

Advanced Stellarators for Economical Fusion

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Goals

- Fusion as a safe, long-term, commercial energy source
 - Electricity
 - Process Heat
- Economically competitive (long term) (typically $\sim \$0.05$ /kW-hr)
- Rapid construction, moderate capital cost (capital cost $\sim \$5$ /W)
- Globally accessible
- Must be safe
- Minimize activated waste by choice of materials

Why Stellarators?

Most successful approach to fusion → magnetic confinement in a torus

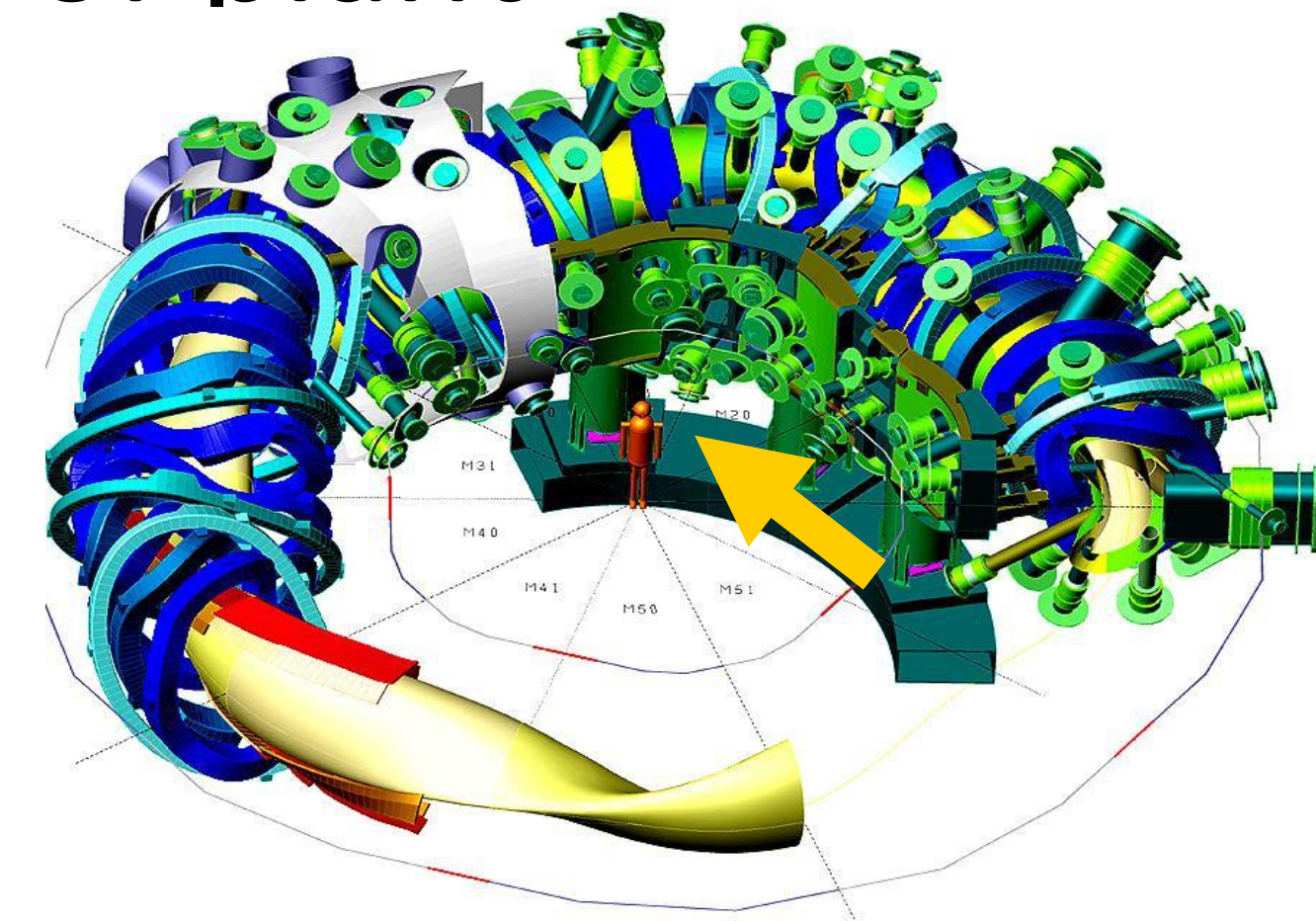
Stellarators have a simpler path to an economical system

- No rapid disruptions (unexpected plasma termination)
- No external current-drive
- Steady-state, static magnetic field → simpler superconducting coils
- Low recirculating power → smaller system & balance of plant

But: Stellarators have a long history of concerns:

- Adequate confinement, particularly of fast ions
- Complex 3D coil shapes ⇒ complicated engineering

These have been solved.



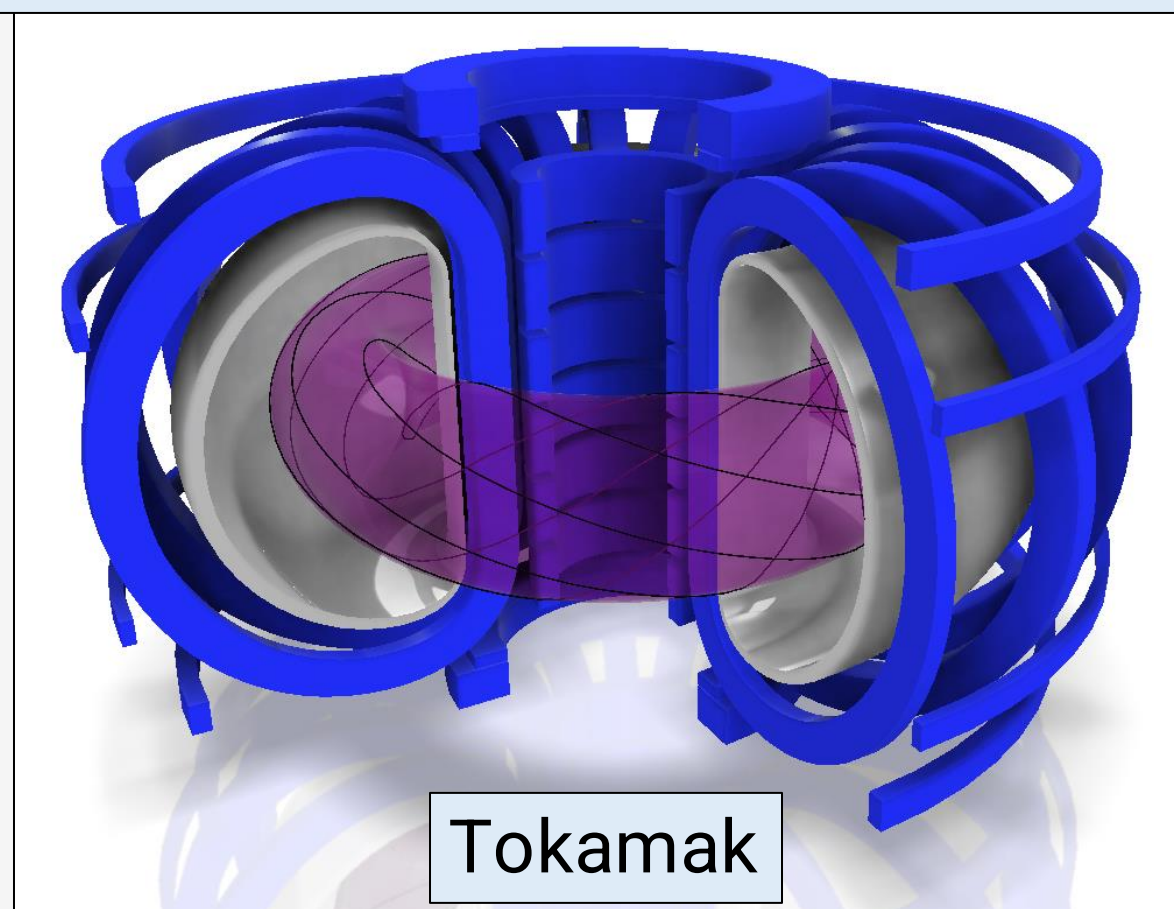
Wendelstein 7-X

Tokamaks & Stellarators

The Stellarator Solves the Existential Problems of Tokamaks

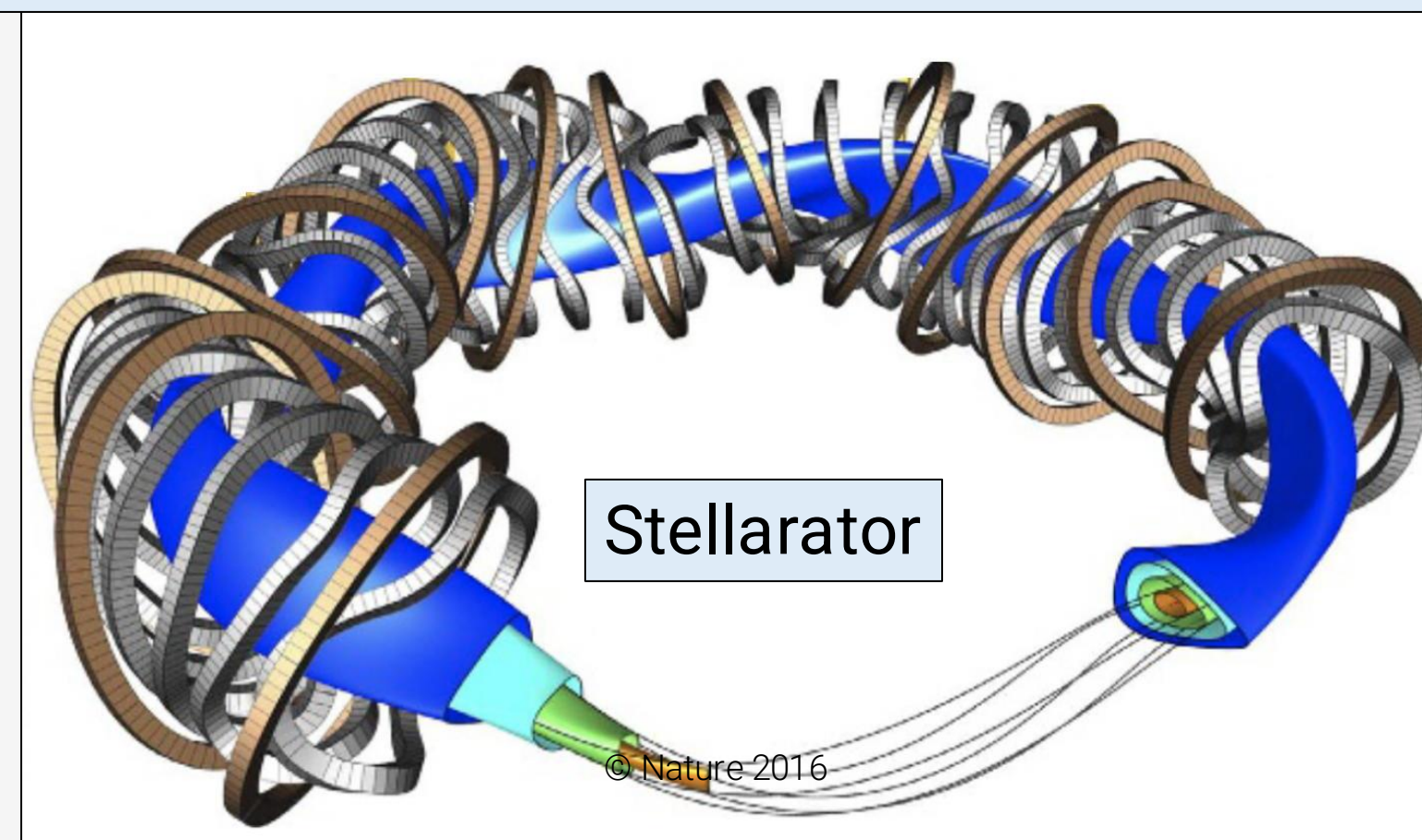
The stellarator magnetic field geometry is the same as in a tokamak – just helically twisted

Tokamaks and stellarator share the same knowledge base



- Plasmas disrupt frequently in present-day tokamaks
 - Potential showstopper
- Steady-state operation is not economical for reactor
- Lower densities and higher temperatures
 - Severe reactor-wall interactions

Crossing operating limits often produces disruptions



- Plasmas much more stable
 - No disruptions
- Intrinsically steady-state without current-drive
- Higher densities and lower temperatures
 - Benign reactor-wall interactions

Soft, higher operating limits, $\beta > 3\%$ quiescent

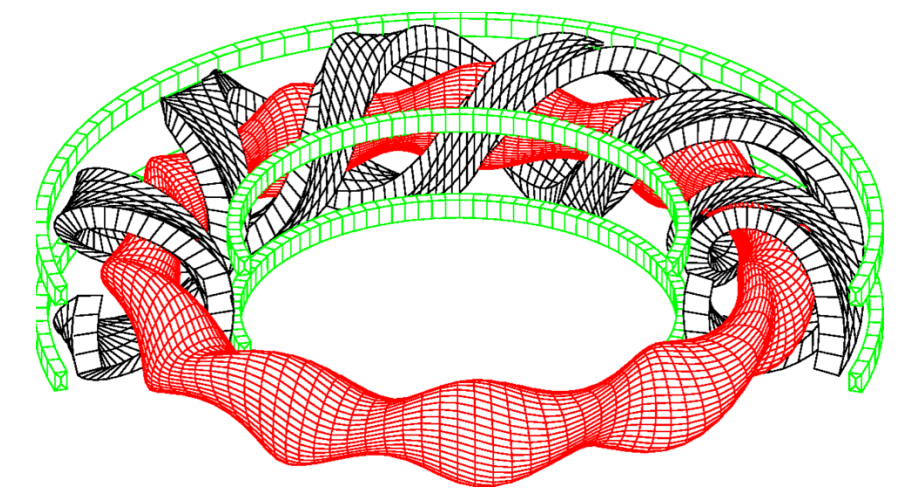
What is New? Advanced Stellarator Results

Wendelstein 7-X (Germany): validated its design optimization:

- Orbit-transport (neoclassical) can be designed to be small, sub-dominant
- Turbulent transport is as predicted theoretically
→ **Successfully modeled by same theory & codes used for tokamaks**
- Turbulence reduced with pellet fueling & peaked density profiles, as predicted
- Energy confinement time similar to tokamaks
- Power and particle exhaust design validated

LHD (Japan) achieved high plasma parameters in deuterium operation:

- Peak $T_i \sim T_e \sim 10$ keV (at low density)
- High plasma pressure at high temperature
 $\beta = \text{plasma pressure} / \text{magnetic pressure}$ up to 5%

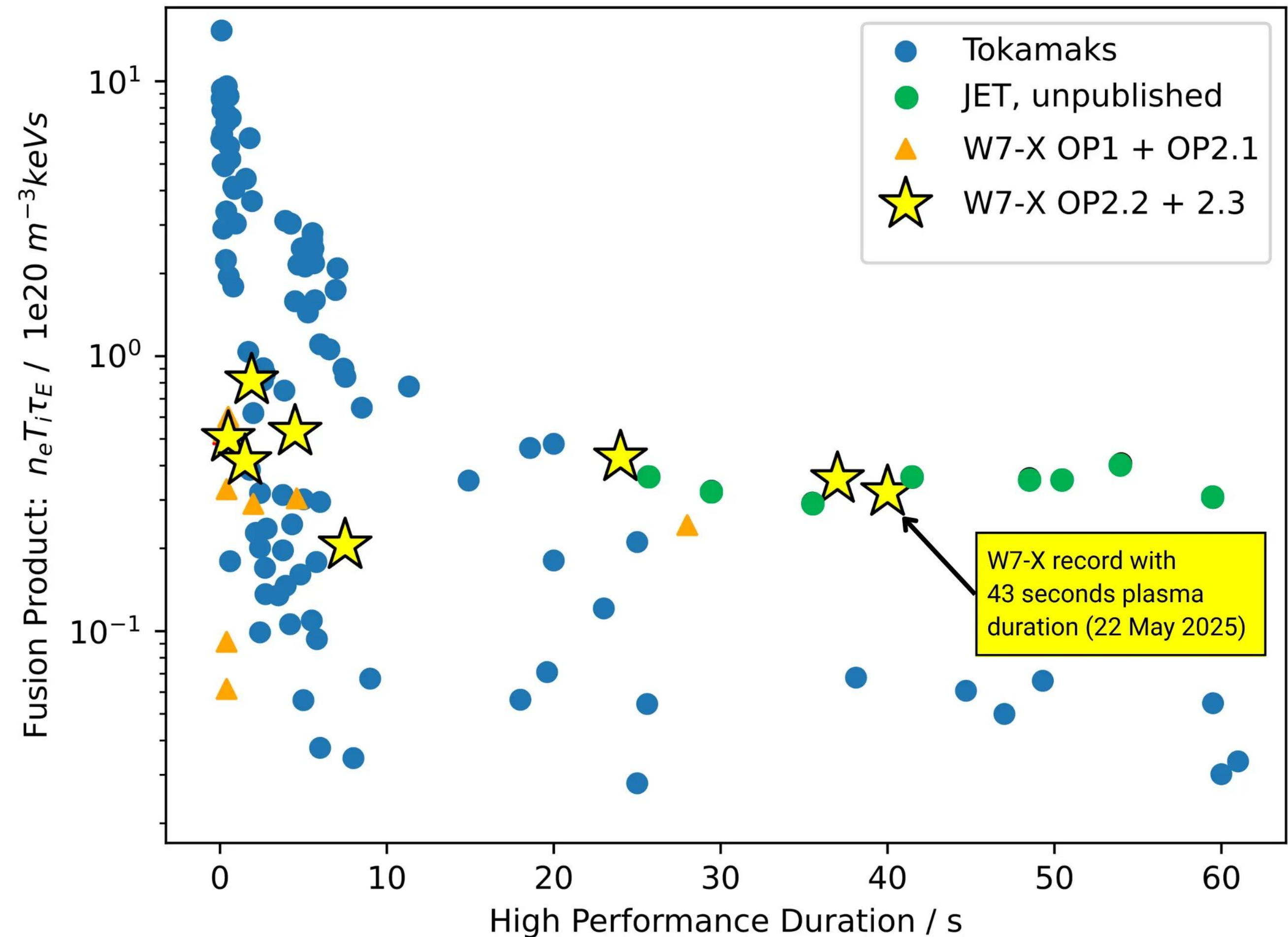


W7-X Fusion Performance Similar to JET

**W7-X Lawson-criteria performance
Similar to JET for durations > 10 sec
(2025 results)**

Even though:

- JET plasma volume
~3 times larger than W7X
- JET max B is higher than W7X



What is New?

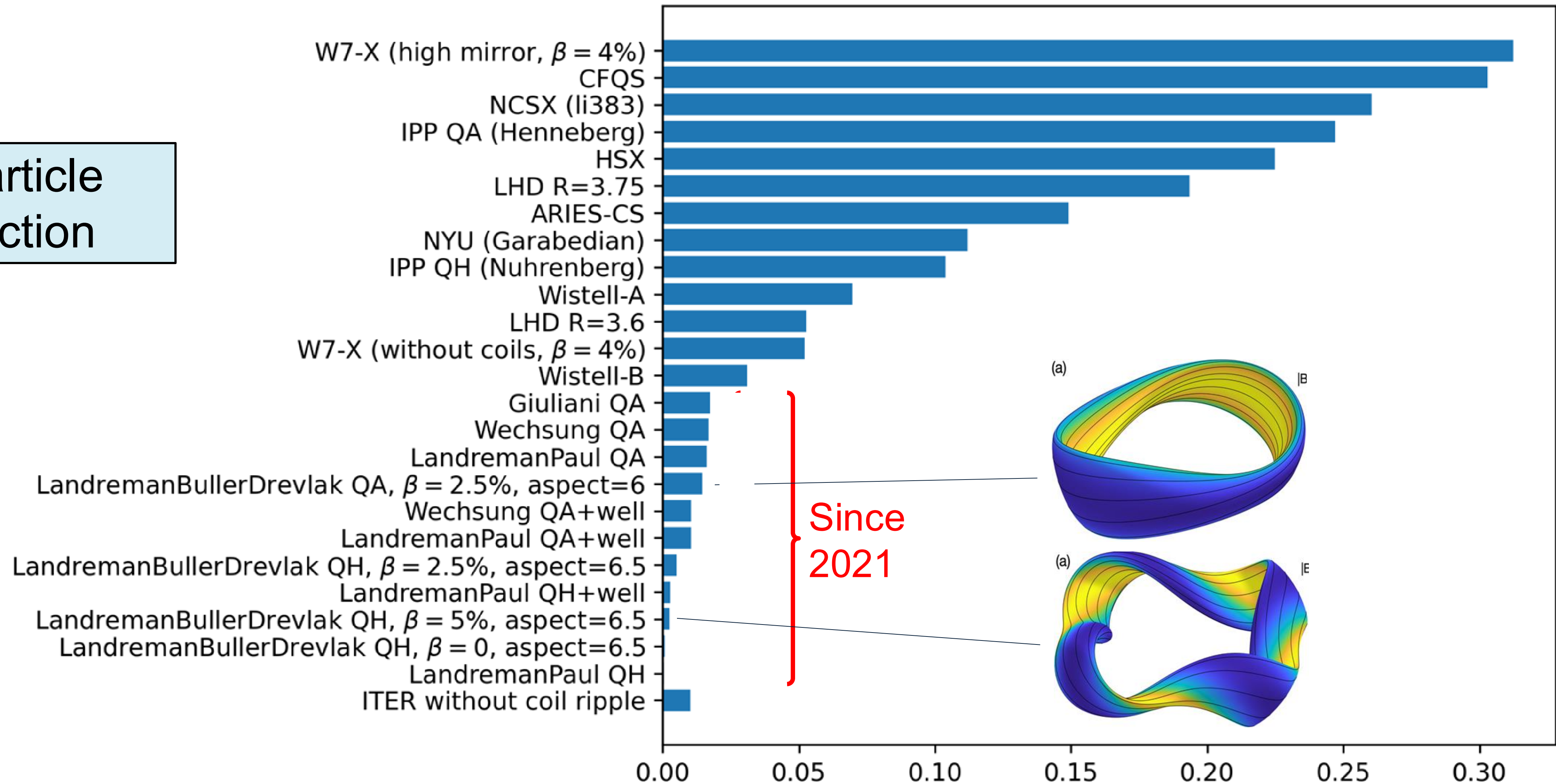
Improved Stellarator Theory & Optimization

Simons Hidden Symmetries Project & wider theory programs world-wide:

- New applied math and computational tools to design magnetic configurations
- New optimization codes (*SIMSOPT*, *DESC*) that exploit the full power of highly parallel computers
- New computational techniques, such as adjoint methods and automatic differentiation
- New methods to optimize and **reduce plasma turbulence**, improve plasma confinement
- Reliable optimization of **fast ion confinement** (e.g. alpha particles from fusion)

Remarkable Theory Progress Optimizing

Alpha Particle
Loss Fraction



-- M. Landreman

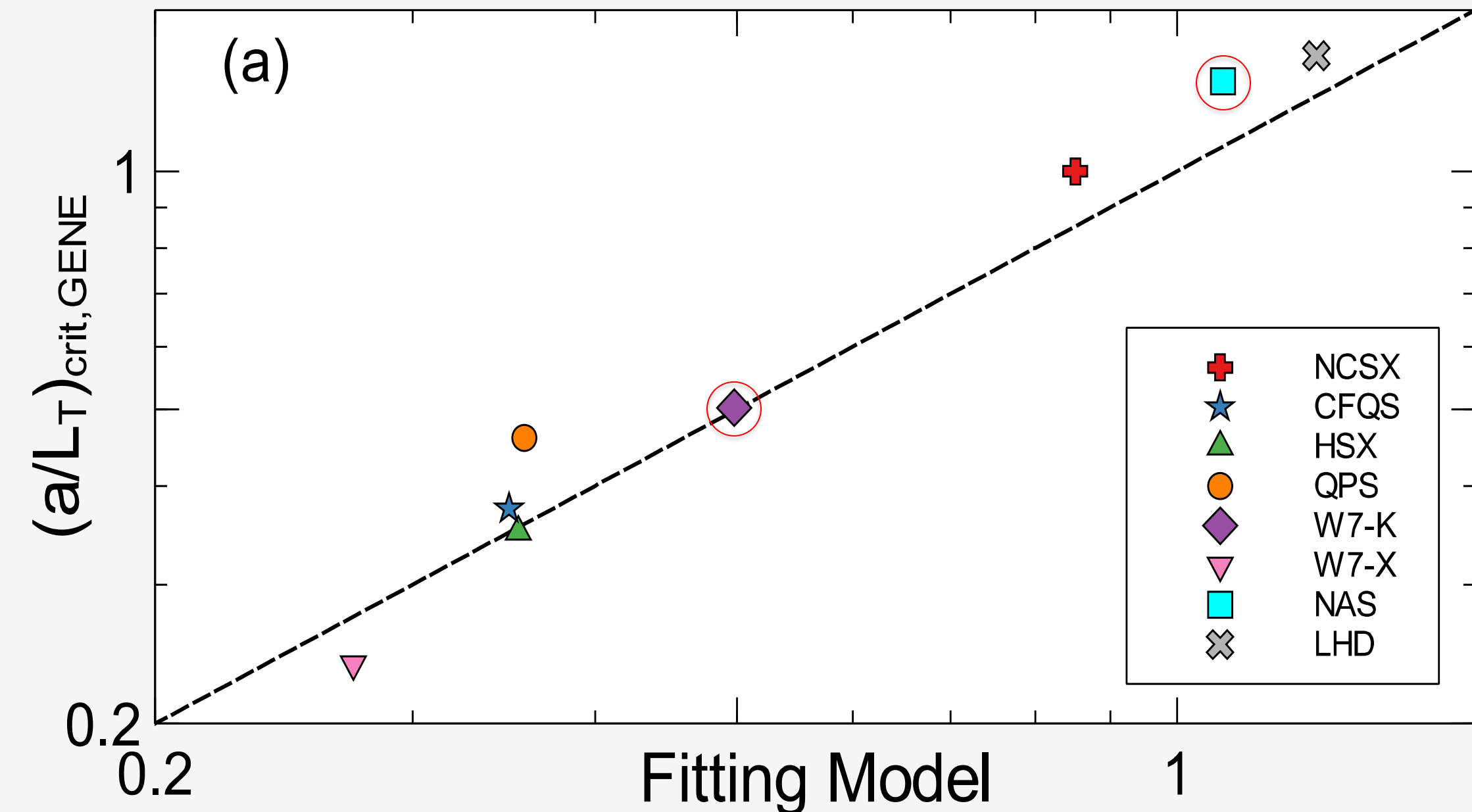
Turbulence Optimization Achieved for Improved Performance and Cost Reduction

High Plasma Confinement is crucial for reduced cost

- Most sensitive parameter determining plant cost and size (both tokamaks and stellarators)
- Next most important parameter is Aspect Ratio $A \equiv R/a$

ITG Critical Gradient

- Scale length of Ion Temperature Gradient turbulence
- Ion temperature profile determined by marginal stability
- Higher corresponds to higher $T_i(0)$ for fixed edge temperature
- Varies strongly across stellarator designs
- Can be improved by design optimization (circled points)
- Generally, $(a/L_{Ti})_{crit}$ increases with decreasing A
- Now: directly optimize non-linear turbulence, predicted profiles
- Higher fidelity than just the critical gradient scale length



$$a/L_{T,crit} = 2.66[(a/R_{eff}) + 8.00(a/L_{||})]$$

G.T. Roberg-Clark et al, arXiv 2022

What is New? Simpler Technology & Construction

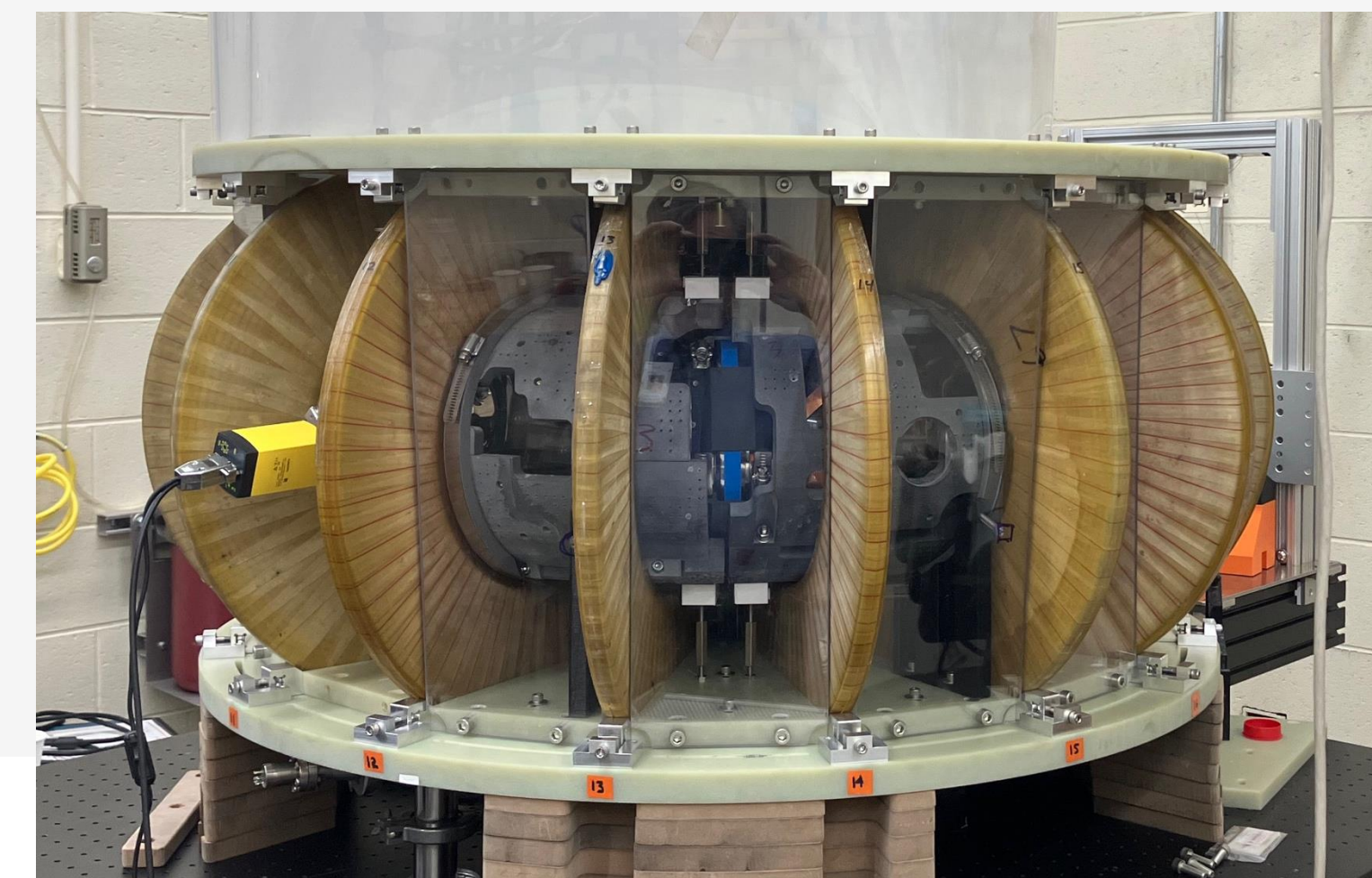
High Temperature Superconducting (HTS) Magnets -- available commercially

- Higher B (magnetic field), higher current density, operating at higher temperature.
- Reduced construction and operating costs (all metal coils)
- Opportunities to substantially reduce superconductor cost identified

Simplify Stellarator 3D-Magnets and system maintenance

- Use of magnetic dipoles, to ease construction and maintenance
- Prototype demonstrated: MUSE (PPPL)
- Worlds first highly optimized Quasi-Axisymmetric stellarator
- Constructed in 1 year, largely by students
Operating now for student research

MUSE PPPL

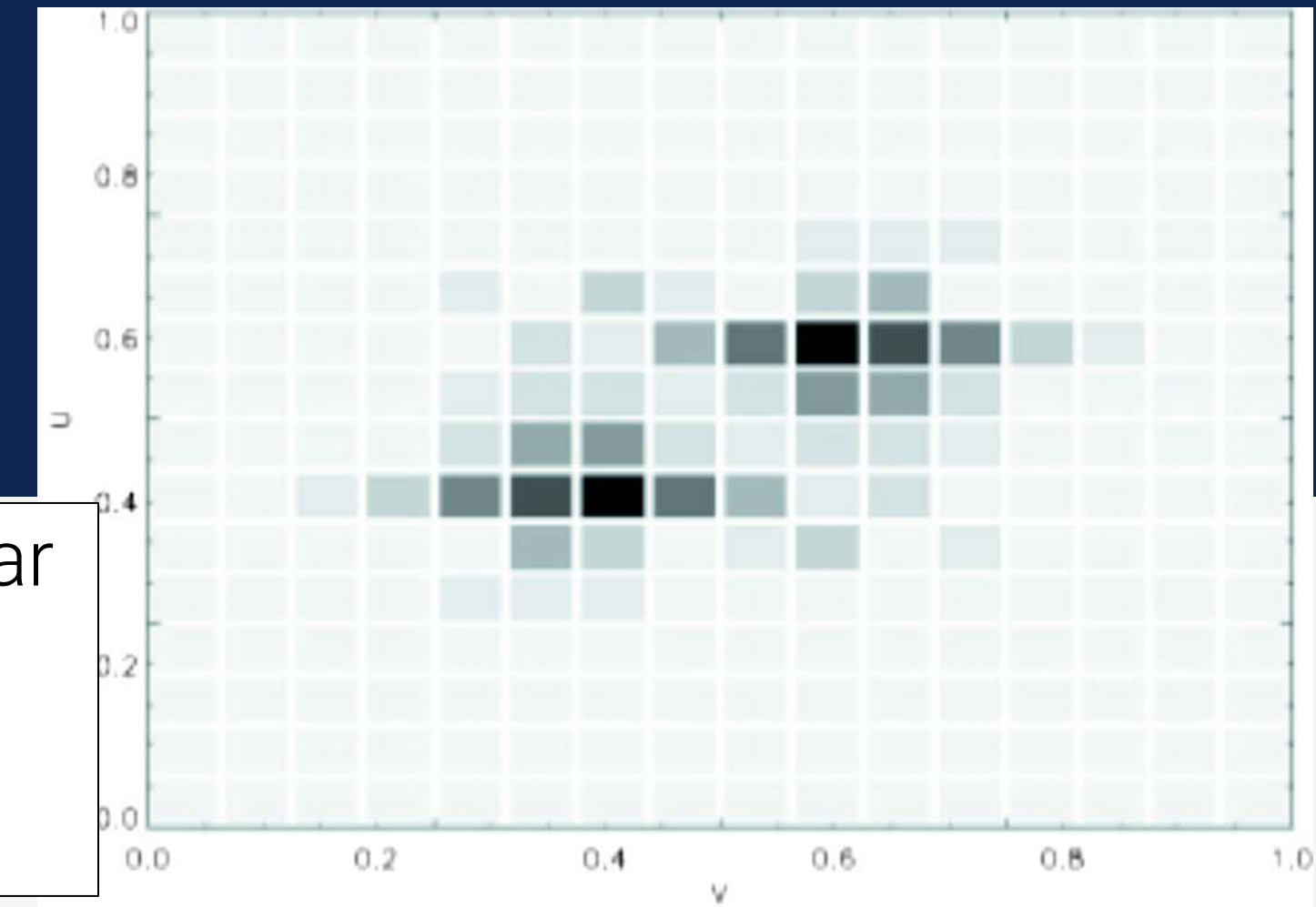


Stellarator Coil Simplified using Magnetic Dipoles

Stellarex is developing methods to simply stellarator construction & Maintenance access

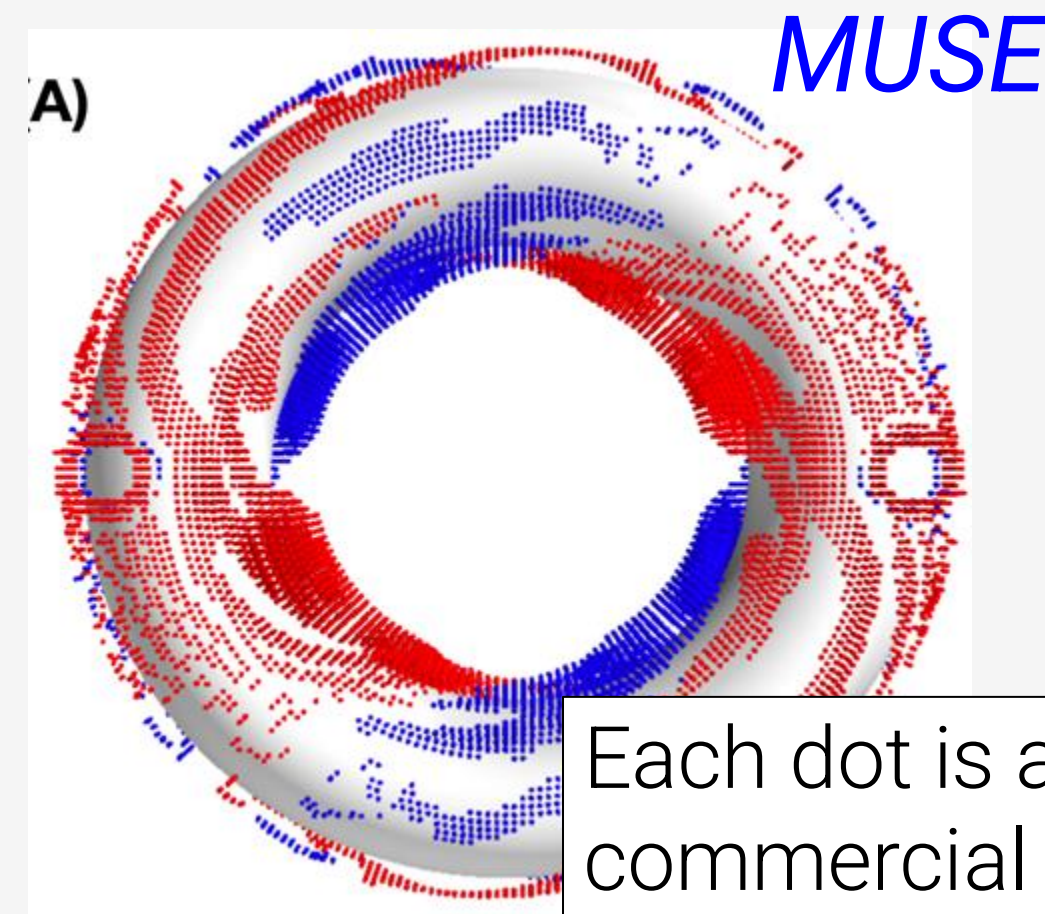
Each square represents one rectangular coil, color represents intensity.

Array is wrapped around torus



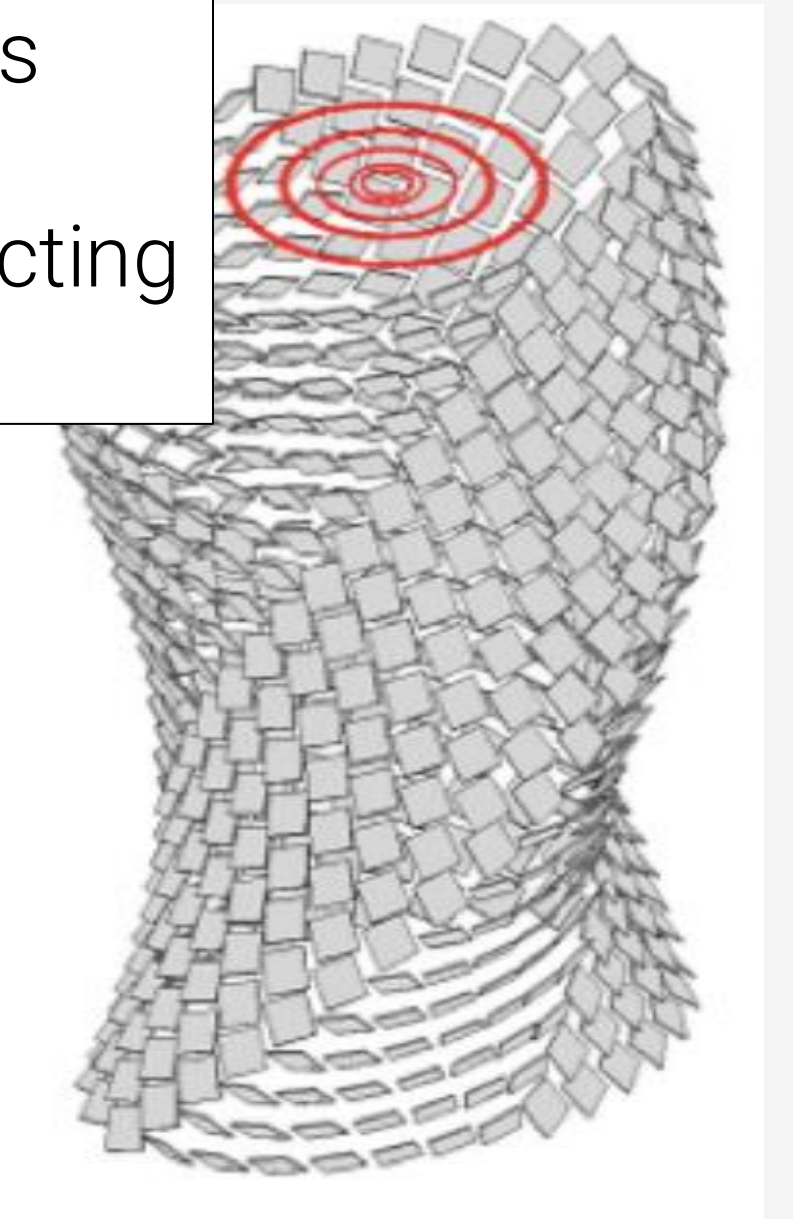
Three methods:

- **Dipole coils (“snake skin”)**
L.P.Ku and A. Boozer Phys. Plasmas (2009)
- **Dipole superconducting diamagnets**
L.Bromberg, **M. Zarnstorff**, et al
Fusion Sci. & Technology (2011)
- **Dipole permanent magnets**
P.Helander, M.Drevlak, **M.Zarnstorff**, S.Cowley
Phys. Rev. Letters (2020)
T.Qian, **M.Zarnstorff**, et al. Nucl. Fusion (2022)



Each dot is a commercial Permanent magnet

Each block is commercial superconducting diamagnet



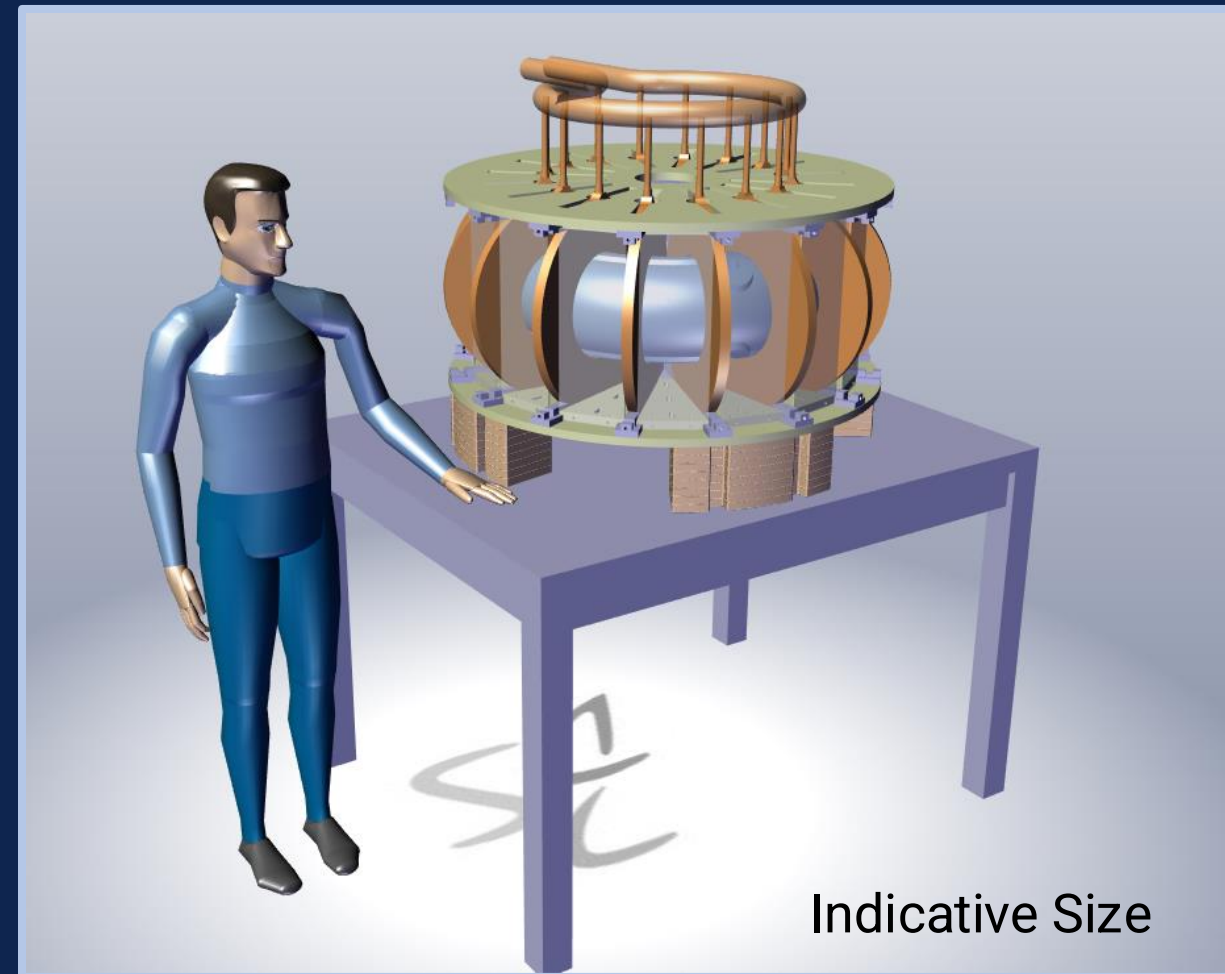
Stellarex is mixing these approaches to optimize the design using a 3D-printed support structure.

Stellarex Plan: Advance to Pilot Plant

- Exploit the new developments and stellarator advantages
- Advance quickly: iterating, testing and validating at increasing scale and confinement performance.
- Aim is to have an optimized burning-plasma pilot plant working in the mid-2030s.

MUSE

2023 PPPL

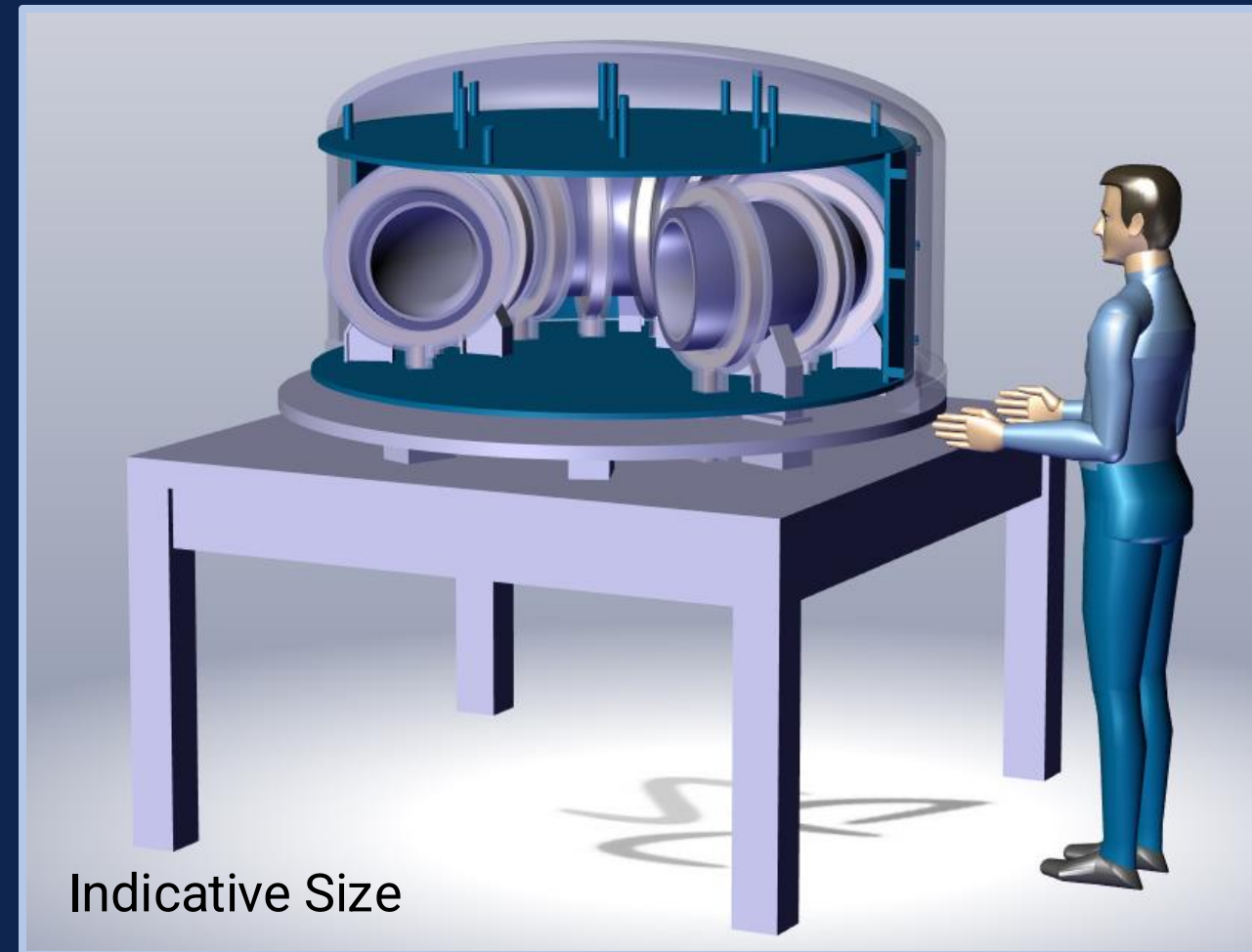


Derisk Dipole Approach

- Copper Coils
- Permanent Magnet Dipoles
- Highly optimized
- Low Power RF heating
- Academic Research
- Location: PPPL

SXA

2027

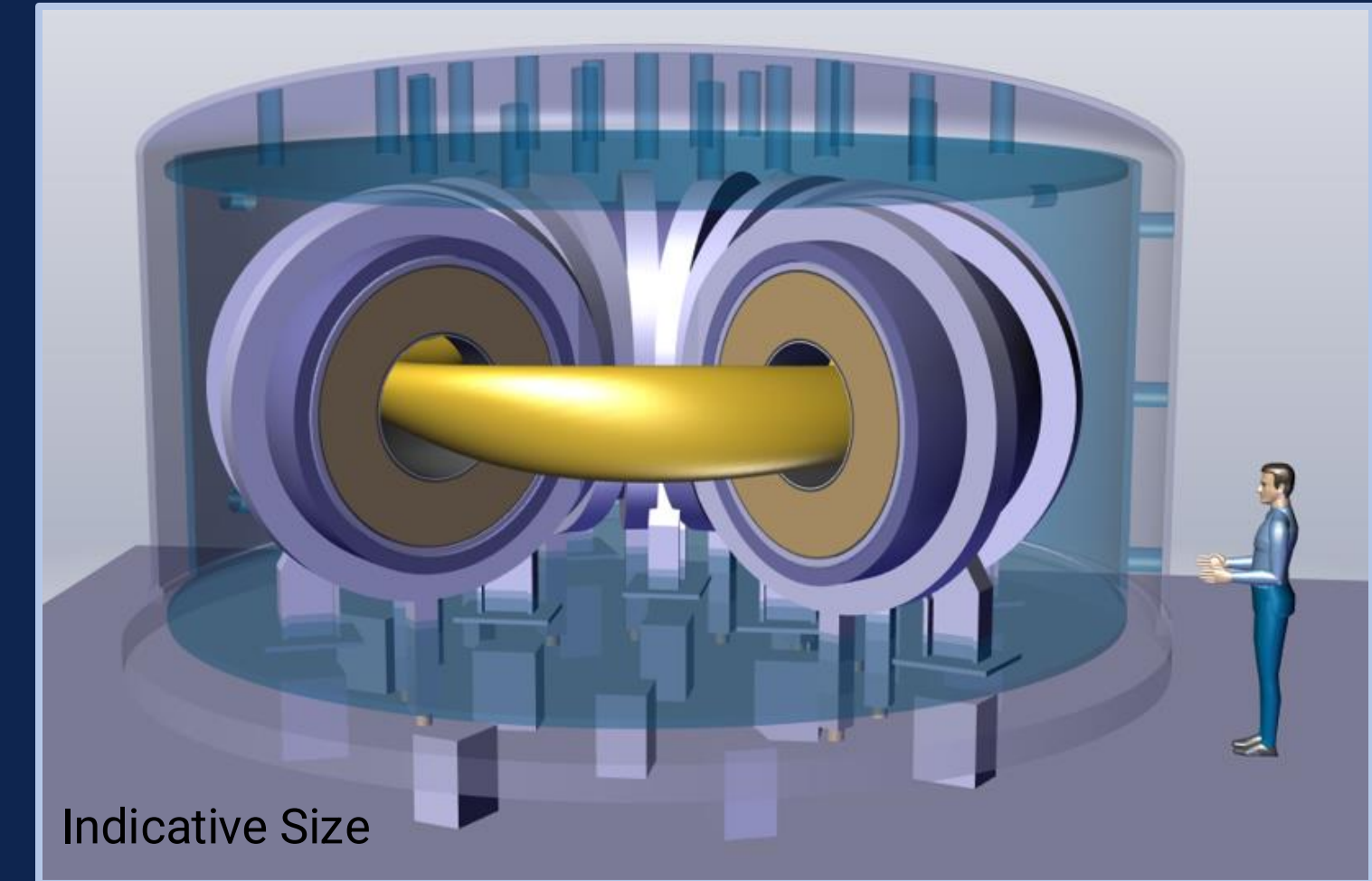


Derisk HTS Dipole Approach

- Superconducting Coils + dipoles
- Moderate Magnetic Field
- Moderate Power
- Academic Research

SX0

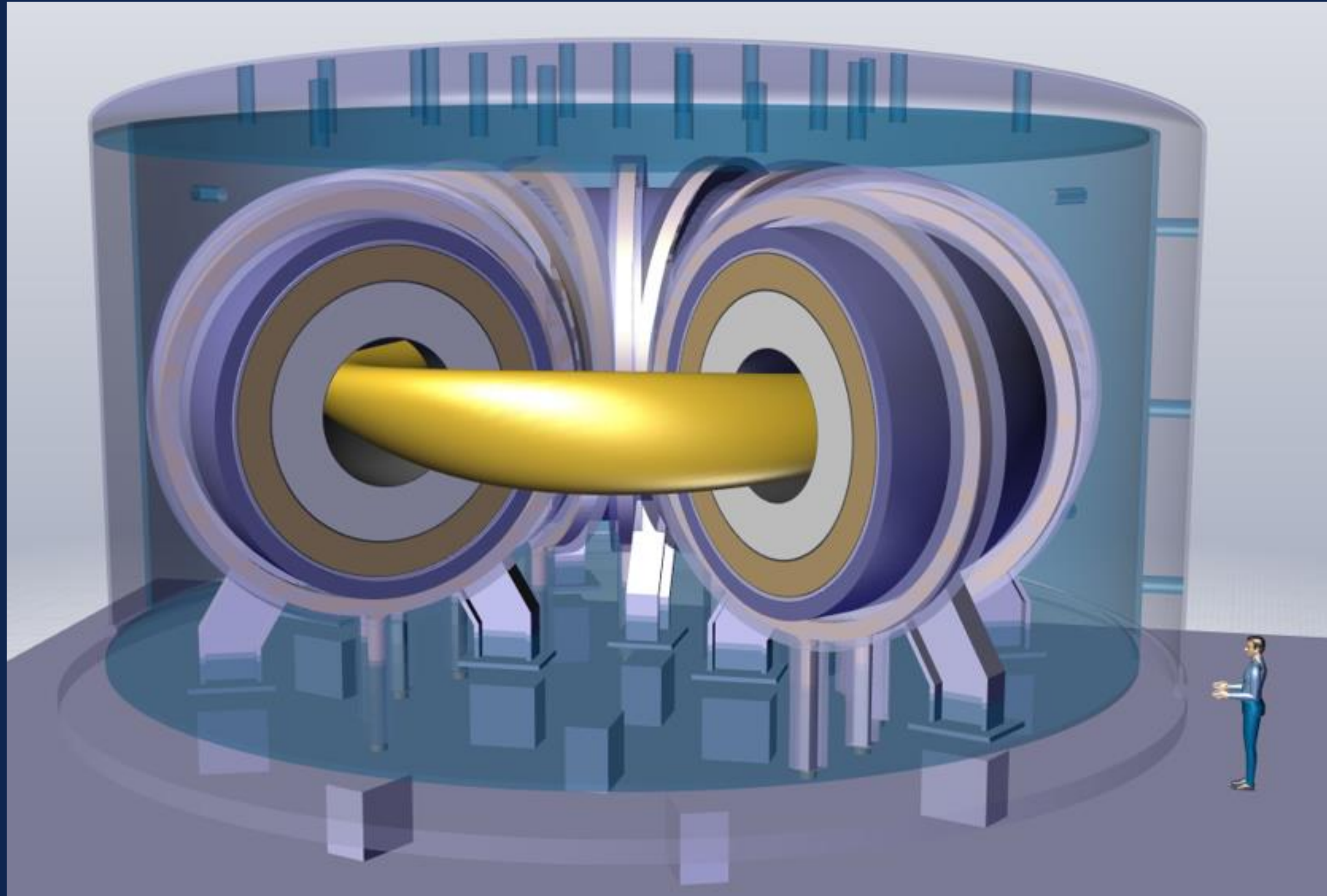
2031



Derisk Q > 1 Integration

- Superconducting Coils
- High Magnetic Field
- High Power
- Q > 1 Demonstration
- Nuclear Fusion R&D

Pre-Conceptual Design of SX1 (Pilot Plant)



- $Q = \infty$ (ignited)
- Input power ~ 20 MW, pulsed (until ignition)
- Fusion power approx. 600 MW
- $H \rightarrow D \rightarrow T$ operation (staged)
- Must be self-sufficient in tritium, i.e. lithium-containing blanket
- Fuel cycle integration system
- Steady-state operation
- Electricity generation up to ~ 250 MW
- Corresponding power and heat rejection sub-systems
- Remote inspection, maintenance, rad waste management

Centre for Fusion Energy (CFE) Launched



Ontario 

Newsroom

NEWS RELEASE

Ontario Investing \$19.5 Million to Establish the Centre for Fusion Energy

New centre will leverage Ontario's nuclear advantage to advance clean energy research and keep Ontario competitive in the global economy

November 28, 2025

[Colleges, Universities, Research Excellence and Security](#)



Atomic Energy of Canada Limited

Science & Technology

Radioactive Waste

Nov 28, 2025

\$33 Million

Federal Government Continues Investment in Fusion Sector to Establish Centre for Fusion Energy

The Centre for Fusion Energy is a partnership between the Government of Canada, the Government of Ontario, Atomic Energy of Canada Limited, Canadian Nuclear Laboratories, Ontario Power Generation, and Stellarex to bolster Canada's growing fusion ecosystem and advance clean energy.

Conclusions

- Fusion has the potential to provide a new, clean energy source
- Stellarators solve the disruption and sustainment challenges for tokamaks
- Recent stellarator advances have demonstrated that their 3d-orbit and turbulent transport can be optimized for improved performance.
- New techniques for constructing stellarators using dipole magnets are simpler, faster, and less expensive than tokamak construction.