Centrifugal Mirror Machines: Confinement Scalings & A Pathway to Fusion

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Overview

- What is a Centrifugal Mirror Machine
- Transport
- Experiments
- Confinement Scalings & Next Step Device

What is a Centrifugal Mirror Machine?

What Is A Centrifugal Mirror

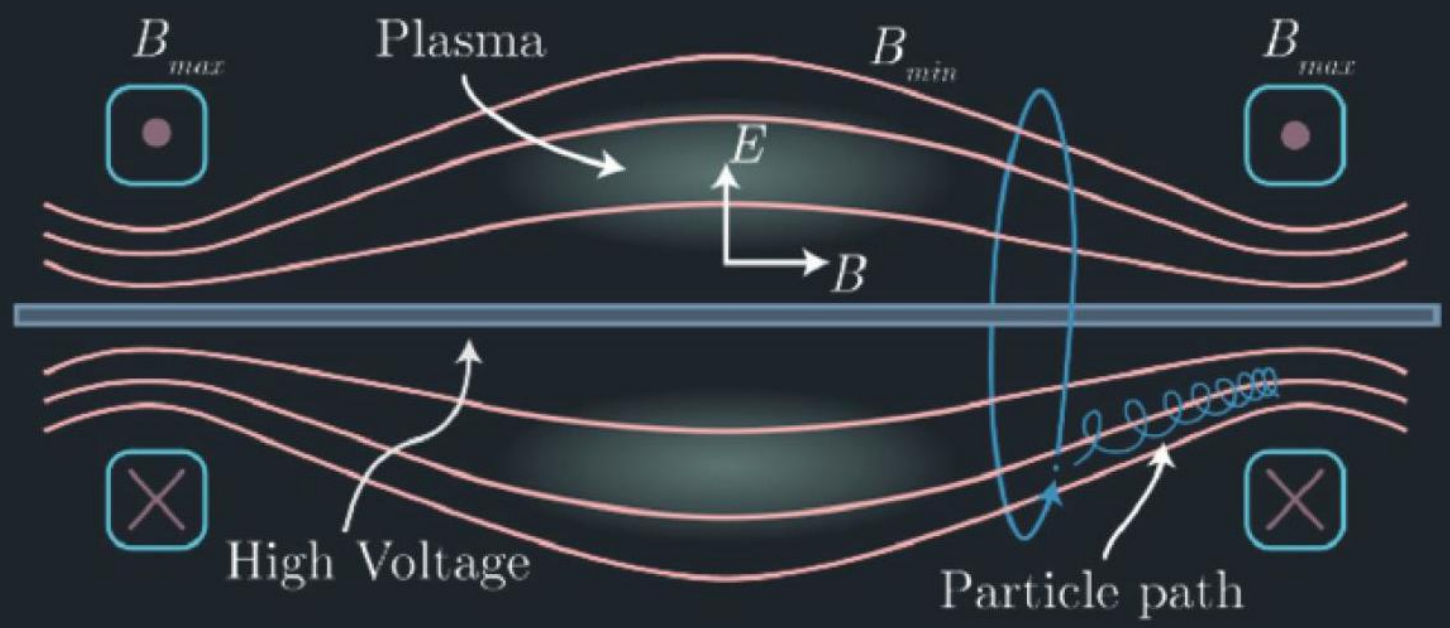
- Simple Mirrors are borderline [Forest, C.; yesterday]
- Main problems are
  - Parallel Losses
  - Interchange Turbulence

What Is A Centrifugal Mirror

What if it rotated?

What Is A Centrifugal Mirror – using E as well as B

- To rotate a mirror, just apply E!
- So long as rotation frequency is small compared to the gyrofrequency, E generates an azimuthal E x B flow!

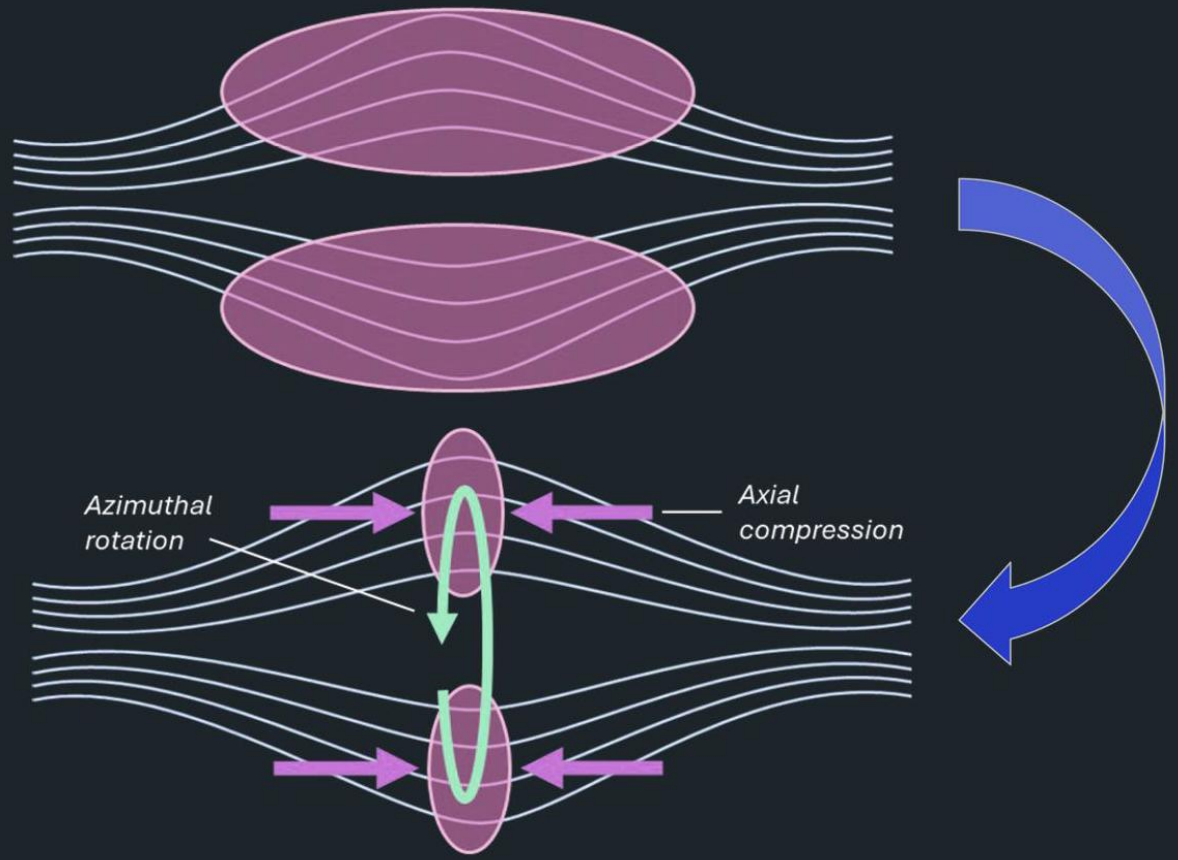


What Is A Centrifugal Mirror

- Parallel confinement is provided by a centrifugal contribution to the potential energy:

$$\varepsilon = Z_s q\phi - \frac{m_s}{2}\omega^2 R^2$$

Confining centrifugal potential



Parallel Transport – Pastukhov Redux

- Any species confined in any potential well - completely equivalent to the electrostatic confinement calculation of Pastukhov
- Confinement is $$\left(\frac{\partial n_i}{\partial t}\right)_{\text{End Losses}} = \left(\frac{2n_i}{\sqrt{\pi}}\right)\nu_i \frac{1}{\ln \mathrm{R_m}} \frac{\exp\left(-\Xi_i/T_i\right)}{\Xi_i/T_i}$$
- Potential drop in a centrifugal mirror

$$\Xi_i = Z_i e\varphi - \frac{1}{2}m_i\omega^2 R^2 \approx \frac{1}{4}m_i\omega^2 R^2\left(1 - 1/\mathrm{R_m}\right) \propto M^2$$

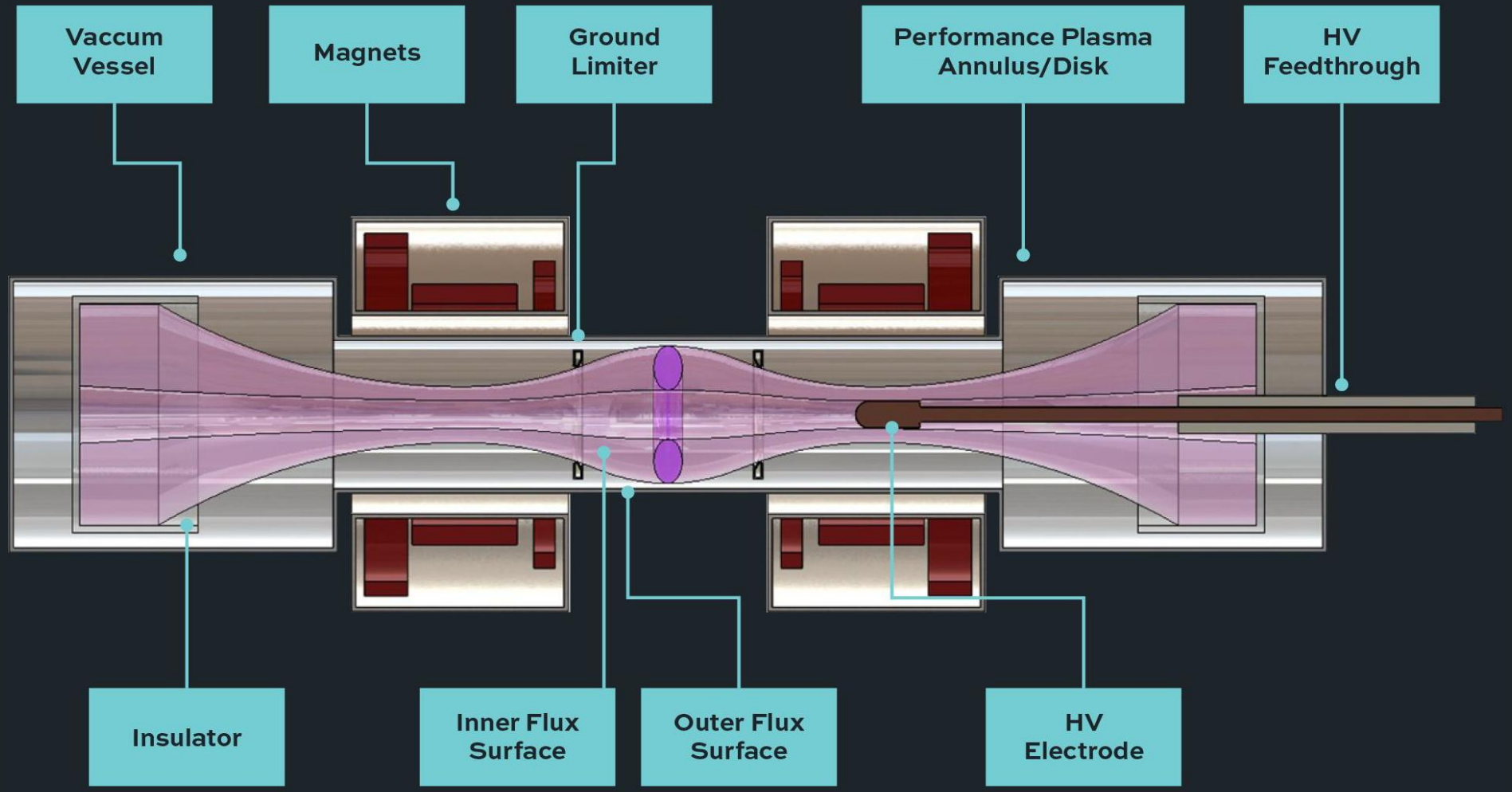
Parallel Transport – Pastukhov Redux

- Well confined if M >> 1, typically M >> 4
- We shall see later that M is not something you prescribe.
- Apply a velocity (via a voltage) and then the temperature is set by transport, and M is a *consequence*

Perpendicular transport – Flow Shear Suppression

- Use Limiters at the edge of the plasma to slow the flow locally
- This drives a flow **profile** – unlike in a torus, no PVG
- Extreme velocity shear -> complete ion-scale turbulence suppression
- Even for K-H (preliminary results in 2D – Tocco/Zhu/Dudson)

A CMM Assembled



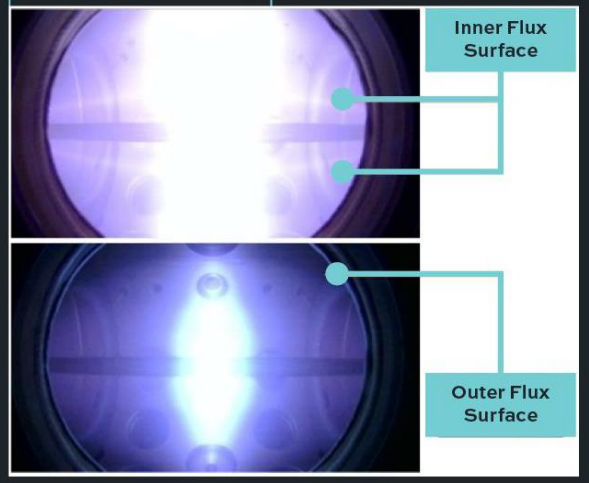
Experimental Efforts

Why haven’t we built one?

- We did!
- Building on historical experiments at UMD (MCX – Ellis & Hassam), CMFX was ARPA-E funded and built at UMD 2020-2023.
- Capable of going to >50kV bias and uses dedicated limiters

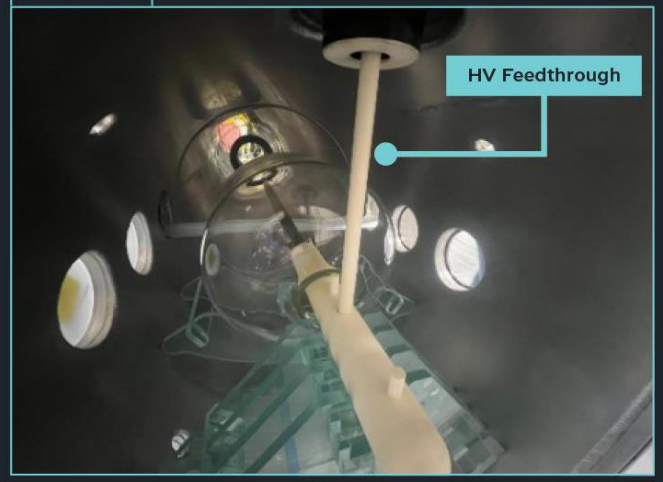
What Was CMFX

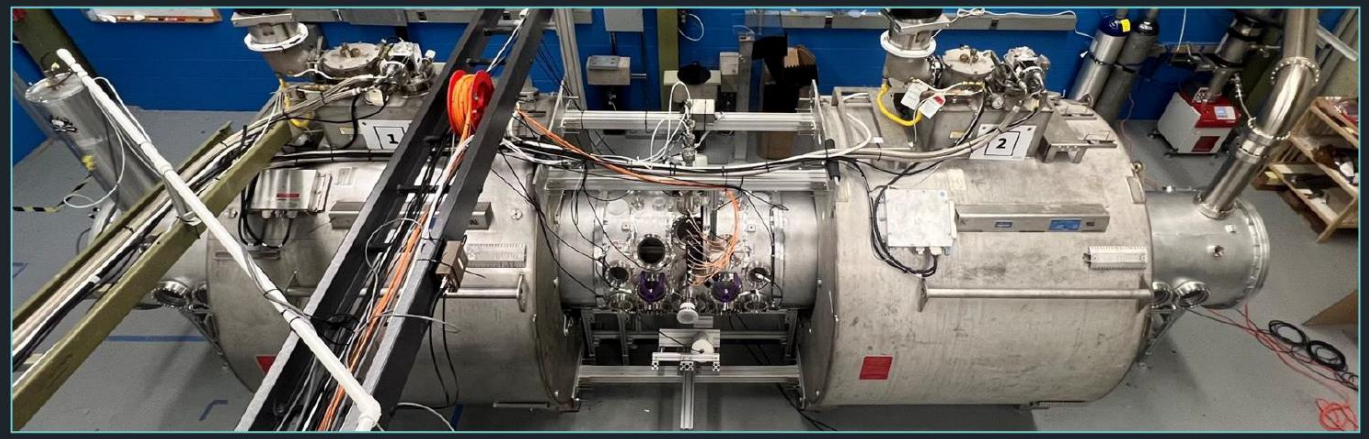
Example Discharge



Axial View

End Cell

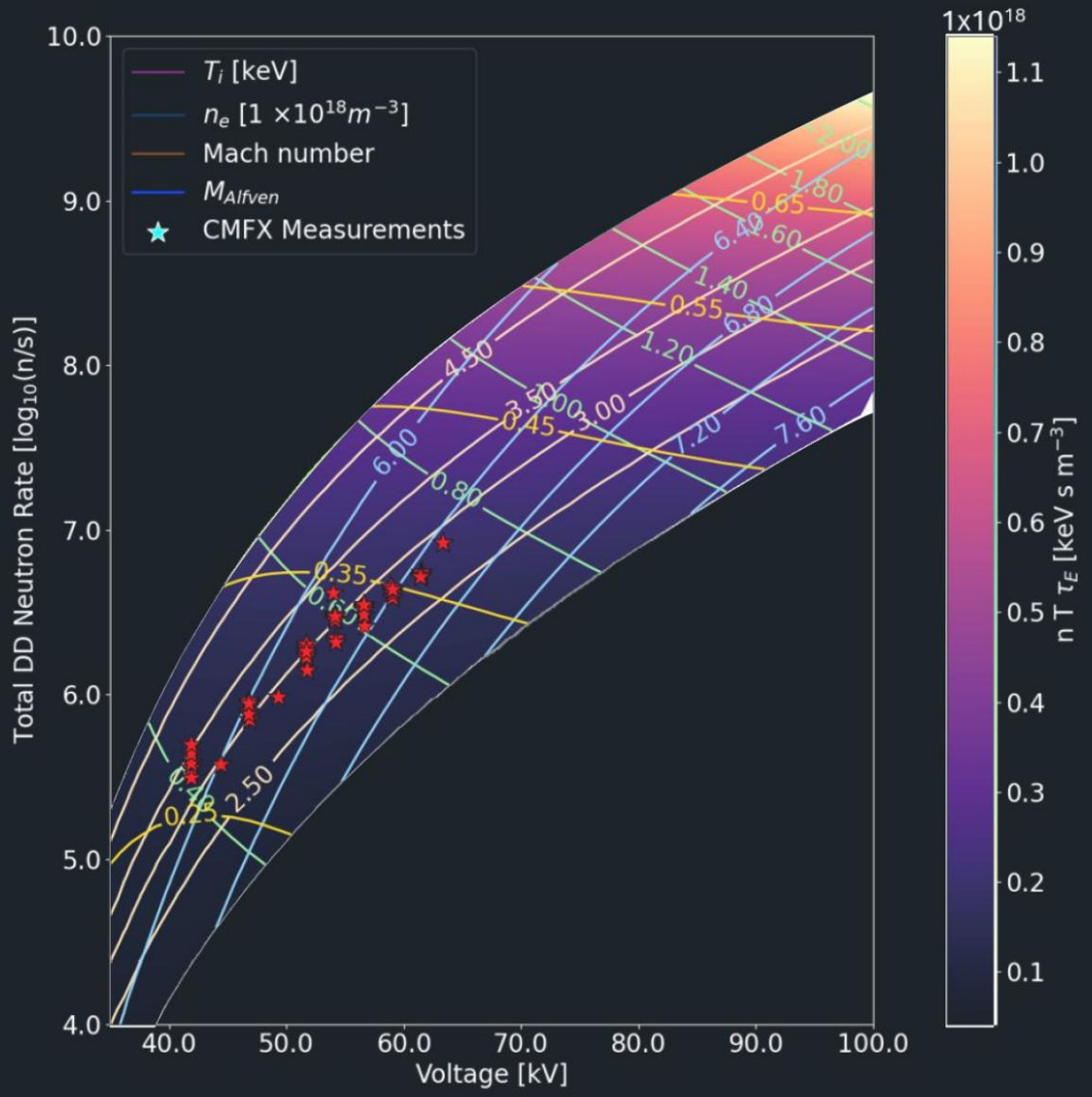




Midplane

What Was CMFX

- Neutron measurements were made by MIT
- Modelling infers T_i , M, n from power balance and neutron rate
- Peak T_i approx. 1 keV, M > 5



Confinement Scalings

0D Transport Model

$$\frac{\partial n_s}{\partial t} + \frac{1}{R}\frac{\partial}{\partial R} R\Gamma_s = S_{n,s},$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_s T_s\right) + \frac{1}{R}\frac{\partial}{\partial R} R q_s = \pi_s^{(R\phi)}\frac{\partial \omega}{\partial R} + Q_s + S_{E,s},$$

and

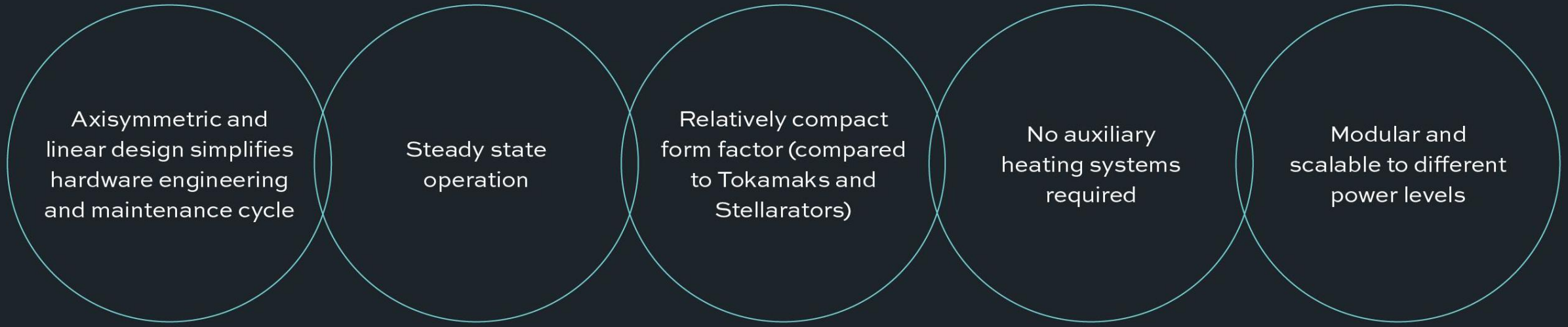
$$\frac{\partial}{\partial t}\left(J\omega\right) + \frac{1}{R}\frac{\partial}{\partial R} R \sum \pi_s^{(R\phi)} = -j_R R B + S_\omega.$$

0D Transport Model

- Parallel losses from Pastukhov
- Perpendicular losses classical (at ion scales)
- Can we estimate scaling laws? (board)

What Next?

Engineering Benefits of Centrifugal* Mirrors



*and other mirrors

GridFire!

- Best of UK & USA
- Building a superstar team in London
- First raise to close Q4 2026, first machine late 2029

GridFire 1

Performance goals

- $T_e, T_i > 1.5$ keV
- n_e (peak) ~ 5×10^{19} per m^3
- $v_\theta \sim 1000$ km/s
- **$nT\tau > 1 \times 10^{19}$ keV s m^{-3}**

Experiment design point

- R_m ($r_m = B_{max}/B_{min}$) = 4-8
- $B_{max} = 4$ T
- $V_{bias} \sim 200$-500 kV
- $r_{min} \sim 0.1$ m, $r_{max} \sim 0.4$ m

(inner and outer radii of the plasma)

Summary

Summary

- Rotating mirrors are potentially a viable path to fusion
- Theory is interesting – and under-explored, come collaborate!