Research Supported by

NSTX

Recent Results from the National Spherical Torus Experiment

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for the NSTX Research Team*
Special thanks: D. Gates, S. Kaye, J. Menard, D. Mueller, M. Peng, S. Sabbagh

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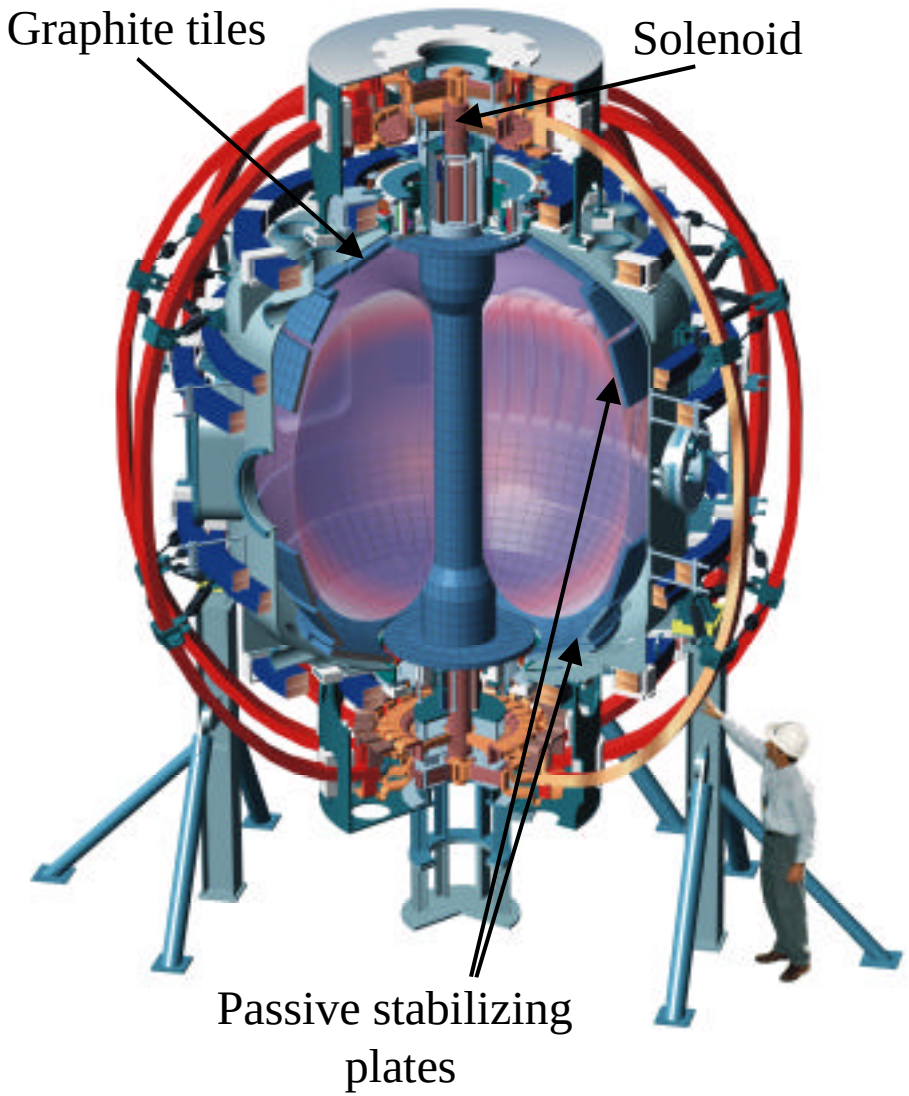
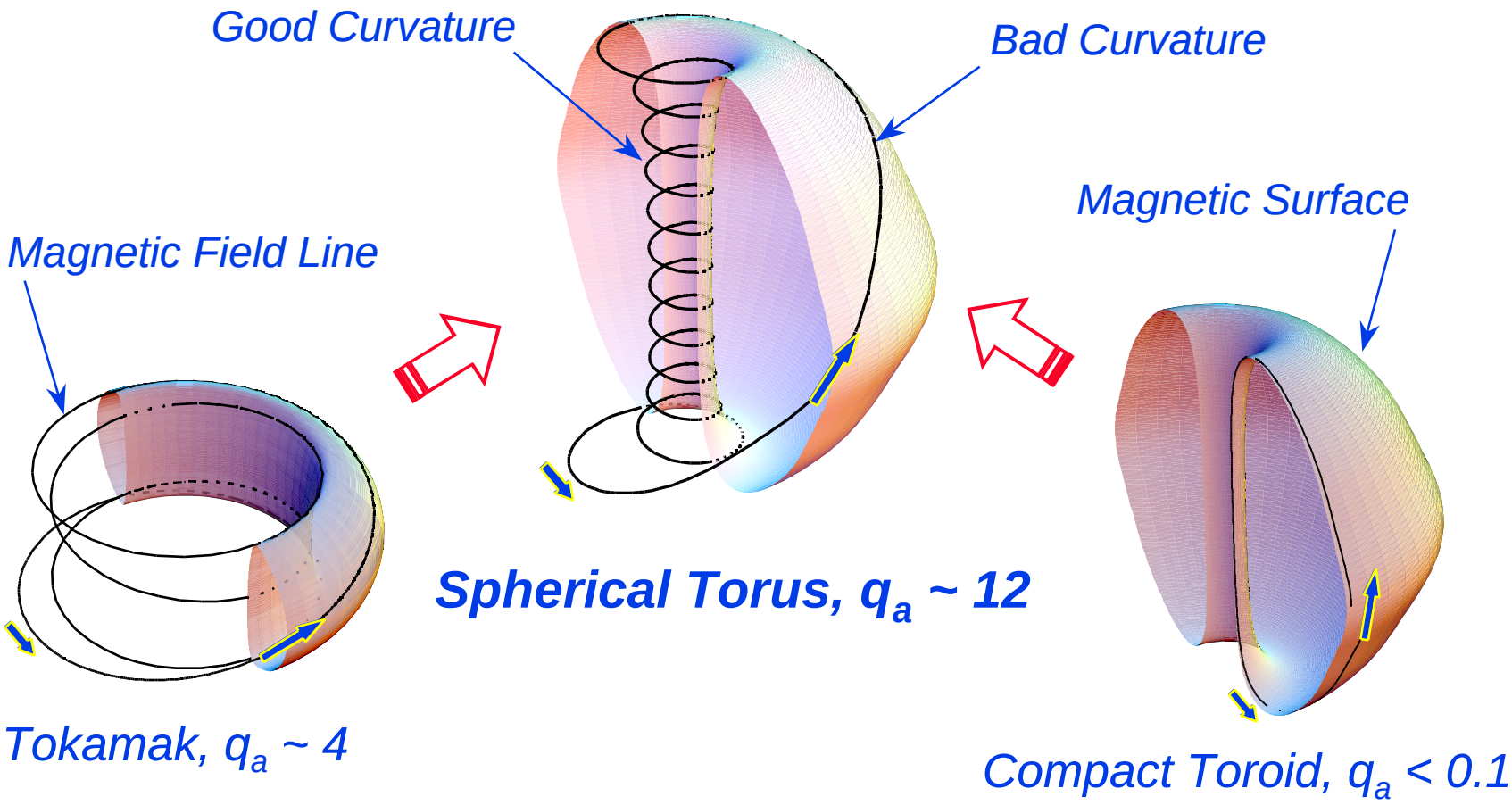
NSTX Explores Low Aspect Ratio (A=R/a) physics regime



Parameters	Design	Achieved
Major Radius	0.85m	A ≥ 1.27
Minor Radius	0.67m	
Elongation	≤2.2	2.5
Triangularity	≤0.6	0.8
Plasma Current	1MA	1.5MA
Toroidal Field	0.6T	0.6T
Heating and Current Drive		
Induction	0.7Vs	0.7Vs
NBI (100keV)	5MW	7 MW
RF (30MHz)	6MW	6 MW
CHI	0.5MA	0.4MA
Pulse Length	≤5s	1s

Reducing Aspect Ratio Maximizes Field Line Length in Good Curvature and Increases Safety Factor, q_a



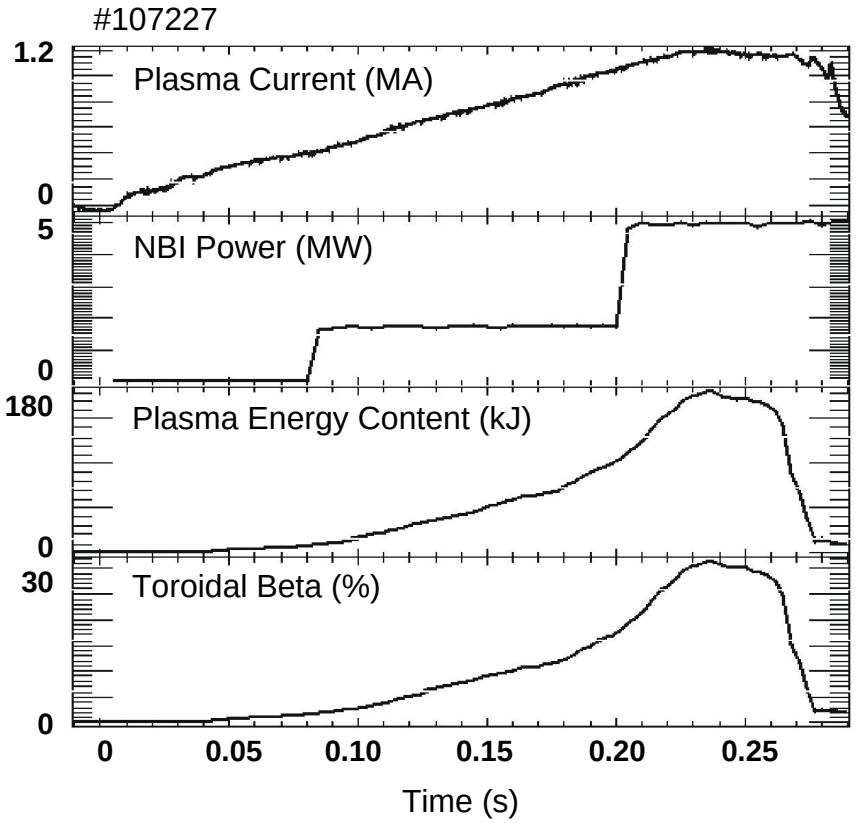
The outboard field lines are closer to CT.

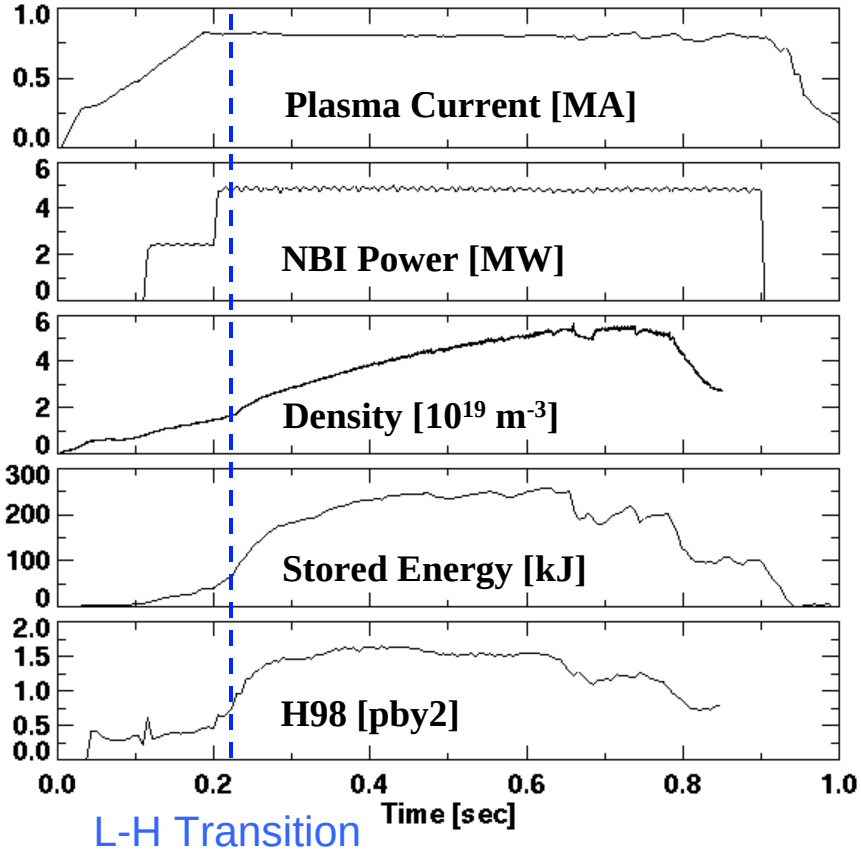
High Performance Plasmas Produced in NSTX

Max β_T = 31.5%
$\beta_N = 5 = 7.4\ell_i > \beta_N$(no-wall)*

$\beta_T = 2\mu_0 \langle p \rangle / B_0^2$

Long-Pulse H-mode
Duration limited by V-sec capability





L-H Transition

NSTX mission to assess attractiveness of spherical torus operation in critical areas

- Stability
  - Theory: higher β limits predicted than conventional aspect ratio tokamaks
  - Experiment: higher β measured, above the theoretical ideal MHD stability limits

    Which non-ideal effects are enabling this?
- Confinement, Transport & Turbulence
- RF heating and current drive
- Coaxial Helicity Injection
- Boundary Physics

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

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

$$\beta_{Tmax} \approx C\, I_p / a\, B_T$$

where

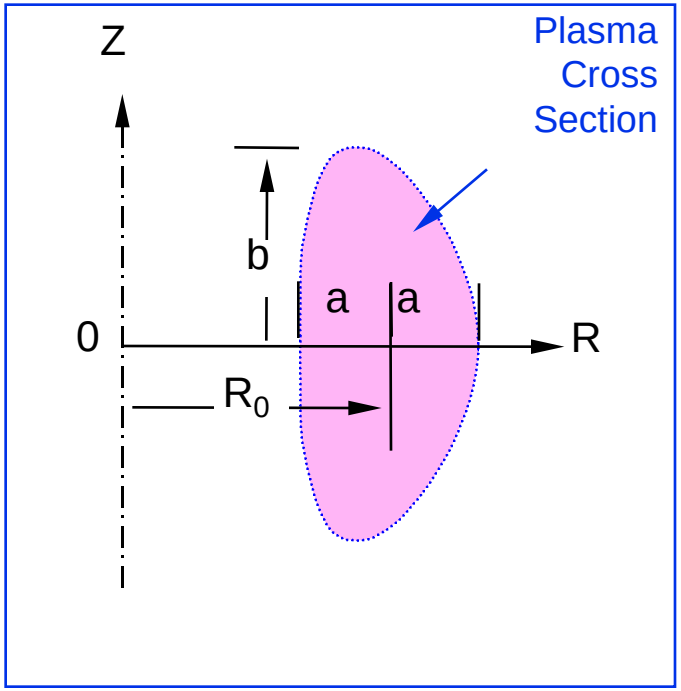
C ~ constant (~ 3 %m·T/MA)

A = R_0/a = aspect ratio

κ = b/a = elongation

I_p = toroidal plasma current

$B_T \approx$ applied toroidal field at R_0

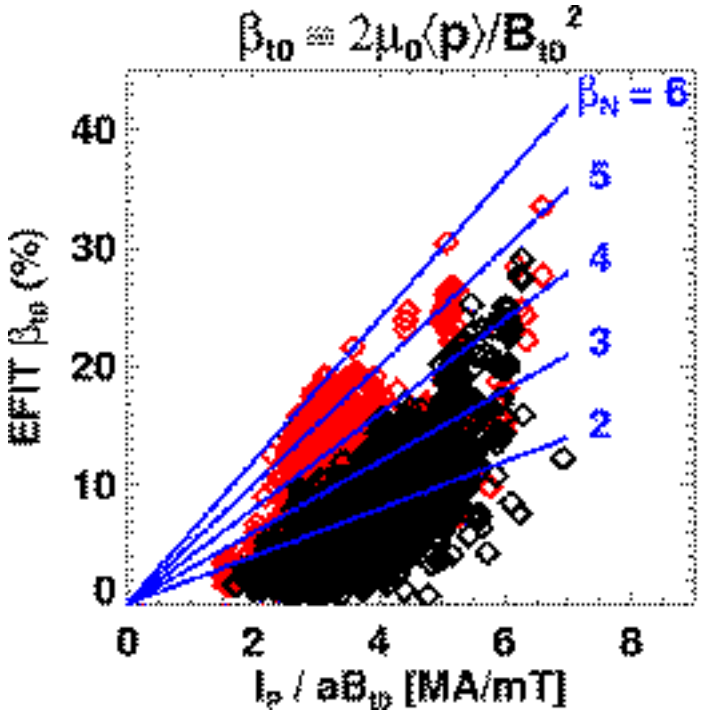


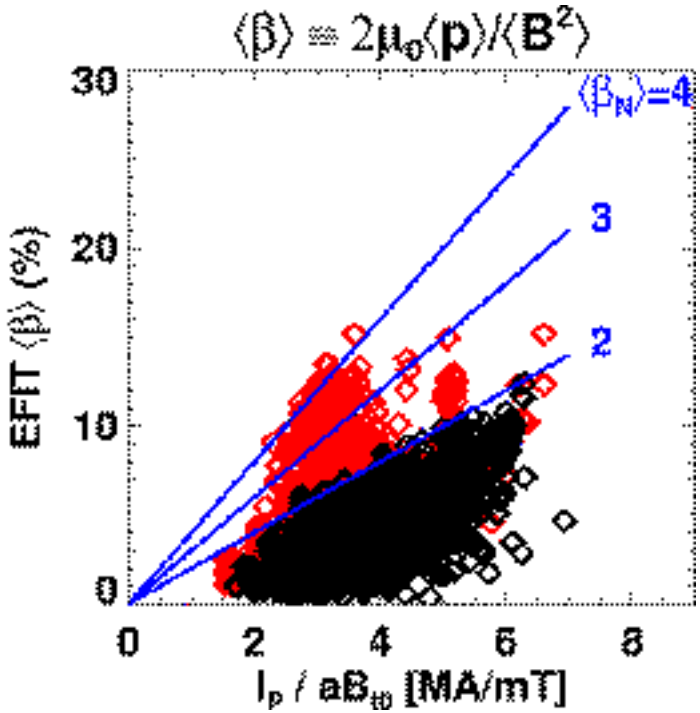
- Peng & Strickler (1986): shape, stability as A → 1
- **STs can achieve higher I/aB than tokamaks, and C ~ 4-6**

NSTX exceeded the ideal stability limit

- $\beta_{N,max} \sim 6.5$
- $\beta_P \leq 1.5$ slightly diamagnetic
- $W_{MAX} \sim 390$kJ

- Last year limited to $\beta_N \leq 2$
- After machine improvements, at or above theoretical no-wall limit of $\beta_N = 3$

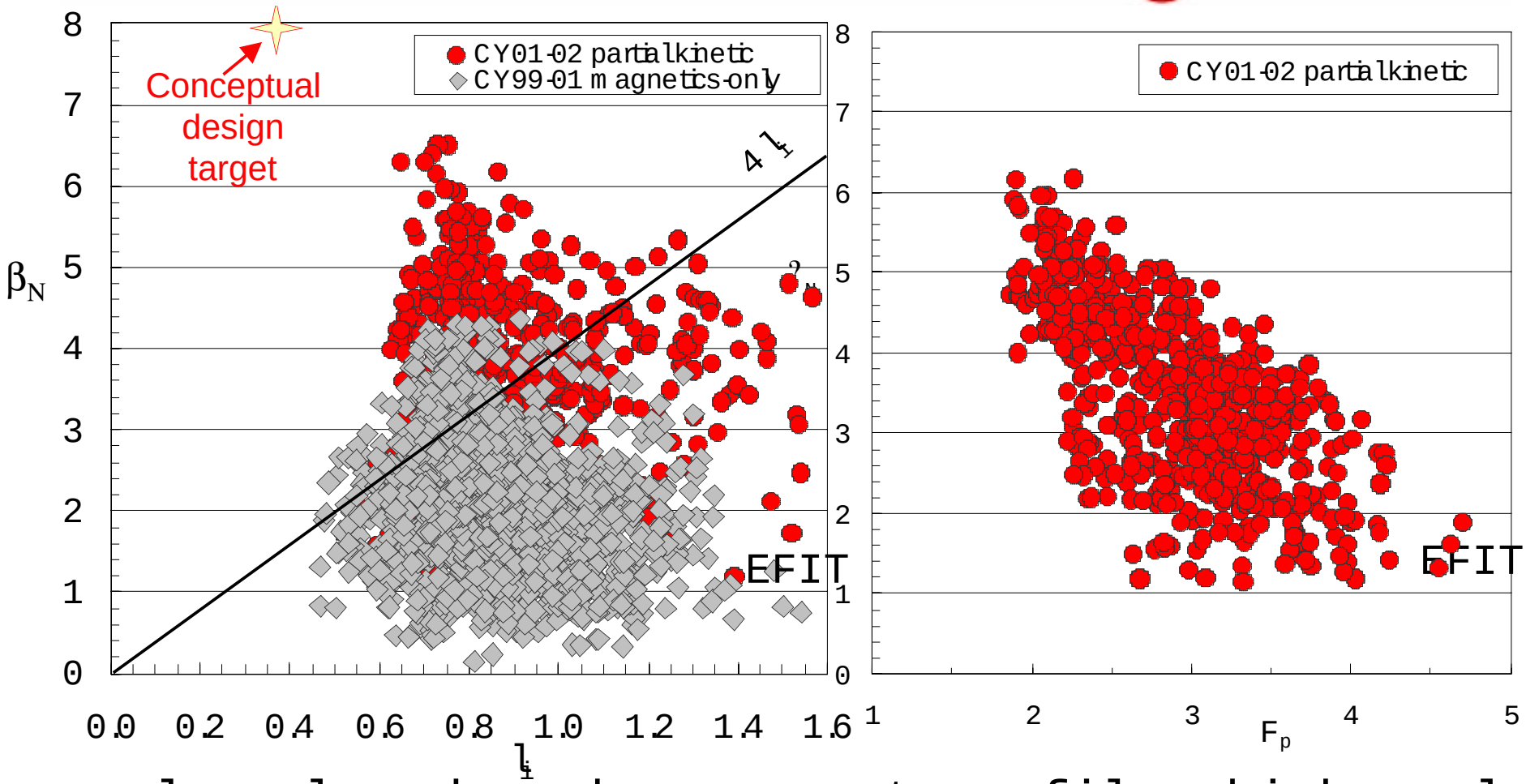




Black data previous year's run Red data CY2002

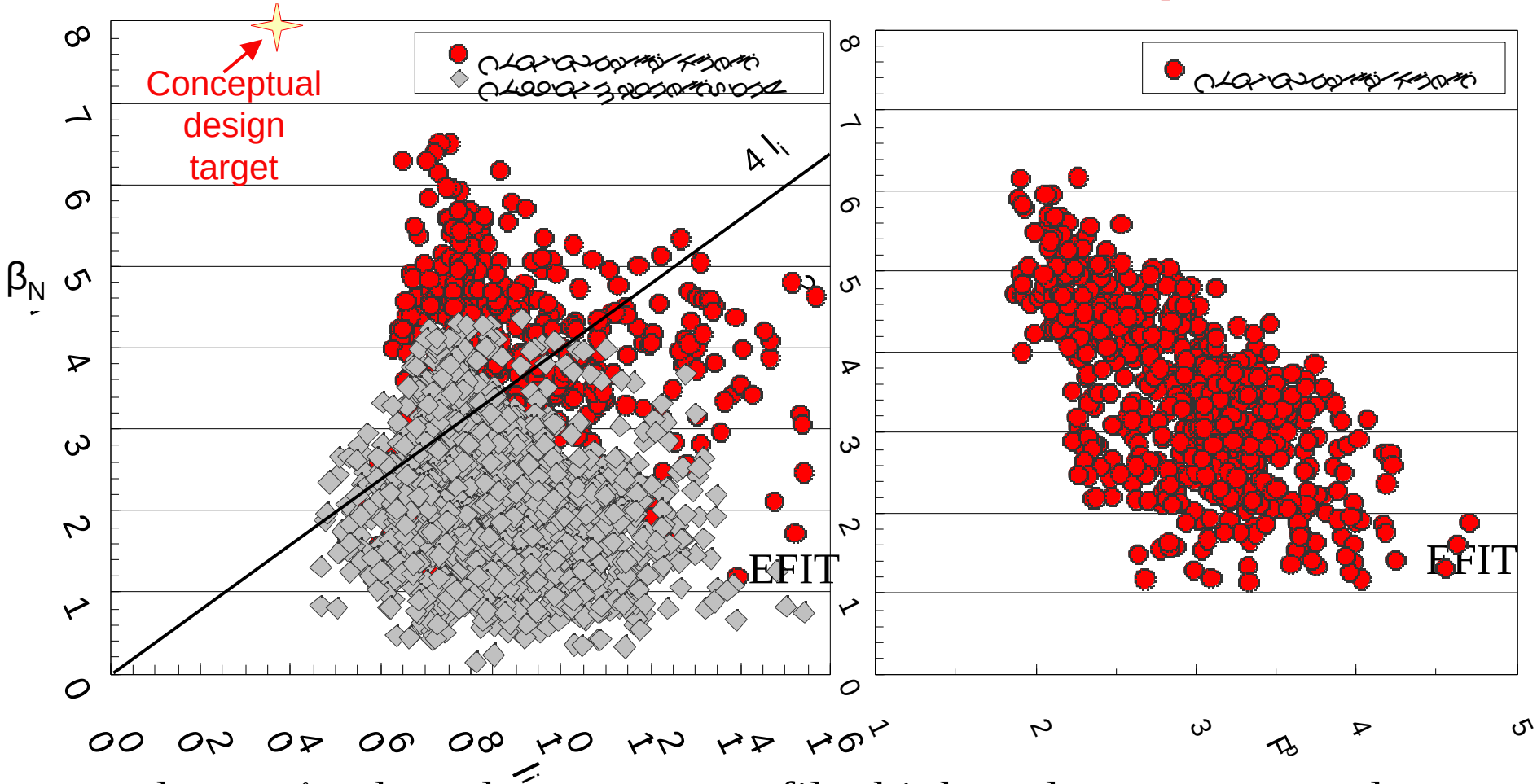
J. Menard

High β_N attained at low internal inductance (l_i) with reduced pressure peaking (F_p)



- lower l_i = broader current profile, higher plas current fraction ('bootstrap current' - non-i

High β_N attained at low internal inductance (ℓ_i) with reduced pressure peaking (F_p)



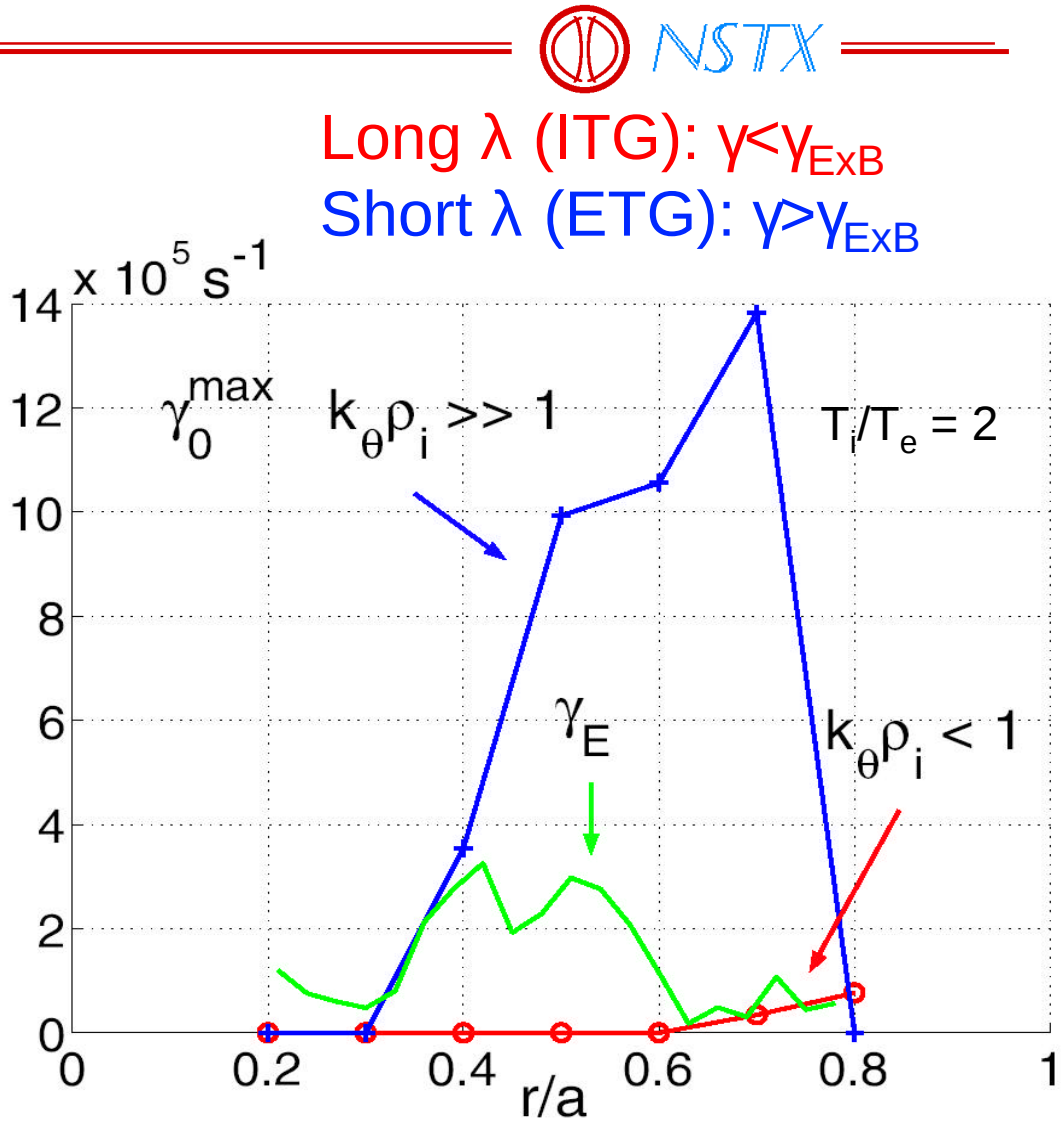
- lower ℓ_i = broader current profile, higher plasma generated current fraction ('bootstrap current' - non-inductive)

Transport & Turbulence Studies Examined Global Confinement and Particle Transport

- Theory :
  - ion turbulence stabilized by electric field shear
  - electron turbulence should dominate transport
- Experiment:
  - global thermal confinement excellent
  - ion impurity transport near neoclassical
  - ions hotter than electrons: need to understand source terms for local thermal transport coefficients

High Radial Electric Field Shear Predicted to Reduce or Suppresses Ion Turbulence

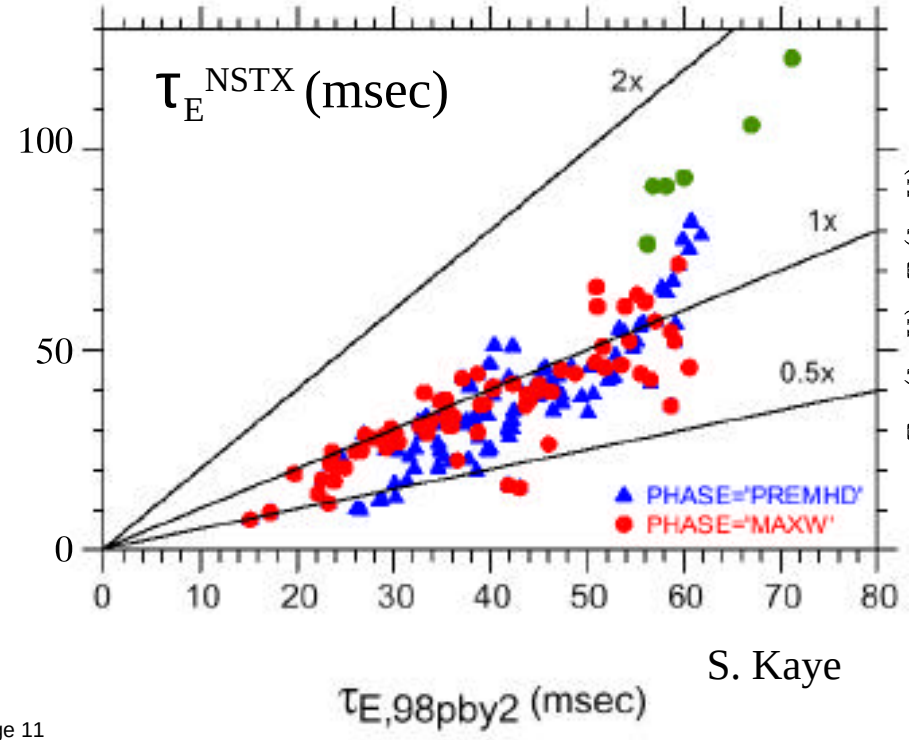
- Electron and ion radial temperature gradients cause instabilities (ETG, ITG)
- Instabilities increase turbulent energy transport
- Shear rate (γ_E) in radial electric field (dE_r/dr) can reduce ion turbulence
- Electron turbulence should dominate thermal transport

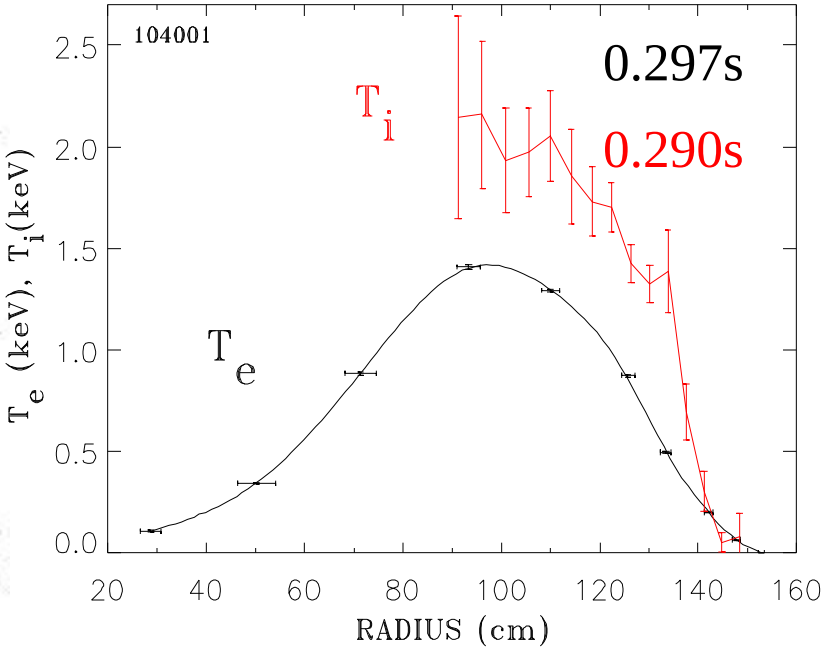


(C. Bourdelle)

Global confinement time exceeds conventional aspect ratio tokamak scalings

- Ratio of NSTX confinement to extrapolation ~ 1.5
  - International database with data from mostly conventional aspect ratio devices in high-confinement mode (H98pby2)
- Anomaly: $T_i > T_e$ in most NBI heated discharges

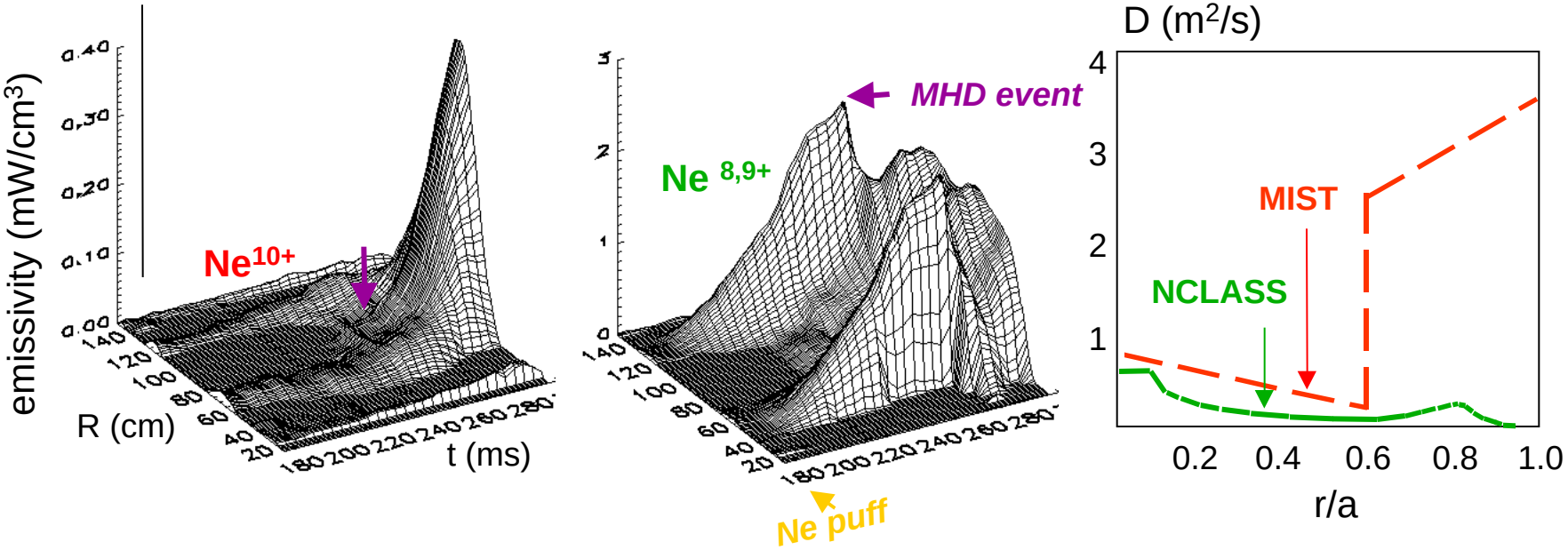




S. Kaye

Neon particle Diffusivity Estimated to be ~ Neoclassical

- **Almost no Neon penetrates into the core until MHD event**
- **Estimated diffusion (MIST) is in the neoclassical (NCLASS) range, for r/a < 0.6**



D. Stutman

Non-inductive Current Drive Crucial for ST

- Small space for solenoid in ST -> limited induction
- RF heating and current drive
  - Theory: good heating and current drive efficiency predicted at high dielectric constant and high β
  - Experiment: heating demonstrated; current drive efficiency demonstrated for short pulses
- Current Initiation via Coaxial Helicity Injection
  - Theory: current multiplication of injected current
  - Experiment: high toroidal current measured, some evidence of closed flux surfaces

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

PPPL & ornl

NSTX

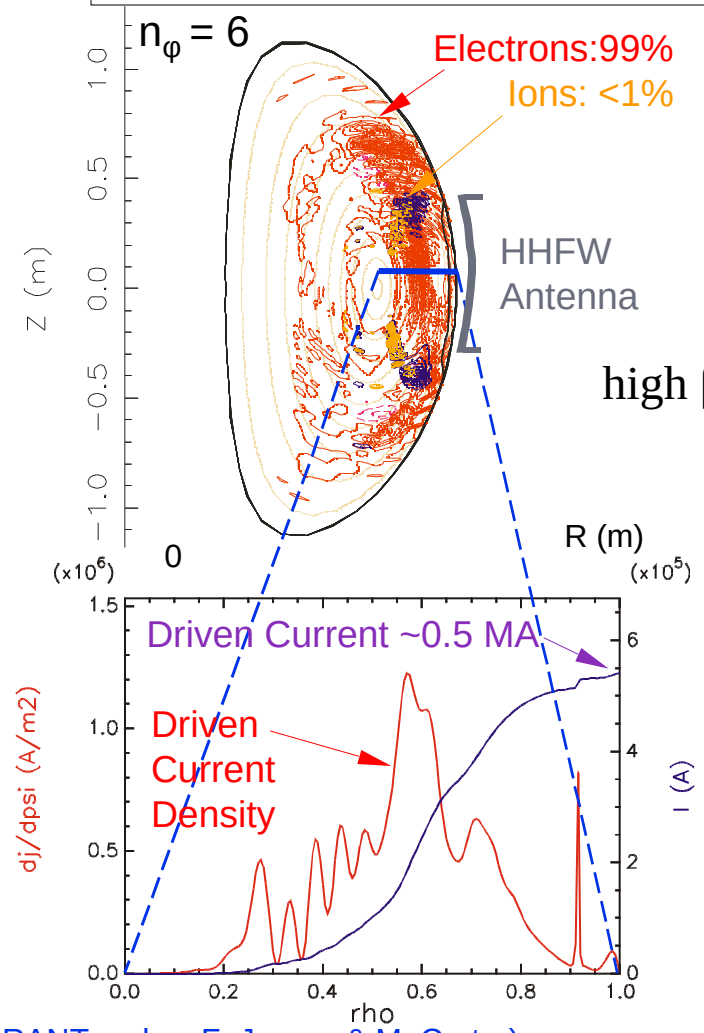
12 HHFW ANTENNA

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

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

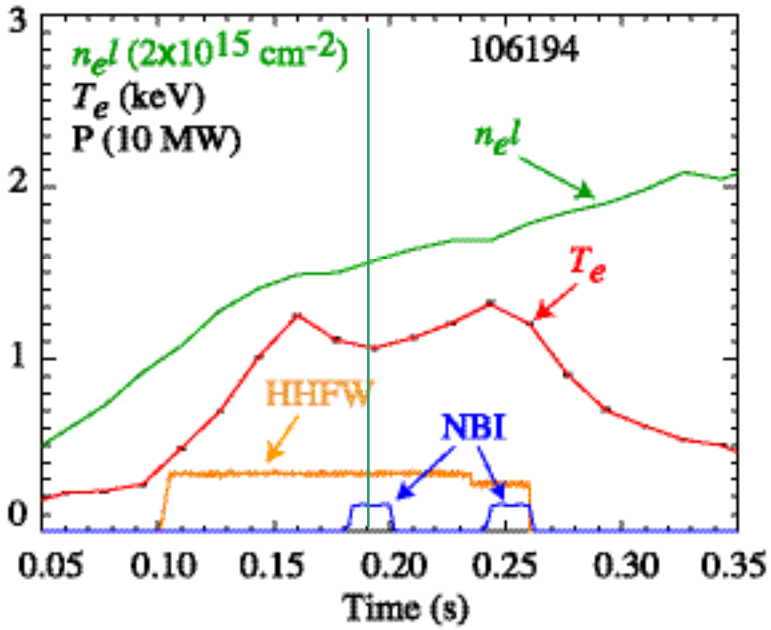
$$\varepsilon = \omega_{pe}^2 / \omega_{ce}^2 \sim 10^2$$

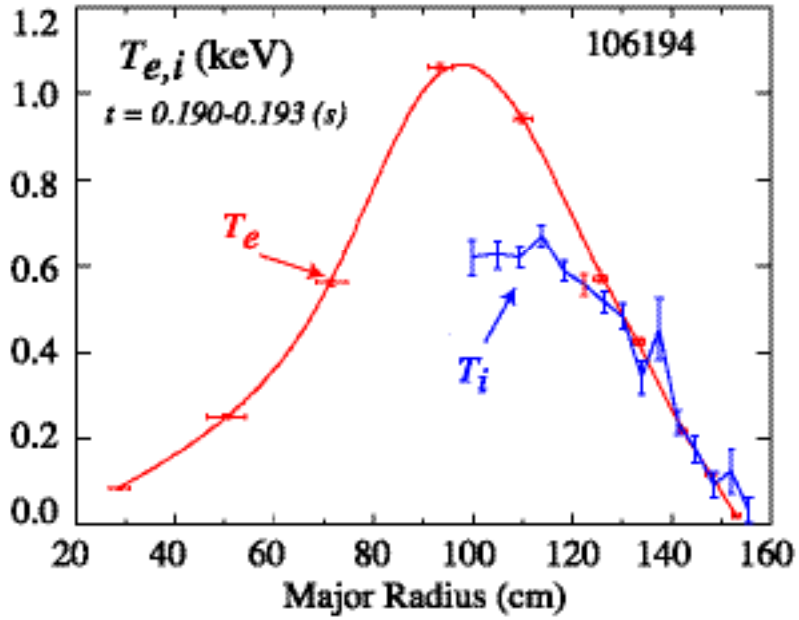
Contours of HHFW Absorption



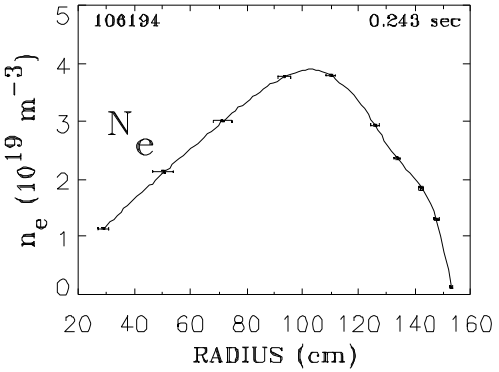
(PICES & RANT codes, F. Jaeger & M. Carter)

HHFW Power Couples to Electrons





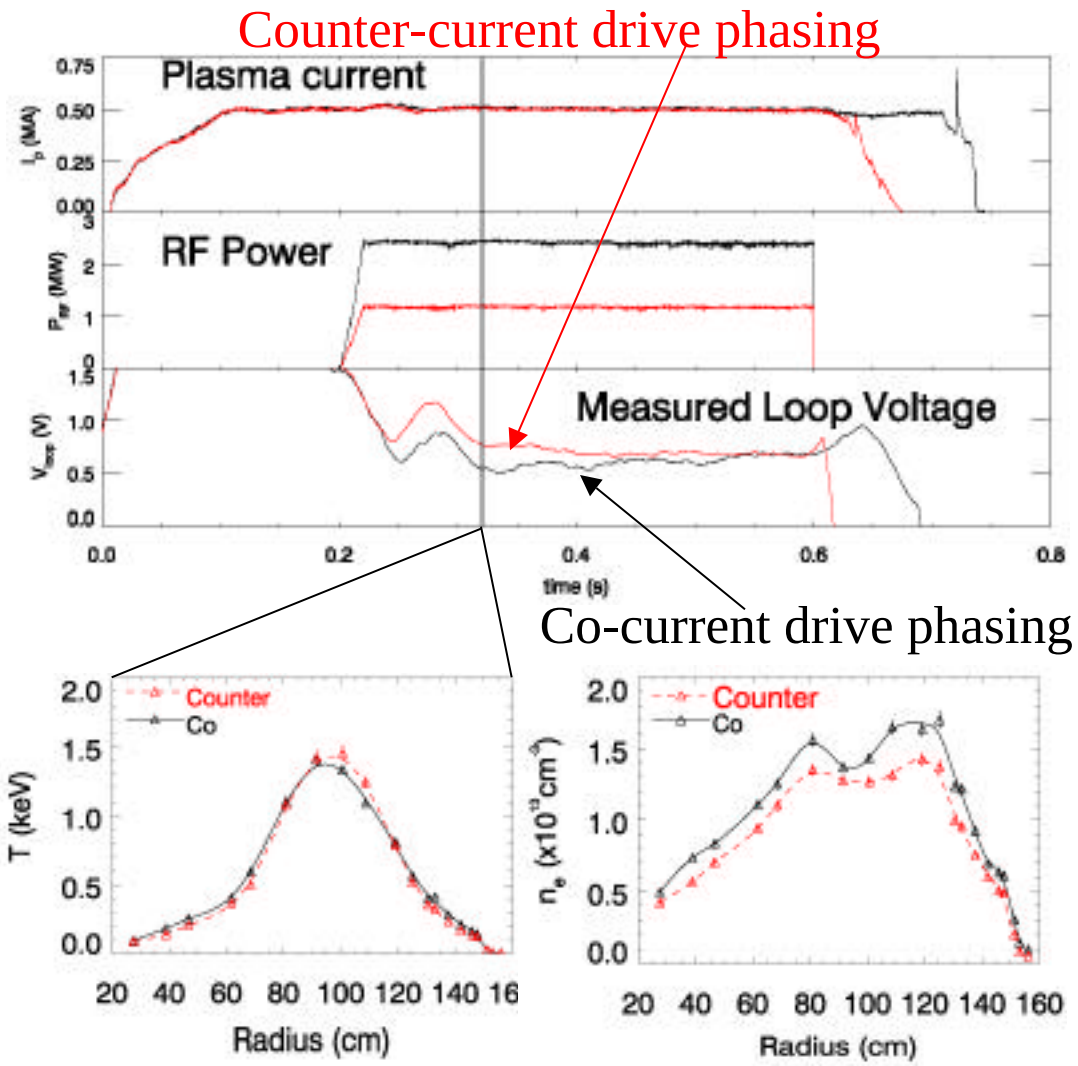
- T_e rises after RF turn-on
- Helium, 0.8 MA, 0.44 T
- $\mathbf{k}_{||}$ = 14 m^{-1} (heating phasing)
- NBI "blips" added to measure T_i



B. LeBlanc

HHFW current drive demonstrated transiently

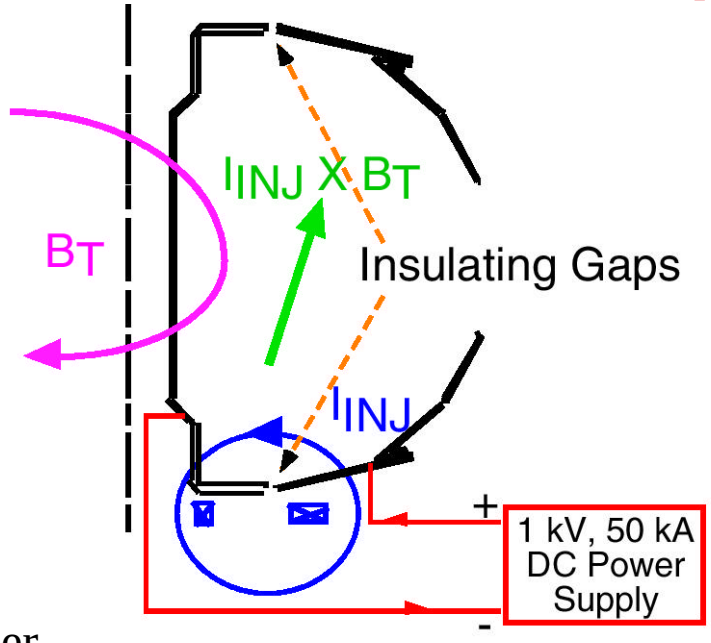
- **Co- vs counter-current drive comparison shows loop voltage difference**
- **Temperature and density profiles matched by adjusting RF power level**

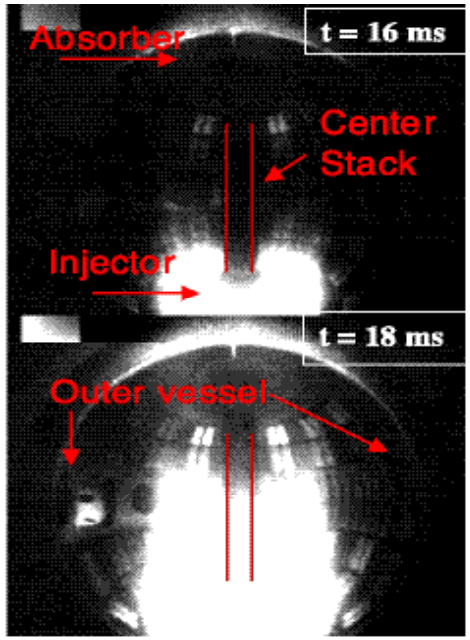


Non-Inductive Initiation Important for ST Development

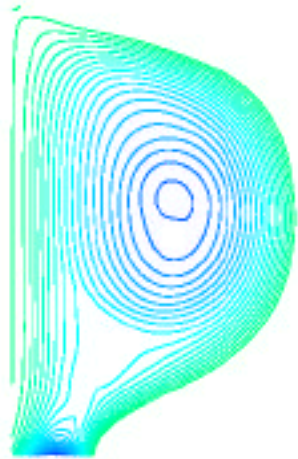
NSTX

Co-Axial Helicity Injection (CHI) Generates Toroidal Current Non-Inductively



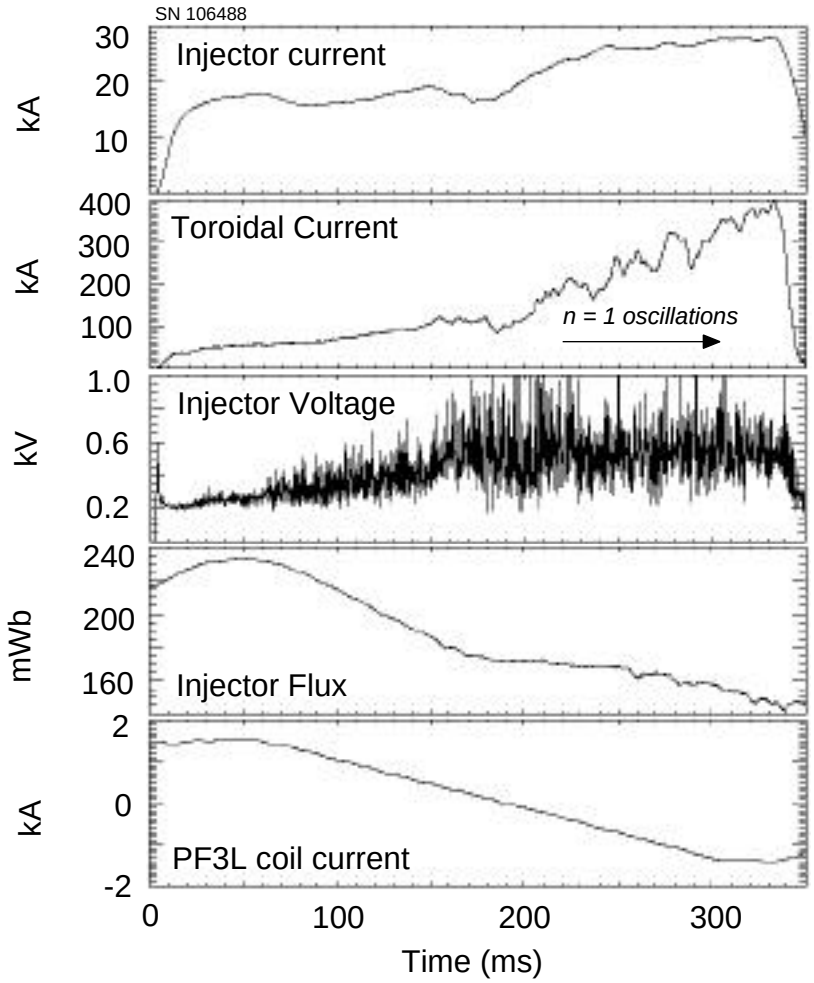


- Inject poloidal current on open field lines in lower divertor
- Plasma moves up into main chamber
  - Injected current restricted to edge
- Toroidal current develops to maintain force-free configuration
- Magnetic reconnection may redistribute edge current to interior, forming closed flux surfaces (need MHD activity)

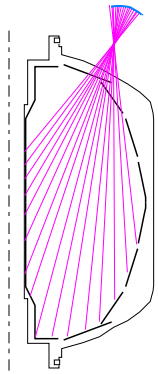


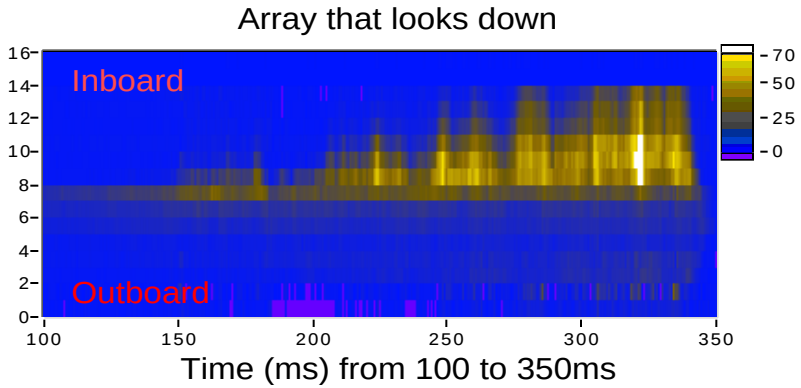
(X. Tang, LANL)

High Toroidal Current CHI Discharge Shows Signs of Possible Flux Closure



- Array of soft x-ray detector sensitive to E_γ > 100eV detect emission from inboard midplane region





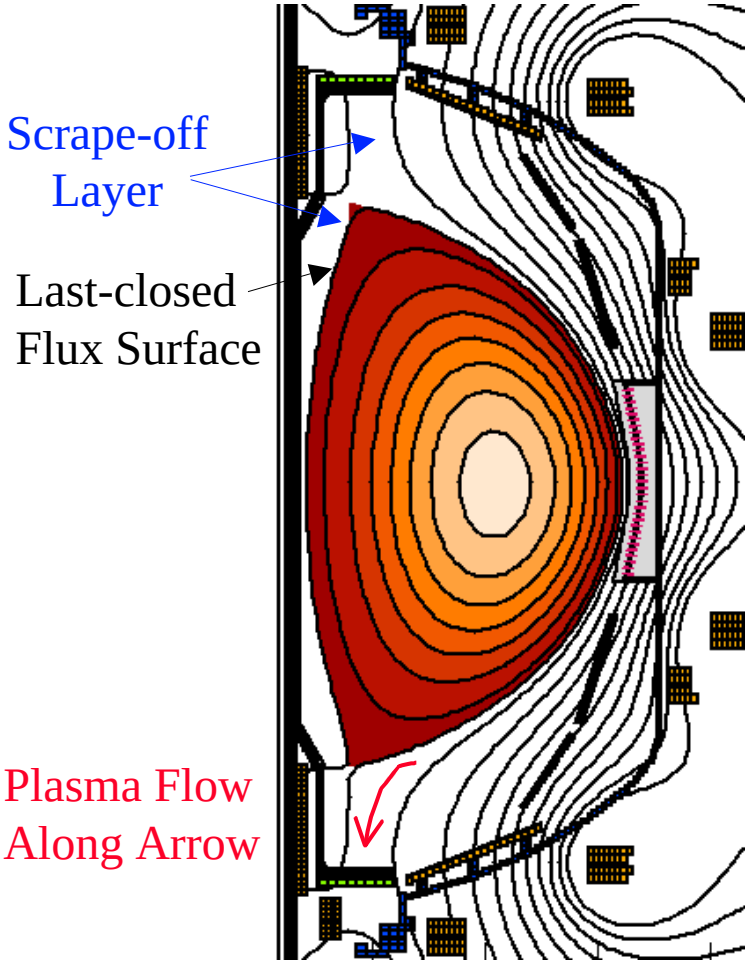
R. Raman, D. Stutman

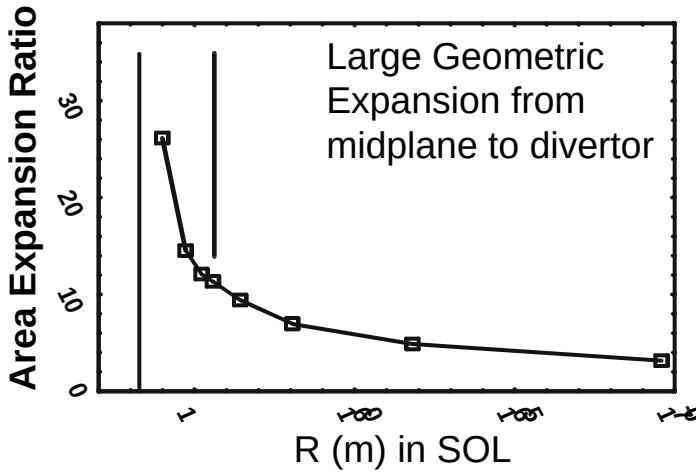
Boundary Physics Focus on Target Plate Heating

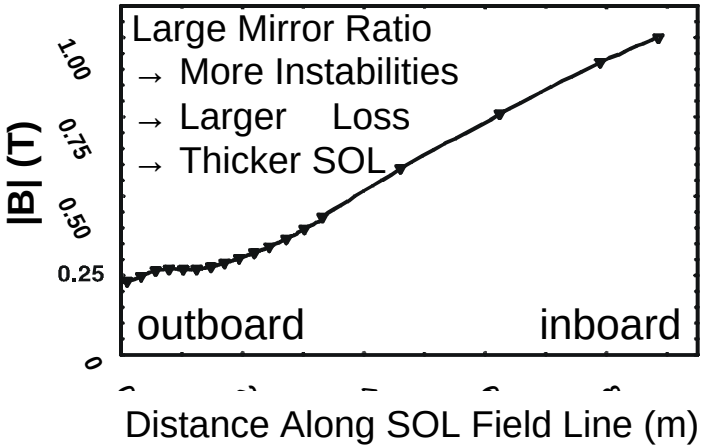
- Theory: opposing physics determines heat flux profile
  - Input power must be removed at wall, and plasma facing components must remain below 1200 ^{0}C
  - magnetic divertor operation (needed for good confinement) concentrates heat flux at target
  - Small major radius in ST implies small wall area
  - high magnetic mirror ratio and large flux expansion in scrape-off layer may lead to broad power deposition area
- Experiment: high peak heat flux and narrow width measured

High cross-field transport and flux expansion could counteract ST compactness for acceptable heat flux peaking

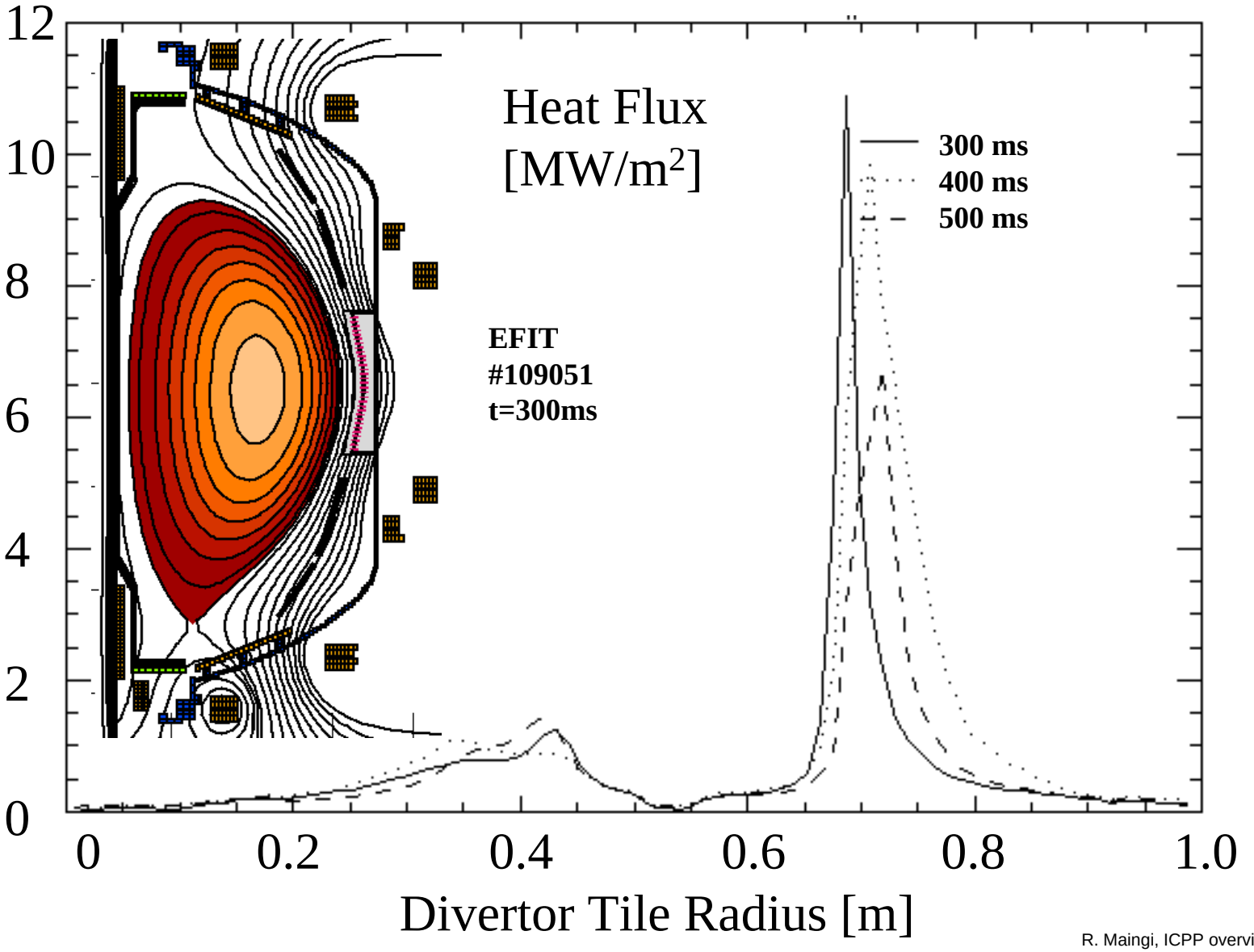
Scrape-Off Layer Geometry of Diverted NSTX Plasma







Peak Heat Flux in High Confinement Mode Would Lead to Tile Overheating for ~ 3sec pulse length



NSTX making rapid progress toward ST assessment

- Exceeded ideal no-wall MHD β limit
  - limit higher than conventional aspect ratio tokamaks
- Global confinement better than anticipated
  - ion paticle transport near neoclassical
- Heating observed from high-harmonic fast wave technique
  - current drive observed transiently
- Plasma initiation demonstrated by Coaxial Helicity Injection
  - some signatures of closed flux surfaces
- Compact ST geometry leads to high peak heat flux
  - need data with 2 divertors to see if peak reduced

U.S. National NSTX Research Team Collaboration and International Research Cooperation

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