Solenoid-Free Startup Experiments in DIII-D

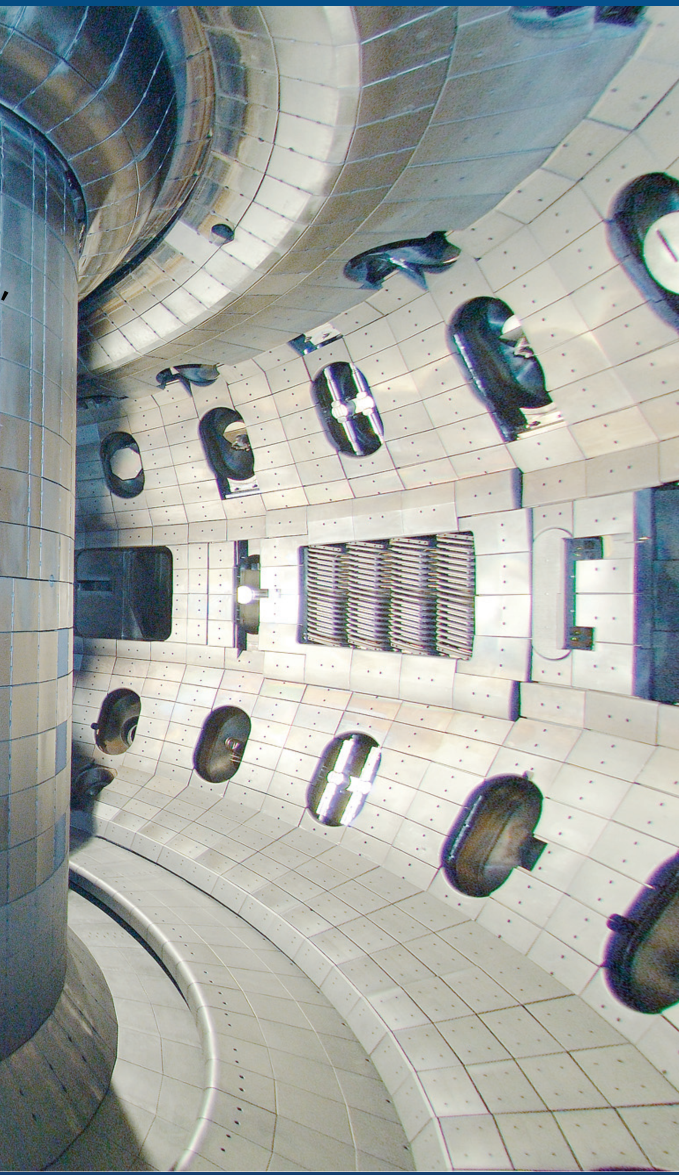
by

J.A. Leuer[1]

with

G. Cunningham[2], N.W. Eidietis[1], D. Gates[3], S-H. Hahn[4], D.A. Humphreys[1], A.W. Hyatt[1], G.L. Jackson[1], J. Lohr[1], M. Murakami[6], D. Mueller[3], Y-K. Oh[4], J.M Park[6], P.A. Politzer[1], R. Prater[1], A.C. Sontag[6], P.T. Taylor[1], M.L. Walker[1], S-W. Yoon[4], J.H. Yu[5]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186, USA
[2]UKAEA Fusion, Culham Science Center, United Kingdom
[3]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[4]National Fusion Research Institute, Daejeon, Korea
[5]University of California - San Diego, La Jolla, CA, USA
[6]Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA



Presented at
Twenty-Third IAEA Fusion Energy Conference
Daejeon, Republic of Korea

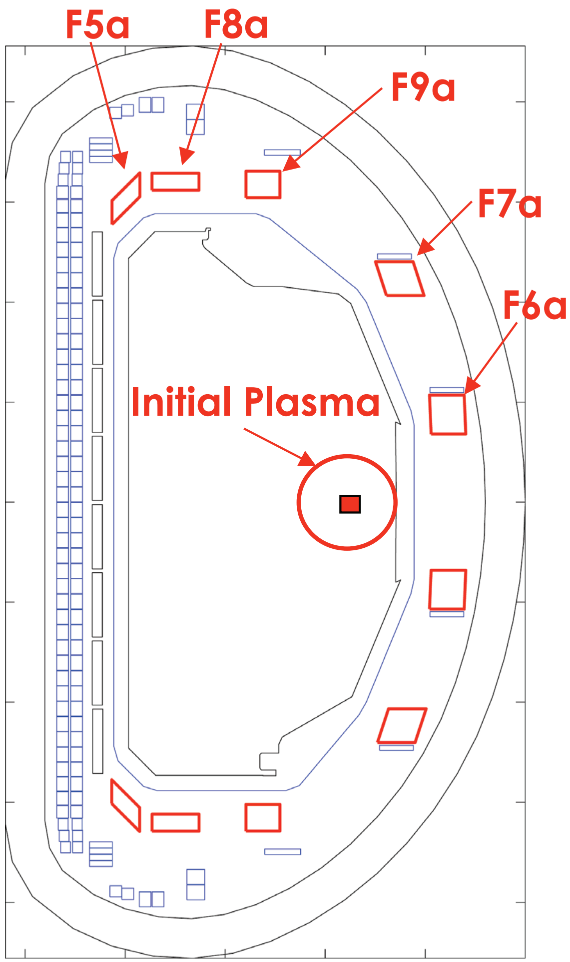
October 11-16, 2010

Abstract

A series of DIII-D experiments was performed to investigate the potential for initiating plasma current using poloidal field (PF) coils located outside the central solenoid region of the DIII-D tokamak, i.e. Solenoidless startup (SS). Inductive plasma current startup was achieved using only divertor and outer PF coils and strong electron cyclotron (EC) heating. Synergistic experiments were carried out using a standard solenoid generated plasma that transitions to non-inductive current drive (CD) using: EC, neutral beam (NB), and fast wave (FW). Conditions obtained in these latter experiments allowed a wide range of parameters to be studied than were obtained in SS experiments, and were designed to quantify the present DIII-D CD capabilities in low current, wall-limited plasmas. The key goal is to transition from the SS scenario to a fully noninductive CD scenario and to establish the feasibility of plasma initiation in a solenoidless tokamak, a requirement for viability of the low aspect ratio (LAR) path to fusion energy. Plasma current to 170 kA was achieved in the SS configuration limited by coil and power supply constraints in the DIII-D system. This was achieved utilizing ~2 MW of EC preionization and heating. Flux conversion to plasma current was only slightly degraded relative to standard DIII-D startup. In the SS scenario, ECCD levels were small and prior to gaining closed loop radial position control, NBCD efficiency was decreased by plasma radial motion. Experiments using our standard solenoid initiation followed by noninductive CD provided valuable insight into the present DIII-D capabilities in plasmas typical of the SS configuration. While full noninductive current drive has been achieved in low current (340 kA), diverted, H-mode helium plasmas [T.C. Simonen, Phy. Rev. Lett. **61**, 15 1988], the present DIII-D capability in a limited, L-mode plasmas has not been previously evaluated. Preliminary CD results indicate substantial non-inductive current can be driven in a limited, L-mode plasma; however, self-sustaining levels with our present 6 co-injection system will require further optimization and possibly H-mode operation. This work was supported by the US Department of Energy under DE-FC02-04ER54698.

Overview

- **Program Objectives**
  - DIII-D startup using non-solenoid coils
  - Develop target for non-inductive current drive
  - Test non-inductive CD using conventional startup
- **Major Results**
  - Generated 170 kA in solenoidless configuration
  - Achieved good flux/Ip conversion efficiency
  - Limited plasma believed to restrict non-inductive CD



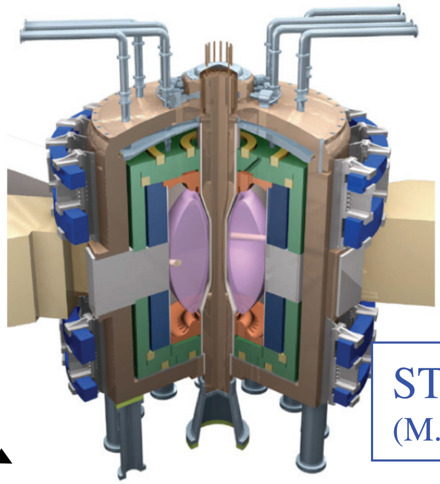
OUTLINE

- **Scenario development**
- **Solenoidless experiments**
- **Conventional limited plasma experiments**

MOTIVATION: Solenoidless Startup Benefits Compact Design

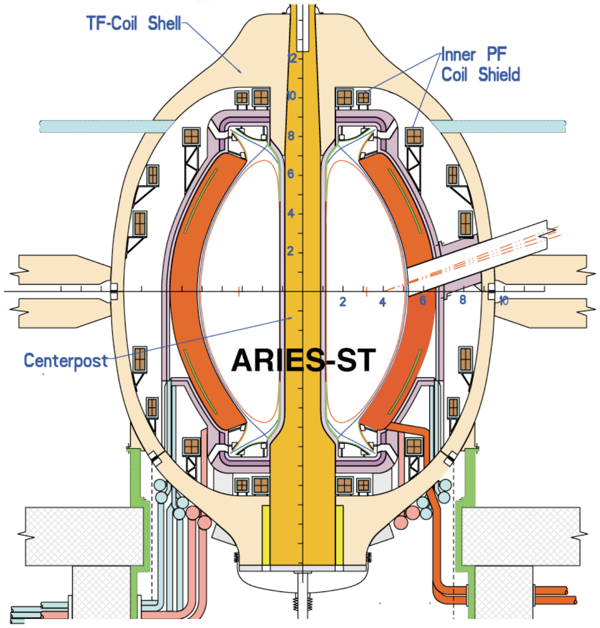
"Solenoid-free plasma startup is essential for viability of ST concept" *

Essential design aspect for ARIES-RS & ST-CTF



ST-CTF
(M. Peng)

- **Elimination of Inner CS coils reduces size**
  - Greatly reduces cost
  - Simplifies center post design
  - Allows for easy installation, maintenance
- **Scenario can benefit conventional tokamak**
  - Scenario superimposes over existing startup
  - Requires small outboard breakdown region
  - Projected to increase initial flux by ~5%-10 %

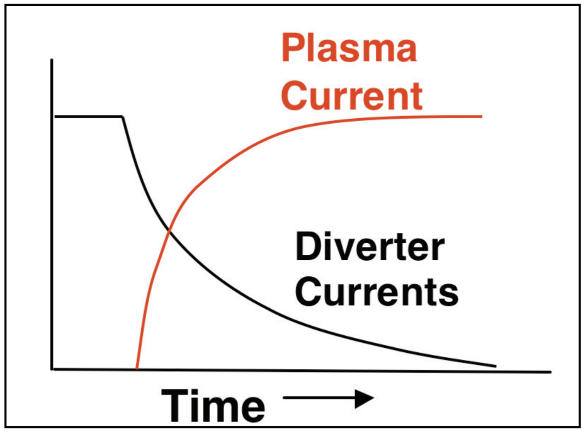


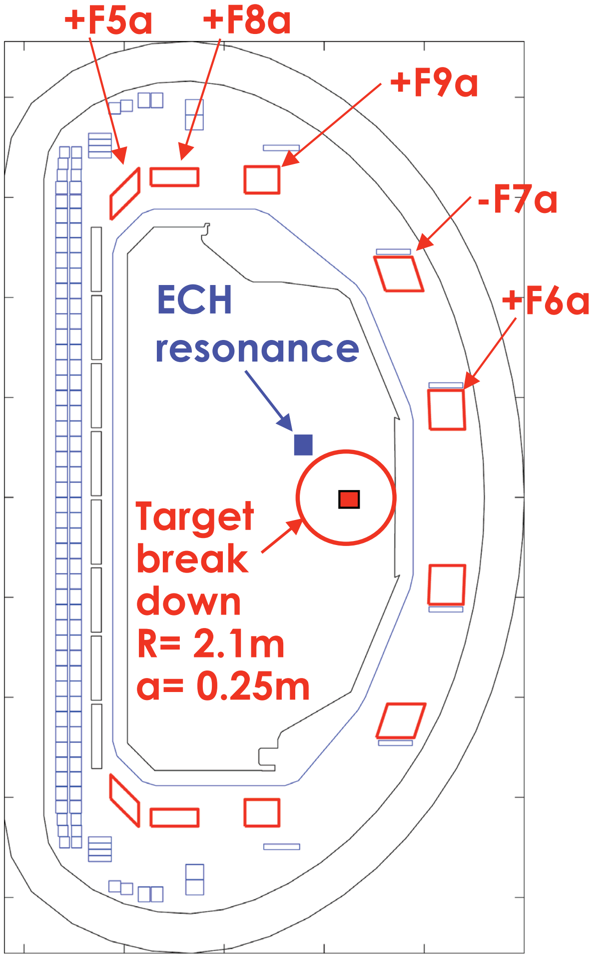
F. Najmabadi, FED 65, (2003) 143.

* R. Raman, 12th Inter. ST Workshop, Oct '06, Chengdu

Scenario Overview

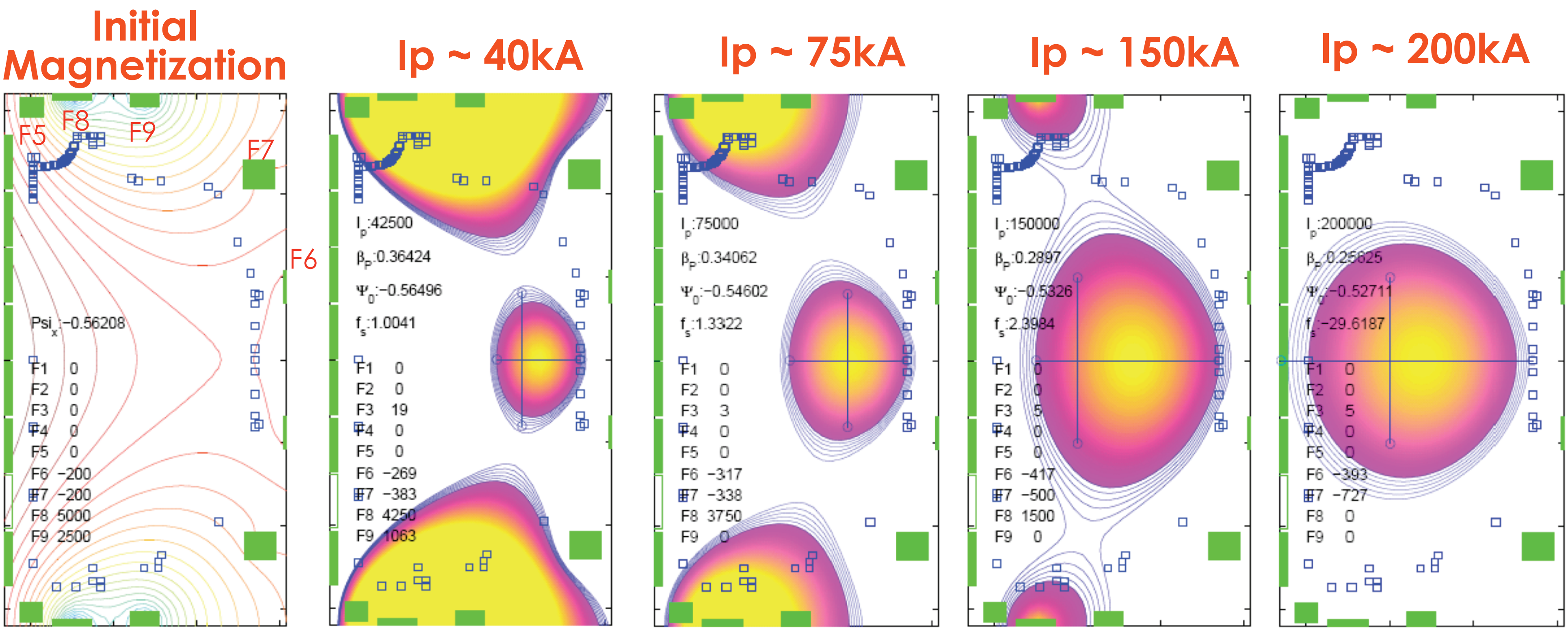
- **Null Formation**
  - High positive current in diverter coils F5, F8 & F9
  - Negative current in F7 to produce null in plasma
  - Small positive current in F6 to optimize null
- **Current Ramp**
  - High ECH power initiated prior to ramp
  - Maximum ramp-down rate in diverter coils
  - F7 maintained to provide radial position
  - F-coil current inductively transferred to plasma (Lenz's Law)



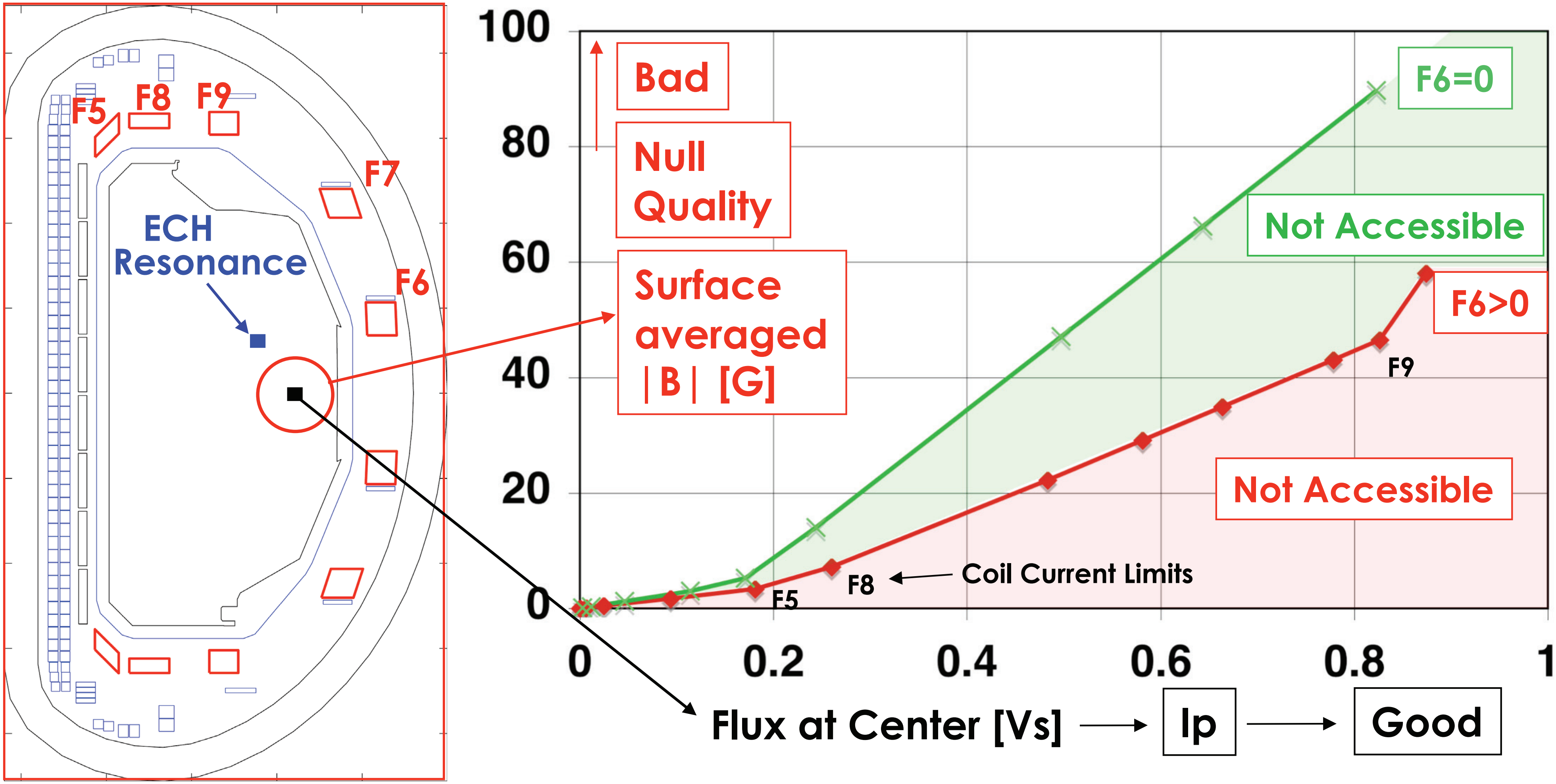


Model Equilibria Provide Valuable Design Insight

- **Assumed flux trajectory provides basis for scenario**
  - Preliminary studies showed 1st order null formation possible
  - Achieved with both F6 & F7 negative
  - However, plasma vertically unstable during initial formation

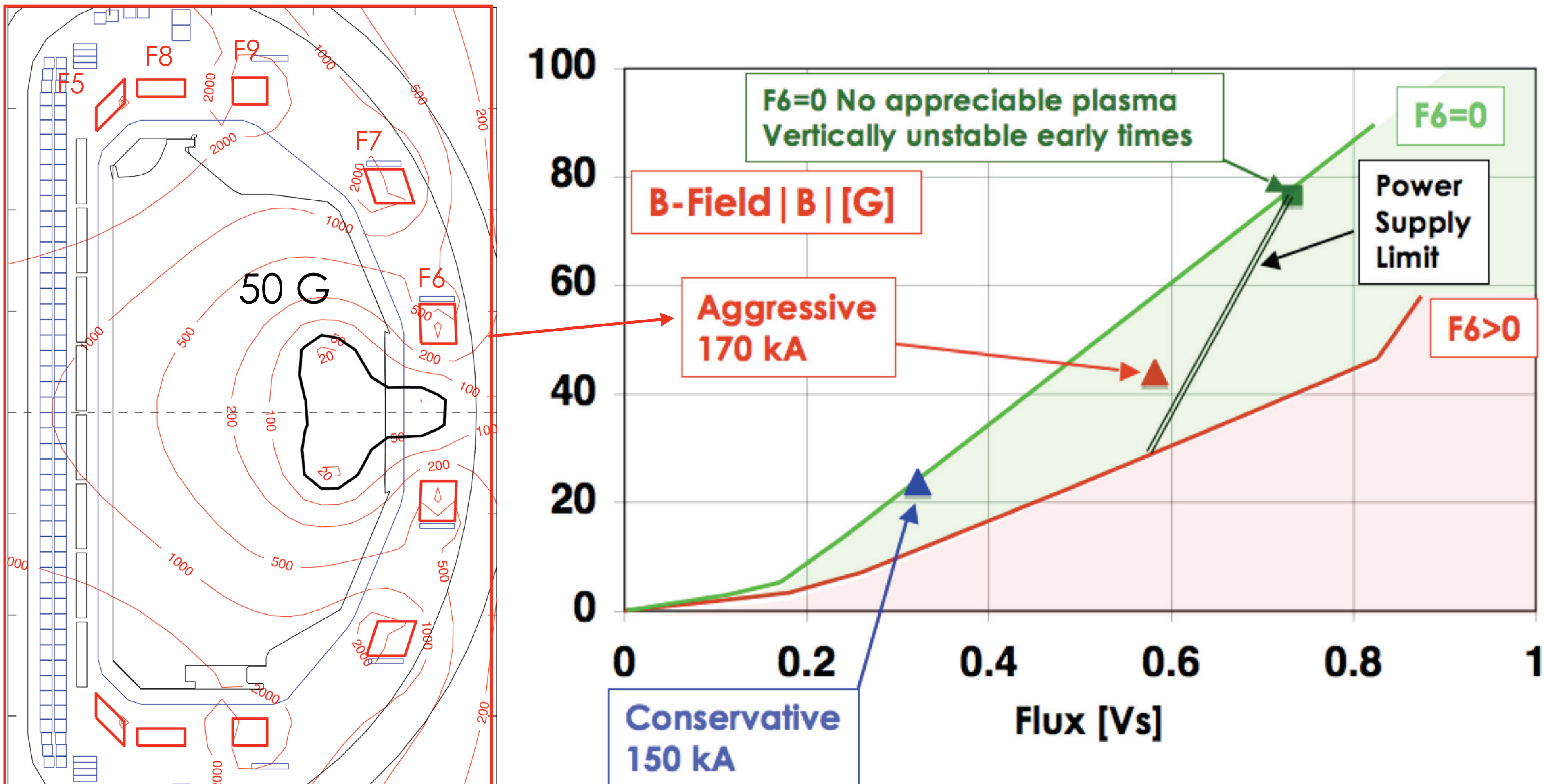


Startup Properties Best Quantified in Null Quality vs Flux Space at Initial Magnetization (IM) State

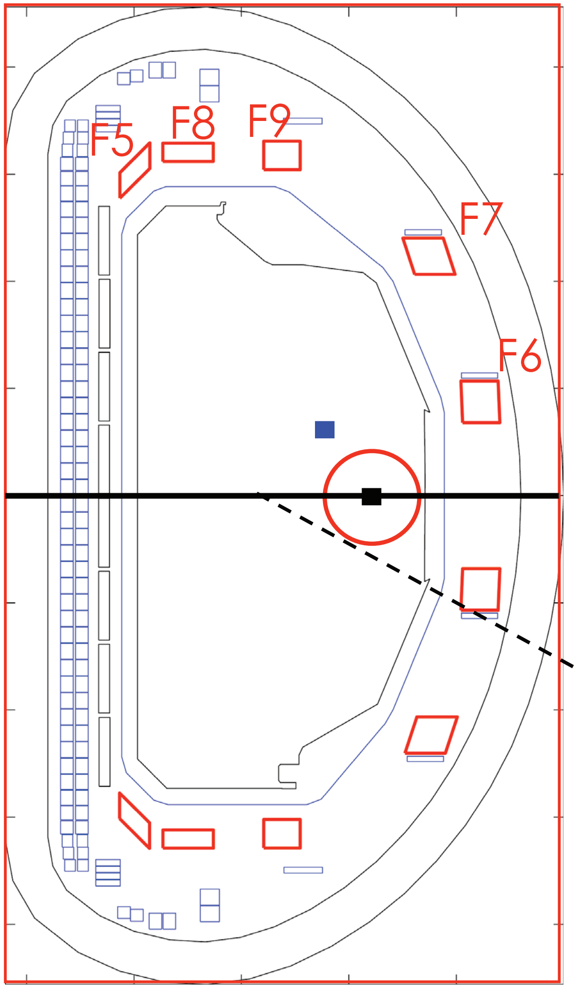


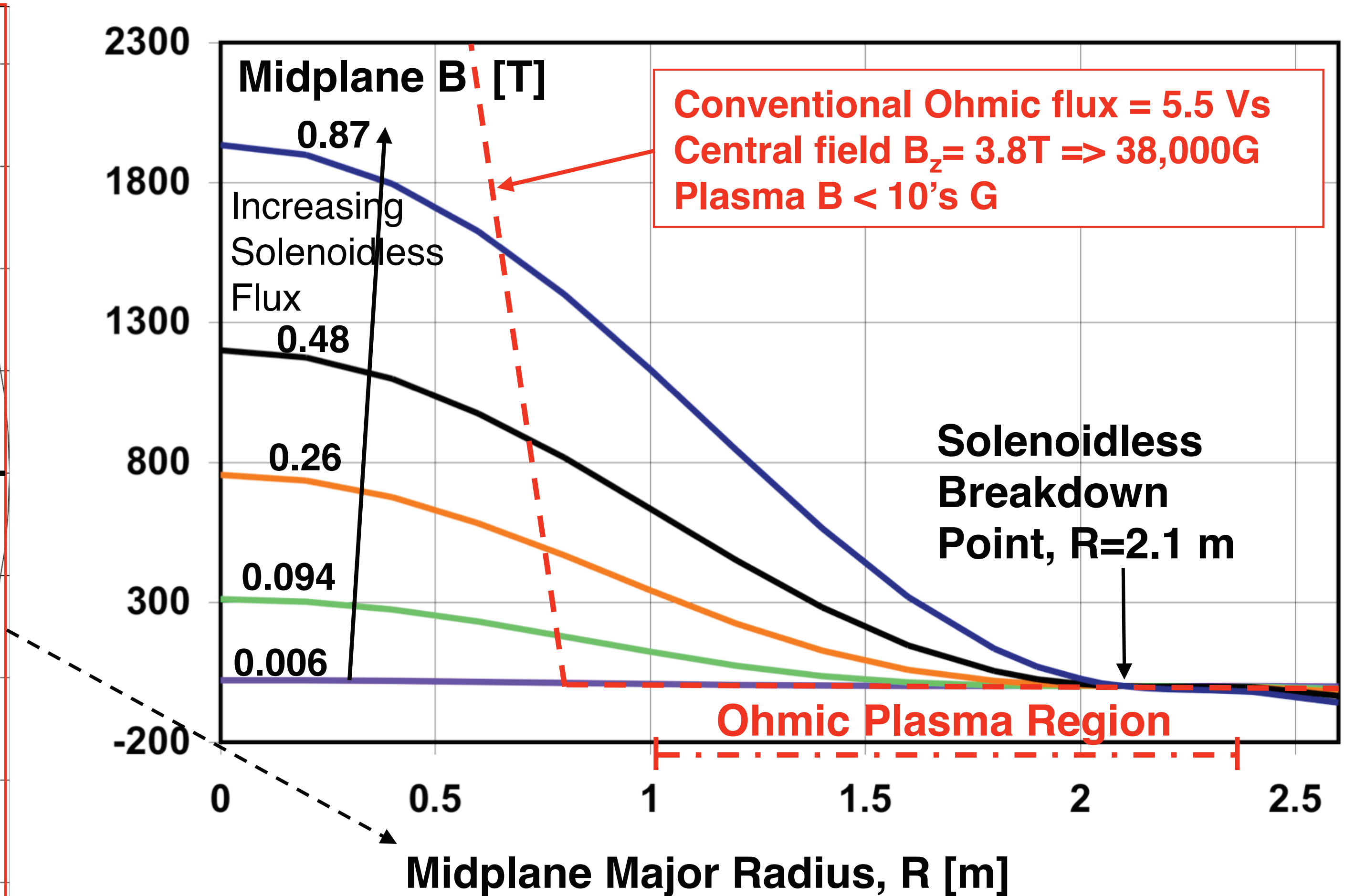
NOTE: Conventional DIII-Startup achieves 5.5 Vs with B < 10 G over most of plasma Chamber

Startup Properties Best Quantified in Null Quality vs Flux Space at Initial Magnetization (IM) State

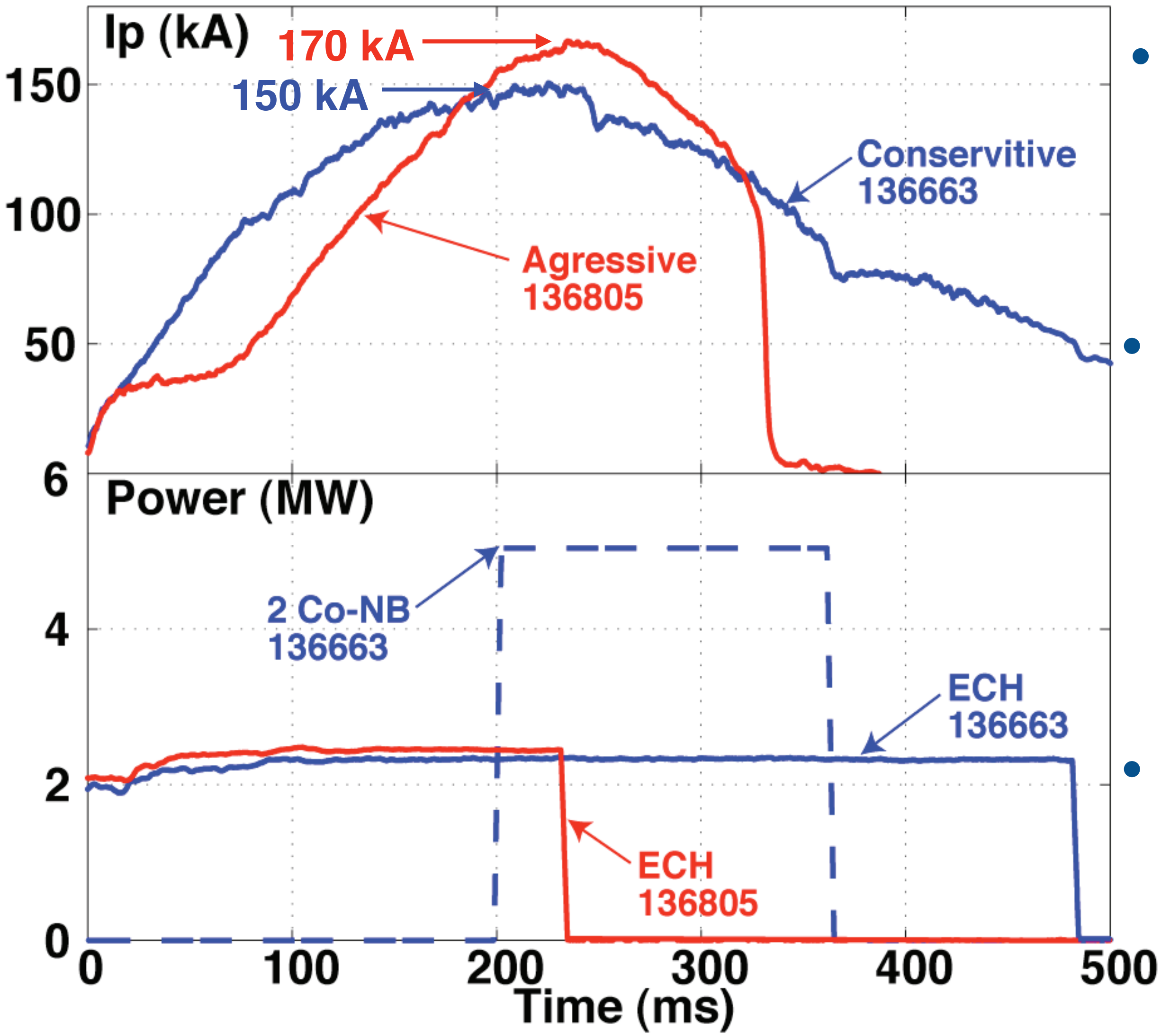


Relative to Solenoidless DIII-D's Conventional Ohmic Startup Produces Large Null and Lots of Flux





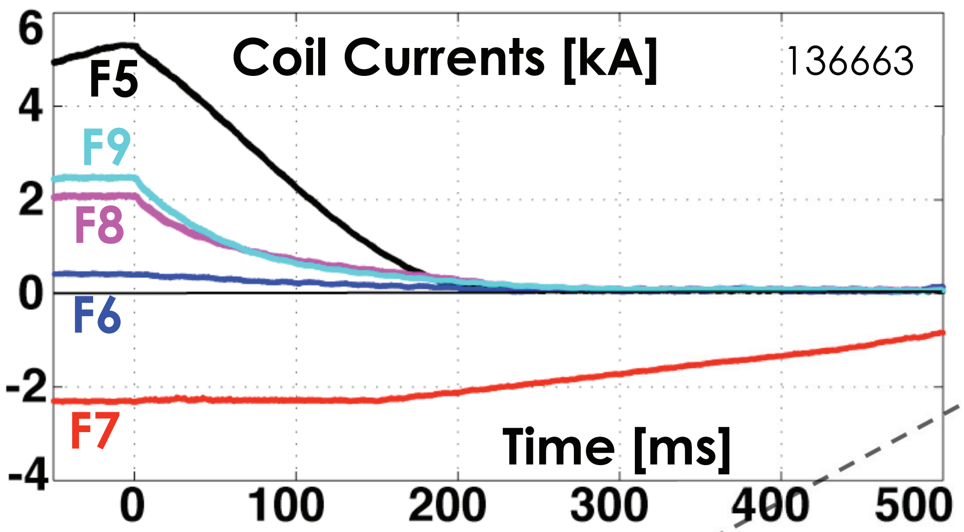
Good Experimental Success Achieved ➡170 kA

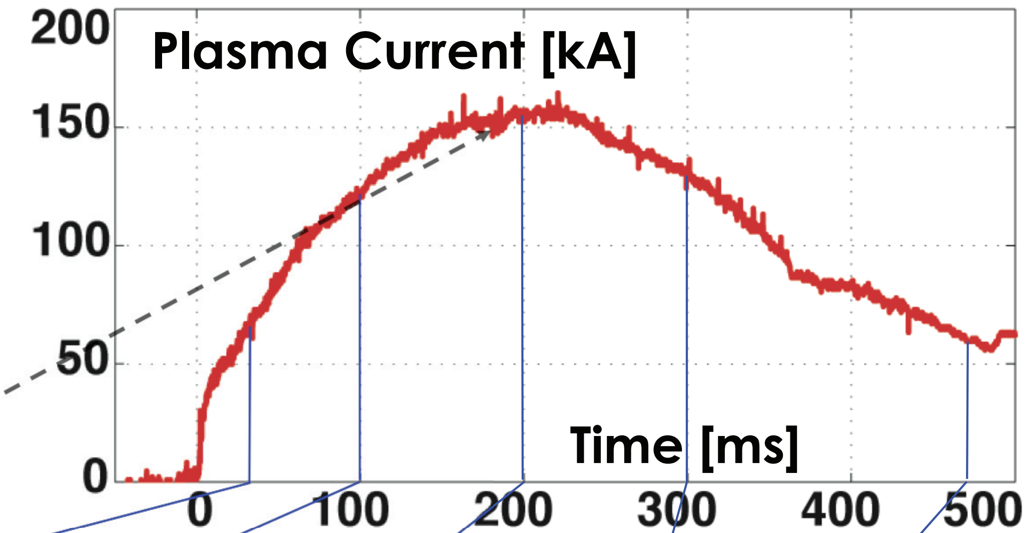


- **Two 1/2 day Experiments**
  - Conservative 150 kA
  - Aggressive 170 kA
- **ECH essential for breakdown and heating**
  - 4 gyrotrons utilized
  - t_{on} = -15 ms pre-ionization
  - 136805 250 ms pulse limit
- **2-Co Beams into 136663**
  - Limited NBCD
    Lack of radial position (R_p) control

Conservative Scenario Worked Well
Flux Utilization Similar to Normal DIII-D ECH Startup

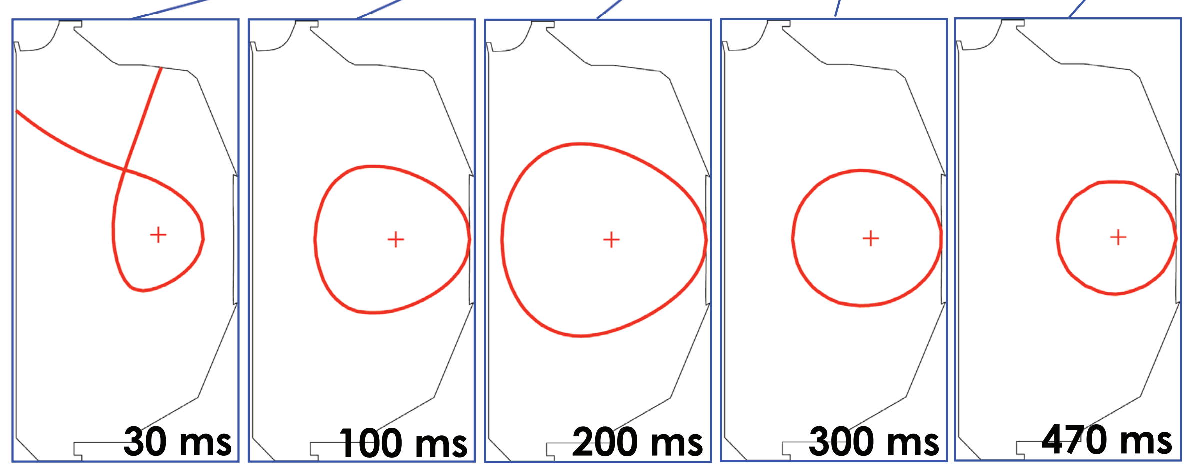
Flux Conversion Efficiency, $C_{ejima} = \Delta\Phi_{res}/(\mu_o R_p I_p) = 0.33$ Best DIII-D ~ 0.3





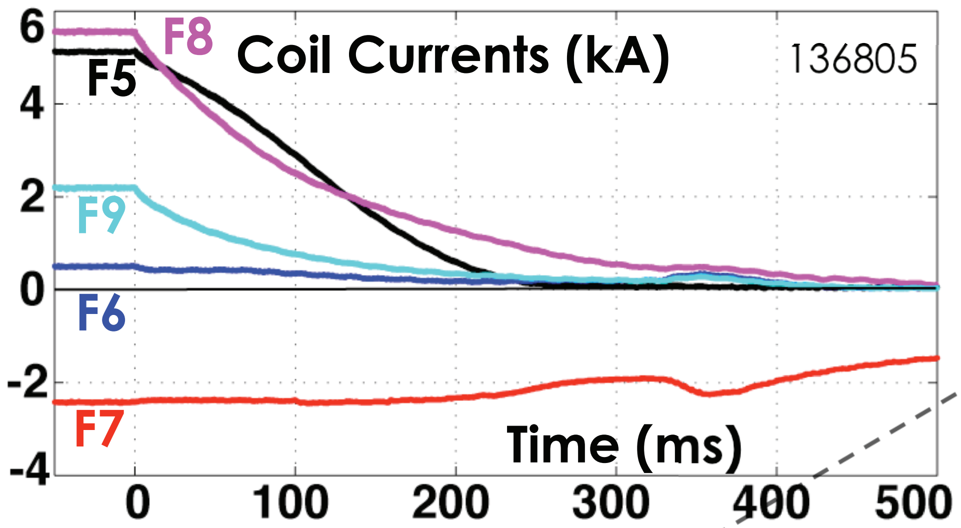
At t= 200ms

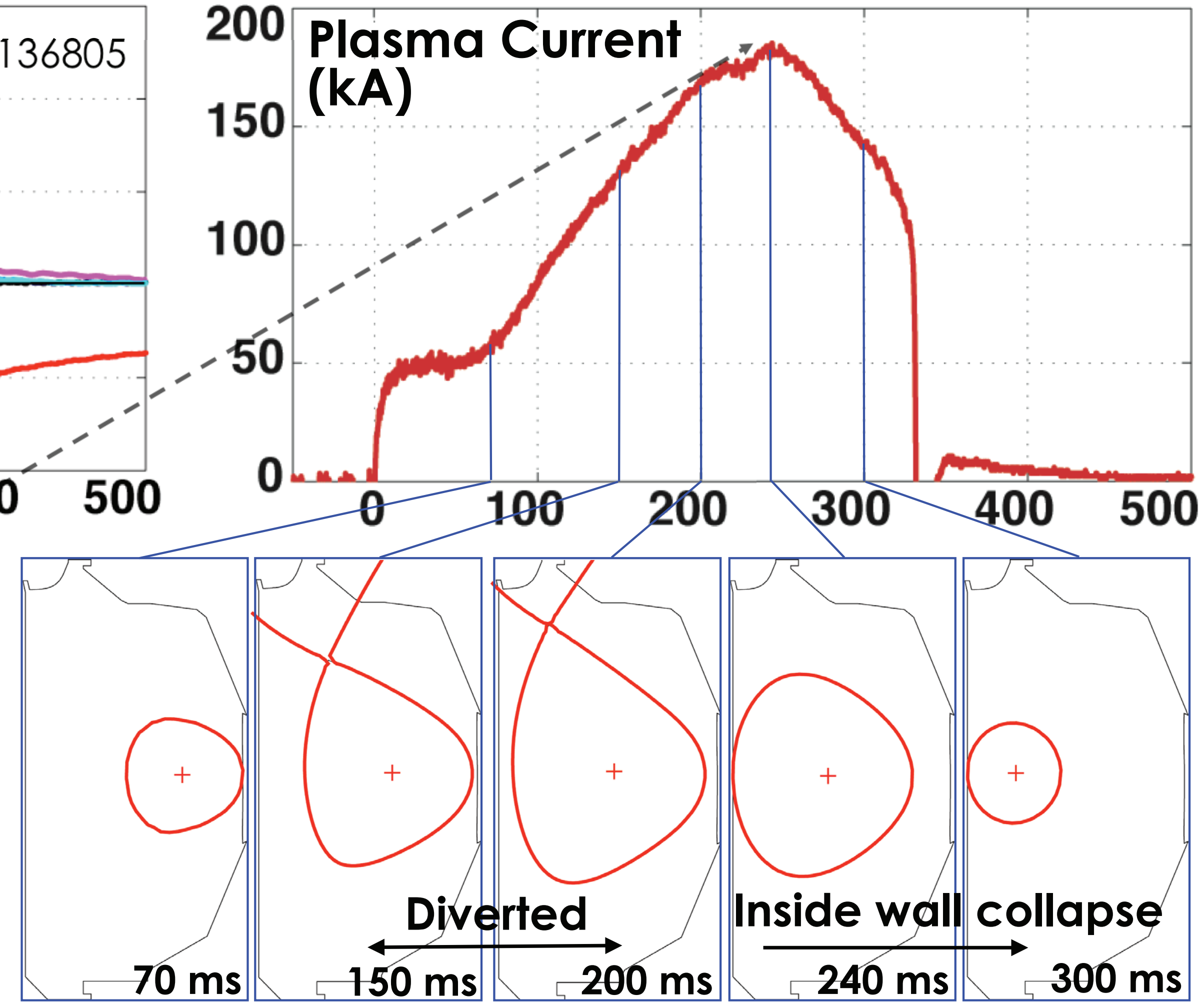
- I_p = 150 kA
- T_e = 1.2 keV
- n_e = $1.7\ 10^{-19}$
- τ_e = 13 ms
- Z_{eff} ~ 4.5



Aggressive Scenario Achieved Maximum Current Short Diverter Period Seen Prior to Coil Current Collapse

Early time I_p dip reduces flux conversion efficiency, C_{ejima} = 0.89





At t= 240ms

I_p = 170 kA

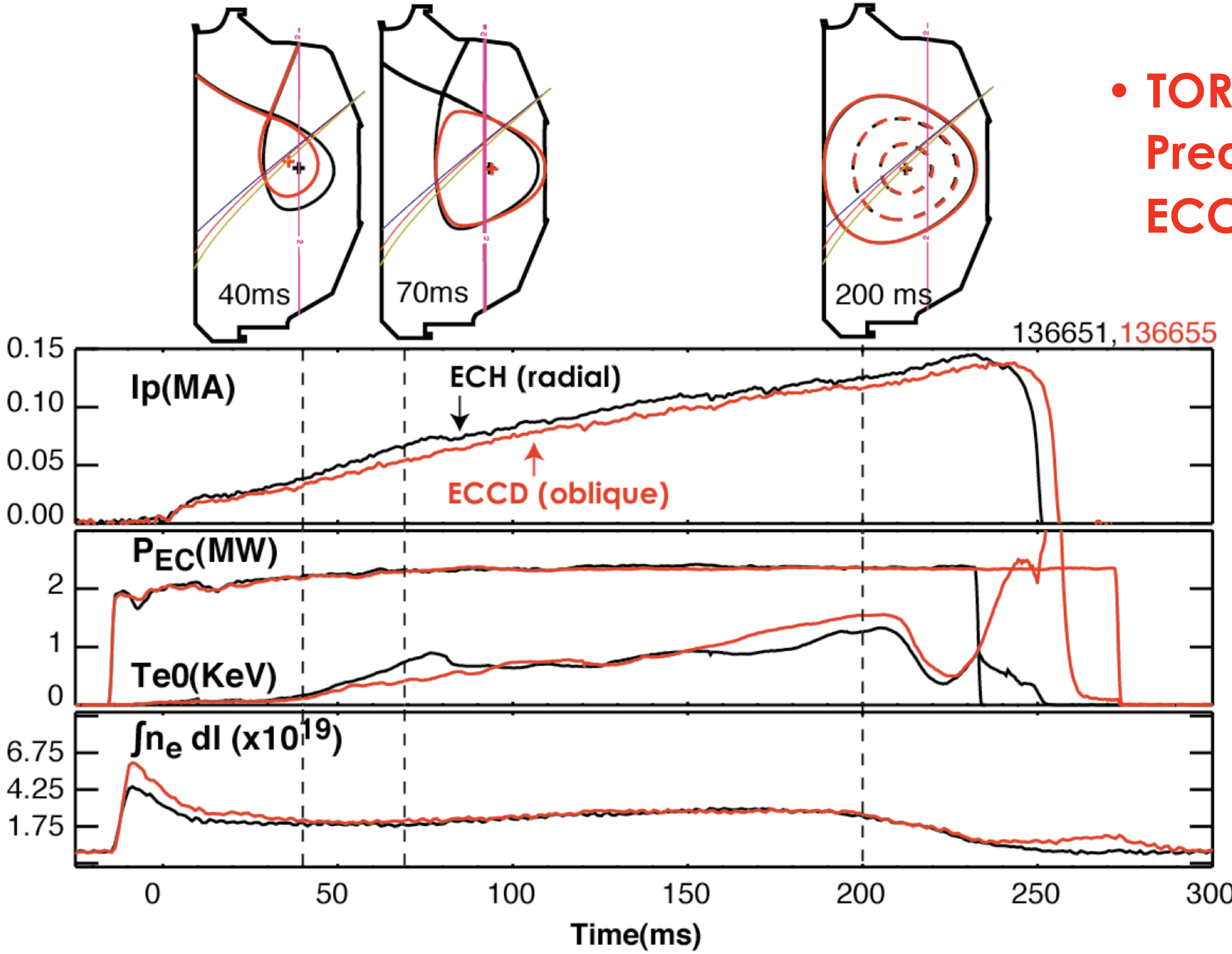
T_e = 2.1 keV

n_e = 1.0 10^{-19}

τ_e = 10 ms

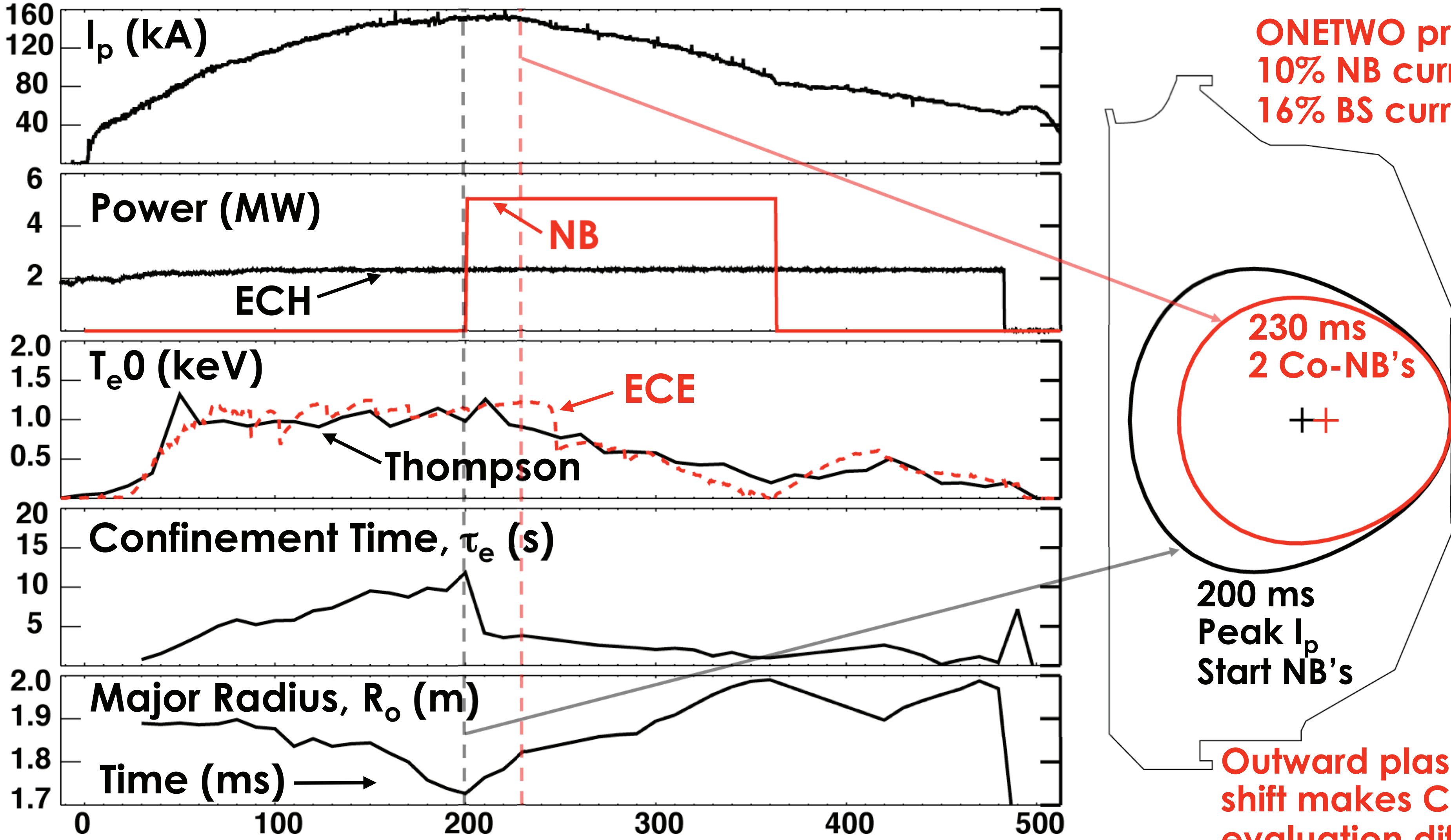
Z_{eff} ~ 4

No Evidence of ECCD in Preliminary Experiment (Heating Effectiveness May Dominate dI_p/dt, not ECCD)



- **TORAY & ONETWO Predict very low ECCD <2%**

Little Evidence of NB CD in Preliminary Experiment

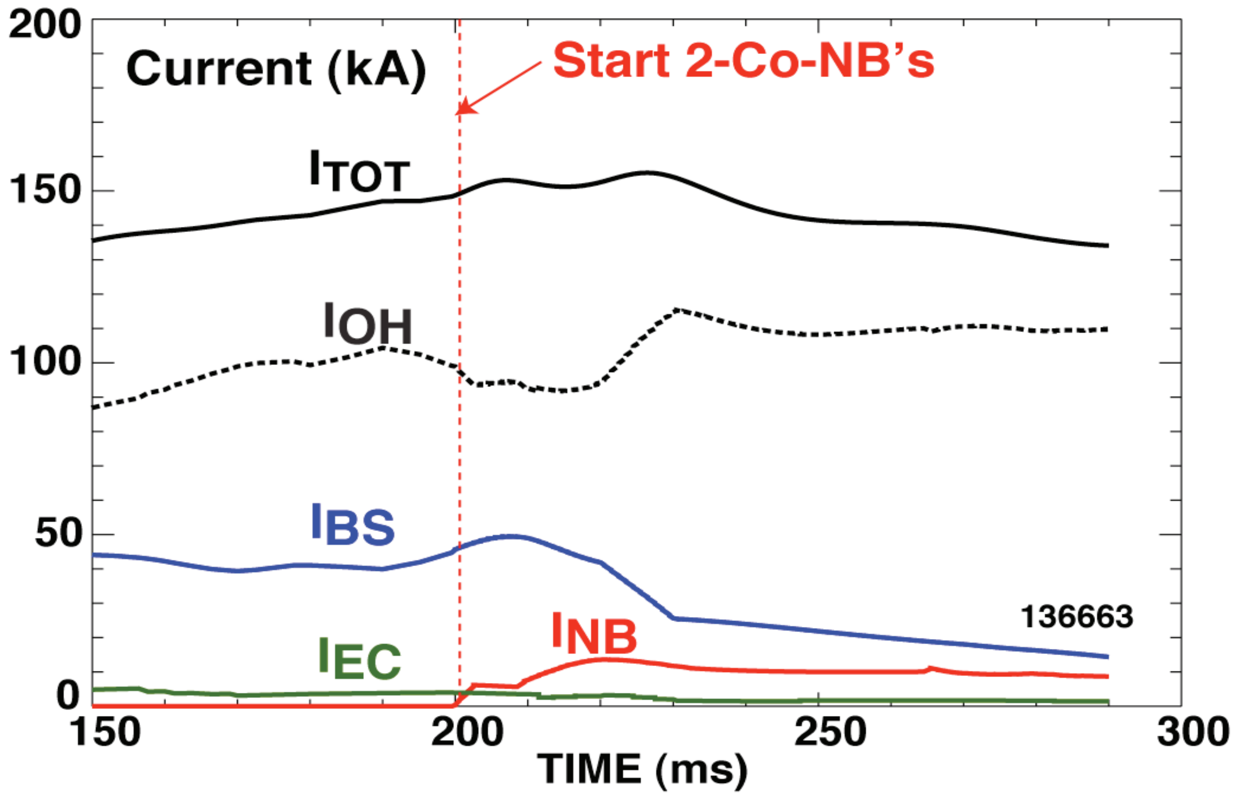


ONETWO predicts
10% NB current
16% BS current

Outward plasma
shift makes CD
evaluation difficult

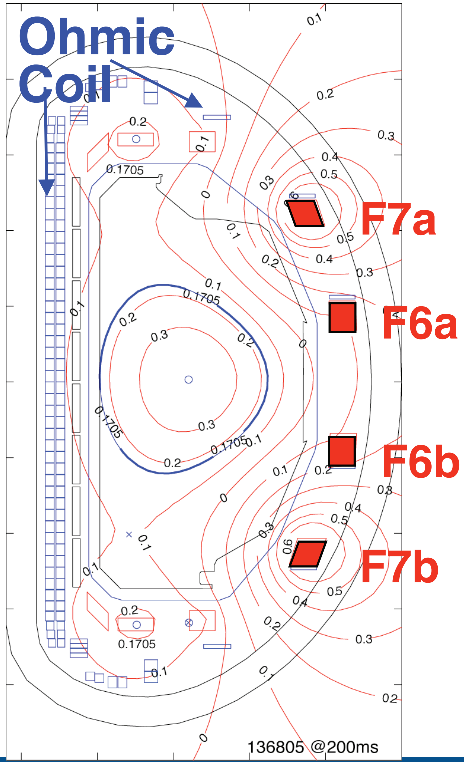
ONETWO Predicts Low Noninductive CD Fraction

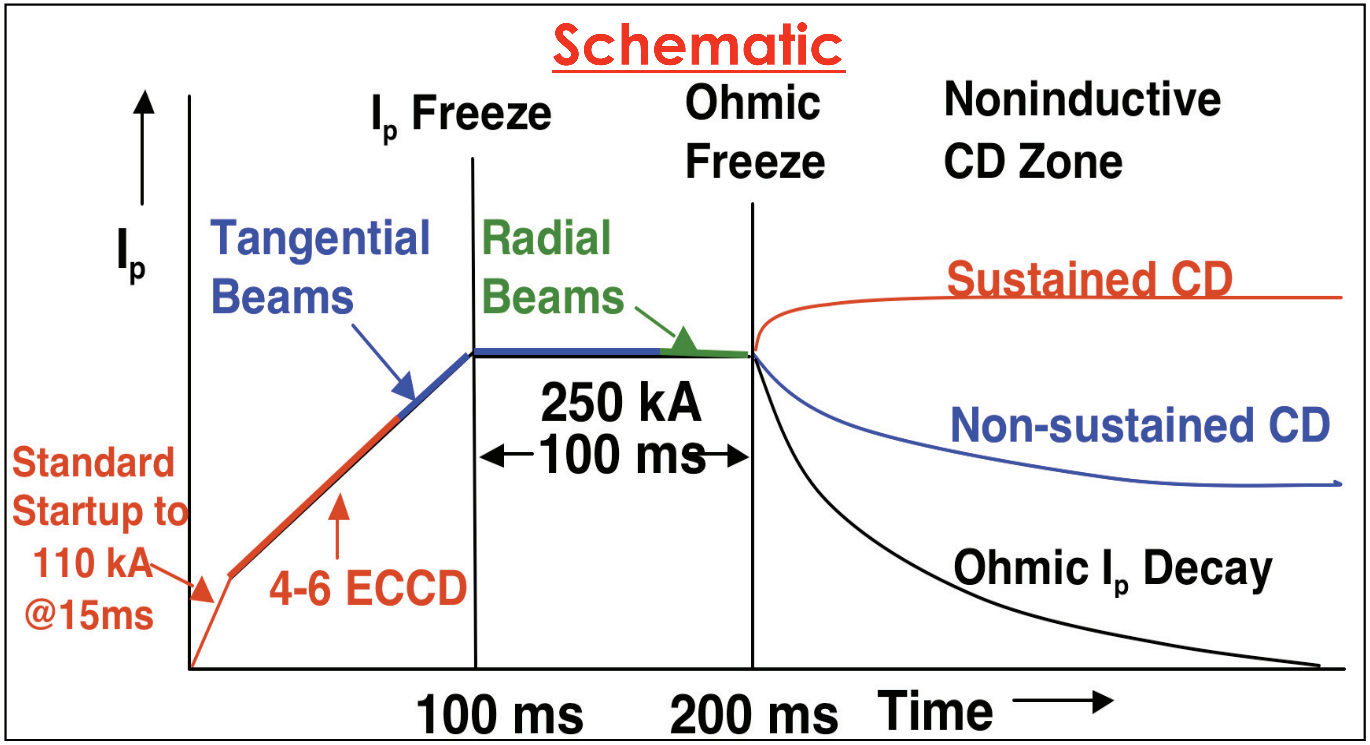
- **NB:** 2 tangential NB sources injecting ~ 5 MW between 200 & 360 ms
- **Model:** ONETWO/NEBEAM using 10 m/s^2 beam diffusion to match W_{mhd}
- **Limitation:** Large diagnostic uncertainty from high power into small plasma
- **CD:** NBCD ~ 10%; Bootstrap ~ 16%; ECCD ~ <2% (similar to TORAY-GA)



Noninductive CD Best Studied Using Conventional Ohmic Startup

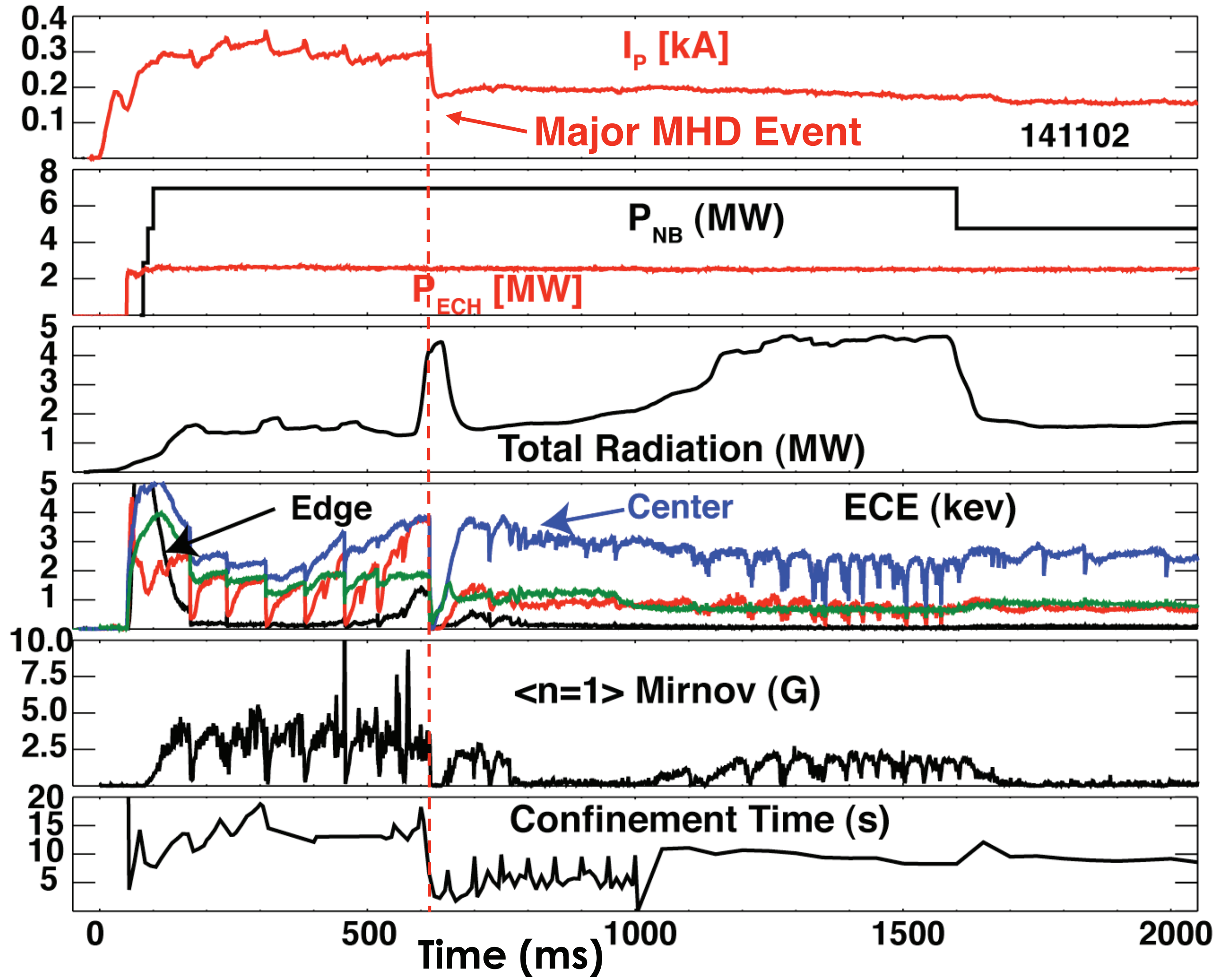
- **Objective:** Determine NBCD in well controlled, low I_p, limited plasma
- **Justification:** Generate target for solenoidless startup => LAR Concept
- **Scheme:** Ohmic + Outside F6 & F7 with handoff to NBCD (EC & FW)
- **Allocation:** 1/2 day => 30 Plasmas
- **Scan:** I_p; NB P_{ow}; ECH P_{ow}; n_e; κ; Fast Wave; NB Voltage





High Power Required for CD Causes Large MHD in Low Current (200–300 kA) Plasma

- MHD events were seen throughout campaign
- Strongly dependent on ECH, NB power and density
- Similar minor events present even in ECH only discharges
- Higher NB power and density seemed to suppress MHD but I_p decay still present

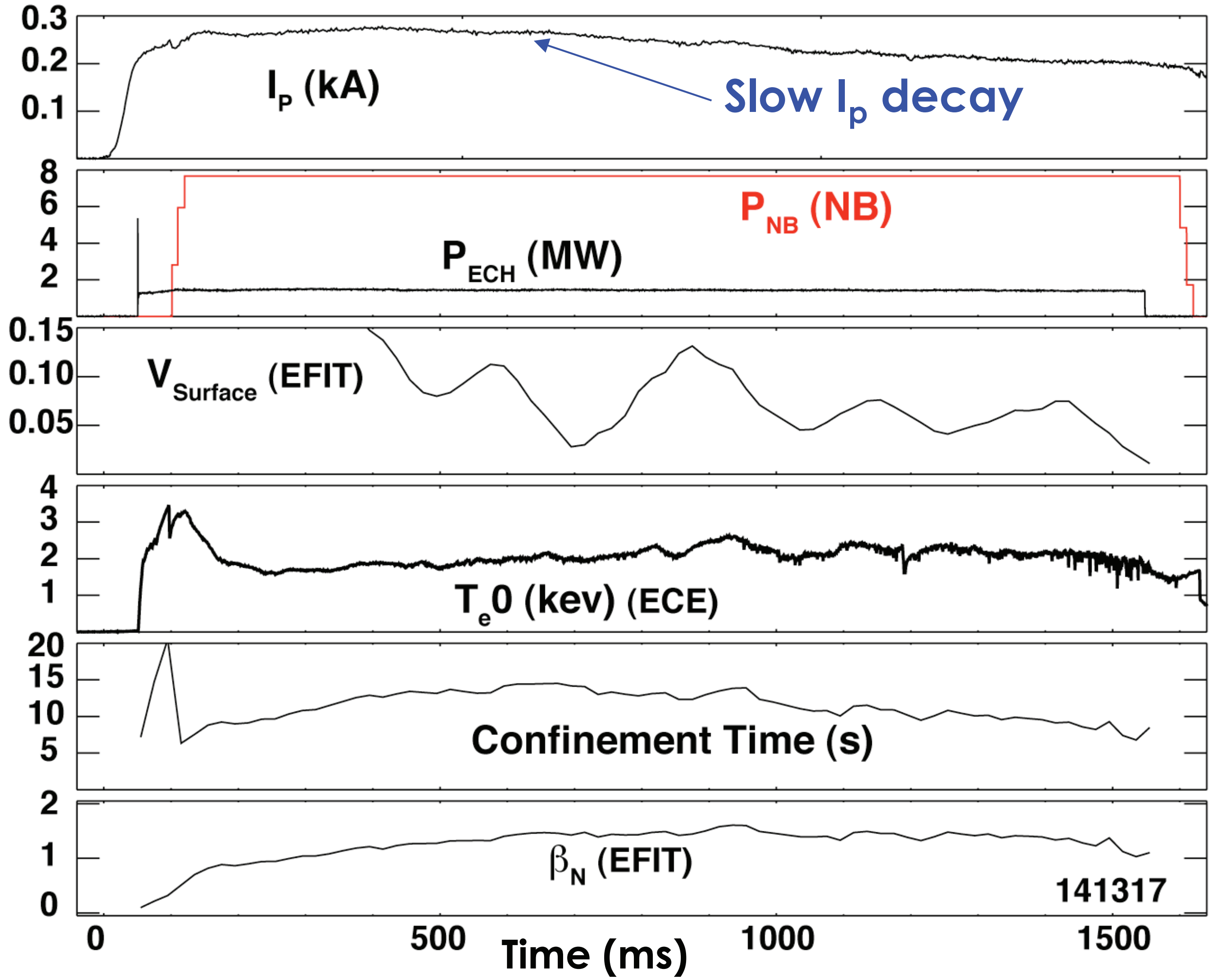


Moderate Power Input Minimized I_p Decay

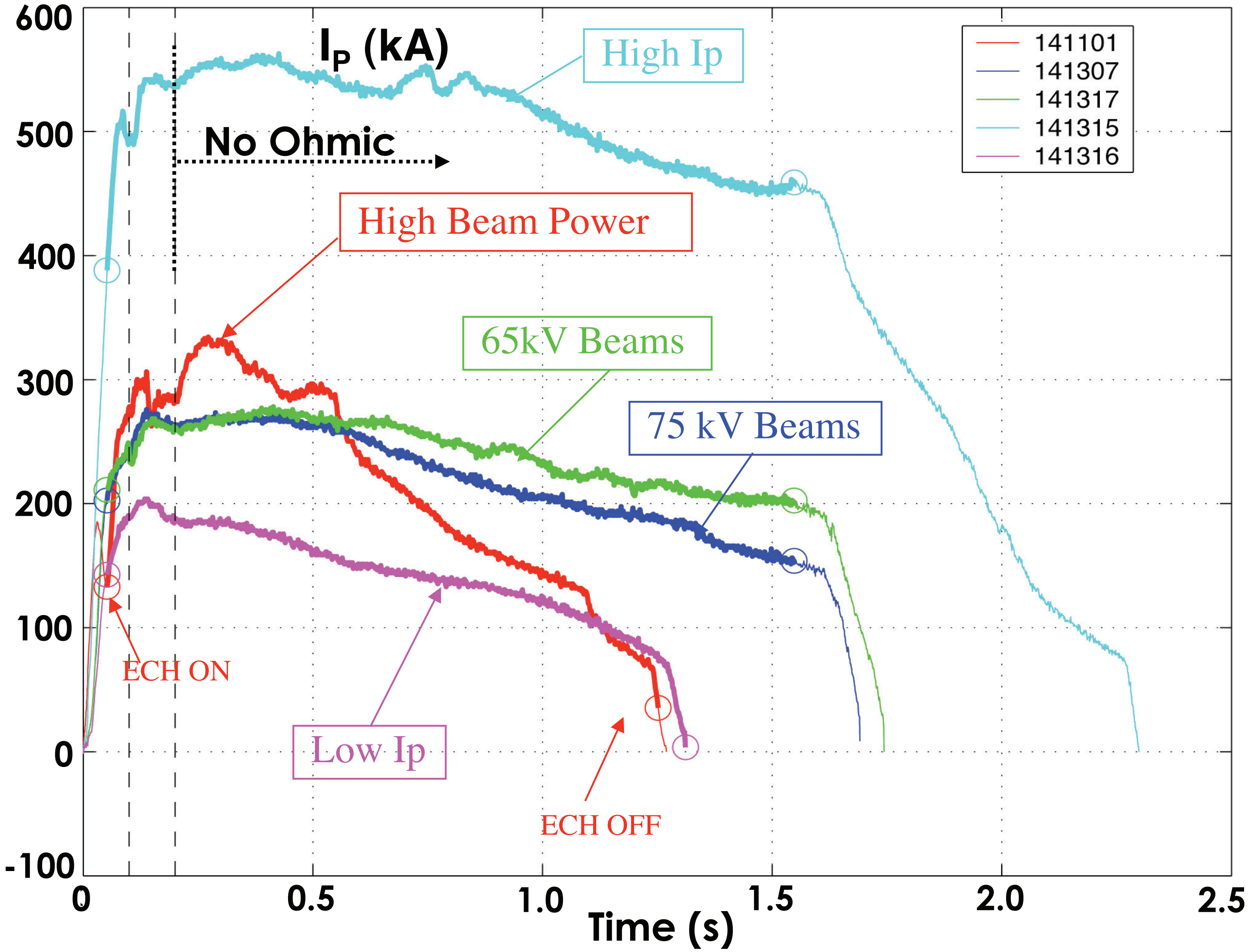
- **MHD events were reduced with lower ECH power and density control**

- **However, our best discharge still resulted in a slow I_p decay**
  - Co-Beams: 3Lt / 1Rt
  - ECH: 3 Gyrotrons
  - 65kV beams
  - $n_e/n_{Gw} \sim 1$

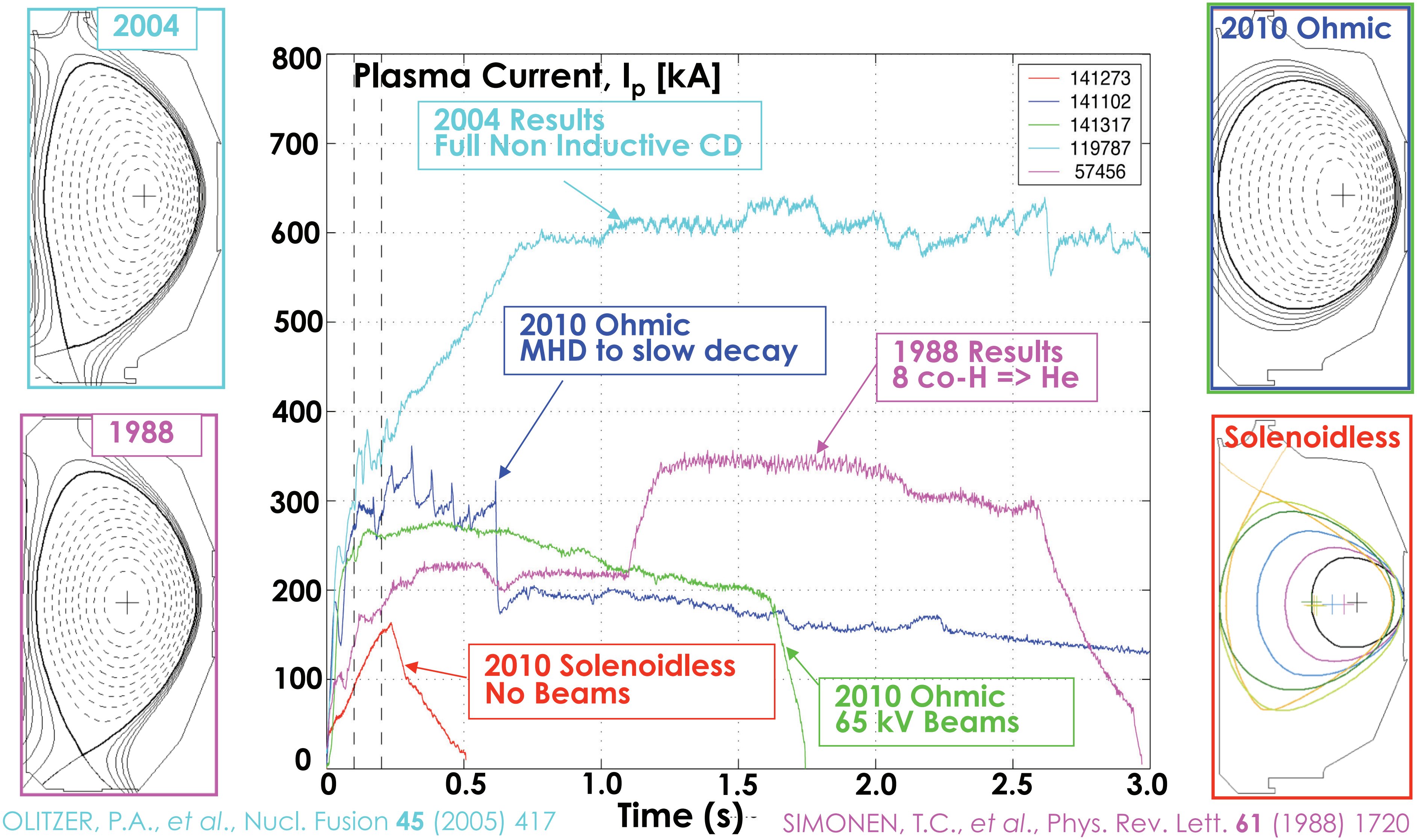
- **=> Limited plasmas are poor non-inductive CD candidates**



Steady State CD Not Found Over Range of Parameters Studied for Limited Plasma



Previous DIII-D CD Experiments in Diverted, H-mode Indicate low τ_e of Limited Plasma May Preclude SS CD



POLITZER, P.A., *et al.*, Nucl. Fusion **45** (2005) 417

SIMONEN, T.C., *et al.*, Phys. Rev. Lett. **61** (1988) 1720

Summary

- **1st Solenoidless operation in DIII-D was very successful**
  - Solenoidless scenario operated as designed
  - Achieved 170 kA plasma current
  - Performed preliminary testing of ECCD and NBCD
- **Ohmic => NBCD in Limited plasma is difficult**
  - Extensive set of parameters studied
  - Severe MHD seen at high power in low Ip plasma
  - NO steady state CD found in Limited plasma
- **Challenges ahead**
  - Perform Ohmic => NB experiments in diverted plasma
  - Establish diverted plasma using solenoidless
- **1st Experiment under new "Torkil Jensen Awards Category"**

In Memory of Phil West

William (Phil) West (1948-2008) was an early leader in solenoidless research at DIII-D and a preeminent researcher in spectroscopy and boundary physics with a 29 year history in the fusion program.

In Memory of Torkil Jensen

Torkil Jensen (1930-2004) was an innovative researcher in the General Atomics Theory Group. The solenoidless research was carried out under the newly created DIII-D "Torkil Jensen Innovative Research Awards Category"