Discharge start-up and ramp-up development for NSTX-U and MAST-U

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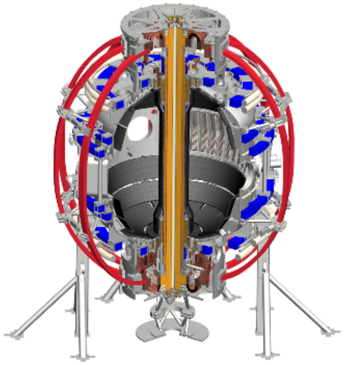
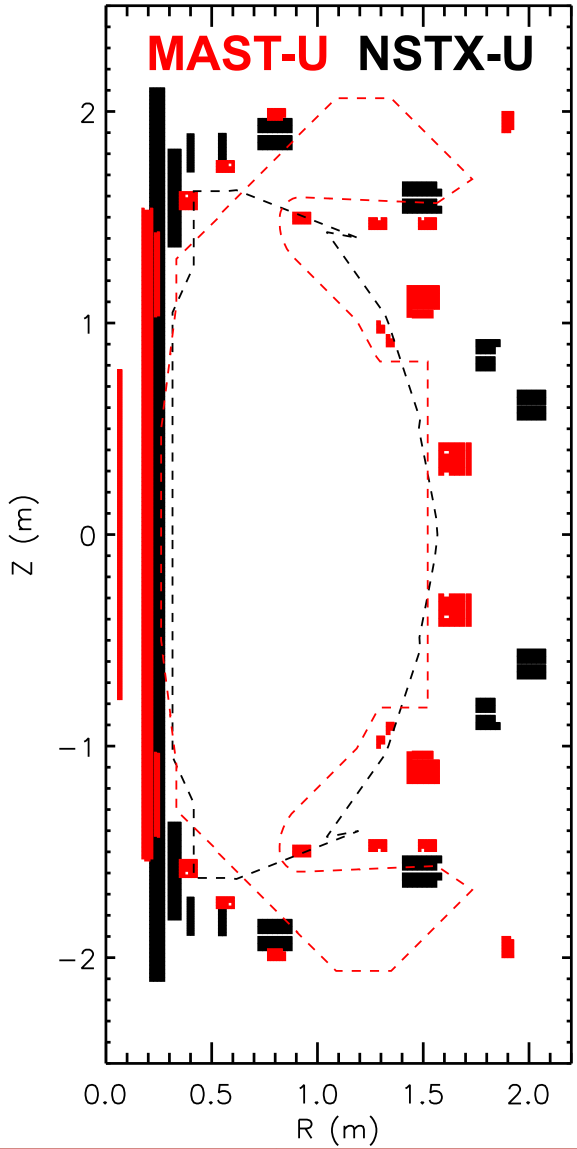
APS DPP Conference
Milwaukee, WI
October 25, 2017



Summary

- Inductive start-up calculations completed for MAST-U and NSTX-U using LRDFIT
  - Achieved similar metrics for breakdown and passive stability within the unique constraints of each device
- High elongation on NSTX-U enabled by an L-H transition during the ramp-up phase
  - L-mode database assembled to identify target conditions for a reproducible L-H timing in ramp-up
  - Vertical oscillations at the time of diverting limited the elongation and hindered reproducible L-H transitions on NSTX-U
- FY18 Research milestone aims to improve control and scenario development tools for the ramp-up phase
  - Supports MAST-U / NSTX-U collaboration on start-up and ramp-up

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
  - Use 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

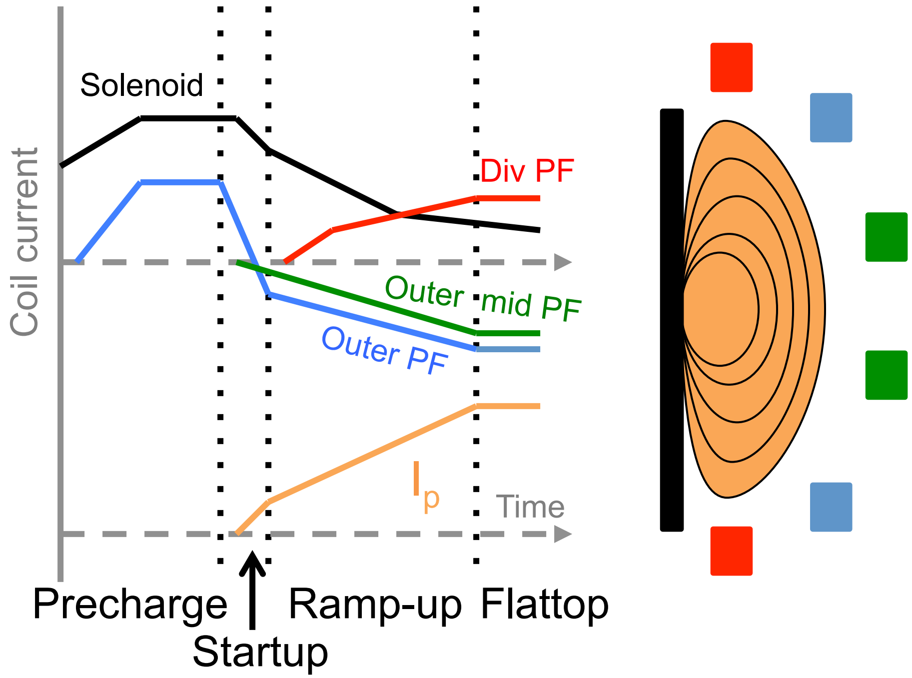
	MAST-U (2018) Planned	NSTX-U (2016) Achieved	MAST-U (stage 1) Planned	NSTX-U (full field) Planned
Max I_p (MA)	1.5	1.0	2.0	2.0
Max B_T at 0.936 m (T)	0.513	0.635	0.684	1.0
NBI (MW)	3.5 (75 keV)	6 (90 keV)	7.5 (75 keV)	12 (90 keV)
t_{pulse} at full field (s)	1	1	5	5

Start-up and Ramp-up collaboration has been initiated between MAST-U and NSTX-U

- ST devices have common goals for optimizing startup and rampup scenarios
  - Develop robust and flexible startup scenarios
  - Maintain broad current profiles (low – l_i) during ramp-up
  - Minimize ohmic flux consumption
  - Achieve reproducible timing of diverting and L-H transition
- Collaboration aims to develop similar models and metrics for optimizing startup and control
  - Accelerate progress in developing and demonstrating scenarios and control necessary for high-performance

Common elements of startup and ramp-up phases on ST devices

- Precharge
  - Solenoid and outer PF coils start with positive current
  - Inject neutral gas, turn on pre-ionization source
- Startup (~ 20 - 40 ms)
  - Ramp solenoid and outer PF current toward zero
    - Achieve a field null and target V_{loop}
  - Ramp outer midplane PF coils to provide equilibrium field
    - Maintain passive R and Z stability



- Ramp-up (I_p > Induced wall current ~ 100 - 300 kA)
  - Transition from pre-programmed coil currents to active control of I_p, plasma shape and vertical stability
  - Transition from limited shape to diverted shape
  - Start external heating (NBI, RF)

Start-up model

- Header slide

LRDFIT code used to examine start-up scenarios for NSTX-U and MAST-U

- LRDFIT is a Grad-Shafranov solver used routinely at NSTX-U for data analysis
  - An additional application is computing the vacuum field evolution for user defined or experimentally realized coil currents
  - Primary tool on NSTX-U for magnetics calibration, axisymmetric wall model development, and breakdown scenario development
- LRDFIT used to develop recipes for first plasma and startup optimization
  - Identify target scenarios with best guess for the wall model
  - Develop prescriptions for scanning parameters independently
    - I_{OH} precharge, V_{loop}, null timing, B_Z/dt, field curvature …
  - Enabled rapid progress with NSTX-U first plasma demonstration and refinement of the 2D wall model for equilibrium reconstructions

Differences between MAST-U and NSTX-U devices that influence start-up

- Shorter solenoid of MAST-U = greater field curvature
  - Motivates including the divertor coils to oppose radial field

- NSTX-U: dB_z/dt provided primarily from a single high-voltage bipolar PF coil set
  - MAST-U: Use a number of lower voltage PF coils to generate target dB_z/dt

- Different induced currents in the conducting structures
  - Copper cooling tubes on NSTX-U generated large induced currents during initial campaign

- Differences in I, V and I^2t limits on OH and PF coils

Startup scenarios use a different number of PF coils

MAST-U

I_{OH} = 45 kA (22.5 kA/turn)
*** Limit for 2018 operations*

10 PF coils sets …

Ramp toward negative current at maximum voltage (350V per coil)

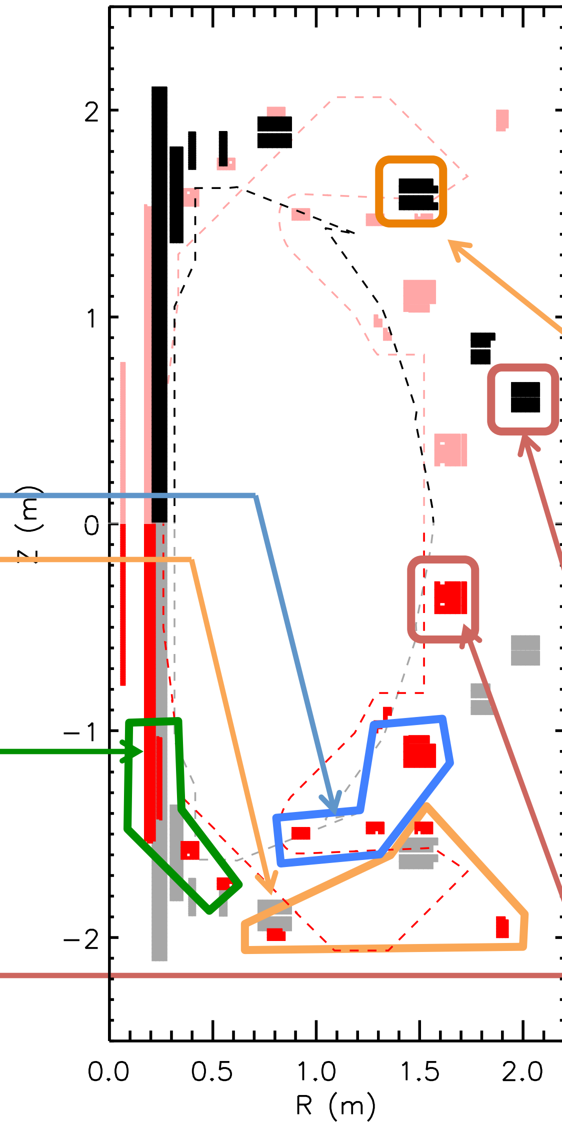
P4 + DP + D6: Ramp from zero current

D5 + D7 + D3: Ramp from pos. current

PX + D1 + D2: Steady positive current to exclude solenoid B_r field

D1, D2 and D3 at 2018 current limit (5 kA)

P5: Ramp from zero current to provide equilibrium field



NSTX-U

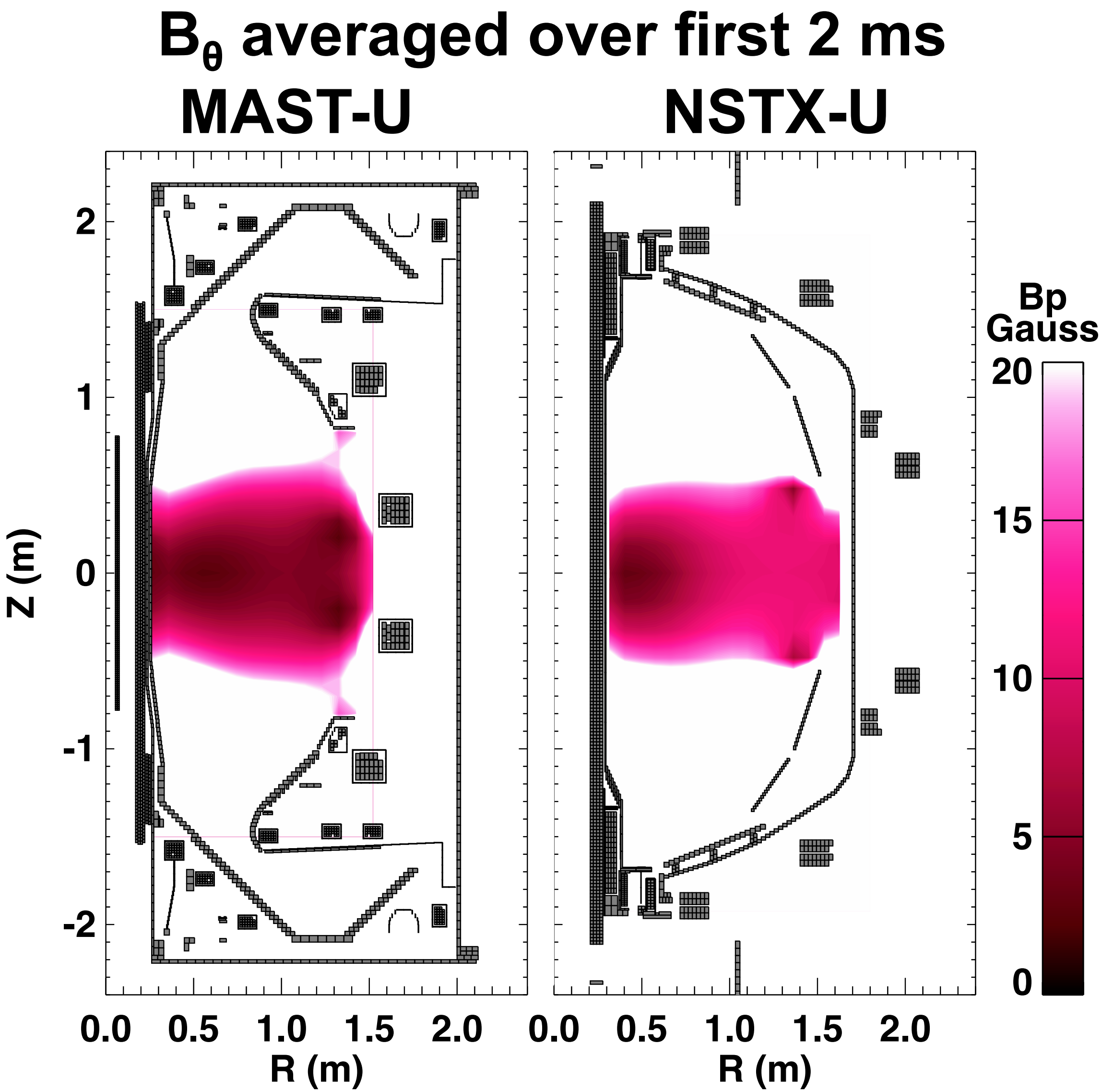
I_{OH} = 20 kA (20 kA/turn)
*** Limit for 2016 operations*

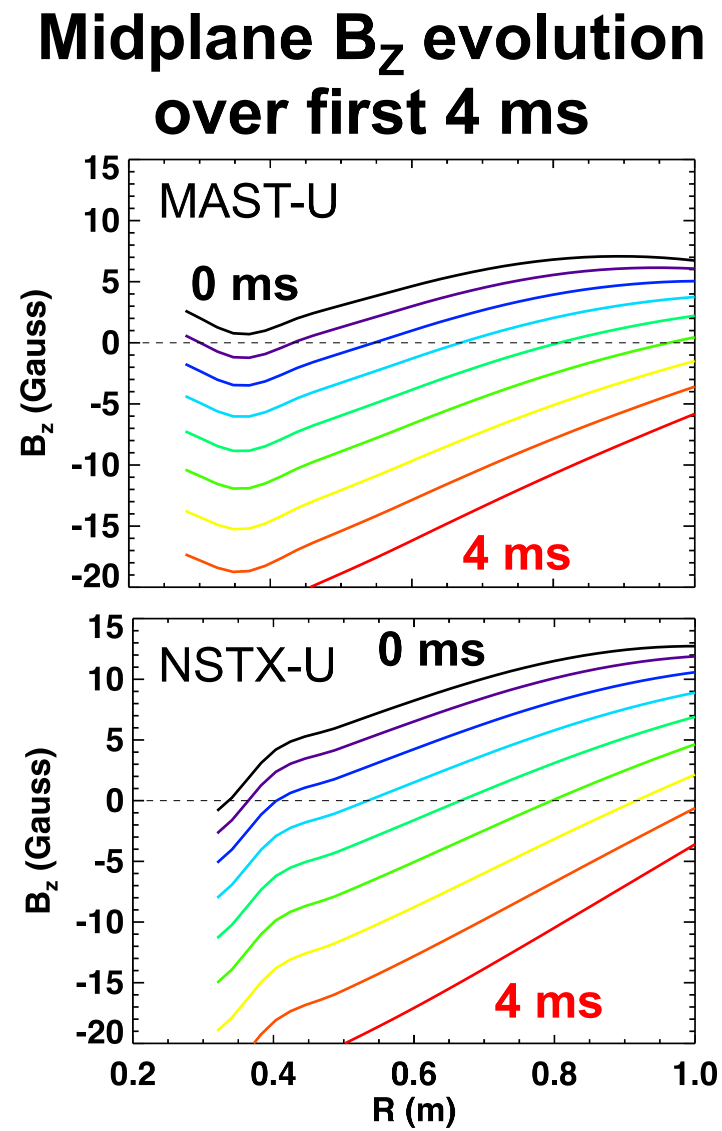
2 PF coils sets …

PF3: Provide positive nulling field, then ramp negative to establish positive field curvature (2 kV per coil w/ bipolar supplies)

PF5: Ramp from zero current to provide equilibrium field

MAST-U can produce a field null with similar spatial and temporal quality to NSTX-U

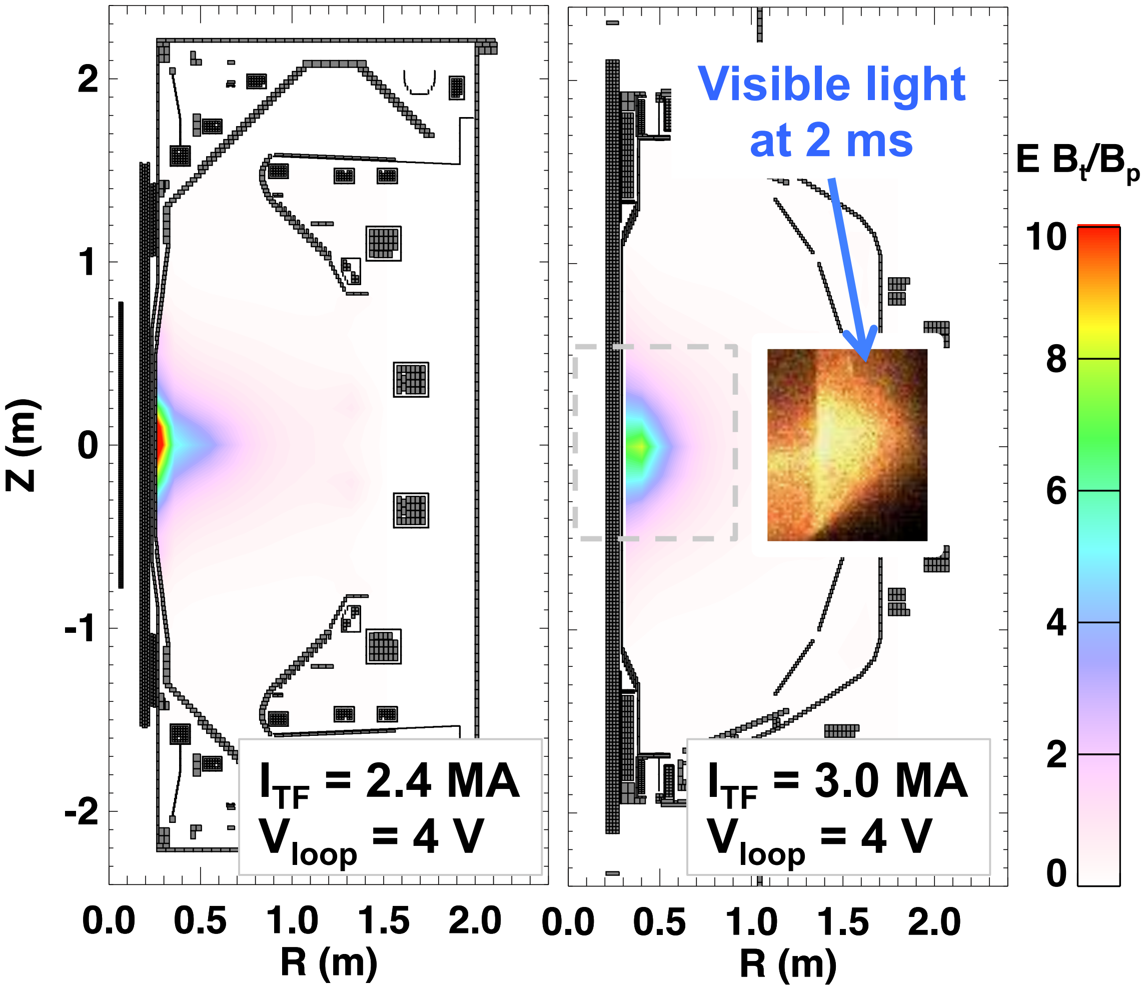




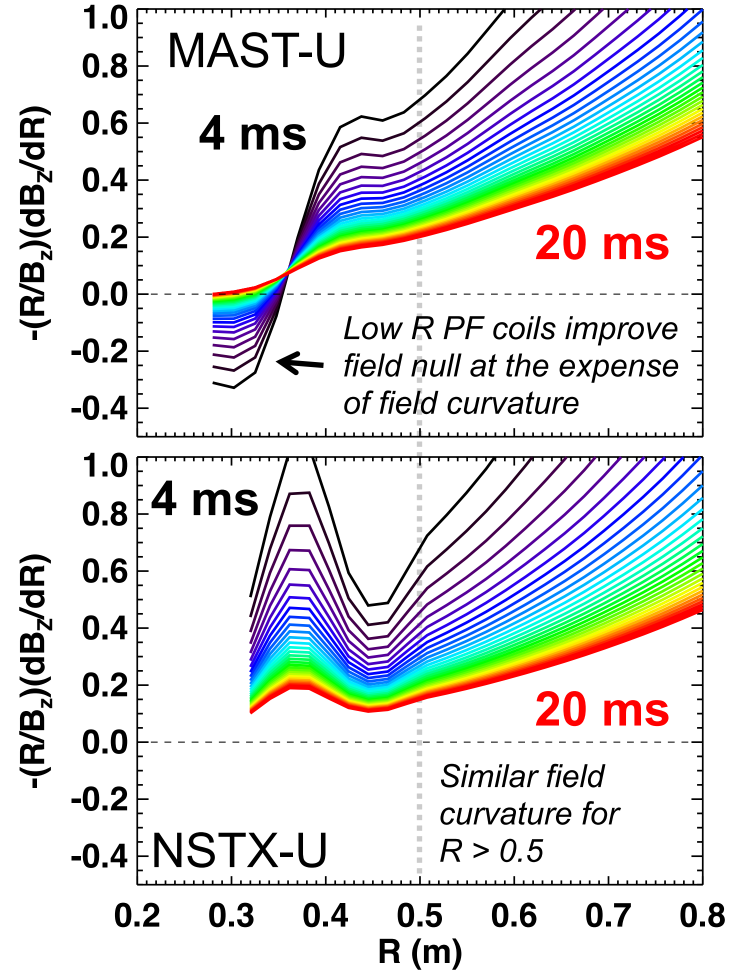
MAST-U breakdown and ramp-up metrics similar to demonstrated NSTX-U scenario

$E_\phi B_\phi / B_\theta$ averaged over first 2 ms

MAST-U   NSTX-U

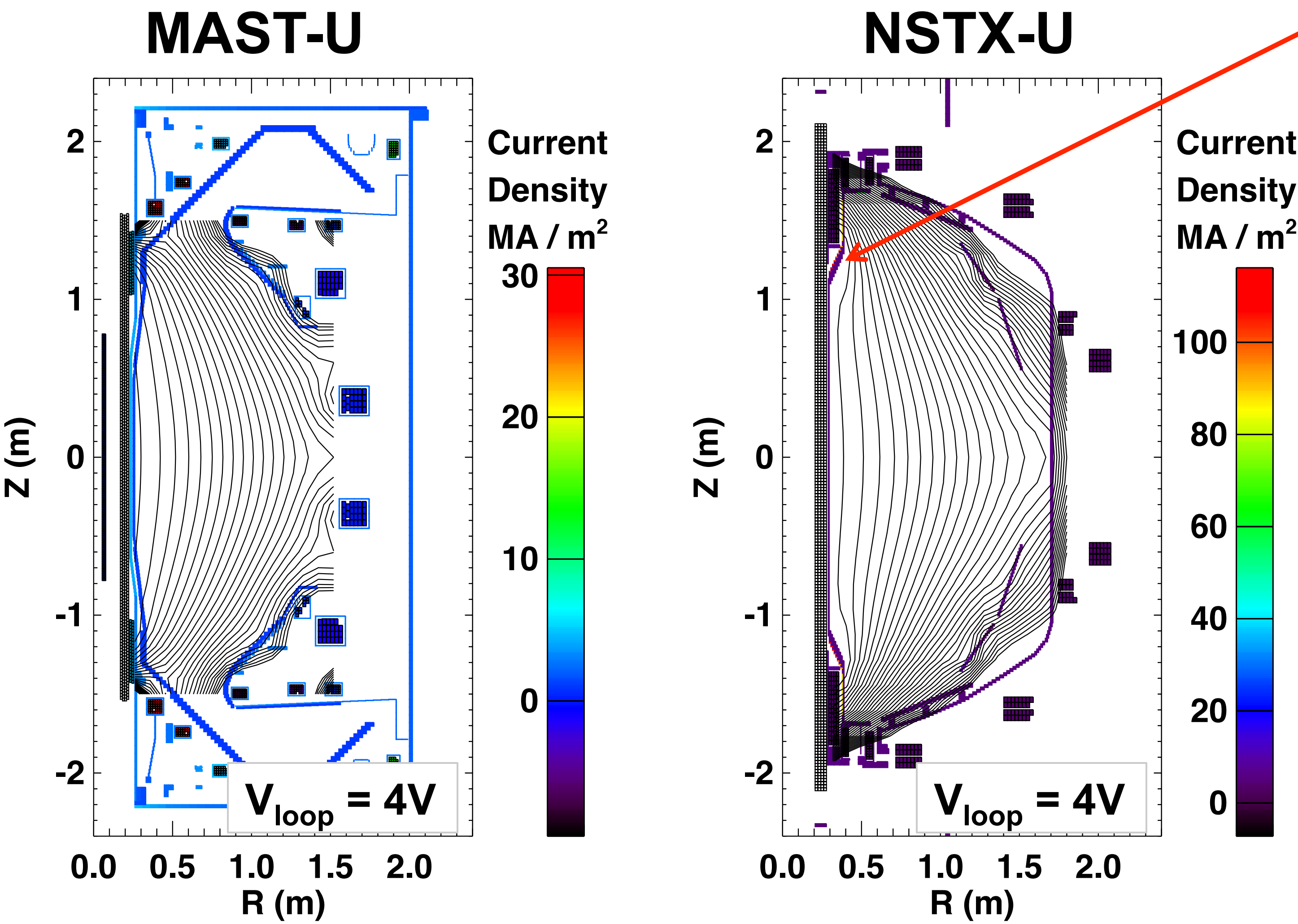


Field decay index evolution in ramp-up



Plasma elongation in ramp-up was limited by large induced wall currents on NSTX-U

Current density (colors) and flux contours at 20 ms



Large induced current in CS crown on NSTX-U limited the early elongation

MAST-U calculations predict modest induced currents

Summary of startup calculations

- MAST-U should be able to achieve a startup scenario similar to startup demonstrated on NSTX-U
  - I_{OH} = 45 kA, I_{TF} = 2.4 MA, V_{loop} ~ 4V satisfying 2018 PF coil limits
  - Caveat: differences in pre-ionization may alter V_{loop} requirement

- Experiments and modeling will further optimize startup
  - What is the optimum dI_p/dt in the first 10 – 20 ms?
    - Larger values tend to keep l_i low, but drives larger wall currents which can degrade passive stability and increase flux consumption
  - What are the limits in the field curvature?
    - Extending the vertical extent of the field null with low-R PF coils typically comes at the expense of field curvature in the ramp-up
    - Aim would be to achieve maximum elongation that remains stable

Analysis of NSTX-U Ramp-up

- Header slide

Early L-H transition enables low-l_i scenario on NSTX-U

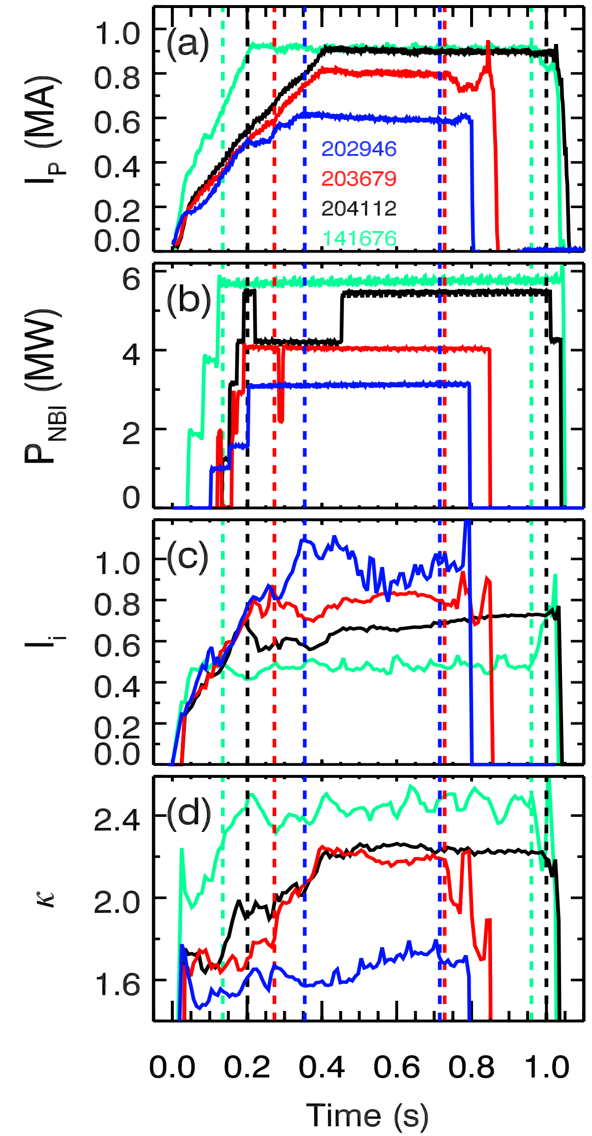
- L-H transition slows current diffusion toward axis
  - Edge pressure gradient increases edge bootstrap current
  - Higher temperature increases current diffusion time
- Stable elongation increases as l_i decreases
  - Larger κ permits larger I_p and β
  - Increases bootstrap current drive
  - Plot shows impact of earlier L-H timing
    - Vertical dashed lines: L-H & H-L transitions
    - Flattop l_i decreases as L-H moves earlier

NSTX
0.44 T
H-mode

NSTX-U
0.62 T
Week 3
No EFC

Week 5
EFC v1

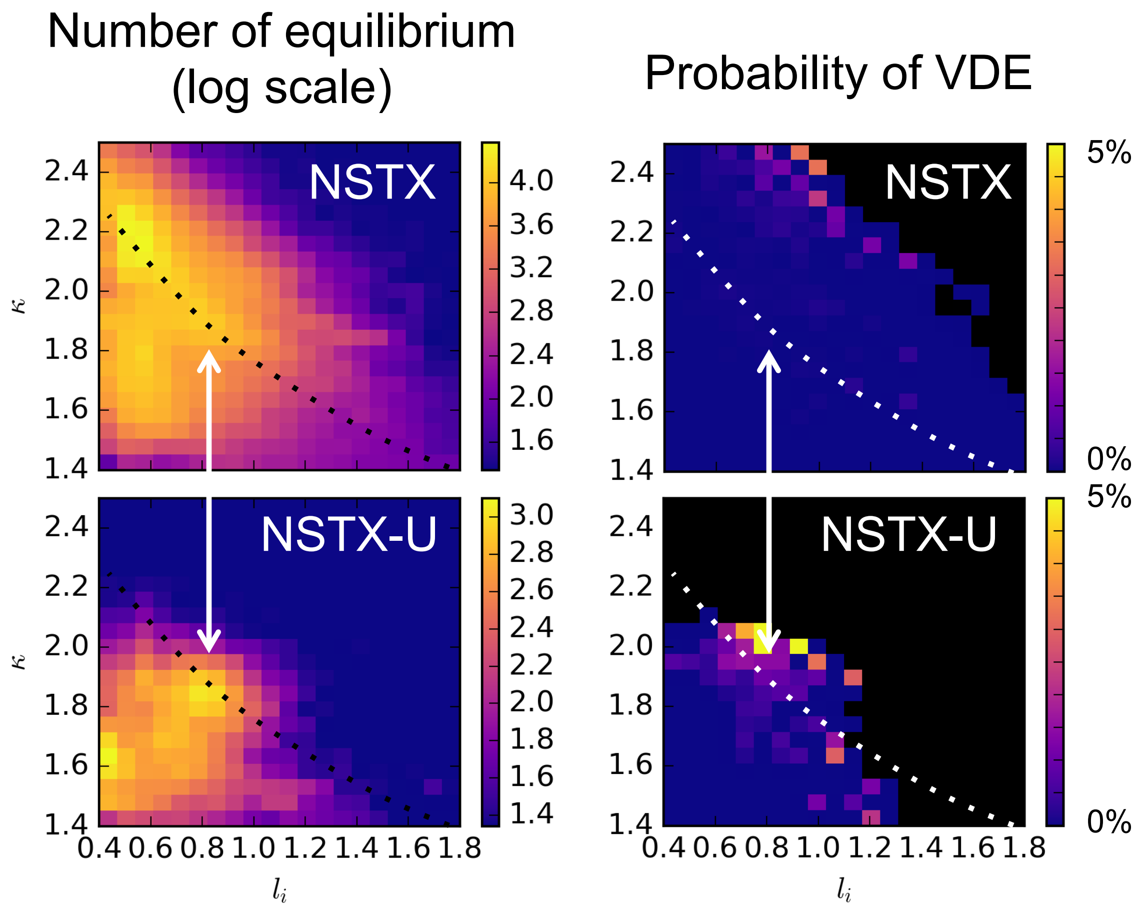
Week 7
EFC v2



Increasing κ in NSTX-U ramp-up will require access to low-l_i

- NSTX-U achieved a similar ramp-up shape to NSTX when l_i = 0.8
- NSTX-U operated much closer to VDE limit in this condition
  - Consistent with increase in aspect ratio
  - Note: still optimizing control and EFC on NSTX-U
- Motivates lowering l_i to expand κ range

EFIT01 for t < 0.3 s



See M.D. Boyer, 11.00041 (next poster)

NSTX-U database provides guidance on target conditions for reliable L-H transition

- Why do some discharges miss the L-H transition?
  - NSTX-U database of times that are diverted L-modes
    - 100 L-mode times and 68 L-H transition times = 168 entries
  - L-mode points: $P_{NBI} \geq 3$ MW for at least 50 ms
    - Beam slowing down time ~ 25 ms

- Identified four criteria for L-H transition (next slide)
  - No discharges miss L-H transition if all four criteria are met
  - $P_{NBI} \geq 3$MW can "power through" with only 3 conditions met

	Total times	L-H times	L-mode times
Satisfy all 4 criteria	39	39 (100%)	0 (0%)
Satisfy 3 criteria	57	24 (42%)	33 (58%)
Satisfy less than 3 criteria	72	5 (7%)	67 (93%)

Target conditions for a reliable L-H transition in the early ramp-up with $P_{NBI} \geq 3$ MW

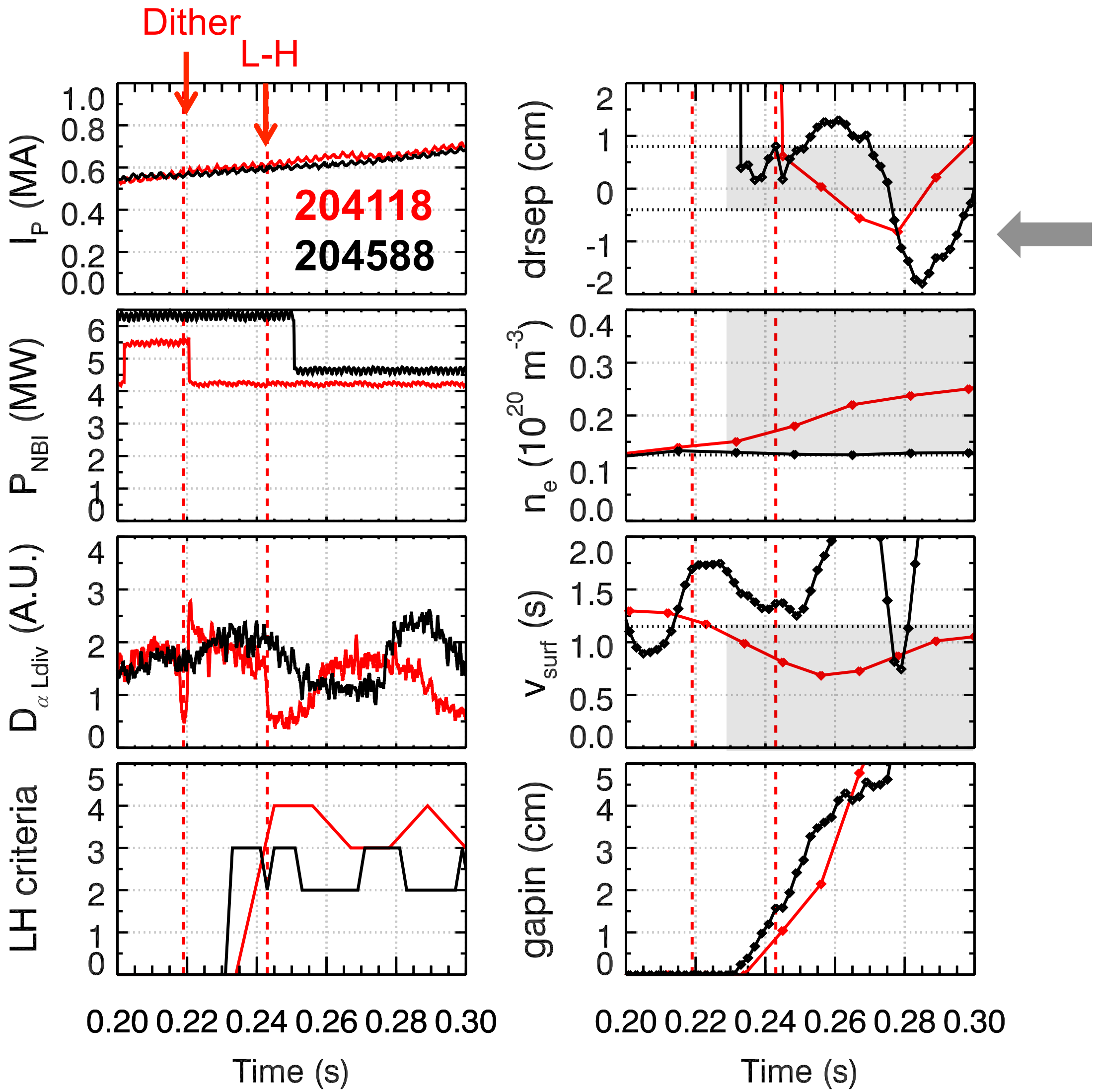
Criteria	Details
$n_e > 1.25 \times 10^{19}$ m^{-3}	Line-averaged density is above a critical value
$V_{surf} < 1.15$ V	Surface voltage (EFIT02) is below a critical value
$\lvert dr_{sep} - 0.2$ cm$\rvert < 0.6$ cm	Shape is near double null (EFIT02) **
O II / $D_\gamma < 1$ (t = 0.15s)	Ratio of lower divertor filterscope channels ^^

** *Offset in dr_{sep} (toward USN) may indicate a systematic error in computing dr_{sep}*

^^ *Filterscope ratio is specific to NSTX-U. It is a general metric for the oxygen content of the plasma, which increases steadily following a boronization*

- Criteria guide targets for early ramp-up
  - Fuel early to get desired n_e target and divert near DN
  - Heat with $P_{NBI} \geq 3$ MW (heating efficiency ~ 50%)
  - Then, pause or slow I_p ramp and fueling to get $V_{surf} < 1.15$V

Vertical oscillation ("bobble") when diverting near DN hindered shot reproducibility



Two repeat shots
(Except **204588** has larger P_{NBI})

Slight differences in shape at time of diverting lead to different behavior of vertical oscillations

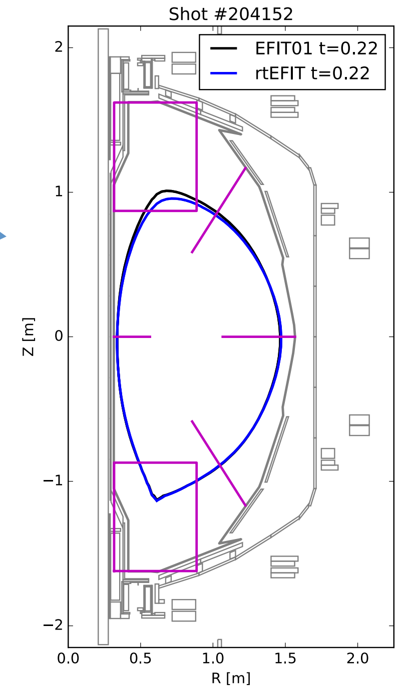
204118 has dither at 0.22s, then an L-H transition at 0.241s

204588 does not have an L-H transition despite larger heating

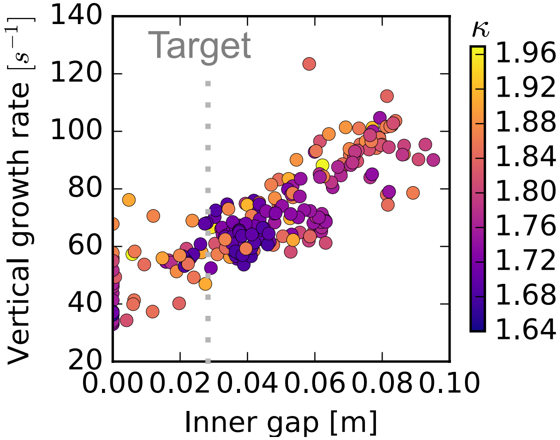
Motion away from DN shrinks plasma volume, increasing V_{surf}, hindering L-H transition from 240 – 260ms

Control and scenario solutions have been identified for mitigating the bobble

- Bobble more likely with large dZ/dt or VDE growth rates at time of diverting
  - "Kick" in dZ/dt may be driven by control algorithm transitions or errors in rtEFIT
  - Overshoot of target inner gap leads to larger VDE growth rate



- Solutions pursued in FY16 operations
  - Flux reference changes from limiter to X-point within a single control algorithm
  - Inner gap feedback improves consistency of diverting time and mitigates overshoot
  - Divert SN, then allow dr_{sep} feedback to alter the shape to near DN



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FY18 Research Milestone on Startup and Ramp-up Modeling

- Extend LRDFIT calculations to include I_p in breakdown
  - Filament model and/or free-boundary GSE solution
- Develop control solutions for ramp-up using TOKSYS
  - Integrates power supply and real-time control with plasma model in order to satisfy system constraints
  - Encompass transition from feed-forward currents with a limited plasma to active position feedback with a diverted plasma
- Optimize NBI heating and current drive with TRANSP
  - Consider impact of density, outer gap, and beam parameters on MHD and fast-ion stability

Summary of Analysis of NSTX-U Ramp-up

- Expanding κ range on NSTX-U is facilitated by achieving an earlier L-H transition
  - NSTX-U achieved similar κ to NSTX with l_i ~ 0.8, but ran closer to VDE stability limit

- A database of diverted L-mode times identified four criteria that improves the reliability of an L-H transition
  - Provides guidance on early ramp-up scenario, such as adding a “pause” to the I_p ramp and fueling

- Vertical oscillations at the time of diverting near DN (“the bobble”) reduced the repeatability of the L-H transition
  - Simulation framework is under development to advance the control and scenario solutions for the ramp-up phase