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Spherical Tokamak Plasma Science & Fusion Energy Development

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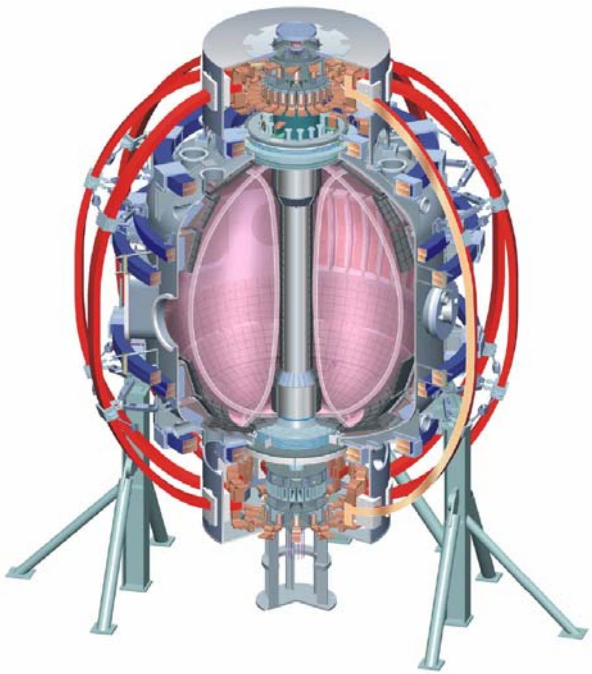

PU Graduate Seminar in Plasma Physics
AST558

April 25, 2005

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Spherical Tokamak (ST) Offers Rich Plasma Science Opportunities and High Fusion Energy Potential

- **What is ST and why?**
- **World ST community**
- **Cost-effective steps to fusion energy**
- **Scientific opportunities of ST**
  - **How does shape (κ, δ, A …) determine pressure?**
  - **How does turbulence enhance transport?**
  - **How do plasma particles and waves interact?**
  - **How do hot plasmas interact with walls?**
  - **How to supply magnetic flux without solenoid?**
- **Wrap-up**

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:

$$\beta_{Tmax} = C\, I_p / a \langle B \rangle \approx 5\, C\, \kappa / A\, q_j; \quad \langle B \rangle \approx B_T \text{ at standard } A$$

$C \approx$ constant (~ 3 %m·T/MA) $\Rightarrow \beta_N$

$\langle B \rangle$ = volume average B $\Rightarrow B_T$

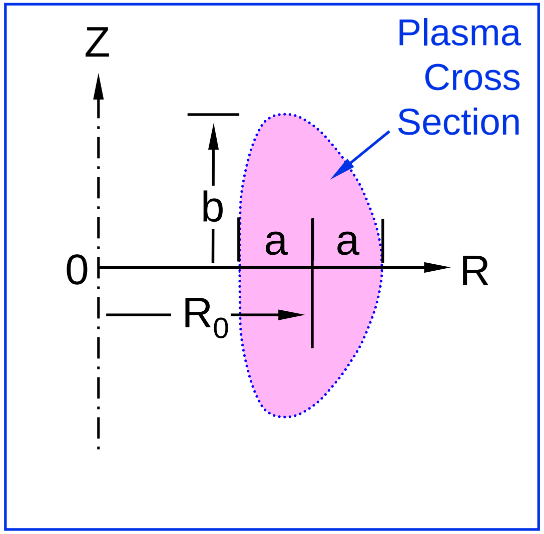
$\kappa = b/a$ = elongation

$A = R_0/a$ = aspect ratio

$q_I \approx$ average safety factor

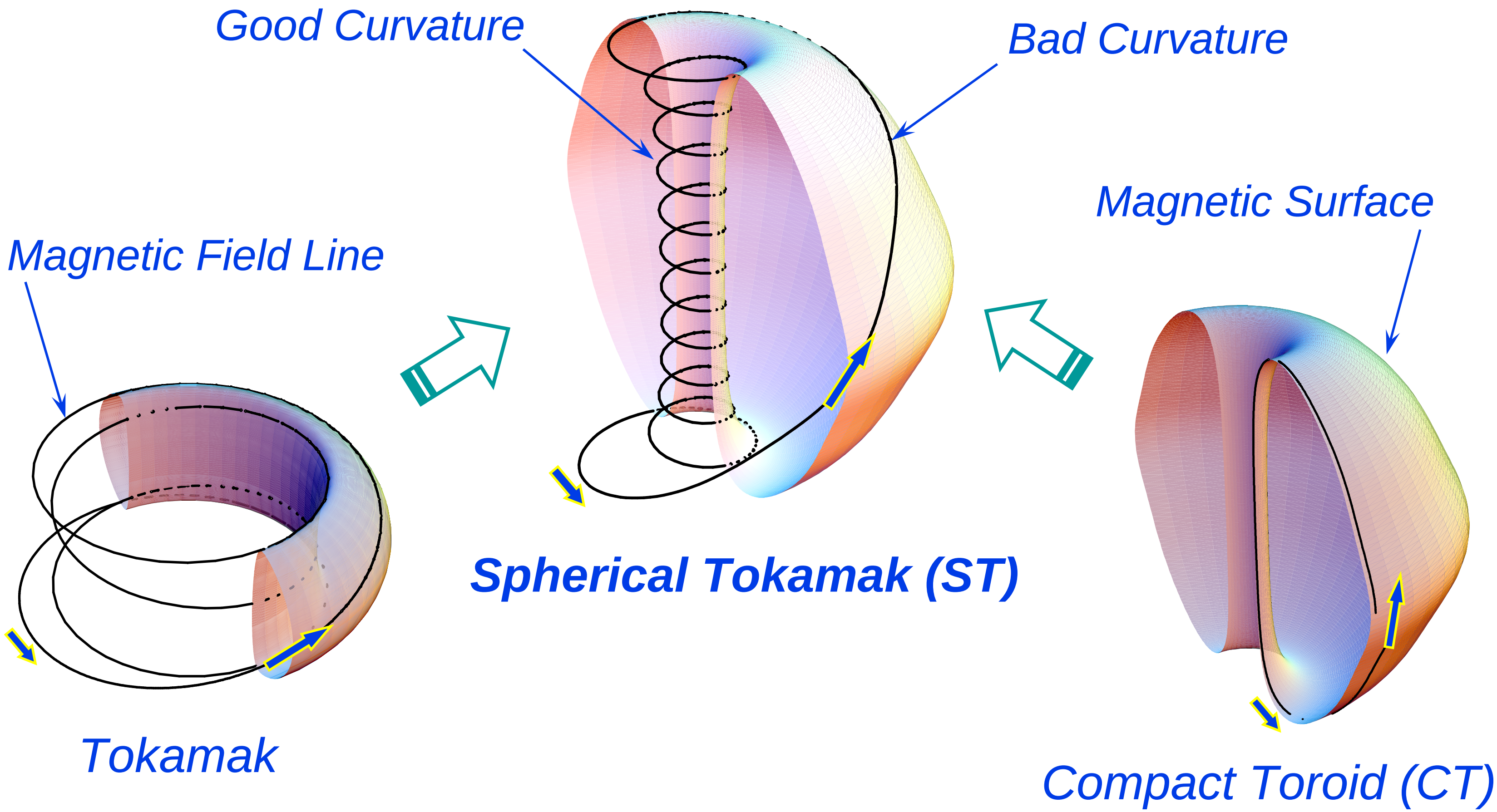
I_p = toroidal plasma current

$B_T \approx$ applied toroidal field at R_0



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

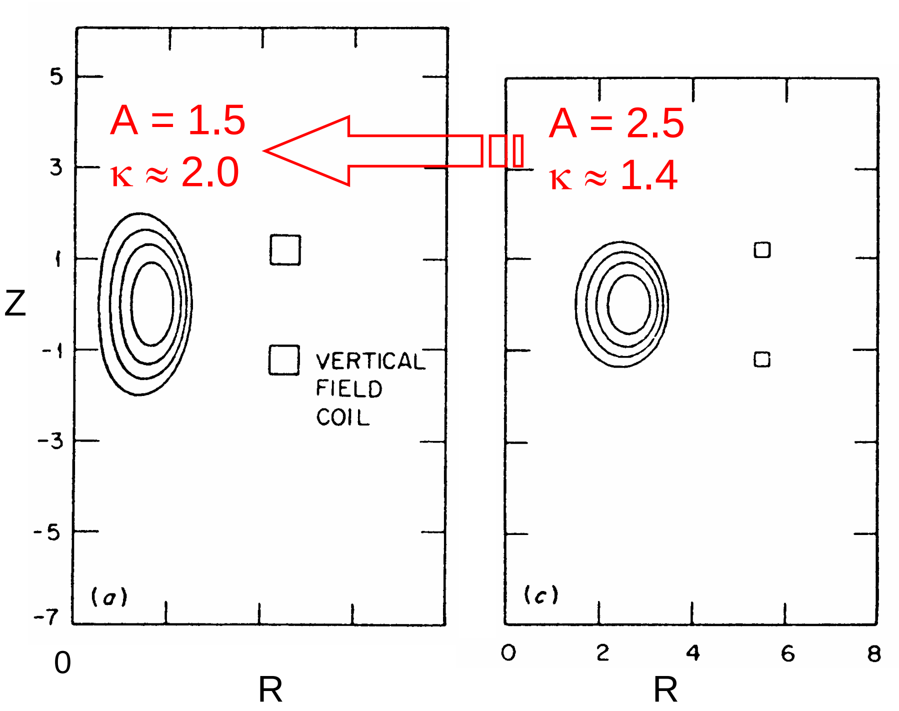
Minimizing Tokamak Aspect Ratio Maximizes Field Line Length in Good Curvature ⇒ High β Stability



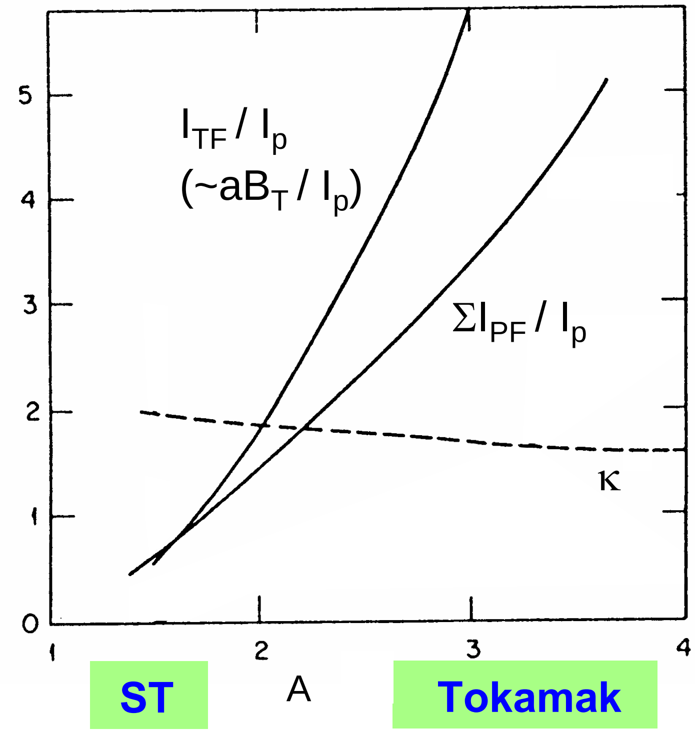
Small-R close to Tokamak & large-R close to CT.

ST Plasma Elongates Naturally, Needs Less TF & PF Coil Currents, Increases $I_p/aB_T \Rightarrow$ Higher β_{Tmax}

Natural Elongation, κ



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

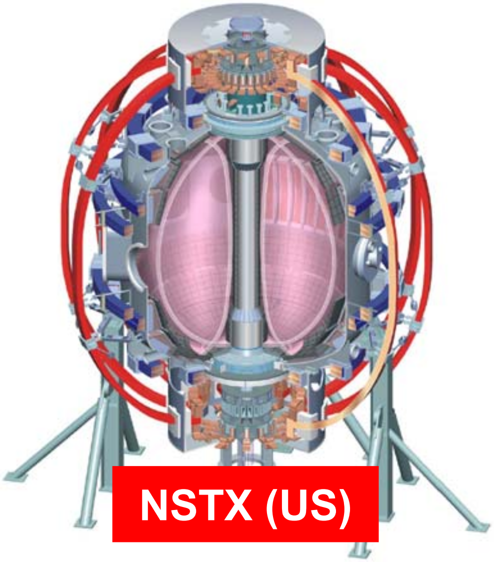


- Naturally increased κ ~ 2; $I_{TF} < I_p$, $I_{PF} < I_p$ $\Rightarrow$ higher I_p; lower device cost
- Increased I_p/aB_T ~ 7 MA/m·T $\Rightarrow$ β_{Tmax} **~ 20%,** if β_N ~ 3
- Increased $I_p\, q_{edge}\,/aB_T$ ~ 20 MA/m·T $\Rightarrow$ improved confinement?

ST Research Is Growing Worldwide

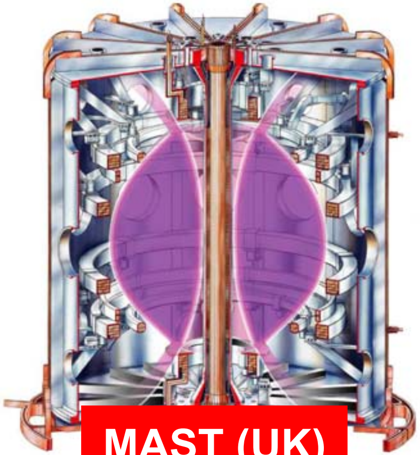
Concept Exploration (~0.3 MA)

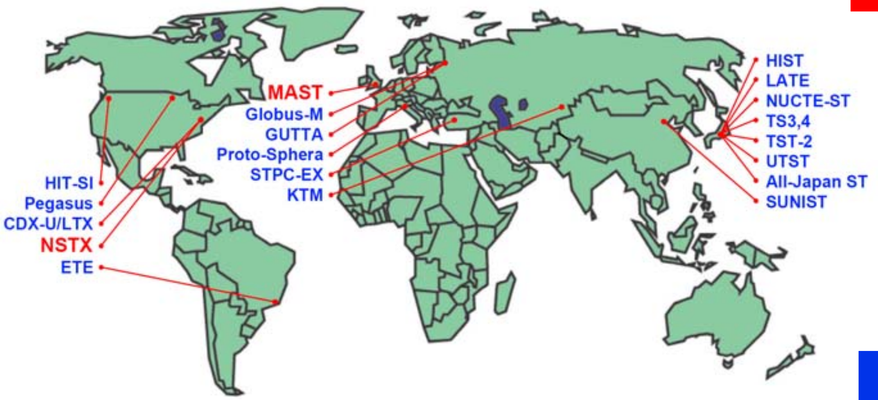
Proof of Principle (~MA)

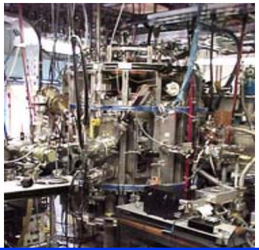

NSTX (US)


HIT-II (US)


Pegasus (US)


MAST (UK)




CDX-U (US)

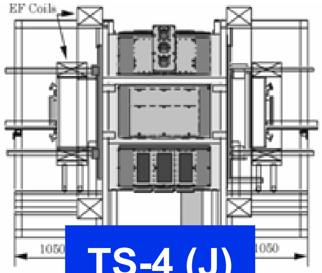

Globus-M (RF)


ETE (B)

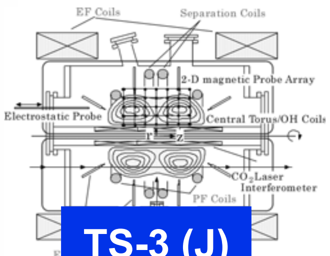

SUNIST (PRC)


HIST (J)


TST-2 (J)

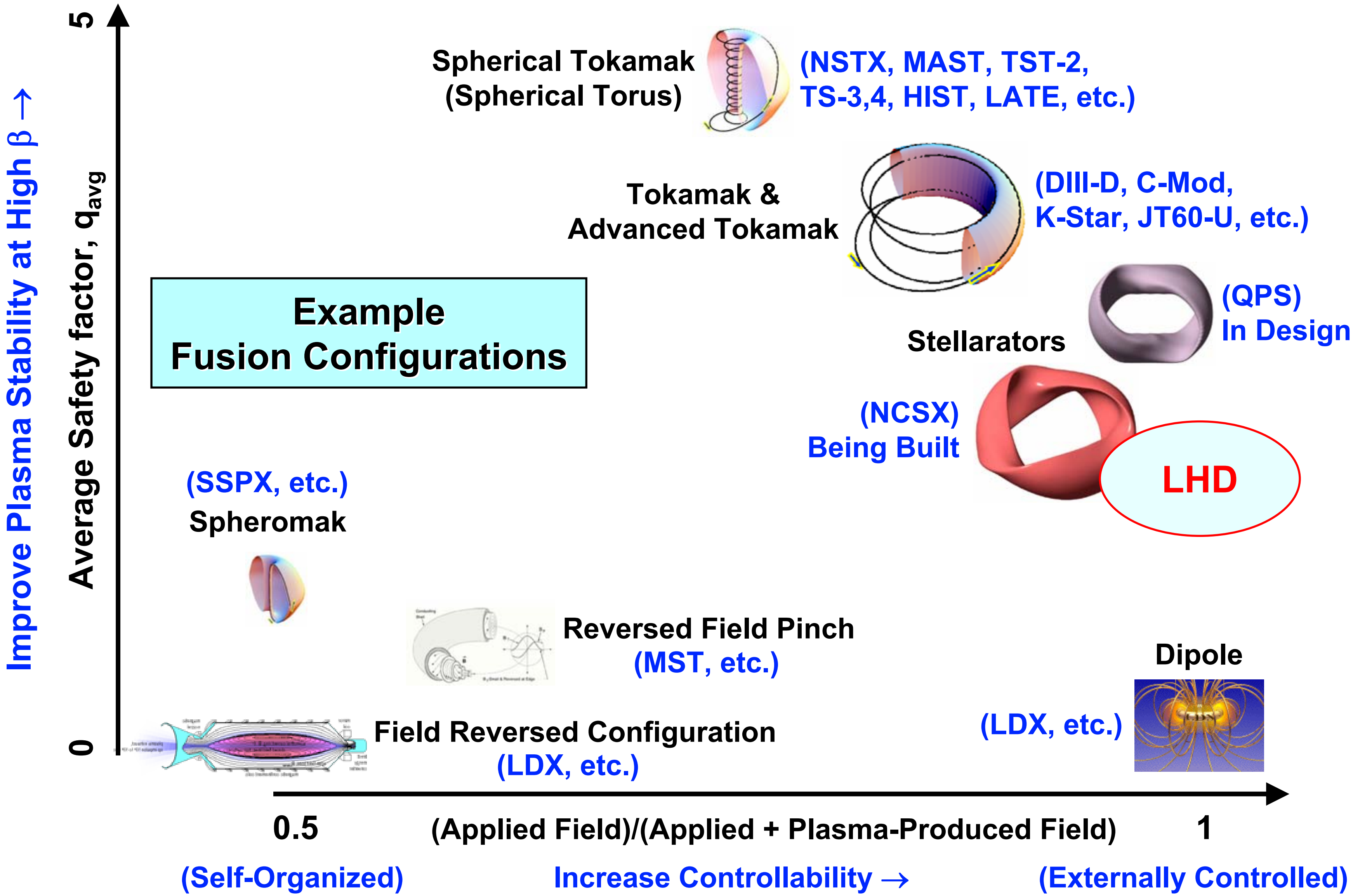


TS-4 (J)



TS-3 (J)

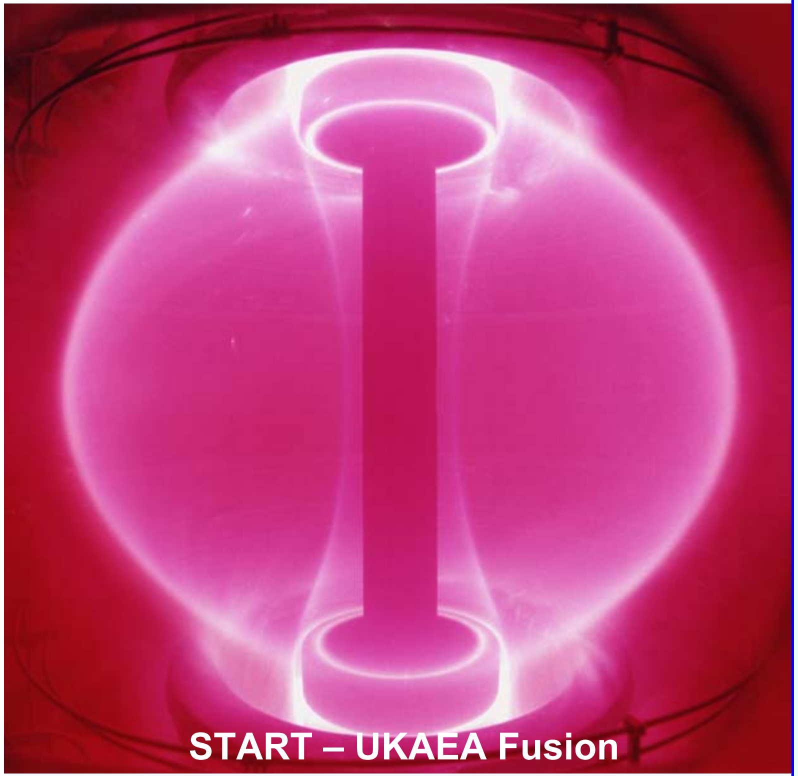
ST Is Closest to Tokamak; Operates with High Safety Factor and More Comparable Self & Applied Fields



Very Low Aspect Ratio (A) Introduces New Opportunities to Broaden Toroidal Plasma Science

ST Plasmas Extends Toroidal Parameters

A = R/a can be ≥ 1.1



How does shape determine pressure?

- Strong plasma shaping & self fields (vertical elongation ≤ 3, $B_p/B_t \sim 1$)
- Very high β_T (~ 40%), β_N & $f_{Bootstrap}$

How does turbulence enhance transport?

- Small plasma size relative to gyro-radius (a/ρ_i~30–50)
- Large plasma flow ($M_A = V_{rotation}/V_A \leq 0.3$)
- Large flow shearing rate ($\gamma_{ExB} \leq 10^6$/s)

How do plasma particles and waves interact?

- Supra-Alfvénic fast ions ($V_{fast}/V_A \sim 4$–5)
- High dielectric constant ($\varepsilon = \omega_{pe}^2/\omega_{ce}^2 \sim 50$)

How do plasmas interact with walls?

- Large B mirror ratio in edge ($M_B \leq 4$, $f_T \rightarrow 1$)
- Strong field line expansion (> factor of 10)

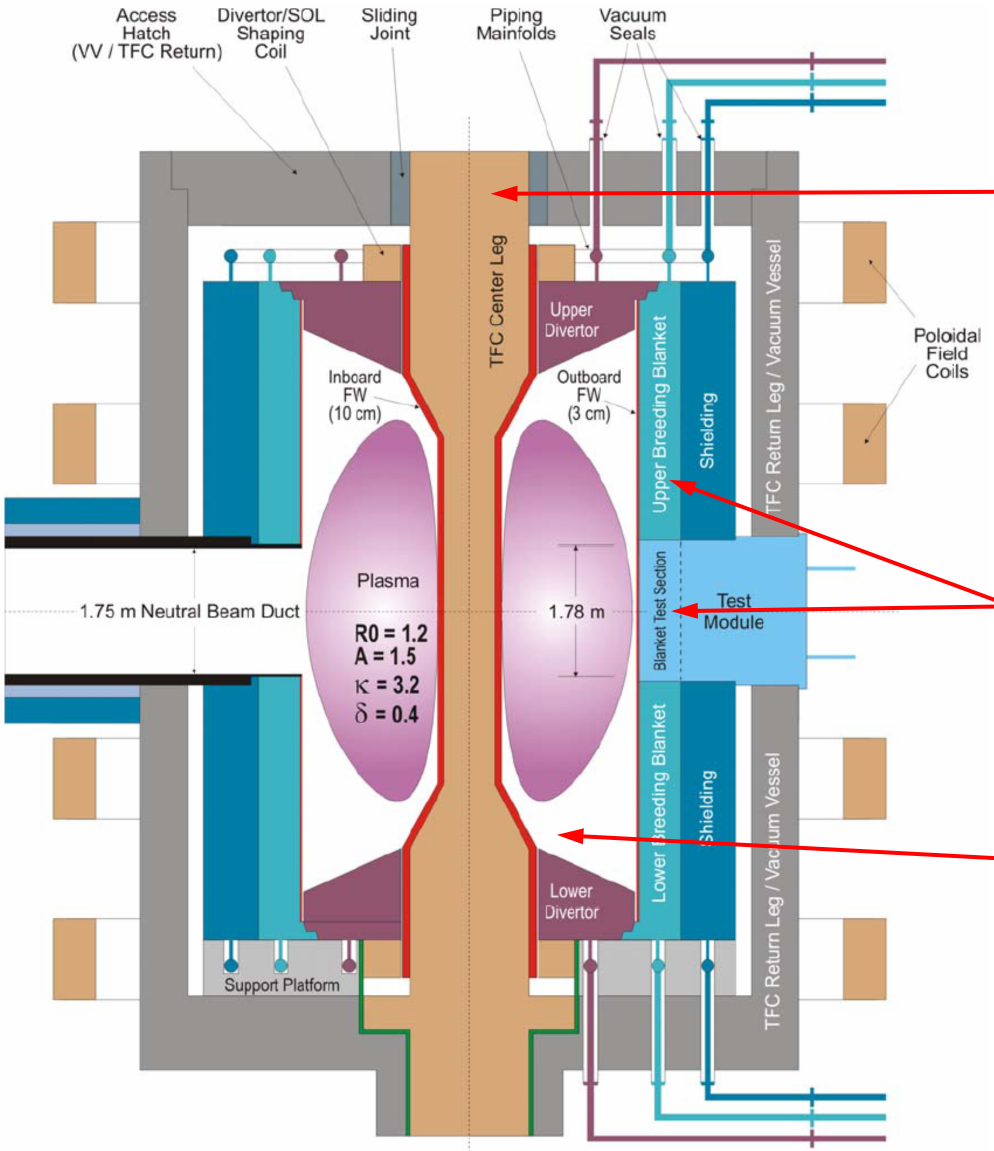
How to supply mag flux without solenoid?

- Small magnetic flux content (~ $\ell_i R_0 I_p$)

Answering the Plasma Science Questions Also Enable Cost-Effective Steps toward Fusion Energy

Plasma Science Questions in Extended ST Parameter Space	⇒	Optimize Fusion DEMO & Development Steps
How does shape determine pressure?	⇒	Lowered magnetic field and device costs
How does turbulence enhance transport?	⇒	Smaller unit size for sustained fusion burn
How does plasma particles and waves interact?	⇒	Efficient fusion α particle, neutral beam, & RF heating
How do hot plasmas interact with wall?	⇒	Survivable plasma facing components
How to supply magnetic flux without solenoid?	⇒	Simplified smaller design, reduced operating cost

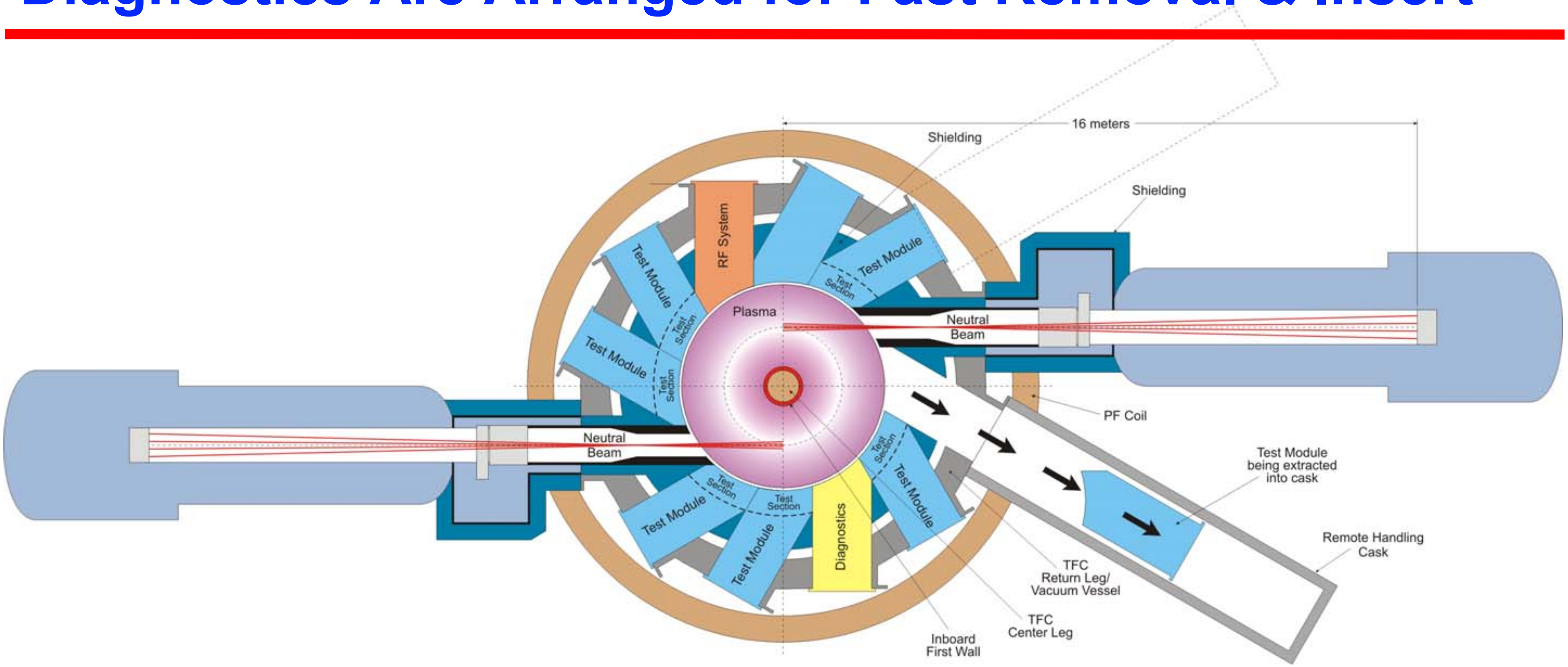
Optimized Device Configuration Features of ST Also Fulfill the CTF Mission Effectively



Features Required by High Duty Factor & Neutron Fluence

- **Single-turn demountable center leg** for toroidal field coil **required** to achieve small size and simplified design.
- **Fast remote replacement** of all fusion nuclear test components (blanket, FW, PFC) & center post **required** to permit high duty factor & neutron fluence.
- **Large blanket test areas** $\propto$ (R+a)κa.
- Adequate **tritium breeding ratio** & **small fusion power** from low A **required** for long term fuel sufficiency.
- **High heat fluxes** on PFC.
- Initial core components could use **DEMO-relevant technologies** (such as from ITER and long-pulse tokamaks).
- **12-MA power supply** – Single-turn TF.

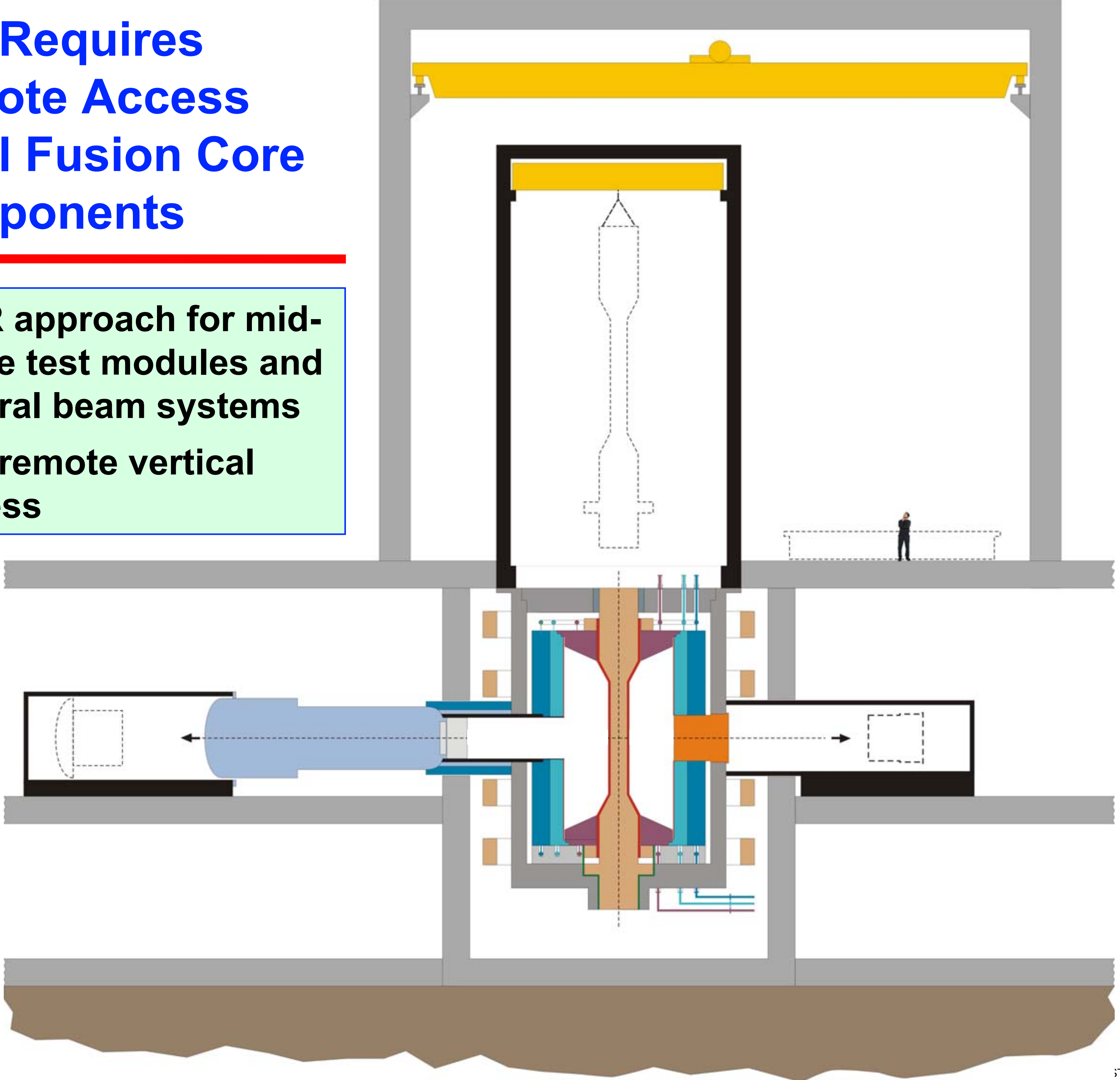
Mid-Plane Test Modules, Neutral Beam Injection, RF, Diagnostics Are Arranged for Fast Removal & Insert



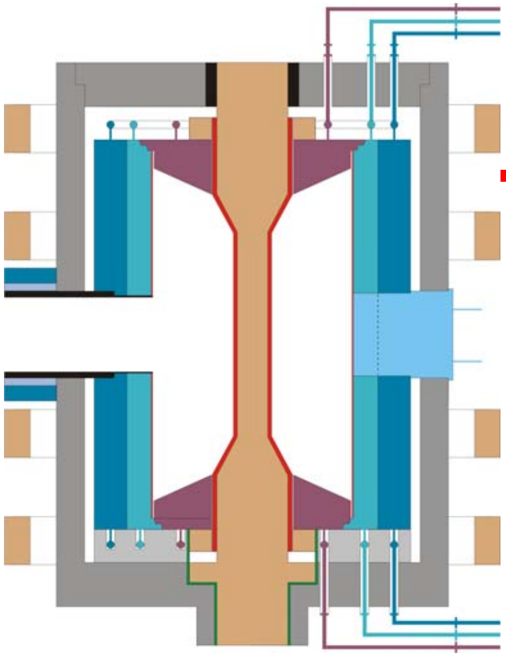
- 8 mid-plane blanket test modules provides ~ 15 m^2 at maximum flux
  - Additional cylindrical blanket test area > 50 m^2 at reduced flux
- 3 m^2 mid-plane access for neutral beam injection of 30 MW
- 2 m^2 mid-plane access for RF (10 MW) and diagnostics
- All modules accessible through remote handling casks (~ITER)

CTF Requires Remote Access to All Fusion Core Components

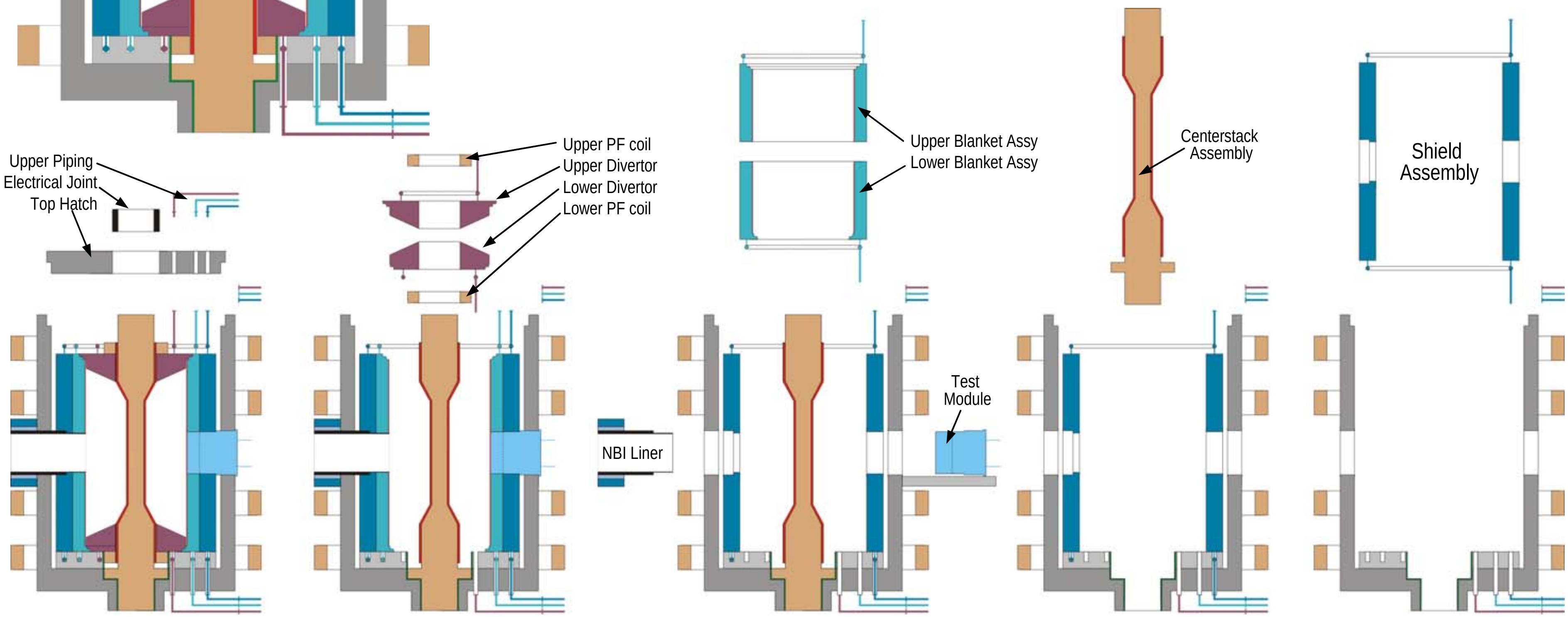
- **ITER approach for mid-plane test modules and neutral beam systems**
- **Full-remote vertical access**



Machine Assembly/Disassembly Sequence Are Made Manageable



- **Hands-on connect and disconnect service lines outside of shielding and vacuum boundaries**
- **Divertor, cylindrical blanket, TF center leg, and shield assembly removed/installed vertically**



- Disconnect upper piping
- Remove sliding electrical joint
- Remove top hatch

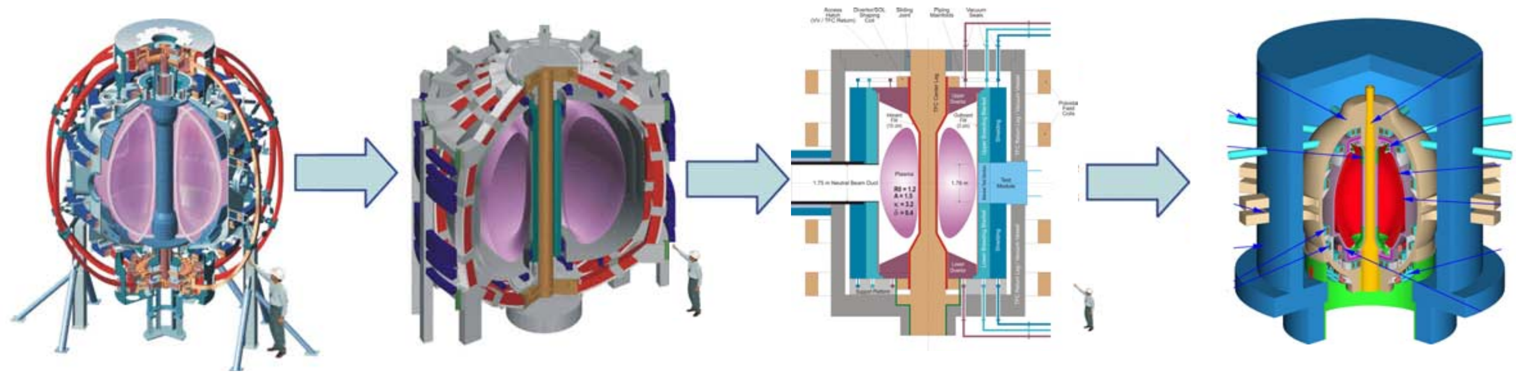
- Remove upper PF coil
- Remove upper divertor
- Remove lower divertor
- Remove lower PF coil

- Extract NBI liner
- Extract test modules
- Remove upper blanket assembly
- Remove lower blanket assembly

- Remove centerstack assembly

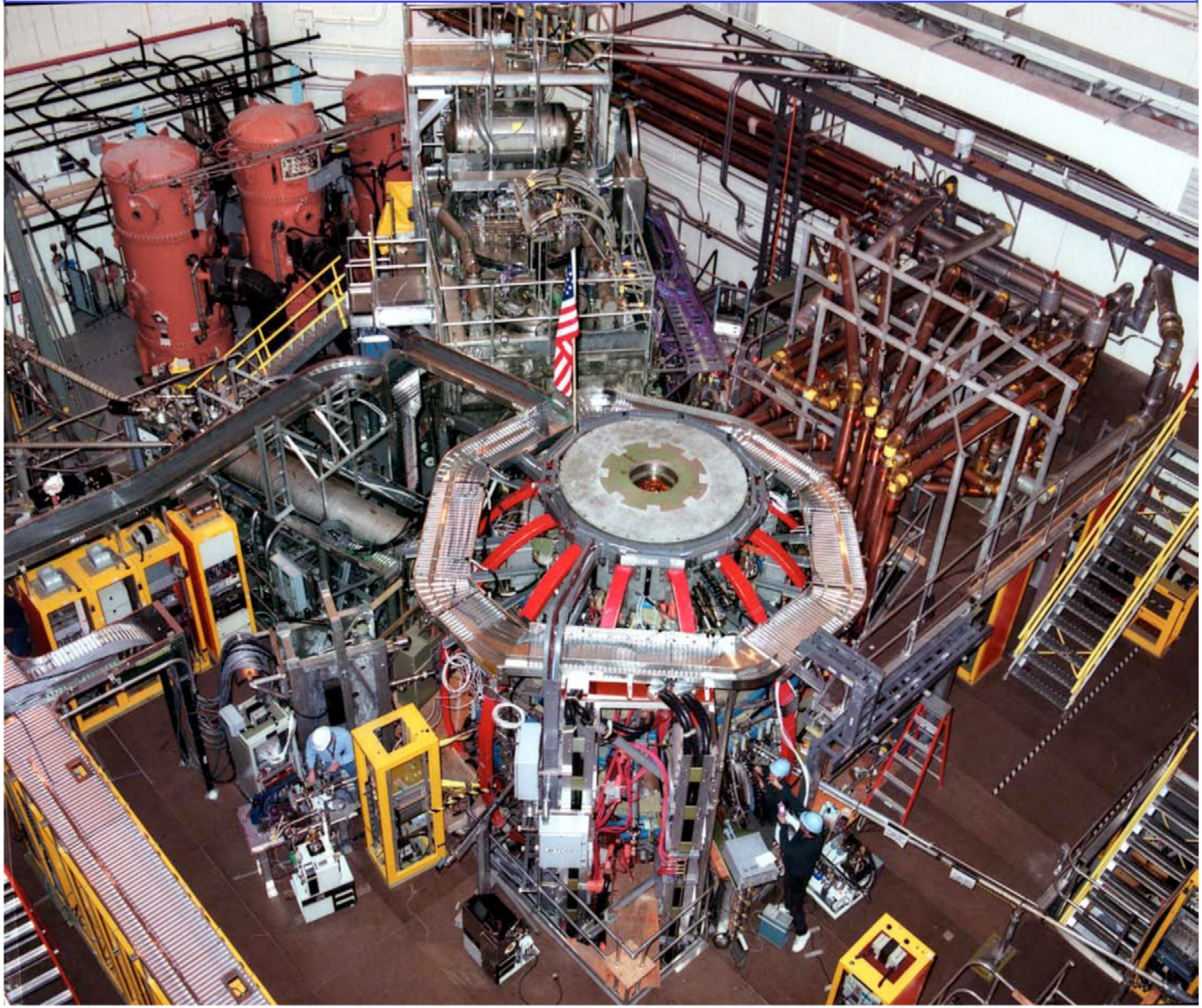
- Remove shield assembly

Future ST Steps Are Estimated to Require Moderate Sizes to Make Key Advances toward DEMO



Device	NSTX		NSST		CTF		DEMO
Mission	Proof of Principle		Performance Extension		Energy Development, Component Testing		Practicality of Fusion Electricity
R (m)	0.85		**~1.5**		**~1.2**		~3
a (m)	0.65		~0.9		~0.8		~2
κ, δ	2.5, 0.8		~2.7, ~0.7		~3, ~0.5		~3.2, ~0.5
I_p (MA)	**1.5**	**1**	**~5**	**~10**	~9	~12	~25
B_T (T)	**0.6**	**0.3**	**~1.1**	**~2.6**	~2.1		~1.8
Pulse (s)	**1**	**5**	**~50**	**~5**	**Steady state**		Steady state
P_{fusion} (MW)	–		**~10**	**~50**	**~77**	**~300**	~3100
W_L (MW/m^2)	–		–		**~1**	**~4**	~4
Duty factor (%)	~0.01		~0.01		**~15**	**30**	60
TFC; Solenoid	Multi-turn; Solenoid		Multi-turn; Solenoid		Single-turn; No-solen.		Single-turn; No-solen.

National Spherical Torus Experiment

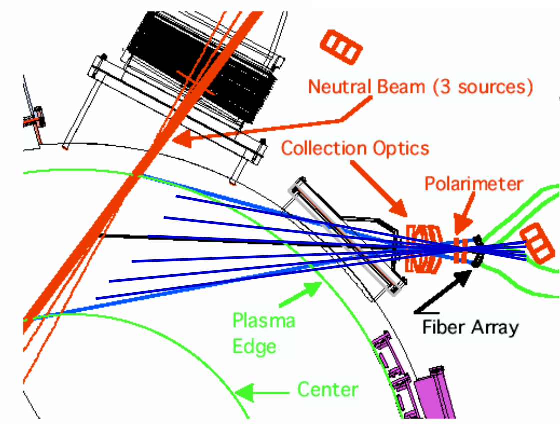


Major Exciting New Tools for FY 05 Run

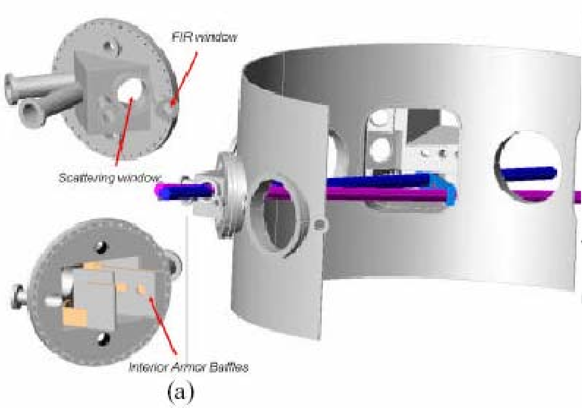
NSTX

8 Ch MSE-CIF for j(r)

Nova Photonics Inc

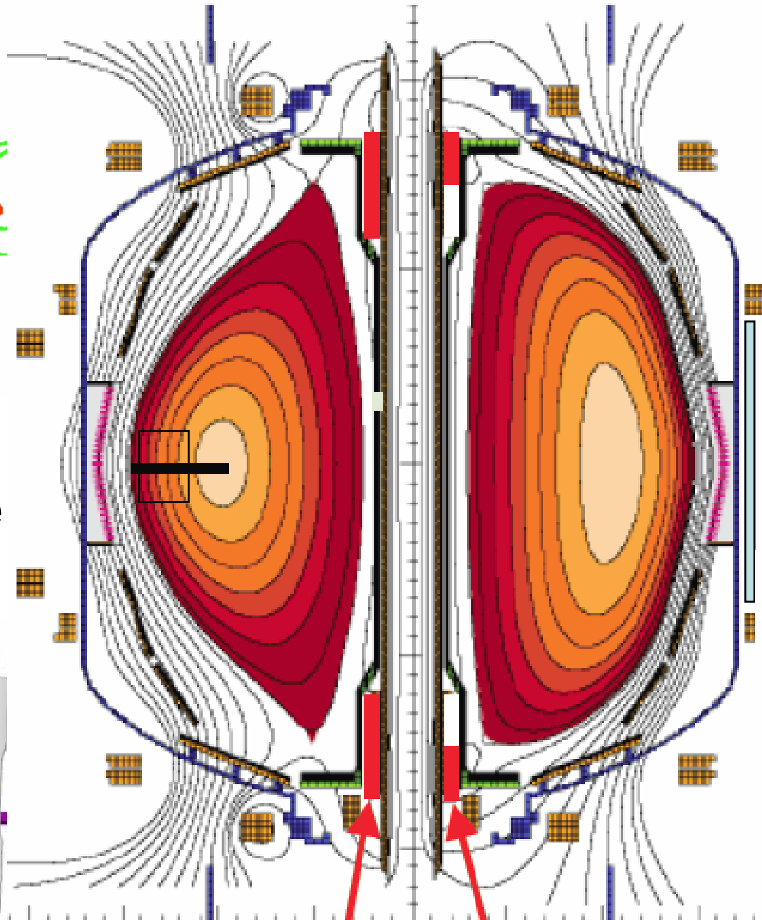


Tangential Microwave High-k Scattering



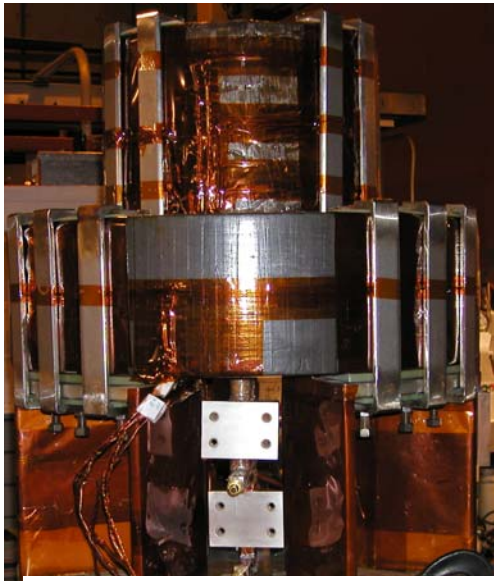
UCD

Achieved 2004 → Goal of 2005 114465

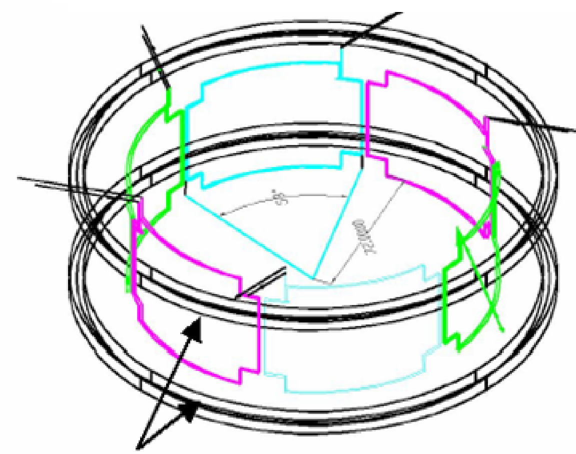


Old PF1A-L   New PF1A-L

New PF1A-L



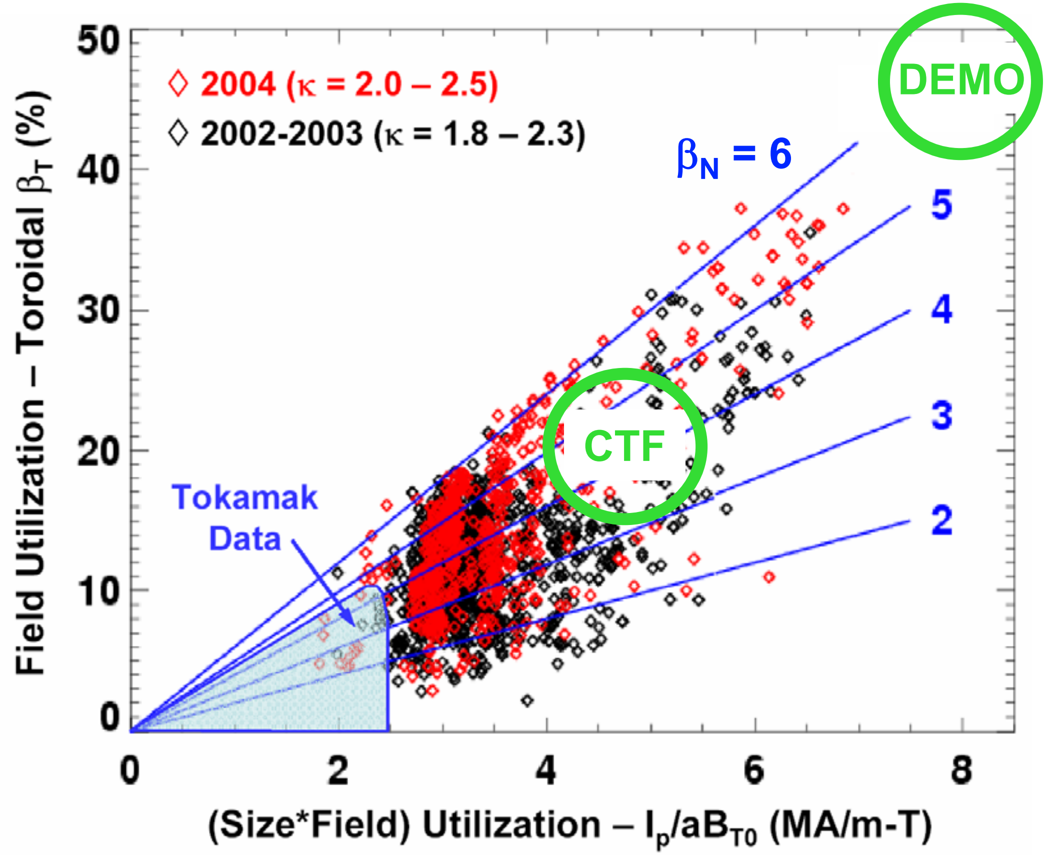
EF/RWM Coils



Columbia

NSTX Exceeded Standard Scaling & Reached Higher I_p/aB_T, Indicating Better Field and Size Utilization

CTF β requirement well within stability Limits, without using active control



Columbia U, LANL, PPPL

- **Verified very high beta prediction** ⇒ new physics:

  $\beta_T = 2\mu_0\langle p\rangle / B_{T0}^2 \leq 38\%$

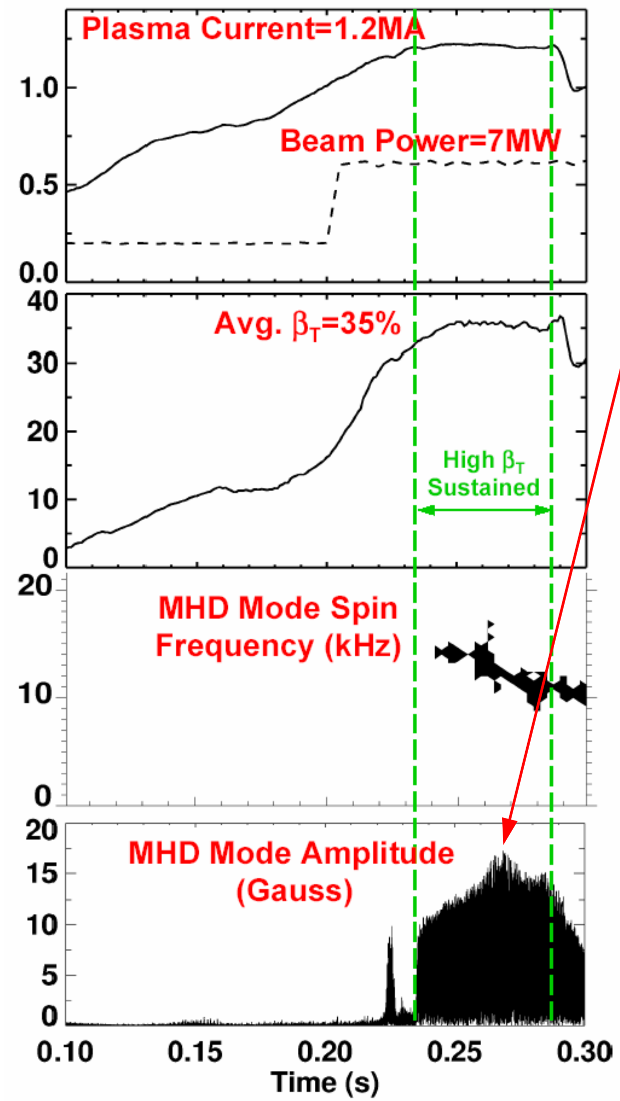
  $\beta_N = \beta_T / (I_p/aB_{T0}) \leq 6.4$

  $\langle\beta\rangle = 2\mu_0\langle p\rangle / \langle B^2\rangle \leq 20\%$

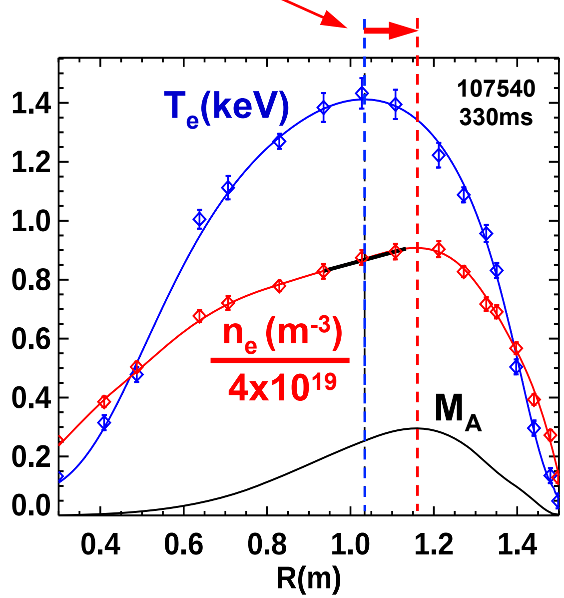
- Obtained nearly sustained plasmas with neutral beam and bootstrap current alone
  - Basis for neutral beam sustained ST **CTF** at Q~2
  - Relevant to **ITER** hybrid mode optimization
- To produce and study full non-inductive sustained plasmas
  - Relevant to **DEMO**

Strong Plasma Flow ($M_A=V_\phi/V_{Alfvén}$~0.3) Has Large Effects on Equilibrium and Stability

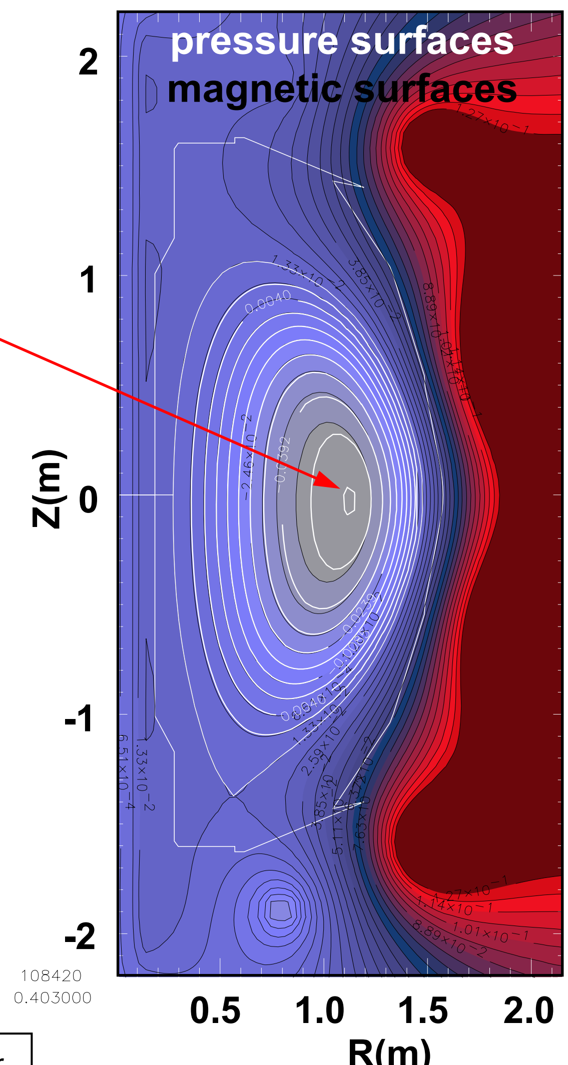
NSTX



- Internal MHD modes stops growing
- Pressure axis shifts out by ~10% of outer minor radius
- Density axis shifts by ~20%

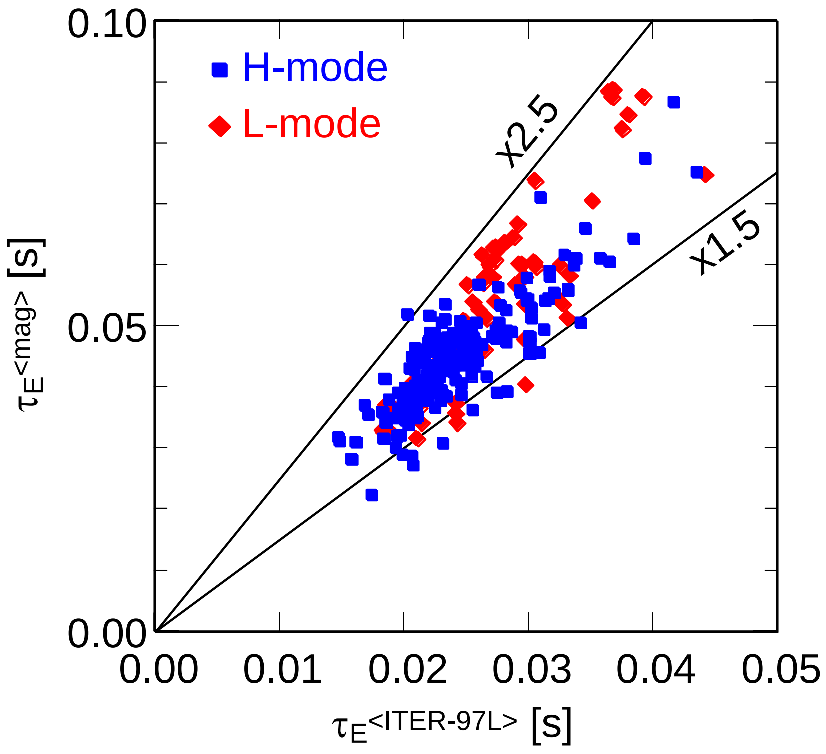


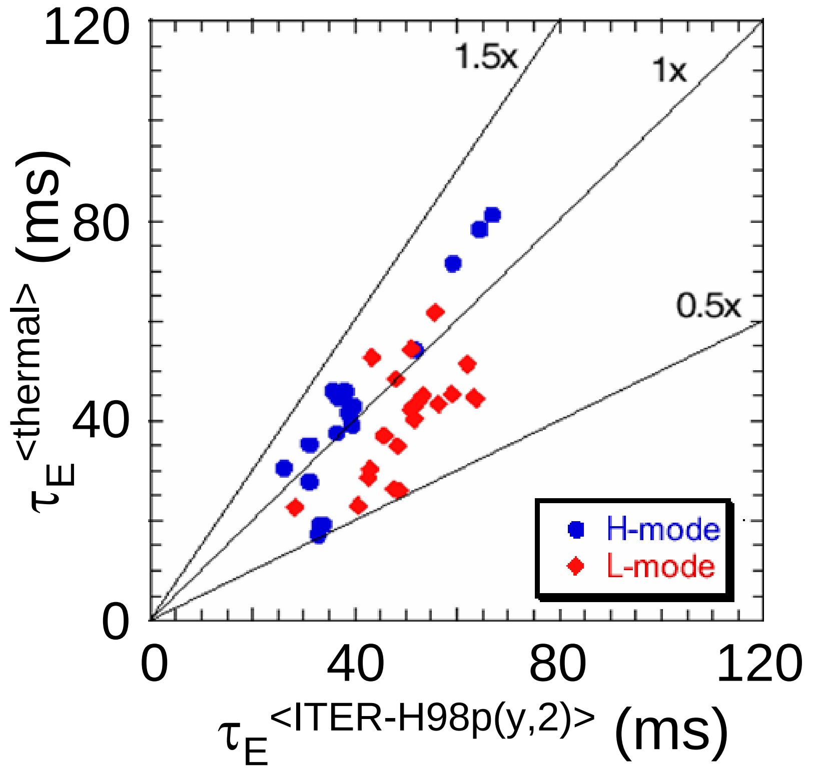
Equilibrium Reconstruction with Flow



Columbia U, GA, PPPL, U Rochester

Global and Thermal τ_E's Compare Favorably with Higher A Database



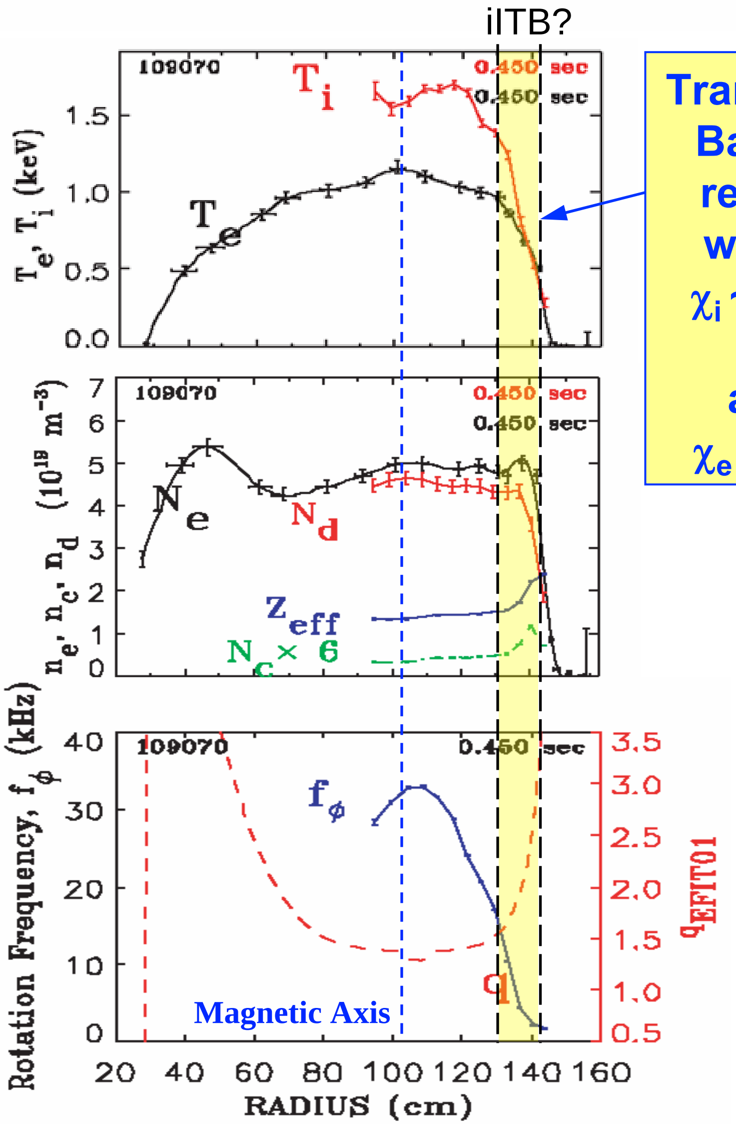


- Compare with ITER scaling for total confinement, including fast ions
- TRANSP analysis for thermal confinement

L-modes have higher non-thermal component and comparable τ_E! Why?

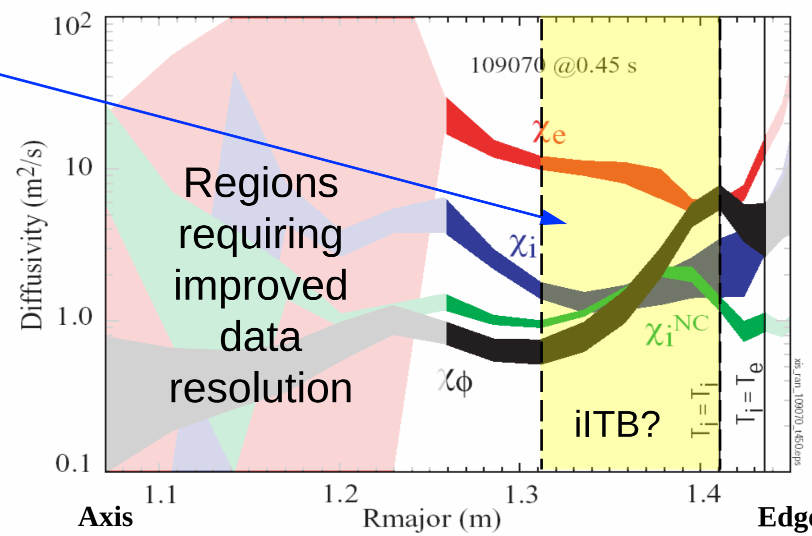
Bell, Kaye, PPPL

Ion Internal Transport Barrier in Beam-Heated H-Mode Contrasts Improved Electron Confinement in L-Mode

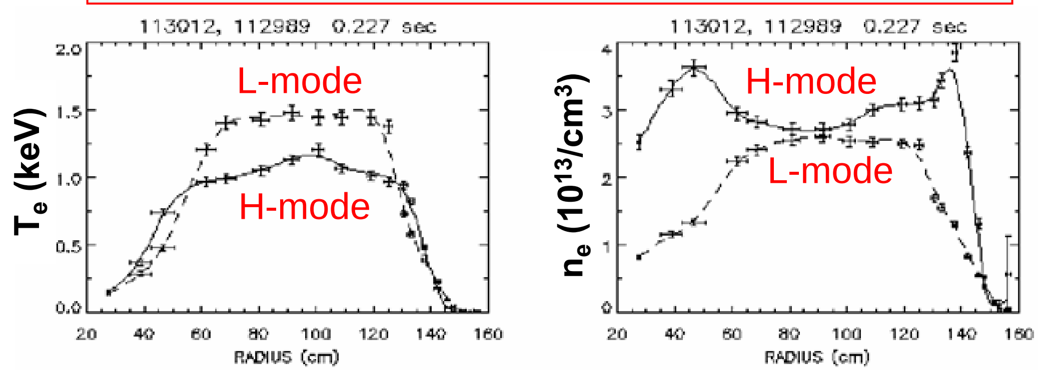


Transport Barrier region where $\chi_i \sim \chi_i^{NC}$ and $\chi_e >> \chi_i$

Kinetic Profile Local Error Sampling



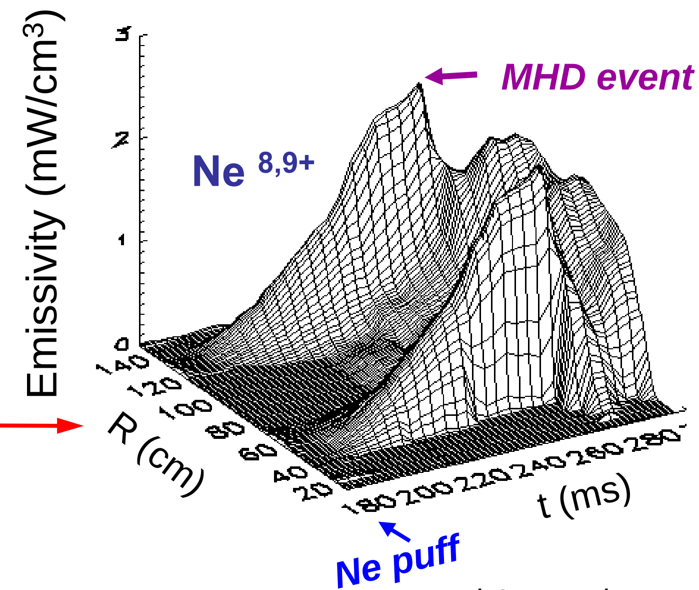
But L-mode plasmas show improved electron confinement! Why?

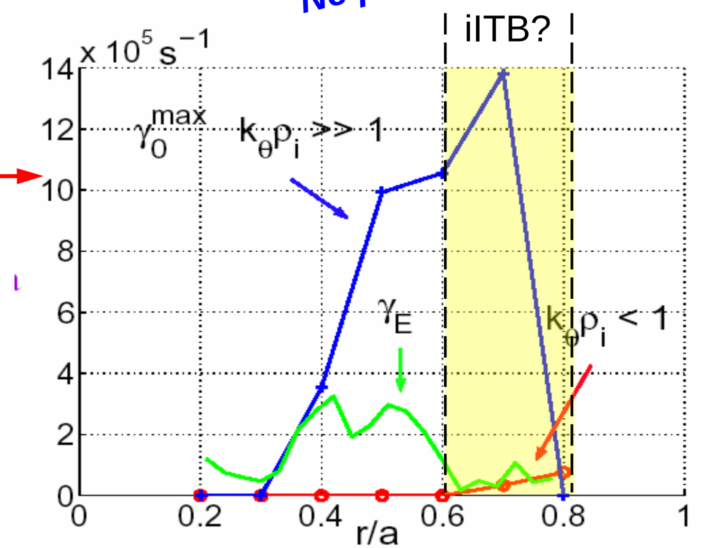


Columbia U, Culham, ORNL, PPPL

Analysis Shows Stability to Modes at Ion Gyro-Scale & Strong Instability at Electron Gyro-Scale (H-Mode)

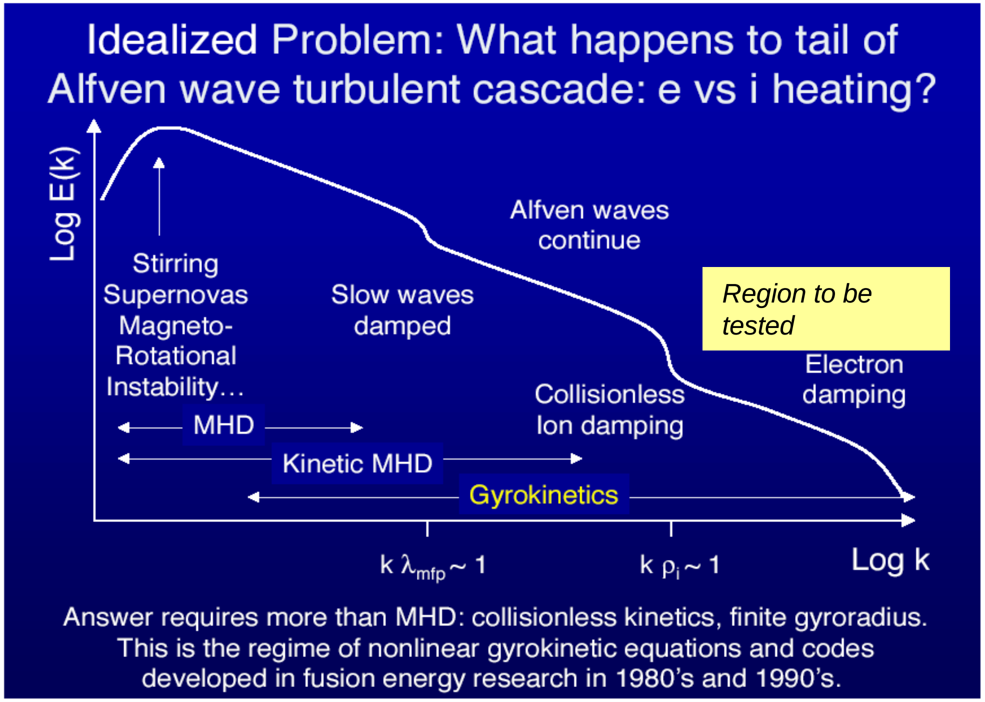
Core Transport Physics	In ion confinement zone
Thermal Conductivity	• $\chi_{ion} \sim \chi_{neoclassical}$ • $\chi_{elec} >> \chi_{ion}$
Impurity Diffusivity	• $D_{imp} \sim D_{neoclassical}$
Micro-instability calculations	• Driven by T and n gradients • $k_\theta \rho_i < 1$ (ion gyro-scale) stable or suppressed by V_ϕ shear • $k_\theta \rho_i >> 1$ (electron gyro-scale) strongly unstable





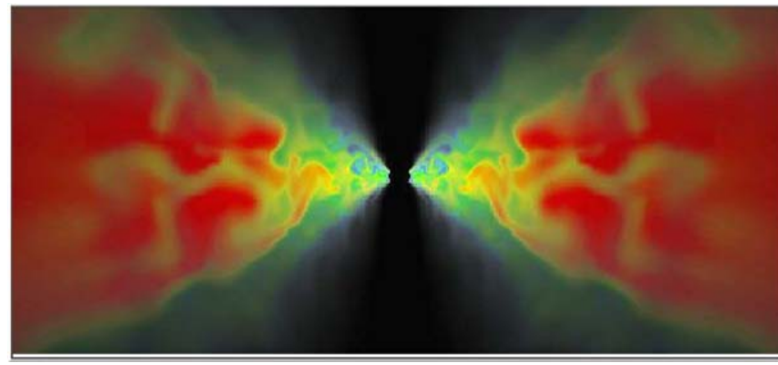
Cadarache, JHU, PPPL, U. Maryland

Detailed Diagnosis and Gyrokinetic Analysis of β ~ 1 Turbulence Has Broad Scientific Importance



Can $k_\perp \rho_i \geq 1$ turbulence at β ~ 1 be understood?

Armitage (U. Colorado)

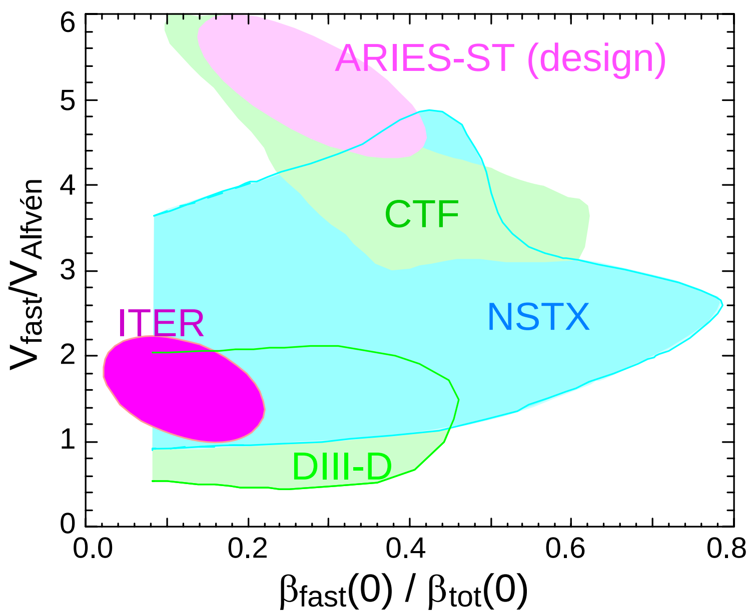


Gyrokinetic turbulence simulation in accretion disk of supermassive black hole at galactic center, assuming damping of turbulence by plasma ions vs. electrons

- Astrophysics turbulence dynamics: cascading of MHD turbulence to ion scales is of fundamental importance at $\beta > 1$
- Fusion's gyrokinetic formalism apply to astrophysical turbulence, covering shocks, solar wind, accretion disks
- Laboratory ST plasmas provide validation of formulism

Kinetic instabilities are an important issue for Spherical Tori and ITER

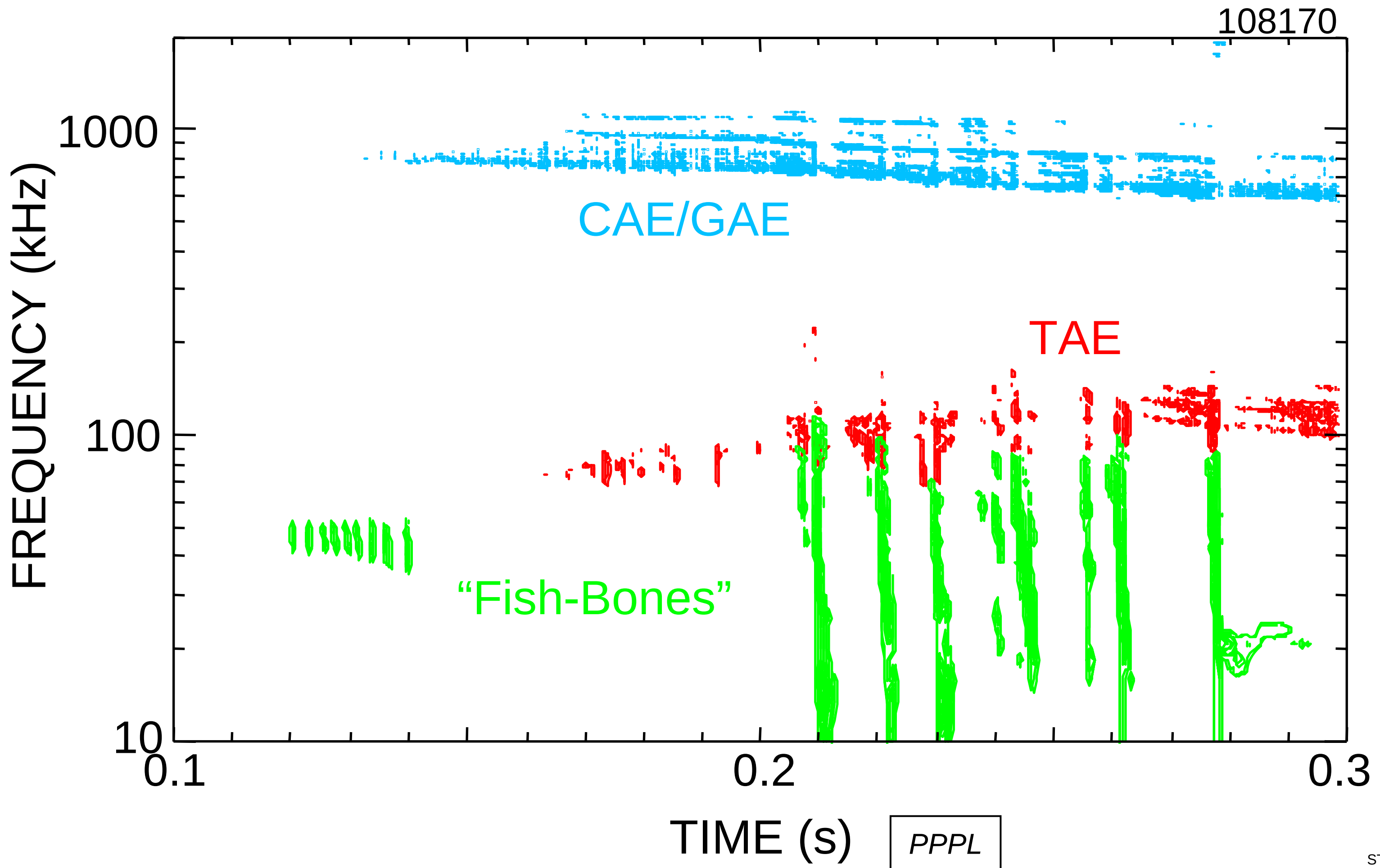
- Energetic particle modes are most ubiquitous, cause most losses
  - Chirping, lower frequency
  - Better overlap precession, bounce and MHD frequencies at low A.
- Toroidal Alfvén Eigenmodes common
  - Fewer induced losses
  - more important at high A



- Compressional Alfvén Eigenmodes and Global Alfvén Eigenmodes are common, but apparently benign.
- Development of M3D,HYM,NOVA codes for prediction/analysis.

A Broad Spectrum of Energetic Particle Driven Modes is Seen on NSTX

Do these Alfvén Eigenmodes (AEs) and fish-bones (f.b.s) Interact to expel energetic particles?

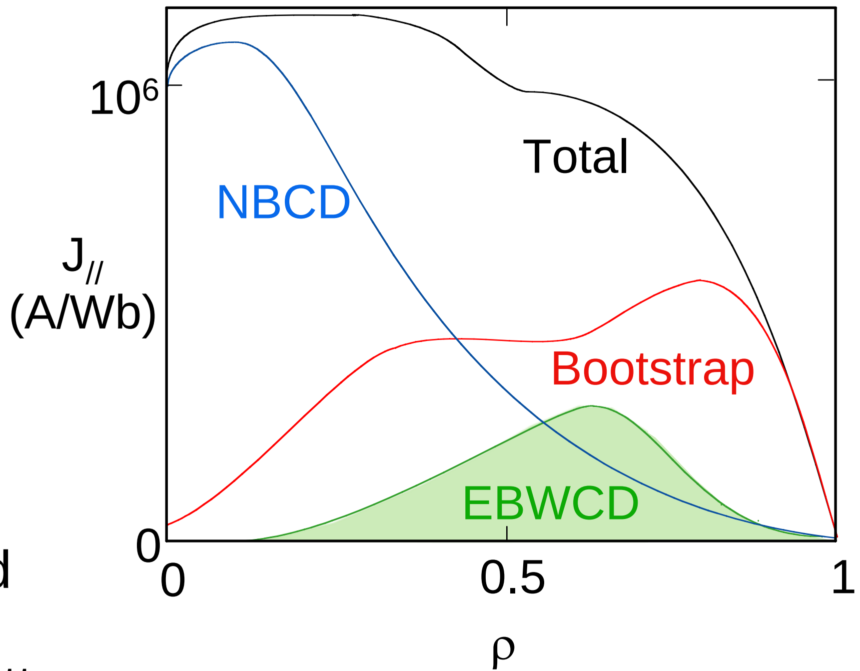


EBW Heating & CD Applied to ST Plasmas Present Unique Opportunities for Scientific & Fusion Energy Research

NSTX

- Off-axis EBWCD may be critical for sustained, solenoid-free, high β ST operation
- Local EBWCD may provide an effective tool for tearing mode stabilization
- EBWCD & heating can assist plasma current startup & ramp-up
- NSTX provides an excellent testbed for evaluating EBW coupling, heating and CD physics at megawatt rf power levels

NSTX, β_t = 42%, β_{pol} = 1.6
B_t = 0.34 T , I_p = 1 MA

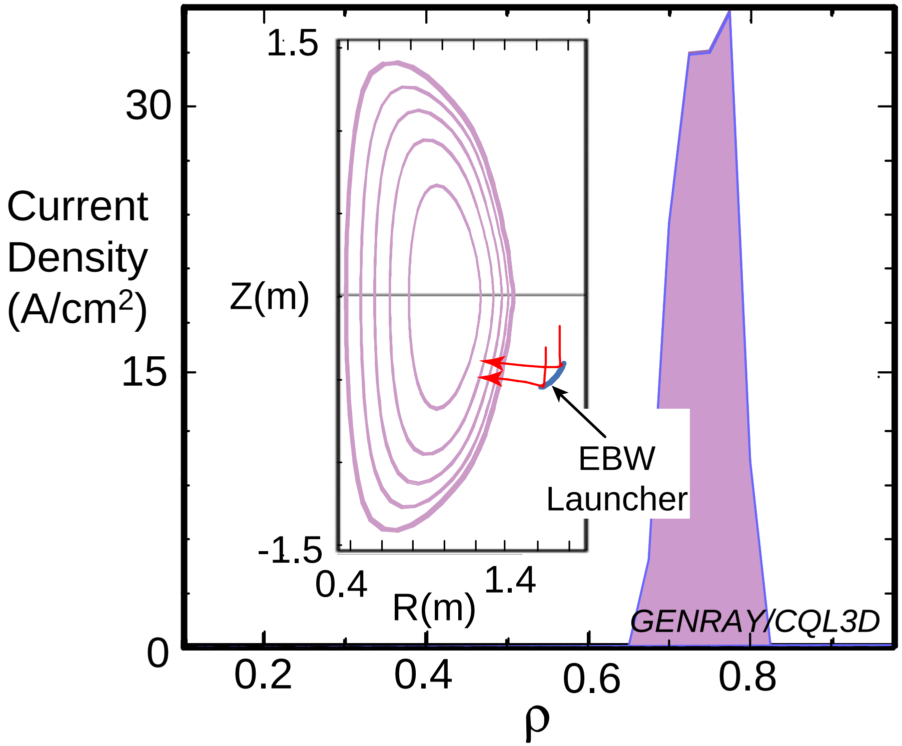


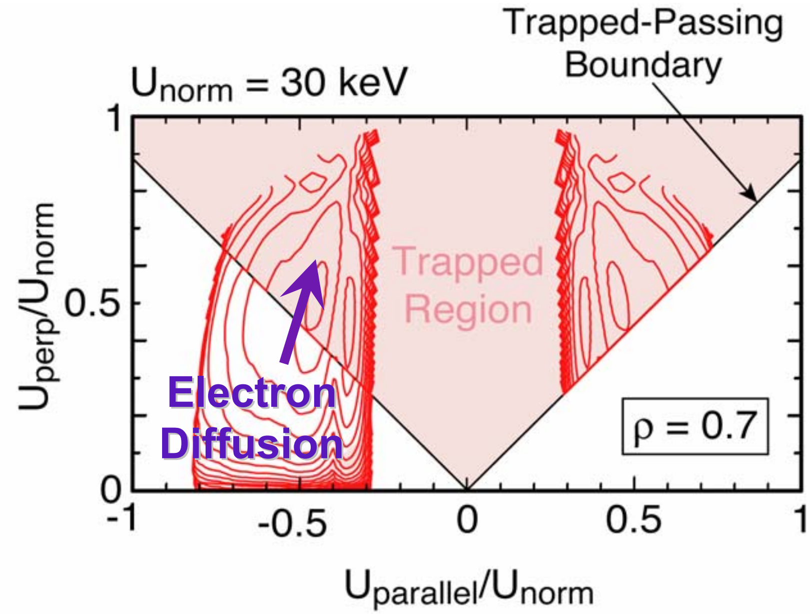
Charles Kessel (*PPPL*)
Tokamak Simulation Code

Modeling Predicts Efficient Local Electron Heating & Off-Axis Ohkawa EBWCD in β ~ 40% NSTX Plasmas

β = 41%

Frequency = 28 GHz
EBW Power = 3 MW
Total Driven Current = 135 kA

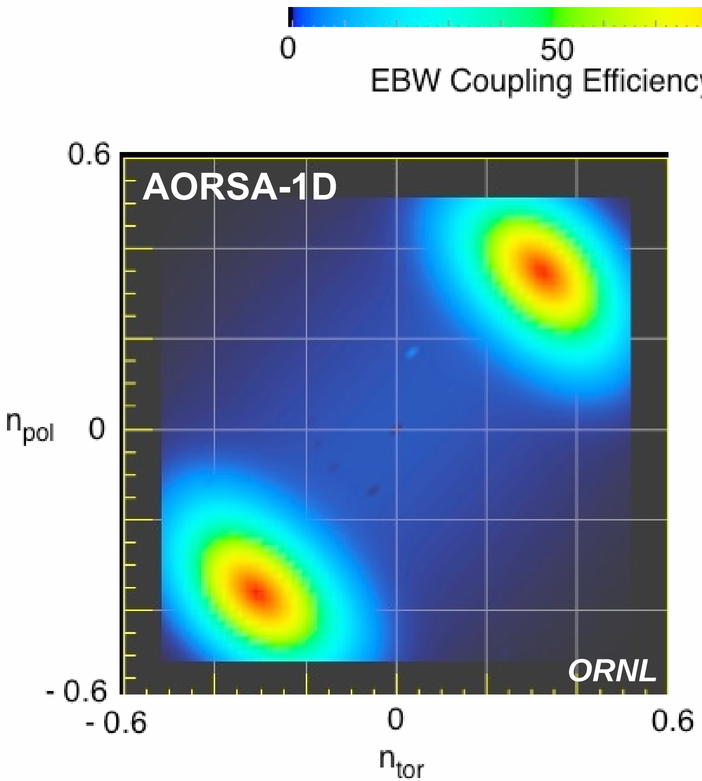


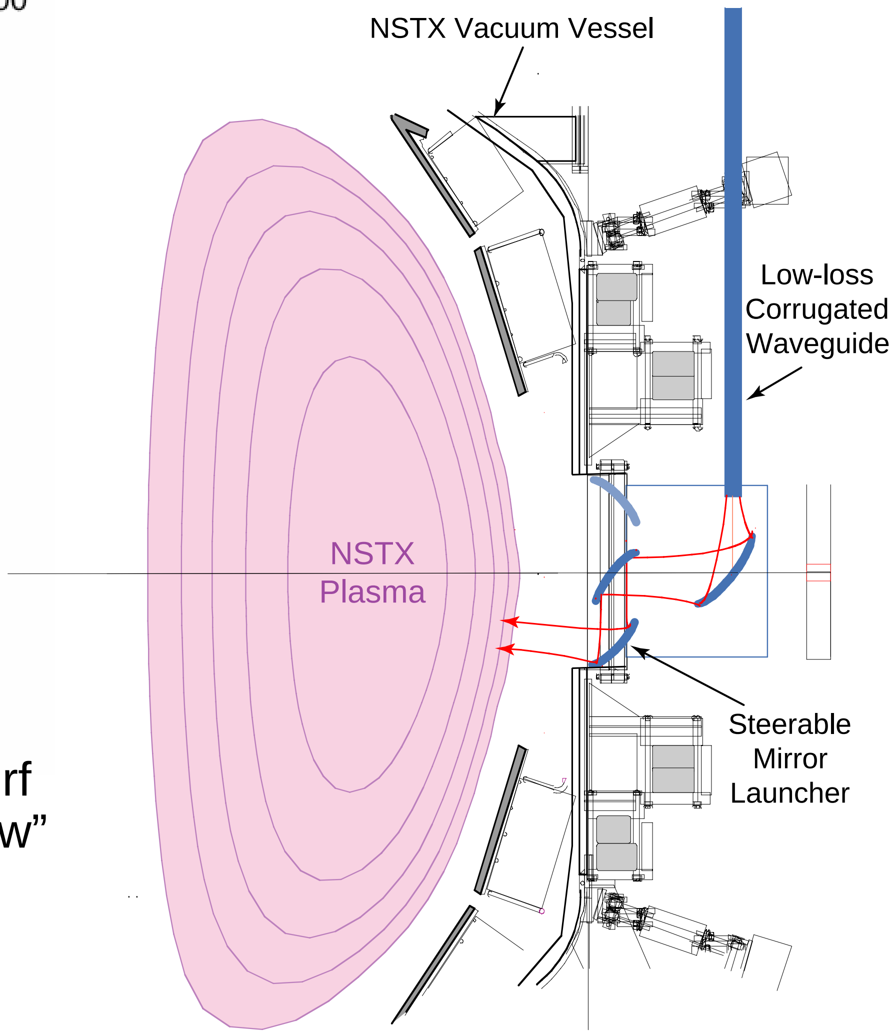


- Strong diffusion near trapped-passing boundary enables efficient Ohkawa EBWCD
- EBWCD-Bootstrap current synergy may provide ~10% enhancement

G. Taylor, *et al*., *Phys. Plasmas* **11**, 4733 (2004)
R.W. Harvey & G. Taylor, to be published in *Phys. Plasmas* **12** (May 2005)

Full Wave Coupling Code Predicts Efficient O-X-B Coupling at ~ 28 GHz into β = 40% NSTX Plasma

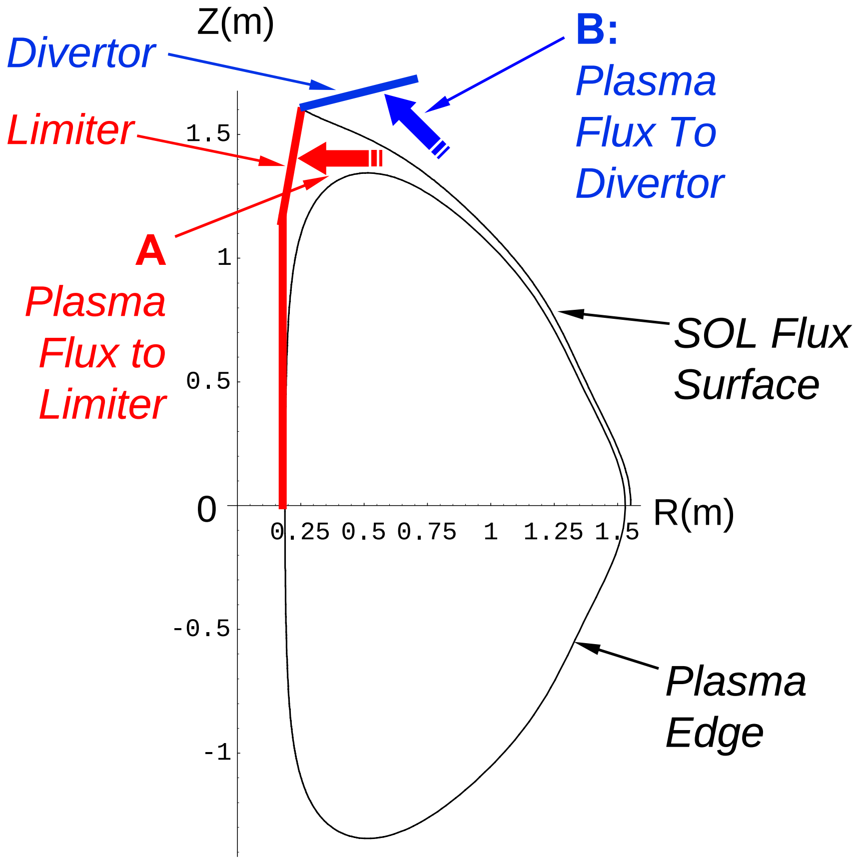


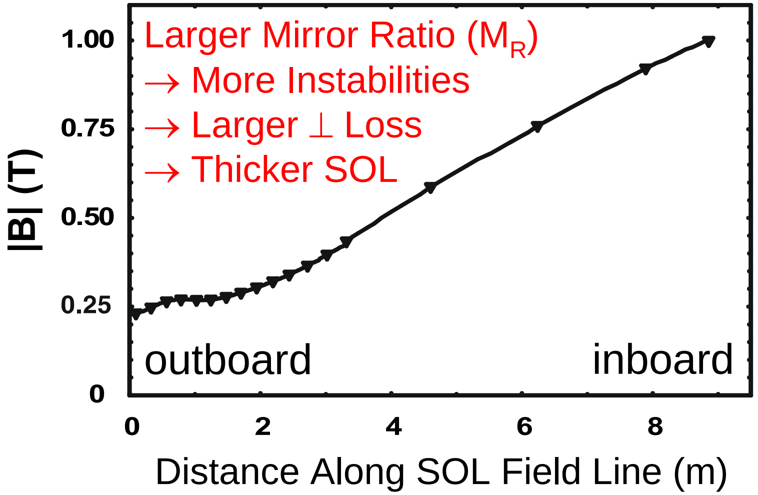


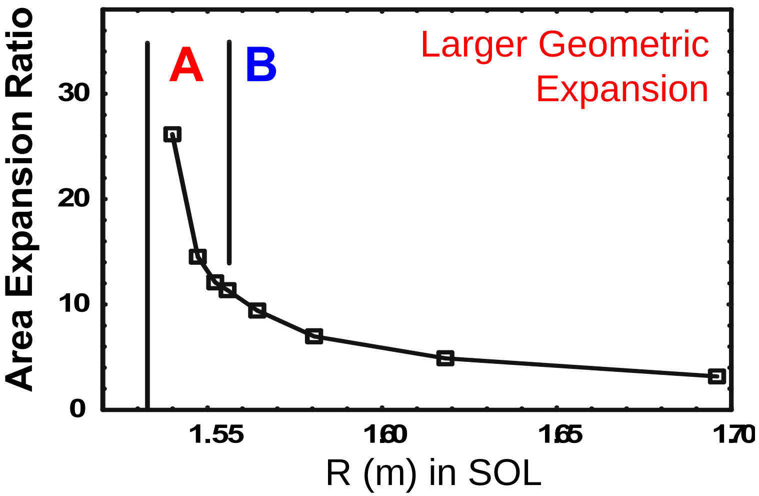
- Steerable mirror launcher aligns 1 MW rf power with high O-X-B coupling "window" (Two launchers for 2 MW)
- Switching between mirrors above and below midplane changes direction of EBW-driven current

ST Plasma Edge Possesses Large Mirror Ratio & Geometric Expansion of Scrape-Off Layer (SOL)

Scrape-Off Layer Geometry of Inboard Limited ST Plasma







Increased SOL Mirror Ratio (M_R) ⇒ Increased Footprint & Decreased Peak of Divertor Heat Flux

Factor of ~2 in R_{div} and M_R

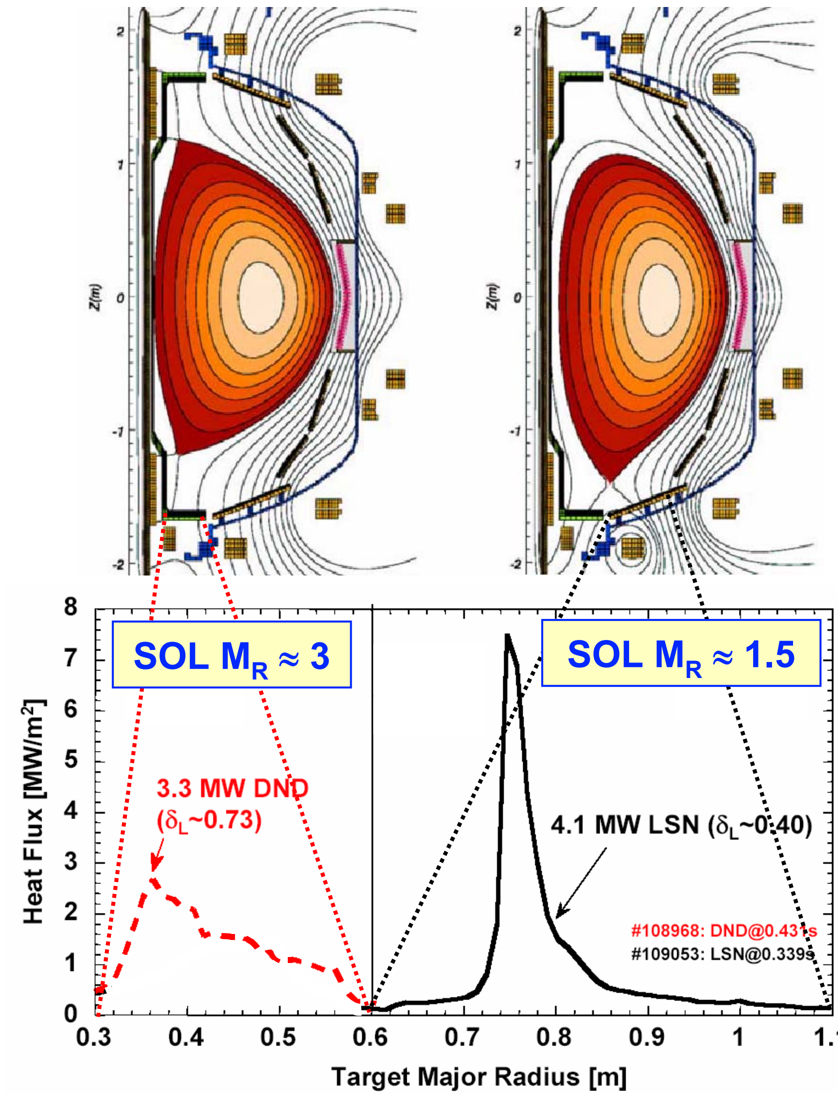
⇓

Factor of ~3 in Δ_{div}

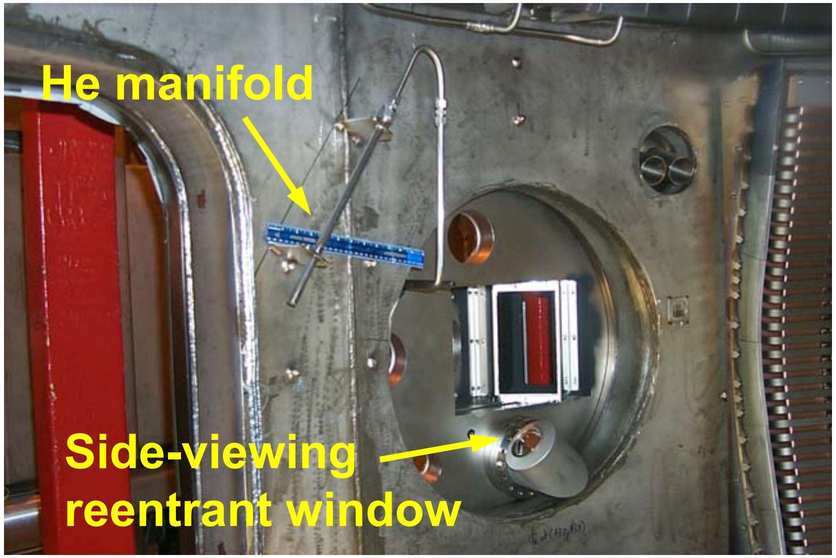
Why?

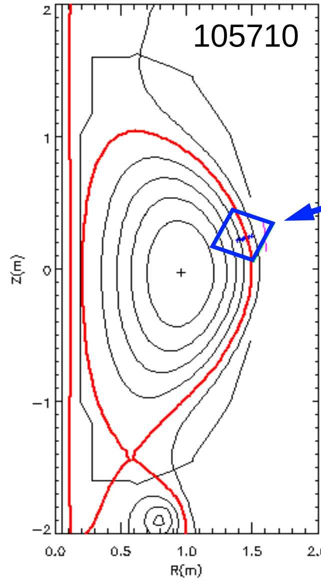
High & Low δ Divertor Bolometer Measurements

R_{div} (m)	0.36	0.75
SOL M_R	~ 3	~ 1.5
Δ_{div} (m)	~ 0.3	~ 0.12

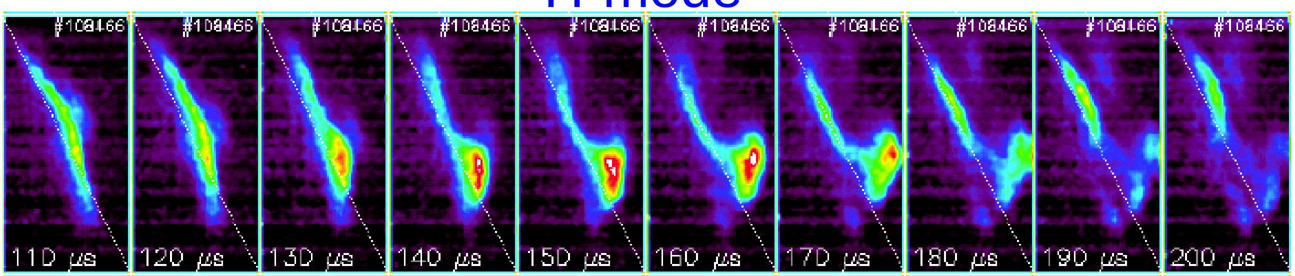


Plasma Edge Studies Reveal Turbulence and "Blobs" Important to Divertor Flux Scaling Studies

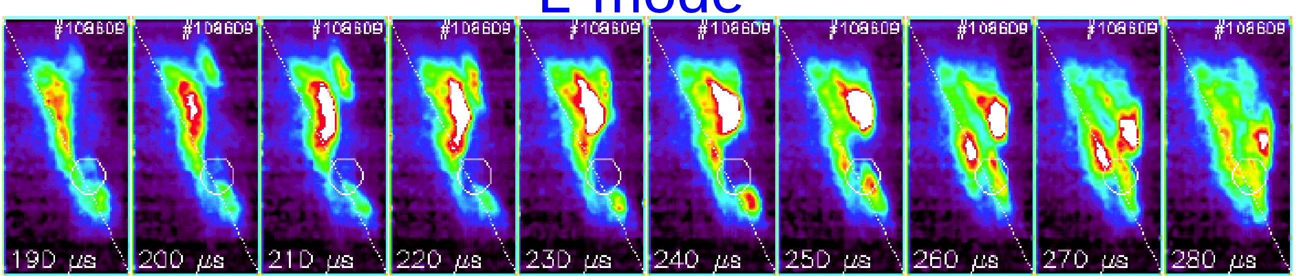




H-mode



L-mode

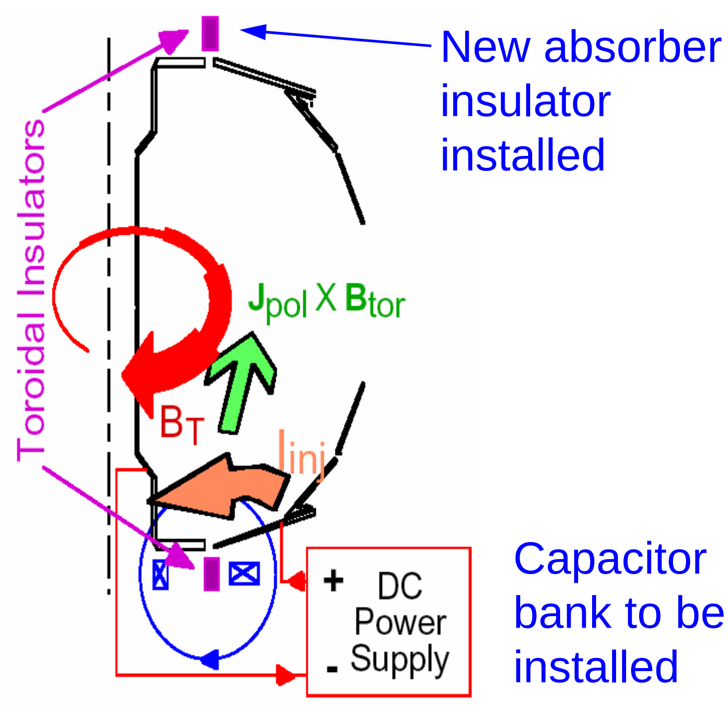


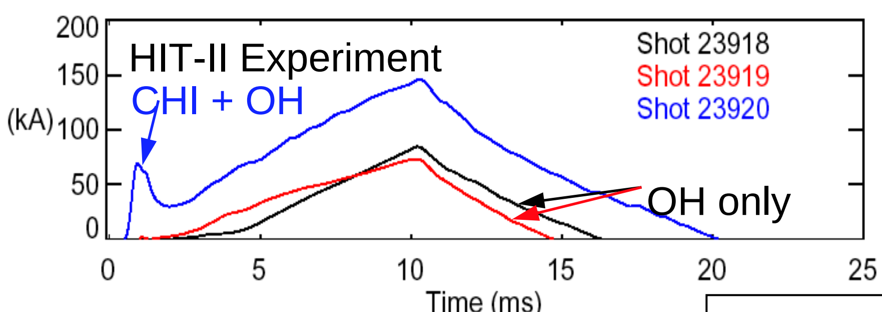
Broadly Based Study:

- **Gas Puff Imaging** views along field lines (PPPL, LANL)
- Very fast camera, 10^5/s (PSI)
- Reflectometers and edge (UCLA, ORNL)
- Reciprocating probe (UCSD)
- Divertor fast camera (Hiroshima U)
- IR Cameras (ORNL), Filterscope (PPPL)
- Modeling (PPPL, UCSD, LLNL, Lodestar)

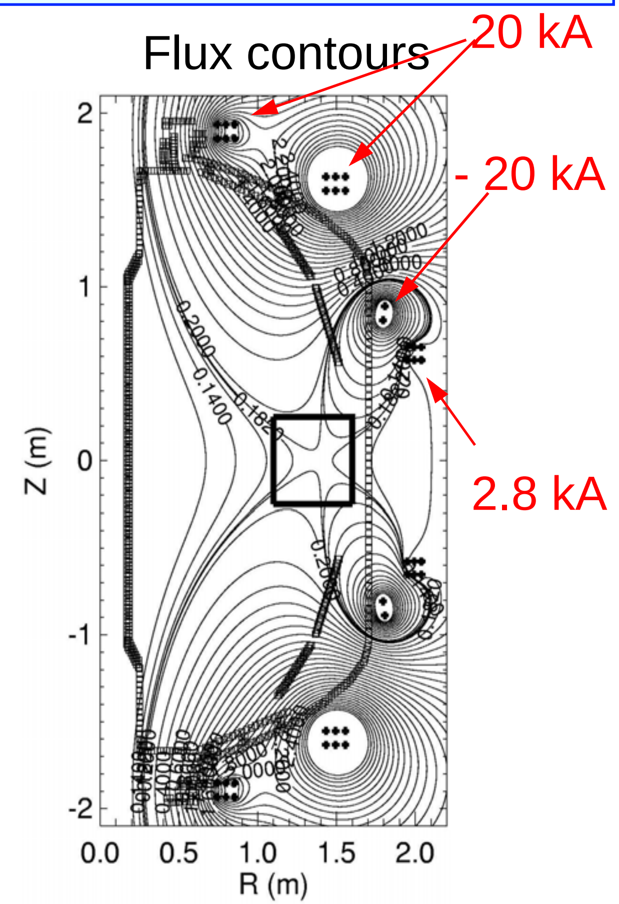
Solenoid Free Start-Up via Coaxial Helicity Injection & Outer Poloidal Field Coil Are Being Tested

Coaxial Helicity Injection Tests



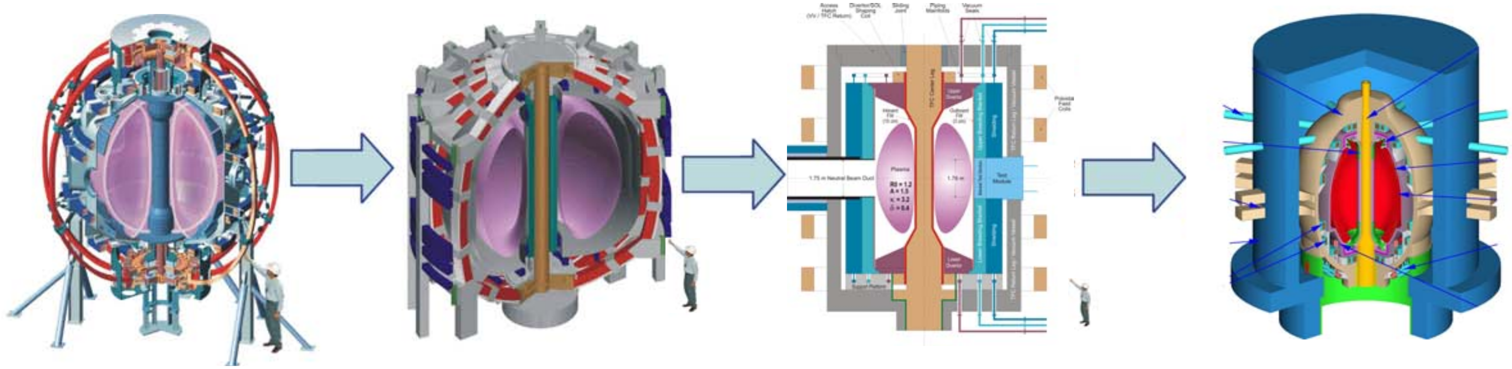


Three Outer Poloidal Field Startup Scenarios, e.g.: Outboard Field Null



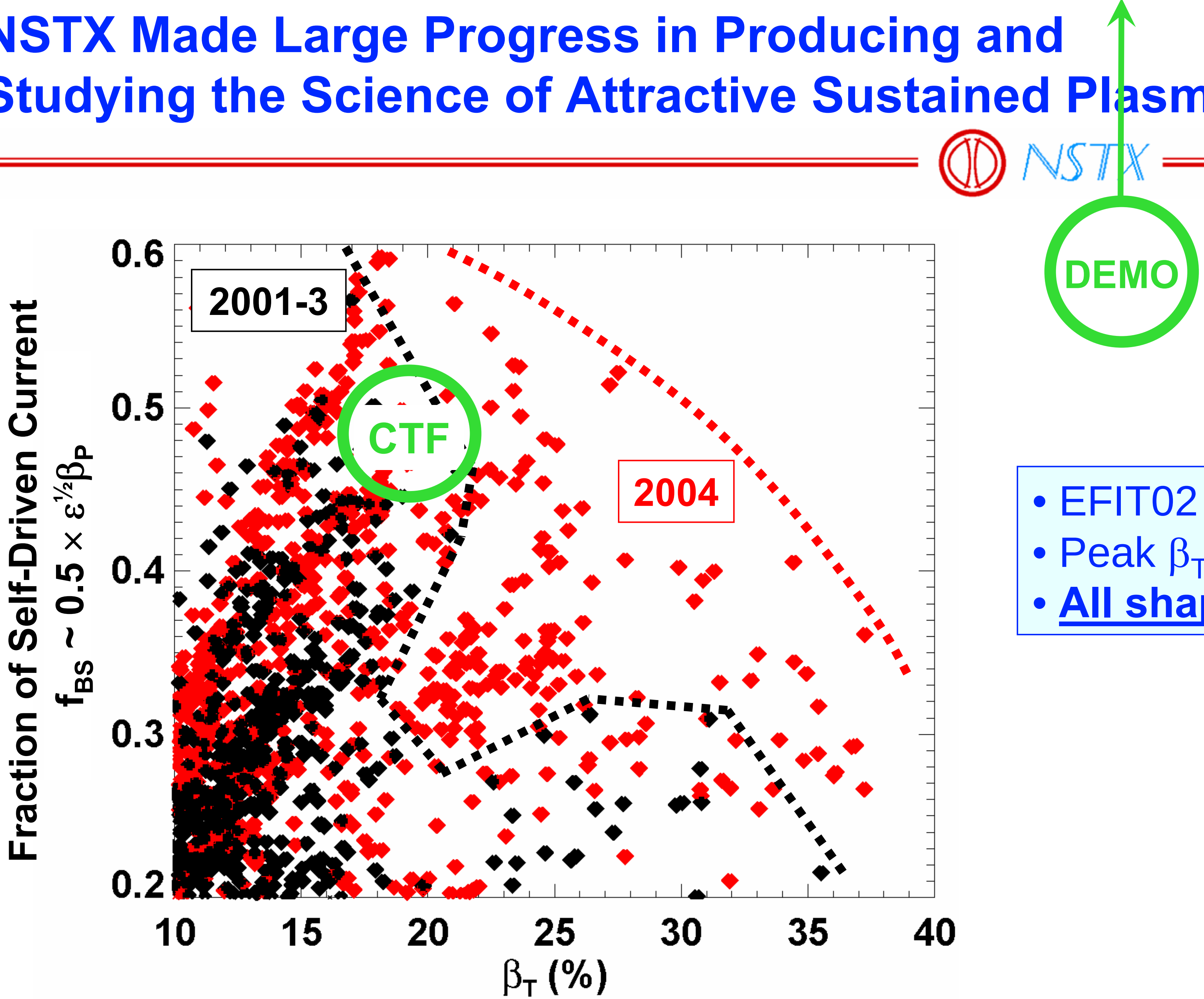
Culham, KAIST, Kyushu-Tokai U, PPPL, U Tokyo, U Washington

Future ST Steps Are Estimated to Require Moderate Sizes to Make Key Advances toward DEMO



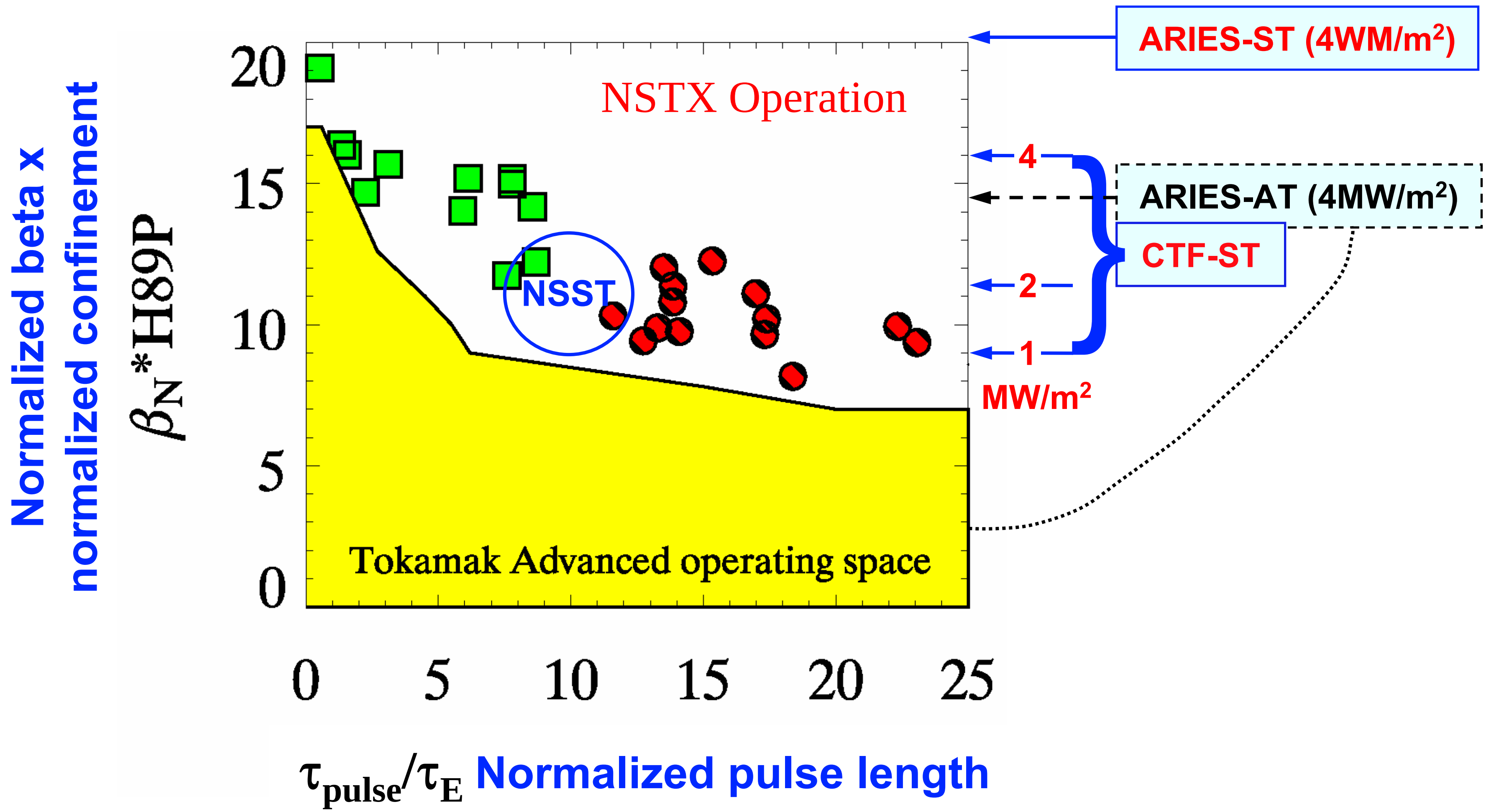
Device	NSTX		NSST		CTF		DEMO
Mission	Proof of Principle		Performance Extension		Energy Development, Component Testing		Practicality of Fusion Electricity
R (m)	0.85		**~1.5**		**~1.2**		~3
a (m)	0.65		~0.9		~0.8		~2
κ, δ	2.5, 0.8		~2.7, ~0.7		~3, ~0.5		~3.2, ~0.5
I_p (MA)	**1.5**	**1**	**~5**	**~10**	~9	~12	~25
B_T (T)	**0.6**	**0.3**	**~1.1**	**~2.6**	~2.1		~1.8
Pulse (s)	**1**	**5**	**~50**	**~5**	**Steady state**		Steady state
P_{fusion} (MW)	–		**~10**	**~50**	**~77**	**~300**	~3100
W_L (MW/m^2)	–		–		**~1**	**~4**	~4
Duty factor (%)	~0.01		~0.01		**~15**	**30**	60
TFC; Solenoid	Multi-turn; Solenoid		Multi-turn; Solenoid		Single-turn; No-solen.		Single-turn; No-solen.

NSTX Made Large Progress in Producing and Studying the Science of Attractive Sustained Plasmas



- EFIT02
- Peak β_T
- **All shapes**

Long-Pulse H-Mode Plasmas Made Large Progress in Physics Basis for Next-Term ST Science Facilities



Well positioned to address the science of sustained high-performance plasmas.

Spherical Tokamak (ST) Offers Rich Plasma Science Opportunities and High Fusion Energy Potential

- Early MHD theory suggested ST could permit high β, confirmed recently by experiments
- ST research is highly collaborative worldwide
- ST enables cost-effective steps toward practical fusion energy
- Recent research identified new opportunities for addressing key plasma science issues using ST
  - Results have been very encouraging in many scientific topical areas

We welcome opportunities to answer questions, more show and tell