2001.2.7-8, JAERI-Naka
COMBINED MEETING OF
DOE / JAERI TECHNICAL PLANNING OF TOKAMAK EXPERIMENT AND
IEA LARGE TOKAMAK WORKSHOP ON EXPERIMENTAL PLANNING

Steady-state Plasma Research in JT-60SC

- Current Drive and Steady-state Operation -

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For JT-60SC Design Team

OUTLINE

1. Introduction
2. Overview of CD and Steady-state Operation
3. Evaluation of Performance
4. Summary

1. Introduction

- **Requirements in JT-60SC**

  Long Sustainment of Fully Non-inductive Plasmas with High β_N, High n_e/n_{GW}, High BS at a Plasma Regime of a Break-even Class

- **Background**

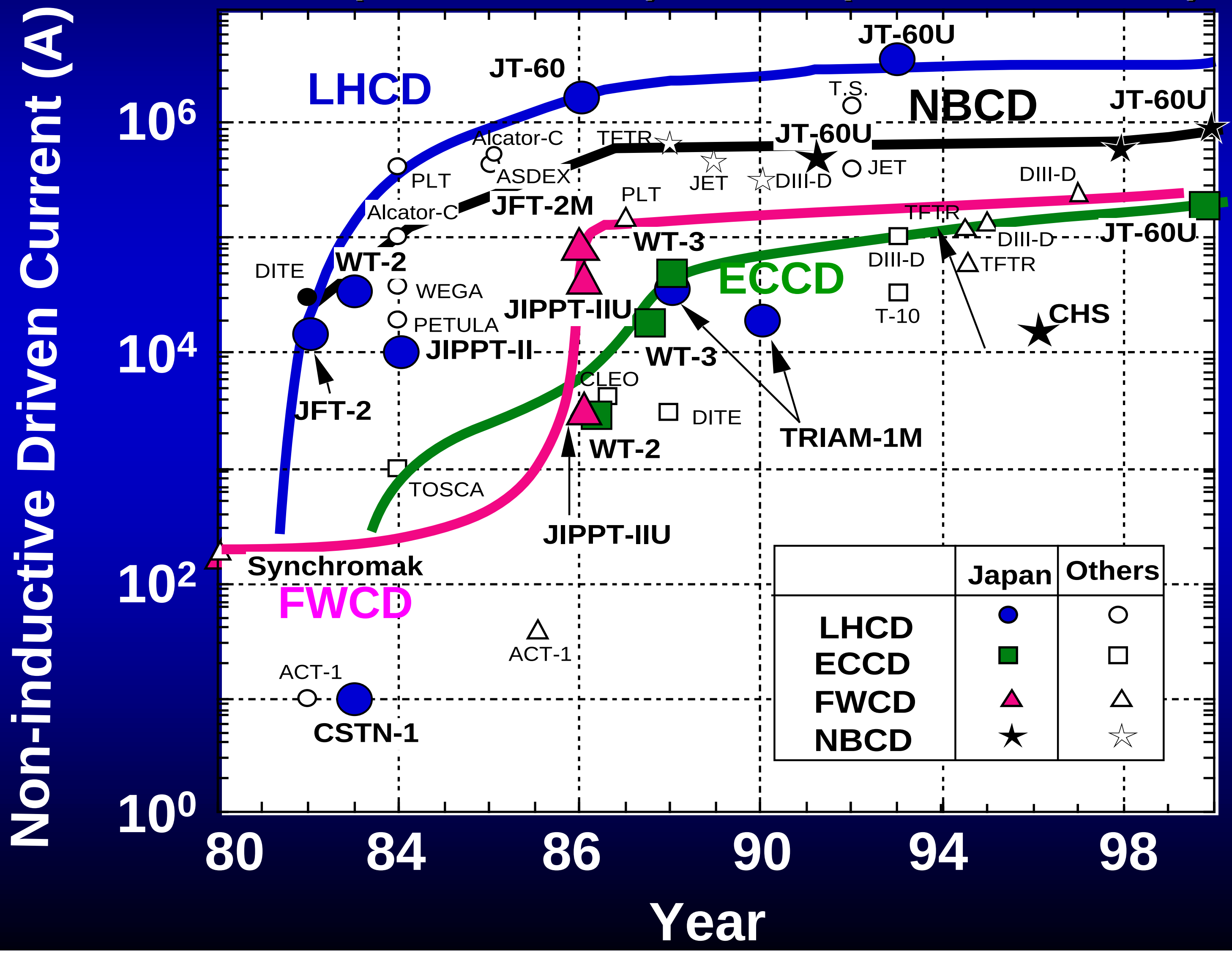
  Japanese Contribution on non-inductive CD

- **Approach in JT-60SC**

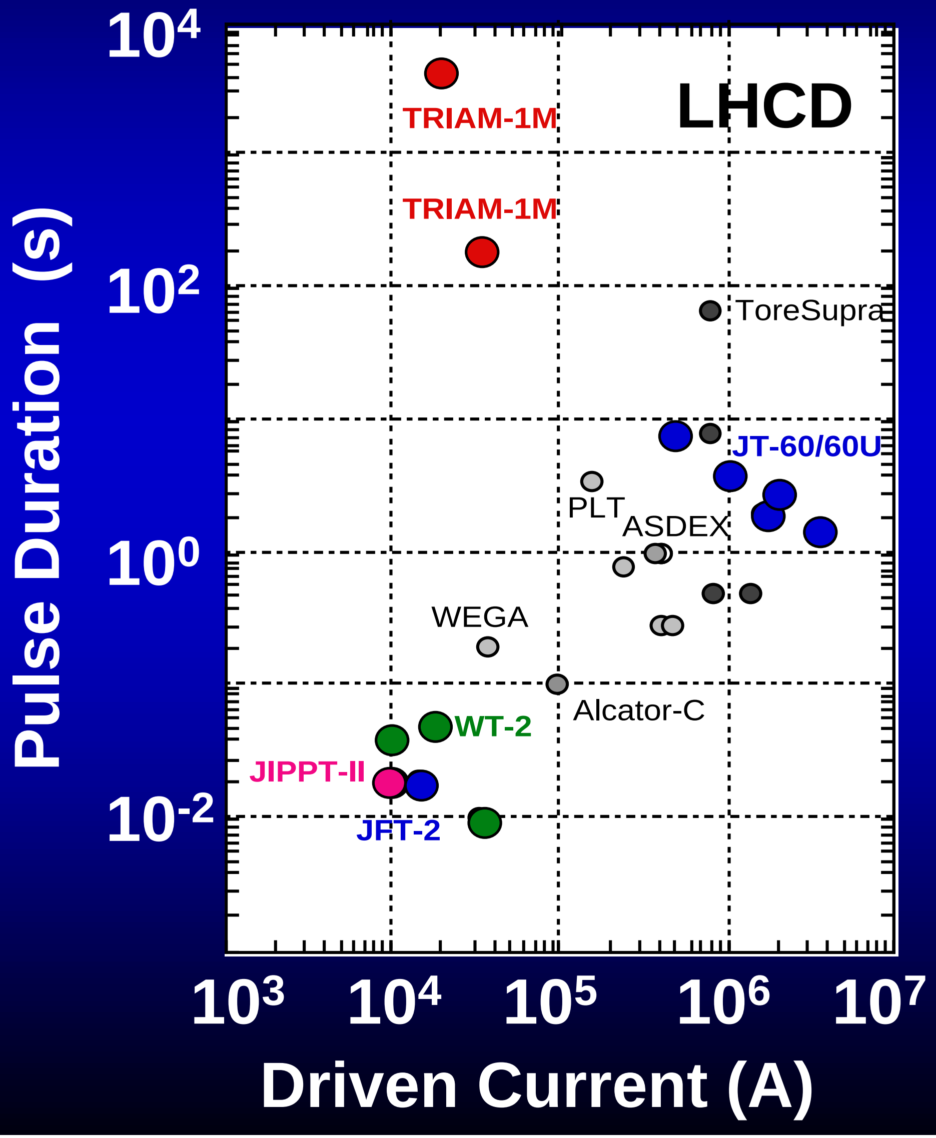
  Based on the JT-60 Results

Japanese Studies trigger Progress

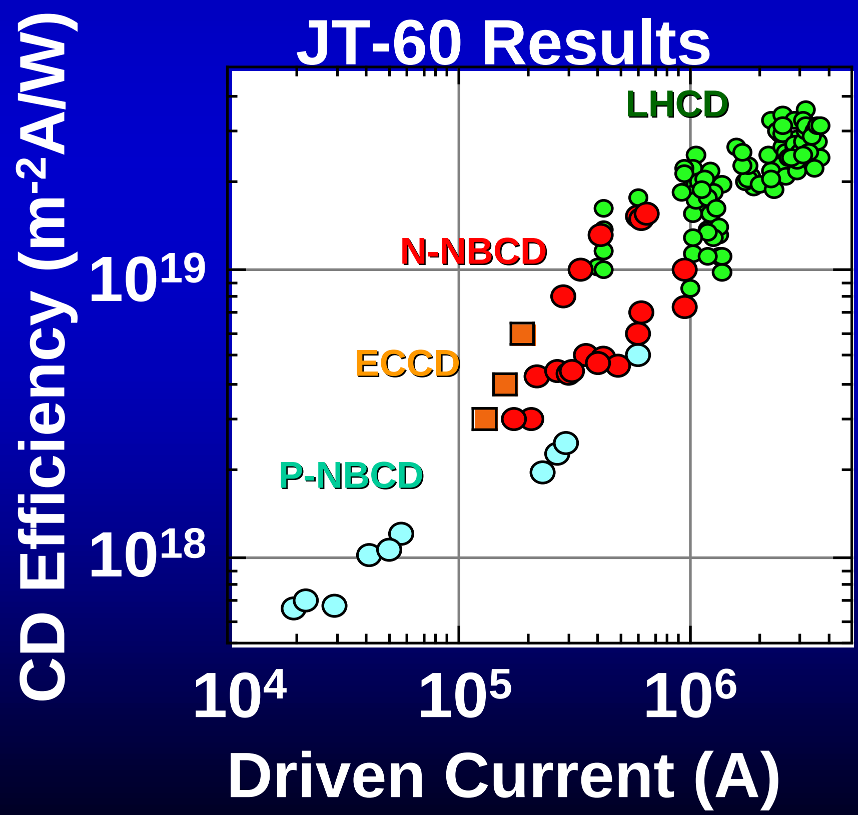
Synchromak (IPP Nagoya, FWCD), WT-2/3 (Kyoto, ECCD), JFT-2/JT-60 (JAERI, LHCD), JT-60U(JAERI, N-NBCD)



Various Non-inductive CD Studies in JT-60/JT-60U



80% BS Current: 1989



Approach to Steady-state Operation

- **Non-Inductive Current Drive**
  Mainly, Neutral Beam CD and Bootstrap Current
- **Current Profile Control**
  Mainly, Combination of P- and N-NBCD
  ECCD (Additional Option: LHCD, P-NBCD)
- **Operation Scenarios based on JT-60 results**
  High β_p H-mode and Reversed Shear mode

Issues

- **Enough CD Power for Non-inductive CD?**
- **Operation Regime at Nominal Power?**
- **Steady-state Solution of Reversed Shear?**
- **Enough Pulse Length(100s) ?**

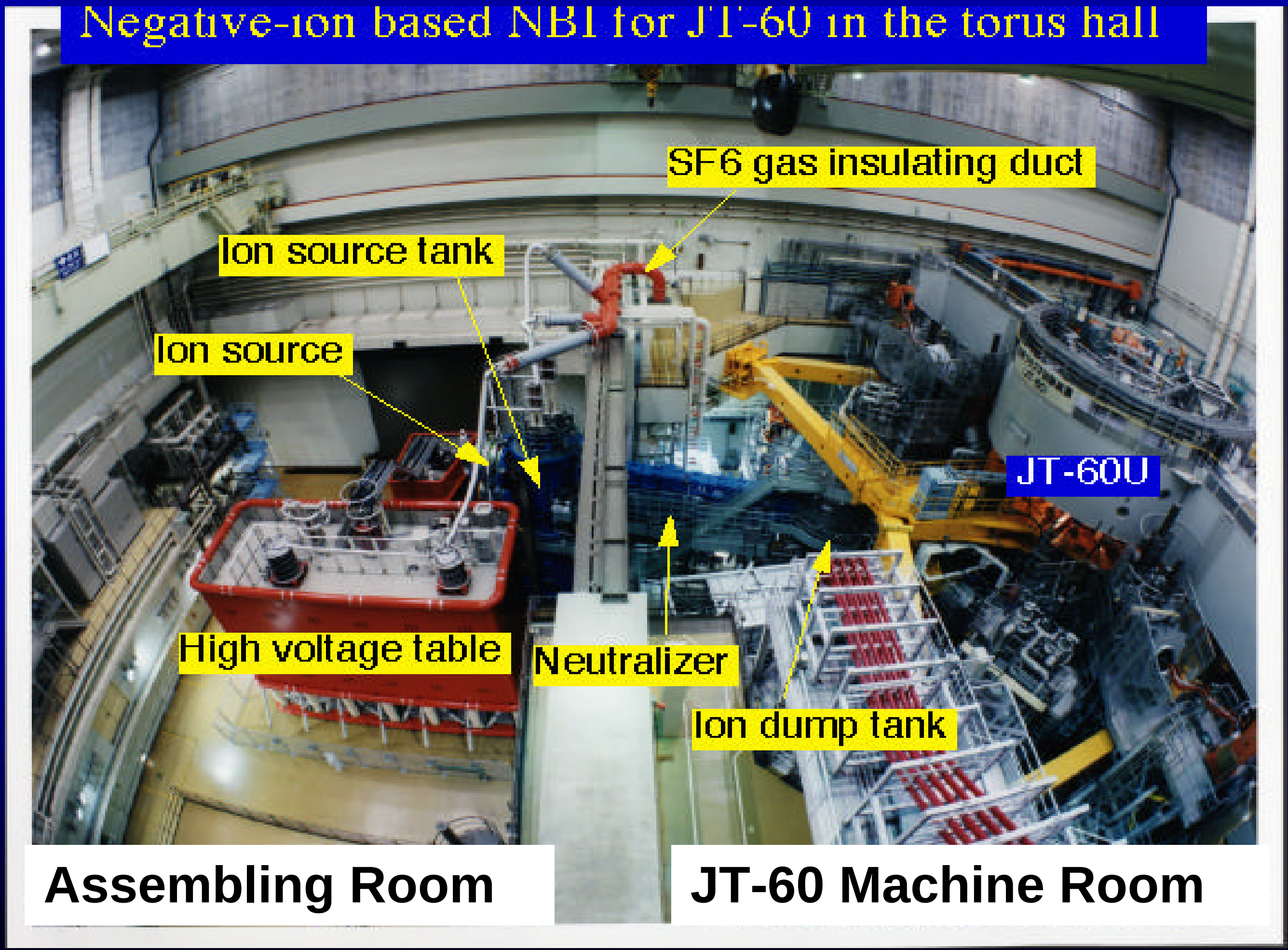
2. Overview of CD and Steady-state Operation Experiments

- N-NBCD
- ECCD
- High β_p ELMy H-mode
- Reversed Shear Mode

N-NBCD Studies in JT-60U

N-NB Operation: From 1996, Design:500 keV, 10MW, 10s

Long Pulse&High Voltage Conditioning during Construction Phase of JT-60SC



Present:
Routine Injection of >4MW, >2s at E_B~350keV

Stable operation with E_B~0.5MeV and 100s is required

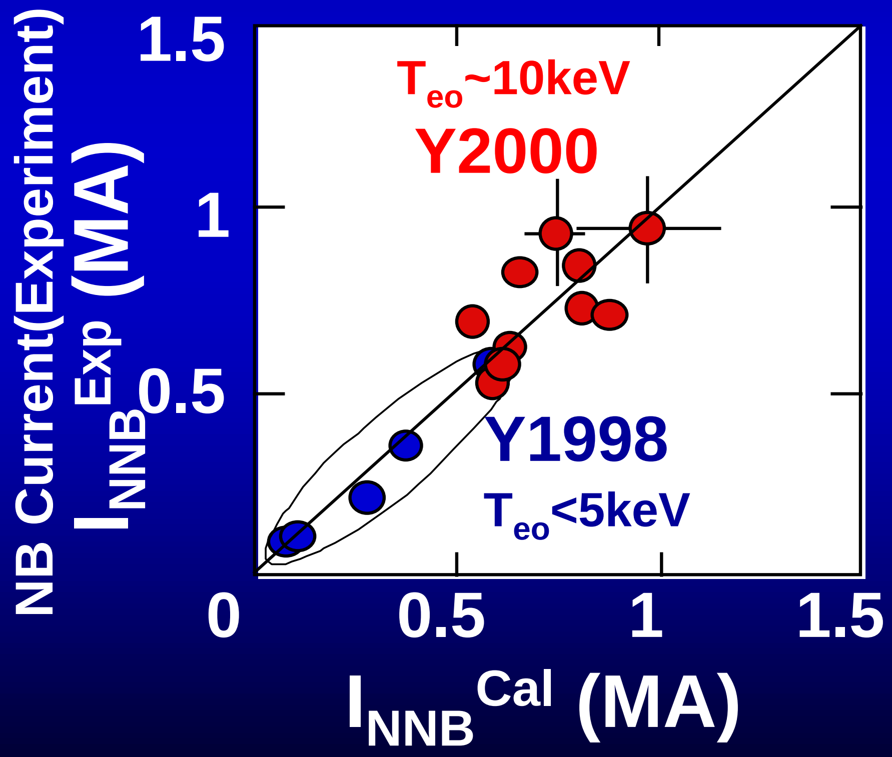
Good Agreement with ACCOME Cal.

1MA N-NB current with η_{CD20}~0.1

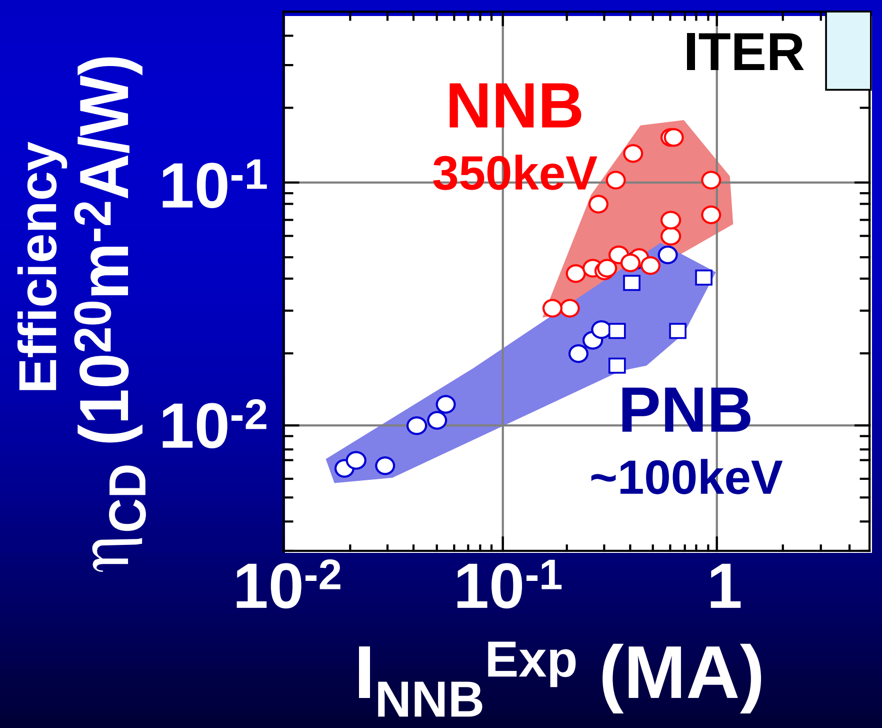
Present stable N-NB Operation : ~4MW, ~2s

EFIT-MSE gives Driven Current and its profile

under collaboration with GA



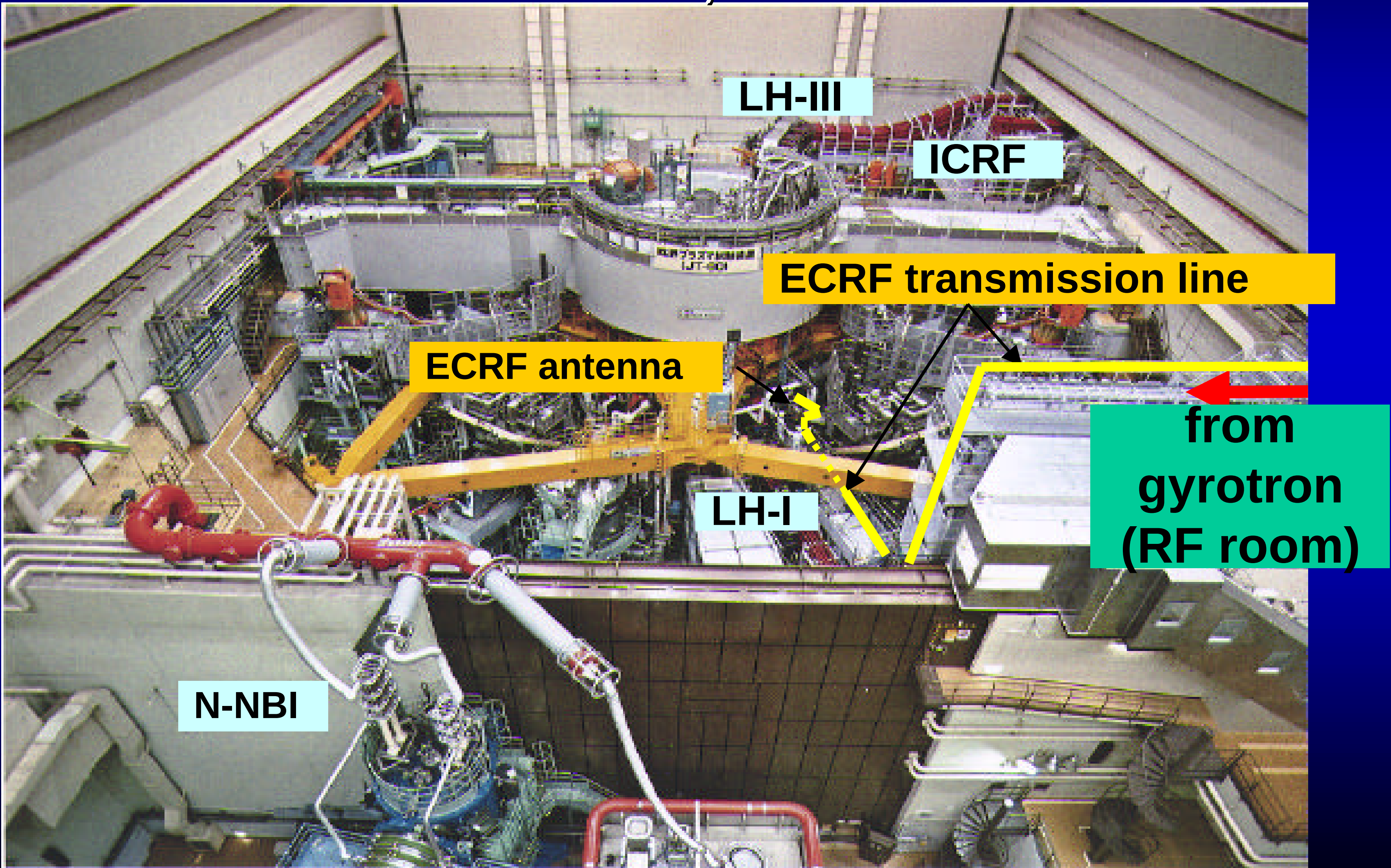
Calculated NB Current



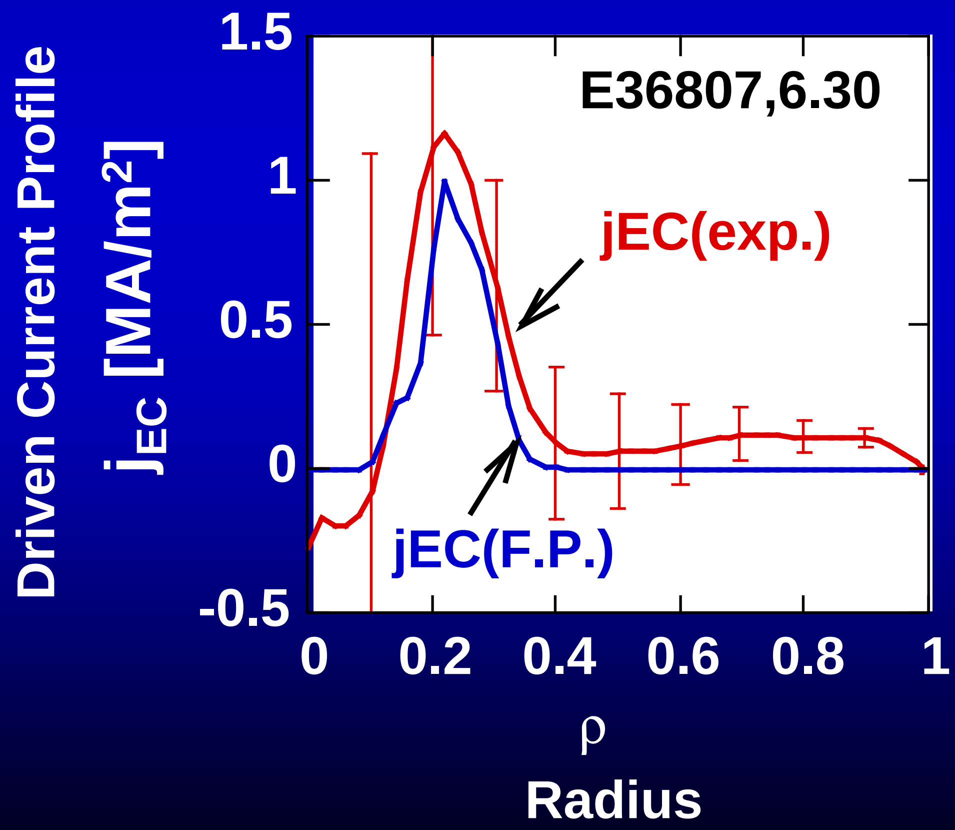
Calculated NB Current

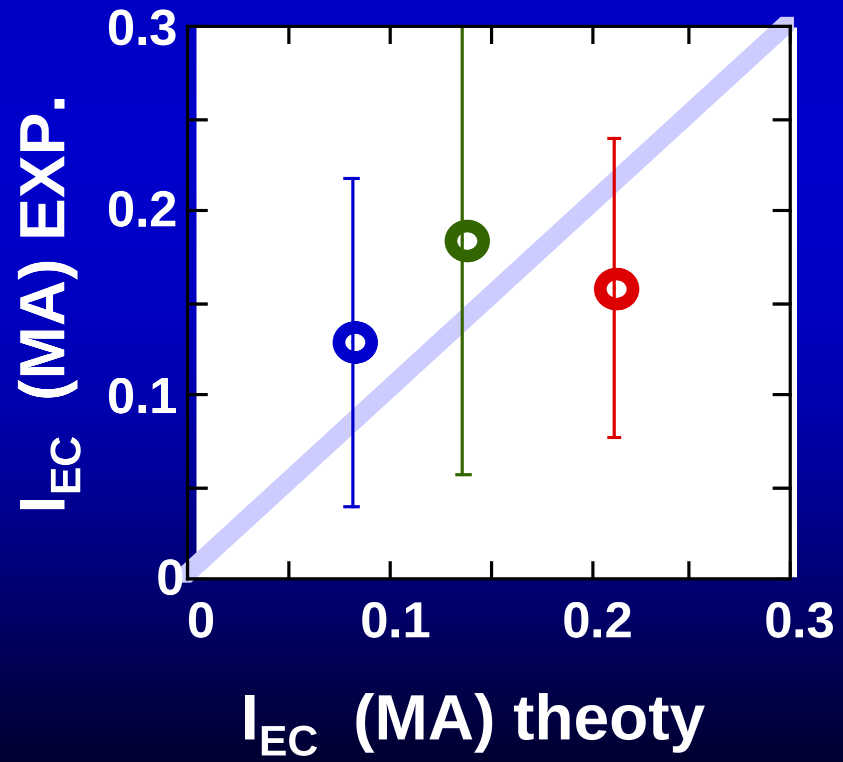
ECCD Studies in JT-60U

110GHz Fundamental O-mode, 4MW in Source
Achieved 2.2MW/2s/3tubes, 0.6MW/6sec/1tube



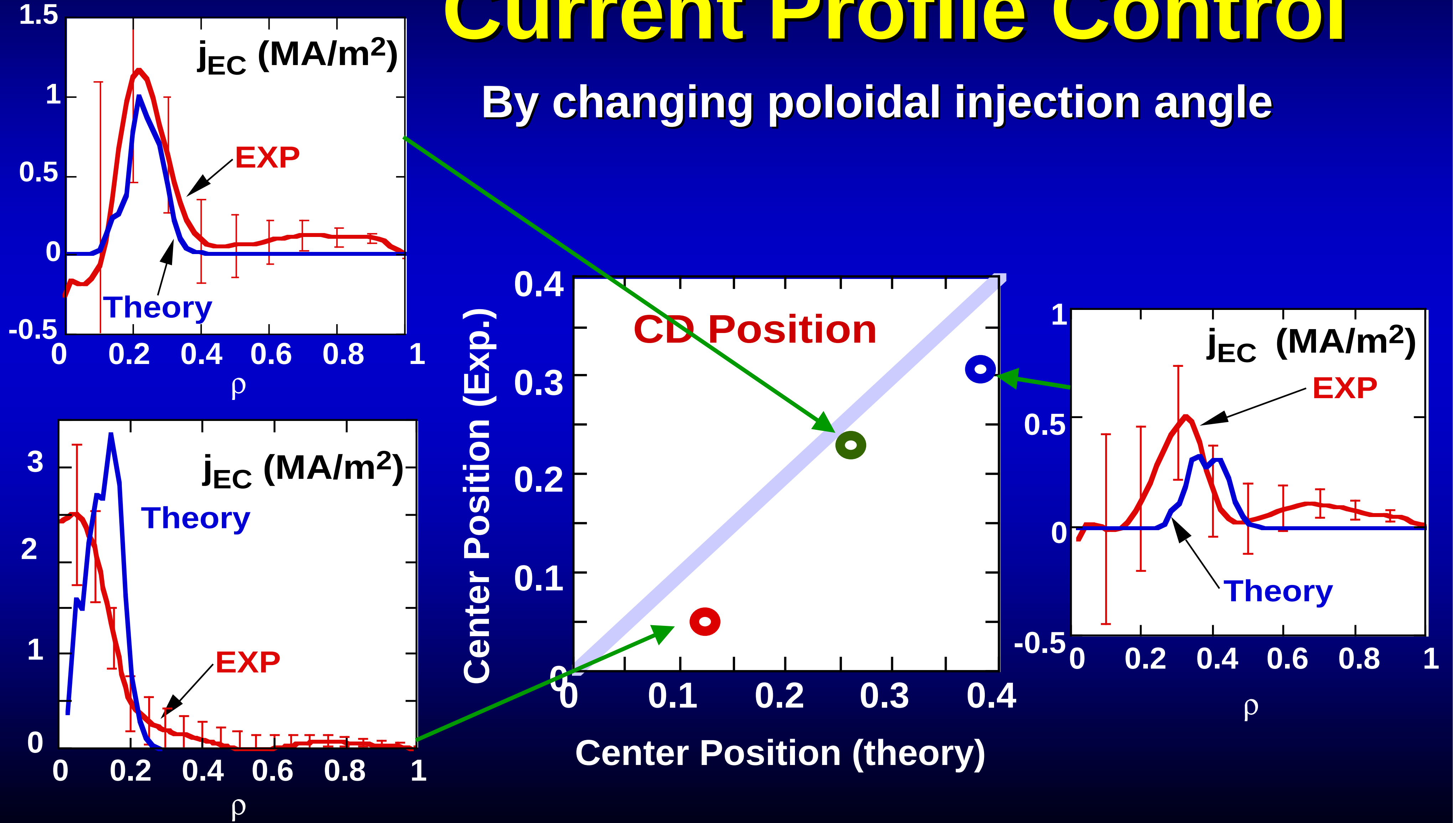
Identified EC Current Agrees with Fokker-Planck Calculation





ECCD is Good Tool for Local Current Profile Control

By changing poloidal injection angle



High Performance Steady-state Operation

Two operation scenarios developed in JT-60U

- **High β_p ELMy H-mode**

  Peaked Pressure Profile
  Normal/Weak Shear

- **Reversed Shear mode**

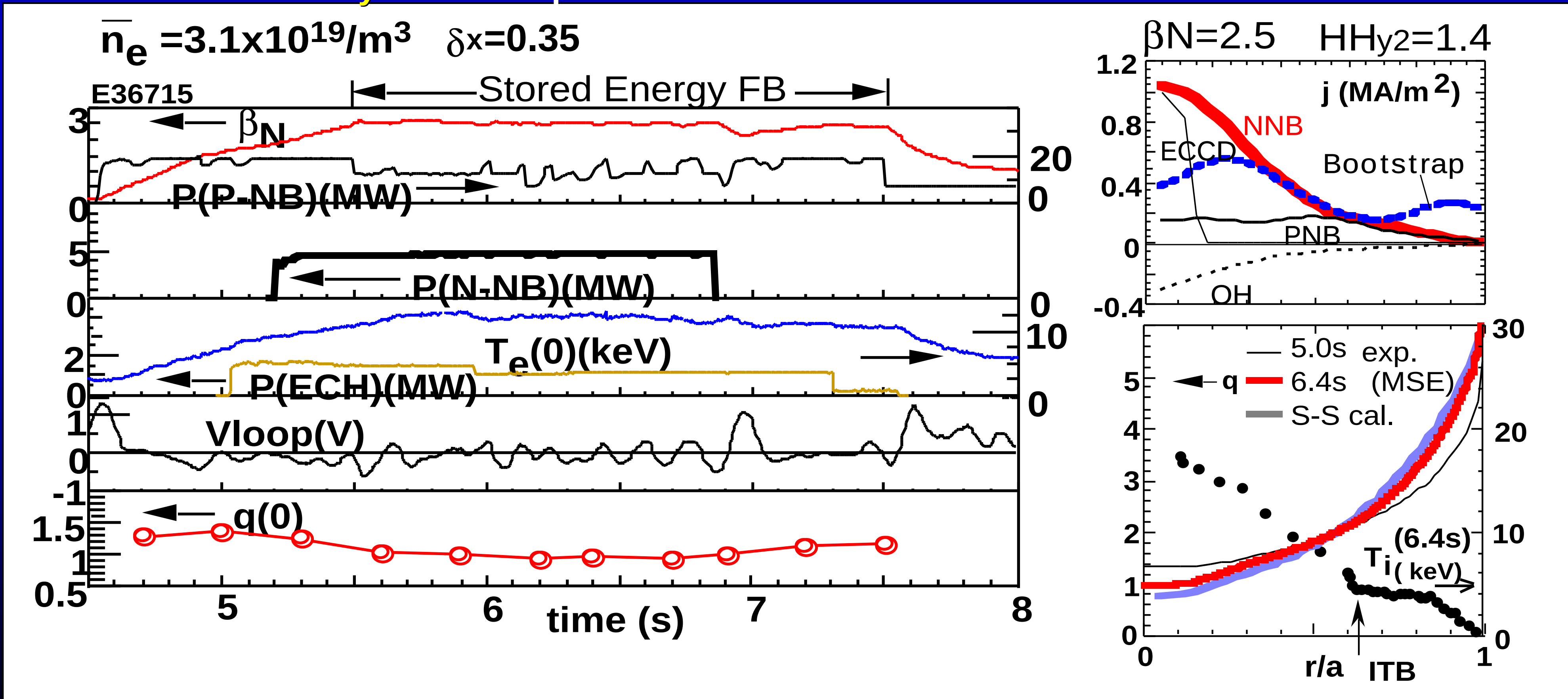
  Box-type Pressure Profile
  Negative Shear

Steady-state Operation with High β_p ELMy H mode

1.5MA/ 3.7T, q_{95}=4.8, NNB (360keV,~4MW), ECH (~1.6MW),

I_{NNB}~0.61MA(η_{CD}=1.5x10^{19}m^{-2}A/W), I_{PNB}~0.26MA, I_{BS}~0.76MA

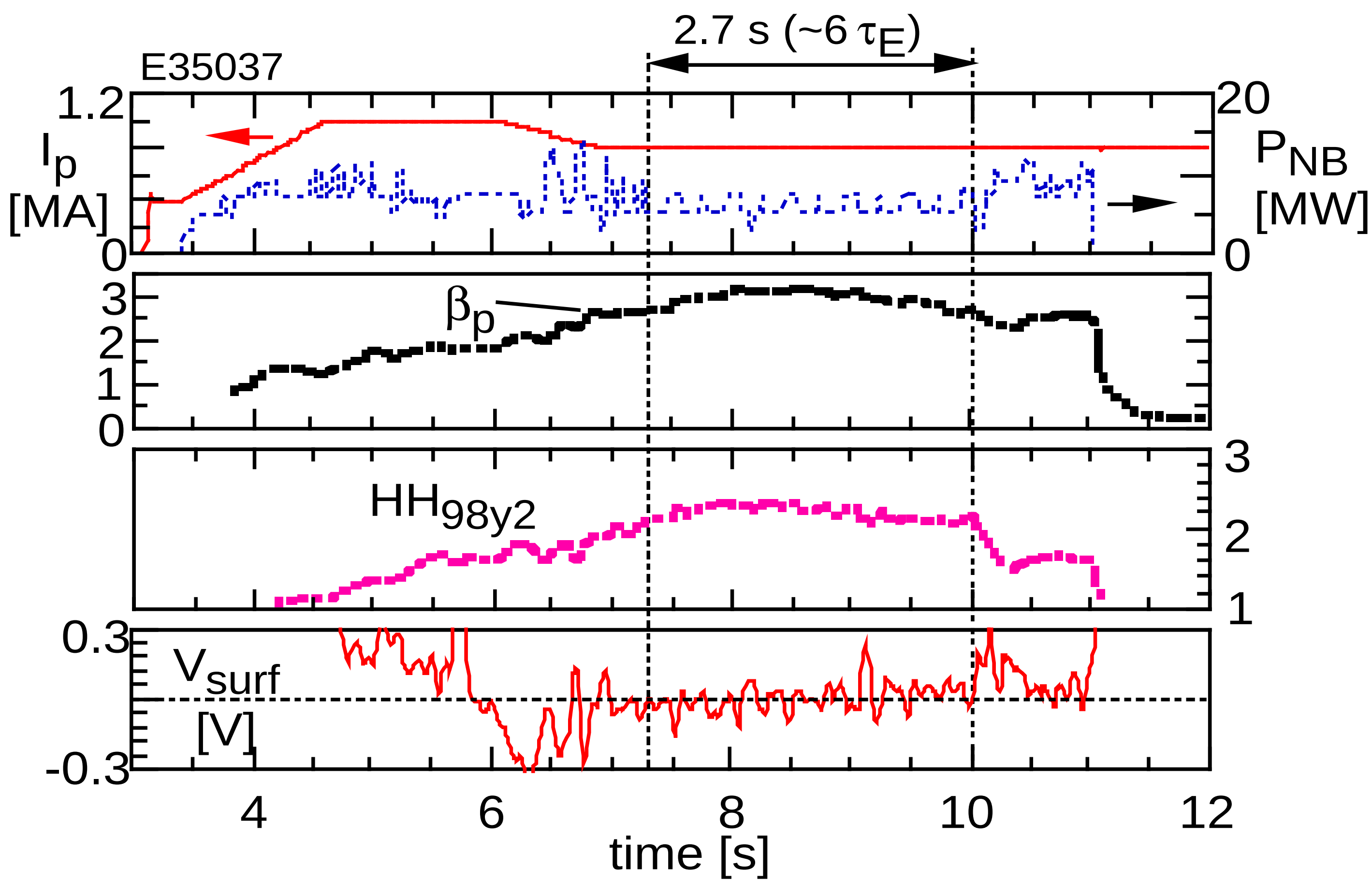
H_{89P}~2.9, **HH_{y2}~1.4**, β_p=1.9, β_N =2.5 for 1.3s

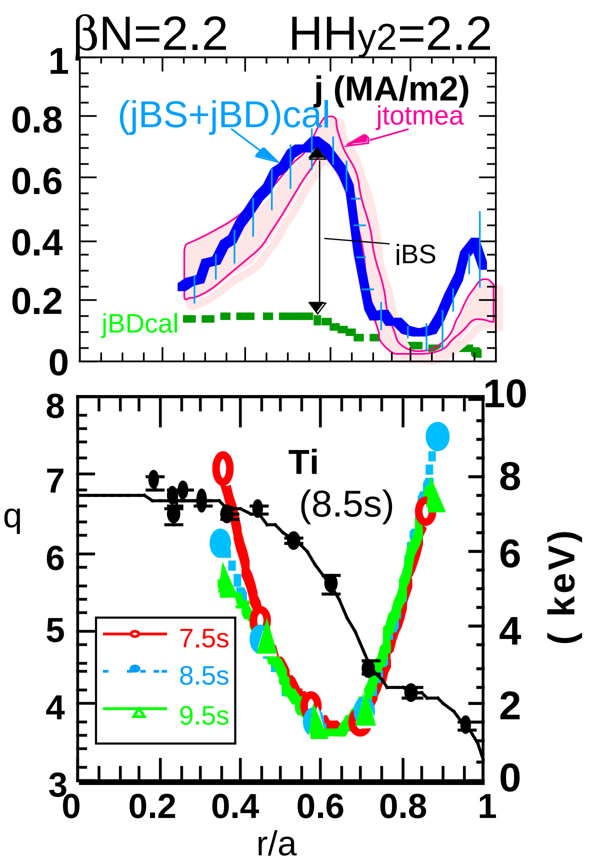


Steady-state Operation with Reversed Shear mode

0.8MA/ 3.4T, q_{95}=9.3, δ_x~0.43, off-axis NBCD(25%), BS~80-88%

H_{89P} = 3.3-3.8, HH_{y2} = 2.1-2.3, β_p=2.6-3.2, β_N =1.9-2.2- for 2.6s

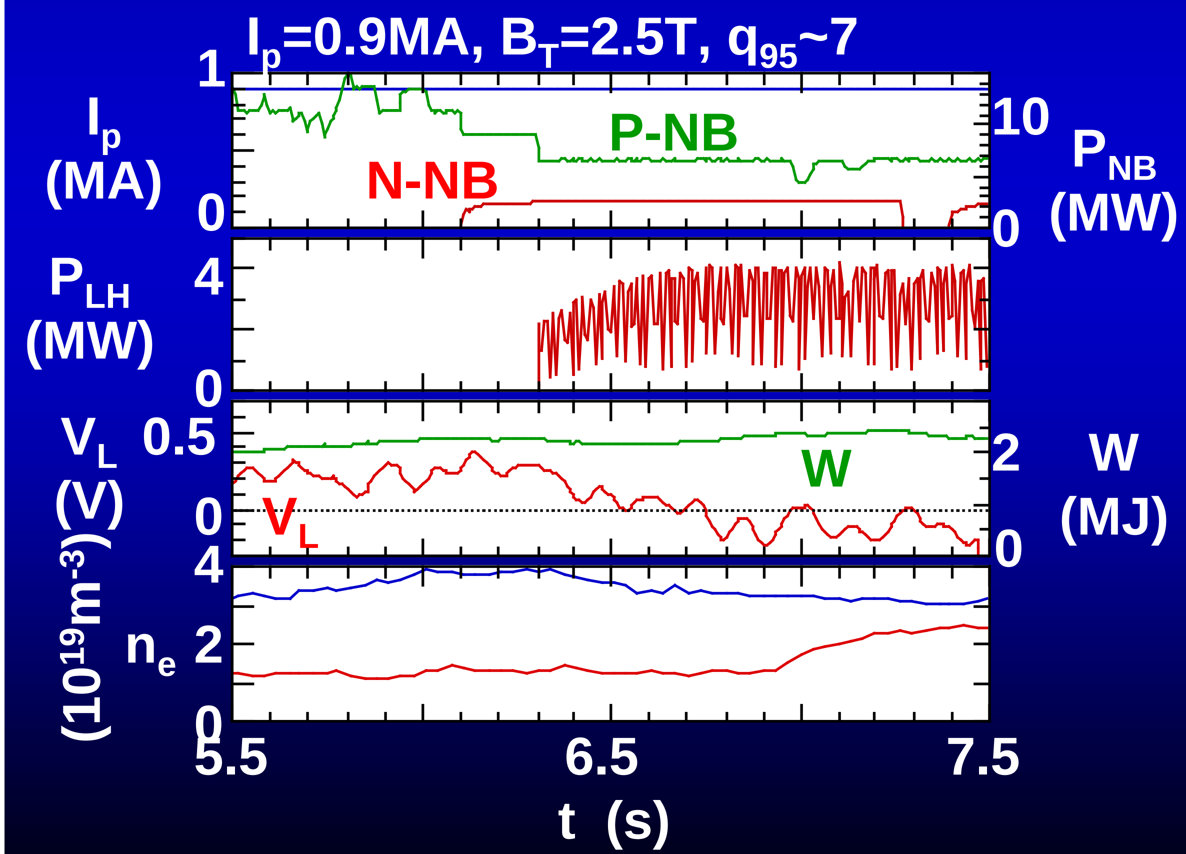


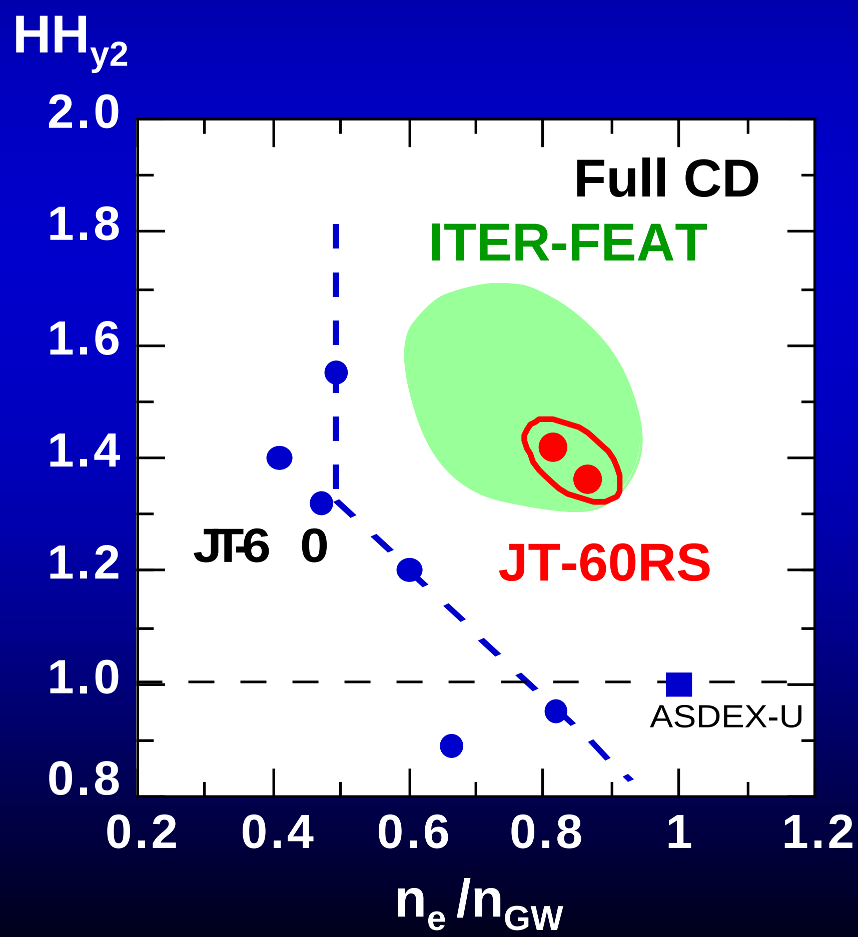


High Density Reversed Shear mode

$HH_{y,2}$ = 1.4, n_e^{ave}/n_{GW} = 0.8, q_{95} = 6.9,

$I_{CD} \sim I_p$, $T_e \sim T_i$ with LHCD current profile control

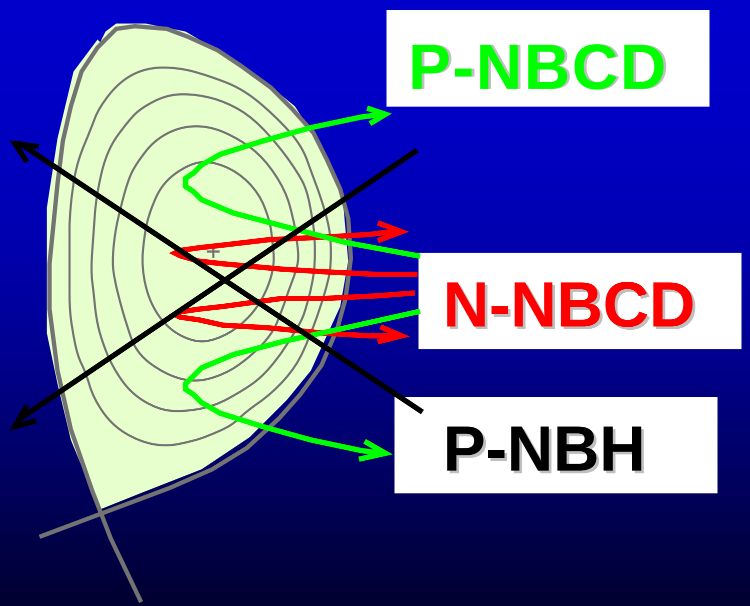


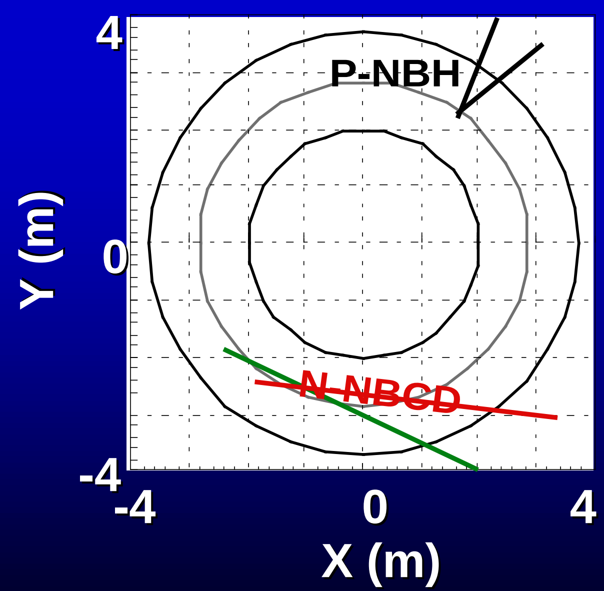


3. Evaluation of Performance

Heating and CD Power for 100s operation

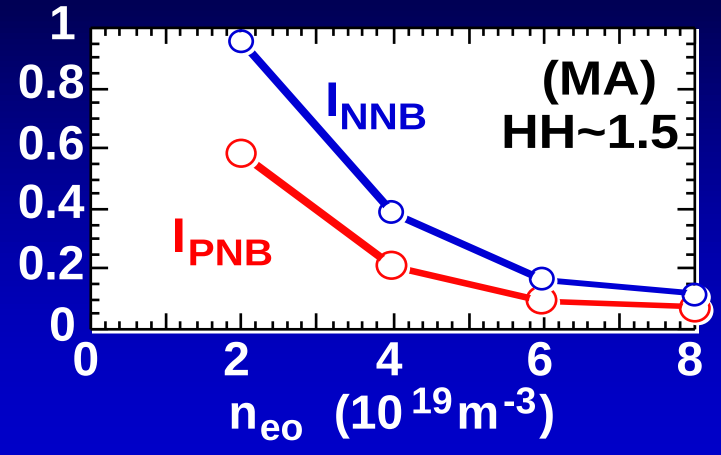
N-NBCD: ≤0.5MeV, ≤10MW,10s/ ~3MW, 100s
P-NBCD: <0.1MeV, <10MW,10s/ ~3.3MW, 100s
P-NBH : <0.1MeV, < 20MW,10s/ ~6.7MW,100s
ECCD :110GHz, <4MW,10s/ ~1.7MW, 100s



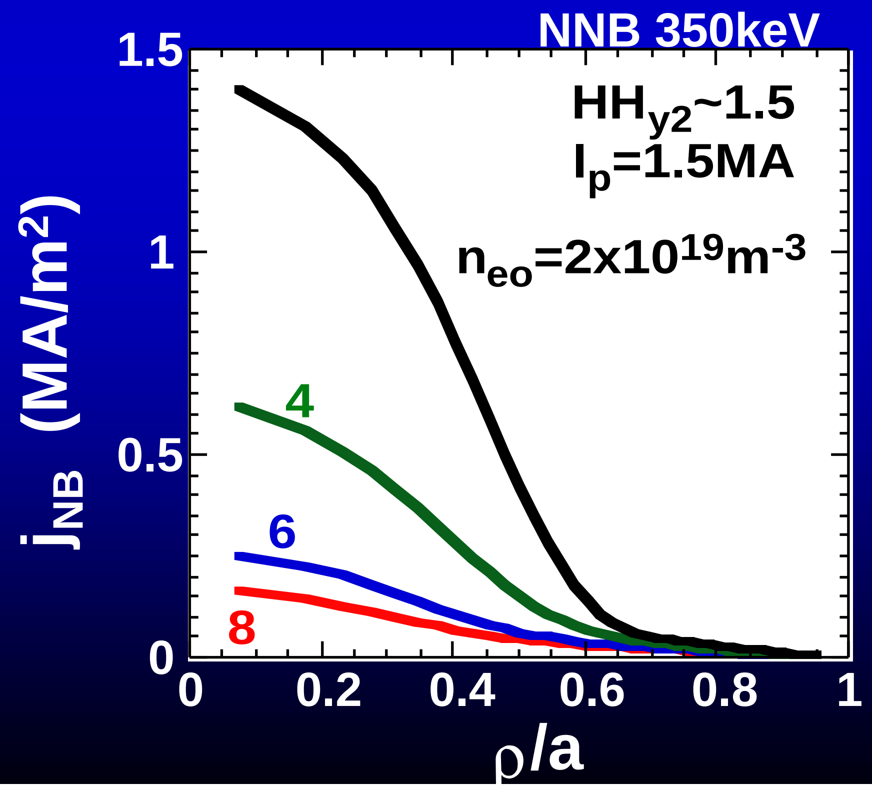


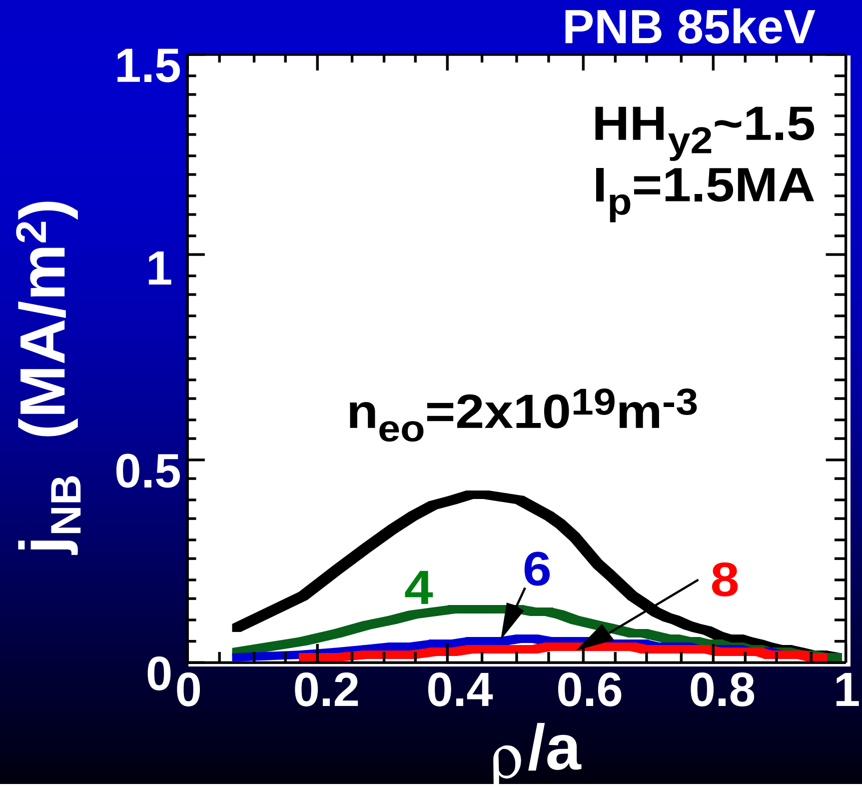
Driven Current Profile for N-/P-NBCD

1.5MA, HH_{y2}~1.5
N-NB: strongly peaked
P-NB: off-axis CD



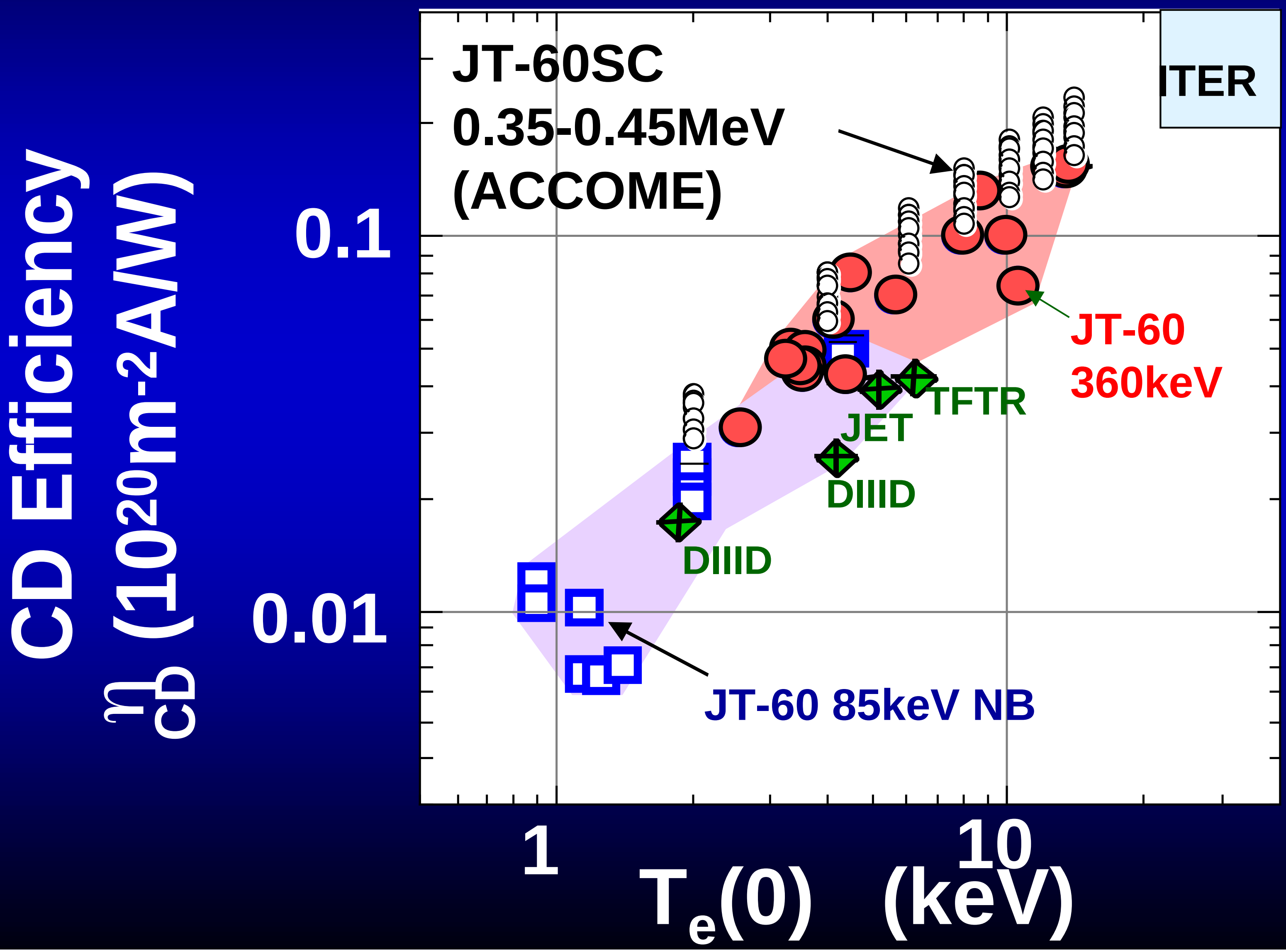
$n = n_o\{0.9\ (1-\rho^2)^{0.5} + 0.1)\}$
$T = T_o\{0.9\ (1-\rho^2)^{1.0} + 0.1)\}$
350keV/3MW, 85keV/3.3MW





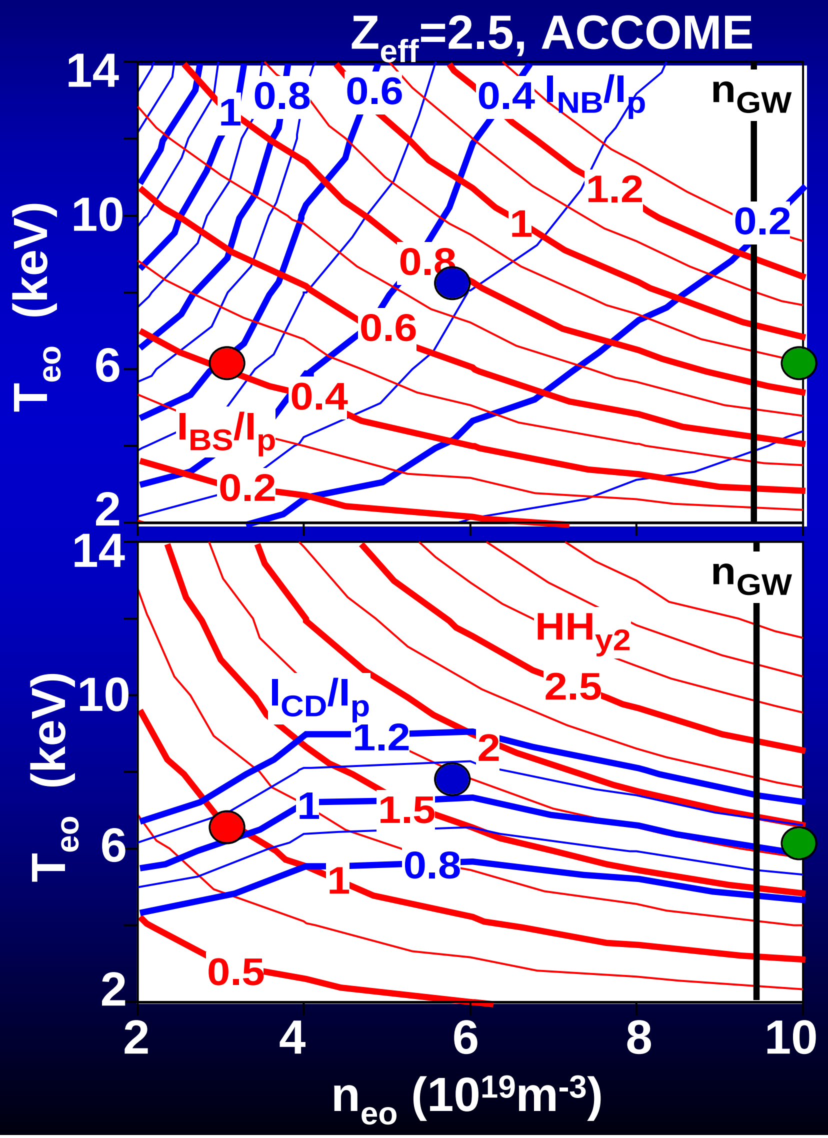
N-NBCD Efficiency approaching ITER regime

CD Efficiency of >2x10^{19}m^{-2}A/W can be expected



CD Performance at 1.5MA

Evaluation of Non-inductive CD by ACCOME Code



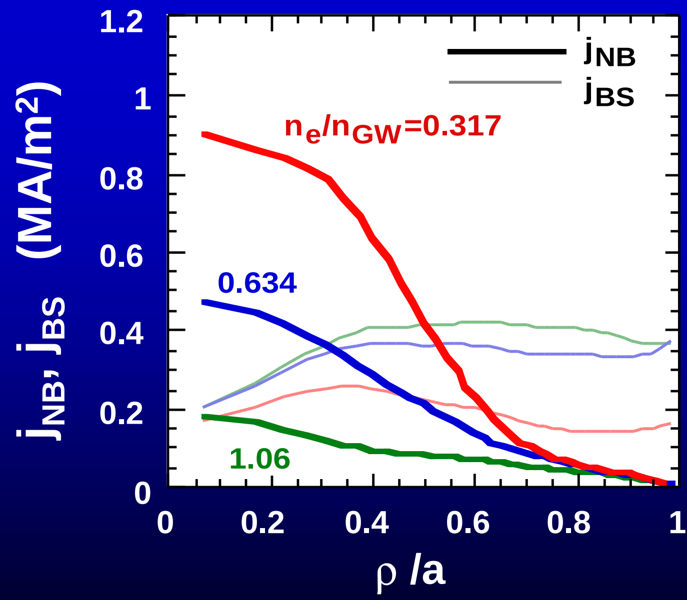
N-NBCD: 350keV(1.5MW+1.5MW)

P-NBCD:85keV (1.65MW+1.65MW)

P-NBH :85keV(3.35MW+3.35MW)

$n = n_o\{0.9\,(1-\rho^2)^{0.5} + 0.1\}$

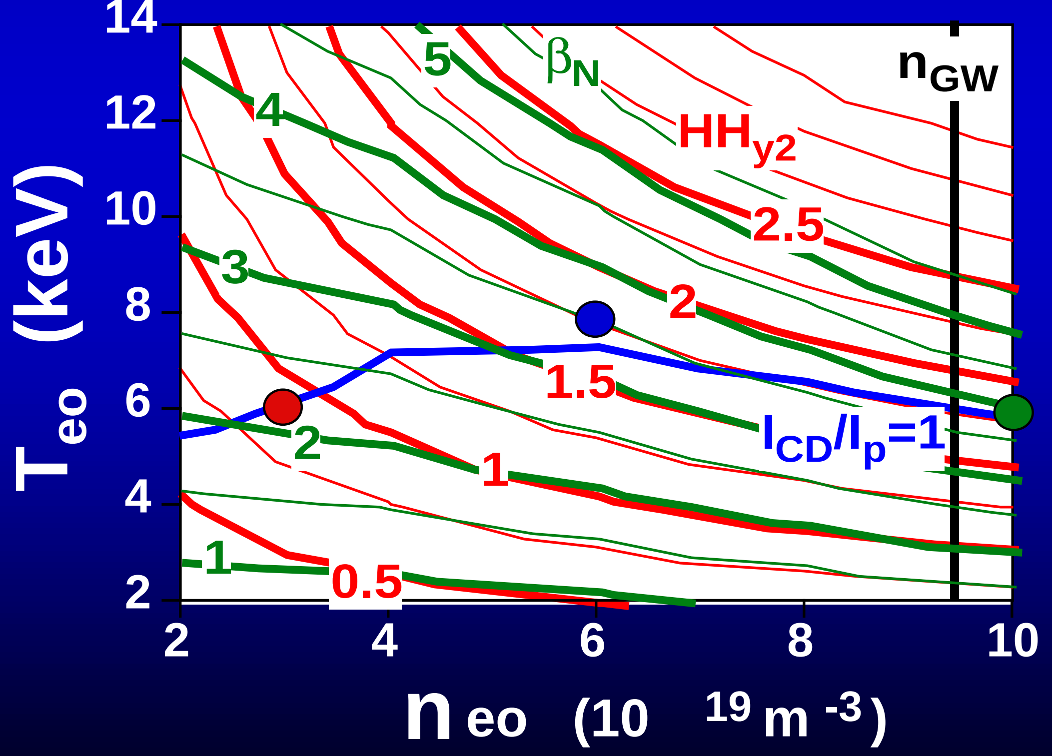
$T = T_o\{0.9\,(1-\rho^2)^{1.0} + 0.1\}$



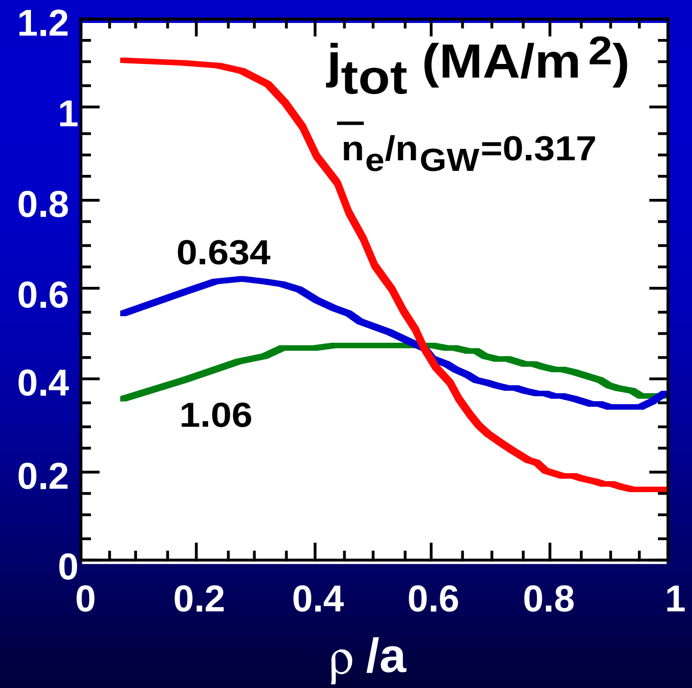
Full CD Regime at 1.5MA

Full CD at n_e/n_{GW}<1.06 with HH_{y2}=0.8-1.8, β_N(2.8T)<4 can be expected at 1.5MA

CD: 350keV/3MW, 85keV/3.3MW,
Heat: 85keV/6.7MW

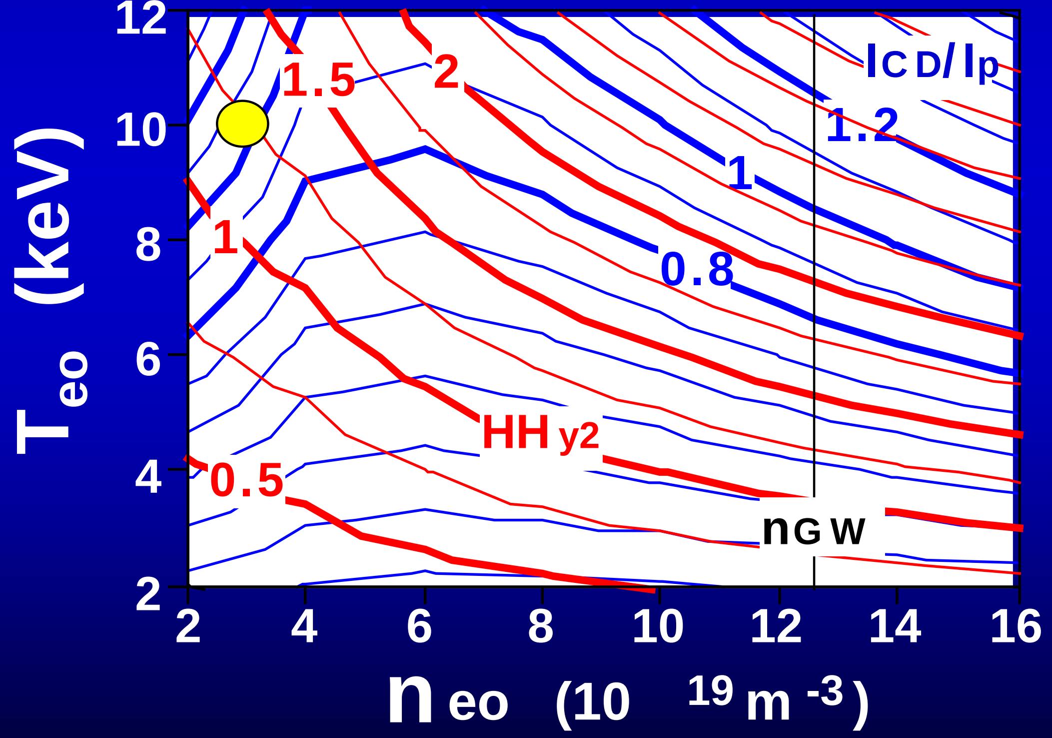


Hollow current is formed at high density regime

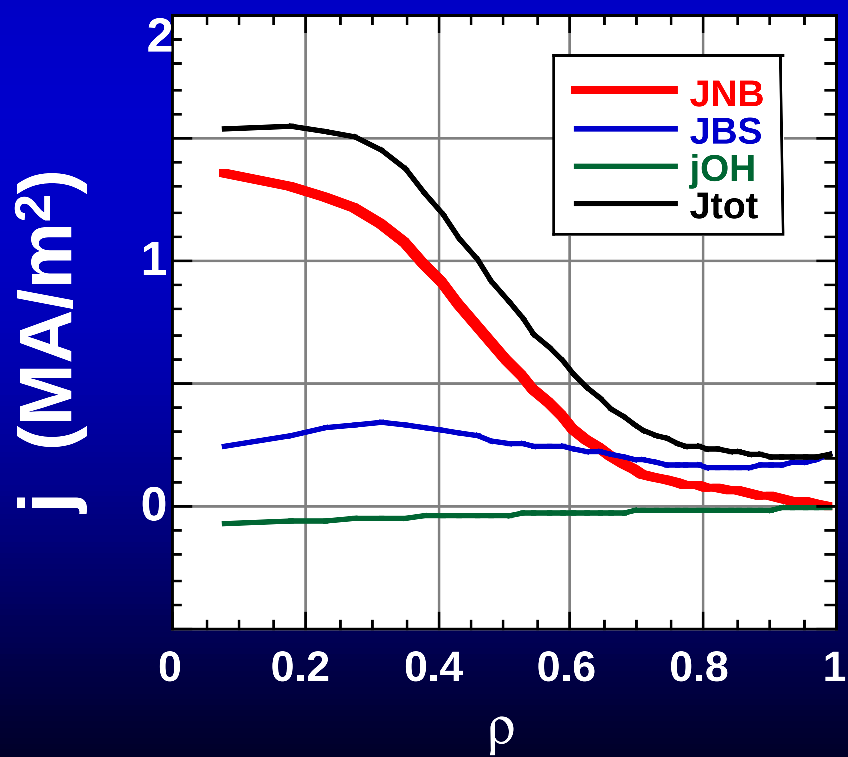


2MA Full CD can be expected at only low n_e regime for normal pressure profile

CD: 350keV/3MW, 85keV/3.3MW,
Heat: 85keV/6.7MW



P_{NB} =13MW, HH_{y2}=1.25
Z_{eff}=2.5, n_e=2.1x$10^{19}$$m^{-3}$
$<T_e>$=5.5keV
I_{NB} =1.29MA, I_{BS} =0.77MA
I_{OH} =-0.06MA



Reversed Shear at 1.85MA

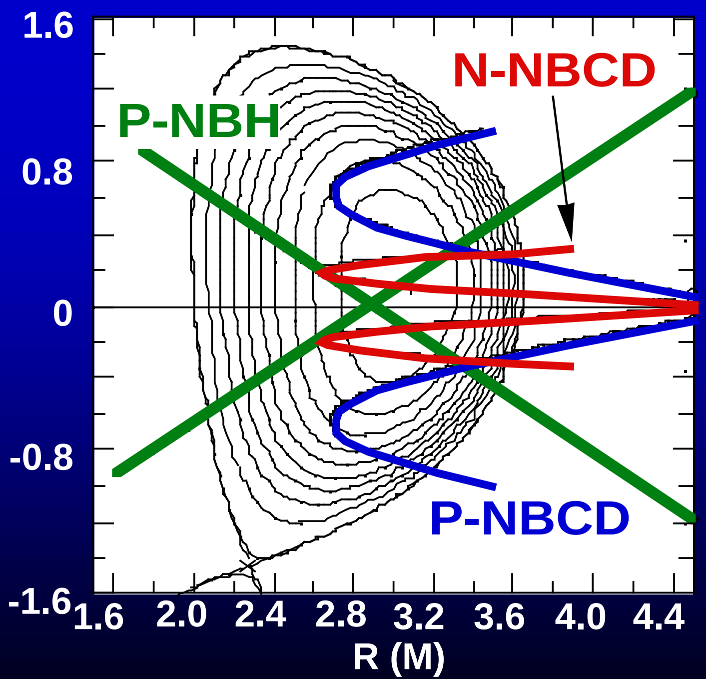
Steady-state solution of Reversed Shear with a wide ITB

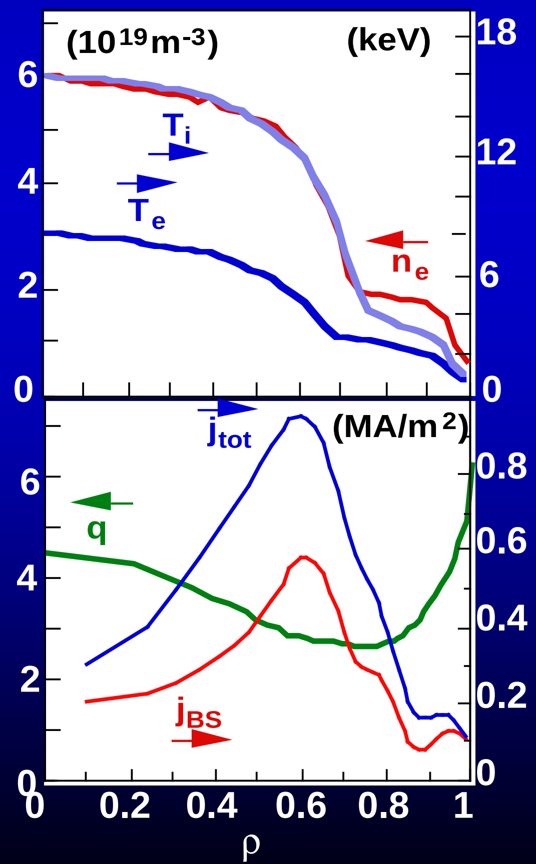
10MW of NBCD Power(85keV)
6.7MW of Perp. NB(85keV)
$\bar{n}_e$=3.17x10^{19}m^{-3}(n_e/n_{GW}~0.4)

→

H_{Hy2}=1.83
I_{NB}/I_p=0.405
I_{BS}/I_p=0.603

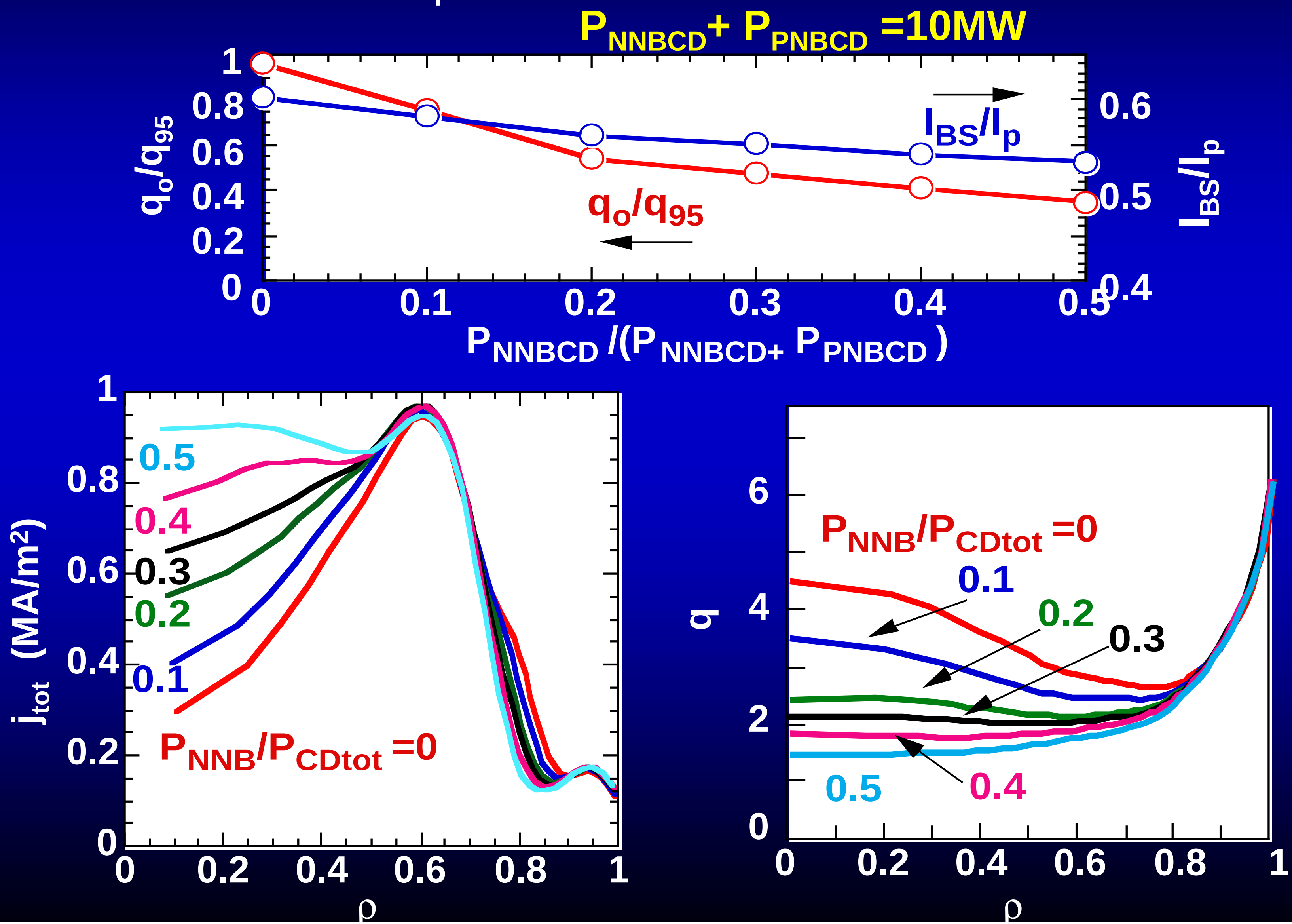
CD: 350keV/0MW, 85keV/10MW,
Heat: 85keV/6.7MW, B_t=2.5T





q_o/q_{95} can be controlled by NBCD

Total NB Power, 16.7MW, I_p=1.85MA, B_t=2.5TNNB : 350keV, P-NB: 85keV

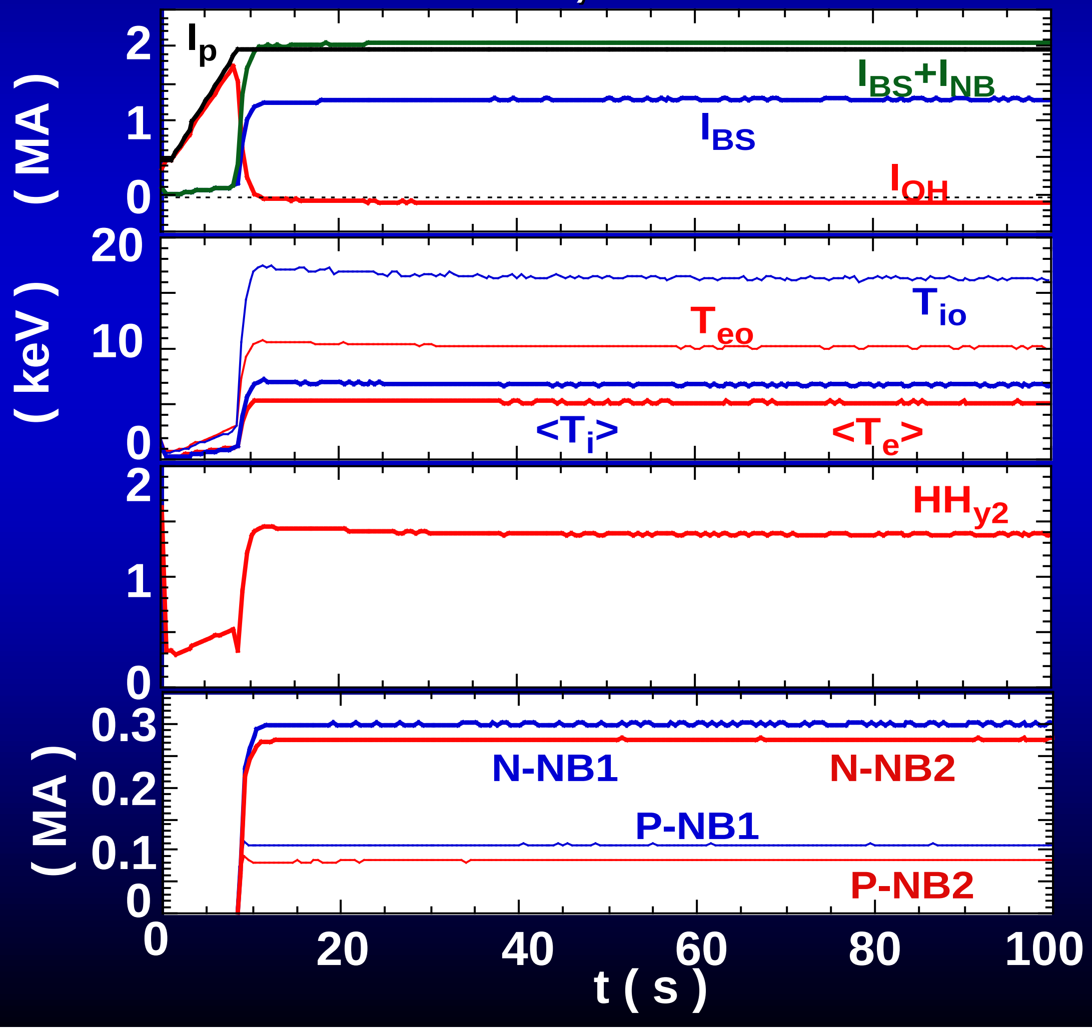


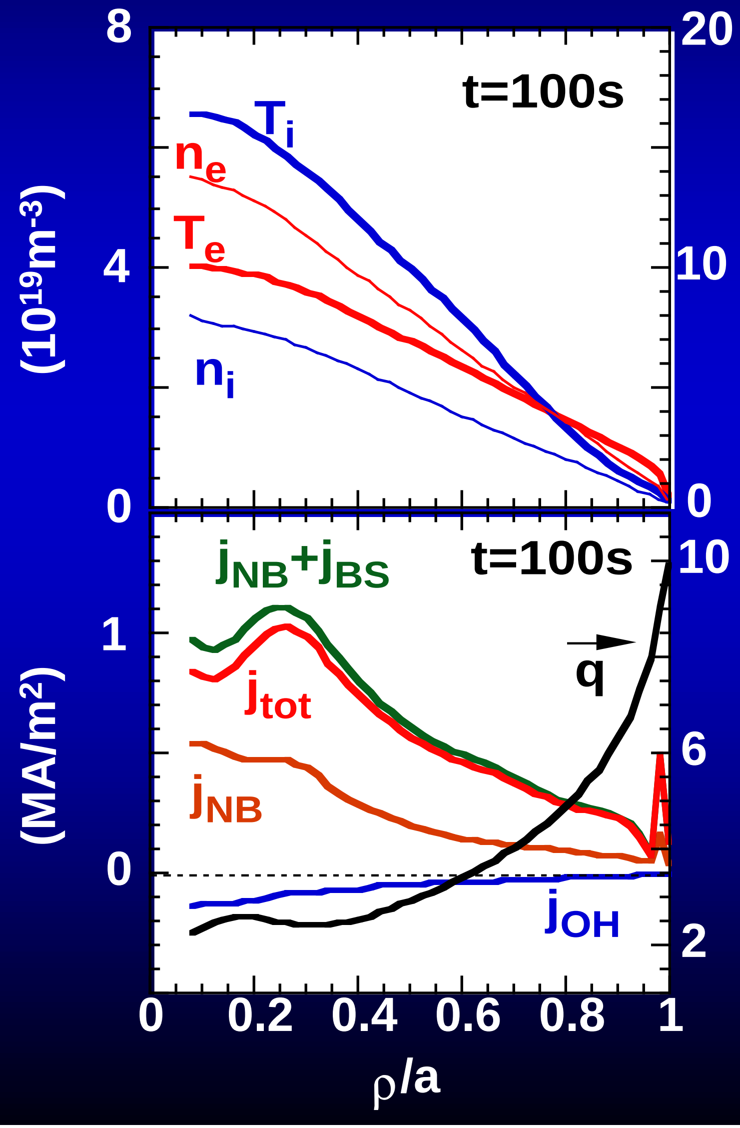
Transport Simulation for High β_p H-mode

Time Dependent TOPICS with Multi-Beam 1D Fokker-Planck NBCD Code

Global Parameter becomes steady-state within several tens seconds

HH_{y2}=1.4, N-NBCD=3MW,
P-NBCD=3.3MW, P-NBH=6.7MW





Almost uniform E_z is formed at 100s

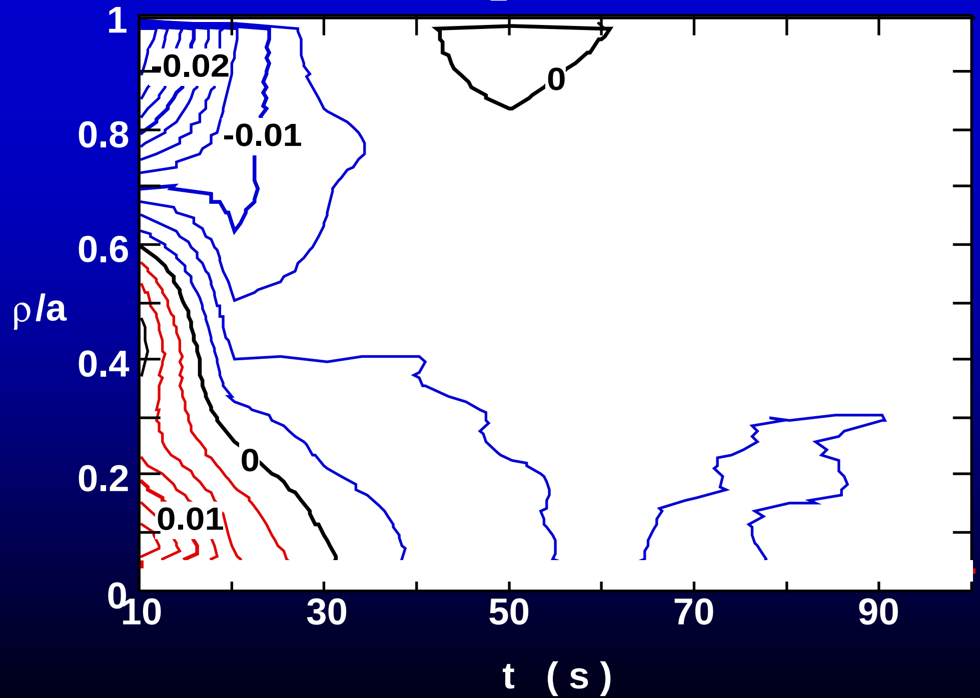
Current profile at 100s is very close to steady-state value

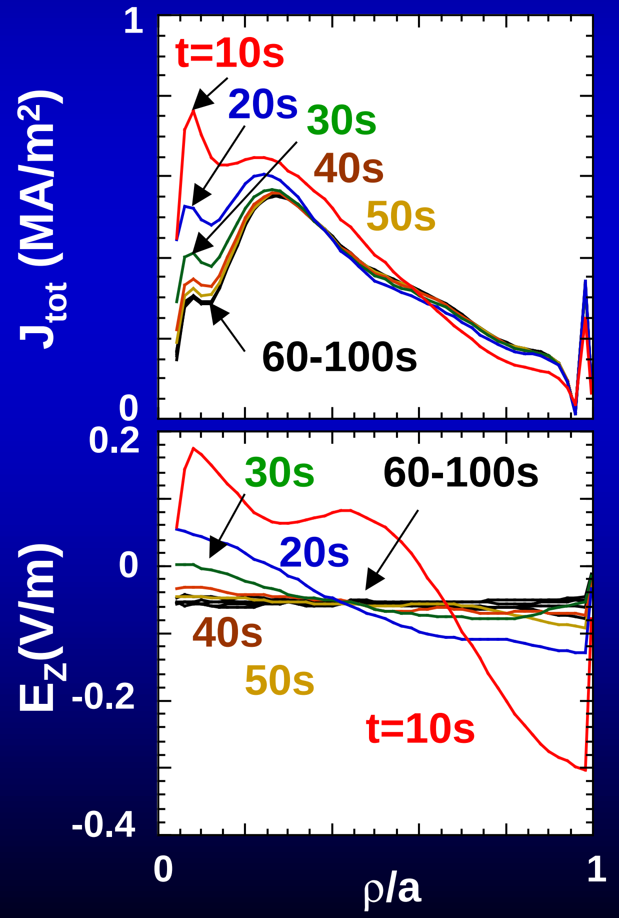
R~2.8m, a~0.85m, κ~1.8, l_i~1, Z_{eff}~2, $<T_e>$~5keV

L_i~1.76μH, R_Ω~6.08x10$^{-8}\Omega$,

$\rightarrow$ $\tau_{L/R}$ ~ 28.9 s

Contour Plot of E_Z (V/m)



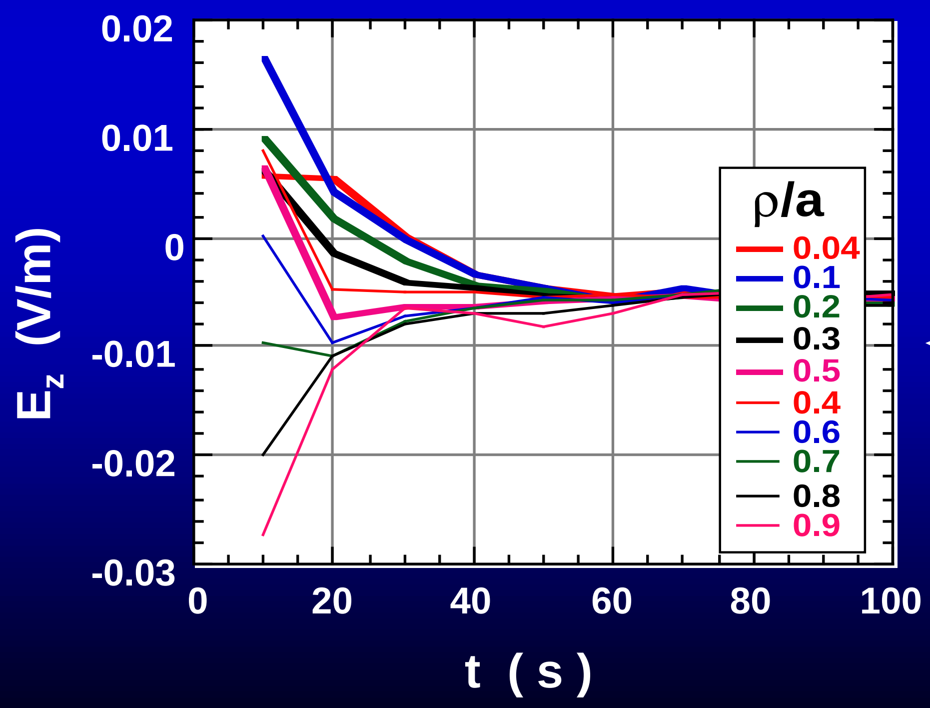


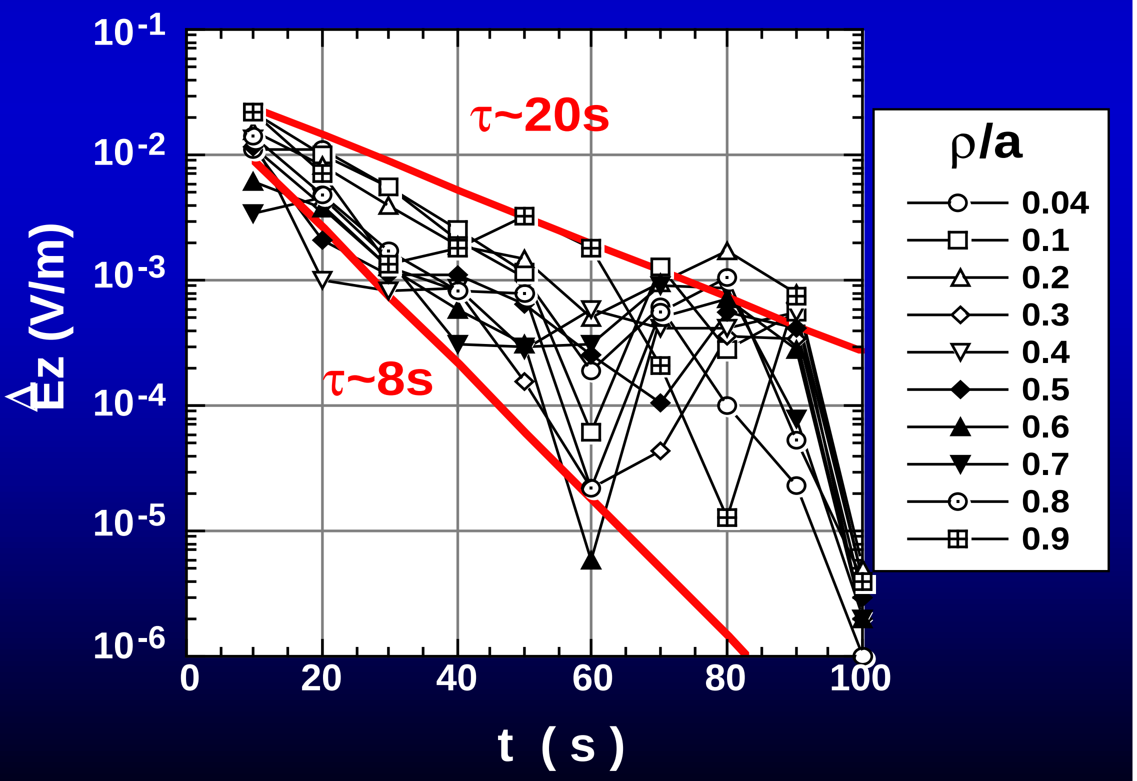
Current Penetration Time

R~2.8m, a~0.85m, κ~1.8, l_i~1, Z_{eff}~2, <T_e>~5keV

L_i~1.76μH, R_Ω~6.08x$10^{-8}\Omega$,

➡ $\tau_{L/R}$ ~ 28.9 s



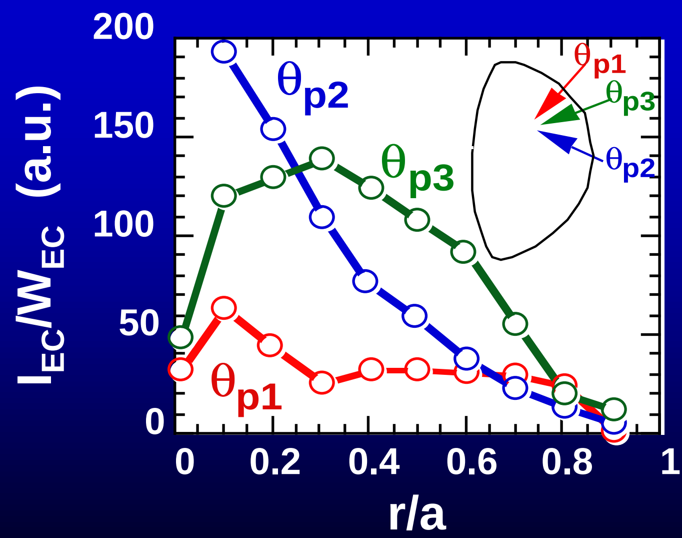


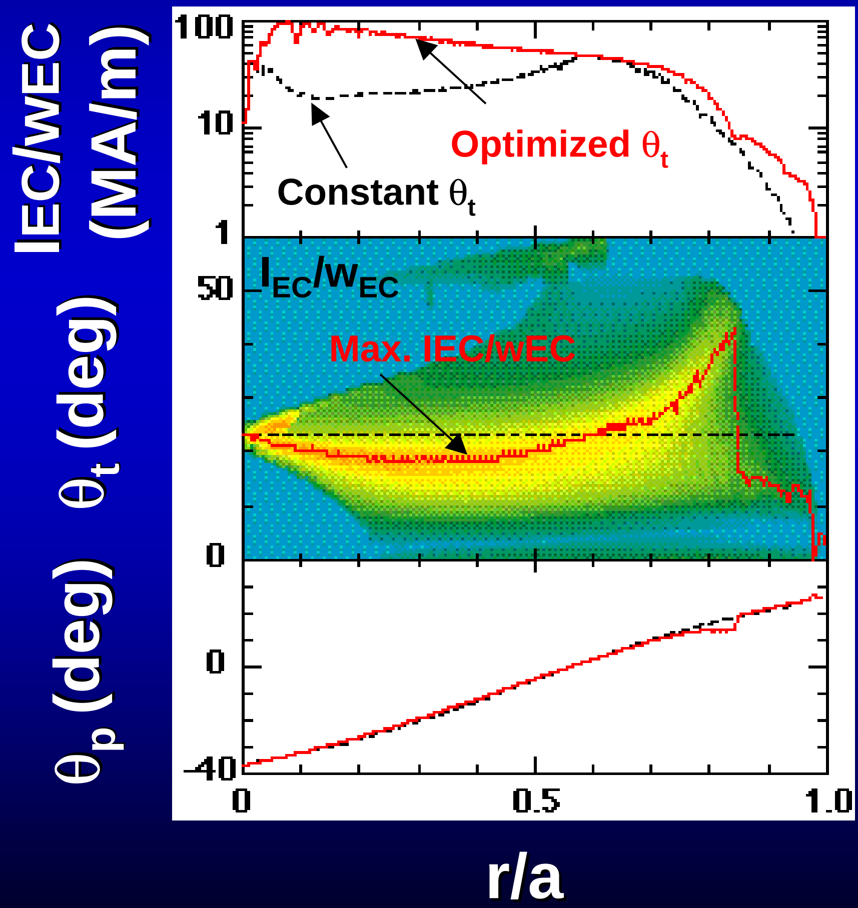
Optimization of ECCD

for Local Current Profile Control

Optimization (for NTM suppression)
- Maximize driven current density
- Minimize width of driven area

By selecting
- Toroidal Injection angle
- Poloidal Injection angle
- Poloidal location of launcher





Strongly Peaked EC Driven Current

ECCD :110GHz Fundamental O-mode (4MW)

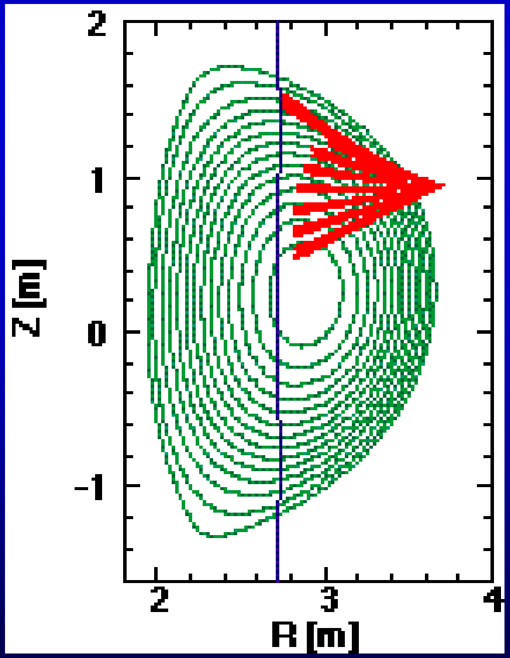
$n_o = 5\times10^{19} m^{-3}$, $T_o = 15keV$

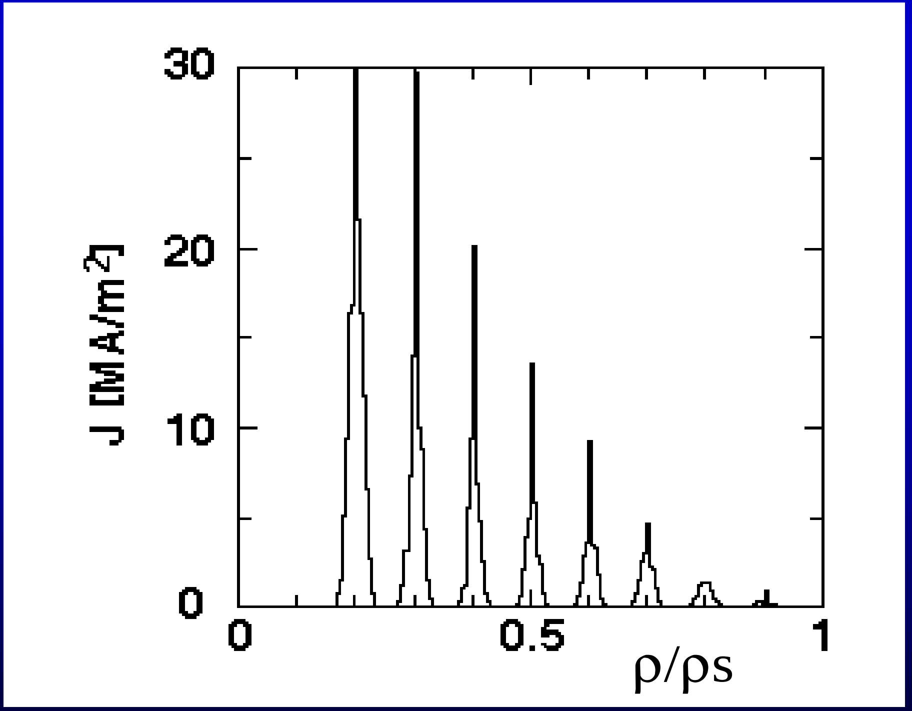
$n = n_o\{0.95\,(1-\rho^2)^{0.5} + 0.05)\}$

$T = T_o\{0.95\,(1-\rho^2)^{1.5} + 0.05)\}$

Driven Current <0.2MA at r/a~0.5

ECCD : not main CD tool
only for local j control





SUMMARY

- 3MW of N-NBCD, 3.3MW of P-NBCD and 6.7MW of P-NBH
  Full CD of $\leq$ 2MA with HH_{y2} ~0.8-1.8
- Integrated Performance will be tested at 1.5MA with HH_{y2}=0.8-1.8 for wide density regime (n_e/n_{GW}<1.06)
- Steady-state Solution of Reversed Shear can be expected
  Full CD of 1.85MA Reversed Shear with HH_{y2} ~1.8
  Control of N-NB Power is important to control q_{axis}
- For High β_p H-mode scenario, 100s is enough to reach nearly steady-state current profile

Remained Issues

- **Operation Scenario for Reversed Shear**
  - Ramp-up Scenario?
    Low dI_p/dt with limited CD/H tools
- **Optional Tools for Peripheral CD?**
  - Additional off-axis P-NBCD?
  - Lower Hybrid Current Drive?
  - Additional ECCD with wide deposition?
- **Momentum Control?**
  - Stabilization of MHD instablility
  - Control of Internal Transport Barrier