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Spherical Tokamak Plasma Science & Fusion Energy

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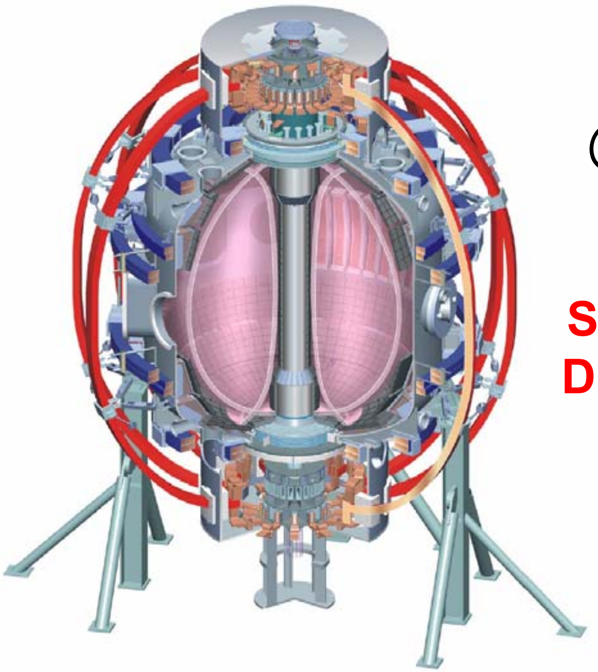
@ Princeton Plasma Physics Laboratory

Second Japan-Korea Seminar on Advanced Diagnostics for Steady-State Fusion Plasma

Korea Basic Science Institute (KBSI)
August 25-27, 2004
Daejon, Korea



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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 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:

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

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

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

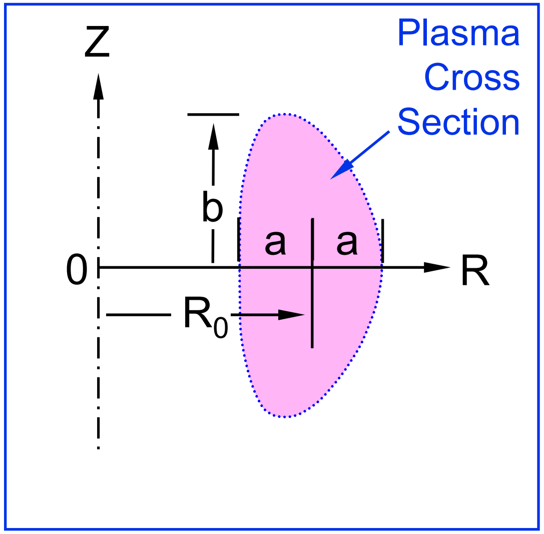
$\kappa = b/a$ = elongation

$A = R_0/a$ = aspect ratio

$q_I \approx$ average safety factor

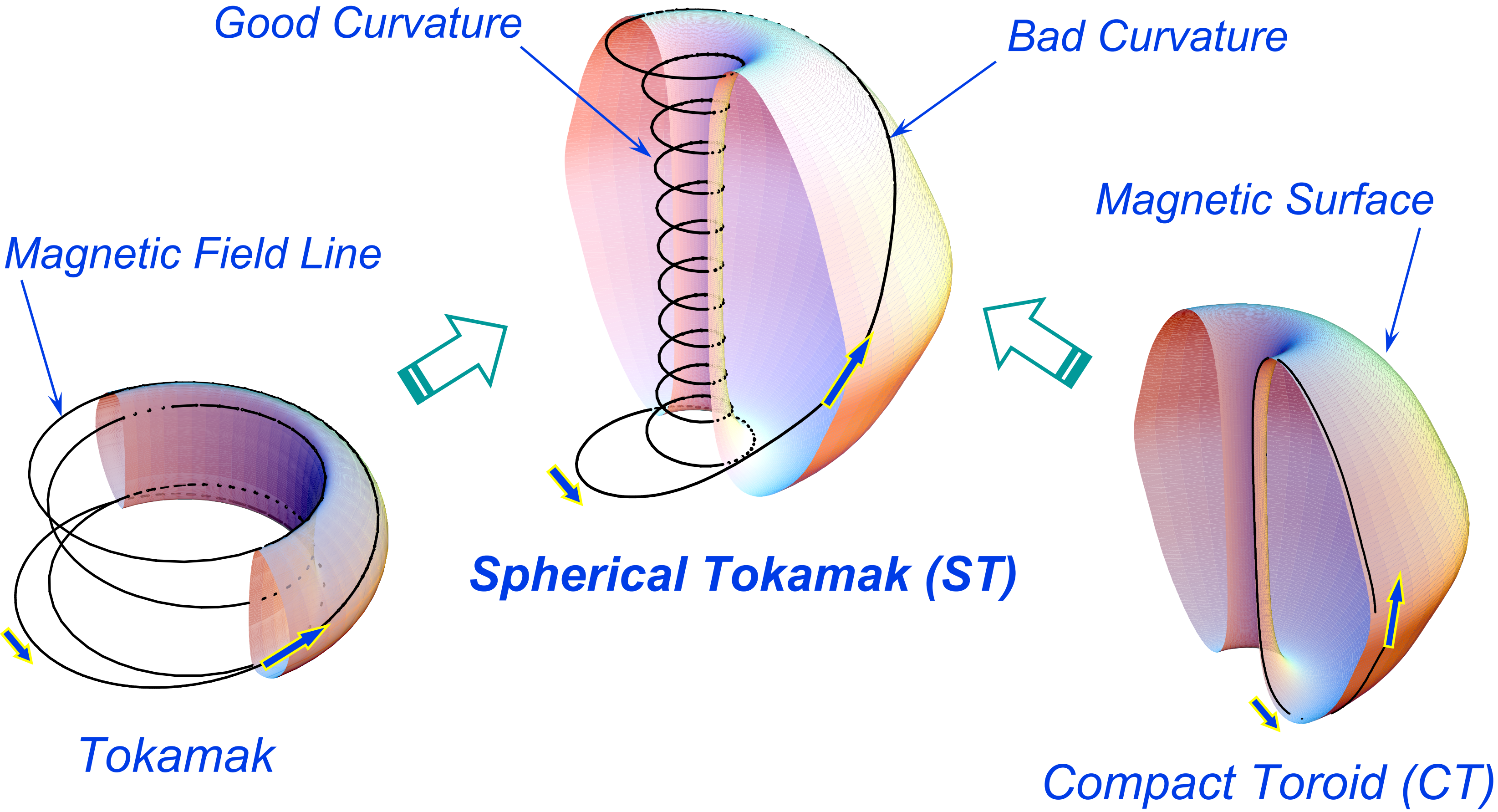
I_p = toroidal plasma current

$B_T \approx$ applied toroidal field at R_0



- Peng & Strickler (1986): **What would happen to tokamak as A → 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



Good Curvature

Bad Curvature

Magnetic Surface

Magnetic Field Line

Spherical Tokamak (ST)

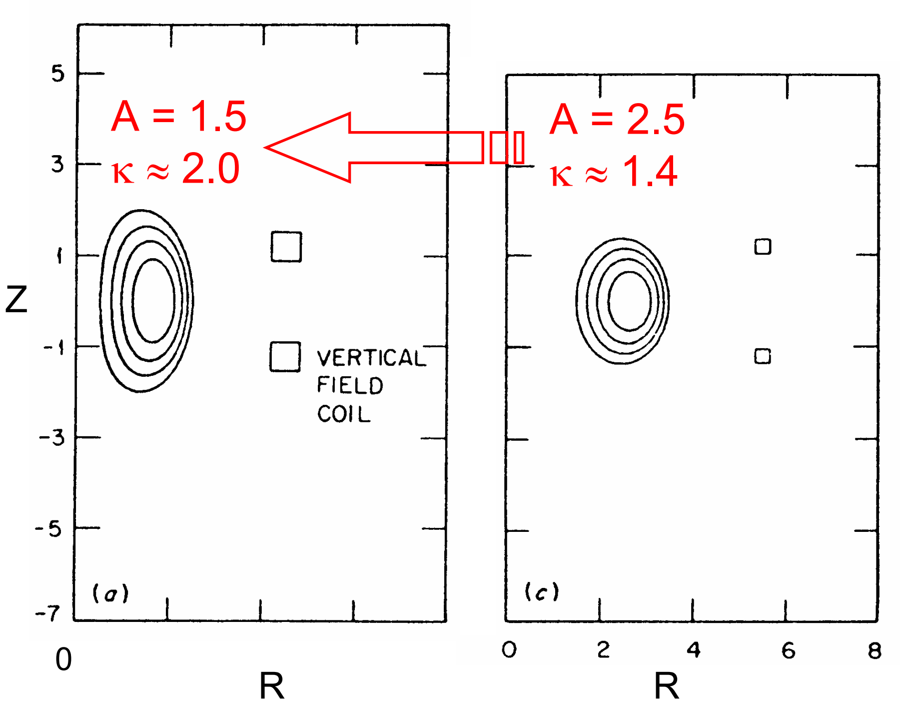
Tokamak

Compact Toroid (CT)

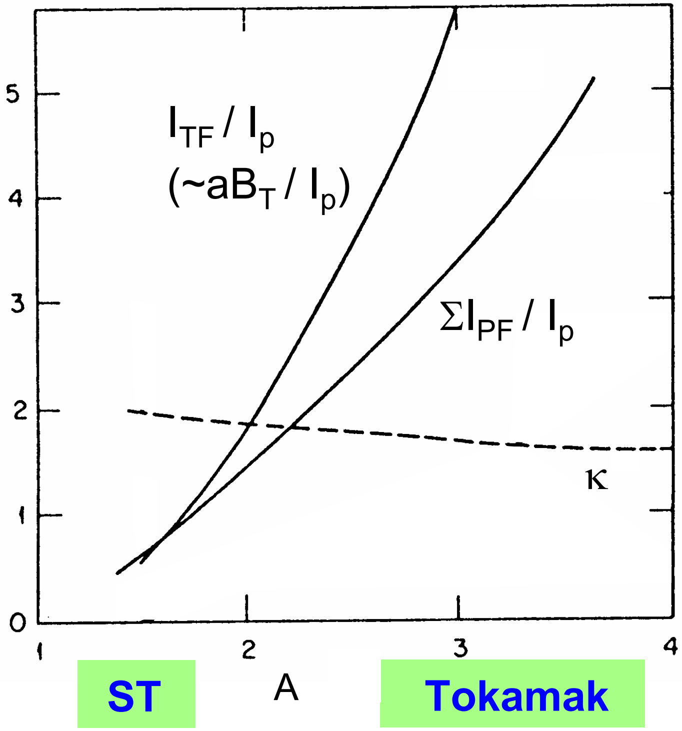
Small-R close to Tokamak & large-R close to CT.

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

Natural Elongation, κ



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



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

START – UKAEA Fusion

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 ($a/\rho_i \sim 30–50$)
- 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

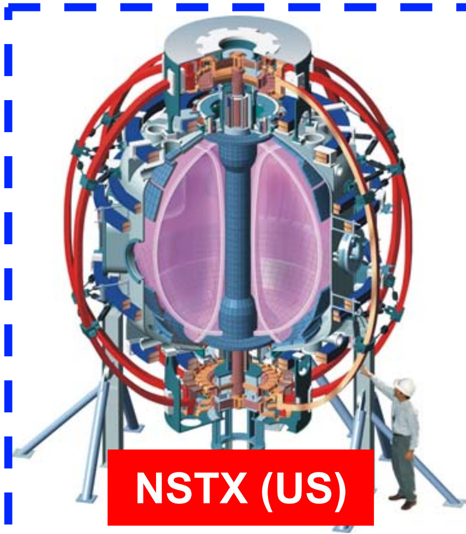
How to supply mag flux without solenoid?

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

ST Research Is Growing Worldwide

Φ **Concept Exploration (~0.3 MA)**

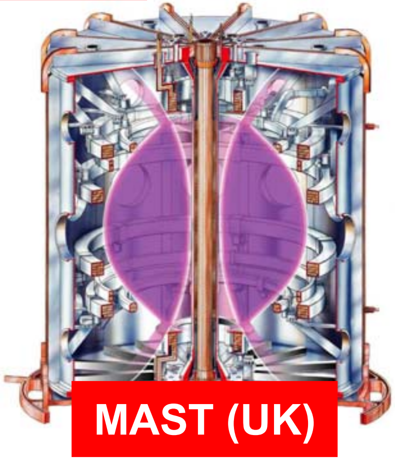
Φ **Proof of Principle (~MA)**



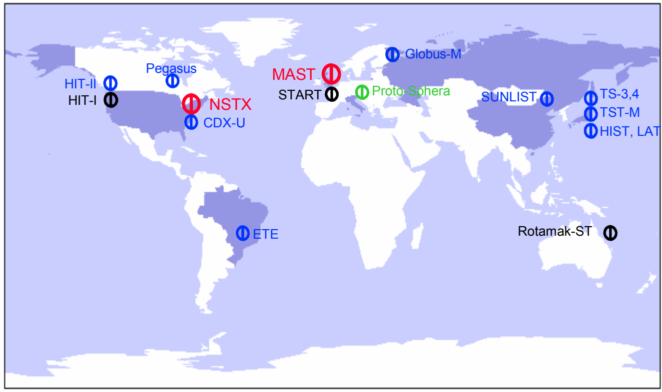
NSTX (US)

HIT-II (US)

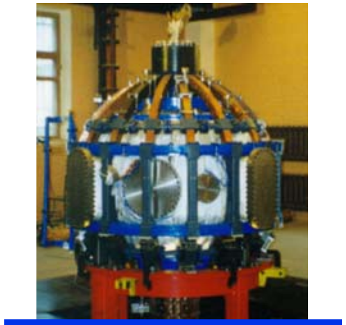
Pegasus (US)



MAST (UK)



CDX-U (US)



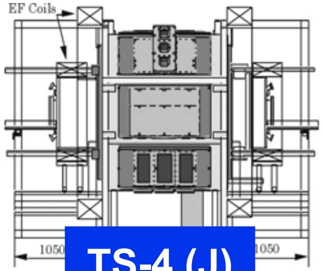
Globus-M (RF)

ETE (B)

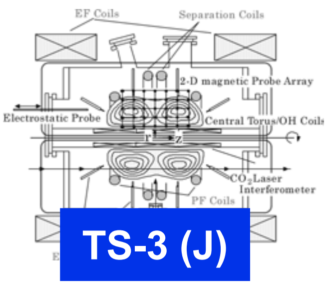
SUNIST (PRC)

HIST (J)

TST-2 (J)



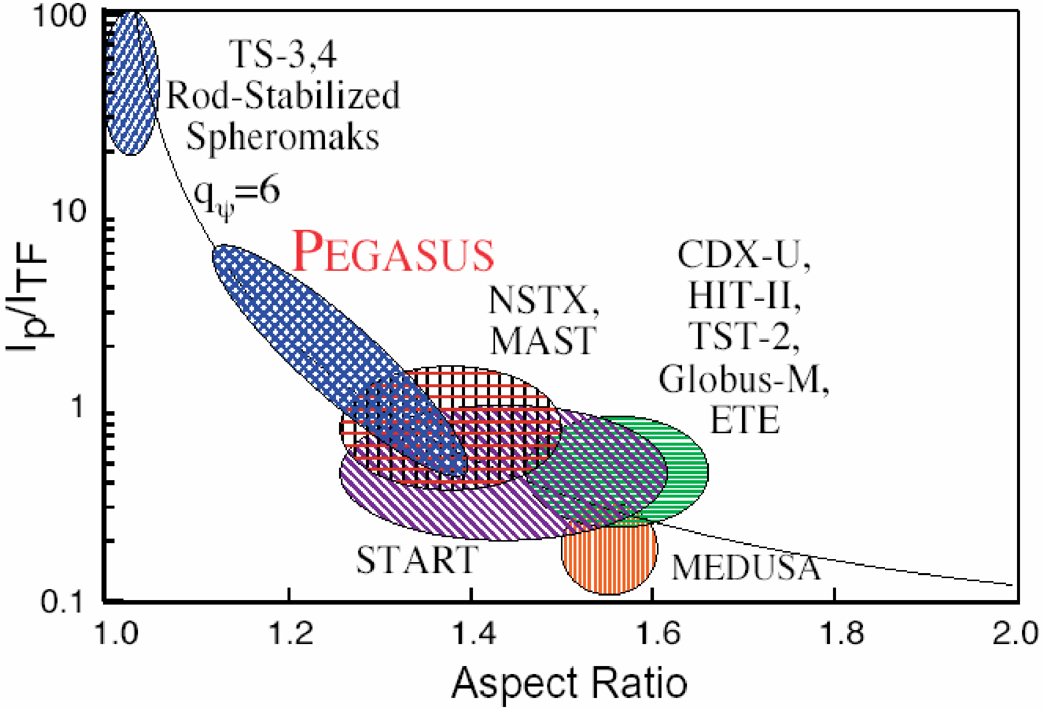
TS-4 (J)



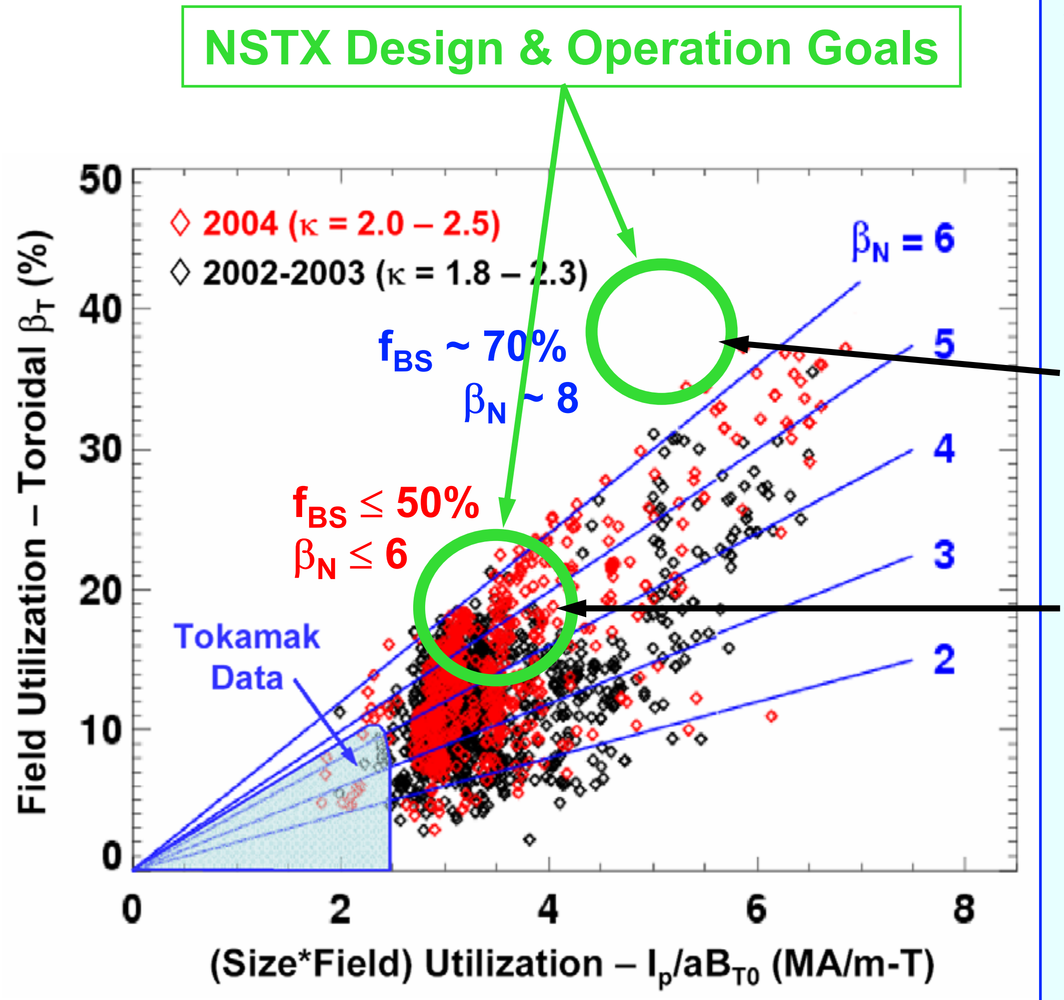
TS-3 (J)

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 Troyon Scaling at Higher I_p/aB_T Indicating Better Field and Size Utilization at Low A



Columbia U, LANL, PPPL

- Obtained high beta values:

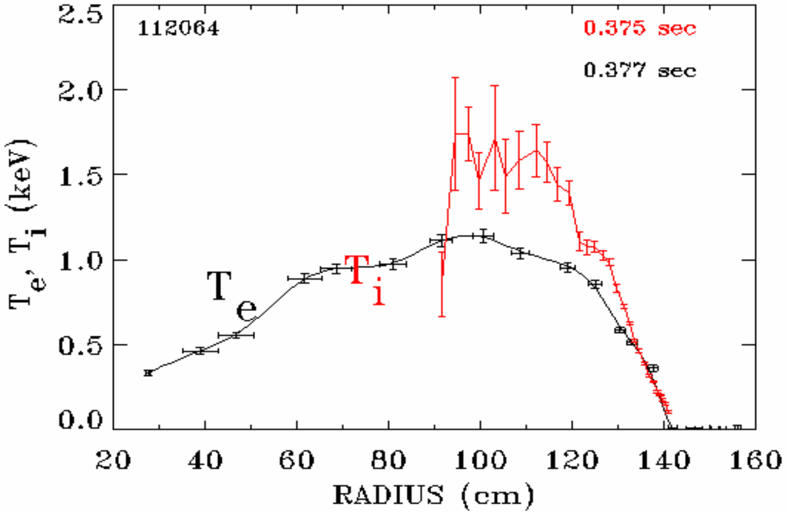
  $\beta_T = 2\mu_0\langle p\rangle / B_{T0}^2 \leq 38\%$

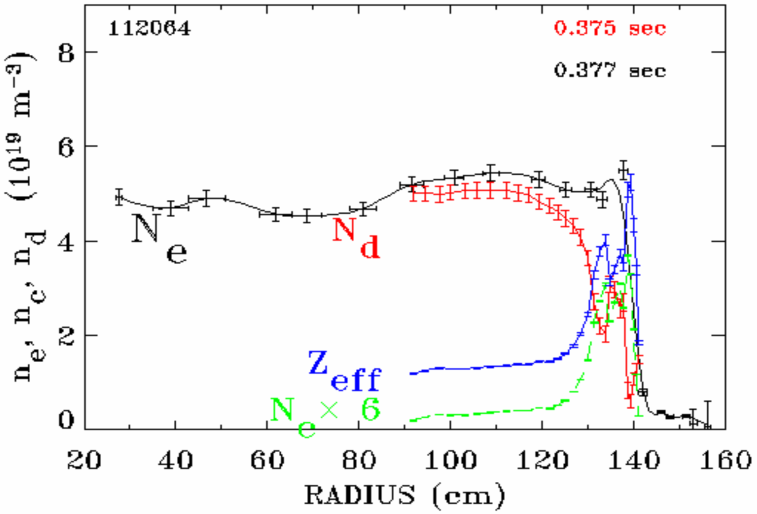
  $\beta_N = \beta_T / (I_p/aB_{T0}) \leq 6.4$

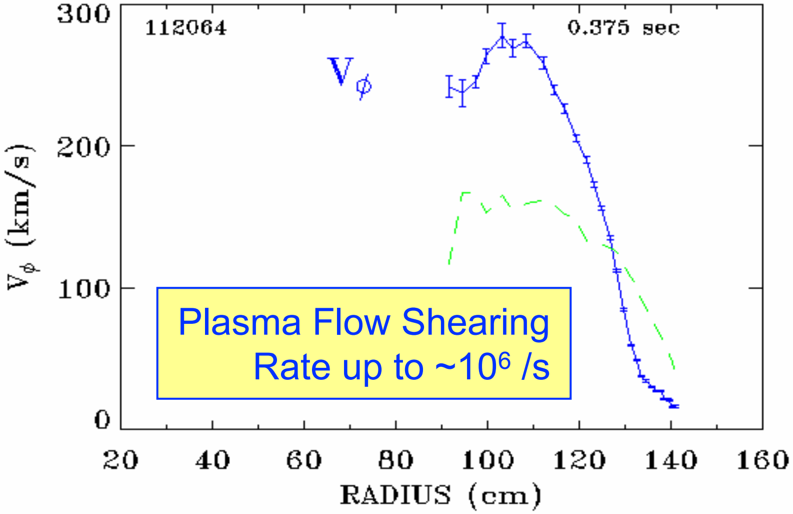
  $\langle\beta\rangle = 2\mu_0\langle p\rangle / \langle B^2\rangle \leq 20\%$

- To produce and study full non-inductive sustained plasmas
  - Relevant to **DEMO**
- Nearly sustained plasmas with neutral beam and bootstrap current
  - Relevant to **ITER** hybrid mode
  - Nearly basis for neutral beam sustained ST Component Test Facility (**CTF**) at Q~2

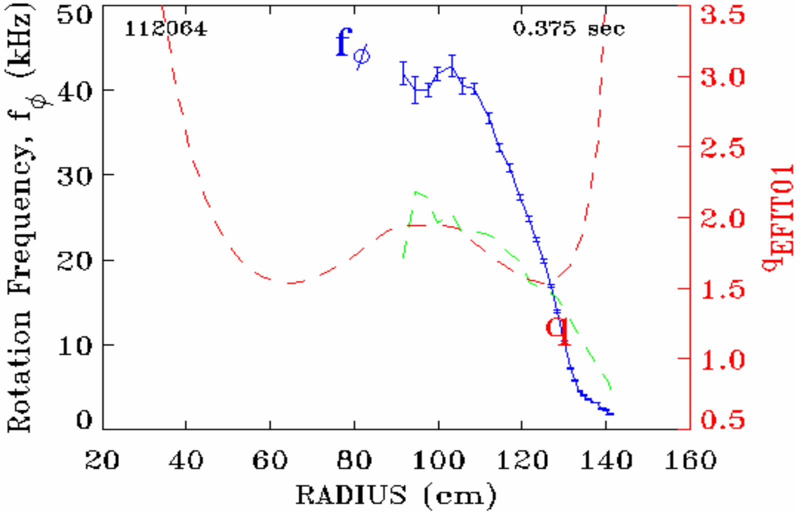
Detailed Measurements of Plasma Profiles Allows Physics Analysis and Interpretations



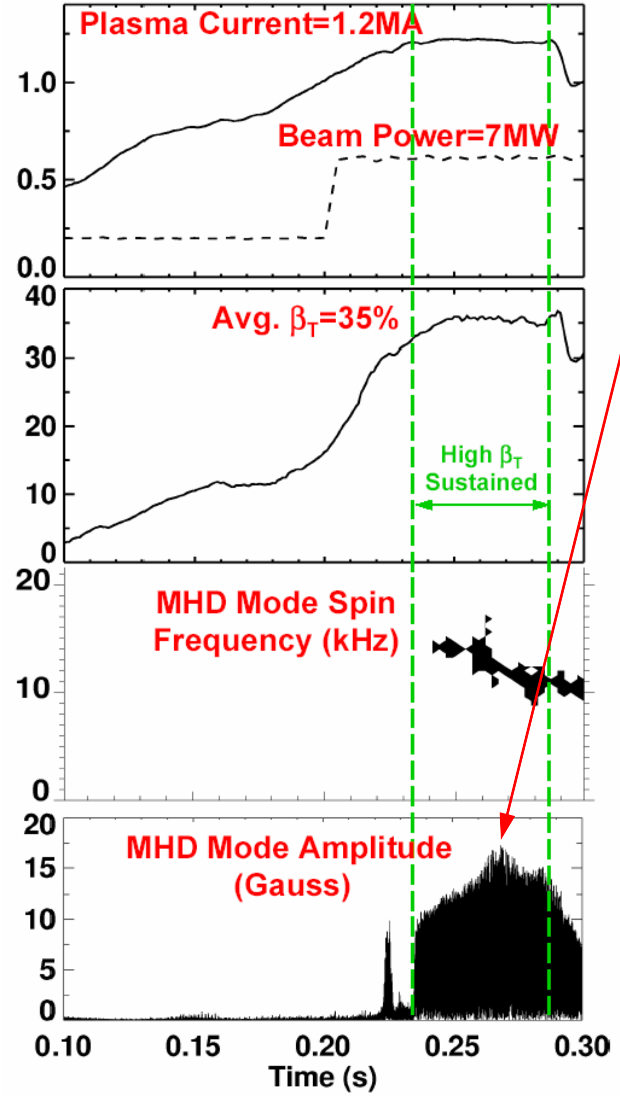




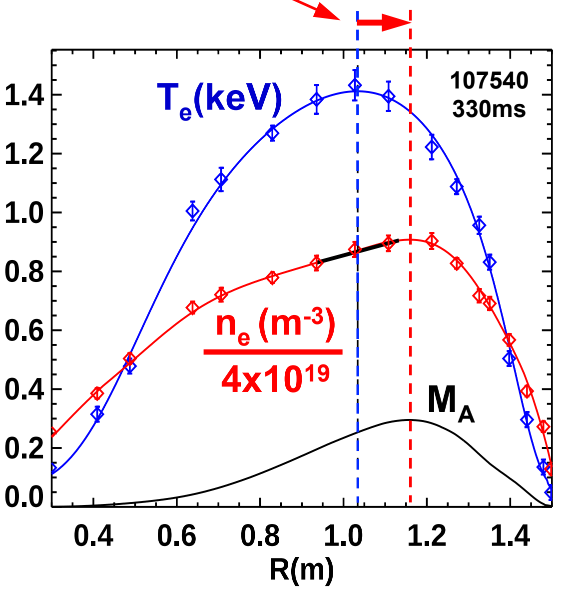
Plasma Flow Shearing Rate up to ~10^6 /s



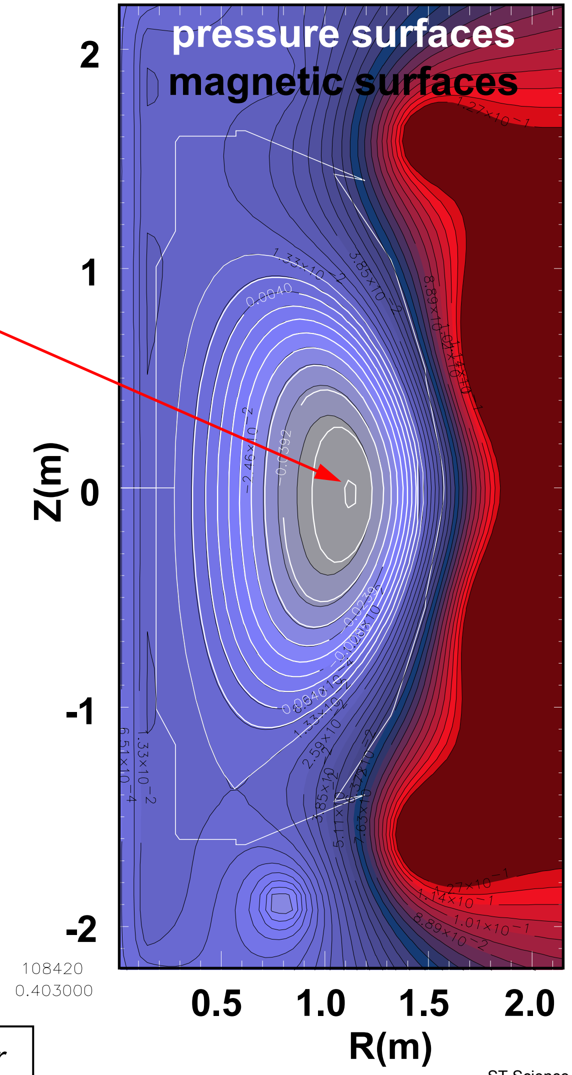
Strong Plasma Flow ($M_A=V_\phi/V_{Alfvén}$~0.3) Has Large Effects on Equilibrium and Stability



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



Equilibrium Reconstruction with Flow



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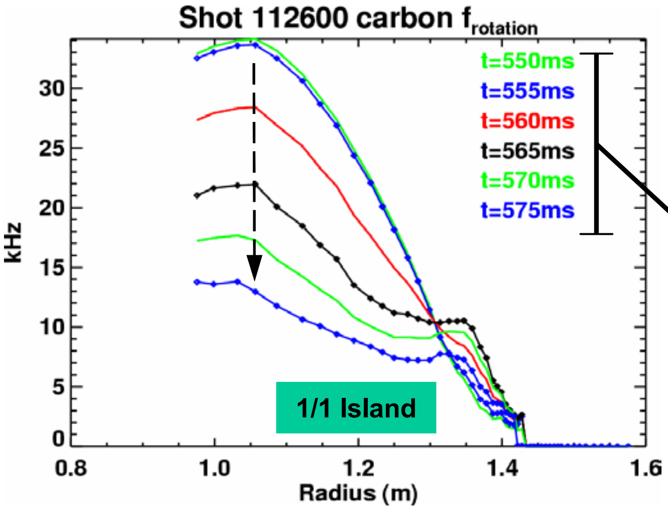
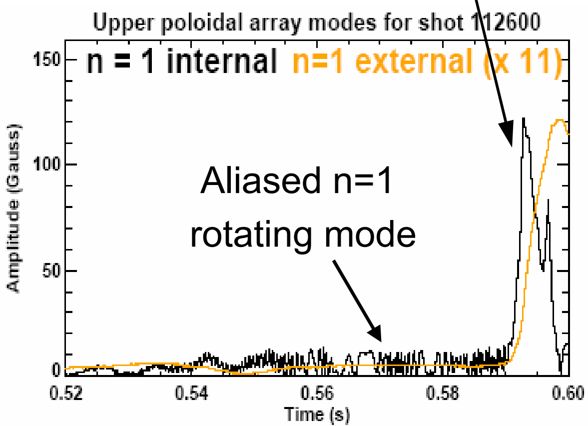
High-Resolution CHERS, SXR, and In-Vessel B_R and B_P Sensors Reveal Strong Mode-Rotation Interaction

NSTX

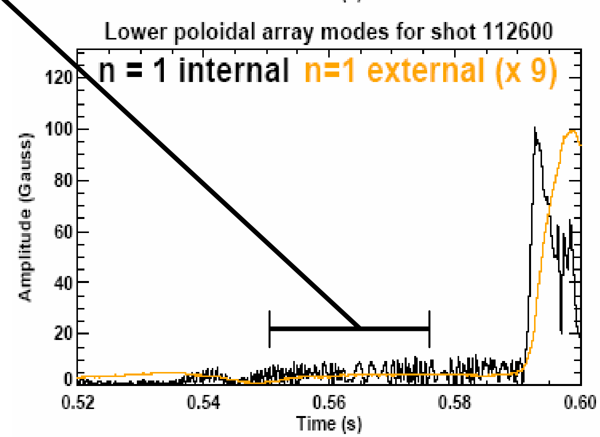
CHarge-Exchange Recombination Spectroscopy (CHERS) shows v_ϕ collapse preceding β collapse


Shot 112600 carbon $f_{rotation}$

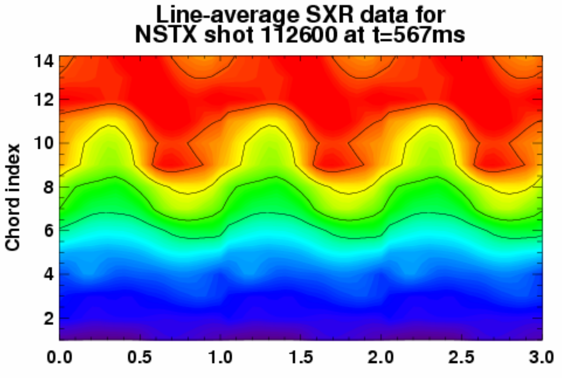
In-vessel sensors measure rotating mode as v_ϕ decays before mode locking

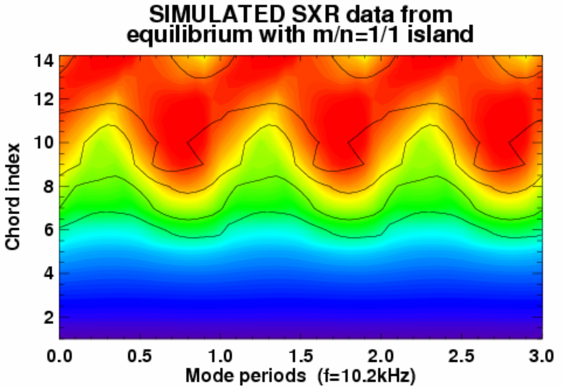

Upper poloidal array modes for shot 112600

Aliased n=1 rotating mode


Lower poloidal array modes for shot 112600

SXR shows rotating 1/1 mode during v_ϕ decay


Line-average SXR data for NSTX shot 112600 at t=567ms

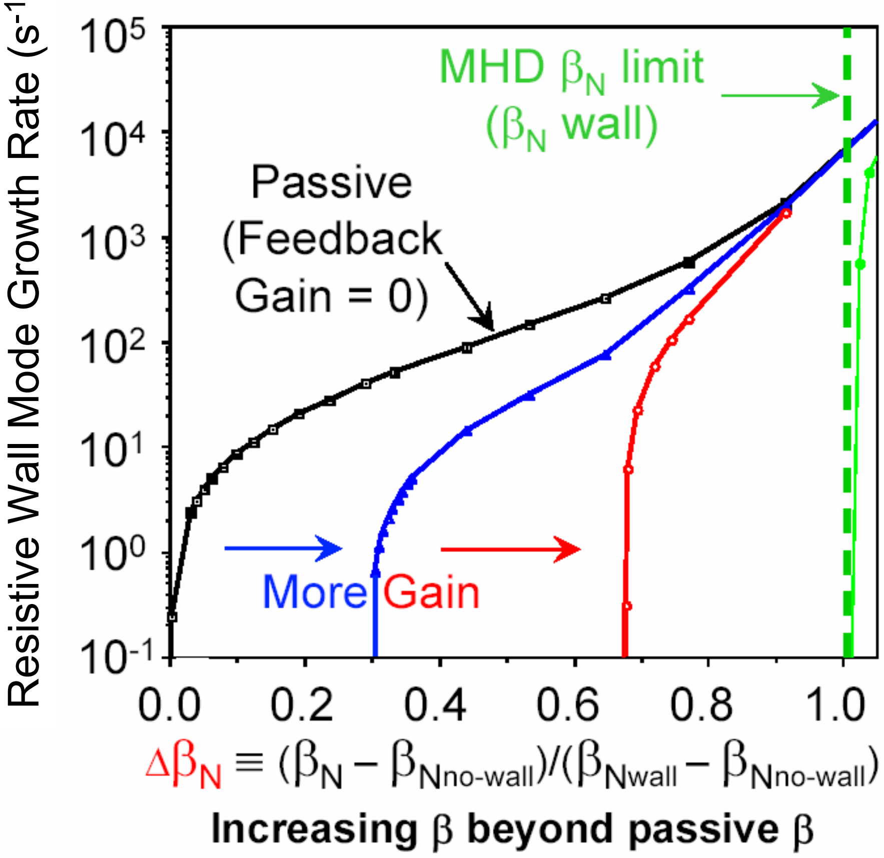

SIMULATED SXR data from equilibrium with m/n=1/1 island

Sabbagh, Bell, Menard, Stutman

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

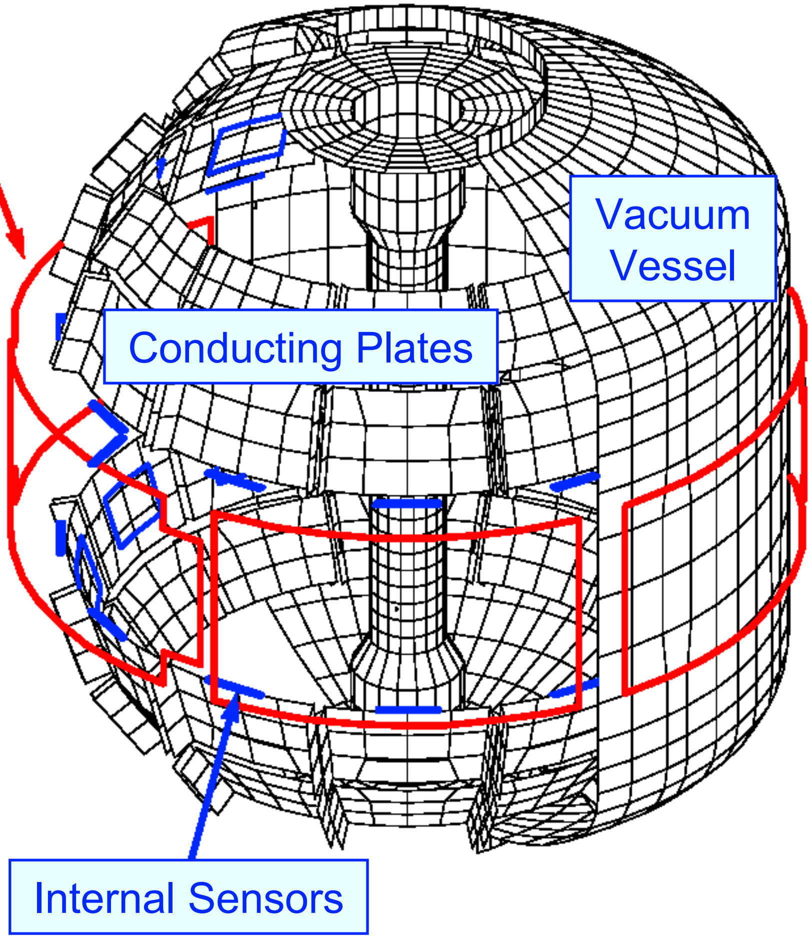
Active Control Will Enable Study of Wall Mode Interactions with Error Fields & Rotation at High β_T

Ex-Vessel Feedback Control Coils are being built



VALEN model of NSTX

(cutaway view)



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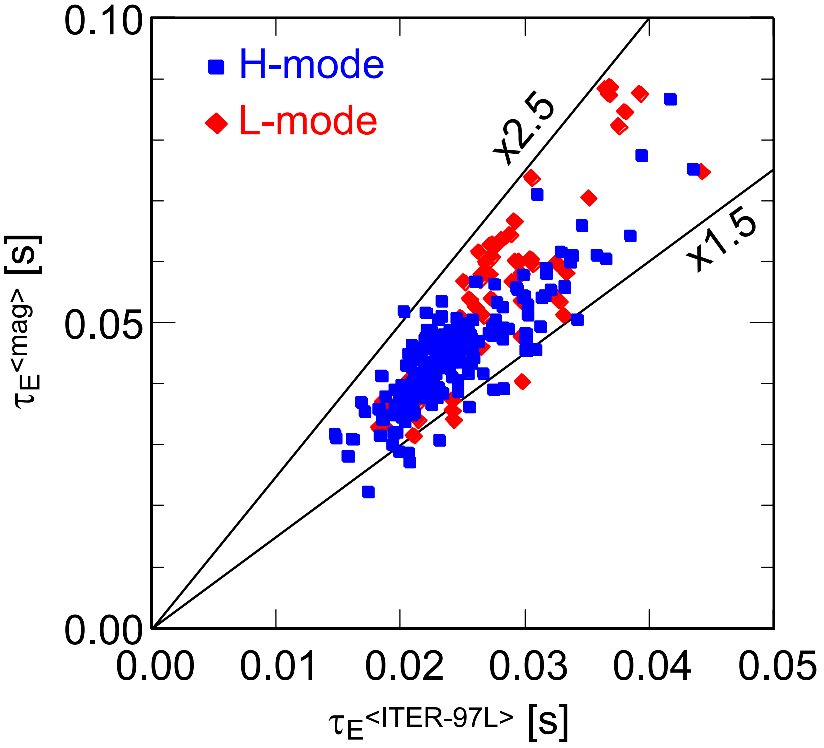
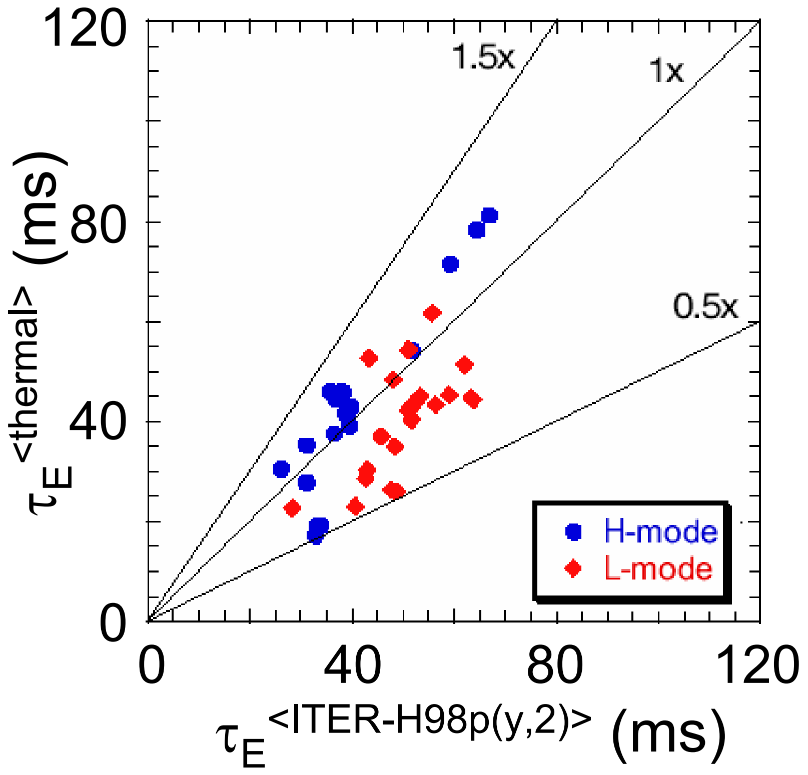
Global and Thermal τ_E's Compare Favorably with Higher A Database





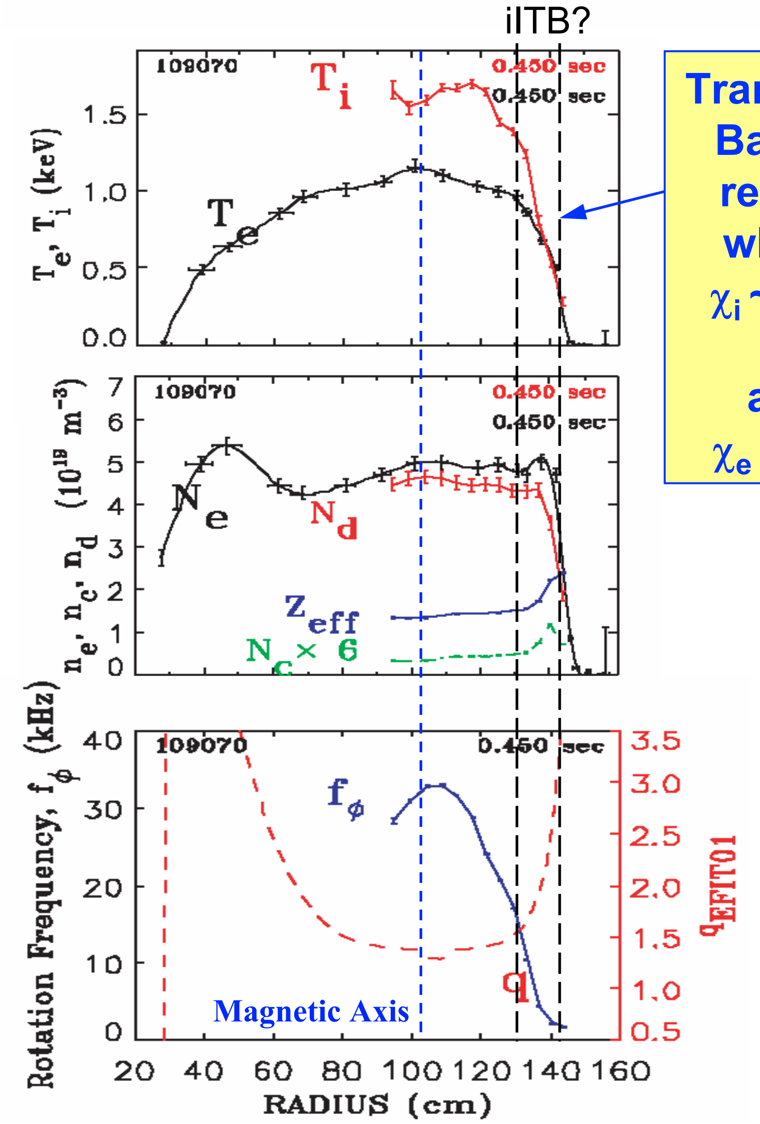
- Compare with ITER scaling for total confinement, including fast ions
- TRANSP analysis for thermal confinement

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

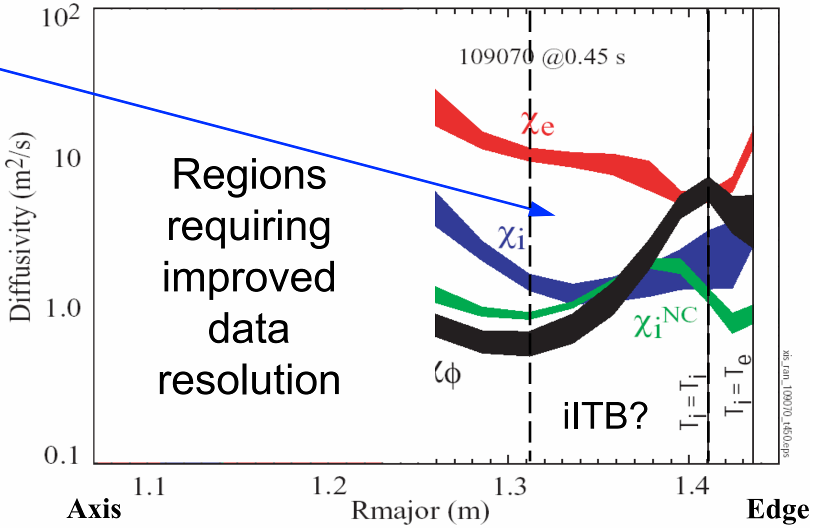
NSTX



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

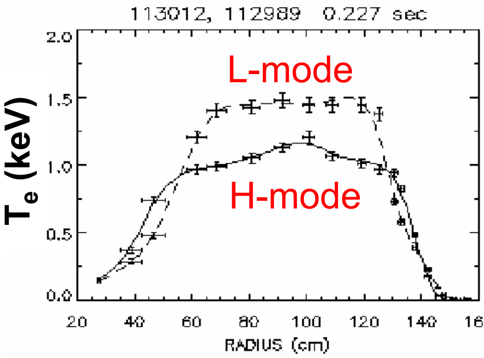
and $\chi_e >> \chi_i$

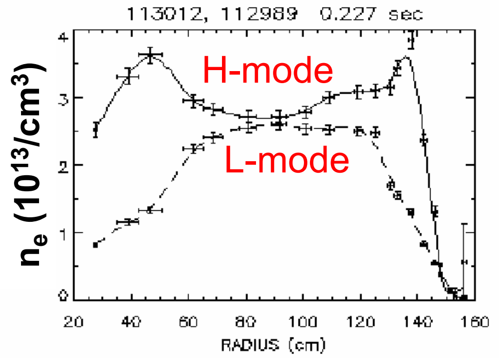
Kinetic Profile Local Error Sampling



Regions requiring improved data resolution

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

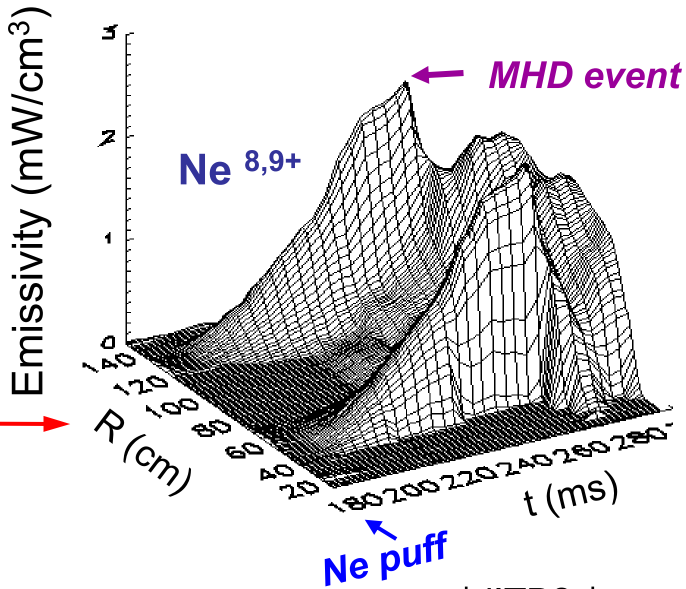


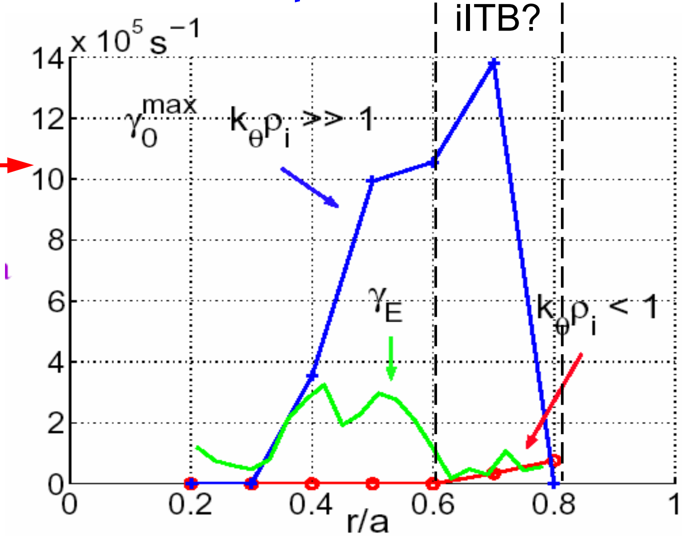


Columbia U, Culham, ORNL, PPPL

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

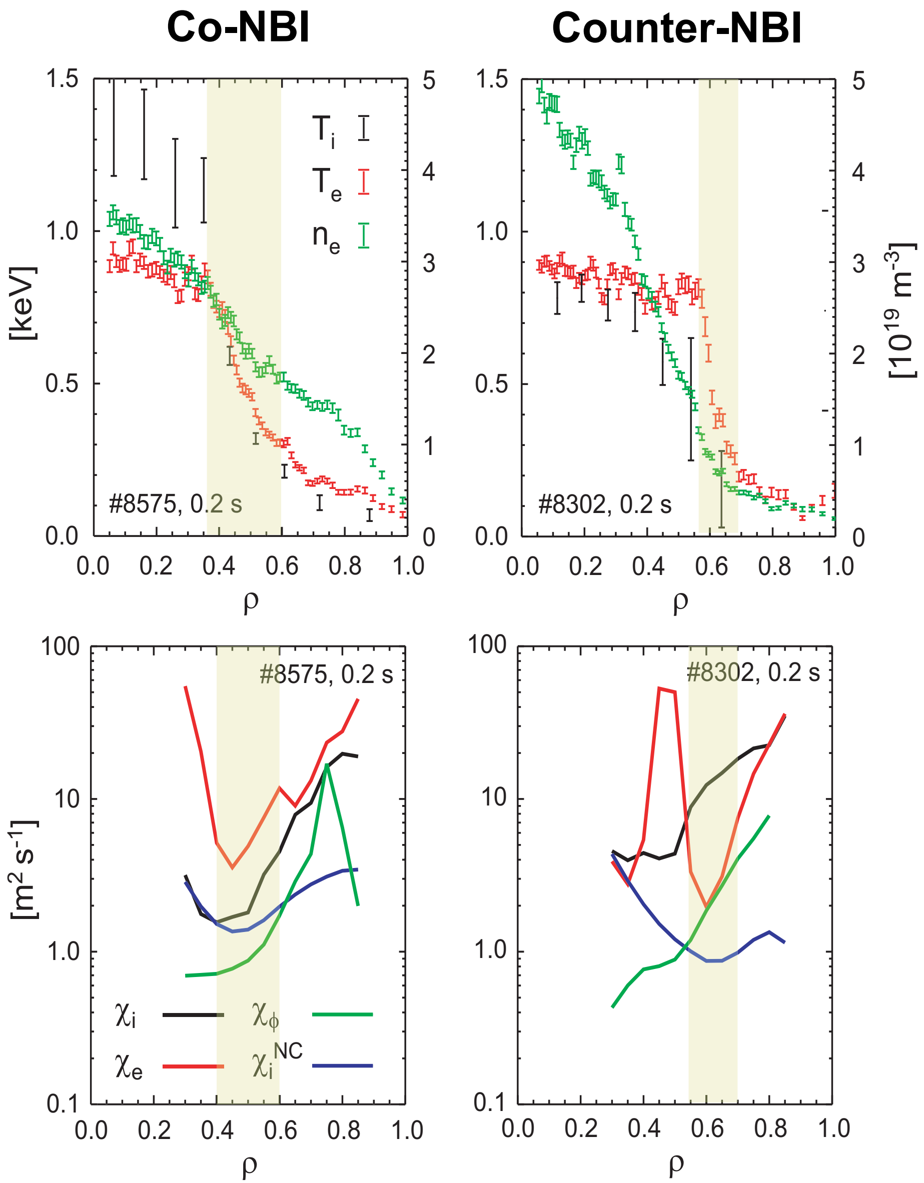
Core Transport Physics	In ion confinement zone
Thermal Conductivity	• $\chi_{ion} \sim \chi_{neoclassical}$ • $\chi_{elec} >> \chi_{ion}$
Impurity Diffusivity	• $D_{imp} \sim D_{neoclassical}$
Micro-instability calculations	• Driven by T and n gradients • $k_\theta \rho_i < 1$ (ion gyro-scale) stable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





Cadarache, JHU, PPPL, U. Maryland

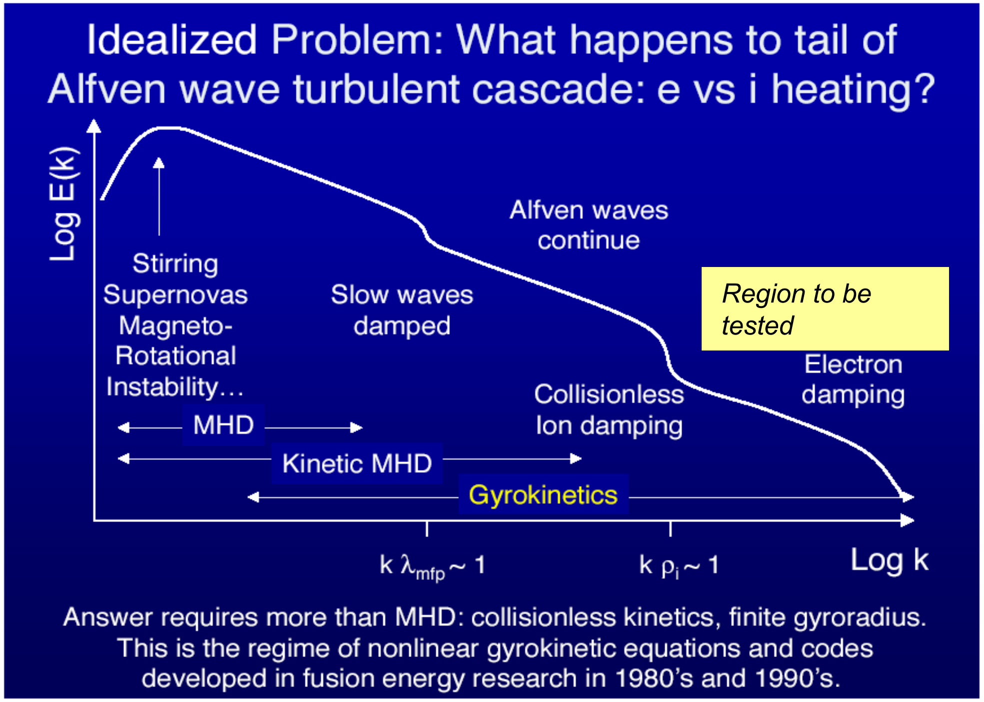
In MAST, However, Counter NBI Reduces Electron Energy Loss



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

- Counter-NBI produces stronger ω_{SE} ~ 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

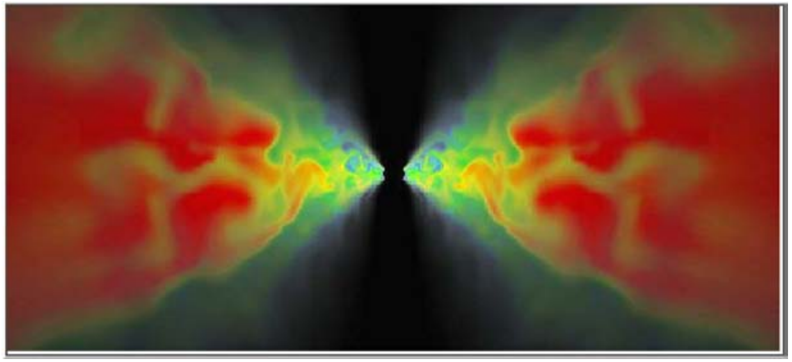


Idealized Problem: What happens to tail of Alfven wave turbulent cascade: e vs i heating?

Answer requires more than MHD: collisionless kinetics, finite gyroradius. This is the regime of nonlinear gyrokinetic equations and codes developed in fusion energy research in 1980's and 1990's.

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

Armitage (U. Colorado)

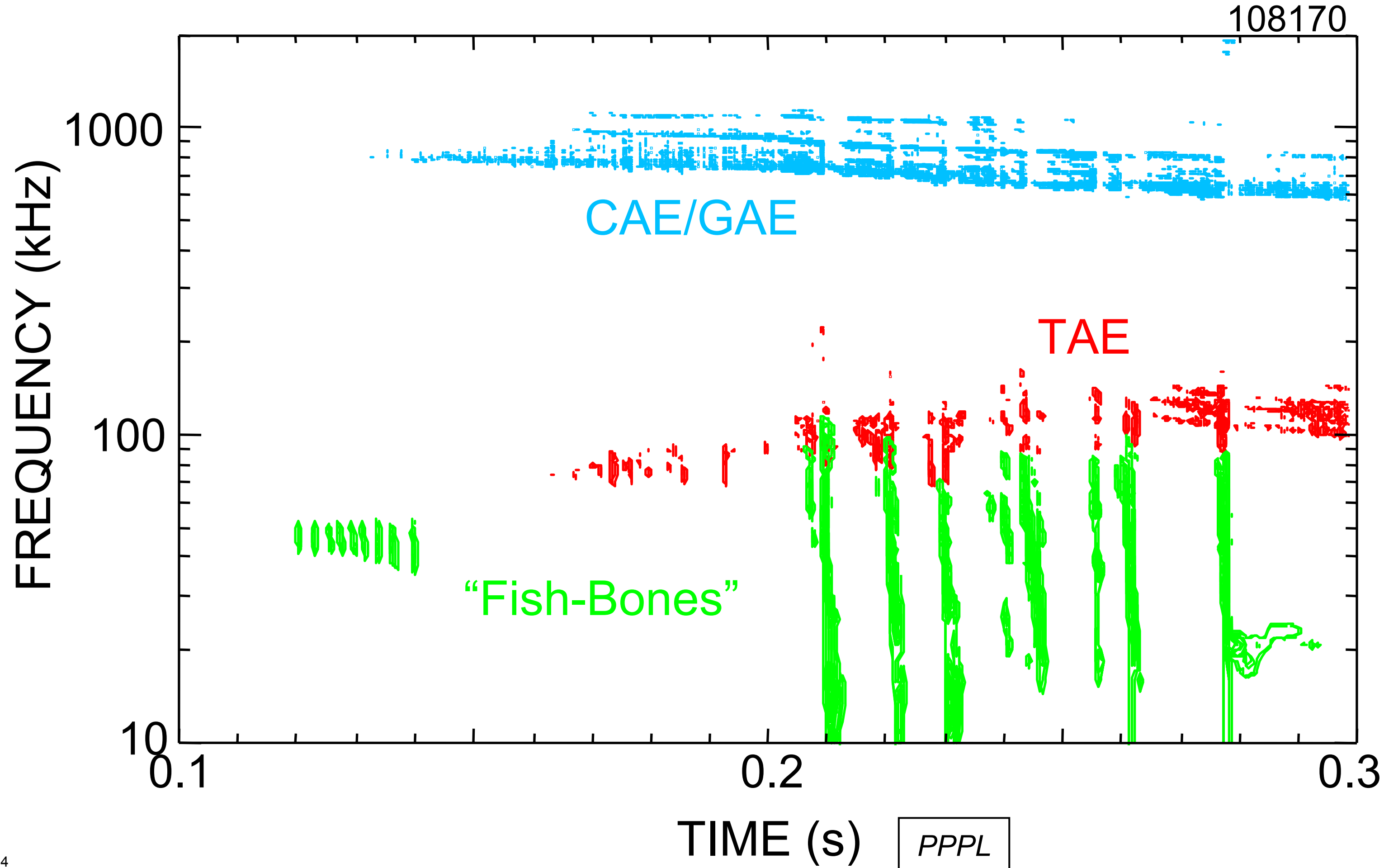


Gyrokinetic turbulence simulation in accretion disk of supermassive black hole at galactic center, assuming damping of turbulence by plasma ions vs. electrons

- 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

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

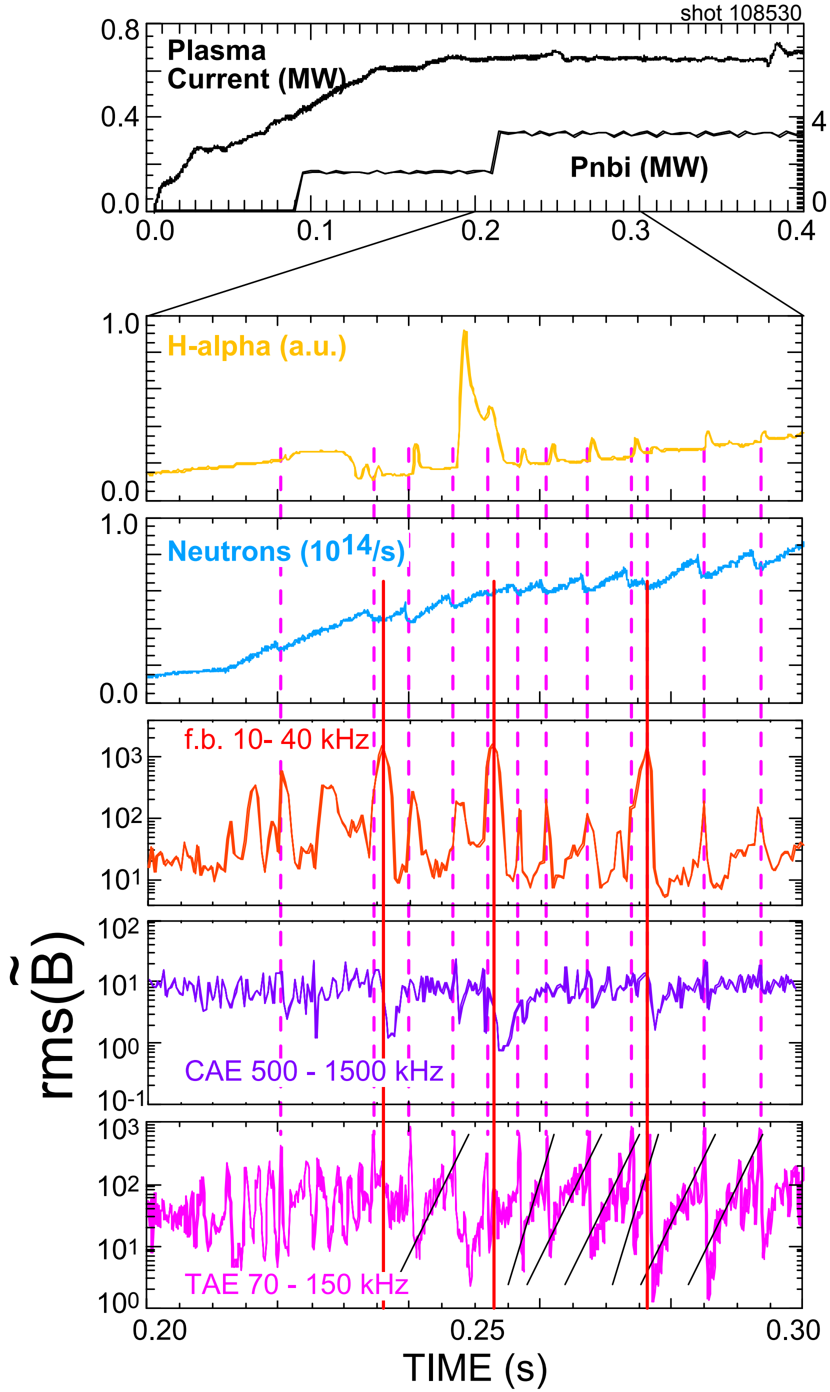
Do these Alfvén Eigenmodes (AEs) and fish-bones (f.b.s) Interact to expel energetic particles?



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

NSTX

(I_p = 0.65 MA, P_b = 3.6 MW, β_{T0} = 10%)



Synchronous sudden activities of

- Edge ionization rises
- D-D neutron drops
- Fish-bone modes rises
- TAE mode crashes
- Separately, asynchronous drops of f.b. and CAE modes
- So far only for $\beta_{T0} \leq$ 10% and $I_p \leq$ 700 kA $\Rightarrow$ high-β stabilization?
- Relevant to lower β burning plasmas (**ITER**)

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

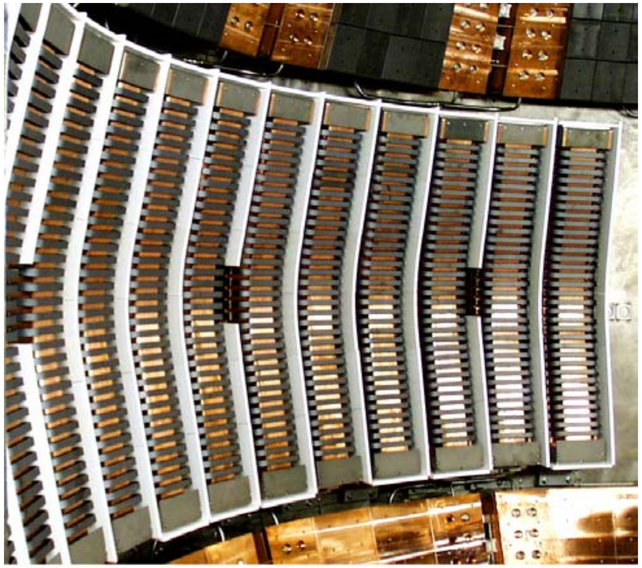
M. Ono (1995): High Harmonic Fast Wave (HHFW) decay (absorption) rate:

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

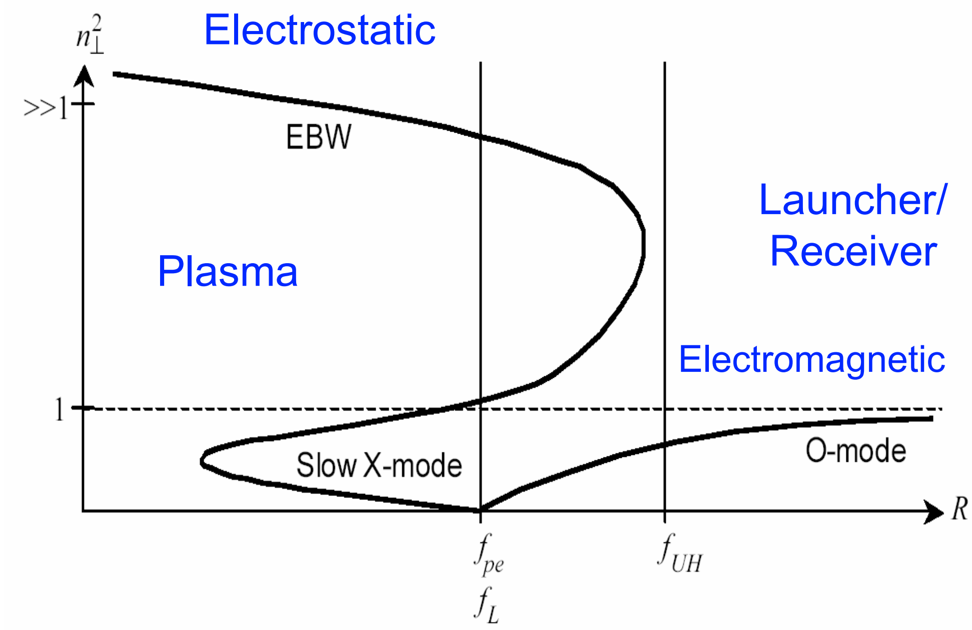
$$\varepsilon = \omega_{pe}^2 / \omega_{ce}^2 \sim 10^2$$

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

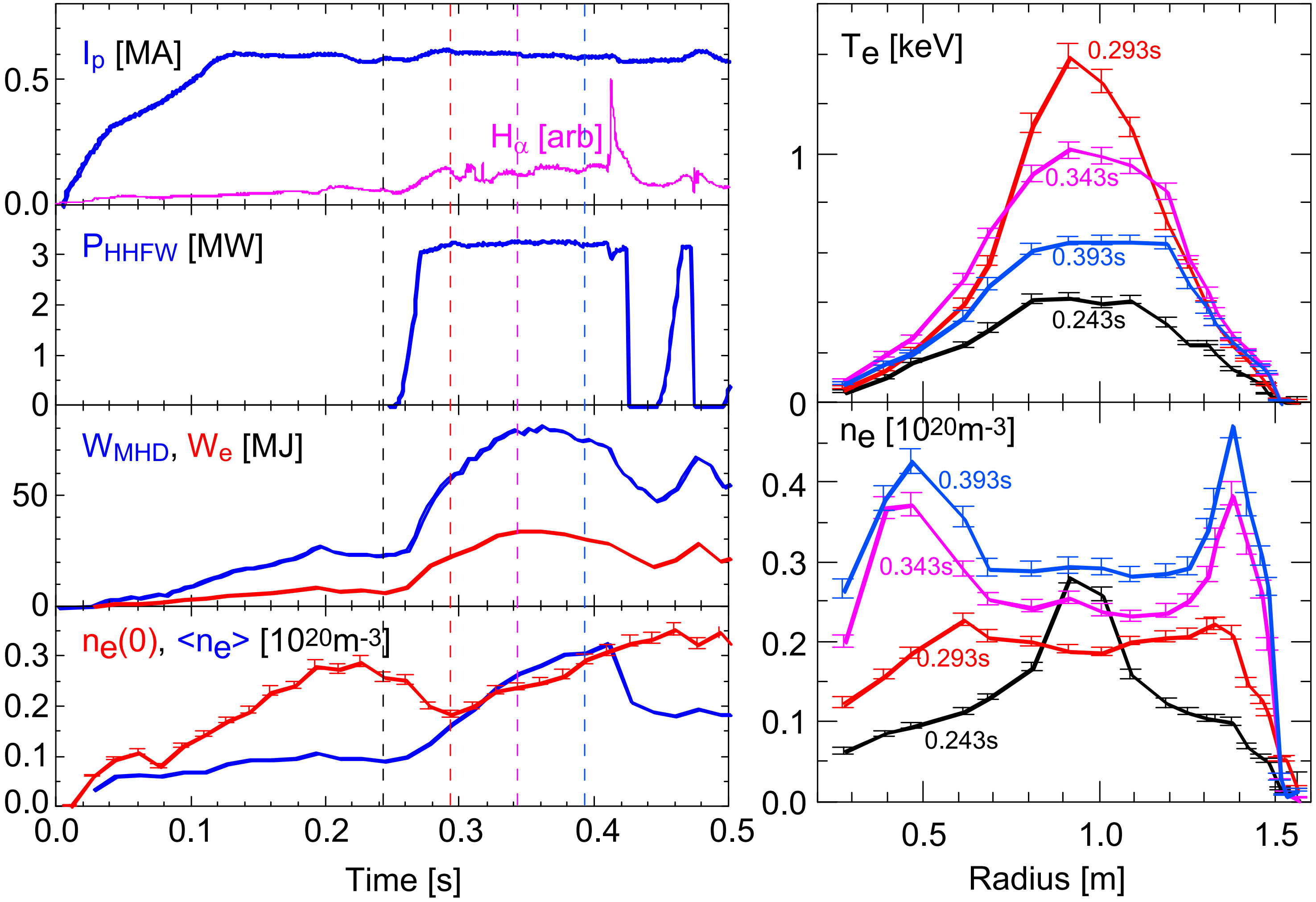
PPPL PRINCETON PLASMA PHYSICS LABORATORY & ornl



12 HHFW ANTENNA



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

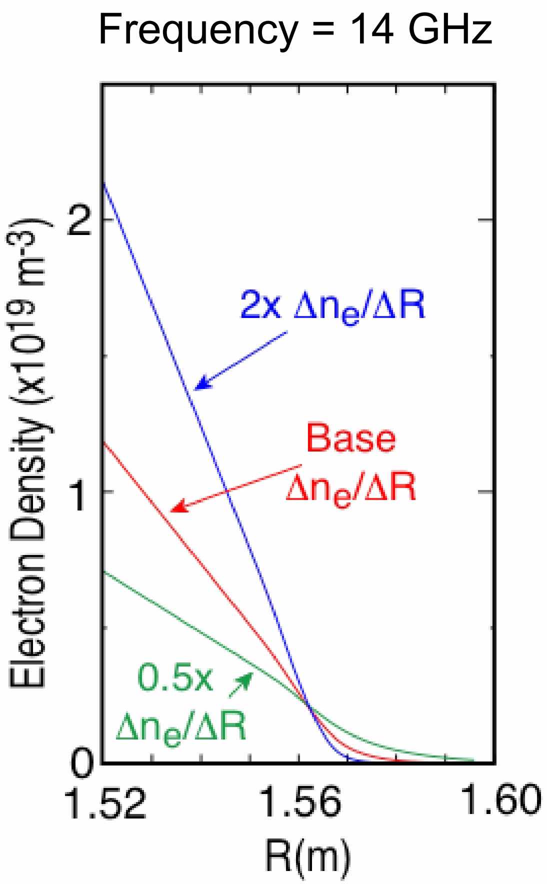


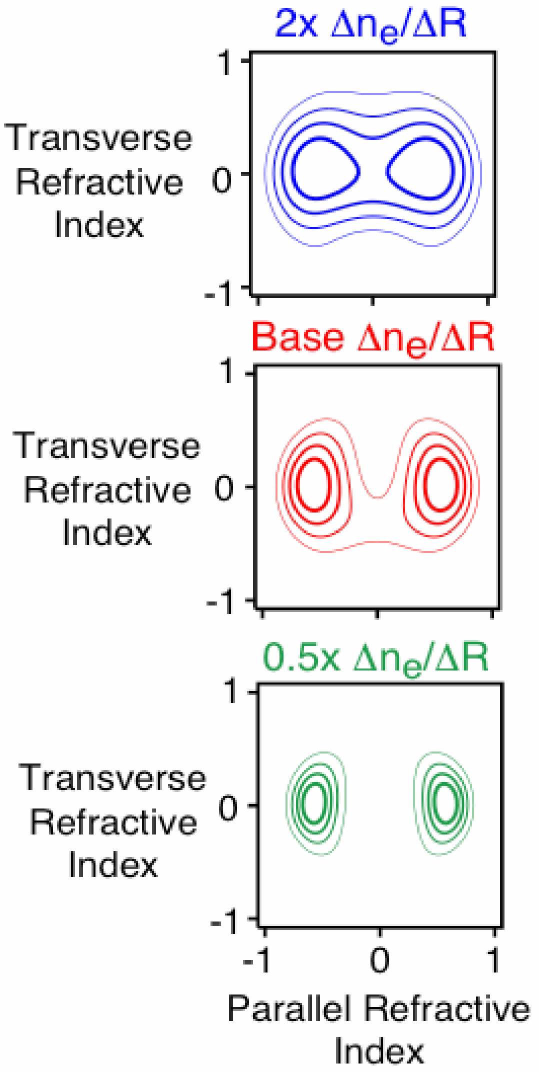
LeBlanc

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

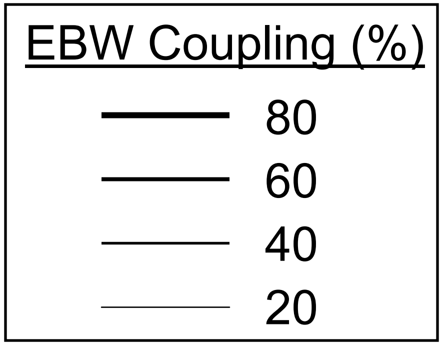
Electron Bernstein Wave: Oblique "O-X-B" Launch Is Resilient to Changes in Edge Density Gradient

Efficient conversion between ECW and EBW predicted.


Frequency = 14 GHz

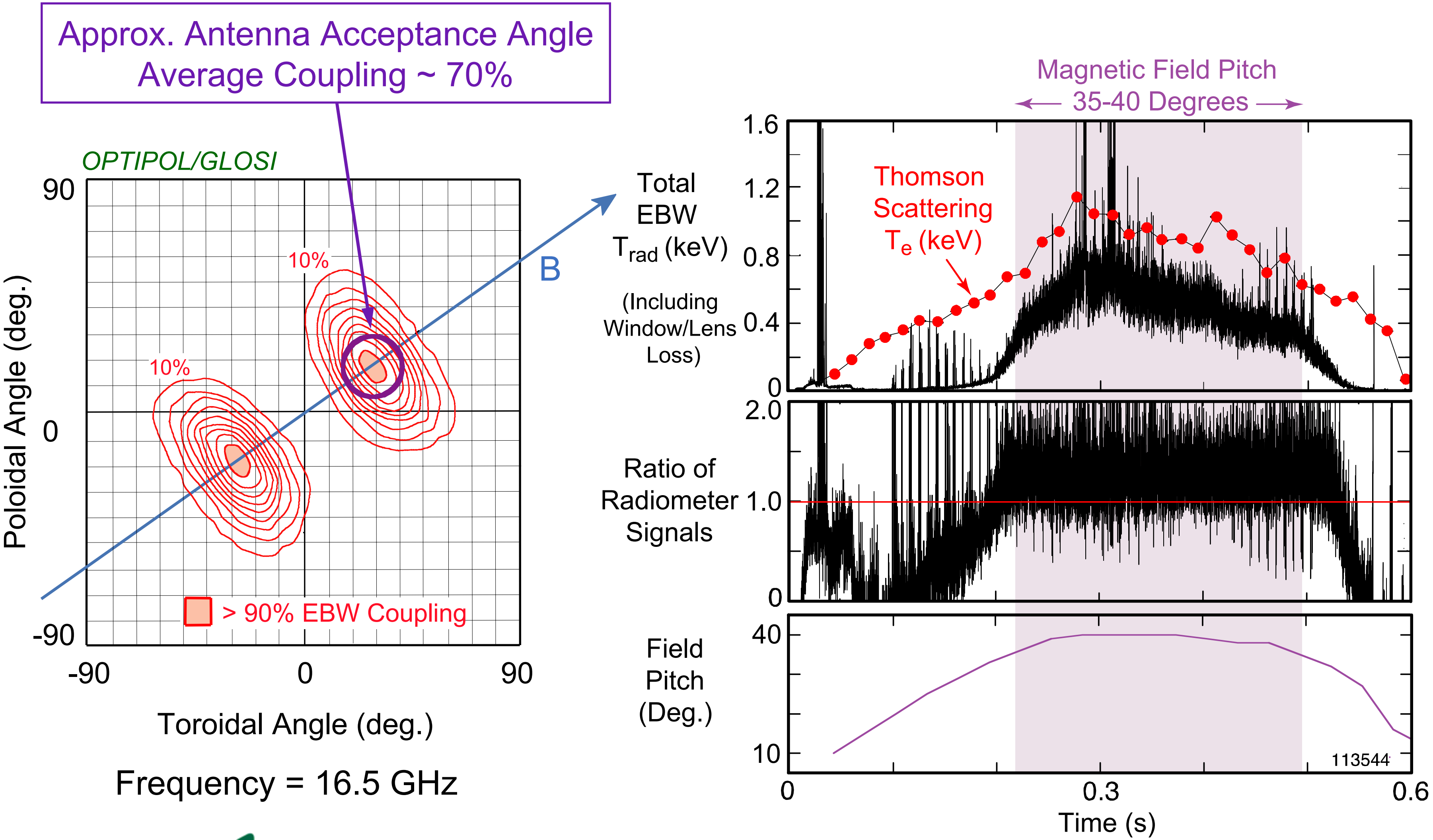


- Optimum $n_{//} = 0.55$; toroidal angle ~ 34° from normal to **B**
- > 75% coupling for O-X-B antenna with ± 5 degree beam spread



OPTIPOL/GLOSI

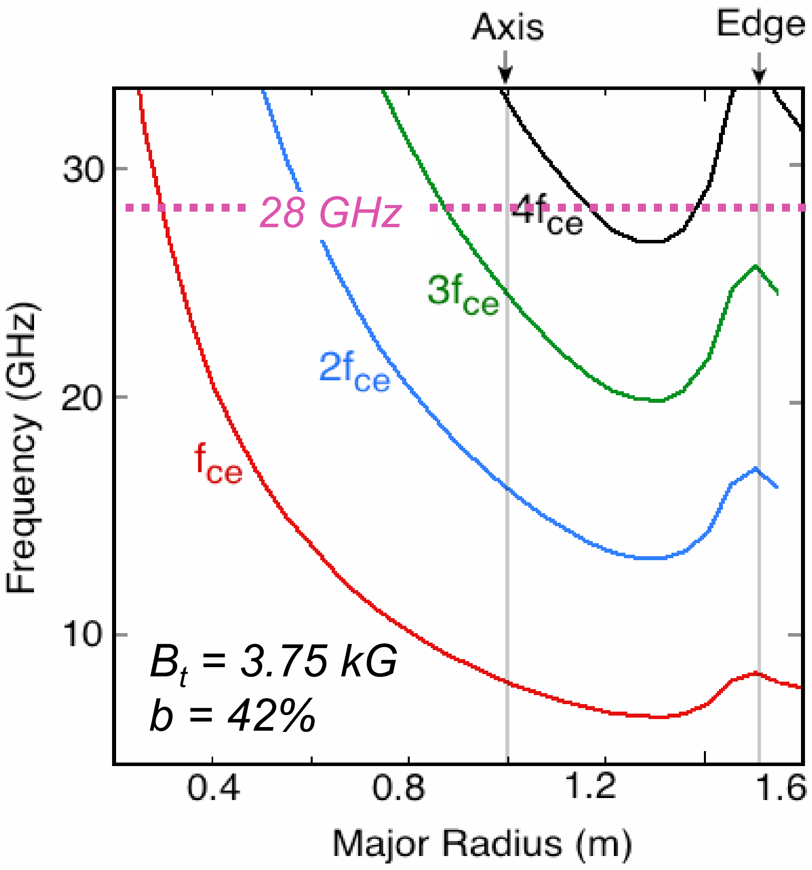
EBW Emission Shows Near-Circular Polarization and T_{rad}/T_e ~ 70%, Consistent with Modeling



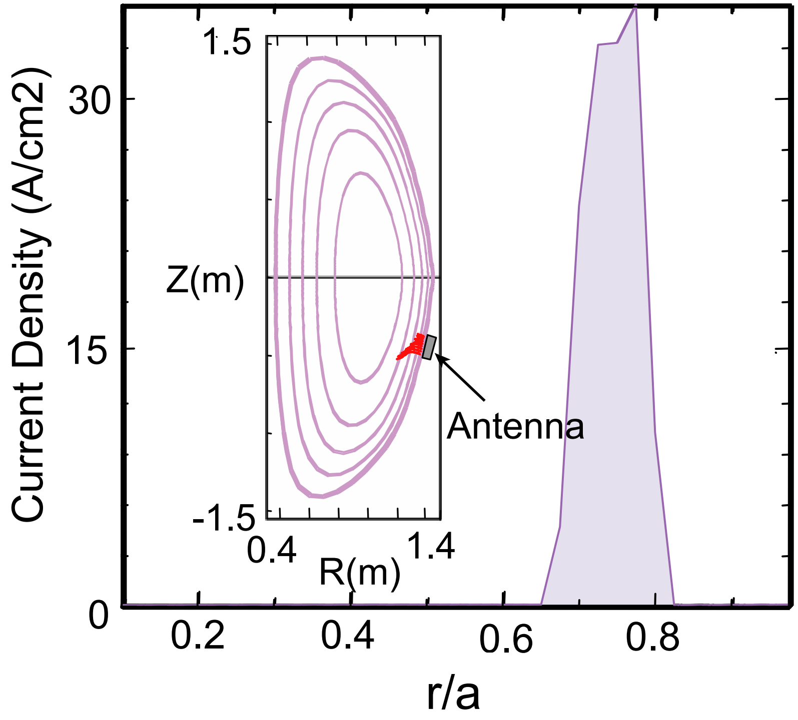
Approx. Antenna Acceptance Angle
Average Coupling ~ 70%

Frequency = 16.5 GHz

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



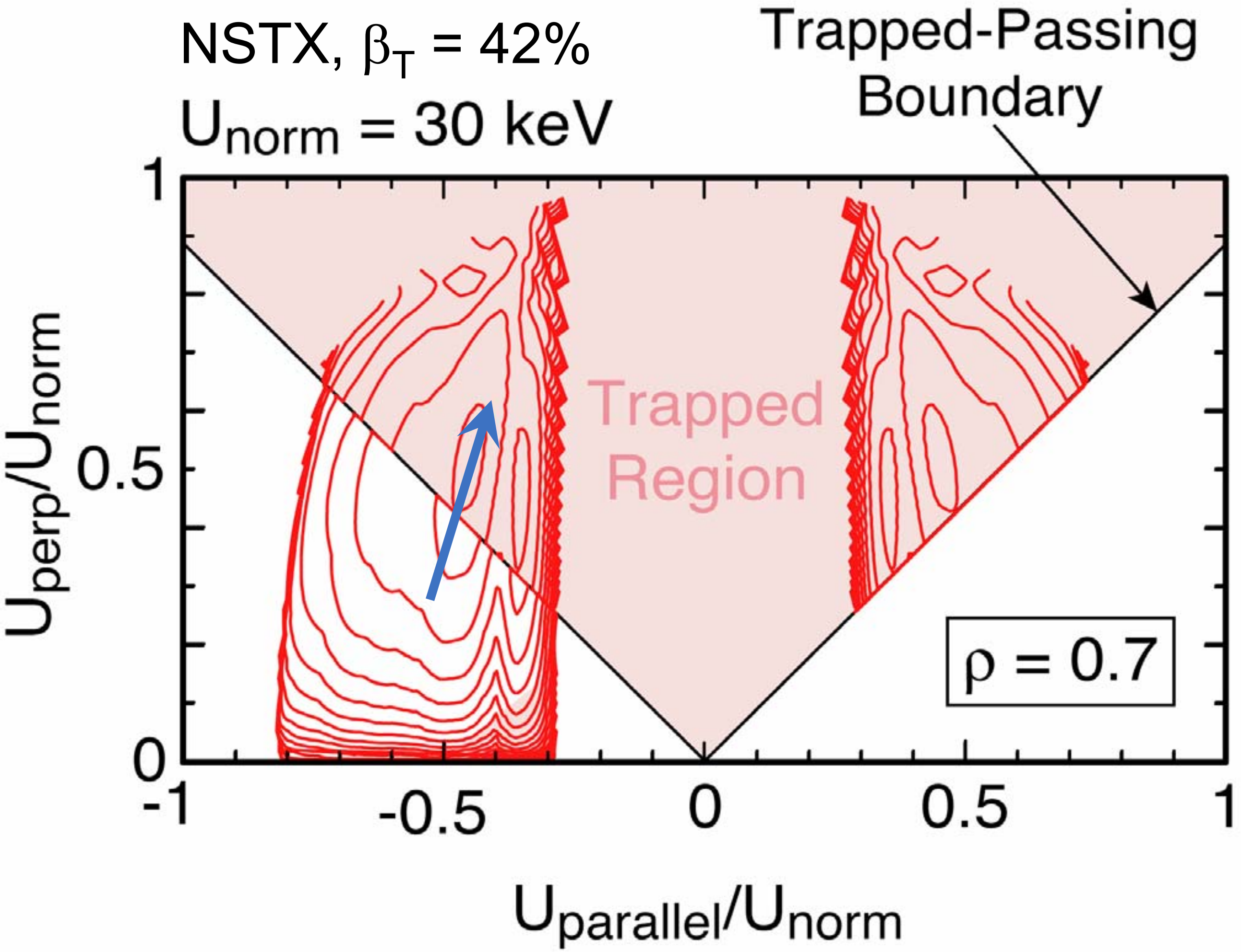
Frequency = 28 GHz
EBW Power = 3 MW
Total Driven Current = 135 kA



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

GENRAY/CQL3D [Bob Harvey, CompX]

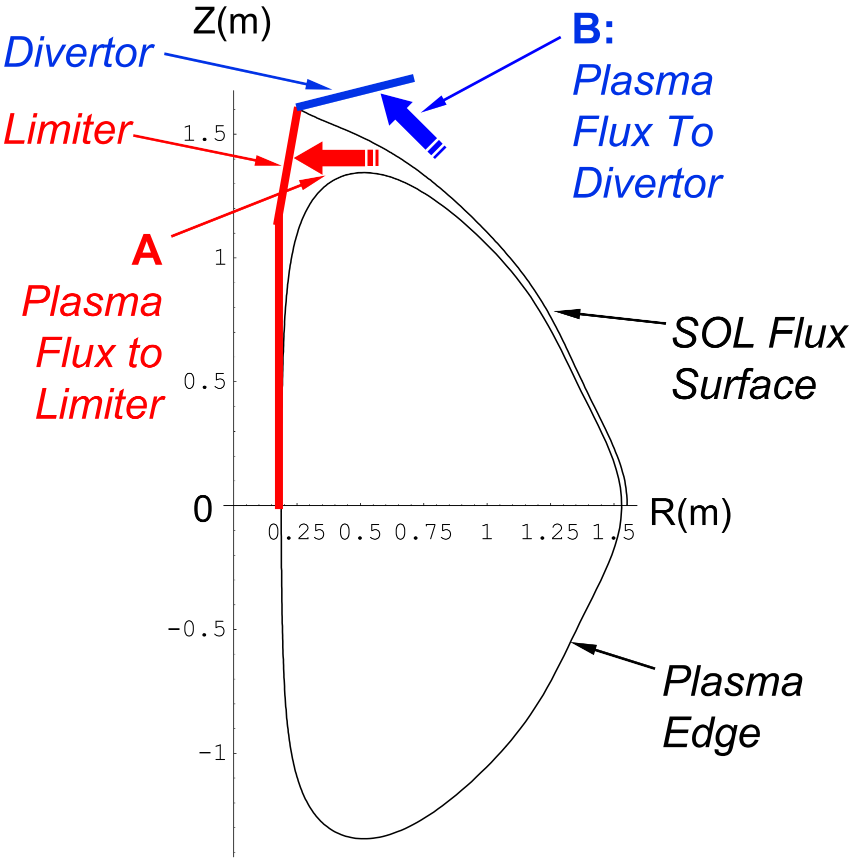
Strong Diffusion Near Trapped-Passing Boundary Enables Efficient Ohkawa Current Drive



CompX *GENRAY/CQL3D*

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

Scrape-Off Layer Geometry of Inboard Limited ST Plasma



Divertor

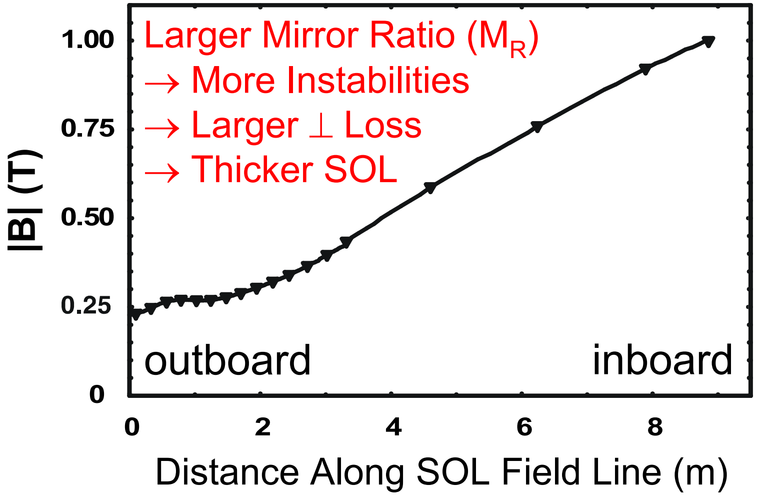
Limiter

B: *Plasma Flux To Divertor*

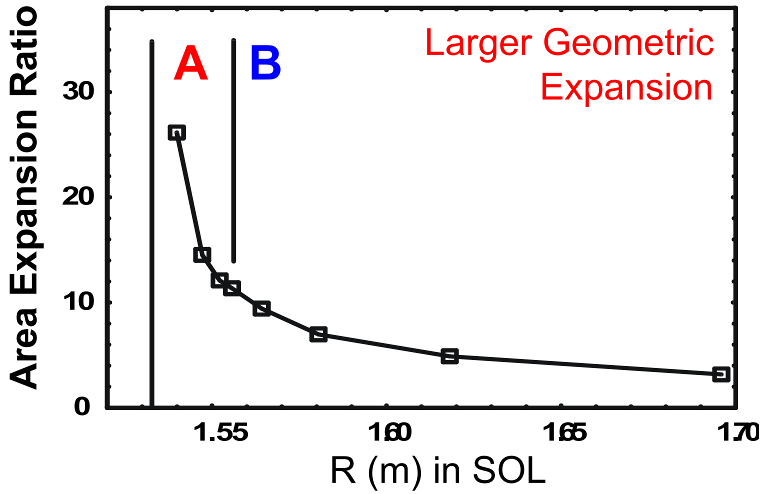
A *Plasma Flux to Limiter*

SOL Flux Surface

Plasma Edge



Larger Mirror Ratio (M_R)
→ More Instabilities
→ Larger ⊥ Loss
→ Thicker SOL



Larger Geometric Expansion

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

Factor of ~2 in R_{div} and M_R

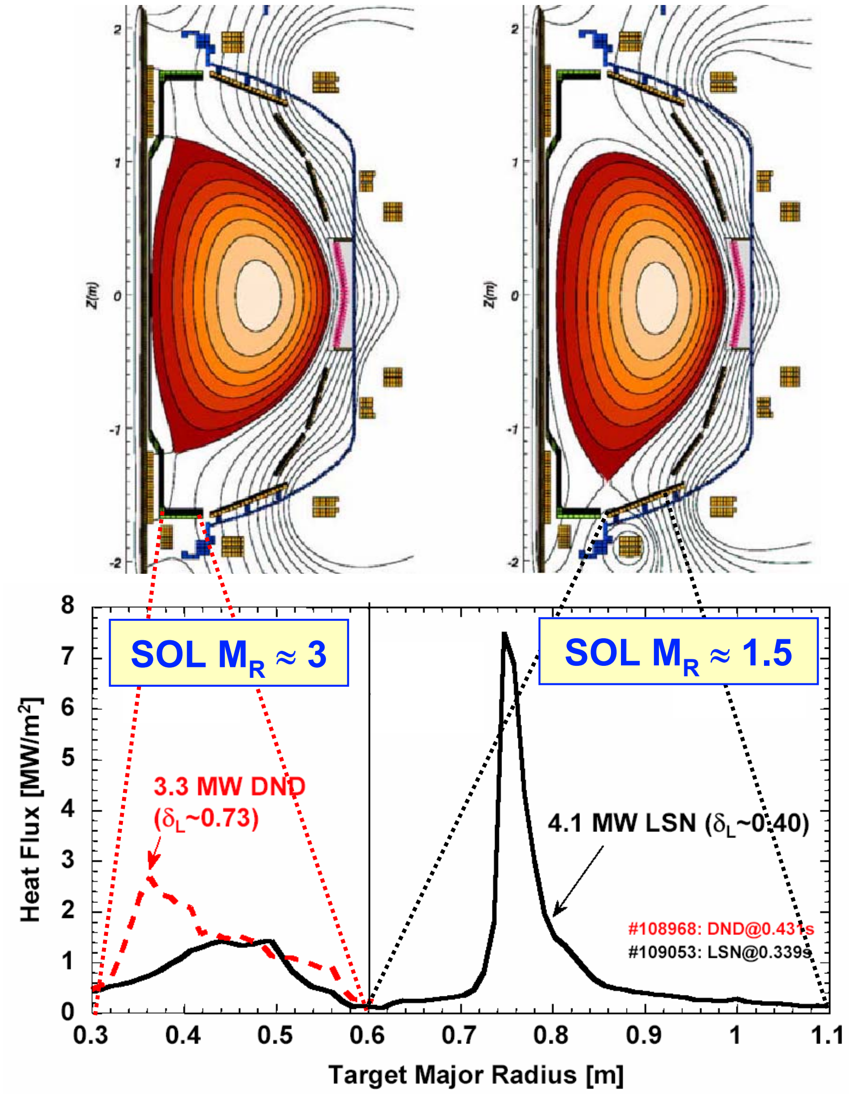
⇓

Factor of ~3 in Δ_{div}

Why?

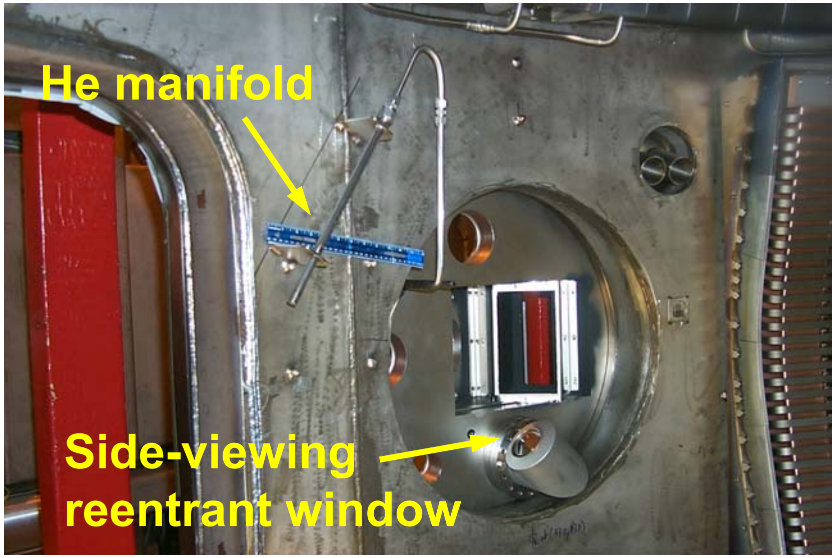
High & Low δ Divertor Bolometer Measurements

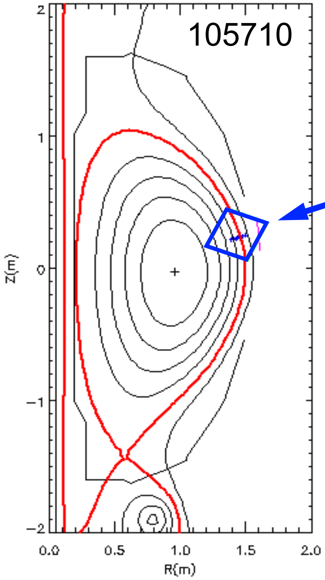
R_{div} (m)	0.36	0.75
SOL M_R	~ 3	~ 1.5
Δ_{div} (m)	~ 0.3	~ 0.12



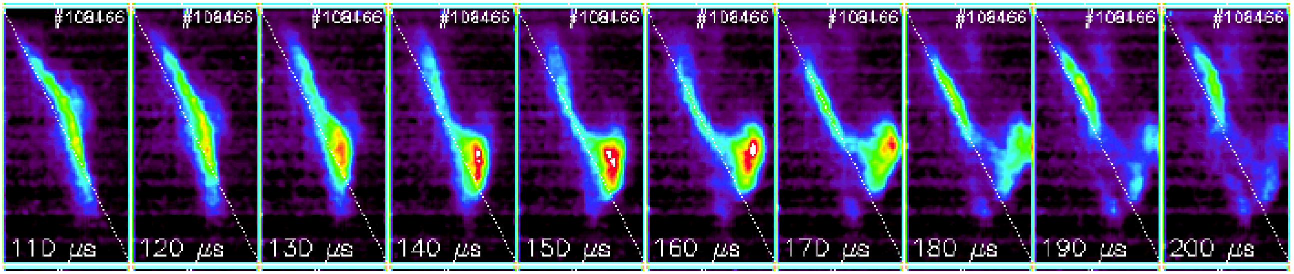
Plasma Edge Studies Reveal Turbulence and “Blobs” Important to Divertor Flux Scaling Studies

NSTX

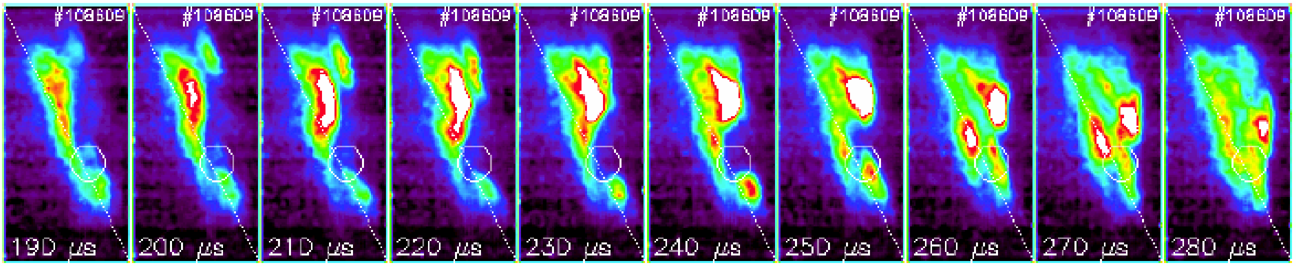




H-mode



L-mode

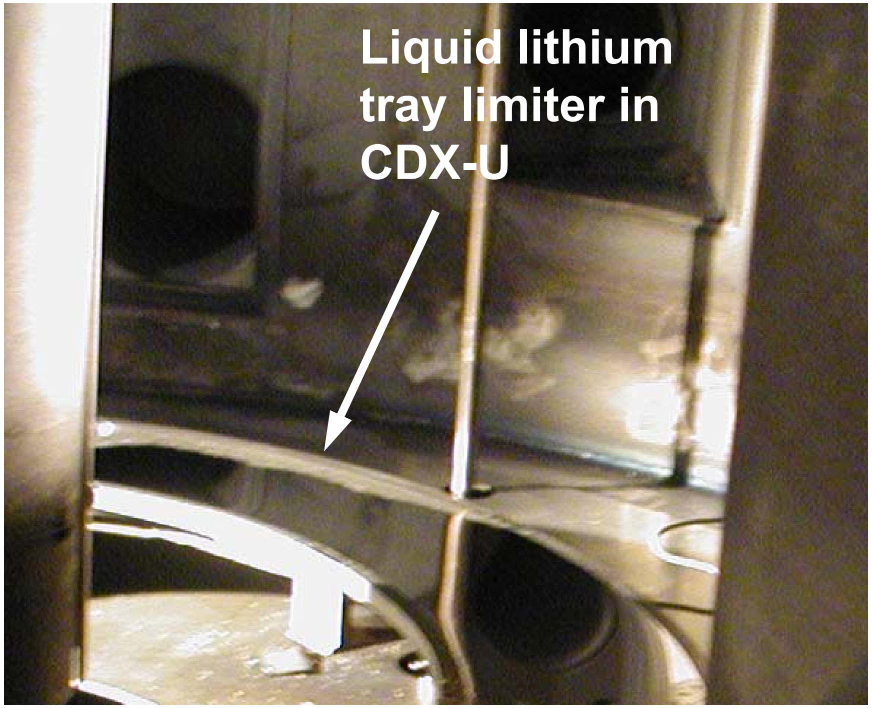


Broadly Based Study:

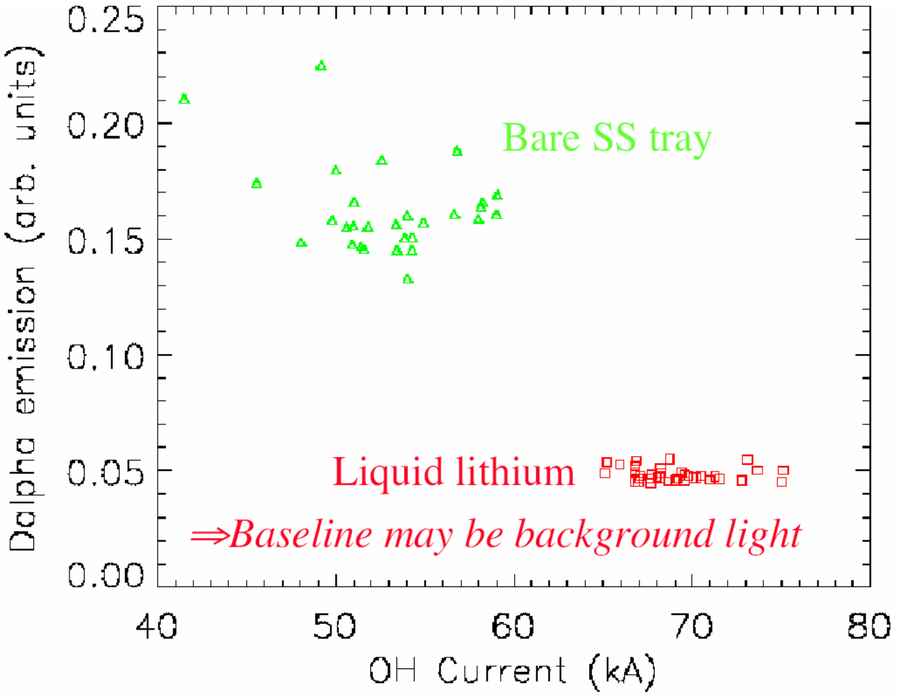
- **Gas Puff Imaging** views along field lines (PPPL, LANL)
- Very fast camera, 10^5/s (PSI)
- Reflectometers and edge (UCLA, ORNL)
- Reciprocating probe (UCSD)
- Divertor fast camera (Hiroshima U)
- IR Cameras (ORNL), Filterscope (PPPL)
- Modeling (PPPL, UCSD, LLNL, Lodestar)

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



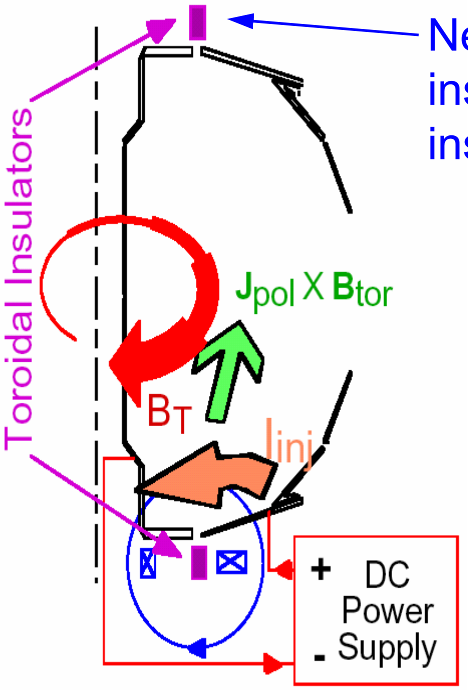
Tray after ~40 discharges.



PPPL, UCSD, ORNL, SNL

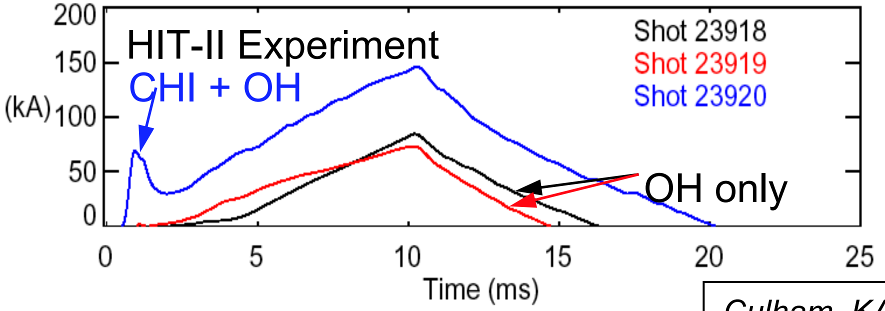
Solenoid Free Start-Up via Coaxial Helicity Injection & Outer Poloidal Field Coil Are Being Tested

Coaxial Helicity Injection Tests

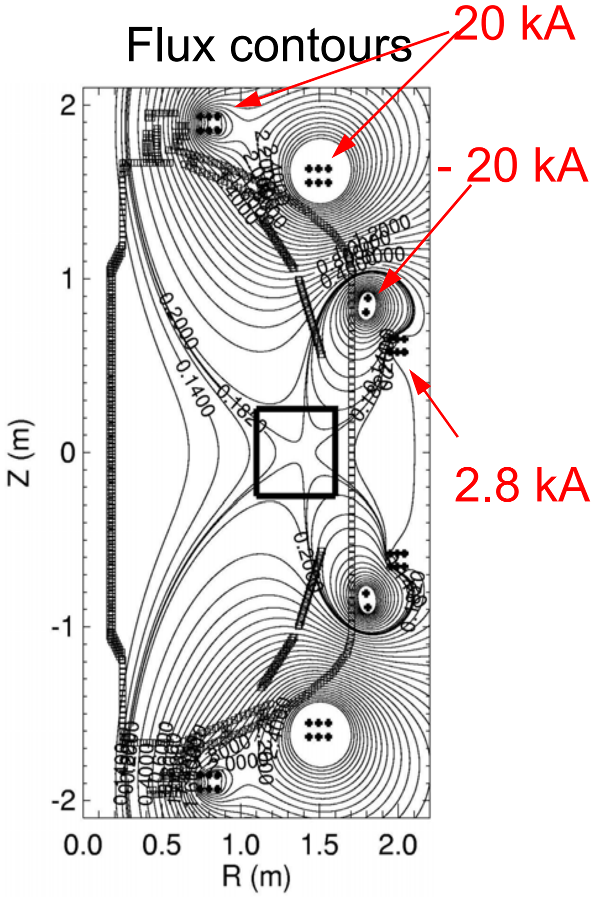


New absorber insulator installed

Capacitor bank to be installed

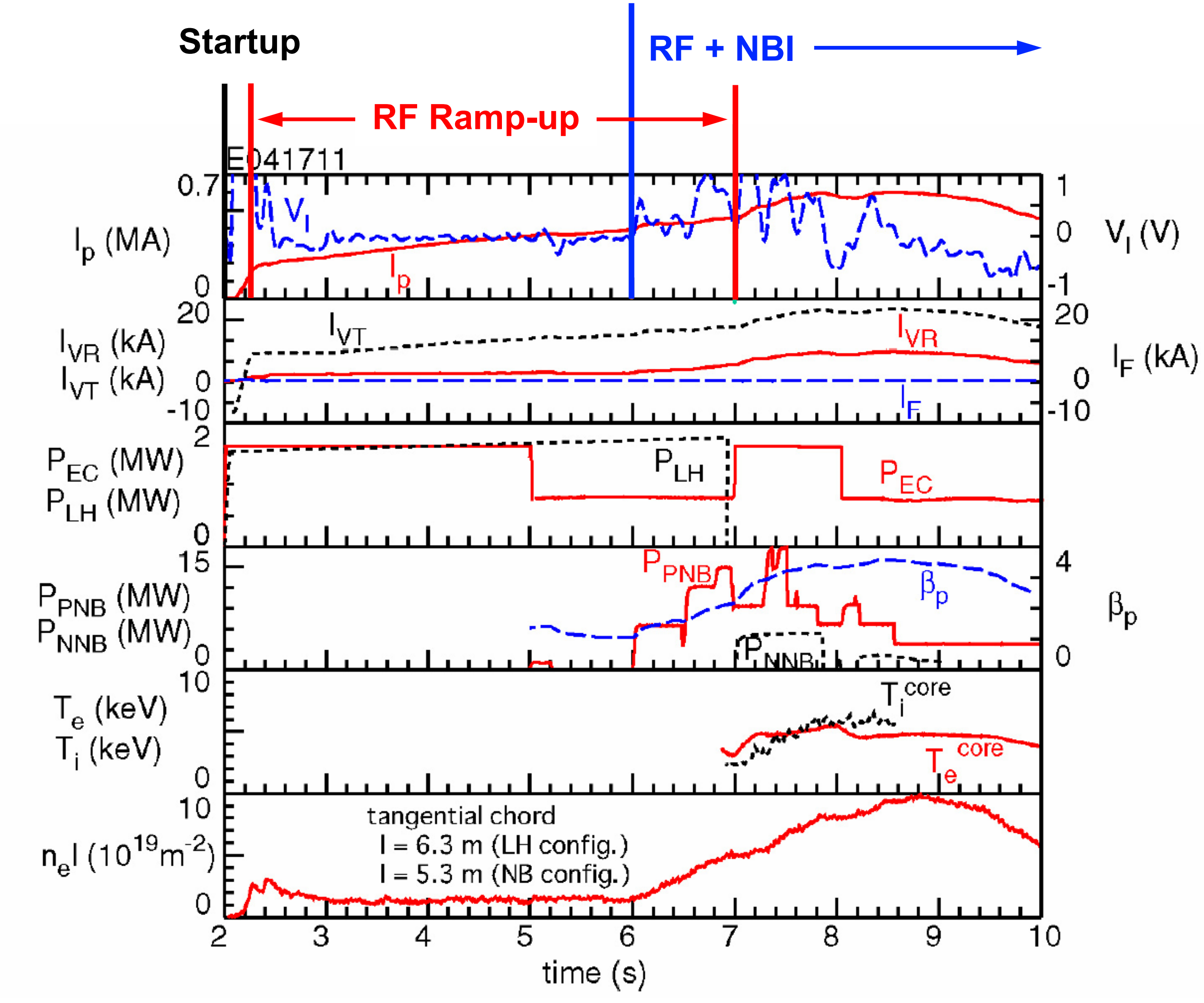


Three Outer Poloidal Field Startup Scenarios, e.g.: Outboard Field Null



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

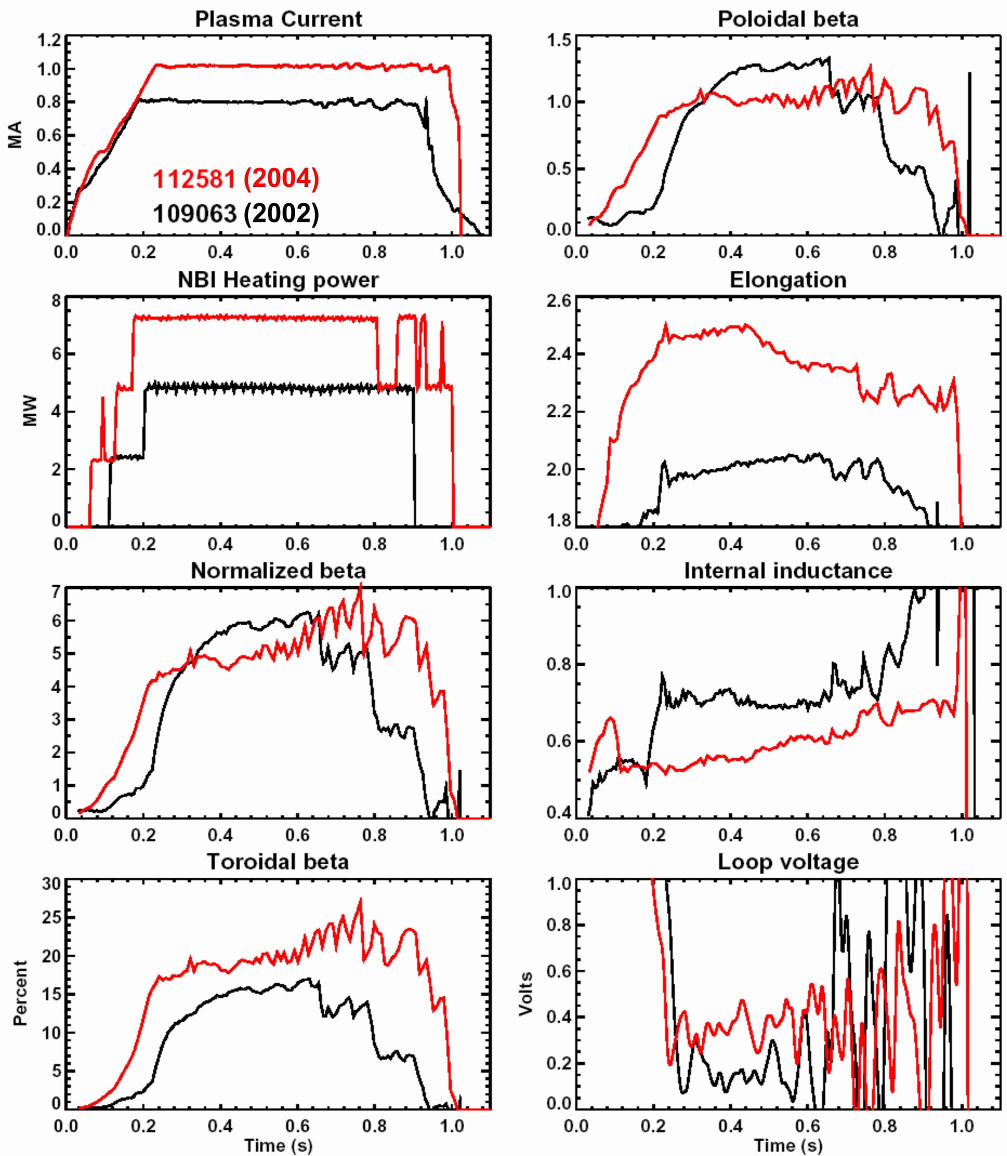
JT-60U Tests on Solenoid-Free Start-Up via RF and NBI Offers Additional Exciting Opportunities



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

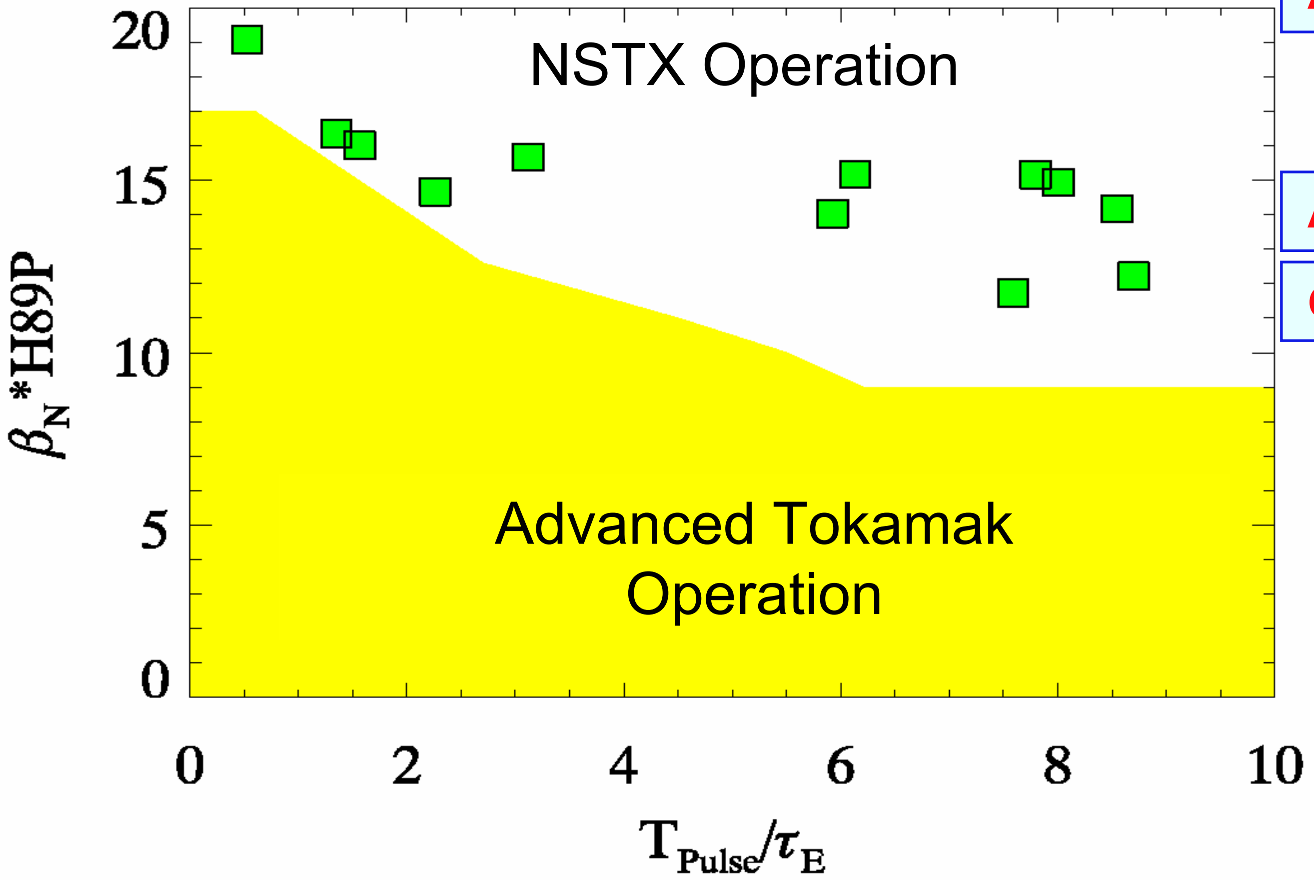
Nearly Sustained Plasmas with Broader Values of κ, ℓ_i, I_p, and β_T Can Contribute to ITER Hybrid Scenario



Co-NBI plasmas:

- Improved vertical control
- Use $\beta_p/\beta_N \sim \kappa^2$ to obtain $\beta_p \gtrsim 1$ and I_{BS} fraction $\lesssim 0.5$
- High $\beta_N \sim 6$ and $\beta_T \sim 20\%$
- Substantially reduced loop voltage
- Need to reduce ELM size
- **Contribute to developing ITER hybrid scenario**
- Also to future Q ~ 2, driven steady state ST plasmas at ~10 MA level (**CTF**).

Long-Pulse H-Mode Plasmas Made Encouraging Progress in toward Future ST Possibilities



Normalized beta x normalized confinement

Normalized pulse length

ARIES-ST

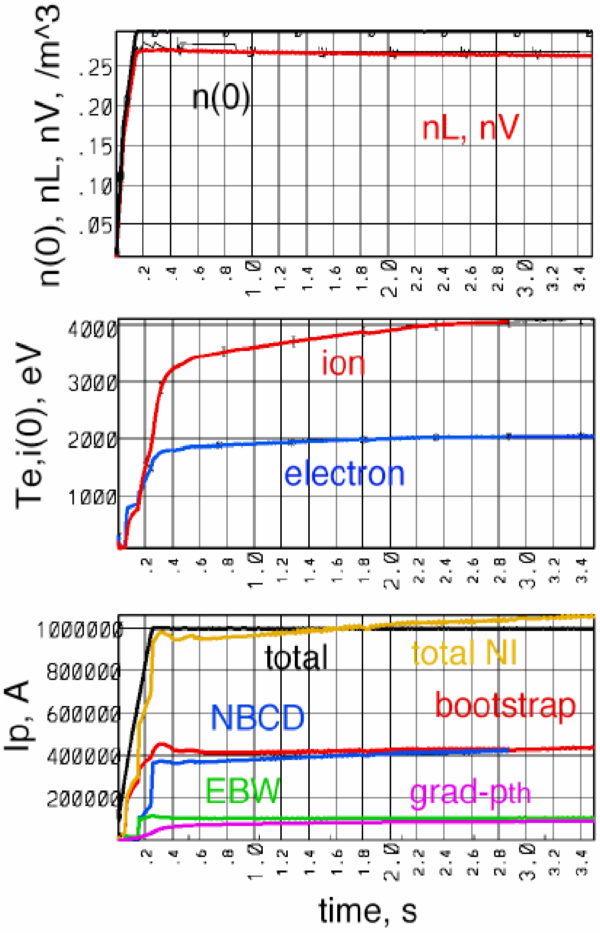
ARIES-AT

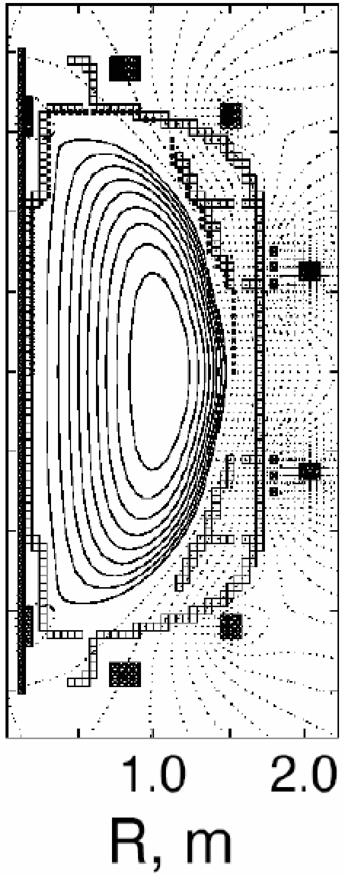
CTF-ST

Understanding long-pulse, high performance plasmas is a major research area.

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

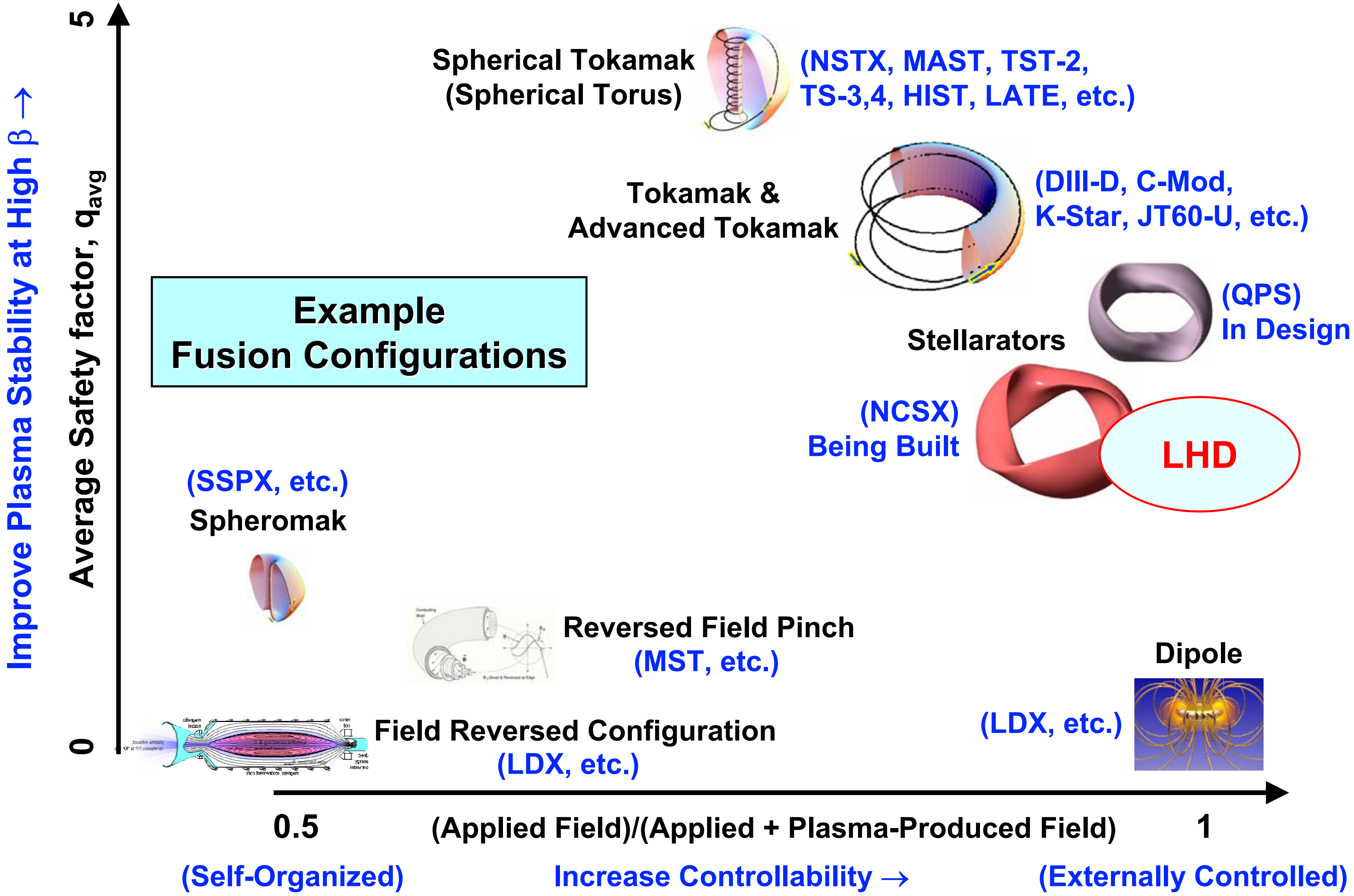
- Enhanced shaping improves ballooning stability
- Mode, rotation, and error field control ensures high beta
- NBI and bootstrap sustain most of current
- HHFW heating contributes to bootstrap
- EBW provides off-axis current & stabilizes tearing modes
- Particle and wall control maintains proper density





CompX, MIT, PPPL, ORNL, UCSD

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



Improve Plasma Stability at High β →

Average Safety factor, q_{avg}

5

0

Example Fusion Configurations

Spherical Tokamak (Spherical Torus)

(NSTX, MAST, TST-2, TS-3,4, HIST, LATE, etc.)

Tokamak & Advanced Tokamak

(DIII-D, C-Mod, K-Star, JT60-U, etc.)

(QPS) In Design

Stellarators

(NCSX) Being Built

LHD

(SSPX, etc.)

Spheromak

Reversed Field Pinch

(MST, etc.)

Dipole

(LDX, etc.)

Field Reversed Configuration

(LDX, etc.)

0.5

(Applied Field)/(Applied + Plasma-Produced Field)

1

(Self-Organized)

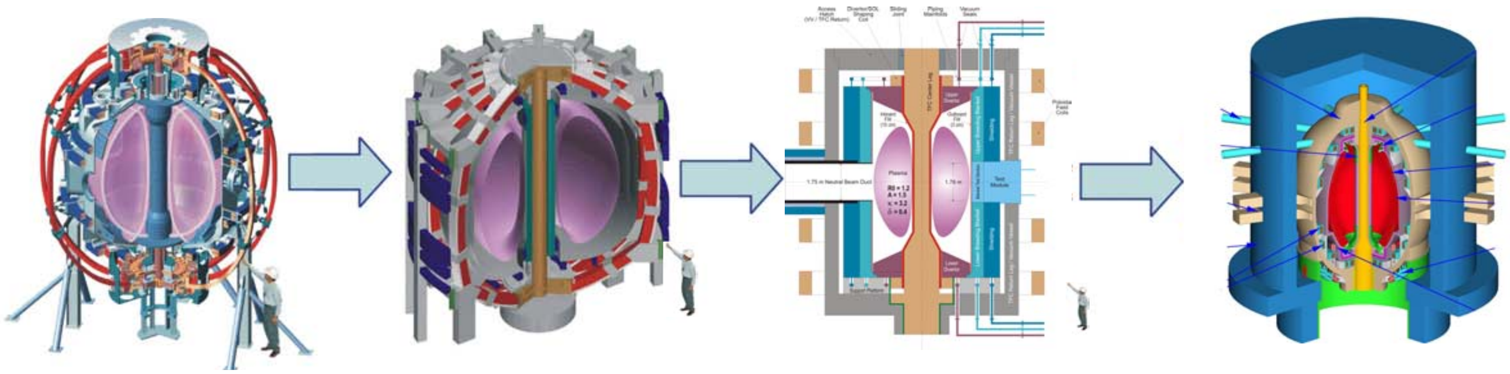
Increase Controllability →

(Externally Controlled)

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

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



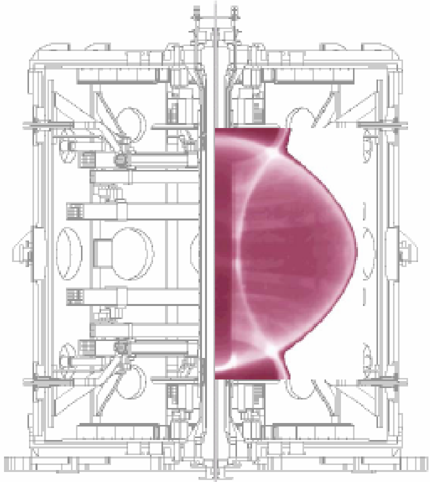
Device	NSTX		NSST		CTF		DEMO
Mission	Proof of Principle		Performance Extension		Energy Development, Component Testing		Practicality of Fusion Electricity
R (m)	0.85		**~1.5**		**~1.2**		~3
a (m)	0.65		~0.9		~0.8		~2
κ, δ	2.5, 0.8		~2.7, ~0.7		~3, ~0.5		~3.2, ~0.5
I_p (MA)	**1.5**	**1**	**~5**	**~10**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

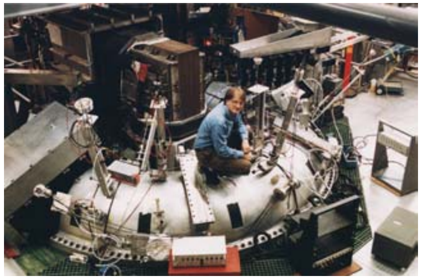
NSTX

- **Exploratory ST's in Japan**
  - **TST-2**: ECW-EBW initiation
  - **TS-3,4**: FRC-like β~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

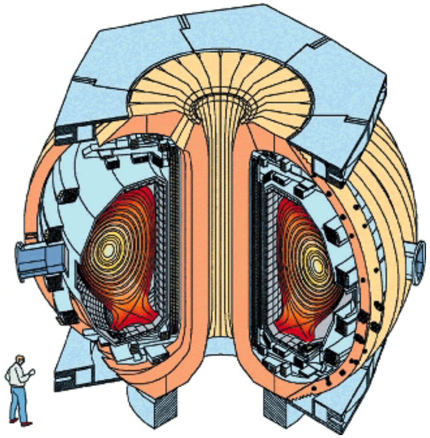
MAST (U.K.)



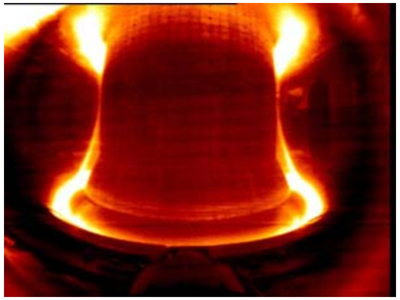
MST (U.S.)



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 hybrid scenario**
- **ST enables cost-effective steps toward practical fusion energy**
- **ST research is highly collaborative worldwide**

I will be pleased to discuss further during the Japan-Korea Seminar.