# ASC XP-954
# Early error-field correction in long-pulse plasmas

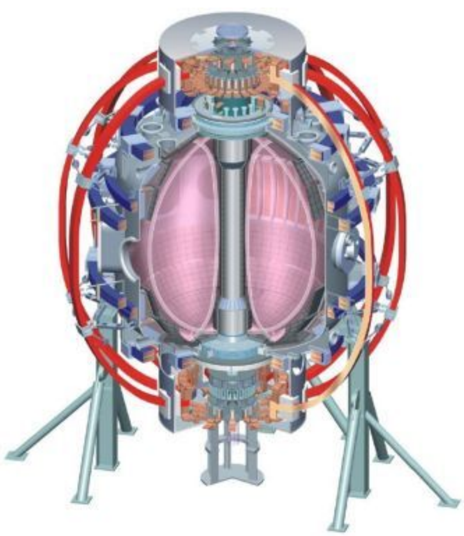
*College W&M*
*Colorado Sch Mines*
*Columbia U*
*CompX*
*General Atomics*
*INEL*
*Johns Hopkins U*
*LANL*
*LLNL*
*Lodestar*
*MIT*
*Nova Photonics*
*New York U*
*Old Dominion U*
*ORNL*
*PPPL*
*PSI*
*Princeton U*
*Purdue U*
*SNL*
*Think Tank, Inc.*
*UC Davis*
*UC Irvine*
*UCLA*
*UCSD*
*U Colorado*
*U Illinois*
*U Maryland*
*U Rochester*
*U Washington*
*U Wisconsin*

**J. Menard, S. Gerhardt, D. Gates**

**(because every tokamak is really a stellarator…)**

**PPPL**
**July 28, 2009**

*Culham Sci Ctr*
*U St. Andrews*
*York U*
*Chubu U*
*Fukui U*
*Hiroshima U*
*Hyogo U*
*Kyoto U*
*Kyushu U*
*Kyushu Tokai U*
*NIFS*
*Niigata U*
*U Tokyo*
*JAEA*
*Hebrew U*
*Ioffe Inst*
*RRC Kurchatov Inst*
*TRINITI*
*KBSI*
*KAIST*
*POSTECH*
*ASIPP*
*ENEA, Frascati*
*CEA, Cadarache*
*IPP, Jülich*
*IPP, Garching*
*ASCR, Czech Rep*
*U Quebec*



# Motivation for "Early error-field correction in long-pulse plasmas"

- Insufficient fueling during LiTER generally results in "unstable" plasma early in discharge
  - Commonly attributed to "locked-modes"
    - Likely seeded by intrinsic error fields
  - But there are other effects of LiTER:
    - Confinement improvement from Li → hit beta limit at fixed $P_{NBI}$
    - Delayed H-mode mode, likely due to reduced density (or other)
  - Most (but not all!) EFC XPs rightly focused on sustaining high beta
- Strong fueling during high-evap LiTER defeats purpose of Li
  - May not even be possible during (effective) LLD operation

- Reduced early EF could reduce mode locking, lower $P_{LH}$
  - Now "know" n=3 EF is from PF5 → early correction easy to test
  - n=1 EF caused by OH×TF, and have correction algorithm in PCS
- Try to get NBI-CD data at lower $n_e$ for FY09 milestone/ITPA
  - Possibility of new operational regimes

# Insufficient fueling during LiTER consistently leads to delayed H-mode and early MHD/locking/disruption

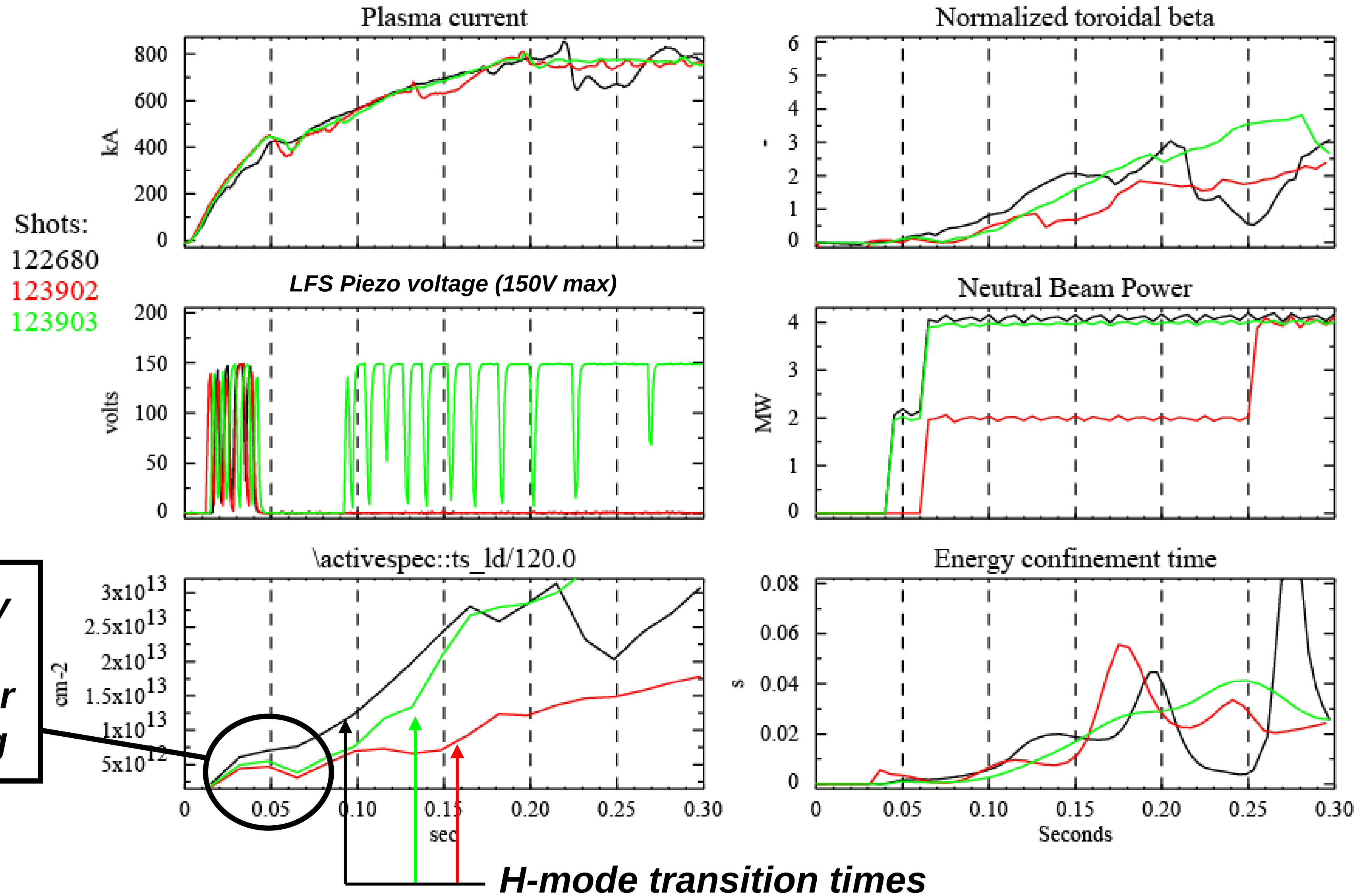
## *Old XP701 data…*

*(there are certainly better examples)*

**Black → reference discharge w/o LITER from 2007**

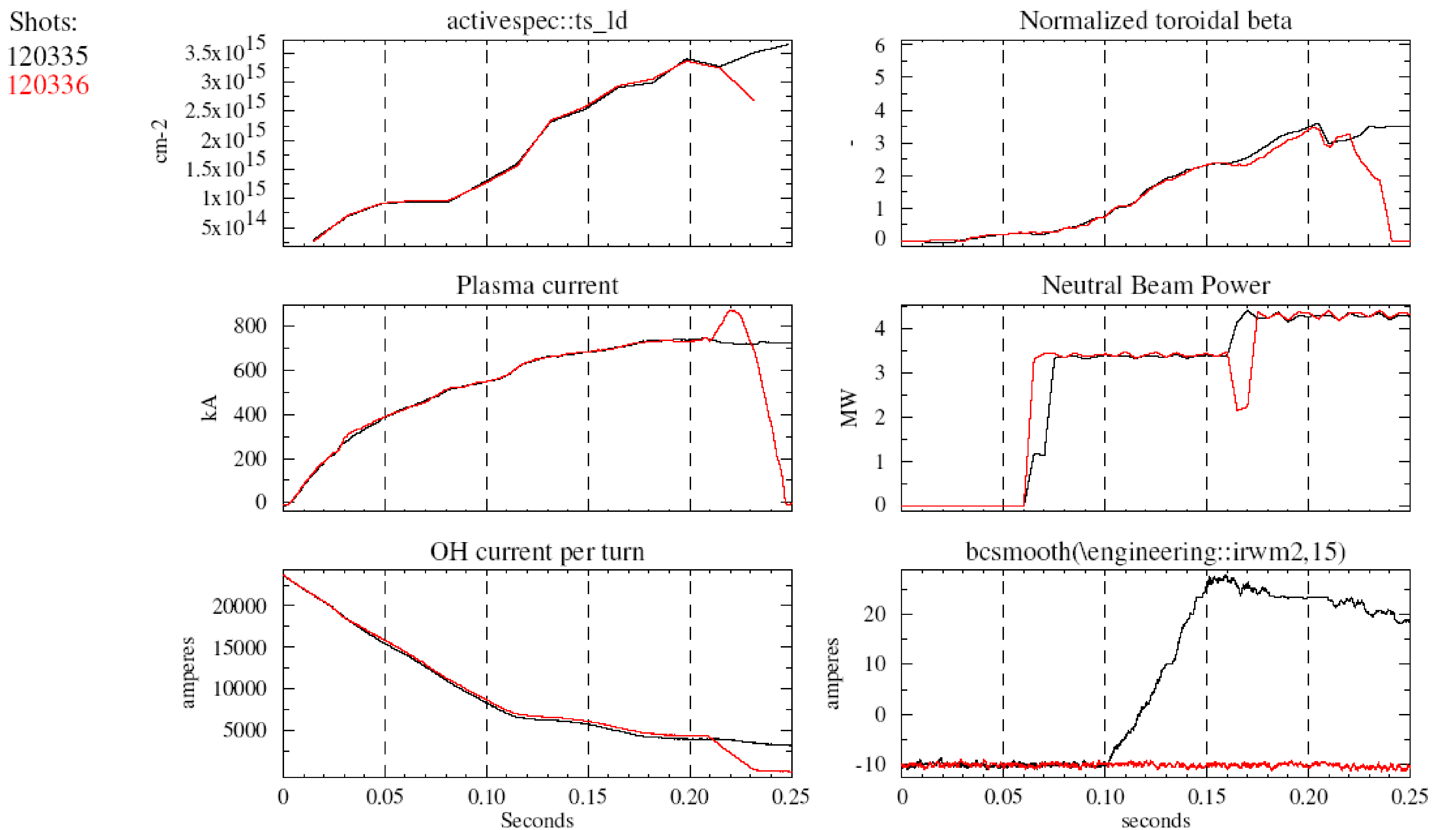
**Red → with LITER (different beam programming unfortunately)**

**Green → Strong LFS fueling needed in $I_P$ ramp to match reference**



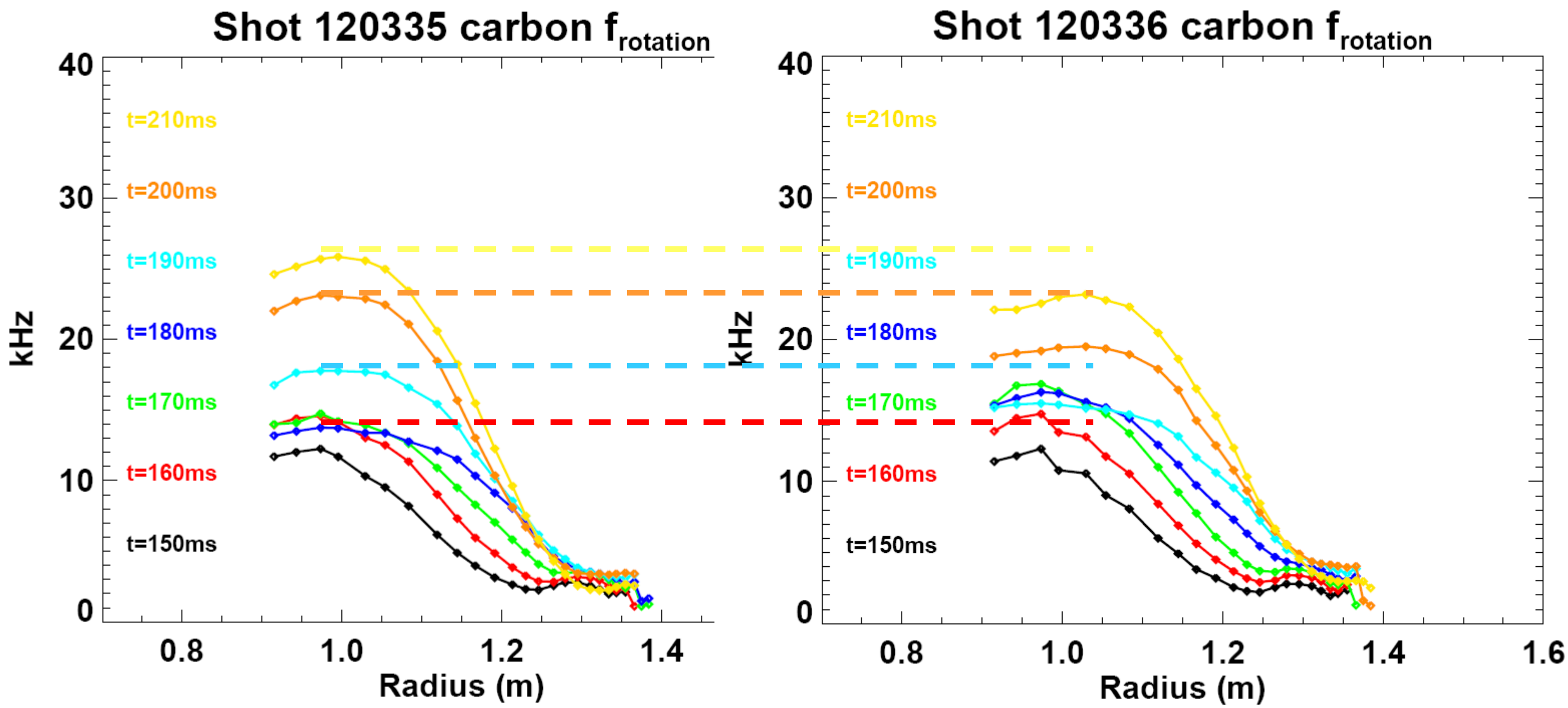

***Early density reduced by factor of 2 for same fueling***

# Applying early n=1 EFC can make early phase less disruptive



# XP614 demonstrated applying early n=1 EFC (based on OH×TF intrinsic EF) can increase early plasma rotation

**Predictive OHxTF EFC on by t=150ms** **EFC off**

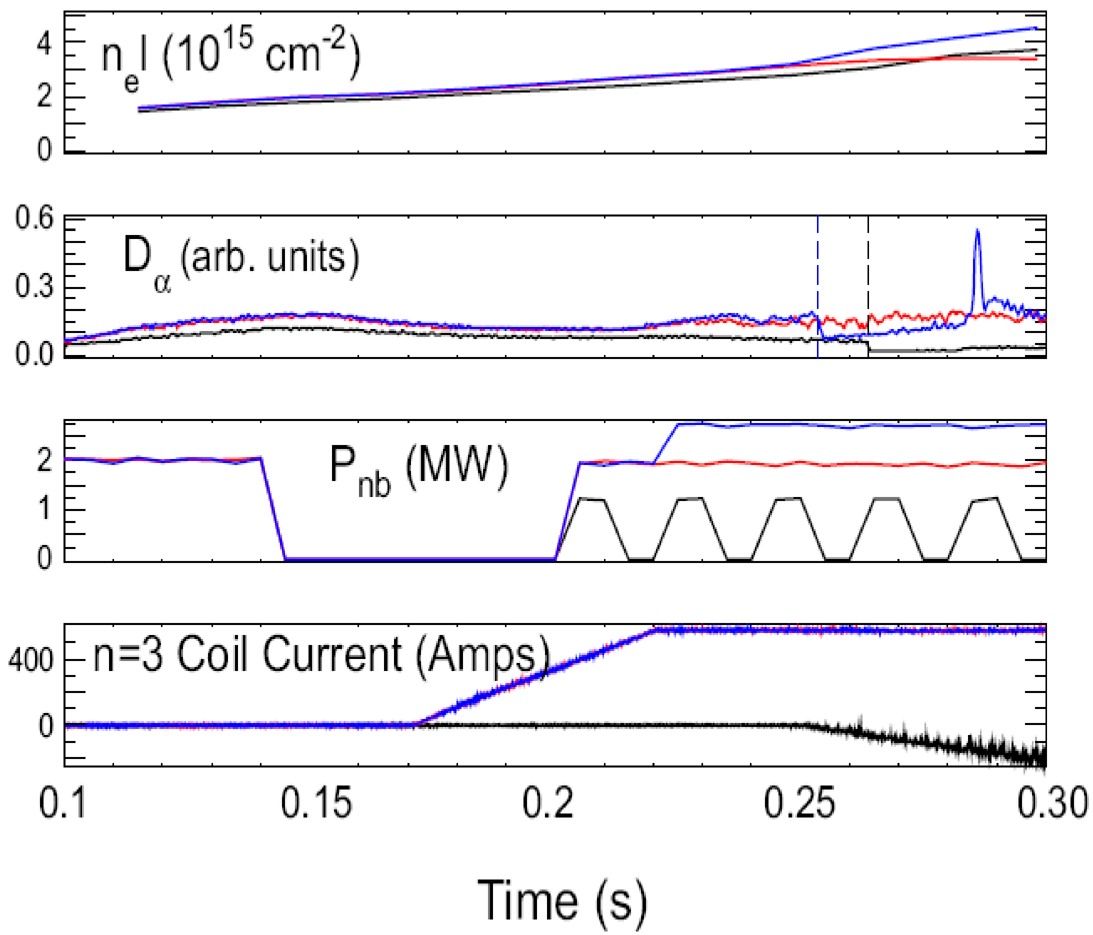


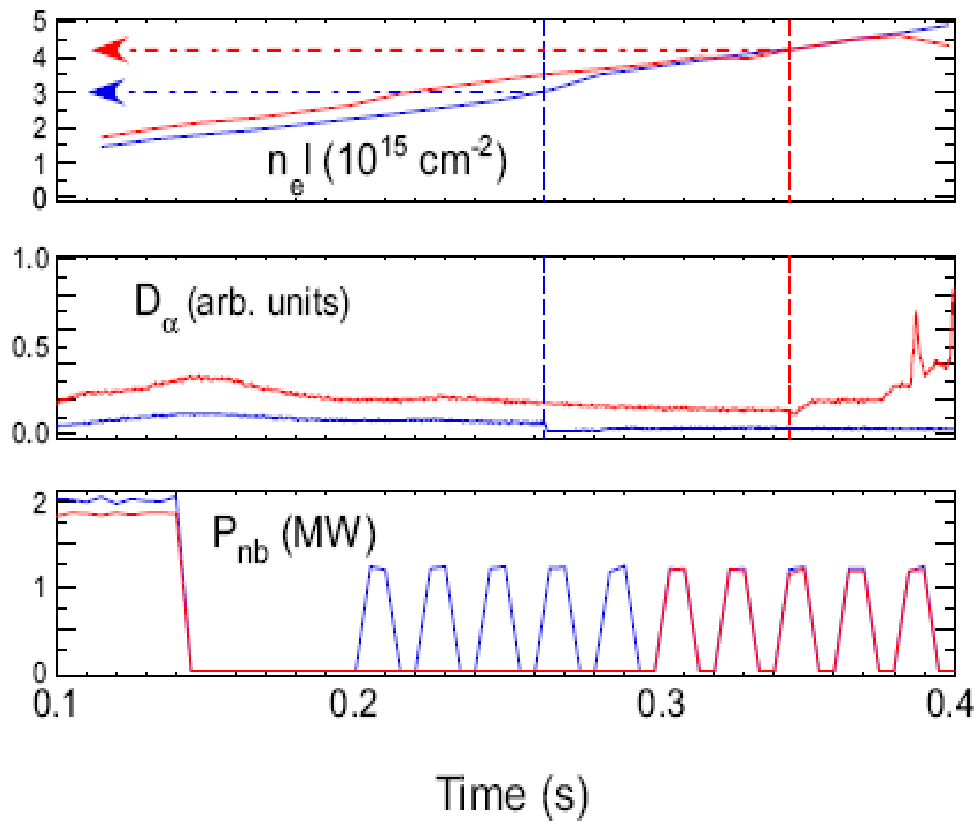
# Kaye XPs show higher EF raises early L-H threshold power

*(the density dependence is weak for intermediate $n_e$ – unexplored for lower $n_e$)*

- $P_{L\text{-}H}$ increases from $P_{NBI}$ ~0.6MW to 2.5MW for 2-4× higher n=3 (including intrinsic n=3 EF)

- $P_{L\text{-}H}$ similar for reference $n_e$ and 50% higher $n_e$

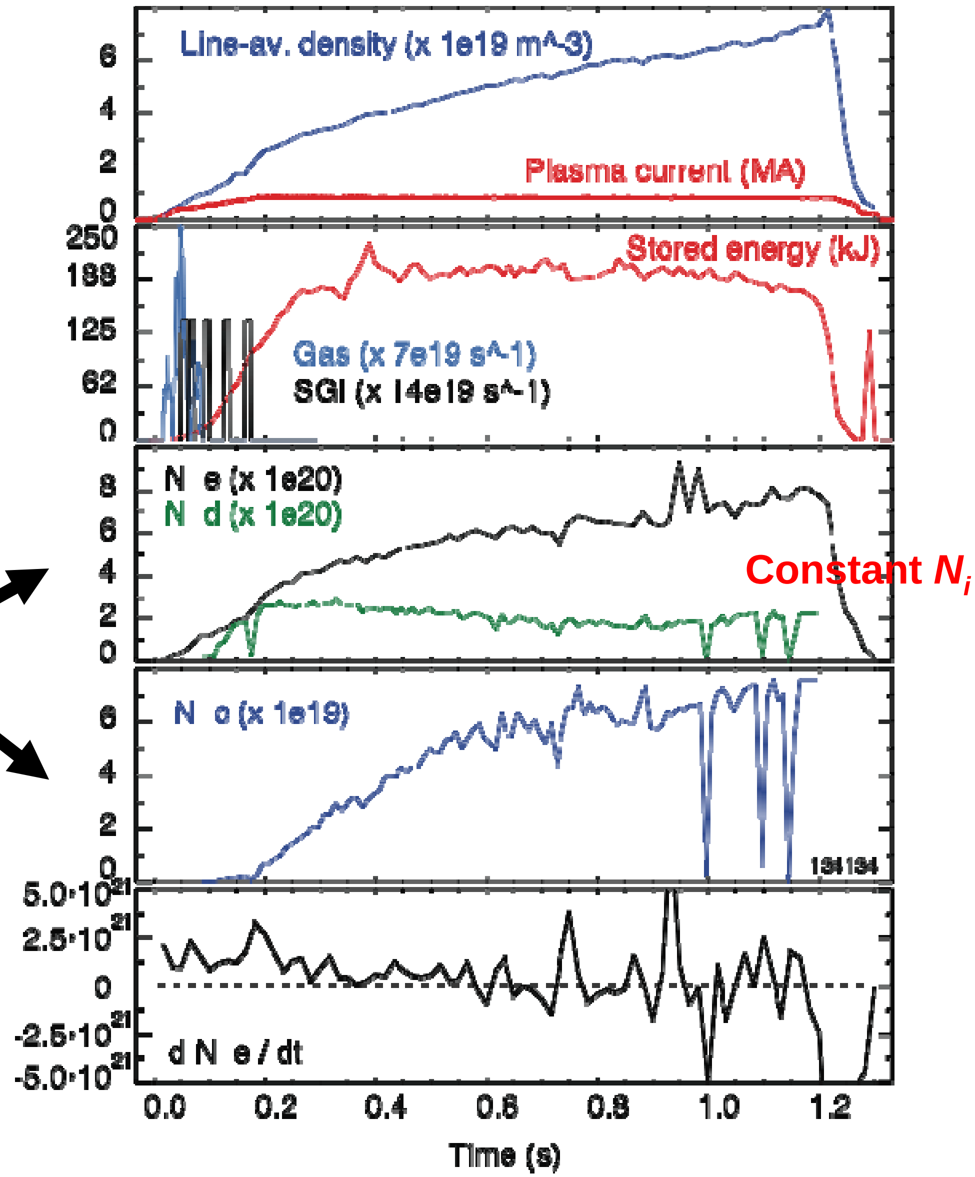



***From Stan Kaye 2009 XPs***

# SGI+LFS can improve early $n_e$ control in long-pulse plasmas
## *(XP-912 Soukhanovskii et al.)*

- SGI-only fueling scenario with ion density control
  - $N_i$ constant, while $N_e$ is rising due to carbon; LITER at 9 mg/min
- SGI could provide early density control, which is useful in this experiment



# Run Plan

1. Reproduce a long-pulse and late-MHD-free discharge at 750-800kA **(3 shots)**
    1. Start with evaporation rate = 10mg/min
        1. Use LITER shutter to fix evaporation duration at 10min with 12min shot cycle
        2. Start from 129125, or recent discharge with 1.2-1.4s period without low-n MHD
        3. Use 16cm outer gaps to reduce impurity density and Zeff
    2. Increase evaporation rate to 20mg/min
        1. Increase fueling as needed to achieve similar early density and long pulse duration
2. Modify early fueling to trigger early MHD event/mode locking
    1. Reduce early NBI power if beta-limit is reached, but maintain early H-mode
    2. Start n=3 EF correction at t=20ms with gain = 200A/10kA (IRWM/IPF5) **(3 shots)**
        1. Assess locking behavior and rotation modification from n=3 EFC
    3. With n=3 EFC off, turn on n=1 OHxTF EFC from XP 614 (120335) **(6 shots)**
        1. Ramp-down OHxTF EFC by t=400ms
        2. Scan timing of OHxTF correction ramp-up in steps of 20ms (moving earlier)
        3. Assess locking behavior and rotation modification from n=3 EFC
    4. Combine early n=3 and n=1 EFC, and assess mode-locking and rotation **(4 shots)**

## 2$^{nd}$ HALF DAY

1. Further reduce early fueling to find threshold of mode locking/MHD **(4 shots)**
2. Working at an early density near and above locking threshold:
    1. Attempt to produce an MHD-stable discharge with reduced late density replacing the LFS/HFS fueling with SGI-based fueling from XP-912 shot 134134 **(3 shots)**
    2. Increase LITER evaporation rate to 30mg/min, adjust SGI fueling for stability **(5 shots)**
3. Increase $I_P$ to 0.9MA and 1MA to assess $n_e$ evolution at higher current **(4 shots)**

**Princeton Plasma Physics Laboratory**

# NSTX Experimental Proposal

## Early error-field correction in long-pulse plasmas

| | | |
|---|---|---|
| **OP-XP-954** | Revision: **0** | Effective Date: **July 30, 2009**<br>*(Approval date unless otherwise stipulated)*<br>Expiration Date: **July 30, 2011**<br>*(2 yrs. unless otherwise stipulated)* |

## PROPOSAL APPROVALS

| | |
|---|---|
| **Responsible Author:** **Jon Menard** | Date July 30, 2009 |
| **ATI – ET Group Leader:** **David Gates** | Date July 30, 2009 |
| **RLM - Run Coordinator:** **Roger Raman** | Date July 30, 2009 |

**Responsible Division: Experimental Research Operations**

**Chit Review Board** (designated by Run Coordinator)

## MINOR MODIFICATIONS (Approved by Experimental Research Operations)

# NSTX EXPERIMENTAL PROPOSAL

TITLE: Early error-field correction in long-pulse plasmas No. **OP-XP-954**
AUTHORS: **J. Menard, S. Gerhardt, D. Gates** DATE: **07/30/2009**

## 1. Overview of planned experiment

The combination of active suppression of n=1 RFA, n=3 pre-programmed error field correction (EFC), and LITER have produced record plasma pulse-durations in NSTX. High elongation + EFC + LITER have produced record poloidal beta and record low flux-consumption in NSTX. This experiment will attempt to systematically lower the plasma density while avoiding disruptive MHD activity by optimizing early error-field correction to reduce mode locking. Reduced density could increase the NBI CD efficiency, and if Te increases at reduced density, density reduction could increase the conductivity and further increase NBI-CD and reduce OH flux consumption. This experiment will focus on discharges with little or no late MHD activity to simplify NBICD analysis, and with sufficient flat-top that the inductive and non-inductive profiles become equilibrated.

## 2. Theoretical/ empirical justification

Reduced density is predicted to increase beam current drive efficiency, and higher Te at reduced density could further increase NBI-CD efficiency and conductivity – all resulting in increased pulse duration and higher non-inductive fraction plasmas. Higher non-inductive fraction is important for improved operation of NSTX and NSTX-Upgrade and is essential to future ST devices such as NHTX and ST-CTF. Variations in plasma density should modify the beam current drive fraction at fixed heating power, thereby providing data for the ITPA IOS group for validating beam current drive models. Finally, this experiment is important for the anticipated operation of the liquid lithium divertor (LLD) which could result in reduced early density and locked-modes if the LLD acts as an effective pump.

## 3. Experimental run plan

**FIRST ½ RUN DAY**

A. Reproduce a long-pulse and late-MHD-free discharge at 750-800kA (3 shots)
   1. Start with evaporation rate = 10mg/min
      i. Use LITER shutter to fix evaporation duration at 10min with 12min shot cycle
      ii. Start from 129125, or recent discharge with 1.2-1.4s period without low-n MHD
      iii. Use 16cm outer gaps to reduce impurity density and Zeff
   2. Increase evaporation rate to 20mg/min
      i. Increase fueling as needed to achieve similar early density and long pulse duration

B. Modify early fueling to trigger early MHD event/mode locking
   1. Reduce early NBI power if beta-limit is reached, but maintain early H-mode
   2. Start n=3 EF correction at t=20ms with gain = 200A/10kA ($I_{RWM}/I_{PF5}$) (3 shots)
      i. Assess locking behavior and rotation modification from n=3 EFC
   3. With n=3 EFC off, turn on n=1 OHxTF EFC from XP 614 (120335) (6 shots)
      i. Ramp-down OHxTF EFC by t=400ms
      ii. Scan timing of OHxTF correction ramp-up in steps of 20ms (moving earlier)
      iii. Assess locking behavior and rotation modification from n=3 EFC
   4. Combine early n=3 and n=1 EFC, and assess mode-locking and rotation (4 shots)

**SECOND ½ RUN DAY**

C. Further reduce early fueling to find threshold where until mode locking/MHD occurs (4 shots)

D. Working at an early density near and above locking threshold:

1. Attempt to produce an MHD-stable discharge with reduced late density by replacing the LFS/HFS fueling with SGI-based fueling from XP-912 shot 134134 (3 shots)
2. Increase LITER evaporation rate to 30mg/min, adjust SGI fueling for stability (5 shots)

E. Time permitting, increase $I_P$ to 0.9MA and 1MA to assess $n_e$ evolution at higher current (4 shots)

# 4. Required machine, NBI, RF, CHI and diagnostic capabilities

The usual diagnostic capabilities are required, NBI voltage on A, B, C = 90, 90, 80kV.

# 5. Planned analysis

EFIT/LRDFIT, TRANSP, MPTS, CHERS, and RWM/EF sensor analysis will be performed.

# 6. Planned publication of results

Results will be published in conference proceedings and/or journal such as Nuclear Fusion or Physics of Plasmas within one year of experiment.

# PHYSICS OPERATIONS REQUEST

TITLE: Early error-field correction in long-pulse plasmas No. **OP-XP-954**
AUTHORS: **J. Menard, S. Gerhardt, D. Gates** DATE: **07/30/2009**

Machine conditions (specify ranges as appropriate)

$I_{TF}$ (kA): up to **63kA** Flattop start/stop (s): **0.0, ~2s**

$I_P$ (MA): **0.75 or 0.8MA** Flattop start/stop (s): **0.2, ~2s**

Configuration: **DN / LSN**

Outer gap (m): **15cm** Inner gap (m): **2-8cm**

Elongation κ: **2.4-2.7** Upper/lower triangularity δ: **0.75 / 0.5**

Z position (m): **0cm**

Gas Species: **D** Injector(s): **CS midplane, outer midplane, SGI**

**NBI** Species: **D** Sources: **A, B, C** Voltage (kV): **90, 90, 80kV** Duration (s): **2s**

**ICRF** Power (MW): **0** Phasing: **0** Duration (s): **0**

**CHI**: **Off** Bank capacitance (mF):

**LITER: On – 10-30 mg/min**

*Either:* List previous shot numbers for setup: 129125 or more recent discharge

*Or:* Sketch the desired time profiles, including inner and outer gaps, κ, δ, heating, fuelling, etc. as appropriate. Accurately label the sketch with times and values.

## DIAGNOSTIC CHECKLIST

TITLE: Early error-field correction in long-pulse plasmas No. **OP-XP-954**

AUTHORS: **J. Menard, S. Gerhardt, D. Gates** DATE: **07/30/2009**

*Note special diagnostic requirements in Sec. 4*

| **Diagnostic** | **Need** | **Want** |
|---|---|---|
| Bolometer – tangential array | | |
| Bolometer – divertor | | |
| CHERS – toroidal | **X** | |
| CHERS – poloidal | **X** | |
| Divertor fast camera | | |
| Dust detector | | |
| EBW radiometers | | |
| Edge deposition monitors | | |
| Edge neutral density diag. | | |
| Edge pressure gauges | | |
| Edge rotation diagnostic | | |
| Fast ion D_alpha - FIDA | | |
| Fast lost ion probes - IFLIP | | |
| Fast lost ion probes - SFLIP | | |
| Filterscopes | | |
| FIReTIP | | |
| Gas puff imaging | | |
| H$\alpha$ camera - 1D | | |
| High-k scattering | | |
| Infrared cameras | | |
| Interferometer - 1 mm | | |
| Langmuir probes – divertor | | |
| Langmuir probes – BEaP | | |
| Langmuir probes – RF ant. | | |
| Magnetics – Diamagnetism | **X** | |
| Magnetics – Flux loops | **X** | |
| Magnetics – Locked modes | **X** | |
| Magnetics – Pickup coils | **X** | |
| Magnetics – Rogowski coils | **X** | |
| Magnetics – Halo currents | | |
| Magnetics – RWM sensors | **X** | |
| Mirnov coils – high f. | **X** | |
| Mirnov coils – poloidal array | **X** | |
| Mirnov coils – toroidal array | **X** | |
| Mirnov coils – 3-axis proto. | | |

*Note special diagnostic requirements in Sec. 4*

| **Diagnostic** | **Need** | **Want** |
|---|---|---|
| MSE | **X** | |
| NPA – ExB scanning | | |
| NPA – solid state | | |
| Neutron measurements | **X** | |
| Plasma TV | | |
| Reciprocating probe | | |
| Reflectometer – 65GHz | | |
| Reflectometer – correlation | | |
| Reflectometer – FM/CW | | |
| Reflectometer – fixed f | | |
| Reflectometer – SOL | | |
| RF edge probes | | |
| Spectrometer – SPRED | | |
| Spectrometer – VIPS | | |
| SWIFT – 2D flow | | |
| Thomson scattering | **X** | |
| Ultrasoft X-ray arrays | **X** | |
| Ultrasoft X-rays – bicolor | | |
| Ultrasoft X-rays – TG spectr. | | |
| Visible bremsstrahlung det. | | |
| X-ray crystal spectrom. – H | | |
| X-ray crystal spectrom. – V | | |
| X-ray fast pinhole camera | | |
| X-ray spectrometer – XEUS | | |