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Integrated Scenario Modeling

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For the NSTX National Team

DOE Review of
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NSTX Integrated Scenario Modeling

- Integration of **plasma models** to simulate the **self-consistent** plasma behavior in a **full discharge**, allowing a wide range of conditions to be studied

- Integrated Scenario Modeling is used to
  - Reproduce/interpret experimental discharge behavior
  - Extrapolate new experiments based on existing discharges
  - Extrapolate new experiments using theory-based predictive capability
  - Establish predictive capability to extrapolate to new devices, such as NSST (Next Step ST) and CTF (Component Test Facility)

Integrated Scenario Modeling is Focused on NSTX Advanced ST Milestones

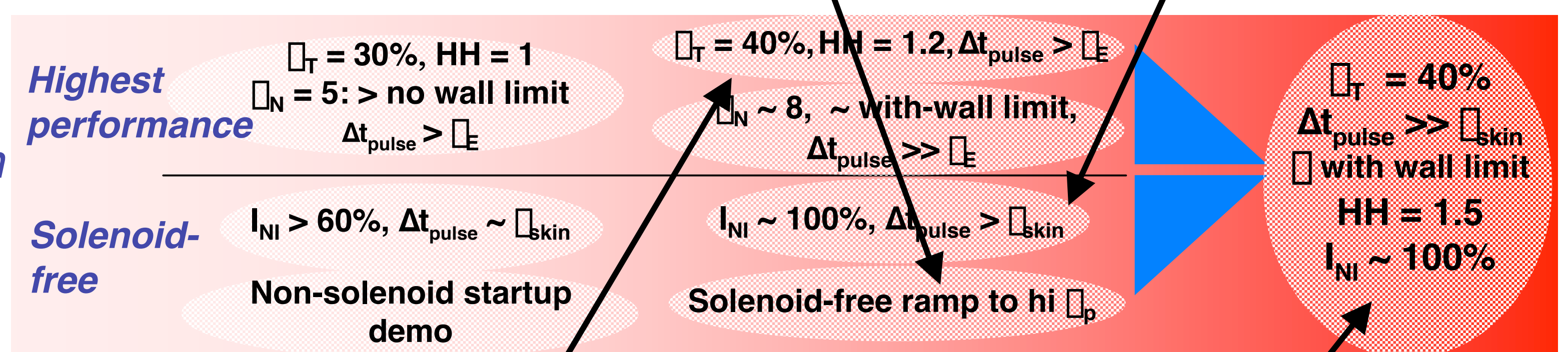
NSTX

I. Non-inductively Sustained for $\square_{flattop} > \square_J$

Study Range of Current Drive Techniques

II. Non-solenoidal Current Rampup

Provide Basis for Future ST Devices



III. High $\square$ and $\square_N$ Operating Targets for $\square_{flattop} > \square_E$

Study Stability, Transport and Edge Physics at High $\square$

IV. Non-inductively Sustained, High $\square$ for $\square_{flattop} >> \square_J$

Study and Demonstrate Integrated Advanced ST Plasmas

Scenario Modeling Identifies the Tools Required for NSTX Advanced ST Operation

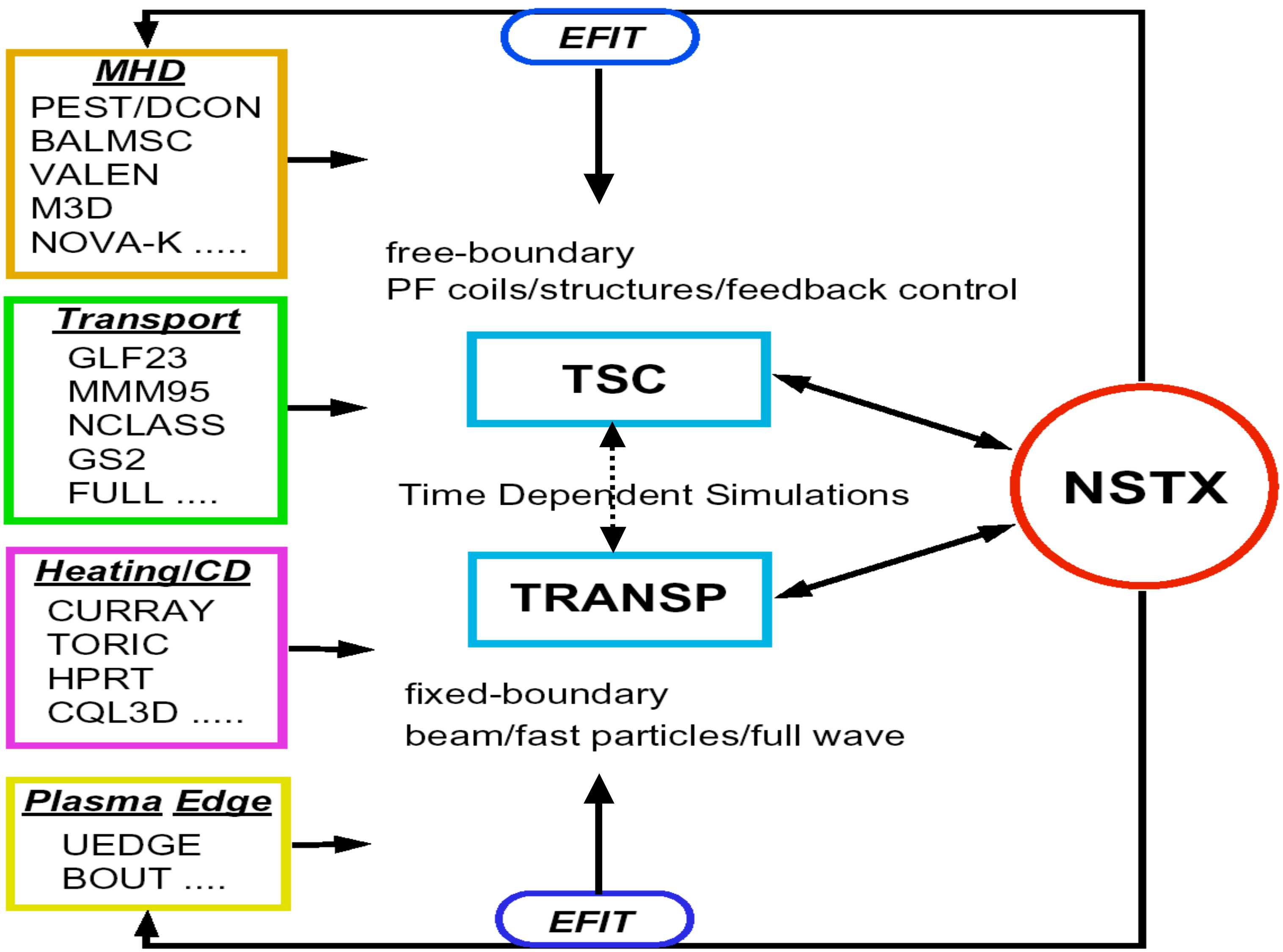
- **HHFW** heating and current drive to provide **non-inductive current** sustainment and **non-solenoidal current rampup** in non-NBI scenarios, and **flexible heating** in with-NBI scenarios.

- **Density control** through **pumping or lithium** is critical for NB and RF current drive. Accessing **density profile control** through pellet or CT injection **improves bootstrap** current fractions.

- **Electron Bernstein Waves** to provide critical **off-axis current profile** control for MHD stability and **NTM control**

- **Modification of PF1** coil allows simultaneous high elongation and high triangularity improving MHD stability.

Flow of Physics Analysis Supporting ISM for NSTX



The Modeling Begins From Experimental Data

Shot 109070 was chosen as a good prototype for longer pulse NBI scenarios (with $t_{flattop}$ = 300 ms, Ip = 800 kA, B_T = 0.5 T) since **flattop > 1 $\square_{skin}$ for Ip and □**

t = 450 ms	I_{NB} = 160 kA
Ip = 800 kA	I_{BS} = 240 kA
Bt = 0.5 T	$I_{\square P}$ = 50 kA
R = 0.88 m	P_{NBI} = 6.2 MW (5+ absorbed)
a = 0.59 m	$T_i(0)$ = 1.75 keV
□ = 2.06	$T_e(0)$ = 1.15 keV
$\square_{ave}$ = 0.45	n(0) = $5.0\square10^{19}$ /m^3
n(0)/<n> = 1.05	$\square_N$ = 5.9, H_{98} = 1.2

Shot 105830 was chosen as a good prototype for HHFW scenarios since it obtained **high electron temperatures** due to an internal transport barrier **(ITB)** and **T_i/T_e < 1**, Ip = 800 kA, B_T = 0.45 T, P_{HHFW} = 2.5 MW

Non-solenoidal current rampup produces plasmas with **no nearby experimental analog**

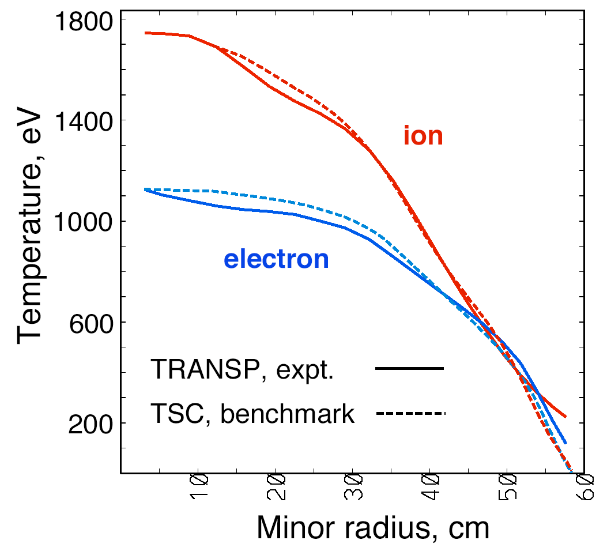
Assumptions Used in Tokamak Simulation Code (TSC)

Benchmark performed on 109070 with TSC

Density profile is fixed, magnitude prescribed versus time

Thermal diffusivities spatially fixed (TRANSP), scaled by IPB98(y,2) global scaling

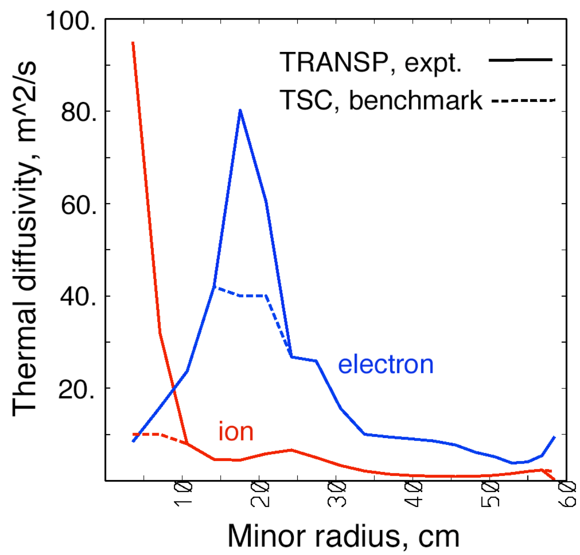
NBI characteristics (W_{beam}, n_{fast}, $H_{NB}(r)$) fixed to 109070, scaled by power

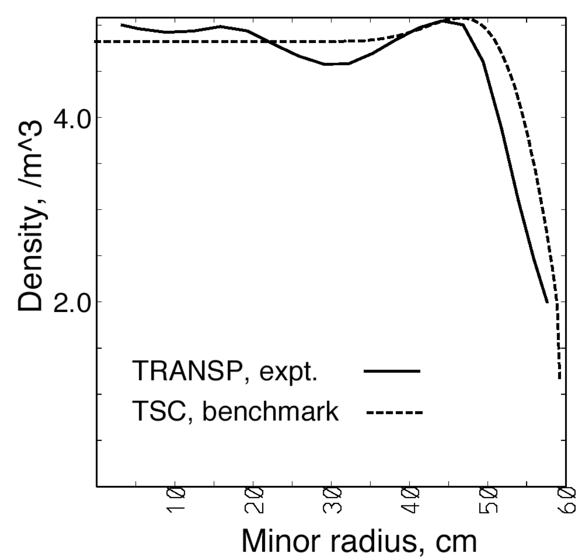


Z_{eff} magnitude and profile fixed to 109070

NBCD benchmarked against TRANSP

HHFW CD from CURRAY





I. Non-inductively Sustained Scenario

Study Range of CD Techniques

- Raise the plasma stored energy
  - Injected 6 MW of HHFW in addition to 4 MW of NBI
  - Injected 6 MW of HHFW and 3 MW of EBW (off-axis)

- Increased plasma elongation (from PF1 mod) and operate at high B_T to raise q_{cyl}
  - q_{cyl} scales as $Bt(1+\kappa^2)$ and f_{bs} q_{cyl}

- Reduced the plasma density
  - Improve CD efficiency of NB, HHFW, and EBW

- Increased density profile peaking
  - n(0)/<n> = 1.1 for NBI + HHFW from lithium pellets or pumping

HHFW CD is strongly reduced by NB fast ions and thermal ion absorption

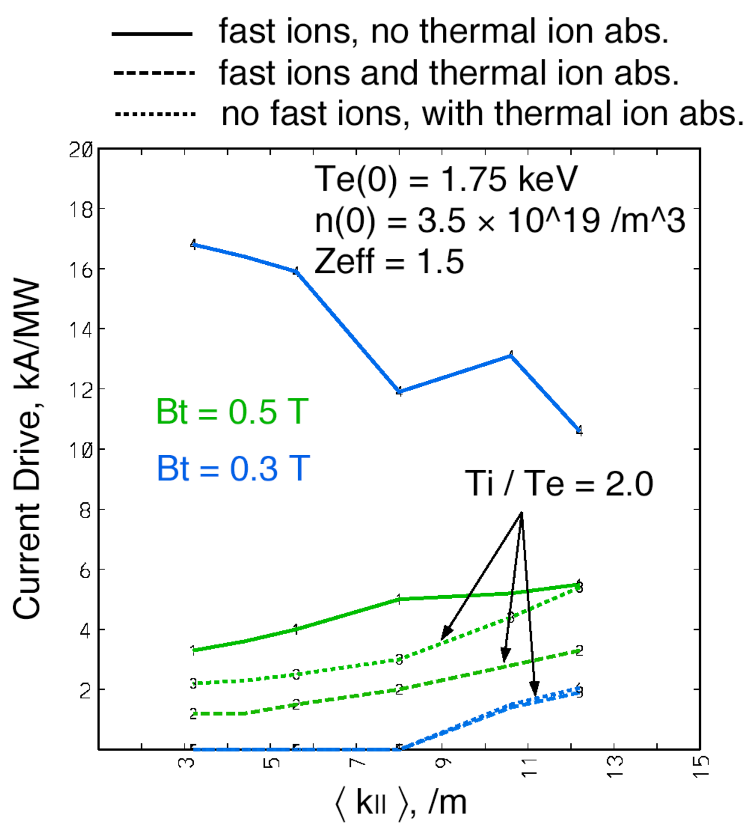
NBI + HHFW can access non-inductive operation for 2 τ_J, and is stable to high-n ballooning* and n=1 kink with wall at 1.5 a

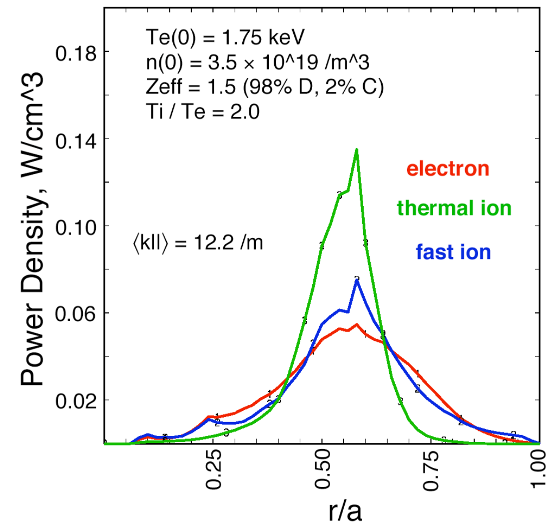
HHFW + EBW (ITB) can access non-inductive operation at high T_e for 1 τ_J

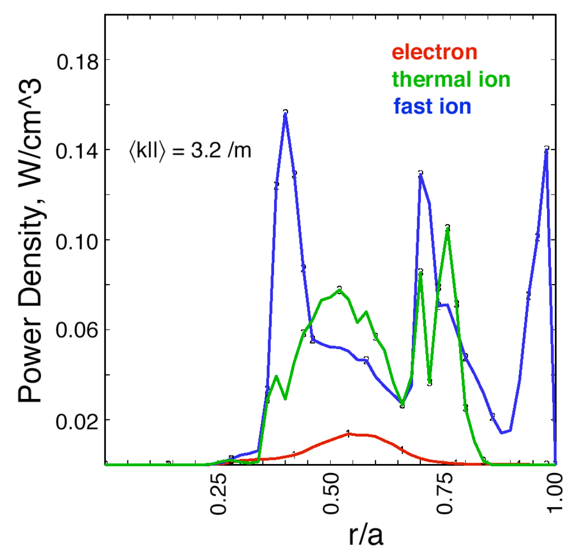
Higher β is critical for higher bootstrap current fractions

CURRAY Indicates Strong Suppression of HHFW CD from NB Fast Ions and for $T_i/T_e>1$

$\langle k_{\parallel} \rangle$ = 5.6 /m	P_e	P_i	P_f
Fast, no therm.	0.16	0.00	0.84
Fast + therm.	0.10	0.44	0.46
No fast, therm	0.15	0.85	0.00







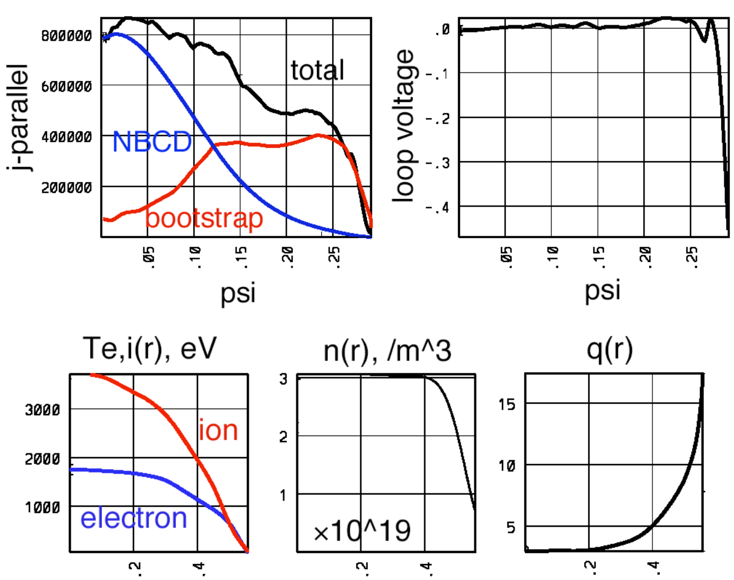
Non-inductively Sustained
NBI Heating and CD + HHFW Heating

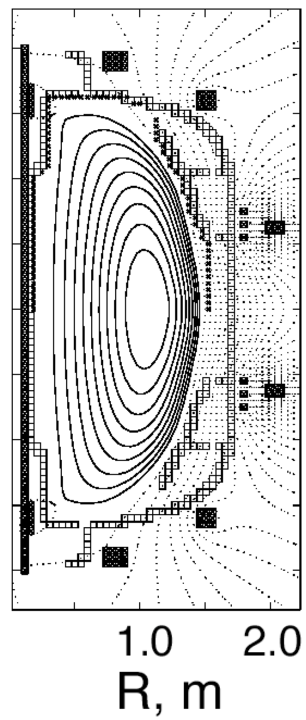
NSTX

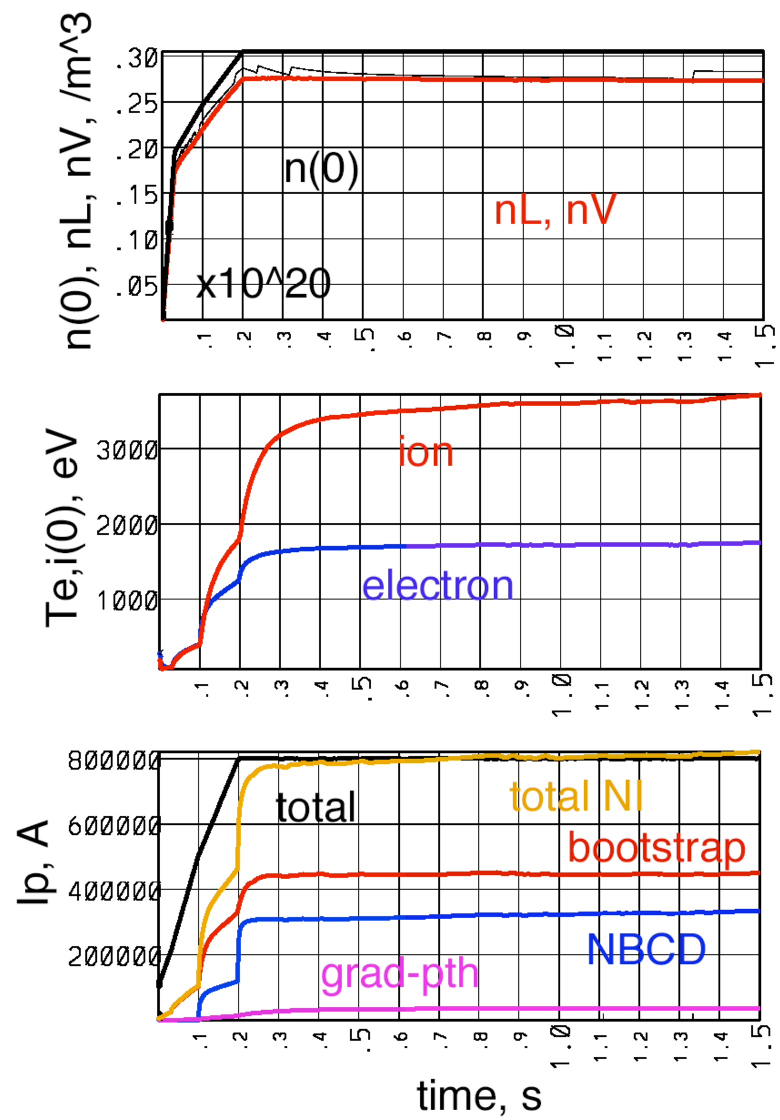
I_p = 800 kA, B_t = 0.5 T
I_{BS} =450 kA, I_{NB} = 335 kA
I_{HHFW} = 0 kA
□= 2.7, □ = 0.9

P_{NBI} = 4 MW, P_{HHFW} = 6 MW
$□_{109070}$, H-mode scaling

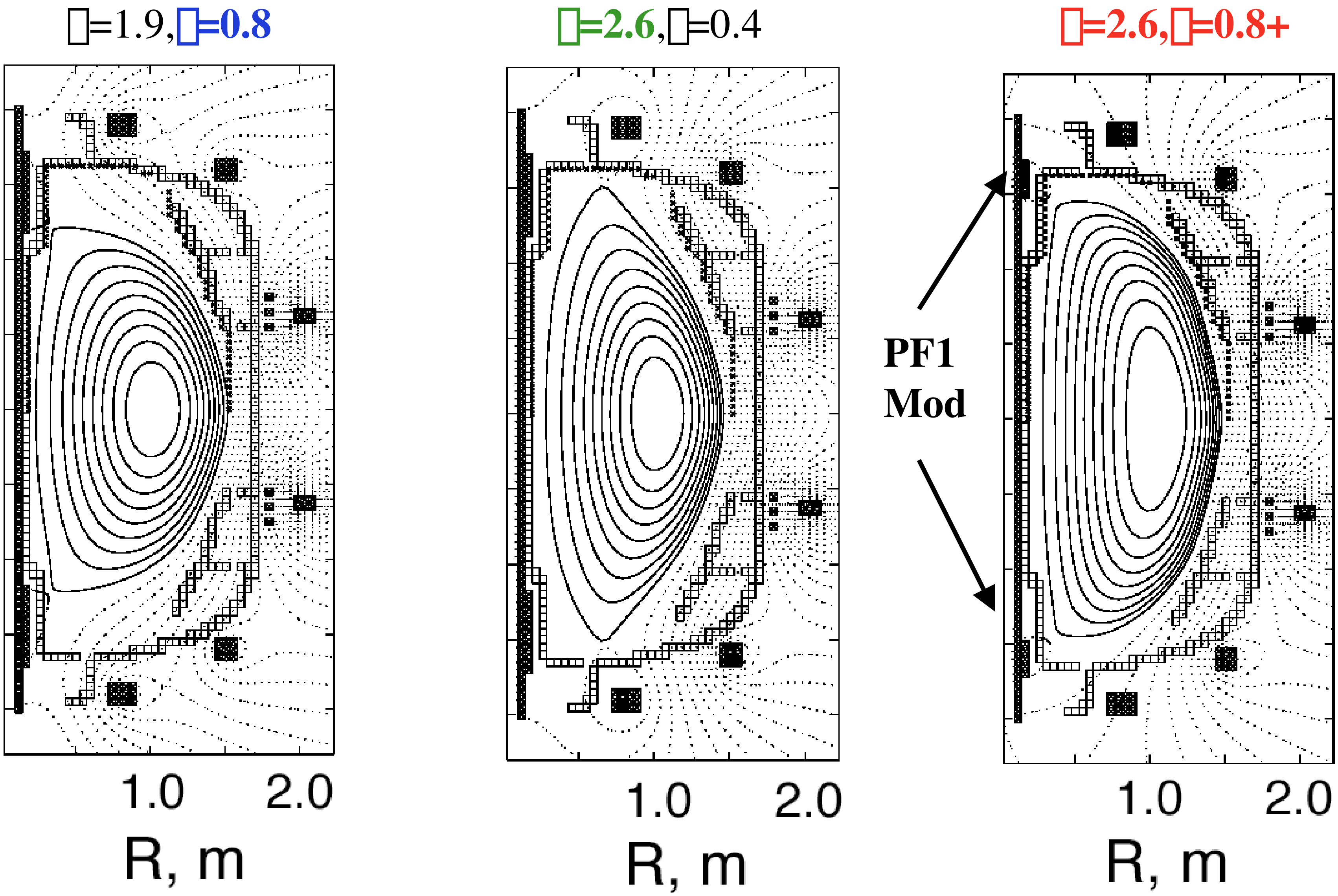
$□_N$ = 6.0
□ = 17.6%
$□_E$ = 27 ms
H_{98}=1.45
q_{cyl} = 4.0
li(1) = 0.5





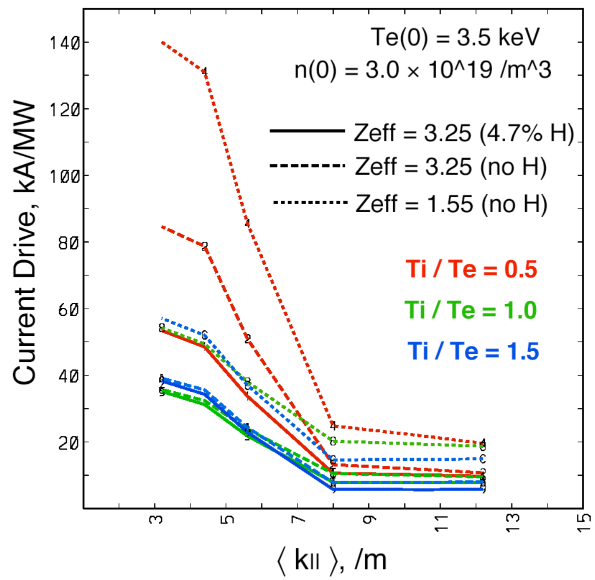


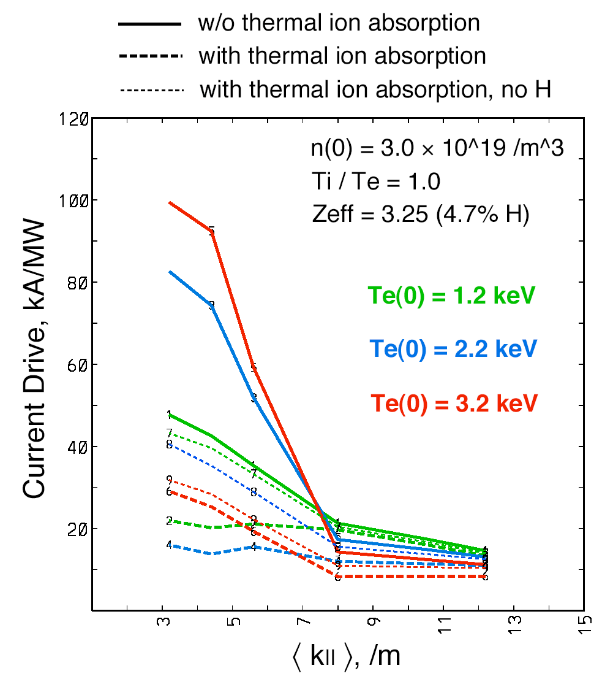
PF1 Coil Modification Leads to Simultaneous High Elongation and High Triangularity

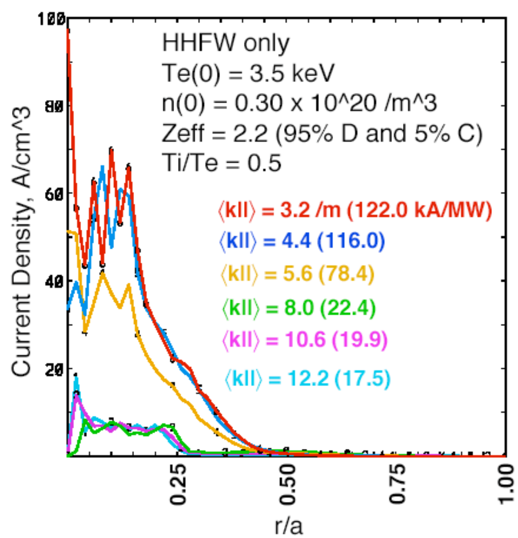


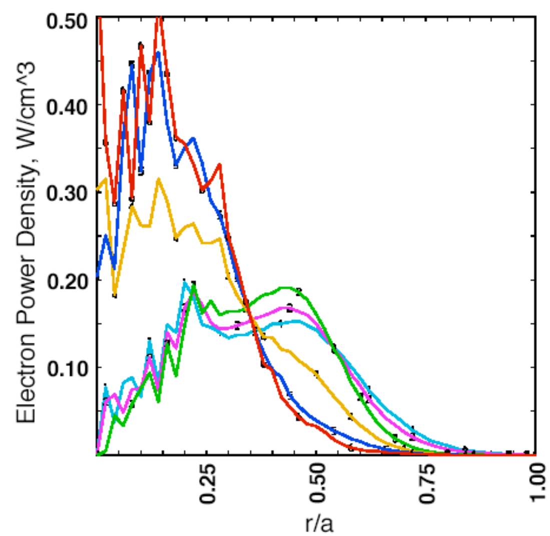
CURRAY Indicates High CD Efficiencies for HHFW with Low $k_{||}$ Spectra with $T_i/T_e < 1$

Thermal ion damping is found to be signficiant for $T_i/T_e \geq 1$, examining this in more detail

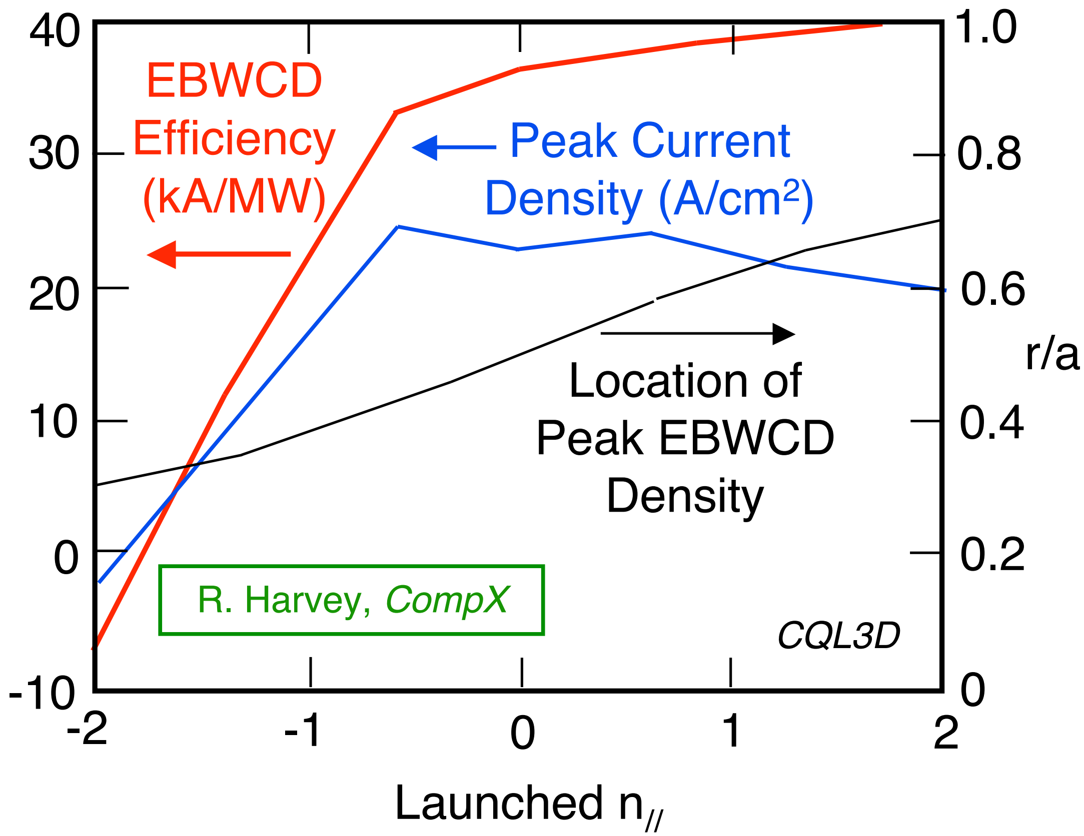






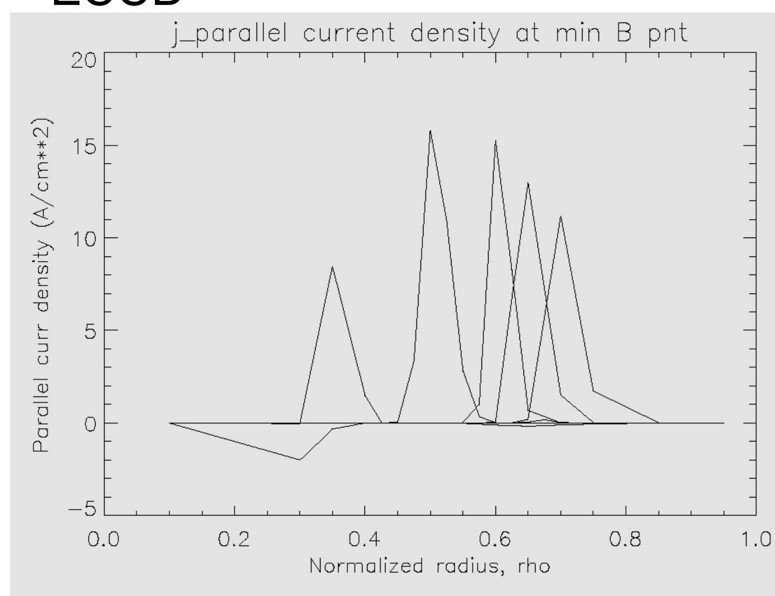


Radial Location of EBW CD is Highly Localized and Can be Varied by Changing Launched $n_{//}$



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

- Positive current results from Okhawa CD
- Plan ~ 4 MW at RF source power to get > 100 kA efficiency increases with r/a
- Normalized CD efficiency, η_{ec} = 0.4, compares favorably to ECCD

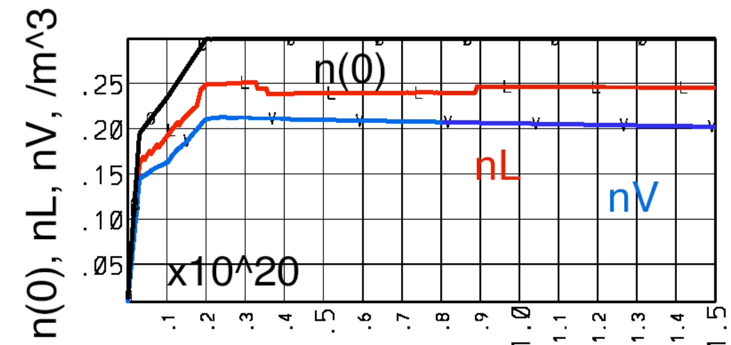


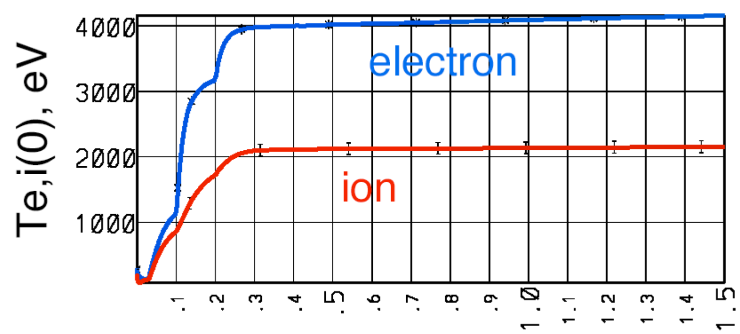
Non-inductively Sustained
HHFW Heating and CD + EBW (with ITB)

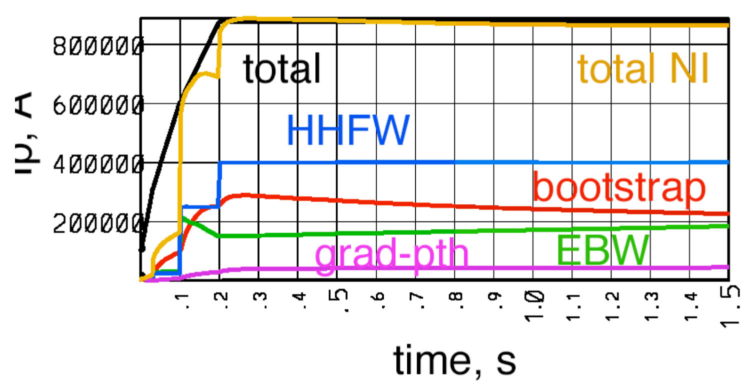
Not high-n or n=1 stable

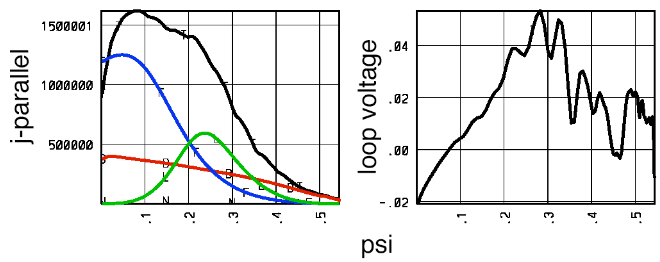
Ip = 875 kA, Bt = 0.5 T
I_{BS} = 260 kA, I_{HHFW} = 400 kA
I_{EBW} = 175 kA
κ = 2.15, δ = 0.4
P_{HHFW} = 6 MW, P_{EBW} = 3 MW
$□_{105830}$, L-mode scaling

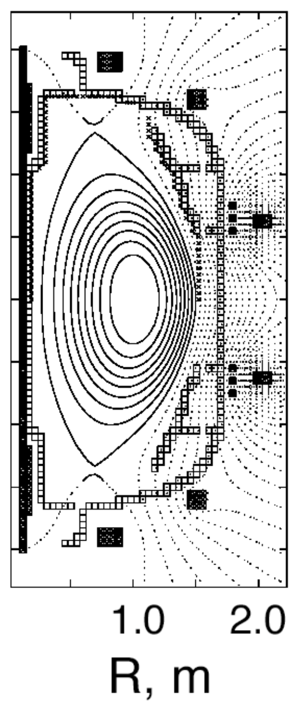
β_N = 3.4
β = 14.5%
τ_E = 17.5 ms
H_{98} = 1.05
q_{cyl} = 3.8
li(1) = 1.0



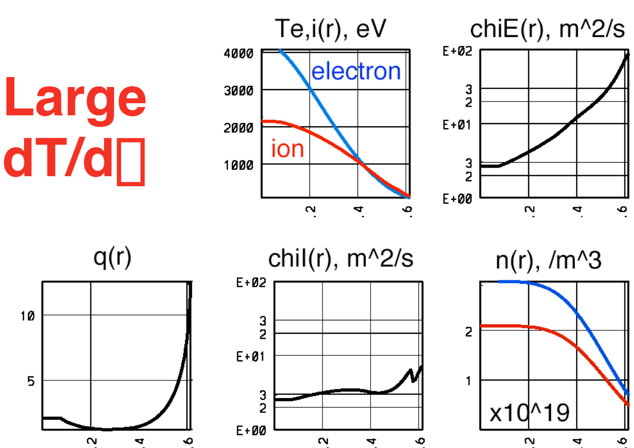








Large dT/d□



II. Non-solenoidal Current Rampup

Provide Basis for Future ST Devices

- Plasma starts conservatively with 100 kA of current
  - Produced by either CHI or PF coil startup
- No current holes are allowed limiting the rampup speed
- HHFW heating and current drive applied in low Ip, low density phase, NBI applied in higher Ip, higher density phase
  - Current is driven by HHFW and bootstrap, then NBI and bootstrap (HHFW CD reduced in this phase)
- Higher elongation and B_T is chosen to raise q_{cyl} to keep bootstrap current high
- PF coils assist the current rampup while they provide equilibrium field

How will current holes affect these scenarios?

Extreme plasmas are generated with high β_P and very low li leading to strong shaping changes

On-axis RFCD improves these scenario's controllability

Non-solenoidal Current Rampup
HHFW CD + BS -----> NBCD + BS

t = 2.0 s

Ip = 415 kA, Bt = 0.45 T

I_{BS} = 311 kA, I_{NB} = 110 kA

I_{HHFW} = 70 kA

□= 2.85, □= 0.45

q_{cyl} = 6.5, li(1) = 0.6

P_{NBI} = 6 MW (3 MW absorbed)

$□_e^{109070}$ = $□_i$, L-mode scaling

□= 10%

$□_N$ = 5.4

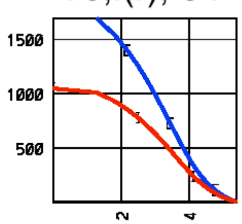
n/n_{Gr} = 0.75

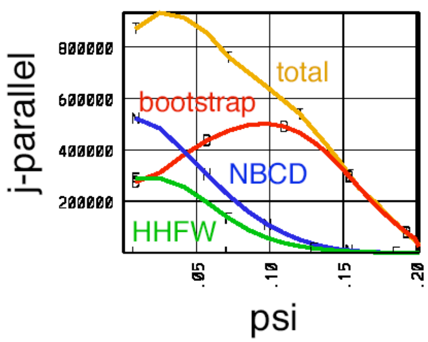
$□_E$ = 15 ms

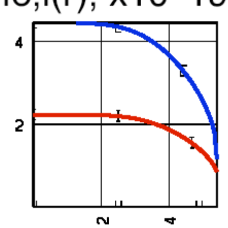
H_{98} = 1.03

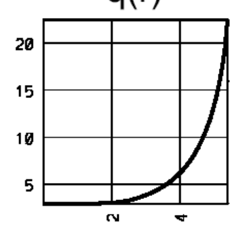
W = 120 kJ

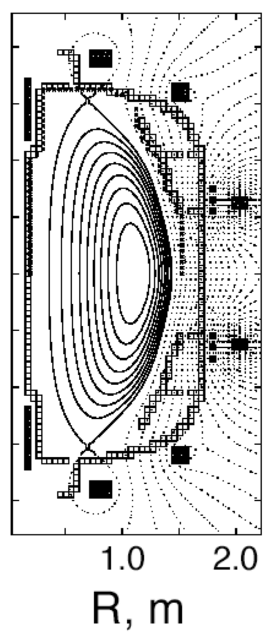
P_{HHFW} = 6 MW

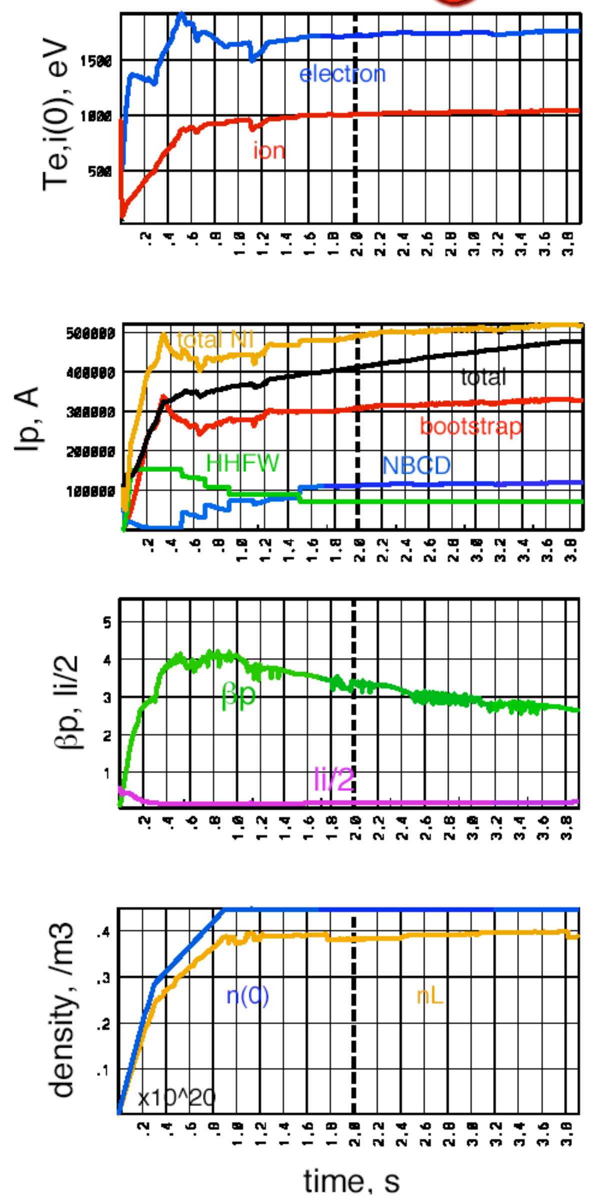












III. Maximum β and β_N Operating Targets

Study Stability, Transport and Edge Physics at High β

NSTX

- Inductive current drive with bootstrap and beam assist
- Access to varying current and pressure profiles through
  - Current ramp rate
  - Density ramp
  - Plasma growth and shaping
  - Heating scenario
- Inject 6 MW NBI (5 absorbed) and 6 MW HHFW
- Utilize simultaneous high elongation and high triangularity from PF1 modification

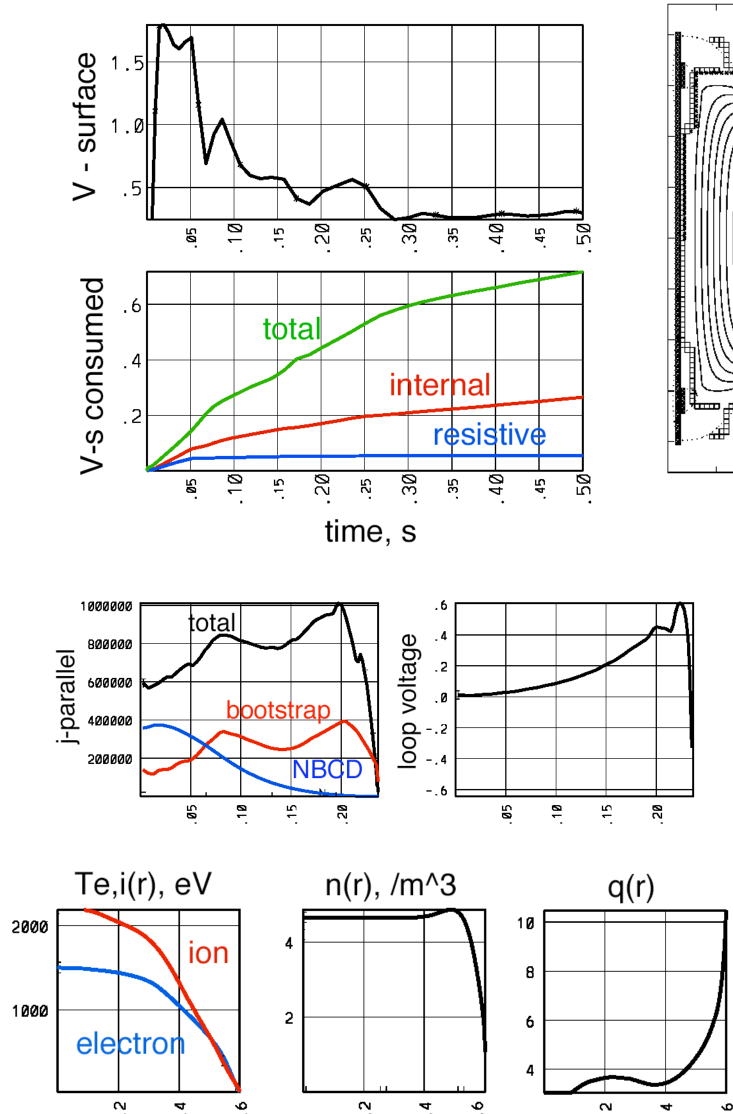
Free-boundary time-dependent simulations can help to optimize the Ip(t), n(t), P(t), and growth phasing

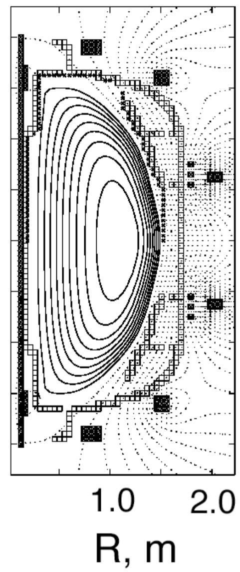
Reached a β = 46% with Ip = 1.15 MA and B_T = 0.36, stable to high-n ballooning* and n=1 kink with outboard wall at 1.5a

Important test of MHD stability theory, and insight into (p, j, q) profile combinations

*except in pedestal region

Maximum □ and □$_N$ Operating Targets
NB and HHFW Heating with Strong I_P Ramp





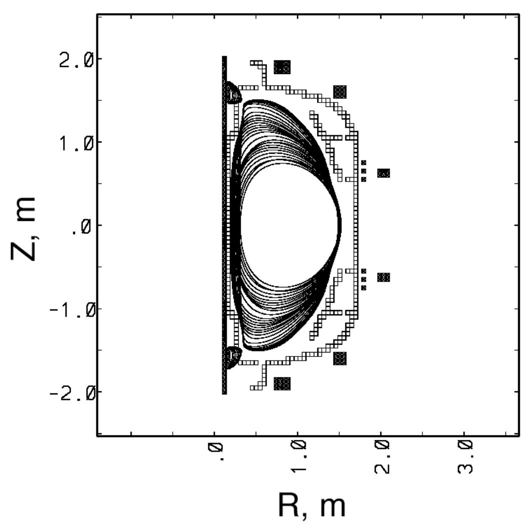
Ip = 1.15 MA, Bt = 0.36 T

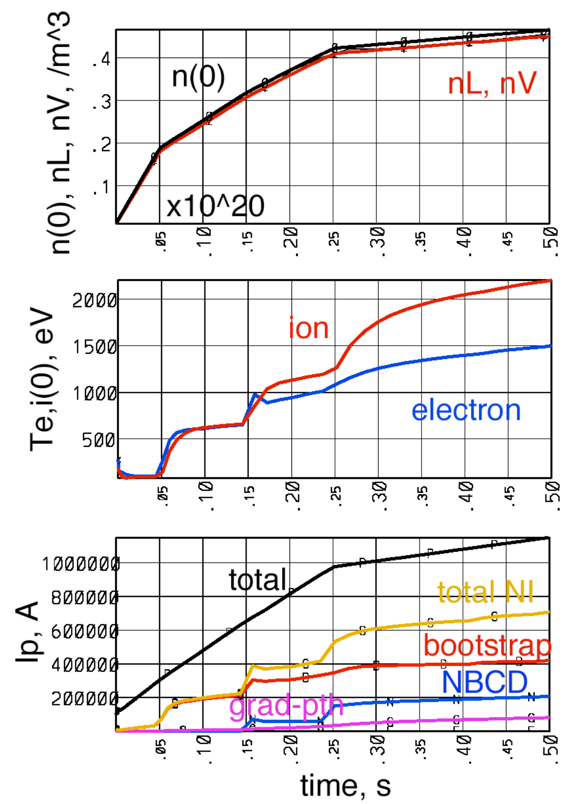
P_{NB} = 5 MW, P_{HHFW} = 6 MW

□= 2.6, □= 0.8

□= 46%, □$_N$ = 8.4

□$_{109070}$, H-mode scaling





IV. Non-inductively Sustained, High β

Study and Demonstrate Integrated Advanced ST Plasmas

NSTX

- Lower B_T to access high β and β_N values and long pulse lengths

EBW off-axis current critical for ballooning stability

- Inject
  - 4 MW NB heating and CD on axis
  - 3 MW HHFW heating on-axis
  - 3 MW EBW heating and CD off-axis

Reach β = 41%, β_N = 8.8, for 4 τ_J with Ip = 1 MA, B_T = 0.36 T

- Utilize simultaneous high elongation and high triangularity from PF1 modification

Stable to high-n ballooning* and n=1 kink modes with outboard wall at 1.5a

- Employ slight density peaking near plasma edge from lithium pellets or pumping, n(0)/<n> = 1.1

PF1 coil modification critical to accessing high β_N by providing high κ and high δ together

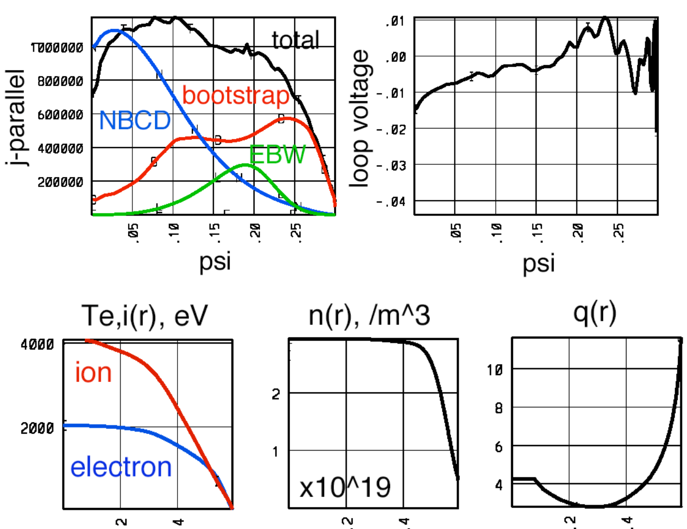
* except in pedestal region

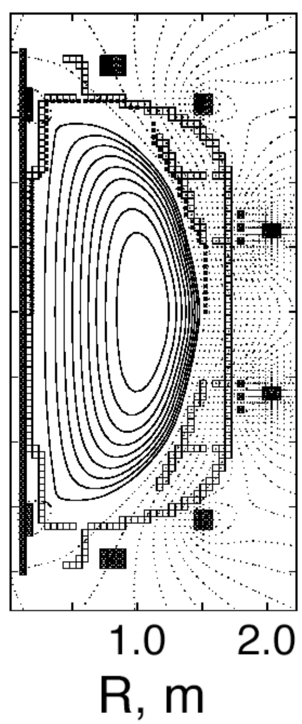
Non-Inductively Sustained High □ Plasma
NB and EBW Heating and CD, and HHFW Heating

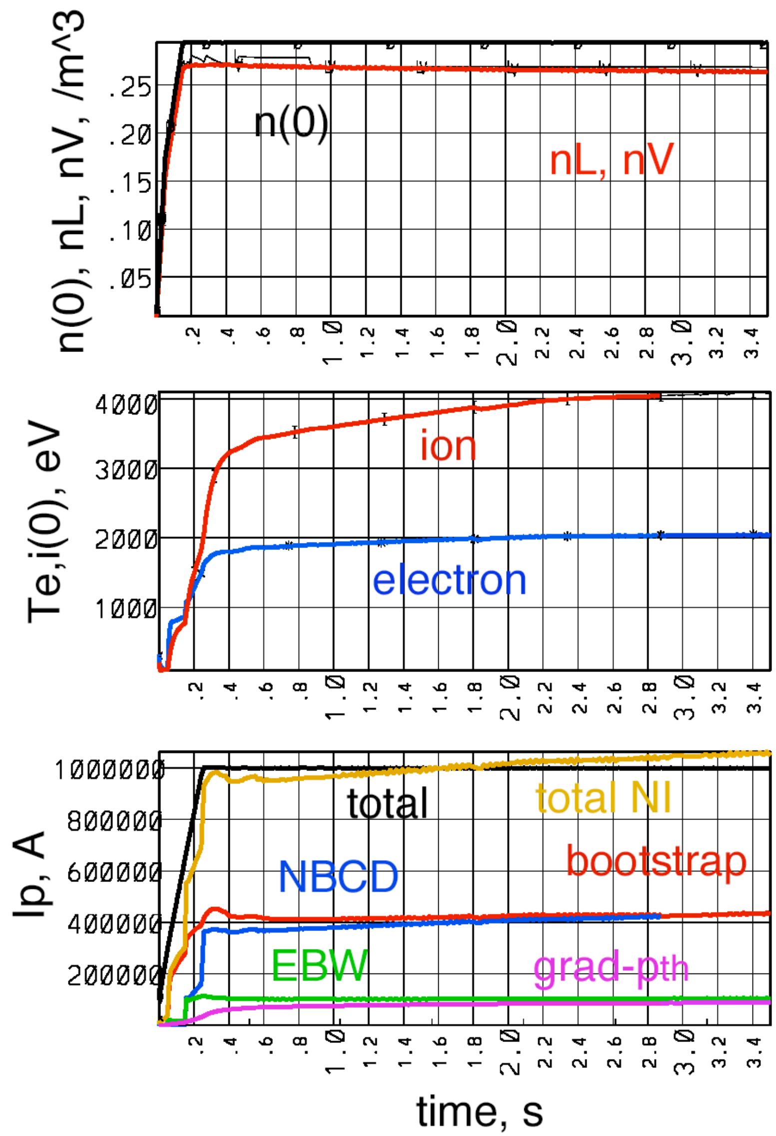
Ip = 1.0 MA, Bt = 0.36 T
I_{BS} = 430 kA, I_{NB} = 430 kA
I_{EBW} = 100 kA
□ = 2.55, □ = 0.83
q_{cyl} = 2.5, li(1) = 0.4

□= 41.3%
$□_N$ = 8.85
$□_E$ = 37 ms
H_{98} = 1.5

P_{NBI} = 4 MW, P_{HHFW} = 3 MW, P_{EBW} = 3 MW
$□_{109070}$, H-mode scaling







Further Investigations and Development for Integrated Scenario Modeling

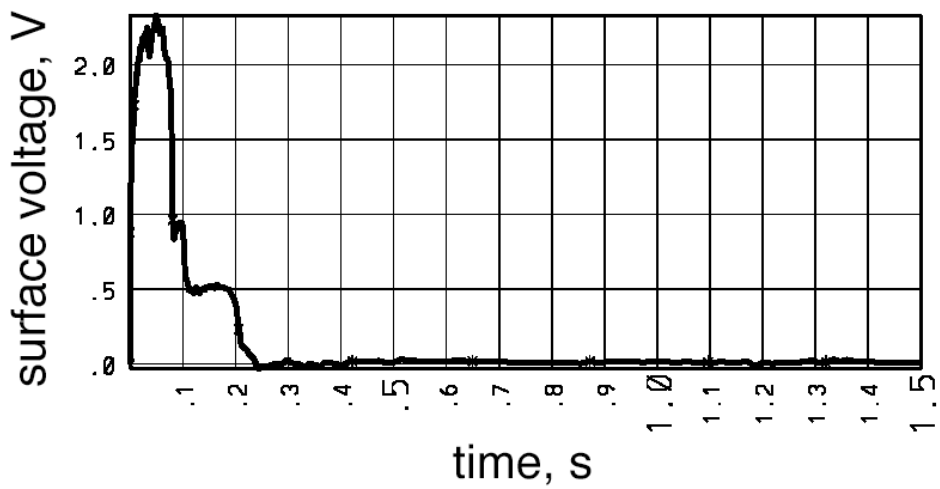
- HHFW CD efficiency
  - Fast ion absorption
  - Thermal ion absorption
  - Install ray-tracing in transport codes
  - Expand scans of plasma parameter dependences especially at high □
- EBW CD
  - Improve modeling and parameter dependences
- NBI analysis
  - Low Ip scenarios
  - Integrate TSC free-boundary features with advanced source models in TRANSP
- Plasma transport
  - Continue to rely on expt. □'s as discharges move closer to scenarios
  - Use NSTX specific global scaling
  - Pursue a GLF23-Low A predictive transport model
- MHD stability
  - Detailed conductor geometry
  - High plasma rotation speeds
  - Impact of higher n modes
  - RWM feedback stabilization
  - NTM's
  - FLR and flow effects on ballooning modes

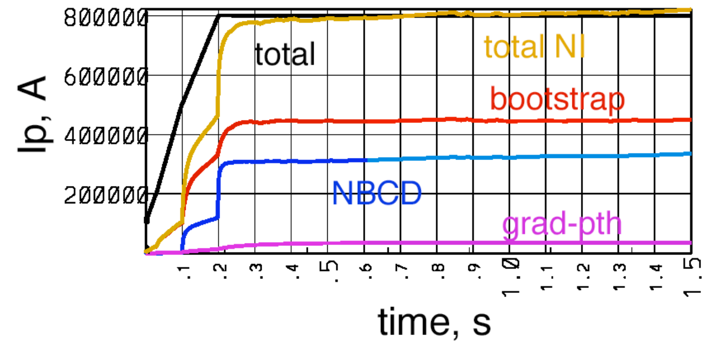
NSTX is Using Integrated Scenario Modeling to Plan Future Experiments

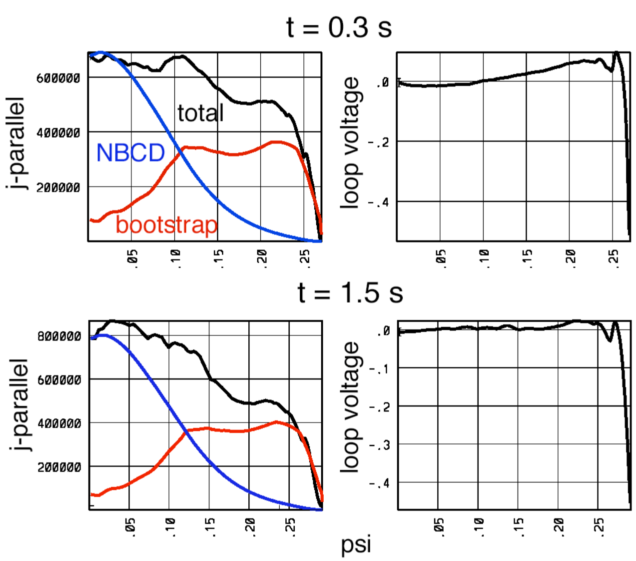
- **Advanced ST plasmas** have been identified
  - Non-inductively Sustained for $\square_{flattop} > \square_{J}$, to study HHFW, EBW, and NB CD techniques
  - Non-solenoidal current rampup, to examine the feasibility for future ST devices
  - High □ and $\square_{N}$ Operating Targets, to study stability, transport and edge physics in high □
  - Non-inductively Sustained, High □ for $\square_{flattop} >> \square_{J}$, to study integrated Advanced ST plasmas
- Identifying the **critical tools to access Advanced ST** plasmas
  - HHFW heating and CD on/near-axis
  - EBW CD off-axis
  - Strong plasma shaping through PF coil modifications
  - Density control
- Continuing to **expand the capability of integrated modeling** to better project behavior of future experiments and devices

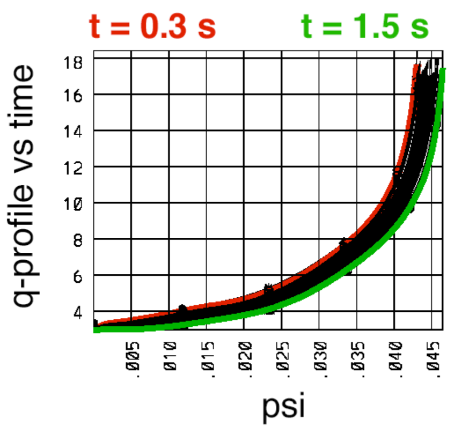
Several Measures are Used to Determine the Stationarity of a Long Pulse NSTX Plasma

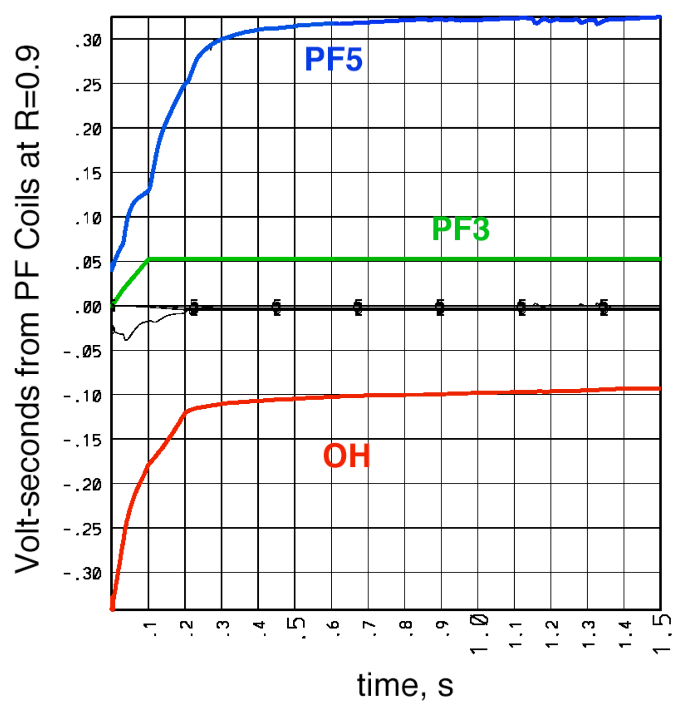
NBI + HHFW Non-inductively Sustained Scenario τ_J = 0.62 s











NSTX Can Operate for Several Current Relaxation Times Depending on the TF Field

$$\tau_J = \frac{\mu_o a^2 \kappa}{12\langle \eta_{neo} \rangle}$$

$$\eta_{neo} = f\left(T_e, f_t, \nu_*, Z_{eff}\right)$$