Supported by

Spherical Tokamak Plasma Science & Fusion Energy Development

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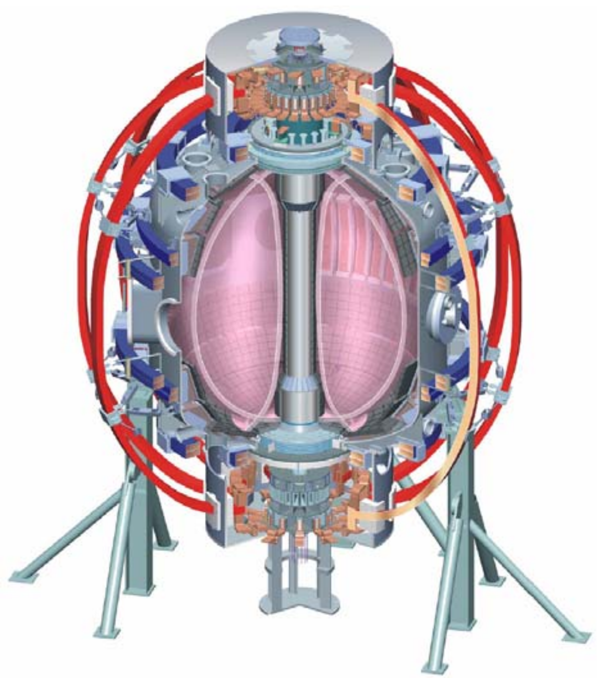
@ Princeton Plasma Physics Laboratory



Joint Spherical Torus Workshop and US-Japan Exchange Meetings (STW2004)

29th September – 1st October, 2004
Kyoto University
Yoshida-Honmachi, Kyoto, Japan

Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
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Nova Photonics
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Niigata U
Tsukuba U
U Tokyo
JAERI
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

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

- What is ST and why?
- 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?
- Contributions to burning plasmas and ITER
- Cost-effective steps to fusion energy
- Collaboration

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:

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

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

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

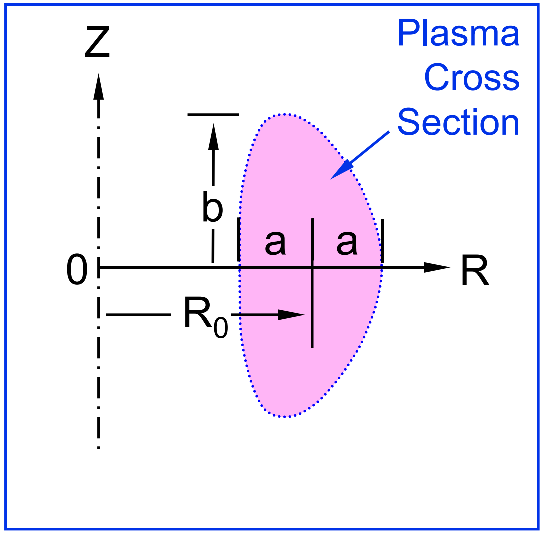
κ = b/a = elongation

A = R_0/a = aspect ratio

$q_l \approx$ average safety factor

I_p = toroidal plasma current

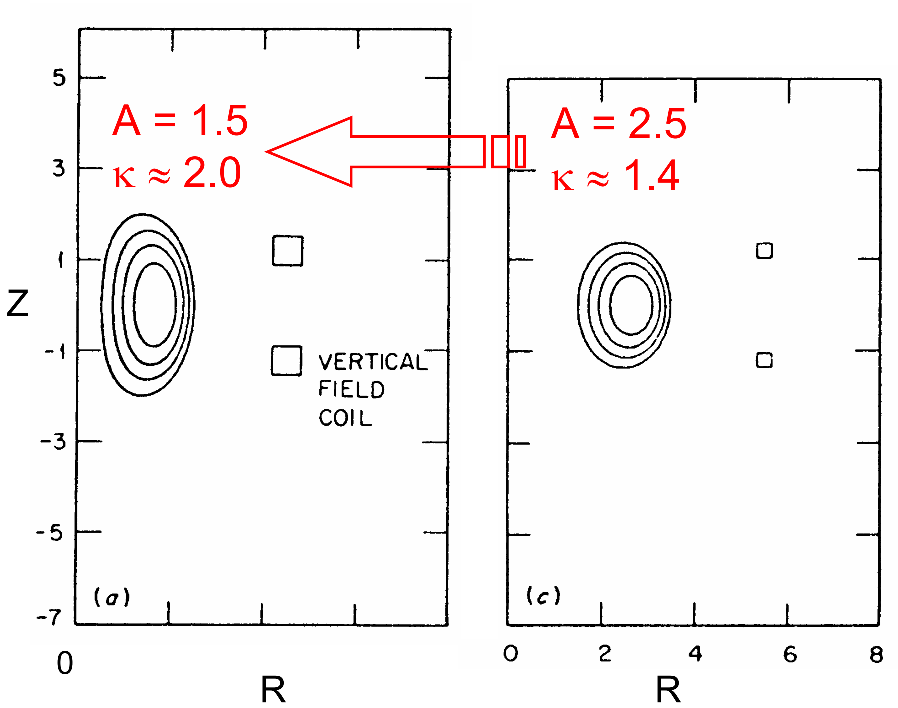
$B_T \approx$ applied toroidal field at R_0



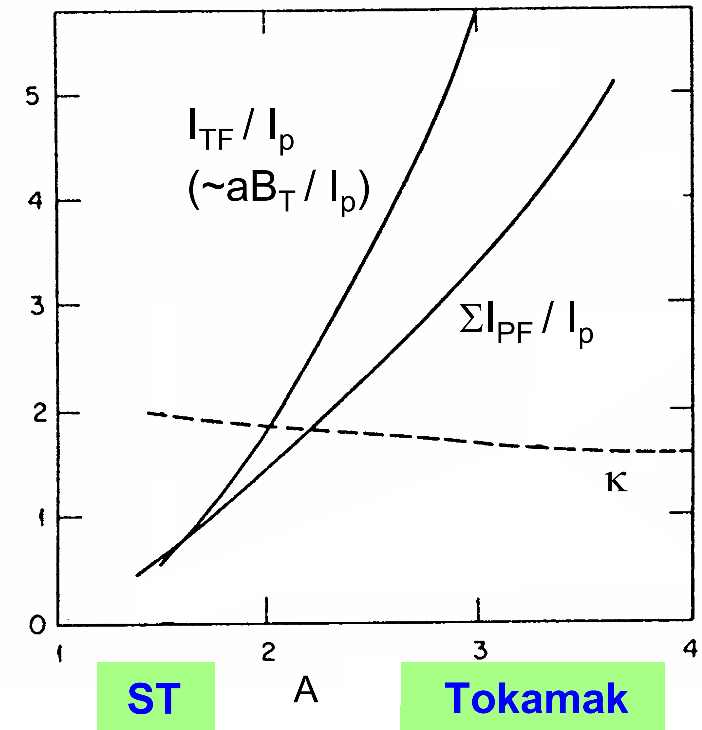
- Peng & Strickler (1986): **What would happen to tokamak as A $\to$ 1?**
  - How would β_N, κ, q_j, change as functions of **A**?

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?

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 ($\varepsilon = \omega_{pe}^2/\omega_{ce}^2 \sim 50$)

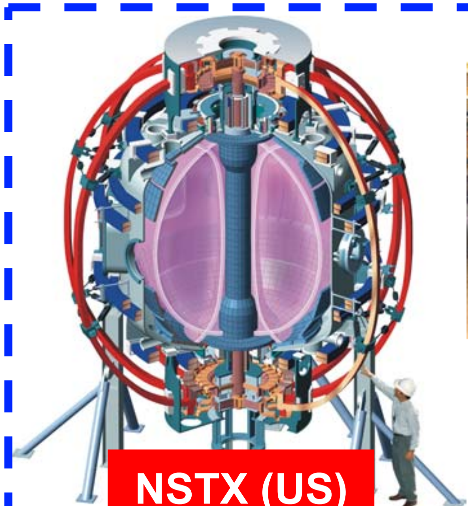
How do plasmas interact with walls?
- Large mirror ratio in edge B field ($f_T \rightarrow 1$)
- Strong field line expansion

How to supply mag flux without solenoid?
- Small magnetic flux content ($\sim \ell_i R_0 I_p$)

ST Research Is Growing Worldwide

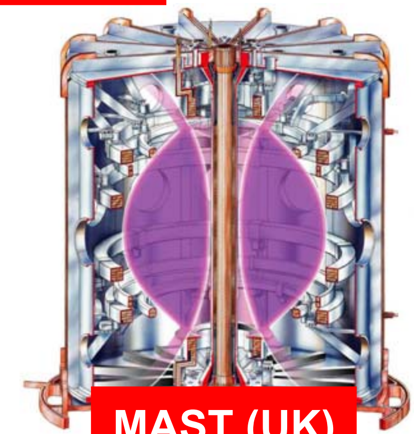
Concept Exploration (~0.3 MA)

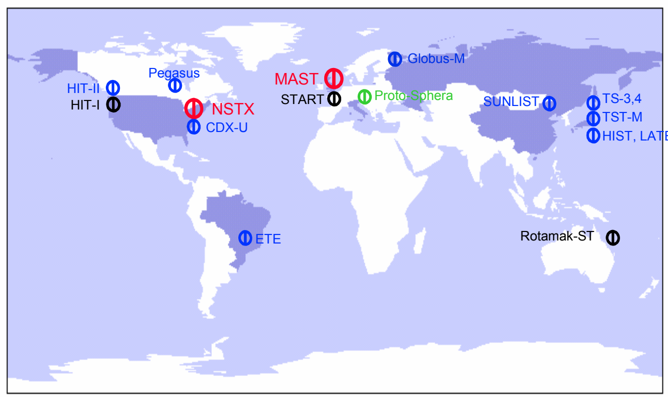
Proof of Principle (~MA)


NSTX (US)


HIT-II (US)

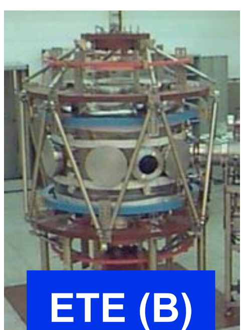

Pegasus (US)


MAST (UK)

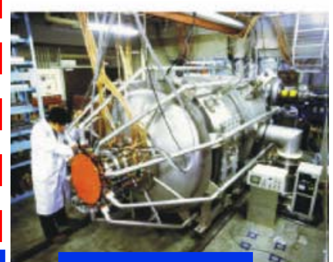



Globus-M (RF)

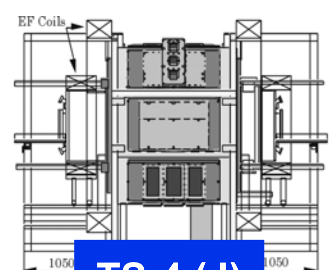

CDX-U (US)


ETE (B)

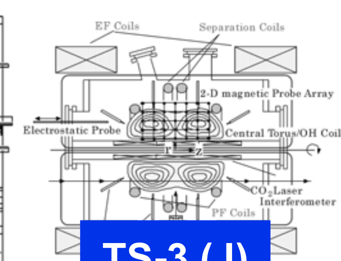

SUNIST (PRC)


HIST (J)


TST-2 (J)



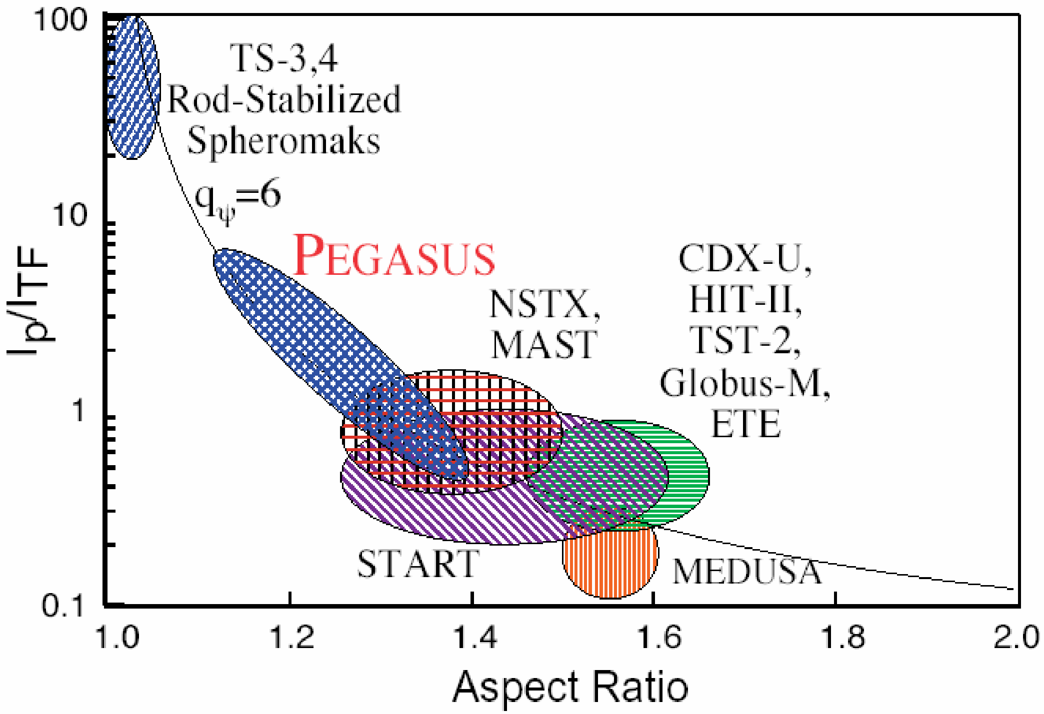
TS-4 (J)



TS-3 (J)

Pegasus Explores ST Regimes As Aspect Ratio → 1

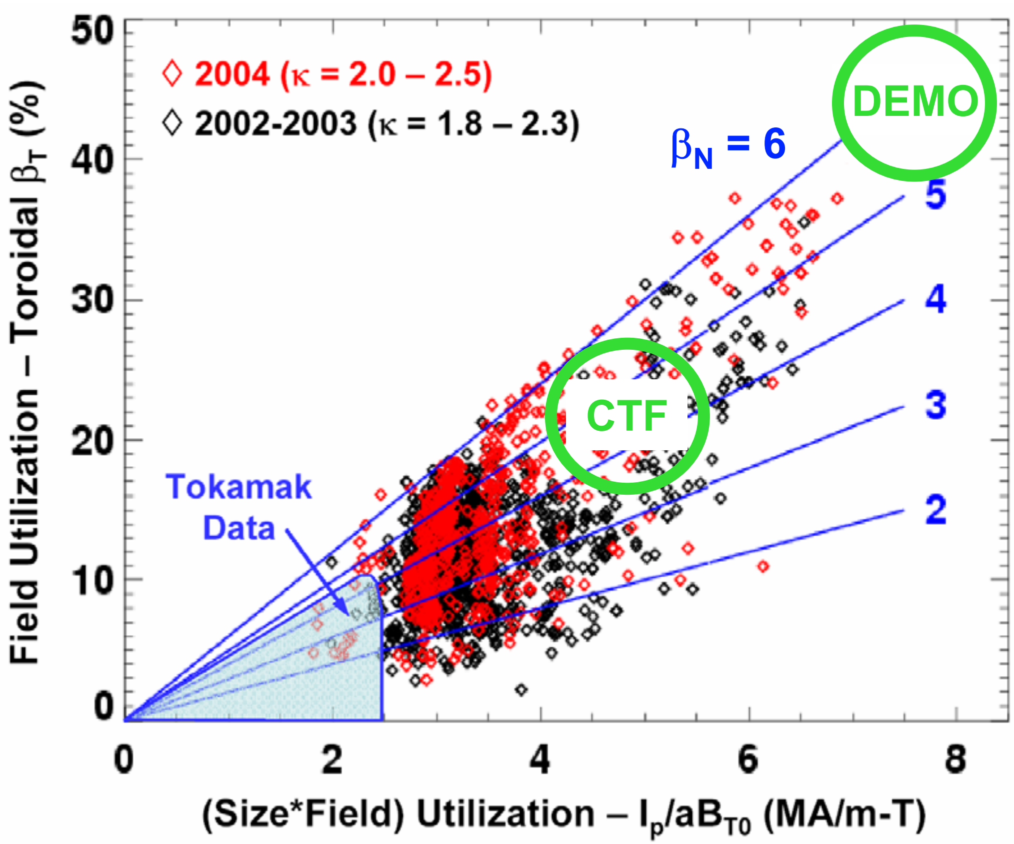
- Stability and confinement at high I_p/I_{tf}
- Limits on β_t and I_p/I_{tf} as $A \rightarrow 1$



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

NSTX

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



Columbia U, LANL, PPPL

- **Verified very high beta prediction** $\Rightarrow$ new physics:

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

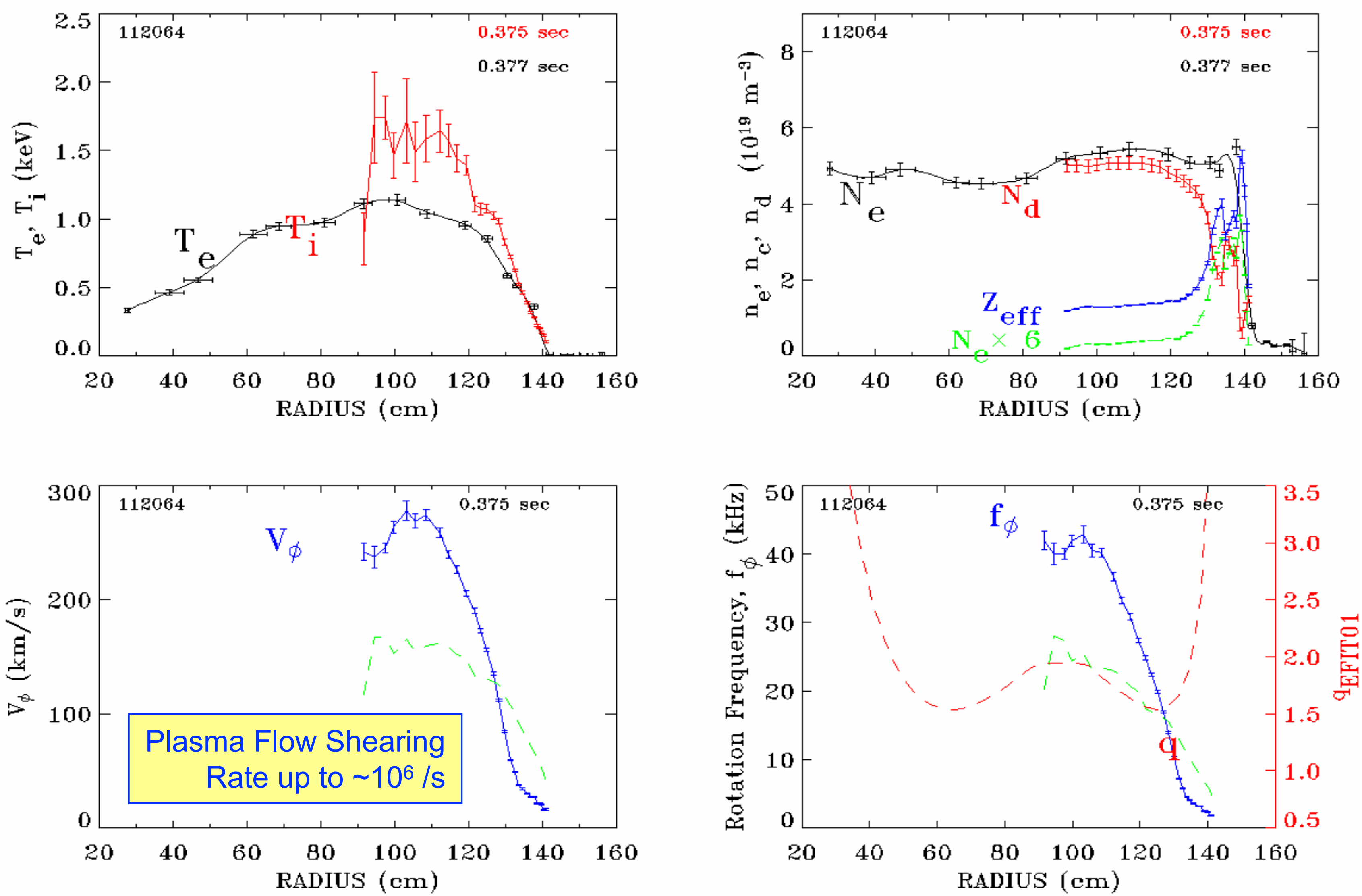
  $\beta_N = \beta_T / (I_p/aB_{T0}) \leq 6.4$

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

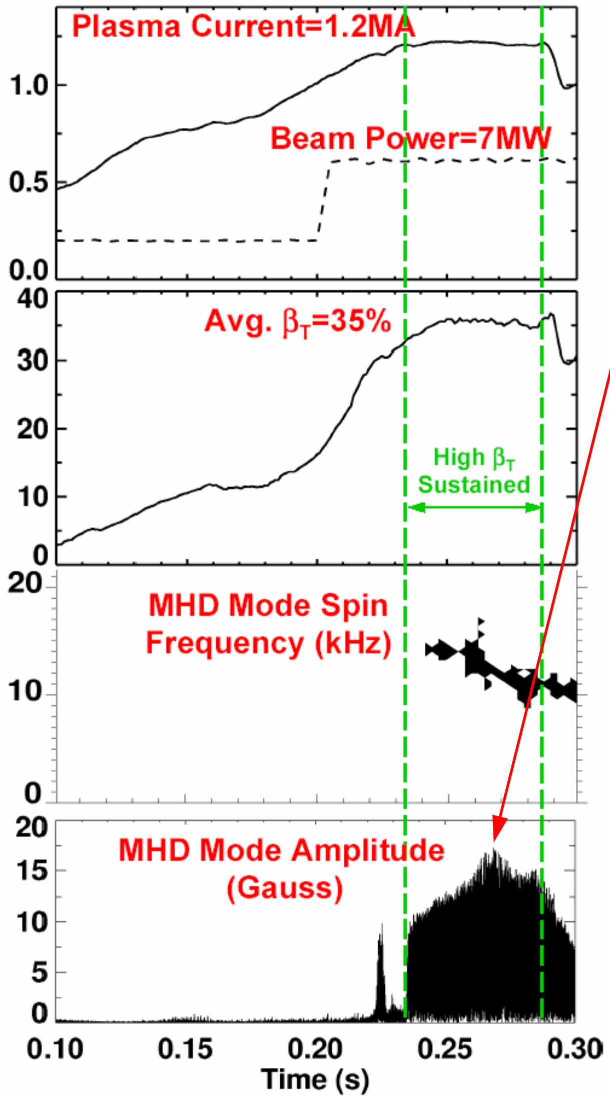
- Obtained nearly sustained plasmas with neutral beam and bootstrap current alone
  - Basis for neutral beam sustained ST **CTF** at Q~2
  - Relevant to **ITER** hybrid mode optimization
- To produce and study full non-inductive sustained plasmas
  - Relevant to **DEMO**

Detailed Measurements of Plasma Profiles Allows Physics Analysis and Interpretations

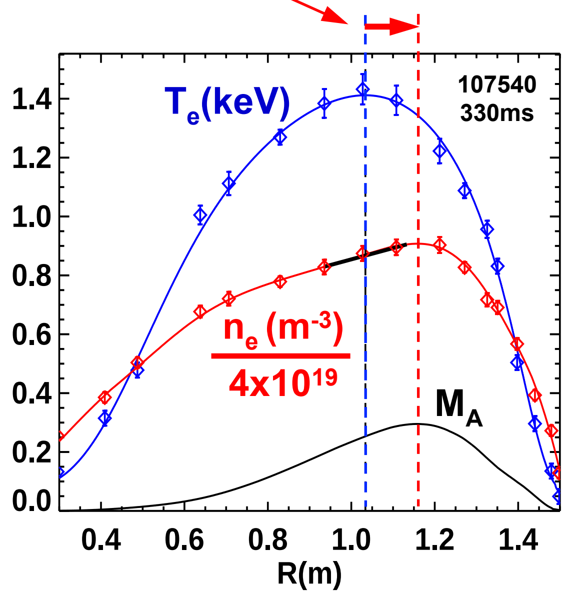
NSTX



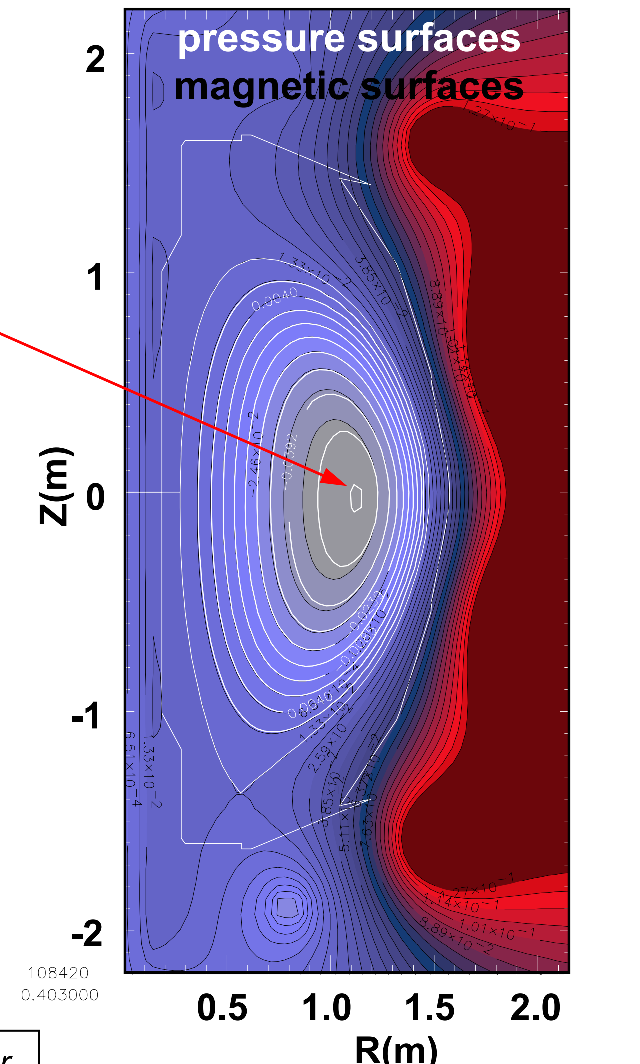
Strong Plasma Flow ($M_A = V_\phi / V_{Alfvén} \sim 0.3$) Has Large Effects on Equilibrium and Stability



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



Equilibrium Reconstruction with Flow

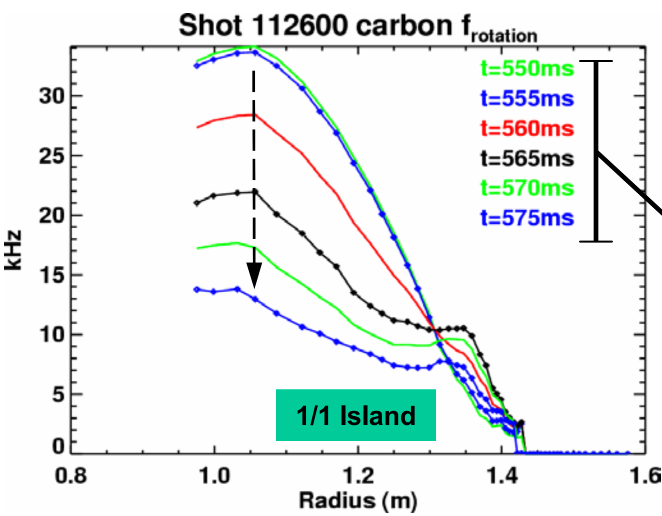


Columbia U, GA, PPPL, U Rochester

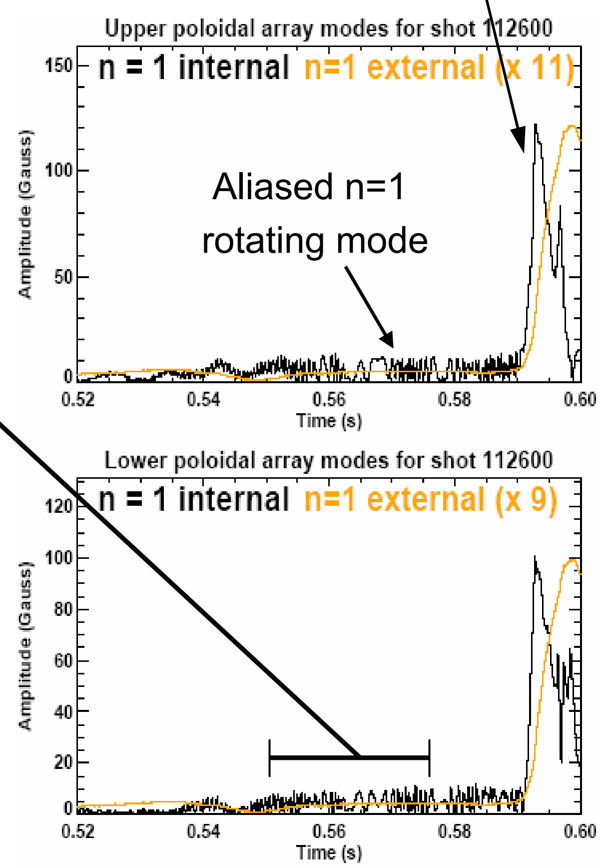
High-Resolution CHERS, SXR, and In-Vessel B_R and B_P Sensors Reveal Strong Mode-Rotation Interaction

NSTX

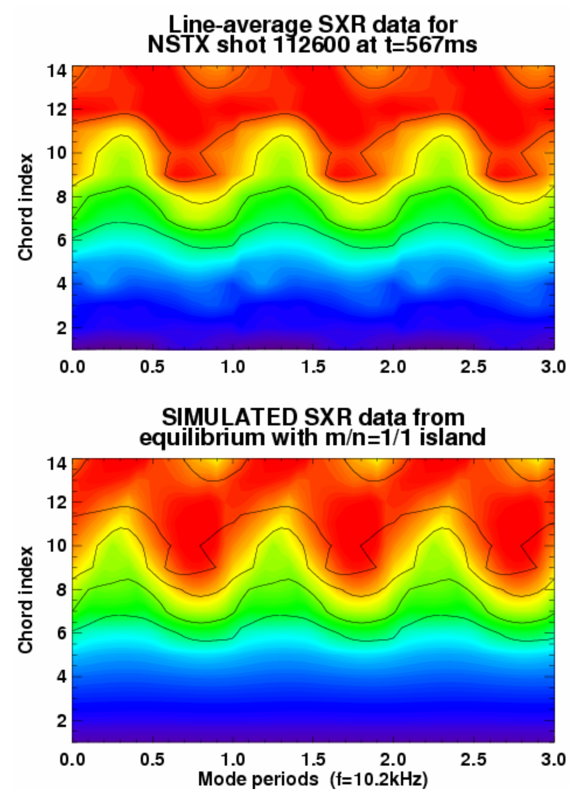
CHarge-Exchange Recombination Spectroscopy (CHERS) shows v_ϕ collapse preceding β collapse



In-vessel sensors measure rotating mode as v_ϕ decays before mode locking



SXR shows rotating 1/1 mode during v_ϕ decay

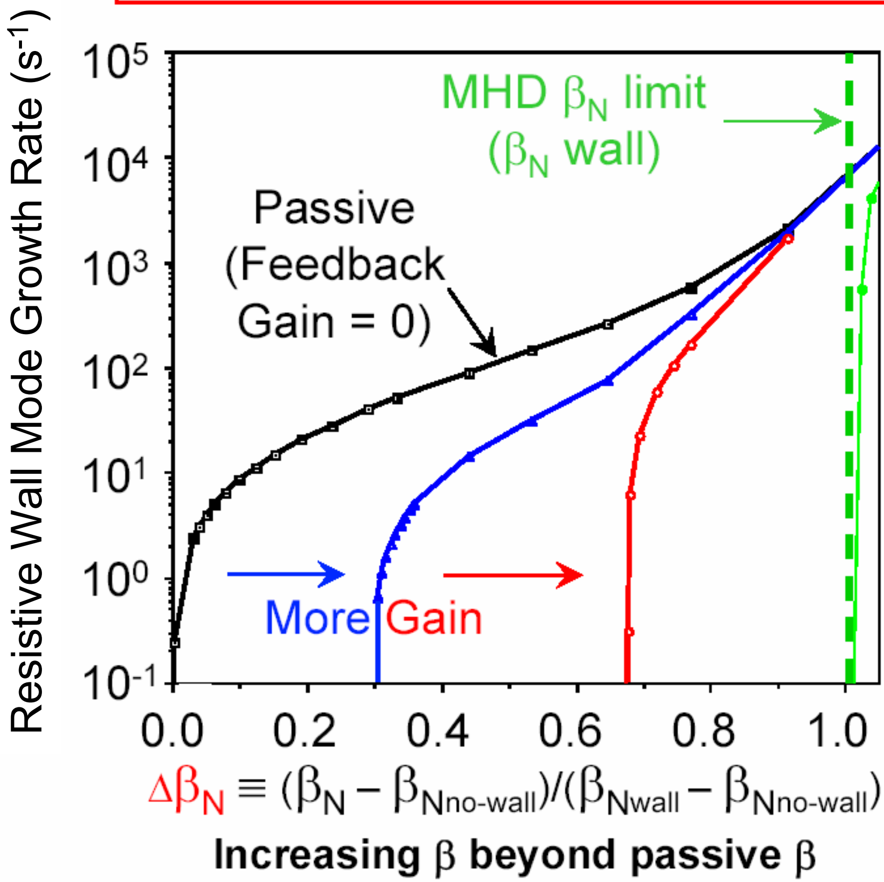


Sabbagh, Bell, Menard, Stutman

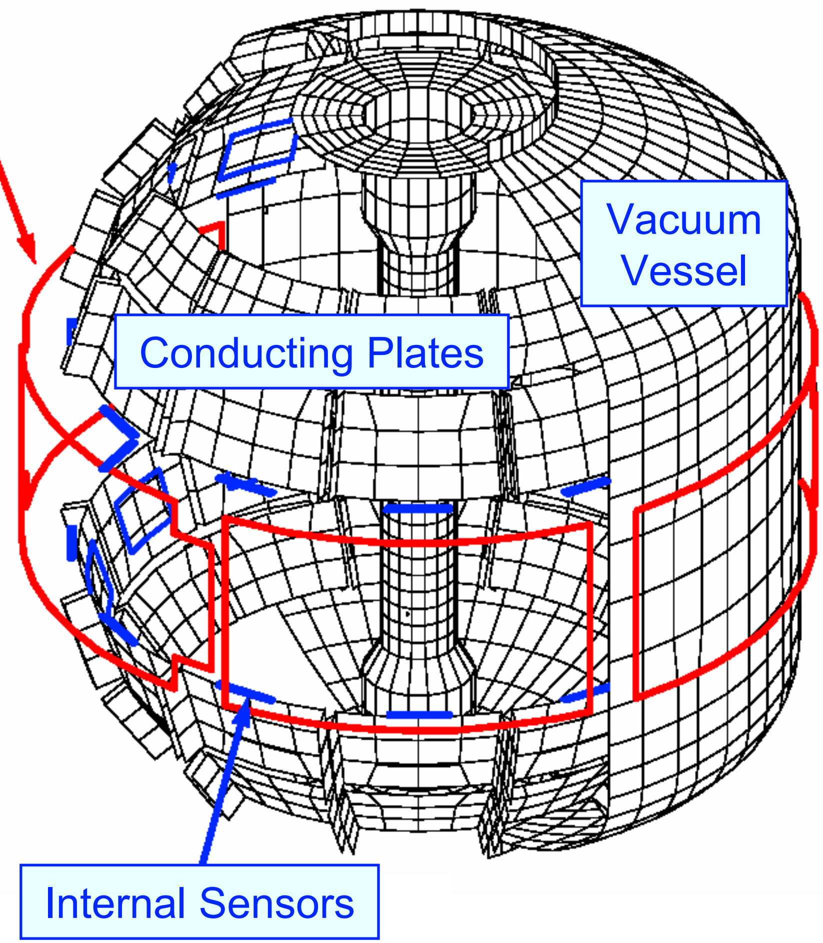
RWM, NTM, 1/1 modes, and rotation physics of high interest to ITER

Active Control Will Enable Study of Wall Mode Interactions with Error Fields & Rotation at High β_T

Ex-Vessel Feedback Control Coils are being built



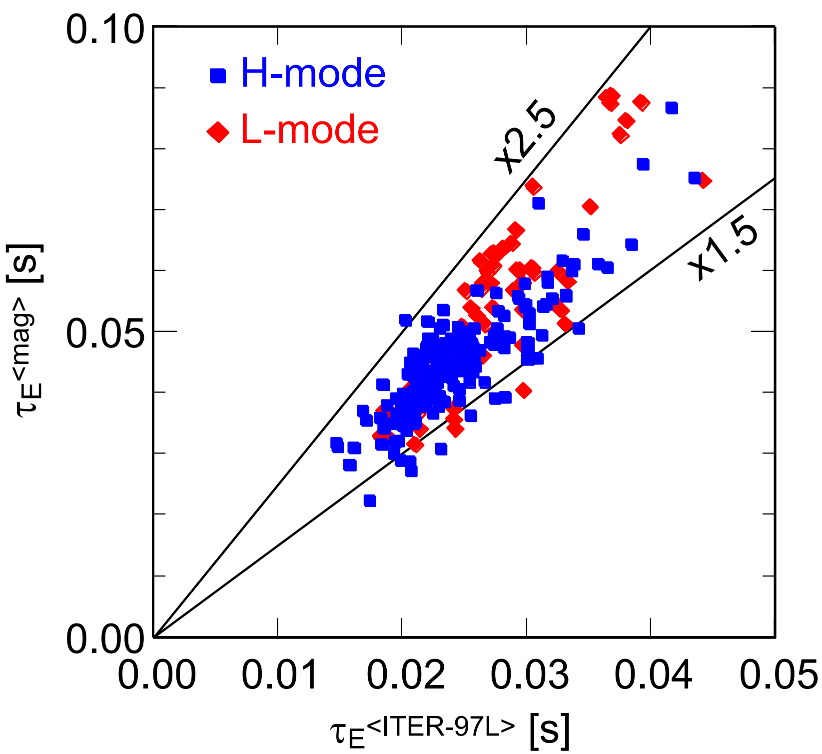
VALEN model of NSTX
(cutaway view)

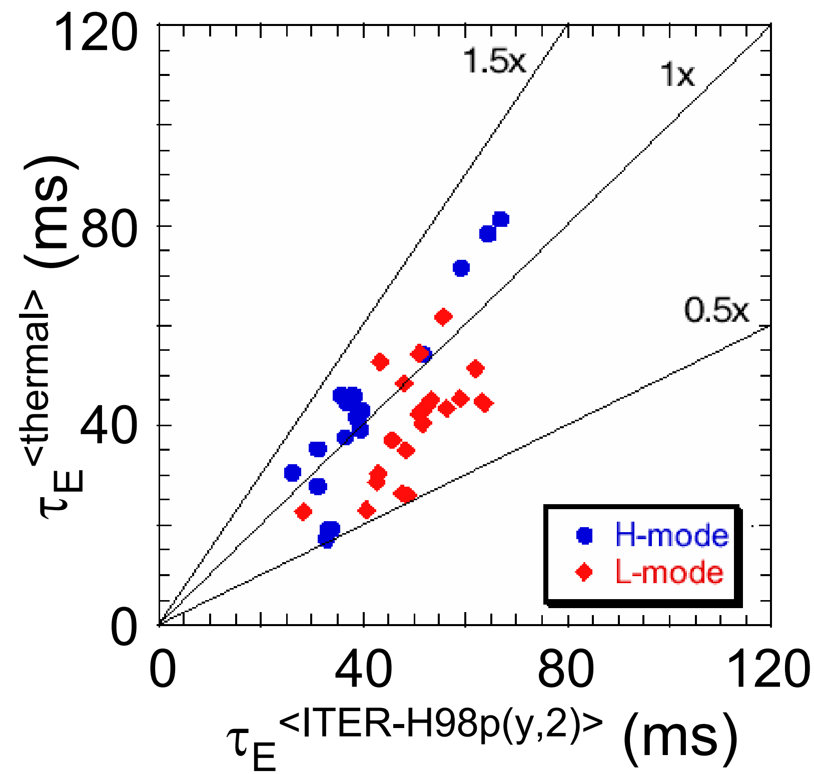


Columbia U, GA, PPPL

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

NSTX





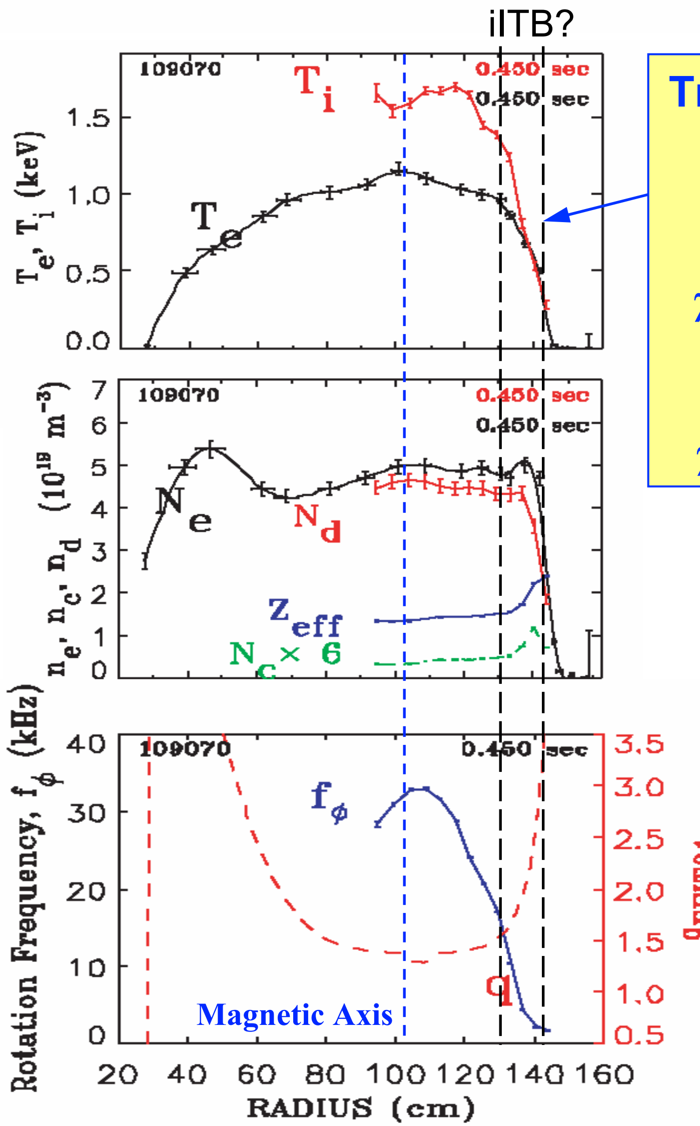
- Compare with ITER scaling for total confinement, including fast ions
- TRANSP analysis for thermal confinement

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

Bell, Kaye, PPPL

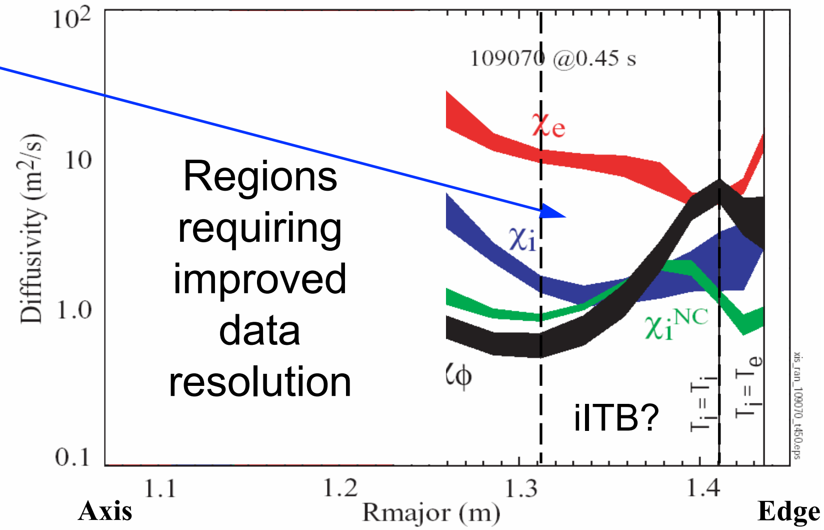
Ion Internal Transport Barrier in Beam-Heated H-Mode Contrasts Improved Electron Confinement in L-Mode

NSTX

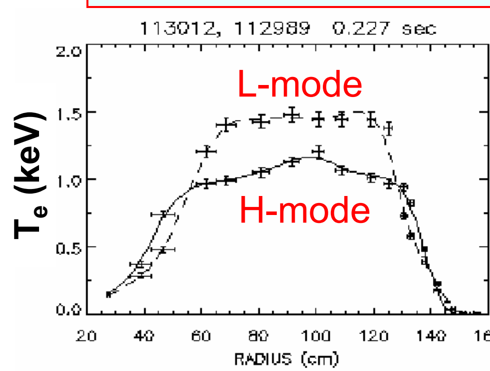


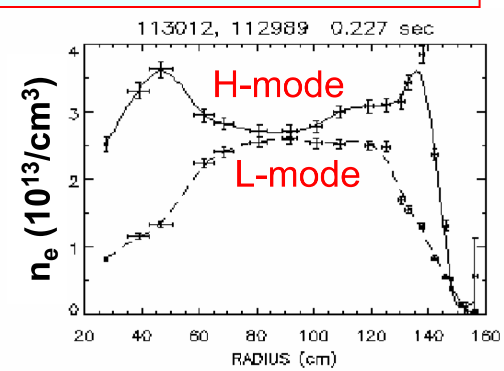
Transport Barrier region where $\chi_i \sim \chi_i^{NC}$ and $\chi_e >> \chi_i$

Kinetic Profile Local Error Sampling



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

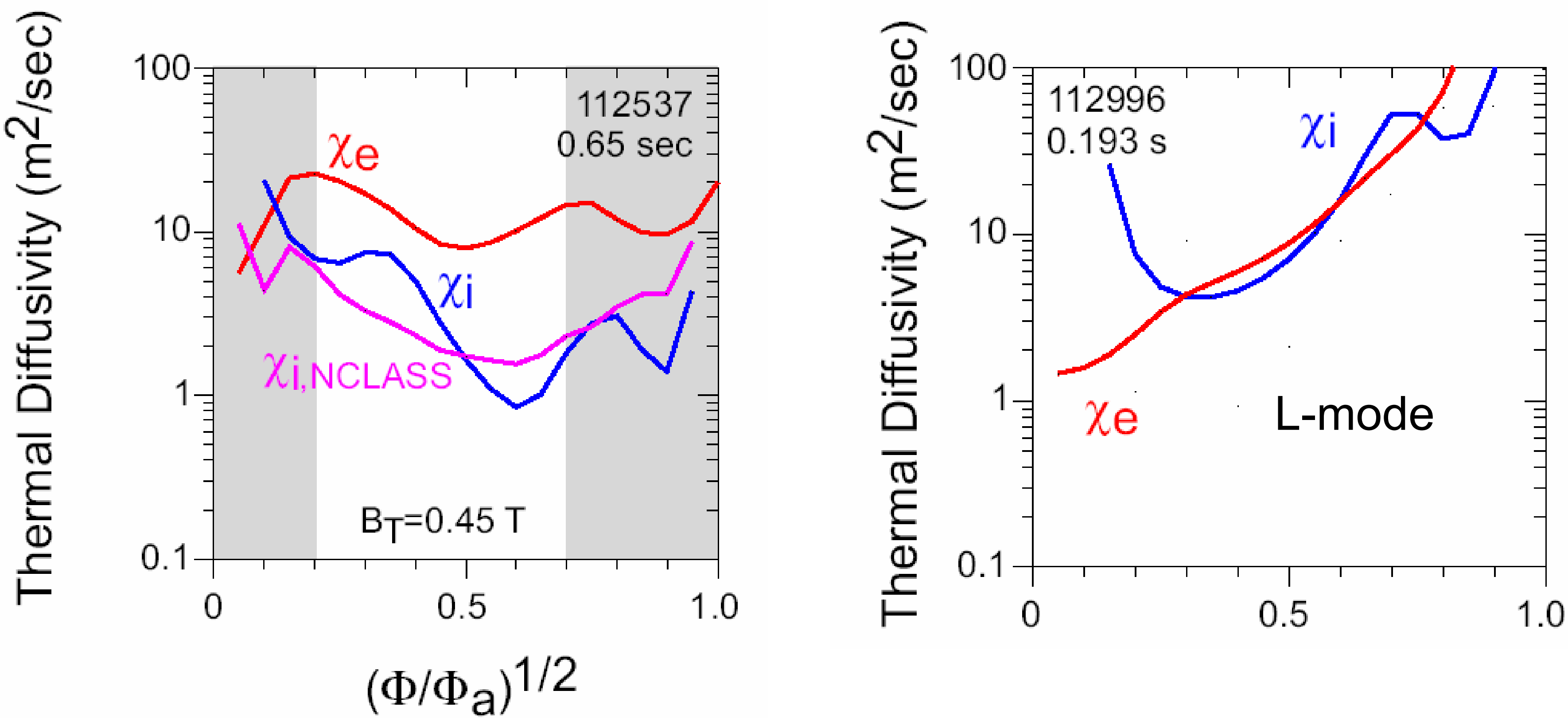




Columbia U, Culham, ORNL, PPPL

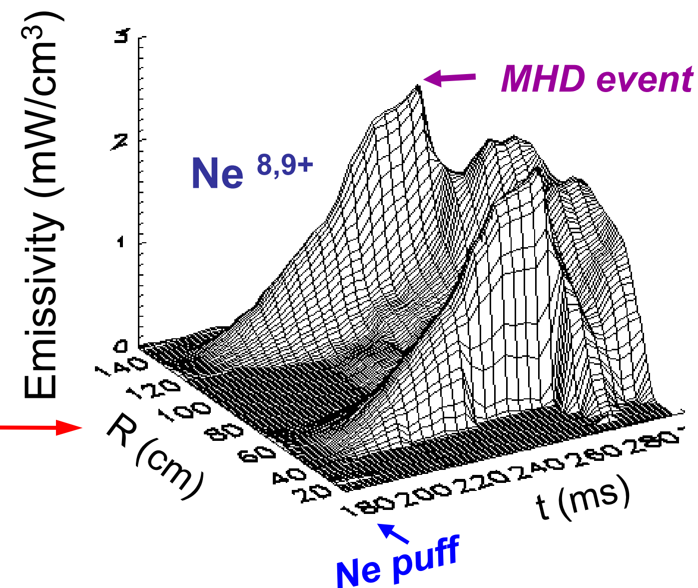
Transport Analysis of NSTX Plasmas Using TRANSP Confirms This Contrast

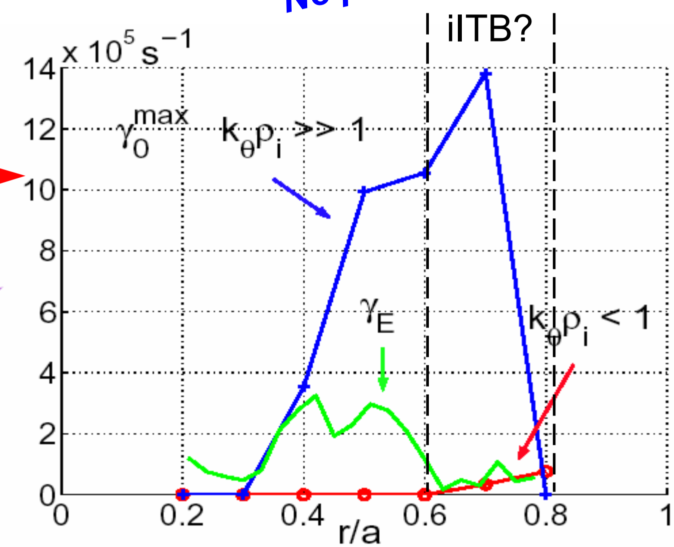
- $\chi_e >> \chi_i \sim \chi_{NCLASS}$ in most H-mode
- $\chi_e \sim \chi_i$ in L-mode
- Diagnostic Resolution improvements continue



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

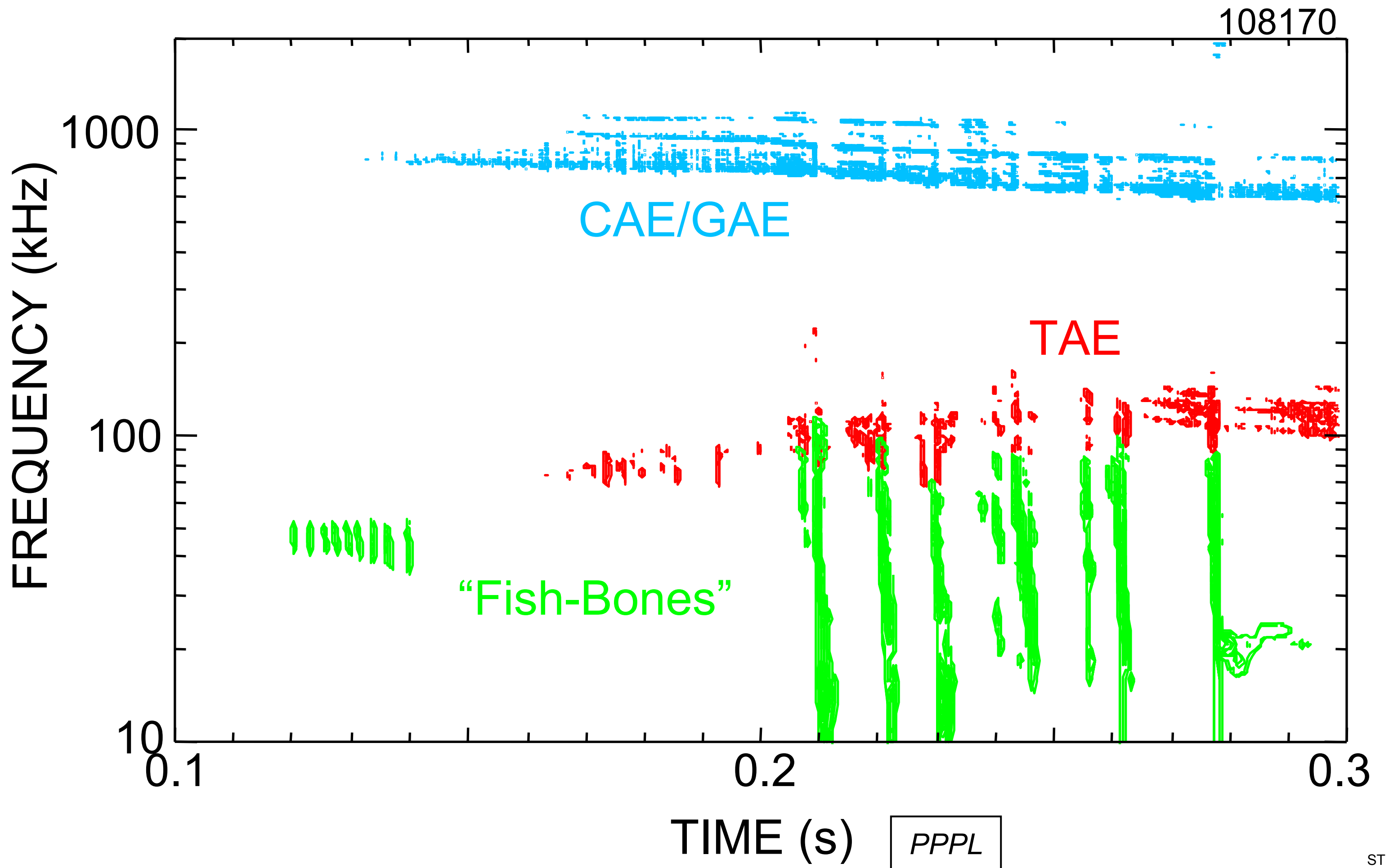




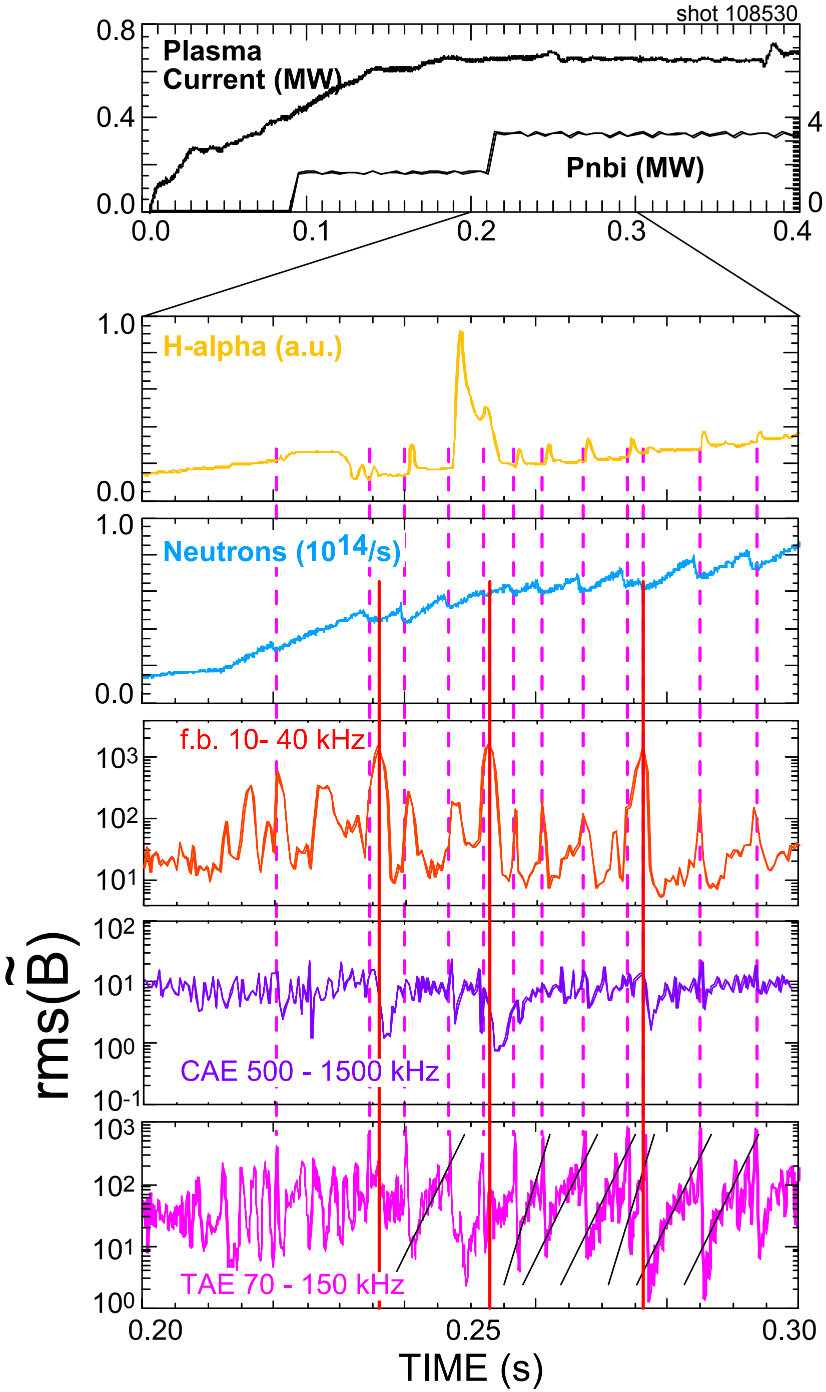
Cadarache, JHU, PPPL, U. Maryland

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?



TAE's, "Fish-Bones," and CAE/GAE's Can Interact to Expel Energetic Particles



(I_p = 0.65 MA, P_b = 3.6 MW, β_T = 10%)

Synchronous sudden activities of

- Edge Dα rises; D-D neutron drops
- Fish-bone modes rises
- TAE mode crashes
- Separately, asynchronous drops of f.b. and CAE modes
- So far observed for $\beta_T \leq 10\%$ and $I_p \leq$ 700 kA $\Rightarrow$ high-β effects?
- NPA measured depletion for 50-80 kV at higher β_T – MHD (m/n=4/2) induced?
- Nonlinear effects relevant to lower β burning plasmas (**ITER**)

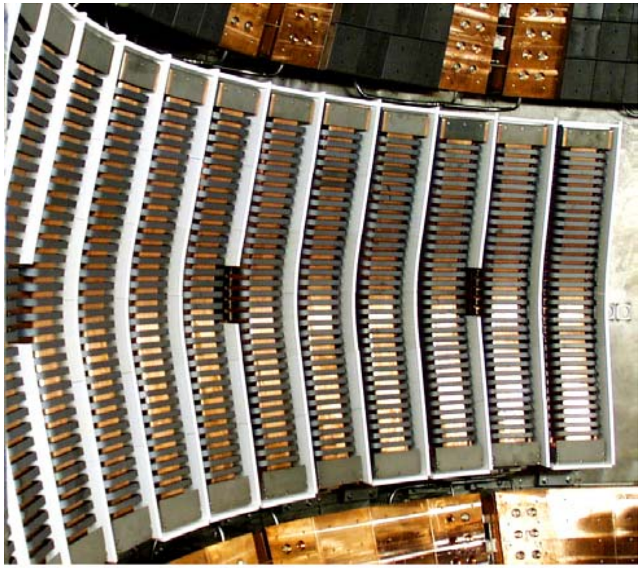
NSTX RF Research Explores High Dielectric (ε ~ 100) Effects for Efficient Heating & Current Drive

M. Ono (1995): High Harmonic Fast Wave (HHFW) decay (absorption) rate:

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

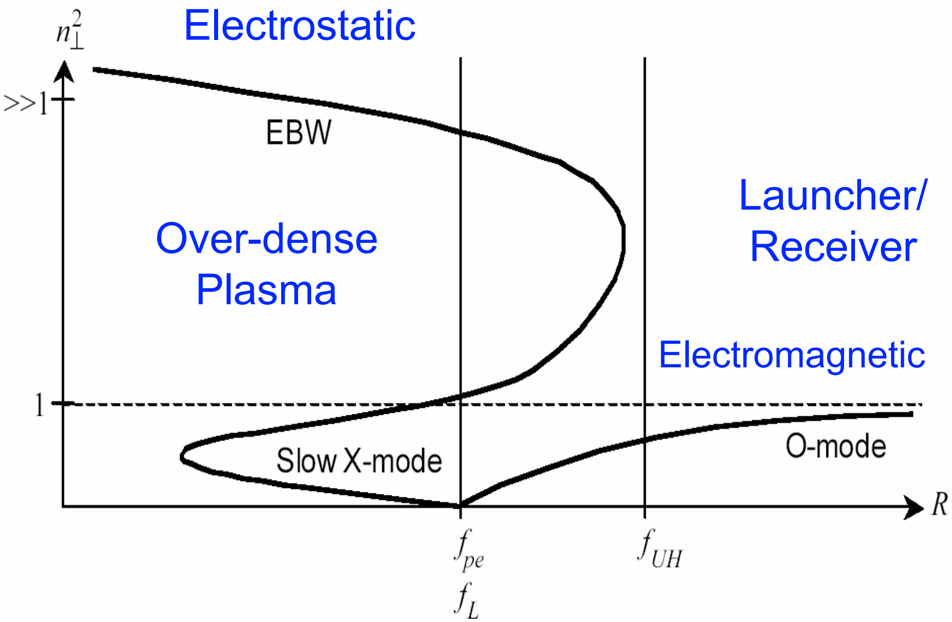
$$\varepsilon = \omega_{pe}^2 / \omega_{ce}^2 \sim 10^2$$

PPPL & ornl



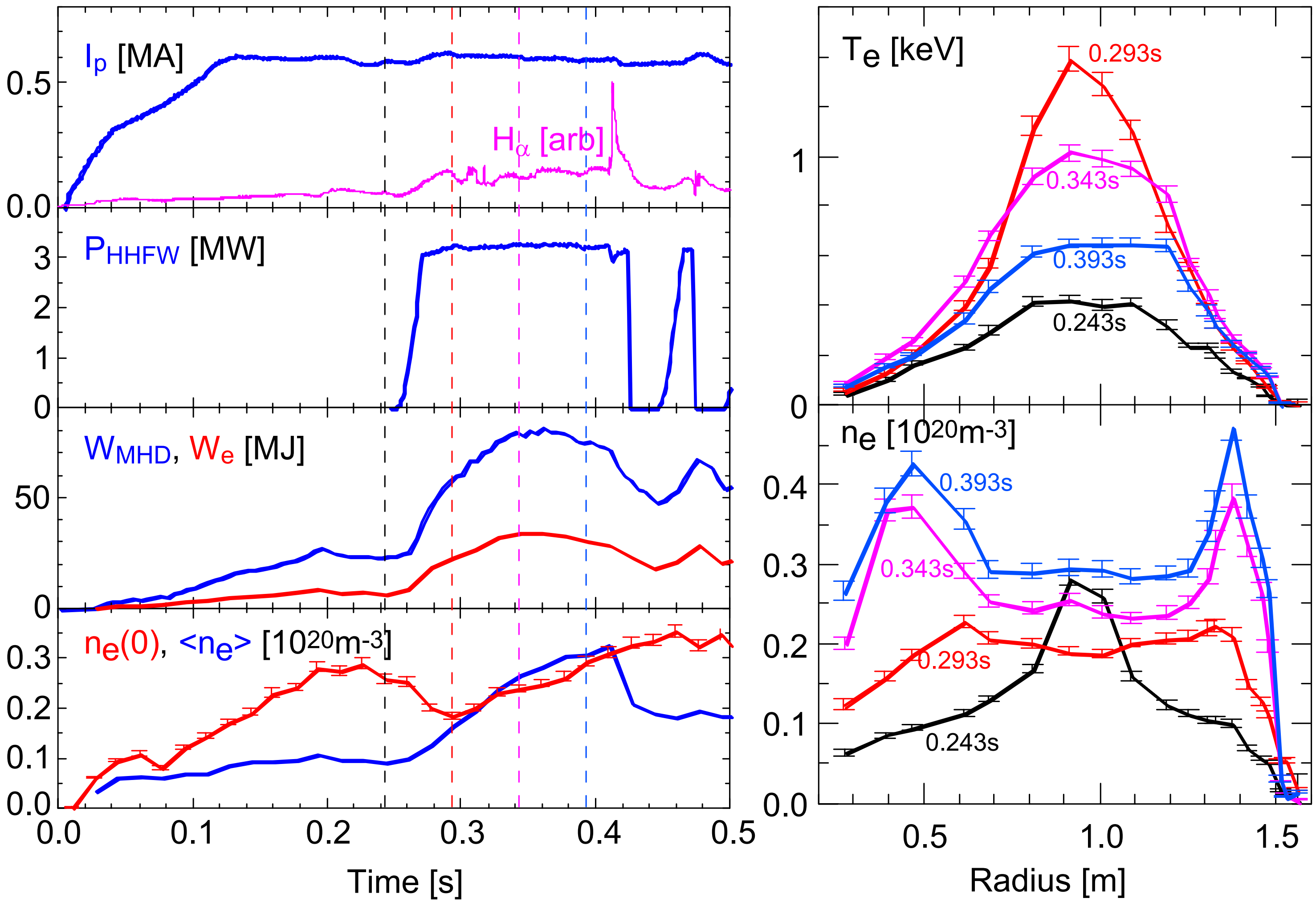
12 HHFW ANTENNA

Laqua et al (1997): Conversion of oblique O-mode to slow X-mode to Electron Bernstein Wave (EBW):



HHFW: Heat Electrons and Trigger H-Modes, Relevant to Slowly Rotating ITER Plasmas

NSTX



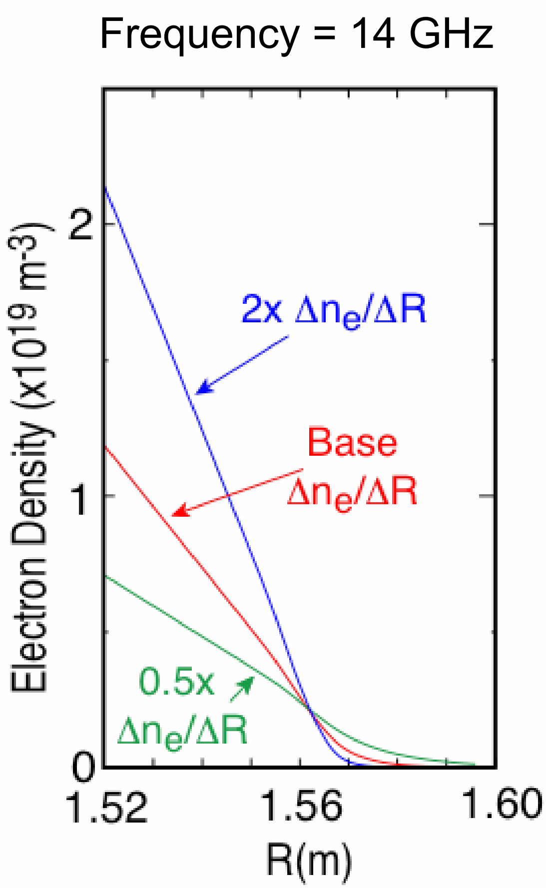
LeBlanc

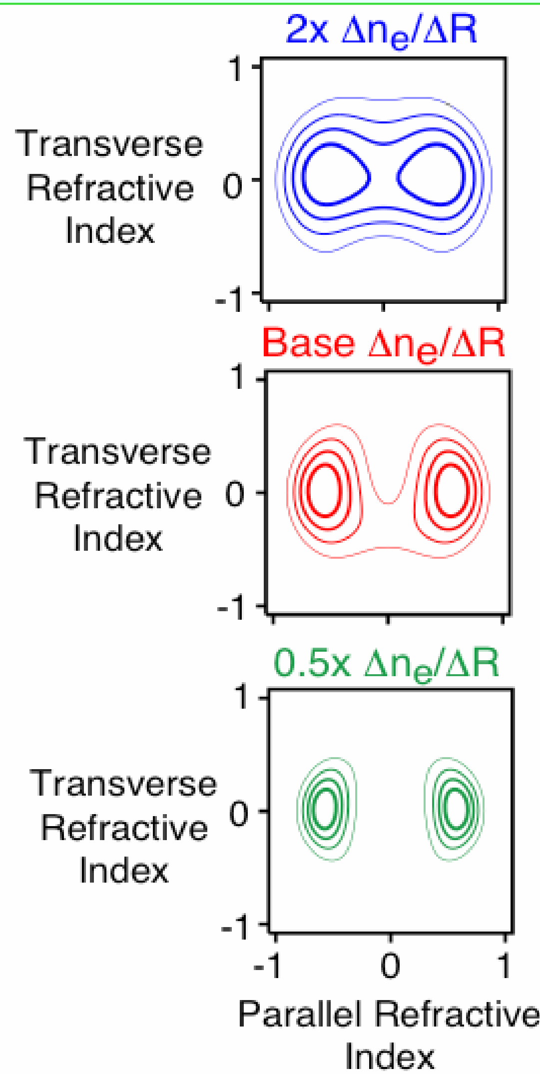
- Antenna operated in 6x(0-π) phasing for slow wave: $k_T \approx 14 m^{-1}$

Electron Bernstein Wave: Oblique "O-X-B" Launch Is Resilient to Changes in Edge Density Gradient

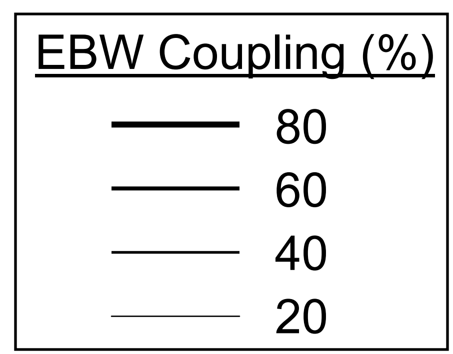
NSTX

Efficient conversion between ECW and EBW predicted.





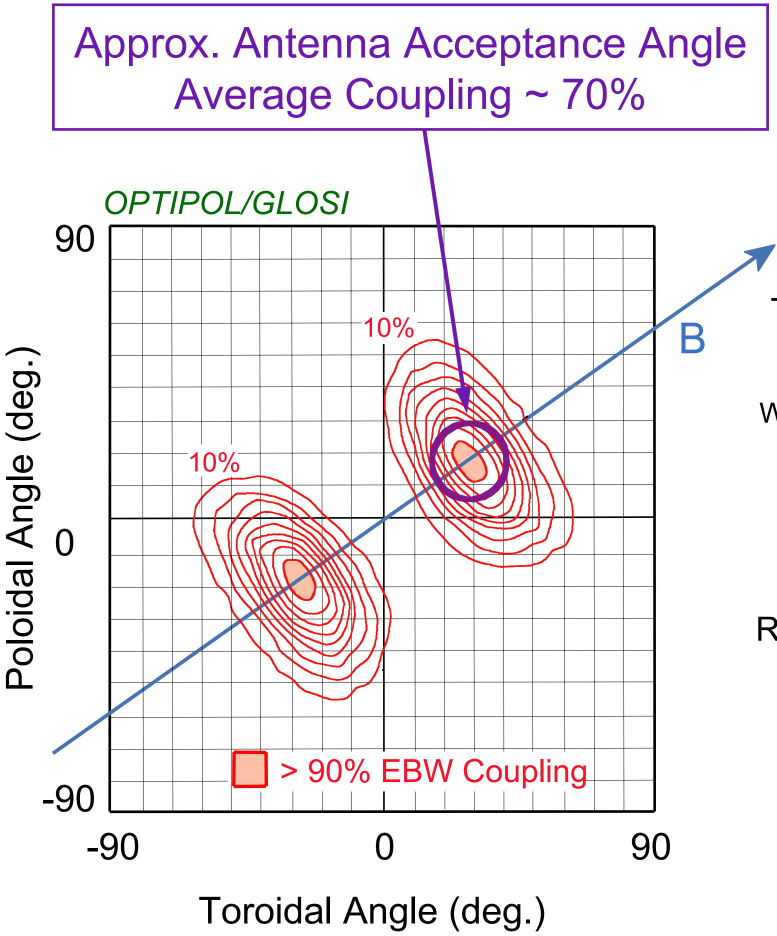
- Optimum $n_{//}$ = 0.55; toroidal angle ~ 34^o from normal to **B**
- > 75% coupling for O-X-B antenna with ± 5 degree beam spread



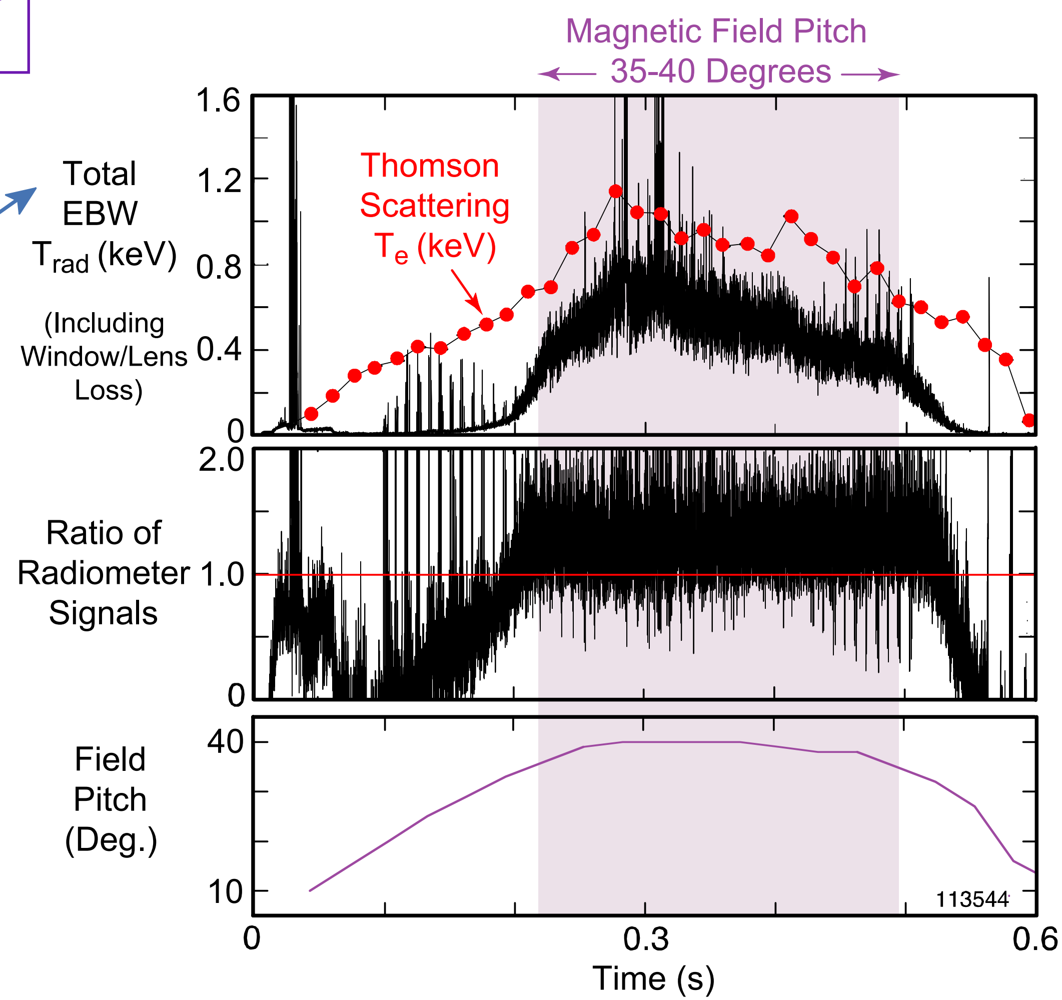
ornl Oak Ridge National Laboratory

OPTIPOL/GLOSI

EBW Emission Shows Near-Circular Polarization and T_{rad}/T_e ~ 70%, Consistent with Modeling



Frequency = 16.5 GHz



Modeling Predicts that 28 GHz EBW Can Drive Efficient Off-Axis Current at Plasma β ~ 40%

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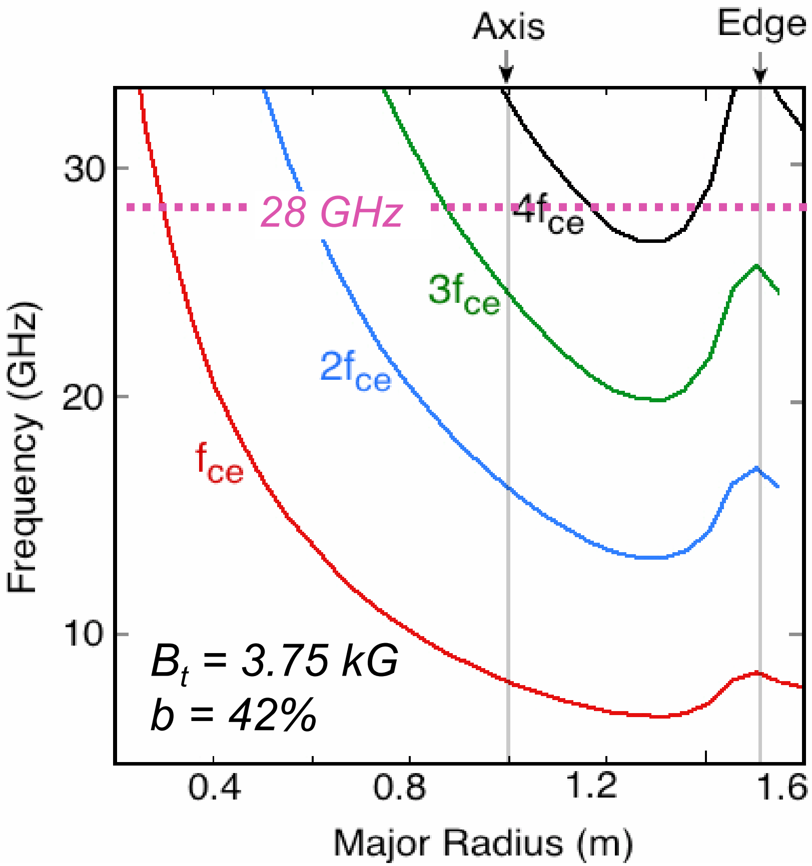
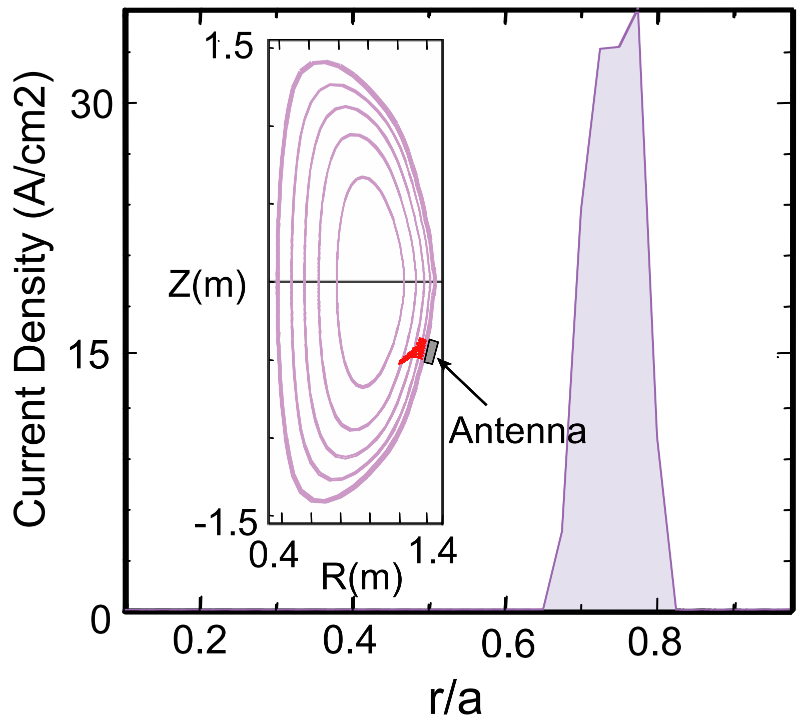


Frequency = 28 GHz

EBW Power = 3 MW

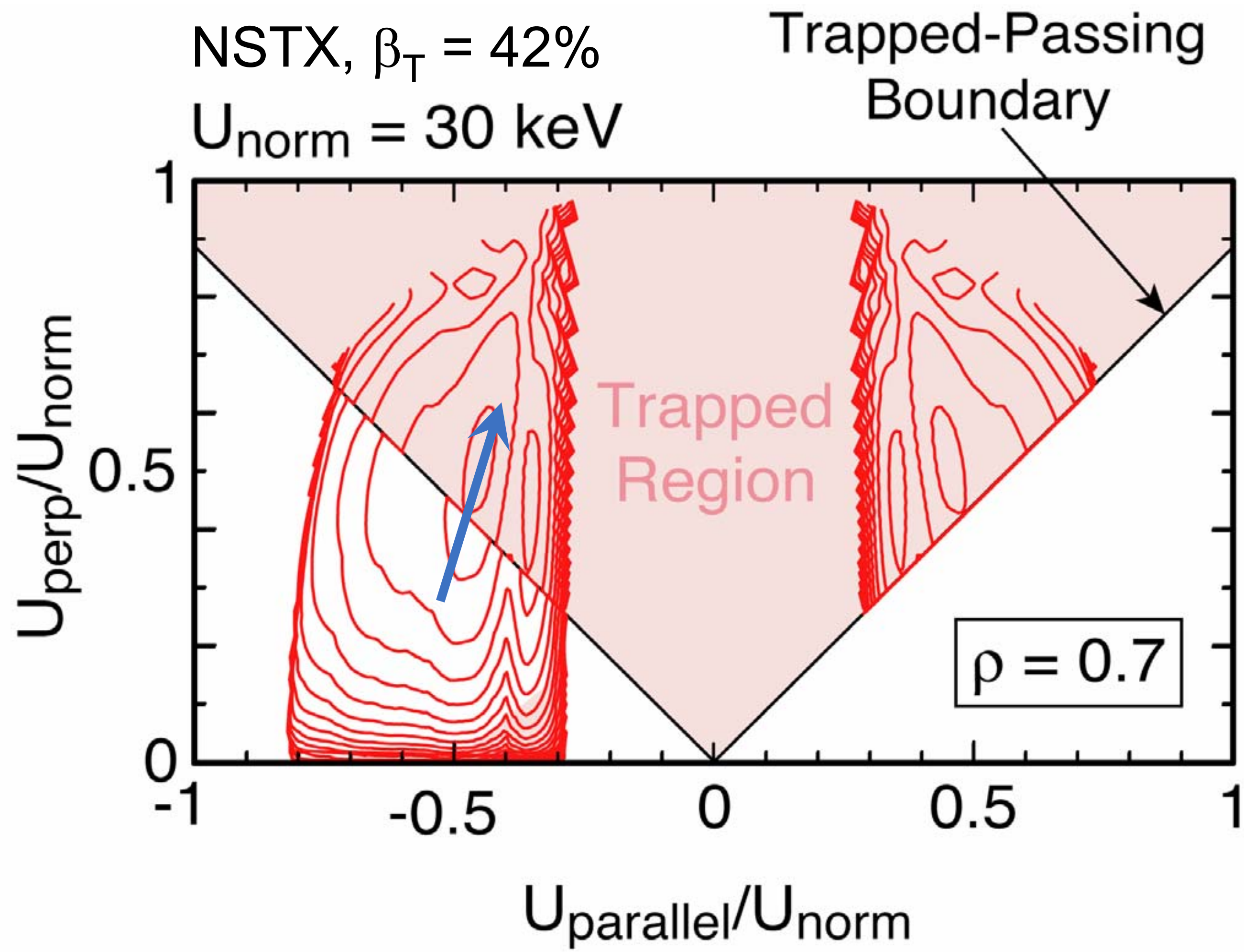
Total Driven Current = 135 kA



- EBW ray tracing, deposition and CD efficiency being studied with GENRAY & CQL3D for frequencies between 14 to 28 GHz

GENRAY/CQL3D [Bob Harvey, CompX]

Strong Diffusion Near Trapped-Passing Boundary Enables Efficient Ohkawa Current Drive

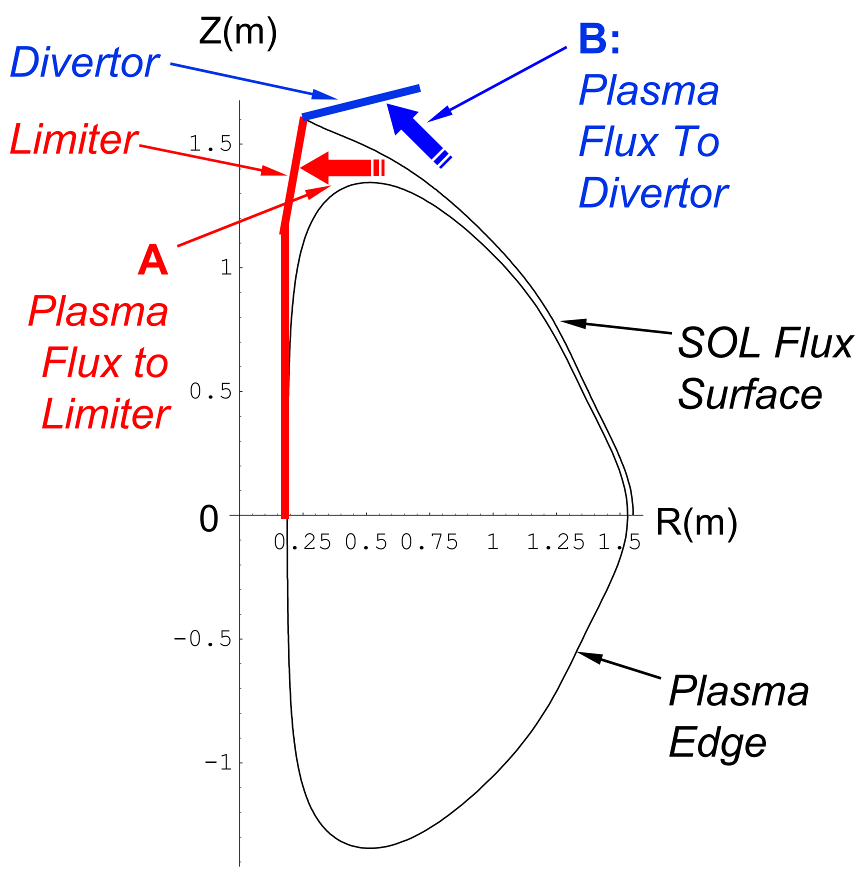


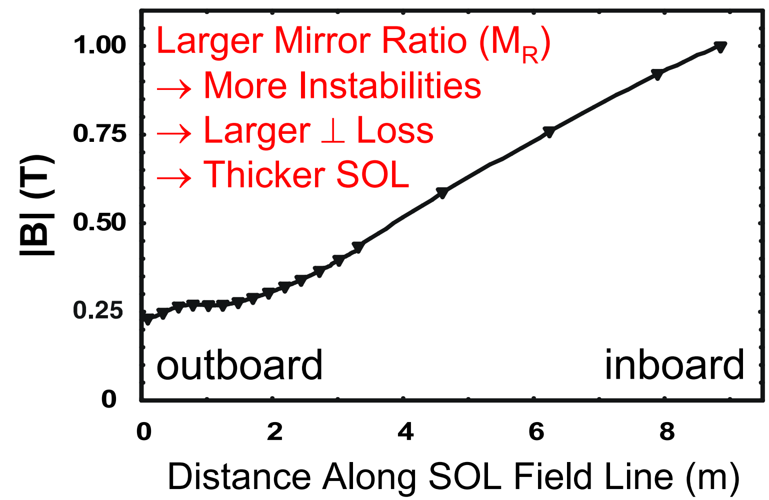
CompX *GENRAY/CQL3D*

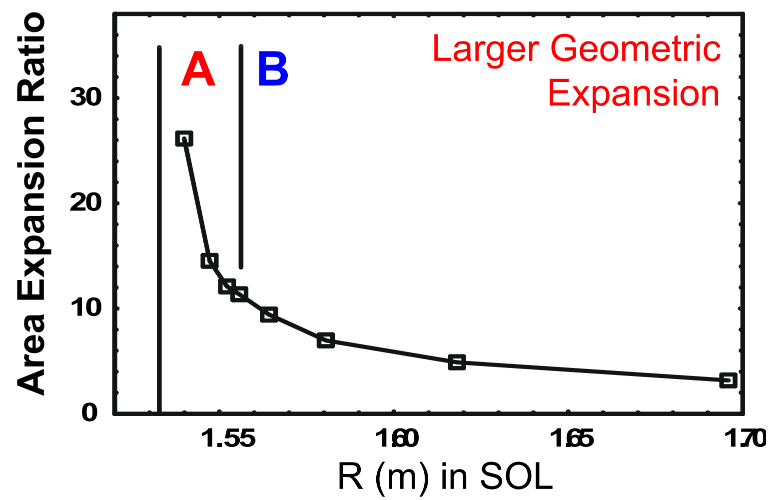
ST Plasma Edge Possesses Large Mirror Ratio & Geometric Expansion of Scrape-Off Layer (SOL)

NSTX

Scrape-Off Layer Geometry of Inboard Limited ST Plasma







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

NSTX

Factor of ~2 in R_{div} and M_R

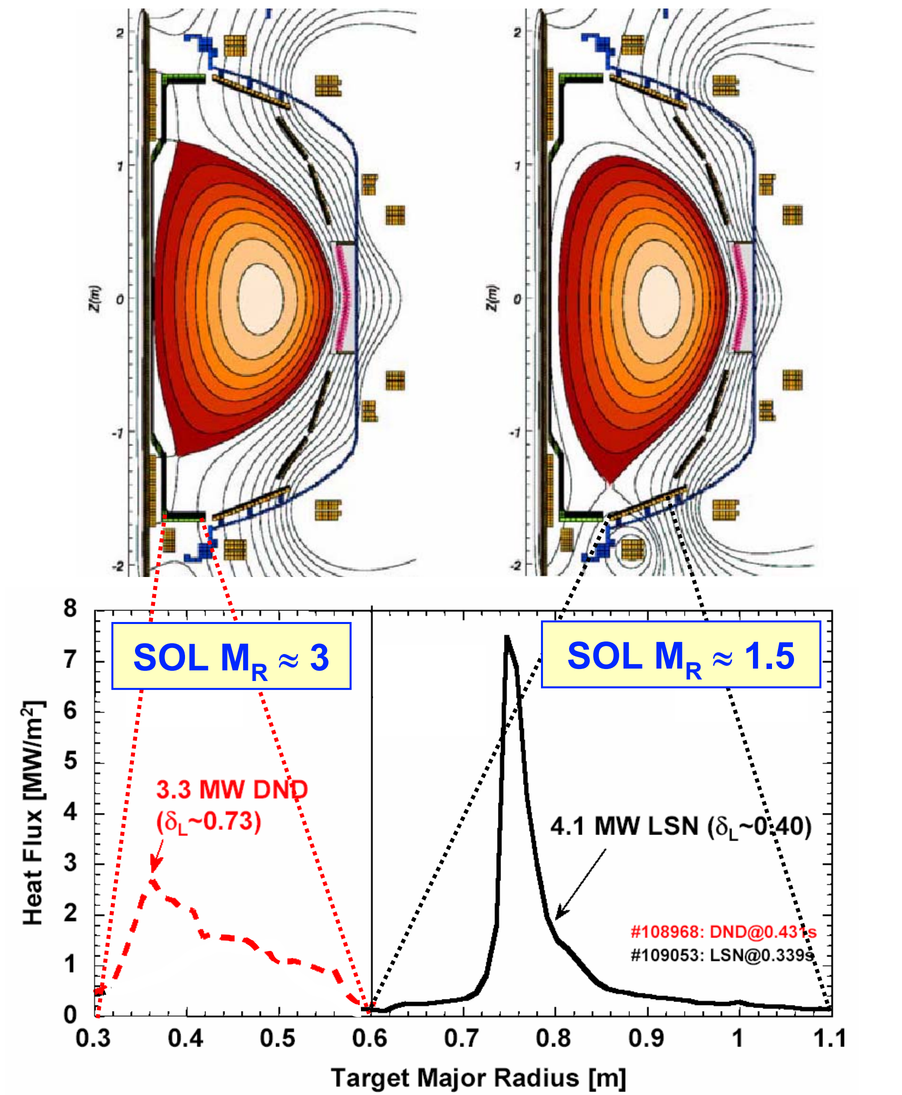
⇓

Factor of ~3 in Δ_{div}

Why?

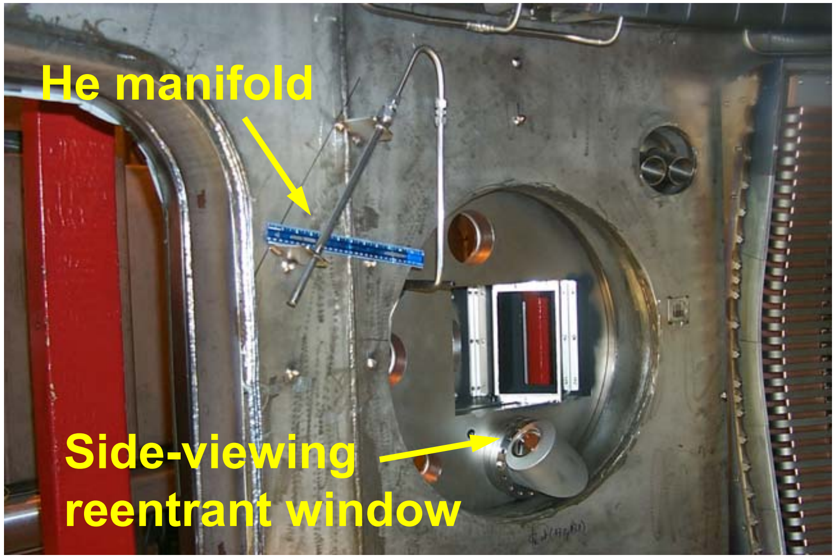
High & Low δ Divertor Bolometer Measurements

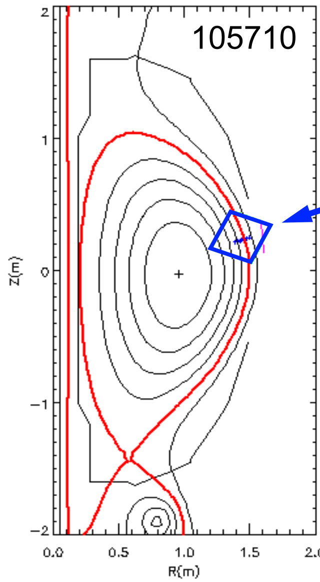
R_{div} (m)	0.36	0.75
SOL M_R	~ 3	~ 1.5
Δ_{div} (m)	~ 0.3	~ 0.12



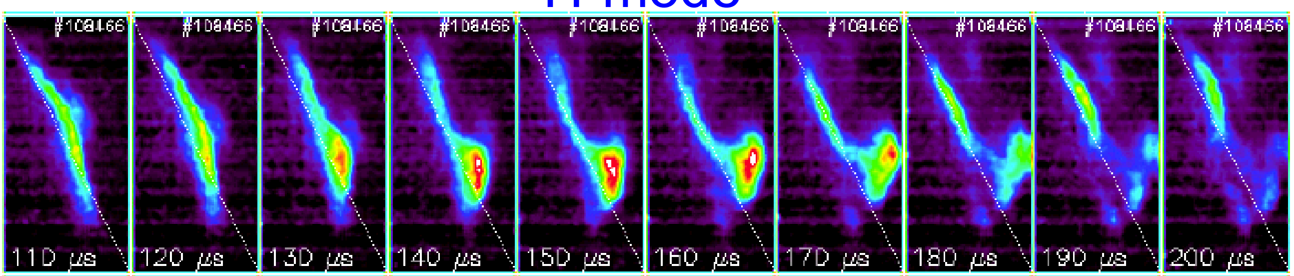
Plasma Edge Studies Reveal Turbulence and "Blobs" Important to Divertor Flux Scaling Studies

NSTX

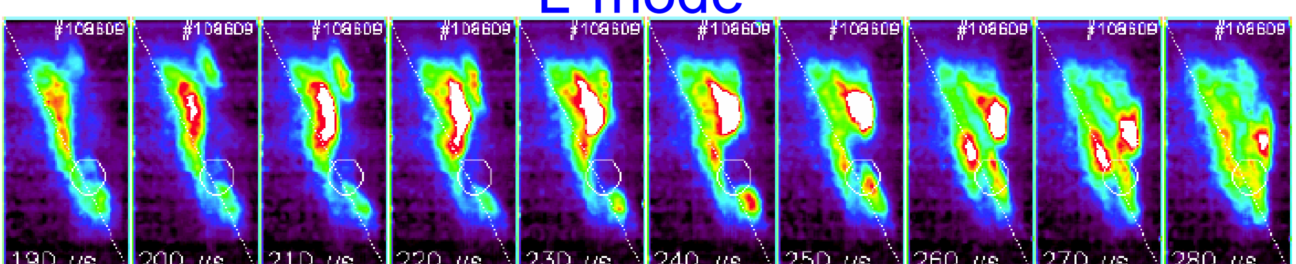




H-mode



L-mode

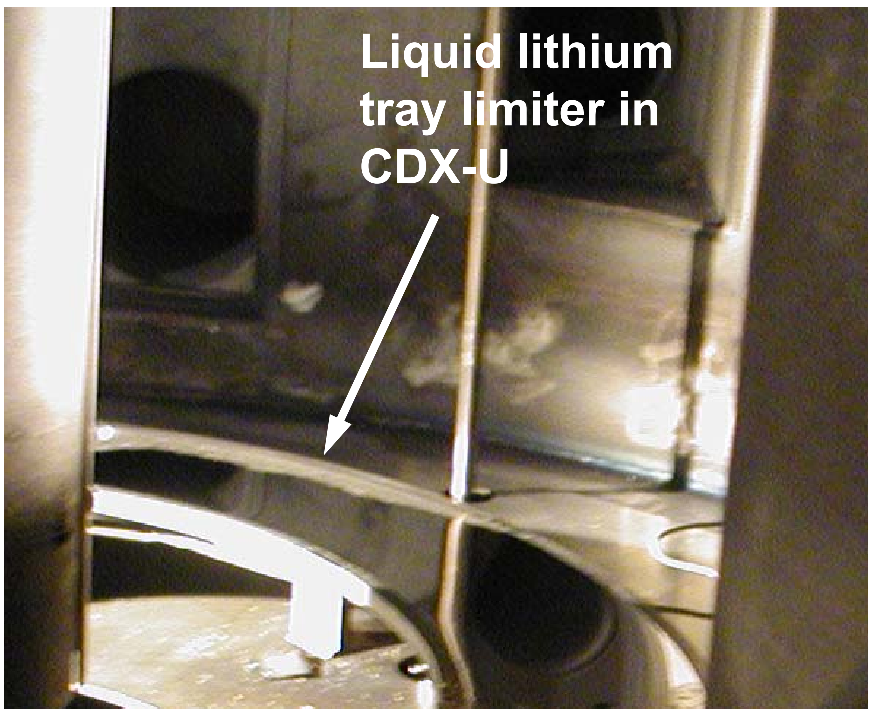


Broadly Based Study:

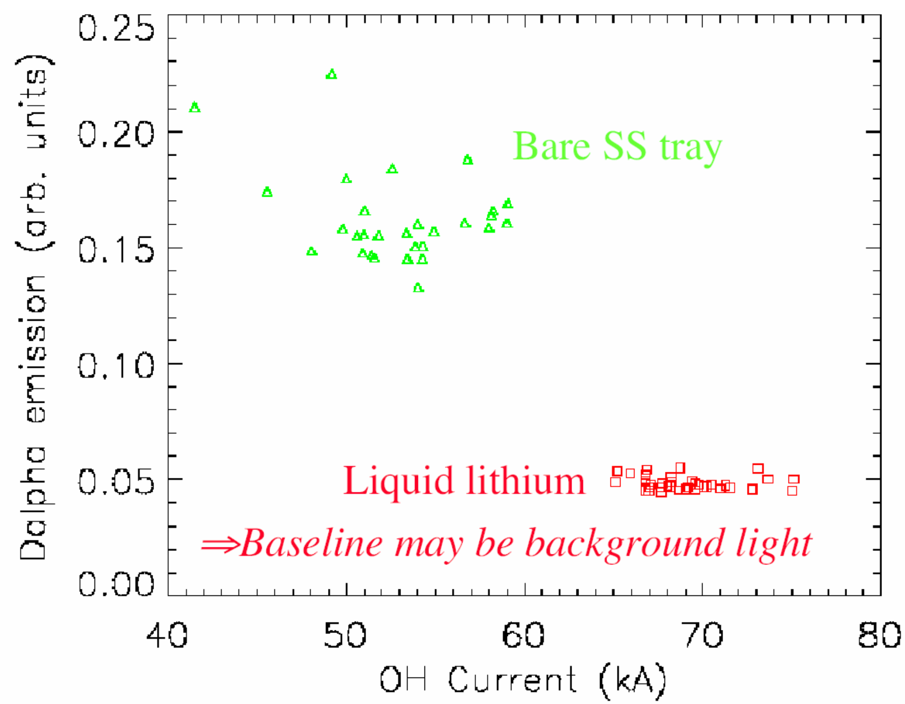
- **Gas Puff Imaging** views along field lines (PPPL, LANL)
- Very fast camera, 10^5/s (PSI)
- Reflectometers and edge (UCLA, ORNL)
- Reciprocating probe (UCSD)
- Divertor fast camera (Hiroshima U)
- IR Cameras (ORNL), Filterscope (PPPL)
- Modeling (PPPL, UCSD, LLNL, Lodestar)

CDX-U Is Testing Innovative Lithium Plasma Facing Component Effects, to Control Recycling

- First successful test of toroidal liquid lithium tray limiter
- Dramatic reduction in plasma edge fuel recycling, lowering impurity influx and loop voltage
- NSTX tests of lithium pellets and lithium wall coating in 2004



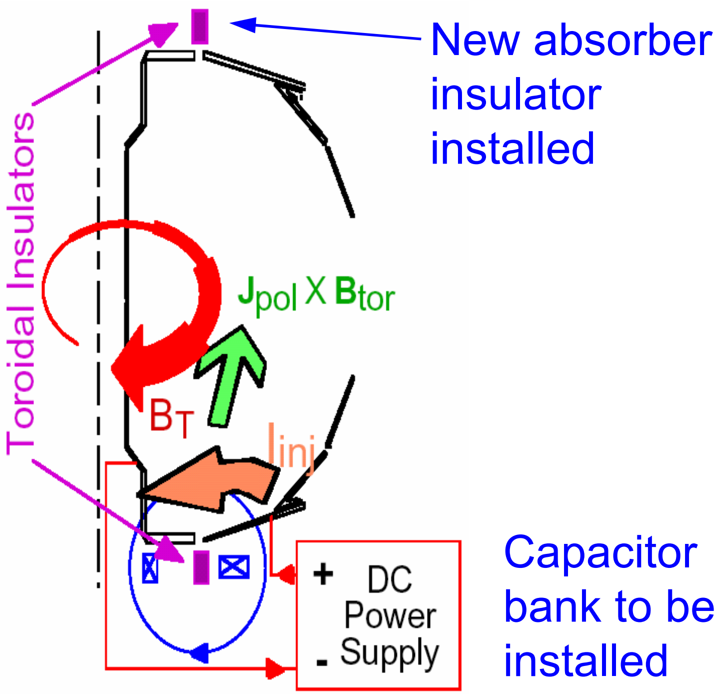
Tray after ~40 discharges.

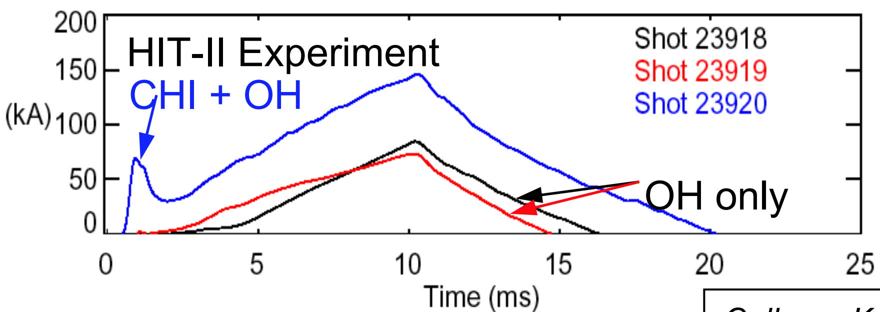


PPPL, UCSD, ORNL, SNL

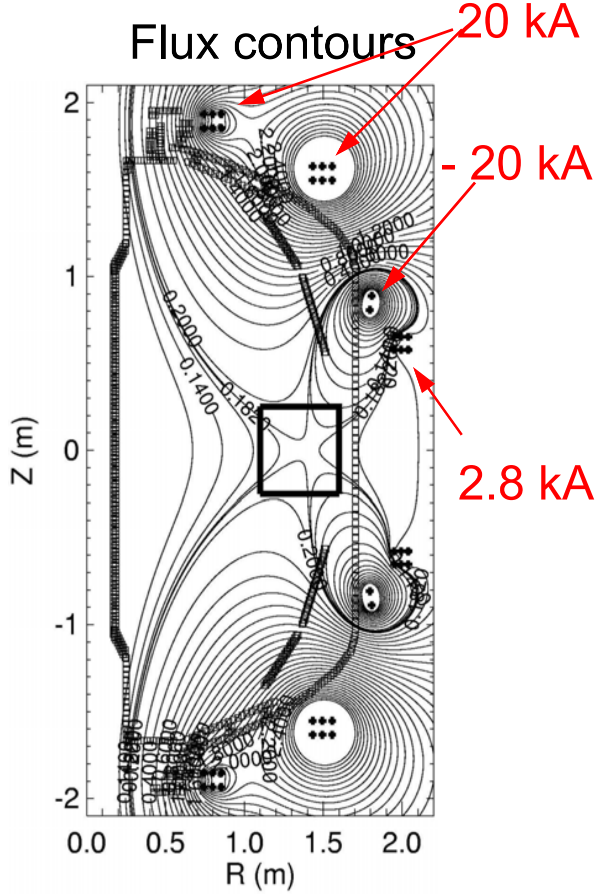
Solenoid Free Start-Up via Coaxial Helicity Injection & Outer Poloidal Field Coil Are Being Tested

Coaxial Helicity Injection Tests



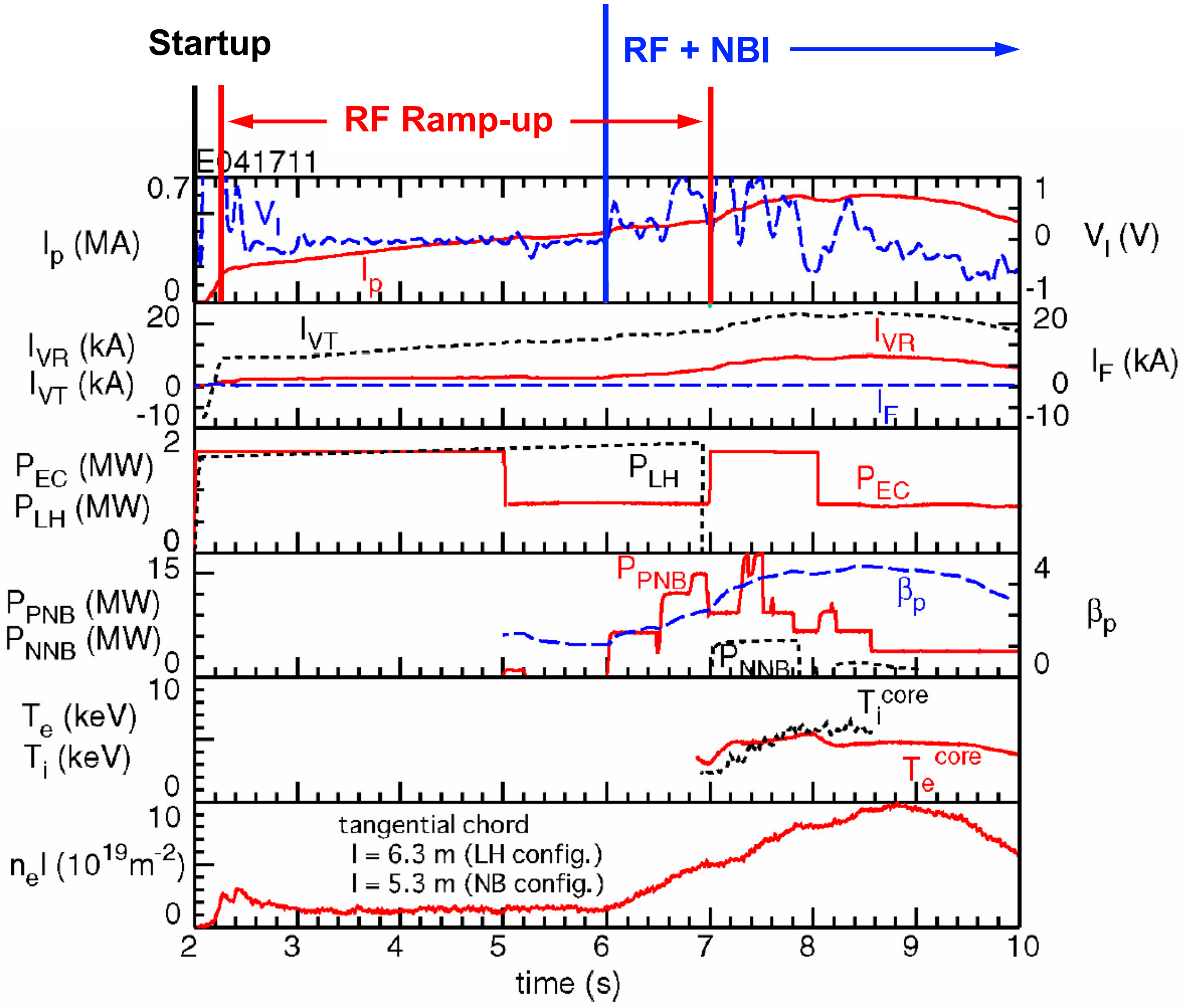


Three Outer Poloidal Field Startup Scenarios, e.g.: Outboard Field Null



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

JT-60U Tests on Solenoid-Free Start-Up via RF and NBI Offers Additional Exciting Opportunities

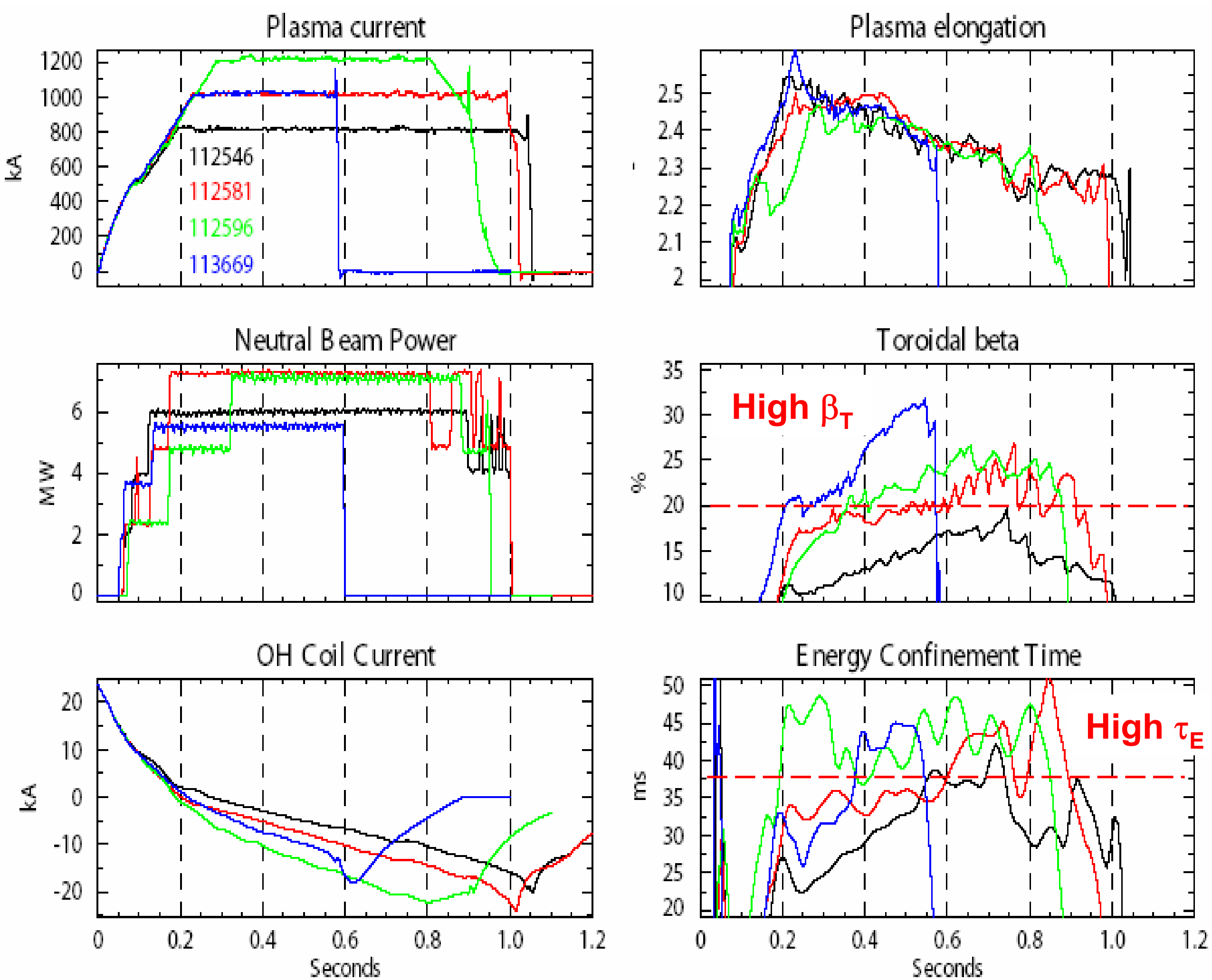


U. Tokyo, JT-60U – JAERI

- **JT-60U**: from 200 kA to 700 kA with LHW + NBI (2002)
- PLT: 100 kA with LHW (1980s)
- CDX-U, TST-2: up to 4 kA with ECH
- MAST: 1-MW ECH
- NSTX: to develop and test up to 4-MW EBW in 5 years
- Utilize outer PF coil induction with simple ramp

Nearly Sustained Plasmas with Broader Values of κ, ℓ_i, I_p, and β_T Can Contribute to ITER Hybrid Scenario

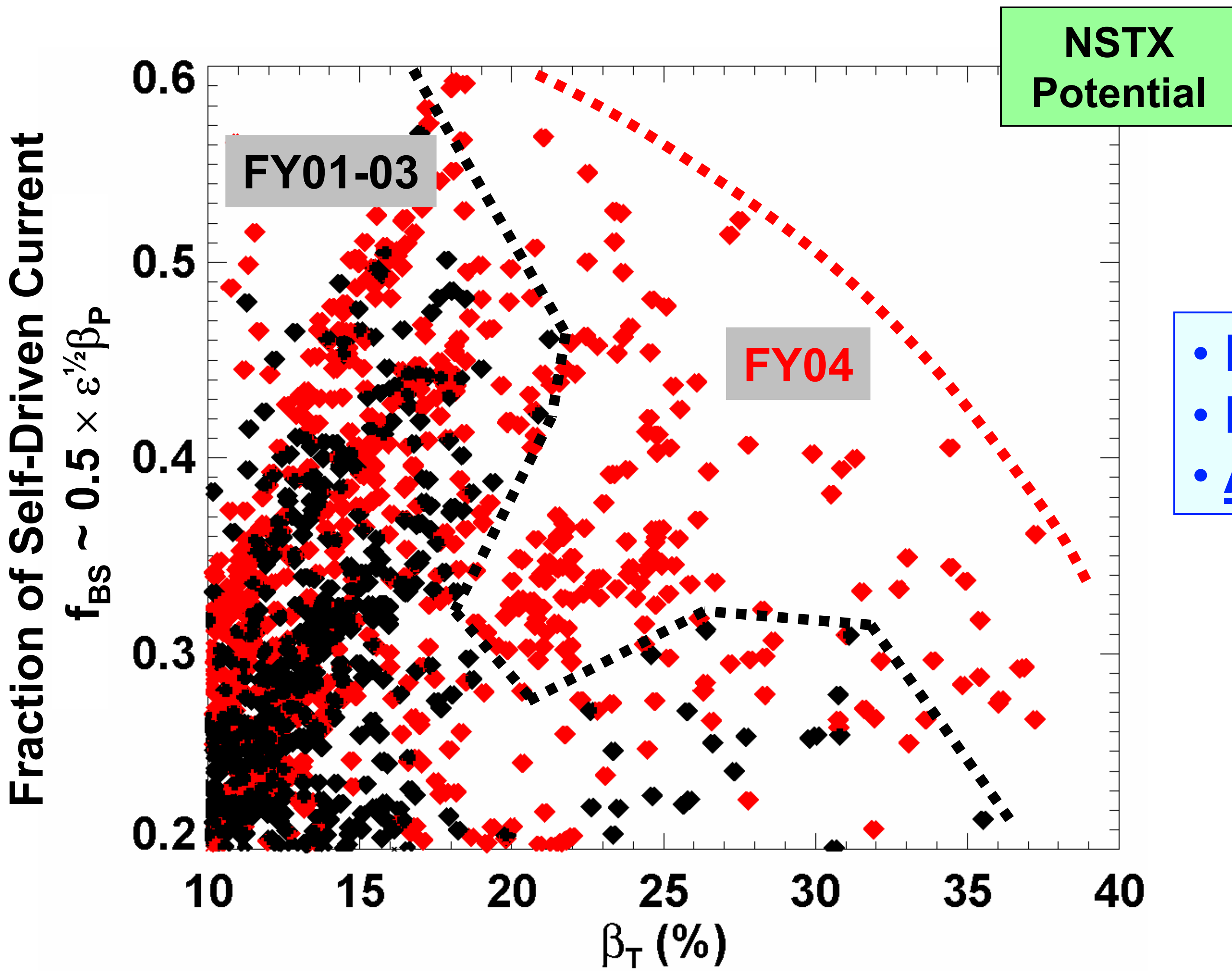
NSTX



Co-NBI plasmas:

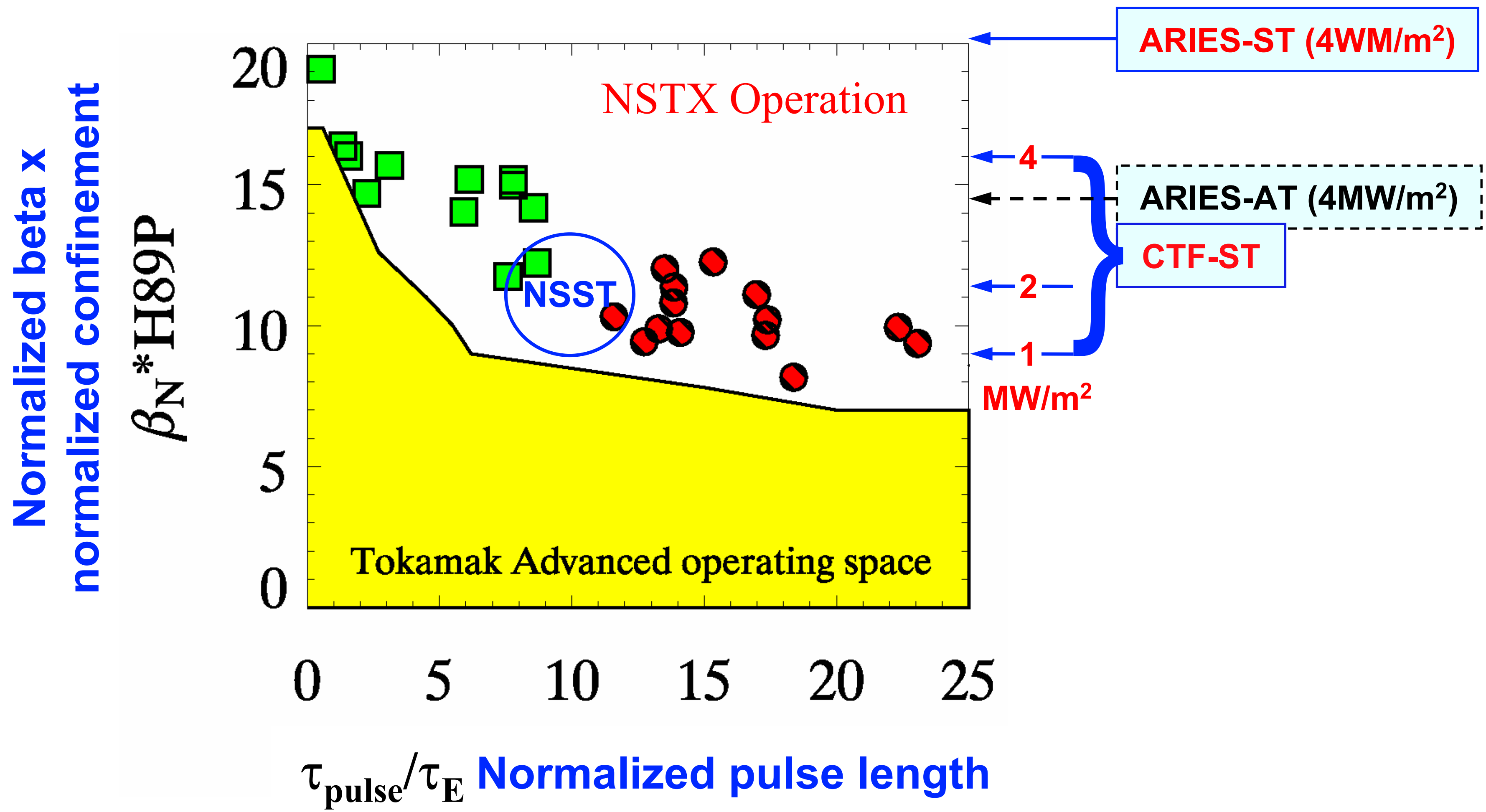
- Improved vertical control $\Rightarrow$ higher κ
- $\beta_p \gtrsim 1$ and $I_{BS}/I_p \lesssim 0.5$
- $\beta_N \sim 6$ and $\beta_T > 20\%$
- Reduced V_L
- **Help developing ITER hybrid scenario**
- **Driven steady state ST plasmas (CTF).**
- Need to reduce ELM size

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

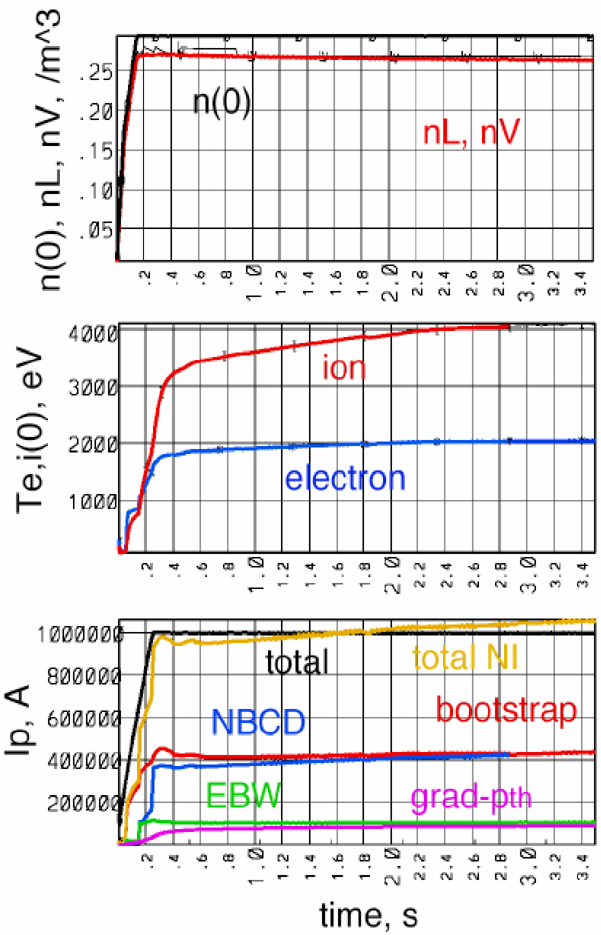


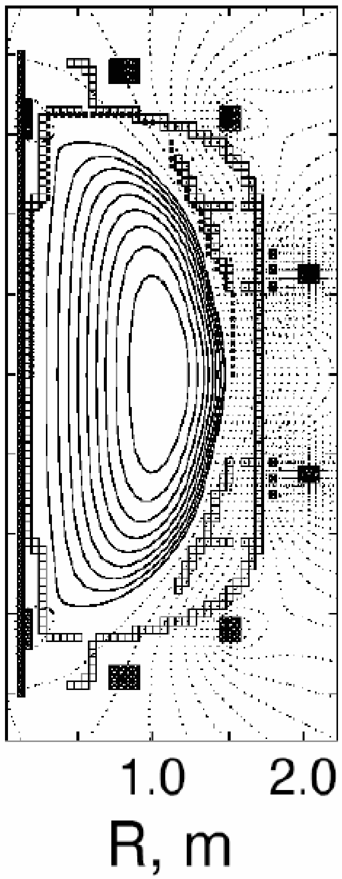
Well positioned to address the science of sustained high-performance plasmas.

Research Topics to Achieve Long-Pulse, High Performance Plasmas Are Identified

NSTX

- Enhanced shaping improves ballooning stability
- Mode, rotation, and error field control ensures high beta
- NBI and bootstrap sustain most of current
- HHFW heating may contribute to bootstrap
- EBW provides off-axis current & stabilizes tearing modes
- Particle and wall control maintains proper density



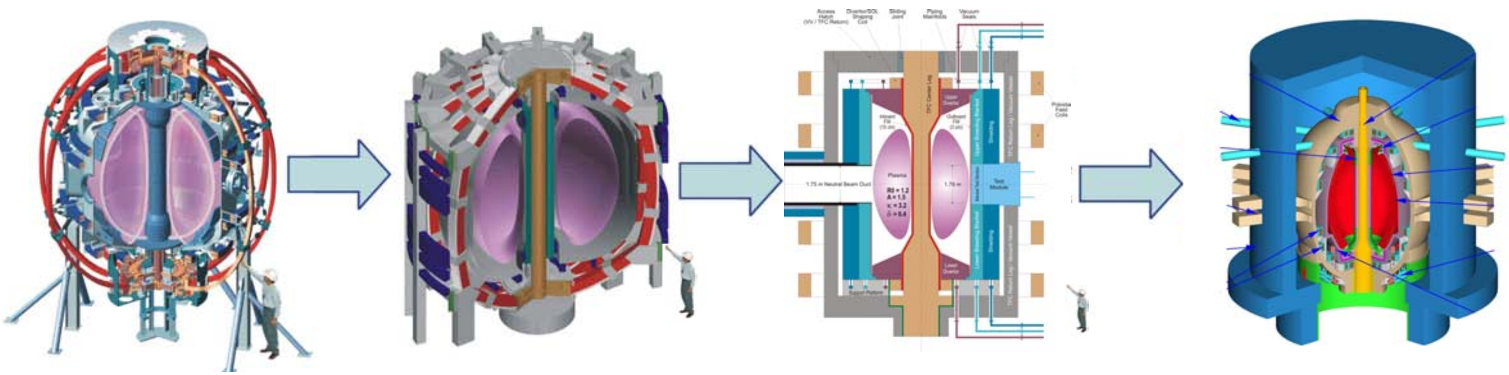


CompX, MIT, PPPL, ORNL, UCSD

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

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

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

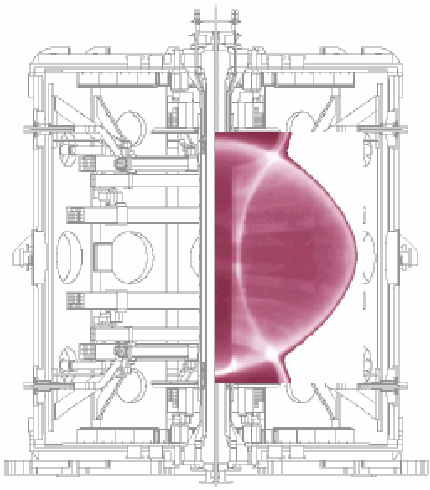


Device	NSTX		NSST		CTF		DEMO
Mission	Proof of Principle		Performance Extension		Energy Development, Component Testing		Practicality of Fusion Electricity
R (m)	0.85		**~1.5**		**~1.2**		~3
a (m)	0.65		~0.9		~0.8		~2
κ, δ	2.5, 0.8		~2.7, ~0.7		~3, ~0.5		~3.2, ~0.5
I_p (MA)	**1.5**	**1**	**~5**	**~10**	~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.

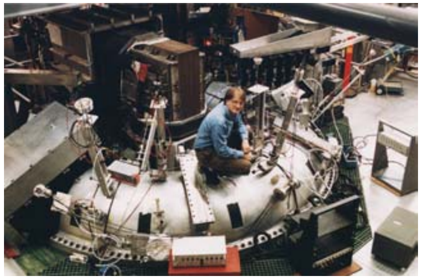
ST Research Has Broad and Growing Opportunities for Collaborations

- **Exploratory ST's in Japan**
  - **TST-2**: ECW-EBW initiation
  - **TS-3,4**: FRC-like $\beta \sim 1$ ST plasmas
  - **HIST**: helicity injection physics
  - **LATE**: solenoid-free physics
- **Active participation in ITPA (ITER)**
  - A and β effects on confinement, ITB, ELM's, pedestal, SOL, RWM, and NTM; scenarios, window coating, etc.
- **ST Database with MAST, U.K.**
  - NBI H-mode, transport, τ_E
  - EBW H&CD (1 MW, 60 GHz), FY03
  - Divertor heat flux studies, FY03-04
  - NTM, ELM characterization
- **DIII-D & C-Mod collaboration**
  - Joint experiments: RWM, Fast ion MHD, pedestal, confinement, edge turbulence, X-ray crystal spectrometer
- **MST:** electromagnetic turbulence, EBW

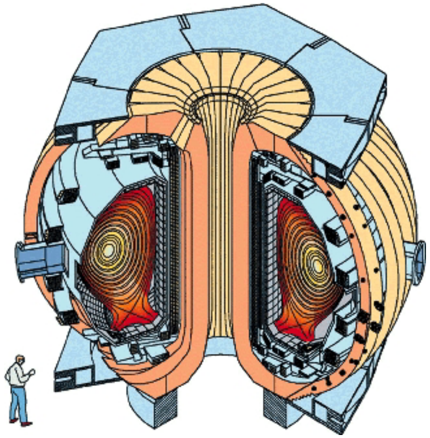
MAST (U.K.)



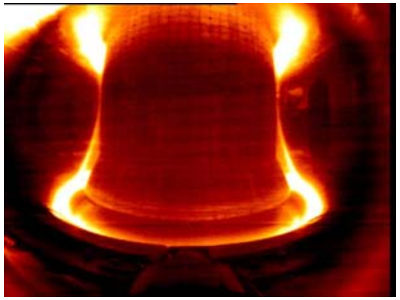
MST (U.S.)



DIII-D (U.S.)



C-Mod (U.S.)

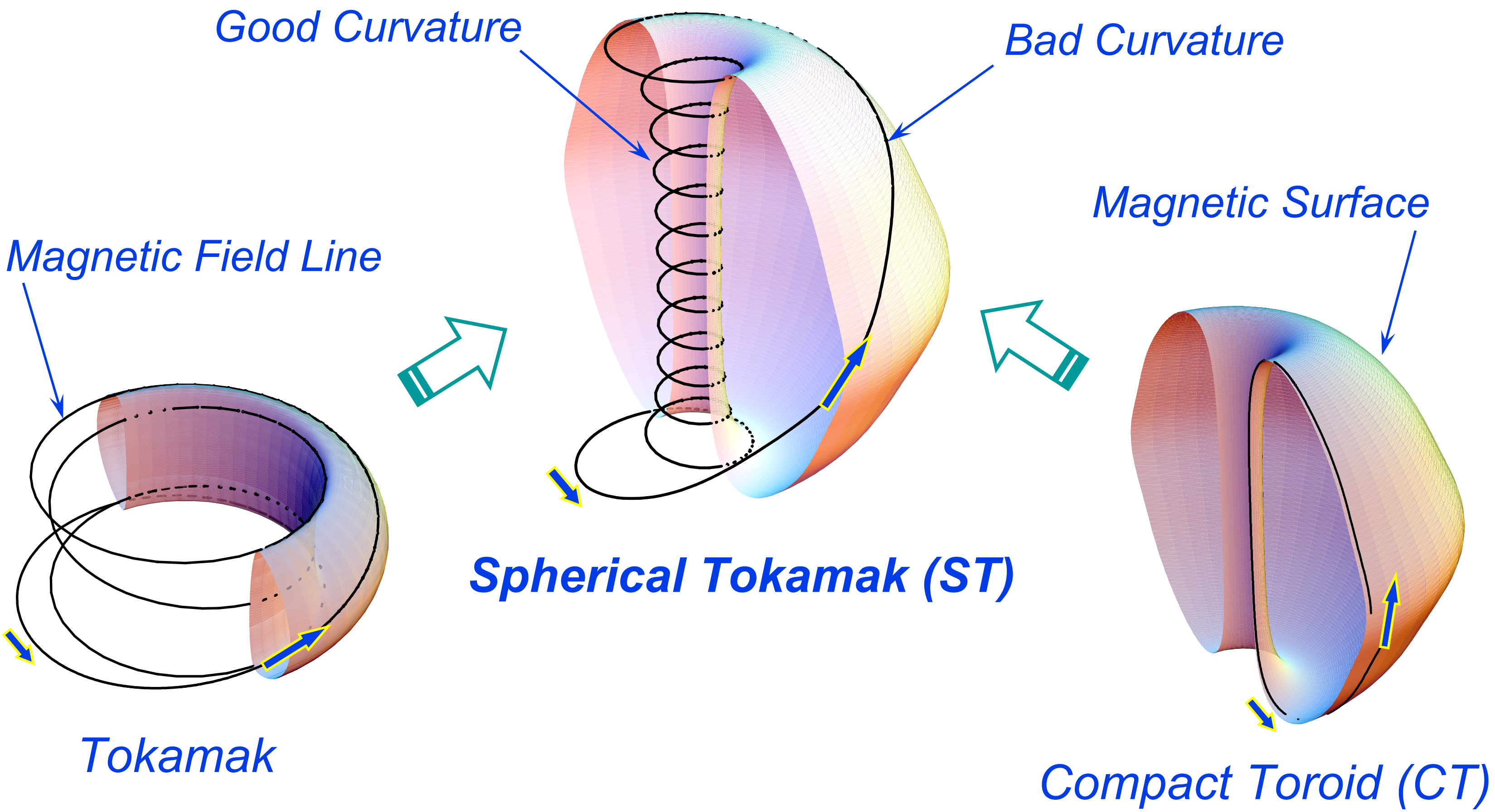


Spherical Tokamak (ST) Offers Rich Plasma Science Opportunities and High Fusion Energy Potential

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

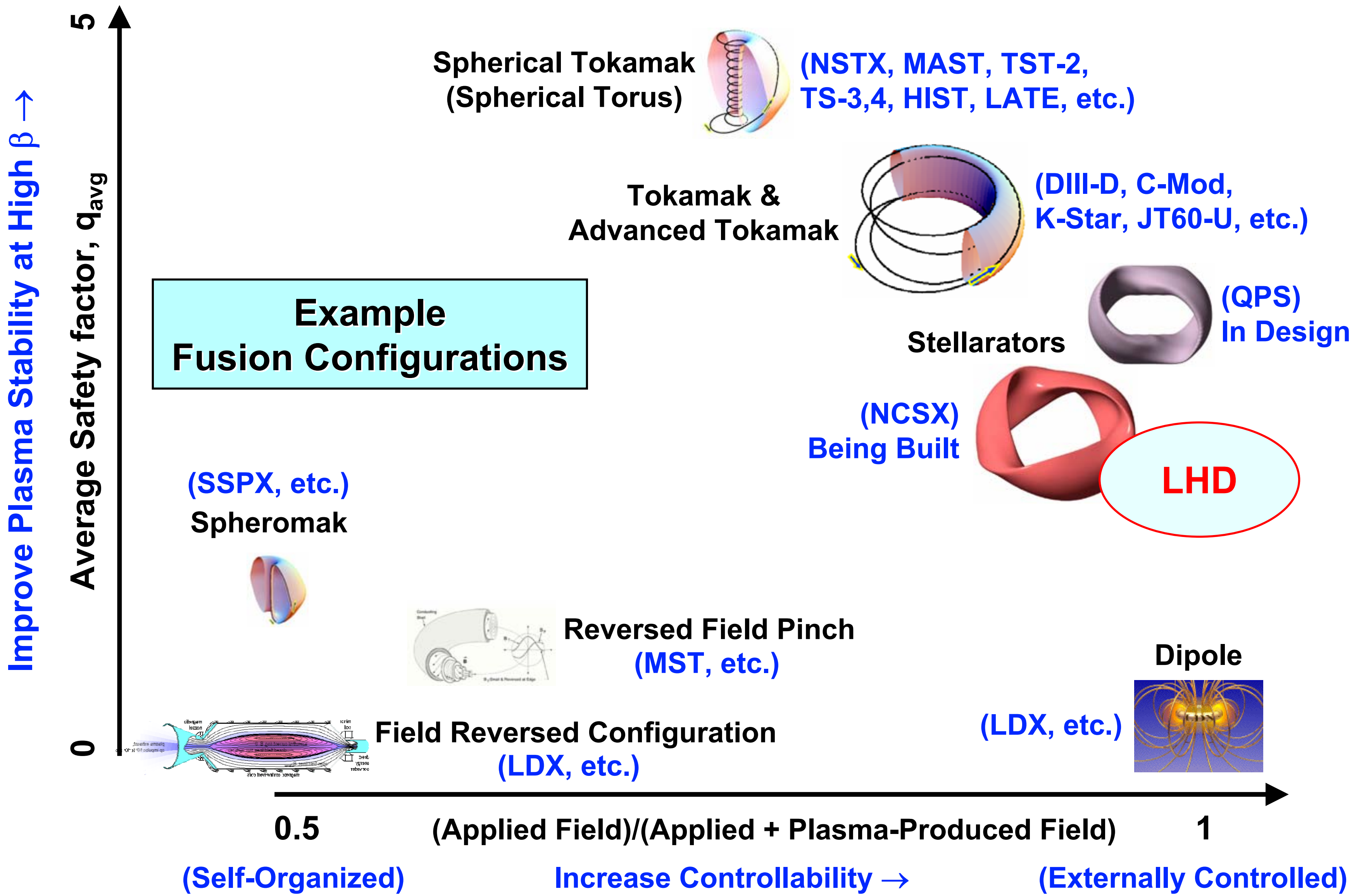
Backup VUs

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

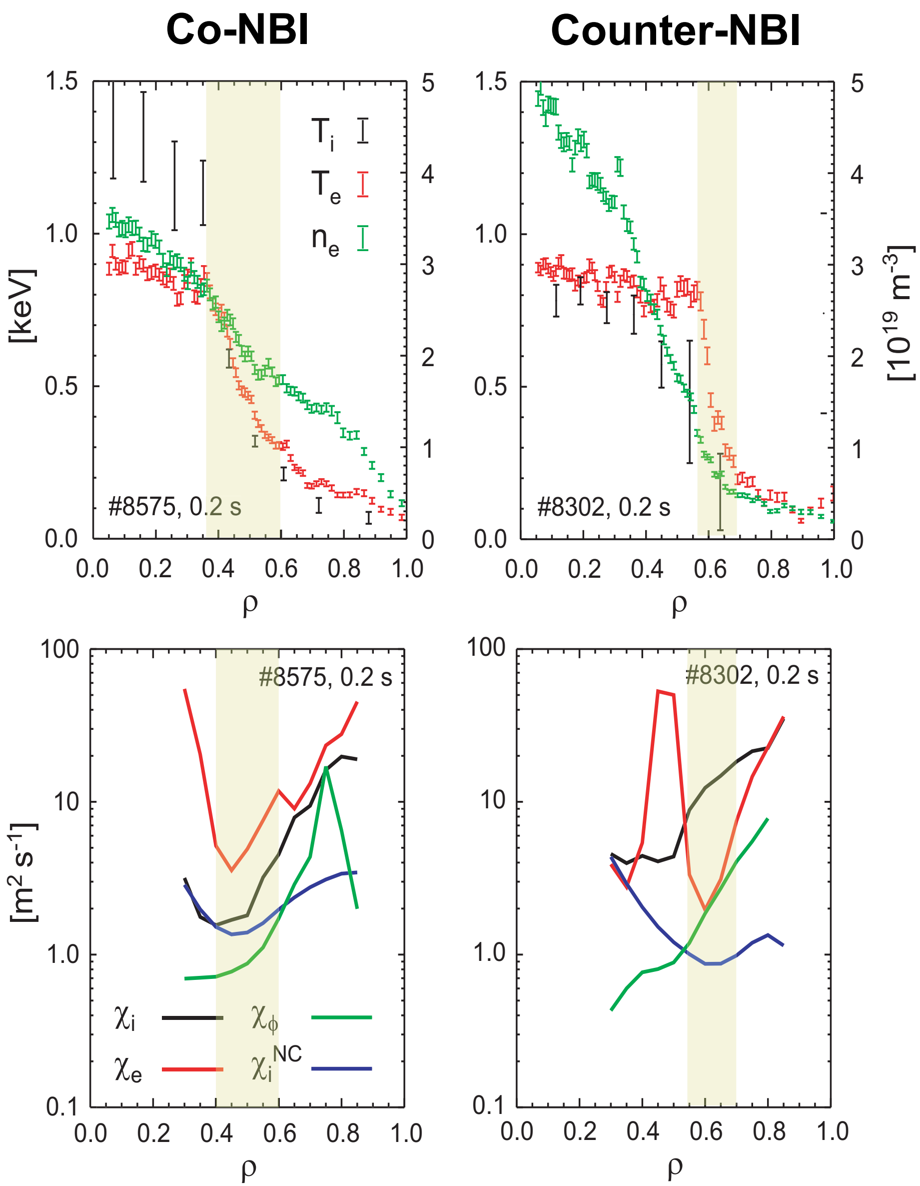


Small-R close to Tokamak & large-R close to CT.

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



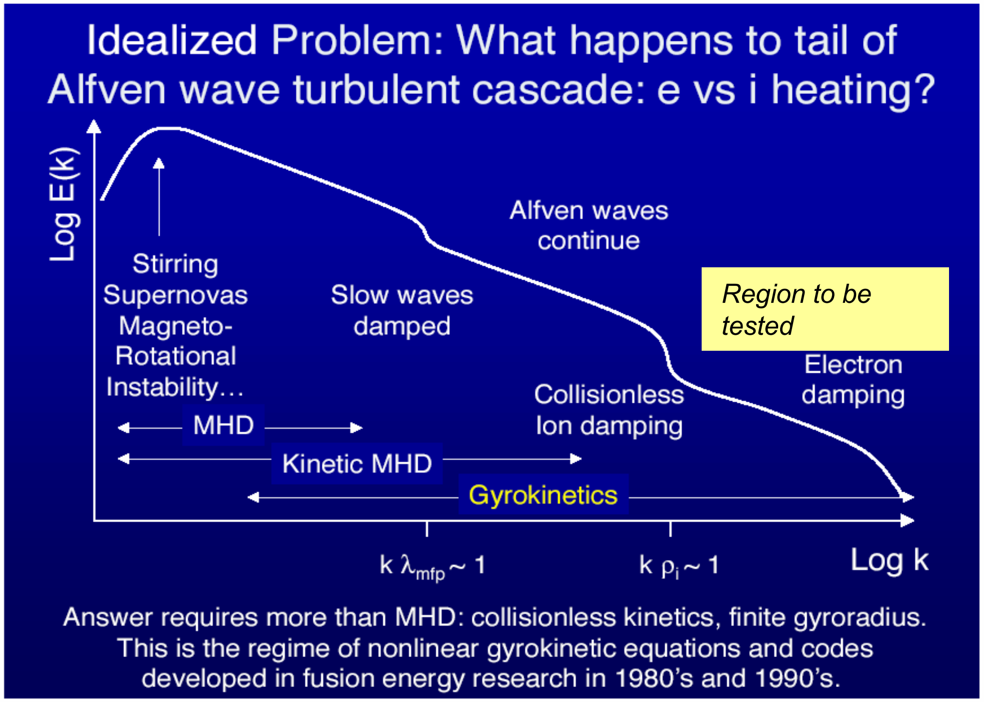
In MAST, However, Counter NBI Reduces Electron Energy Loss



High flow shear scenario on MAST (Co- & Counter-NBI)

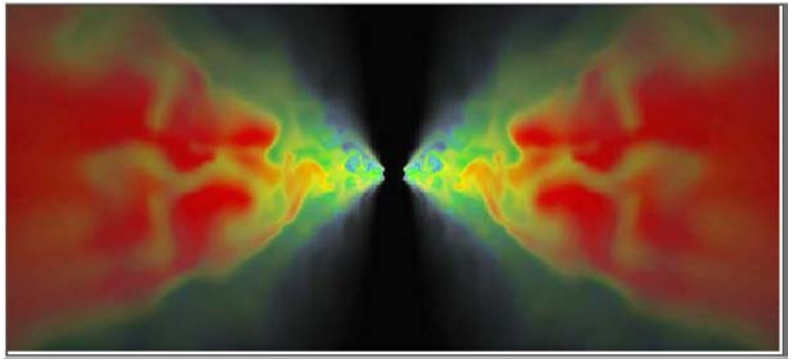
- Counter-NBI produces stronger $\omega_{SE} \sim 10^6\ s^{-1}$ and strong local reduction in χ_e at broader radius
- Pressure gradient contribution to E_r reinforces that due to V_ϕ with ctr-NBI
- Strong ExB flow shear and weak magnetic shear s ~ 0 produced by NBI heating during current ramp
- With co-NBI ion thermal transport reduced to N.C. level $\chi_i \sim \chi_i^{NC}$ with weaker reduction in χ_e
- Strong ExB flow shear $\omega_{SE} > \gamma_m^{ITG}$ and s ~ 0 at minimum of $\chi_{i,e}$

Detailed Diagnosis and Gyrokinetic Analysis of $\beta \sim 1$ Turbulence Has Broad Scientific Importance



Can $k_\perp \rho_i \geq 1$ turbulence at $\beta \sim 1$ be understood?

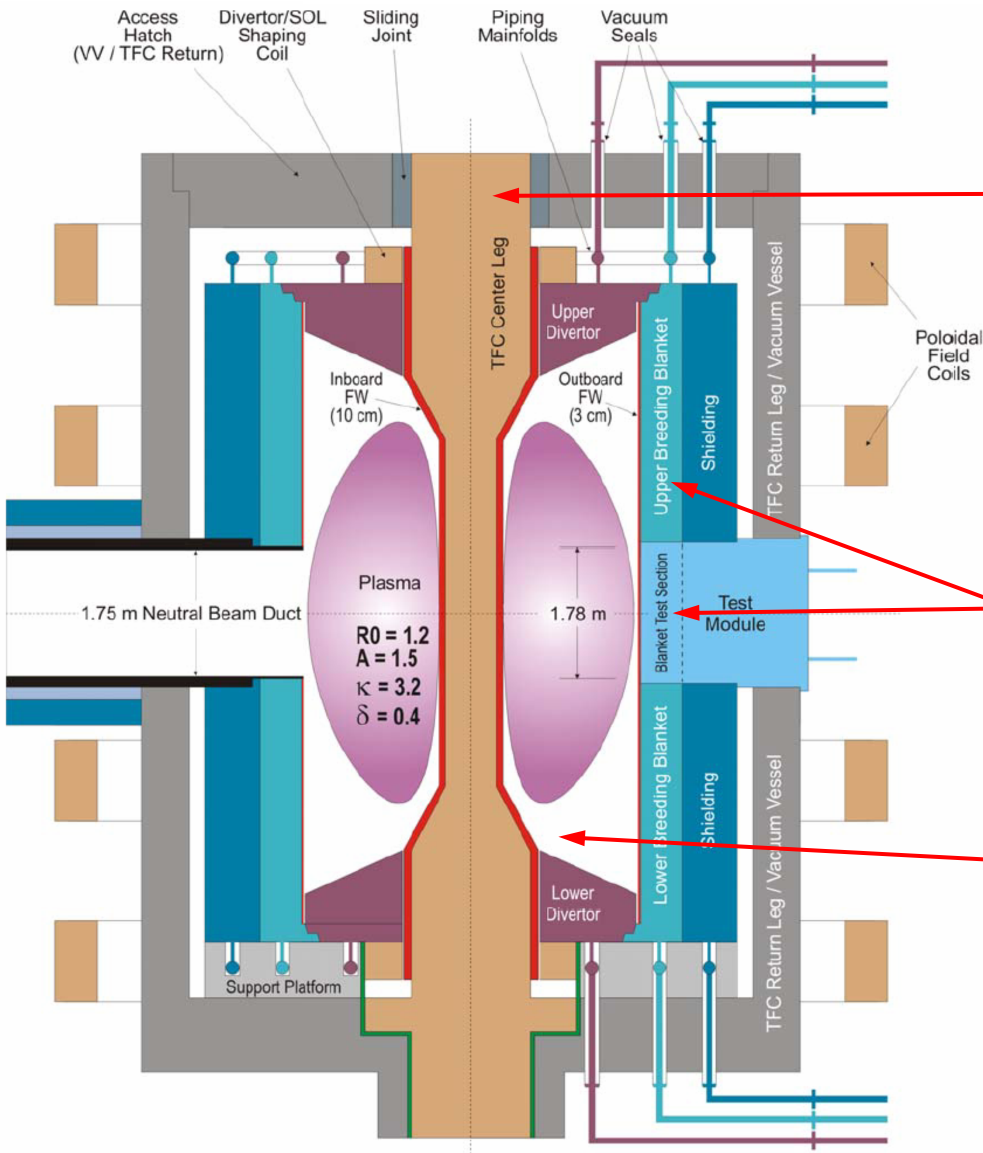
Armitage (U. Colorado)



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

Optimized Device Configuration Features of ST Can 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.