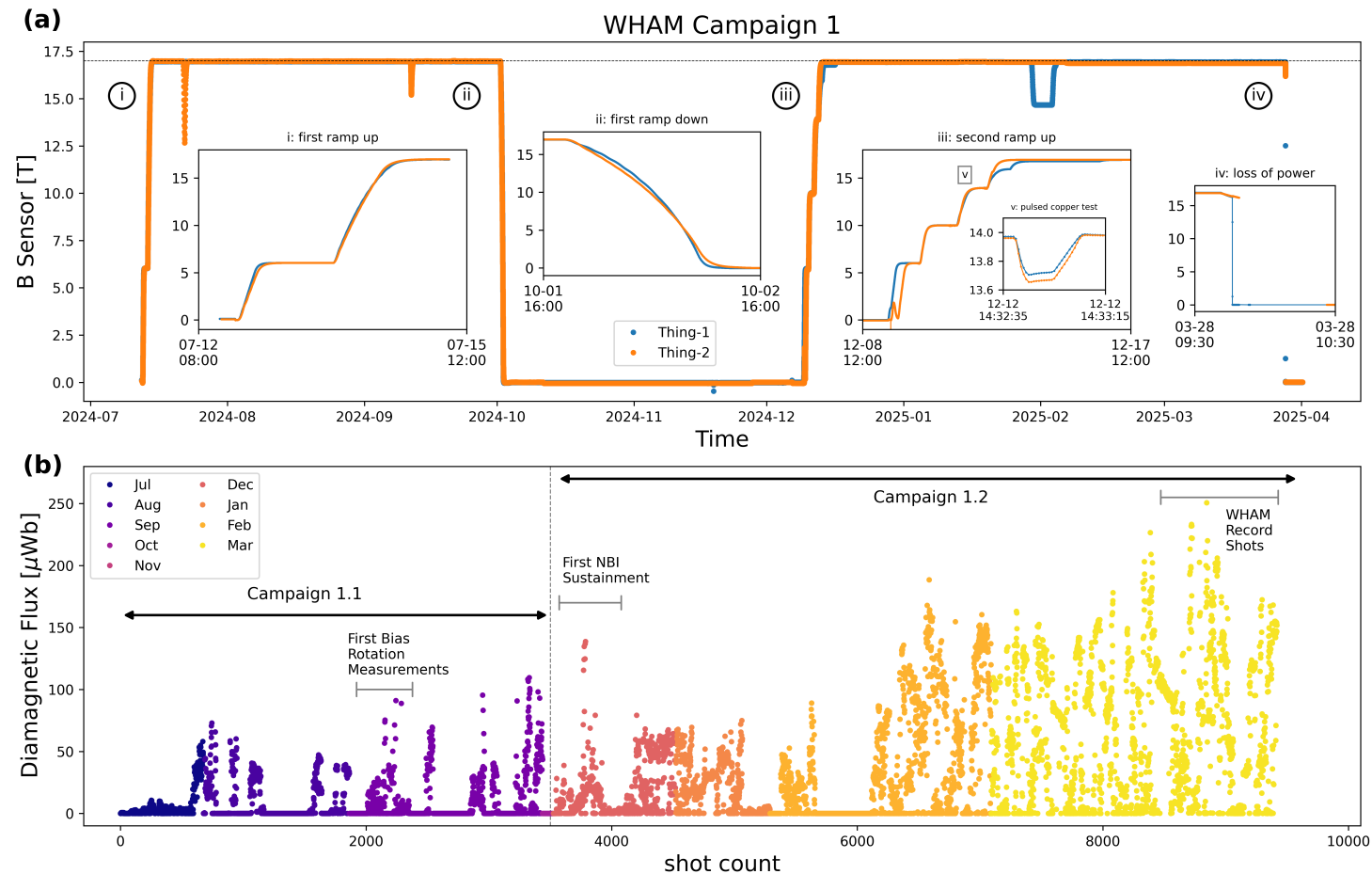
[Comment](#)



The most powerful magnets
ever used in a fusion machine

17 Tesla

WHAM HTS sets world record with multi month 17.0 T operation



ECH System

The gyrotron is a vacuum tube that produces high power microwaves.

ECH pulse responsible for plasma start up.

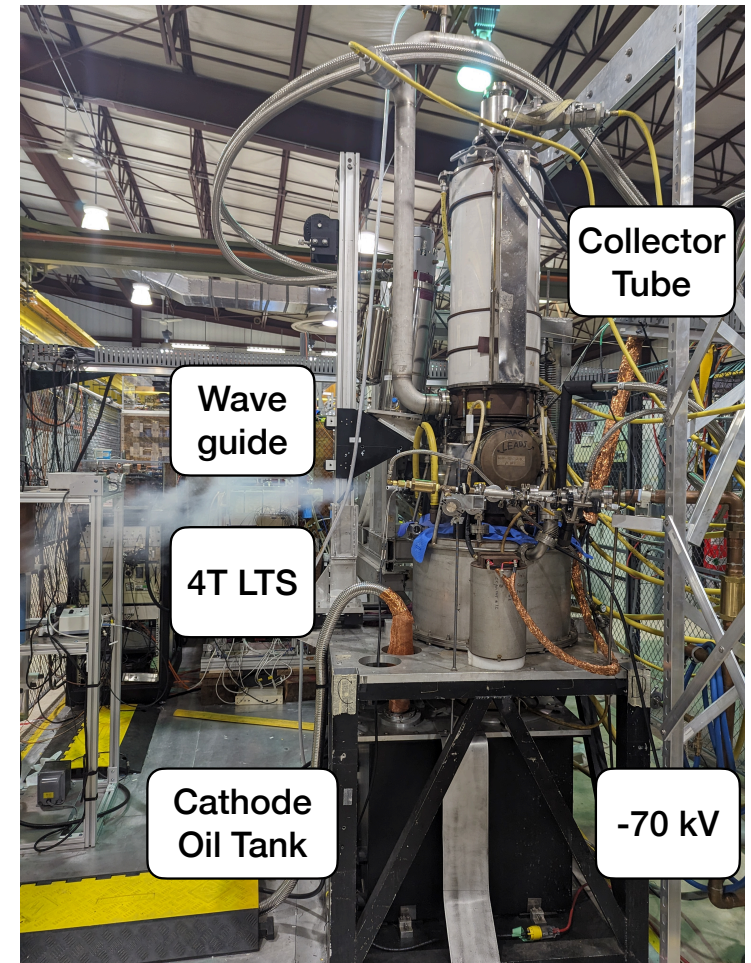
HVPS capacitor bank is modulated between 400-600 V to generate 100-400 kW.

Pulse length 5-10 ms. Sets WHAM shot lifetime.

110 GHz resonant at 4T. Liquid He cooled LTS.

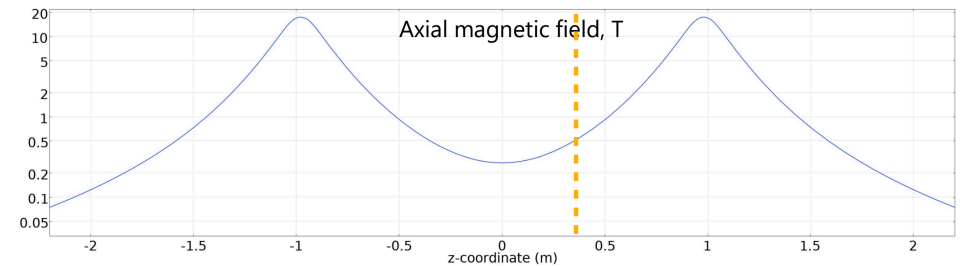
High density operation enabled by high mirror field.

Generates long lived collisionless fast electrons.

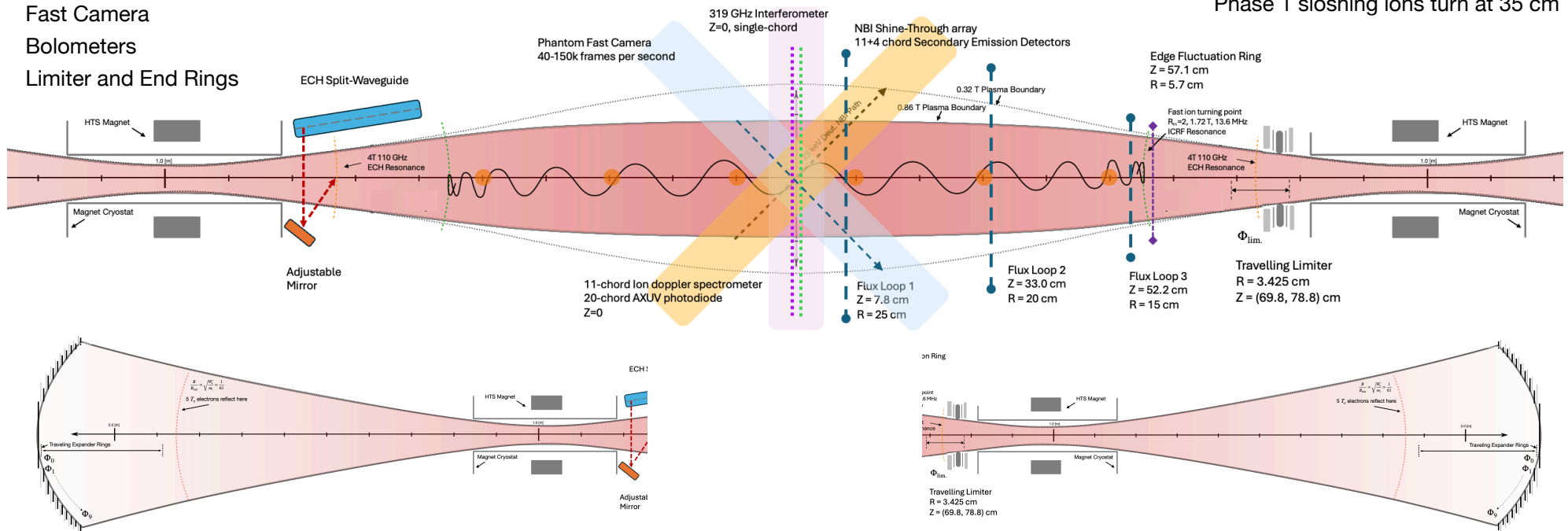


Diagnostic Overview

NBI
Sloshing Ions
ECH
Flux Loop
Interferometer
Fast Camera
Bolometers
Limiter and End Rings

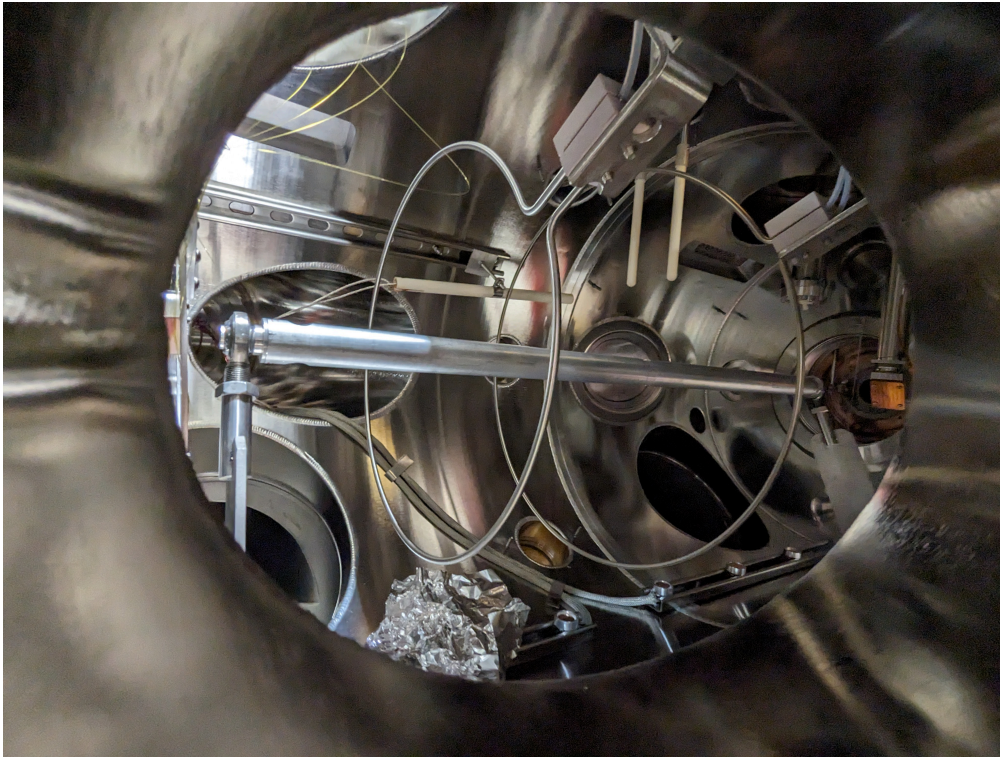


Phase 1 sloshing ions turn at 35 cm



Aspect ratio correctly scaled. 2m mirror-to-mirror column.
4m endring-endring. Midplane radius ~15 cm.

Diamagnetic Flux Loops



Change in flux used to measure plasma pressure and infer stored energy.

$$\begin{aligned}\beta(t) &= 1 - \left(1 - \frac{\Delta\Phi}{\Phi_0}\right)^2 \\ &= 2\frac{\Delta\Phi}{\Phi_0} - \left(\frac{\Delta\Phi}{\Phi_0}\right)^2 \\ &\approx 2\frac{\Delta\Phi}{\Phi_0},\end{aligned}$$

Two turns to cancel capacitive coupling.
Fastened at 3 points to reduce mechanical oscillation (not shown).

Interferometer

Two color interferometer. 319 GHz base frequency.
15 MHz intermediate frequency.

Relative phase is proportional to line-integrated density.

$$\begin{aligned} k &= \frac{1}{c} \sqrt{\omega^2 - \omega_p^2} \\ &= \frac{\omega}{c} \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \\ &\approx \frac{\omega}{c} \left(1 - \frac{1}{2} \frac{\omega_p^2}{\omega^2}\right) \\ &= \frac{\omega}{c} - \frac{\omega_p^2}{4\pi f c} \\ &= \frac{\omega}{c} - \left(\frac{e^2}{4\pi f c \epsilon_0 m_e}\right) n_e \end{aligned}$$



$$\Delta\phi = \phi_{air} - \phi_{plasma} = \frac{1}{n_0 L} \int n_e dl$$

$$n_c = \frac{\epsilon_0 m_e}{e^2} (2\pi f)^2 = 1.27 \times 10^{21} \text{ m}^{-3}$$

$$n_0 L = \frac{4\pi f c \epsilon_0 m_e}{e^2} = 3.79 \times 10^{17} \text{ m}^{-2}$$

$$\Delta n = 2\pi n_0 L = 2.38 \times 10^{18} \text{ m}^{-2}$$

Fringe skips occur, at which the phase extraction algorithm jumps a multiple of 2π .

Summary of Key Results

1. Magnets work! Team is learning quickly

- 1. plasma formation with ECH works extremely well over a broad range of densities, covering gas dynamic as well as classical mirror confinement regimes

2. Vacuum and Wall conditions Matter!

- $\langle E_i \rangle$ and τ_E limited by CX losses ($\langle E_i \rangle \sim 1 - 2$ keV)
- T_e is limited by high Z radiation (< 100 eV as measured by Thomson)

3. Electrode biasing is essential in all situations for improving stability and performance (including NBI sustainment)

- $\beta \sim 10\%$

4. ECH creates a substantial hot electron component that is governed by classical pitch angle scattering losses

- consistent with earlier experiments but at much higher densities (than DCX/ELMO)
- Fast electrons exhibit classical confinement (although there is evidence for hot electron interchange at low densities)
- likely important (or could be optimized) for MHD stabilization

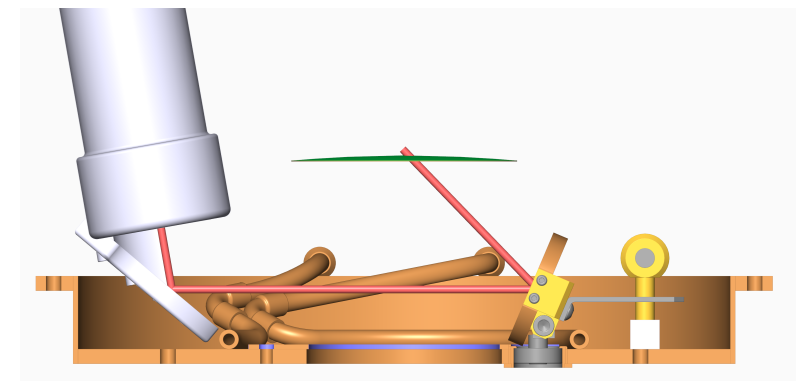
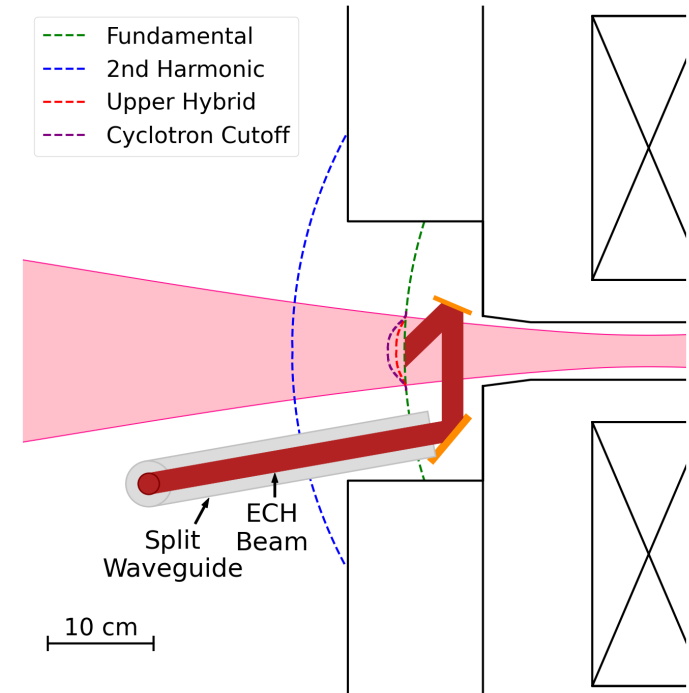
5. Diagnostics and Analysis Tools are rapidly evolving

- Equilibrium Reconstruction are essential for interpreting experiment, and provide clear evidence of both sloshing ions and sloshing electrons, and first set of performance metrics

3. ECH Experiments

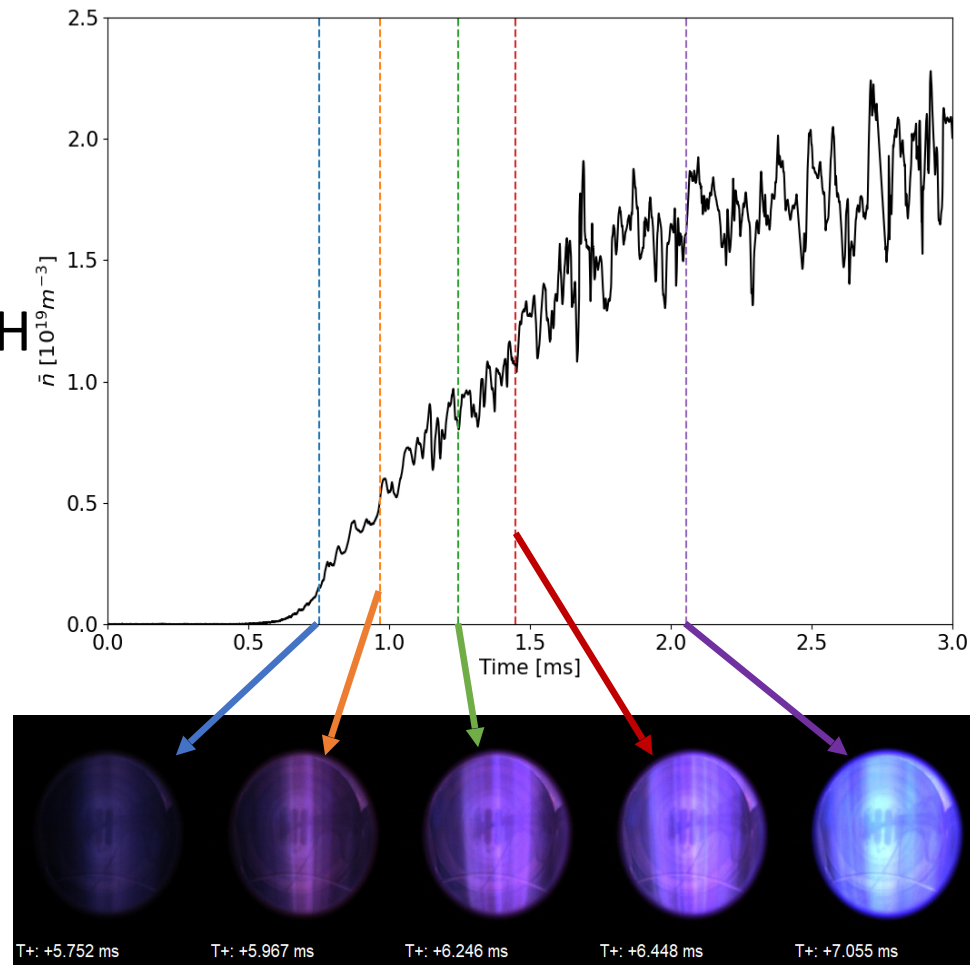
X1 Beam Path in WHAM

- 3.93T resonance is $\sim 5\text{cm}$ from magnet cryostat
 - Due to cyclotron cutoff, ECH must be launched from the high field side (HFS)
- “Split waveguide” used to transmit ECH
 - Biased to 2kV
- Second mirror elliptically curved and rotatable
 - Focuses ECH onto resonance
 - Radial deposition controlled through rotation



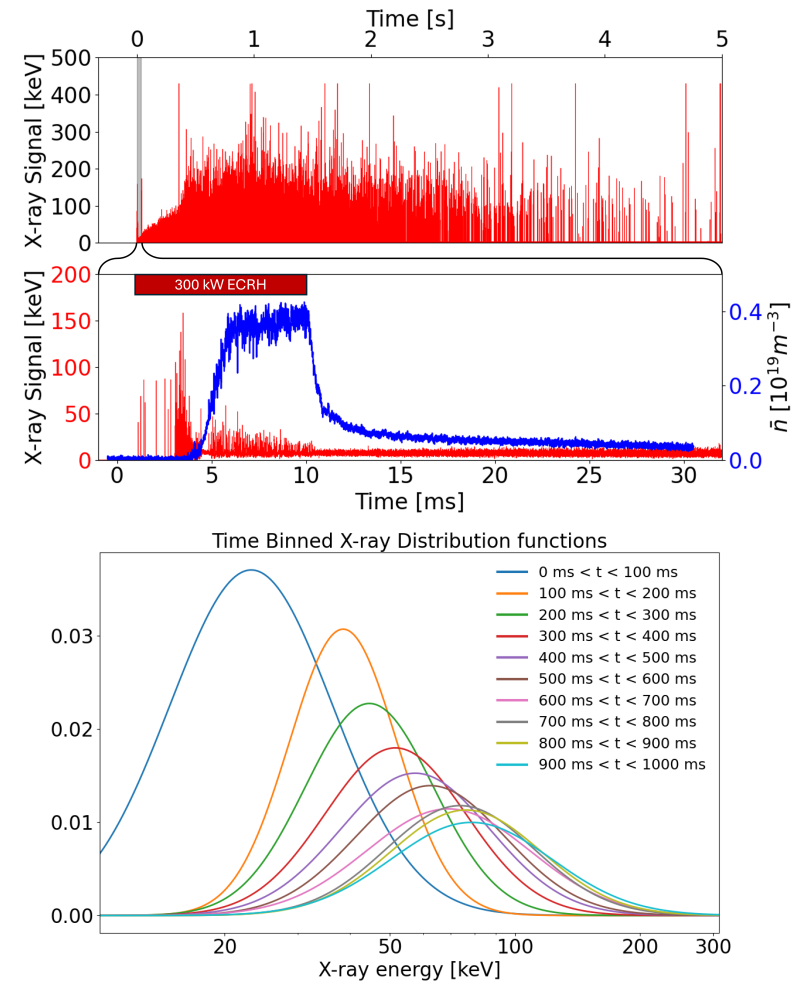
X1 Easily Produces Fully Ionized Plasmas

- Rapid density buildup after plasma breakdown
 - <2ms rise time
 - Densities from $1\text{E}18$ - $1\text{E}20\text{ m}^{-3}$
- No lower limit has been found for ECH breakdown power
 - Tested down to 20 kW
 - Incomplete ionization at very low power
- Allows for breakdown of entire plasma column despite focused ECH beam
 - Plasma diameter at 4T ~ 7 cm
 - ECH diameter at 4T ~ 1.5 cm



Hot Electrons of $E > 500\text{keV}$ have been observed

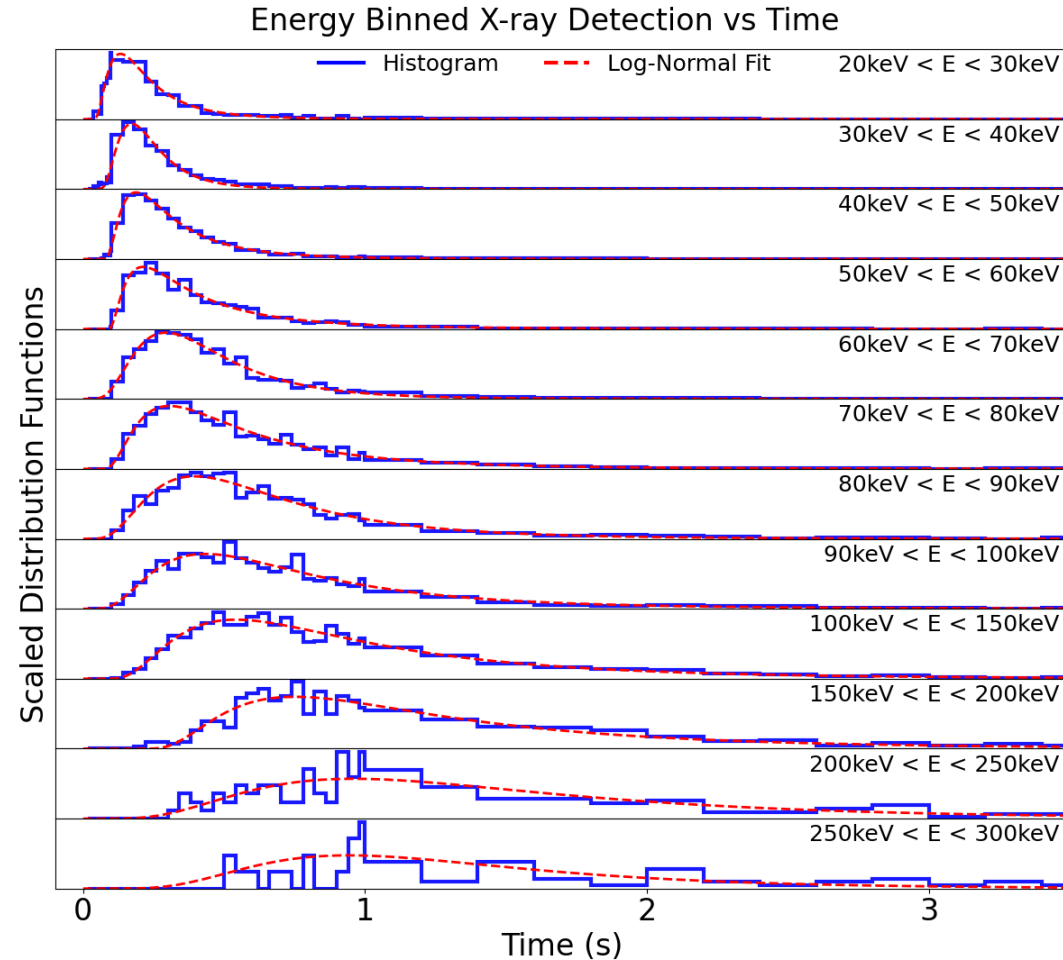
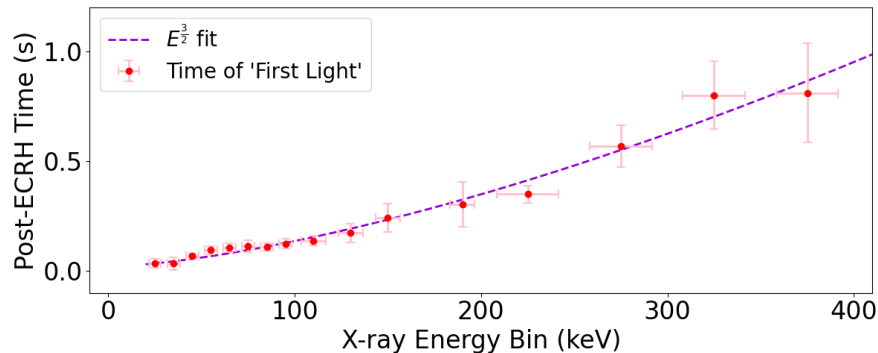
- Main evidence comes from hard x-ray emission
 - Bremsstrahlung of lost hot electrons on plasma facing components
- Majority are seen well after ECRH has ended
 - Initial burst during breakdown
 - Spectrum hardens with time
 - “Maxwell’s Demon” like behavior



Afterglow electrons are classically confined

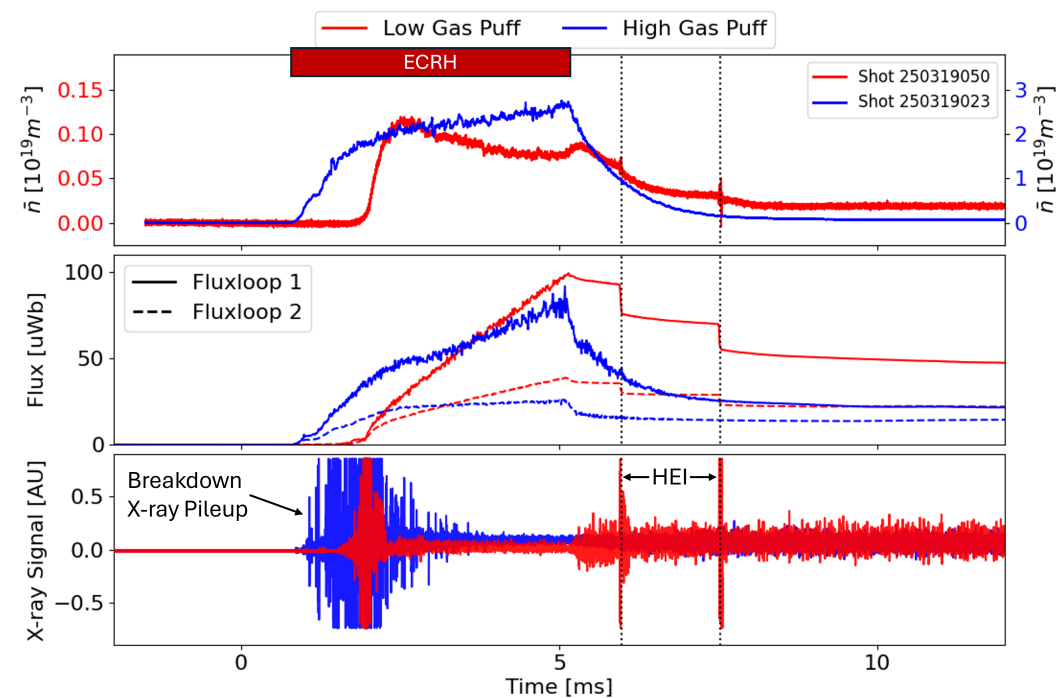
- At high enough energy, electrons become near collisionless
- Confinement time $\sim E^{3/2}$
- Consistent with experimental observation of first light
- Density prediction consistent with afterglow

$$\nu_{\perp}^{\text{cl}}(E) \simeq (1+Z_{\text{eff}}) \frac{\bar{n}_x e^4 \ln \Lambda}{4\pi \epsilon_0^2 m_e^2 c^3} \frac{\gamma}{(\gamma^2 - 1)^{3/2}}, \quad \gamma = 1 + \frac{E}{m_e c^2}$$



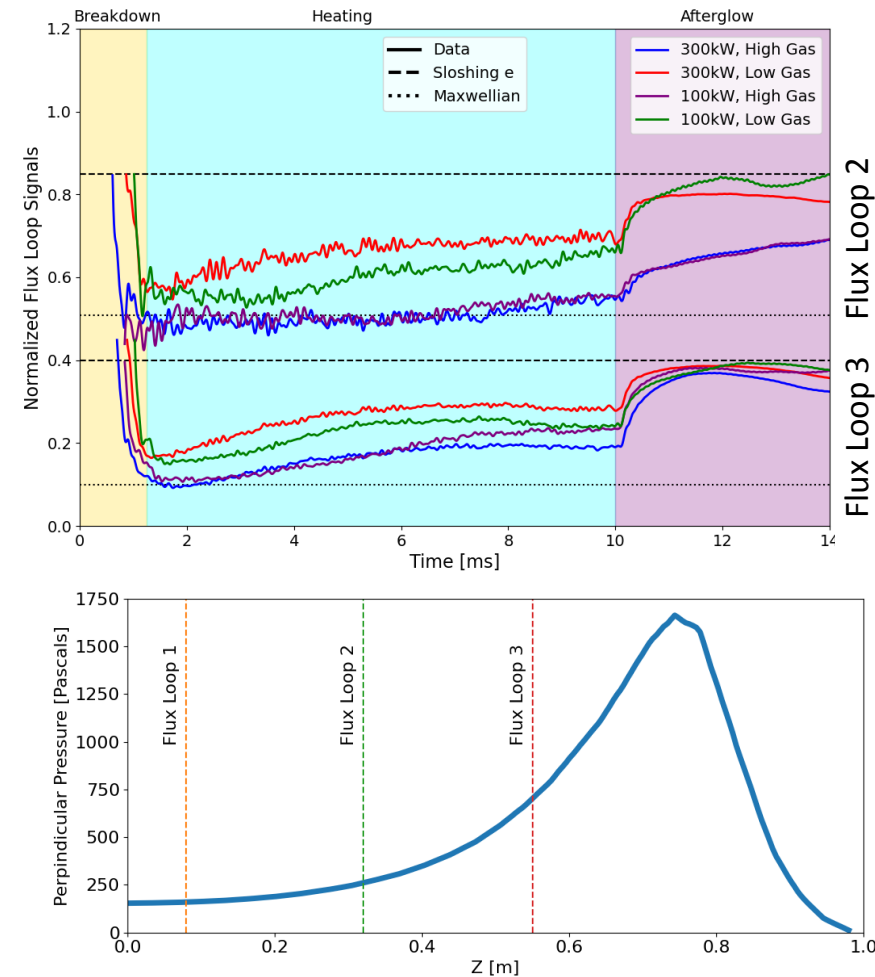
Hot electrons observed in flux loops

- In lower density plasmas ($<10^{19}$), a large portion of flux remains after ECH ends
- Very small density also remains
- Thought to be high energy, sloshing electrons
 - Turning point near 4T resonance
- Not observed in high density or NBI fueled plasmas
 - Potentially killed by high neutral pressure



Flux Loop Response Consistent with Sloshing Electrons

- Analytical models give predictions for flux loop measurements
 - Pressure profiles differ significantly between Maxwellian and sloshing populations
- Flux measurement ratios can show this difference
 - Predicts the fraction of plasma pressure contained in each mode

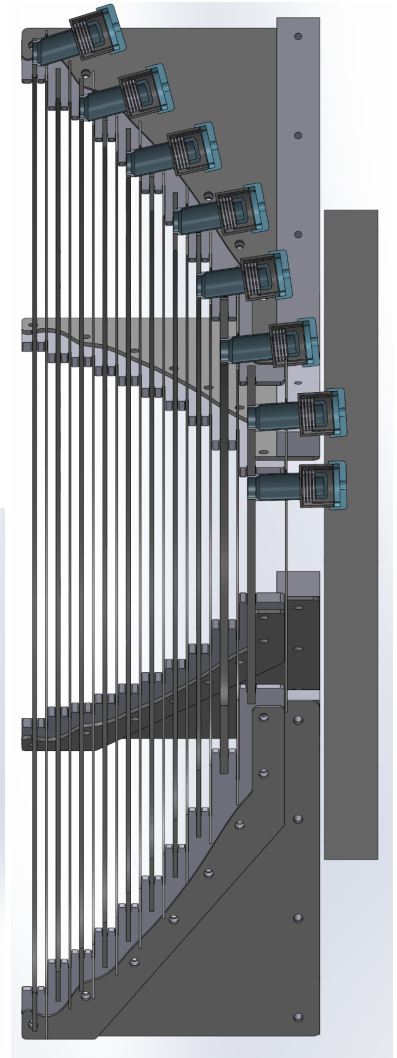
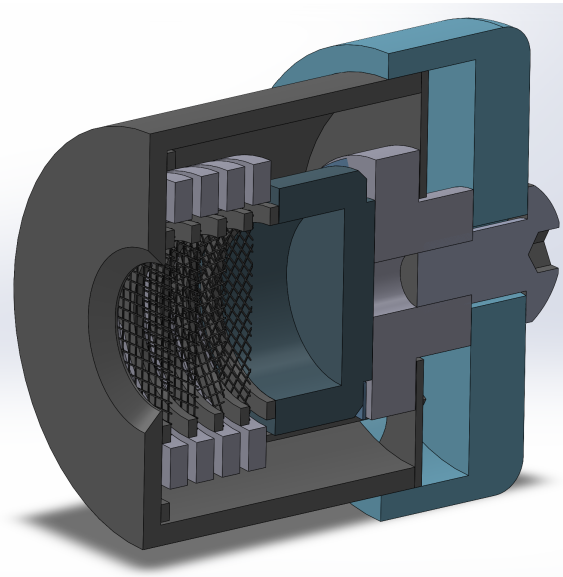
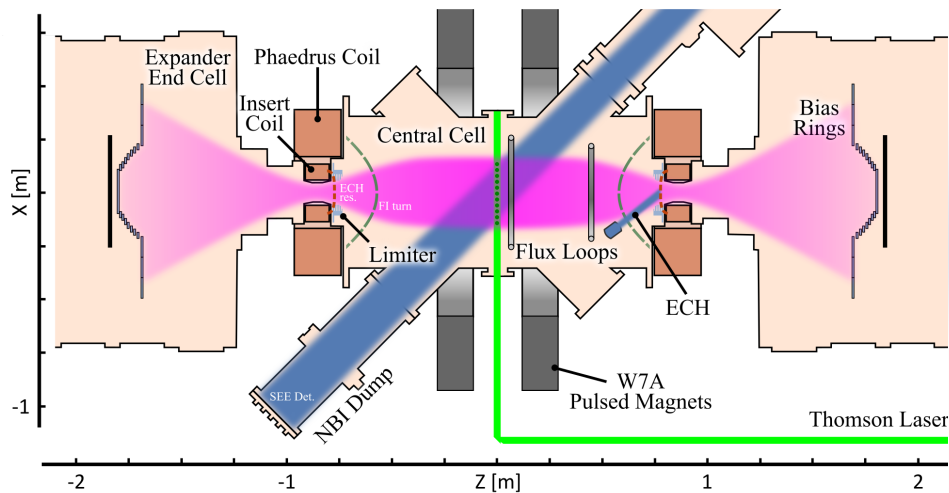


5. Direct Energy Conversion

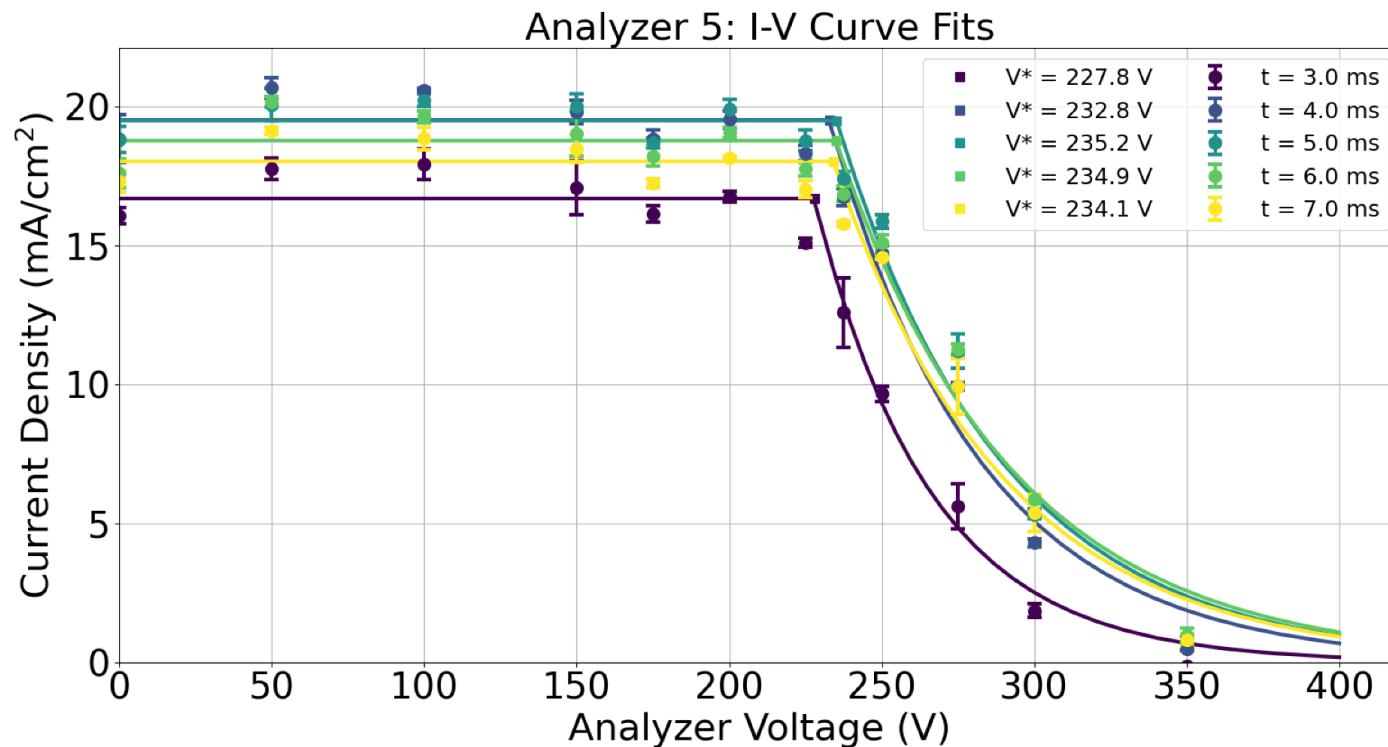
Endloss analyzers at WHAM

Array of gridded end loss analyzers is embedded in the end ring structure to measure the distribution function of escaping ion flux with maximum energy of 3 keV

Analyzers are aligned along the magnetic field lines and allow measurement of full radial profile of ion flux with high time-resolution at fixed analyzing voltage



Measurement ion end loss distribution



A piecewise fit is applied, consisting of a plateau and exponential decay.

The knee point V^* corresponds to the ambipolar potential drop towards the end-wall.

The ion temperature is derived from exponential part of the fitted function.

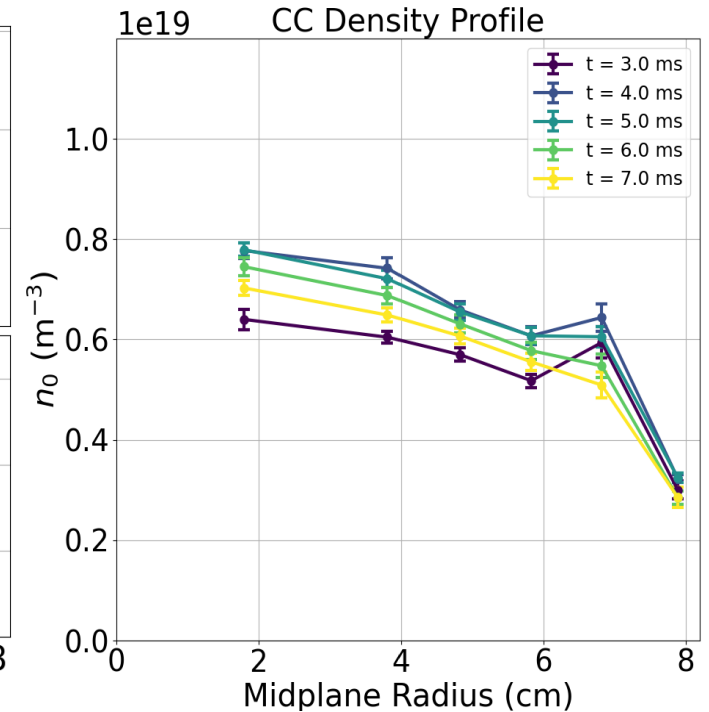
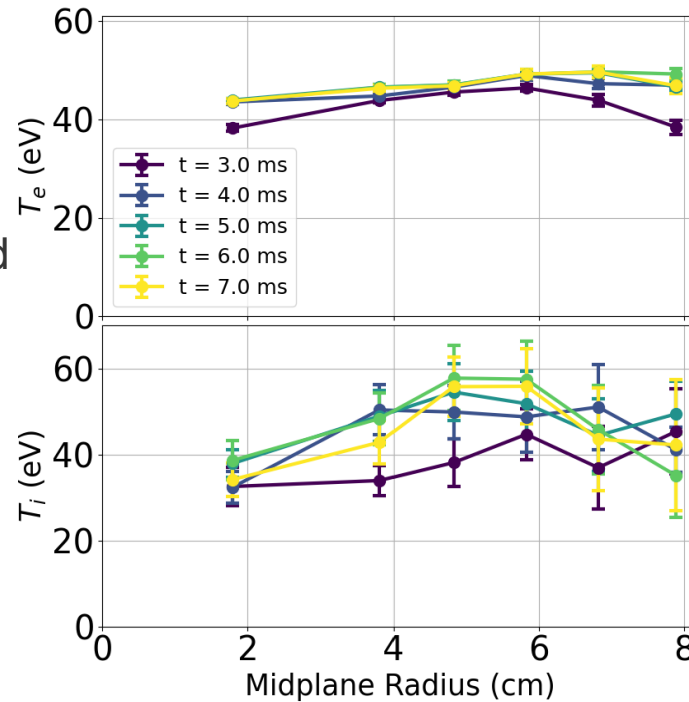
Measurements of plasma temperature profile

Electron temperature is estimated as $T_e \sim V^* / 5$

To calculate plasma density in the central cell, the ion flux (q_i) is projected to the mirror bore using expansion ratio of ~ 150

The density is estimated using the gasdynamic formula [1]:

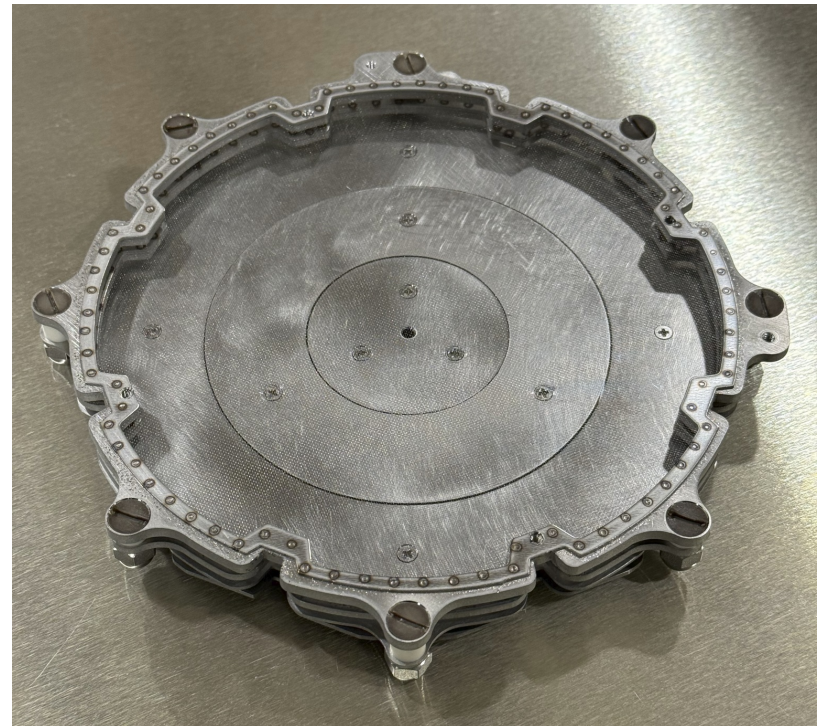
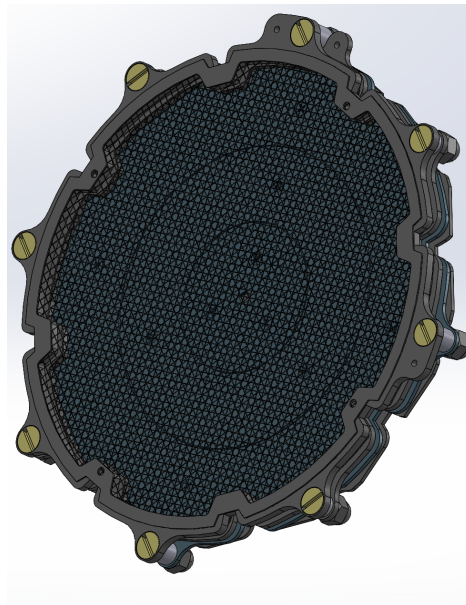
$$n = \frac{q_i}{1.53 \sqrt{\frac{T_e}{2\pi m_i}}}$$



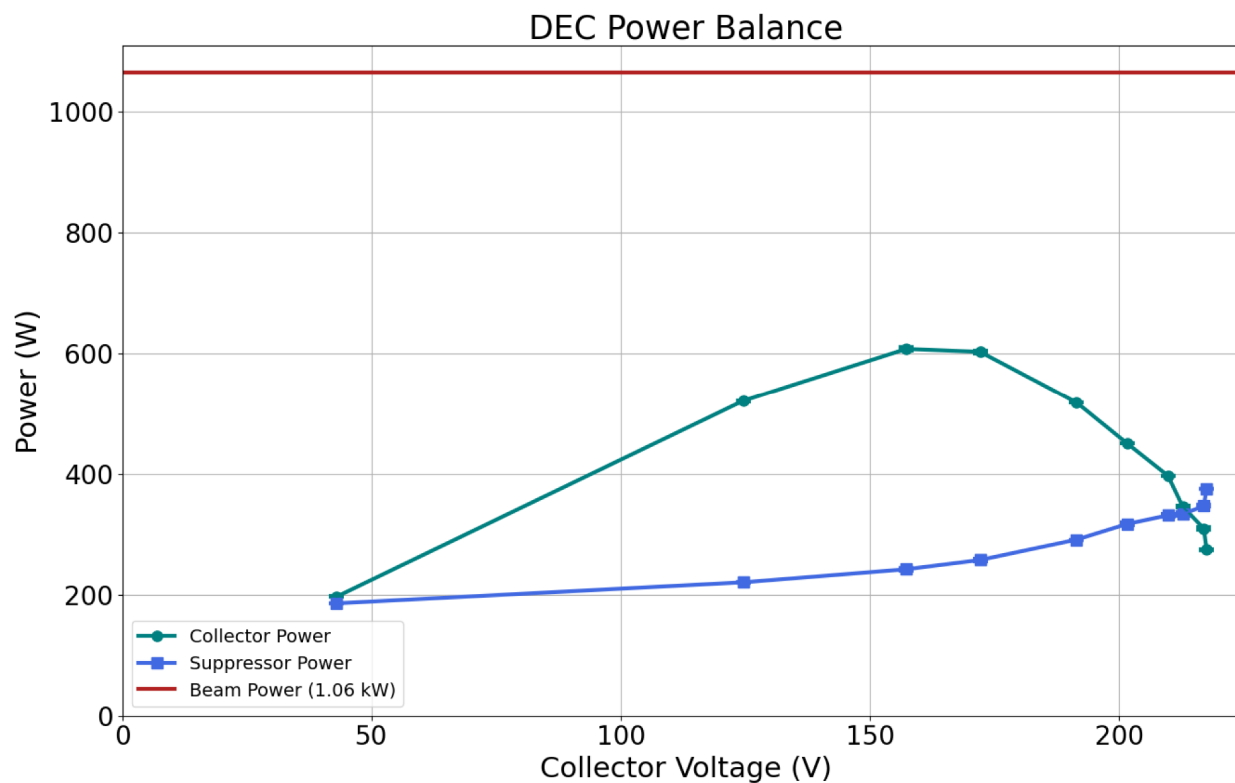
Experiments on direct energy conversion

A single stage direct energy converter (DEC) has been successfully installed in place of WHAM's south end plate.

Prior research on direct energy conversion in mirror was conducted at the Tandem Mirror Experiment (TMX) in the 1980's. At optimum performance, such experiments collected ~67W at an efficiency of 48%.



Preliminary results on DEC



The available ion power incident on the DEC (“beam power”) is found from current density and ion energy distribution measured by the end loss analyzers.

Scanning the collector voltage identifies parameters of peaked collector power, corresponding to maximum efficiency. Recent preliminary results have demonstrated a maximum net efficiency in WHAM of 34%.

Thank you!