NSTX-U

NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

Update on Startup Scenario Development for MAST-U

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Thanks to the MAST-U team, especially:
Andrew Thornton, Andrew Kirk, Lucy Kogan

NSTX-U / Magnetic Fusion Science Meeting
September 24, 2018

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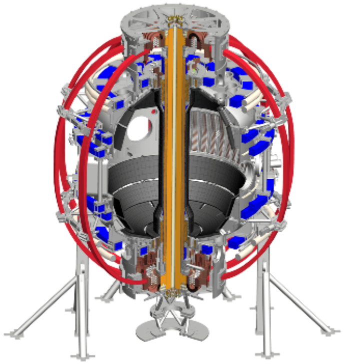
CULHAM CENTRE FOR FUSION ENERGY

PPPL

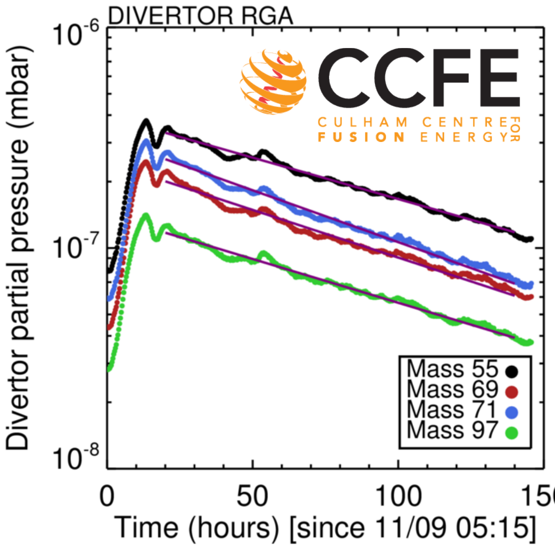


Outline

- Status of MAST-U preparations for operations
- Direct induction startup on NSTX-U and MAST-U
- Empirical startup metrics for vacuum field calculations
- Predictive calculations for MAST-U startup using a reduced set of D-coils

First bake of MAST-U tiles completed

- High temp bake of tiles to remove potential hydrocarbon impurities
  - Tile temperature: 120 - 230°C
  - Outer vessel temperature: 110°C
- Partial pressure of high mass impurities decreased 87% during divertor RGA monitoring
  - Started bake with RGA at midplane
    - Very few high mass impurities from hot divertor tiles made it into main chamber
  - Implemented RGA in divertor mid-bake in order to monitor high mass removal
- Putting in a shift on the bake team →



MAST-U operations planned for 2019

- Now - Feb 2019: PASS commissioning, TF remediation, off-coil commissioning
- Winter/Spring 2019: Bake II, NBI commissioning
- Spring 2019: Integrated power supply and coil testing
  - Digital coil protection, first PCS tests, magnetics calibrations, NBI arc and conditioning into calorimeter
- Spring/Summer 2019: Plasma startup and scenario dev.
  - Limited and diverted discharges
  - Starting with 1.5 MW (one beam), increasing to 4 MW (two beams)

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MAST-U and NSTX-U use a similar inductive startup scenario

Precharge solenoid to positive current.

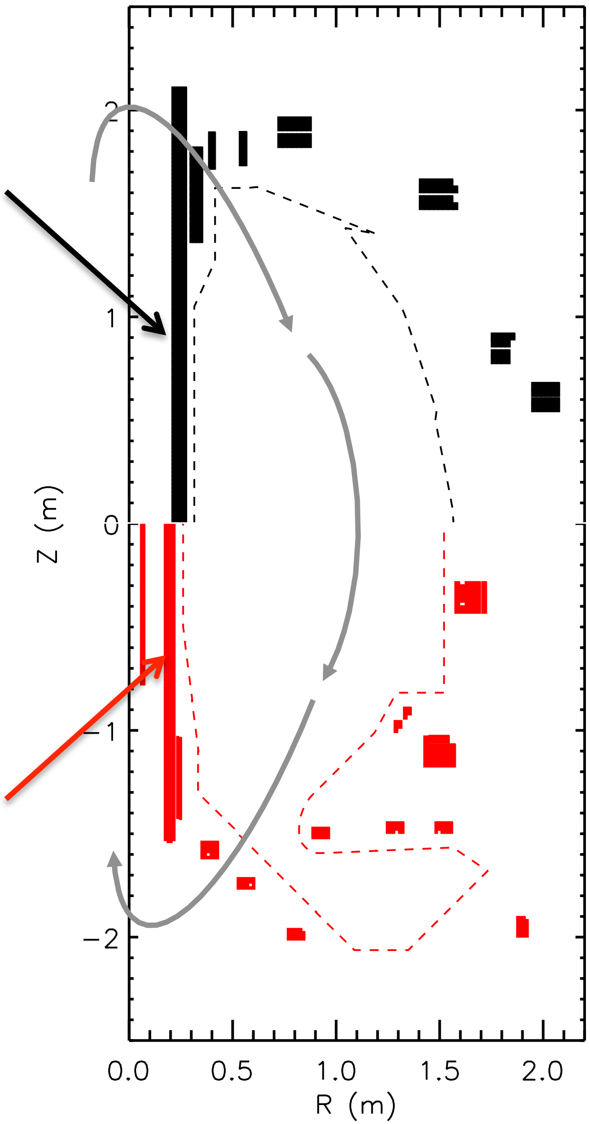
Produces fringe field in confining B_Z direction with good poloidal curvature.

NSTX-U

I_{OH} = 20 kA (20 kA/turn)
*** Limit for 2016 operations*

MAST-U

I_{OH} = 45 kA (22.5 kA/turn)
*** Limit for phase 1 operations*



MAST-U and NSTX-U use a similar inductive startup scenario

Off-midplane, large-R coils produce nulling field and correct any up-down asymmetry.

Ramp fast from positive to negative current in order to produce confining field with good poloidal curvature after breakdown

NSTX-U

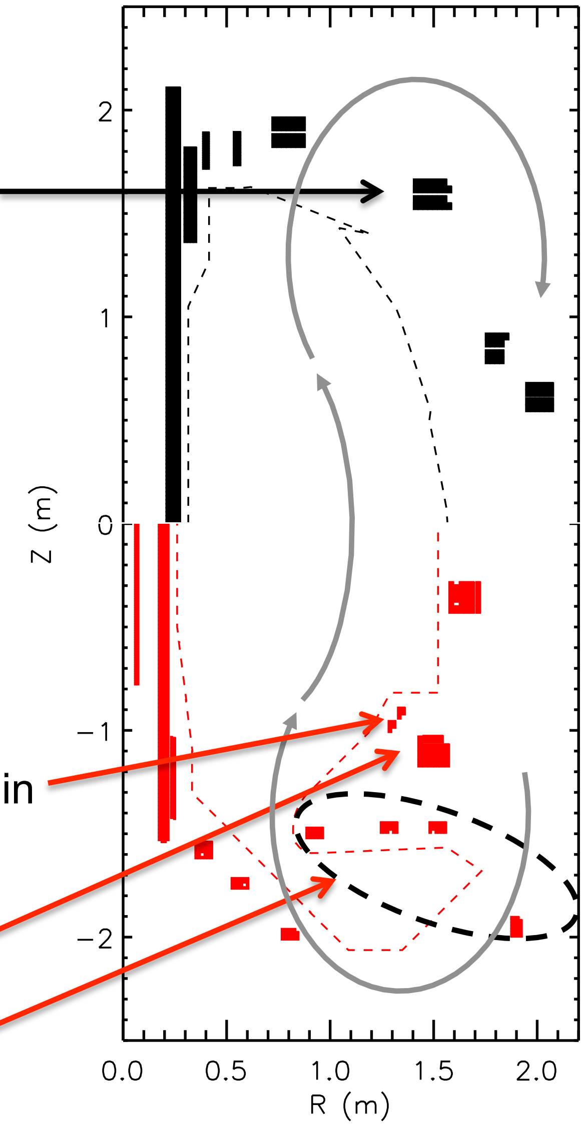
PF3: Bipolar, 67 V per turn
Upper and lower coils have separate power supplies

MAST-U

P6: Bipolar. Up-down wired in anti-series

P4: Unipolar, 12V per turn

DP, D6, D7, D5
Bipolar, ~15V per turn



MAST-U and NSTX-U use a similar inductive startup scenario

Small-R coils increase vertical extent of null by cancelling radial field

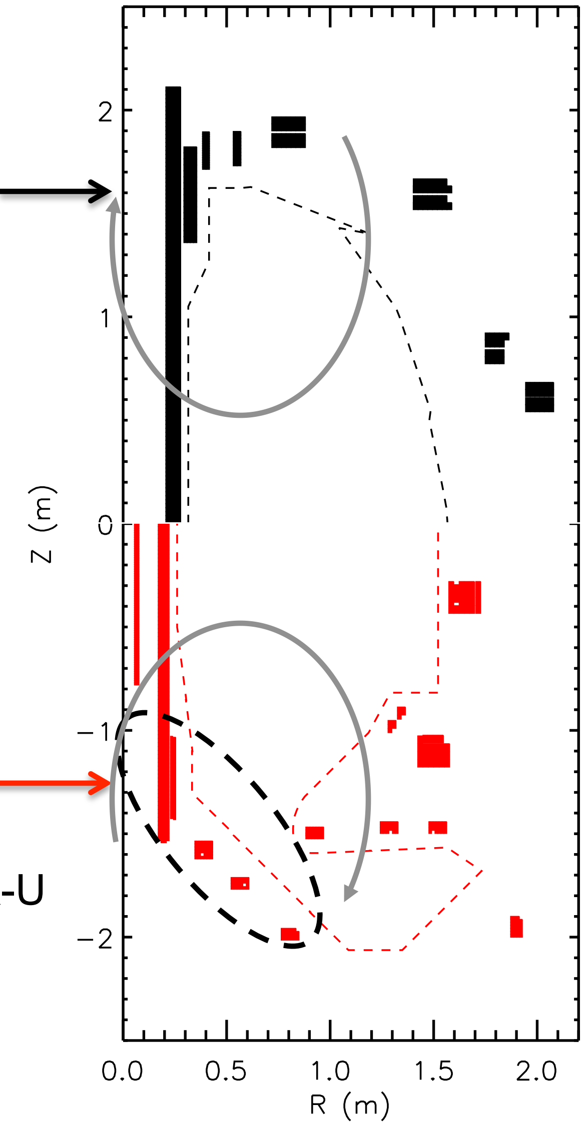
Hold steady at positive current or ramp down to avoid vertical instabilities as plasma boundary grows

NSTX-U

PF1A and PF2: Unipolar
- Have not been used in startup scenarios, but could be

MAST-U

PX, D1, D2, D3: Bipolar
- Must be used to get a similar null quality to NSTX-U



MAST-U and NSTX-U use a similar inductive startup scenario

Near-midplane, large-R coils provide equilibrium field after breakdown.

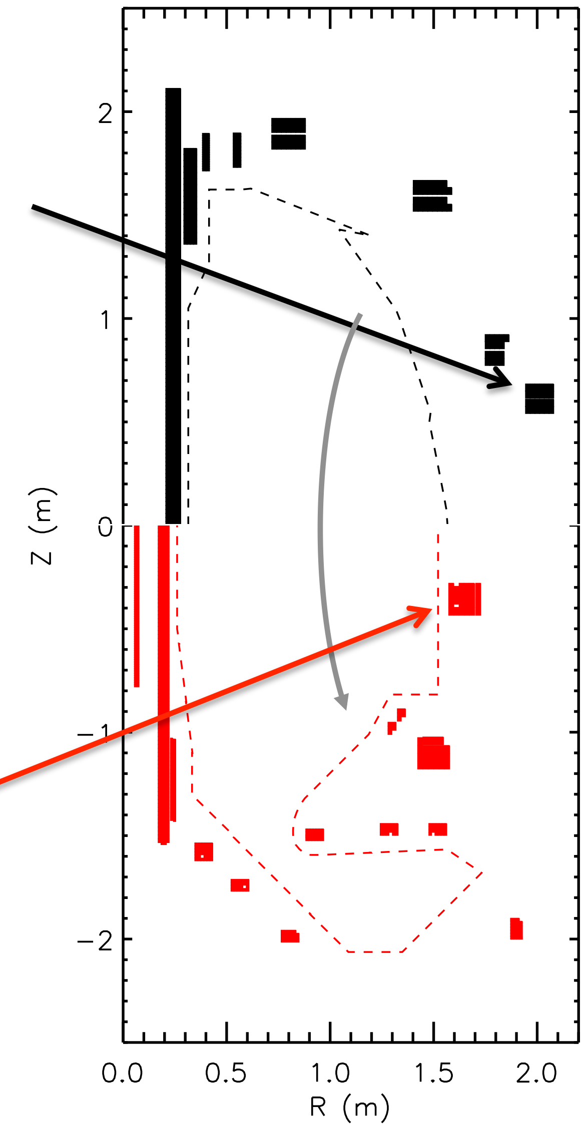
Reduces the good poloidal curvature.

NSTX-U

PF5 or PF4: Unipolar
Up-down wired in series

MAST-U

P5: Unipolar
Up-down wired in series



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- **Empirical startup metrics for vacuum field calculations**
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Vacuum field calculations can guide startup scenario development

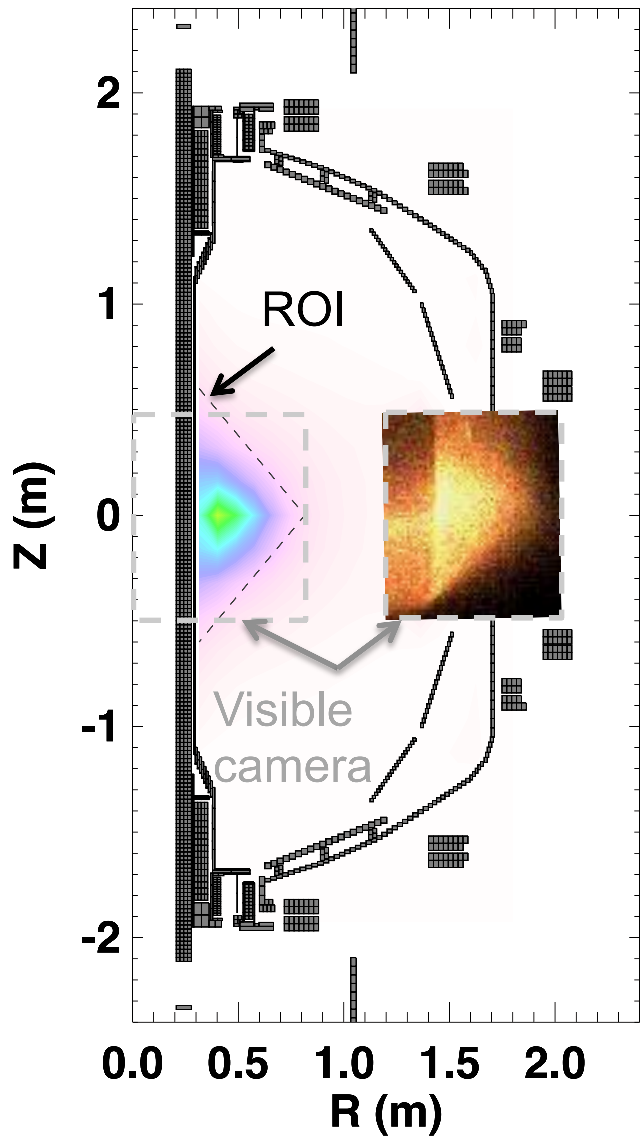
- LRDFIT (IDL) code identified as shared tool for vacuum field calculations (Monday Physics Meeting 9/25/17)
  - Optimization of axisymmetric wall model for reconstructions
  - Magnetic sensor calibration
  - Inductive startup planning

- Interpretative calculations for NSTX, NSTX-U and MAST verify wall model and derive metrics for predictive calculations

- Predictive calculations support development of startup procedures for NSTX-U and MAST-U
  - Develop a "menu" of options for startup
  - Develop a "recipe" for scanning around an operating point
  - Identify critical systems for first plasma
  - Provide P.O.s a tool to gain intuition and interpret results

Predictive startup scenario calculations benefit from establishing 1-D metrics

- B and E fields vary in time + 2D space
  - Spatially average over an ROI to easily compare different scenarios
- Four metrics for evaluating startup
  - Breakdown (B_θ null and V_{loop})
  - Equilibrium (B_Z field evolution ~ I_p)
  - Vertical stability (dB_R/dZ)
  - V_{loop} sufficient for dI_p/dt (~ dB_Z/dt)
- Must satisfy constraints
  - Precharge mitigates early breakdown
  - Power supply and coil I and V limits
  - Coil heating and force limits



Metric 1: Lloyd parameter must be similar to previous results on STs

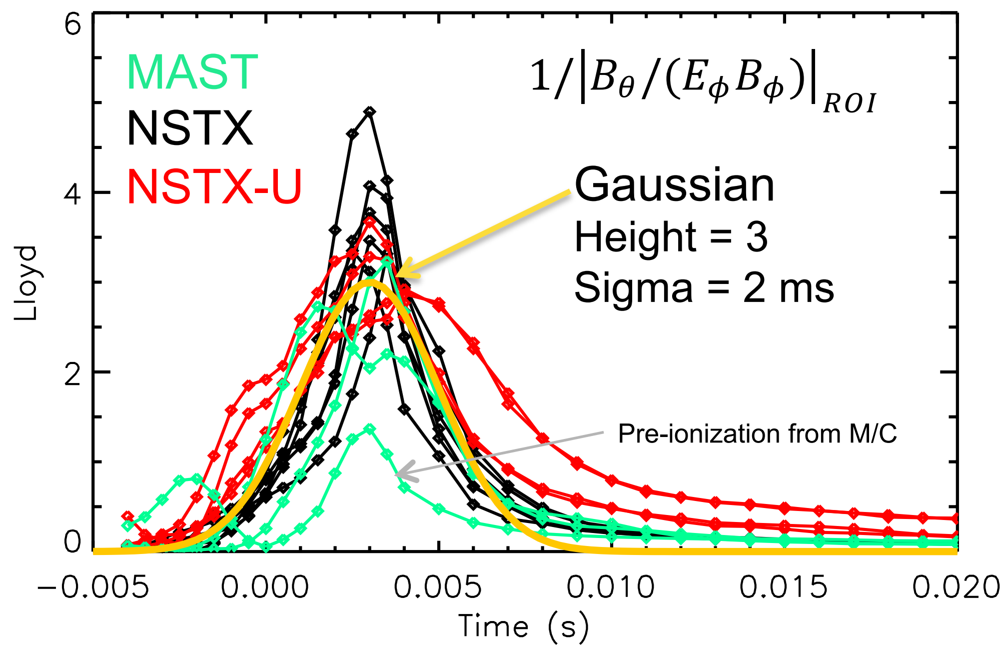
- "Lloyd" parameter ($E_\phi B_\phi / B_\theta$) is a metric for breakdown
  - Breakdown more likely with …
    - Longer connection length of open field lines (B_θ field null)
    - Larger toroidal electric field (loop voltage)
  - Calculations have singularity where $B_\theta = 0$
    - Averages dominated by computational resolution of singularity

- Several options considered:

$$1/\left|B_\theta/(E_\phi B_\phi)\right|_{ROI} \qquad \left|E_\phi B_\phi\right|/\left|B_\theta\right|$$

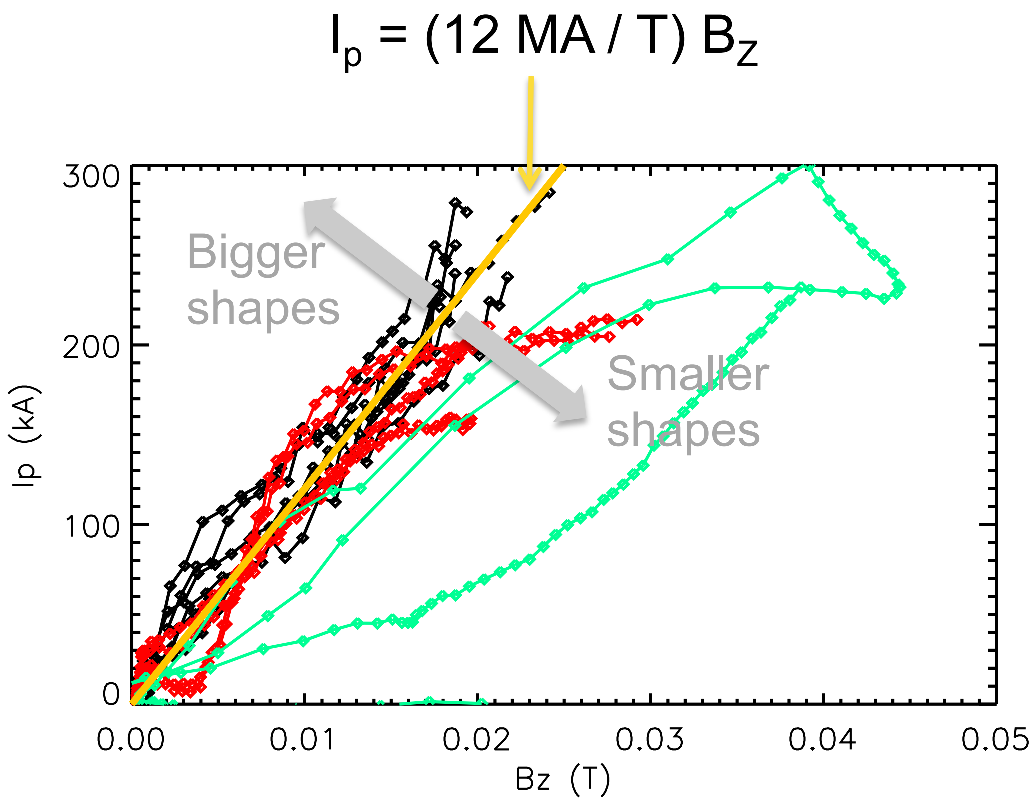
$$\left|E_\phi B_\phi/(B_\theta + B_{NA})\right|_{ROI}$$

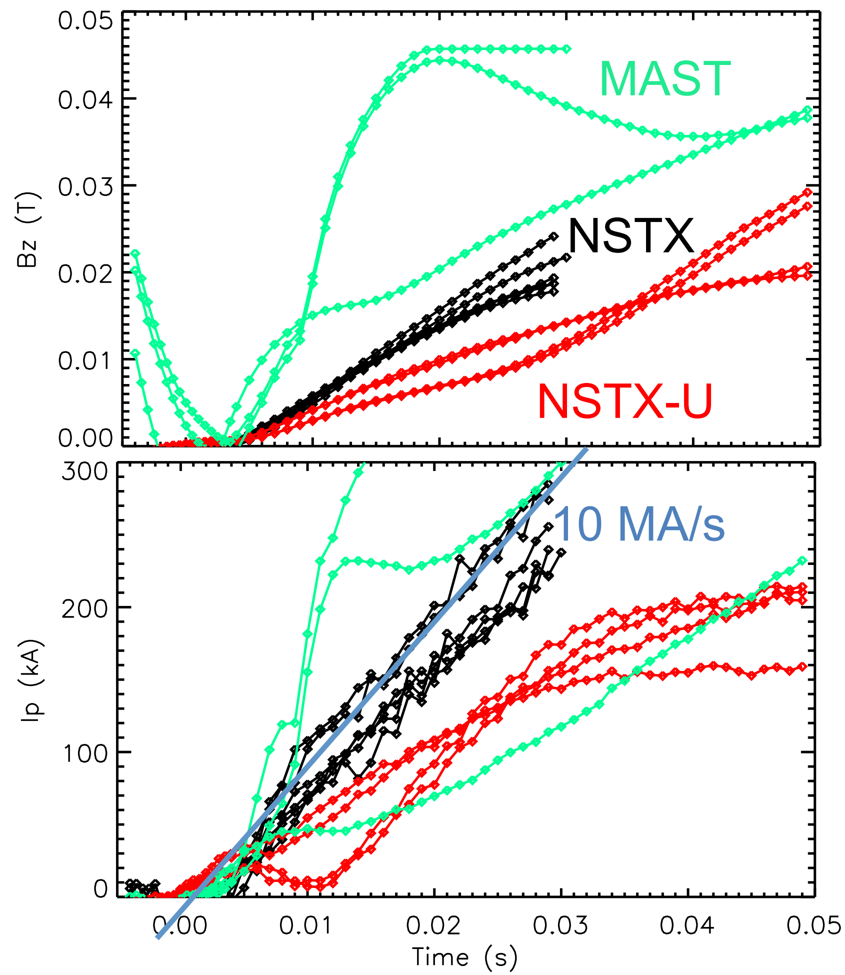
  - I settled on the first definition as the preferred metric
    - Retains importance of aligning max E and B_ϕ with field null
    - Does not require an assumption on non-axisymmetric fields



Metric 2: Vertical field must increase to provide sufficient equilibrium field

- I_p proportional to B_Z averaged over ROI for MAST, NSTX and NSTX-U





Metric 3: Must provide sufficient loop voltage for dI_p/dt during ramp up

Surface voltage during ohmic current phase:

$$V_{surf} = L_i \frac{dI_p}{dt} + \frac{1}{2} I_P \frac{dL_i}{dt} + V_{res} \qquad L_i = \mu_0 \frac{R_0}{2} \ell_i$$

Assume …

$$\frac{1}{2} I_P \frac{dL_i}{dt} \sim 1\mathrm{V} \qquad V_{res} \sim 4\left(\frac{\mathrm{V}}{\mathrm{m}}\right) R_0$$

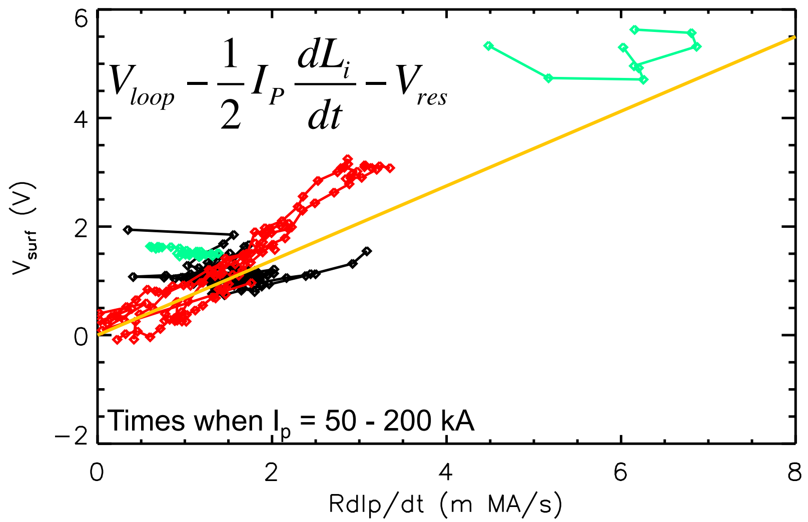
Interestingly, a simpler relationship does even better …

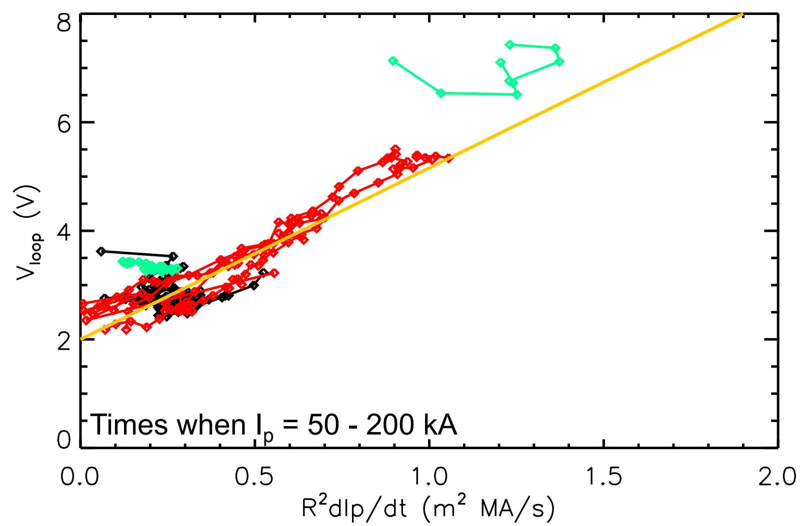
$$V_{loop} = 3.17\, R_0^2 \frac{dI_p}{dt} + 2$$

I made this the metric ….

$$V_{loop} \Big/ \left(3.17\, R_0^2 \frac{dI_p}{dt} + 2\right) \sim 1$$

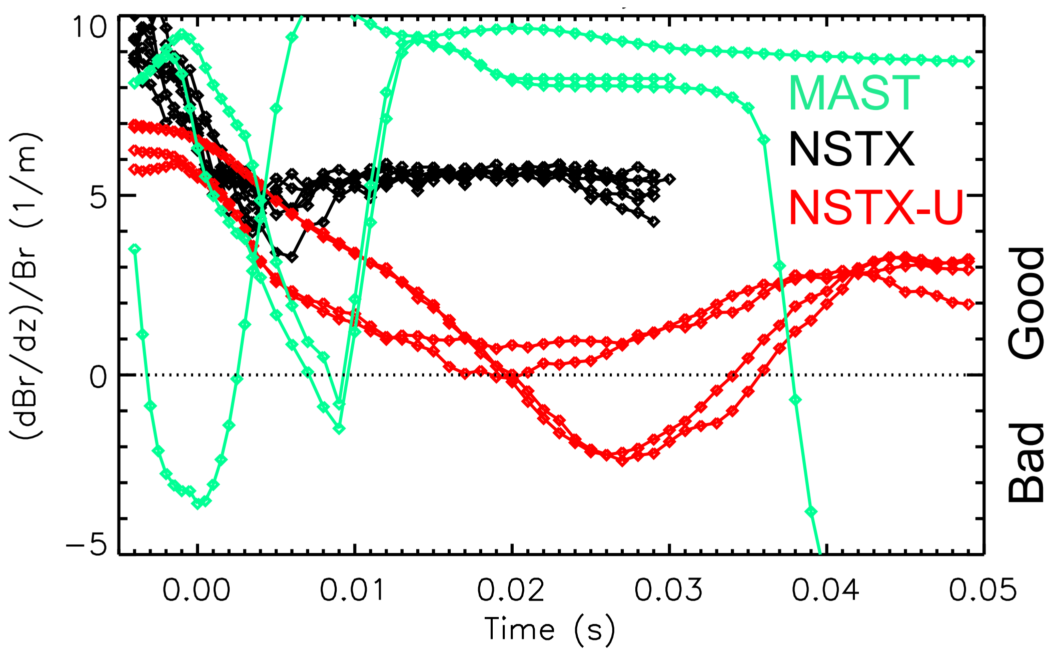
For times when I_p > 50 kA





Metric 4: Poloidal field must provide passive vertical stability

- Derived assuming current is force-free: $J_\phi \sim B_\phi$
  - Consider fractional change in F_Z from dZ motion
    - Positive: change in vertical force opposes motion
    - Negative: requires stabilization from wall or active feedback



$$\frac{\displaystyle\int_{boundary} \frac{dB_R}{dZ} \bullet \hat{R}\, dS}{\displaystyle\int_{Volume} |B_R|\, dV} > 0$$

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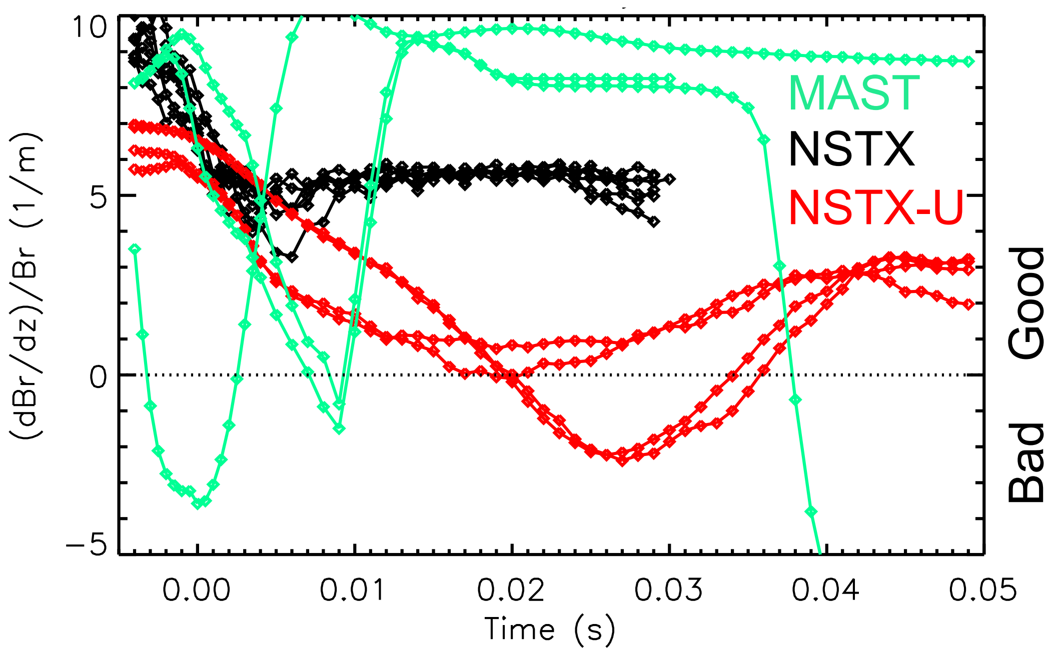
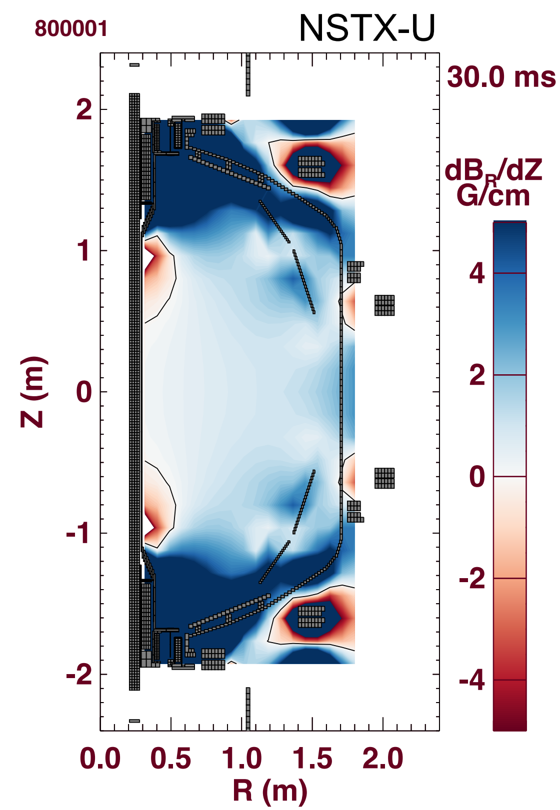
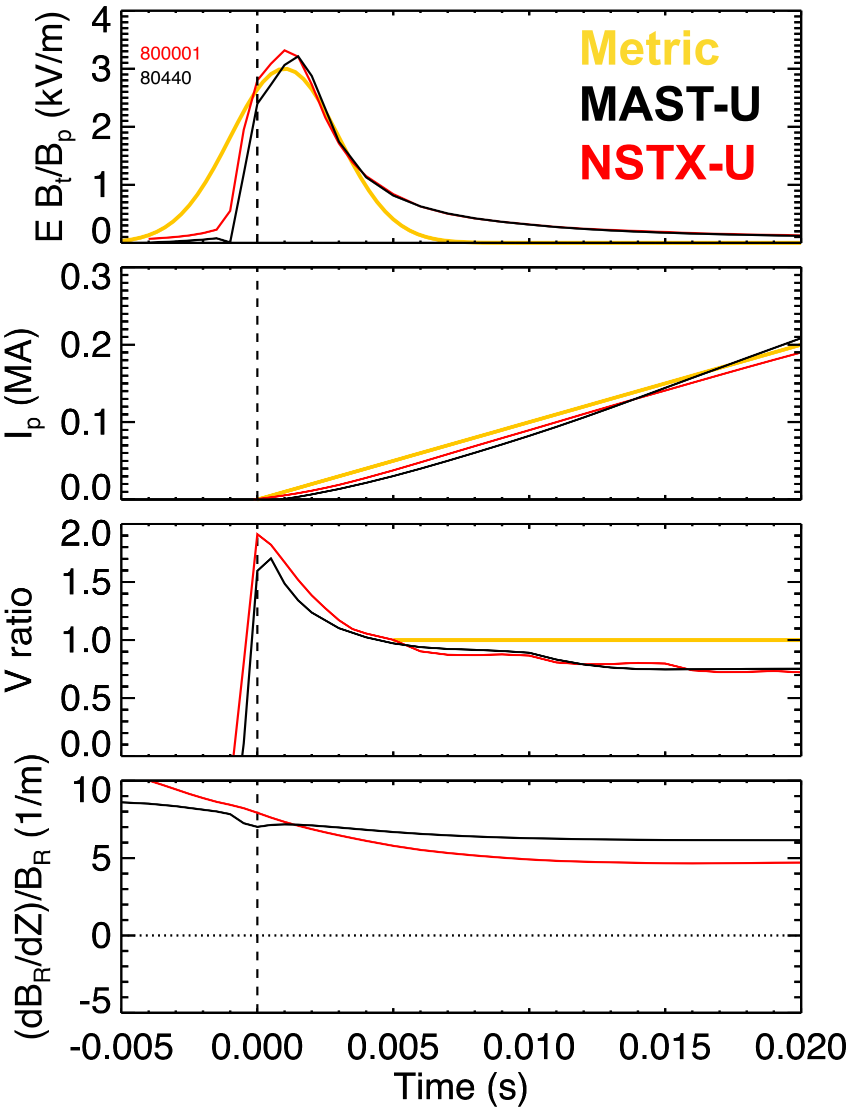




- Vertical stability on NSTX-U hurt by copper cooling tube currents

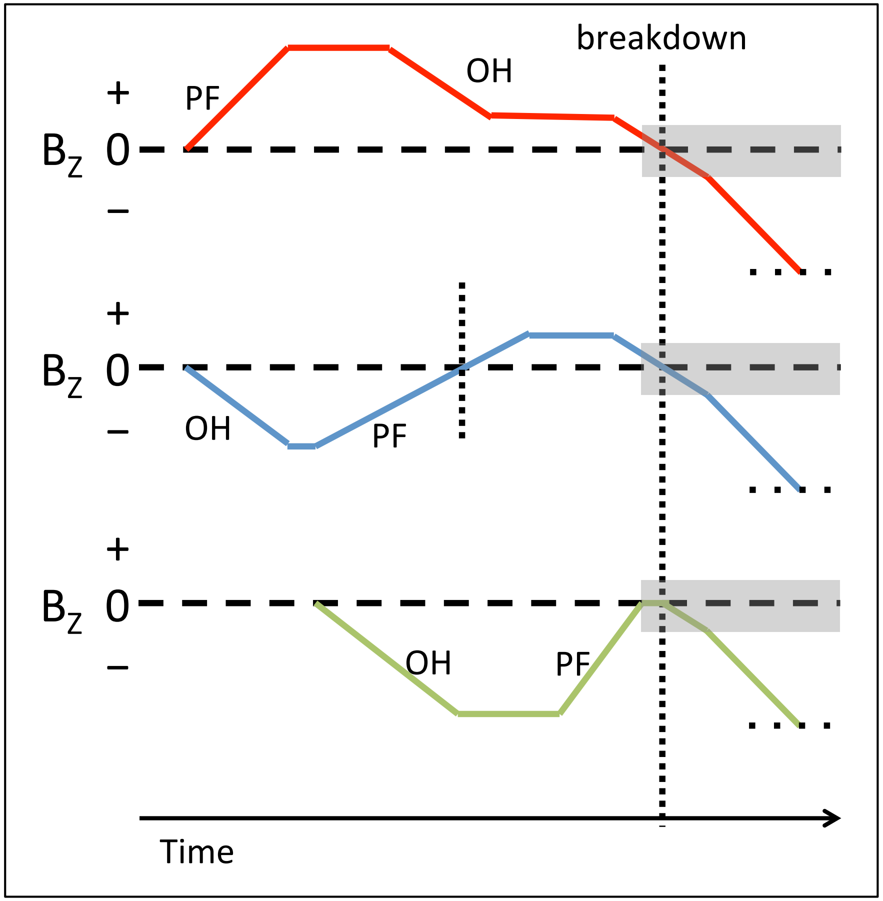
Comparable Startup Scenarios Developed for MAST-U and NSTX-U

- Modified 20 kA OH precharge NSTX-U startup to be more like NSTX
  - Calculations include copper cooling tubes
- Designed comparable scenario on MAST-U
  - Using coil limits for first run
- Presented at 2017 APS
  - Metrics developed summer 2018 quantify agreement



Precharge impacts the startup scenario and must be included in scenario development

- NSTX(-U)
  - Long pre-fill for active feedback on vessel pressure
  - No zero-crossing allowed
- MAST-U
  - Limit heating of D-coils
  - Inject gas 15 ms prior to discharge
  - Zero crossing must happen before this, or V_{loop} carefully tailored near zero-crossing
- "The kiss"
  - Not resilient, but can work



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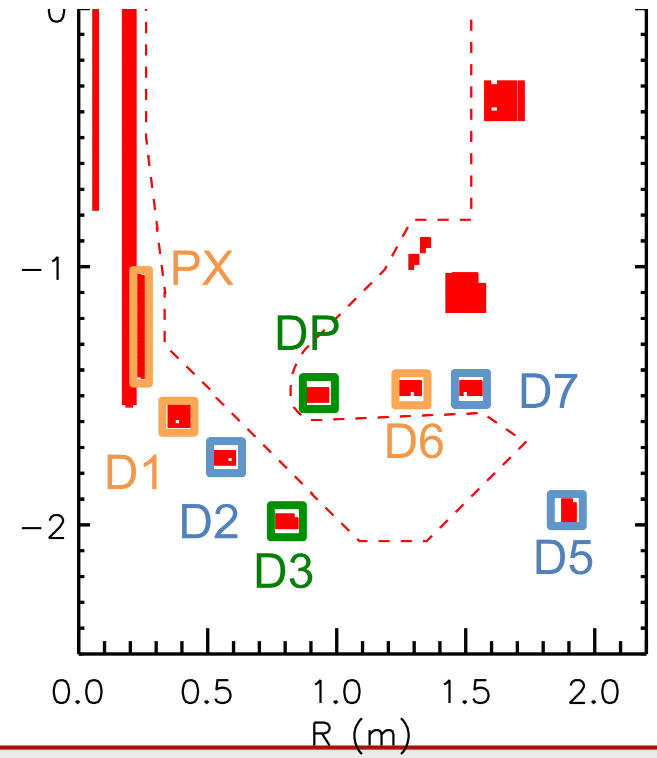
MAST-U Startup scenarios will use D-coils

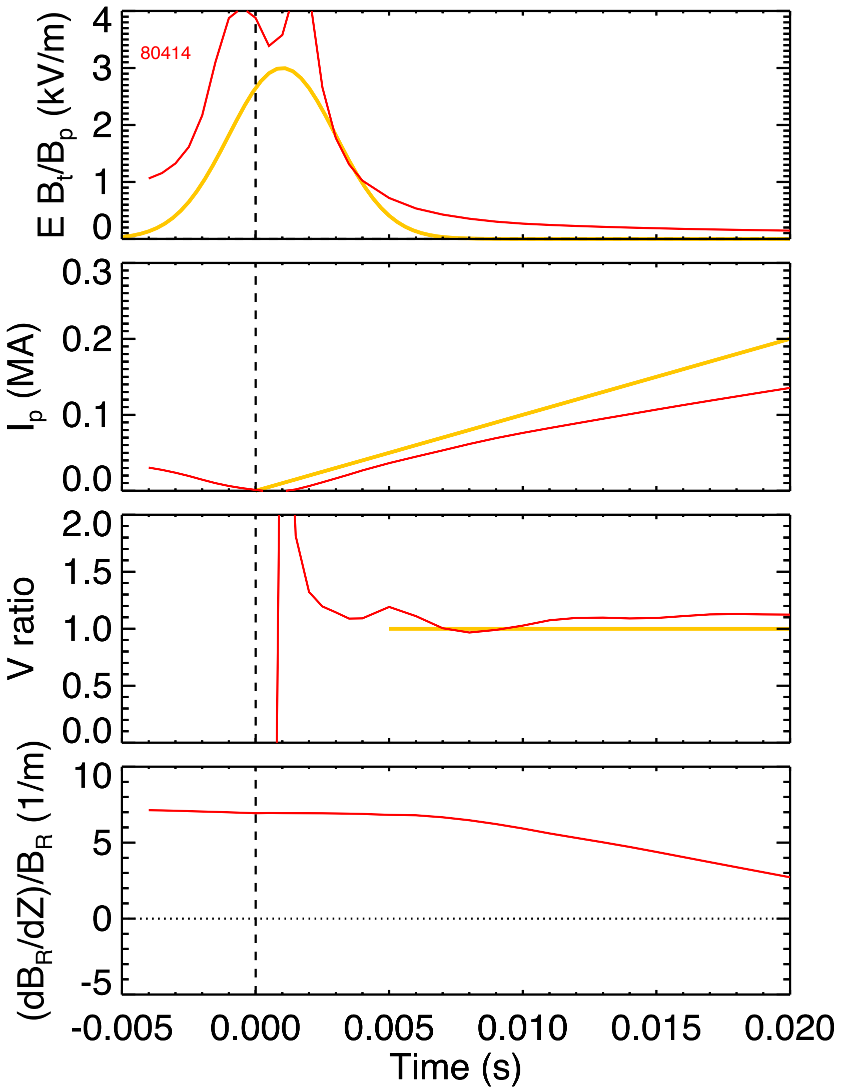
- APS17 scenario used all 8 of the D-coils (includes PX)
  - P4,D3,D5,D6 and D7 at or near voltage limit to get 10 MA/s
  - D1,D2,D3 and D5 at or near current limit with P1 = 45 kA
    - Current limit is a conservative level established for the first campaign
  - Aimed for a mix of inverting and rectifying H-bridge circuits with no zero crossings

- Advantageous to develop startup scenarios using fewer D-coils
  - Can the scenario be simplified with P1 = 45kA and dI_p/dt >10 MA/s?
  - What are the most critical D-coils for startup?
  - How does this limit the operational parameters of startup?



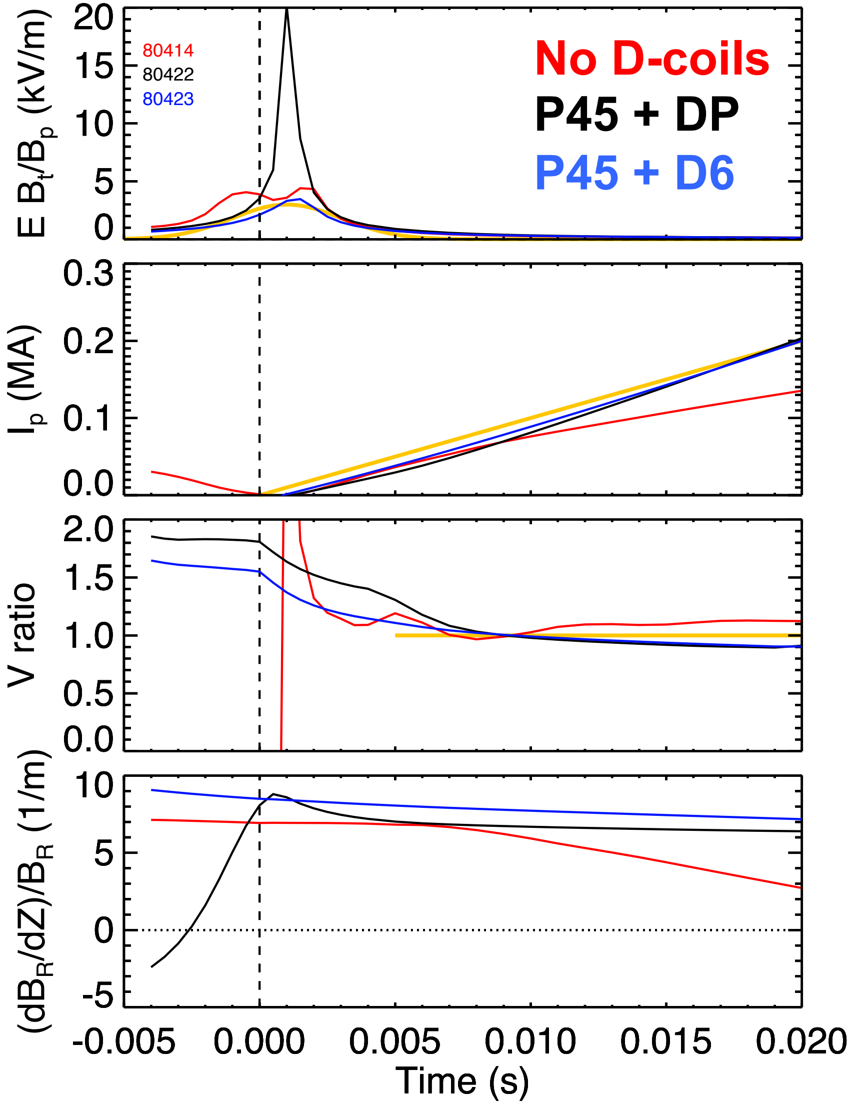
Breakdown with only P4 and P5 (no D-coils) seems viable with smaller dI_p/dt

- One option: Reverse P4 or P5 current
  - Flash of light, but little chance of I_p flattop
- Another option: Large V_{loop} to produce the nulling field from wall currents
  - Ramp P1 from +45 to +7 kA prior to breakdown
- Cons:
  - Very dependent on wall currents
  - Uses “the kiss” precharge
  - Slower I_p ramp than target
  - P4 at max voltage
- Pros:
  - Simple
  - Good breakdown and stability metrics

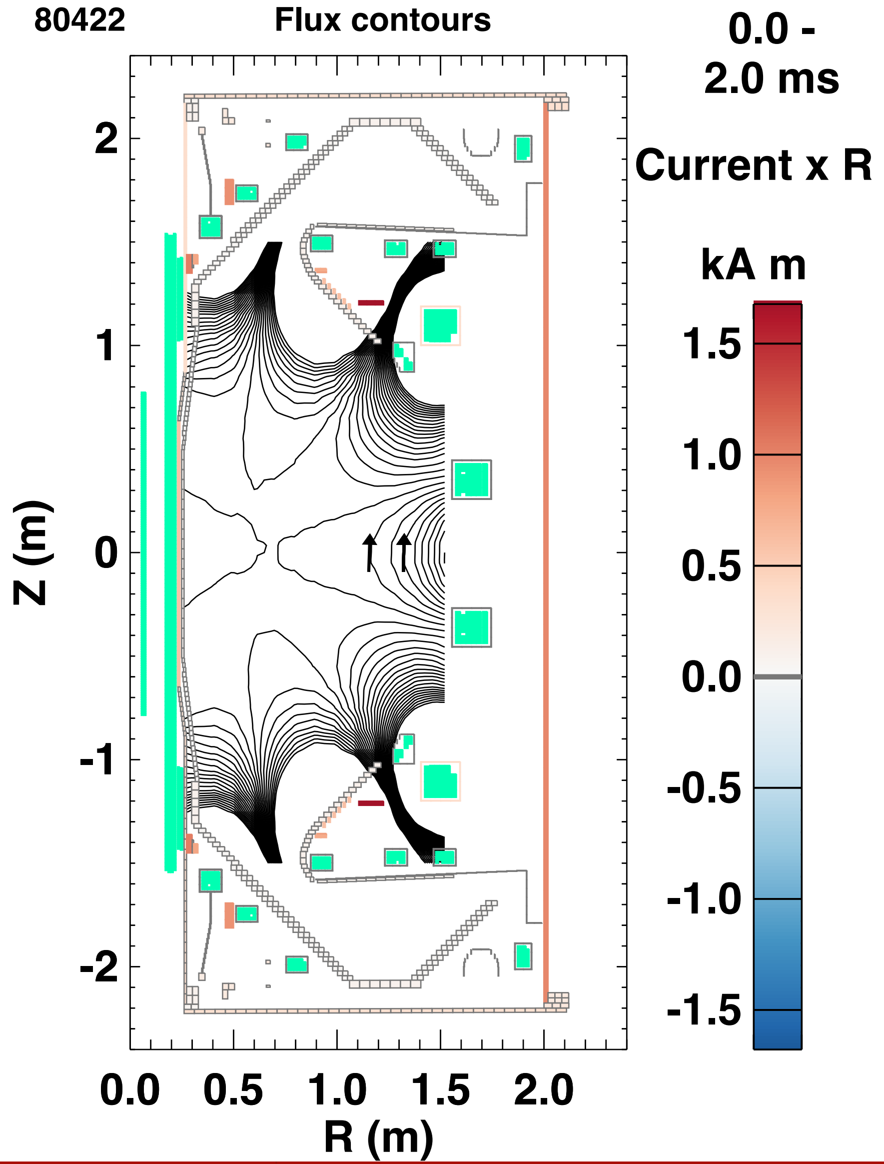


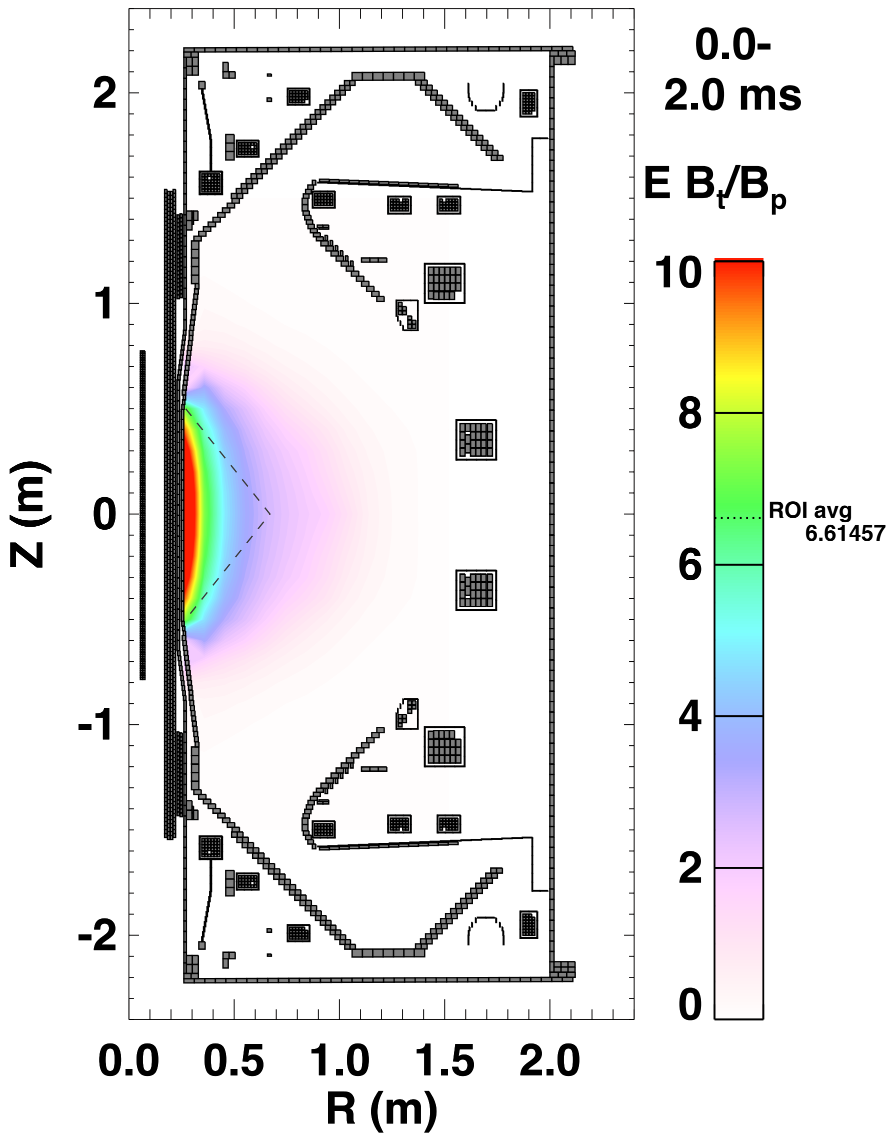
If only one D-coil available, DP or D6 seems to be the best

- Change pre-charge so B_Z ramps through breakdown
  - Ramp P1 from +45 kA at max V_{loop} to generate wall current
- Add DP
  - I_{P1} = 11 kA at breakdown
  - Produces high-order null
  - Max voltage on DP and P4
- Add D6
  - I_{P1} = 16 kA at breakdown
  - Null has limited vertical extent
  - Headroom on vertical stability and I_p ramp rate



DP is in a good spot to make a high order null with P1 ~ 11 kA

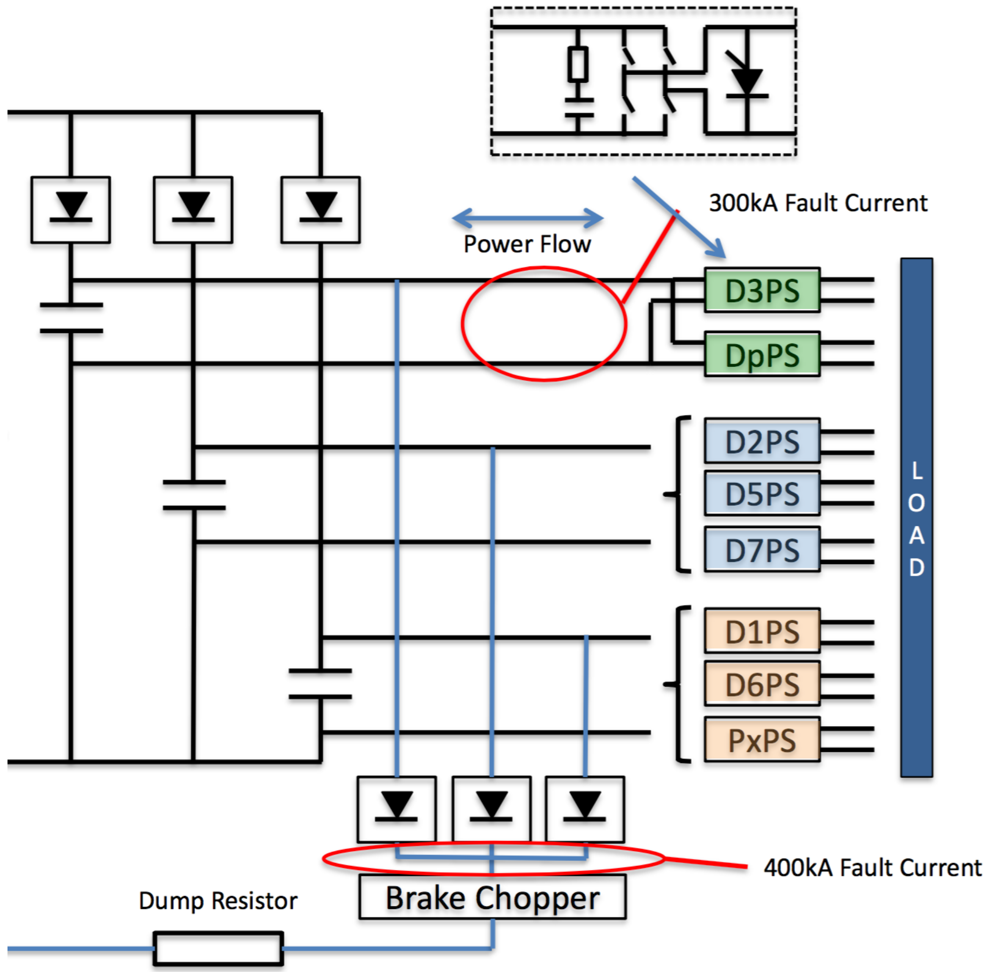


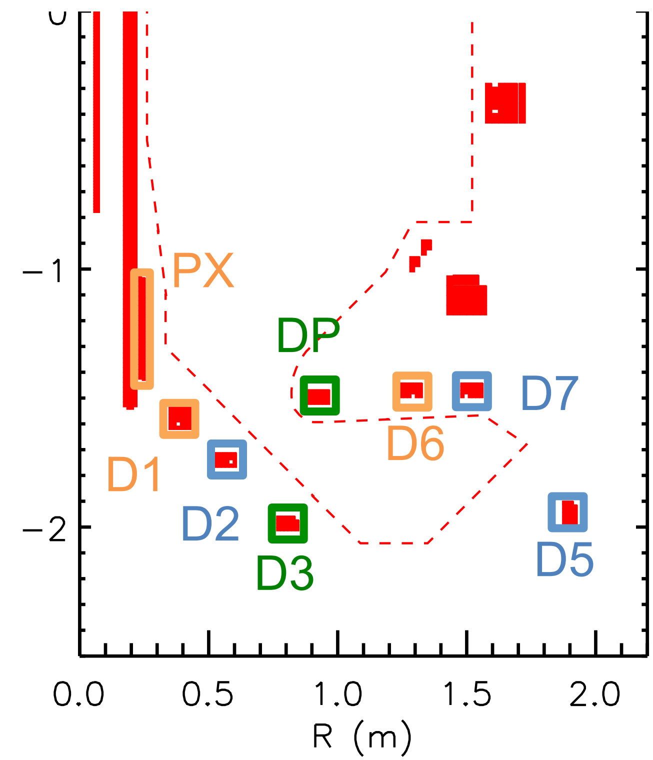


Summary of having no or one D-coil

- Startup with no D-coils seems viable
  - Use "the kiss" precharge, limit I_p ramp rate
- Add one inner D-coil (PX, D1) …
  - Hard to incorporate in startup, but could be used for making a diverted shape later
- Add one outer D-coil (DP, D6)
  - Can use a precharge with B_Z ramp through breakdown
  - DP can improve breakdown metric and enable dI_p/dt ~ 10 MA/s
  - D6 provides headroom on dI_p/dt and vertical stability
- Scenarios provide a simple route to making IWL plasmas
  - Rely on large induced currents in wall to provide nulling field and maximize P1 precharge

Scenarios developed considering one D-coil per DC Link





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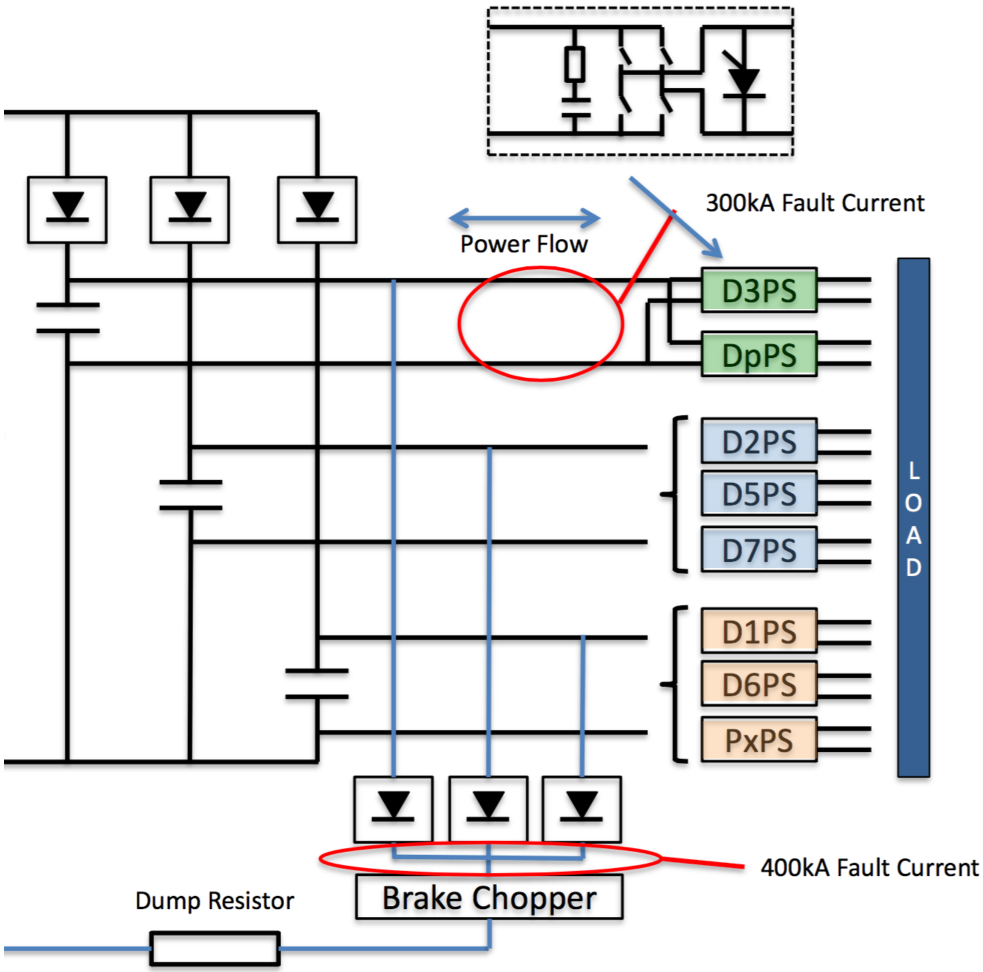
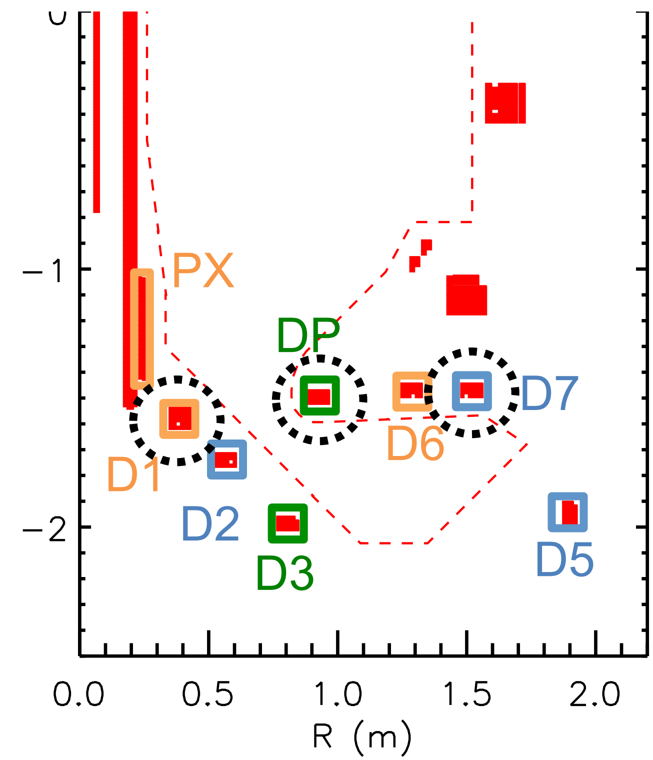
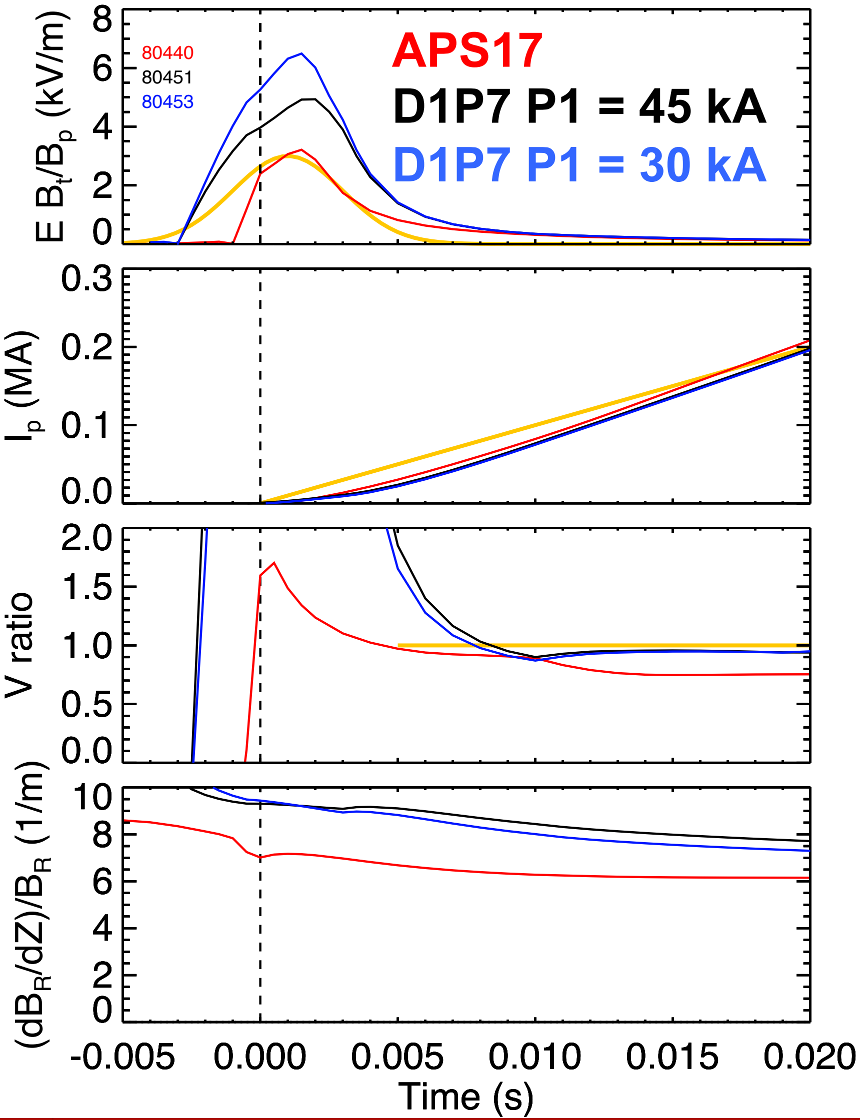




Viable scenario exists at max P1 precharge using one D-coil per DC link

- D1, DP, D7 most attractive scenario
  - Can operate with P1 precharge = 45 kA
    - All 3 D-coils operate at max current
  - Second choice is D2, DP, D6
    - D6 has a lower current limit than D7
- Using max V_{loop} (~ 7V) at breakdown
  - Get acceptable breakdown with smaller null compared to APS17 (V_{loop} = 4 V)
  - Increases influence of induced currents
- Lower field from low-R coils allows higher voltage on P5 to increase B_Z
  - P4, DP and D7 ramp at max voltage
- Decreasing P1 precharge increases ability explore trade-off between null quality and vertical stability
  - D1 vs D7 balance in ramp-up



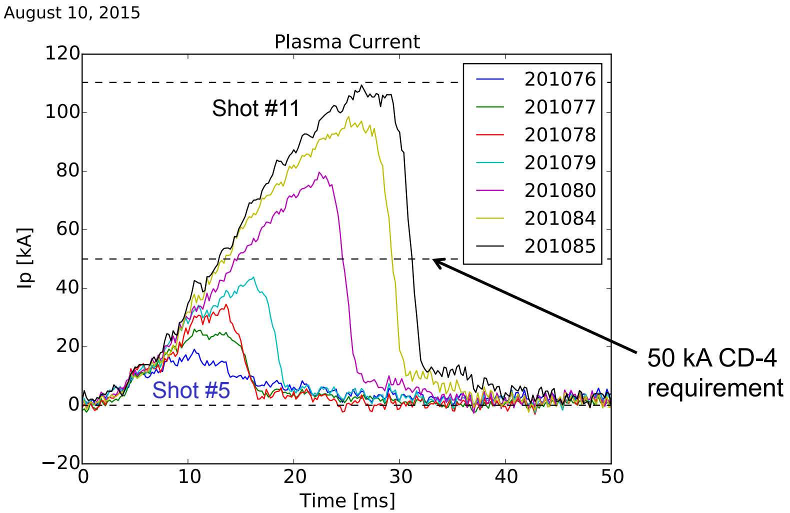
Summary

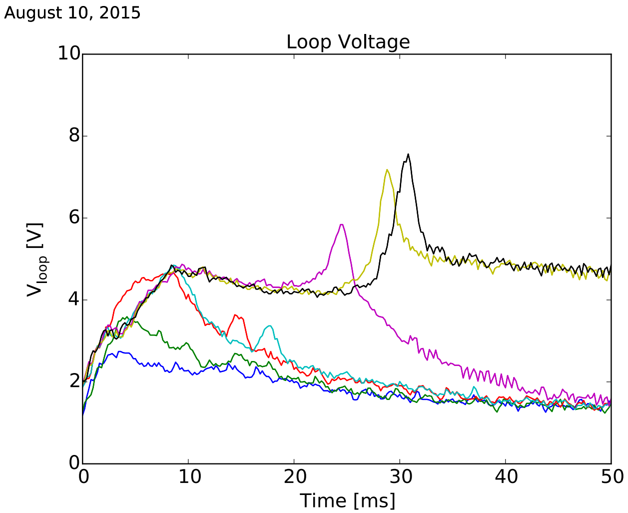
- Tools and intuition now exist such that the menu of options for MAST-U startup can be expanded quickly
  - Integrated tests will inform power supply performance
    - Particular interest is behavior when operating near maximum voltage on a number of coils
  - Vacuum field shots for magnetic calibrations will motivate modifications to the wall model
- New calculations simplify the startup scenario and provide viable options if not desirable to use all D-coils
  - Reduce low-R coil current (smaller null, more V_{loop}) allows larger P5 voltage during ramp-up (more vertically stable) reducing need for large-R coils
  - Identified D1, DP and D7 as most valuable D-coils for startup

Backup

Recipe derived from vacuum field calculations accelerated first plasma on NSTX-U

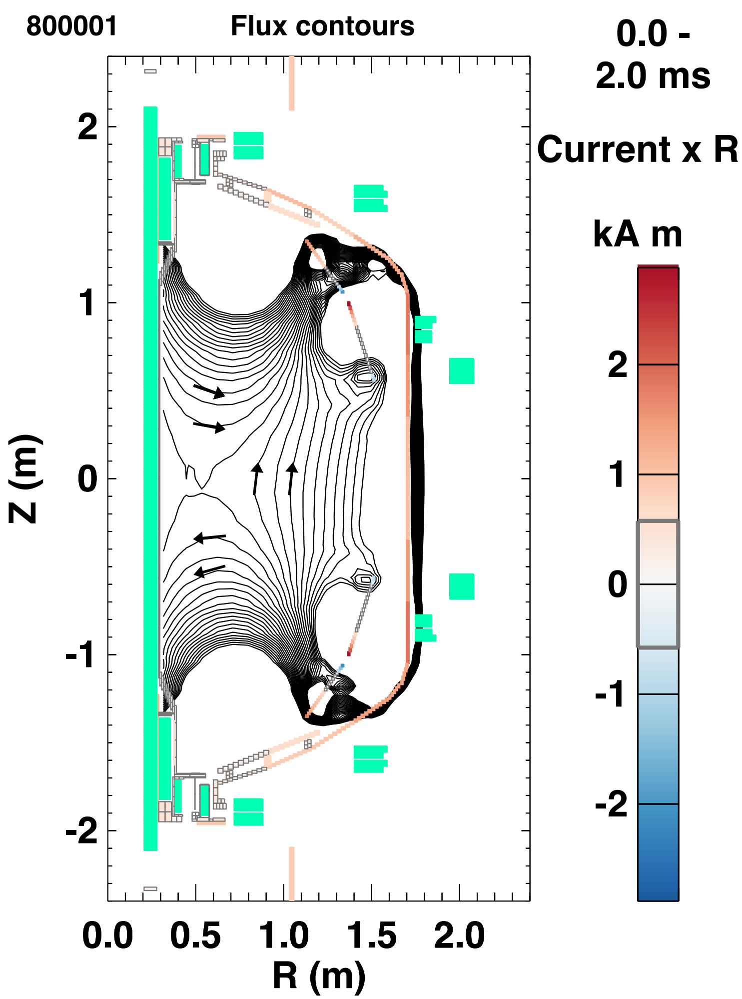
- First few shots showed null timing was late
  - Null timing inferred from magnetics
- Once flash of light was around t = 0, increased V_{loop}
  - Required changes to PF3 to keep null timing the same
- Last two shots, change up-down balance
- Later in the run, the first shot that increased I_{OH} from 8 kA to 20kA worked



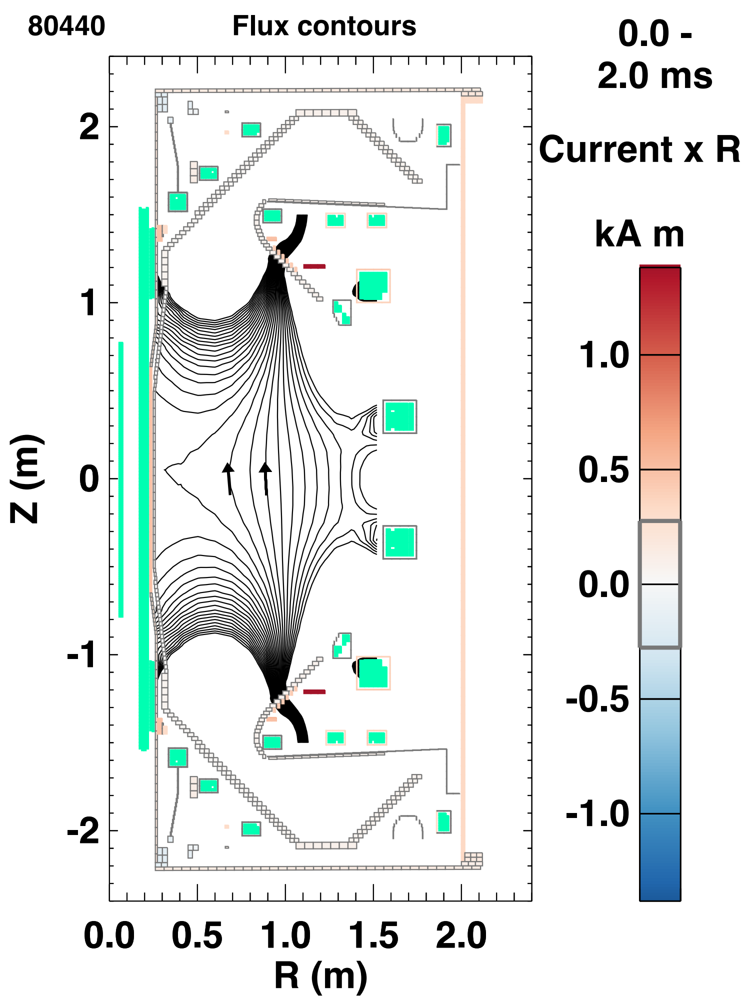


Induced wall currents are of similar magnitude at breakdown

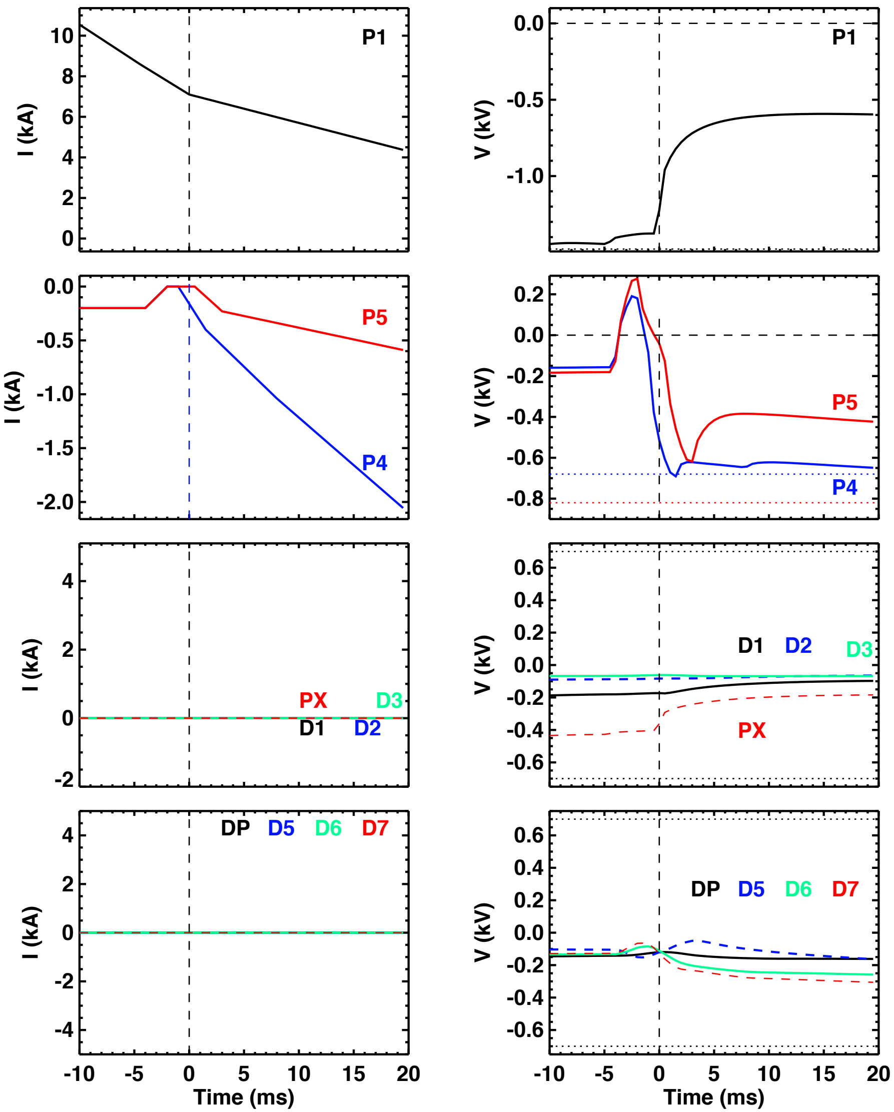
NSTX-U



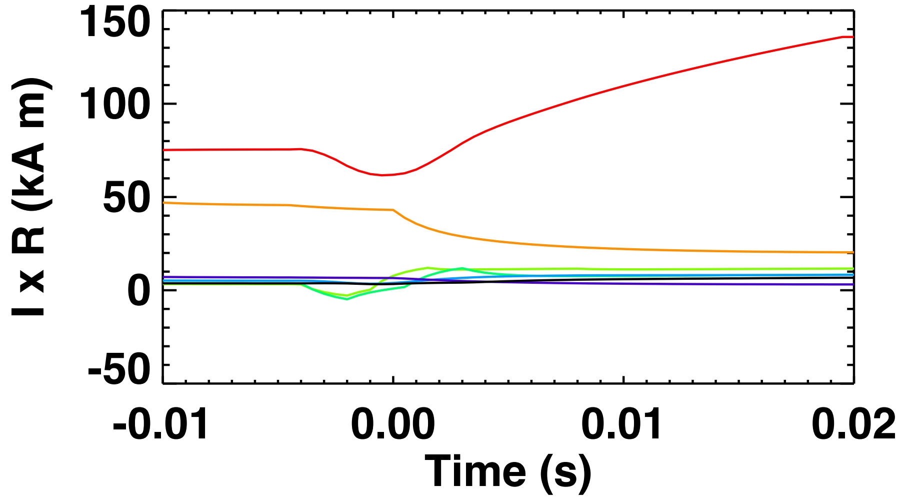
MAST-U



Summary of currents for P4-P5 only

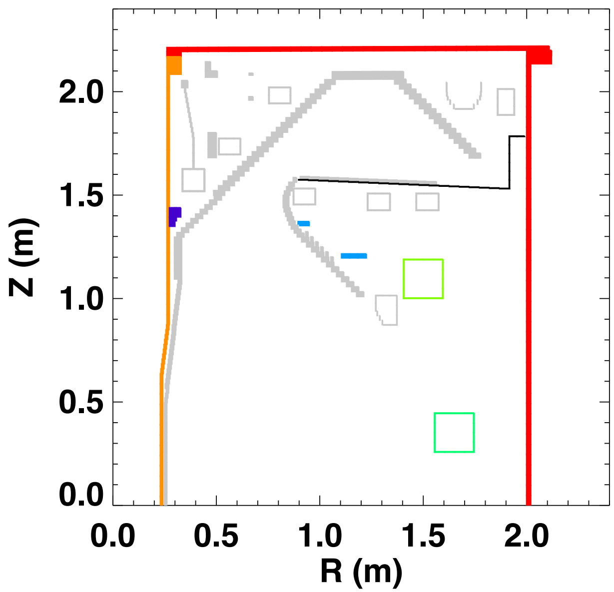


Total induced currents

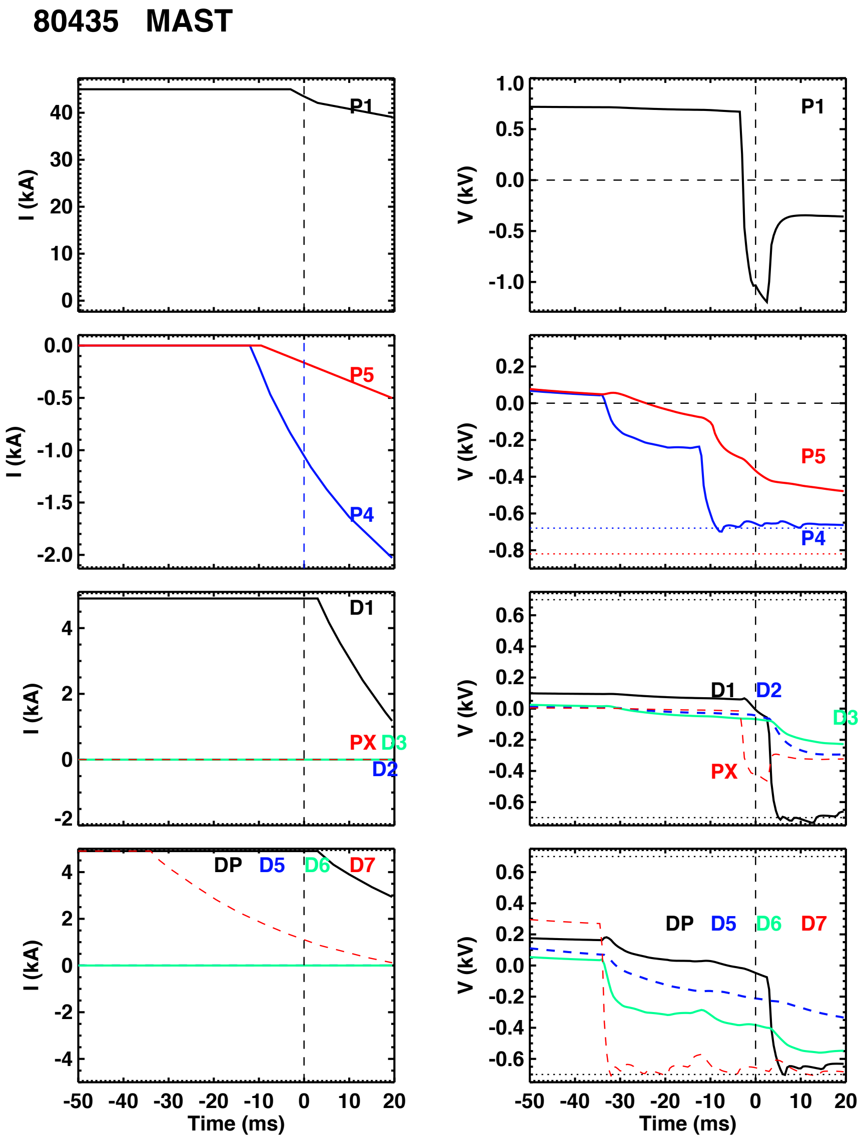


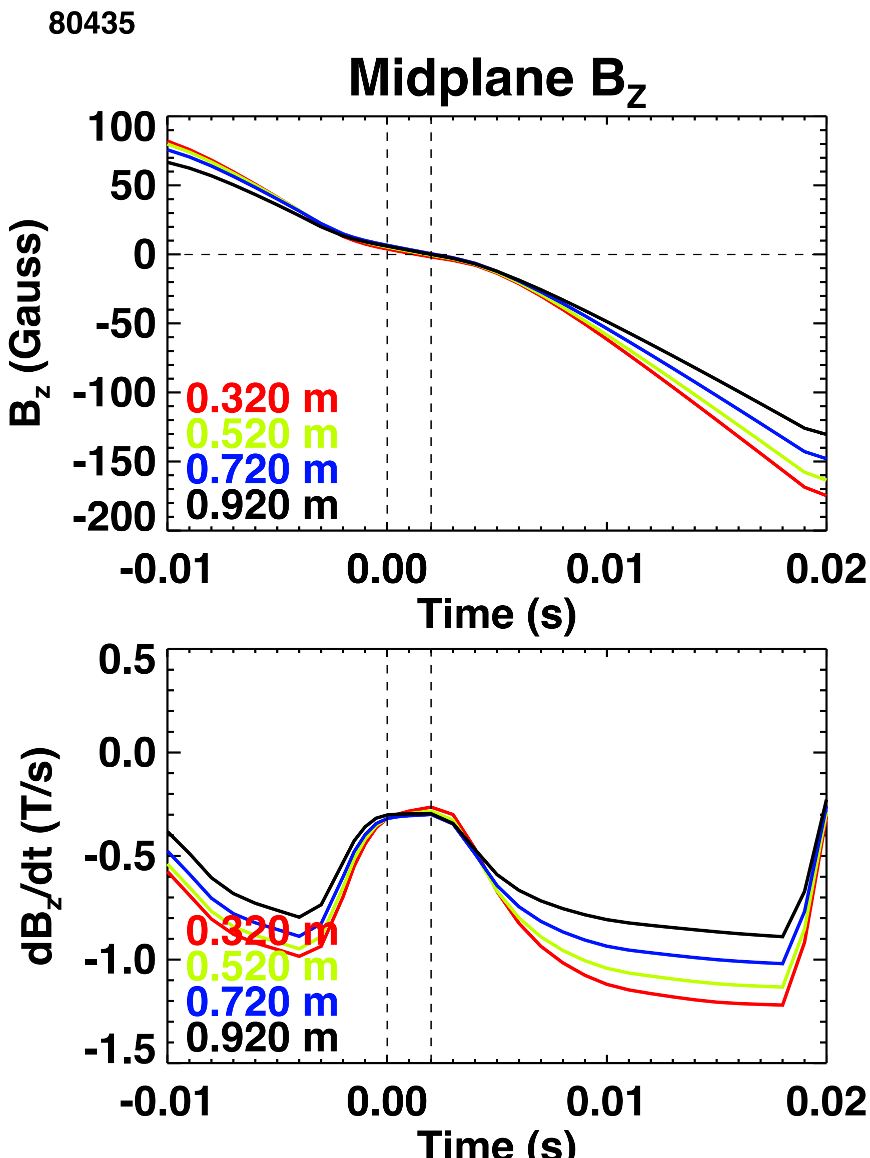
Seven largest:

- vessel
- centrecolumn
- p4_case
- p5_case
- ring_plate
- triangle
- gas_baffle



Example using D1/7 with DP





Using max V_{loop} (~ 7V) at breakdown