[CT1.01]

Scientific Opportunities of Spherical Torus Plasmas

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- Columbia University
- Fusion Physics and Technology
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- Sandia National Laboratory
- University of California at Davis
- University of California at Los Angeles
- University of California at San Diego
- University of Washington

Plan of Presentation

- Motivation
- What is a Spherical Torus (ST)?
- Scientific Opportunities & Challenges
- Present Status & Future Vision
- Conclusion

Tokamak Theory in Early 1980's Showed Maximum Stable β_T Increased with Lowered Aspect Ratio (A)

- A. Sykes et al. (1983); F. Troyon et al. (1984) on maximum stable toroidal beta β_T:

$$\beta_{Tmax} \approx \beta_N I_p / a B_T \approx 5 \beta_N \kappa / A q_j$$

where

β_N ~ constant (~ 3 %m·T/MA)

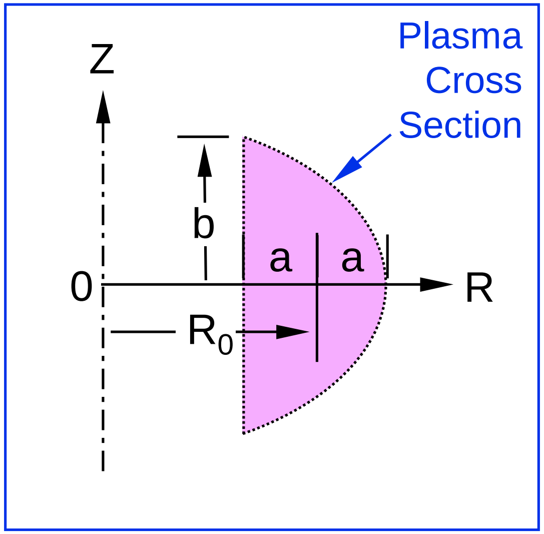
κ = b/a = elongation

$A = R_0/a$ = aspect ratio

q_j ≈ edge safety factor

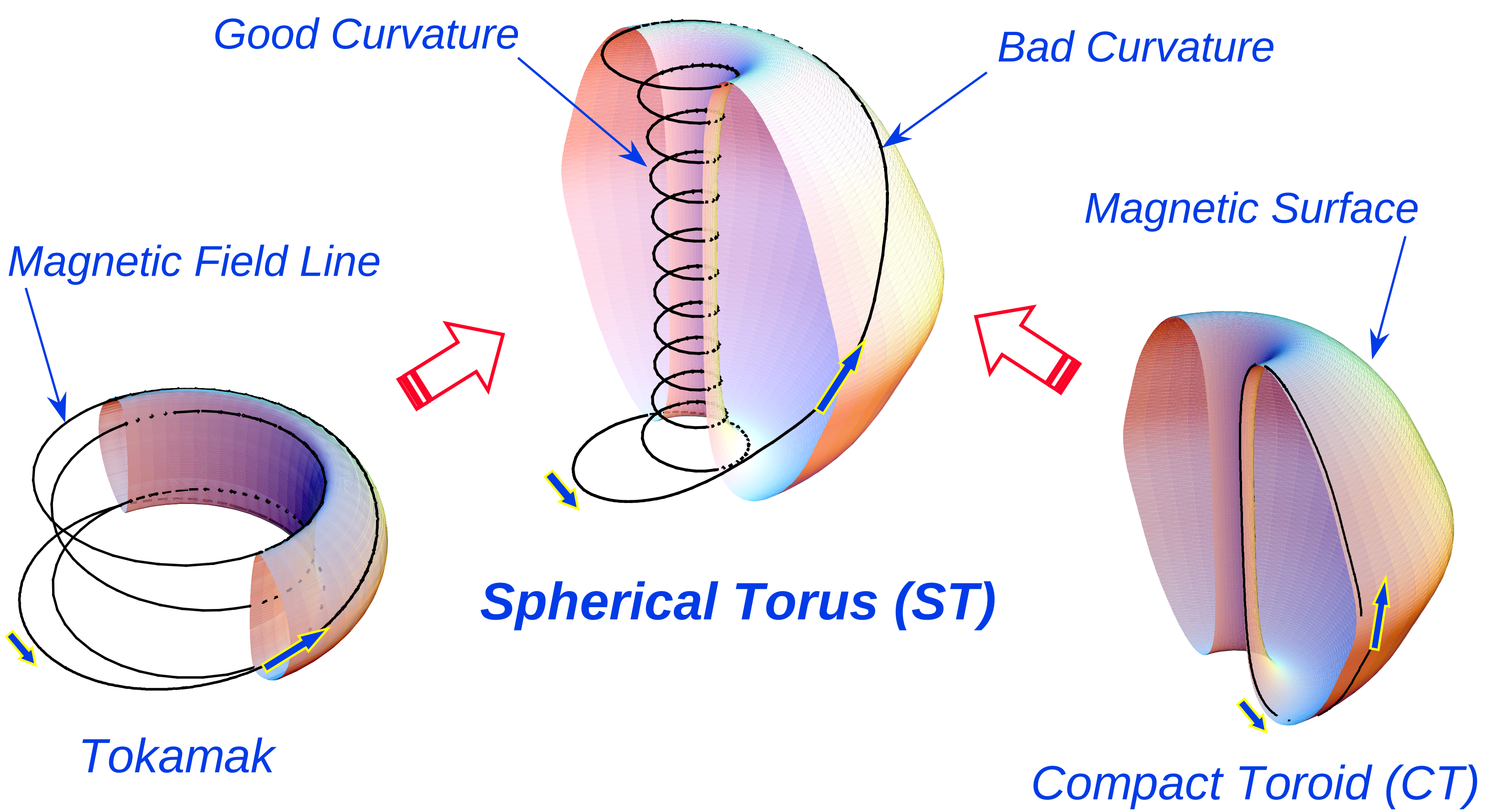
I_p = toroidal plasma current

B_T ≈ applied toroidal field at R_0



- Peng & Strickler (1986): **What would happen to tokamak as A → 1?**
  - How would β_N, κ, q_j, change as functions of **A**?

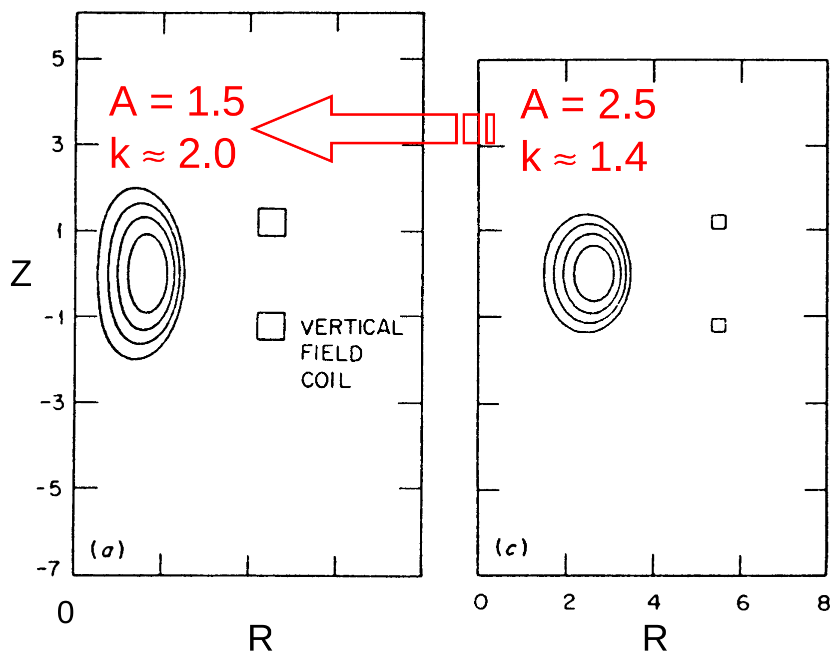
Minimizing Tokamak Aspect Ratio Maximizes Field Line Length in Good Curvature



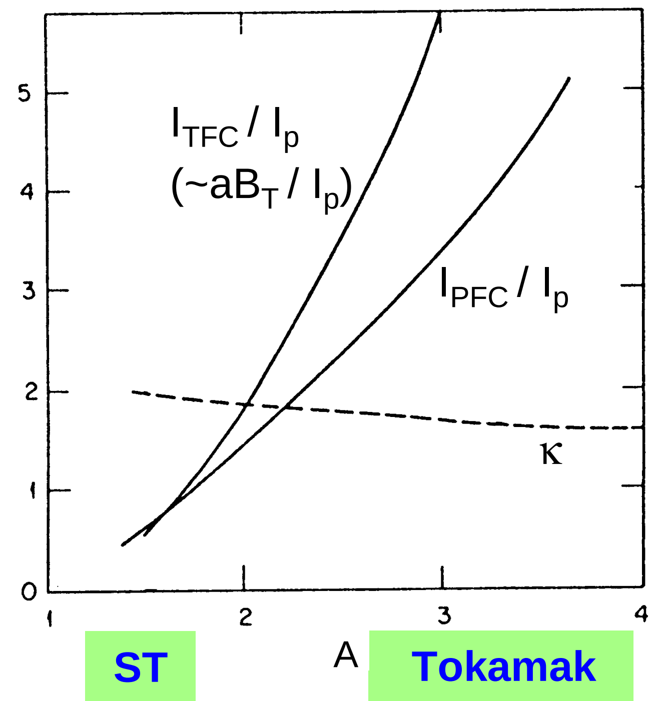
The outboard field lines are closer to CT.

Spherical Torus Plasma Elongates Naturally, Uses Less Coil Currents, and Increases I_p/aB_T & β_{Tmax}

Natural Elongation



Coil Currents/I_p (q_{edge}~2.5)

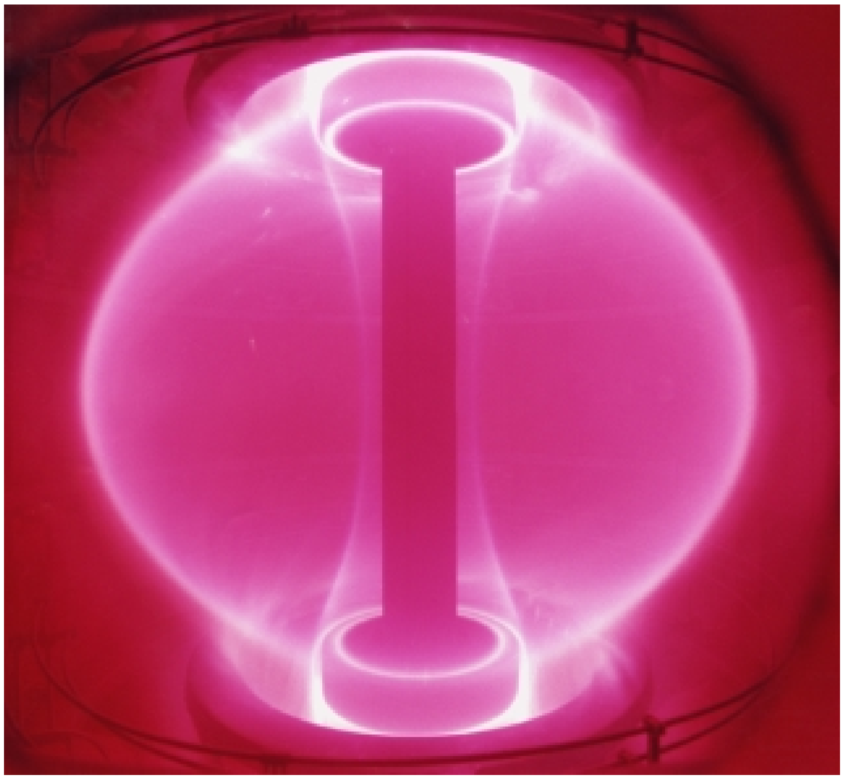


- Elongates naturally to $\kappa \sim 2$; $I_{TFC} < I_p$, $I_{PFC} < I_p$
- $I_p/aB_T \sim 7$ MA/m·T ⇒ **β_{Tmax} ~ 20%,** if $\beta_N \sim 3$
- Also, $I_p\, q_{edge}/aB_T \sim 20$ MA/m·T ⇒ strong "shaping"

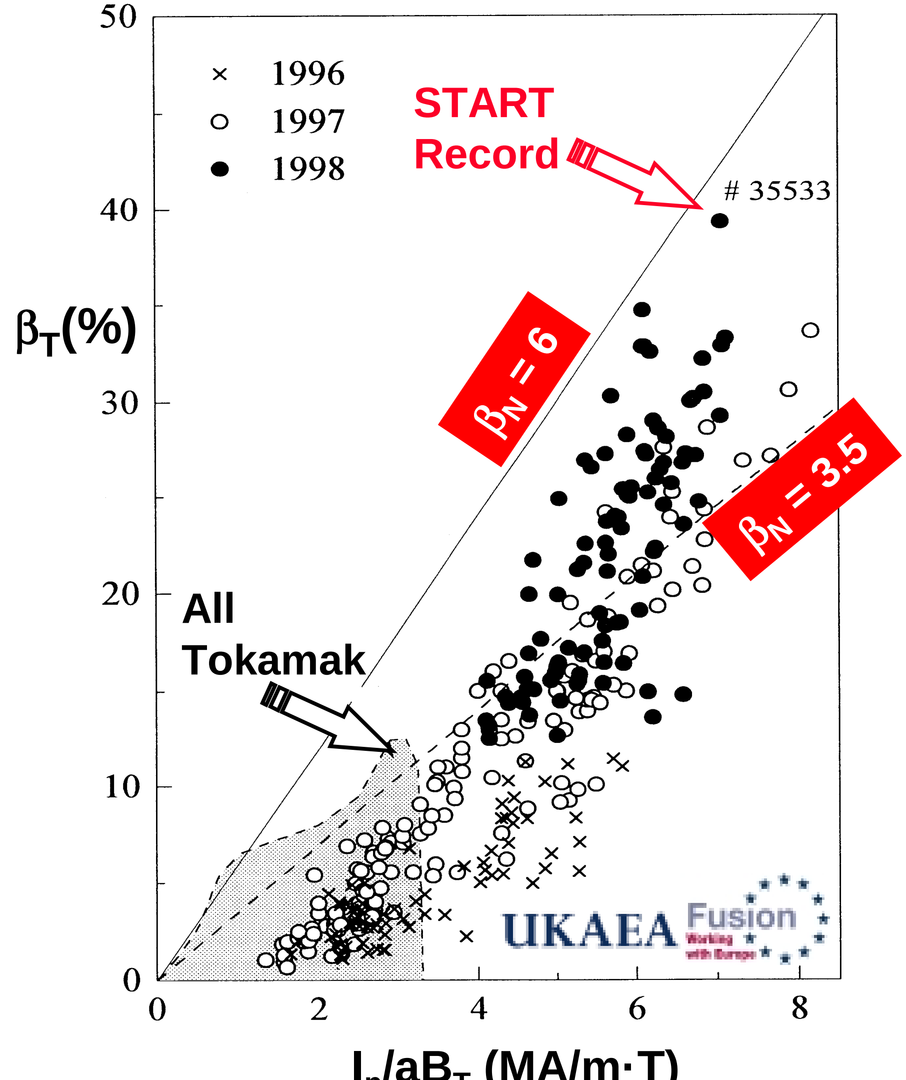
Record High β_T (~40%) was Achieved by START (U.K.) in 1998

START

(Courtesy of A. Sykes & START Team, U.K.)



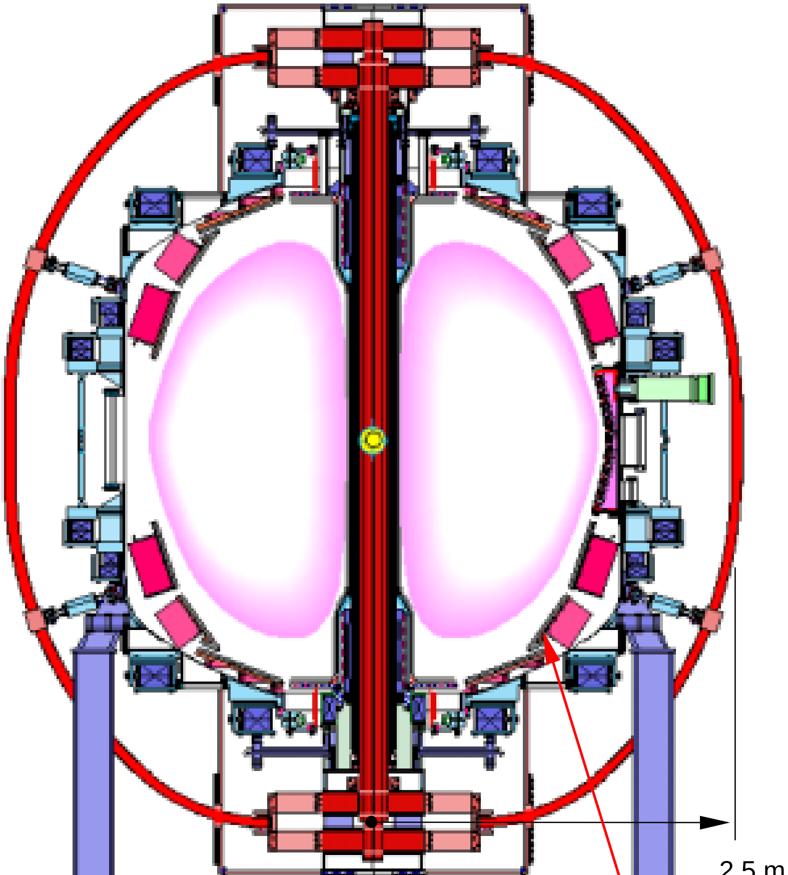
1 m



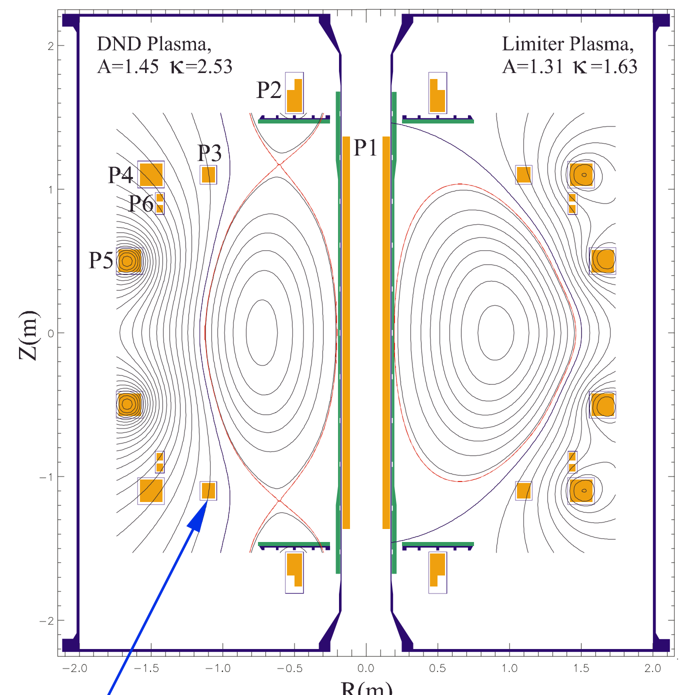
- *I_p ~ 250 kA, ⟨β⟩→ 15%, for ~10 ms*
- *Low q_{95} ~ 3, κ ~ 1.8, no nearby wall*
- *β_N can be higher than 3*

Major MA-Level Experiments, MAST and NSTX, Are Built to Investigate High-β ST Physics

NSTX (U.S.)



MAST (U.K.)

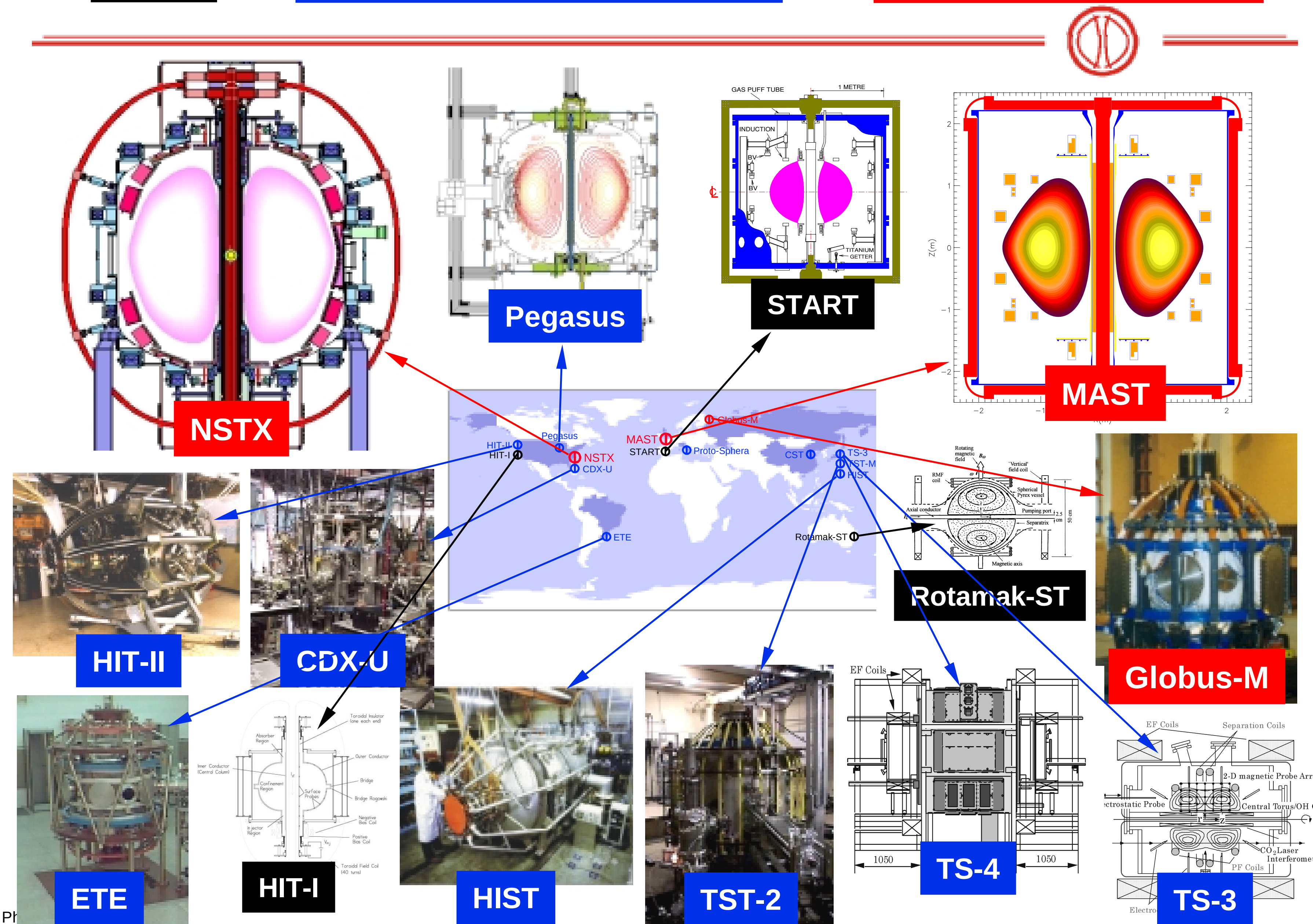


UKAEA Fusion

	NSTX	MAST	
• Nearby Conducting Shell	Yes	No	(beta limits)
• Poloidal Field Coils	Ex-vessel	In-vessel	(plasma shaping flexibility)

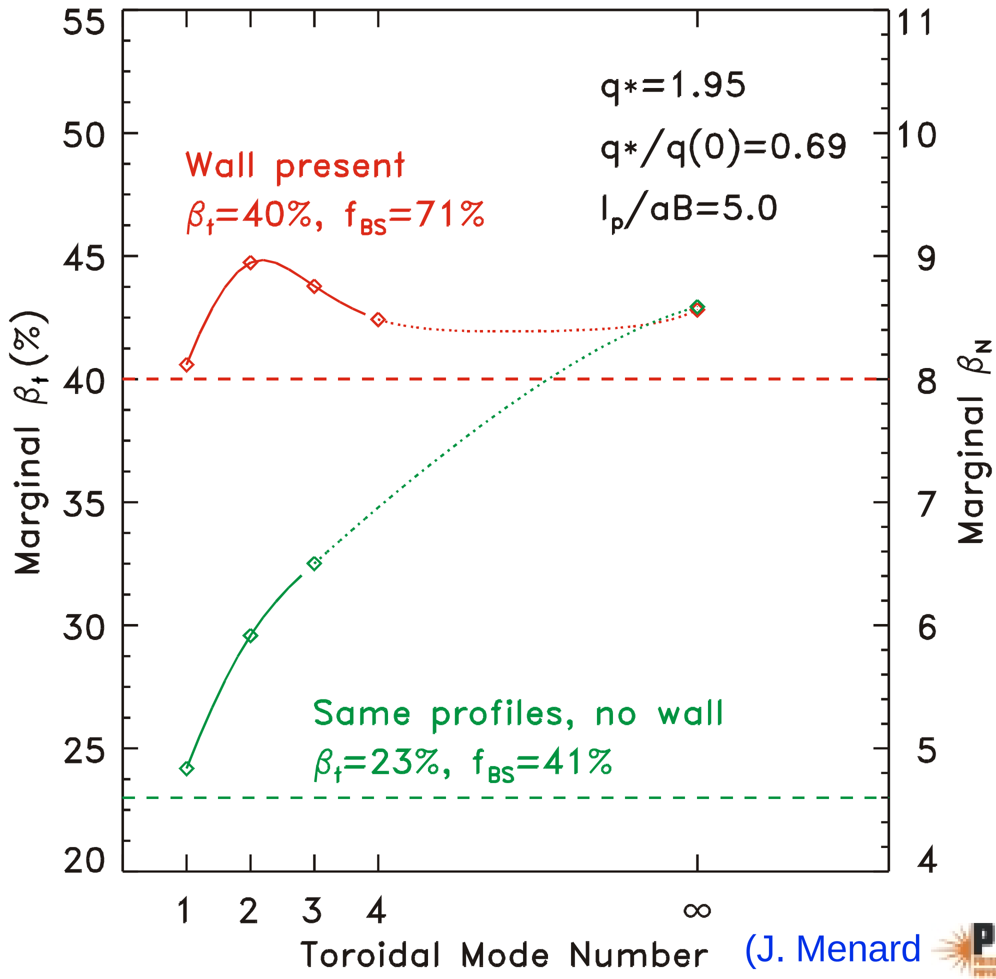
World ST Program Has Grown Rapidly Since 1990

Retired | **Concept Exploration (~0.3 MA)** | **Proof of Principle (~MA)**



NSTX Provides Opportunities Study Wall-Stabilized Beta Limits at q ~ 10 and κ ~ 2

κ = 2.0, β_T = 23–40%, C = 4.5–8, q_{edge} ~ 10



(J. Menard PPPL)

Capabilities

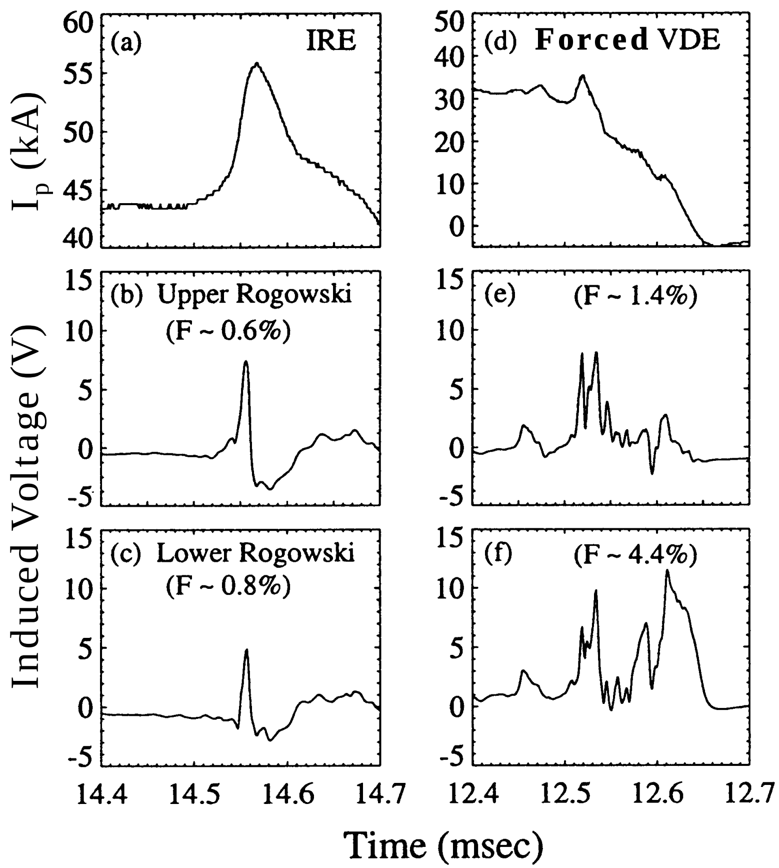
- R_0 = 0.85 m
- I_p ~ 1 MA
- Plasma heating
  - NBI (5 MW)
  - HHFW (6 MW)
  - ECW/EBW (<1 MW)
- Plasma shape control

Stability at high q?

Spherical Torus May See Only Modest Impact of Disruption-Induced Halo Currents

- CDX-U and START measured **modest I_{halo} fraction** (F < 5%) during disruption-like events

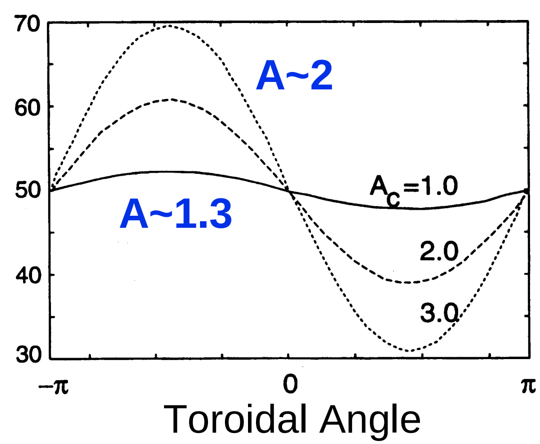
(Courtesy of M. Ono and CDX-U Team)

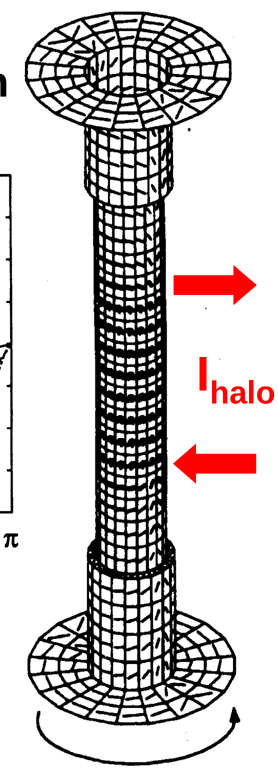


- Eddy current simulation indicates **strong symmetrization** at low A

⇒ Reduced forces

Vert. Current Distribution on Center Post

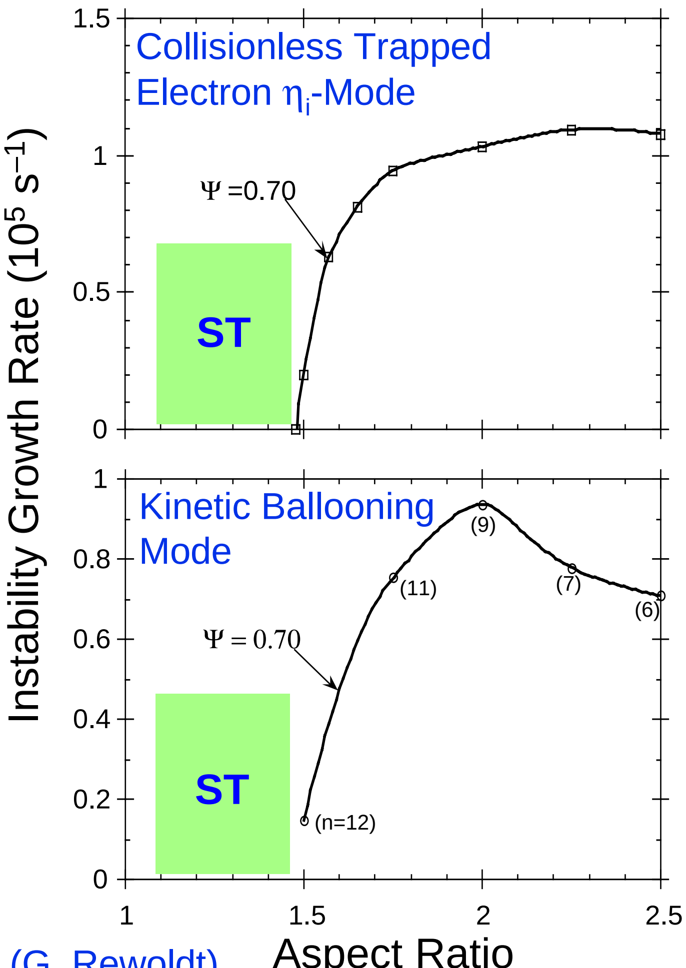




(N. Pomphrey
J. Bialek PPPL)

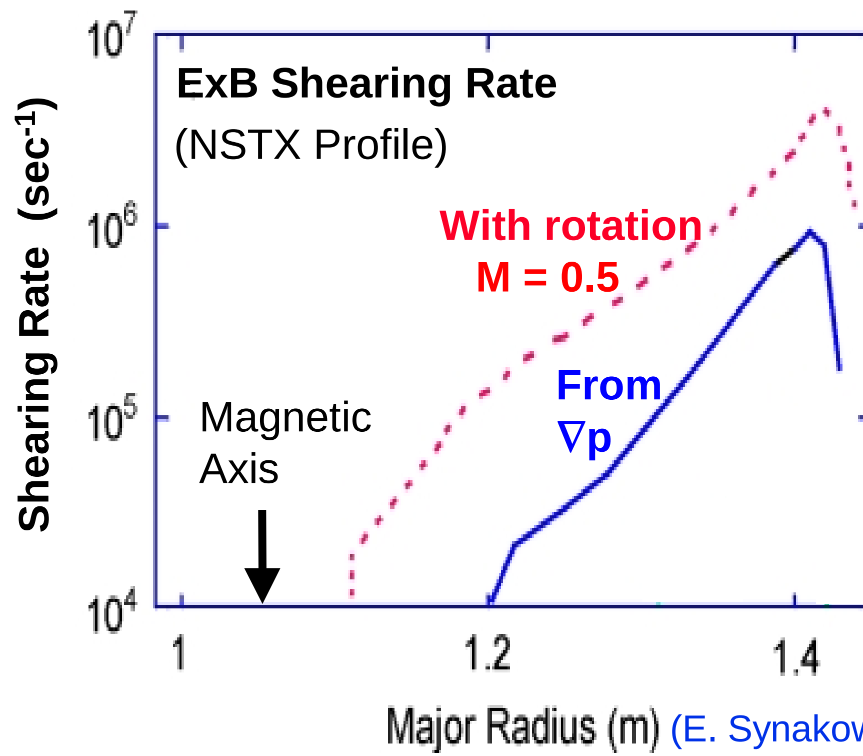
Turbulence May Be Much Reduced in NSTX

Reduced Microinstabilities



(G. Rewoldt)

Increased Stabilization



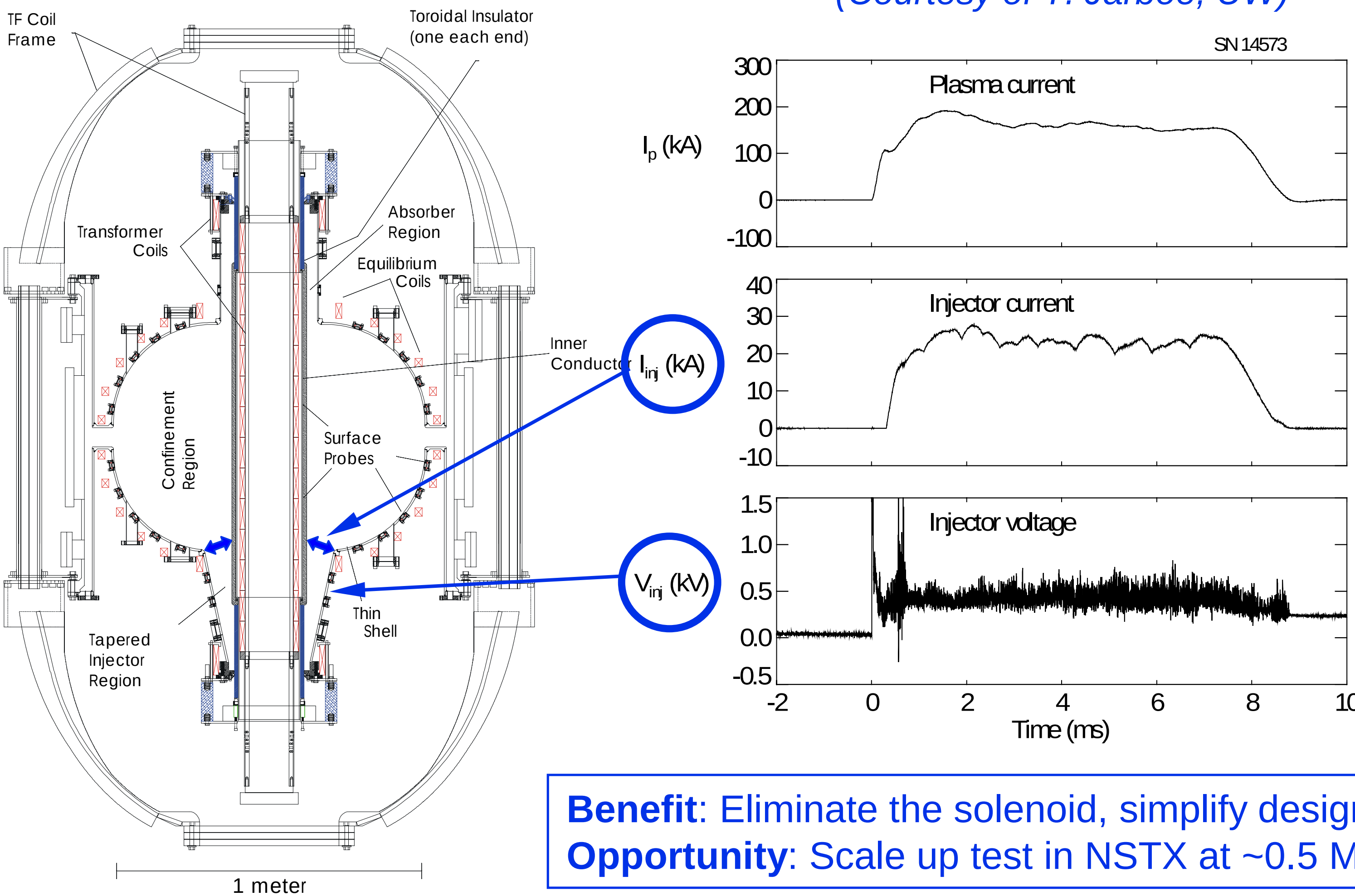
(E. Synakowski)

- **Opportunity:** Flow shearing rates >> microinstability growth rates
- **Challenge:** Is reduced turbulence compatible with stable high β?

Coaxial Helicity Injection (CHI) Draws on CT Research for Noninductive Current Drive in ST

HIT-II UW

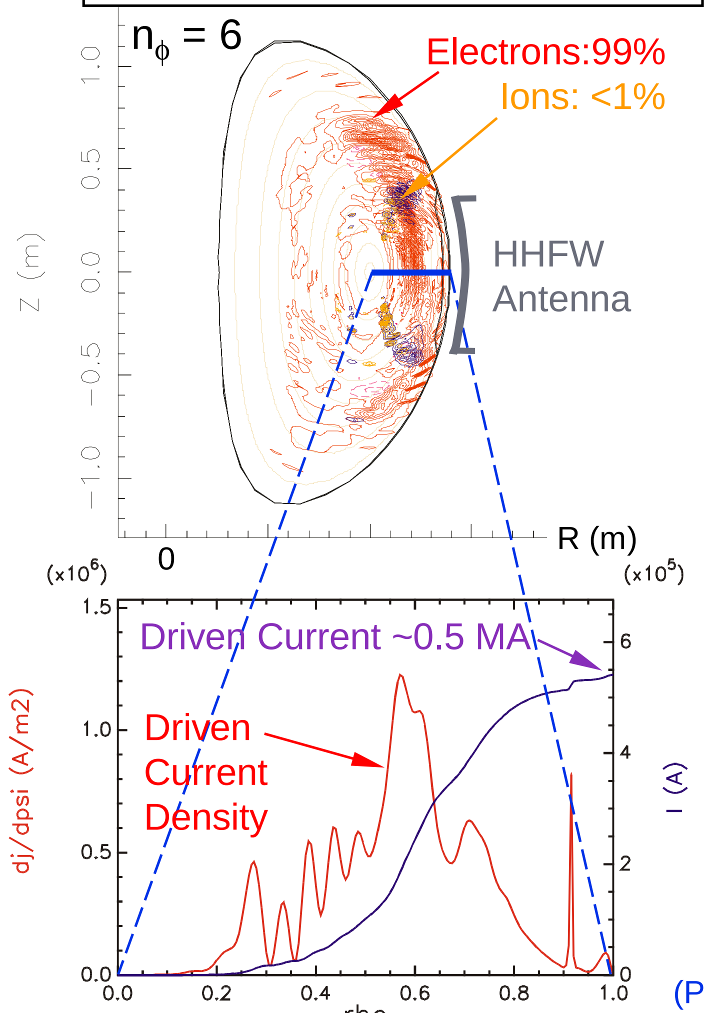
(Courtesy of T. Jarboe, UW)



Benefit: Eliminate the solenoid, simplify design
Opportunity: Scale up test in NSTX at ~0.5 MA

High Harmonic Fast Wave Utilizes High ε (~100) in ST for Efficient Heating & Current Drive

Contours of HHFW Absorption

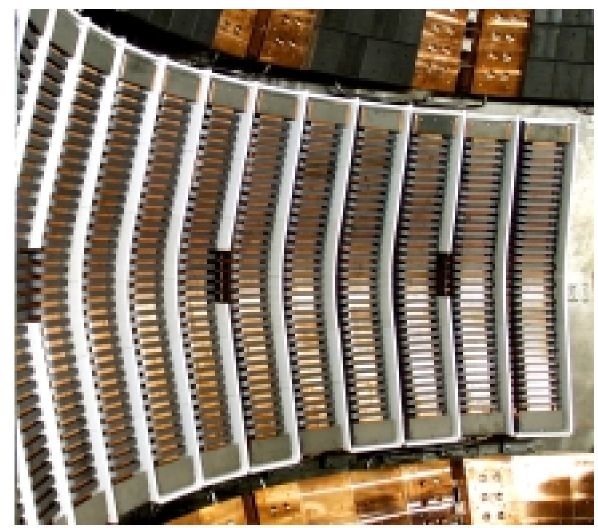


M. Ono (1995): Fast wave decay (absorption) rate:

$$k_{\perp im} \sim n_e / B^3 \sim \varepsilon / B,$$

$$\varepsilon = \omega_{pe}{}^2 / \omega_{ce}{}^2 \sim 10^2$$

PPPL & ornl

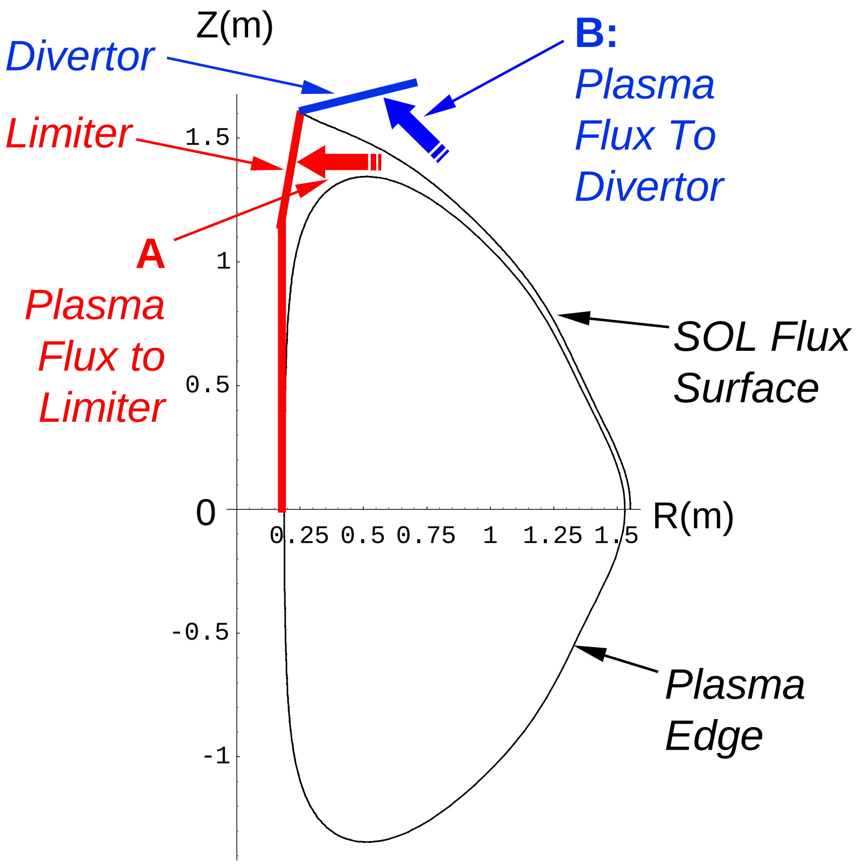


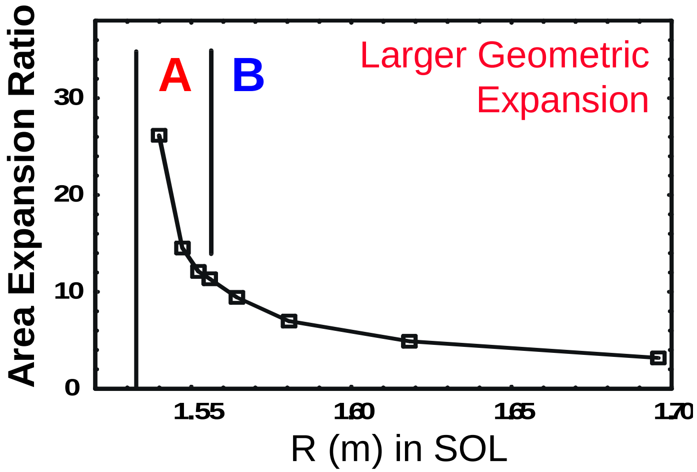
12 HHFW ANTENNA

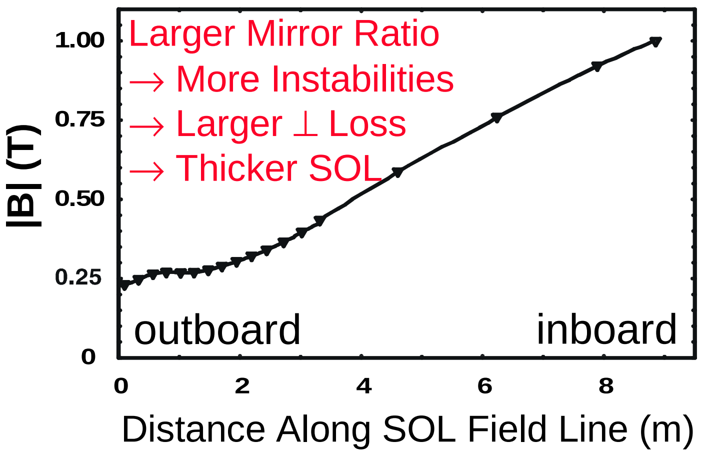
(PICES & RANT codes, F. Jaeger & M. Carter ornl)

Heat Fluxes Can Be Dispersed Over Large Wall Areas

Scrape-Off Layer Geometry of Inboard Limited ST Plasma

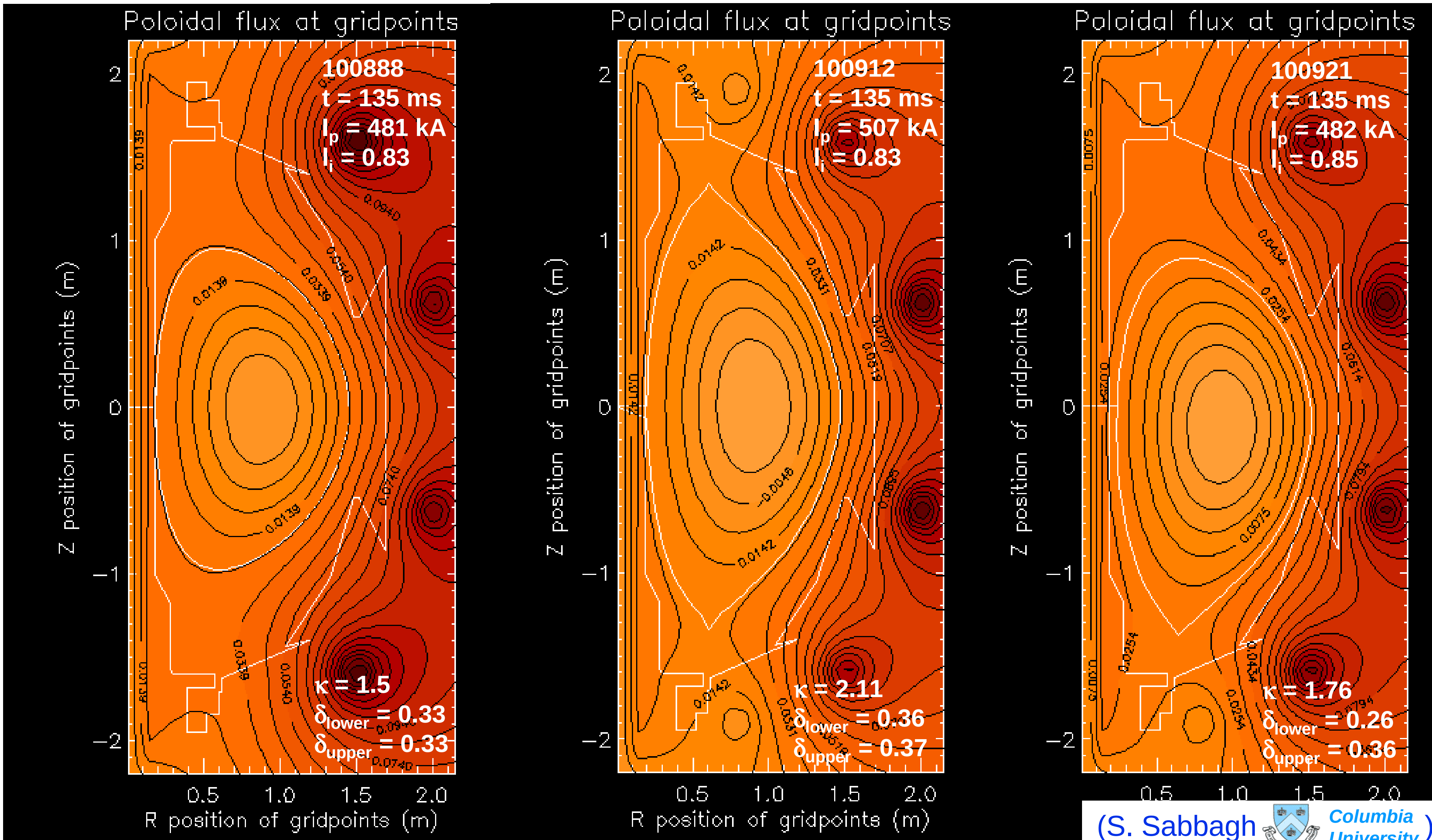






Various Plasma Shapes Have Been Produced in NSTX, Also Needed for SOL Investigations

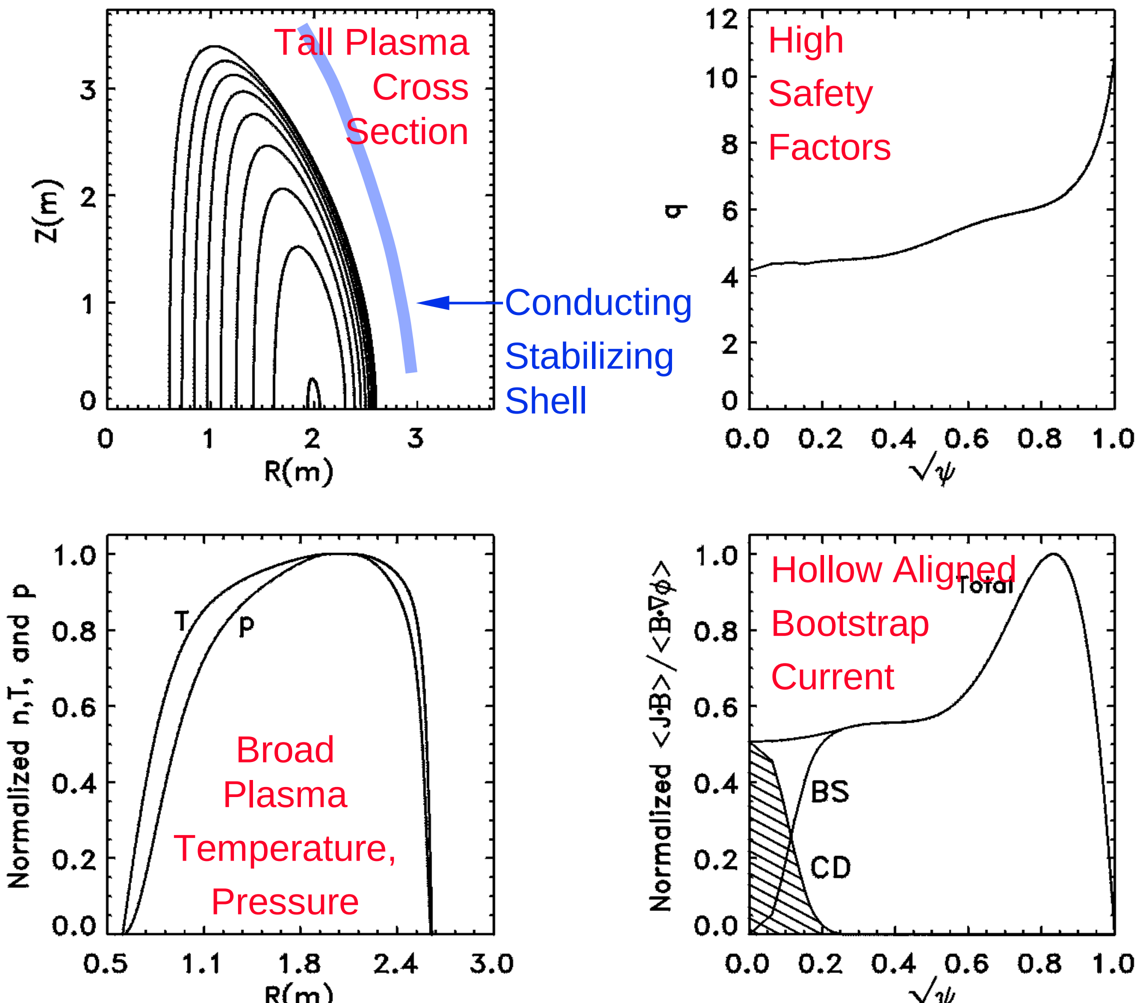
Wall Limited | **Double-Null Divertor** | **Single-Null Divertor**



(S. Sabbagh Columbia University)

Recent Stability Calculations Suggest Route to Self-Sustaining Higher β ST Plasmas

$\kappa = 3.4$, $\beta_N = 8.2$, $\beta_T = 56\%$, $\langle\beta\rangle = 42\%$, $f_{BS} = 99\%$, $q_{edge} \sim 11$

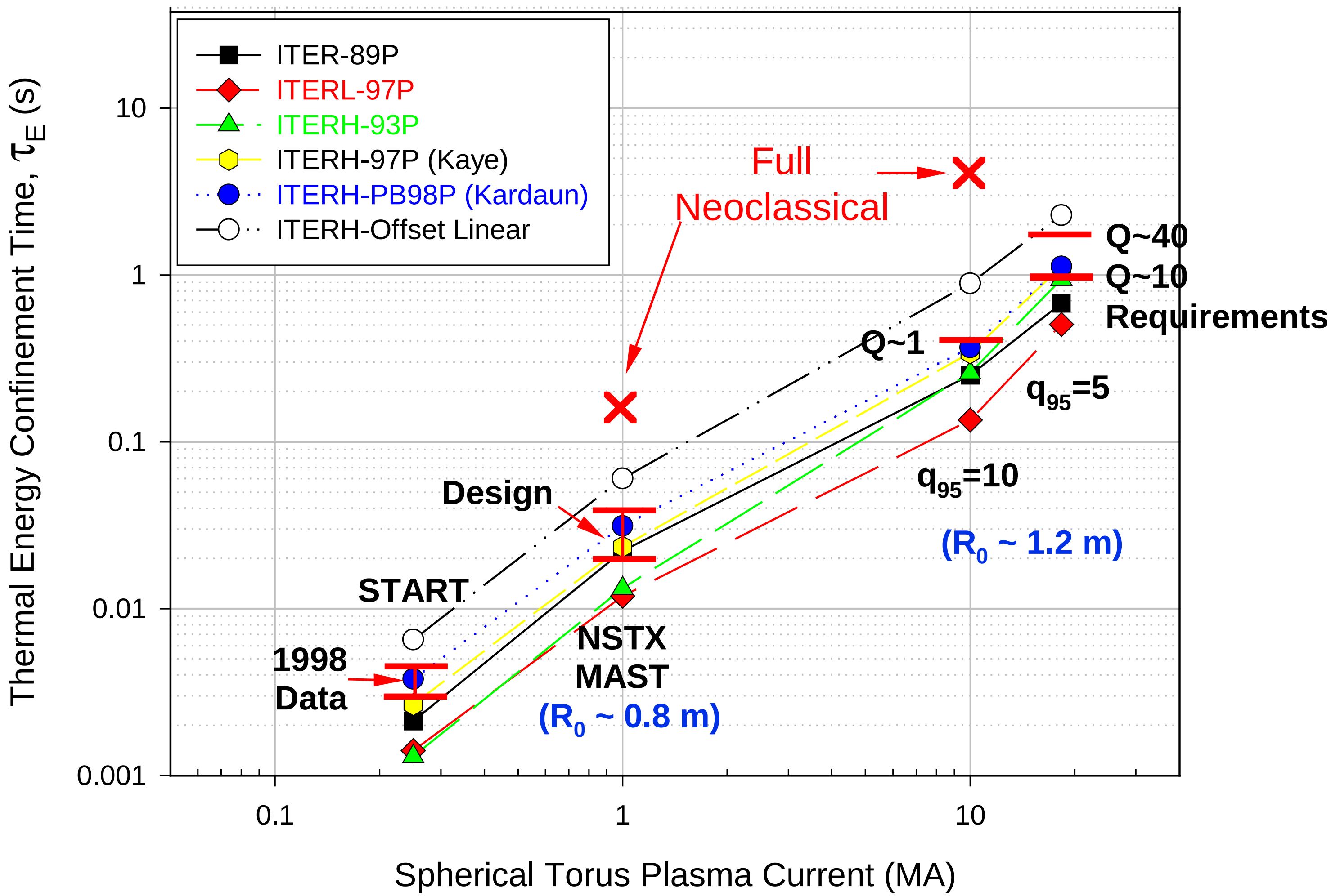


Challenges

- Vertical stability
- Disruptions
- Resistive Wall Mode stability & control
- Neoclassical tearing mode stability
- Profile tailoring
- Bootstrap current alignment

(J. Menard, PPPL)

Enhanced Confinement Projects to High Performance



ST experiments will improve understanding of plasma transport.

ST Introduces Additional Possibilities of Intriguing Plasma Behaviors

- **Strong magnetic well (~30%), near-omnigenous orbits**
  - Guiding-center orbit compression, reduced neoclassical transport?
  - Stability of “Fishbone” modes?
- **Large Pfirsch-Schlüter current**
  - Stabilization of neoclassical tearing modes at high β?
- **$v_{sound} \sim v_{Alfvén,}$ where local $\beta \sim 1$**
  - “Dynamic” equilibrium with strong plasma flow?
  - Influence on stability and turbulence?
- **$v_{fast} >> v_{Alfvén}$ for fast ions or fusion α particles**
  - New classes of Toroidal Alfvén Eigenmodes, and effects?
- **Larger ρ_i* (=ρ_{ci}/a) ~ 0.03 – 0.01**
  - Thicker pedestal in H-mode plasmas?
- **Extreme low A (~1.1)**
  - Connections to FRC and Spheromak?

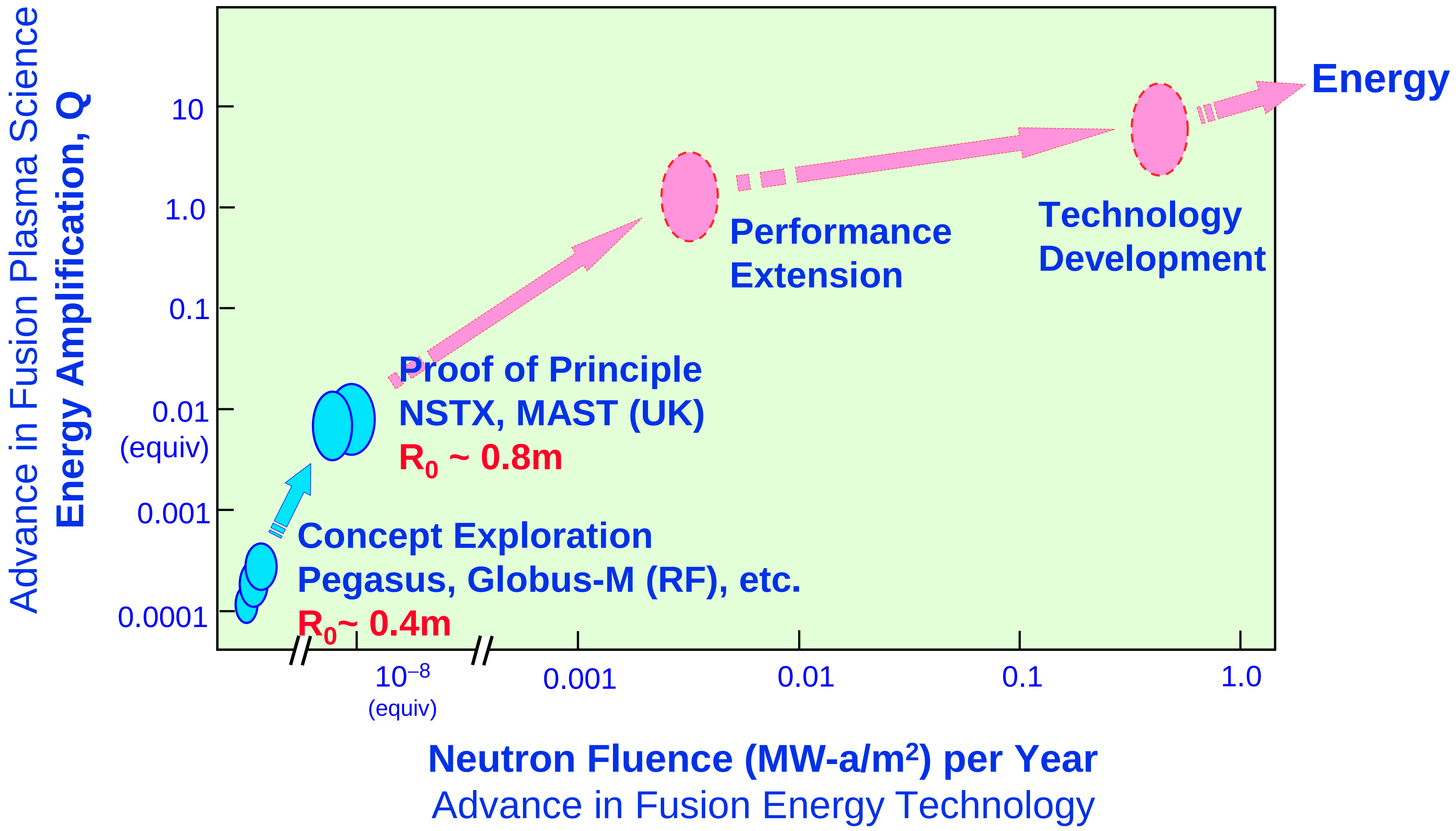
Spherical Torus Introduces Both Exciting Fusion Science and a Possible Practical Route to Energy

Promise:	***SCIENCE***	↔	***ENERGY***
	High Pressure, Low Field	↔	Low Device Cost
	Suppressed Turbulence	↔	Small Unit Size
	Dispersed Exhaust	↔	Reliable First Wall
	Self-Sustaining Current	↔	Lowered Operating Cost
	Startup Without Solenoid	↔	Simplified Compact Configuration

New Challenge: SCIENCE, TECHNOLOGY

Startup Without Solenoid	↔	Noninductive Startup Physics
	↔	Single-Turn Center Conductor
	↔	Recirculating Power, Lifetime

ST Development Path to Fusion Energy Science & Technology May Be More Affordable



Spherical Torus Plasmas Offer Exciting Scientific Opportunities

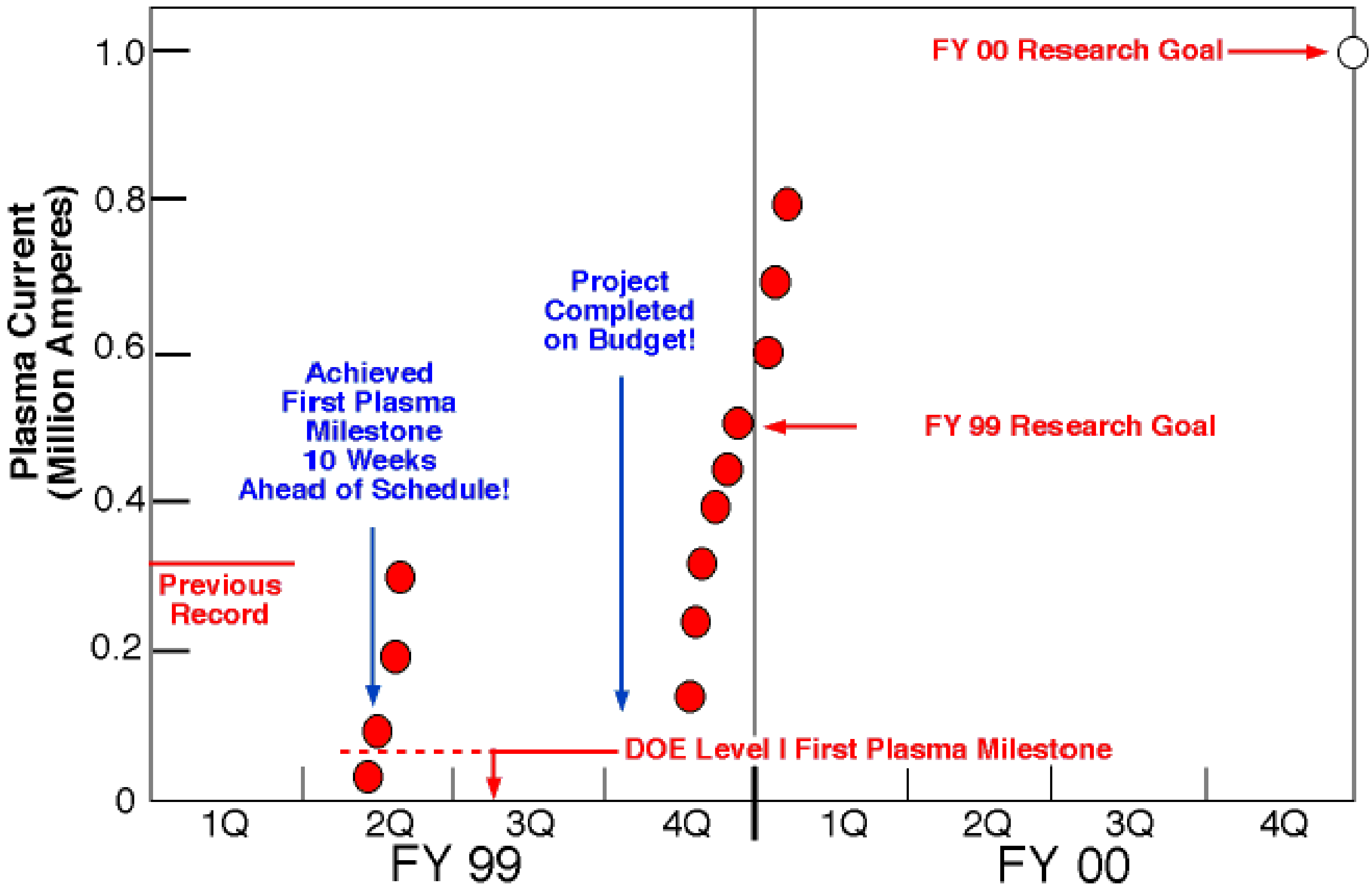
- Derived from Tokamak and Compact Toroid research
- Offers exciting scientific opportunities and challenges for fusion
  - Order-unity β
  - Good confinement
  - Self-sustained current
  - Dispersed heat fluxes
  - Full noninductive startup
- Introduces new physics features to be explored
- May offer affordable steps to advance fusion energy science
- NSTX, Pegasus, HIT-II, CDX-U in the U.S., together with ST experiments around the world, are ready to address key issues

Sessions and Papers of Interest to ST Studies

- **[DI1.02]** Mon PM **Y Ono**: FRC & ST
- **[FP1.73]** Tue AM **C Sovinec**: Electrostatic Current Drive
- **[GO2.18]** Tue PM **K Williams**: Turbulence Modeling
- **[GM2.04]** Tue PM **C Williams**: ST Fusion Space Propulsion Vehicle
- **[JP1.75–107]** Wed AM **M. Ono et al.**: NSTX & [UP2.52] Fri AM Diagnostics
- **[KP1.89]** Wed PM **M Kotschenreuther et al**: Novel Reactor
- **[RP1.36–41]** Thur PM **R Fonck et al**: Pegasus
- **[RP1.42–48]** Thur PM **R Majeski, R Kaita et al**: CDX-U
- **[RP1.49]** Thur PM **M Carter**: RF Modeling
- **[RP1.50–56]** Thur PM **T Jarboe et al**: HIT-II, HIT-SI
- **[RP1.57–60]** Thur PM **Y Ono et al**: TS-3, TS-4
- **[RP1.61–62]** Thur PM **Y Takase et al**: TST-2
- **[RP1.63 –64]** Thur PM **M Nagata et al**: HIST

Fri Noon - Sun Noon: ***6th International ST Workshop + US-Japan Workshops on ST & Phys. Of Innovative (CT) High-Beta Fusion Plasma Confinement***

NSTX is Racing up in Plasma Current!



NSTX Achieved Peak Current at 800 kA Briefly, and ~500 kA for ~80 ms