NSTX-U

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Inductive Startup Scenarios for NSTX-U

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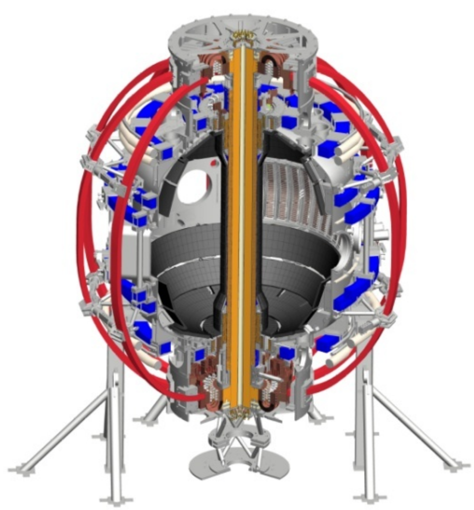


New Inductive Startup Scenarios are Needed for NSTX-U

- Startup is a pre-programmed sequence for breakdown and plasma evolution to I_p ~ 150 kA
  - PF3, PF5 and OH currents are pre-programmed
    - Two criteria: field null around t=0 and equilibrium field is consistent with I_p
    - Outer gap and I_p feedback start at 20ms with I_p ~ 150 kA
  - Prefill via vessel pressure feedback
  - ECH pre-ionization

- NSTX-U cannot use the NSTX startup scenarios
  - OH flux and fringing field is larger
  - Vessel structure, and thus induced vessel currents, are different
  - Initial breakdown must be at a larger major radius

- CD-4 requires breakdown with I_p > 50kA

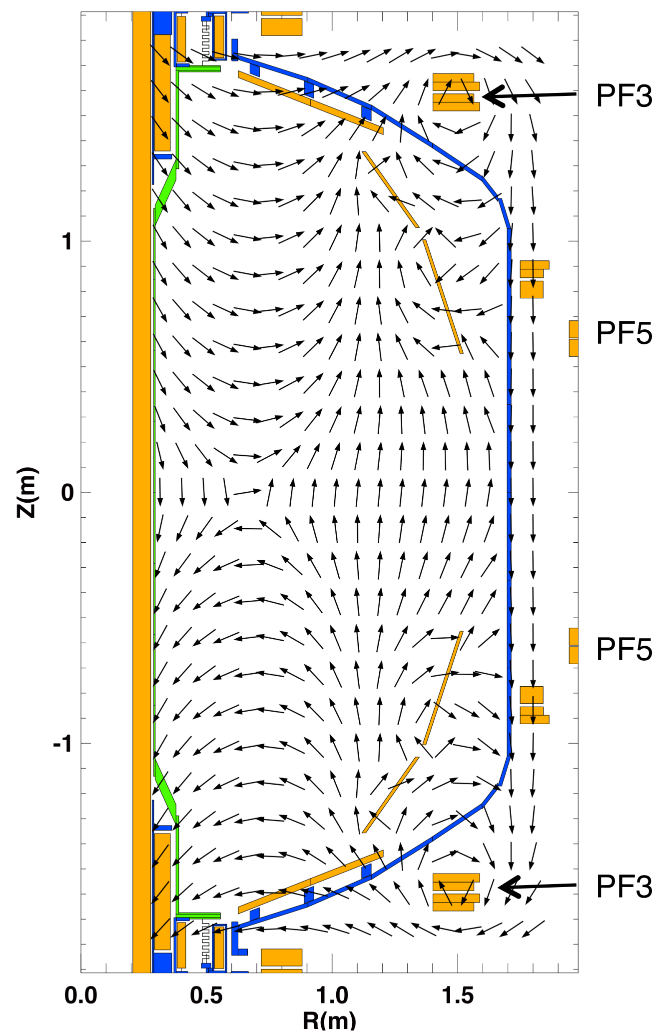
Outline

- Breakdown considerations and metrics
- NSTX inductive startup scenario
  - LRDFIT calculation of breakdown requirements is consistent with experiment
- Development of NSTX-U startup scenarios
  - Use LRDFIT calculations to prepare scenarios and gain intuition on trade-offs when optimizing startup for NSTX-U
    - CD4: 8 kA OH precharge
    - Full: 24 kA OH precharge

Inductive Breakdown: Form a Poloidal Field Null with Strong Toroidal Field and Appreciable Loop Voltage

- Solenoid fringing fields contribute to vertical field (B_Z)
  - Pre-charge direction adds "confining" B_Z
  - Bipolar PF3 coils provide nulling field
    - Also vertical stability after breakdown
  - PF5 provides equilibrium B_Z
    - Energized immediately after breakdown
  - NSTX does not have inboard PF coils to decouple OH field from B_Z
    - PF3 fields for null are dependent on OH pre-charge and ramp rate
- Loop voltage via current ramps
  - Ramping OH and PF provide positive loop voltage in all examples

Special case with small vessel currents for illustration



Metrics for Minimum Electric Field for Breakdown and Sustainment are Used to Evaluate Startup Scenarios

Minimum E_ϕ for breakdown

$$E\,[\text{V/m}] > \frac{\left(1.25\times10^{4}\right) P\,[\text{torr}]}{\ln\left(510\; P\;[\text{torr}]\; L[\text{m}]\right)}$$

$$L = h\;B_\phi / B_\perp$$

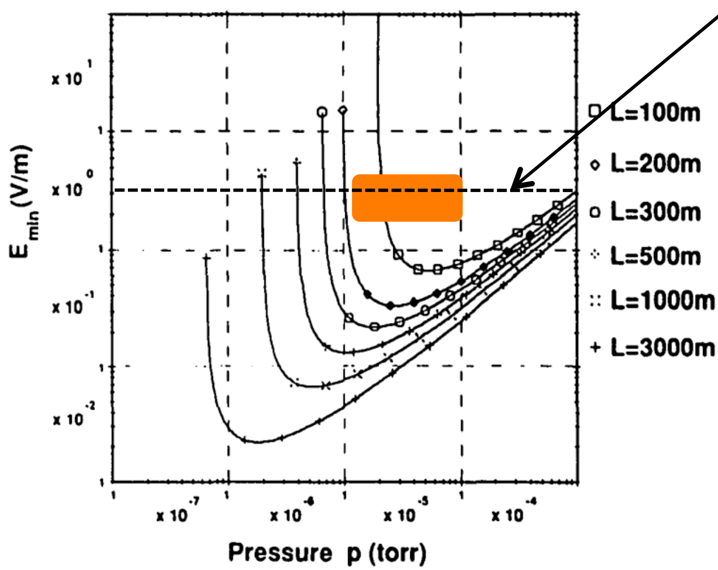


FIG. 25. Minimum electric field for breakdown, E_{min}, in deuterium, as a function of pressure for various values of toroidal connection length L.

Minimum E_ϕ for sustainment

"Lloyd Parameter"

$$\frac{E_\phi B_\phi}{\langle B_\perp \rangle} > 1\,\text{kV/m}$$

Fizzle: a breakdown, that is not sustained → typically sets the lower limit on electric field

A. Tanga, et al. "Tokamak Startup" (1986)
B. Lloyd et al., NF (1991)

Lloyd Parameter Provides a V_{loop} Target for Reliable Startup

- Empirical relationship from early days of JET:
  - Proportional to electric field times the length of the helical field line

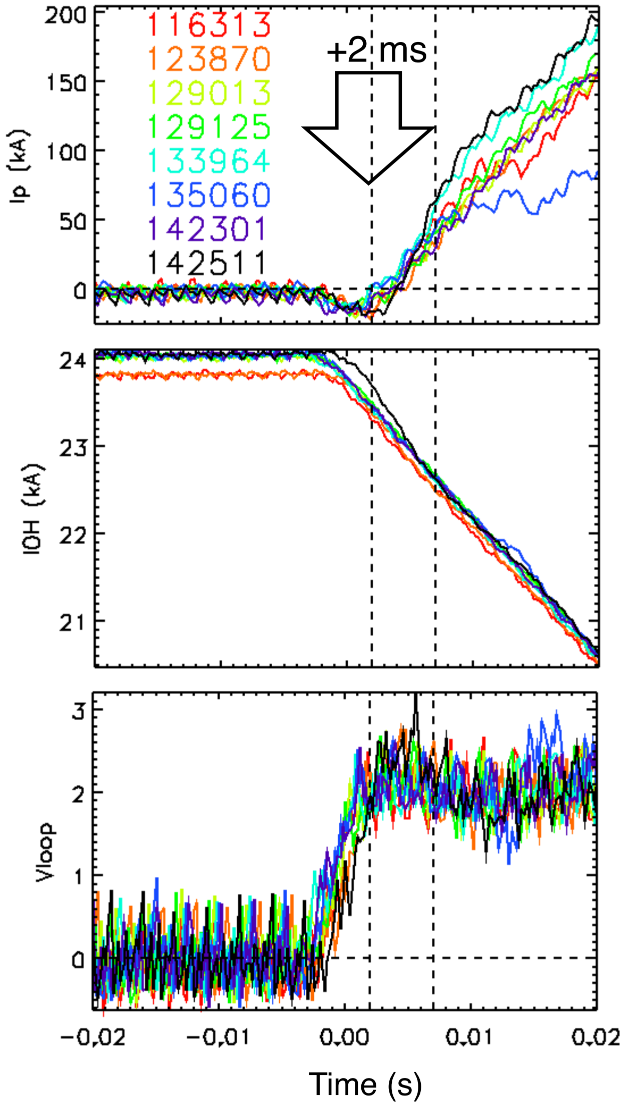
$$\frac{V_{loop} I_{TF}}{R^2 \langle B_\perp \rangle} > 3.14 \frac{\text{V MA}}{\text{m}^2\ \text{G}}$$

- R^{-2} dependence means:
  - NSTX-U will initially need about twice the loop voltage to get same Lloyd parameter:

$$V_{NSTX-U} \sim \frac{(.35\ \text{m})^2}{(.25\ \text{m})^2} V_{NSTX} \sim 2V_{NSTX}$$

  - Doubling I_{TF} to full field will make $V_{NSTX\text{-}U} \sim V_{NSTX}$

Typical NSTX Breakdown Scenario



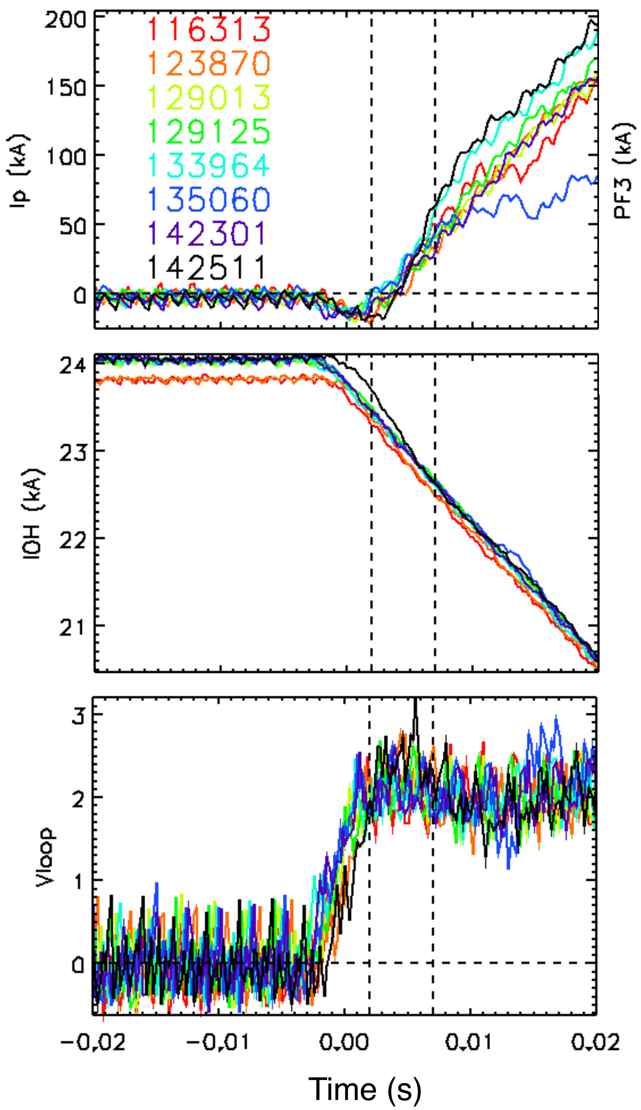
First jump up in I_p around +2ms

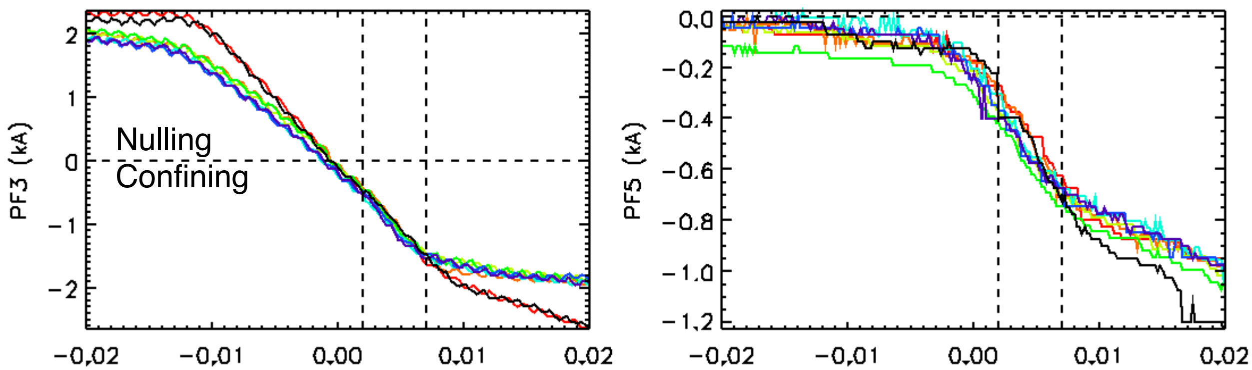
Initial I_p ramp ~ 50 kA / 5 ms = 10 MA/s

Ohmic coil has 22 kA – 24 kA pre-charge
Ramp begins ~ 5ms prior to breakdown

V_{loop} ~ 2 V at inboard midplane
Additional 0.5 – 1.0 V from PF ramps at larger R

Typical NSTX Breakdown Scenario

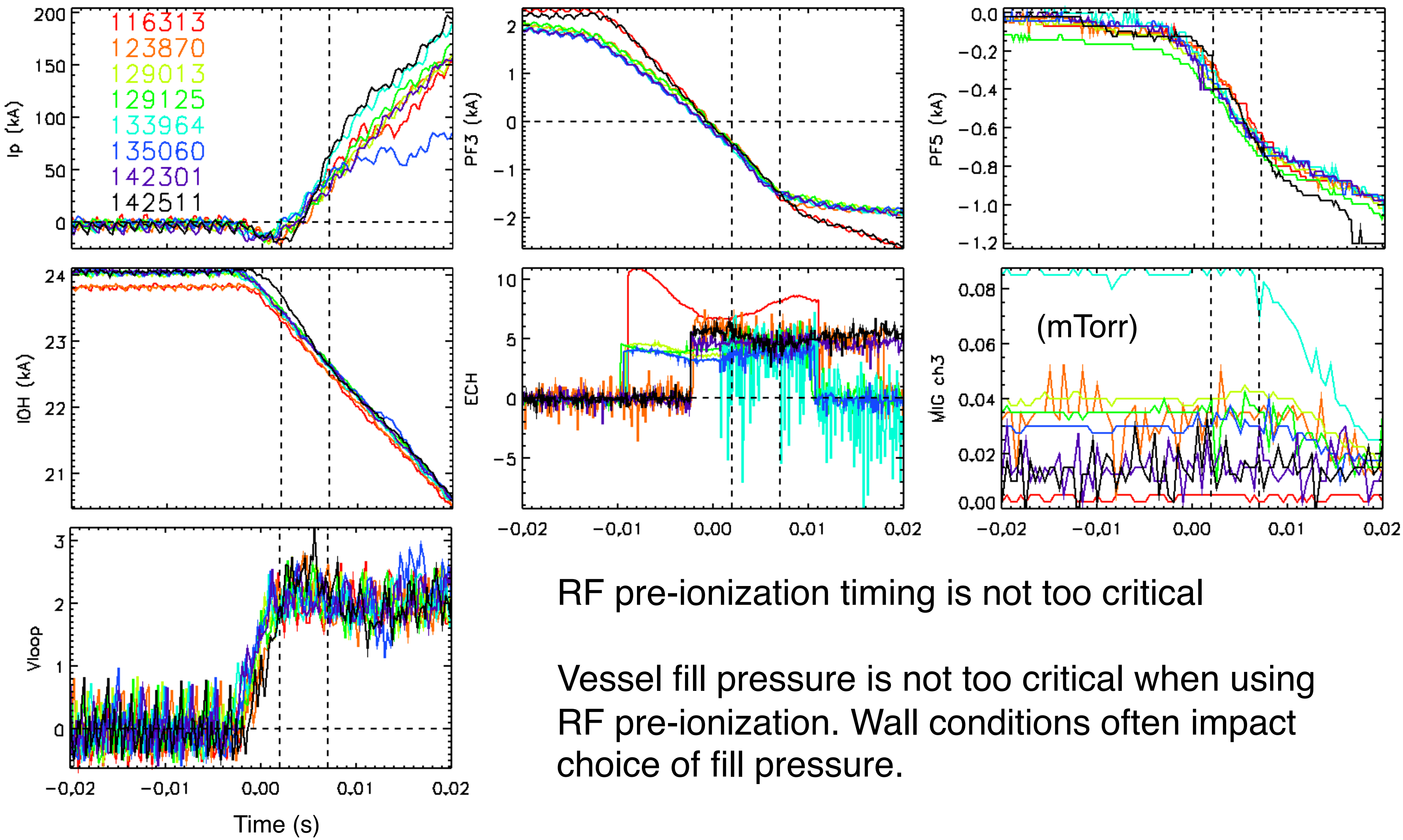




- PF3U/L are bipolar coils
  - PF3 coil current is “confining” at breakdown
  - “Nulling” field comes from vessel currents induced by current ramp

- PF5 ramp after breakdown
  - Current ramp begins at t=0 to provide confining field with increasing I_p

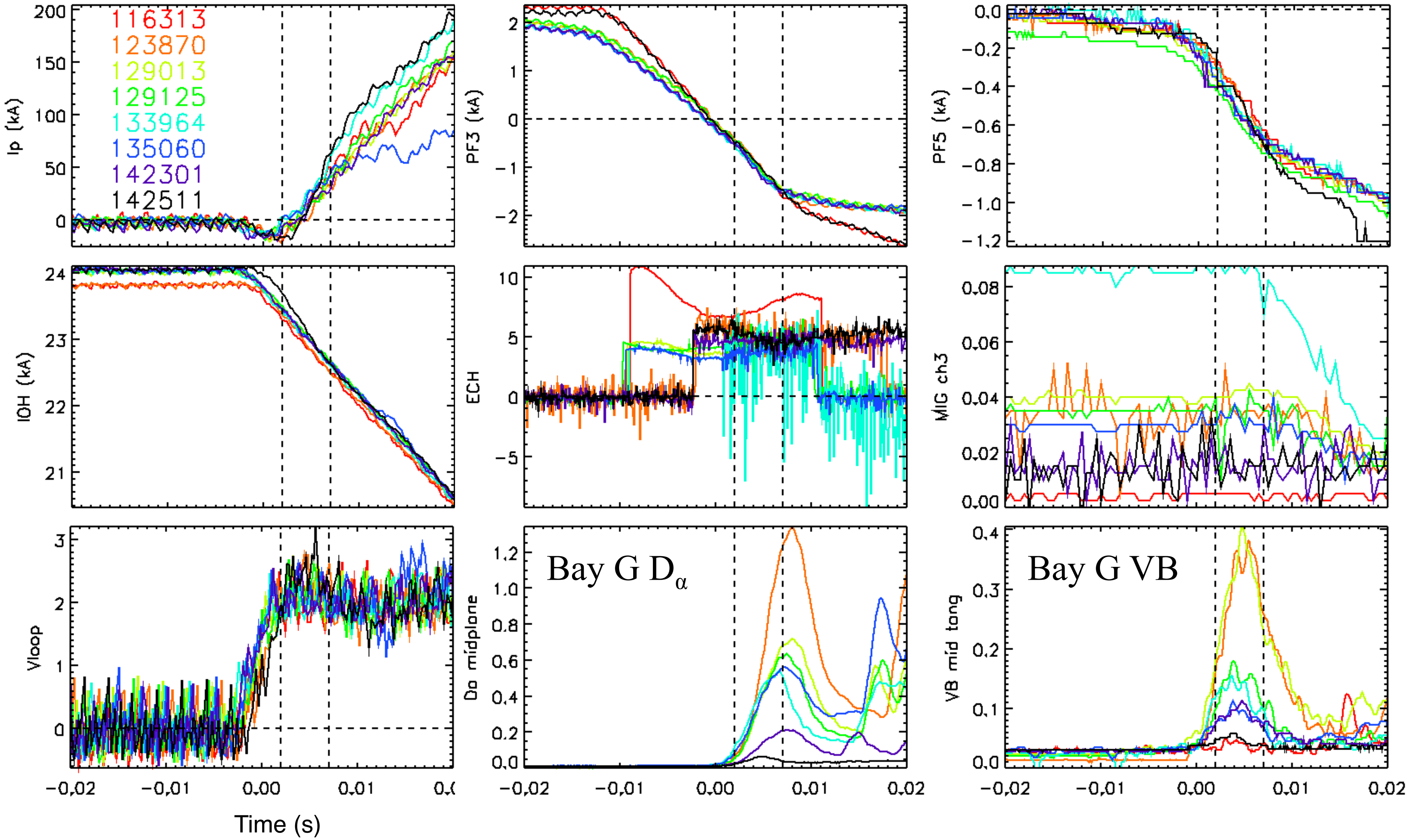
Typical NSTX Breakdown Scenario



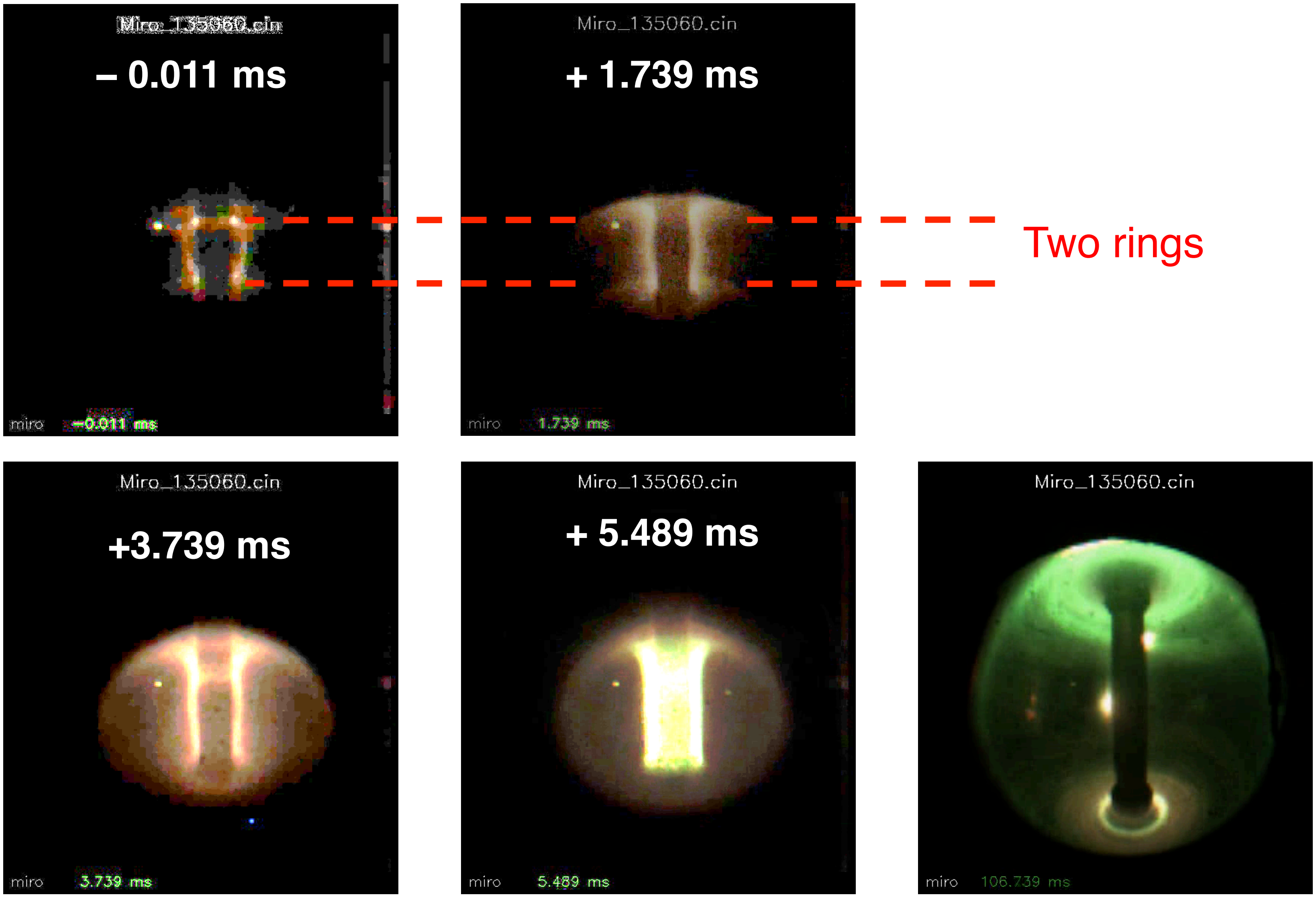
RF pre-ionization timing is not too critical

Vessel fill pressure is not too critical when using RF pre-ionization. Wall conditions often impact choice of fill pressure.

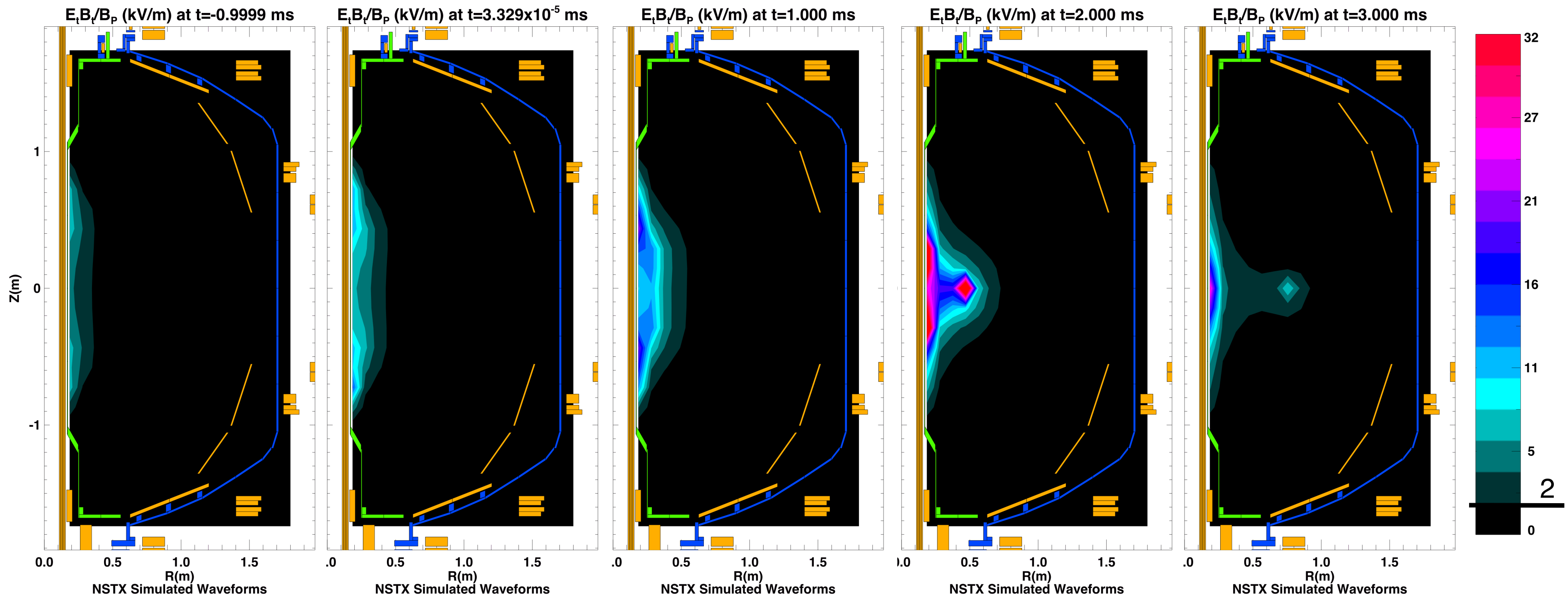
Typical NSTX Breakdown Scenario



Fast Camera Captures First Light Around CS



LRDFIT Calculation of Lloyd Parameter Consistent with NSTX Observations



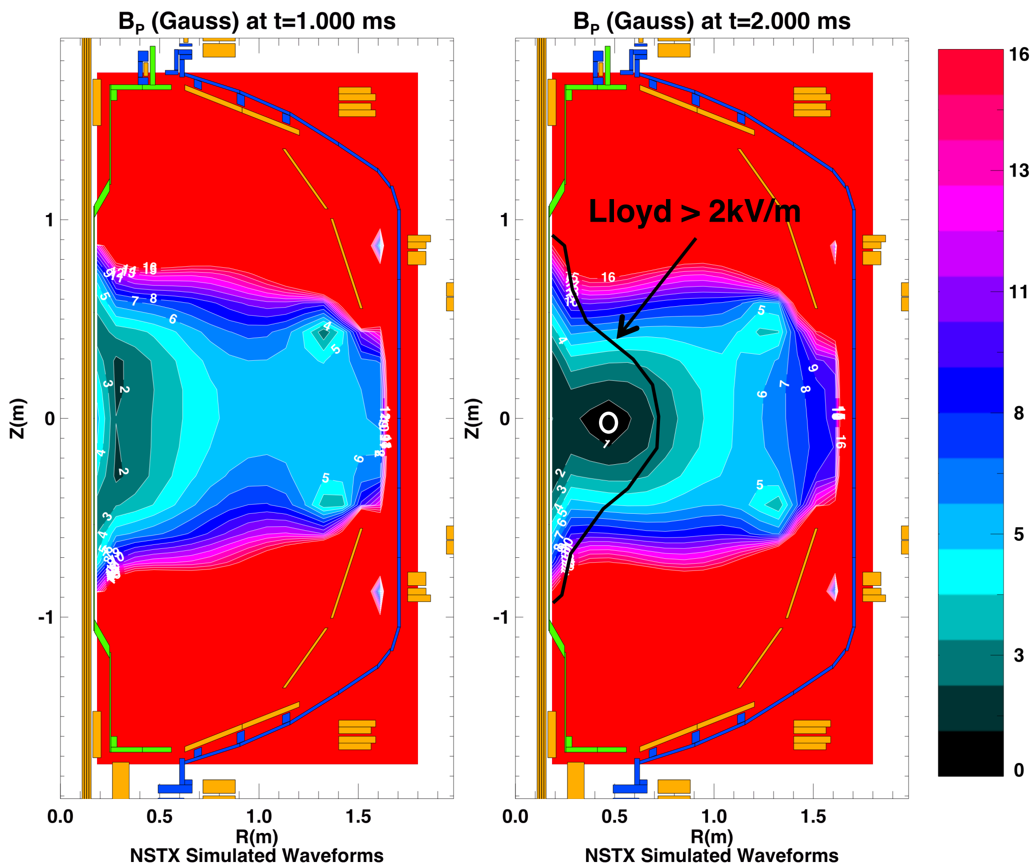
- 1 ms 0 ms +1 ms + 2 ms + 3 ms

Two vertically separated rings on CS …… Merge

$E_tB_t/B_p > 2$ kV/m starting at -1ms, but reaches maximum around 2 ms.

V_{loop} ~ 2.75 V at Field Null Near Inboard Midplane

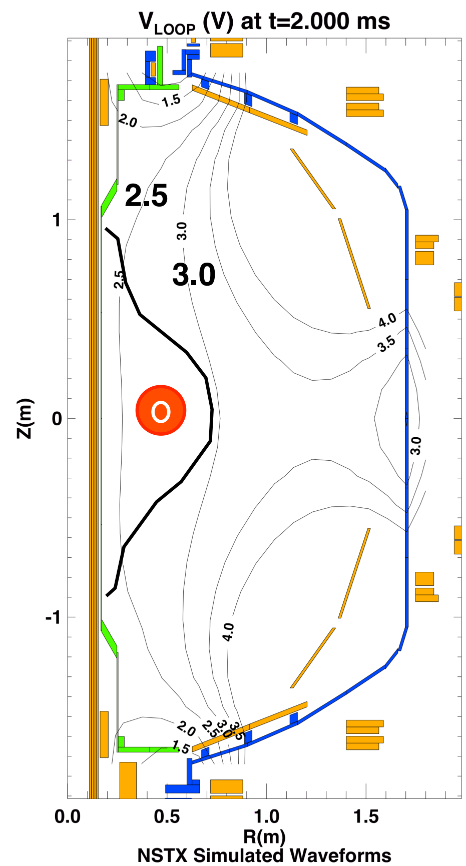
Poloidal Field Nulls



+1 ms

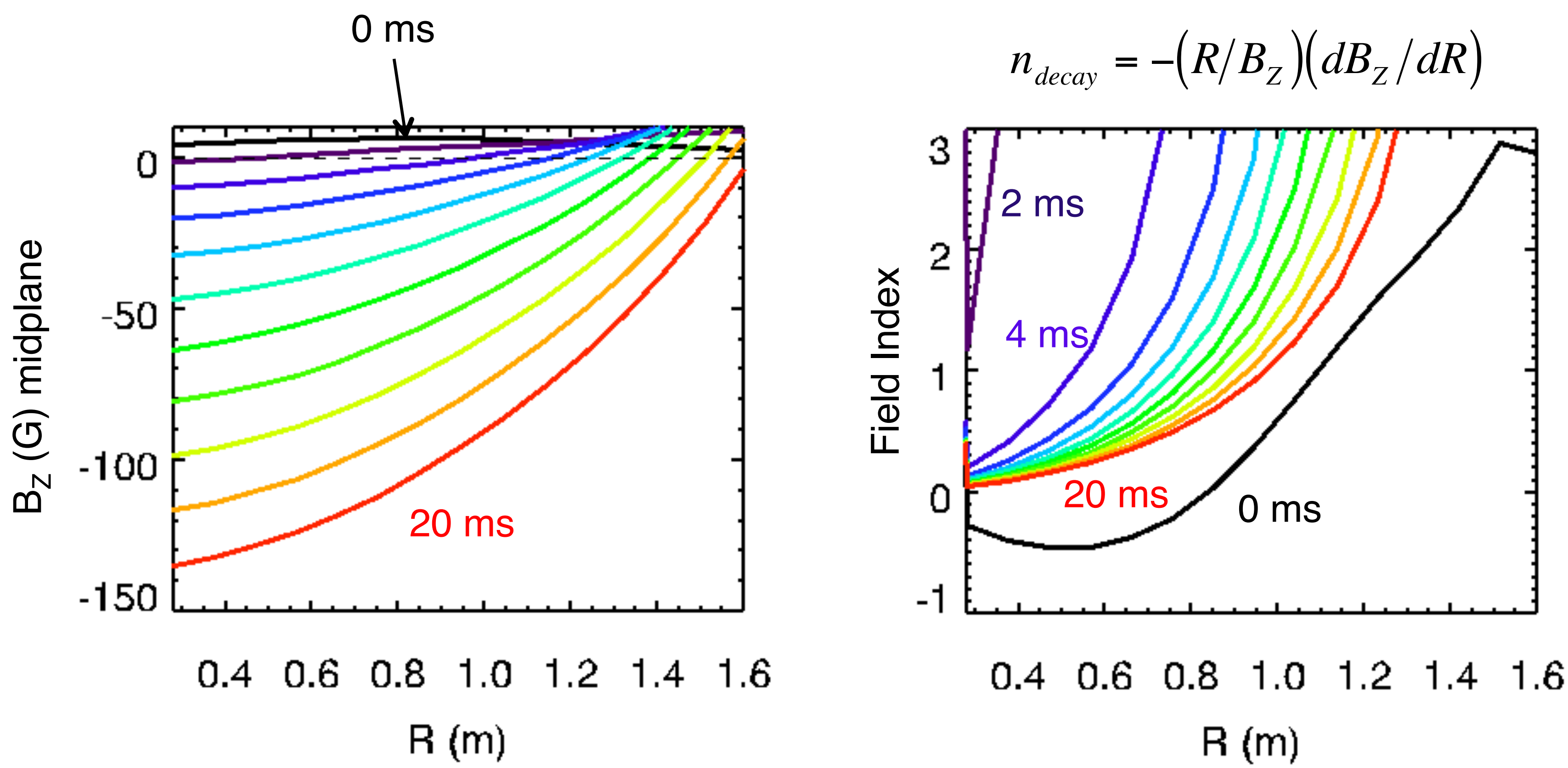
+ 2 ms

Loop Voltage



+ 2 ms

PF3 and PF5 Currents Increase After Breakdown to Provide Equilibrium Field with Good Field Index



Each line represents 2 ms interval

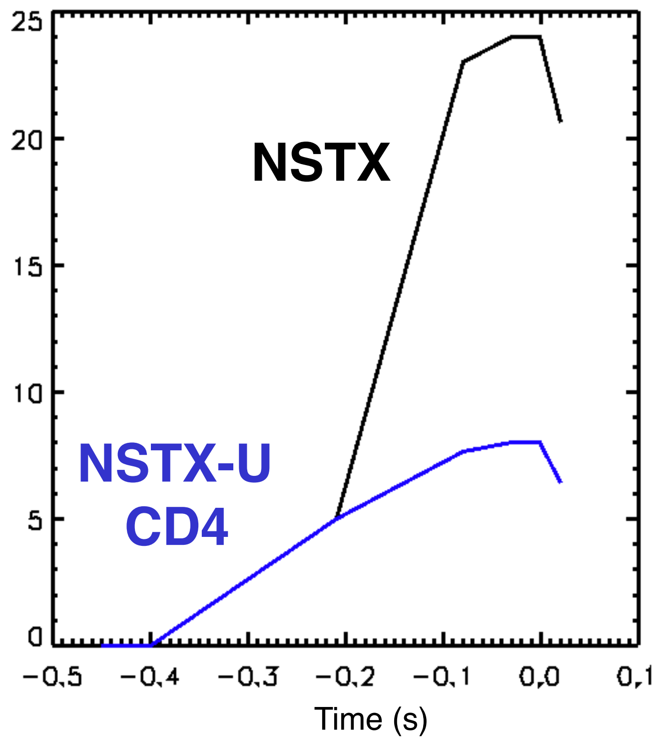
Conclusions from LRDFIT Models of NSTX Breakdown

- LRDFIT calculations for breakdown scenario consistent with experimental observations
  - Breakdown near CS in two rings, pulls off CS around +2ms
    - Maximum value and largest region of Lloyd parameter > 2kV/m at +2ms
  - Good field index for vertical stability following breakdown

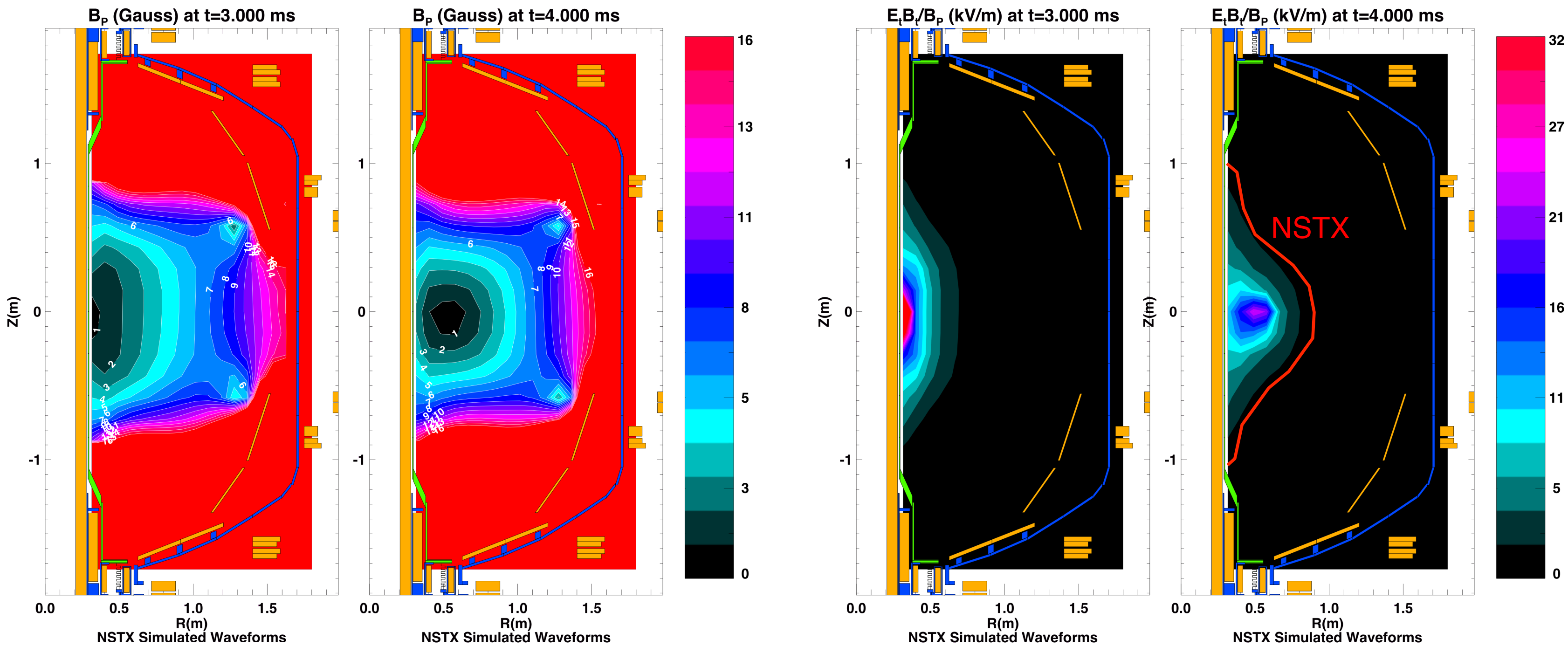
- Nice result since null is highly dependent on induced wall currents and OH fringe fields
  - Proceed with using LRDFIT as a predictive tool for NSTX-U

CD4 Startup Scheme: Use the Same TF, PF3 and PF5 Currents, Change OH Current

- Start with something close to NSTX experience for CD4
- Reduce OH precharge to 8kA
  - New OH flux is 3 times larger
  - Same OH fringe B_Z as 24kA on NSTX
- Halve the OH ramp rate
  - Gives 1.5 times more V_{loop}
    - V_{loop} ~ 4.2 V
  - Lots of headroom for higher V_{loop}
    - Will I_p increase too fast at larger V_{loop}?



Null Formation, Lloyd Criteria Similar to NSTX with 24 kA OH Precharge



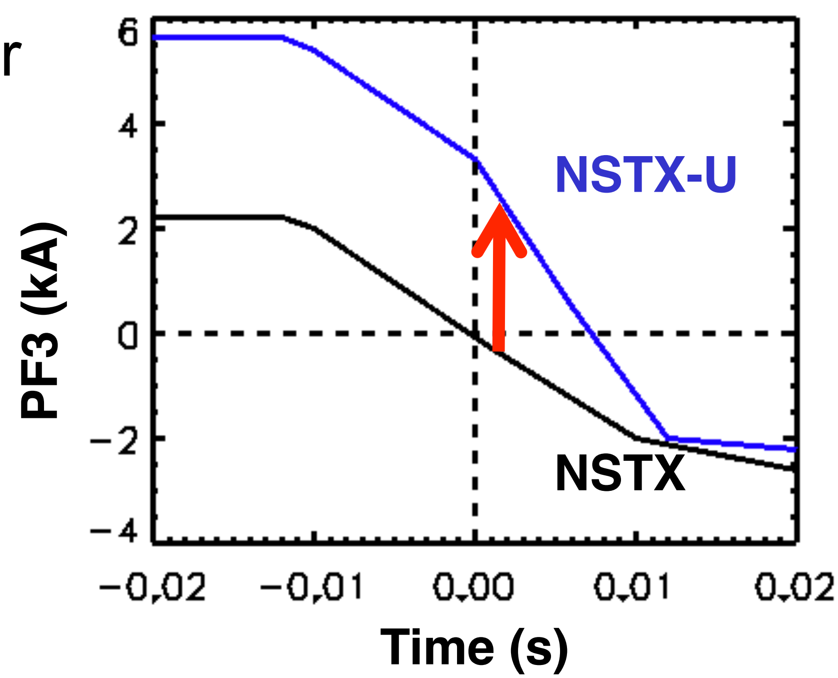
+3 ms +4 ms +3 ms +4 ms

NSTX-U Startup Scenario for 24 kA OH Precharge Will Require More Development

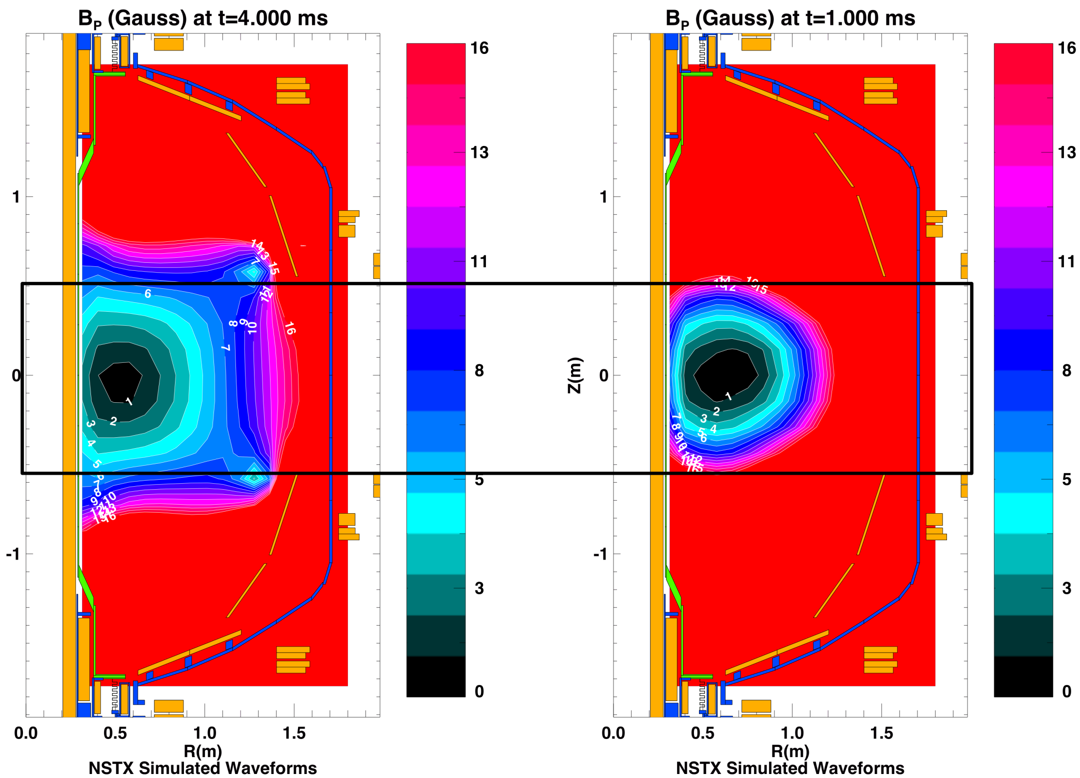
- +8 to -24 kV OH swing would double NSTX volt-seconds
  - Acceptable for commissioning and initial physics with 3 - 5 s H-mode flattop

- OH precharge > 8kA needed for long pulse

- Larger precharge requires more startup development
  - PF3 current at breakdown is more positive due to larger OH fringe



Field Null is Region is Smaller, Good Lloyd Parameter Region is not as Tall with OH at 24 kA

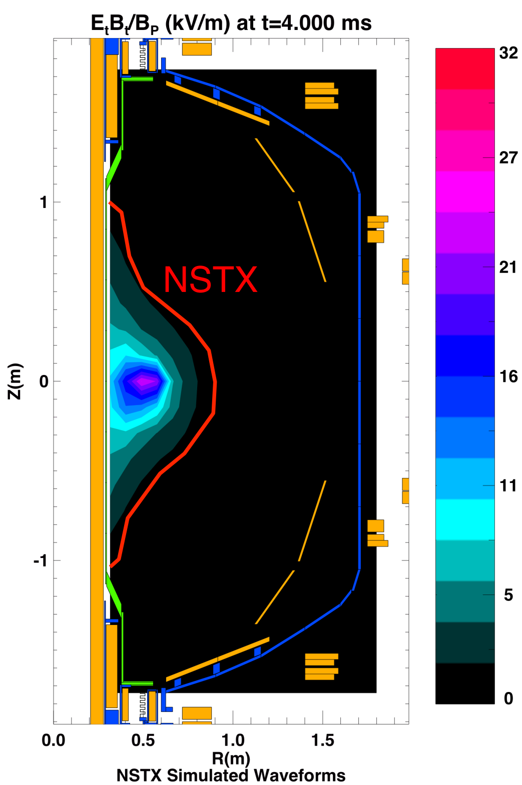


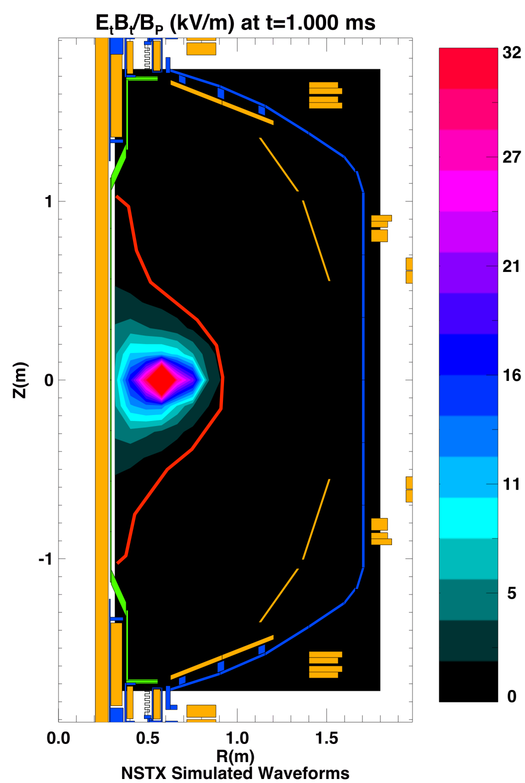
Will the reduced height of the null (shorter helical length of field lines) impact breakdown?

+8 OH precharge

+24 OH precharge

Field Null is Region is Smaller, Good Lloyd Parameter Region is not as Tall with OH at 24 kA





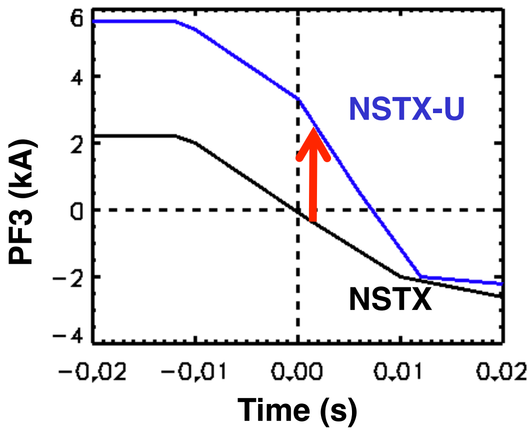
Increased V_{loop} at breakdown compared to 8kA precharge to get Lloyd > 2 kV same radial extent

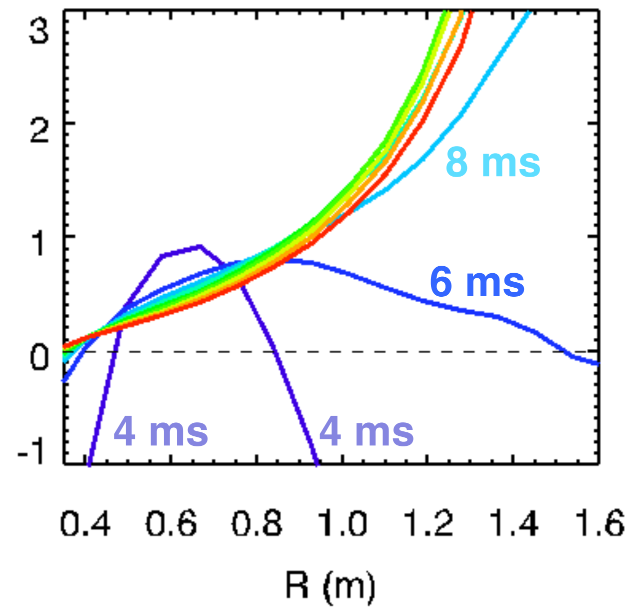
+8 OH precharge
V_{loop} ~ 4.0 V

+24 OH precharge
V_{loop} ~ 5.5 V

Vertical Stability After Breakdown May be An Issue

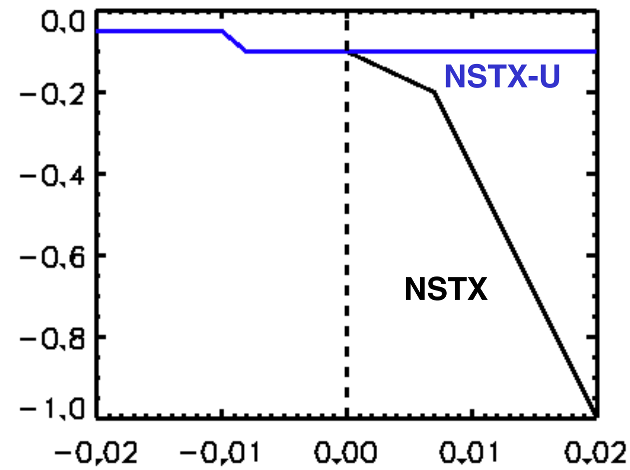
- PF3 current at breakdown is more positive
- Maximum PF3 ramp after breakdown
  - Apply coil voltage maximum: 2 kV
  - Field index is marginal (< 0) until 5 ms
    - Will the plasma go vertically unstable?
- Possible solutions:
  - Use PF1 or 2 to increase good curvature field immediately after breakdown
  - Use PF4 to provide additional nulling field
    - PF4 would not be available for making low squareness shapes unless it was bipolar



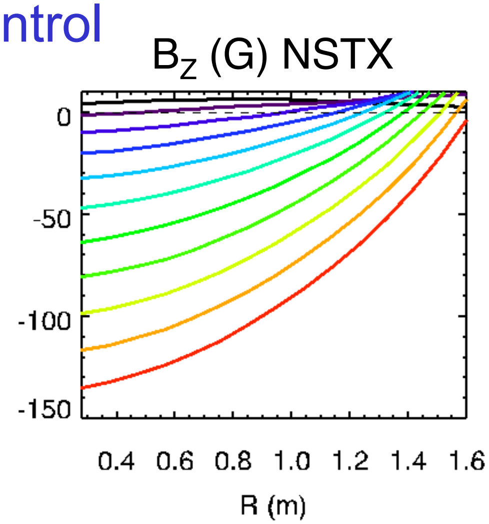


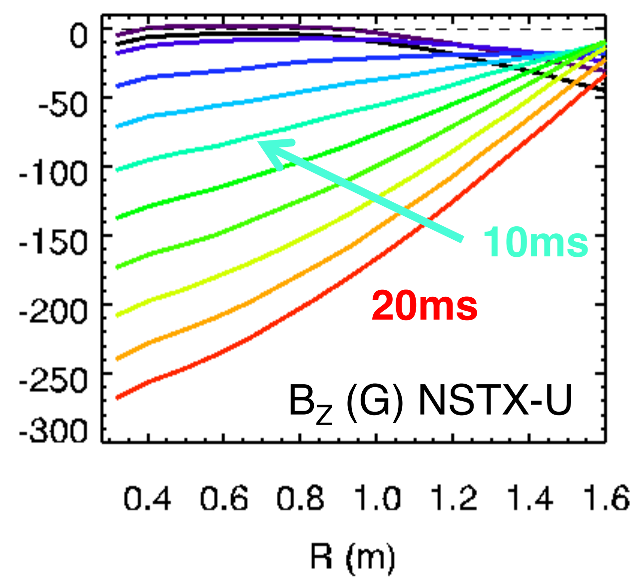
Another Potential Issue: Vertical Field Evolution Exceeds NSTX Even with PF5 Near Zero

- OH fringe field + PF3 provides equilibrium field without PF5
  - B_Z x 2 compared to NSTX
  - Will gap control be happy starting from low PF5 current?

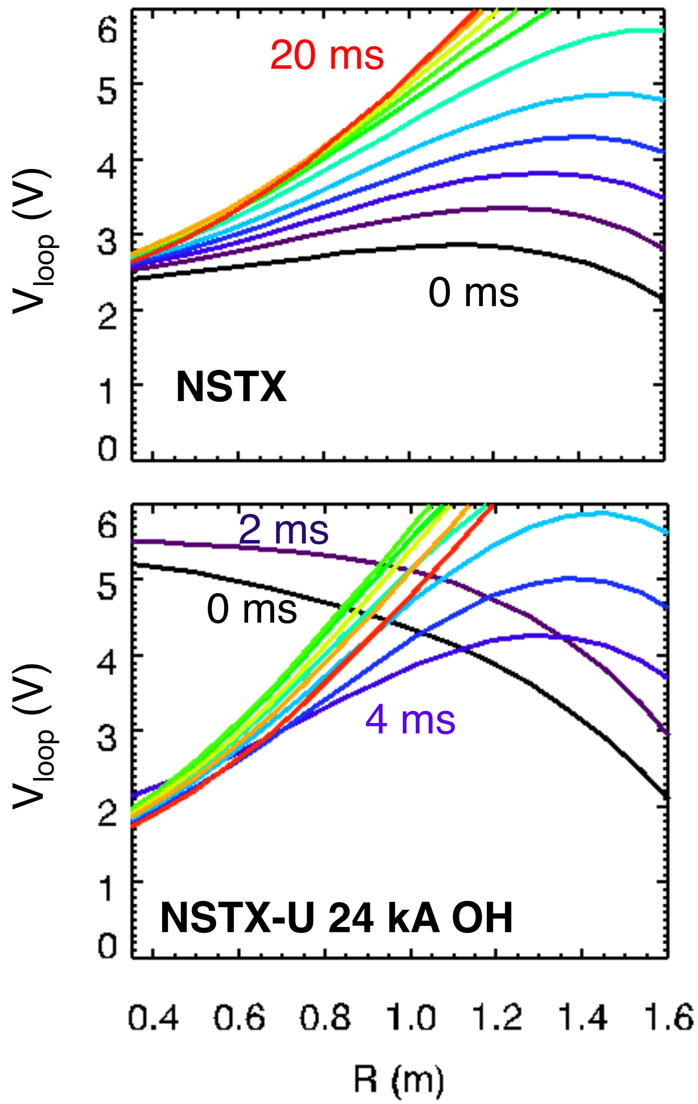


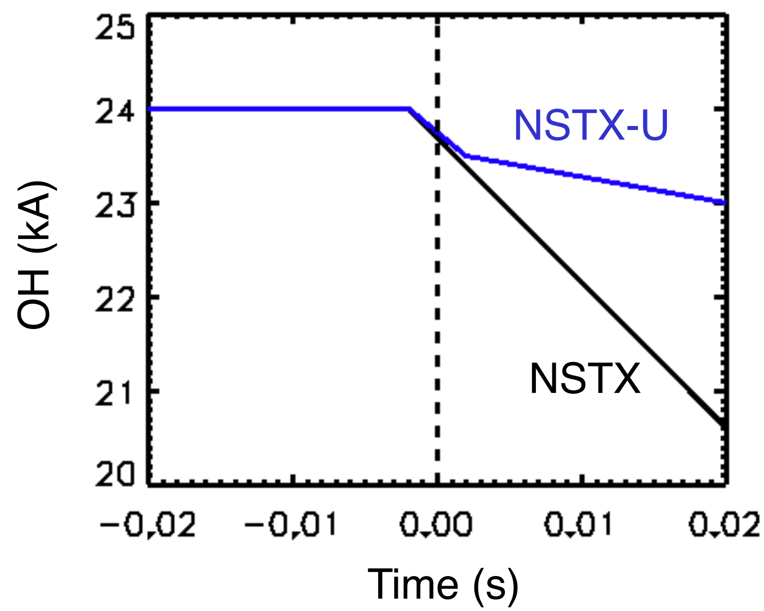
- Possible solutions
  - Delay start of gap control
  - Ramp I_p faster
  - Operate at smaller field index
  - Use PF4 for nulling field





V_{loop} Requirements for Breakdown and I_p Ramp May Require Disjointed OH Ramp Rates Around t = 0





- V_{loop} ~ 5.5 for Lloyd similar to NSTX
- V_{loop} ~ 4 at R = 0.8 for I_p ramp
  - Aggressive PF3 ramp increases V_{loop} at large R in NSTX-U case

LRDFIT Modeling Provides a Tool for Prediction and Interpretation of Inductive Startup Scenarios

- LRDFIT modeling and NSTX measurements in agreement
  - Lends confidence that LRDFIT captures necessary wall currents and OH fringe field to develop breakdown scenarios and interpret results
- CD4 on NSTX-U will use scenario similar to NSTX
  - NSTX-U OH fringe field at 8 kA similar to NSTX at 24 kA
  - PF3 and PF5 waveforms provide equilibrium field with good field index provided I_p ramp is similar
- First XMP of NSTX-U commissioning will develop startup scenarios at larger OH precharge
  - Satisfy null formation and a good field index with PF3 only?
  - Evaluate issues with low PF5 current and transition to gap control
  - Evaluate issues with smaller PF null for breakdown
  - Motivate adding new PF coils to startup scenario

Vacuum field at 20ms: B_p ~ 140G with Good Field Index for Vertical Stability (n_{decay} ~ 1) at R = 0.95 m