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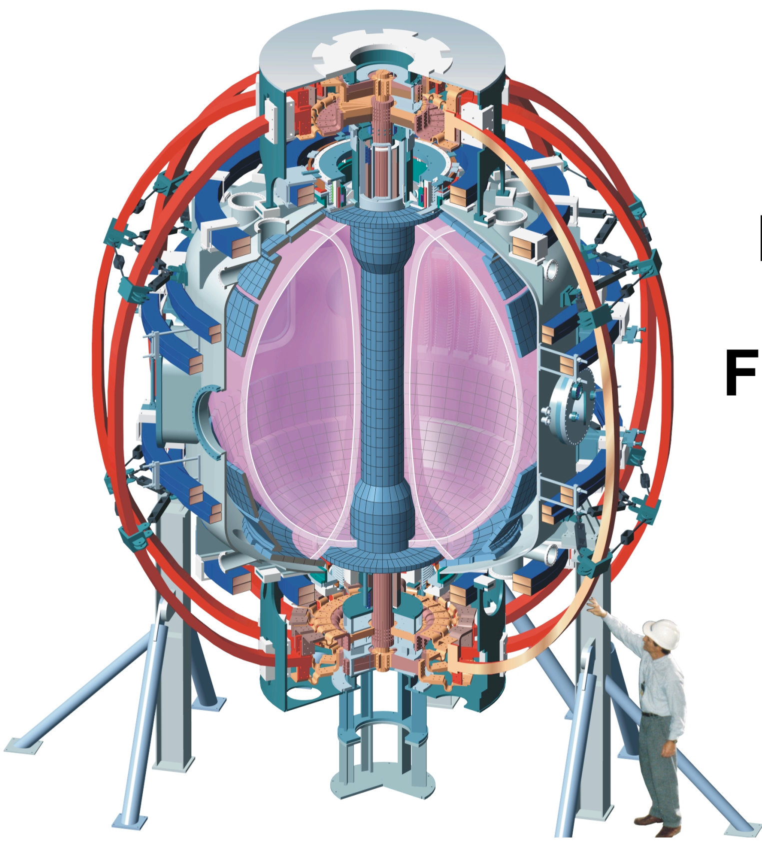
Highlights (and Challenges) on Steady State Operations in NSTX



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Steady State Operation
and Energetic Particles
ITPA 2003,
St. Petersburg, Russia,
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NSTX Contributions to ITPA Steady-State Operation and Energetic Particles

NSTX

- High power heating and current drive systems for R ~ 1 m:
  - 7 MW NBI system operational
  - 6 MW HHFW (ICRF) system operational
  - 4 MW EBW system planned (Off-axis CD and NTM stabilization)

- Physics regimes of interest:
  - Physics of steady-state operation: □-pulse >> □-skin
  - Already exploring V_{Fast} >> V_{Alfven} regimes (Fishbone, TAE, CAE, etc.)
  - Contribute to A, □, □, □ physics data base

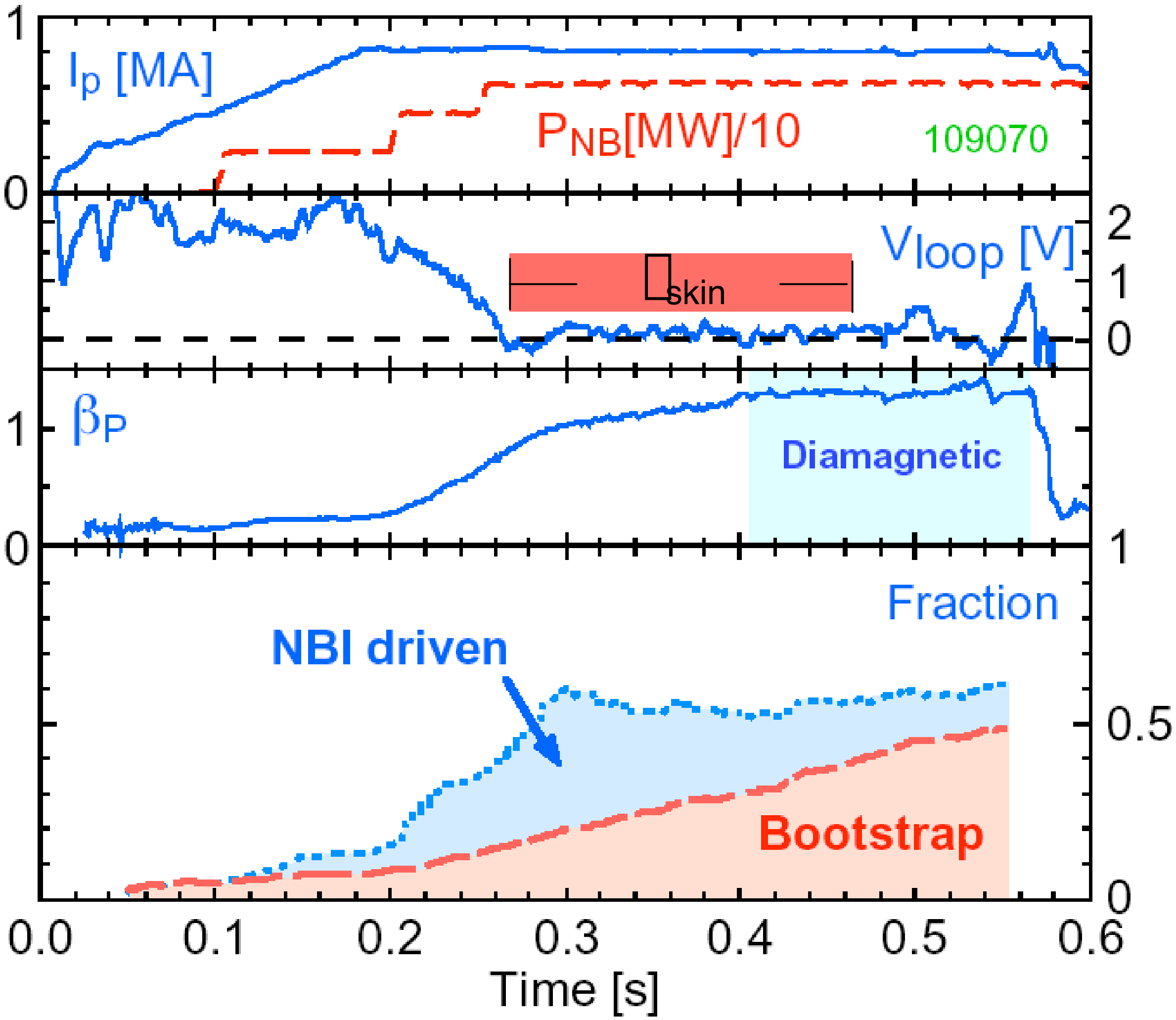
- Advanced toroidal physics explored
  - Above “no-wall” limit plasma already accessed
  - Active feedback coils to be installed

- Power and particle control systems
  - Divertor lithium wall coating and cryo-pump planned

Modern plasma diagnostic and real time control systems

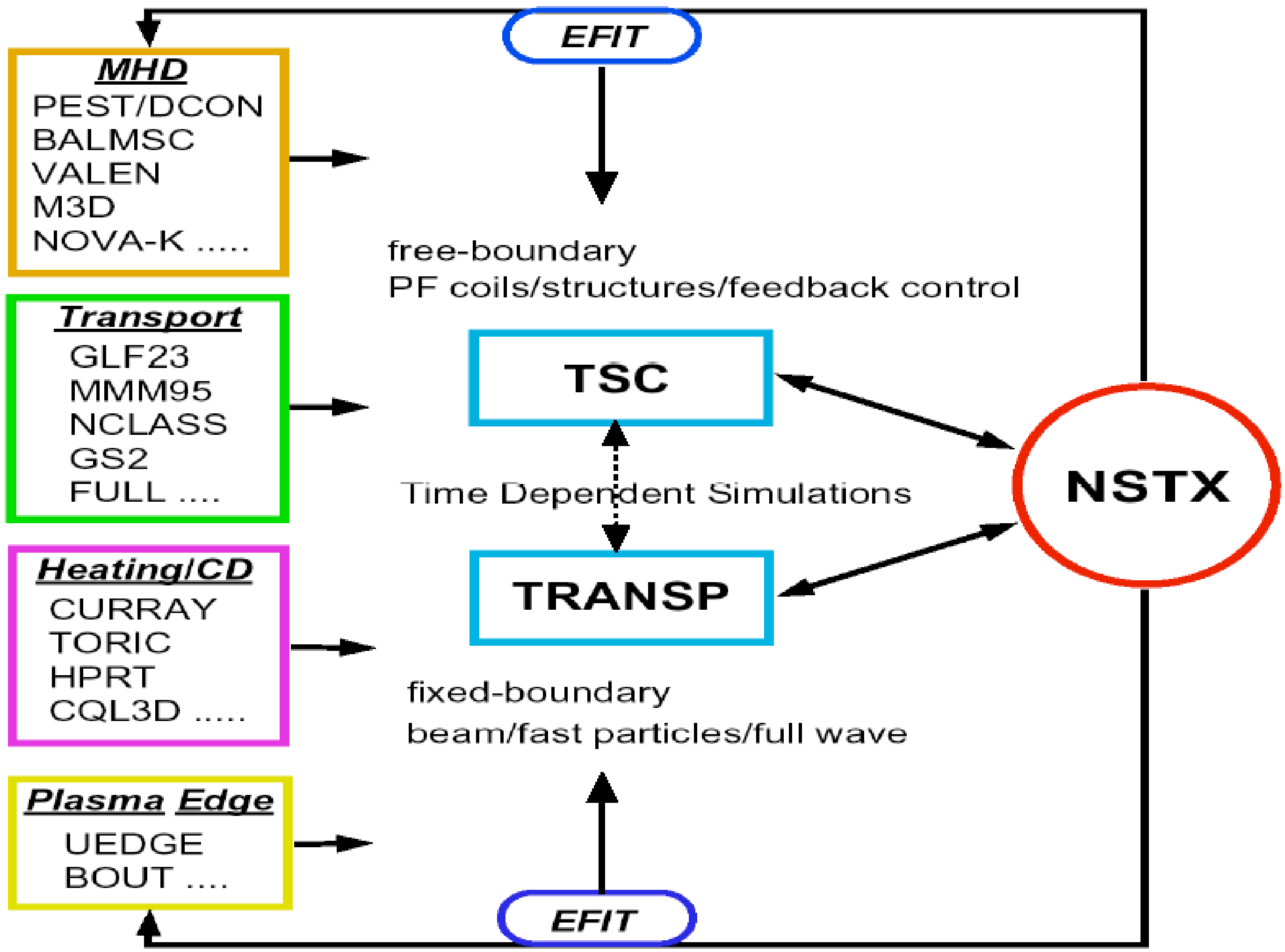
High Fraction of Non-Inductive Currents Achieved in Long-Pulse High β_{pol} Discharges

NSTX

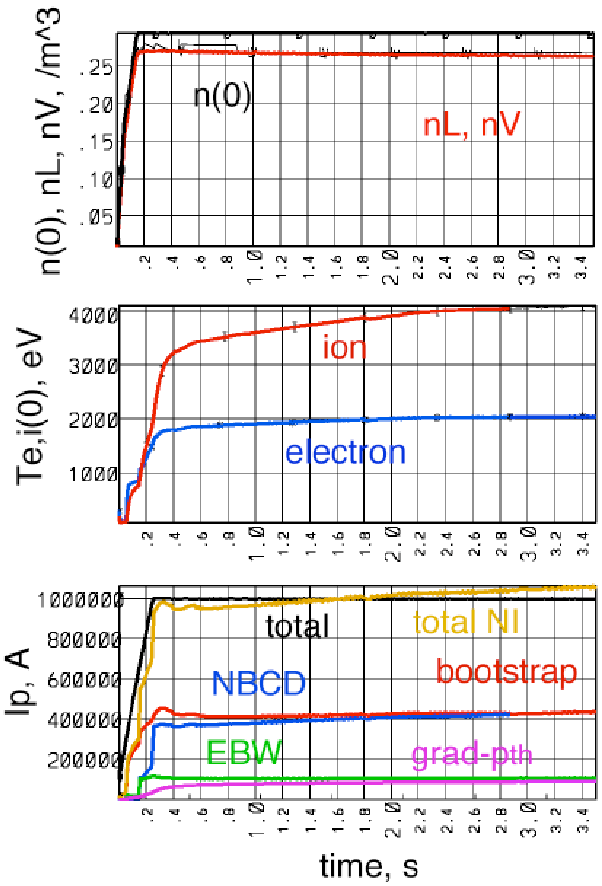


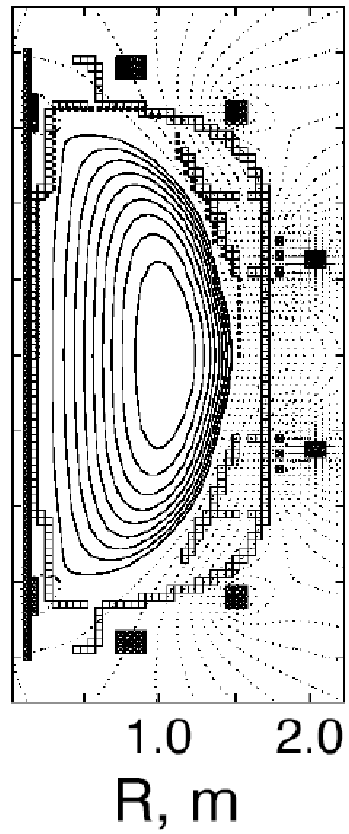
- $\epsilon\beta_p \sim 1$, I_{NI} Fraction = 60%
- β_N = 5.8 > no-wall stability limit
- β_N $H_{89p} \sim 15$ at β_T = 15% sustained over τ-skin, constant l_i
- However, density still evolving; need particle control

NSTX Integrated Scenario Modeling For Steady-State Operations



NSTX Utilizes Advanced Tokamak Physics to Achieve Steady-State Operations



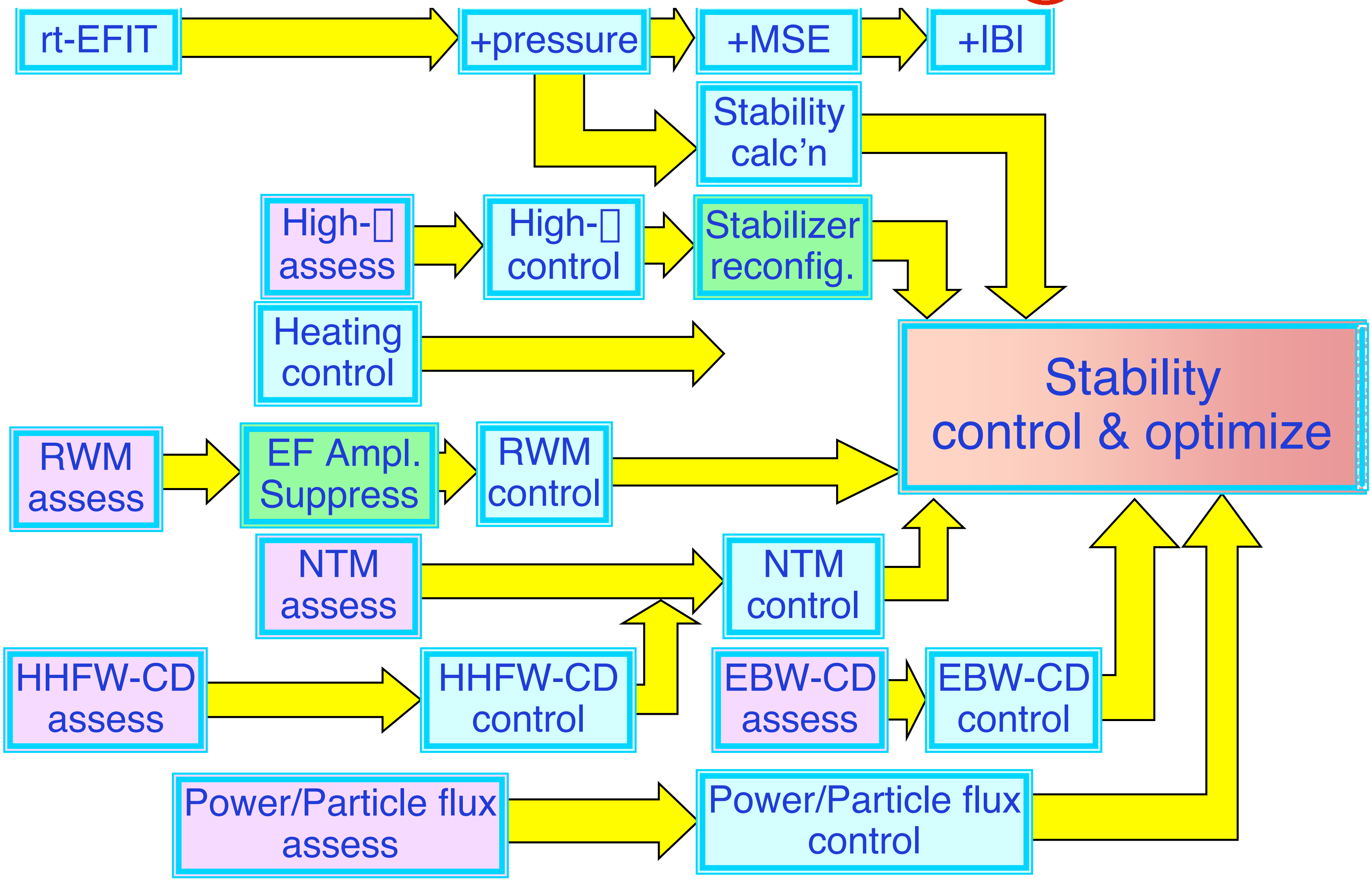


TSC Simulation, C. Kessel, et al.,

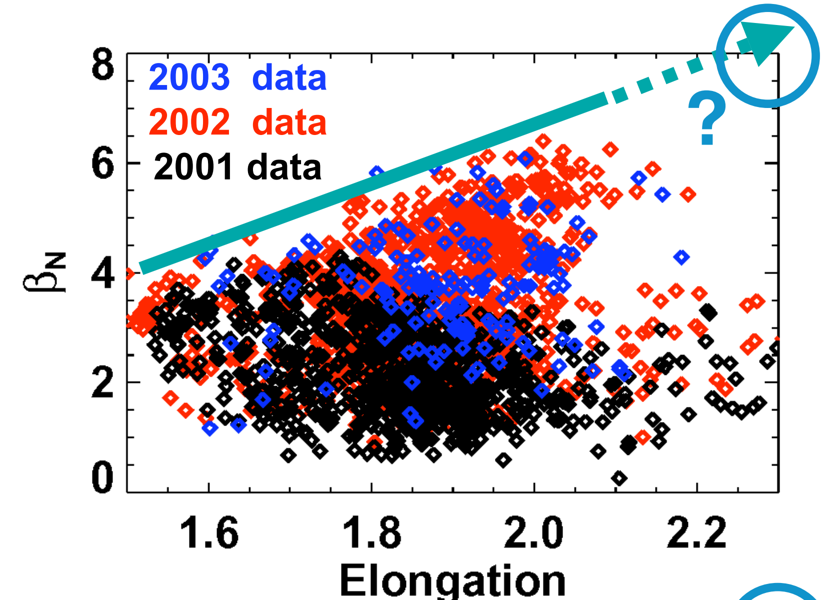
40% β_T , I_{NI} = 100%, $\tau_{pulse} >> \tau_{skin}$

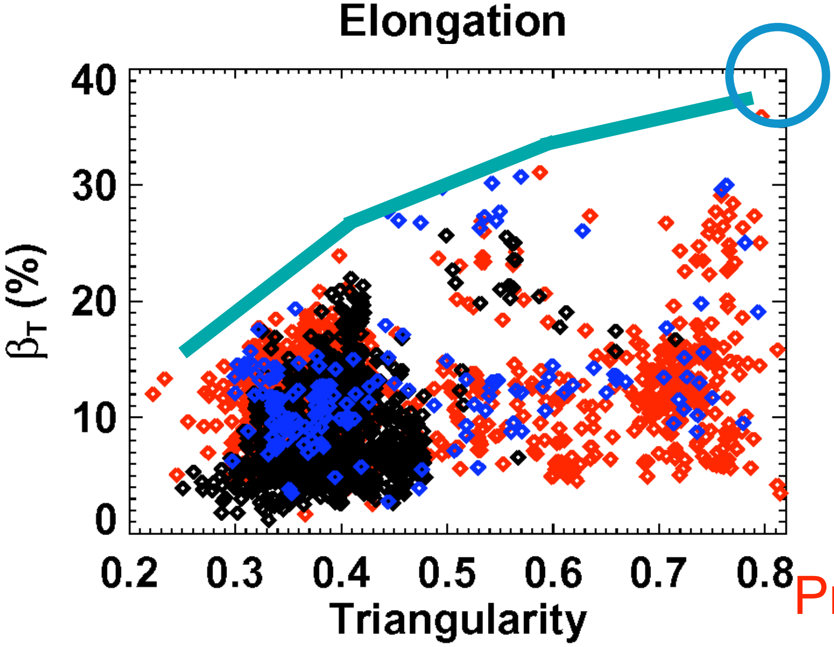
- *Enhanced shaping* improves ballooning stability
- Near with-wall limit => likely that mode control + rotation are key
- Particle control required to maintain moderate n_e for CD
- EBW provides off-axis CD to keep q ~ 2 & stabilize NTMs
- NBI CD, bootstrap current significant part of the total
- HHFW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

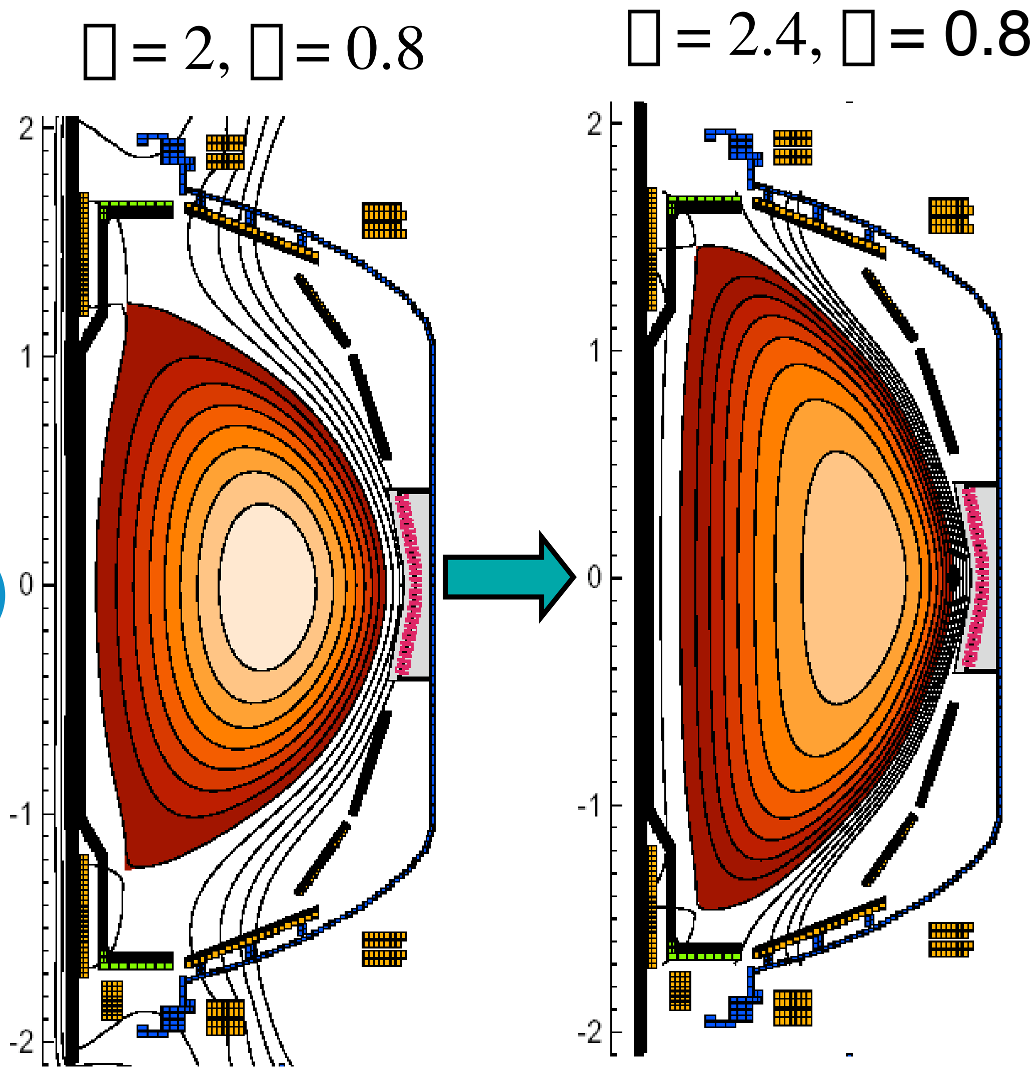
Steady-State Operation Requires Integration & Control Built on Diagnostics and Actuators



Stability theory and data motivate shaping enhancements

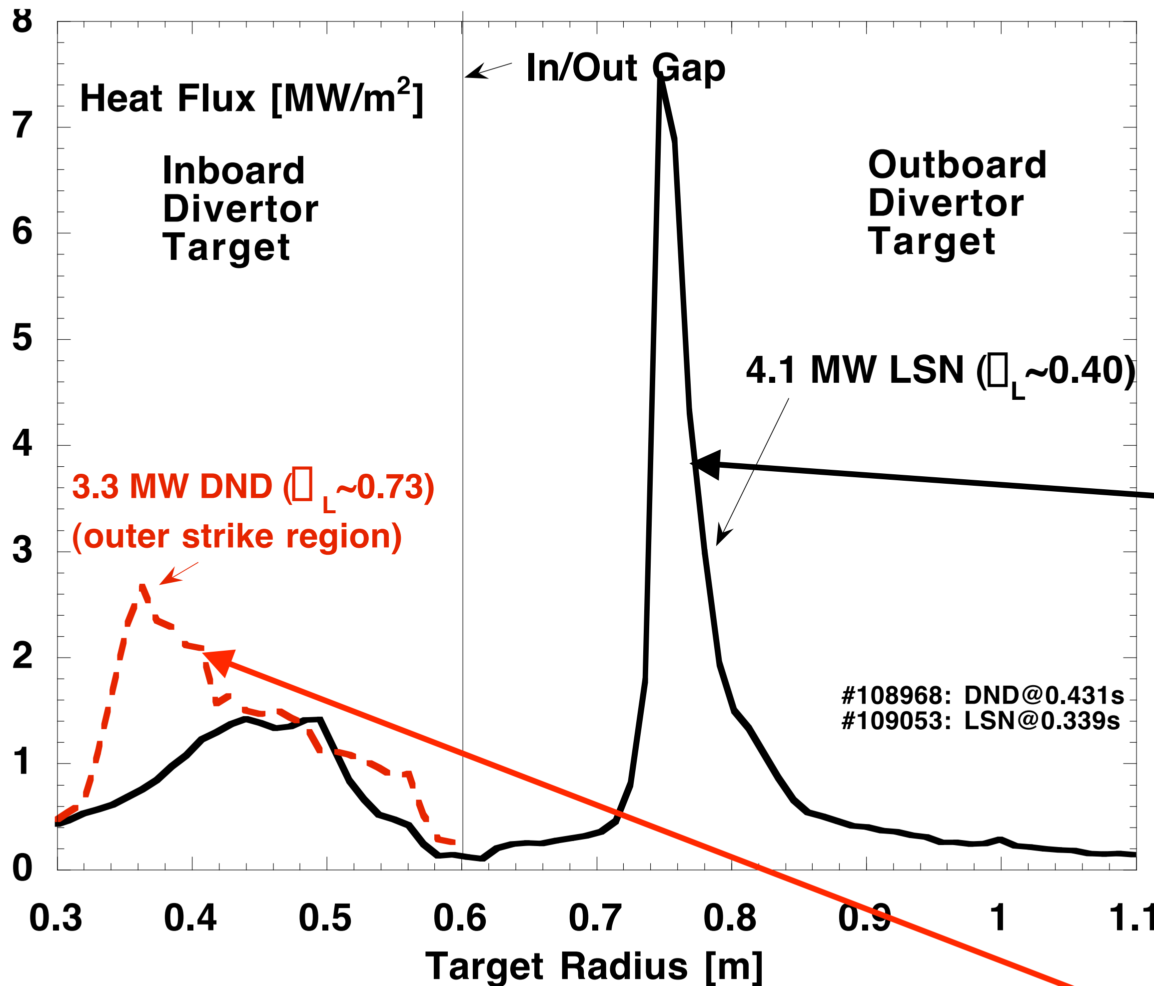


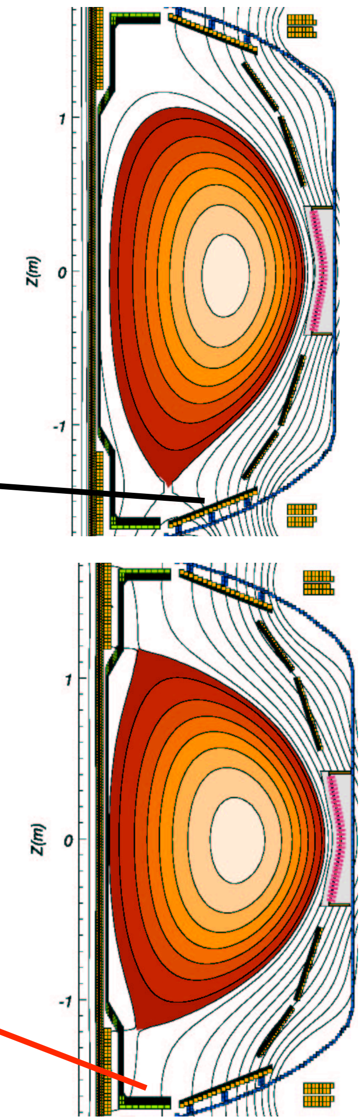




Proposed path to β_T=40%, β_N=8 (100% j_{NI})

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





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

Divertor Cryo-Pump Can Provide Needed Density Control

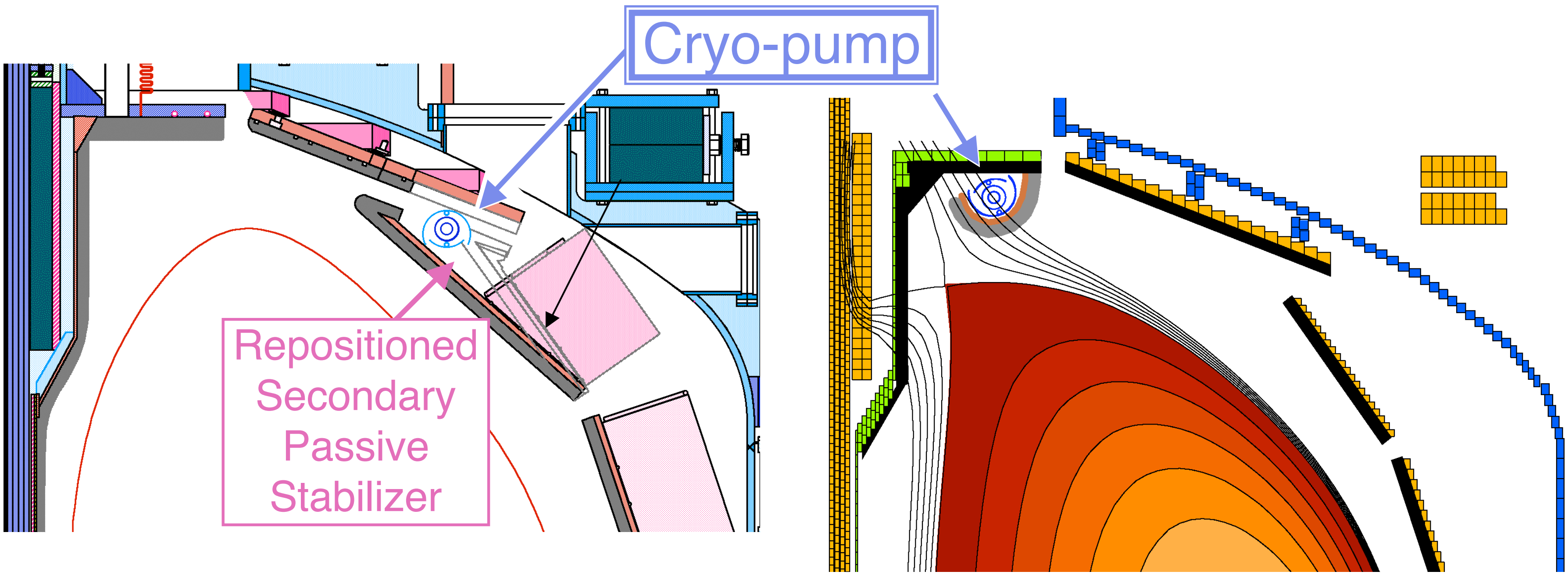
NSTX

1. Behind secondary plates

- Suitable for □≤ 0.5
- Requires plate relocation

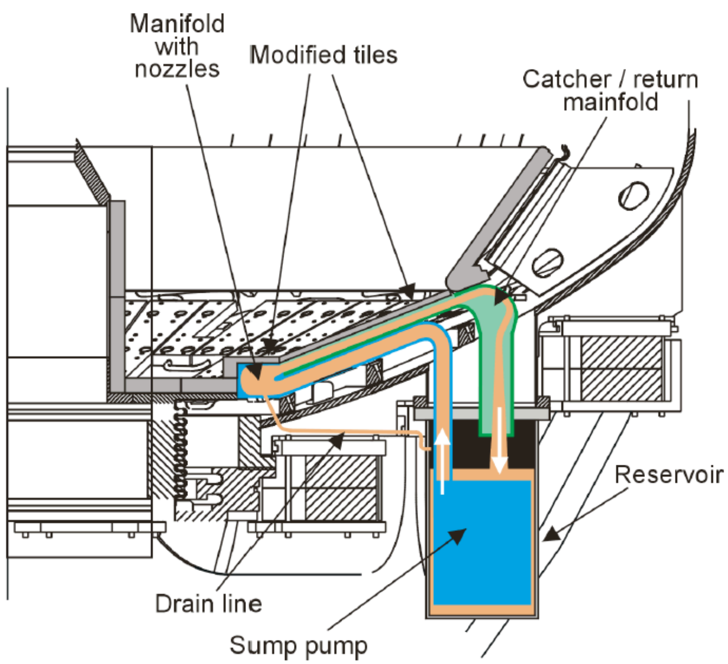
2. Shield on inner divertor

- Suitable for □~ 0.8
- Installation on center stack
- Relatively inexpensive



Liquid Lithium Surface Module Will Address Important Reactor Issues

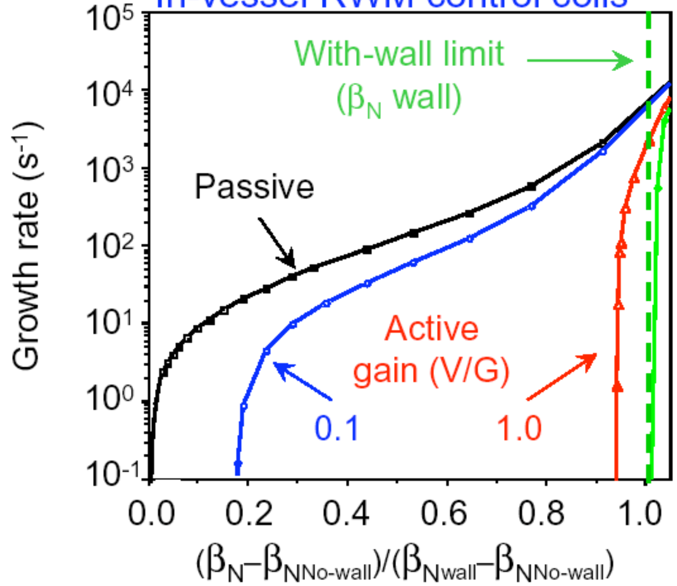
- Development under aegis of ALIST group of VLT
- A potential solution for *both* power and particle handling
  - Tantalizing possibilities for advanced regimes
  - Liquid Li tray in CDX-U dramatically reduced recycling

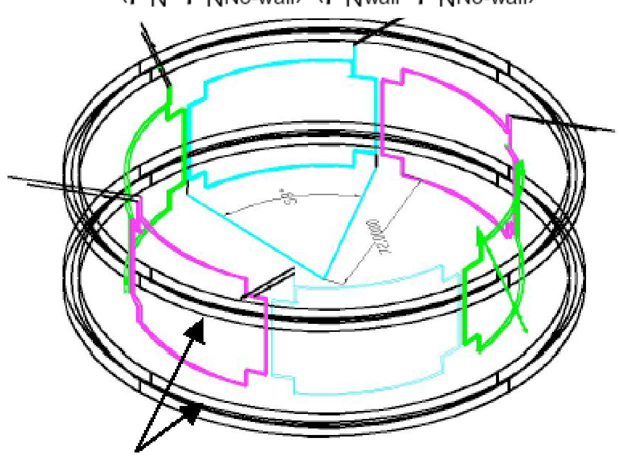


- Modules ~1m^2 close to plasma
- Flow liquid Li at 7 – 12 m/s to avoid evaporation at full power
- Installation in FY'08

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

In-vessel RWM control coils

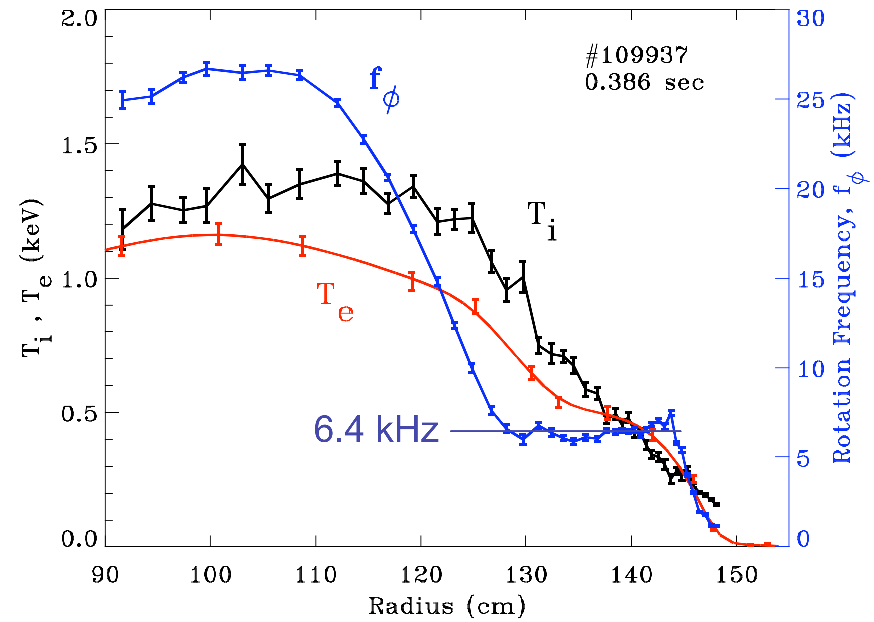


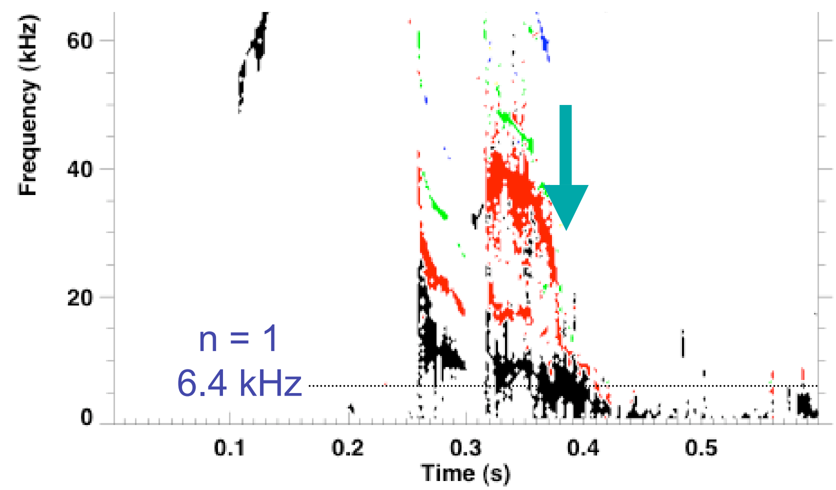


PF5 coils (main vertical field)

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

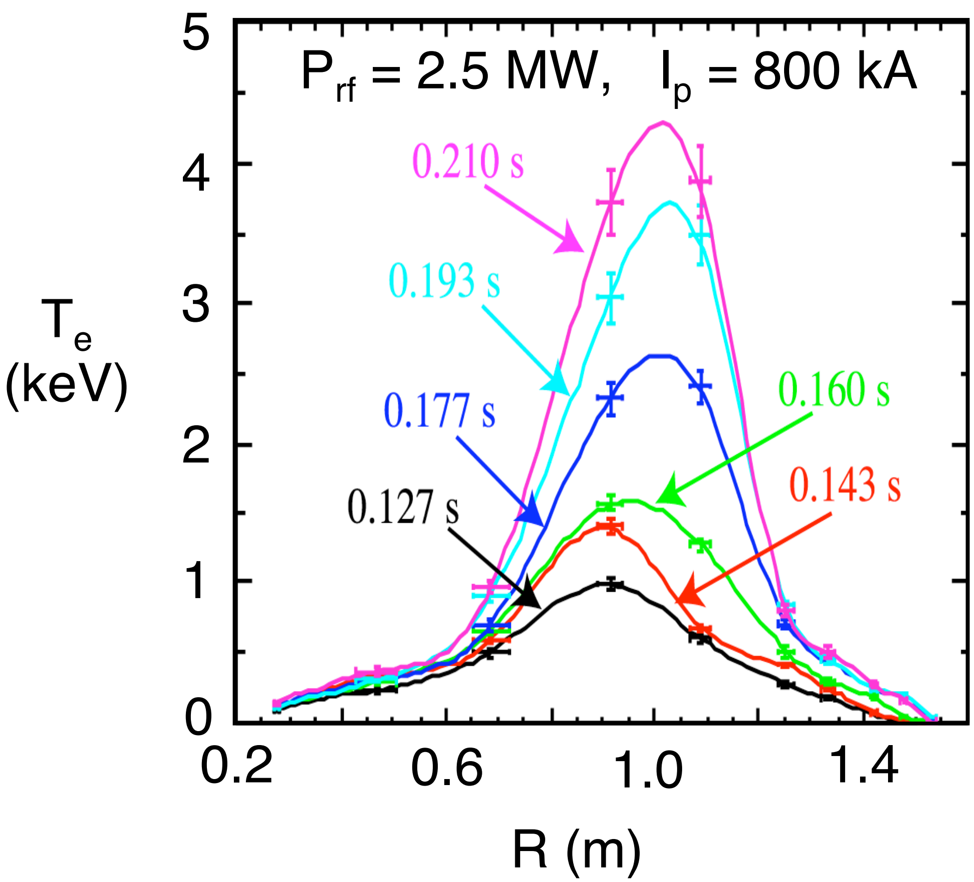
Detailed kinetic diagnostics are now available





Some HHFW-Heated Discharges Exhibit Internal Transport Barrier Behavior

NSTX

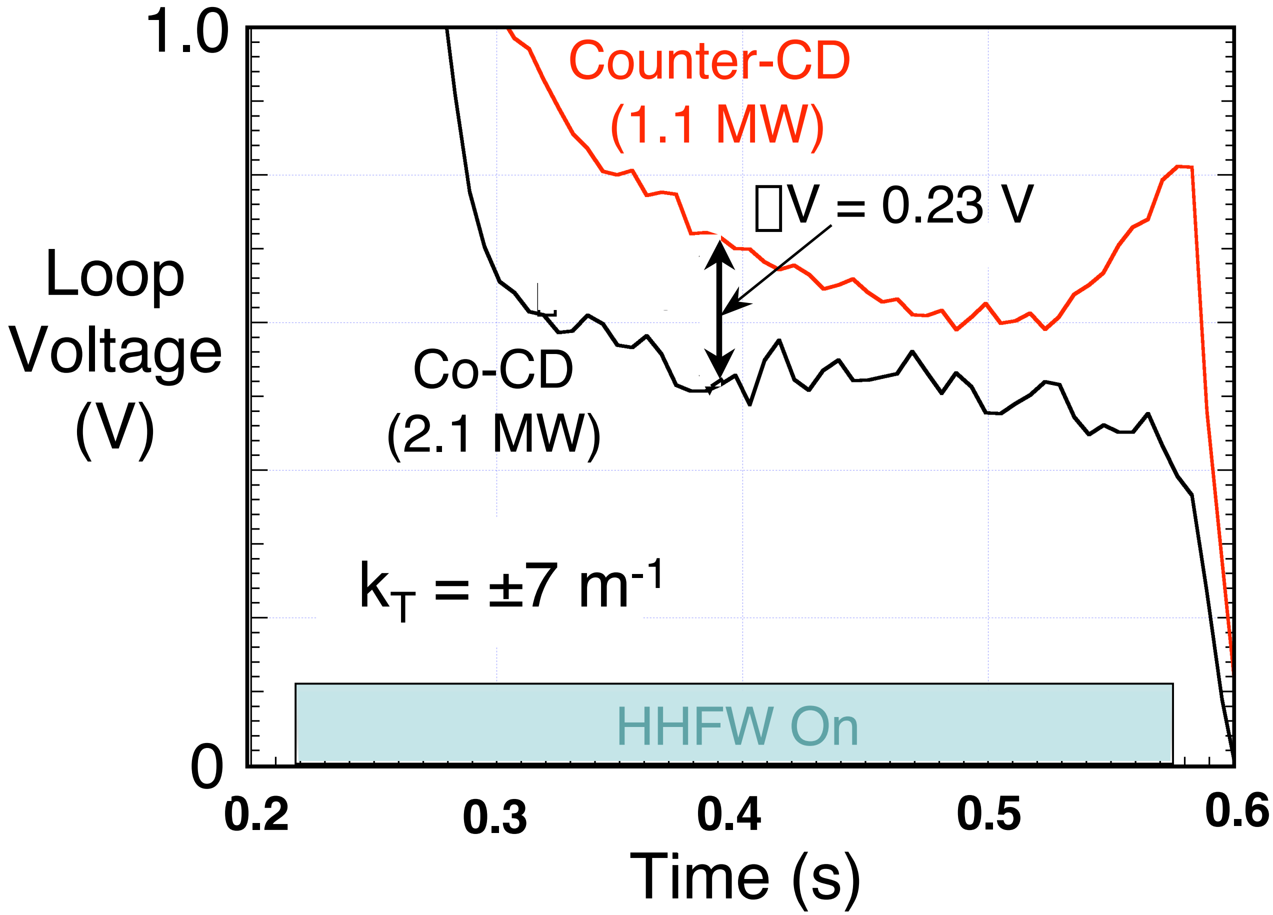


- T_e increases strongly inside half radius
- Density profile doesn't show change
- $T_i(0)$ rises with $T_e(0)$
- χ_e progressively decreases with time in the central region
- $\nabla T_e(r) \rightarrow j_{bt} \rightarrow$ Rev. shear $\rightarrow$ T_e ITB generated

If electron ITB location can be controlled, it will greatly enhance our ability to sustain advanced plasmas.

Less Loop Voltage to Maintain I_P With Co Phasing; Magnetics Analysis Estimates I_{cd} = 110 kA (0.05 A/W)

NSTX

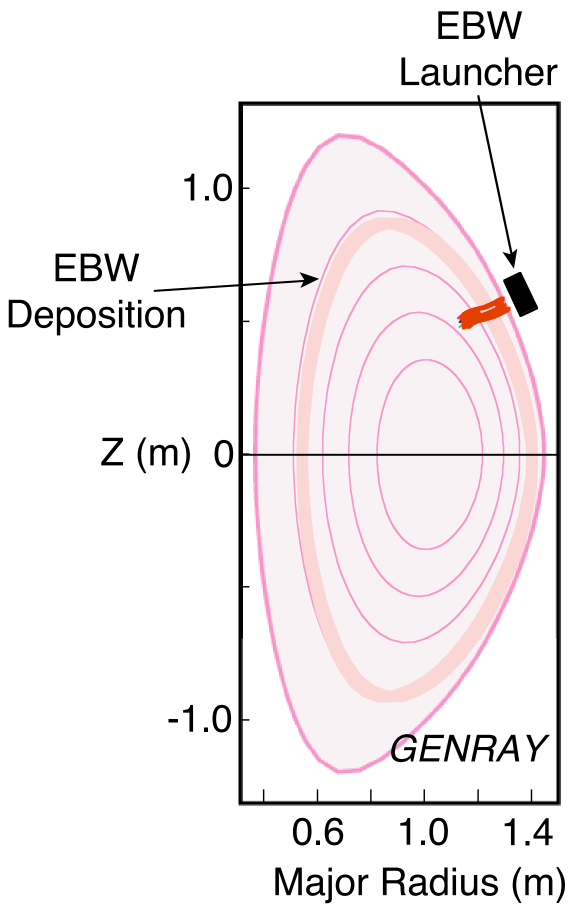


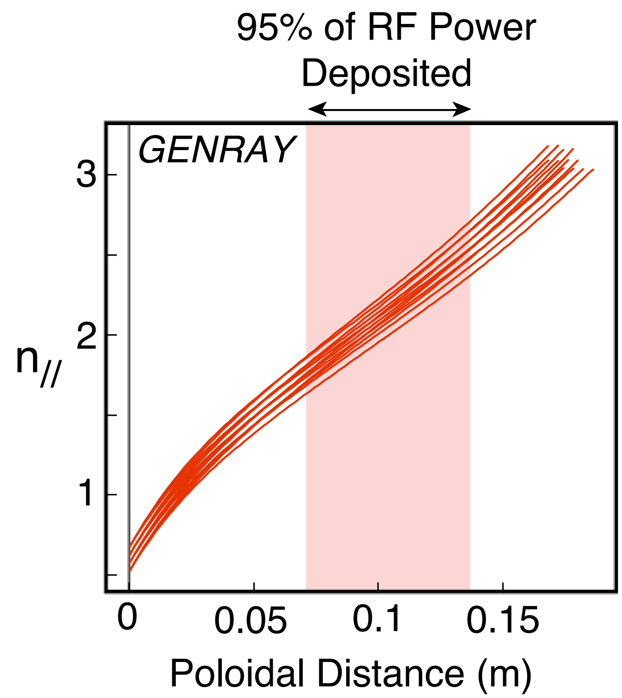
- Plasmas matched for central T_e
- Higher heating efficiency for Counter-CD found
- q(r) dependence on $□_e$?
- q(r) diagnostics being implemented

- TORIC I_{cd} = 95 kA (0.05 A/W)
- CURRAY I_{cd} = 162 kA (0.08 A/W)

Placing EBW Launcher Well Above or Below Midplane Produces Large $n_{//}$ Shifts Needed for Efficient EBWCD

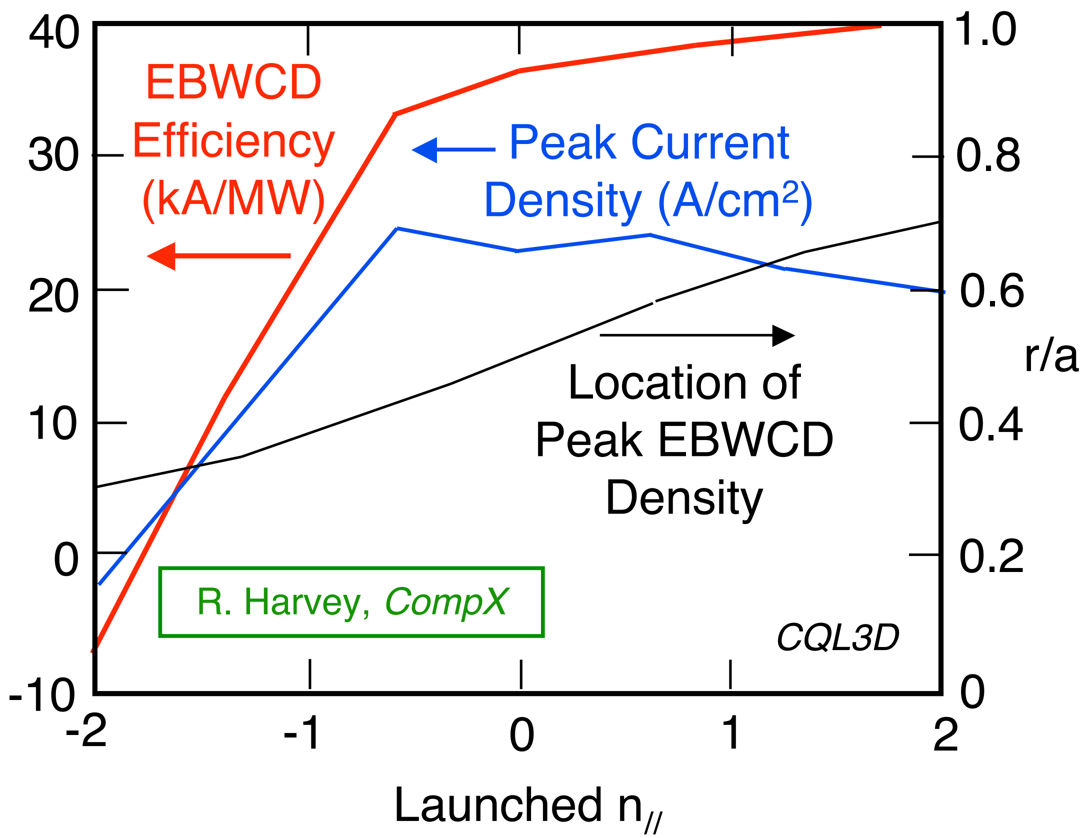
NSTX





15 GHz RF launched at 65^o above mid-plane, with $0.5 < n_{//} < 0.7$ into β = 30% NSTX equilibrium

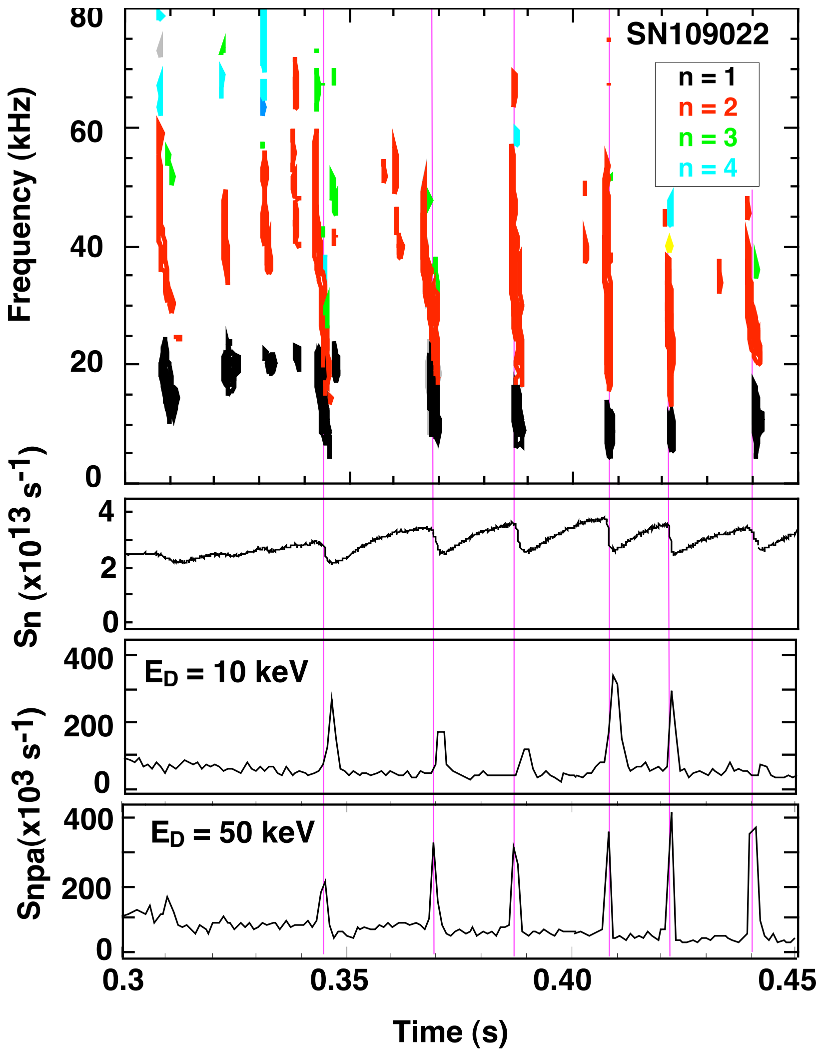
EBWCD could provide efficient off-axis current drive through "Ohkawa" CD



1 MW of 15 GHz RF launched at 65º above mid-plane, into □ = 30% NSTX equilibrium

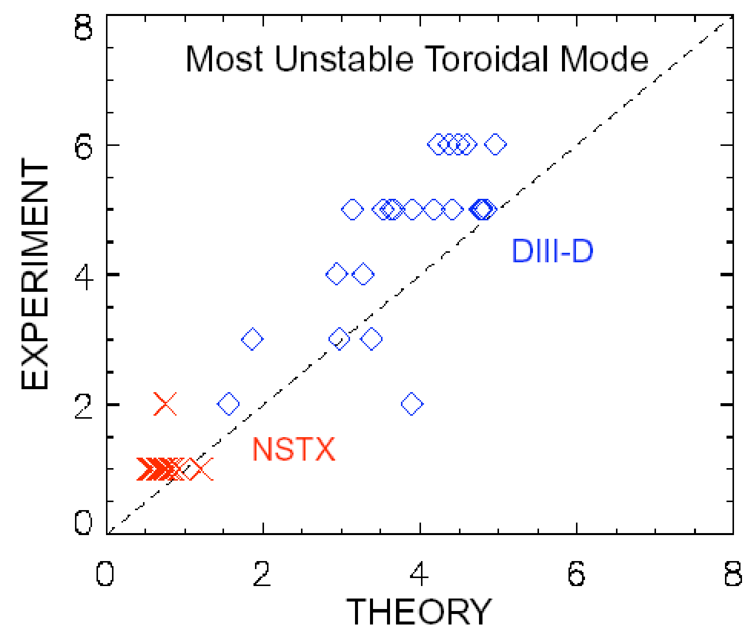
- EBW heats barely passing electrons into trapped region resulting in "CD".
- Plan ~ 4 MW at RF source power to get > 100 kA ; efficiency increases with r/a
- Normalized CD efficiency, $\square_{ec}$ = 0.4, compares favorably to ECCD

Energetic Particles
NSTX Accesses $v_{Fast} > v_{Alfvén}$ Physics



- *n* > 1 modes interpreted to be TAE
  - *n* = 1 as “bounce” fishbones
- Transport of core fast ions by *n*=2 mode
  - Fast ions then destabilize *n*=1, ions lost

NSTX/DIII-D Similarity Experiment Finds TAE Mode Number Scales as Expected



NSTX's contribution to ITPA steady-state and energetic particles

Spherical Torus

- NSTX facility is a good test bed for steady-state advanced operations
  - High heating and CD power systems (11 MW at ~ 1 m)
  - Wide physics parameters accessible
  - Modern control and diagnostic systems
- High performance plasma was sustained for □-pulse > □-skin
  - $□□_p \sim 1$, I_{NI} Fraction = 60%
  - $□_N$ = 5.8 > no-wall stability limit
  - $□_N$ H_{89p} ~ 15 at $□_T$ = 15% sustained over □-skin, constant
- Integrated scenario modeling shows a promise for □-pulse >> □-skin operation
  - TSC simulation together with other specialized codes used with NSTX data
- Tools are being implemented and planned to support advanced operations
  - Inner poloidal field modification to allow high □ and □ operations
  - Divertor pumps to control heat and particles
  - RWM coils to control MHDs
  - 4 MW EBW to control j(r) and NTMs
- NSTX is also exploring relevant energetic particle regime of $\mathbf{v}_{Fast} > \mathbf{v}_{Alfvén}$
  - Various modes (fishbone, TAE, CAE, etc.) identified