Stellarators: twisty tokamaks that could be the future of fusion

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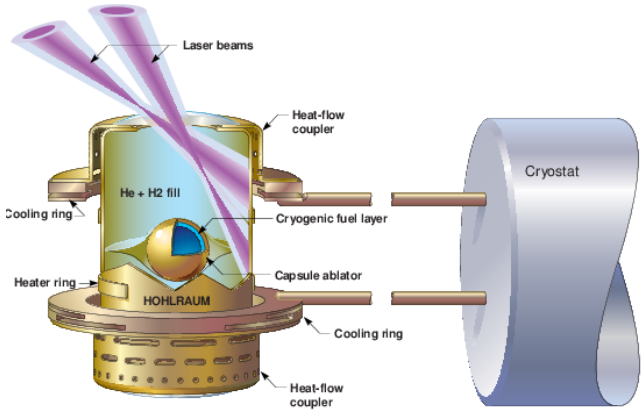
Morning of theoretical physics, 27/05/2023

Alternatives

- Inertial confinement fusion - see next talk



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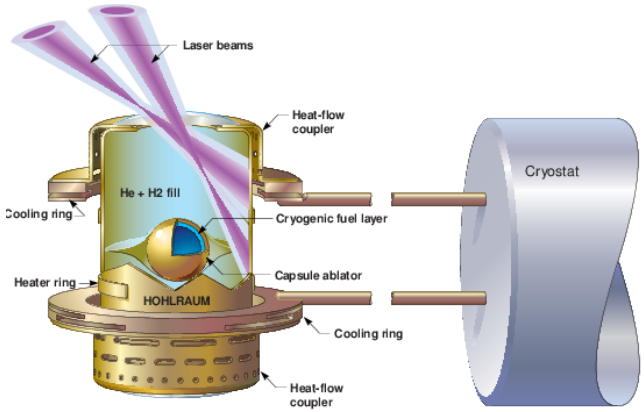
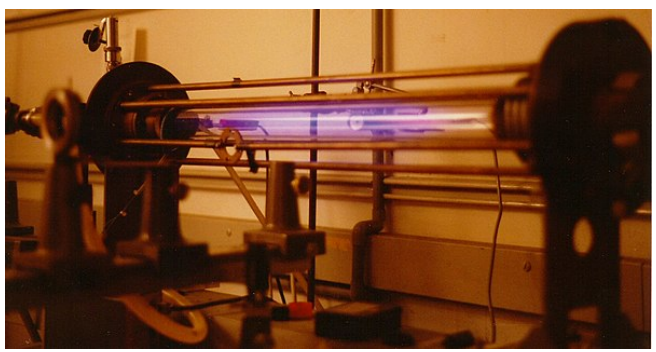
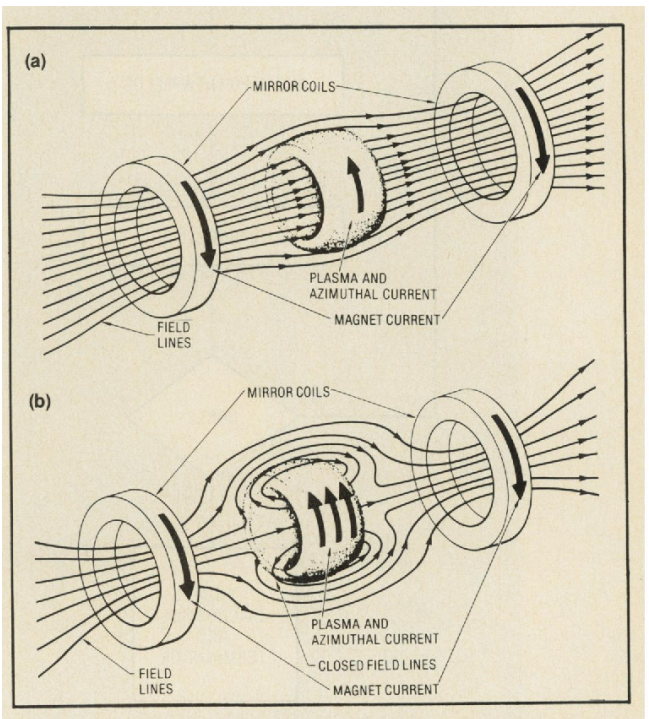


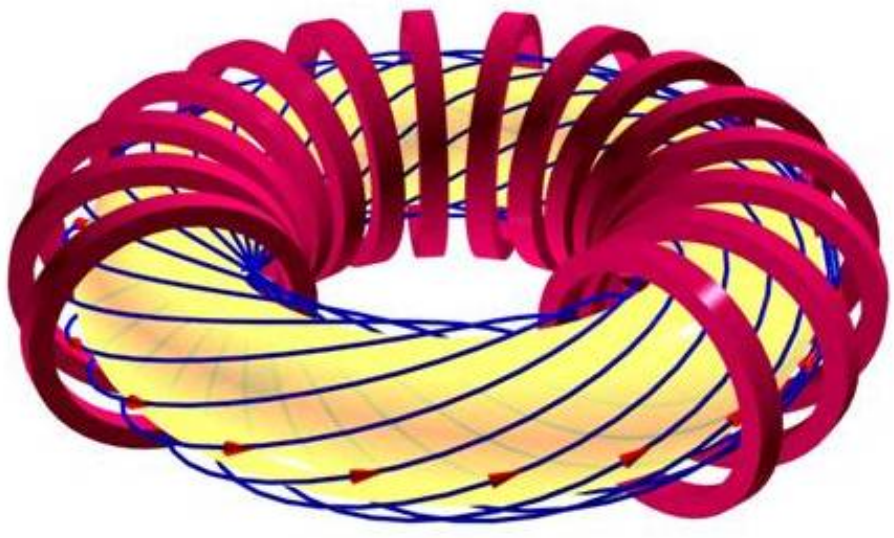
- Z-pinch





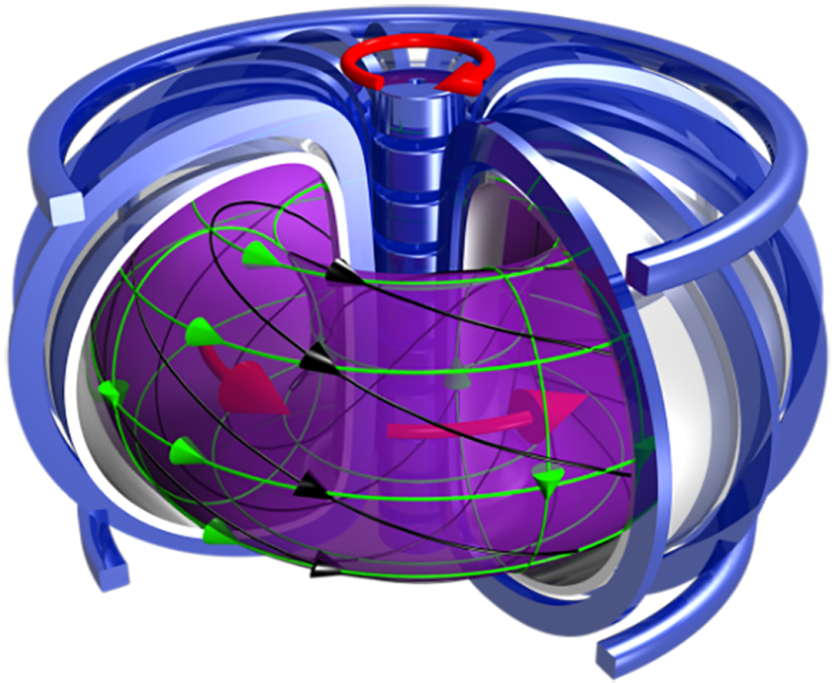
- (Rotating) magnetic mirror devices

Defining Features of Tokamaks



- Tokamaks are azimuthally symmetric
- Driven by current through centre + poloidal magnets
- They have a torioidal current which produces poloidal magneic field

Problems of Tokamaks



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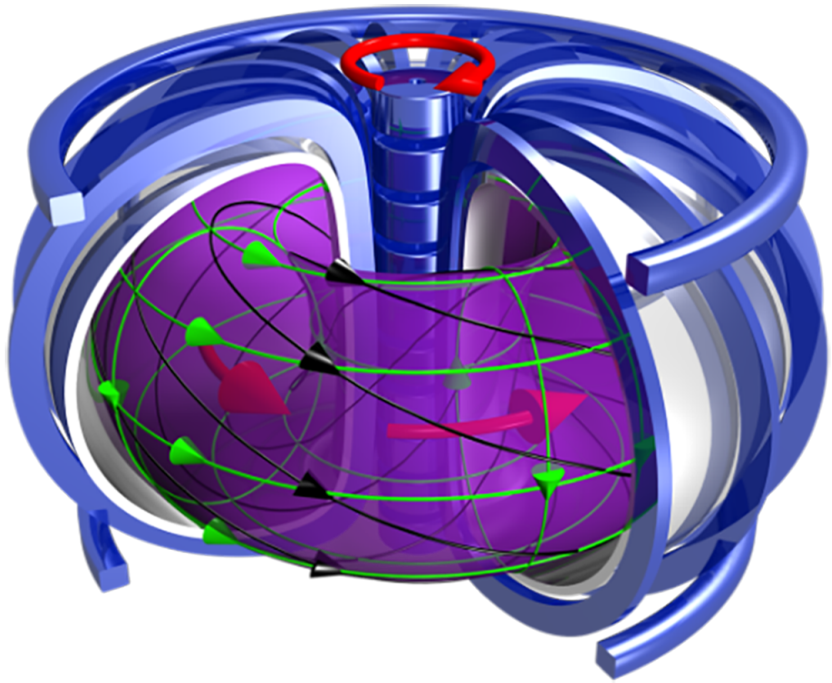

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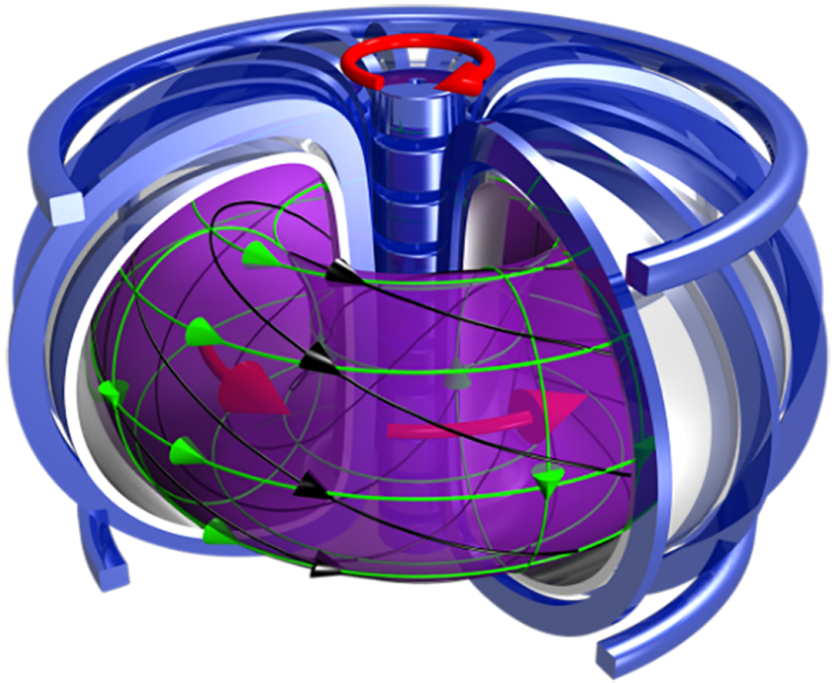

- Need to charge up capacitor for discharge → discontinuous use
- Transformer induced electric field drives toroidal current → instabilities
- Restrictions on density (empirical) → bad for fusion

Introducing: The **Stellarator**

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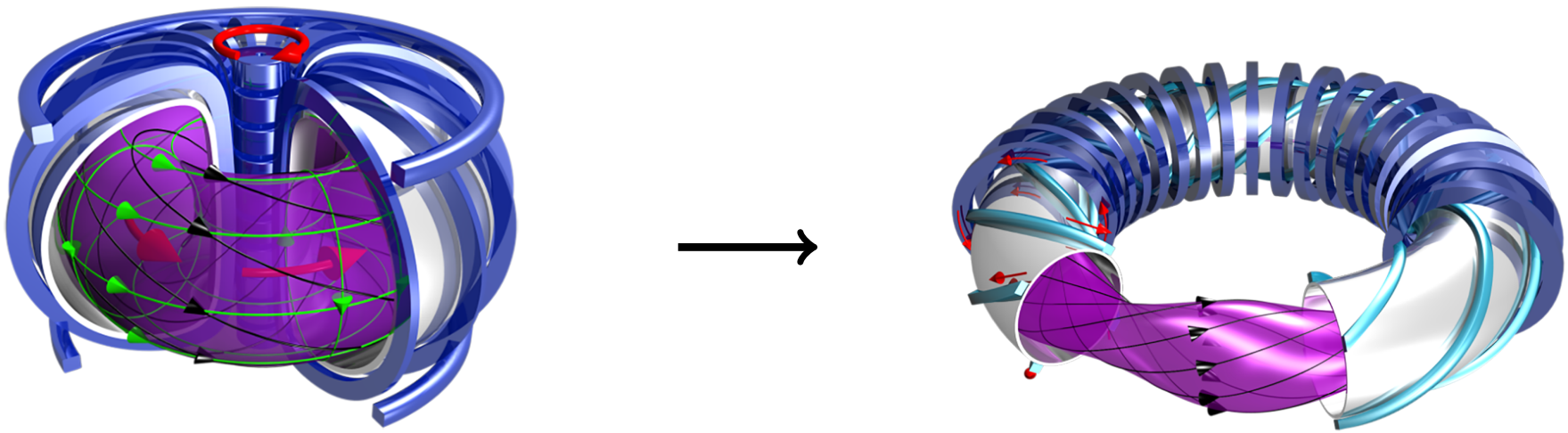
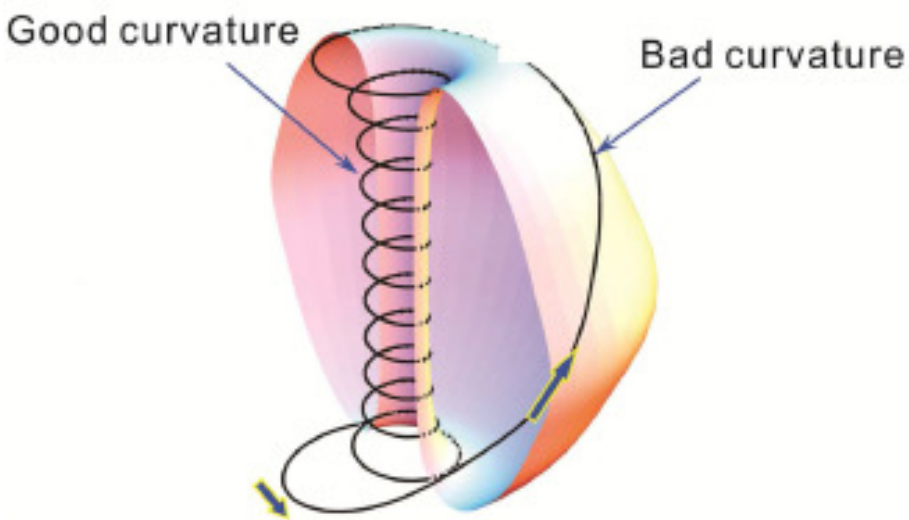


Take a tokamak and twist it

What Devices Are Allowed?

- Fusion devices require temperature and density gradients

  This results in "good" and "bad" curvature regions



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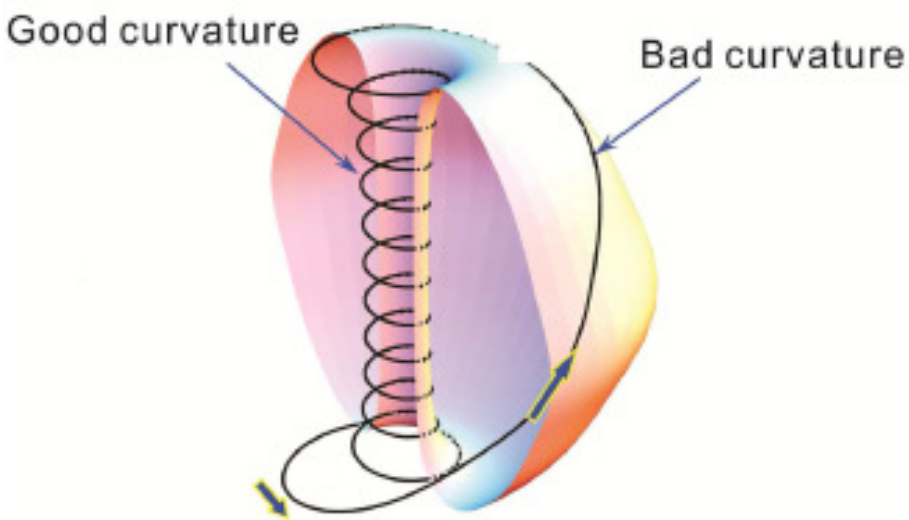

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$$q = \frac{\#\text{ of toroidal turns}}{\#\text{ of poloidal turns}} > 1$$

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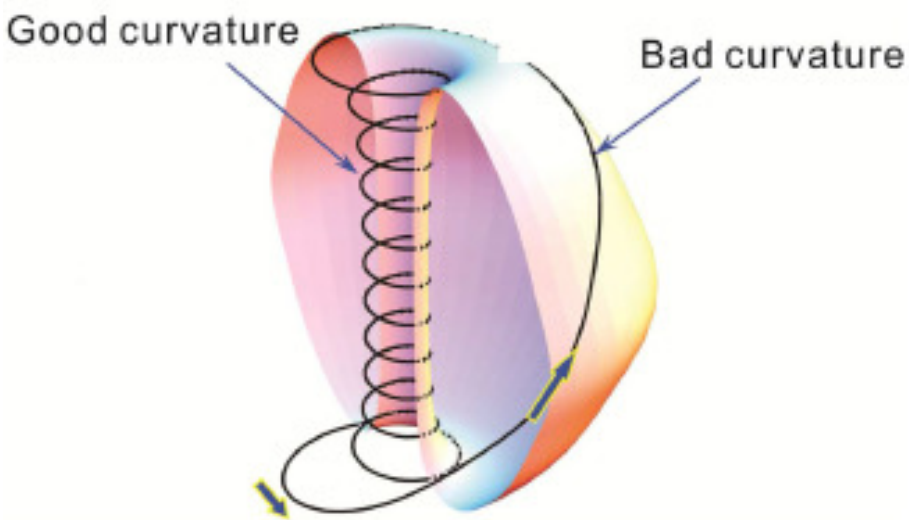

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- How to do this for non-axisymmetric devices require clever thinking

Thinking Outside the Non-Axisymmetric Box

What should we be cautious about?

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- Neoclassical Transport

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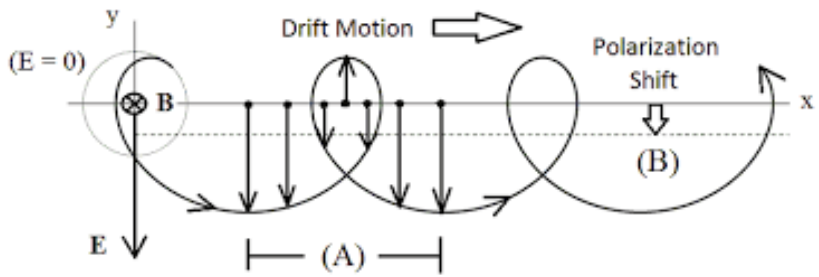
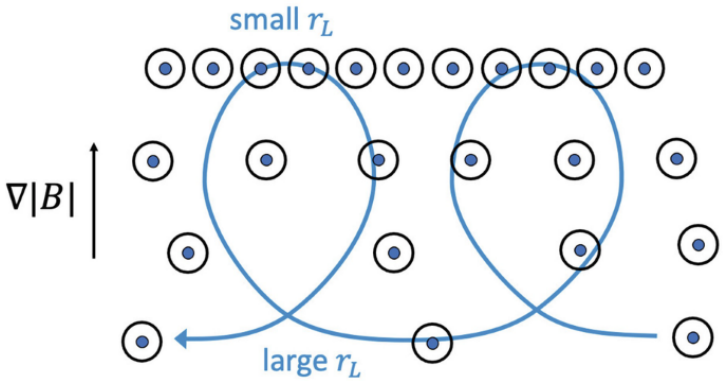
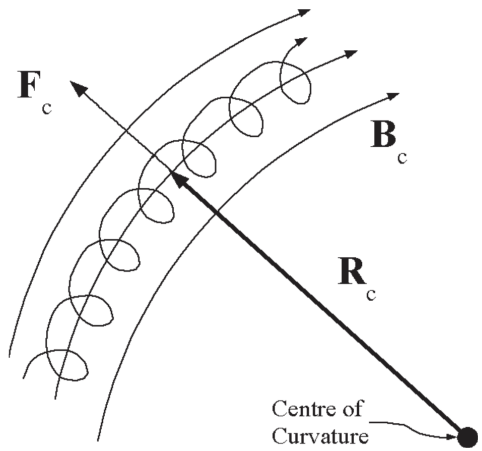
- $\boldsymbol{E} \times \boldsymbol{B}$ drift



- Curvature and gradient-driven drifts





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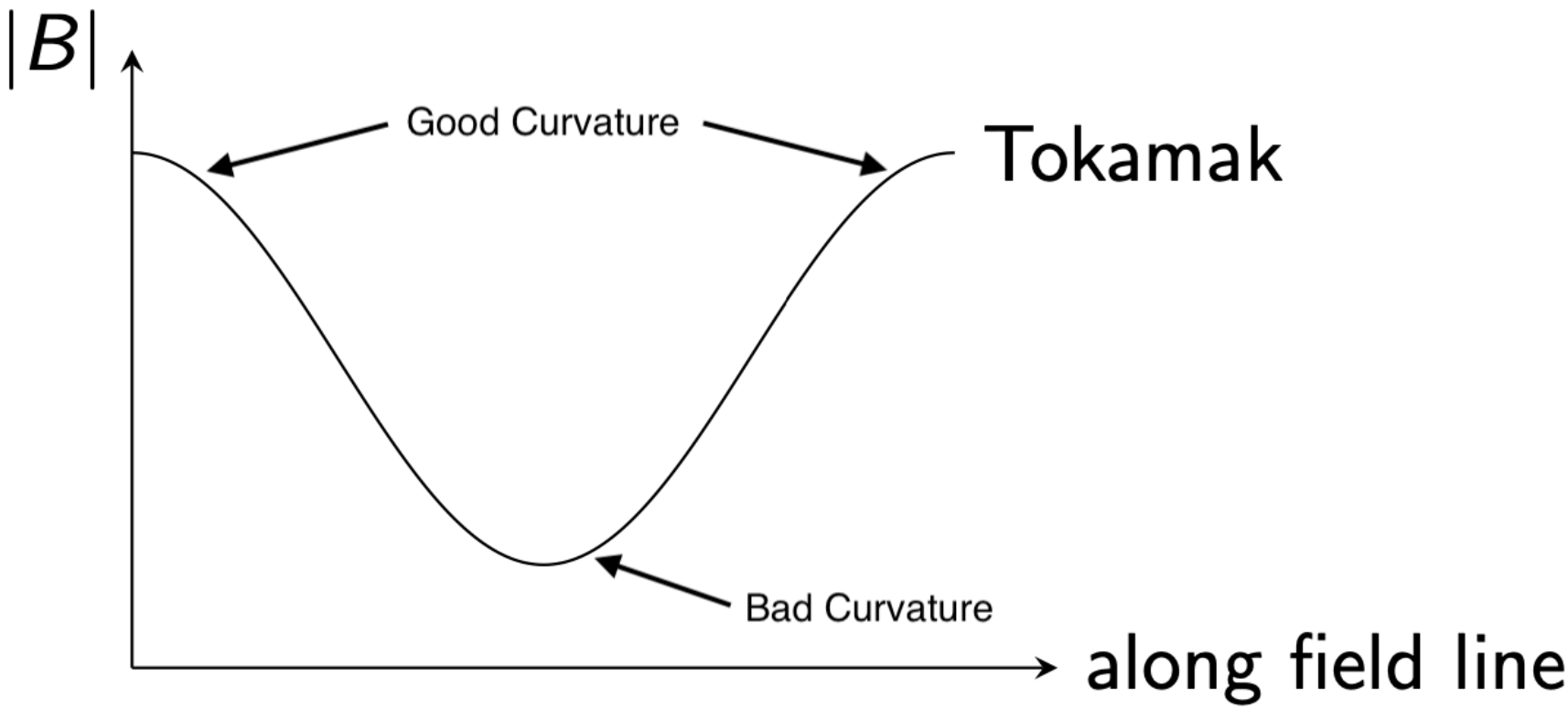

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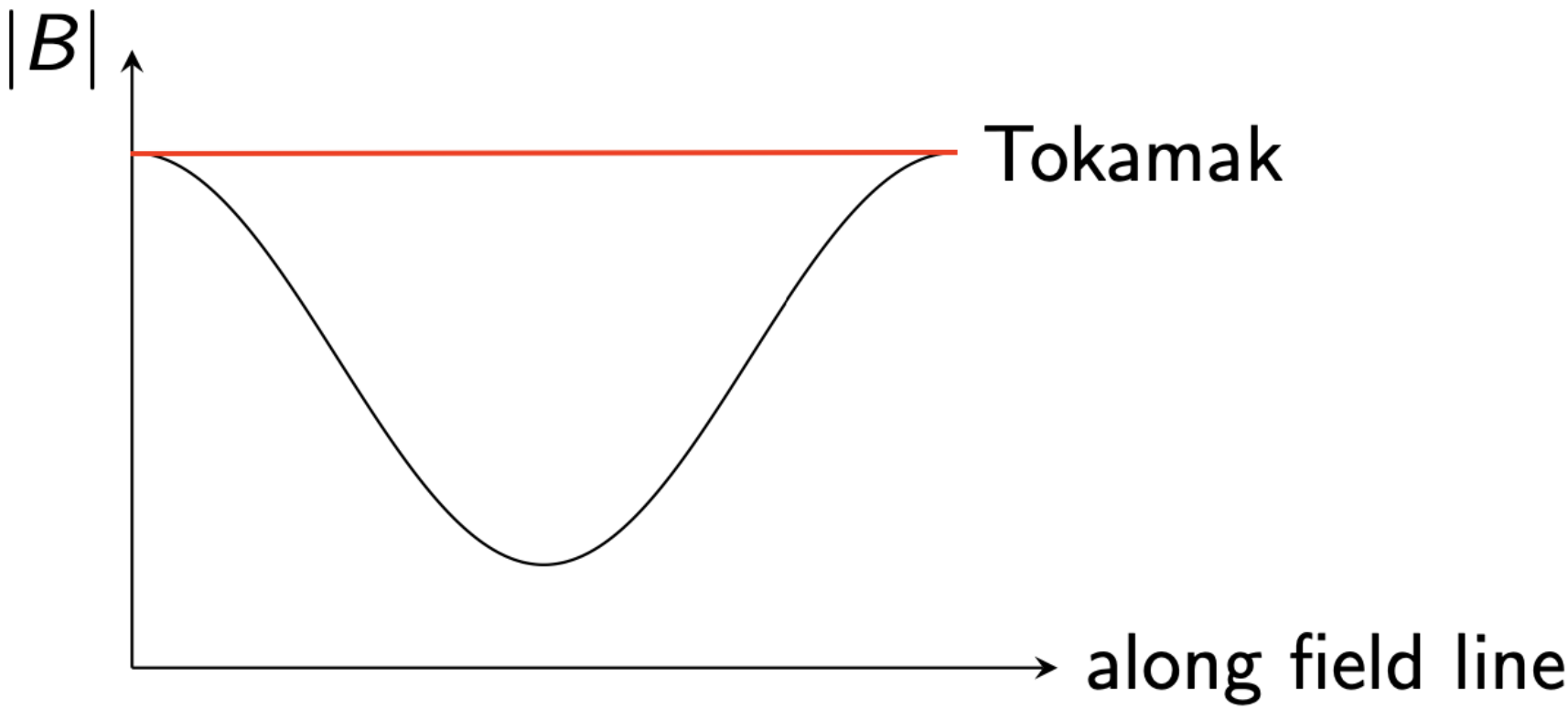

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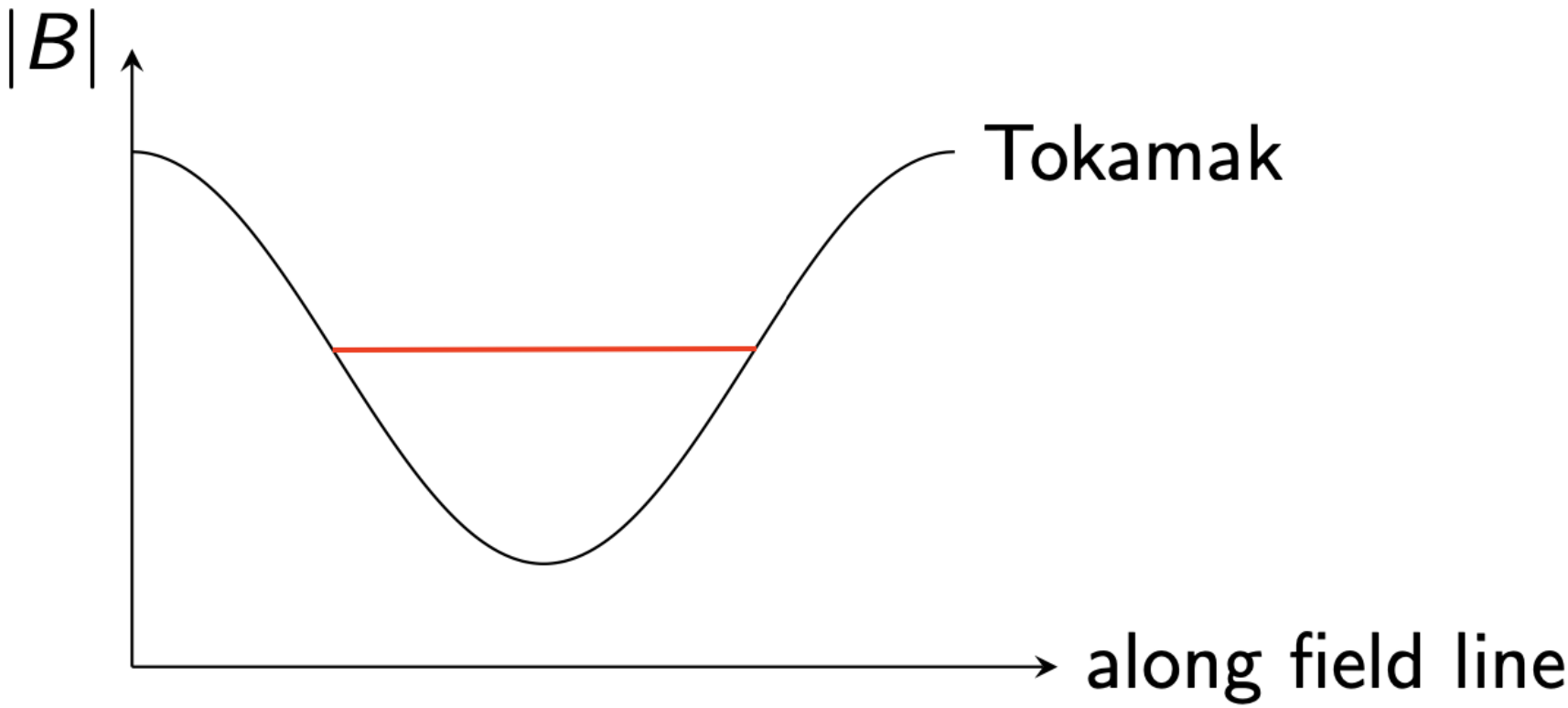

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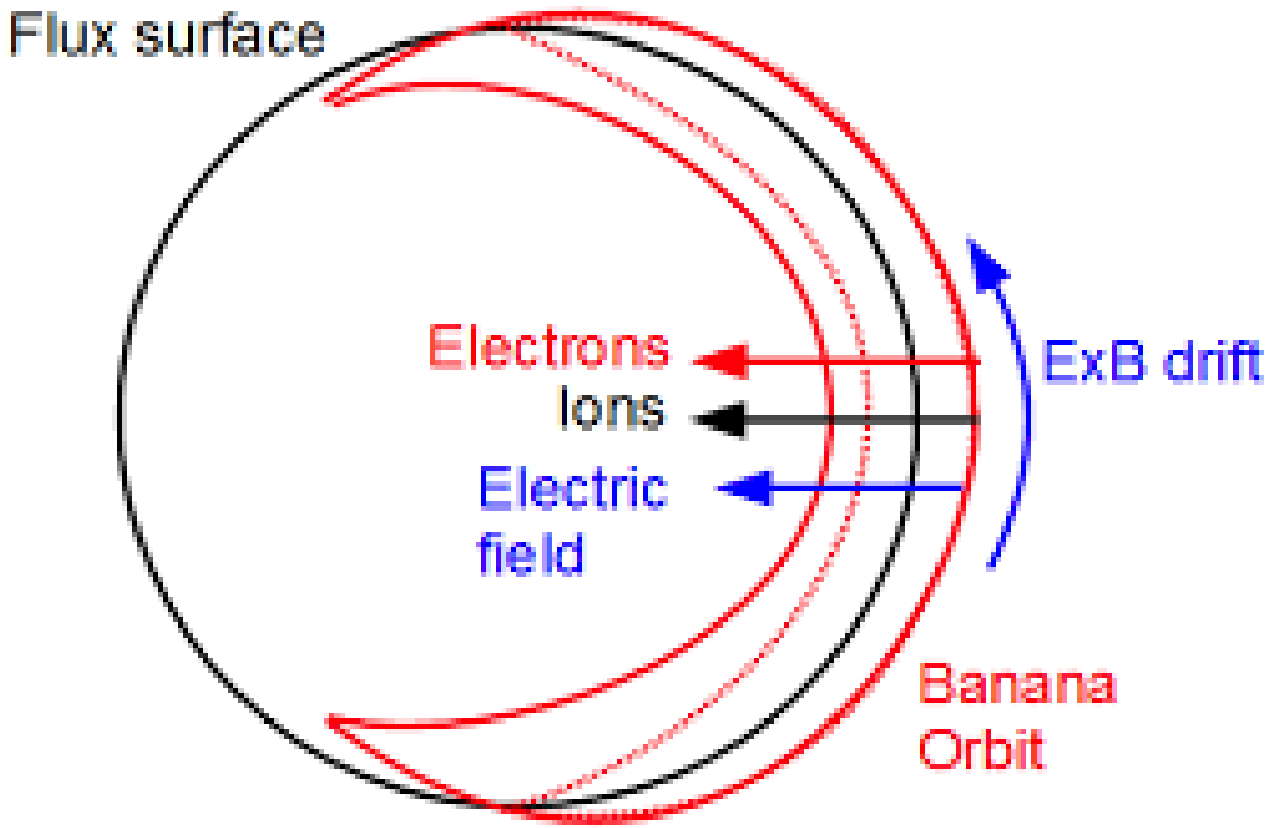

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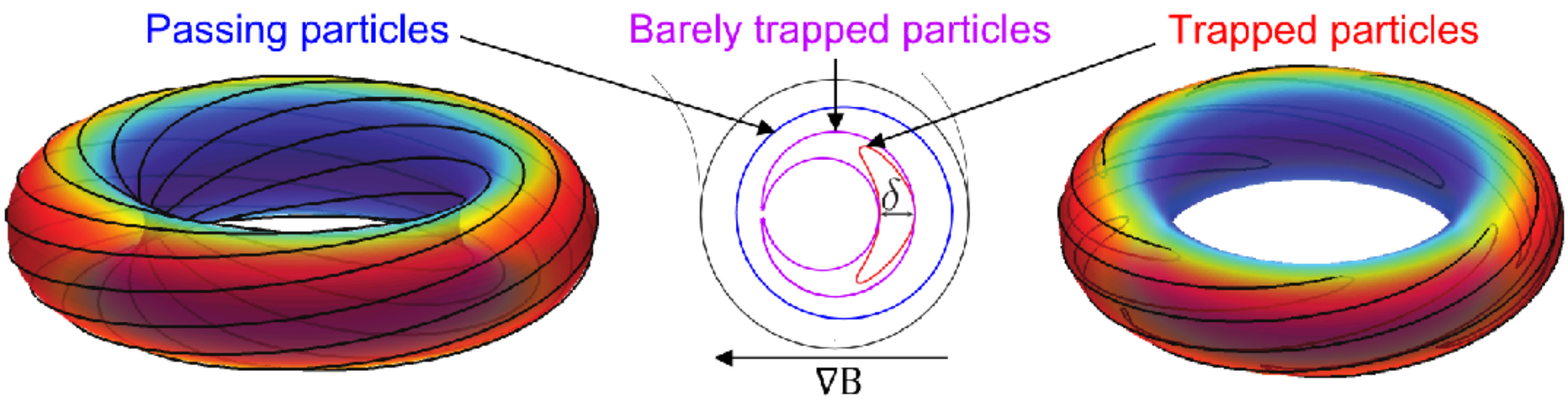

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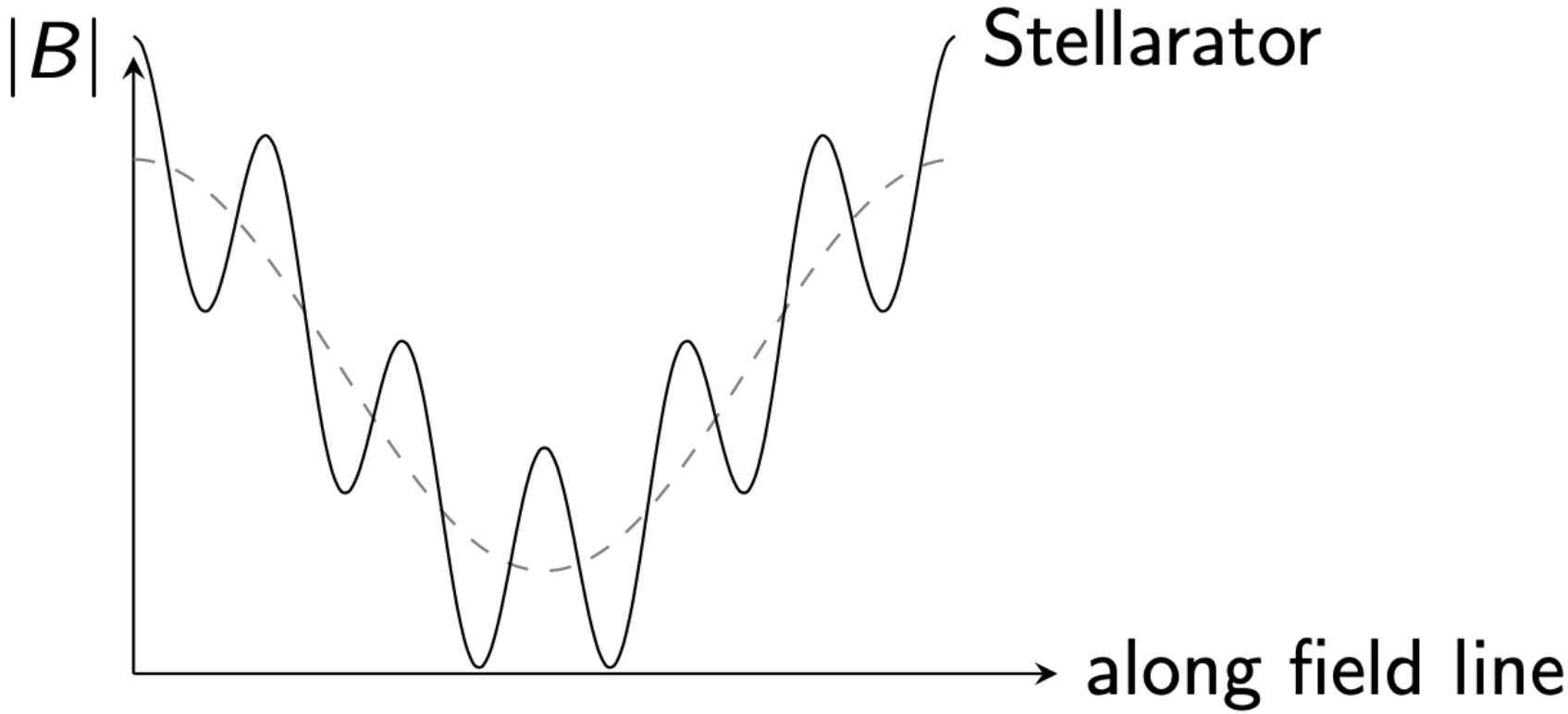

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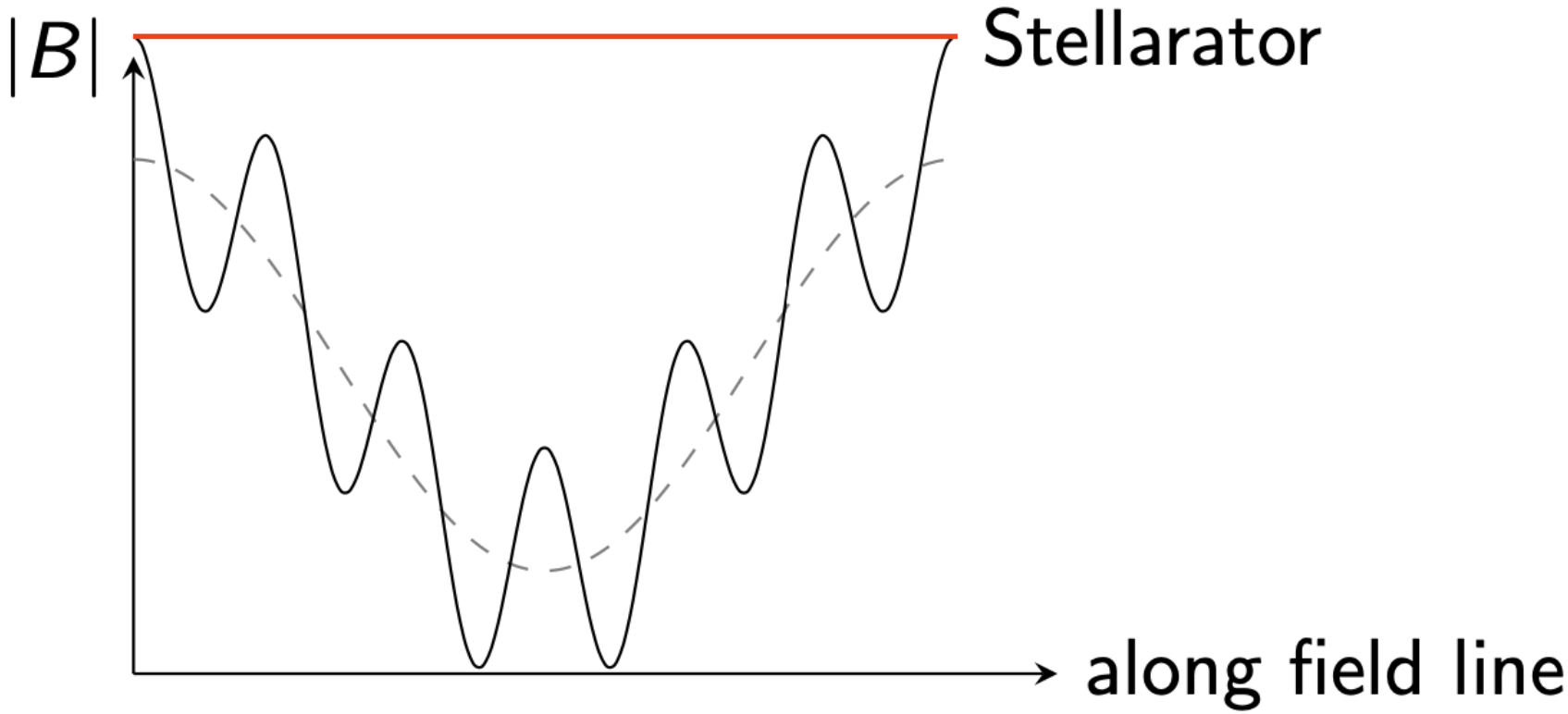

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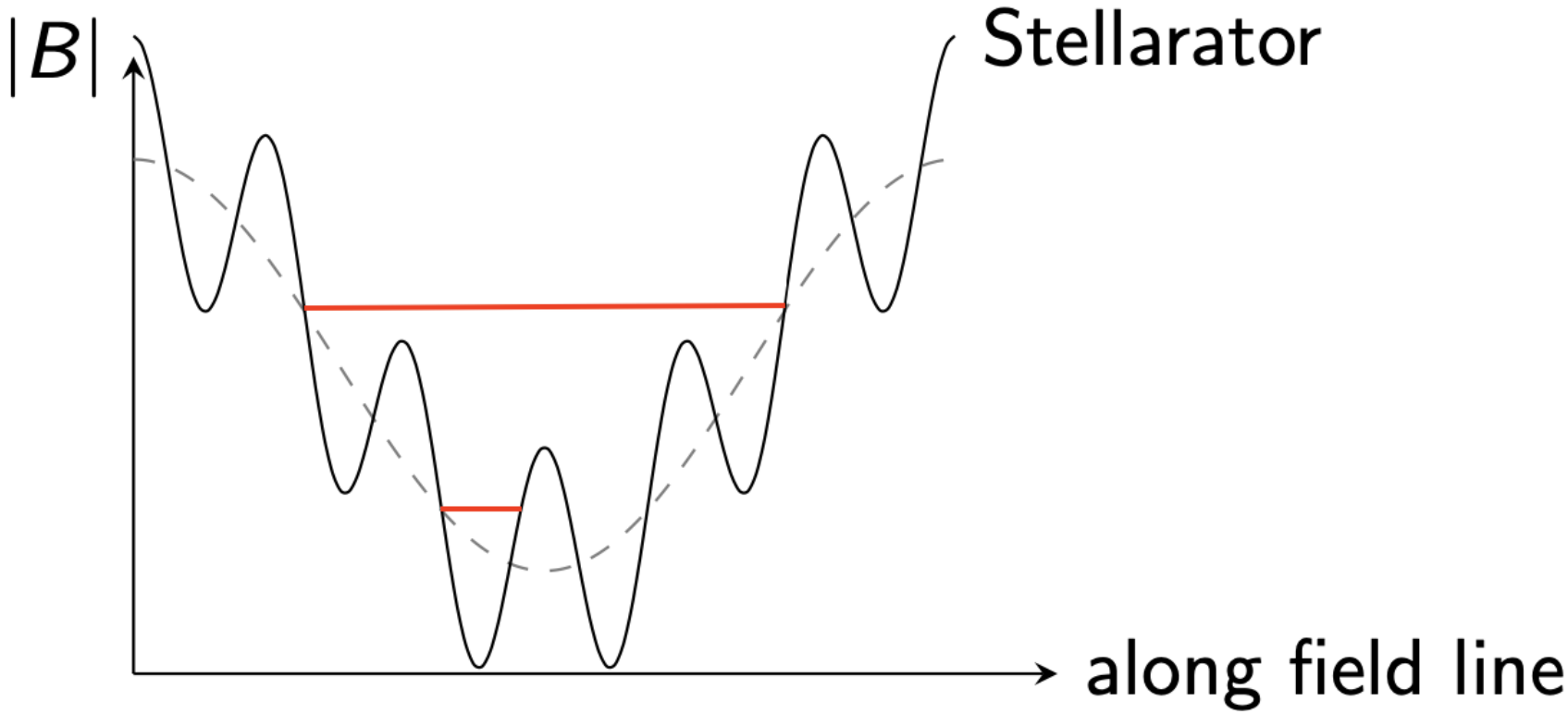

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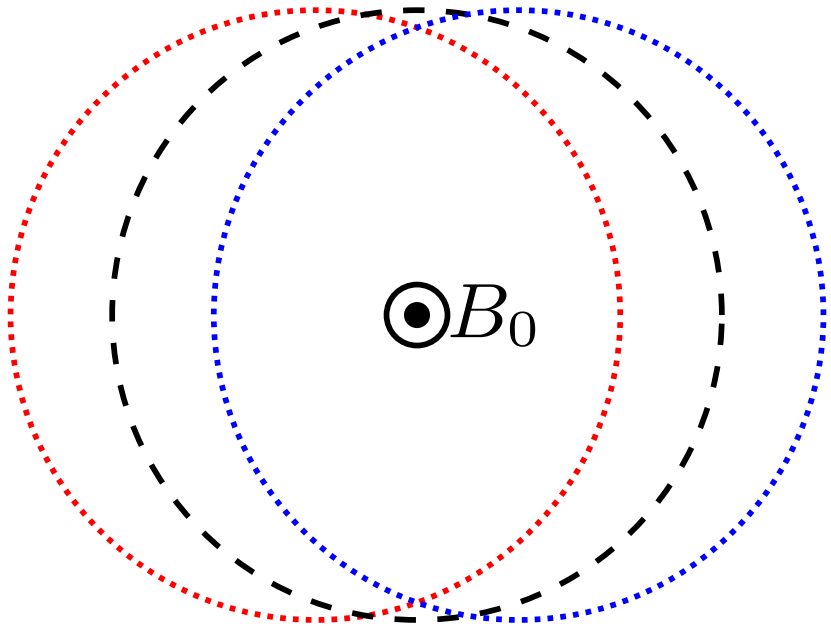
To Symmetries and Beyond!

Require time-averaged radial magnetic drifts away from flux surface to vanish for all particles



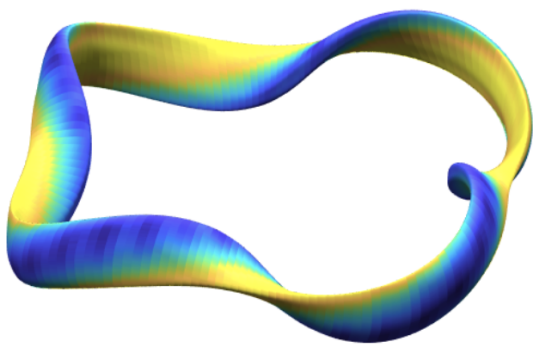
Otherwise neoclassical transport is amplified

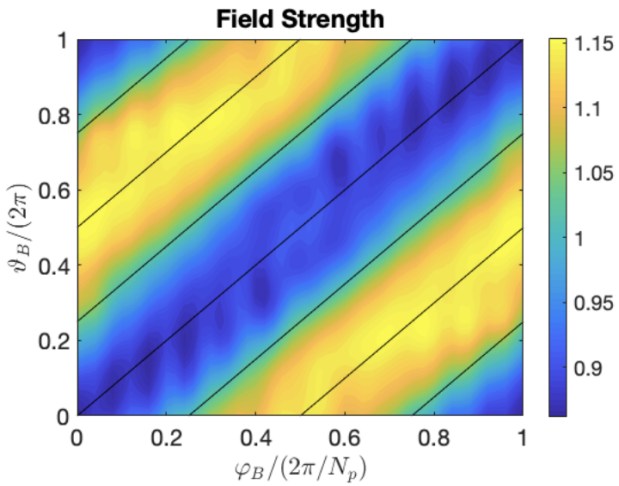
To Symmetries and Beyond!

- We all know and love symmetries $\rightarrow$ leads to conserved quantities
- Quasi-symmetry; $B = |\boldsymbol{B}|$ has a continuous symmetry in certain coordinate systems

To Symmetries and Beyond!

- Particle orbits and neoclassical transport are the same in quaisymmetric devices as in truly axisymmetric ones
- "Unwrap" stellarator with certain transformation and magnetic field looks the same to particles





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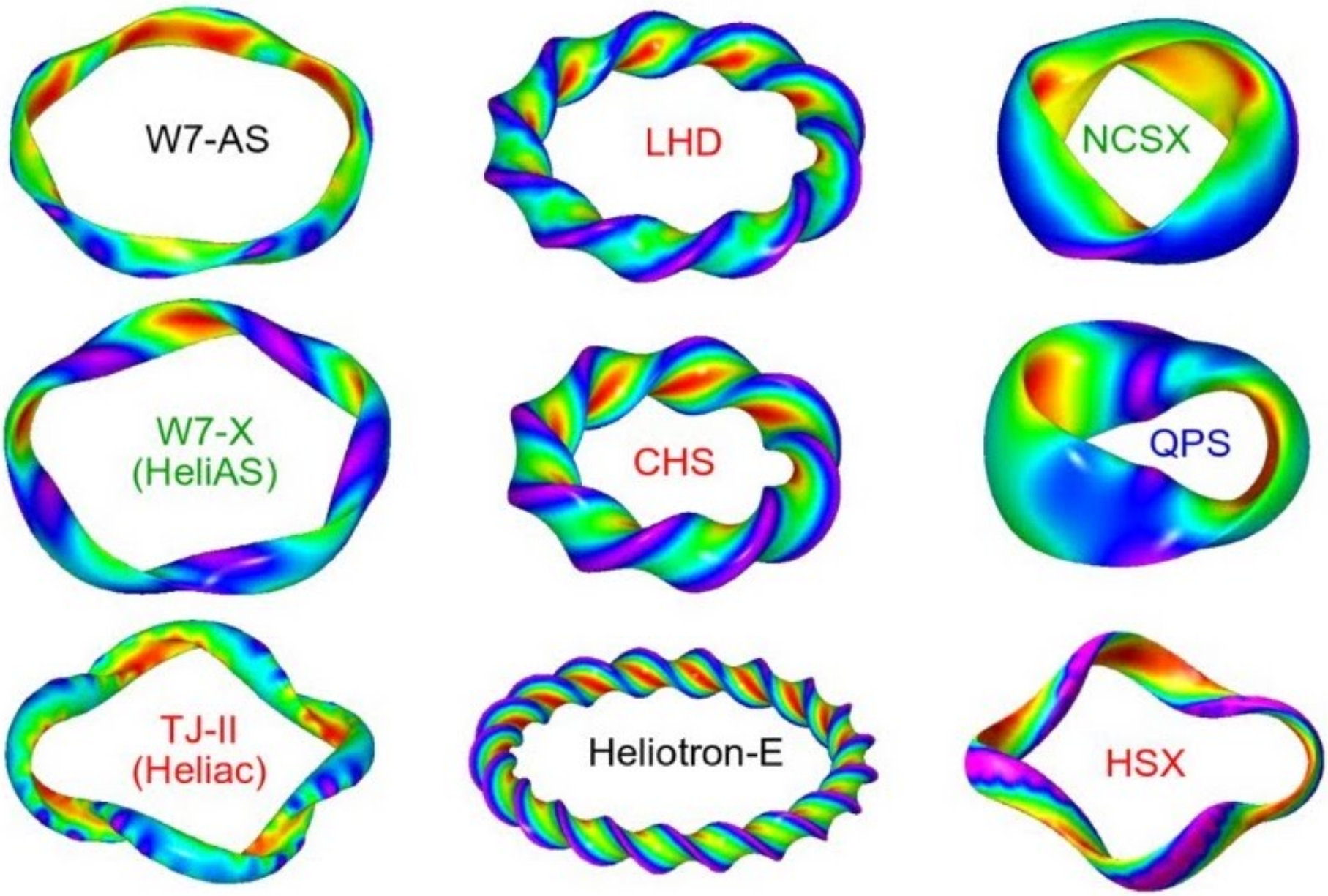
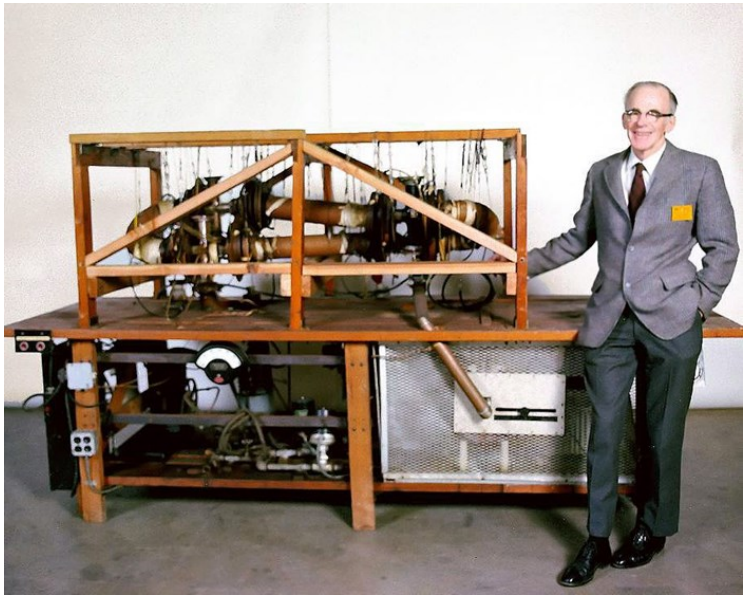


So we have our demands...
but why stellarators??

A Brief History of ~~Time~~ Stellarators

- Stellarators were first conceptualised by Lyman Spitzer in 1951 before tokamaks (1958)



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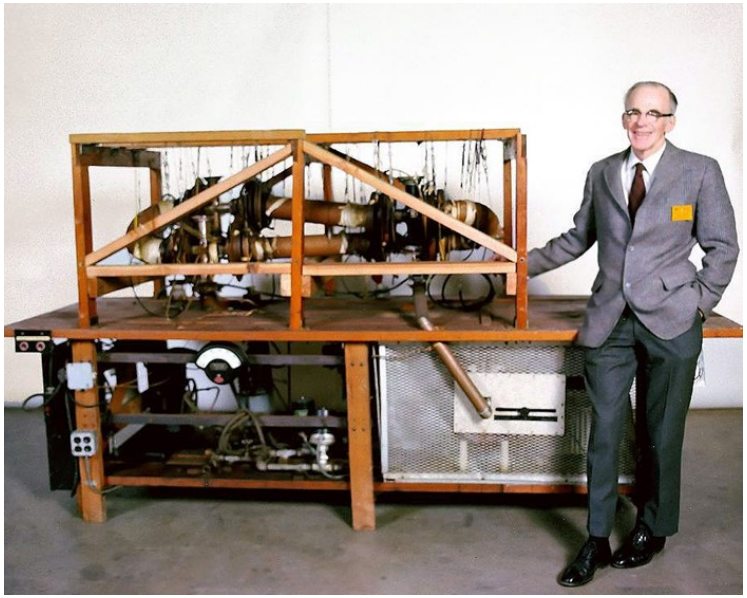

- Soviet Union introduced the world to the tokamak in 1968 and the stellarators took a back seat

A Thorn in the Side of Stellarators

"I try to avoid hard work. When things look complicated, that is often a sign that there is a better way to do it."

- Frank Wilczek (Nobel Prize winner 2004)

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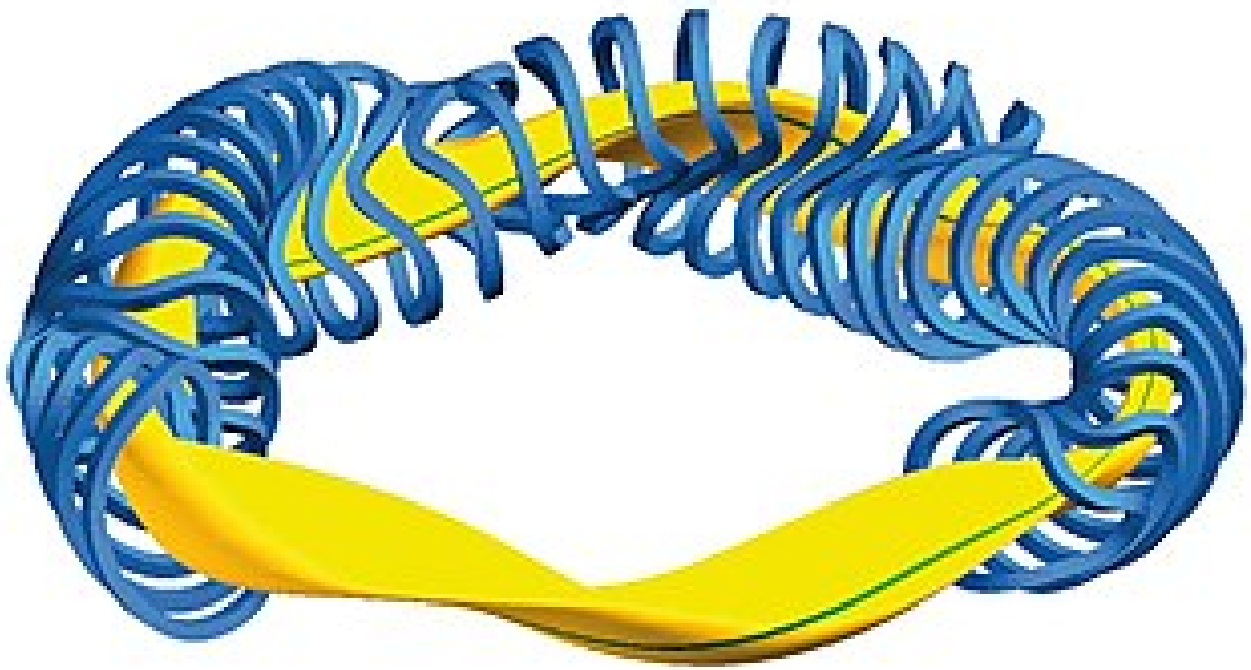
- Initially found to be neoclassically dominated - symmetries not perfect
- Soviet tokamaks were superior than stellarator performance
- Tokamaks were objectively simpler and more attractive to engineers

Neoclassical Transport - The Rise and Fall of Stellarators?

- Numerical advancements allowed us to optimise neoclassical transport
- Neoclassically optimised stellarators have been built - W7-X in Greifswald, Germany



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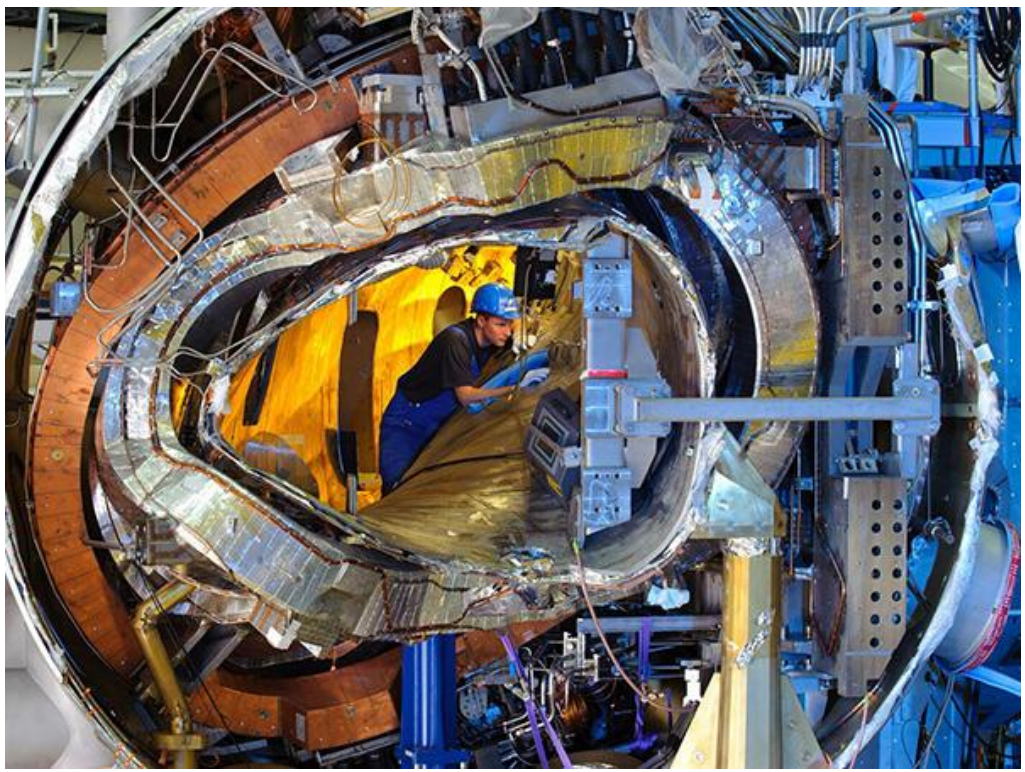

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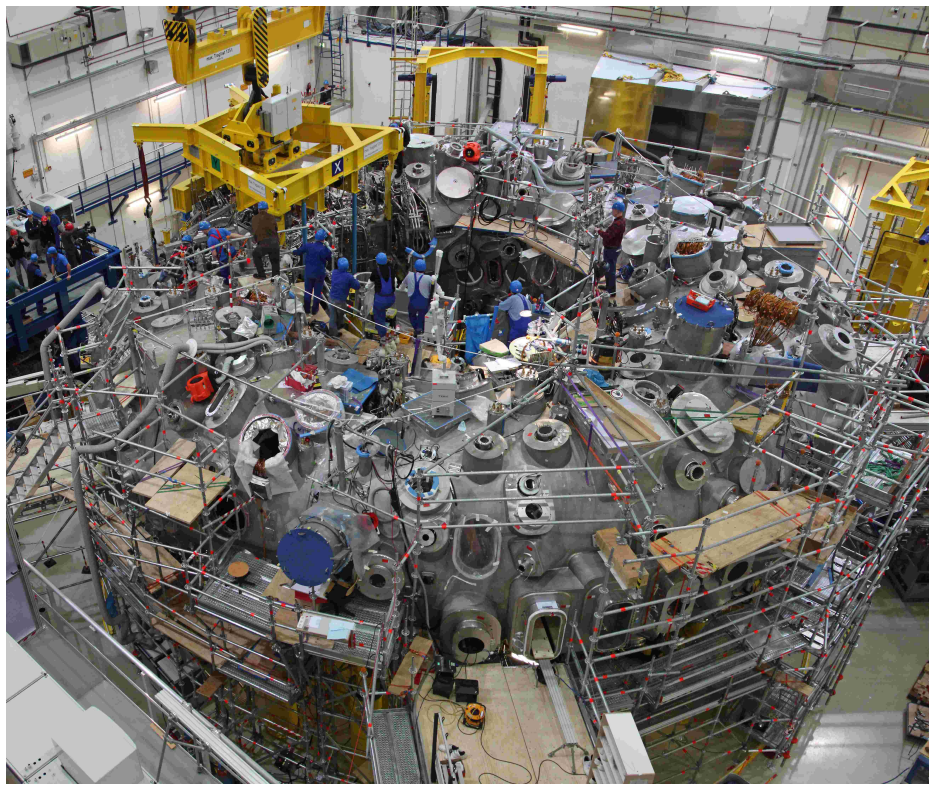

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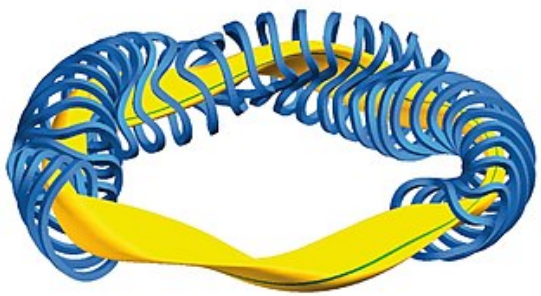

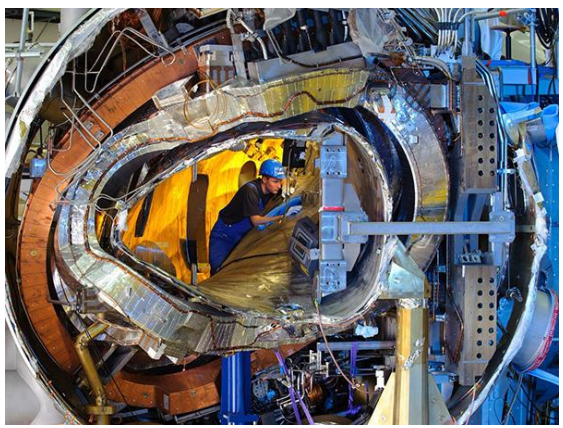

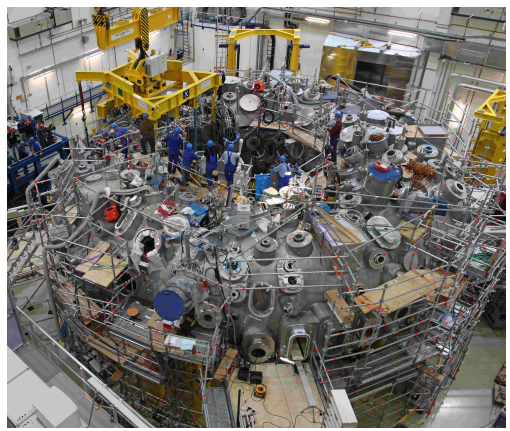

Now on a level playing field with tokamaks

Advantages of Stellarators

- Stellarators are driven purely by external coils - can have continuous operation
- They do not have a toroidal current - fewer instabilities/disruptions
- Have a higher density limit than tokamaks
- Potential for better confinement

- Tokamaks are discontinous in use
- Tokamaks have toroidal current leading to instabilities
- Tokamaks have density limit
- Tokamaks currently don't have good enough confinement for fusion

~~Advantages~~ Disadvantages of Stellarators

- Stellarators are driven purely by external coils - can have continuous operation
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- Have a higher density limit than tokamaks
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- Stellarators have complicated geometries, and even more complicated coils!
- Self-generated current reduces external current drive dependence
- Bigger gradients - potentially more turbulent instabilities
- Not guaranteed nested flux surfaces

Where Are We Now?

There seems to be as many disadvantages as there are advantages

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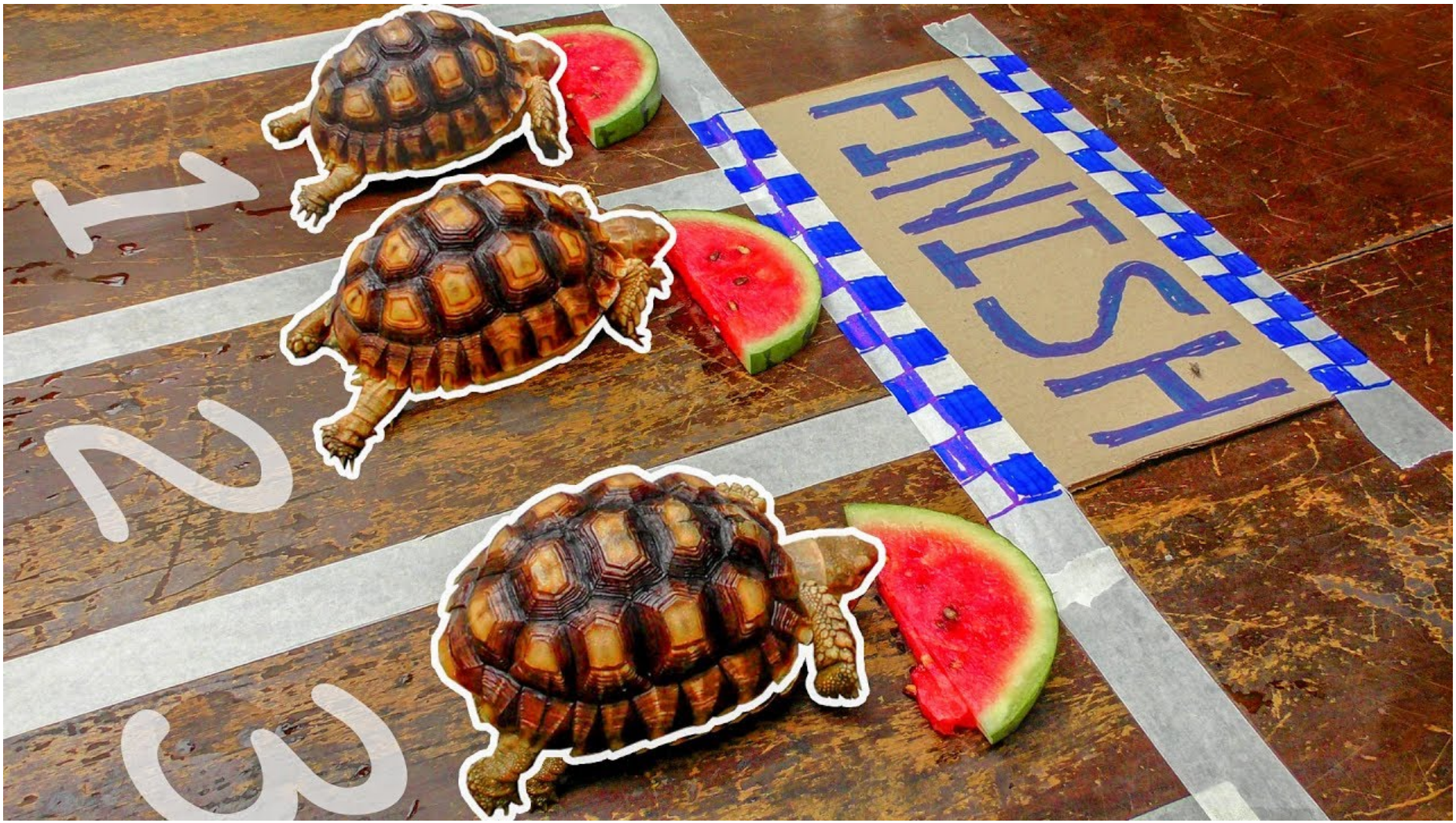

Where There Are Problems There Are Physicists

- Understanding new physics (if any) in stellarators
- Optimising magnetic field configuration
- Optimising coils for error
- Research into turbulent transport

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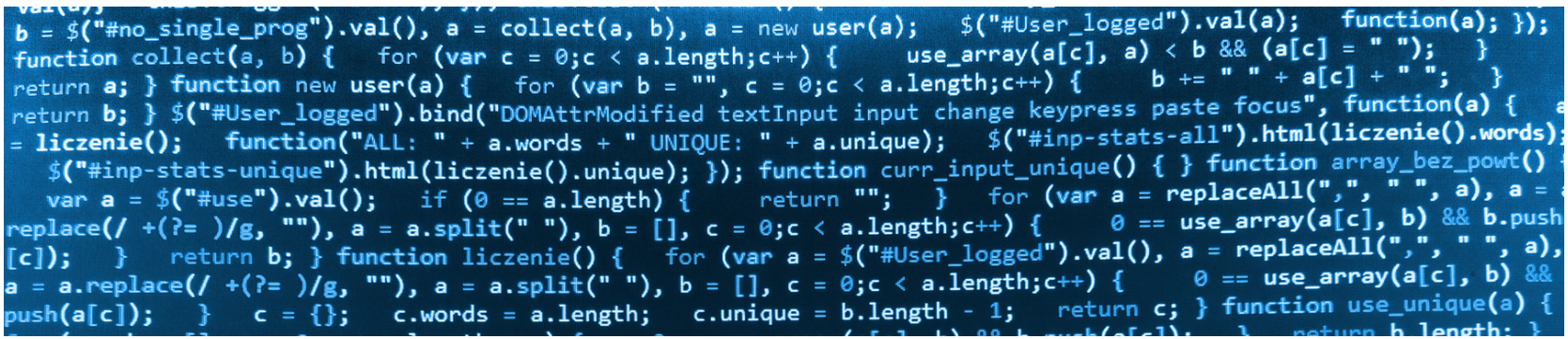
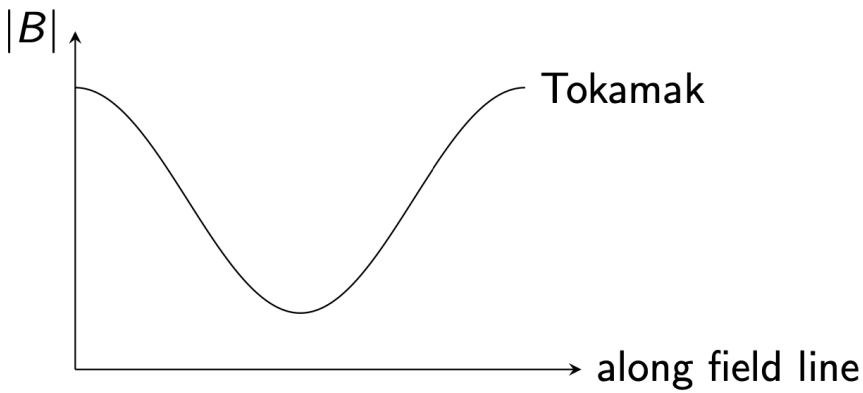
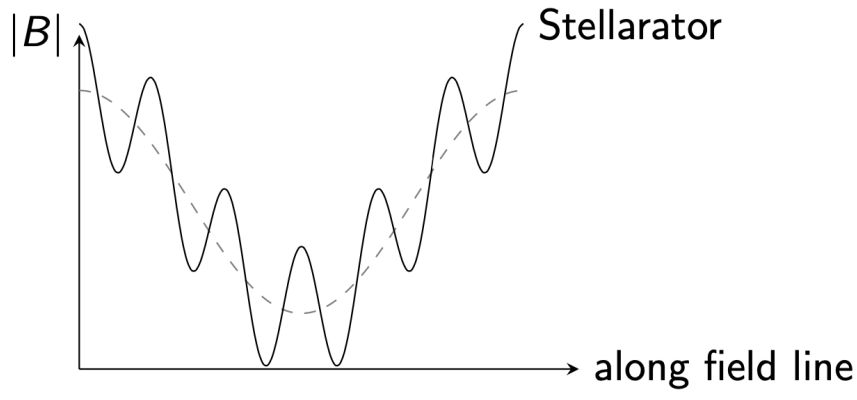
Solution? **Codes**



Why Stellarators Are Potential The Future of Fusion

Stellarators biggest problem may be their biggest strength





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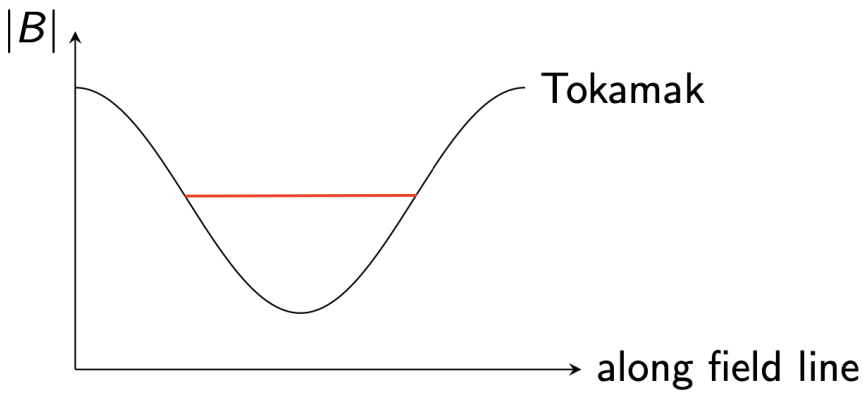

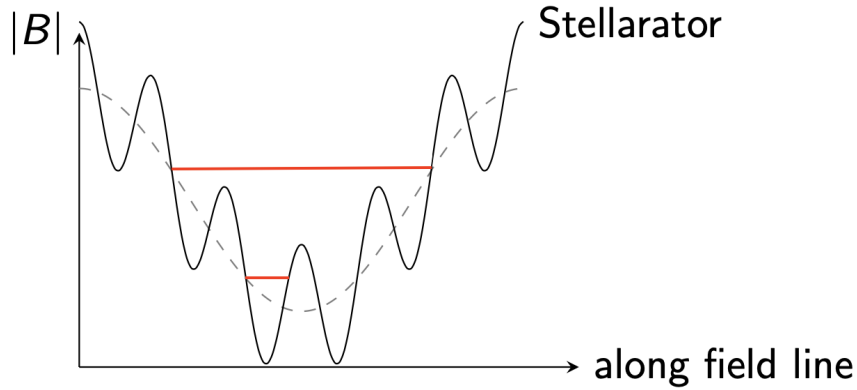

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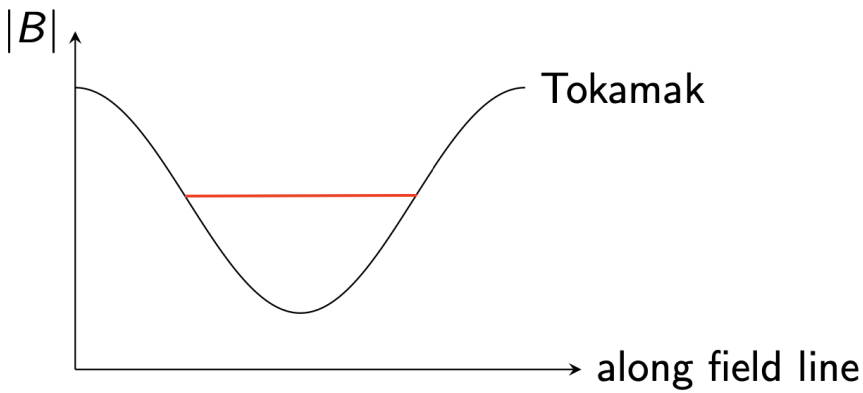

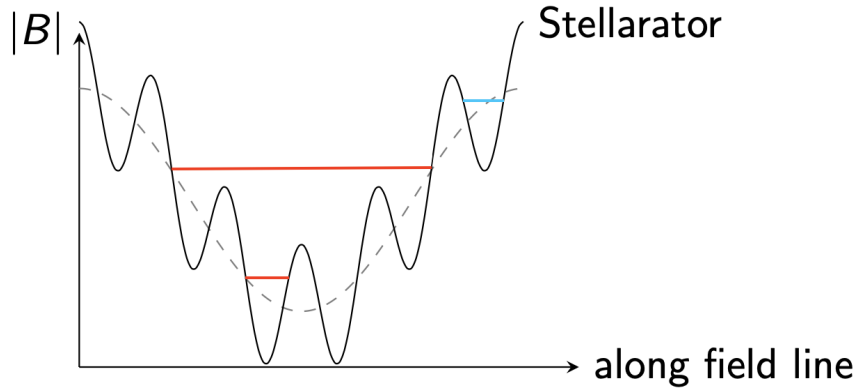

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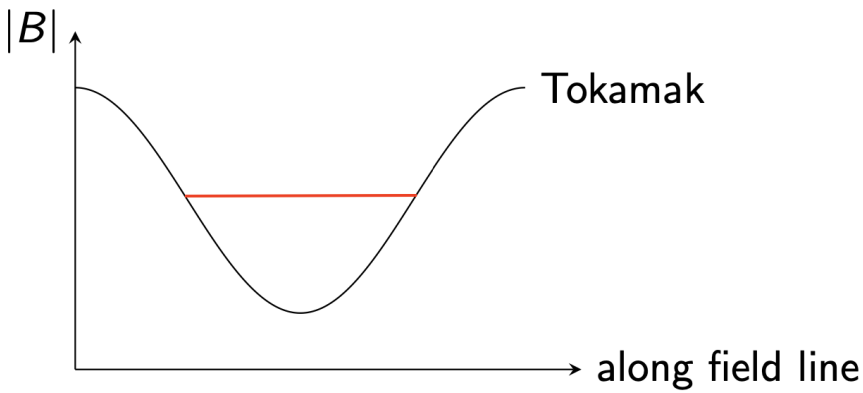
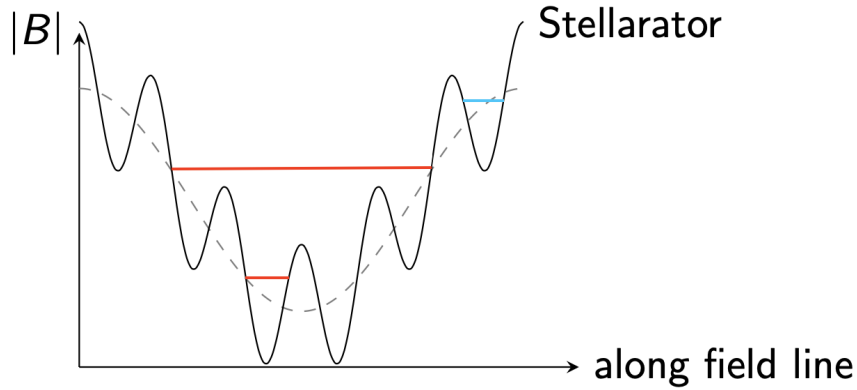
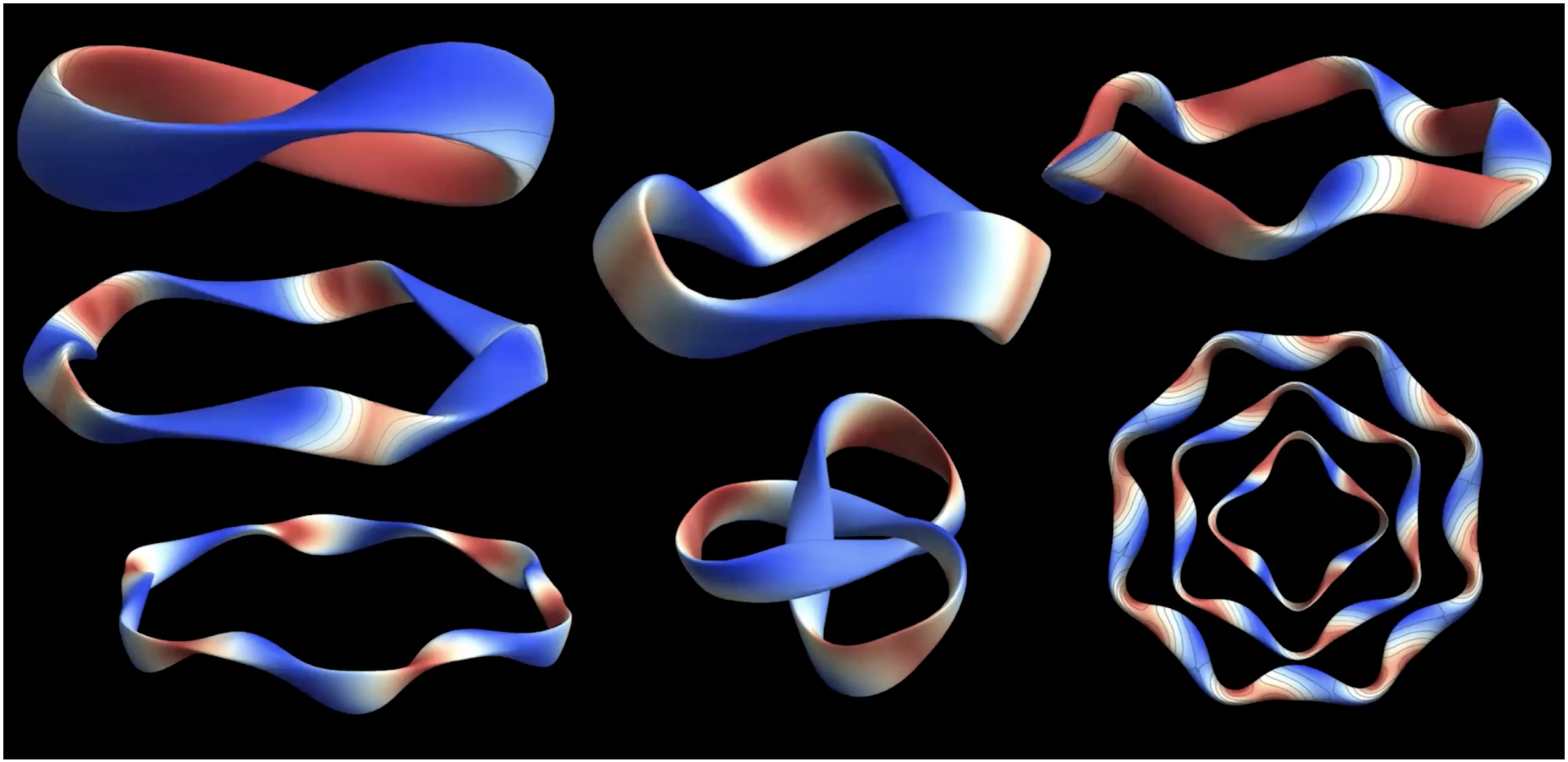




Bigger Parameter Space = Opportunities for Control

Why Stellarators Are Potentially The Future of Fusion



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Thank You!