RECENT PROGRESS OF LOW-ASPECT RATIO EXPERIMENTS

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Outline

Properties of Low Aspect Ratio Plasmas

Plasma Performance in ST’s

Issues in Technology and Techniques

Future Directions (?)

"Spherical Torus" Extends Tokamak to Extreme Toroidicity

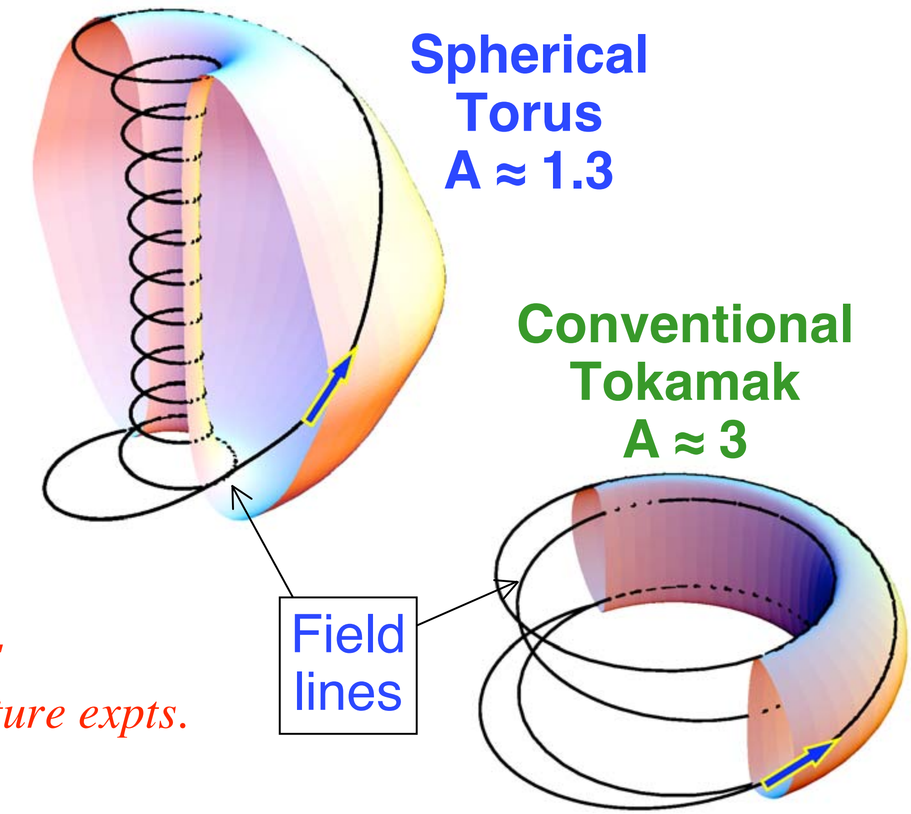
- **Motivated by potential for increased** β *(Peng & Strickler, 1980s)*

$$\beta_{max}\ (= 2\mu_0\langle p\rangle/B_T^2)\ =\ C\cdot I_p/aB_T\ \propto\ C\cdot\kappa/\mathbf{A}q$$

B_T:	toroidal magnetic field on axis;
$\langle p\rangle$:	average plasma pressure;
I_p:	plasma current;
a:	minor radius;
κ:	elongation of cross-section;
A:	**aspect ratio (= R/a);**
q:	MHD "safety factor" (> 2)
C:	Constant ~3%·m·T/MA *(Troyon, Sykes - early 1980s)*

- **Confirmed by experiments**
  – $\beta_{max} \approx 40\%$ *(START - UK, 1990s)*

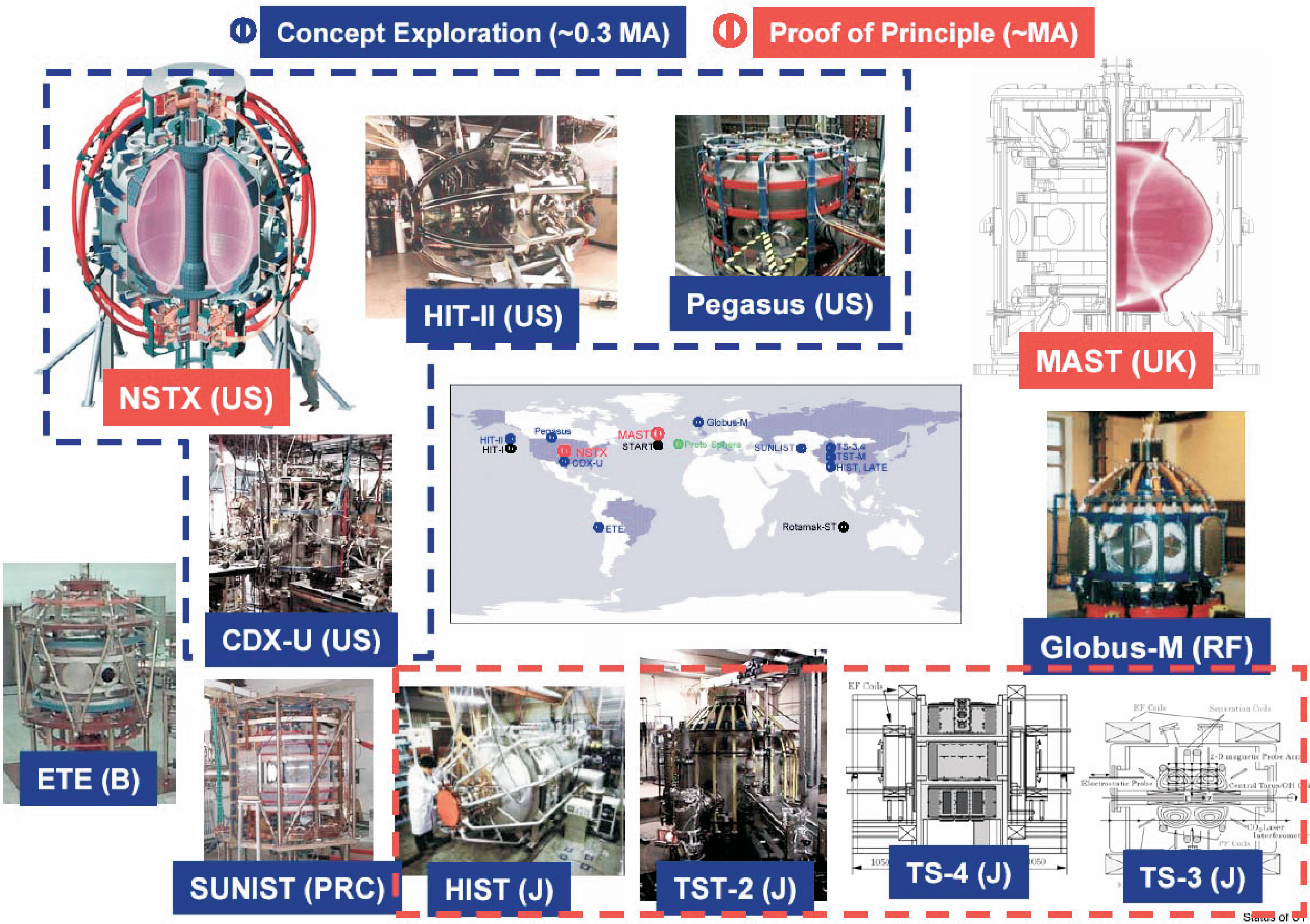
- Two Goals for ST Research:
  – *Explore long-term fusion potential of ST*
  – *Advance tokamak physics to optimize future expts.*



ST Research Can Address Extended Parameter Space in Support of Fusion Energy Science Goal

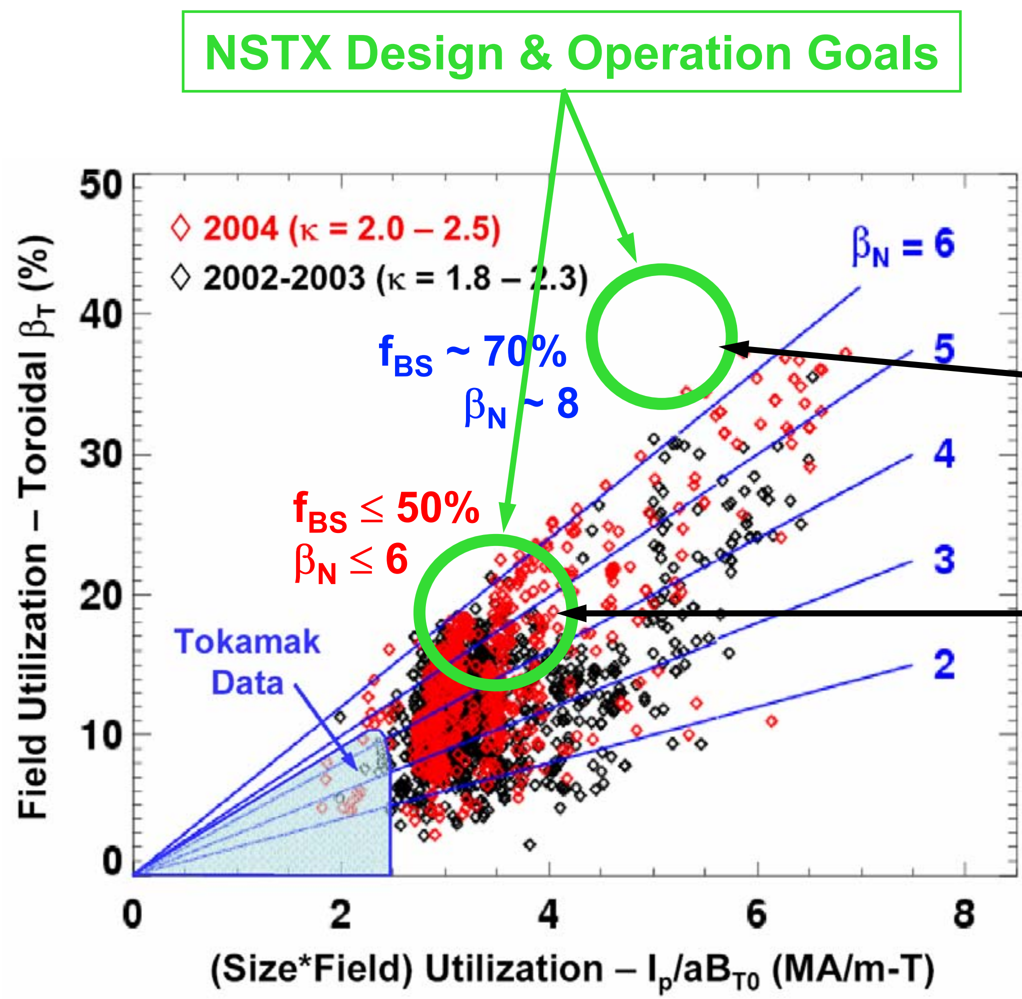
Plasma Science of Extended Parameter Space	⇒	Goal: Optimize Fusion DEMO & Development Steps
1) Stable high β_T, β_0 & bootstrap current fraction	⇒	Lowered magnetic field and device costs
2) Effective wave-energetic particle-plasma interactions	⇒	Efficient fusion α particle, neutral beam, & RF heating
3) Reduced turbulence	⇒	Smaller unit size for sustained fusion burn
4) Dispersed plasma fluxes	⇒	Survivable plasma facing components
5) Solenoid-free startup & sustainment	⇒	Simplified smaller design, reduced operating cost
6) Attractive sustained burning plasma properties	⇒	Steady state fusion power source

Spherical Torus Research Is Growing Worldwide



Status of ST

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



- Obtained high beta values:

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

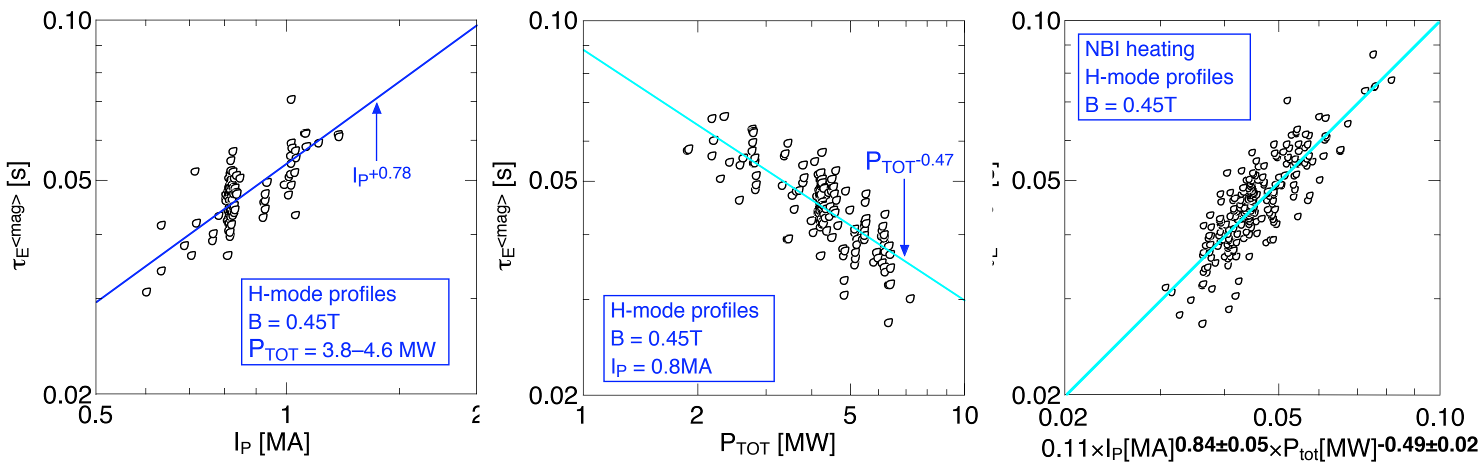
  $\beta_N = \beta_T / (I_p/aB_{T0}) \leq 6.4$

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

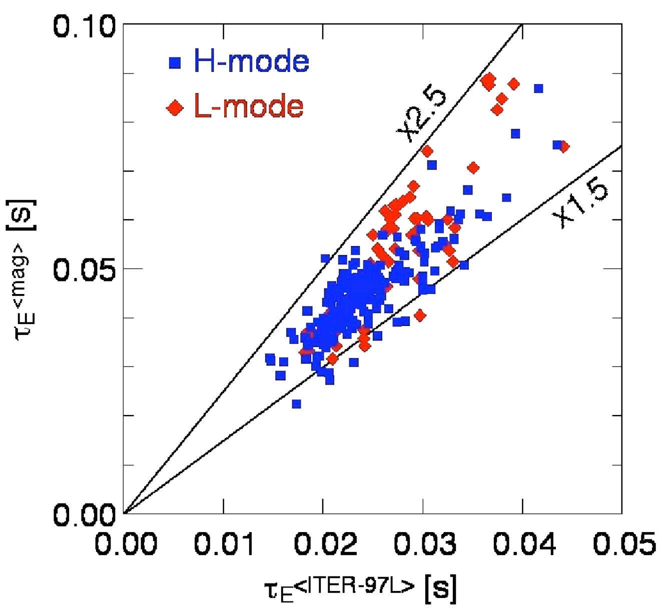
- To produce and study full non-inductive sustained plasmas
  - Relevant to **DEMO**
- Nearly sustained plasmas with neutral beam and bootstrap current
  - Relevant to **ITER** hybrid mode
  - Nearly basis for neutral beam sustained ST Component Test Facility (**CTF**) at Q~2

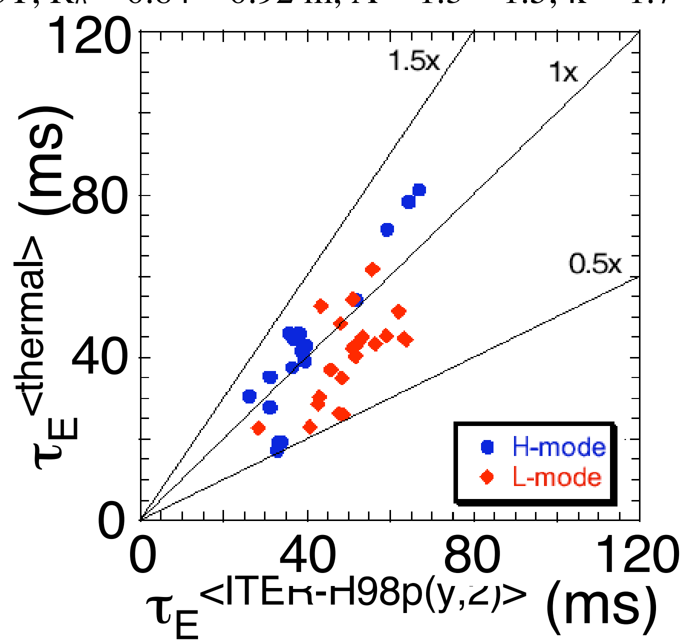
Columbia U, LANL, PPPL

With NBI, Tokamak Trends Reproduced



- D-NBI heated H-modes at time of peak stored energy; B_T = 0.45T, R_0 = 0.84 – 0.92 m, A = 1.3 – 1.5, κ = 1.7 – 2.5

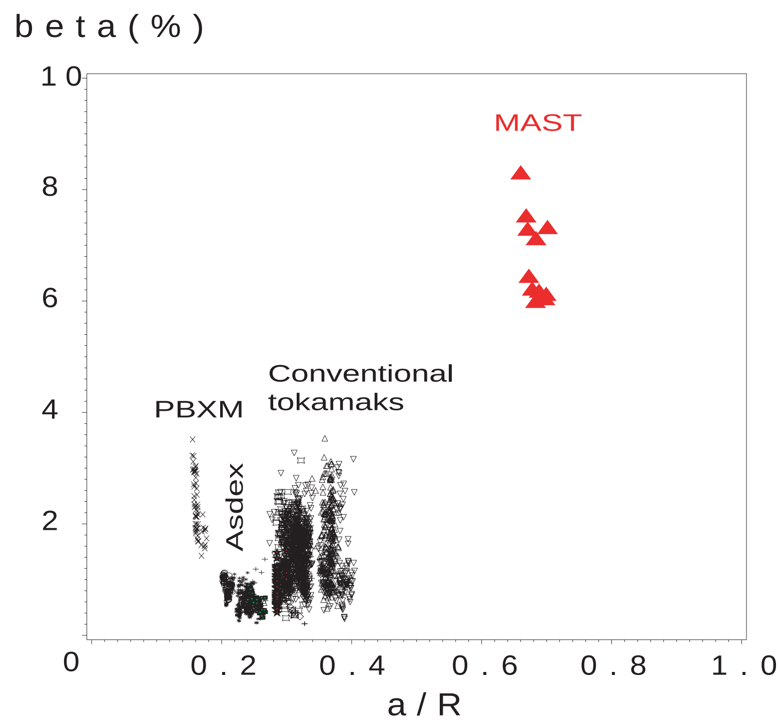




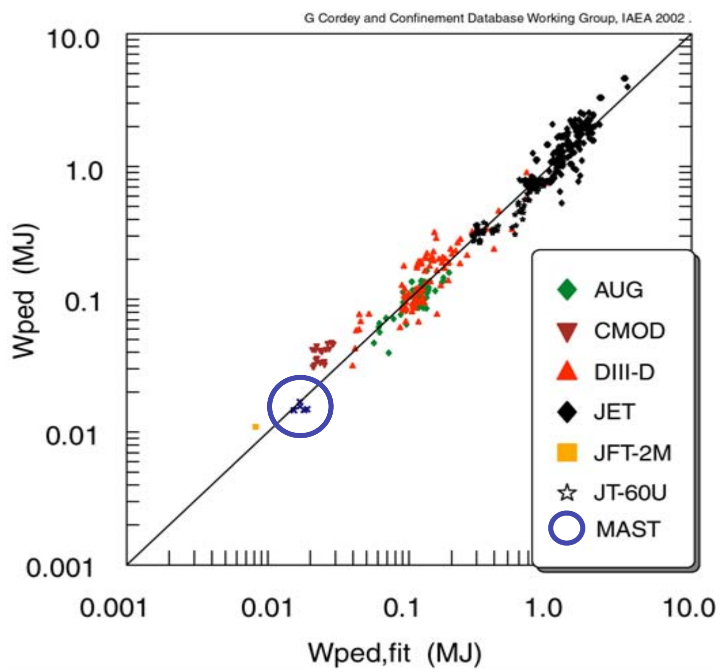
- Total confinement, including fast ions
- TRANSP analysis for thermal confinement

Confinement & Transport

MAST data significantly extend confinement databases e.g. should give greater confidence in ε and β dependencies



Dataset improved e.g. spread in ε mainly determined by plasmas with conventional D-shaped cross-section
$\Rightarrow \tau_E^{MAST} \sim \tau_E^{IPB98y2}$ but MAST data support somewhat stronger ε dependence ($\tau_E \propto \varepsilon^{0.8}$) than IPB98y2 scaling [Valovic IAEA 2004]



MAST data also exert strong leverage on two-term models of confinement:

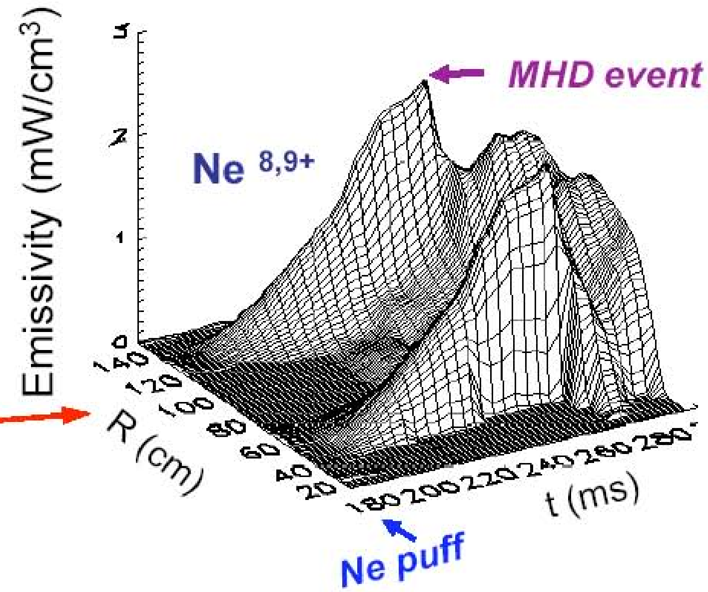
$W_{ped} \propto \varepsilon^{-2.13\pm0.28}$ [Cordey et al NF 2003]

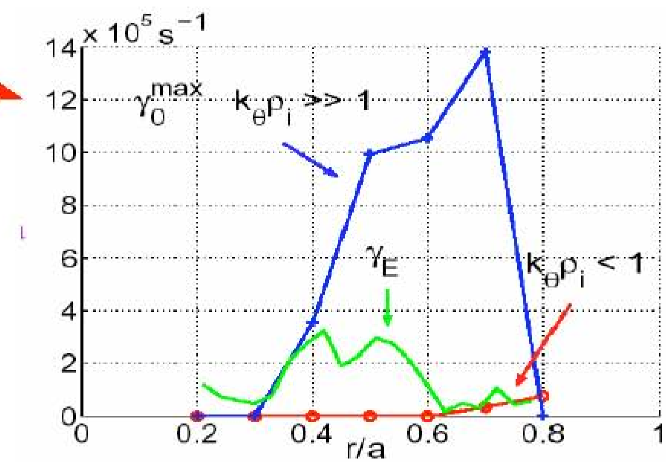
UKAEA Fusion Working in Europe

In NBI H-Mode Plasmas, Ion Energy and Particle Diffusivities are Very Low, But not the Electrons

Core Transport Physics	NSTX Results
Thermal Conductivity	• $\chi_{ion} \sim \chi_{neoclassical}$ • $\chi_{elec} >> \chi_{ion}$
Impurity Diffusivity	• $D_{imp} \sim D_{neoclassical}$
Micro-instability turbulence theory	• 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



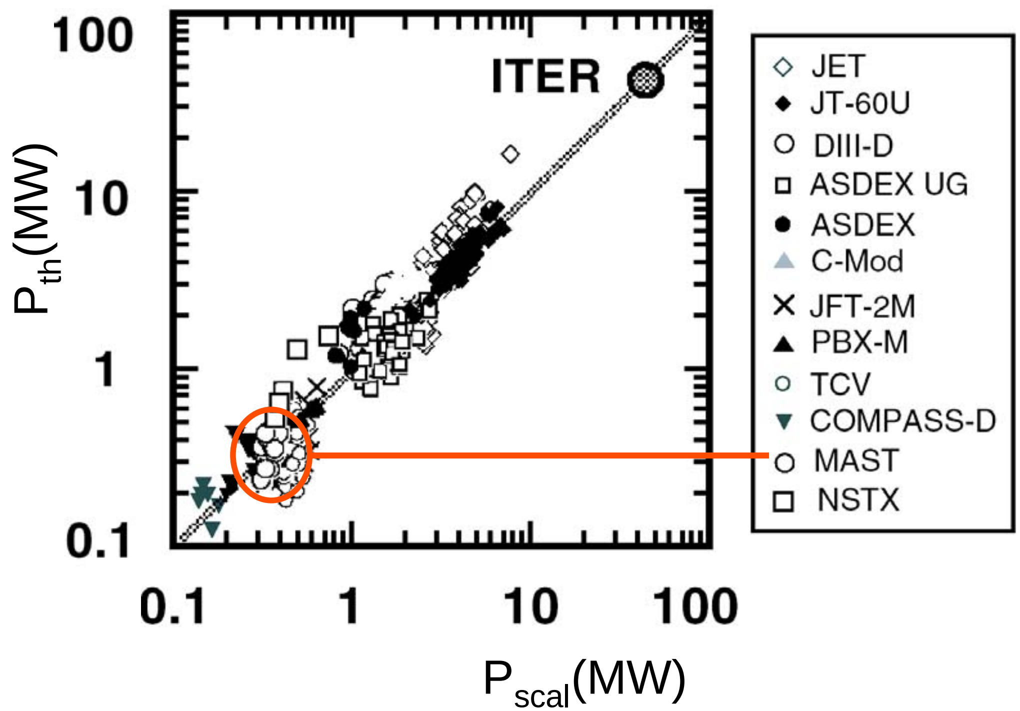


H-mode Power Threshold

Low A data:

- clearly favour $P_{th} \sim S$ rather than $P_{th} \sim R^2$
- favour dependence on $|B_{out}|$ rather than $B_t(0)$

$$|B_{out}|^2 = B_t^2 + B_p^2$$



The (non-linear) aspect ratio dependence is not yet well-determined - postulated by Takizuka et al that it may take a form related to fraction of untrapped particles

$$P_{scal} \propto |B_{out}|^{0.7} n_e^{0.7} S^{0.9} F(A)^{\gamma}$$

[Takizuka et al PPCF 2004]

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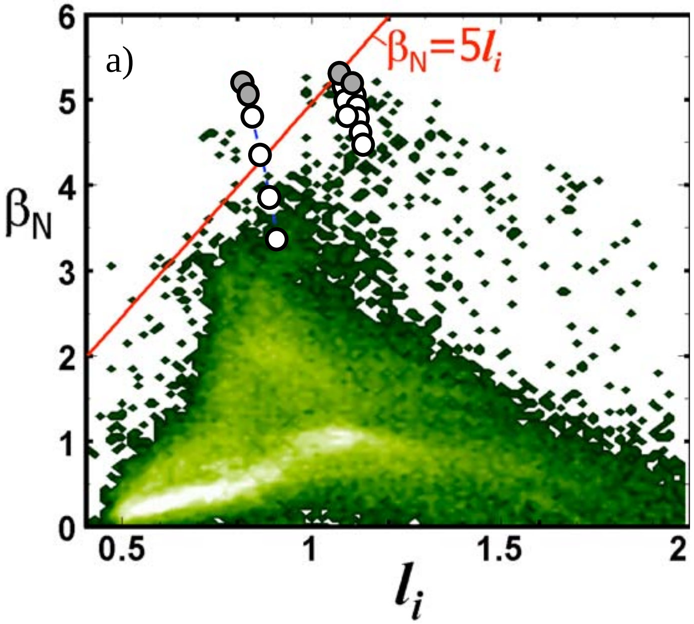
Stability



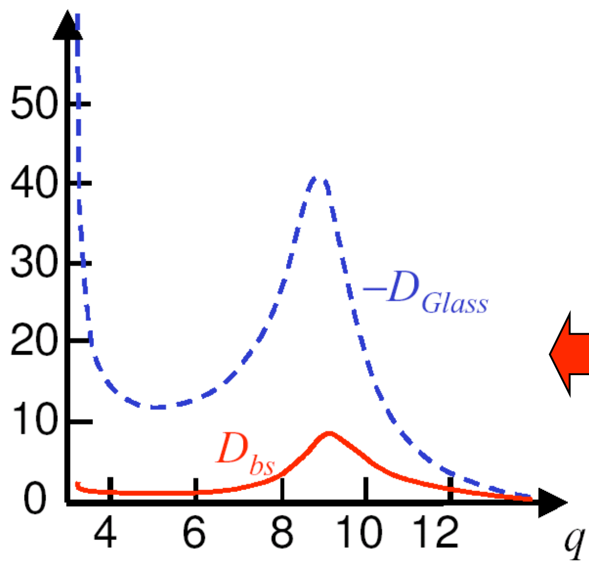
By avoidance of NTMs $\beta_N > 5$, ($\beta_N > 5l_i$) has been achieved in MAST
⇒ approaching ideal no-wall beta limit.

KINX calculations

- unstable
- stable

f_{BS} ~ 40%, W_{fast} ~ 15 - 20%

Sawtooth triggered NTMs have been observed in MAST - island evolution confirms strong role of field curvature stabilisation (Glasser) term at low A



Taking the Sauter NTM model, benchmarked against MAST it appears that the STPP may be stable to NTMs

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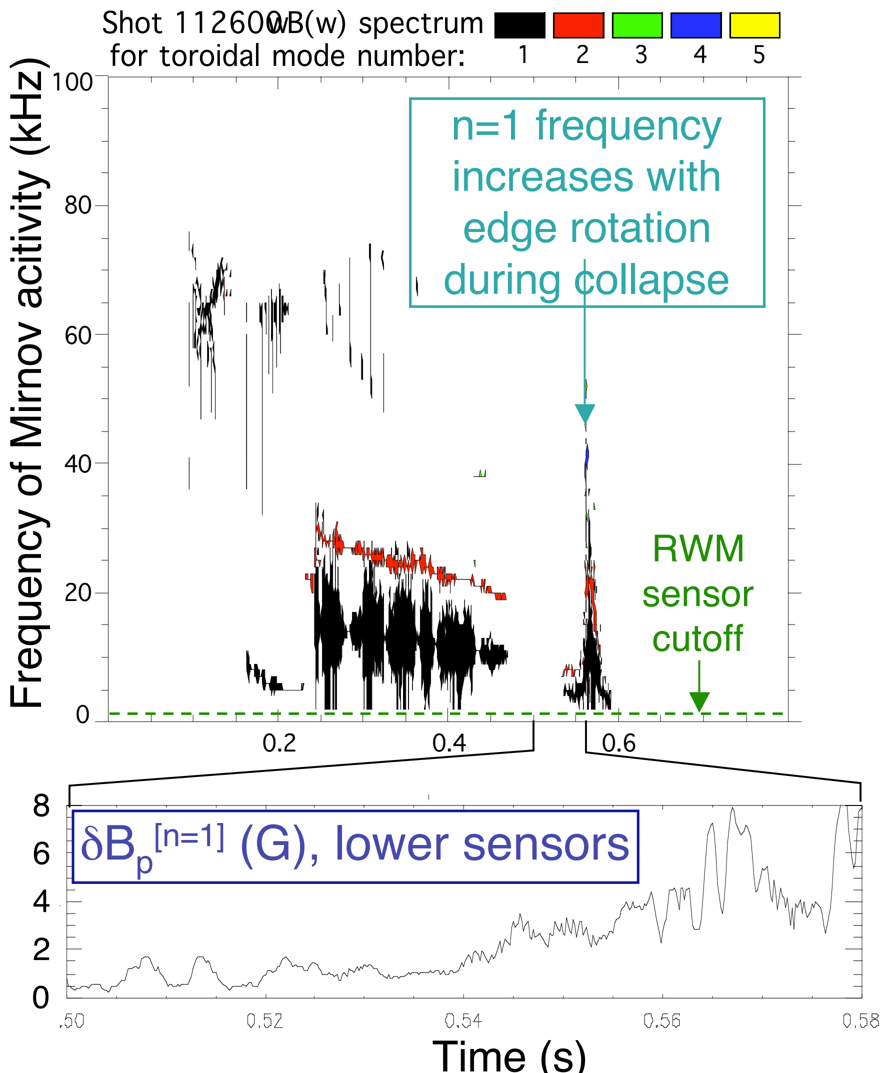
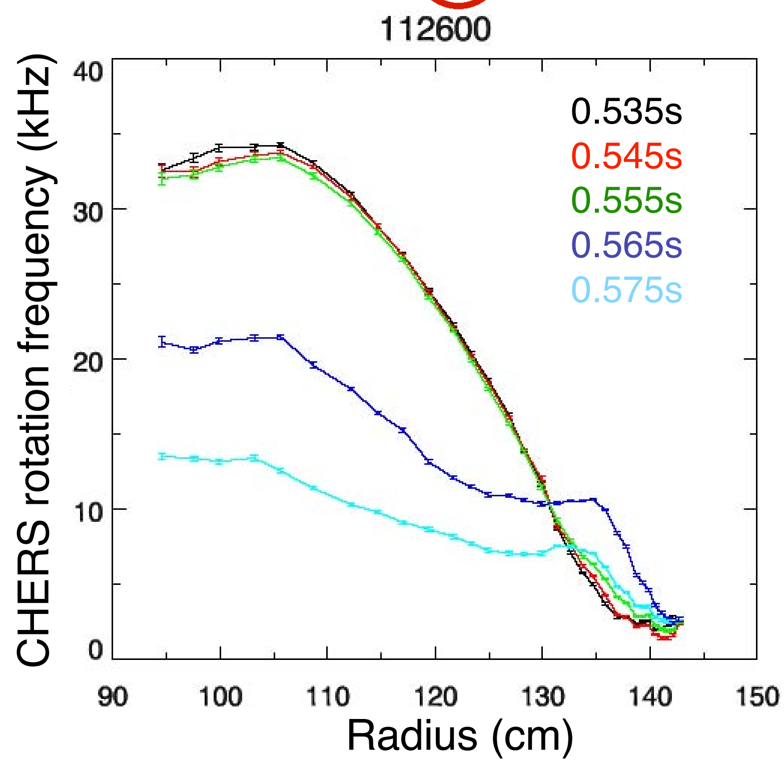
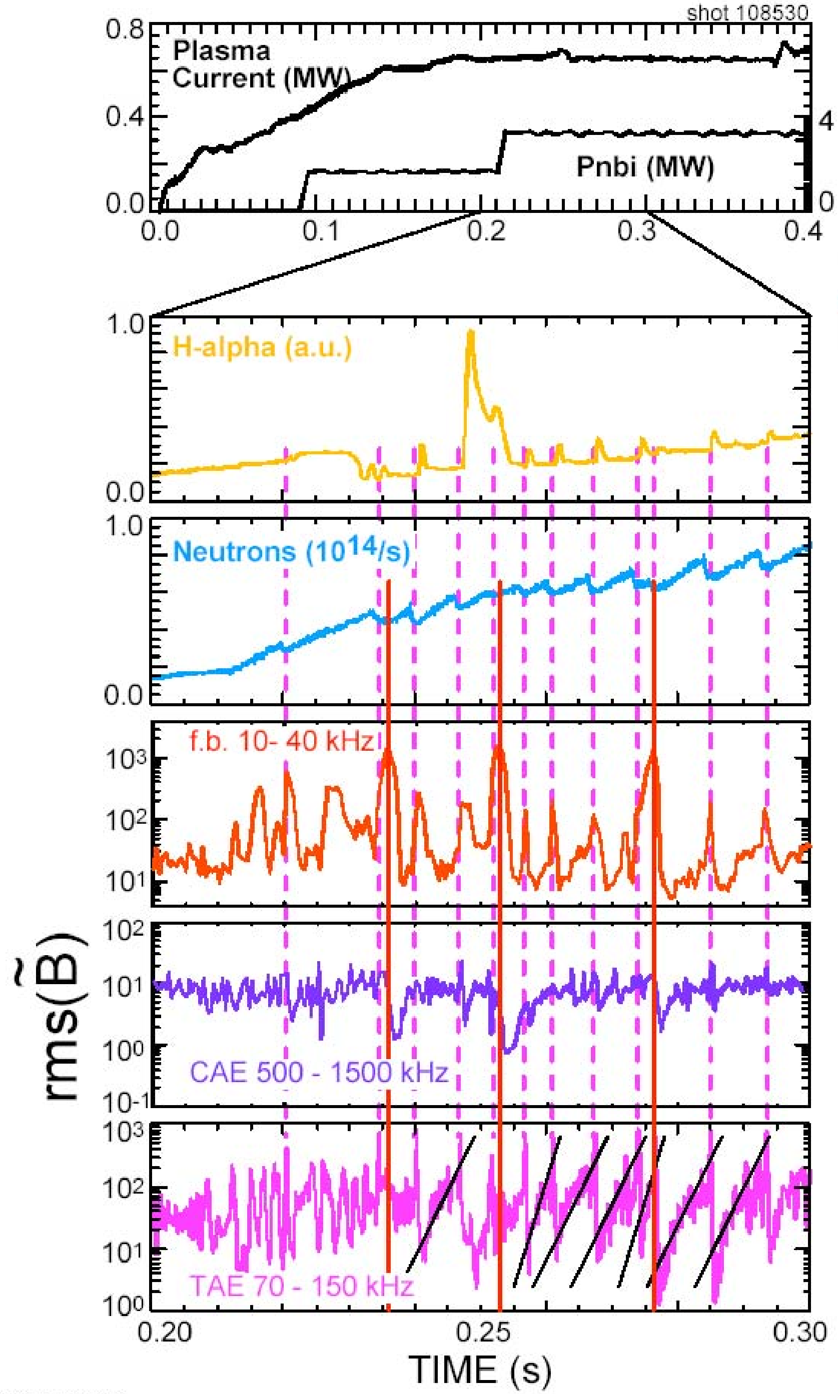
RWM Sensors Detect Mode in High β_T Plasma





- Global rotation collapse consistent with neoclassical viscosity due to ideal RWM perturbation

Sabbagh, Bell, Menard



TAE's, f.b.'s, and CAE/GAE's Can Interact to Expel Energetic Particles

NSTX

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

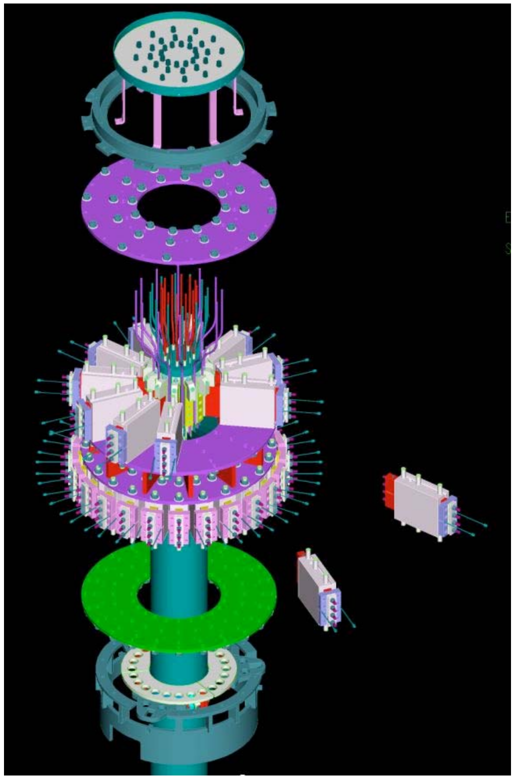
Synchronous sudden activities of

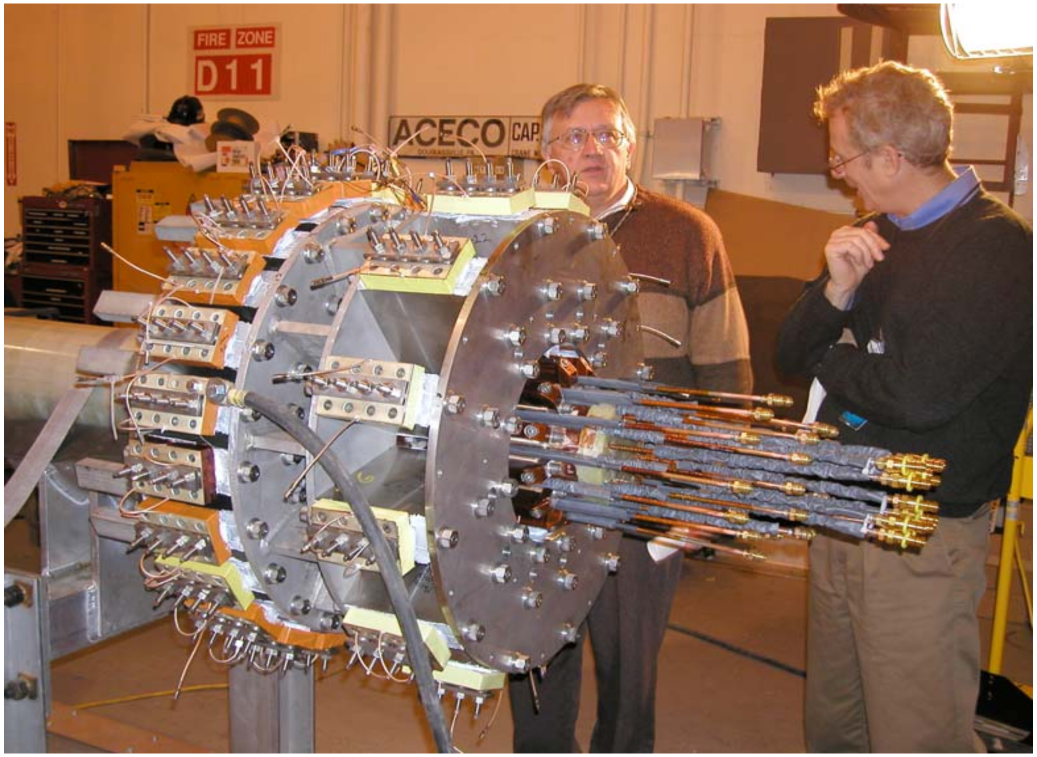
- Edge ionization rises
- D-D neutron drops
- Fish-bone modes rises
- TAE mode crashes
- Separately, synchronous drops of f.b. and CAE modes
- Only when $\beta_{T0} \leq 10\%$ and $I_p \leq 700$ kA, relevant to moderate β devices
- Relevant to burning plasmas

PPPL

Spherical Torus Center-Stack is a Challenge

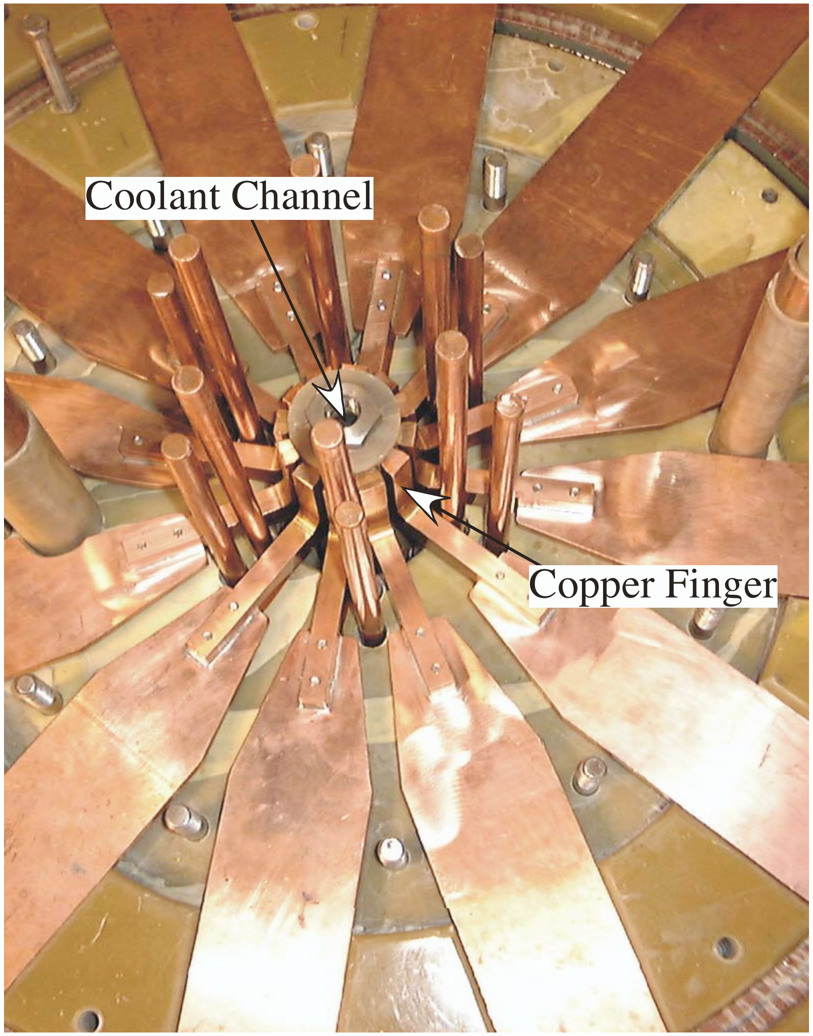
- **NSTX: Now Operating With a New Center Bundle for Toroidal Field Coil**
  - Joint failure in February ‘03
  - New, stronger bundle constructed after redesign, modeling and review
  - Continuous monitoring installed; OK at 0.45 T for ~ 1200 shots



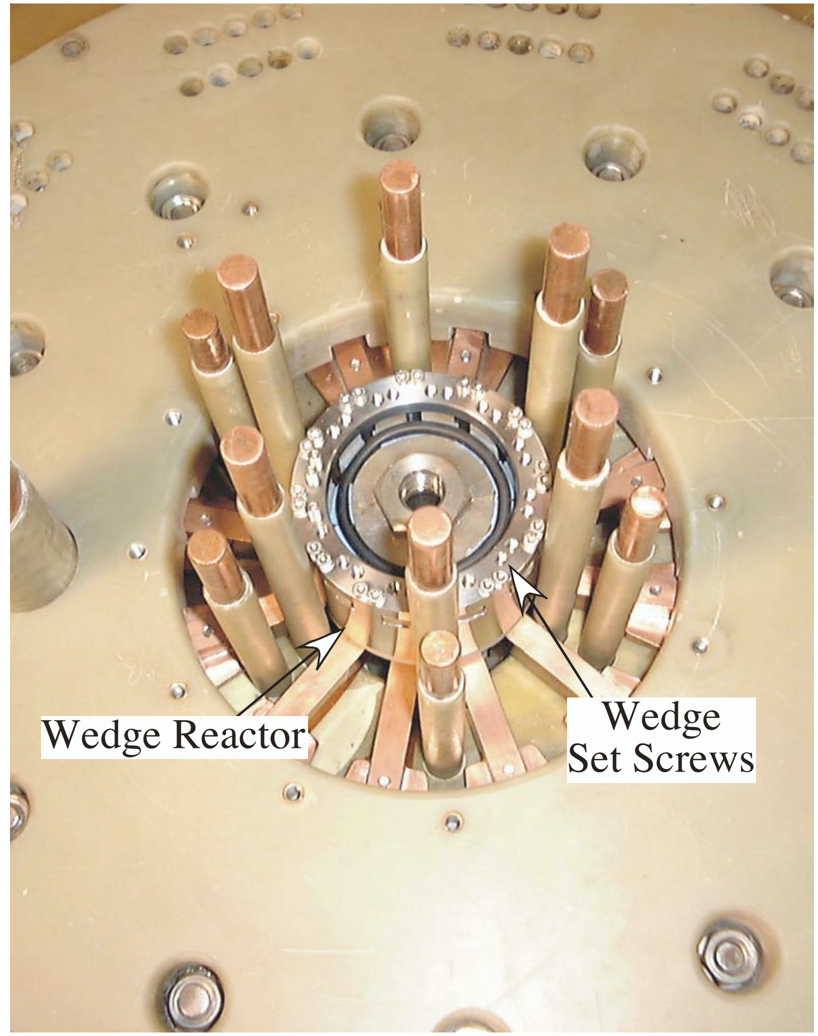


PEGASUS Toroidal Field Upper Joint Assembly

Bare TF Assembly

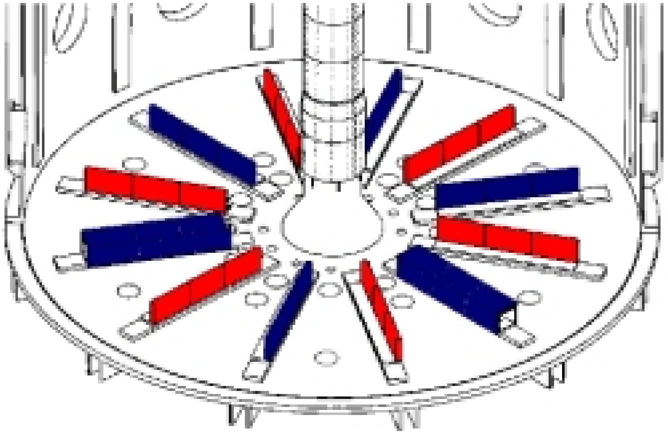


Fully Assembled TF Joint



- Cylindrical spring reactor with wedges compresses joints
- Silver mesh used on contact area to ensure high local pressure and low net joint resistance

Divertor Electrical Biasing



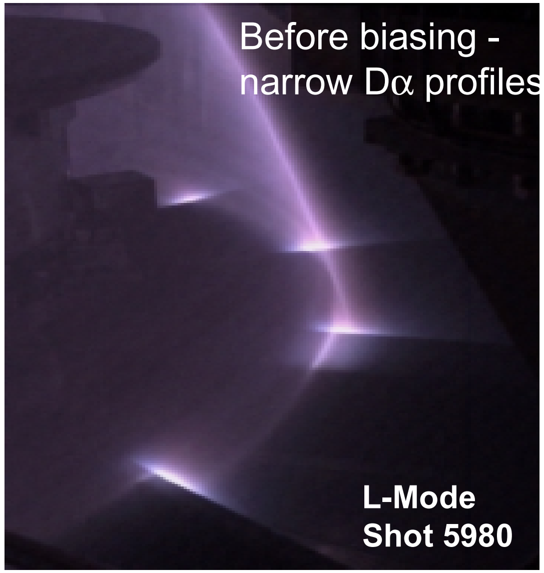
- **Toroidally <u>asymmetric</u> biasing**

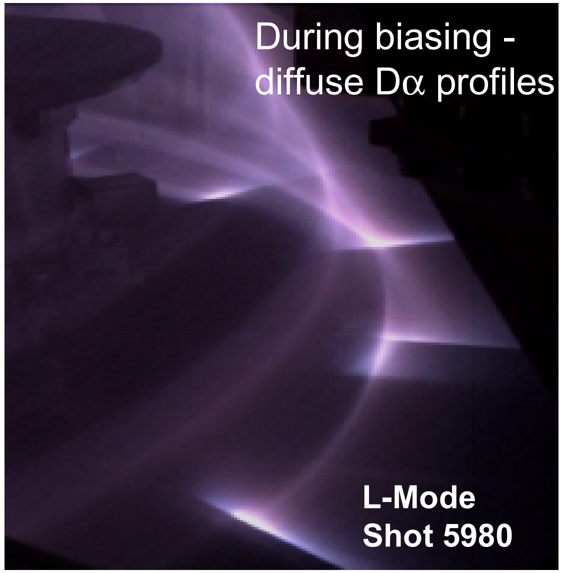
⇒ Potential variations in SOL

⇒ ExB driven convective cells $\mathbf{v} = c\dfrac{\mathbf{B}\times\nabla\varphi}{\mathrm{B}^2}$

⇒ SOL broadening

⇒ **Reduction of power density**



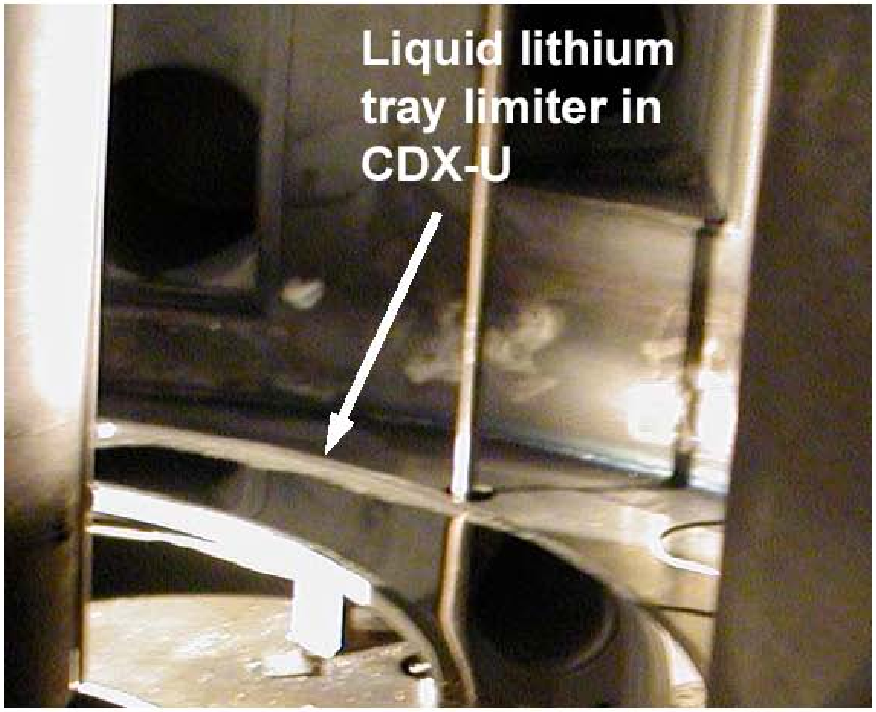


G Counsell et al

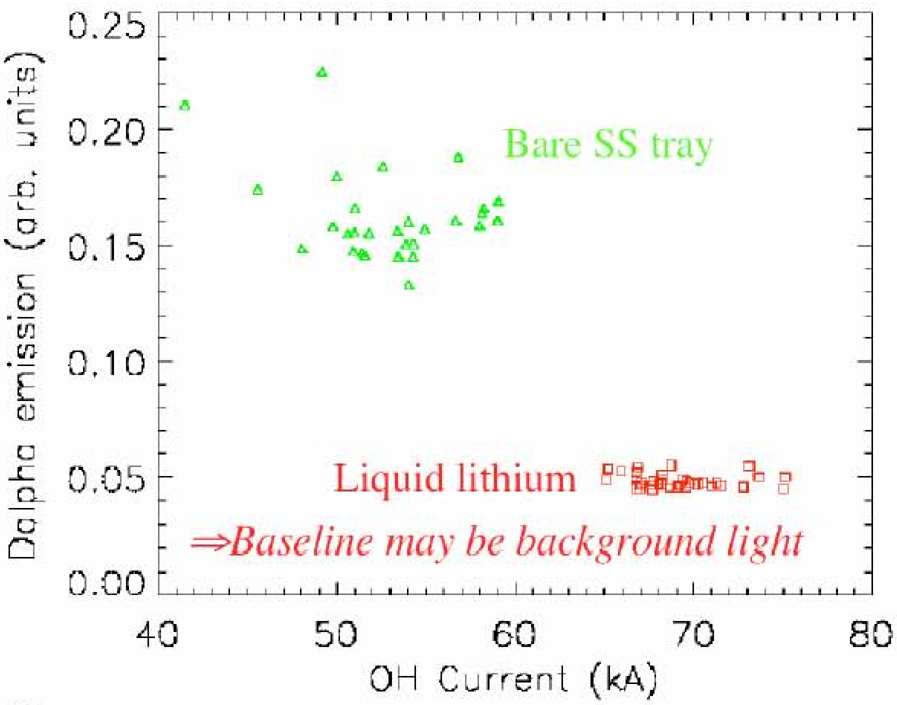
UKAEA Fusion Working in Europe

CDX-U Is Testing Innovative Lithium Plasma Facing Component Effects

- 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

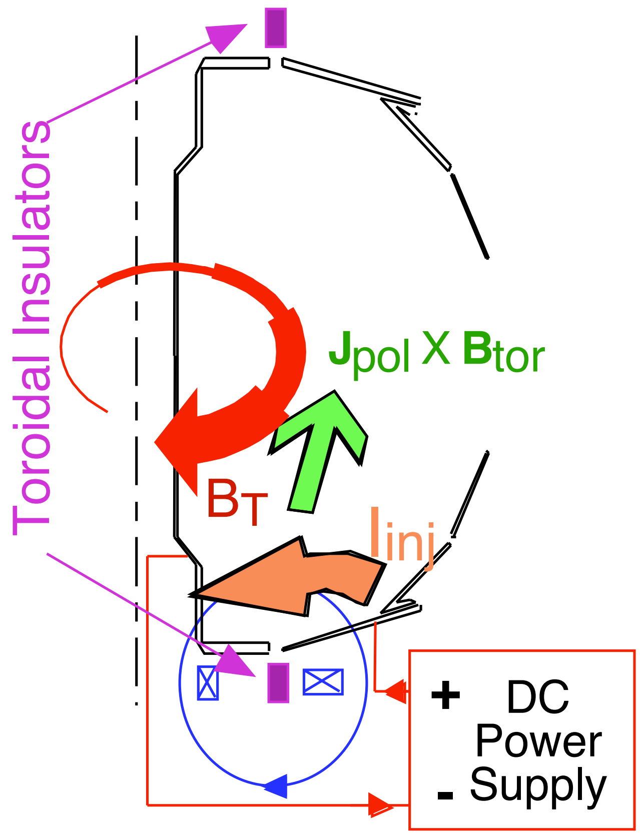


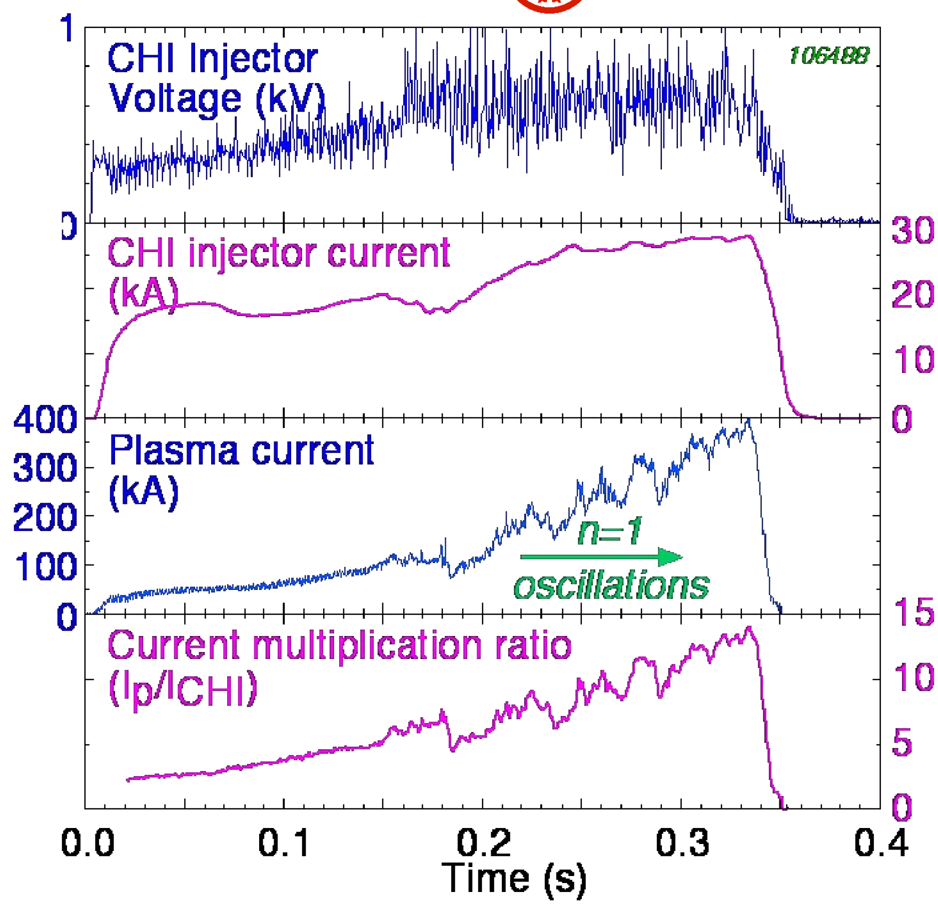
Tray after ~40 discharges.



PPPL, UCSD, ORNL, SNL

CHI Has Generated Significant Toroidal Current Without Transformer Induction

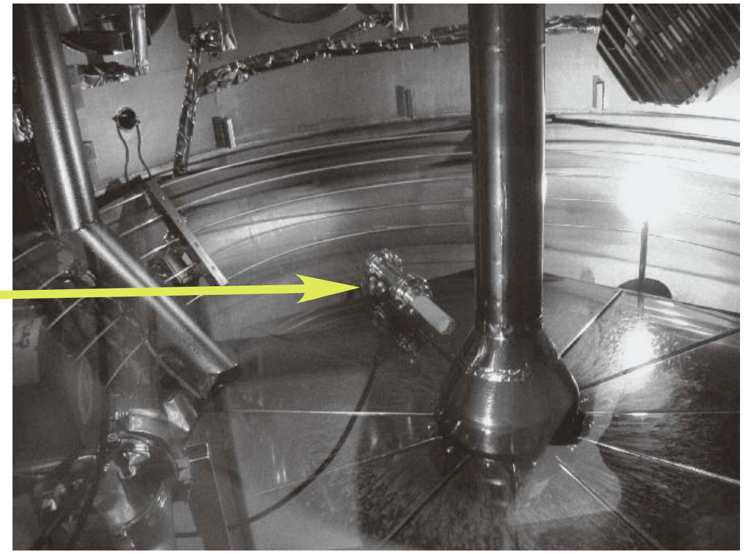


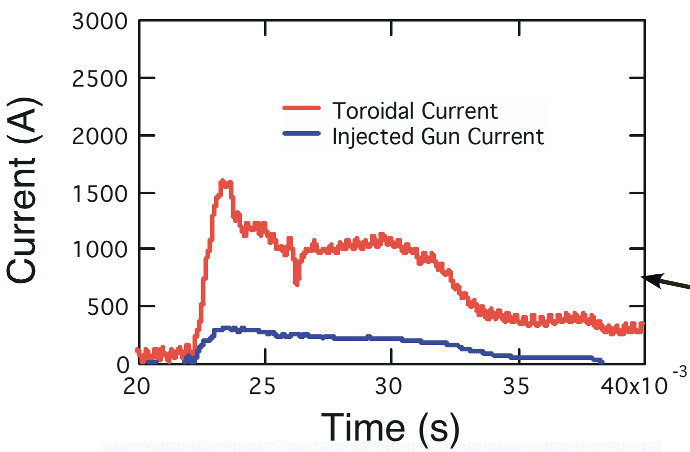


- Goal to produce reconnection of current onto closed flux surfaces
  - *Demonstrated on HIT-II experiment at U. of Washington, Seattle*

Noninductive Startup in PEGASUS with Simple Plasma Gun(?)

- Single gun installed for near-toroidal injection in divertor reigion
- Current amplification up to 17 so far
- Clear reconnection and state change above a threshold in power/helicity(?)
- No optimization of gun or geometry yet; no info on magnetic surfaces

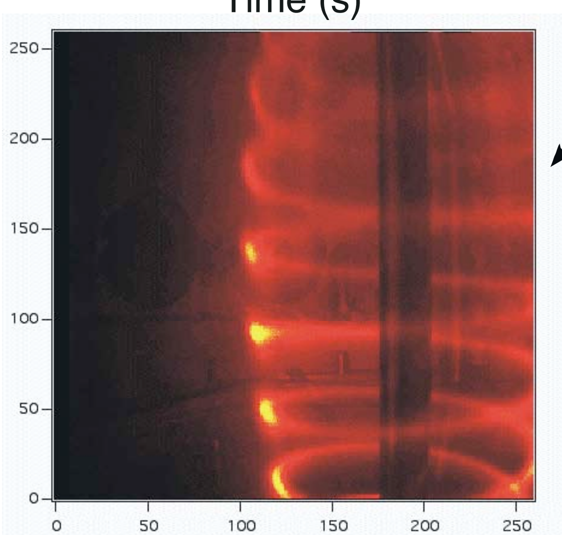


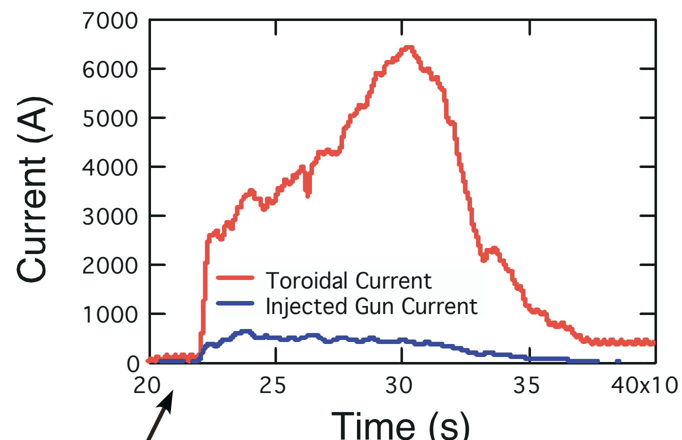


SN 24434 V_{bias} = 50 V

Low current density

=> No amplification
No reconnection

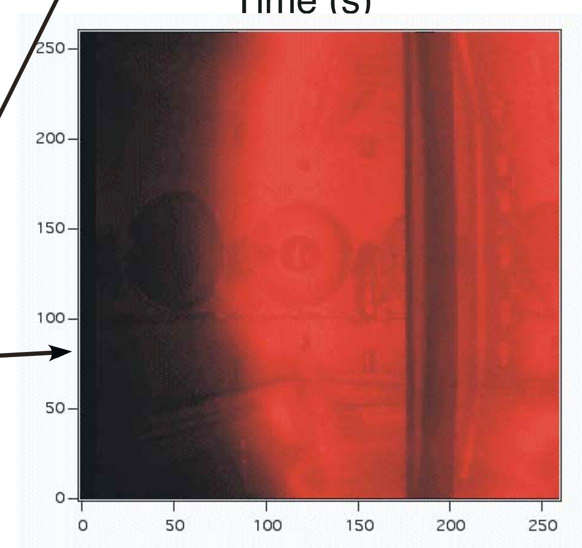




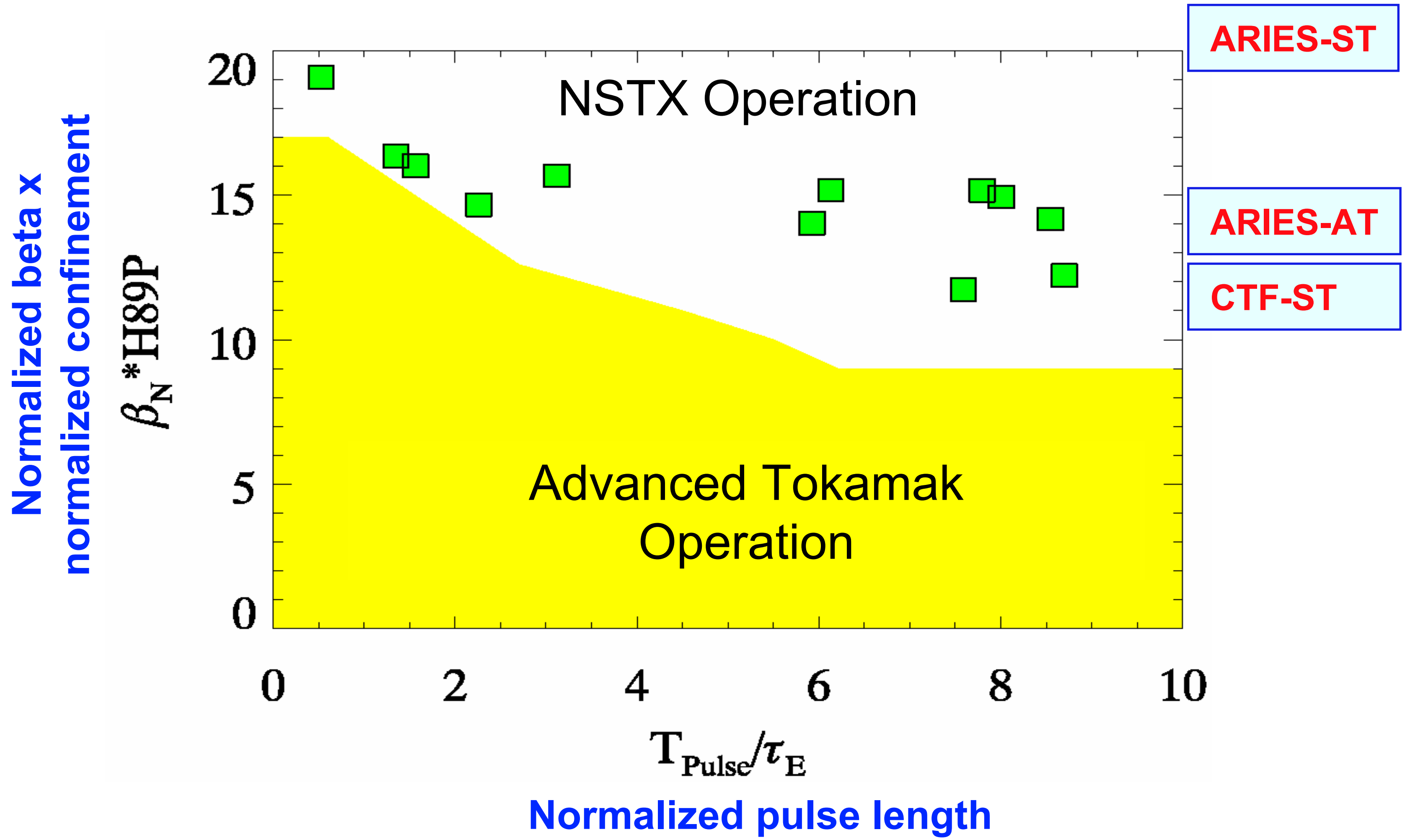
SN 24438 V_{bias} = 400 V

High current density

=> Net amplification
Reconnection (?)



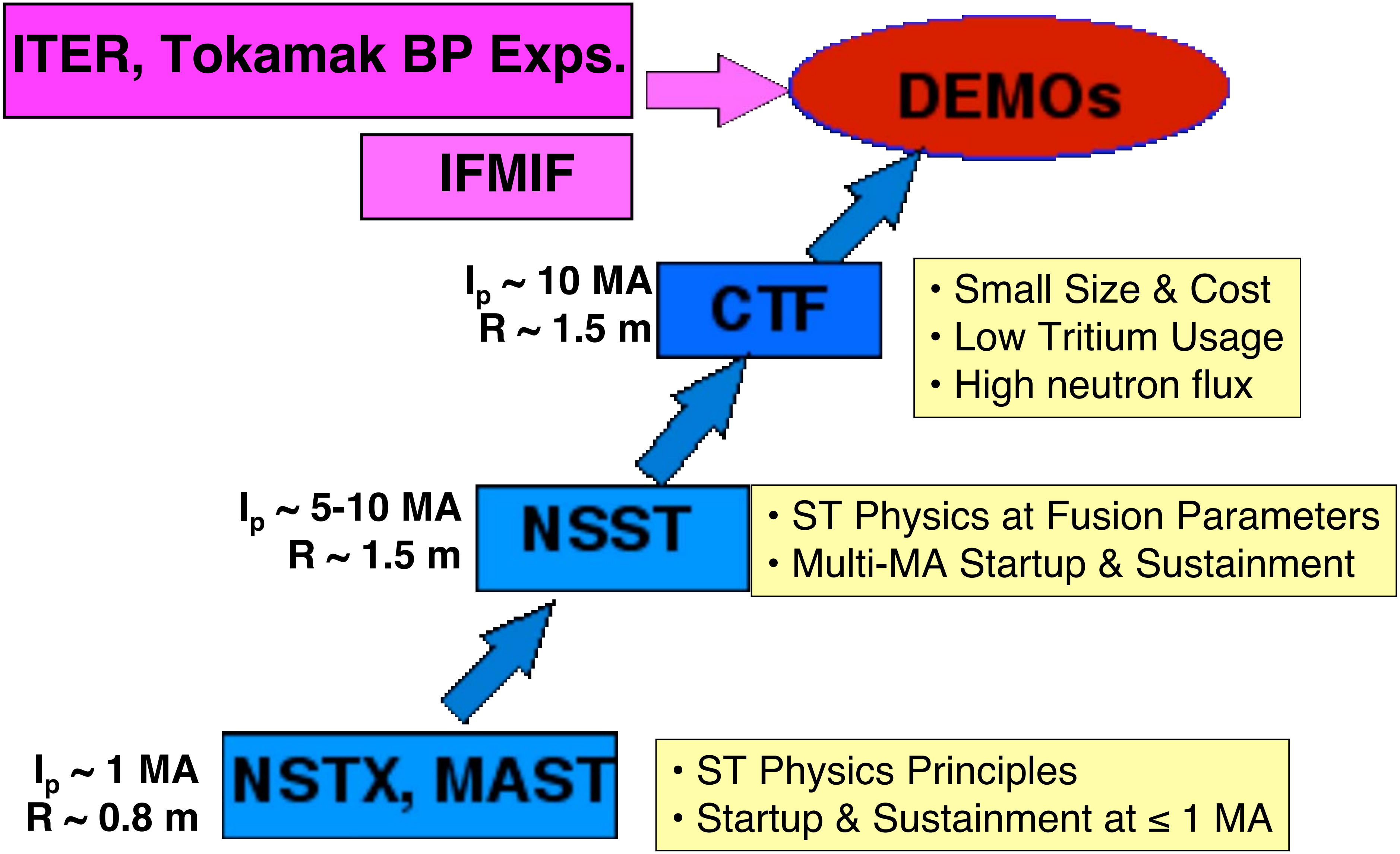
Long-Pulse H-Mode Plasmas Made Encouraging Progress in toward Future ST Possibilities



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

ST Devices Can Make Key Cost-Effective Contributions to Fusion Energy Development

Spherical Torus



Summary: Exciting Times in ST-land!

- Properties of low-A plasmas (high β_t, low B_{TF}, strong shaping, etc.) strongly influence plasma behavior

- The ST may offer cost-effective steps to attractive fusion concepts
  - *Rapid development due to strong overlap with tokamak physics*

- ST research is expanding the knowledge base for conventional tokamaks
  - *Expansion of tokamak databases; extension to extremes of parameters*
  - *Contribute to burning plasma optimization in future BP experiment*

- The present generation of PoP-class ST's - NSTX and MAST - are exhibiting attractive confinement and stability properties
  - $\beta_t \sim 40\%$, $\beta_N > 5$, *near ideal no-wall limit*
  - $\chi_i \approx \chi_{i\text{-}neo}$, *reduced* χ_e *(MAST),* $\tau_E \sim \tau_E$*(IPB98(y,2)*

- Range of smaller CE experiments addressing specific issues in support of ST program

- Critical science and technical challenges looming
  - *Noninductive startup and sustainment - New CD techniques needed*
  - *Shaping optimization for stability*
  - *RWM control*
  - *Current and pressure profile control*
  - *Particle and wall control; exhaust; divertor; edge*
  - *MHD and fast particles*
  - *Innovative centerstack, divertor designs*
  - *etc.*

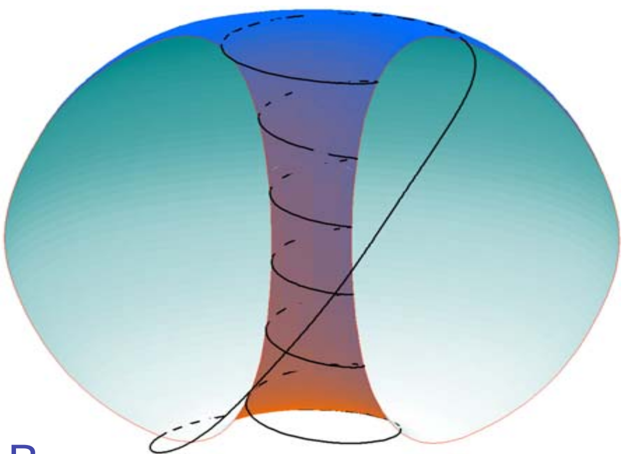
Properties of Low A Plasmas

Improved stability
+ good confinement
⇒ high beta
(β ~ 40% in START, NSTX)

Increased decoupling of j(r) & q(r)

High shaping (κ, δ)
⇒ high I_p capability
High performance at low B

⇒ super-Alfvenic ions
Fast particle driven instabilities



$B_p(R+a) \sim B_t$
⇒ large field line tilt & low parallel power density in the outboard SOL

Strong paramagnetism

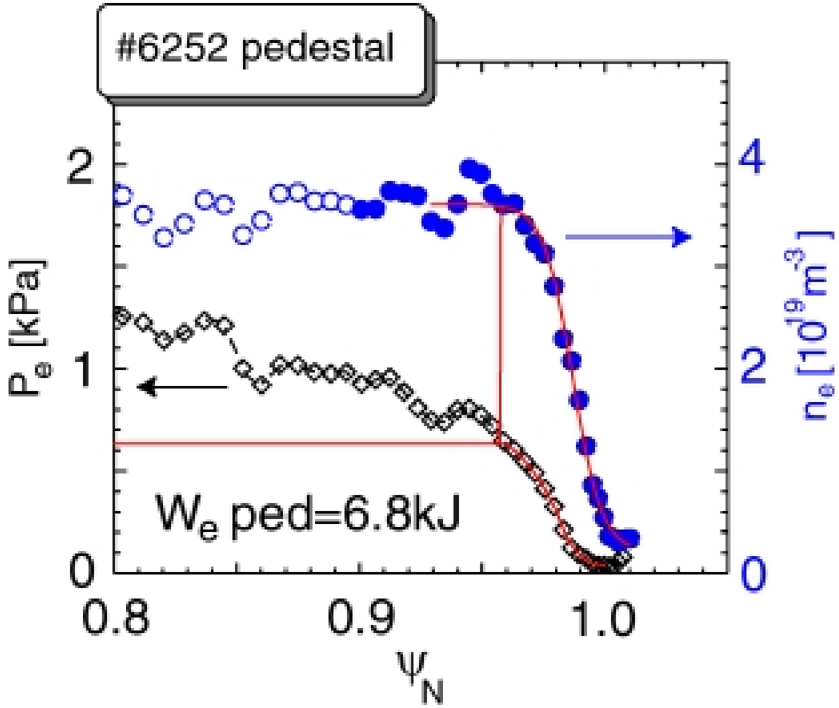
$B_t(R-a) / B_t(R+a) \sim 5$
⇒ enhanced trapping

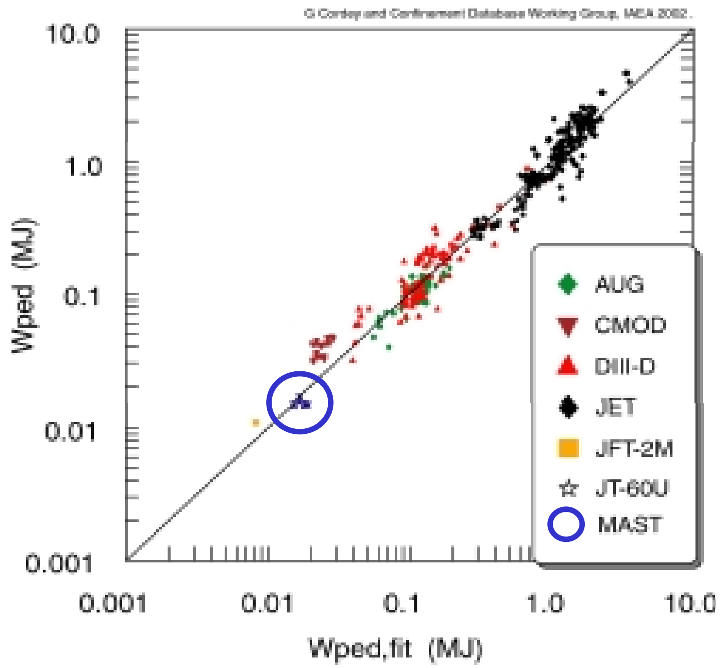
Impact on transport, resistivity

Low moment of inertia
⇒ high flow velocity ($V_\phi \sim V_i^{th}$)

Large inherent ExB flow shear
⇒ suppression of micro-instabilities (ITG)

Pedestal Scaling





MAST pedestal energy calculated from full electron pressure profile.

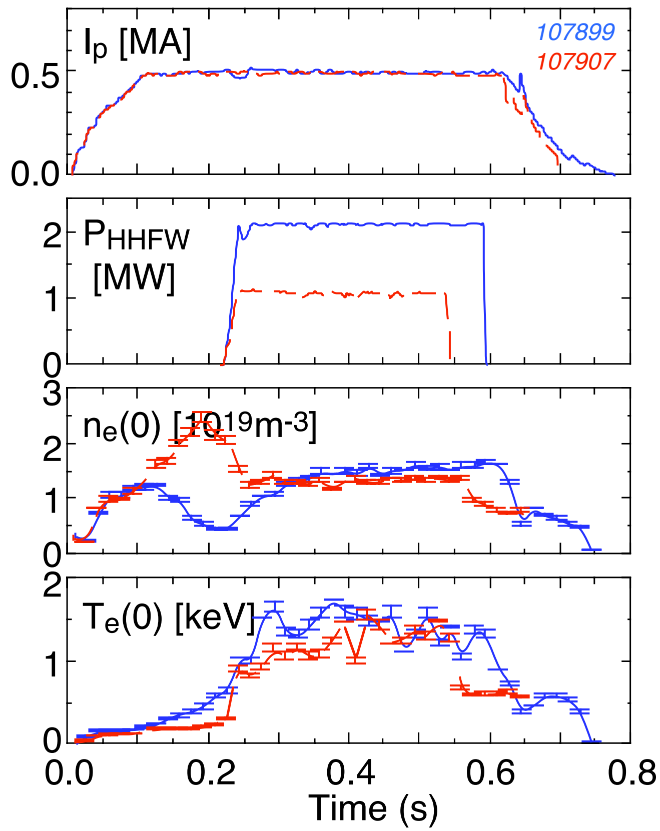
Without MAST: $$W_{ped,fit} \propto I^{1.4} R^{1.37} P^{0.50} n^{-0.15} B^{0.32} \kappa_a^{1.21} m^{0.2} \left(q_{95}/q_{cyl}\right)^{1.6}$$

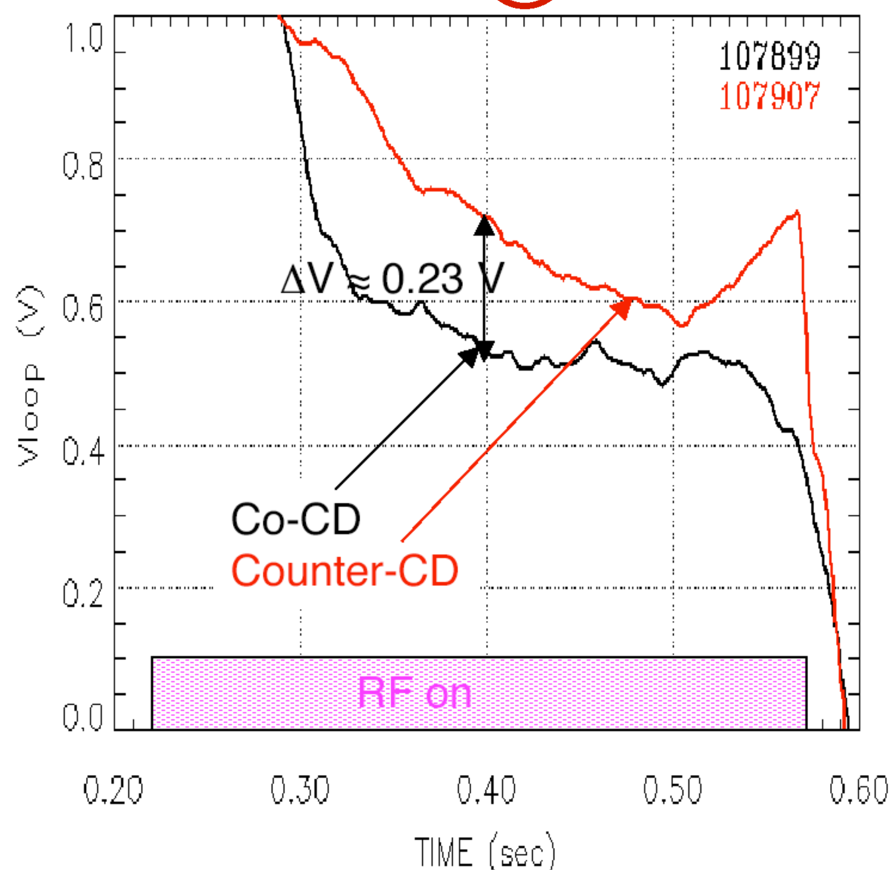
With MAST: $$W_{ped,fit} \propto \left(\frac{a}{R}\right)^{-2.13} I^{1.58} R^{1.08} P^{0.42} n^{-0.08} B^{0.06} \kappa_a^{1.81} m^{0.2} \left(q_{95}/q_{cyl}\right)^{2.09}$$

M. Valovic et al

UKAEA Fusion Working in Europe

Evidence for Current Drive by HHFW with $k_T \approx \pm 7 m^{-1}$ in Co and Counter CD Phasing



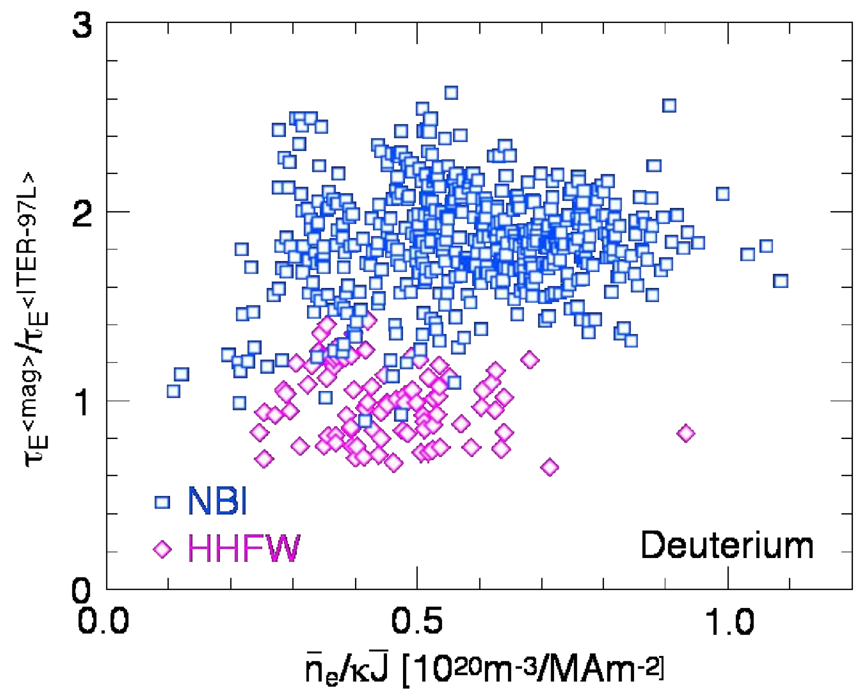


- Phase velocity matches 2keV electrons
- 150 kA driven current from simple circuit analysis
- Modeling codes calculate 90 – 230 kA driven by waves

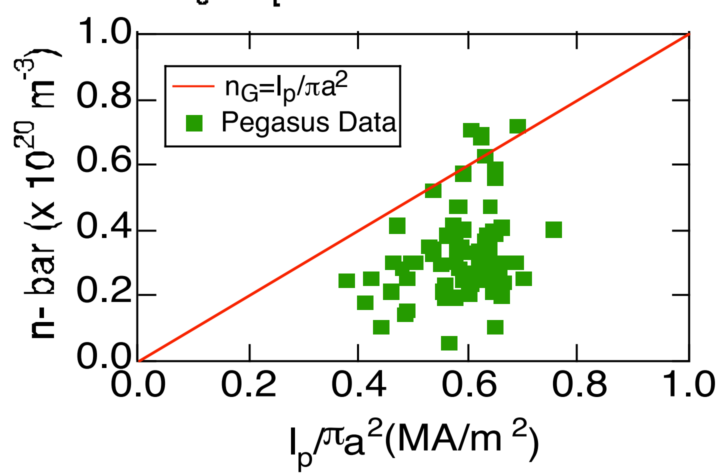
Ryan (ORNL)

Densities May Exceed the Greenwald Limit

- NSTX: with Gas Fueling + NBI Heating
  - Observe little degradation in confinement at high density
  - Regression to dataset shows
    - Incremental efficiency of deuterium gas is low
    - $dN_e/dN_{D,gas}$ = 5 – 10 %
    - NBI fueling is very efficient
    - $dN_e/dN_{D,NBI}$ = 95 – 105 %



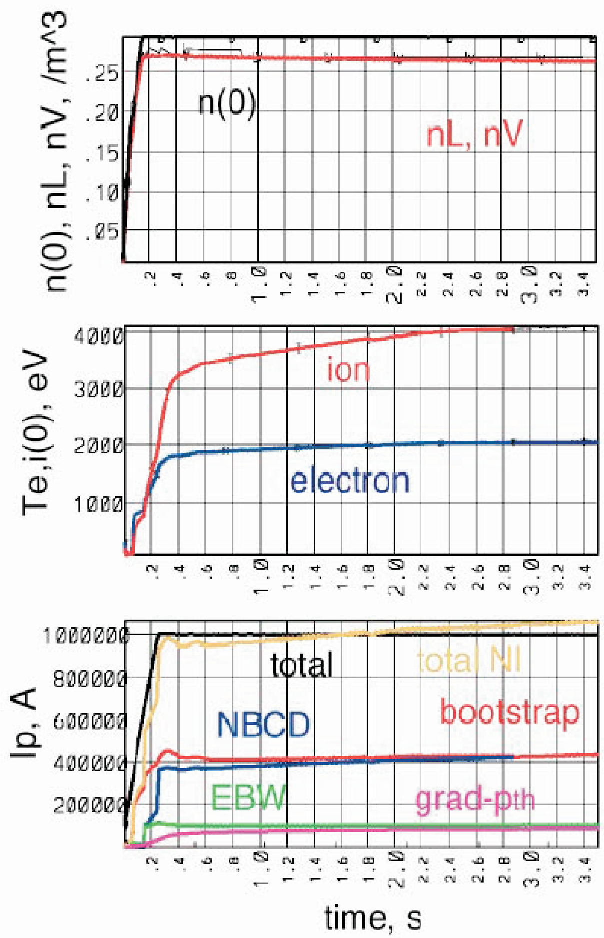
- Pegasus: with Gas Fueling + OH Heating
  - No clear limit to date

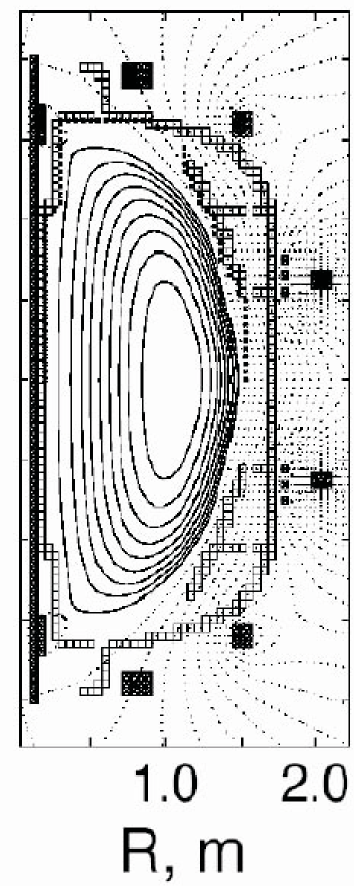


Tools for Long-Pulse, High Performance Plasmas Are Identified

NSTX

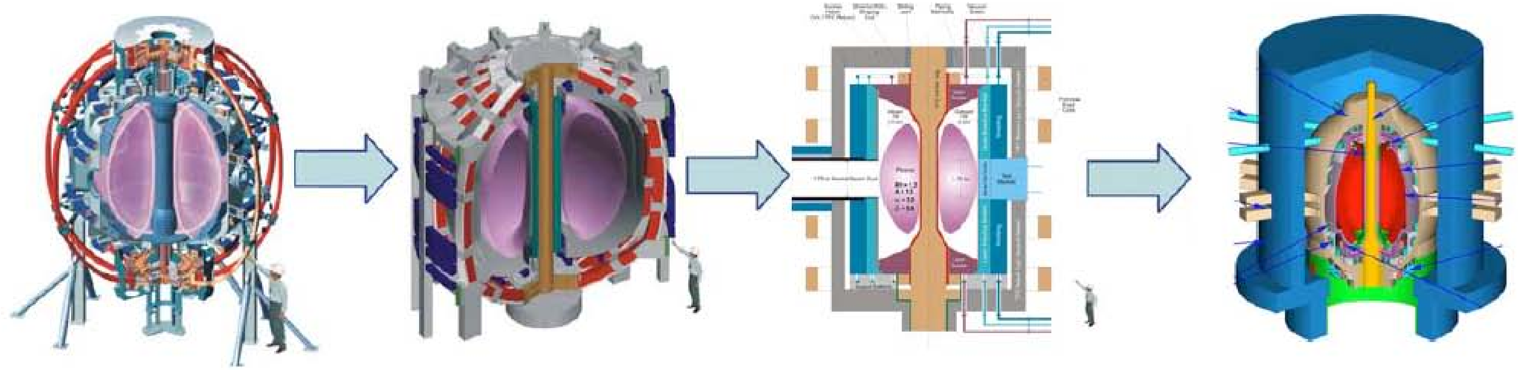
- Enhanced shaping improves ballooning stability
- Mode, rotation, and error field control ensures high beta
- NBI and bootstrap sustain most of current
- HHFW heating contributes to bootstrap
- EBW provides off-axis current & stabilizes tearing modes
- Particle and wall control maintains proper density





CompX, MIT, PPPL, ORNL, UCSD

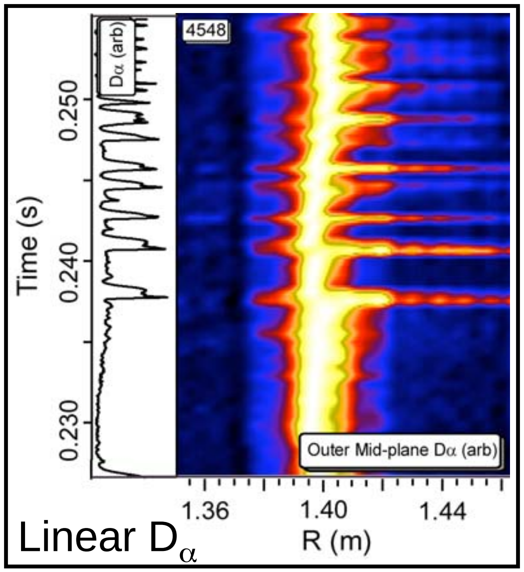
Future ST Steps Are Estimated to Require Moderate Sizes to Make Key Advances toward DEMO

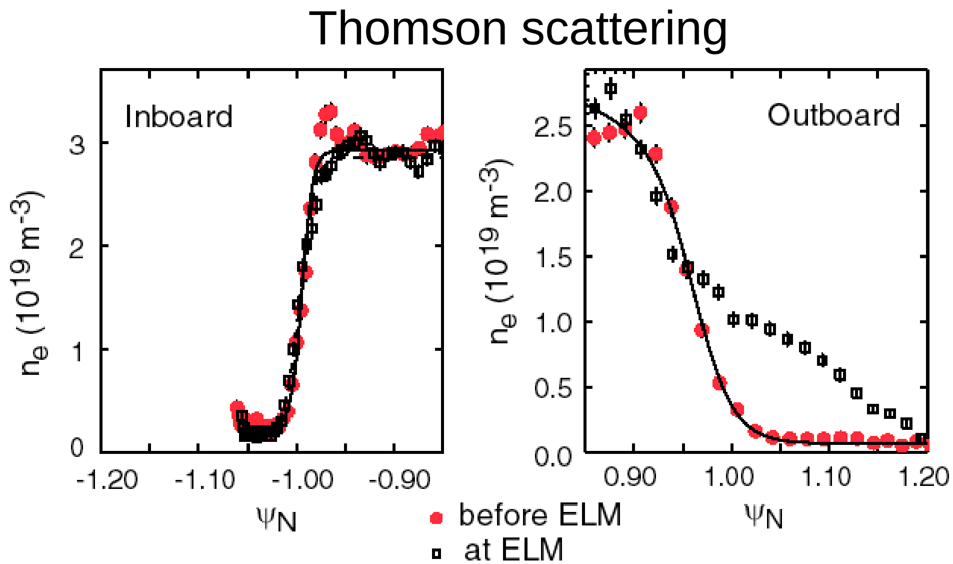


Device	NSTX		NSST		CTF		DEMO
Mission	Proof of Principle		Performance Extension		Energy Development, Component Testing		Practicality of Fusion Electricity
R (m)	0.85		**~1.5**		**~1.2**		~3
a (m)	0.65		~0.9		~0.8		~2
κ, δ	2.5, 0.8		~2.7, ~0.7		~3, ~0.5		~3.2, ~0.5
I_p (MA)	**1.5**	**1**	**~5**	**~10**	~10	~12	~25
B_T (T)	**0.6**	**0.3**	**~1.1**	**~2.6**	~1.7	~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 (%)	~0.05		~0.05		**~15**	**30**	60
TFC; Solenoid	Multi-turn; Solenoid		Multi-turn; Solenoid		Single-turn; No-solen.		Single-turn; No-solen.

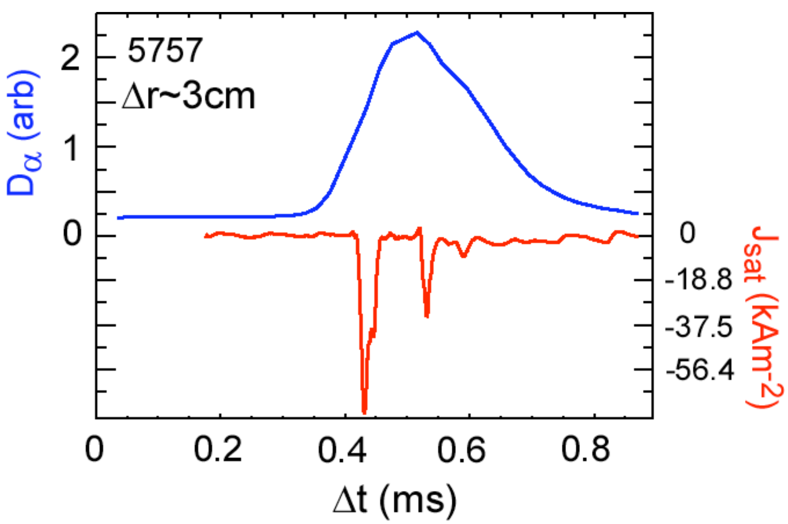
ELMs

ELMs associated with large radial effluxes at outboard side ($\langle v_r \rangle \sim 0.75$ kms^{-} ,
RP observes large j_{sat} out to ~15 cm





Ballooning nature of ELMs



RP data + edge plasma toroidal velocity measurements consistent with n ~ 10 filamentary structure

Kirk et al Phys. Rev. Lett. 92 (2004) 245002

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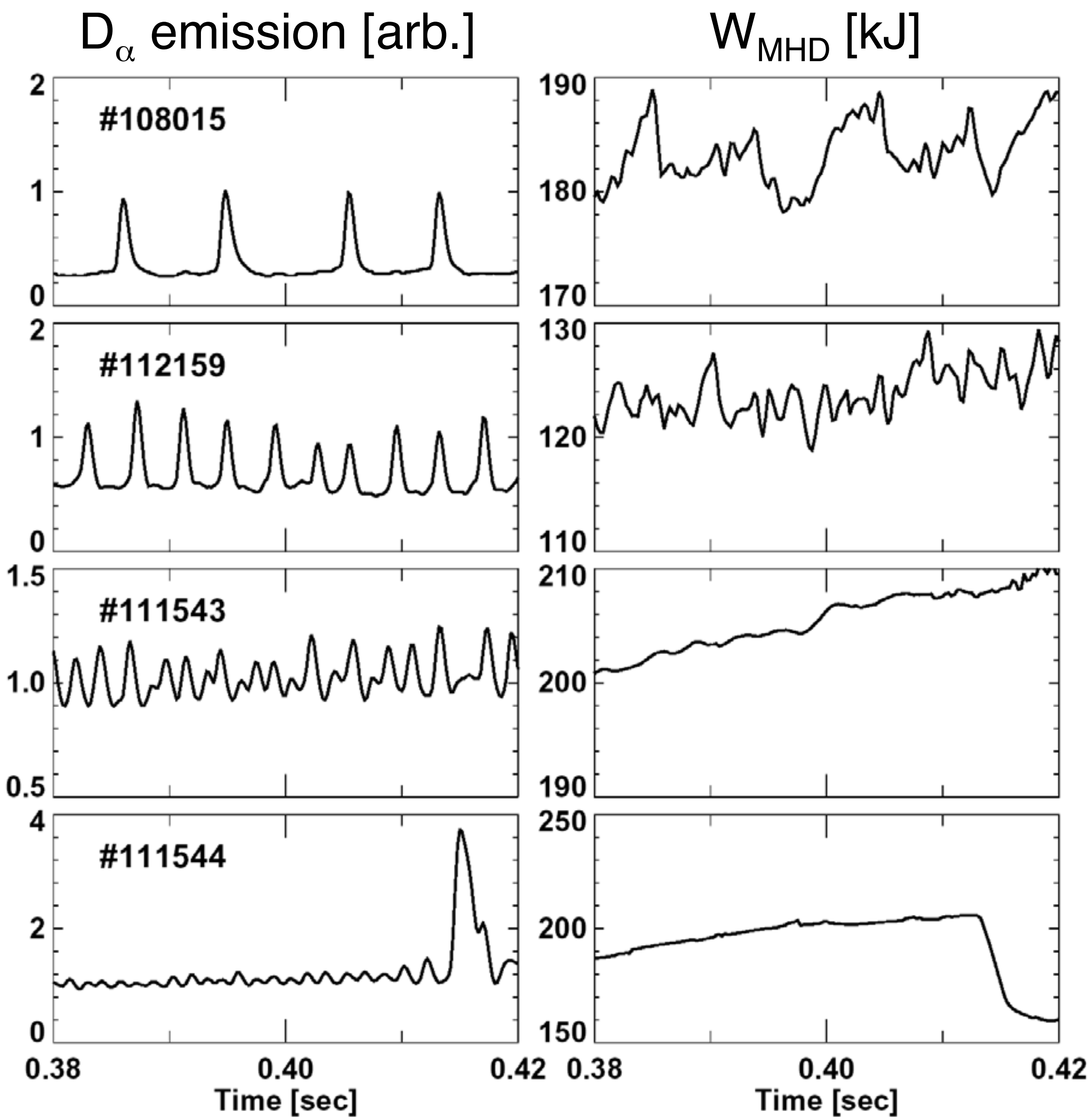
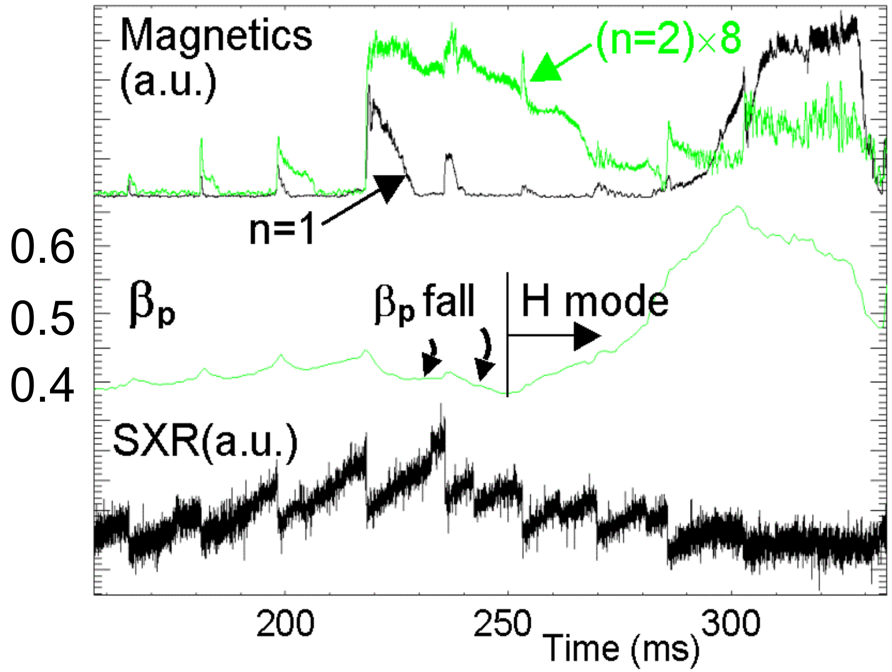
Control of ELMs Critical to Optimizing β



- **Type I**
  - Mid ΔW_{MHD}
  - Magnetic signature
  - No precursor
- **Type III**
  - Small ΔW_{MHD}
  - Magnetic signature
  - High frequency precursor
- **NEW, Type V**
  - Imperceptible ΔW_{MHD}
  - Magnetic signature
  - No precursor
- **Mixed Type V + 'Giant ELM'**
  - Large ΔW_{MHD}
  - May couple to core mode

Neoclassical tearing modes (NTMs)

Sawtooth triggered NTMs (m/n = 3/2, m/n = 2/1) observed in MAST



3/2 NTM is excited close to its saturated size and at β_p close to β_p^{crit} $\Rightarrow$ strong seeding process

R. Buttery et al

3/2 NTM reduces confinement by typically ~ 10%; approximate agreement with Chang & Callen belt model

2/1 NTM can trigger H→L transition followed by mode locking and disruption

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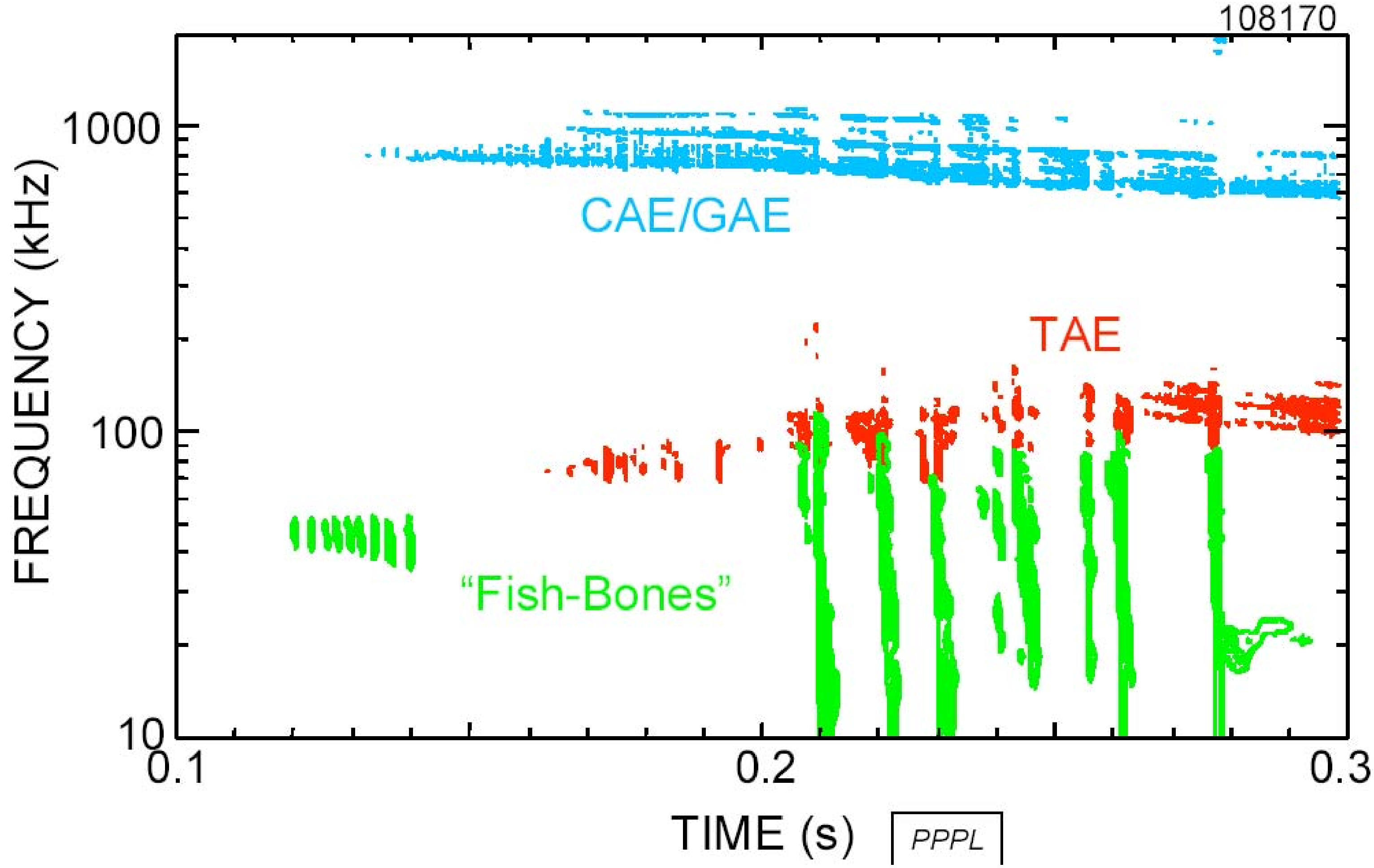
A Broad Spectra of Energetic Particle Driven Modes Are Seen on NSTX

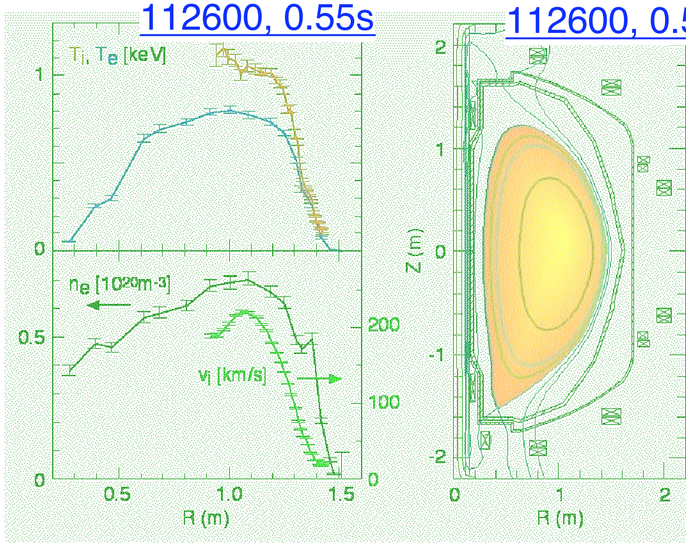
NSTX

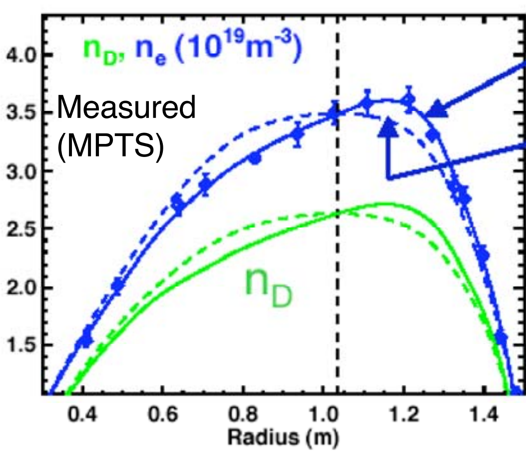
Do these Alfvén Eigenmodes (AEs) and fish-bones (f.b.s) Interact to expel energetic particles?



High Rotation & Large Gradients in T_i, v_i

112600, 0.55s   112600, 0.55s





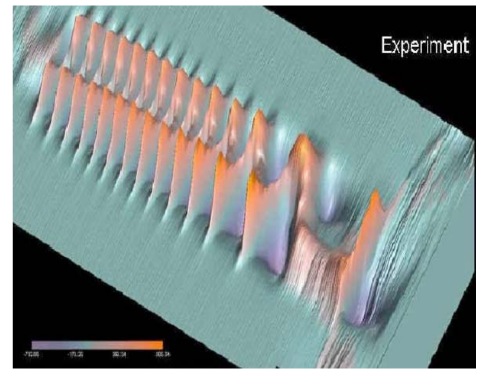
$n_e(\psi,R)$ (MHD model with centrifugal effects)

$n_e(\psi)$ (assuming density a flux function)

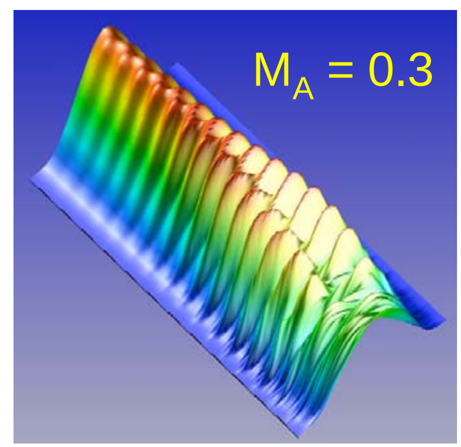
- Density shows in-out asymmetry
  - Effect of high Mach number of driven flow

High v_ϕ/v_A Affects Equilibrium & Stability

- **Experiment**: kinks do not grow but saturate



- **Theory**: with rotation, growth rate reduced by factor 2 - 3 (**M3D**)



Exhaust

STs - small area of inboard divertor targets may lead to high power densities

But favourable divertor target power distribution:

- large ratio of outboard to inboard separatrix area (~ x4) in low A plasmas
- equal up-down power distribution in DND

High B_p/B_t in outboard SOL leads to low parallel power densities:
⇒ local target protrusions intercept a small fraction of power efflux so ST is less sensitive to tile mis-alignment for example

Increases practical feasibility of advanced divertor schemes such as the cascading pebble divertor

Non inductive current initiation needed for STs

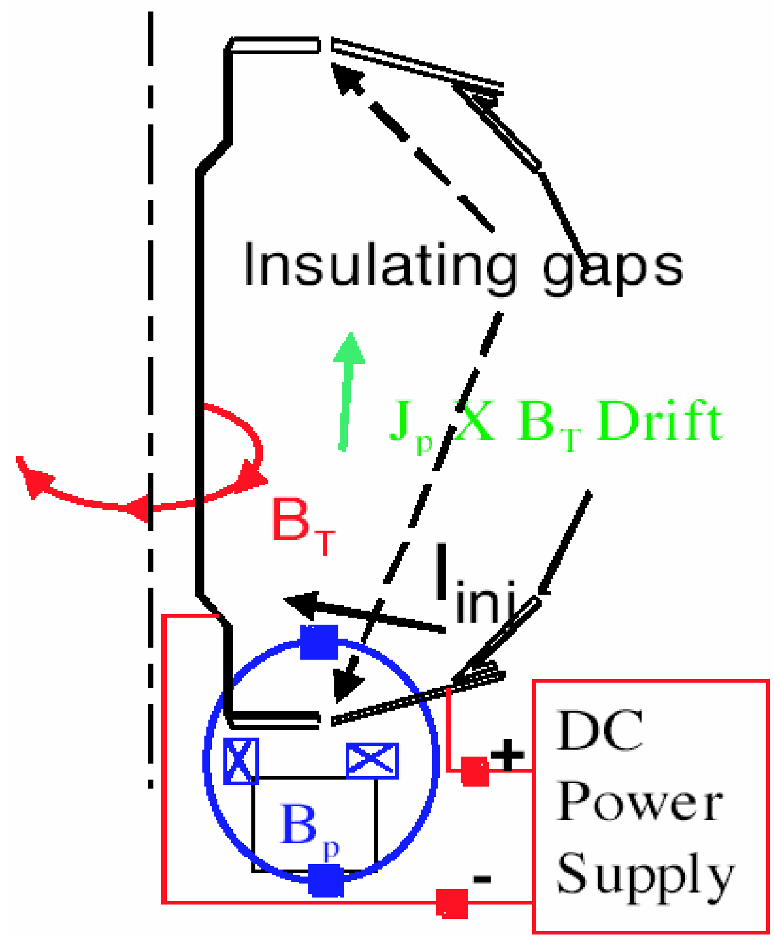
- The favorable properties of the ST arise from its very small aspect ratio, which leaves very restricted space for a central solenoid and related neutron shielding

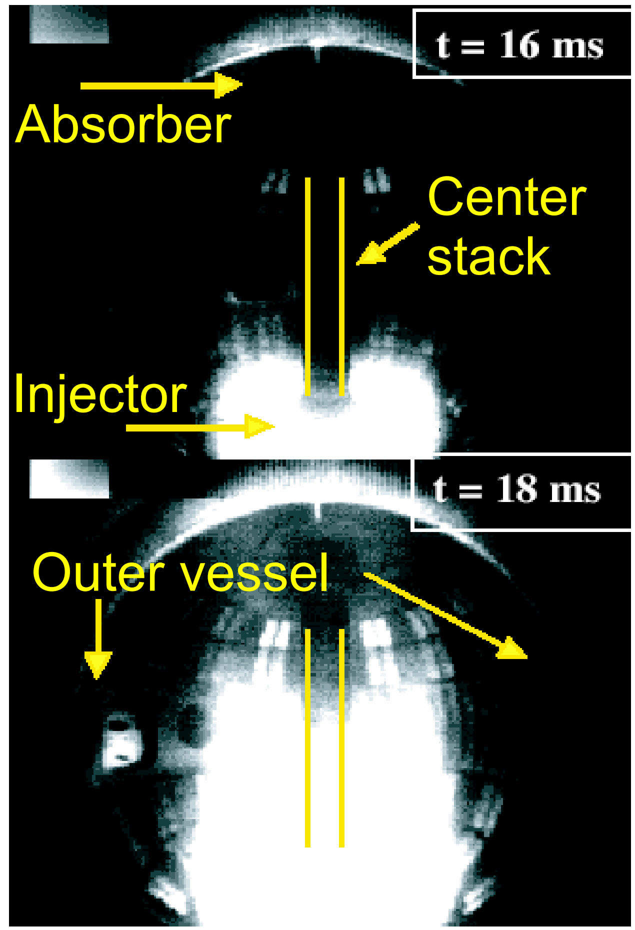
- Solenoid-free plasma start-up is essential for the viability of the ST concept

- Elimination of the central solenoid also simplifies the engineering design of tokamaks (e.g., AIRES AT & RS)

- CHI is capable of both plasma start-up and edge current in a pre-established diverted discharge

Implementation of CHI on NSTX





Fish-eye images of NSTX vessel

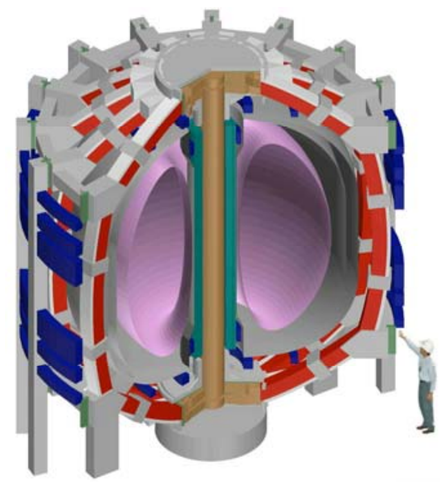
CHI discharge initiates in the injector region

Expect reconnection processes to redistribute edge current to the interior, forming closed surfaces

NSST Mission Elements

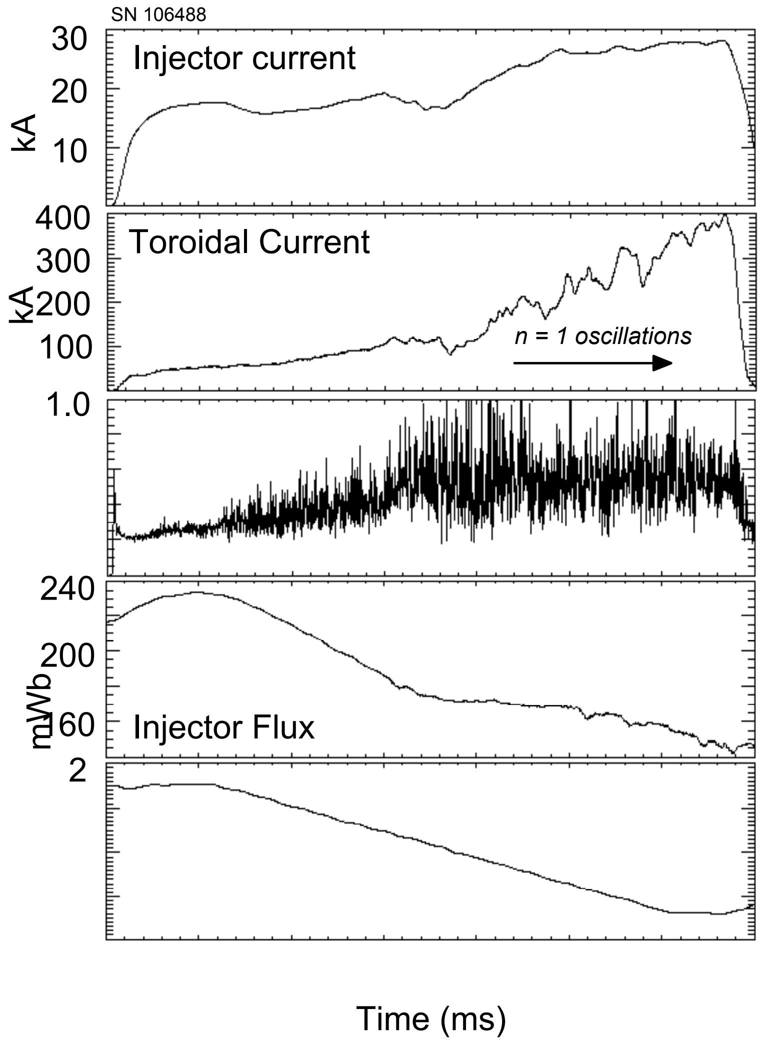
NSST

- ST Physics at Fusion Parameters
  - Non-Ohmic Start-up an Non-inductive Sustainment
  - Plasma Confinement and Stability
  - Power and particle handling
  - Alpha physics at high beta
  - Advanced ST Physics

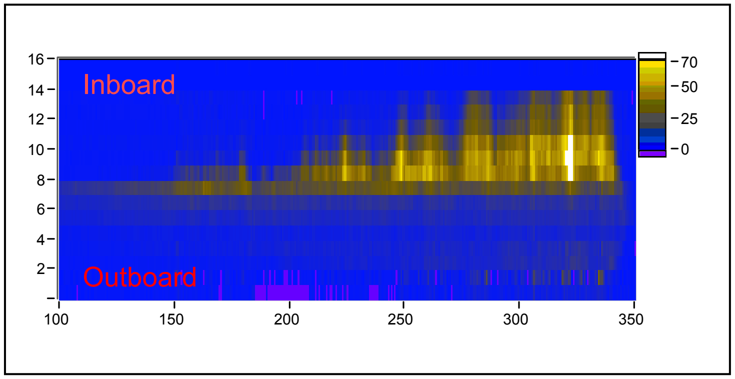


- Provide physics basis for an ST-based compact CTF
- Develop Adv. ST Physics scenarios for CTF, DEMO, and Power Plant
- Contribute to General plasma / astrophysics/ fusion science
  - high β waves/turbulences, energetic particles, magnetic reconnections

Obtained 390 kA with current multiplication of 14 in 330 ms long discharges (steady-state CHI)



- Evidence for good *n=1* oscillations deemed necessary for flux closure
- ESC and EFIT reconstructions consistent with but not conclusive of flux closure
- Evidence for higher temperature from SXR's

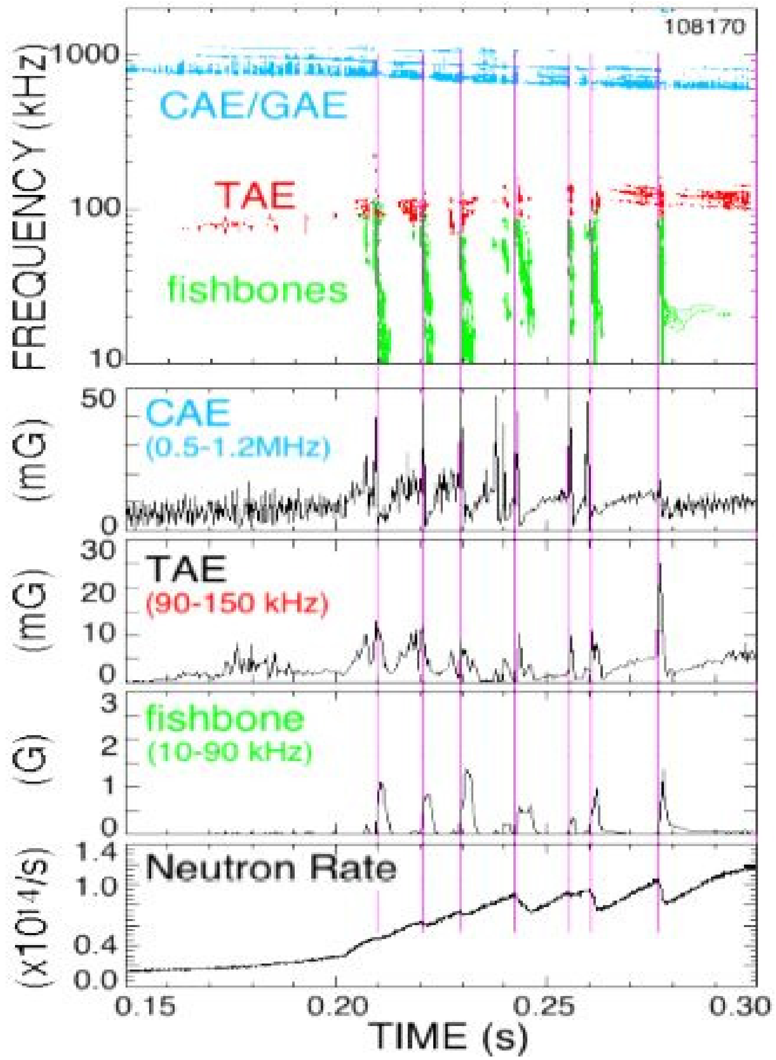


Soft x-ray profiles (E > 100 eV)
D. Stutman (Johns Hopkins)

SS CHI: Voltage is applied for as long as the current needs to be sustained

Variety of Kinetic Instabilities Occurs with NBI

NSTX

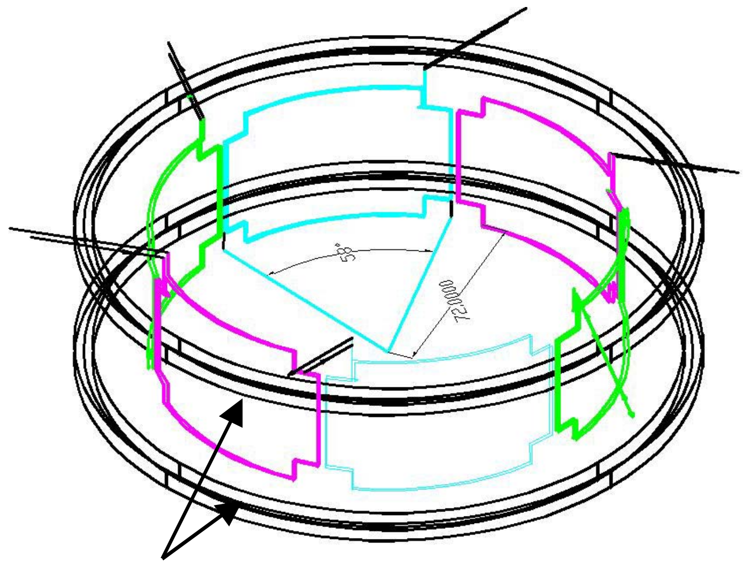


Fredrickson

- Some modes correlated with fast ion losses
  - TAE
  - "fishbones"
- “Fishbones” are different at low aspect-ratio
  - Possibly driven by bounce-resonance
- All modes interact

Developing Capability for Active Control of Resistive Wall Modes

- 6 external correction coils being installed during this run
  - Operate as opposing pairs driven by three switching amplifiers

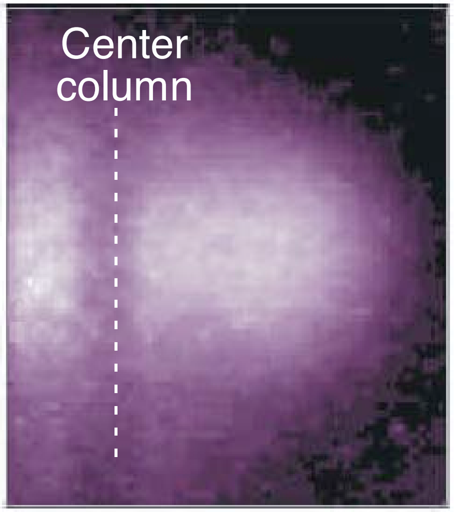


PF5 coils (main vertical field)

- Planning to process sensor data in real-time through plasma control system for feedback control

PEGASUS: ST q-profile has low central shear

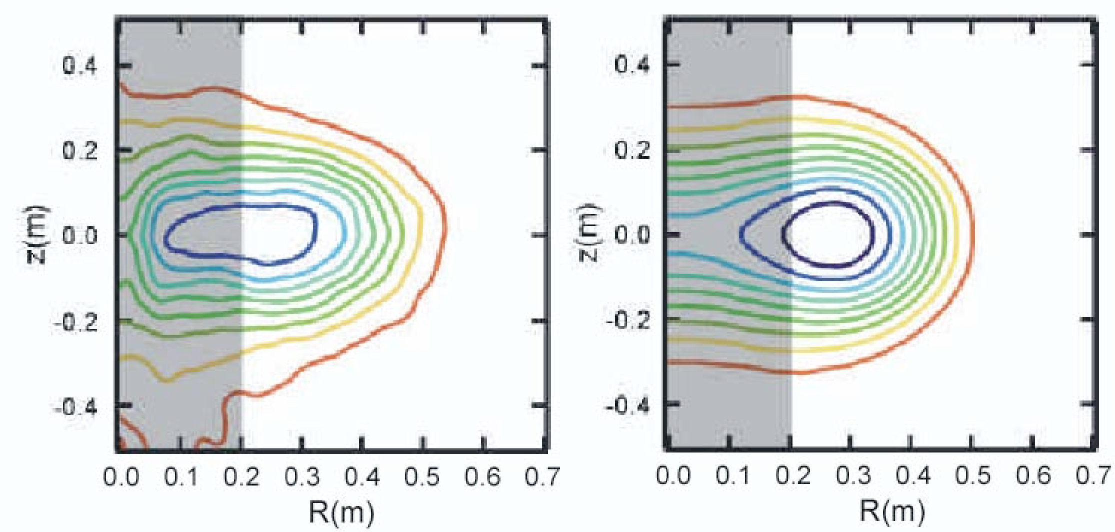
Tangential PHC SXR image

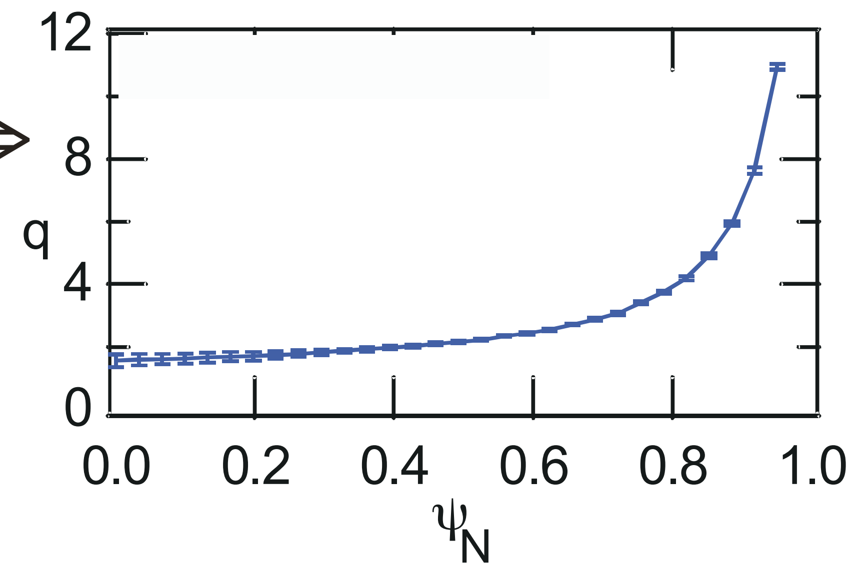


- 2D soft x-ray image constrains q-profile
  - Constant-intensity surfaces determined
  - Mapped into flux space
  - G-S equilibrium with SXR constraints
- Measured q-profile ⇒ low central shear

Image Contours:

Measured / Reconstructed

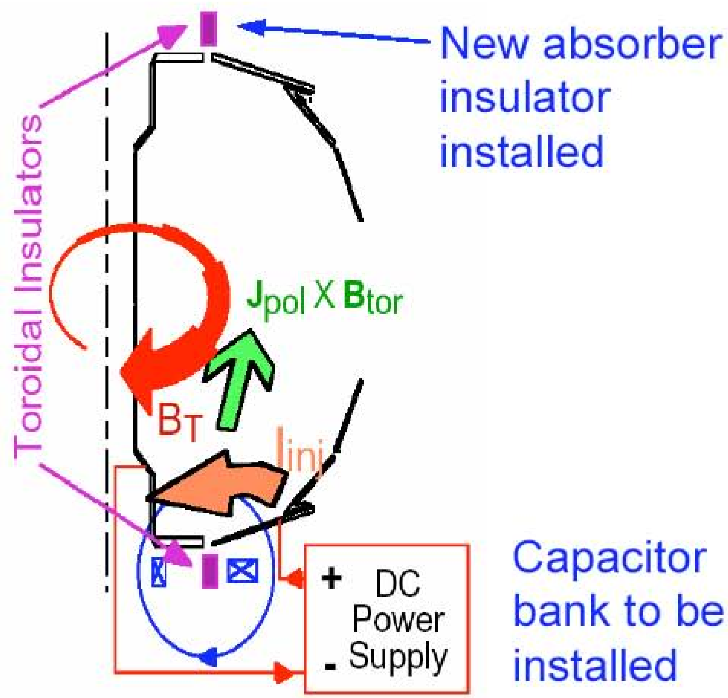


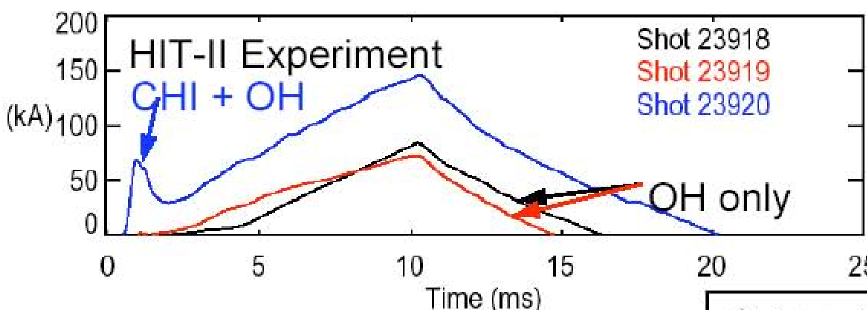


Solenoid Free Start-Up via Coaxial Helicity Injection & Outer Poloidal Field Coil Scenarios to be Tested

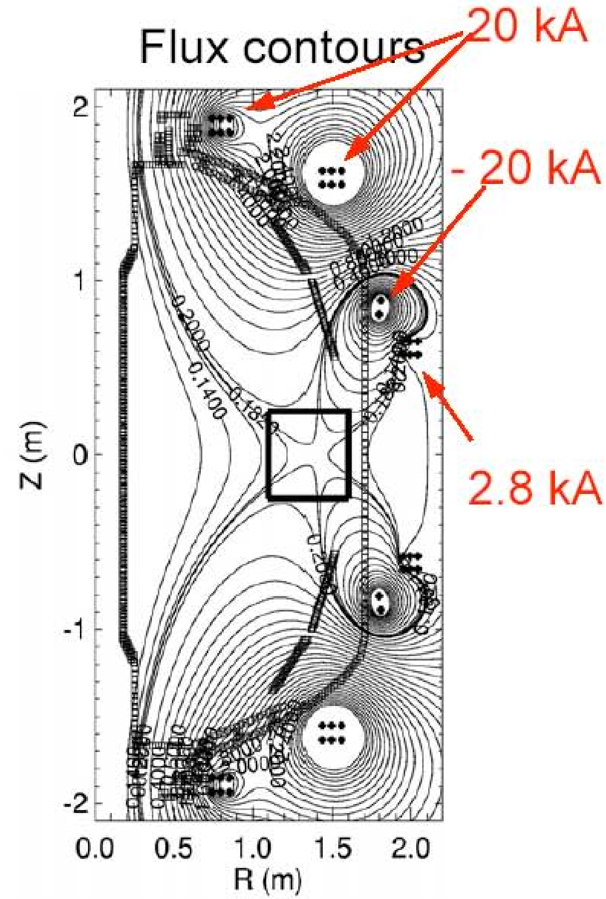
NSTX

Coaxial Helicity Injection Tests





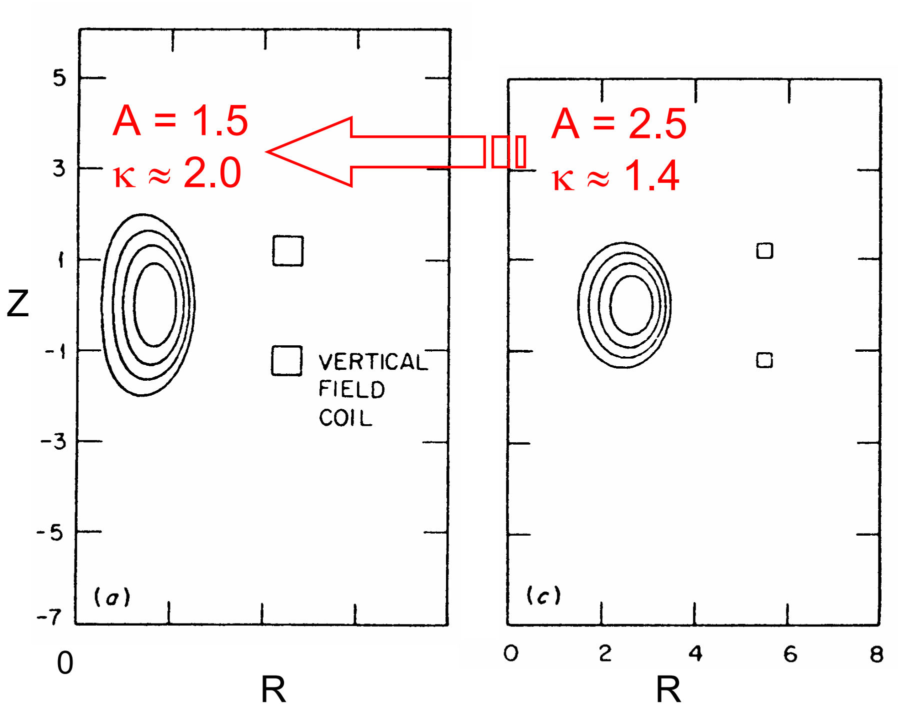
Three Outer Poloidal Field Startup Scenarios, e.g.: Outboard Field Null



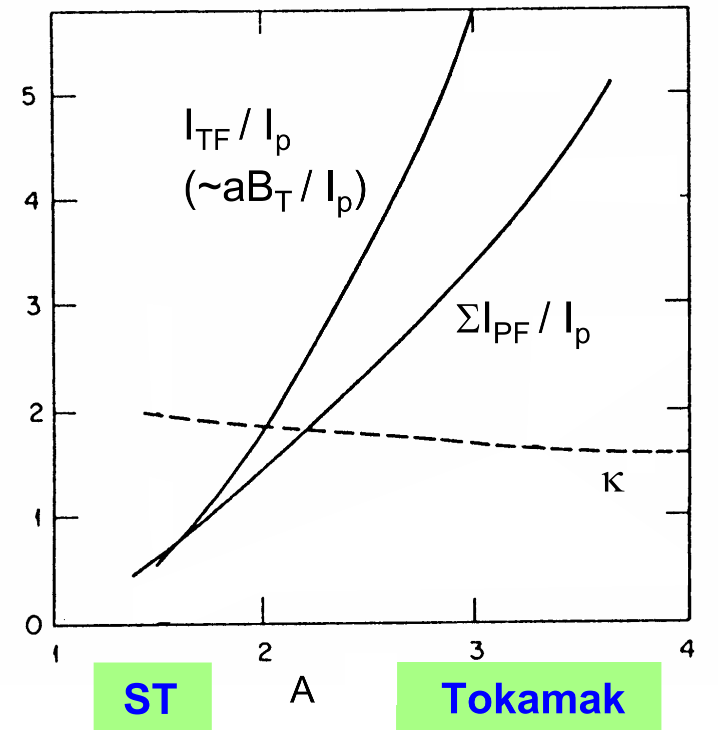
Culham, KAIST, Kyushu-Tokai U, PPPL, U Tokyo, U Washington

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

Natural Elongation, κ



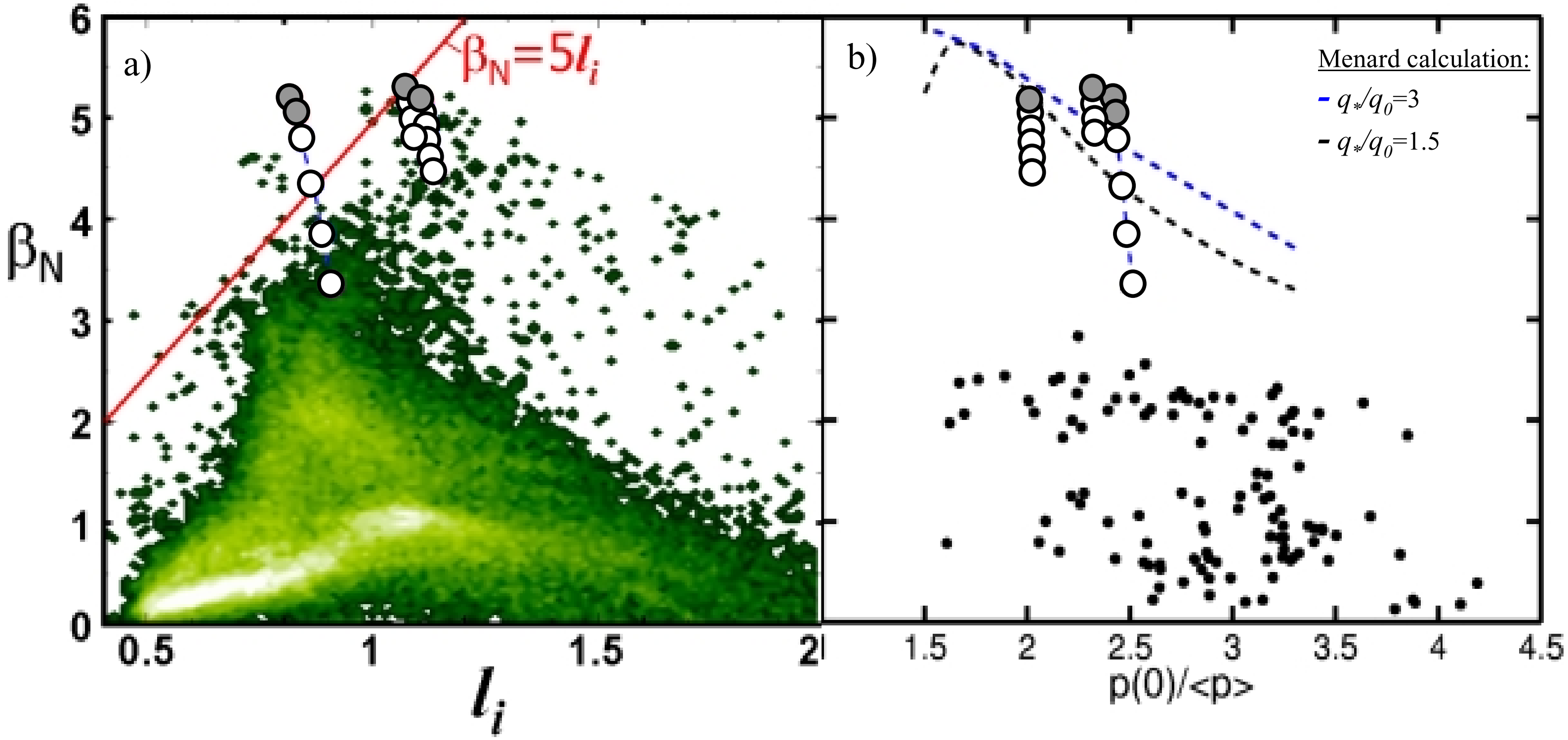
Small Coil Currents/I_p (q_{edge}~2.5)



- 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 β_N ~ 3
- Increased $I_p\, q_{edge}/aB_T$ ~ 20 MA/m·T ⇒ improved confinement?

Ideal no-wall beta limit approached

By avoidance of NTMs $\beta_N > 5$, ($\beta_N > 5l_i$) has been achieved, approaching the ideal no-wall beta limit



● unstable

○ stable

R. Buttery, M Gryaznevich et al

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High β_t and Improved Confinement Achieved

NSTX

- Long H-modes with High Elongation and Triangularity Provides Route to High β
- Reducing error fields & H-modes improved performance in 2002
- Improved vertical position control & earlier H-modes opened operating window this year
  - Propagation latency in digital control system reduced to ~700μs
  - Lower internal inductance in H-mode allows higher elongation
  - Capability for higher κ, δ allowed higher I_P/aB_T