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Spherical Torus

Progress towards high performance, steady-state Spherical Torus

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For the US Spherical Torus Program

(NSTX, PEGASUS, HIT-II, CDX-U, Theory)

Paper I.4-4

- V. K. Gusev, I-1.04
- R. J. Akers, I-2.07

EPS 2003, St. Petersburg, Russia, July 7 - 11, 2003

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Comp-X
General Atomics
INEL
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TRINITI
KBSI
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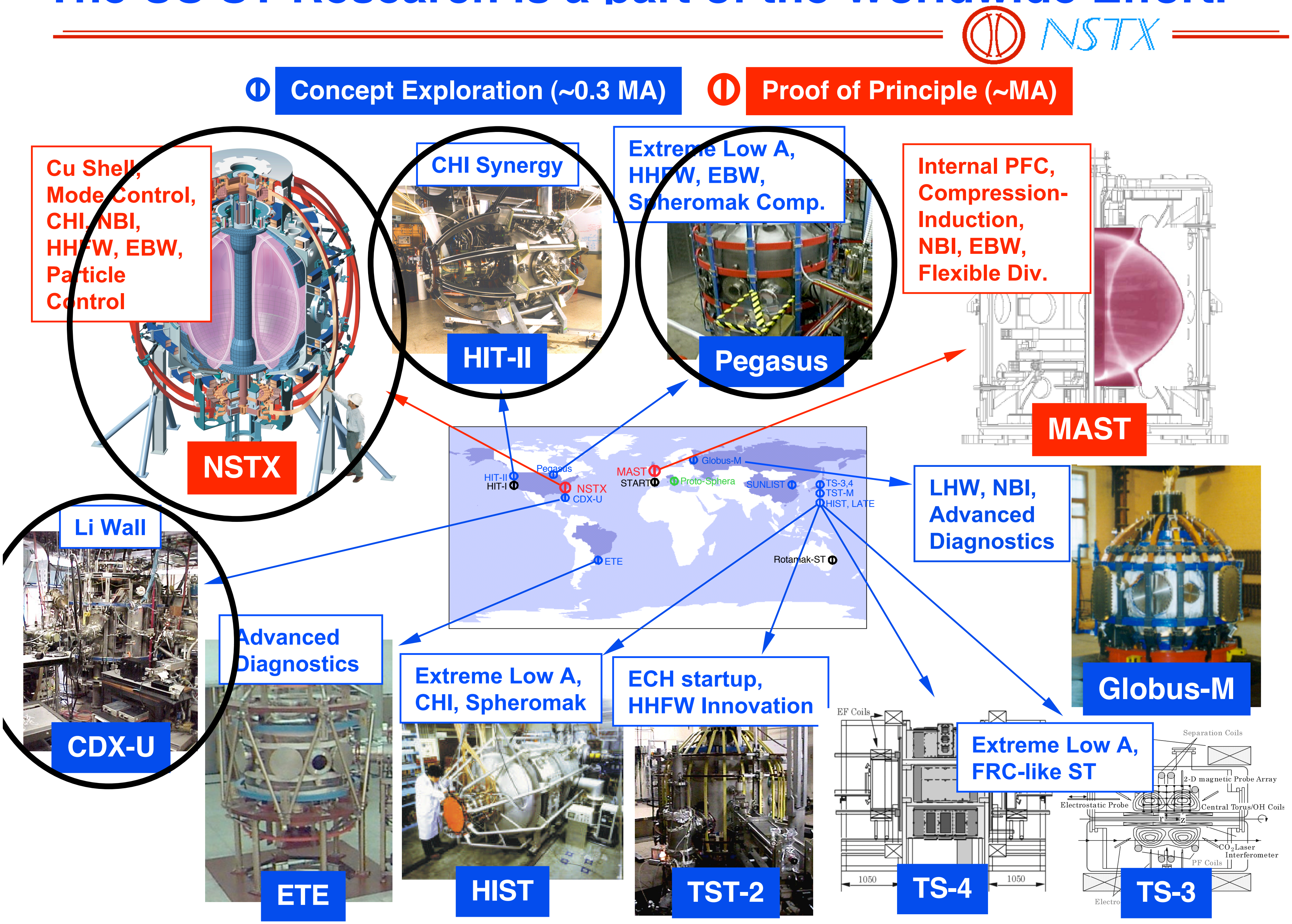
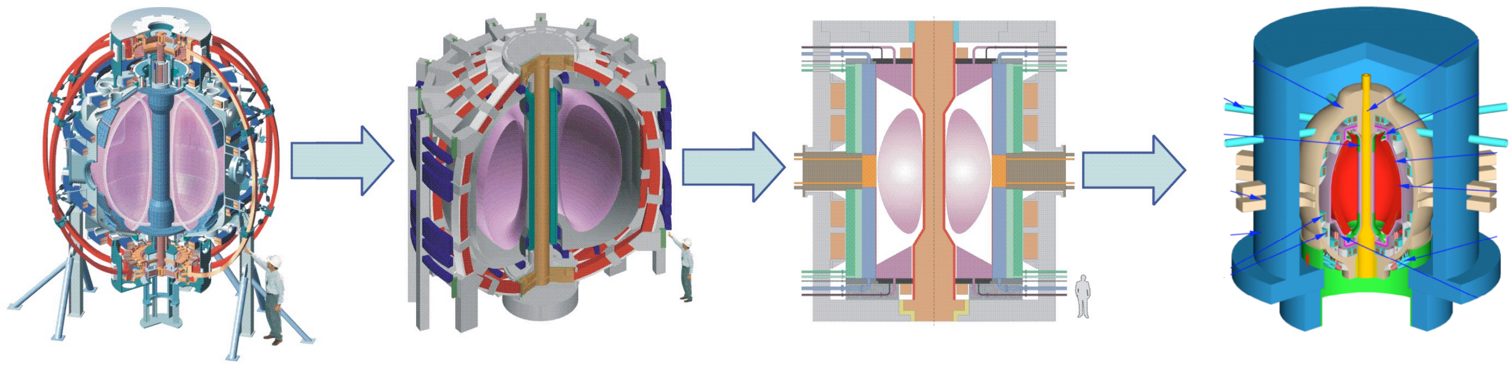
CEA, Cadarache
IPP, Garching
IPP, Jülich
U Quebec

The US ST Research is a part of the Worldwide Effort.



Cost-Effective ST Steps in Parallel with ITER



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		~3.4
a (m)	0.65		0.9		~0.8		~2.4
□, □	2.5, 0.8		2.7, 0.6		~3, ~0.4		~3.2, ~0.5
I_p (MA)	1.5	1	10	5	~11		~30
B_T (T)	0.6	0.3	2.6	1.1	~2.2		~1.8
Pulse (s)	1	5	5	50	Steady state		Steady state
P_{fusion} (MW)	□		50	10	~70	~280	~3000
W_L (MW/m^2)	□		□		~1	~4	~4
TF coil	multi-turn		multi-turn		single-turn		single-turn

SCIENTIFIC CHALLENGES OF HIGH PERFORMANCE STEADY-STATE OPERATIONS

Spherical Torus

- MHD Stability at High $\square_{\square}$ and $\square_{\square}$: Fusion power at low toroidal field with high bootstrap current fraction.

  $\square_{\square}$ ~ 20%, $\square_{\square}$ ~ 6 for CTF

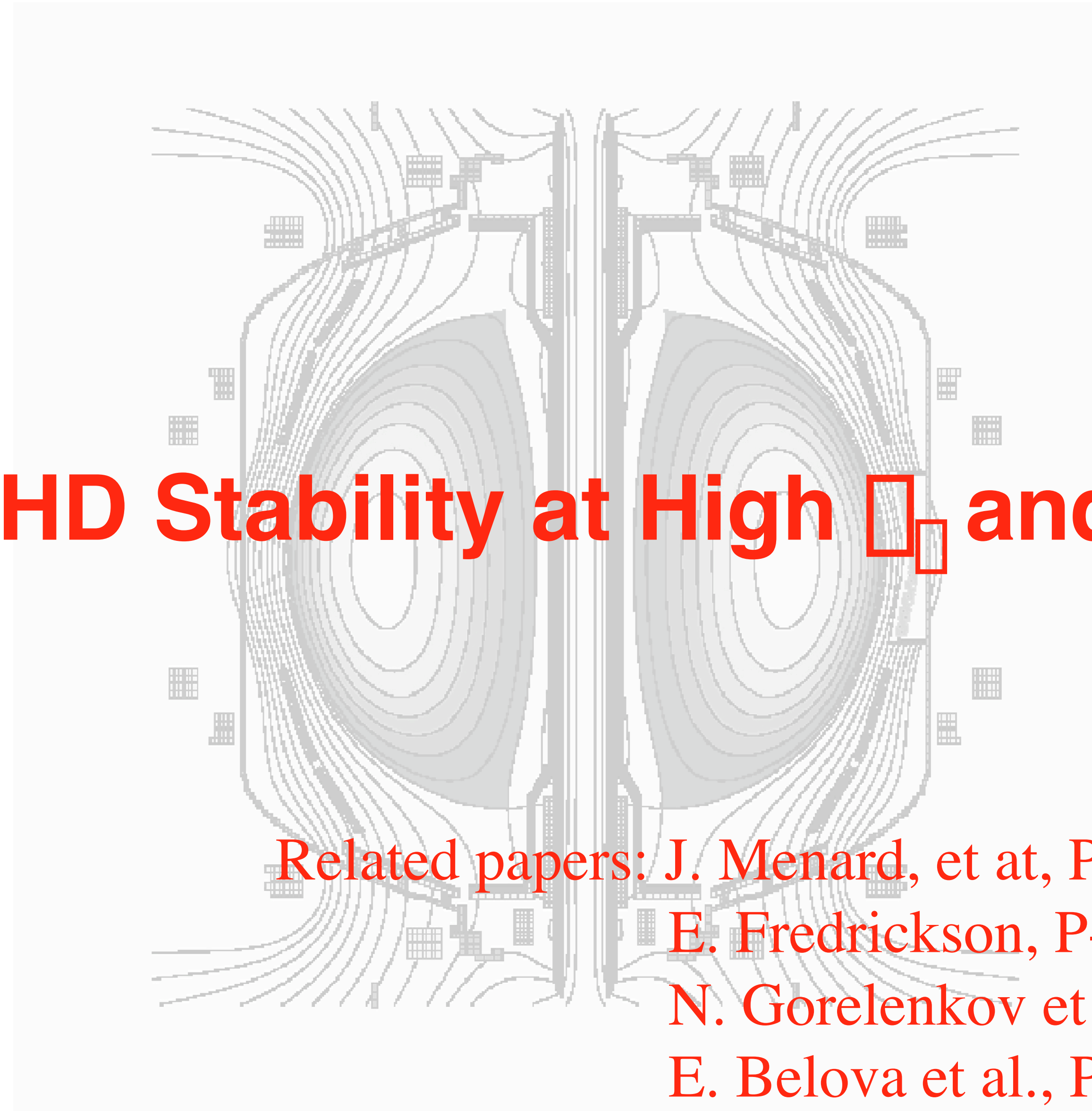
  $\square_{\square}$ ≥ 40%, $\square_{\square}$ ~ 8 for Power Plants (advanced regime)

- Transport and Confinement: High performance at small size.

  $H_{98pby,2}$ ~ 1.4 - 1.7 with good electron confinement required.

- Power and Particle Handling: Small major radius increases P/R by a factor of ~ 2 to 3, but much greater flux expansion to a given field-line inclination.
- Solenoid-Free Start-Up: Elimination of solenoid required for compact reactor design.

- Plasma Sustainment: Non-inductive sustainment of high confinement, high beta plasmas for times >> $\square_{skin}$

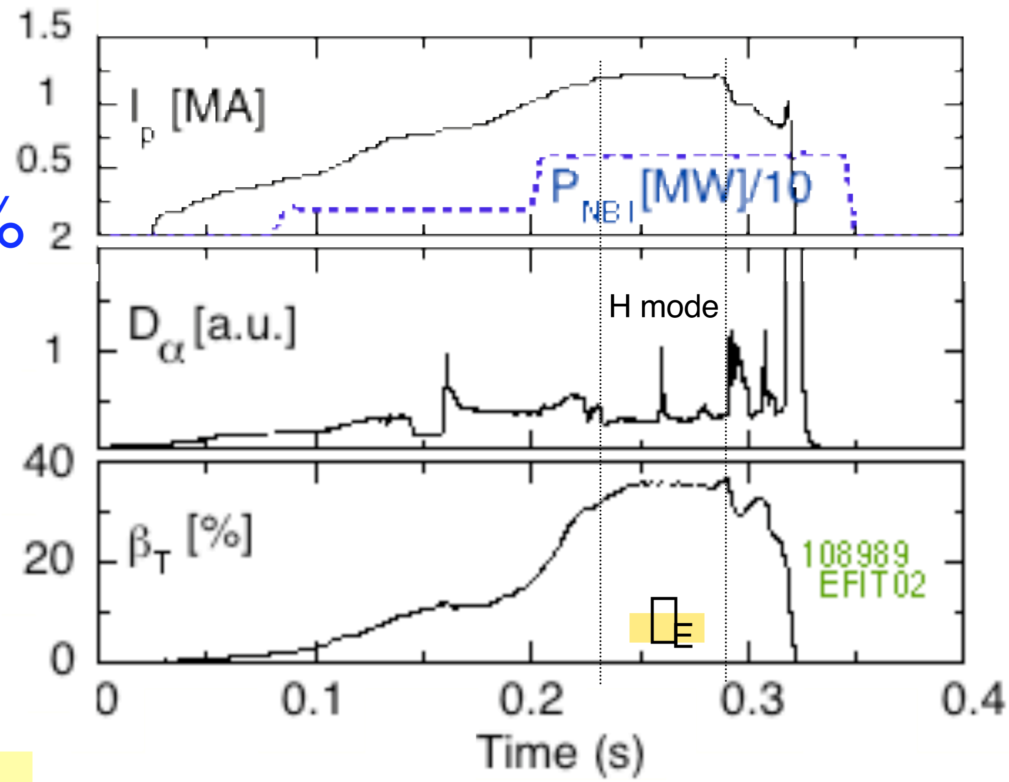


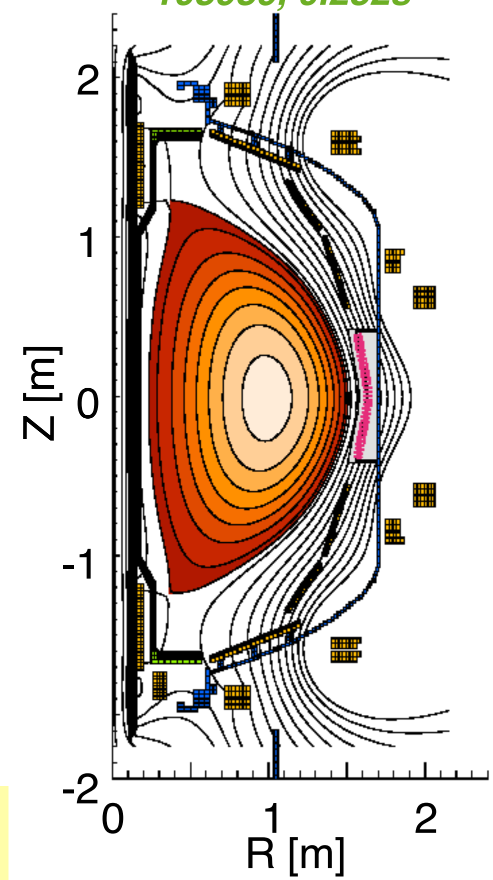
MHD Stability at High $\square_{\square}$ and $\square_{\square}$

Related papers: J. Menard, et at, P-3.101
E. Fredrickson, P-3.99
N. Gorelenkov et al., P-3.103
E. Belova et al., P-3.102

High beta maintained for duration > τ_E

β_T = 35%





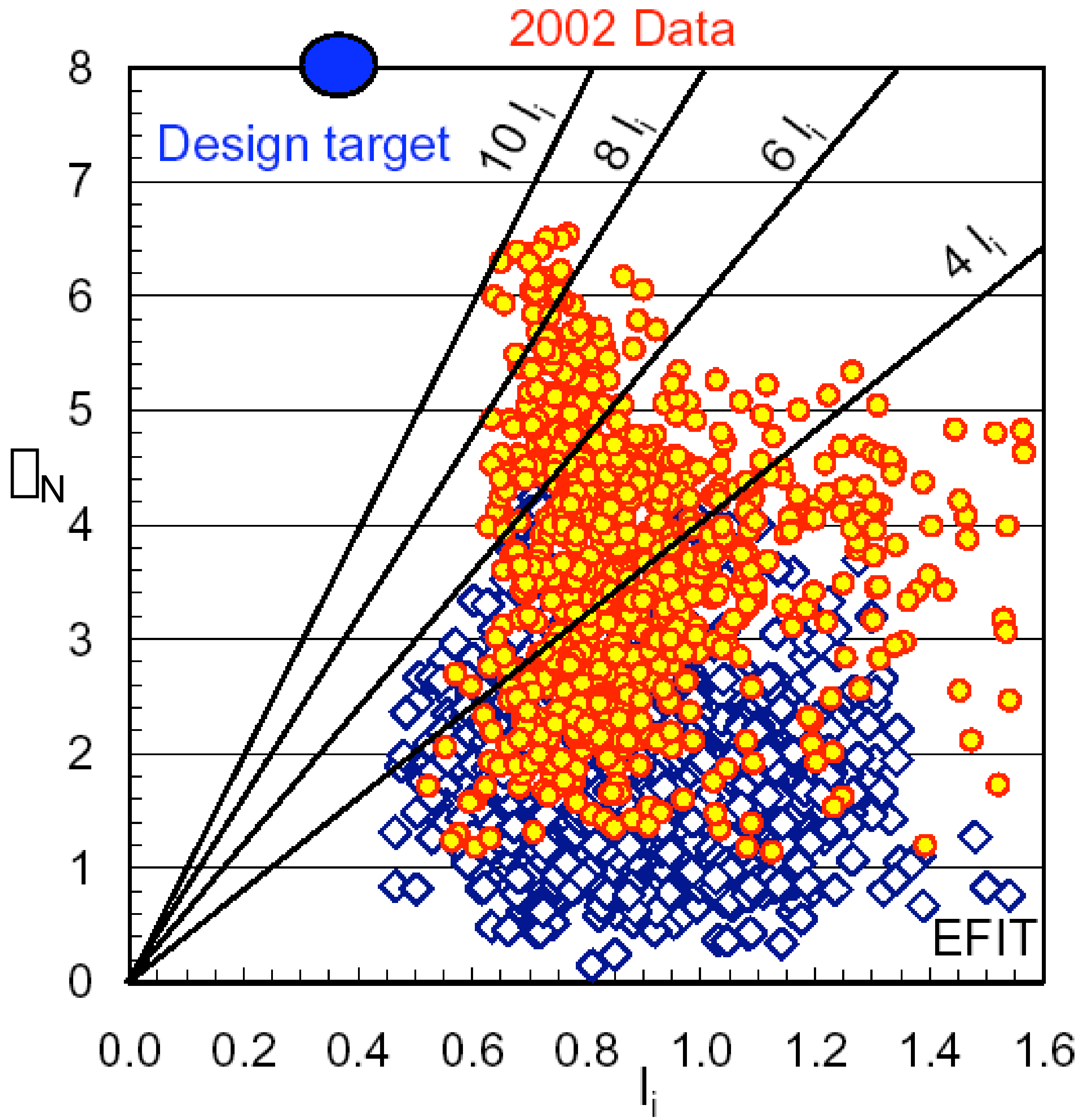
$\beta_T \equiv \dfrac{\langle p \rangle}{B_{T0}^2/2\mu_0}$

- H-mode: routine access
  - broadens pressure profile
- β_N = 5.5, l_i = 0.6

B_T = 0.3T, A = 1.4
κ = 2.0, δ = 0.8
q(0) = 1.4 (EFIT)

D. Gates, et al, PoP (2003)

NSTX is progressing toward its beta goal of β_T = 40%, β_N = 8



◇ 2001

β_N / l_i= 6 limit seen

Improvements:

- Error field reduction
- Wall + rotation
- Wall conditioning

● 2002-2003

β_N / l_i= 10 reached!

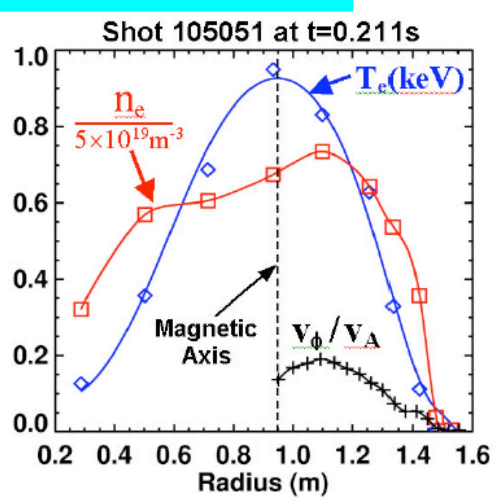
S. Sabbagh, J. Menard, et al

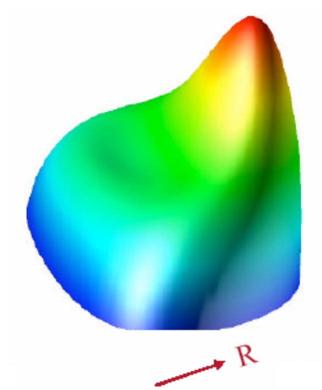
$$\beta_N \equiv 10^8 \beta_T \, a \, B_T / I_p$$

Influence of high V_f/V_A already seen in equilibria: relevant to saturation or stabilization?

NSTX

R. Bell, LeBlanc, Menard

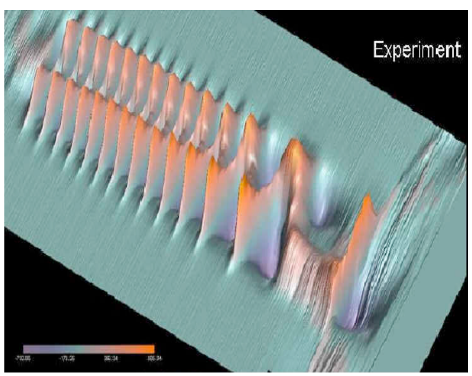




M3D: Park

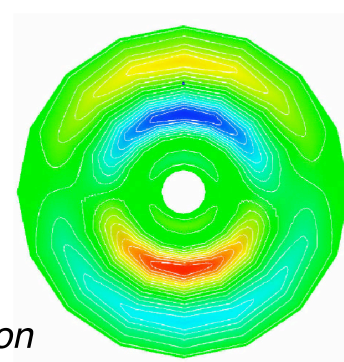
- Experiment: Density shows in-out asymmetry
- Effect of high Mach number of driven flow

- Experiment: kinks saturate

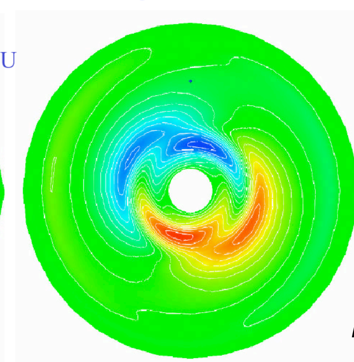


Stutman (JHU)

- Theory: $V_{\square}' \sim \square^{in}_{MHD}$ => growth affected by high flow shear: impact on kink & ballooning?

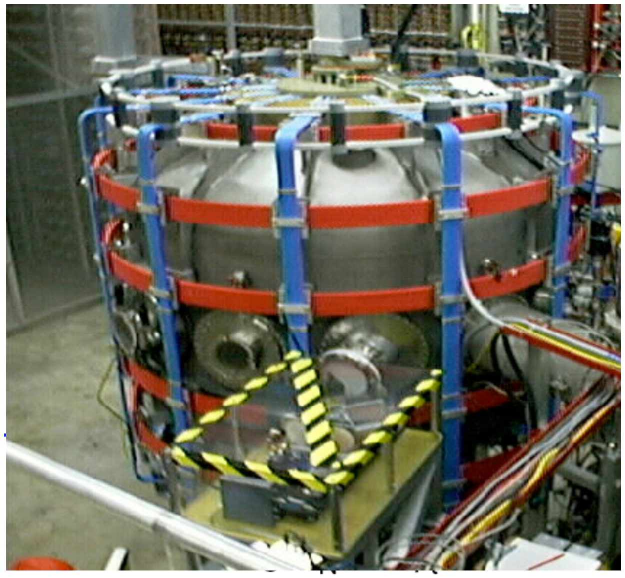


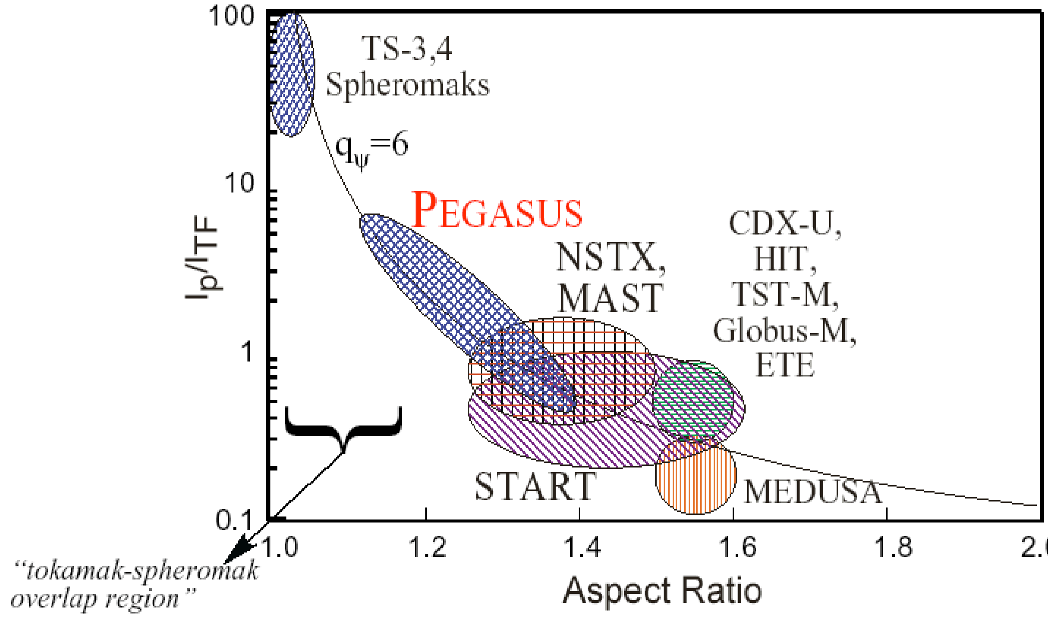
No rotation

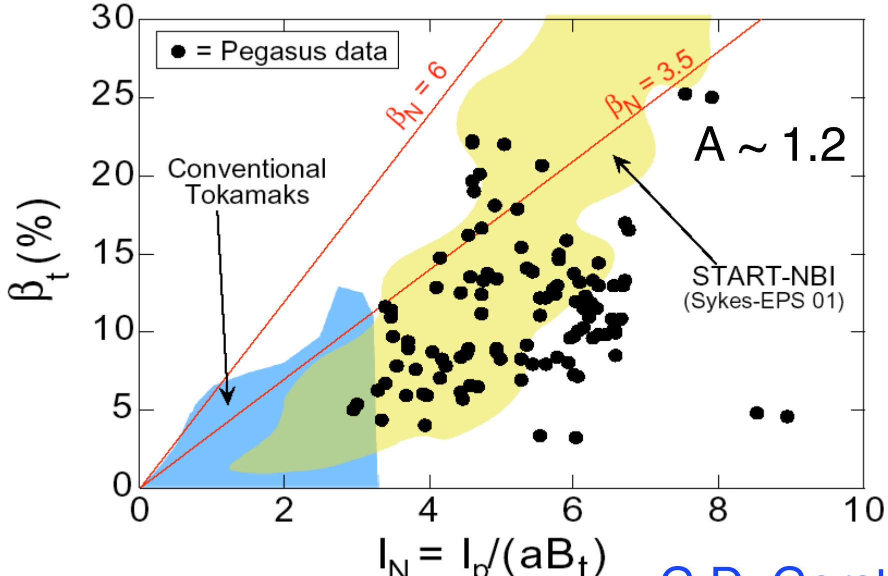


$M_A = 0.2$

PEGASUS Mission: Explore plasma limits as A→1





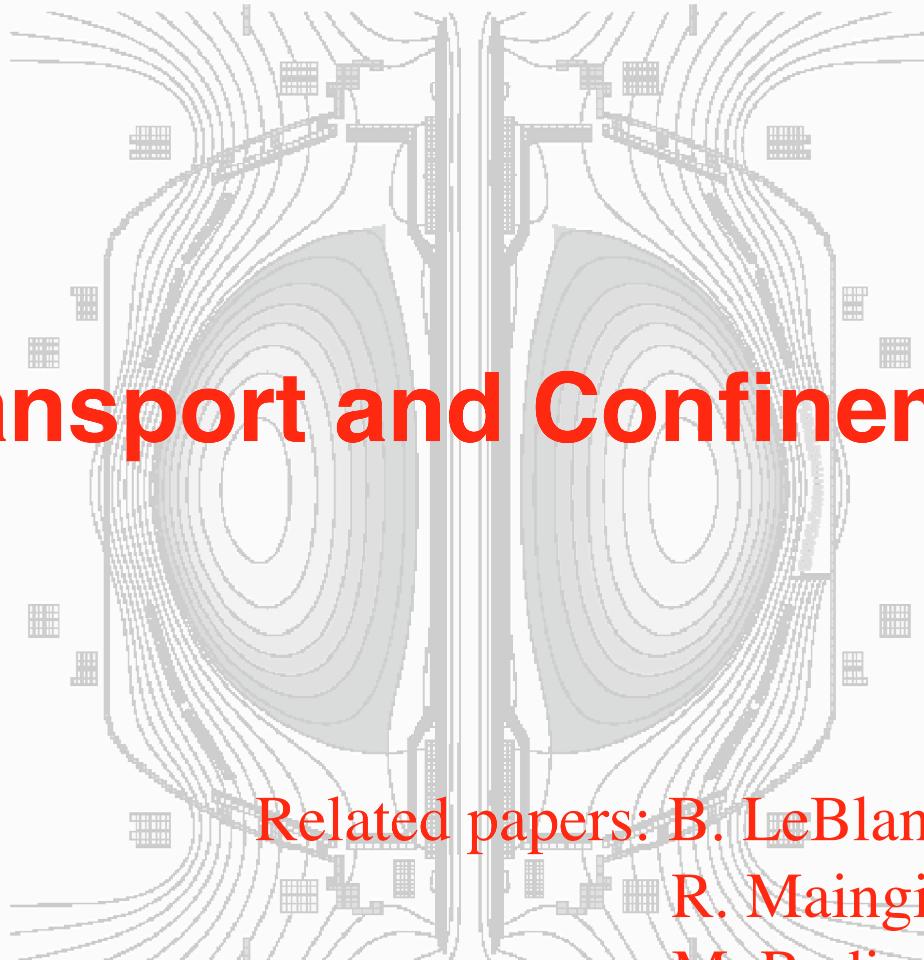


PEGASUS PLANS:

- 200 kW HHFW heating
- Fast TF ramp
- Improved shaping control
- Increased OH capability
- lower A

G.D. Garstka, et al., PP (2003)

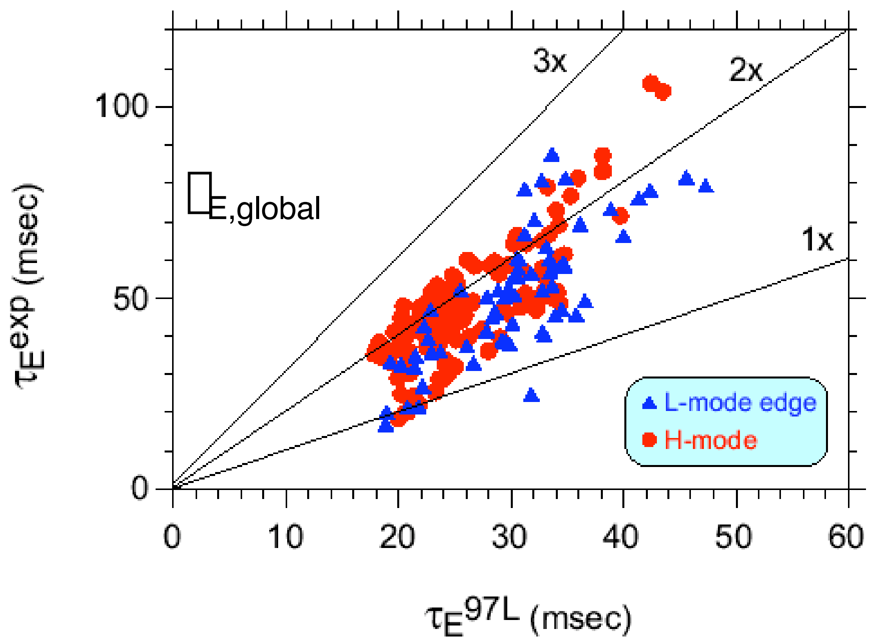
Transport and Confinement

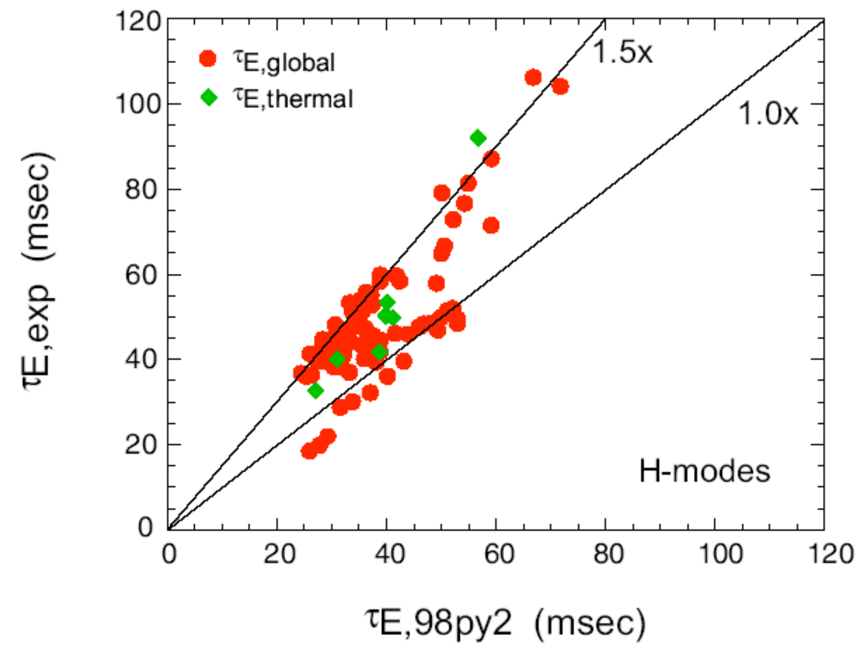


Related papers: B. LeBlanc, et at, P-3.98
R. Maingi, et al., P-3.97
M. Redi, et al., P-4.94
D. Stutman, et al., P3.100

Global Confinement Exceeds Predictions from Conventional Aspect Ratio Scalings

NSTX





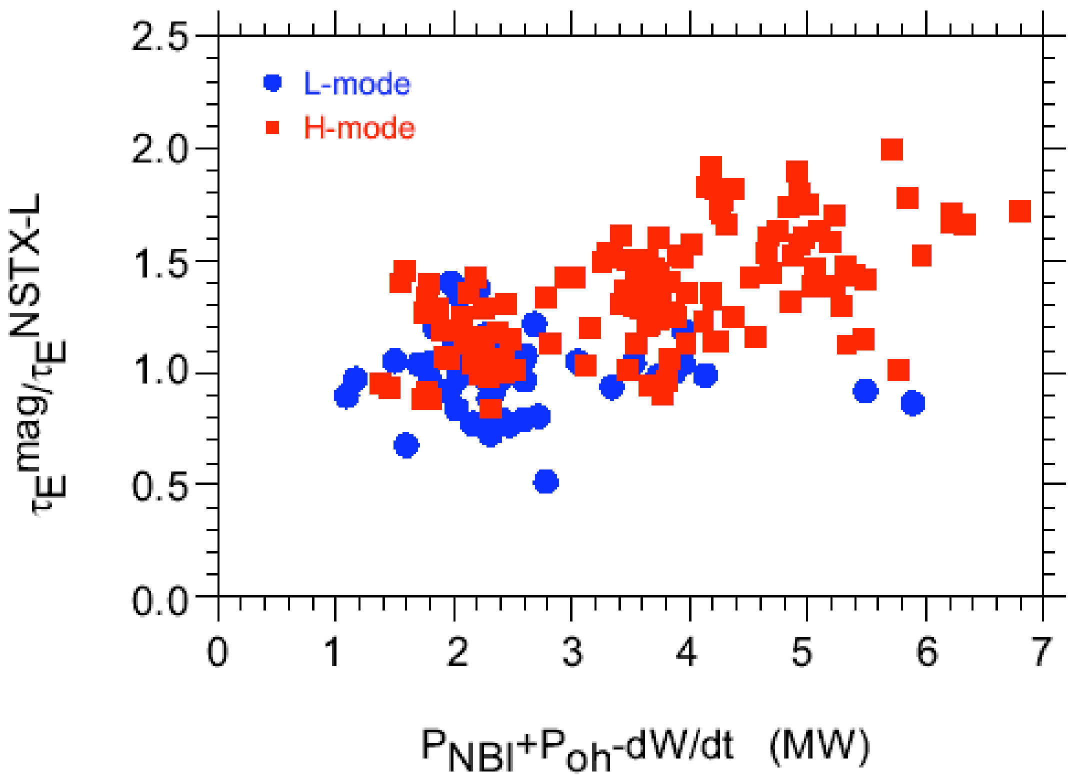
- Quasi-steady conditions
- $\tau_{E,global}$ from EFIT magnetics reconstruction
  - Includes fast ion component
- $\tau_{E,thermal}$ determined from TRANSP runs

- Ip ≤ 1.5 MA
- E_T ≤ 0.4 MJ with 12 m^3
- Routine H-mode access
- β_T ≤ 35%, $\epsilon\beta_p$ ≤ 1, β_N ≤ 6
- τ_E ≤ 100 msec

NSTX NBI L-modes Exhibit Similar Parametric Scaling as Conventional Aspect Ratio Devices

NSTX

$\tau_E^{NSTX-L} \sim I_p^{0.76} B_T^{0.27} P_L^{-0.76}$



Accurate determination of R/a dependence is an active ITPA research topic

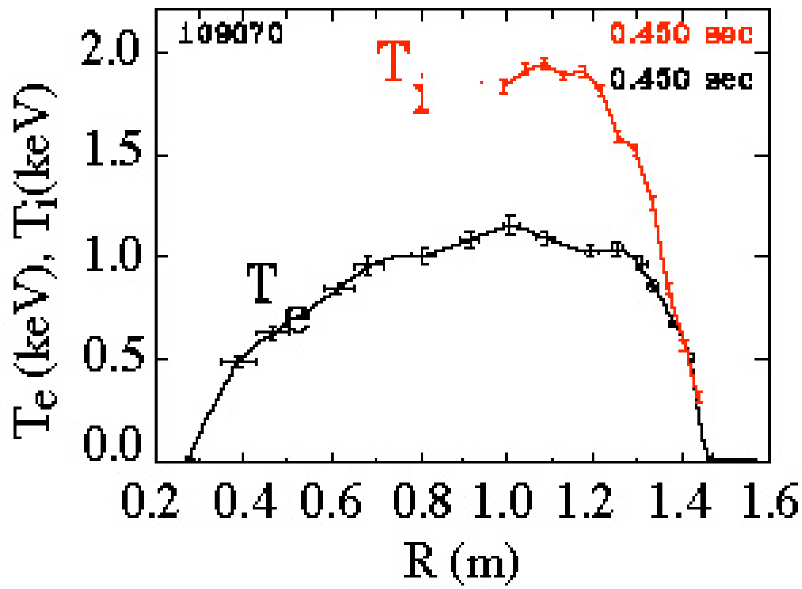
Favorable power dependence in H-mode $\tau_E \sim P^{-0.50}$

- Other H-mode parametric dependencies not yet well determined

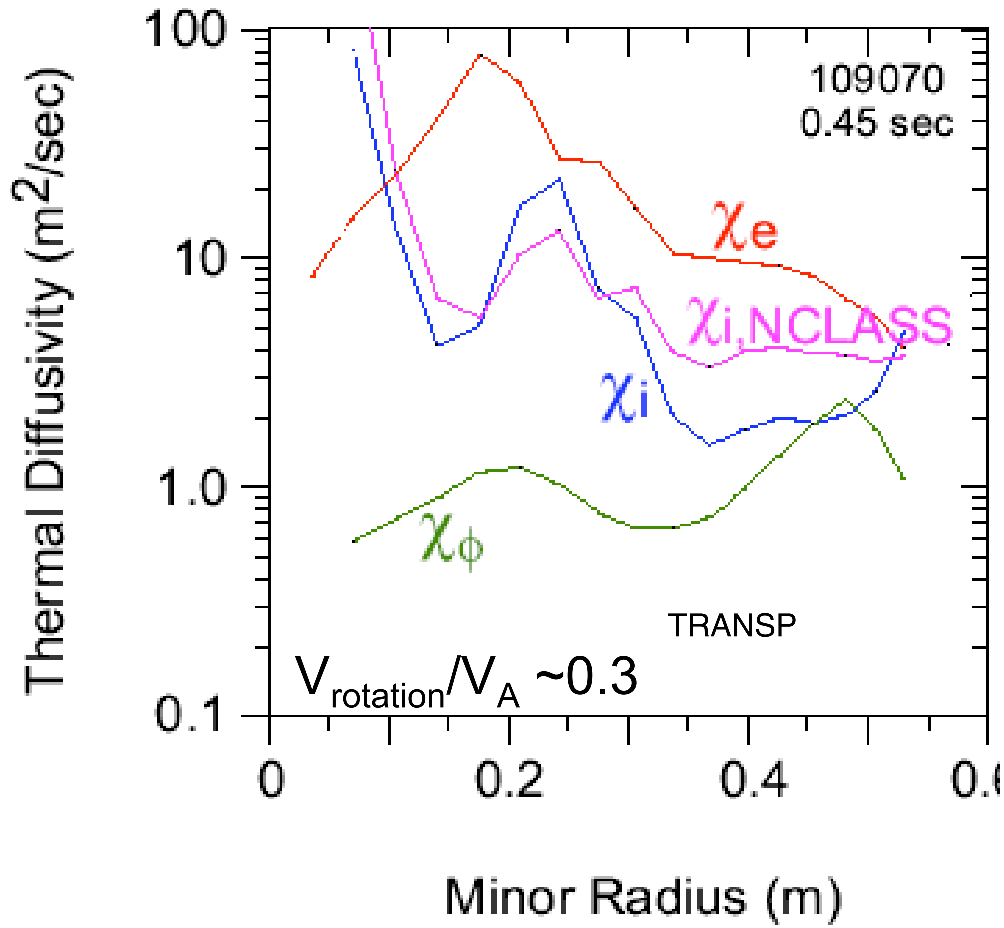
S. Kaye, et al.,

Good Ion Confinement Suggests Suppression of Long Wavelength Turbulence

Transport behavior of NBI heated NSTX discharges



$\chi_\phi \ll \chi_i \approx \chi_{neo} < \chi_e$



- $\chi_i \sim \chi_{neo}$ and $\chi_\phi \ll \chi_i$

  $T_i \gg T_e$
- χ_e has an unusual profile.

Te(r) parabolic than bell shaped.

Theory guides NSTX transport physics research

Microstability and turbulence simulations are done with, FULL, GS2*, GYRO. GTC

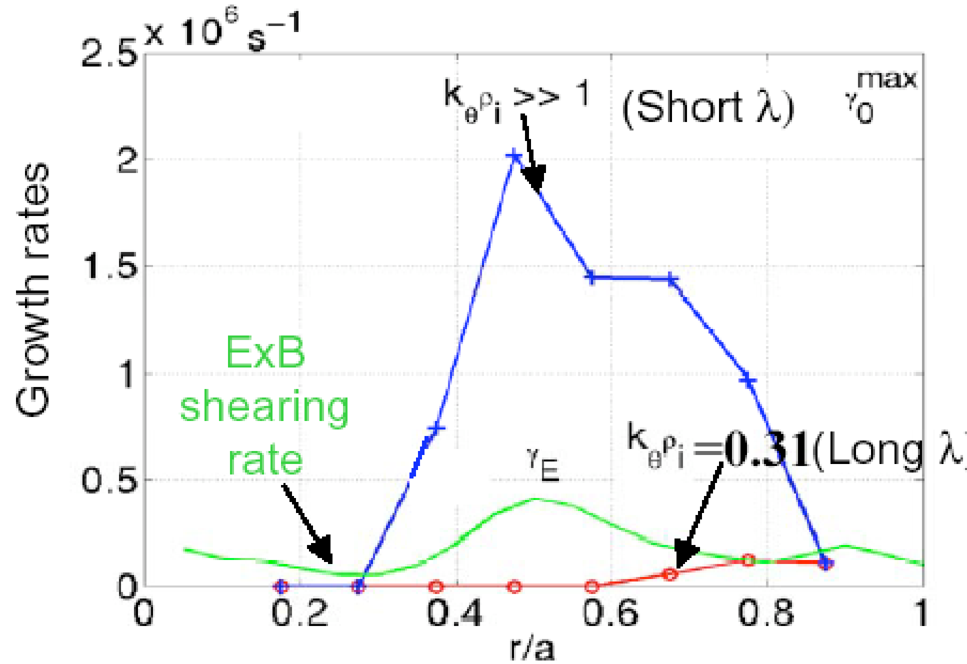
GS2 linear analyses shows that

- ExB shearing rate stabilizes long l, ITG modes
- short l ETG modes not stabilized, may dominate transport
- Modes that are usually sub-dominant, (tearing parity), may play a role

Diagnostics and localized heating, EBW, will test theory

Non-linear studies – GS2

+ global (GTC & GYRO) in future

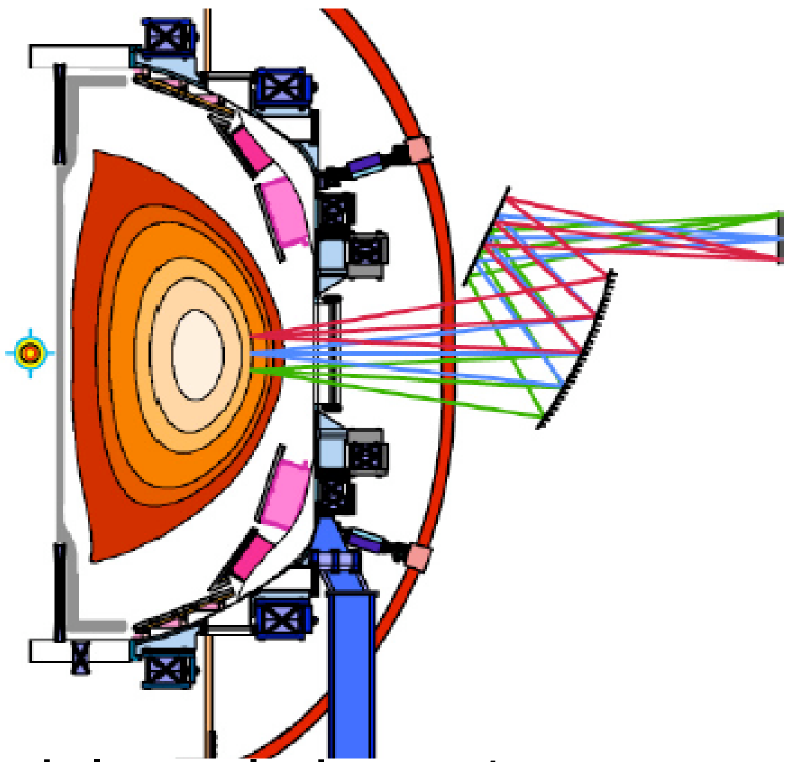


Bourdelle (Cadarache)

NSTX can provide a unique test-bed to understand electron transport and eventually to control it.

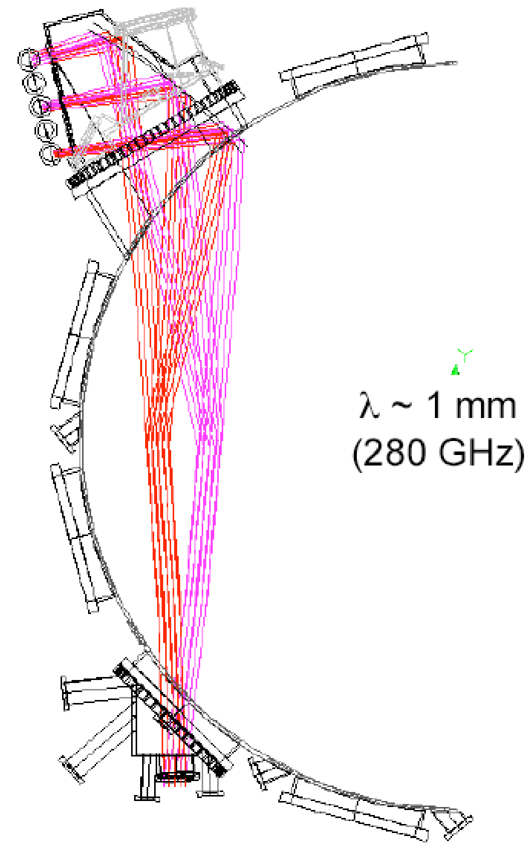
Advanced Turbulence Diagnostics Planned

Low-k turbulence
Imaging reflectometry is



Spatial resolution ~ 1 cm
$K_{\perp}$ resolution ~ 0.2 - 3 cm-1

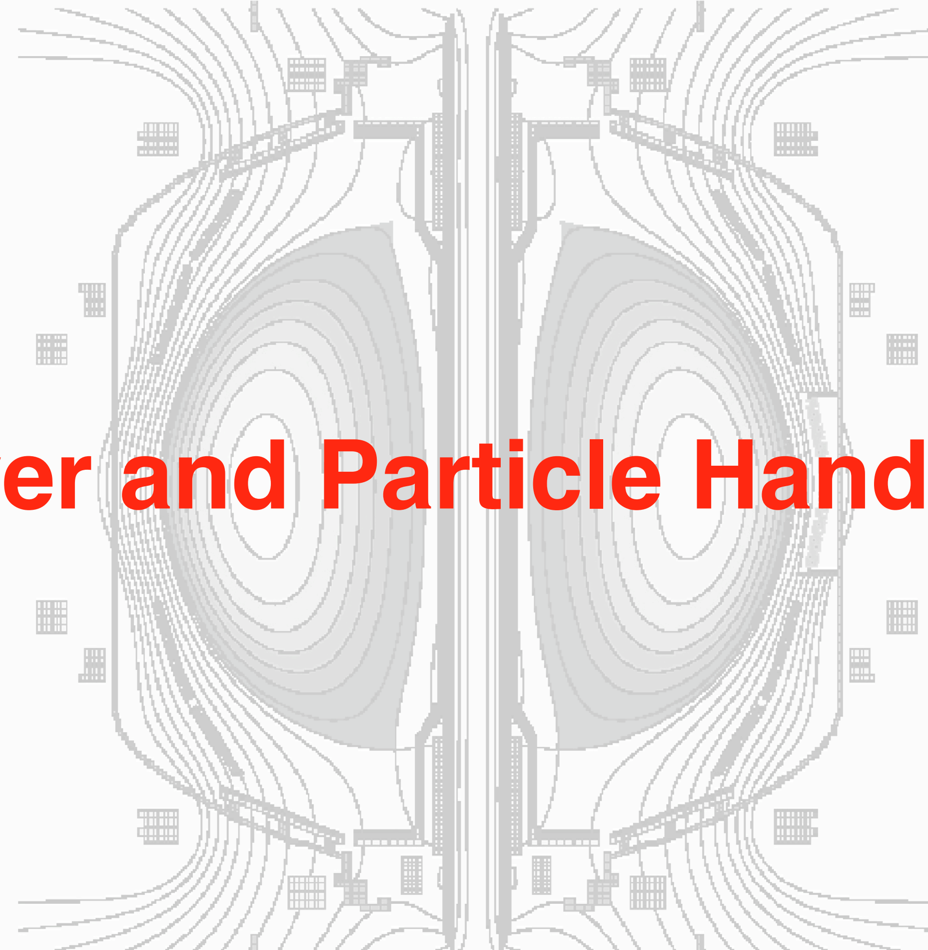
High-k turbulence
Tangential microwave



$k_{\perp}\rho_e$ ~ 0.1-0.3 at r/a ~ 0.4 - 0.8

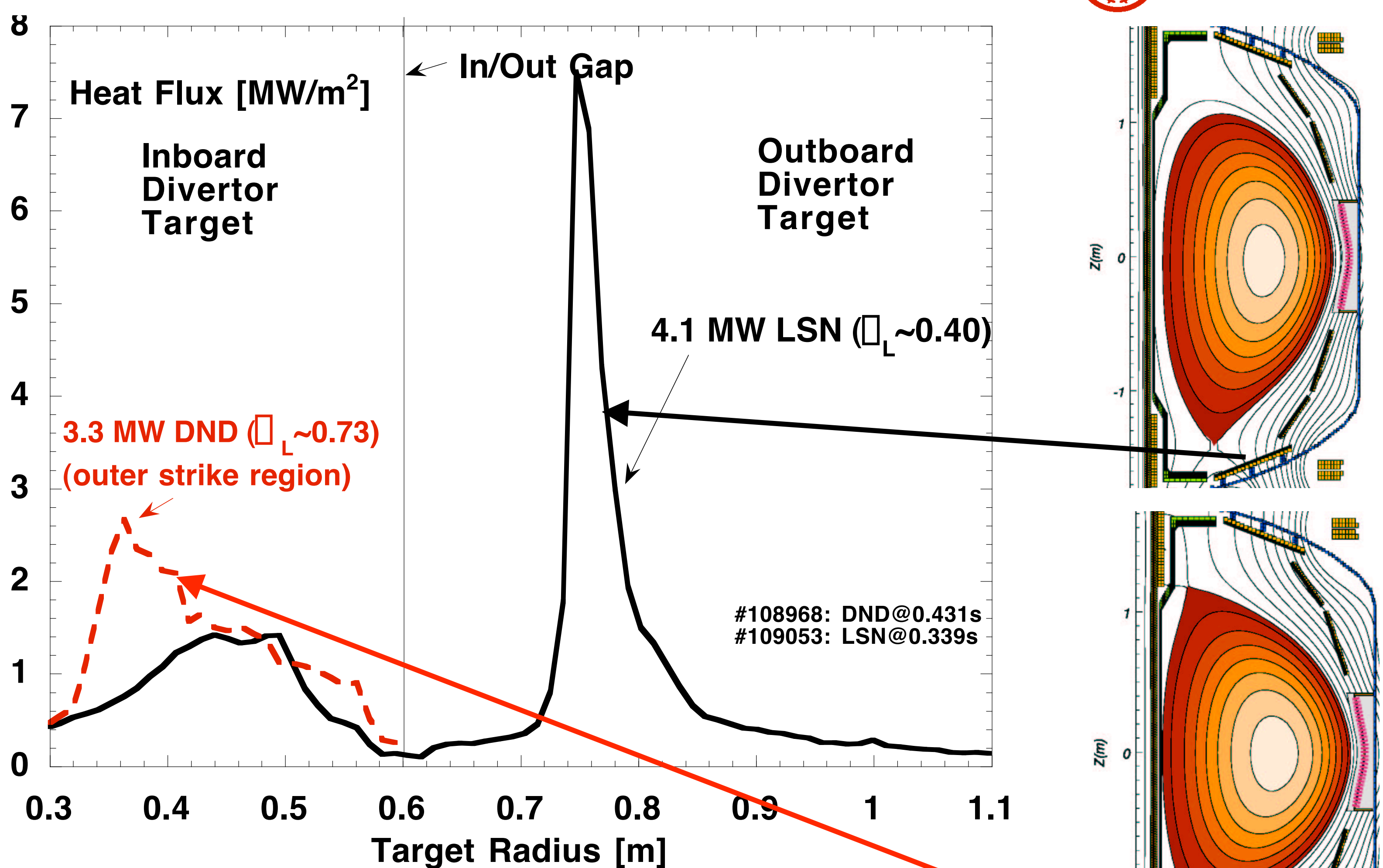
E. Mazzucato, H. Park, N. Luhmann, T. Munsat

Power and Particle Handling



Related paper: V.A. Soukhanovskii, et at, P-3.179

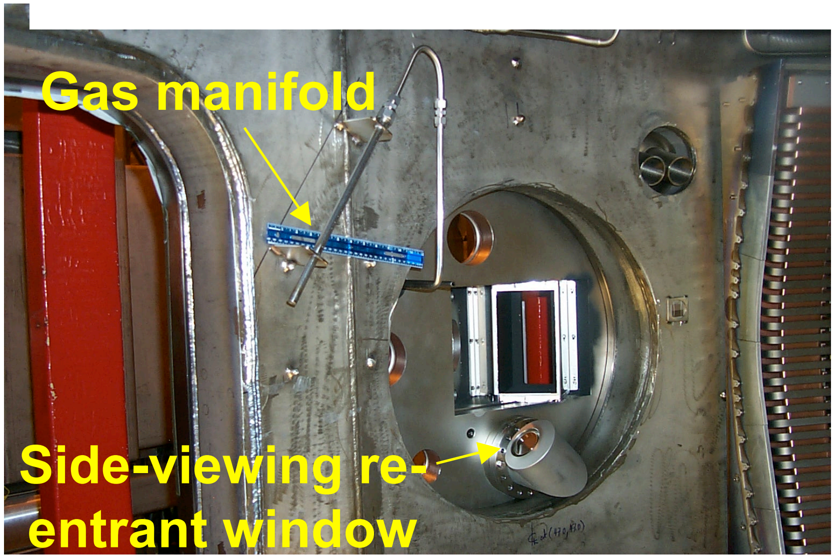
Peak heat flux increased with NBI power in LSN and was reduced in DND relative to LSN

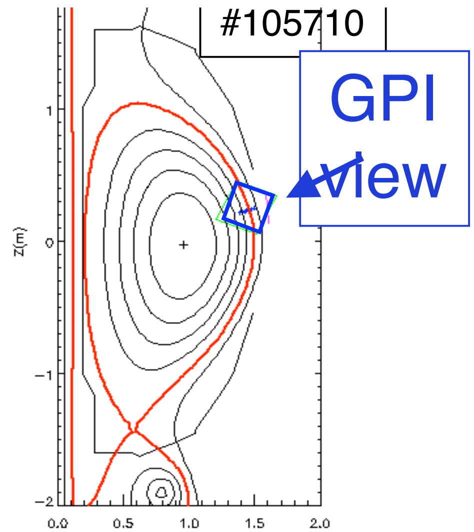


High δ, DND configuration appears to provide an attractive power handling solution.

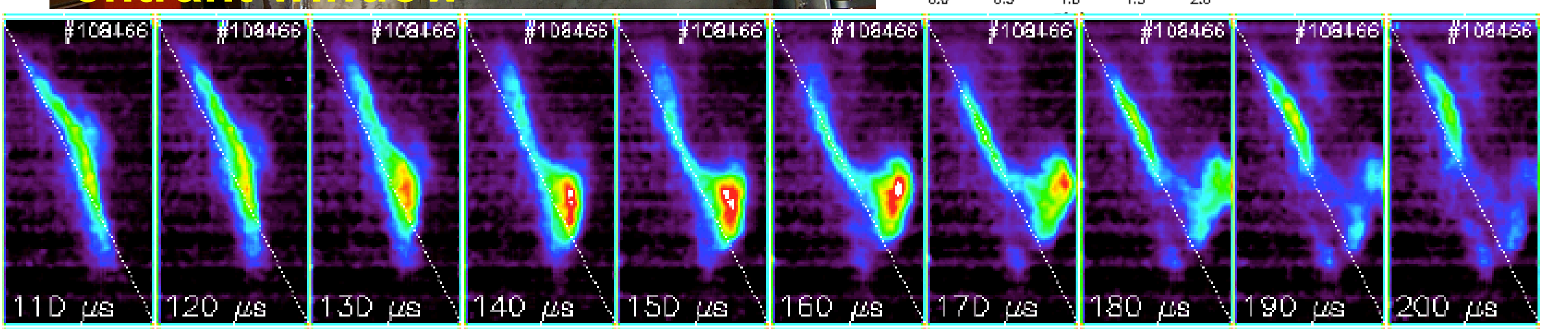
Intermittent plasma objects observed with gas puff imaging diagnostic

NSTX

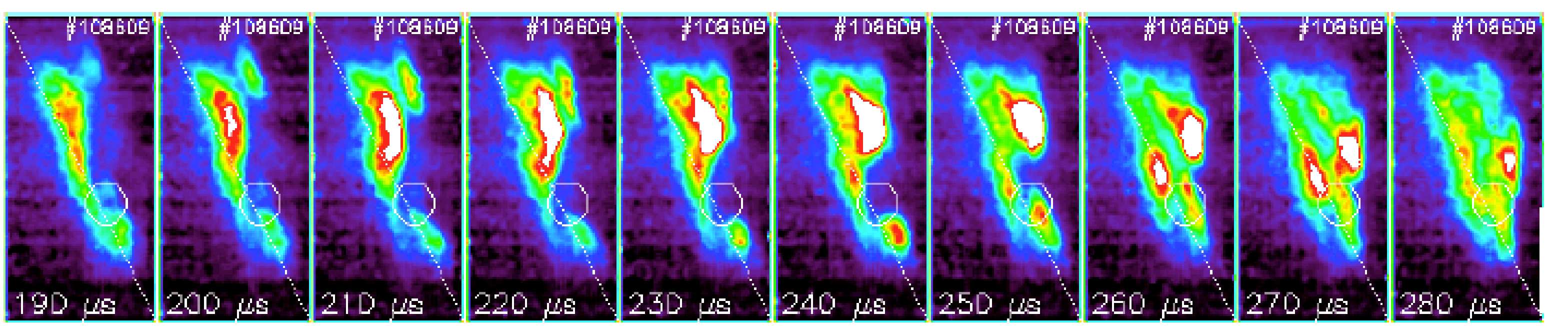




Reflectometers and edge (UCLA,ORNL) reciprocating probe also observe intermittency(UCSD)



H-mode

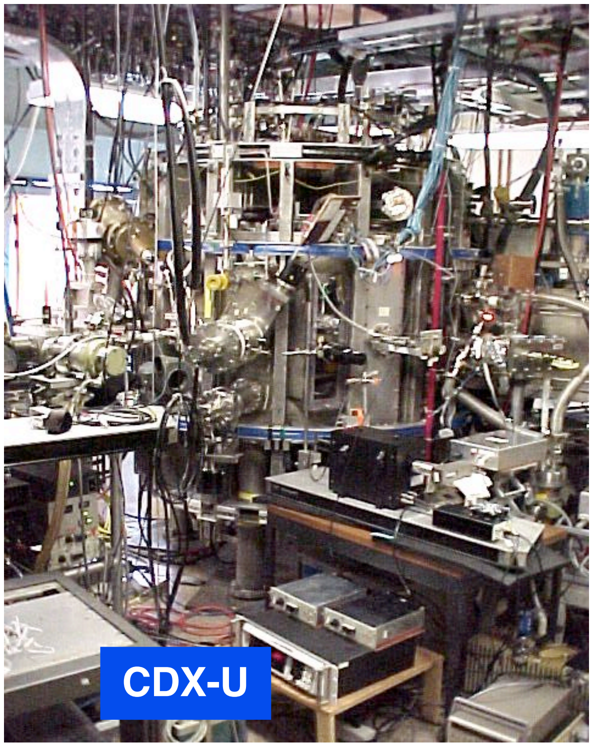


L-mode

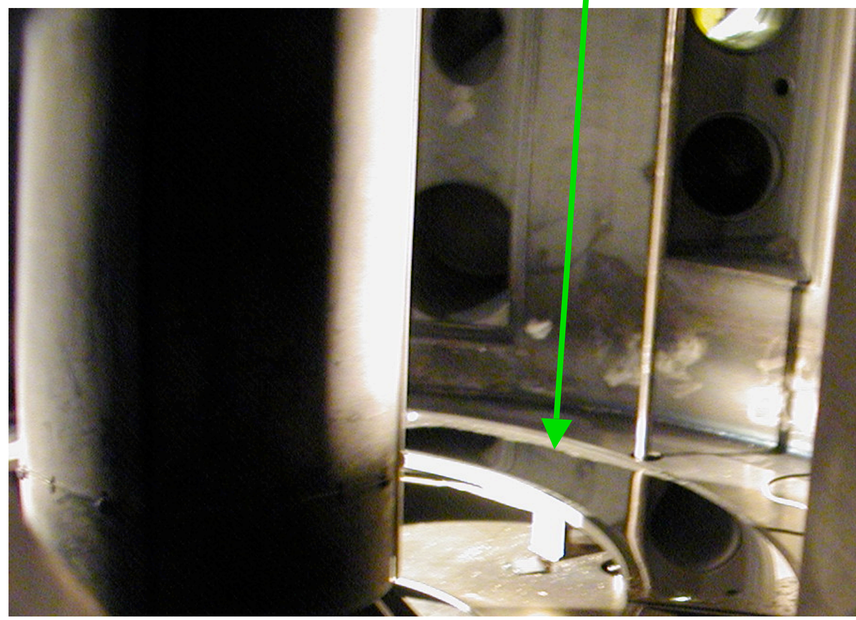
Zweben (PPPL)
Maqueda (LANL)

CDX-U is investigating liquid lithium PFCs*

Li Wall



Note reflections in metallic lithium



Loquid lithium filling technique developed by UCSD - PISCES group.

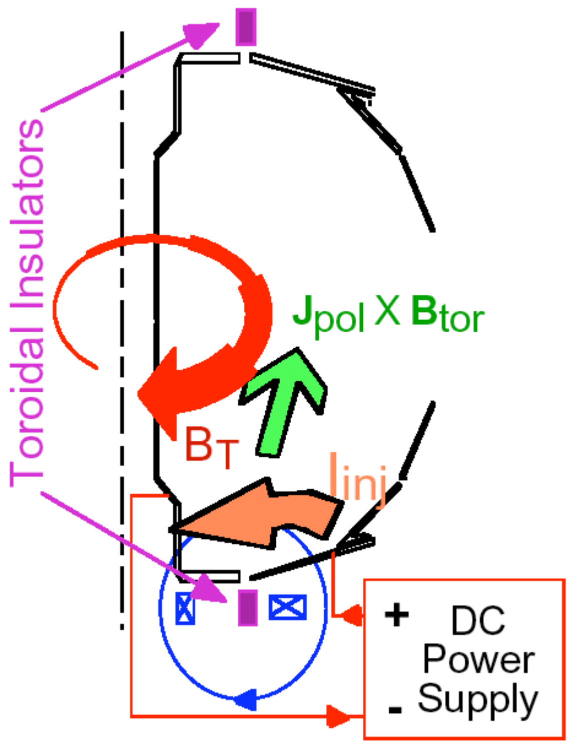
R. Majeski et al., JNM (2003)

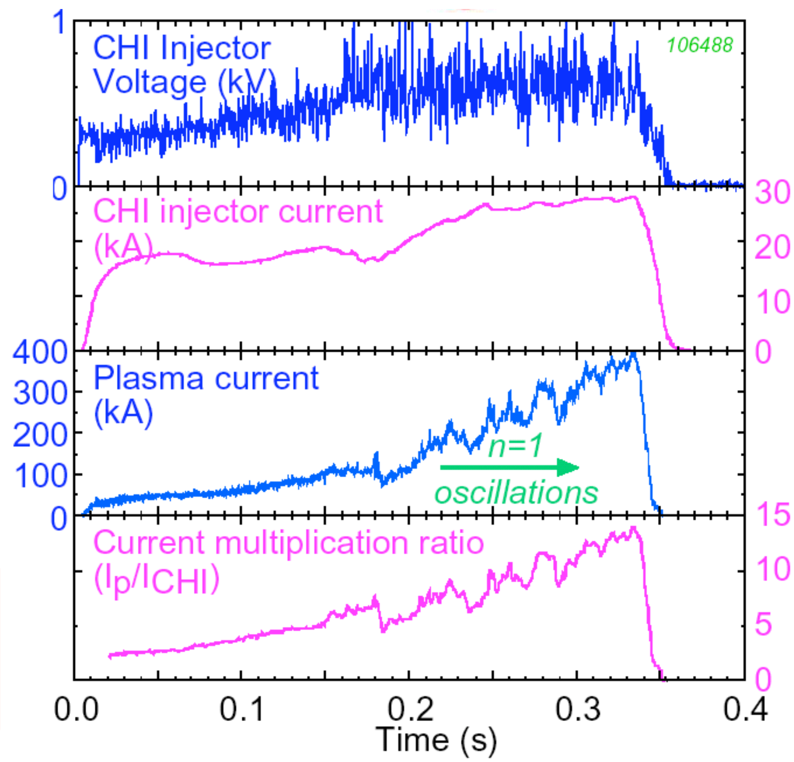
- Gas requirement up x5
- Oxygen, carbon impurities virtually eliminated
- Immediate 30% increase in peak I_p, discharge duration
- Loop voltage to sustain current dropped from 2.0 → 0.5V

Solenoid-Free Start-Up

- Coaxial Helicity Injection
- Outer poloidal field start-up

CHI Generated Large Toroidal Current in NSTX

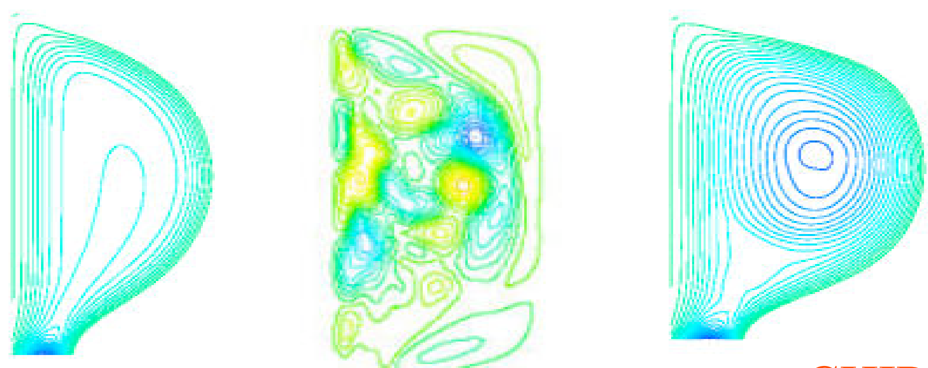




Goal is to control discharge evolution to promote relaxation of toroidal current into closed flux surfaces

NSTX: Univ. of Washington, PPPL

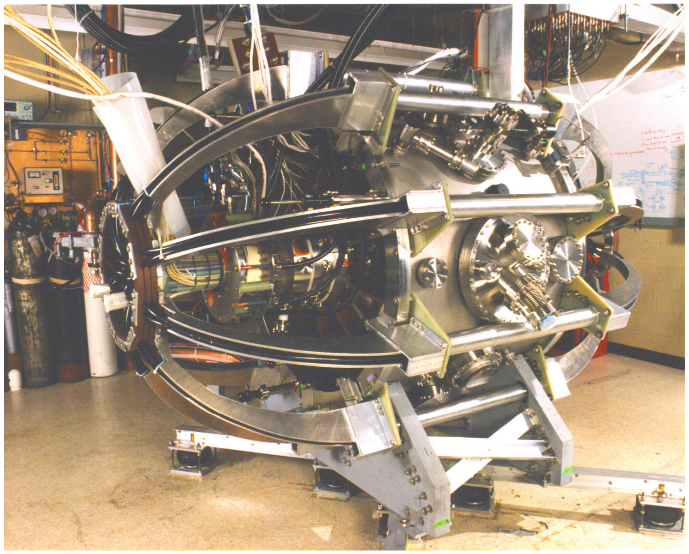
- CHI requires 3-D MHD simulation of flux closure and reconnection
  - –CHIP, M3D, NIMROD

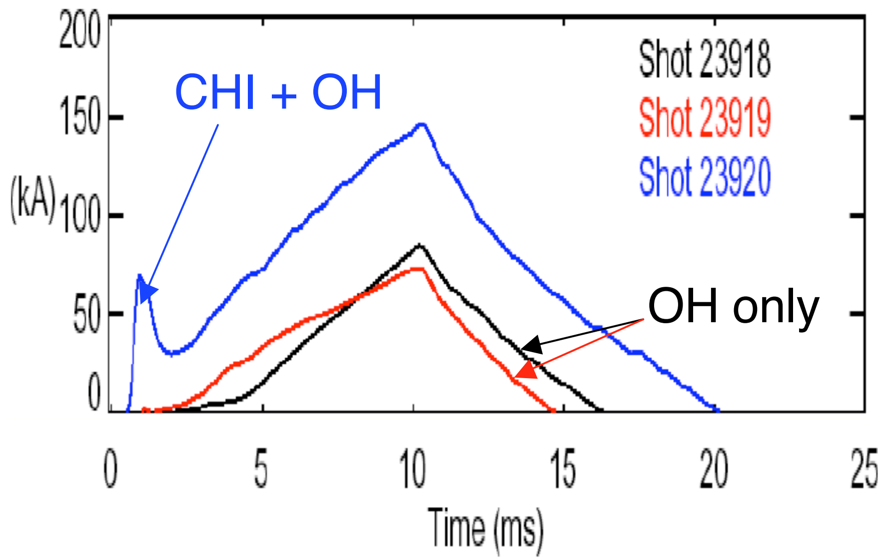


CHIP - LANL

HIT-II developed a new CHI startup method

NSTX





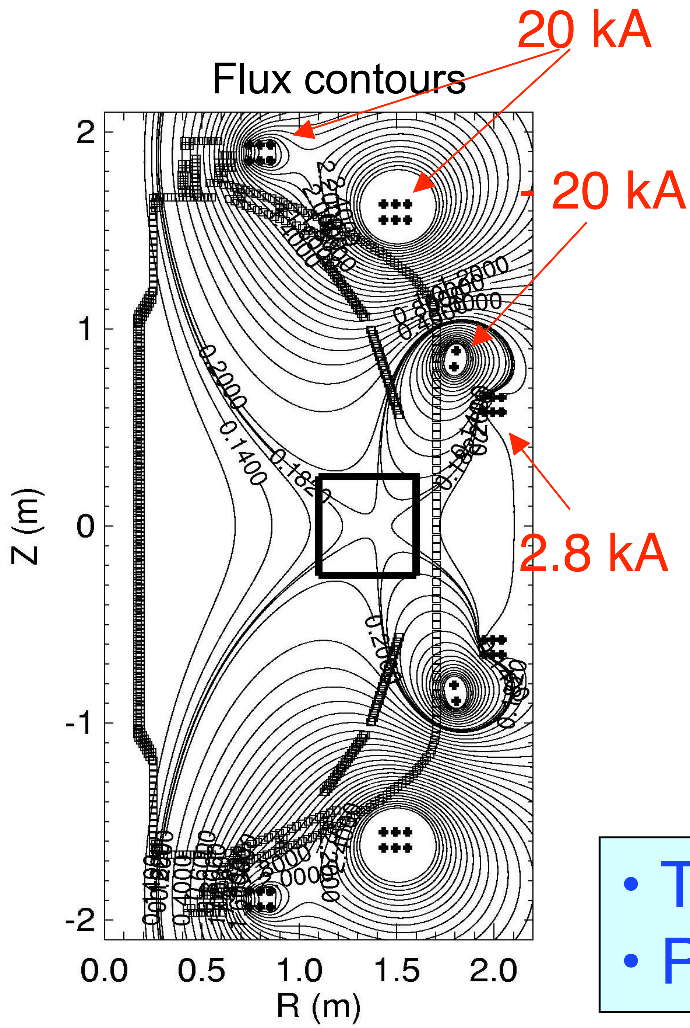
- CHI started discharges coupled to inductive discharges saved volt-seconds
- CHI started discharges much more robust and less sensitive to wall conditions
- CHI started discharges produced record plasma currents on HIT-II (265kA)

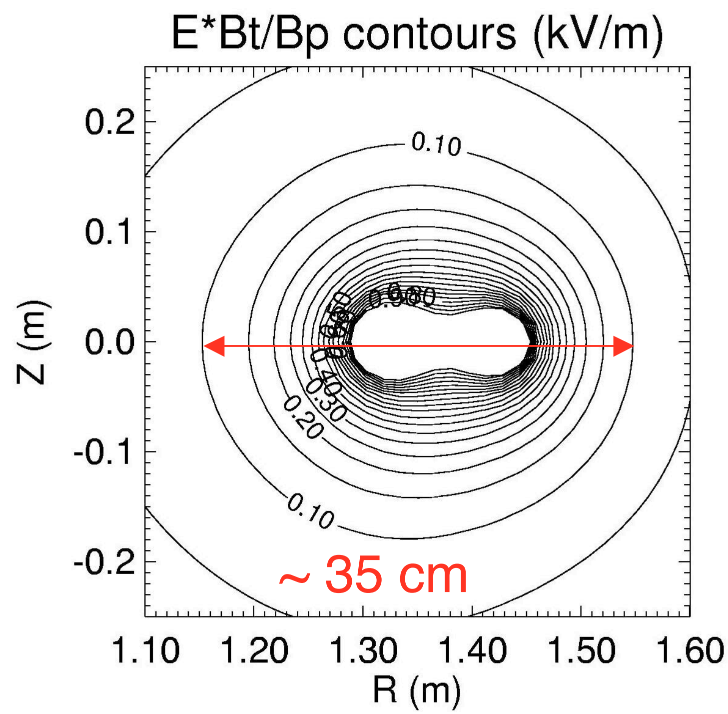
NSTX plans to test the CHI assisted OH start-up concept.

R. Raman, et al., PRL (2003).

Outer Poloidal Field Coil Only Start-Up

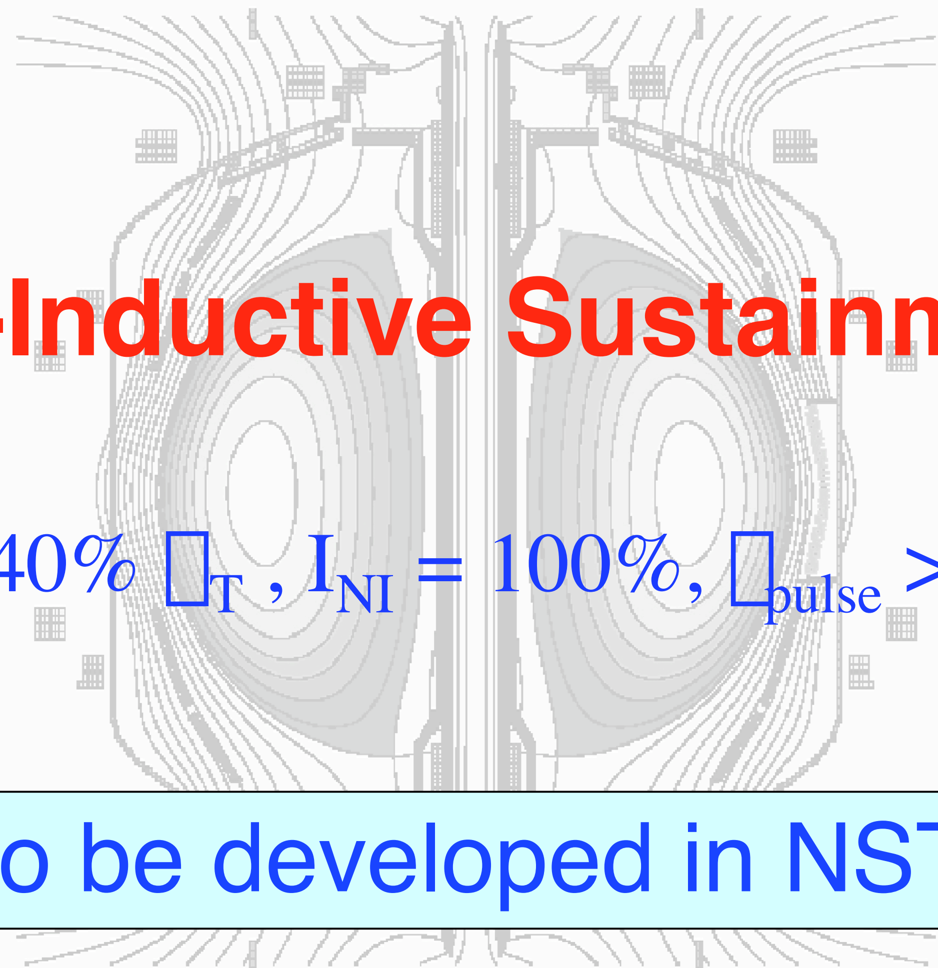
In ST geometry, a qualify field null can be formed by outer PF coils while retaining significant flux for current ramp up.





- To be tested on NSTX to ~ 300 kA.
- Physics extendable to future STs.

W. Choe, M. Ono



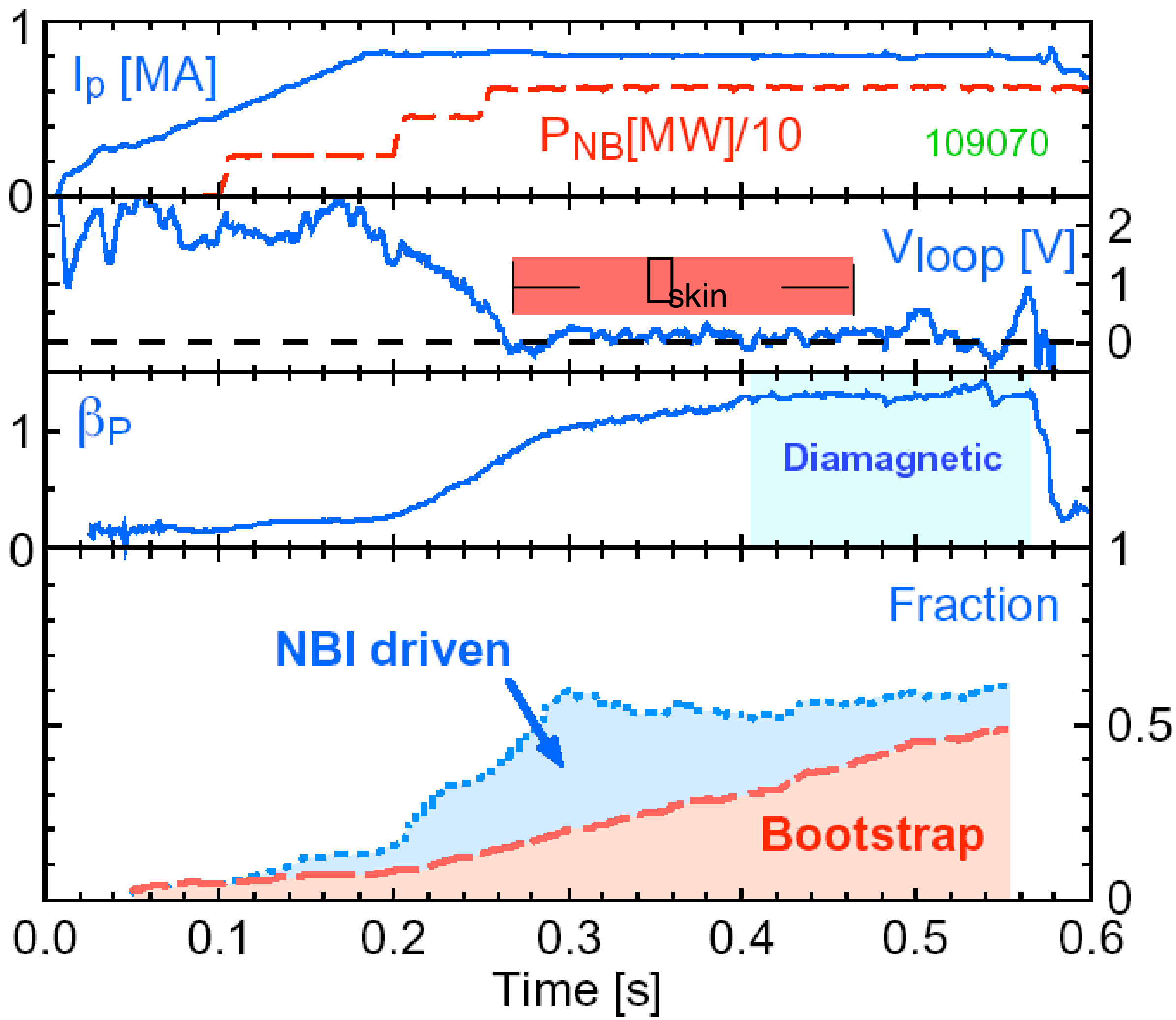
Non-Inductive Sustainment

Goal: 40% β_T , I_{NI} = 100%, $\tau_{pulse} >> \tau_{skin}$

To be developed in NSTX

High Fraction of Non-Inductive Currents Achieved in Long-Pulse High β_{pol} Discharges

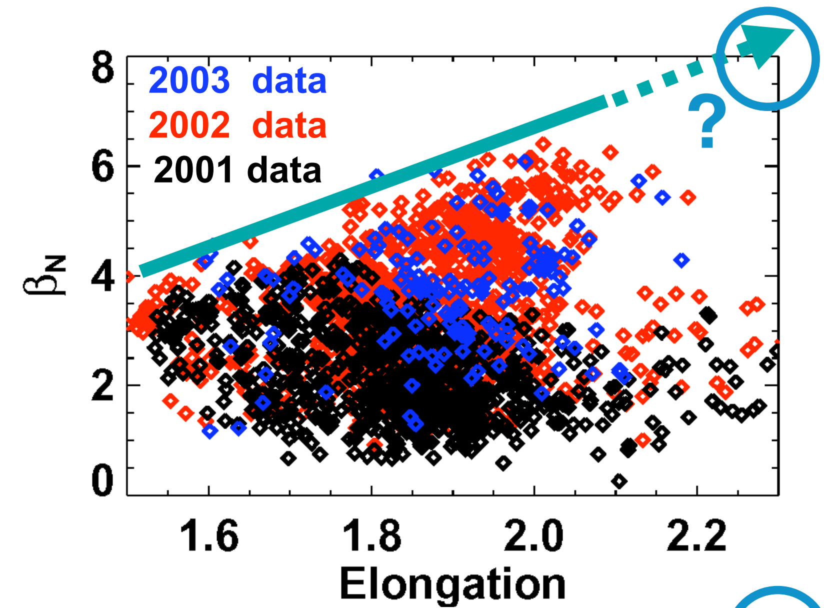
NSTX

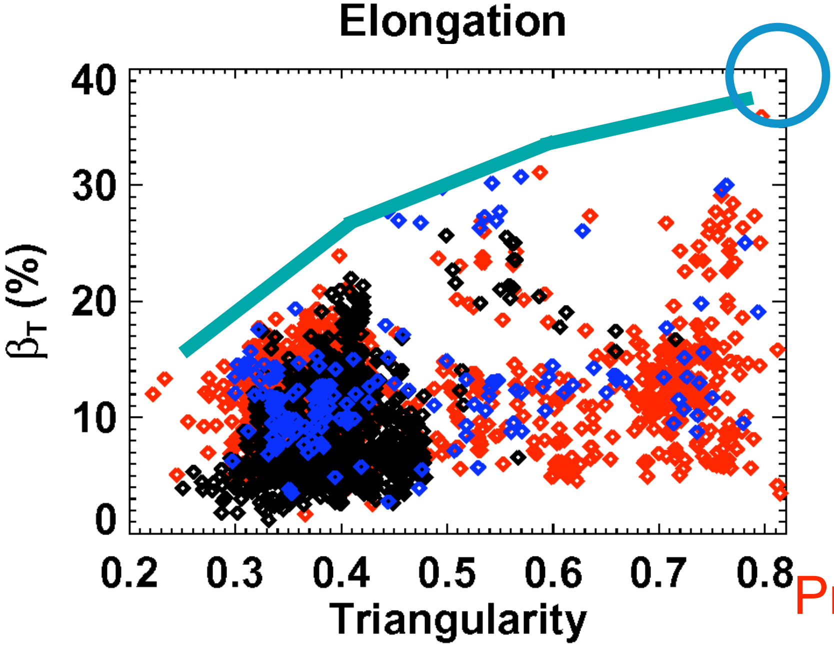


- $\varepsilon\beta_p \sim 1$, I_{NI} Fraction = 60%
- β_N = 5.8 > no-wall stability limit
- $\beta_N H_{89p} \sim 15$ at β_T = 15% sustained over τ-skin
- ~ parameters needed for CTF
- Density still evolving; need particle control

Stability theory and data motivate shaping enhancements

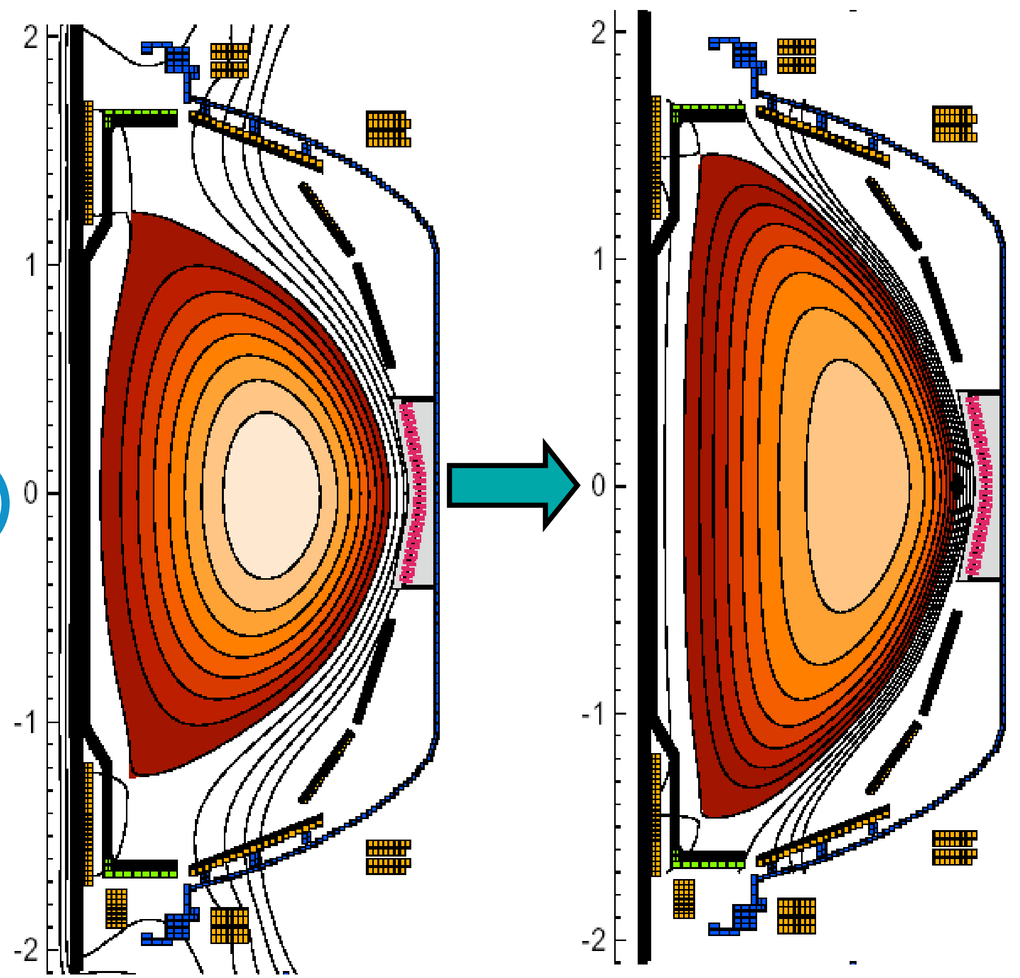
NSTX





□ = 2, □ = 0.8

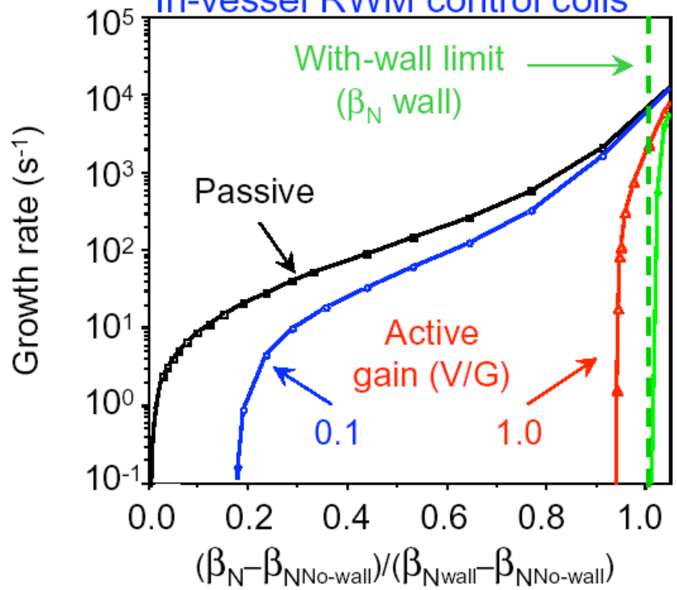
□ = 2.4, □ = 0.8

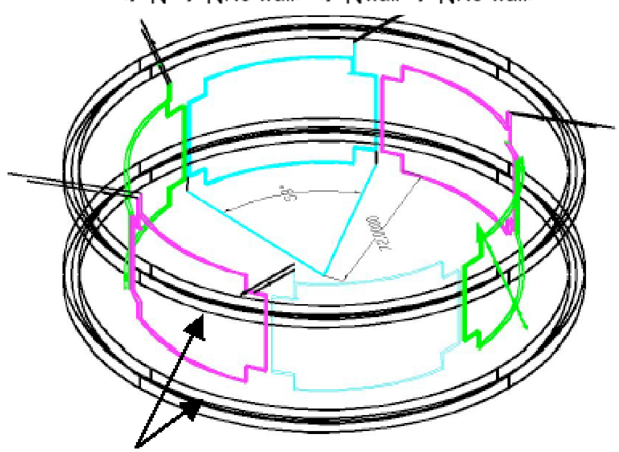


Proposed path to $□_T$=40%, $□_N$=8 (100% j_{NI})

NSTX Active Feedback Control Coils To Help Achieve ~ Ideal MHD Limits

In-vessel RWM control coils

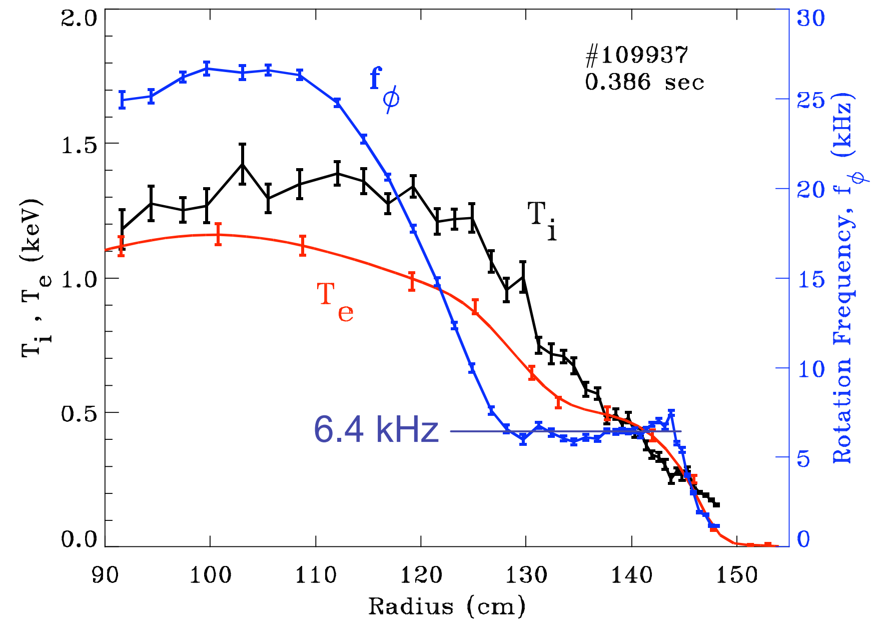


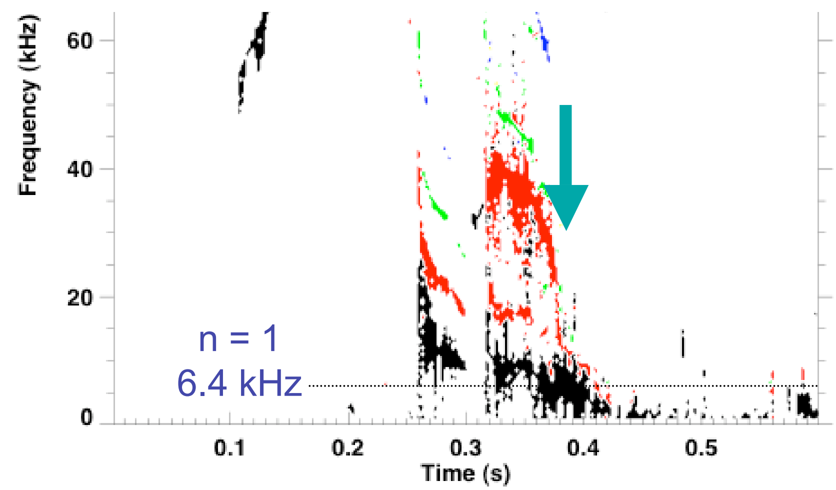


PF5 coils (main vertical field)

Valen code. J. Bialek, S. Sabbagh, Columbia U

Detailed kinetic diagnostics are now available

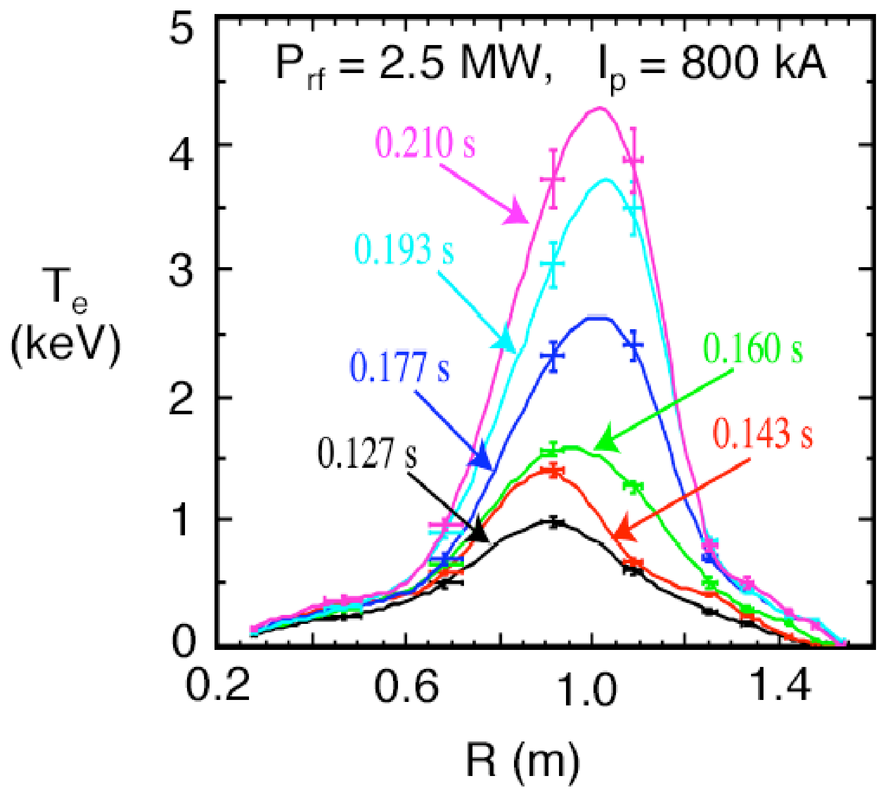




High Harmonic Fast Wave Provides Heating and Current Drive in High Dielectric □~ 50 ST Plasmas

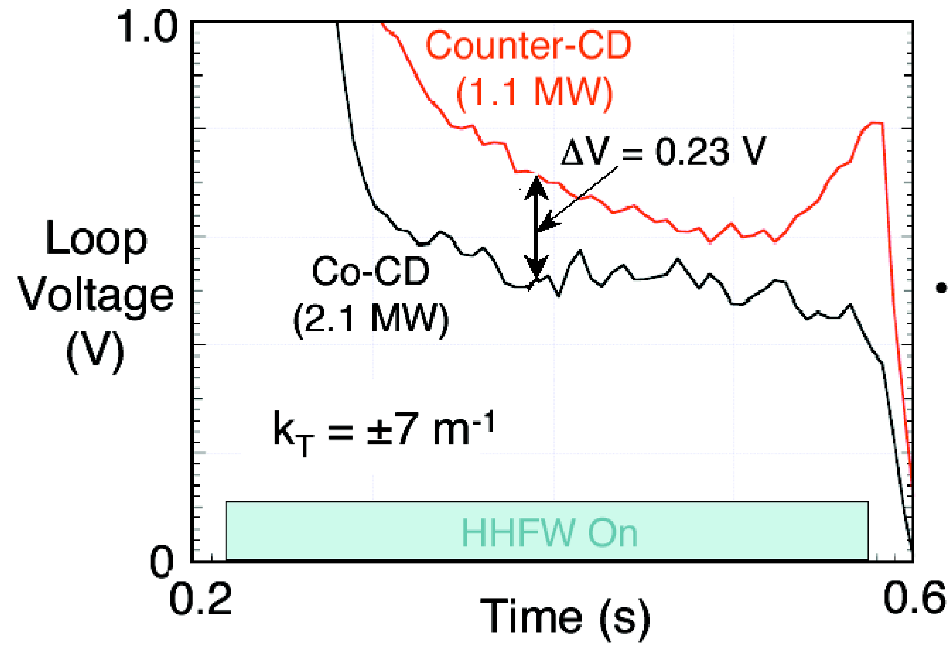
NSTX

Electron heating demonstrated



- Heating observed over wide range in wave phase velocity
- Evidence for electron ITB found

HHFW current drive demonstrated



- Differences in V_{loop} with co and counter-directed waves indicate ~ 100 kA of current drive consistent with theoretical modeling

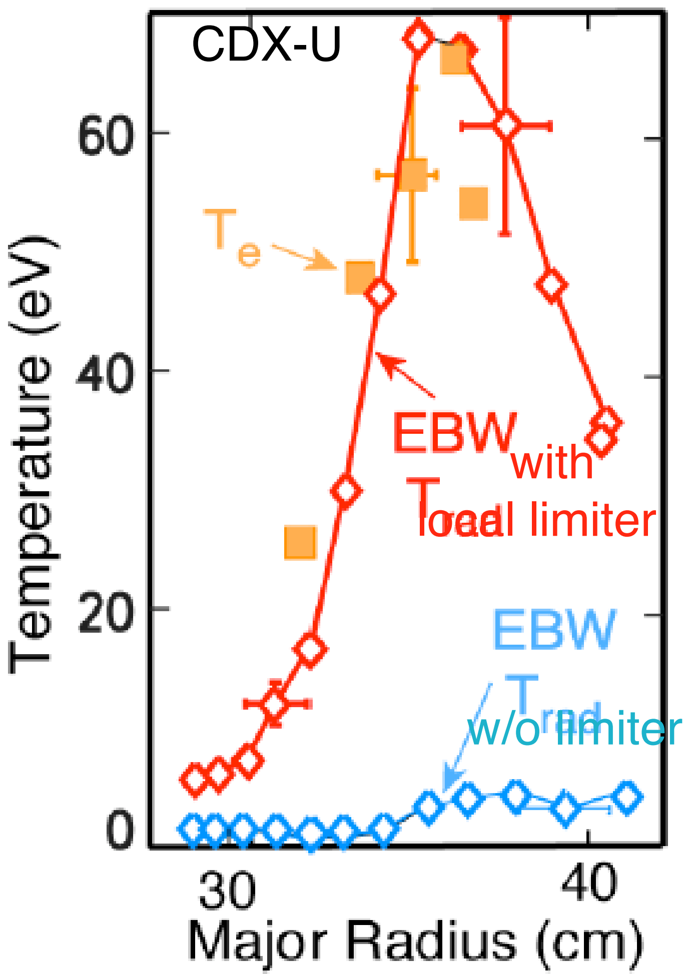
P.M. Ryan et al., NF(2003)

HHFW + NBI interaction investigated. S. Medley et al., P-3.96

Radial Location of EBW CD is Highly Localized and Can be Varied by Changing Launched $n_{//}$

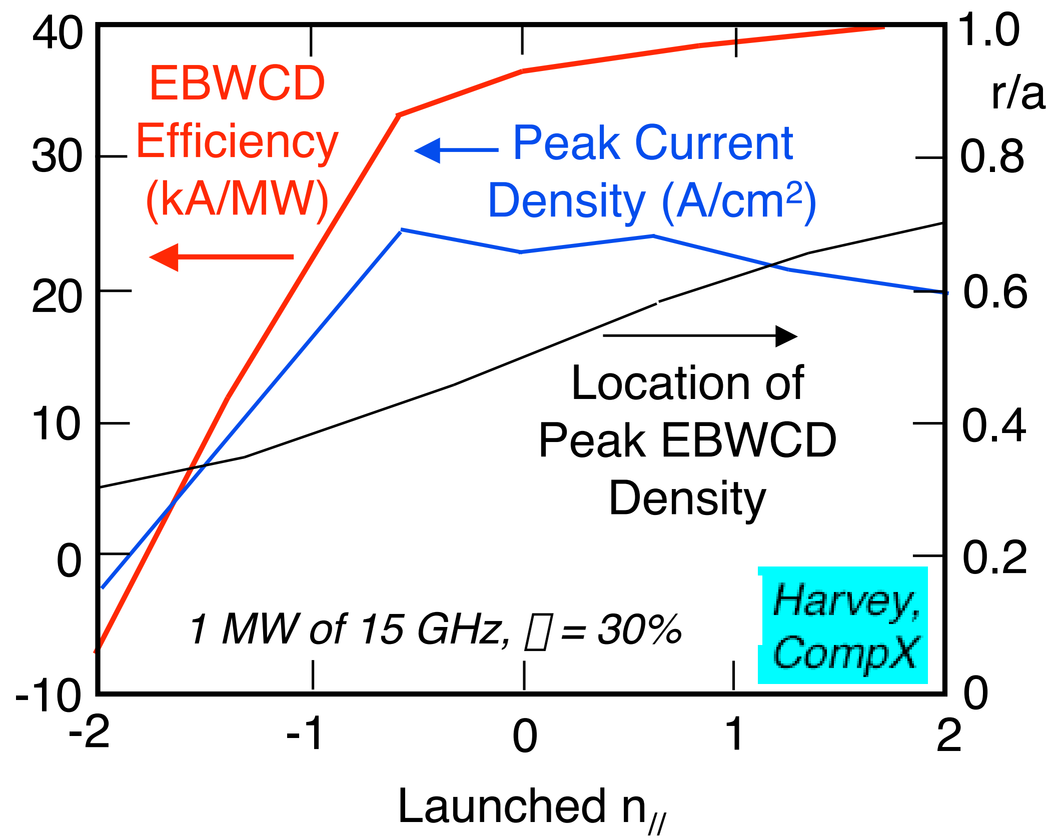
NSTX

X-B Conversion



Exp:B. Jones et al, PRL (2003)

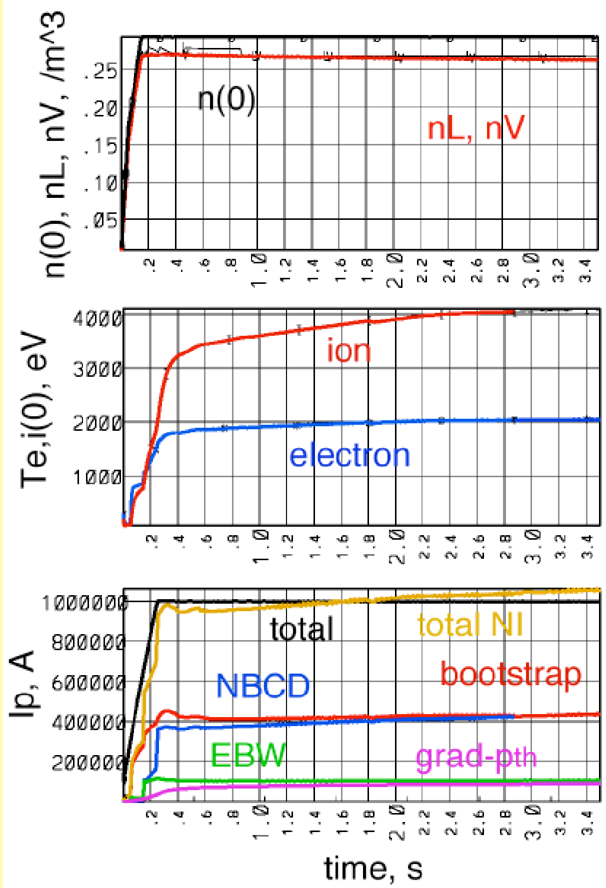
Theory: A.K. Ram et a. PoP(2002)

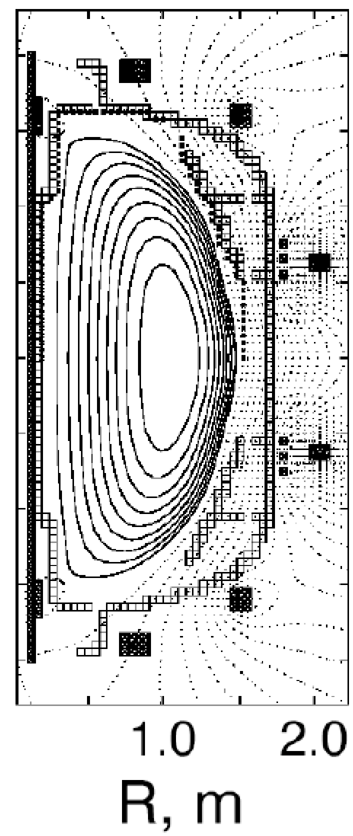


- Positive current results from Ohkawa CD; efficiency increases with r/a
- Normalized CD efficiency, ζ_{ec} = 0.4, compares favorably to ECCD
- Plan ~ 4 MW EBW to get > 100 kA

40% β_T , I_{NI} = 100%, $\tau_{pulse} >> \tau_{skin}$ within reach using the additional tools that are planned

- *Enhanced shaping* improves ballooning stability
- Near with-wall limit => likely that mode control + rotation are key
- Particle control required to maintain moderate n_e for CD
- EBW provides off-axis CD to keep q ~ 2 & stabilize NTMs
- NBI CD, bootstrap current significant part of the total
- HHFW heating contributes to bootstrap, raises T_e





TSC Simulation, C. Kessel, et al.,

ST RESEARCH IS MAKING RAPID PROGRESS

Spherical Torus

- MHD Stability at high $□_□$ and $□_□$
  - 35% $□_T$ achieved on NSTX.
  - PEGASUS is producing 20% beta with just OH at low A~ 1.2.
  - Simultaneous high □ and □ should allow $□_T$ ~ 45% with RWM stabilization
- Good confinement behavior $H_{98pby,2}$ ~ 1.4 at high beta
  - Neo-classical $□_i$ correlates with plasma rotation (sheared flow stabilization).
  - Very low $□_□$ led to $V_{rotation}$ ~ 0.3 V_A
  - Diagnostics for high and low k fluctuations planned – turn on and off low-k?
- Power and Particle Handling:
  - High □ ~0. 8 configuration shows a large reduction in peak heat flux.
  - CDX-U has successfully tested liquid lithium limiter. Aggressive plans for NSTX.
- Two Approaches being pursued for Solenoid-Free Start-Up
  - Coaxial helicity injection is pursued on NSTX with HIT-II collaboration
  - Outer-poloidal field coil start-up research is initiated.
- Plans are in place to Sustain High Performance Plasmas
  - $□_N$ H_{89p} = 15 at $□_□$ = 15% sustained for $□_{skin}$ exceeded no-wall limits.
  - 4 MW 15 GHz EBW should provide flexible off-axis current drive
  - 40% $□_T$ should be sustainable fully non-inductively

Thanks to the NSTX, CDX-U, HIT-II, PEGASUS and Theory Teams

Spherical Torus

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40% β_T , I_{NI} = 100%, $\tau_{pulse} >> \tau_{skin}$ within reach using the additional tools that are planned

- Enhanced shaping improves MHD stability
  - PF 1a modification to allow high $\kappa \leq 2.4$ and high $\delta \leq 0.8$
- Near with-wall limit => mode control + rotation
  - Active feedback coils to be installed
- Particle control required to maintain moderate n_e for CD
  - Divertor lithium wall coating and cryo-pump planned
- 7 MW NBI CD, bootstrap current significant part of the total
- 6 MW HHFW heating contributes to bootstrap, raises T_e
- EBW provides off-axis CD to keep q ~ 2 & stabilize NTMs
  - 4 MW 15 GHz EBW system planned