U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Startup development for MAST-U

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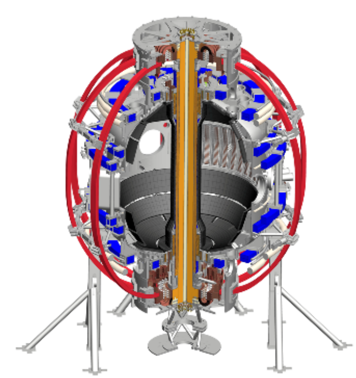
Thanks to CCFE MAST-U team, especially:
Andrew Thornton, Andrew Kirk, Lucy Kogan

NSTX-U Monday Science Meeting
September 25, 2017

CCFE CULHAM CENTRE FOR FUSION ENERGY

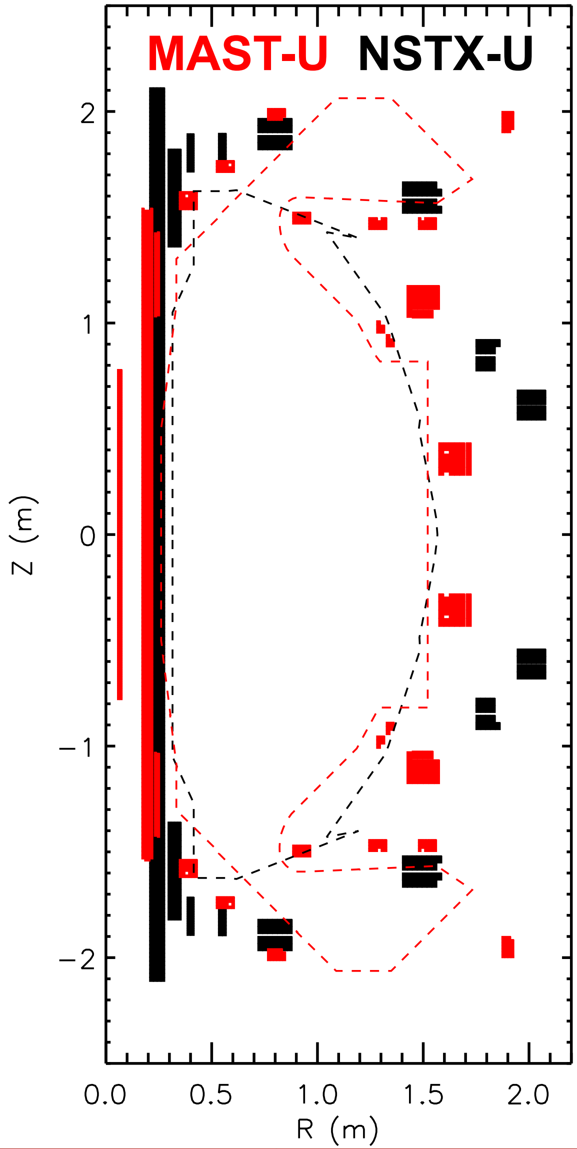
PPPL



Outline

- Overview of MAST-U and NSTX-U scenario and control collaboration
- Review of NSTX-U startup calculations
- Comparison between LRDFIT calculations and MAST results
- Predictive startup calculations for MAST-U

MAST-U and NSTX-U are STs that have complementary scientific missions



- MAST-U has unique divertor configuration
  - Novel closed Super-X divertor concept to isolate divertor from main chamber
  - Leverage ST configuration for divertor optimization studies at high heat flux
- NSTX-U has unique heating and current drive flexibility at high field
  - Explore confinement and stability at high non-inductive fraction
  - Inform aspect ratio optimization of future devices

	MAST-U (stage 1a)	NSTX-U (full field)
Max I_p (MA)	2.0	2.0
Max B_T at 0.93 m (T)	0.685	1.0
NBI (MW)	5 (75 keV)	12 (90 keV)
t_{pulse} at full field (s)	2	5

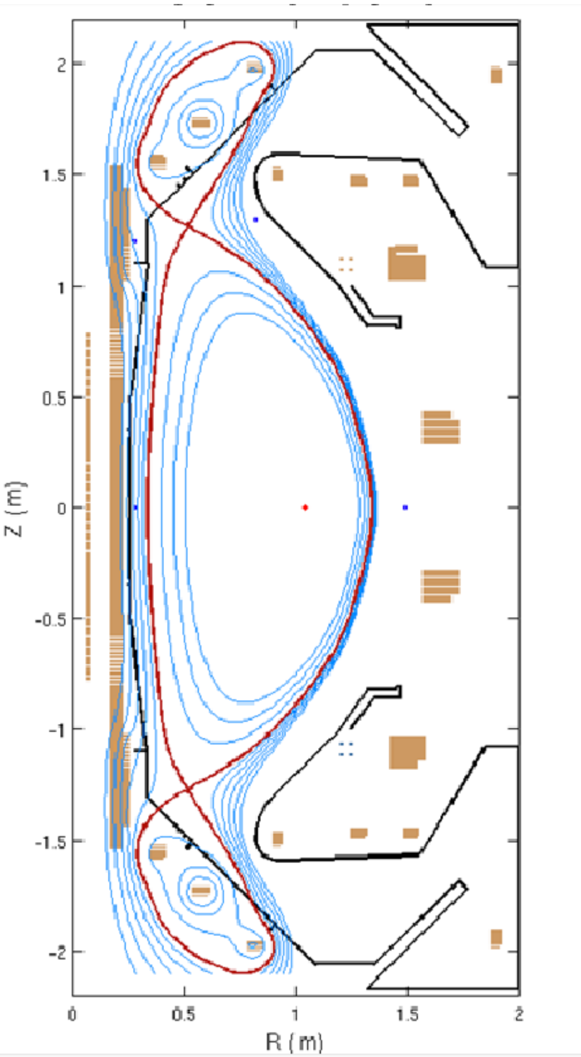
MAST-U Operations planned for 2018

- Phase 1: Pump Down, bake prep
  - Successfully pumped down to target vessel pressure
  - Aim to be ready to bake: October, 2017
- Phase 2: Vessel bake
  - Two stages of bake, first without windows, then with windows
  - Complete gas calibration (24 out of 76 total injectors!)
- Phase 3: Integrated power supply testing
  - Includes first use of PCS and magnetics calibrations
- Phase 4: Plasma Startup
  - Target 100 kA limited plasma
  - Develop equilibrium reconstruction
  - Spring, 2018

Picture of centre column, nose and divertor armour

MAST-U Operations planned for 2018

- Phase 5: Limiter plasma
  - 0.5 MA for > 0.2 s flattop with outer gap control, start EFC
- Phase 6: Conventional Divertor
  - Elongate, push l_i lower with NBI, ramp-up optimization, L-H transition
  - Tune vertical control to extend elongation
  - Tune PCS for boundary control
  - Continue EFC, fueling optimization
  - Condition surfaces
- Phase 7 – 9: Demonstrate and leverage extended outer divertor leg
  - Second half of 2018



Collaboration on Scenario and Control development between MAST-U and NSTX-U

- ST devices have common goals for optimizing startup and rampup scenarios
  - Develop robust and flexible startup scenarios
    - Assisted by active feedback control (vertical stability, shape, density …)
  - Maintain broad current profiles (low – l_i) during ramp-up
    - Increase κ, delay or avoid $q_0 = 1$ instabilities …
  - Minimize flux consumption of startup

- Collaboration aims to develop similar models and metrics for optimizing startup and control
  - Enables more effective sharing of knowledge and work
  - Accelerate progress on demonstrating advanced scenarios and control

Visited CCFE this summer to begin to participate in MAST-U startup process

- Examined tools for planning startup scenarios for MAST-U
  - FIESTA (MATLAB) code: used for scenario development on MAST
    - Code support and MATLAB license posed issues for the future
  - LRDFIT (IDL) code was chosen as a shared tool for vacuum field calculations
    - Code maintained by PPPL, many IDL users at CCFE
- Ported LRDFIT code to CCFE and demonstrated vacuum field calculations for comparison to MAST data
- Demonstrated utility of LRDFIT as a planning and control room tool for magnetic calibrations and startup development
- Began predictive calculations for MAST-U startup
  - First customer for device description files needed for EFIT
- Wrote a User's Guide and trained MAST-U team members on performing vacuum field calculations with LRDFIT
  - Multiple users now producing results and motivating code development

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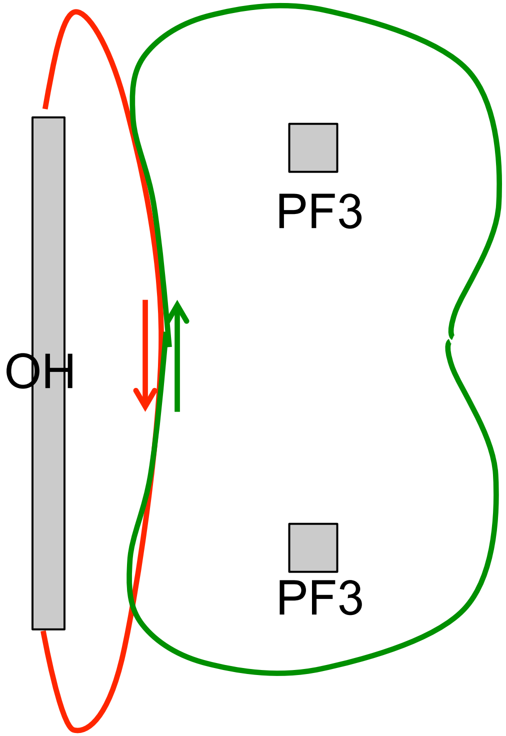
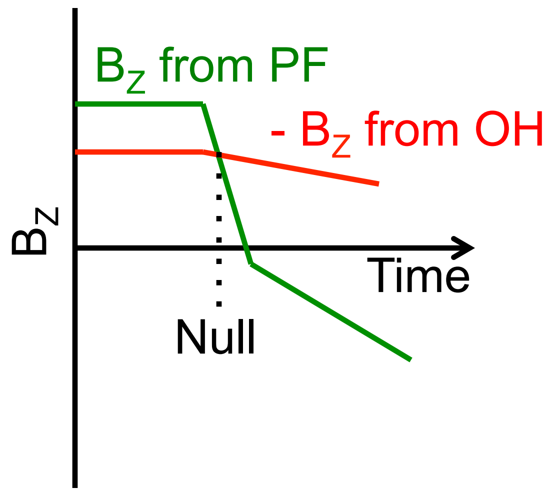
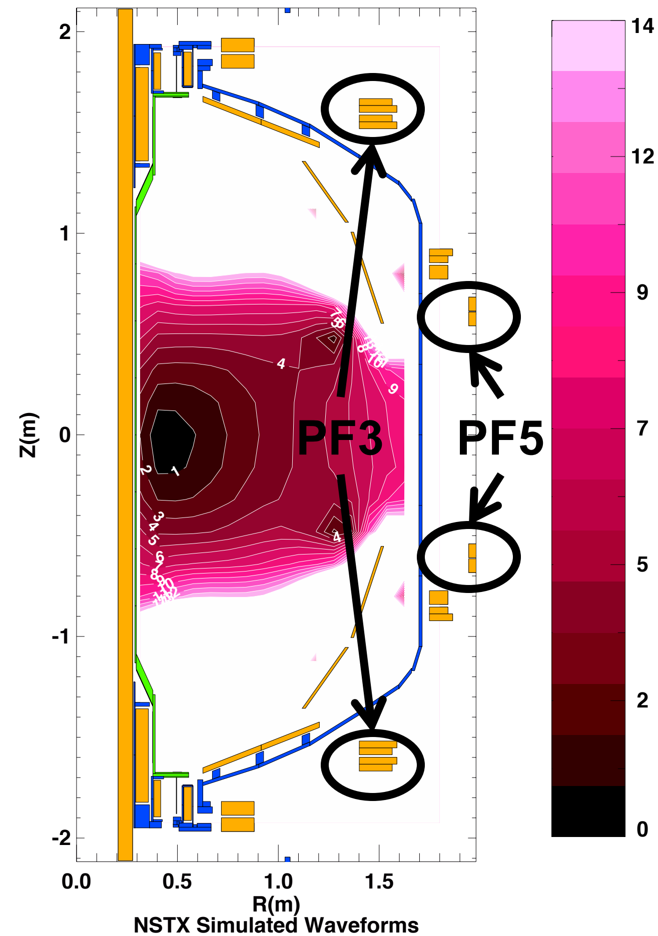
Inductive startup on NSTX-U uses a single PF coil set to null solenoid field

- Solenoid provides confining B_Z
  - Bipolar PF3 coils null this field
  - V_{loop} via ramping OH and PF3 fields





Simulated B_p fields at breakdown (Gauss)



Inductive startup on NSTX-U uses a single PF coil set to null solenoid field

- Solenoid provides confining B_Z
  - Bipolar PF3 coils null this field
  - V_{loop} via ramping OH and PF3 fields
- Null field sensitive to induced wall currents
  - About 200 kA passive toroidal current in conducting structures at breakdown
- PF3 and PF5 coils provide additional B_p following breakdown
  - Must maintain passive R and Z stability

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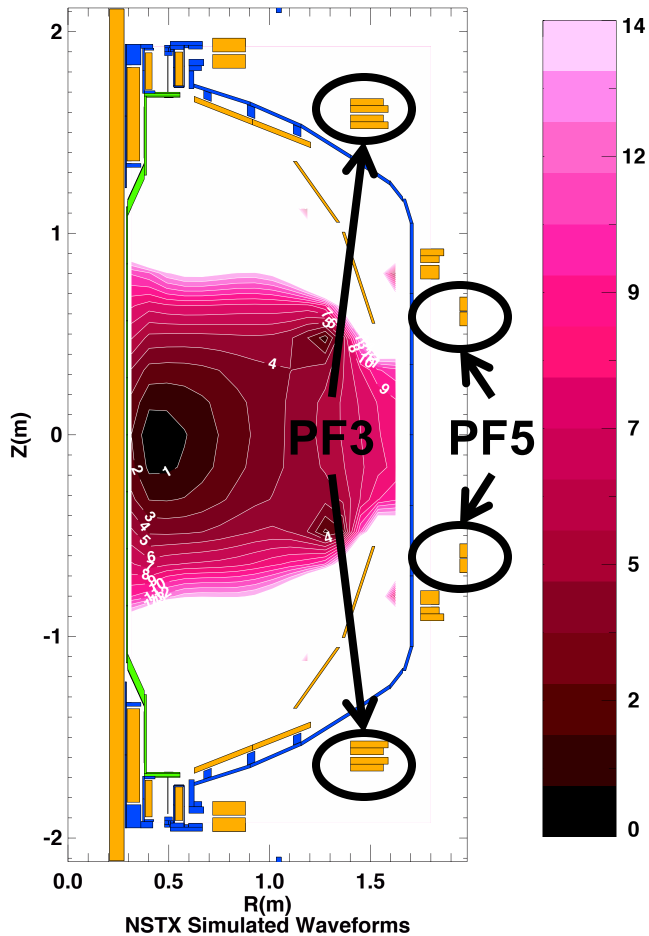


Vacuum field portion of LRDFIT used to develop startup scenarios for NSTX-U

- LRDFIT: LR circuit model with Data FITting capabilities
- Written by Jon Menard as a tool for computing Grad-Shafranov equilibria (GSE) with magnetic and kinetic constraints
  - Code is primarily written in the IDL language
- Contains a user interface for drawing coil currents in order to calculate the vacuum field structure including wall currents
  - This capability enables a platform for predictive calculations
- LRDFIT can also compute GSE solutions
  - Wall currents computed using an SVD fit to magnetics
    - Plasma is treated as resistive conducting elements
  - Multiple GSE solutions calculated in parallel
    - Fixed evolution for wall currents removes time-dependency
    - SVD solution provides an initial poloidal flux distribution that is close to the final result

LRDFIT is a popular analysis tool at NSTX-U

- Calibrate magnetics and improve wall model
  - Develop 2D wall model based on CAD drawings
  - Run vacuum shots and compare measurements to model
    - Evaluate discrepancies … is it the sensors or the wall model?
  - Wall model and magnetics important for EFIT calculations

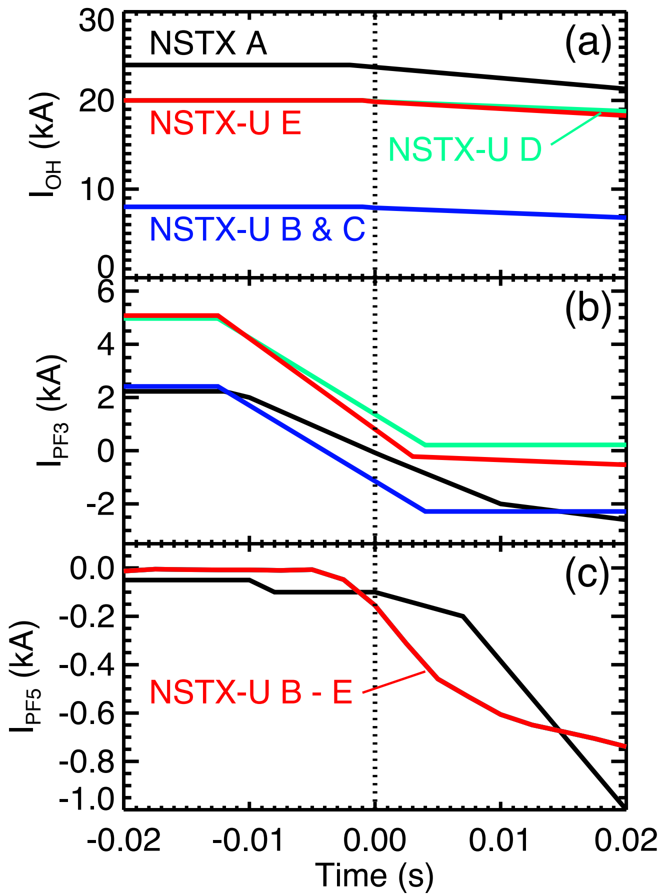
- Develop recipe for breakdown scenario
  - Maintain null timing, good field index and dBz/dt for different I_{OH} precharge and target V_{loop}
  - Evaluate wall currents for different precharge scenarios
  - Develop targets for first plasma attempts

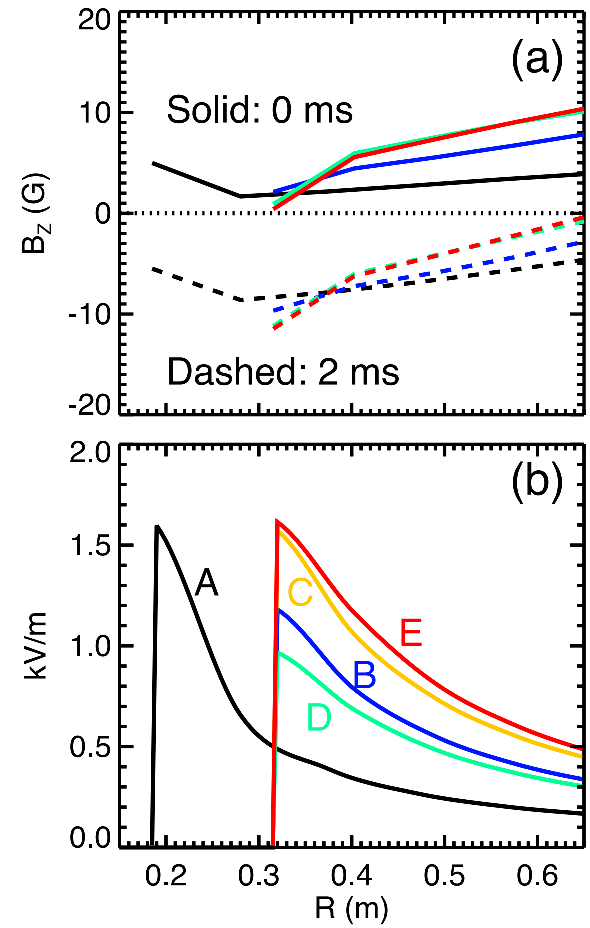
- LRDFIT is a second tool for computing GSE solutions
  - LRDFIT provides researchers an easy way to tinker with GSE solutions
    - Although OMFIT is now providing a similar capability
  - For example, launch a bunch of GSE solutions with different constraints

LRDFIT calculations for NSTX-U used to evaluate startup scenarios

How should I_{PF3} change with V_{loop} and I_{OH} to achieve desired null timing, null quality, field index and B_Z/dt?

	I_{TF} (MA)	I_{OH} (kA)	V_{loop} (V)	B_{NA} (G)
A	**2**	**24**	**2**	**16**
B	3	8	3	16
C	**3**	**8**	**3**	**10**
D	3	20	3	16
E	**3**	**20**	**4**	**10**

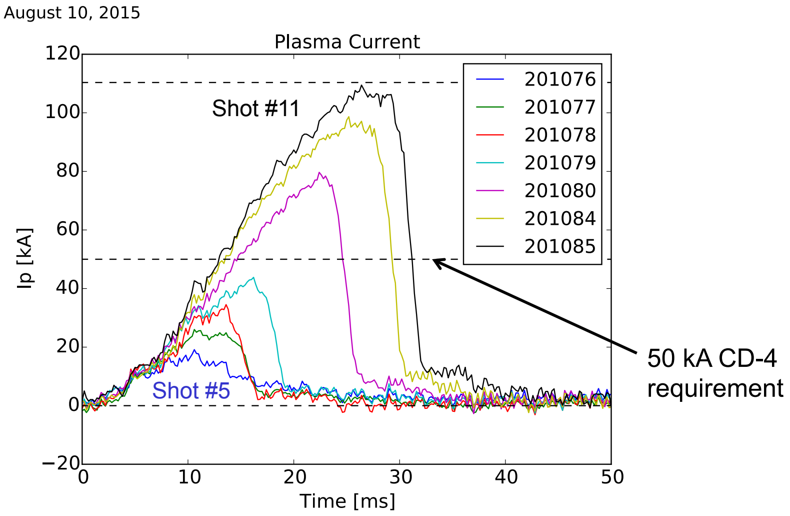


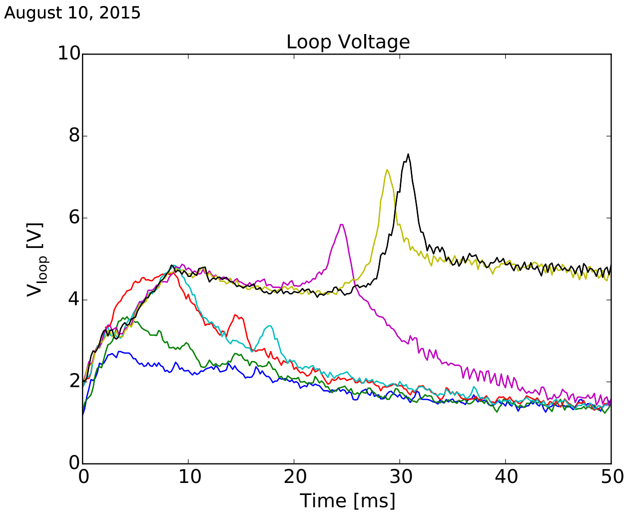


$$\frac{V_{loop} I_{TF}}{10\pi R^2\left(B_\theta + \langle B_{\theta,NA}\rangle\right)}$$

Construction milestone satisfied on ninth discharge attempt

- 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





Goal: Support development of MAST-U startup using similar calculations

- MAST primarily relied on merging-compression startup
  - Targeted experiments on MAST demonstrated "direct induction" (DI) startup in preparation for MAST-U

- MAST-U will use DI startup
  - Calculations were completed using FIESTA during design phase to demonstrate null formation within coil current and stress limits
    - Calculations did not include induced wall current
    - Calculations did not connect precharge – breakdown – rampup phases
  - Desire to evaluate expected V_{loop} requirement
    - Filament pre-ionization system planned for the first campaign
  - MAST-U team has been welcoming of participation in planning and execution of startup activities

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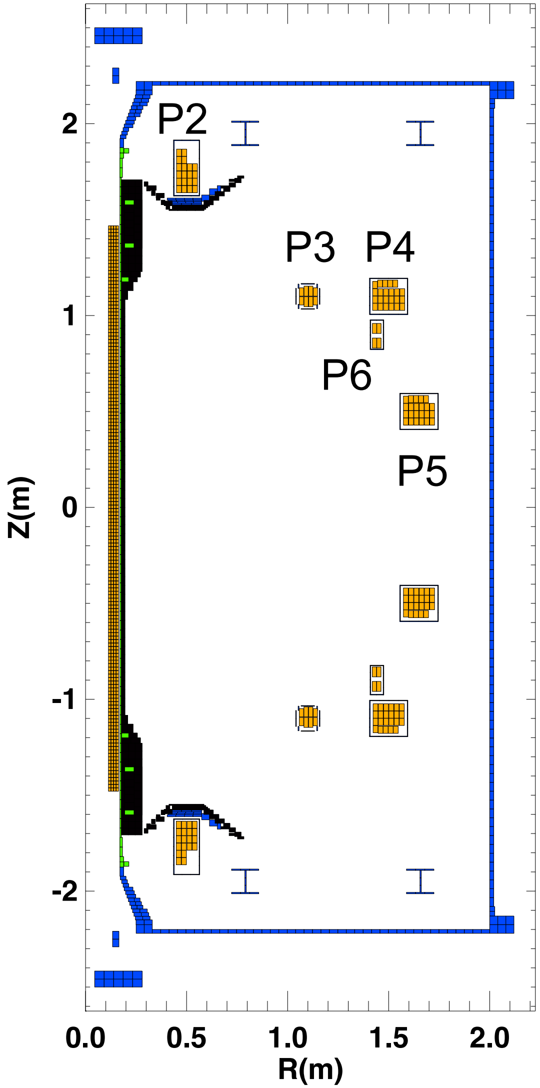
LRDFIT configured to calculate vacuum fields for MAST

- Ported LRDFIT to the CCFE computer system
  - First time LRDFIT has been run outside of PPPL
  - Remove/replace NSTX specific code
  - Write I/O needed for MAST device
- Develop device description for MAST
  - Two versions existed for two codes: EFUND and EFIT++
    - EFUND used to estimate wall currents as a constraint to EFIT ++
- Compare vacuum field calculations to magnetic measurements to demonstrate the utility of LRDFIT



LRDFIT vacuum field calculation can help refine the device description

- Overall, agreement between LRDFIT calculations and MAST vacuum field data was very good

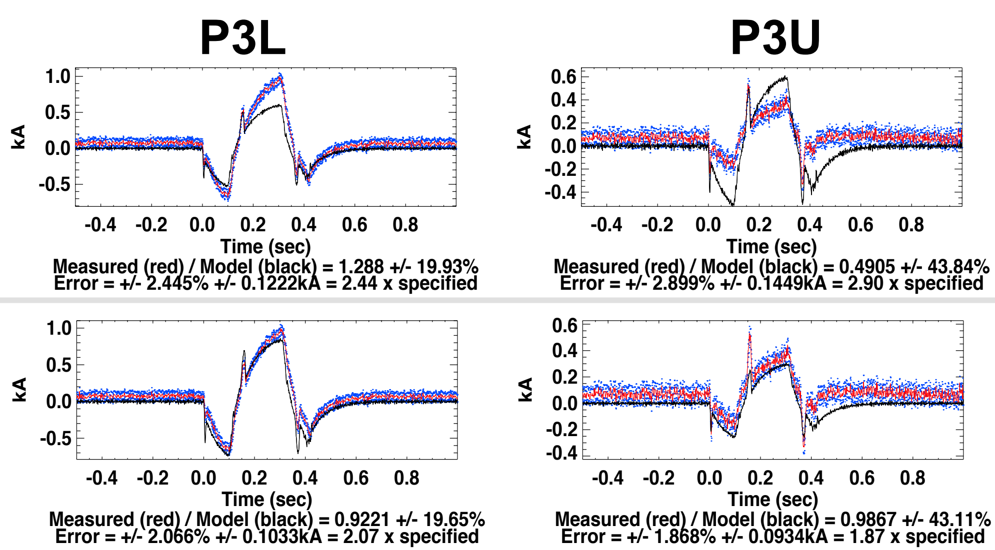
- Largest disagreement was induced P3 case current
  - P3L 70% lower resistance than stainless steel
  - P3U 200% higher resistance than stainless steel

Stainless steel P3 cases

Black: LRDFIT
Red: Signal
Blue: Signal error bars

Altered P3 case resistance

26747 OH + TF only



LRDFIT is a valuable tool for interpreting startup results

- Presented at the MAST-U Session Leader training course on startup
  - Session leader (MAST) = Physics Operator (NSTX)

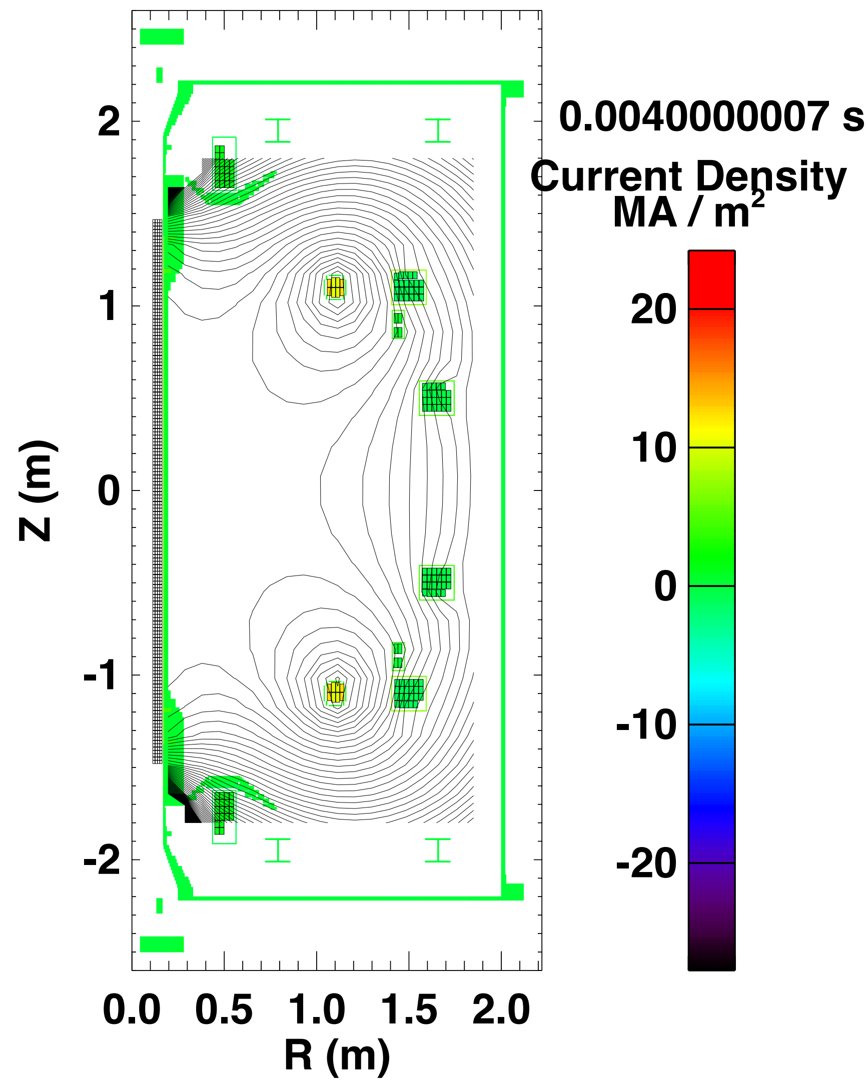
- Illustrated how a startup scenario could be evaluated using diagnostics and LRDFIT

- Further demonstration that the code and 2D wall model are in good shape for MAST calculations

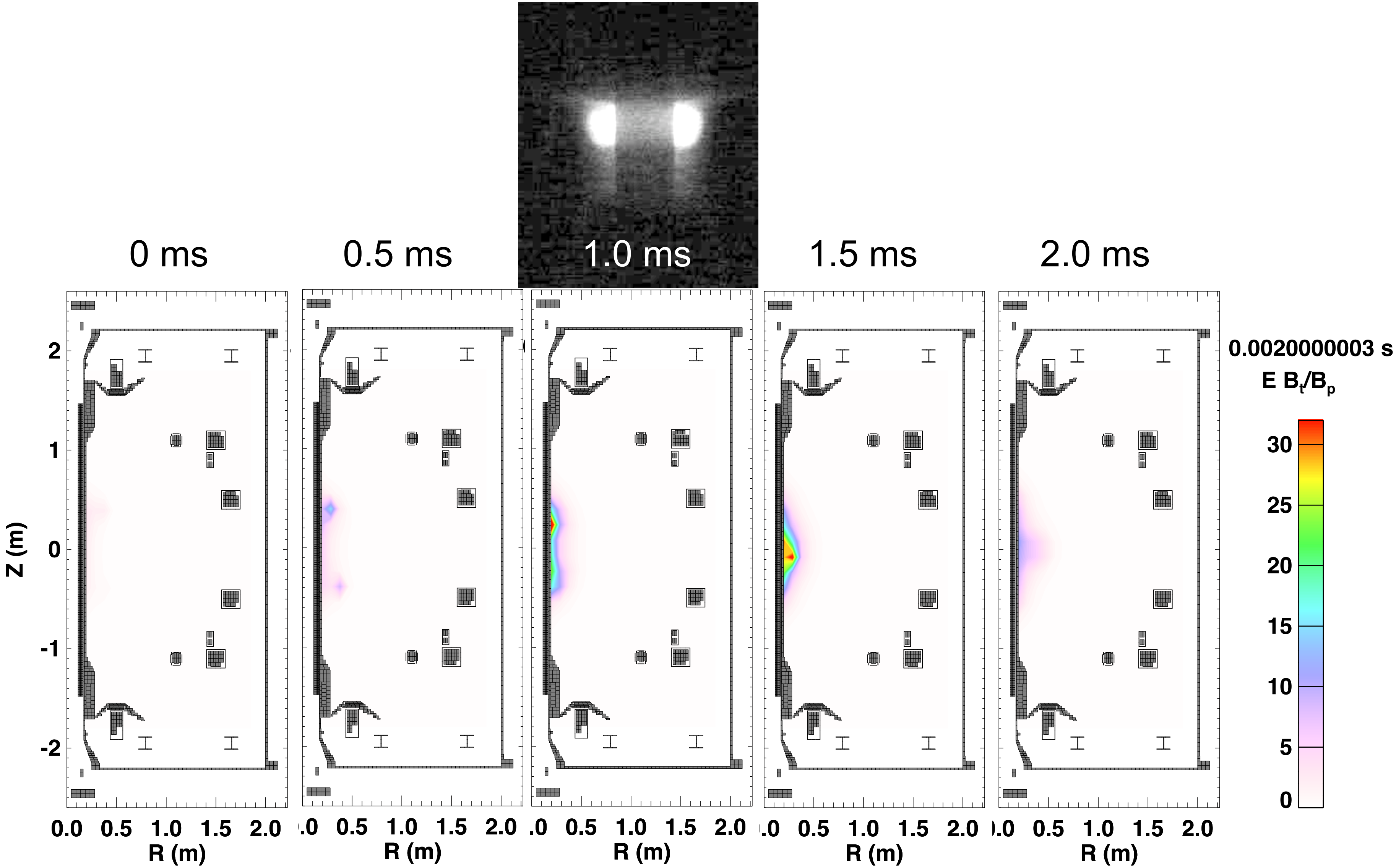
MAST conducted experiments to demonstrate DI startup

- Only two coil sets available to provide nulling field
  - P2: Unipolar pos. current
  - P3: Cap bank pos. current

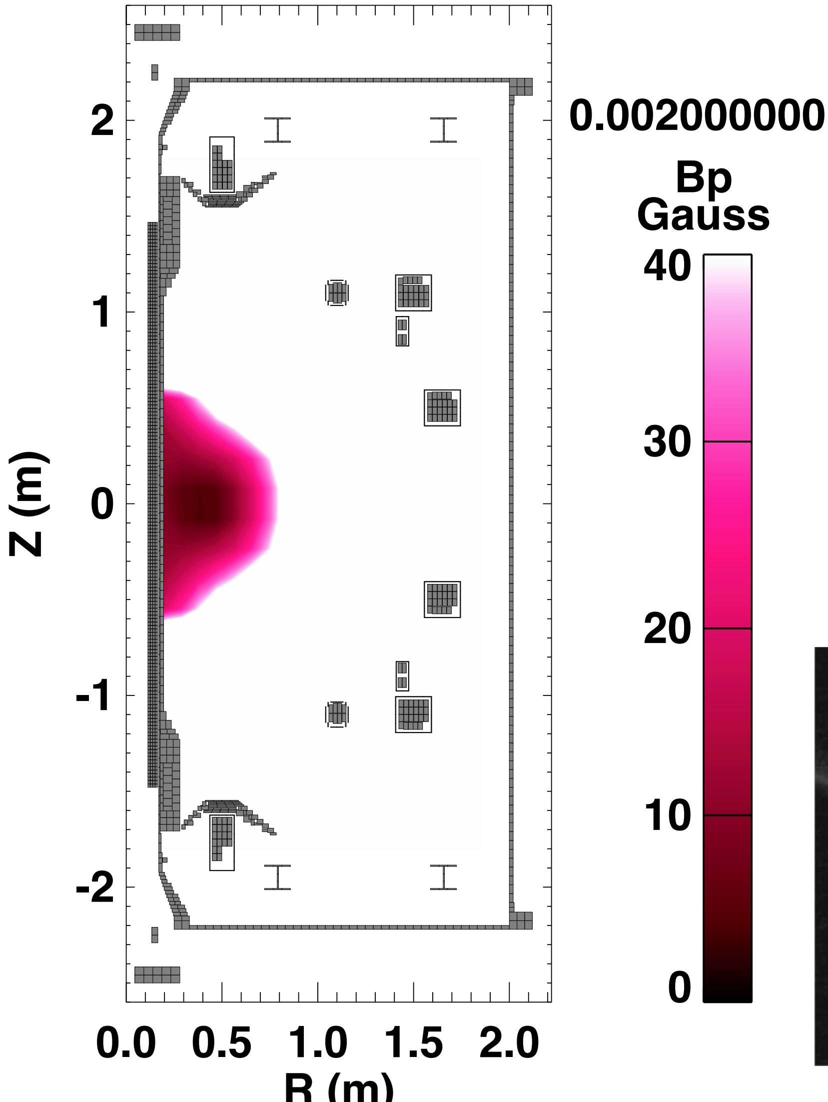
- Lowest V_{loop} DI startup scenarios used static P3 to null solenoid fringe field
  - Form null, then ramp P4 & P5

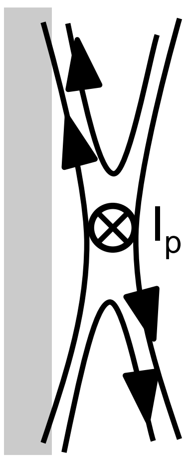


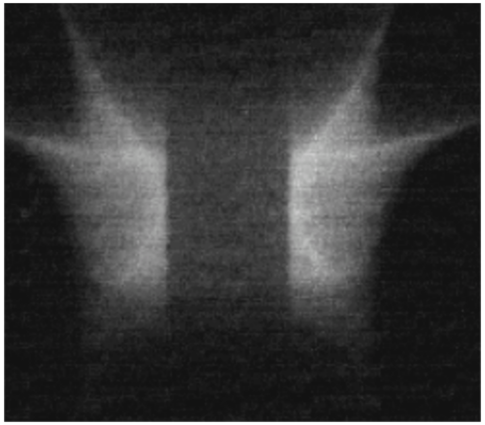
First light at +1 ms near center column

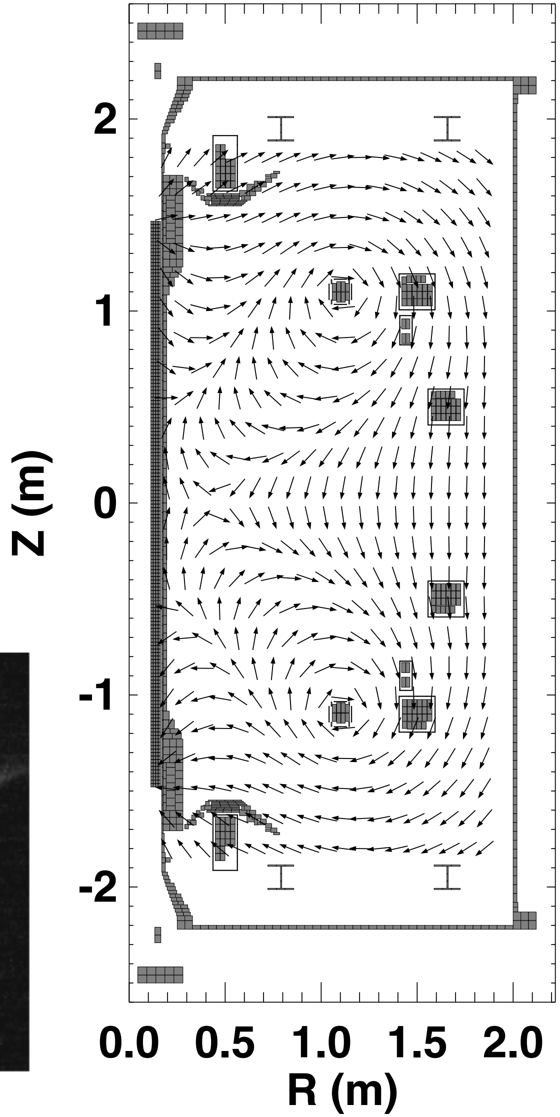


At + 2 ms, a decent null, but field on inboard edge is the wrong direction

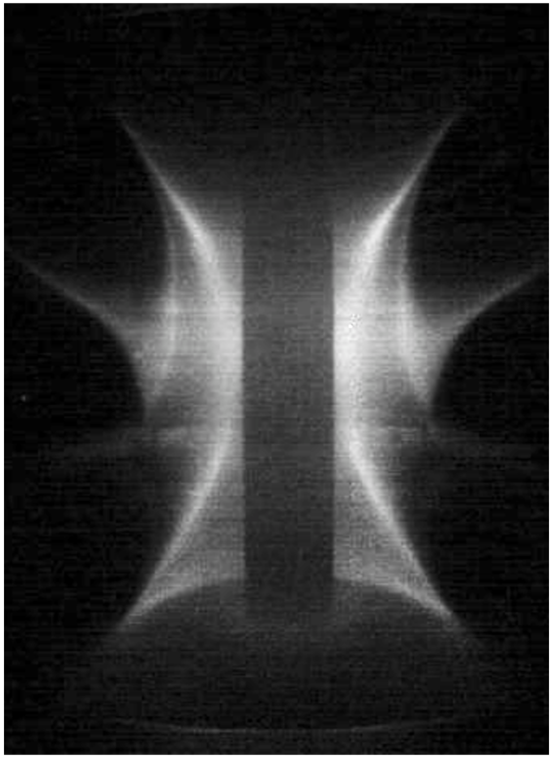


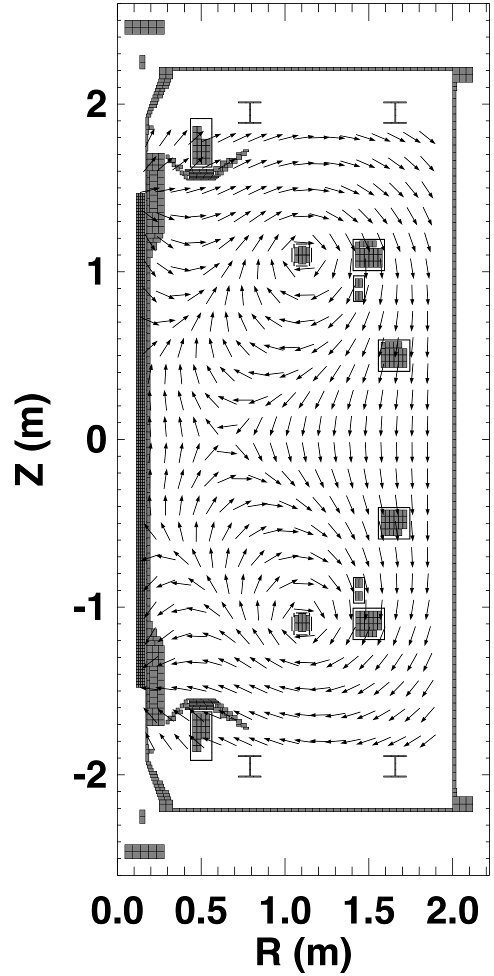


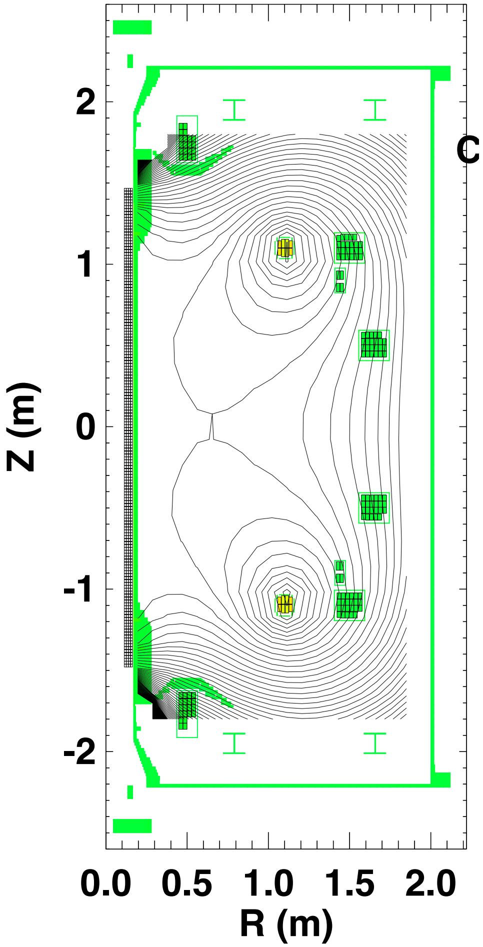




Flashlamp at 3 ms increases ionization, but B_Z still in the wrong direction inboard of null

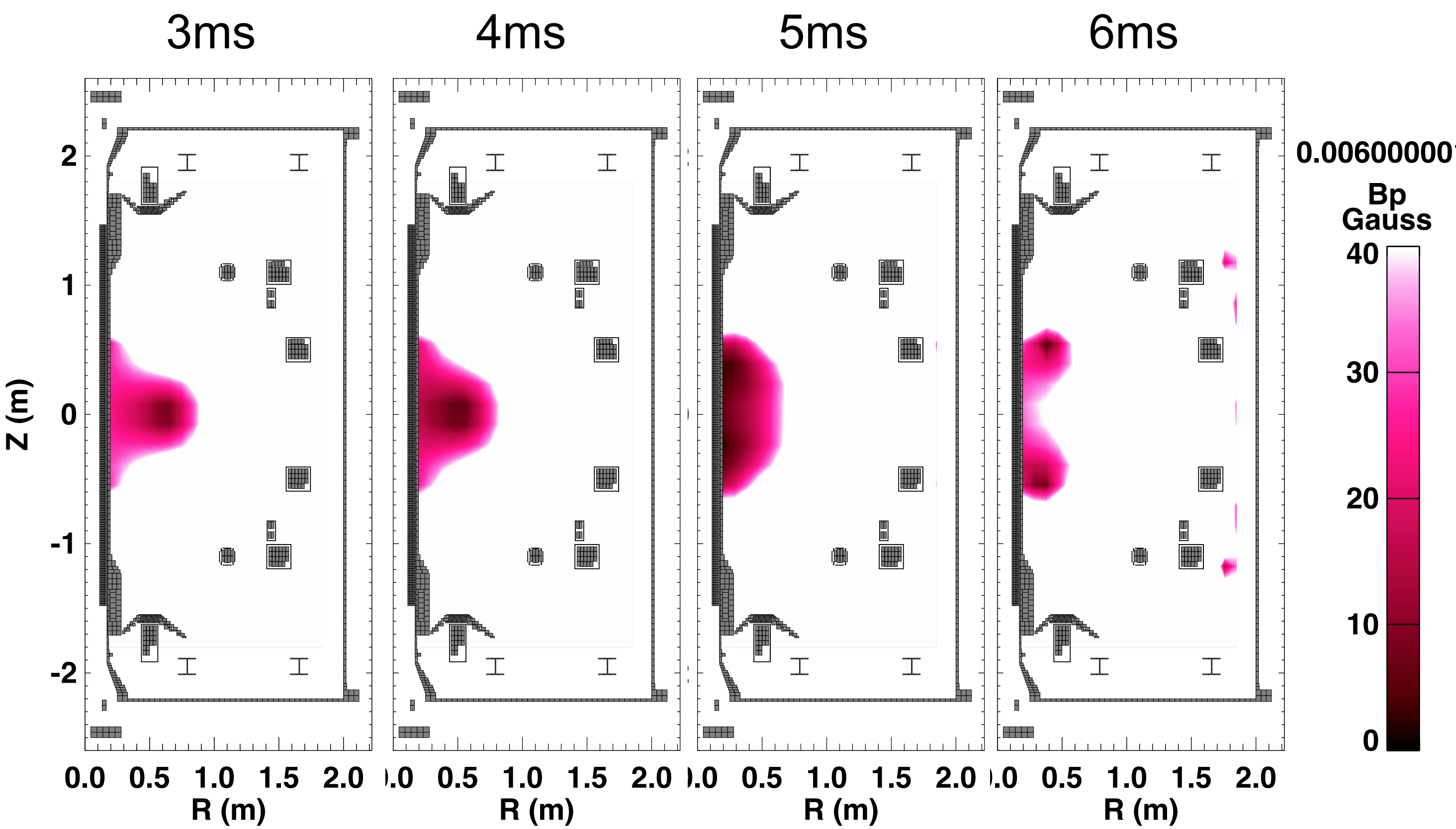


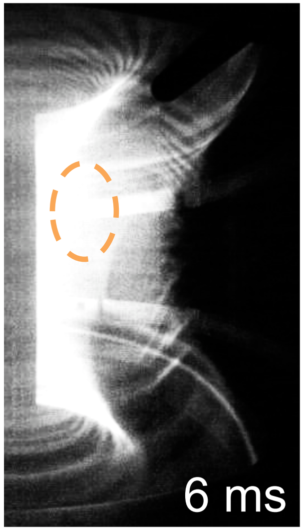




P4 and P5 ramp starts at 3 ms, pushes null inwards

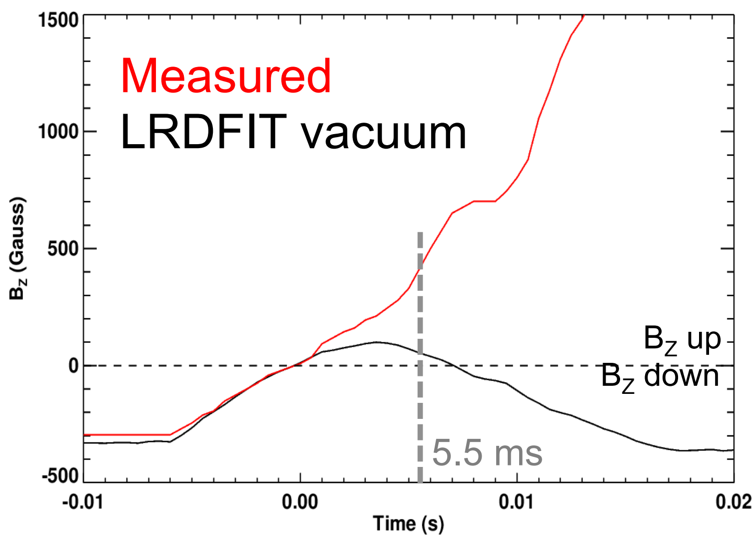
Camera suggests stable current channel first forms in null above midplane

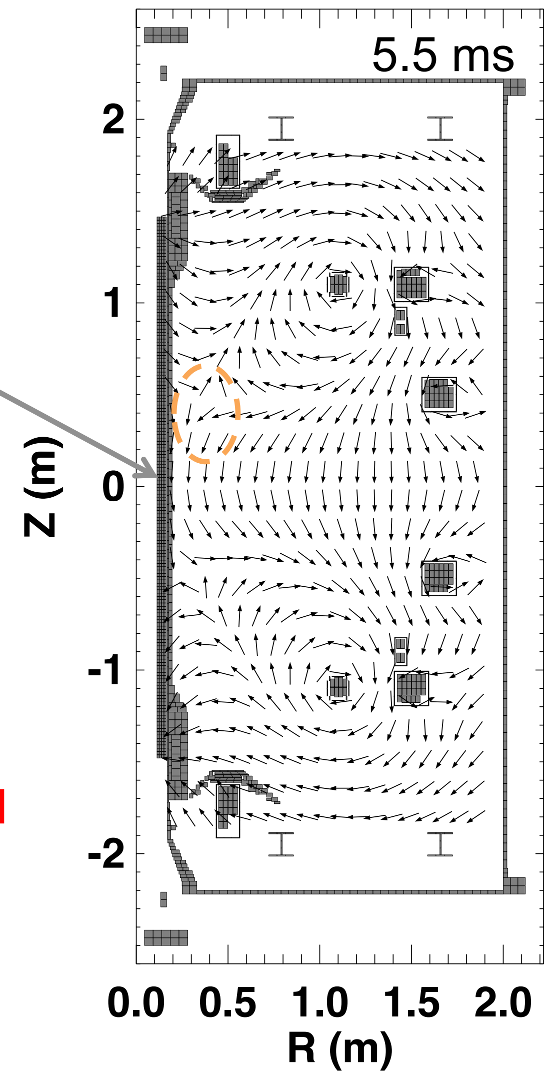


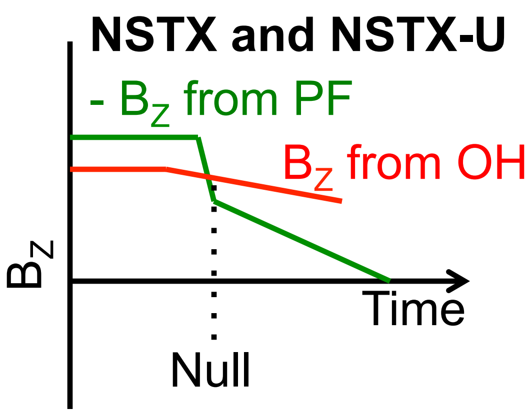


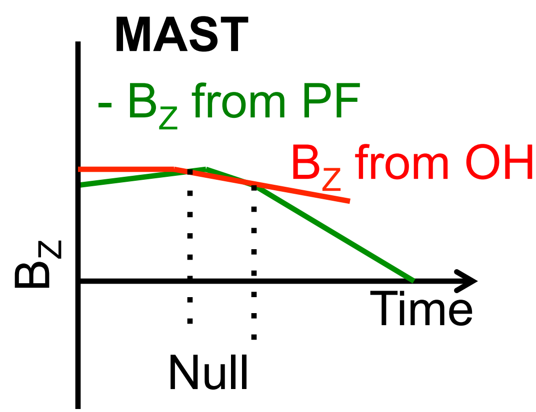
Closed flux surfaces can form with correct B_Z direction on inboard edge of null

Inboard midplane B_Z sensor



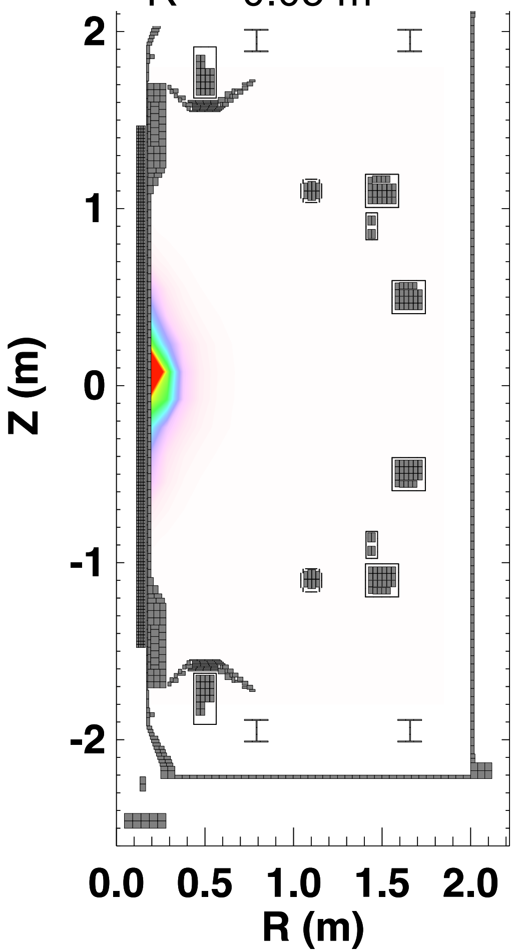




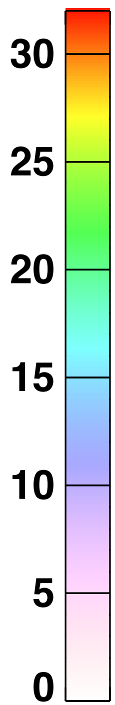


Lloyd criteria similar to NSTX and NSTX-U

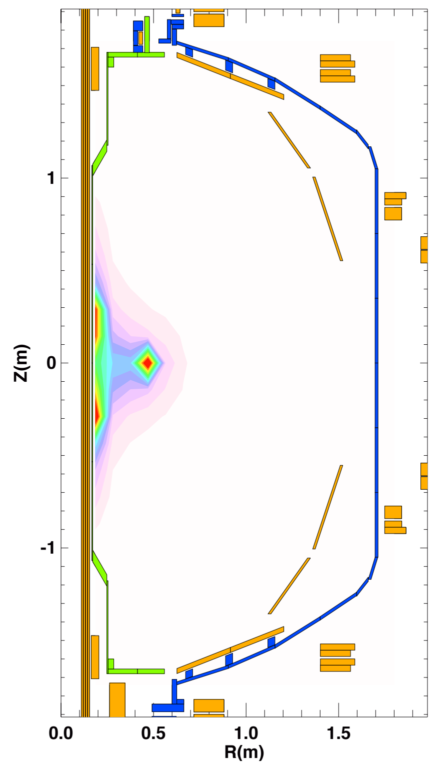
MAST
V_{loop} = 7 V
I_{TF} = 2 MA
R^2 = 0.05 m^2



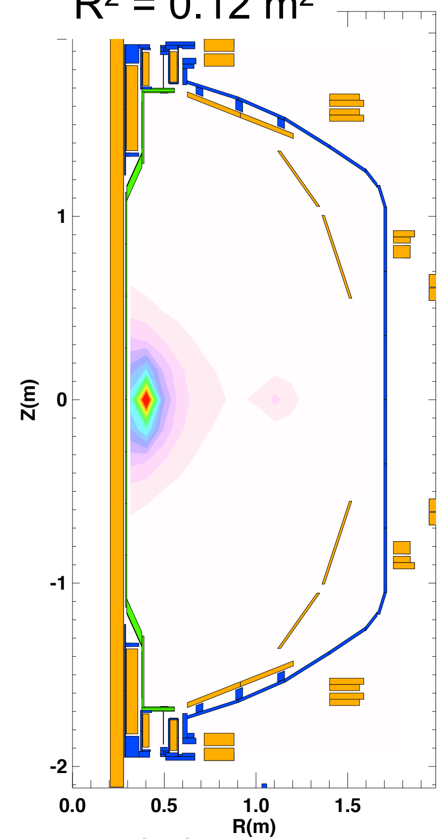
$$\frac{V_{loop} I_{TF}}{10\pi R^2 B_\theta}$$



NSTX
V_{loop} = 2 V**
I_{TF} = 2 MA
R^2 = 0.04 m^2

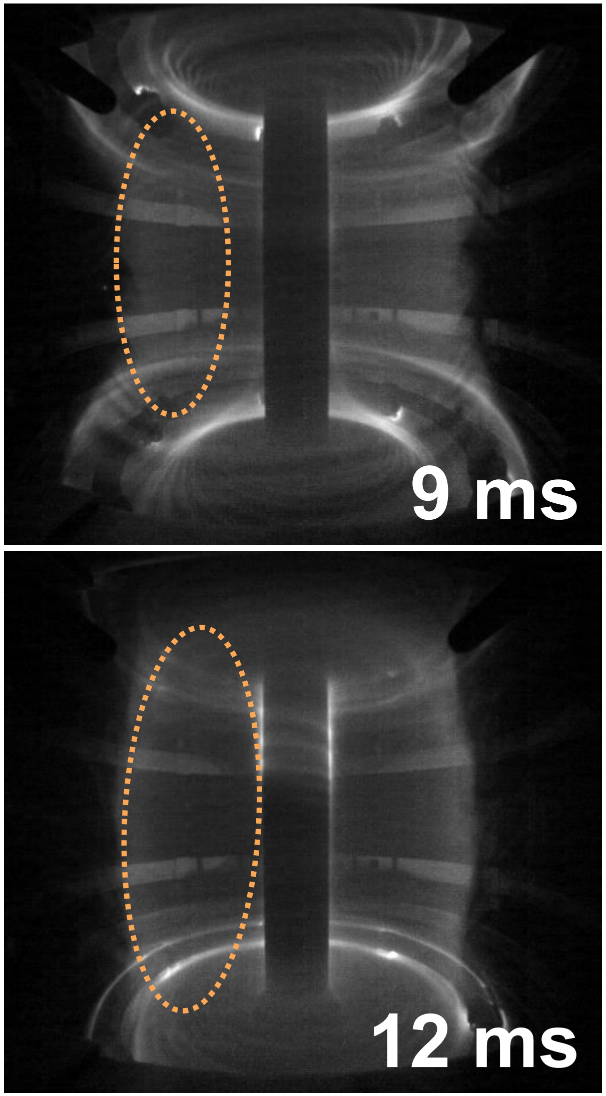


NSTX-U
V_{loop} = 4 V**
I_{TF} = 3 MA
R^2 = 0.12 m^2



** I_p ramp on NSTX and NSTX-U
2 – 4 x slower than MAST

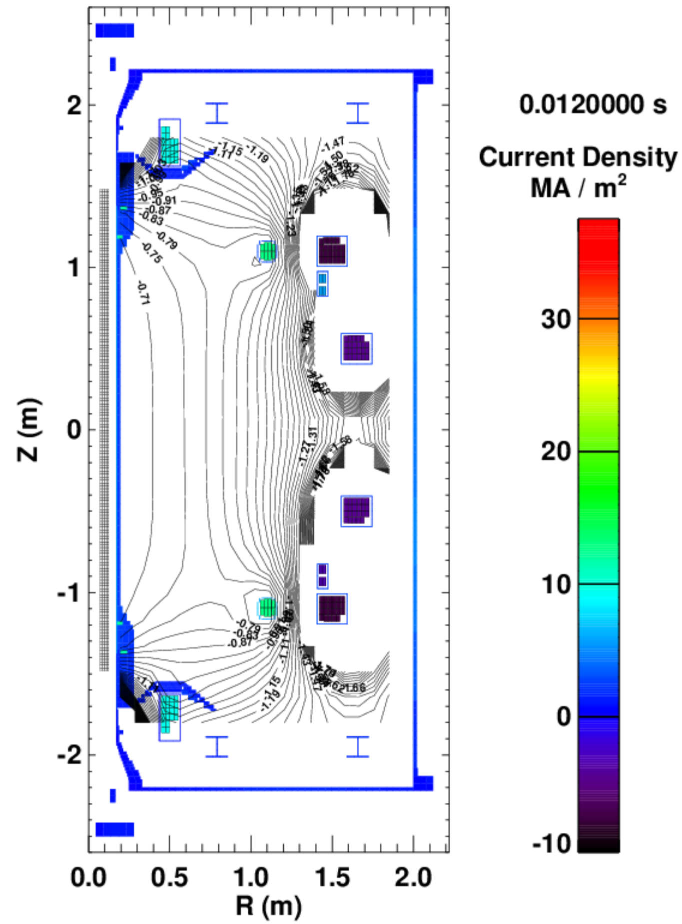
Camera images suggests plasma diverts or limits on outboard surfaces from about 6 - 12 ms



P3L forms the primary X-point
Consistent with more positive case current
(P6 is correcting for case current asymmetry)

Inboard limited at top …

Diverted at bottom



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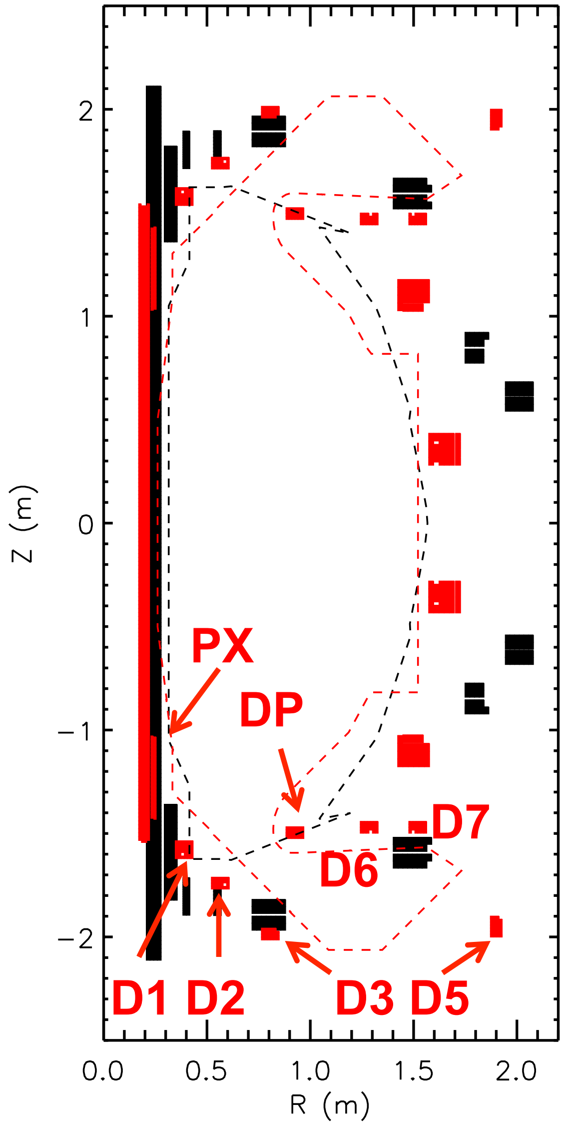
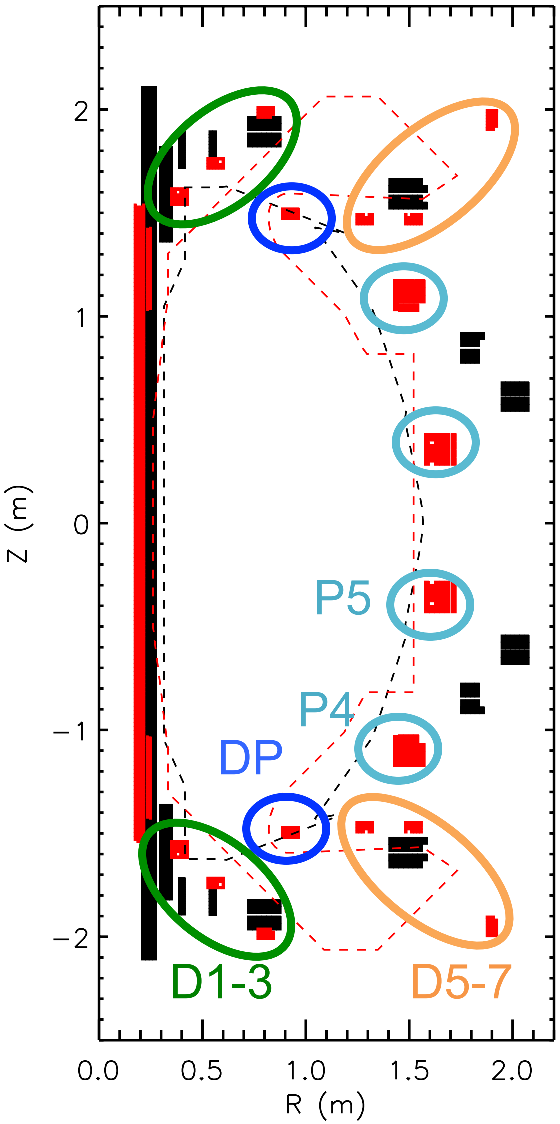
Unique aspects of the MAST-U breakdown scenarios



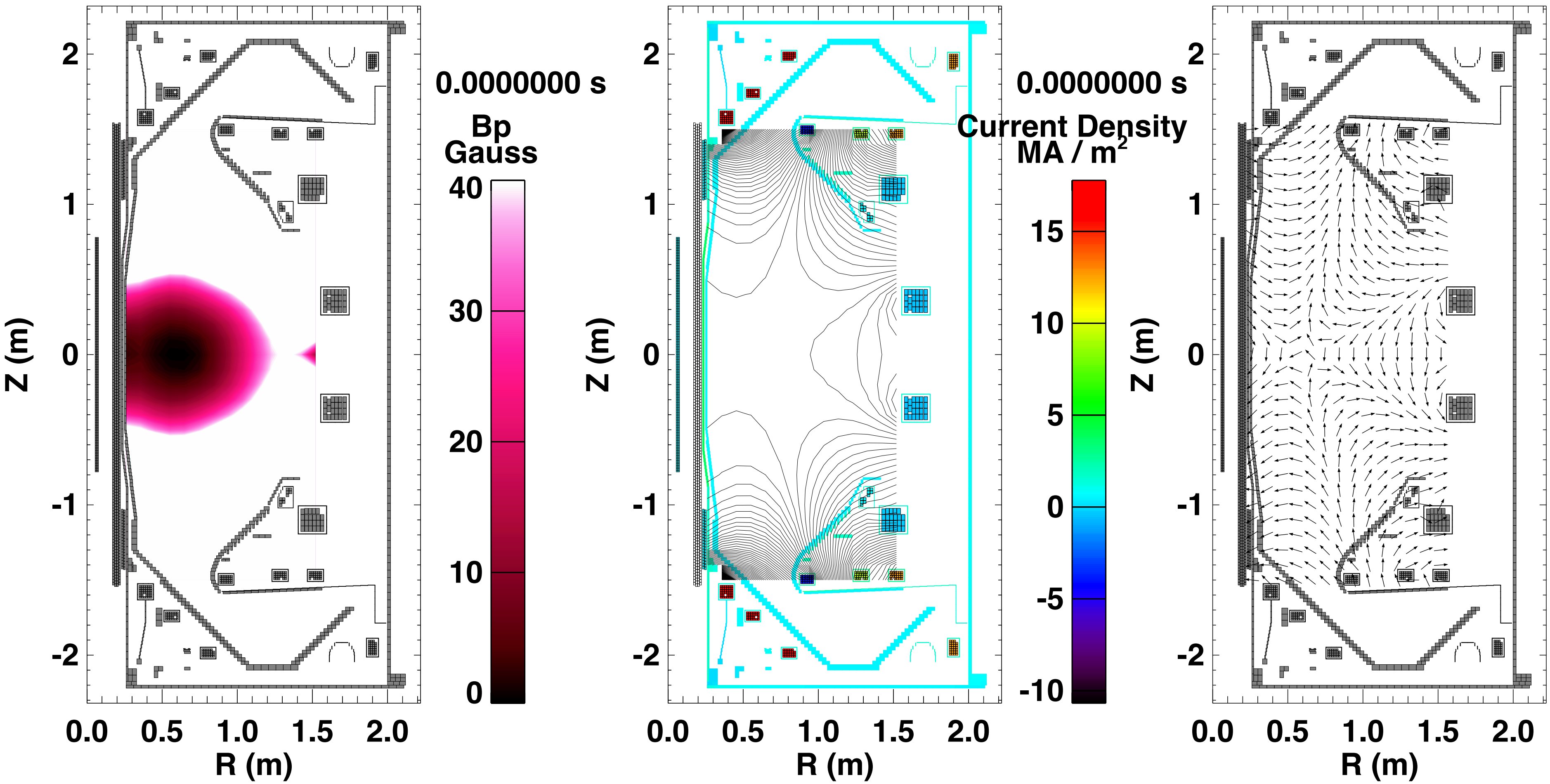
- Solenoid is shorter than NSTX-U
  - More curved fringe field that reduces the vertical extent of a null
  - May require larger V_{loop}
- Eight bi-polar can provide nulling field
  - Lots of free parameters in precharge, null and early ramp up
  - Use a unique power supply scheme
    - Separate IGBT H-bridges with small groups sharing DC links
    - May motivate having certain supplies rectifying while others are inverting

Example MAST-U breakdown scenario with I_{OH} at max current for first campaign



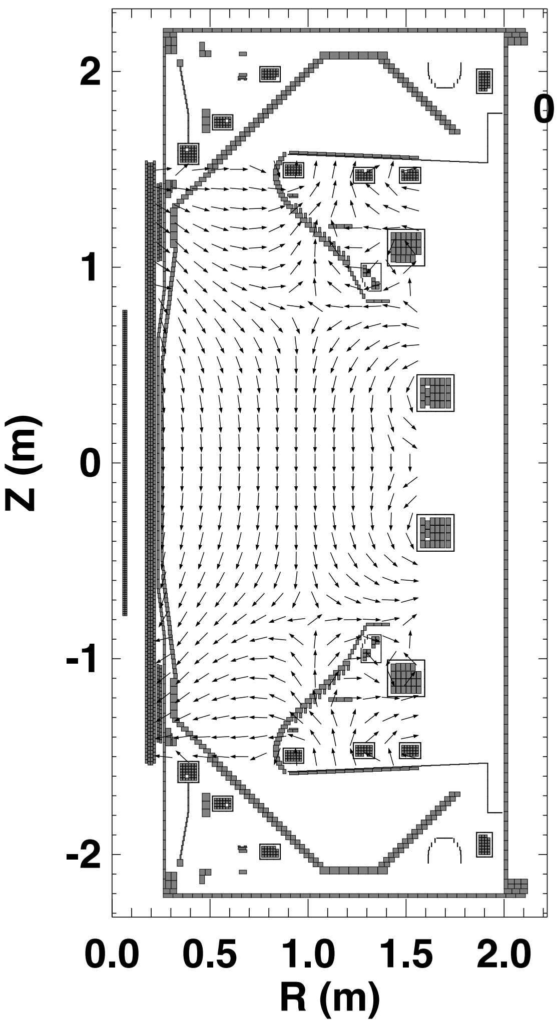
- Aim to keep D-coil current below 3 kA
  - Minimize heating and stress
- Use D1, D2, D3 like an extension of the solenoid
  - Steady positive current in preparation for diverting later in the ramp up
- Use D5, D6, D7 like PF3 on NSTX-U
  - Swing them fast from positive current toward zero
  - Swing DP from zero to negative current
- Use P4 and P5 to form a higher order null and provide confining field

Example of a higher-order null at t=0

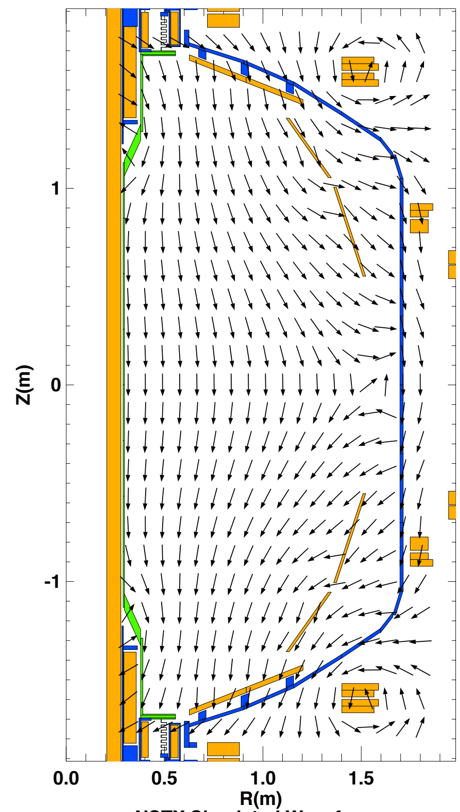


Decent vacuum field configuration at 20 ms for a limited plasma with I_p ~ 150 kA

MAST-U



NSTX-U



<u>Preliminary results:</u>
Present work is focusing on optimizing the field configuration in the early ramp up while satisfying the I and V constraints of the power supplies

Planned collaborative activities on startup development for MAST-U

- Identify a target breakdown scenario for MAST-U
  - Achieves desired breakdown metrics
  - Optimizes early rampup for passive vertical and radial stability
    - Working with MAST-U team to understand power supply behavior near maximum voltage request
- Develop breakdown recipes for scanning parameters in the control room
  - Typically scan I_{OH} precharge, V_{loop} and null timing
  - How does the PF coil precharge impact the scenarios?
- Power supply testing (early 2018) will provide first opportunity to refine 2D wall and power supply models
- Support magnetics calibration and first plasma attempts in spring, 2018

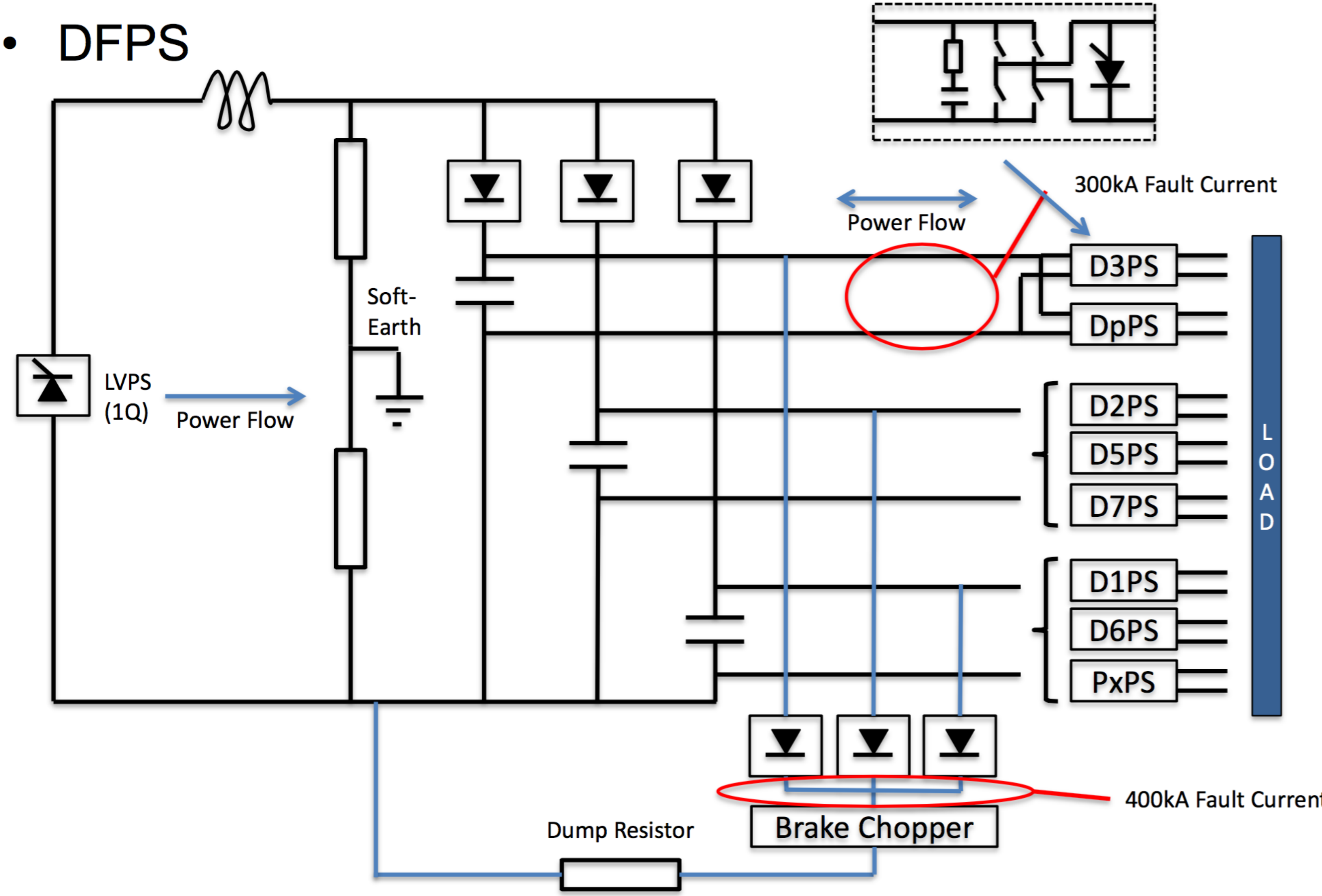
Summary

- Summer visit enabled significant progress on MAST-U and NSTX-U collaboration on startup development
- Vacuum field calculation portion of the LRDFIT code is now running on CCFE
  - MAST-U team members using LRDFIT to guide startup plans, including magnetic calibrations and scenario development
  - Data I/O demonstrated with MAST data
  - Good agreement between LRDFIT calculations and data
- Demonstrated utility of LRDFIT for interpreting startup results and refining the 2D device description
- MAST-U startup scenario calculations are underway
  - Goal is to identify target scenarios for the first plasma attempts and develop recipe for scanning parameters

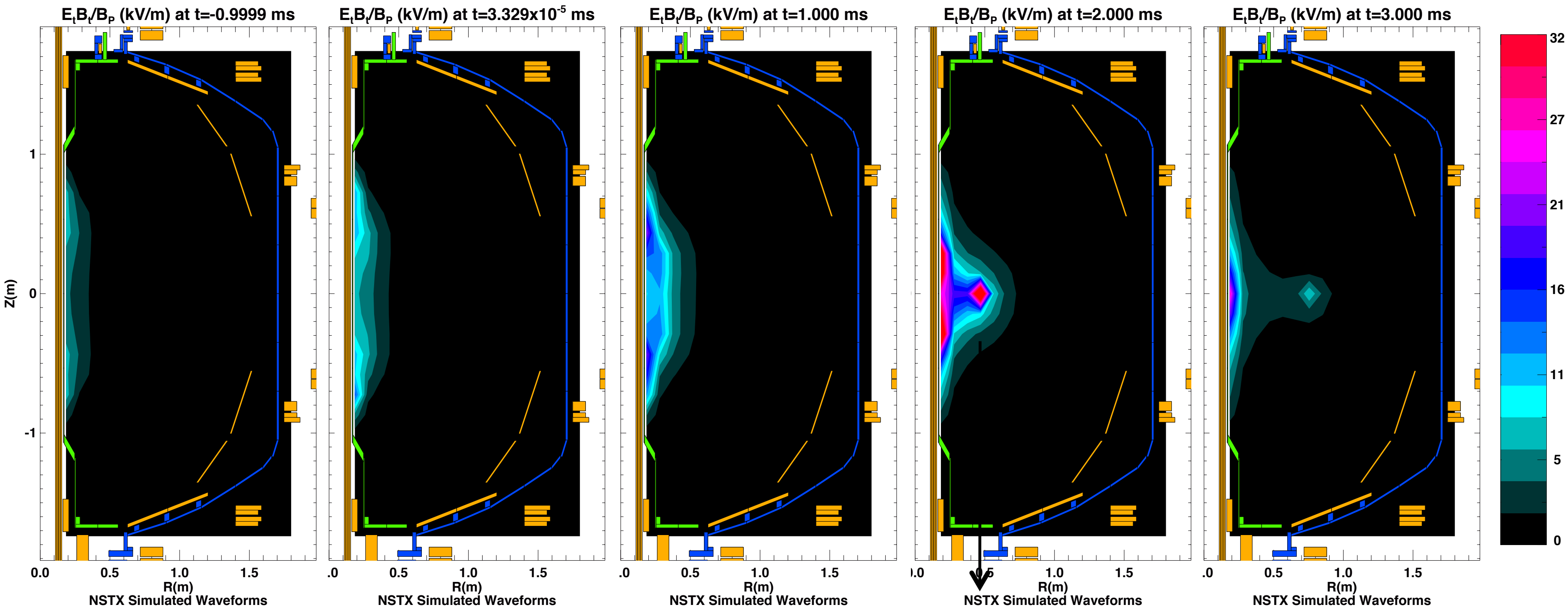
Backup

MAST-U D-coil Power Supply

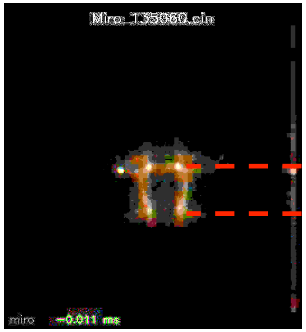
- DFPS



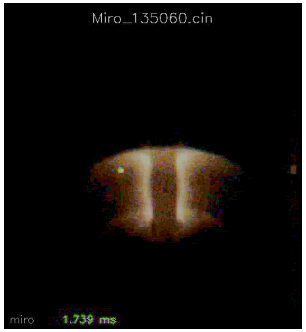
Calculations match timing of breakdown and brief appearance of two rings

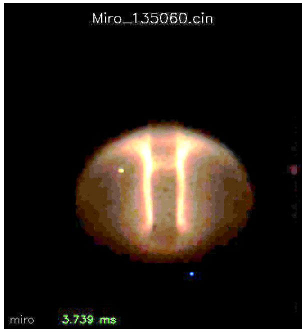


- 1 ms 0 ms +1 ms + 2 ms + 3 ms

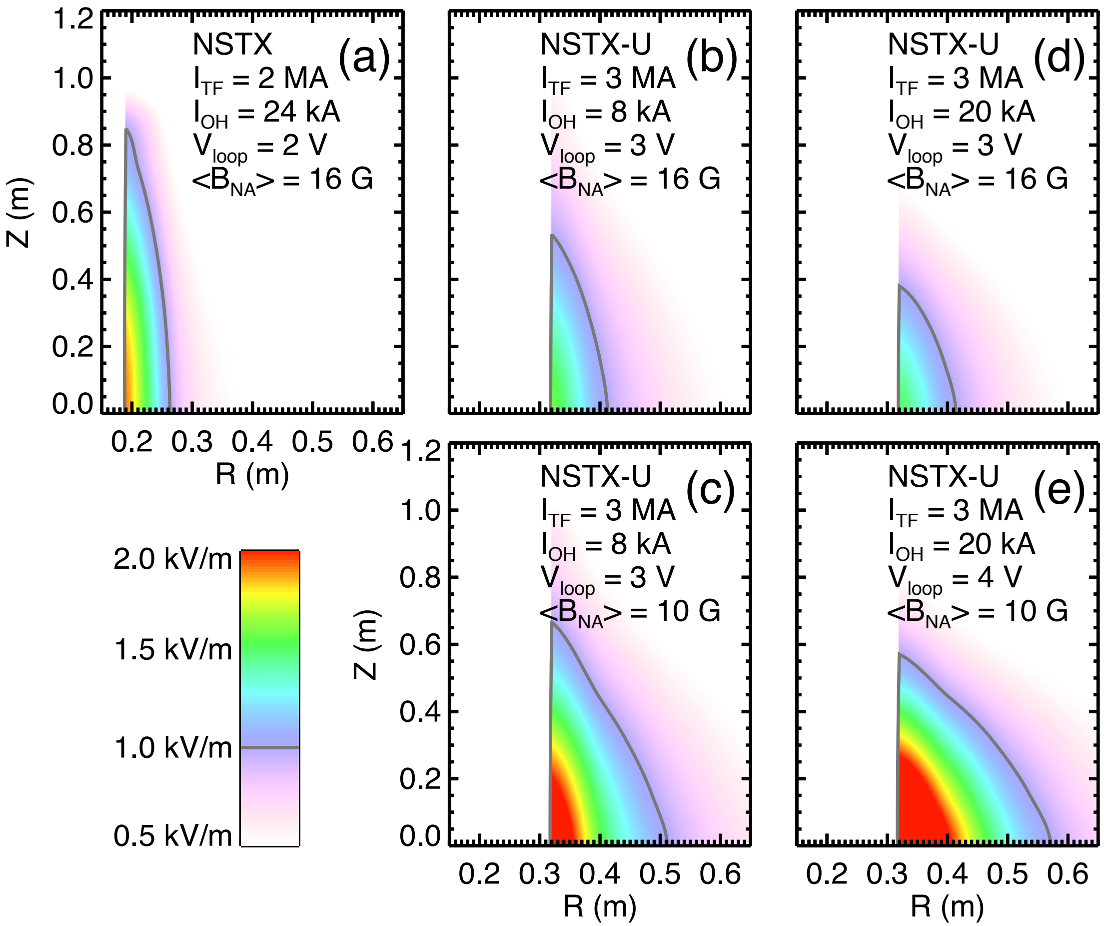


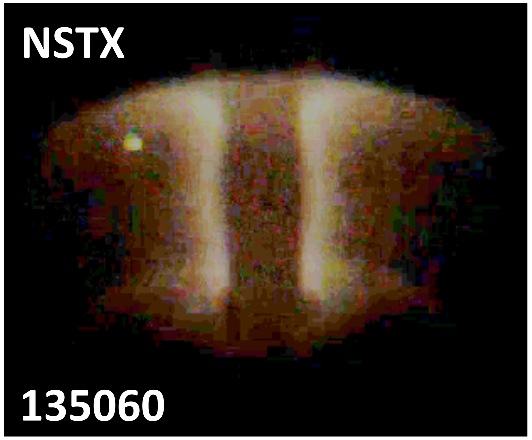
Two rings

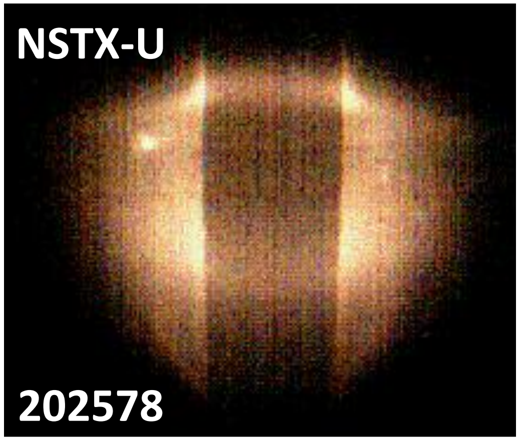




Field null calculations capture qualitative differences in the breakdown region

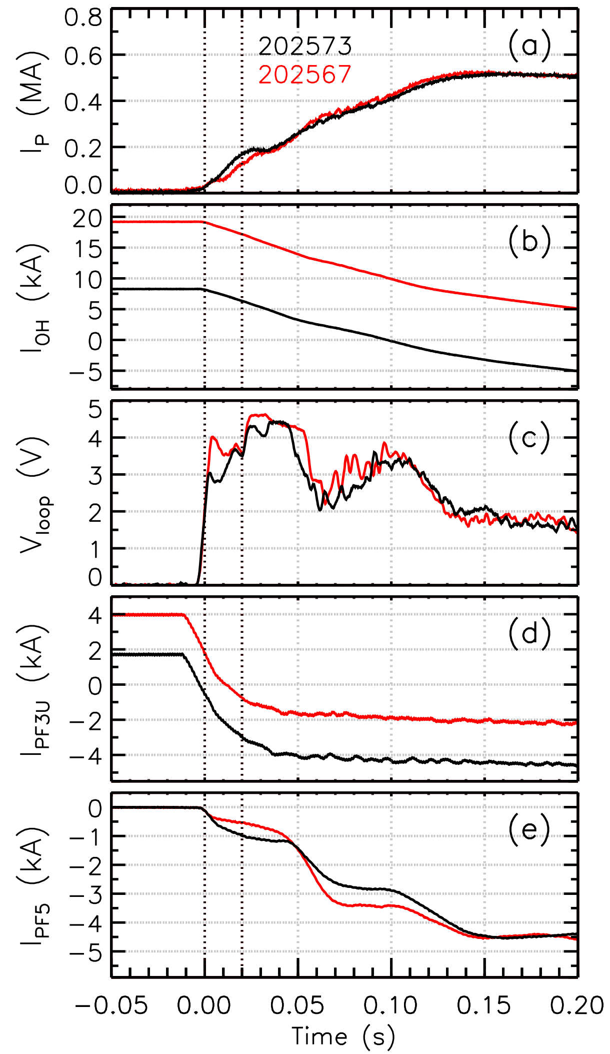






Breakdown scenarios at 8 and 20 kA precharge were routinely used

- V_{loop} increased with larger precharge
- Discharge evolution very similar after first 20ms at either precharge
- There was an up-down asymmetry that is not captured in the model
  - Quantitative comparisons between model and experiment are ongoing



An example shot of low V_{loop} DI startup

MUN 08.371

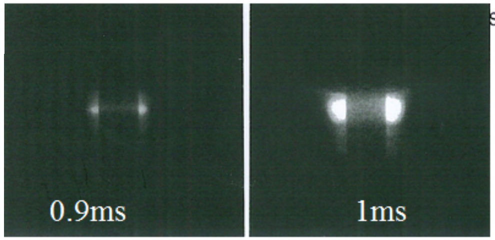
Start-up on MAST and MAST-U without P3

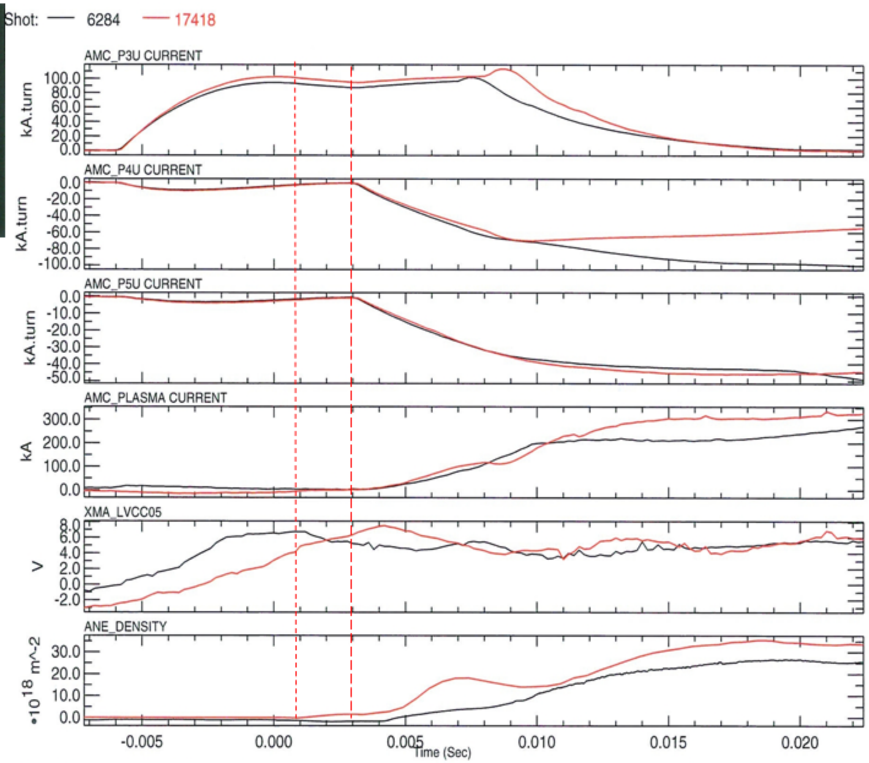
USING CENTRAL SOLENOID

A Sykes, M Istenic

Presentation at MAST – U meeting, 22 Sept 08

Breakdown easy in 'DI' shots using constant low value of P3 to give null – pre-ionisation not necessary, for example Ohmic #17418 started at 0.9ms (before flashlamp at 3ms)





Similar to NSTX field configuration

A calculation including the M3 wall model (FIESTA)