Externally Controlled Configurations
Spherical Torus & Compact Stellarator

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SEAB Fusion Energy Task Force
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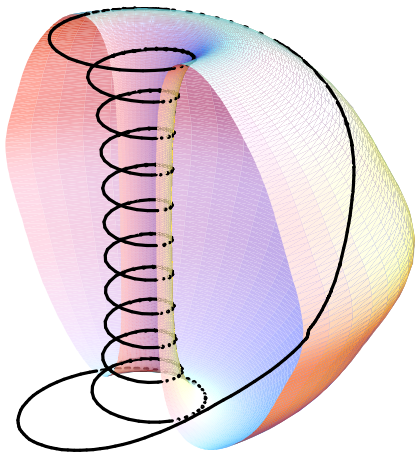
Externally Controlled Configurations Enable Optimized Design

External windings or externally driven plasma currents produce main magnetic fields.

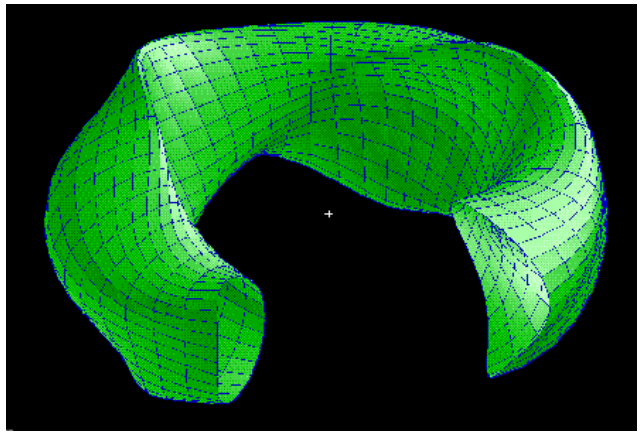


Design configuration for desired properties:
good confinement, stability

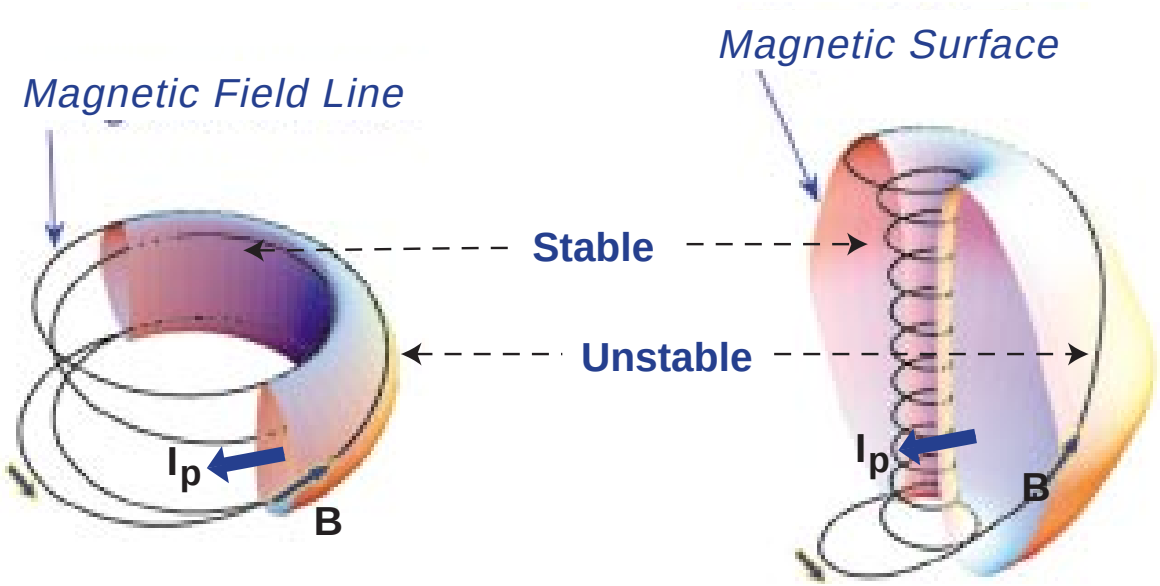
New designs: more compact or simpler,
lower development cost,
more attractive end-product

Spherical Torus and Compact Stellarator:

- strong shaping (2D or 3D) for higher β-limit
- flow shear for confinement enhancement
- reduce disruptivity



ST Maximizes the Good-Curvature Field Line Length over the Bad-Curvature Field Line



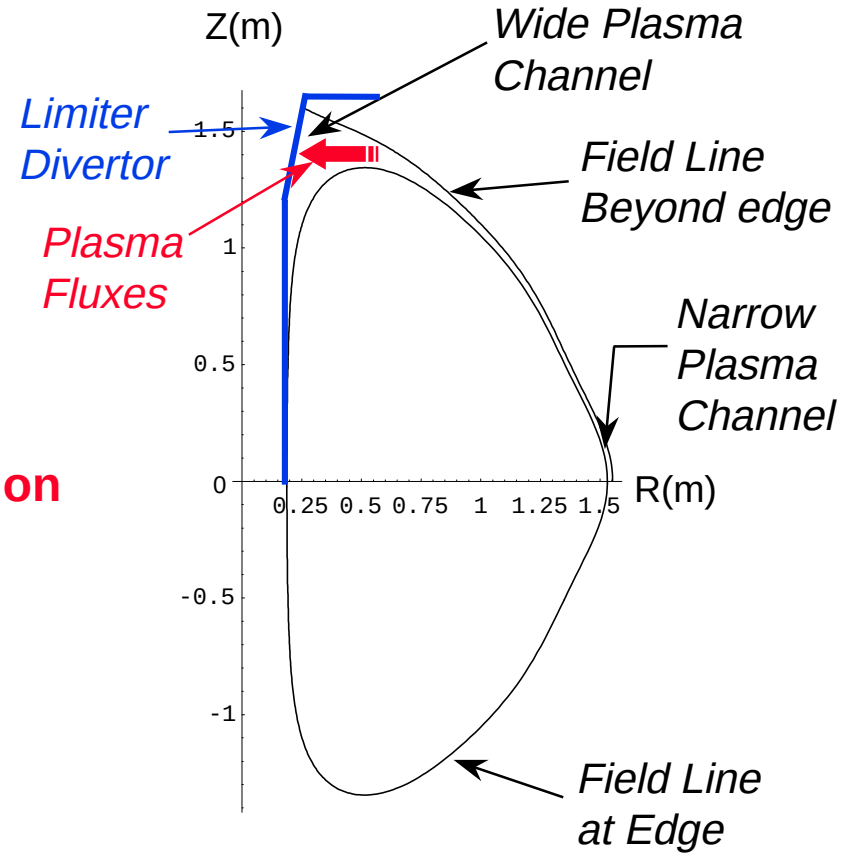
Tokamak
(A = 4, κ= 2, q = 4)

Spherical Torus
(A = 1.25, κ= 2, q = 12)

This leads to very high β and widens ST parameter domain.

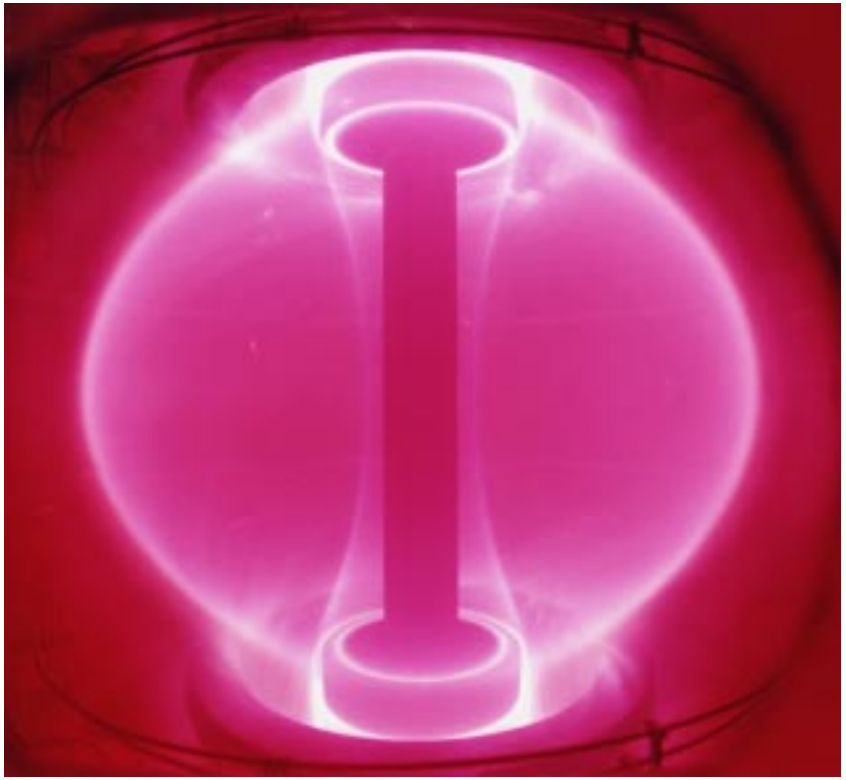
Spherical Torus Research Advances Magnetic Fusion Science into New Territories

- **Order-Unity Stable Beta-Toroidal**
- **Turbulence-Transport Suppression**
- **Self-Sustaining Configurations (via Bootstrap current)**
- **Helicity Injection Startup (similar to spheromak)**
- **Enhanced Plasma Exhaust Dispersion**



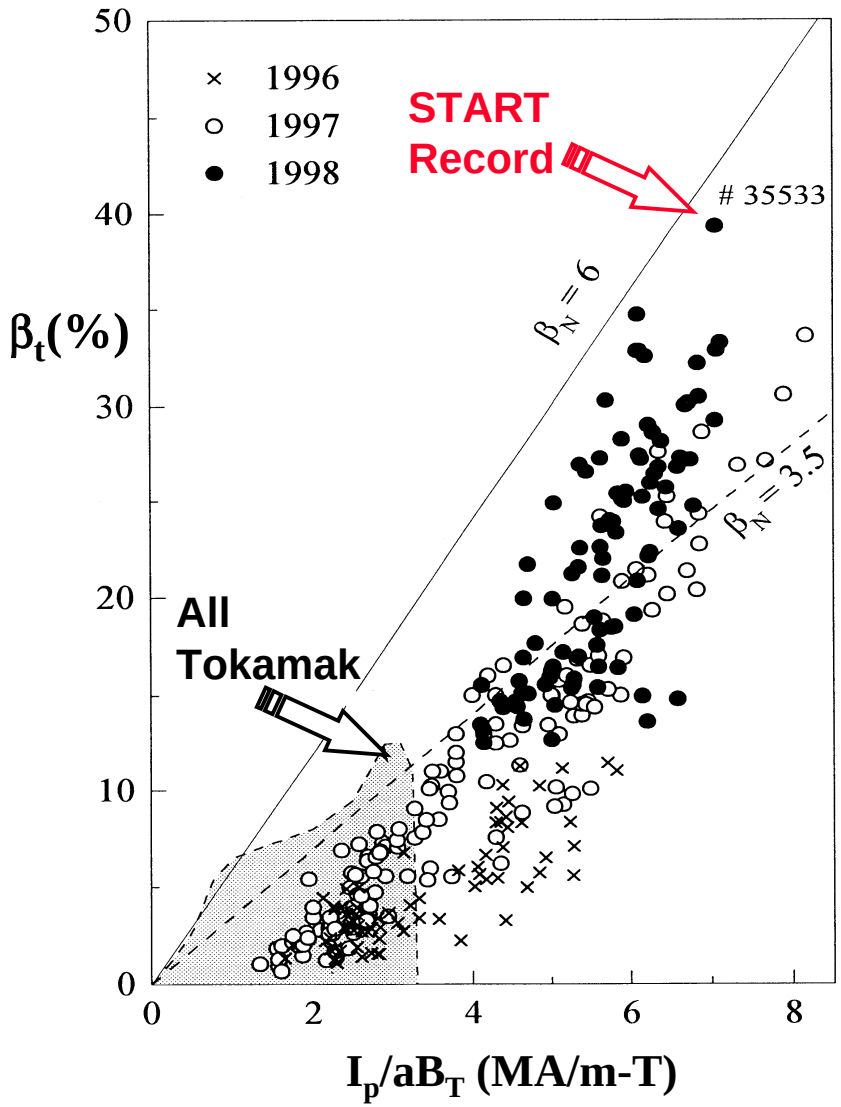
Concept Exploration Experiments Confirm Promise of ST Stability and Confinement

(Courtesy of START Team, U.K.)



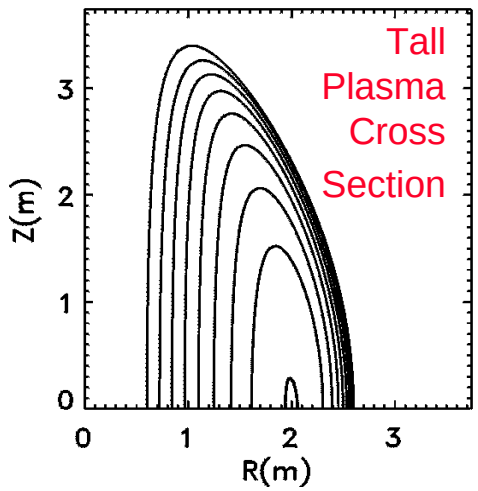
1 m

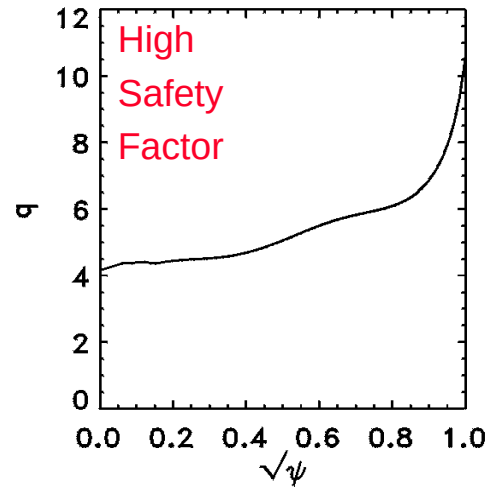
- *Average toroidal $\beta_T \rightarrow$ 40% ($\langle\beta\rangle \rightarrow$ 15%)*
- *Good confinement*
- *~1/3 of NSTX Plasma Size*

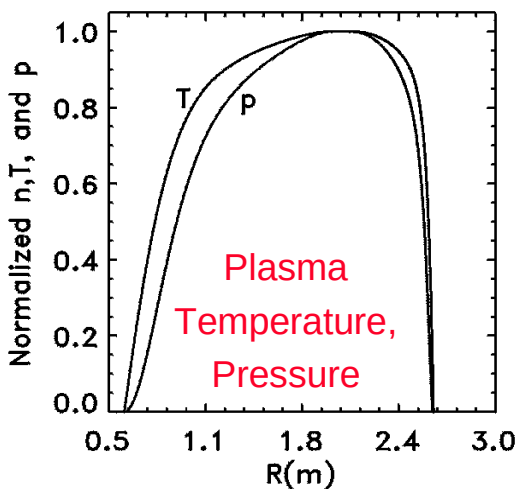


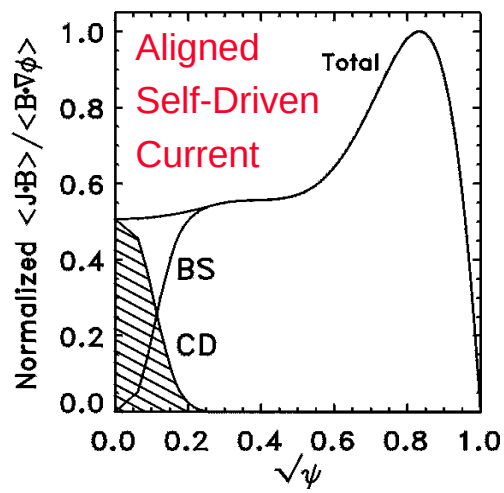
ARIES Team Identified Potential for ST to Self-Sustain at Very High Stable Beta (β)

$A = 1.6$, $\beta_N = 8.2$, $\beta_T = 56\%$, $\langle\beta\rangle = 0.42\%$, $f_{Bootstrap} = 99\%$



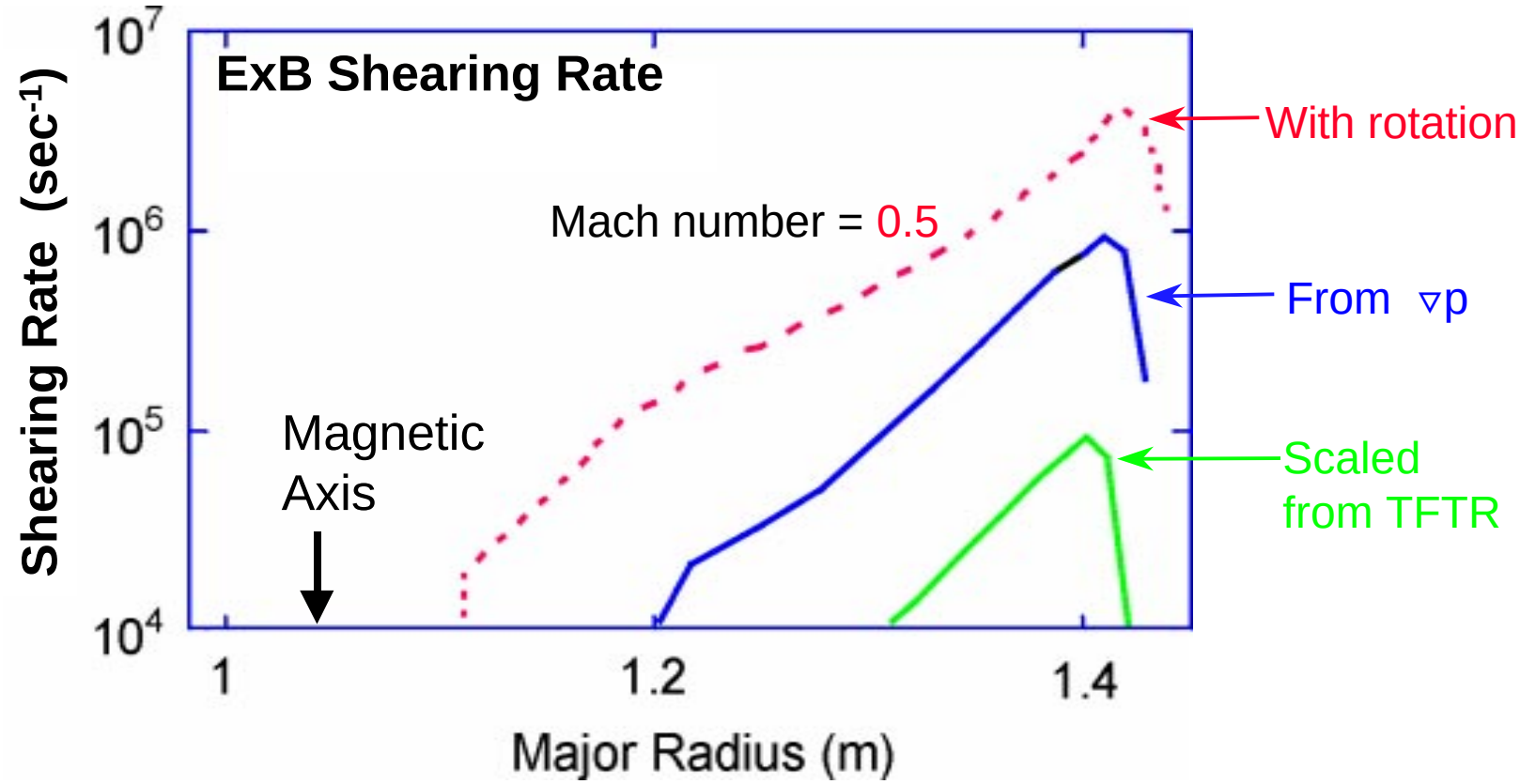






- Theoretical β-limit
- Self-sustained by bootstrap current
- Close fitting wall required for kink (long-wavelength MHD) stability
- May require feedback (as in tokamaks)
- Experiment: can this be achieved?

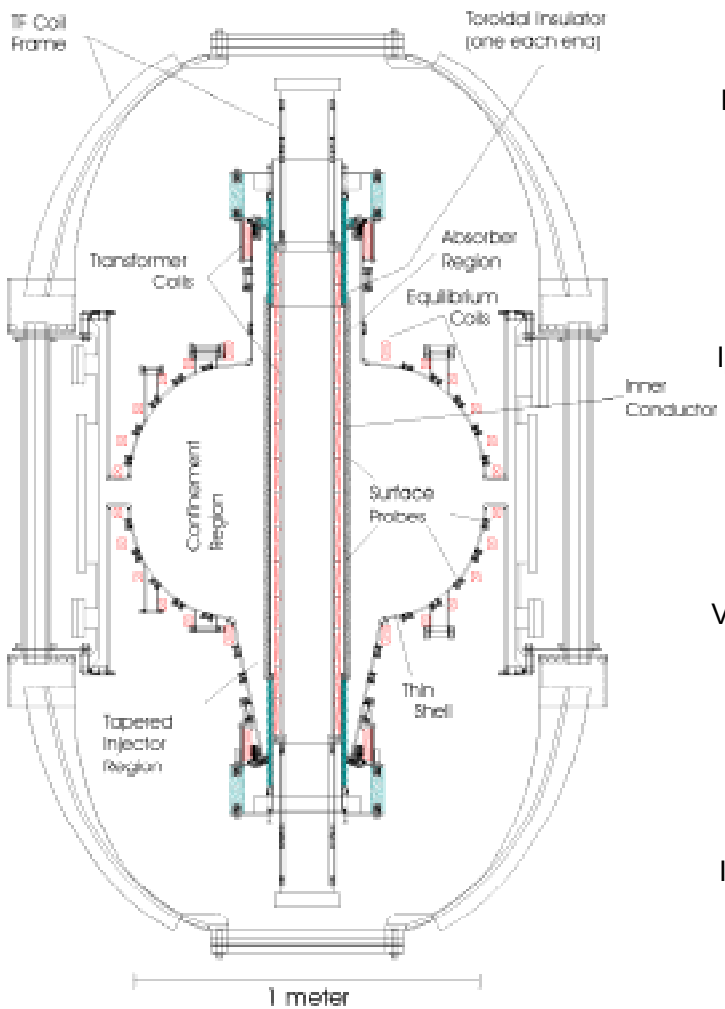
Turbulence May Self-Stabilize in Spherical Torus

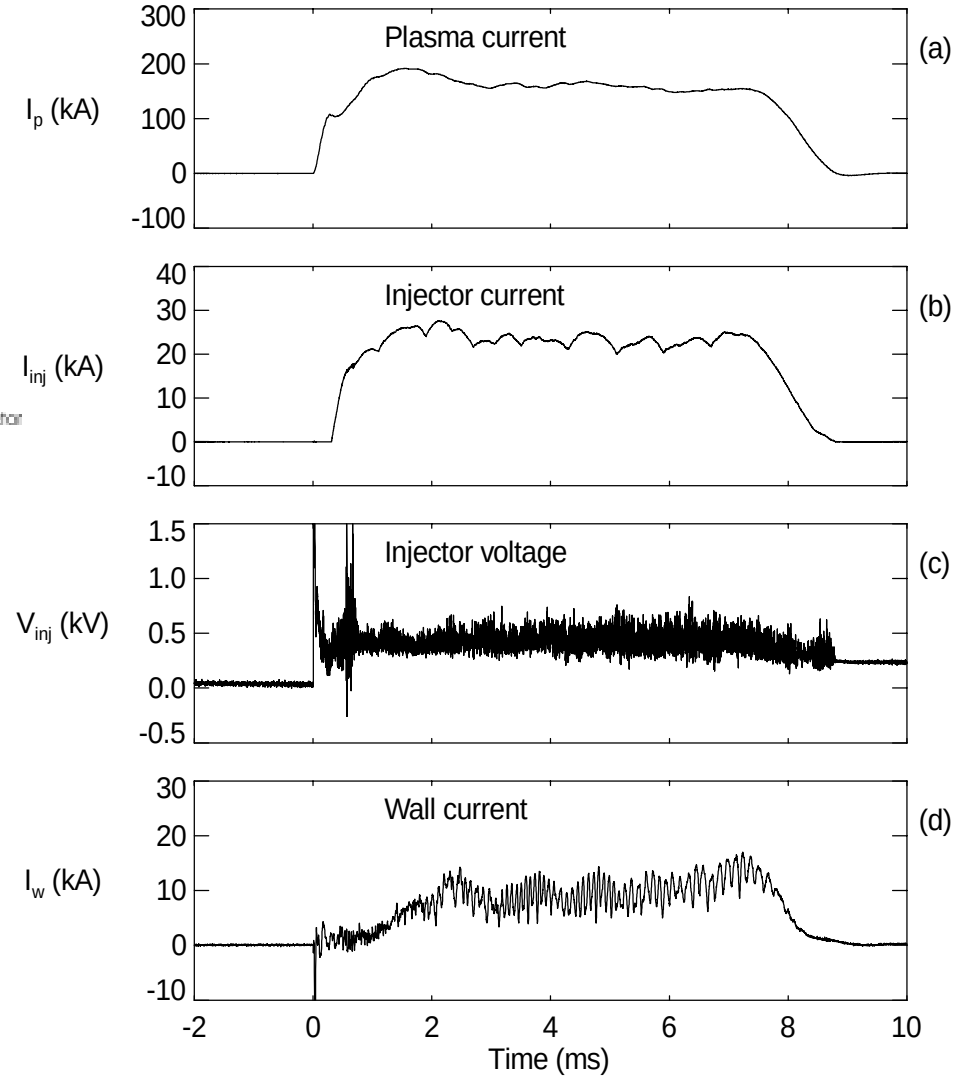


- Very high flow-shearing rates calculated, due to low magnetic field required
- Theory: stable to turbulent transport for R/a below 1.5
- Recent optimizations find self-consistent ST reactor designs with: no significant turbulent transport, high-β_T, bootstrap sustained.

Helicity Injection Startup Simplifies Coils

Demonstrated on Concept-Exploration Experiment HIT-II



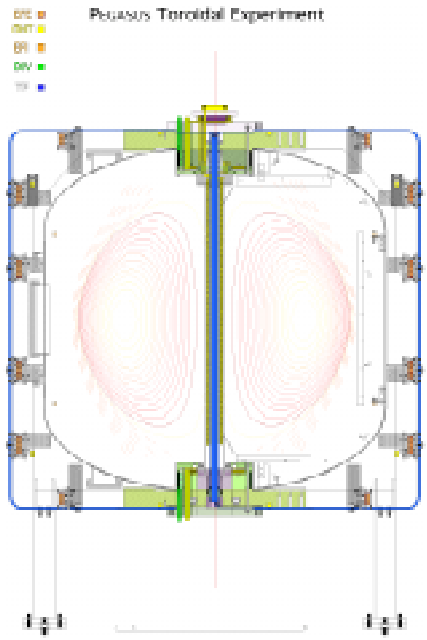


Plasma current driven via reconnection of externally driven DC current

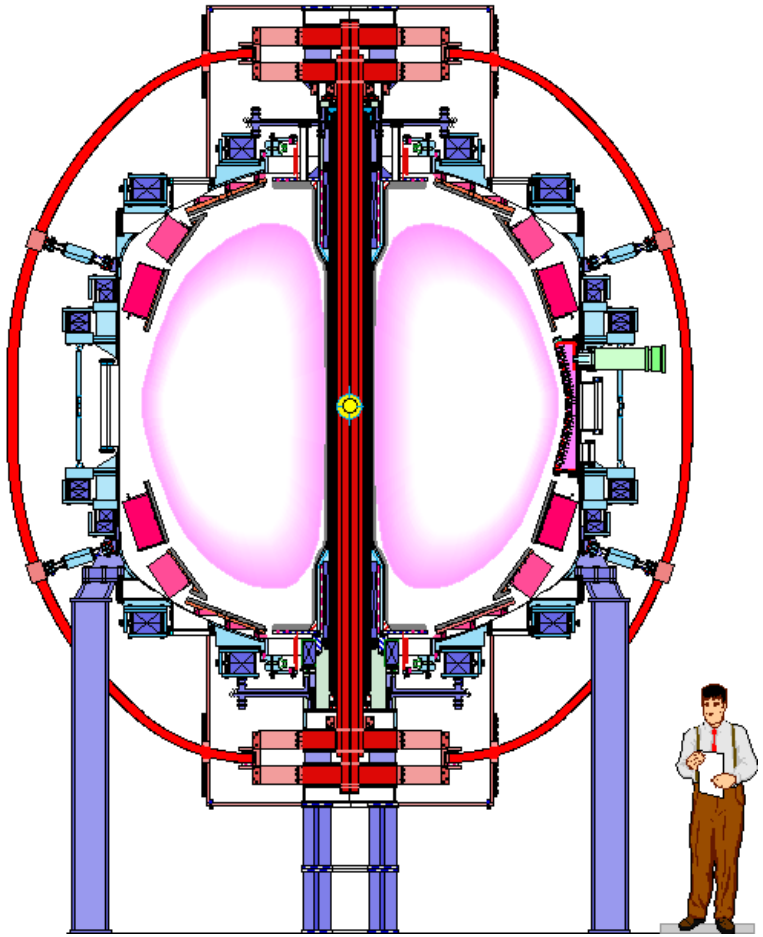
New U.S. Spherical Torus Experiments

affordable steps toward attractive fusion power

PEGASUS



NSTX



Concept Exploration

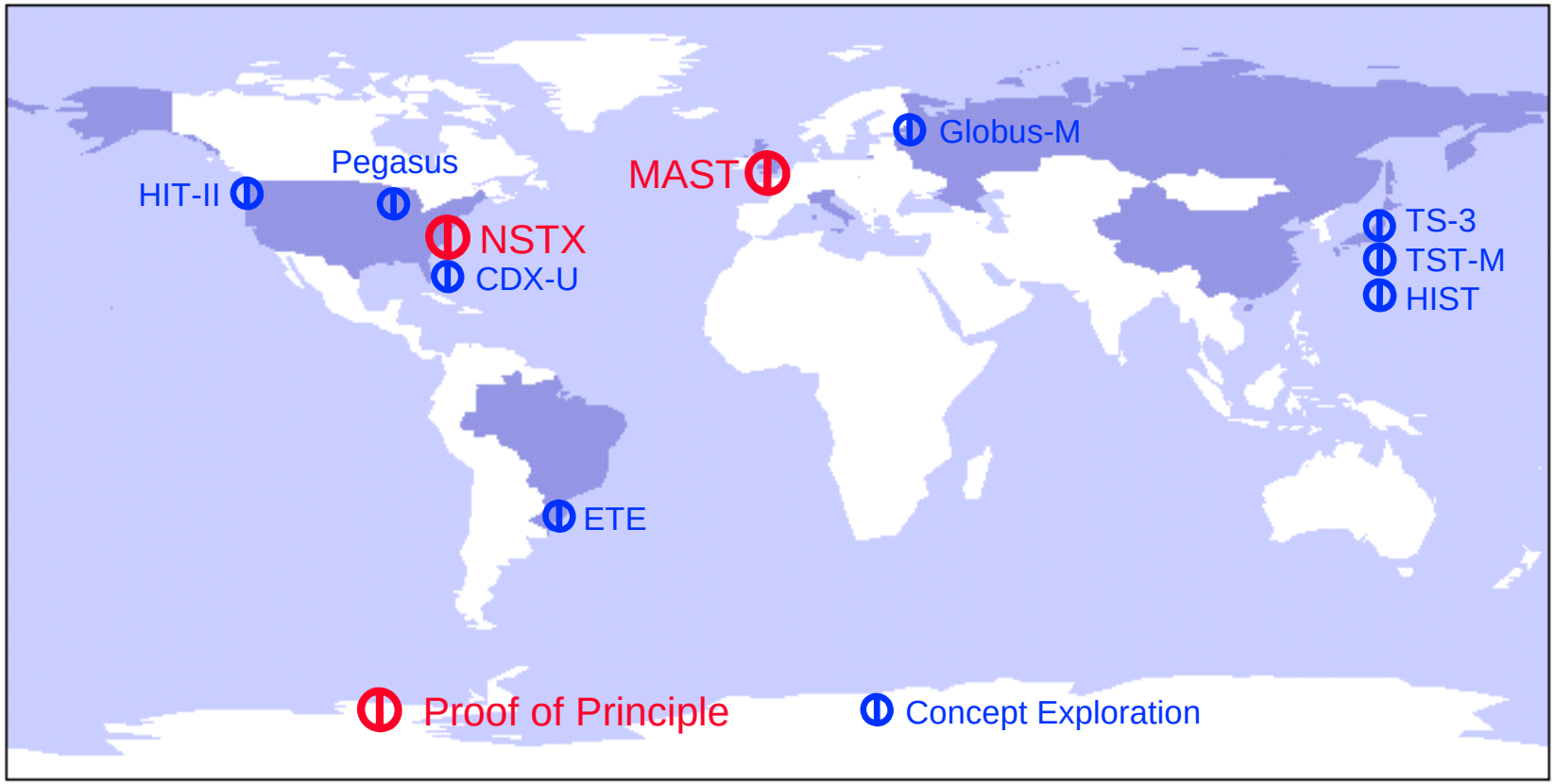
of extreme low aspect ratio, R/a → 1.1

Proof of Principle

testing β-limits, confinement, sustainment

World ST Program Has Grown Rapidly

Since 1990



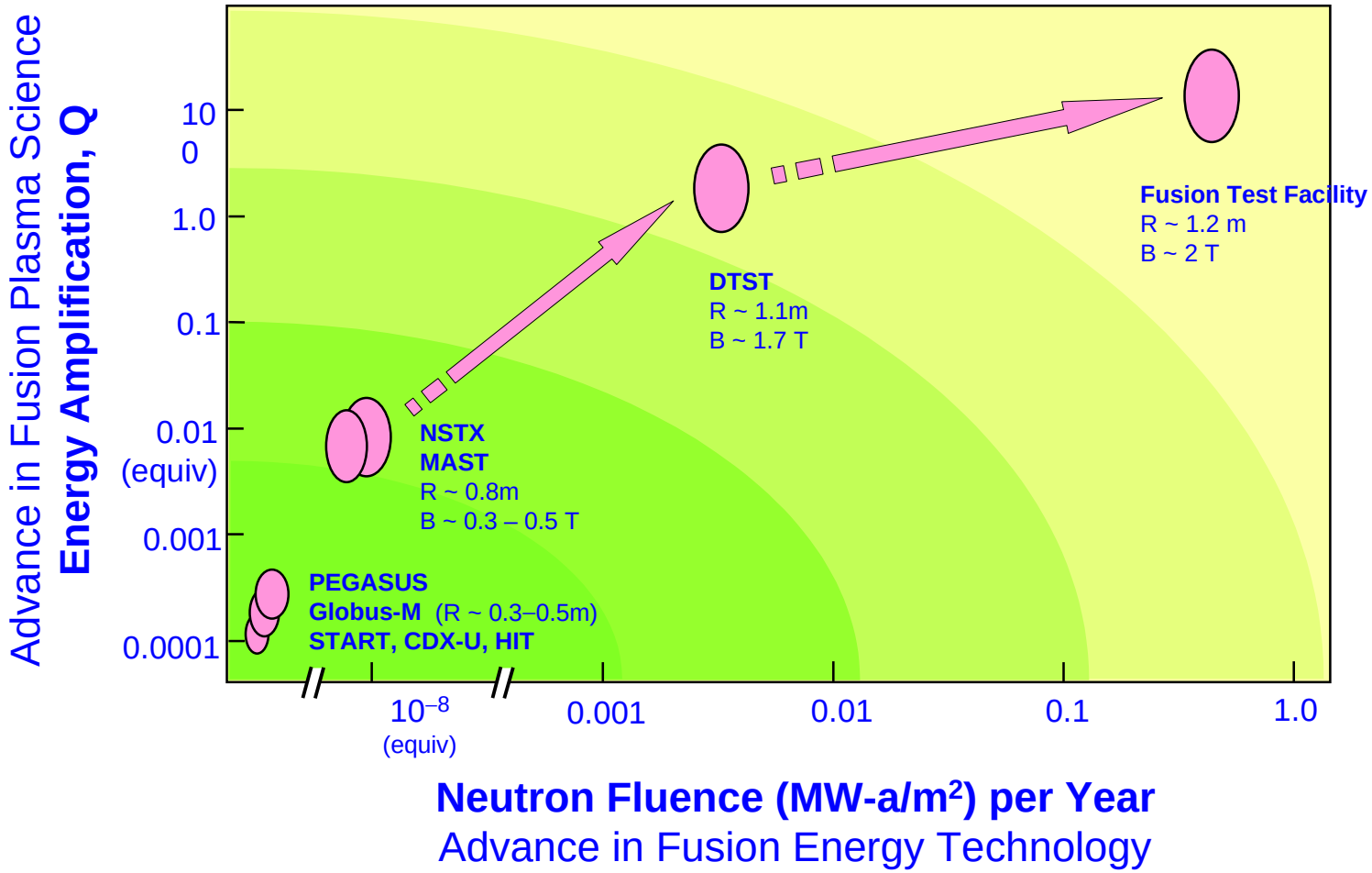
Complementary Proof of Principle Experiments:

	NSTX (U.S.)	MAST (U.K.)
Startup:	Helicity Injection	Compression
Stability:	Conducting Shell	Internal Coils
RF Heating:	HHFW (6 MW)	ECH (2 MW)

Spherical Torus Promises Exciting Scientific Advances towards Practical Fusion Energy

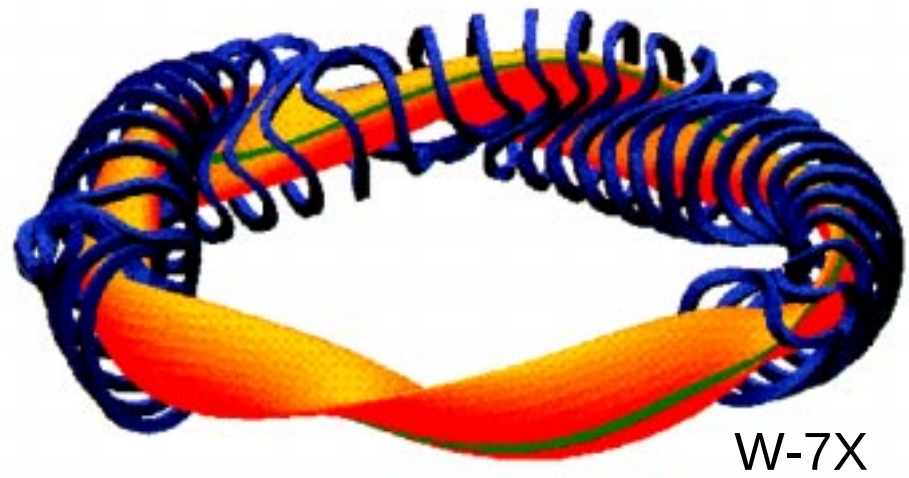
Science	→	***Energy***
Order-Unity Stable Beta-Toroidal	→	Low Device Cost
Helicity Startup, Self-Sustaining Current	→	Simplified Magnets
Turbulence Transport Suppression	→	Small Unit Size
Plasma Exhaust Dispersion	→	Reduced Wall Heat Flux
	⇒	Lower development costs

ST Can Advance Fusion Science and Technology Using Small-Size Devices



Stellarators: 3D Shaping Provides Flexibility

- Toroidal magnetic confinement systems, like tokamaks and STs
  - but, not symmetric !
- Disruptions are not observed in stellarators, even at highest parameters.
- External coils can supply whole magnetic field $\Rightarrow$ eliminates need for external current drive $\Rightarrow$ steady state
- Can choose 3D shape to optimize stability, transport

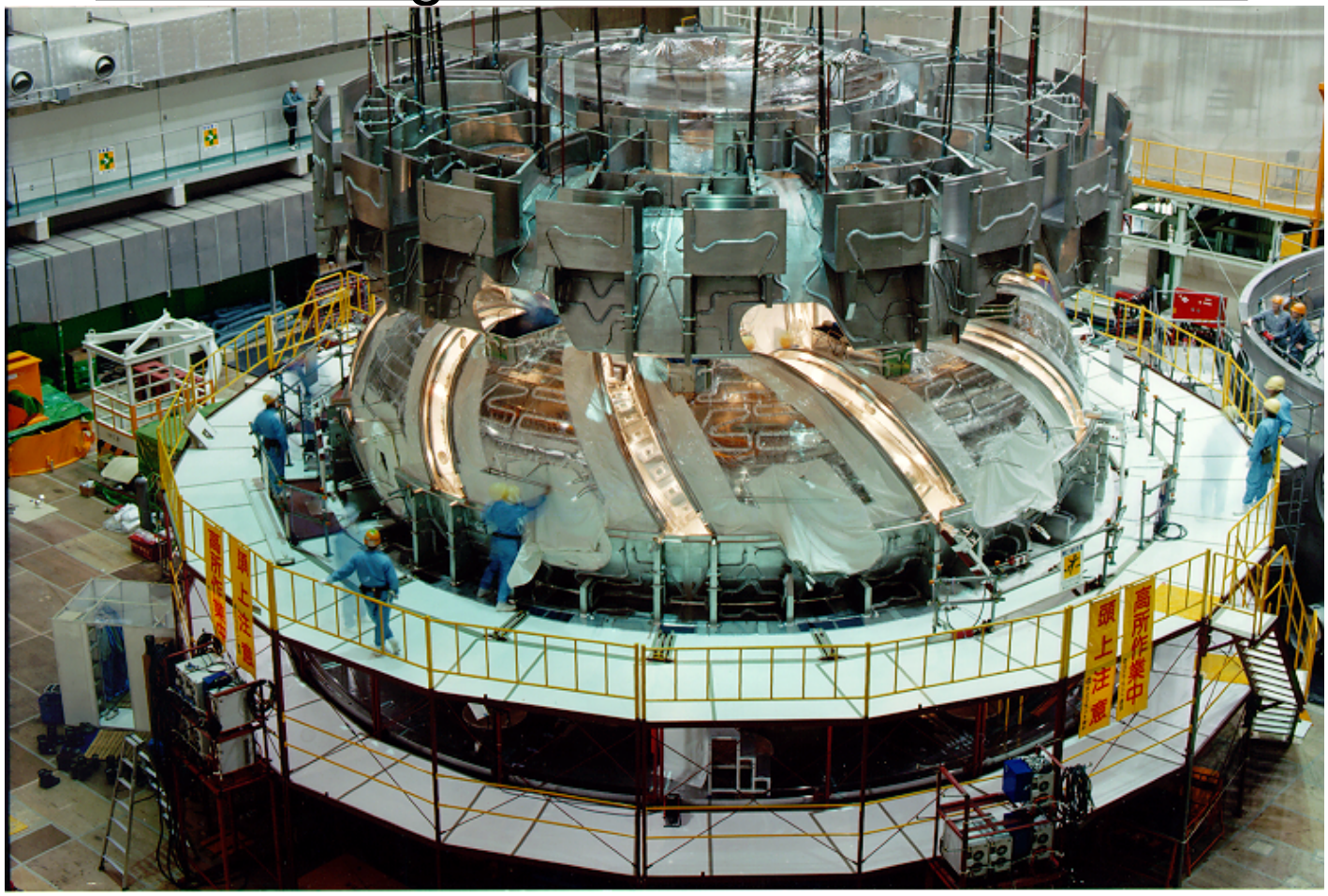


W-7X
~2006

$\Rightarrow$ In the world program, only new large experiments are stellarators
LHD (Japan), W7-X (Germany) ~$1B each, superconducting

But, extrapolate to large, low power density systems

LHD Has >10x the Volume, Heating Power, and Pulse Length of Previous Stellarators



Japan
op. in 1998

- R = 3.9 m, B = 3(4) T, P ~ 40 MW
- Expect T_i~ 10 keV, τ_E > 0.2 s, $n\tau T$ ~10^{20}

Proposed U.S. Program in Compact Stellarators

- Revolution in theoretical understanding + recent experimental results
  $\rightarrow$ numerical design of attractive compact stellarators

  – excellent plasma confinement
  – high β stability
  – design to theoretically stabilize troubling instabilities
    e.g. long-wavelength external kink
  – eliminate disruptions

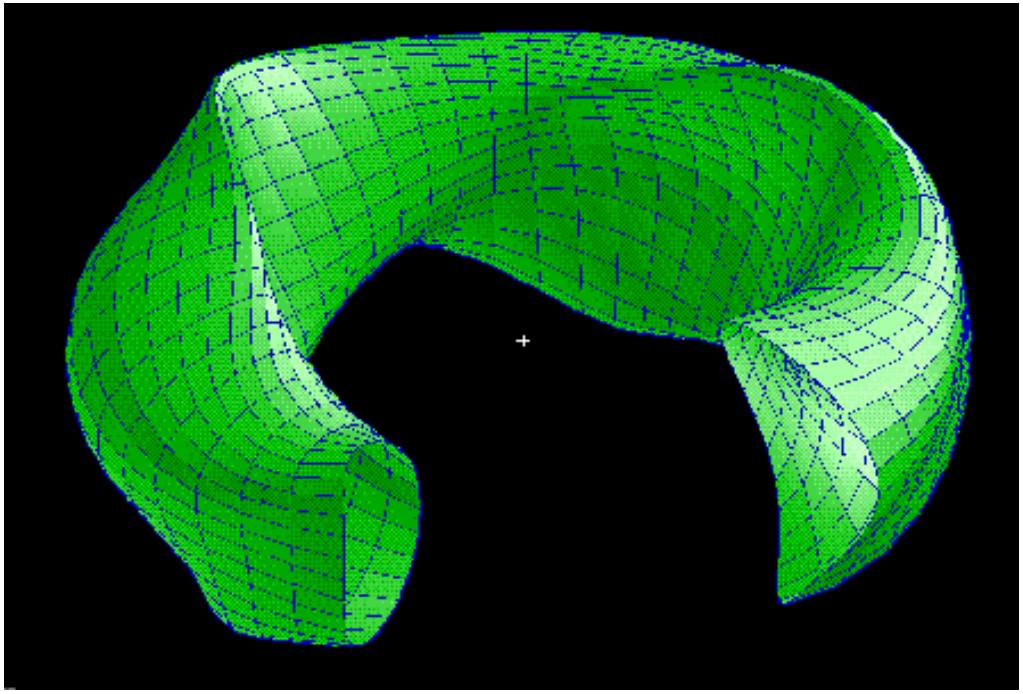
- Combine physics advances with stellarator flexibility
  $\rightarrow$ more compact designs

  – Existing optimized stellarators have high aspect ratios, $R/\langle a \rangle \sim 8 - 11$
  – can get $R/\langle a \rangle \sim 3 - 4$ using improved stability and some bootstrap current
    $\Rightarrow$ reduce size & cost of experiments, raise reactor power density

NCSX: National Compact Stellarator Experiment

PPPL, ORNL, Auburn U.,Columbia U., NYU, U.Texas, U.Wisconsin

- R/<a> =3.4



- Theoretically:
  stable $\beta \geq 4\%$ to ballooning,
  neoclassical-tearing

  Stable to external kink
  without conducting wall
  or feedback
  $\Rightarrow$ simpler system

  Vertical stability without feedback system!

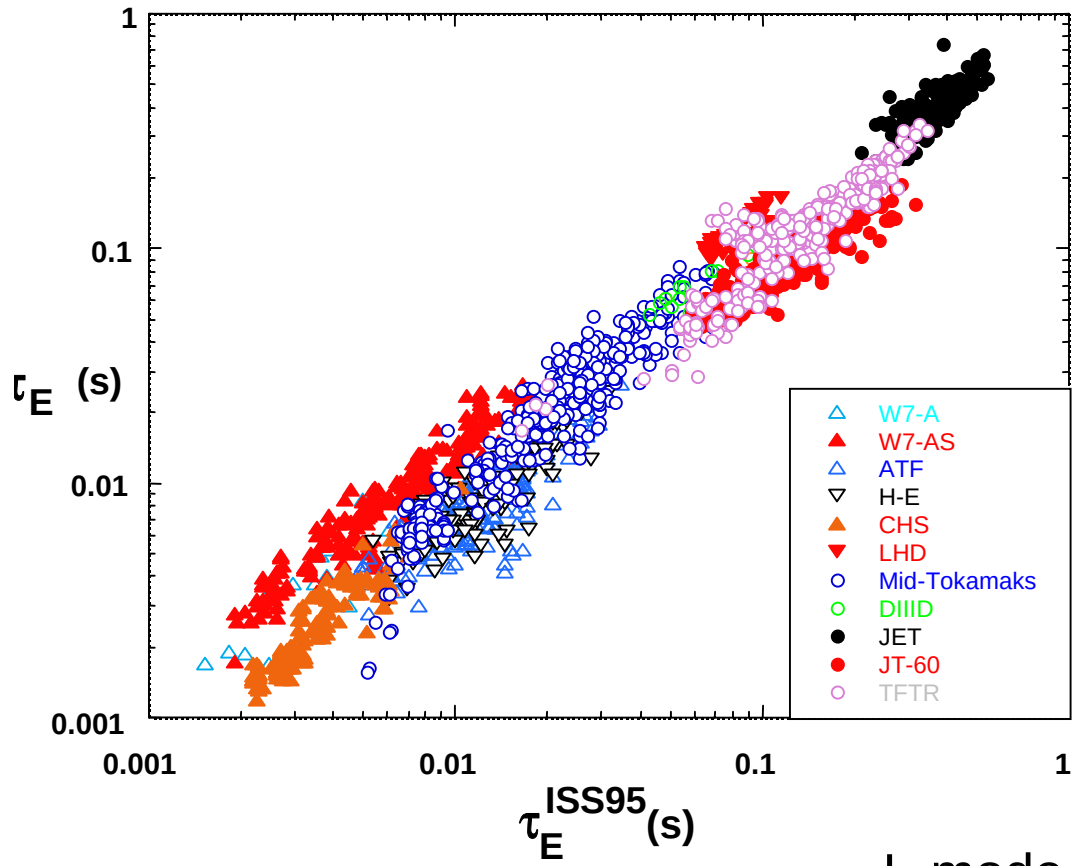
- Experiment: test stability, immunity to disruptions at high β

- <u>Proposal</u>: build re-using components of existing tokamak

Stellarators & Tokamaks Have Similar Confinement, Empirically

- Measured global energy confinement time vs. empirical stellarator regression fit.
- Stellarators & Tokamaks, interspersed
- Enhanced confinement modes observed in both stellarators & tokamaks

  Confinement enhancement stronger in tokamaks, so far



L-mode

NCSX Transport Optimization: Quasi-Axisymmetry

- 3D shape of standard stellarators $\Rightarrow$ orbits can have resonant perturbations, become stochastic $\Rightarrow$ be lost

  $\Rightarrow$ rotation is strongly damped

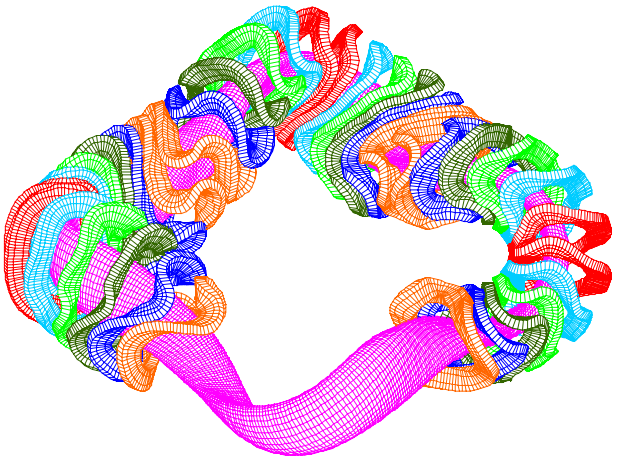
- NCSX is designed to be 'quasi-axisymmetric'
  i.e. to be nearly axisymmetric in magnetic ("Boozer") coordinates

  $\Rightarrow$ should have transport very similar to tokamaks
  including ability to manipulate flow shear to control transport

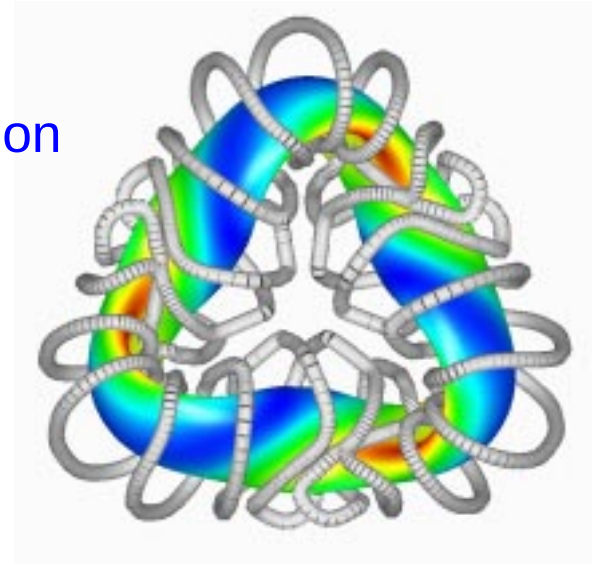
- Experiment: test turbulent transport stabilization in a stellarator using flow shear, as developed in tokamaks.

Concept Exploration Stellarators
Test Fundamental Principles, Complement NCSX

- **HSX (1999)**
  - first test of quasi-symmetric transport optimization
  - high effective helicity, $q_{eff} \sim 1/3$
  - $R/\langle a \rangle = 8$



- **QOS (Proposed)**
  - First test of non-symmetric W7-X optimization
  - Optimized for reduced bootstrap current
  - $R/\langle a \rangle \sim 3 - 4$



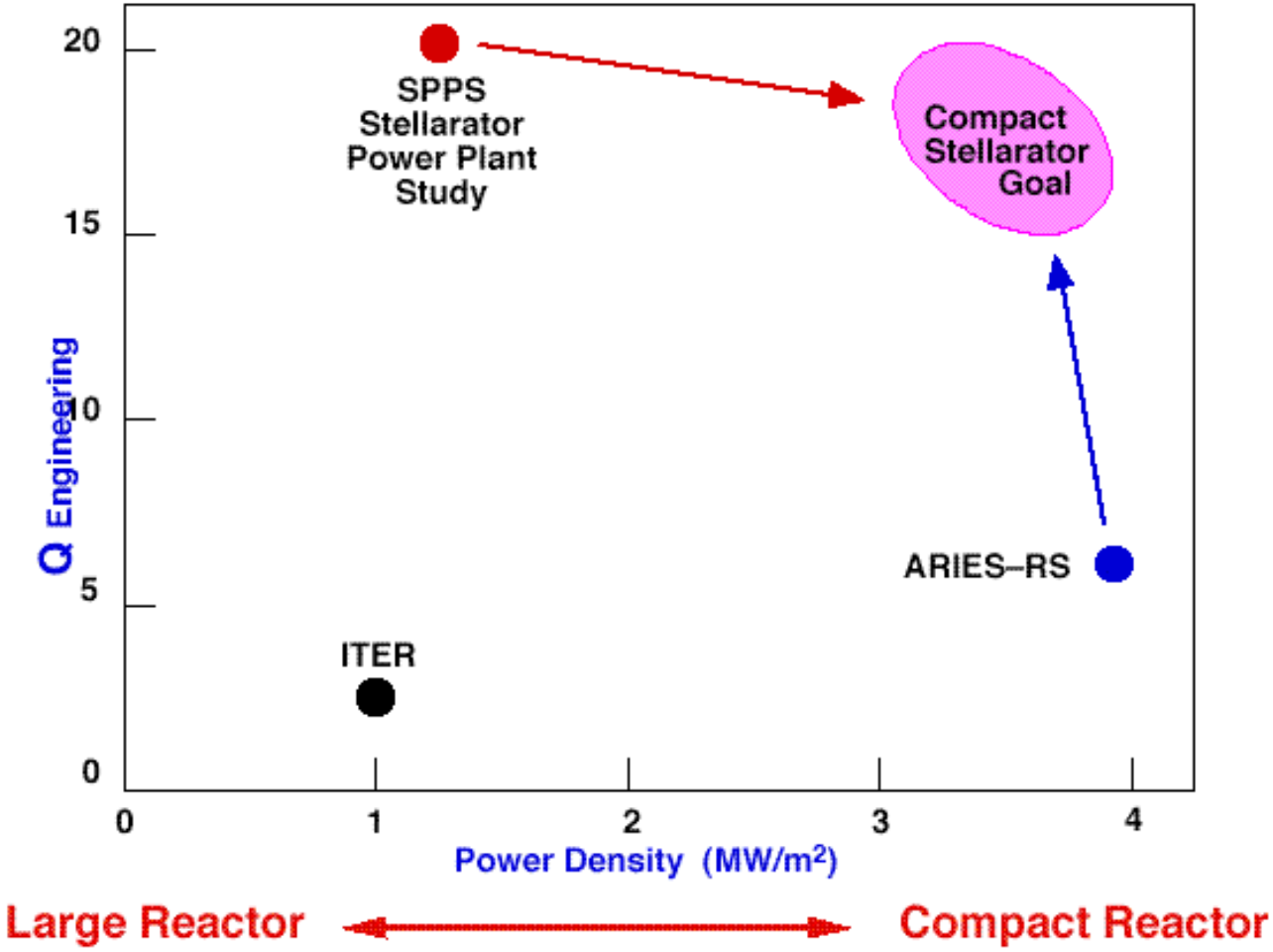
Compact Stellarators Offer New Paths Forward

Scientific Advances towards Practical Fusion Energy

Science	→	***Energy***
Disruption-less	→	Reduced Risk, Costs
No or Reduced External Current Drive	→	Steady State Low Recirculating Power
Low Aspect Ratio	→	Smaller Unit Size
Transport Optimization	→	Reduced Size

Demonstrating these Capabilities will give new 3D-shaping tools for all MFE Configurations

The Compact Stellarator Could Combine the Best Features of Tokamaks and Stellarators



- Compact, power density similar to tokamaks
- Without disruptions or external current drive

Summary

- Externally controlled configurations allow scientific design of optimized configurations and experiments

- Building on advances in understanding from experiment, theory, and computational modeling, novel attractive configurations are available to advance MFE

  – Spherical Torus
  – Compact Stellarator
  – Other configurations at CE stage: Dipole

  Common theme: more compact, lower development cost

- Need to test these ideas experimentally
  – To test & develop our understanding of magnetic fusion physics
  – To explore attractive options for fusion energy development