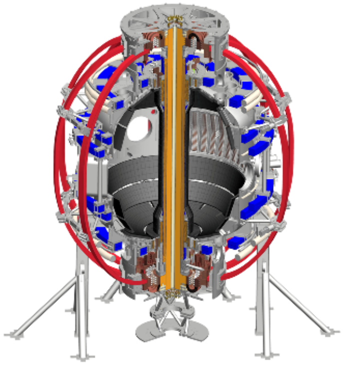
Startup and Ramp-up Development for NSTX-U (XMP-101, 126, 128)

Devon Battaglia

On behalf of the NSTX-U team

NSTX-U FY16 Results Review
September 21, 2016



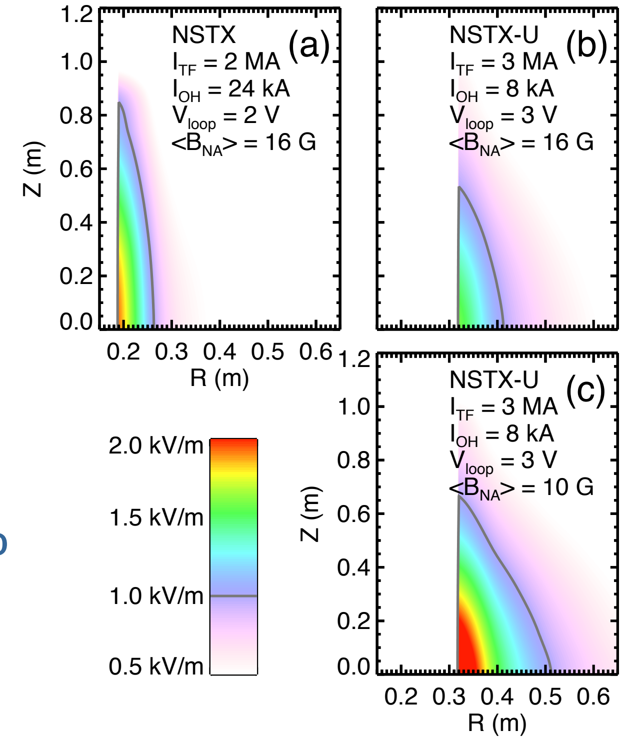
XMP-101: Inductive Startup on NSTX-U

- Startup (first 20ms) from NSTX modified for NSTX-U
  - Breakdown region at larger major radius
  - Conductive wall structures are different
    - About 200 kA total inductive current in structures at breakdown
  - Desire to operate with a range of ohmic precharge

- LRDFIT modeling supported development and interpretation of XMP-101
  - CD-4 achieved within 7 shots using 8 kA ohmic precharge
  - First shot using 20 kA ohmic pre-charge was successful
  - Quantitative comparisons between model and experiment are on-going

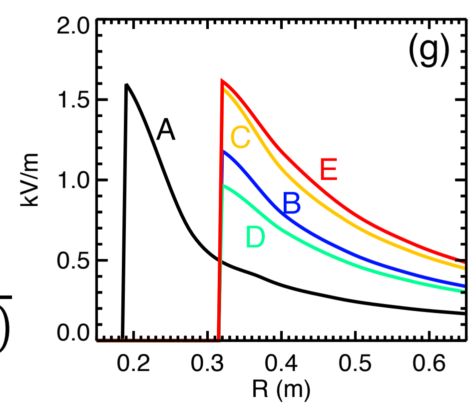
Needed less V_{loop} than anticipated from calculations for NSTX-U

- Smaller V_{loop} needed for breakdown compared to model predictions
  - 8 kA OH precharge: V_{loop} ~ 3V (first 2 ms)
    - Model predicted V_{loop} ~ 4V
    - Scales to V_{loop} = 2 V at B_T = 1T
  - Model matches experiment if the 3D error field near inboard midplane reduced ~ 40%
    - Consistent with smaller OH x TF tilting



- Breakdown region has smaller Z, larger R extent compared to NSTX, consistent with model

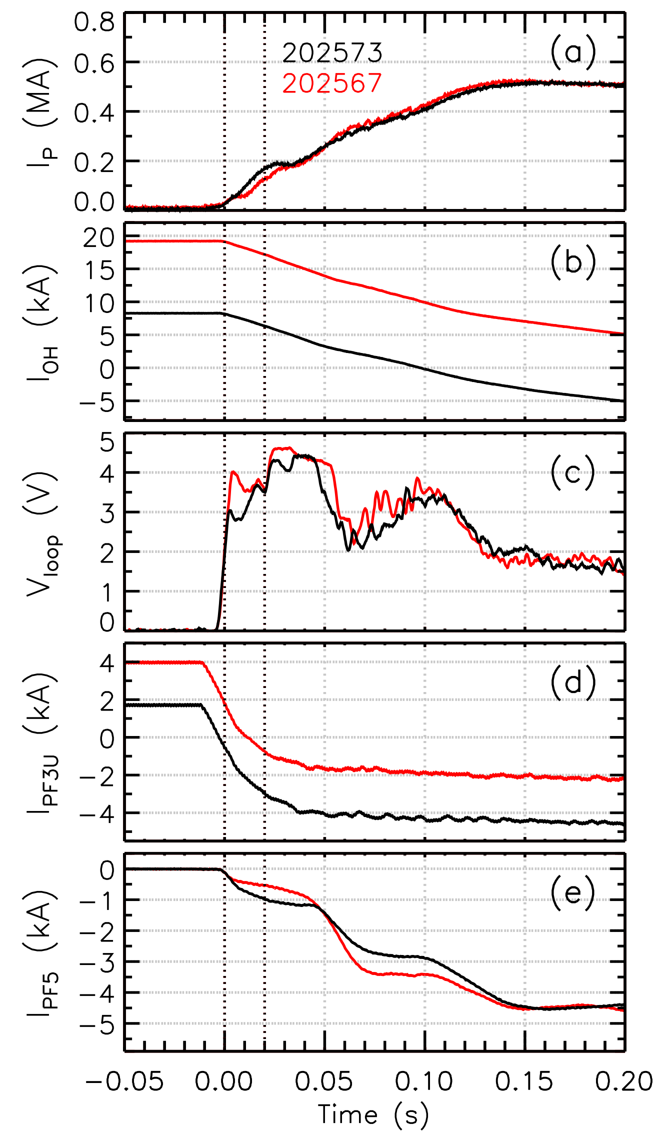
$$\frac{V_{loop} I_{TF}}{\pi R^2 \left(B_\theta + \langle B_{\theta,NA} \rangle\right)}$$



Breakdown calculations led to viable startup scenarios at two OH precharge levels

- Larger V_{loop} needed with larger ohmic precharge
  - Size of field null reduced at larger I_{OH}
  - 25% increase in V_{loop} matches calculations comparing 8 and 20 kA cases

- 8 and 20 kA OH precharge routinely used
  - Both scenarios retained passive R and Z stability, and achieved > 100 kA by 20ms



One outstanding question is an up-down asymmetry at breakdown

- Model does not reproduce up-down asymmetry
  - Unbalanced PF3 currents (~ 200A) needed to center plasma
  - Imbalance is larger at larger I_{OH} precharge
- Possibilities …
  - Is wall model incorrect?
    - Adding induced currents near PF1A improves model agreement → cooling tube issue?
  - Is the magnetization of the floor rebar important?
  - Is the motion of the solenoid midplane important?
  - Is there an issue with measuring the PF3 current?

Shape and timing of breakdown region matches camera images by adding induced current to PF1A coils

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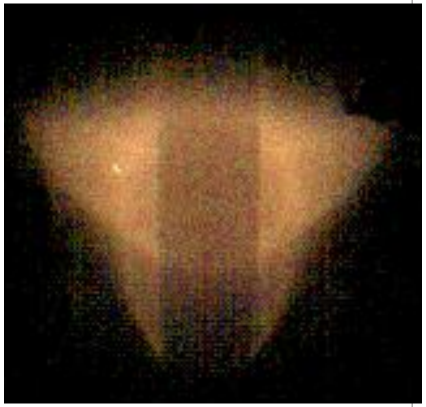
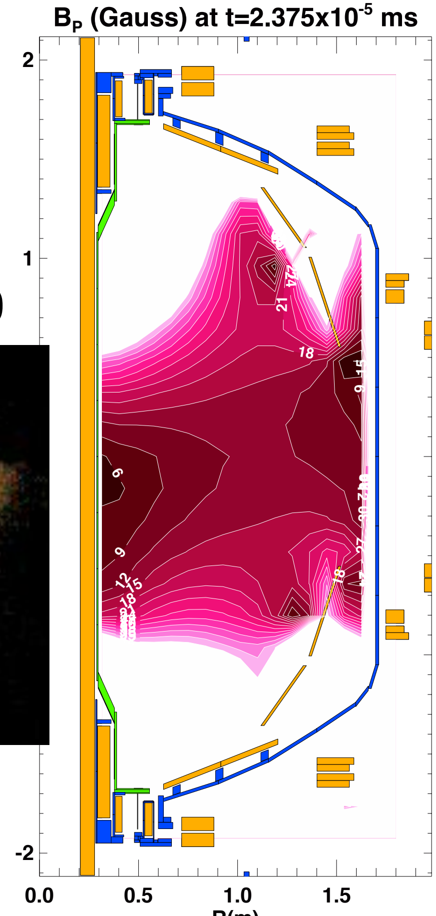


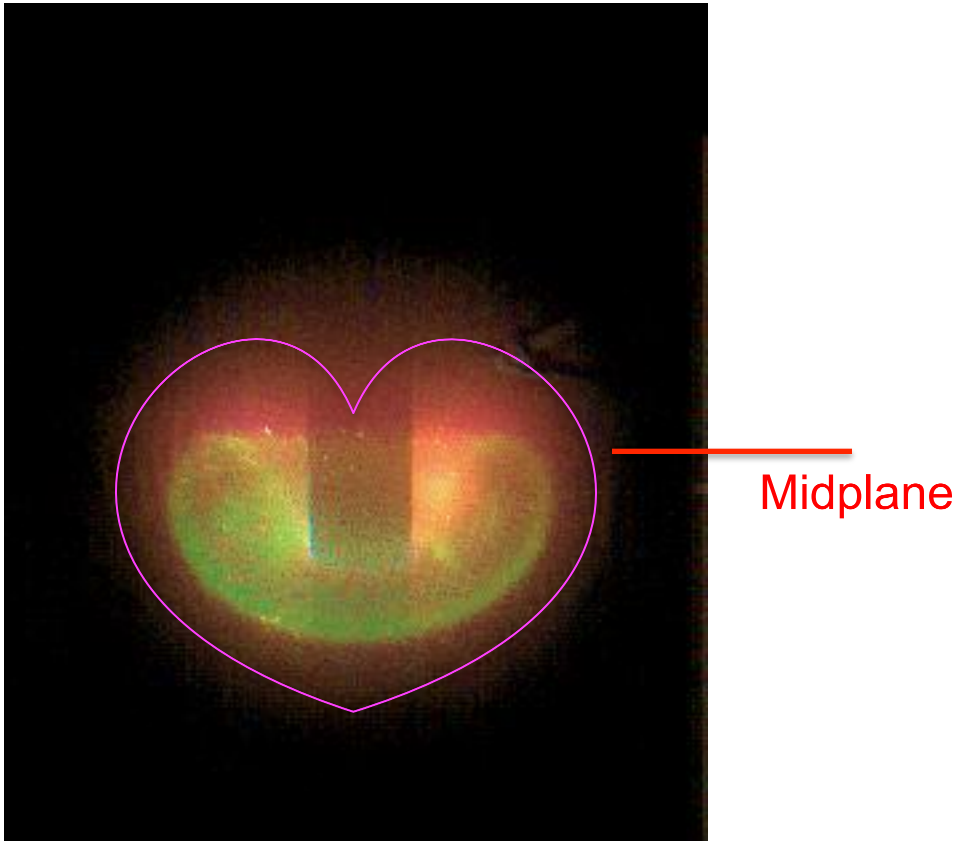


Future activities for XMP-101

- 20 kA precharge scenario needs improvement
  - I_p rise delayed ~ 4ms compared to 8 kA precharge scenario
    - Leads to larger flux consumption
  - Calculations indicate that PF3 ramp should have been faster
- Scale breakdown scenarios to different TF and OH precharge
  - 8kA precharge scenario demonstrated 0.35 – 0.65 T
  - 20 kA ohmic scenario demonstrated 0.55 – 0.65 T
  - Develop library of breakdown scenarios and/or fancy breakdown algorithm

NSTX-U sends its love

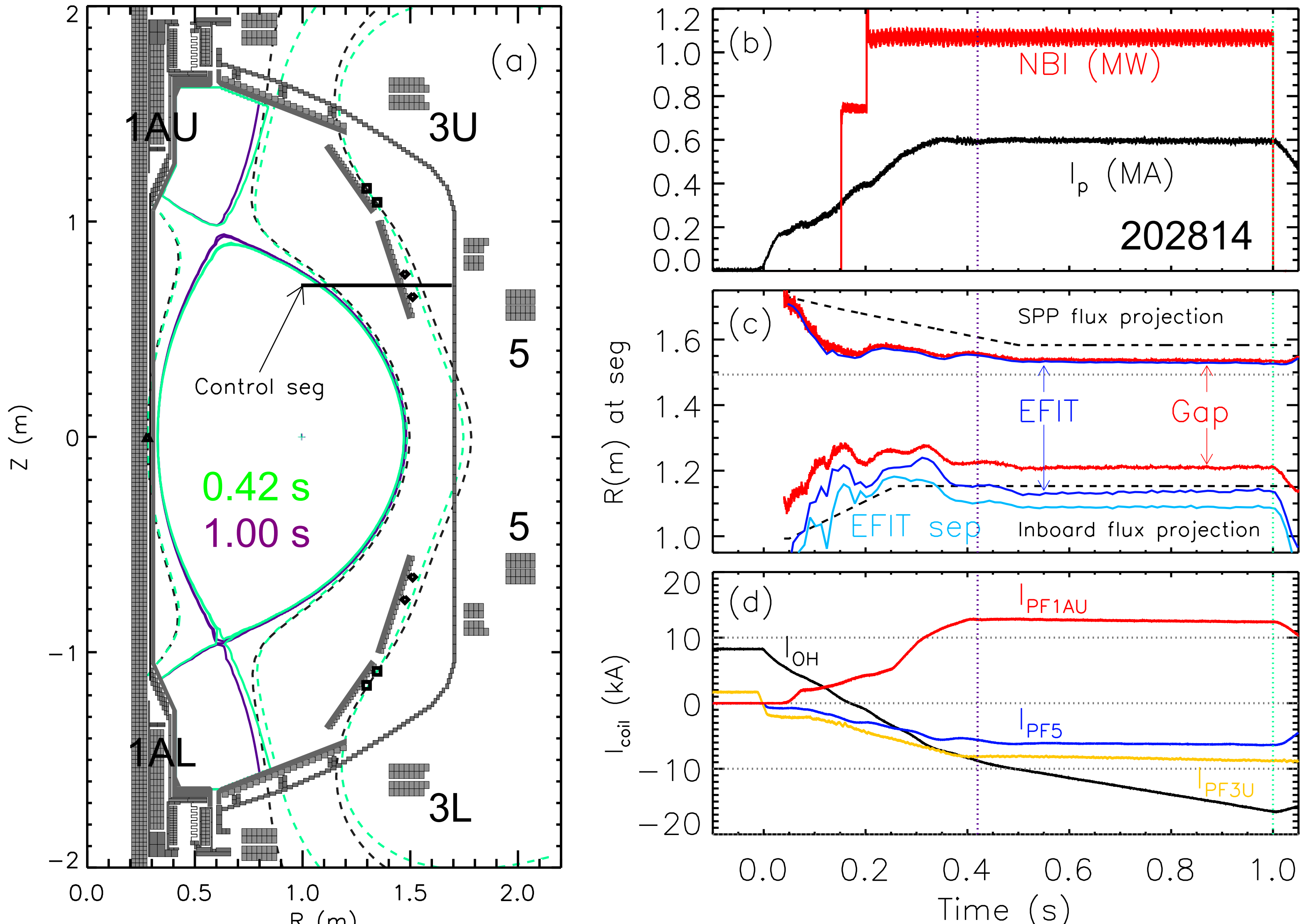
Balanced PF3 coil currents with a 20kA OH precharge



Transition to ramp-up control algorithms starts at 20ms

- I_{OH} transitions to I_p control (XMP-126)
  - Transition strategy, PI gains similar to NSTX
- I_{PF3}, I_{PF5} transition to Gap control algorithm (XMP-126)
- Additional I_{PF3U}, I_{PF3L} voltage request from VPC (XMP-105)
  - Vertical position control → See Dan's talk
- Divertor coil current in relational control (XMP-128)
  - $I_{PF} = A\ I_p + B\ I_{OH} + C$
  - "B" and "C" terms new for NSTX-U
  - Second term ("B") compensates for changing OH fringe field
- Some or all PF currents transition to ISOFLUX control when $I_p > 350$ kA
  - First two weeks ran with Gap and Relational Control for entire shot (XMP-128)
  - Dan's talk will cover rtEFIT and ISOFLUX details and results
- LFS gas in flow rate control
  - Typically switched to HFS fueling around 150ms using new 0.25" diameter system
    - New valves provide ~ factor two reduction in the length of the gas injection (~ 0.4 s)

Ramp-up shape algorithms were used to control first DN discharges (XMP – 128)



On-going and future work on discharge ramp-up (20 ~ 250 ms)

- Measure and correct EF during ramp up
  - Optimum EFC during ramp-up different than flattop
    - See Clayton's talk
- Analysis of MHD and flux consumption vs …
  - Ramp rate, EFC, wall-conditioning, shape, etc.
- Control inner gap and X-point position using ISOFLUX control prior to diverting
  - Important for H-mode access, ramp-up dynamics
    - See Dan's talk
  - Getting close to finishing this task during last week of ops

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NSTX-U

H-mode scenario development on NSTX-U (XMP – 142, 151)

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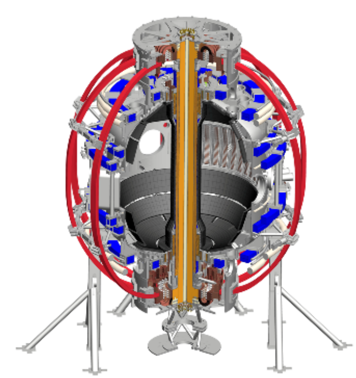
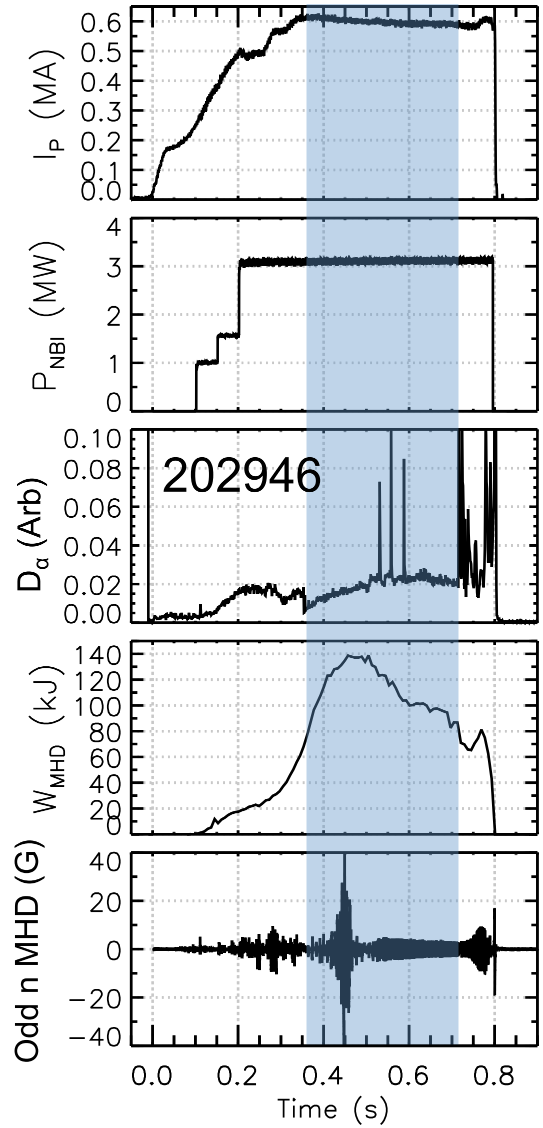
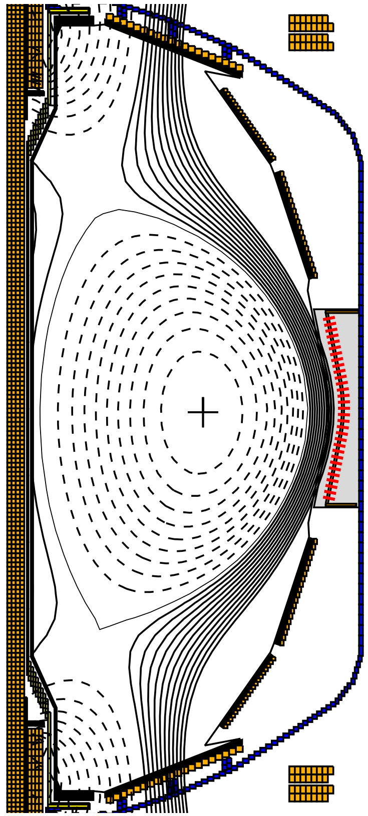
PPPL

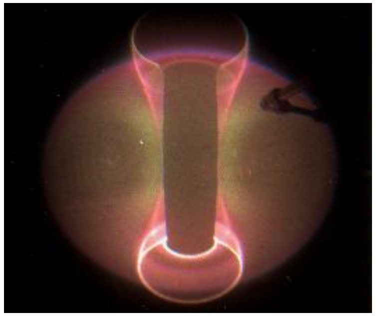


H-mode first observed during 2nd week of plasma operations (January)

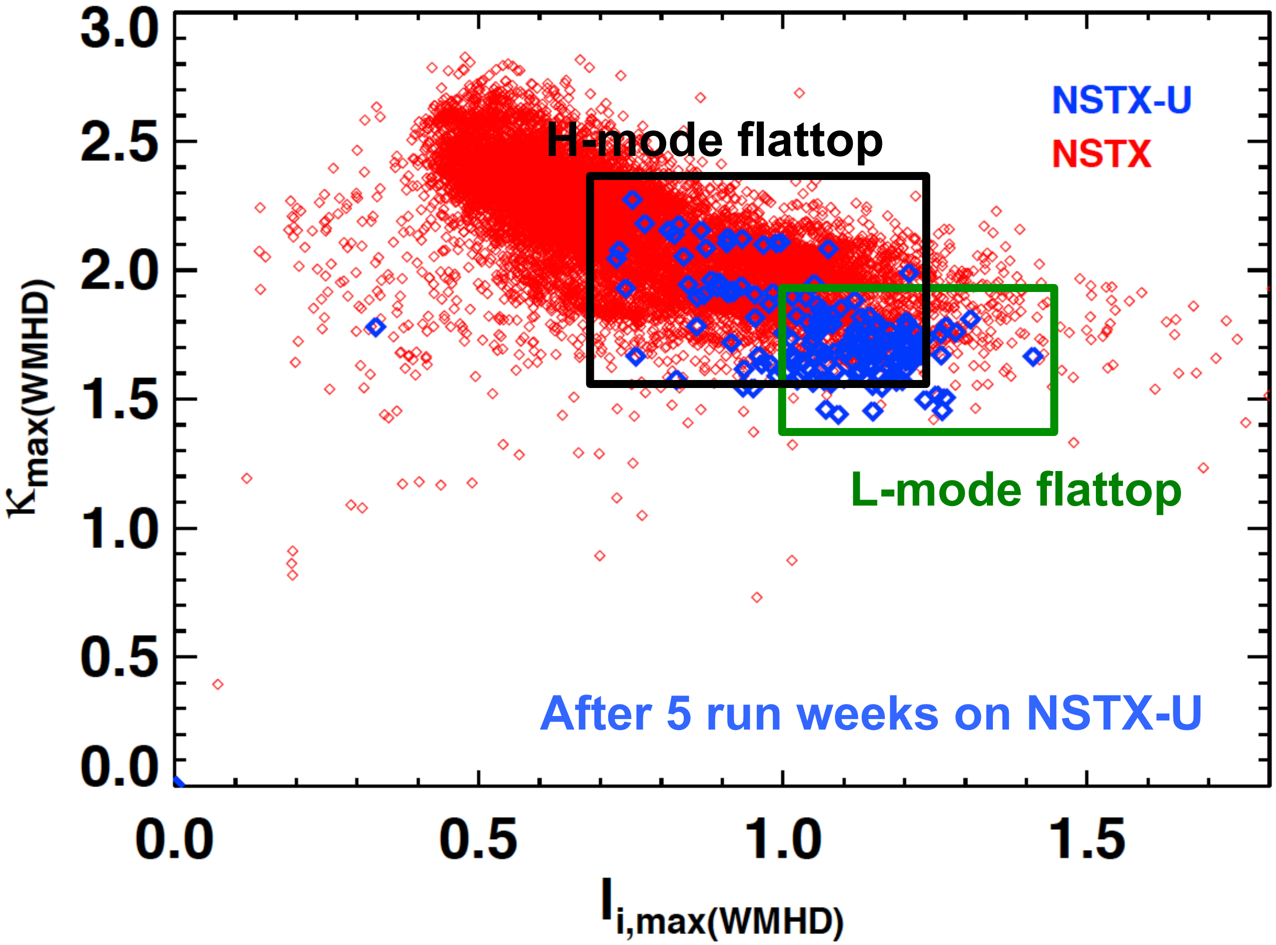
- First time diverting and using D fueling
  - No ISOFLUX, no EFC
- L-H at $P_{NBI} > 1.0$ MW
  - Up to 3 MW of NBI available
- L-H transition in flattop
  - MHD activity soon after
- "ELM-free" H-mode periods ~ 0.3s
  - P_{RAD} and n_e rise, H-mode ends with H-L back transition







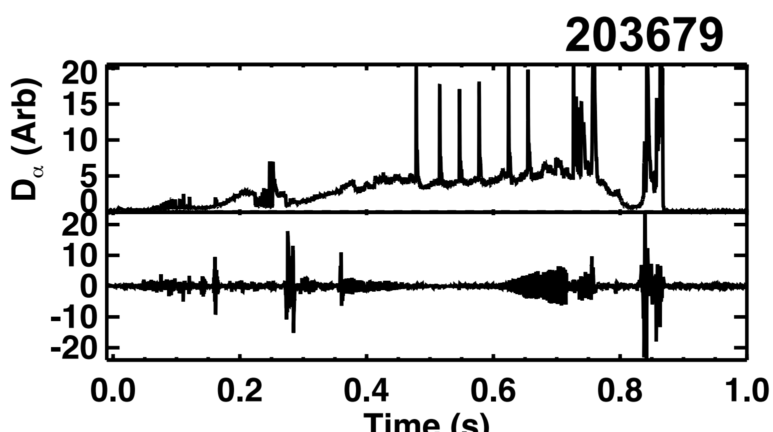
H-mode can access lower l_i, thus vertically stable at larger κ

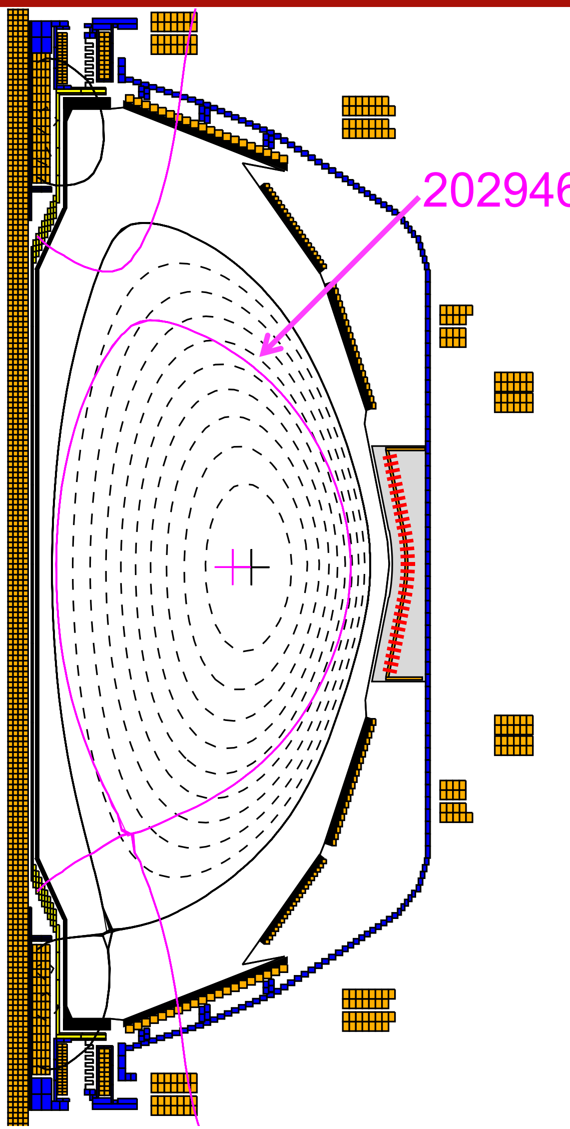


Flattop l_i strongly impacted by the timing of the L-H transition

High κ shape established during 5th run week (March)

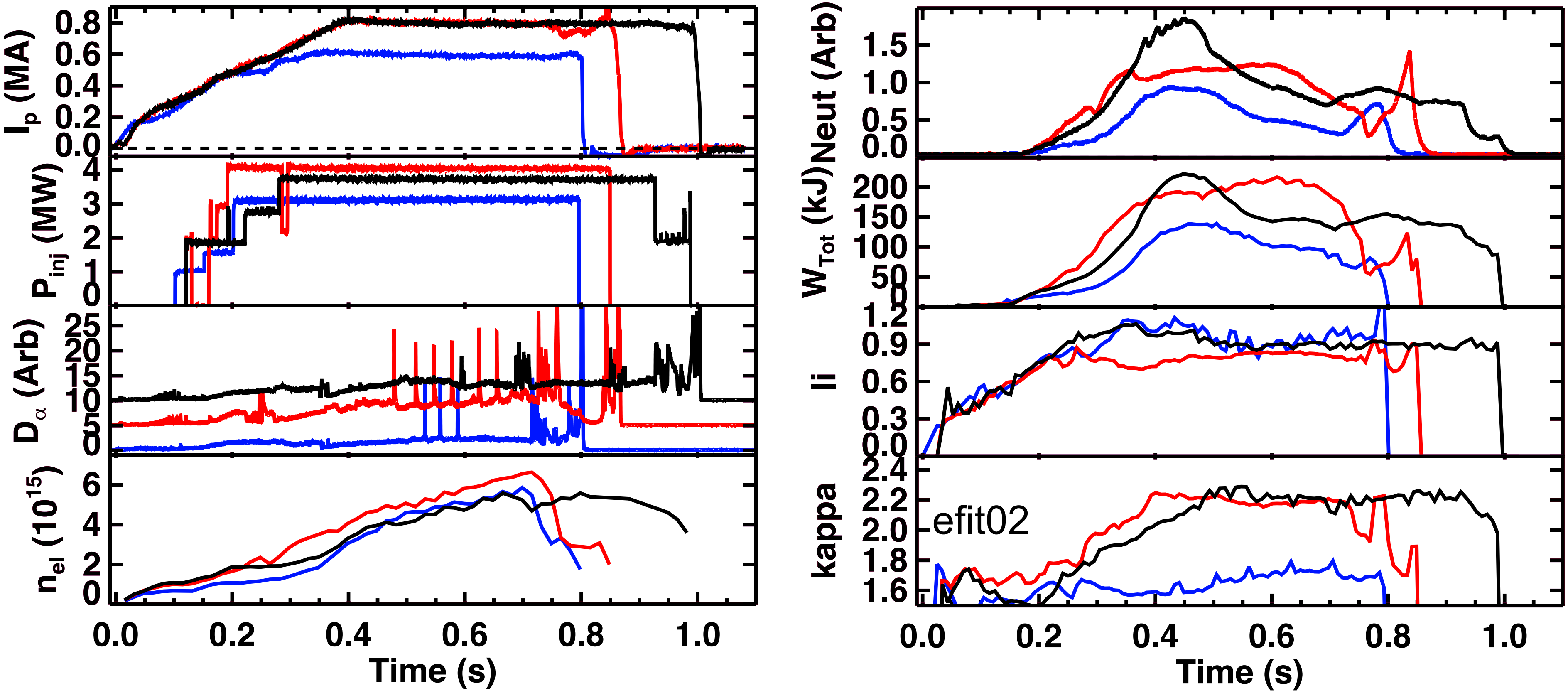
- ISOFLUX control of outer boundary
  - PF1A and PF2 in relational control
- Established κ ~ 2.2, l_i ~ 0.8 shape
  - First power on inboard divertor plate
- First version of low-beta EFC
- Up to 4MW of NBI heating
- Full-bottle boronization
- Period of MHD quiescence with regular ELMs observed in one shot





First shot to put power on inner div had ELMs and maintained W_{TOT}

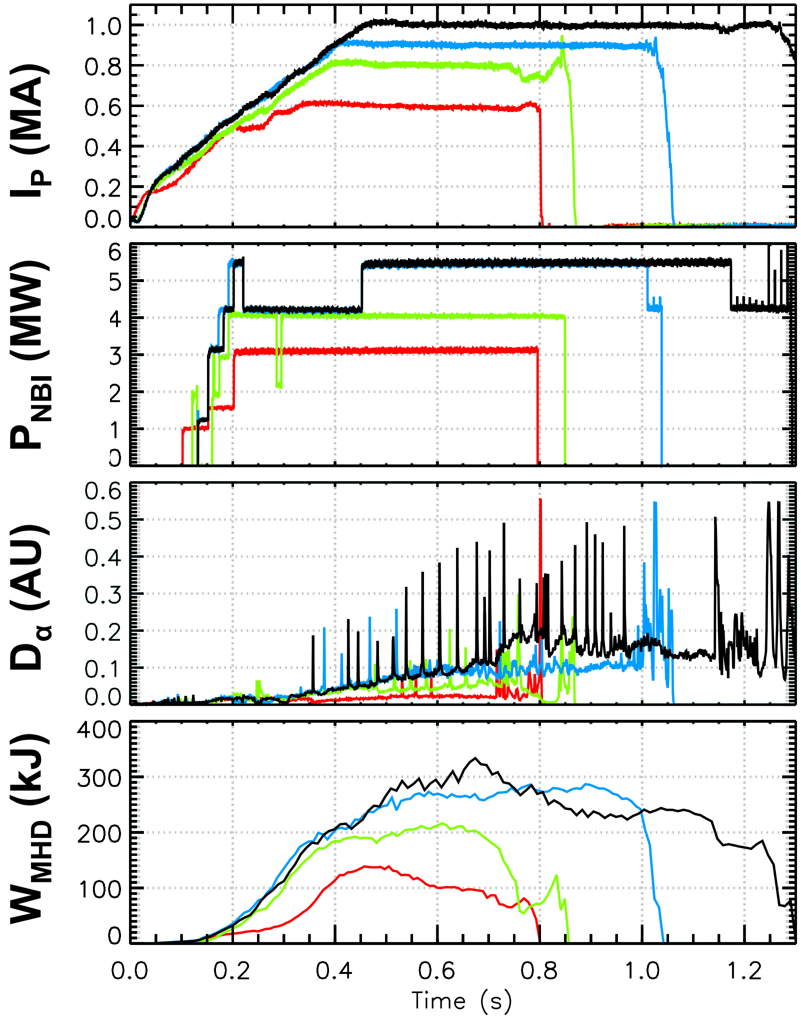
202946: Best H-mode in January period
203655 and **203679**: Best H-mode in Feb-March period



Took about 5 shots to recover wall conditions after putting power on inner div, which had not been baked as well as the outer divertor

Best H-mode day of the run during 7th run week (April 4)

- Updated version of EFC
  - Increased stable β_N/l_i from 4.4 to 6 when $q_{min} < 2$
- Up to 5.5 MW of NBI
  - Maintained ELMs at high n_e
- Operations followed full-bottle boronization
- Same shape as March with power on inner divertor

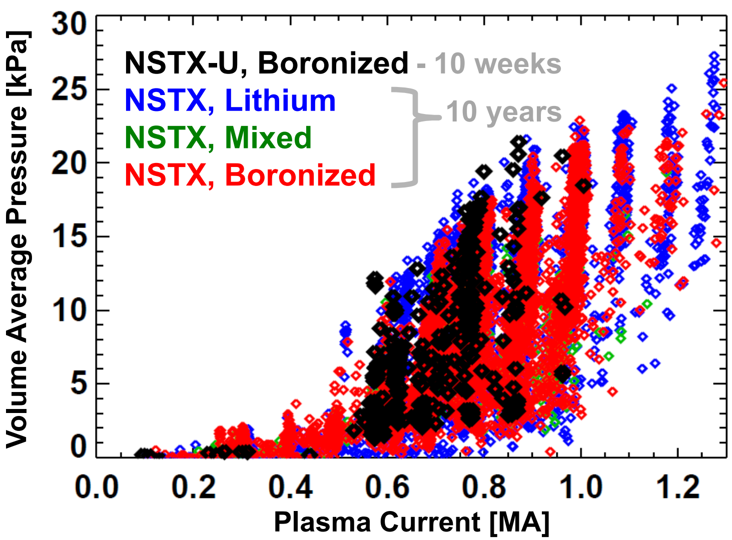


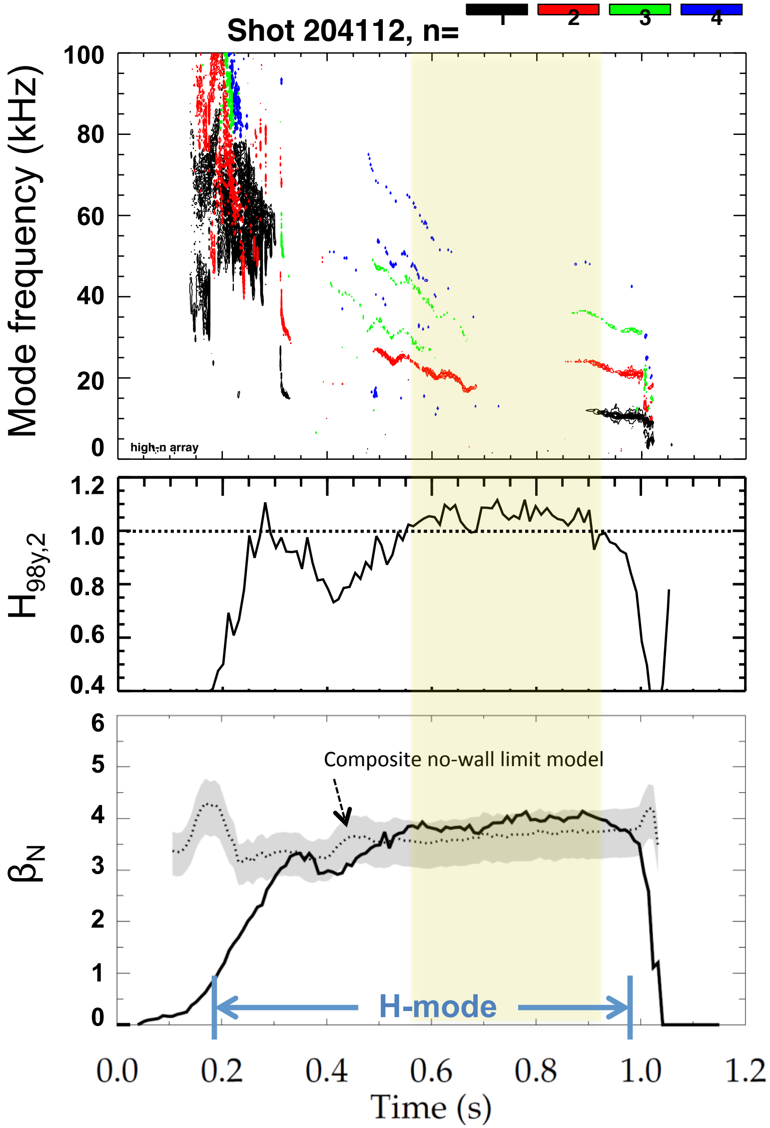
202946	Feb – no EFC
203679	March – EFC v1
202112	April – EFC v2
202118	April – EFC v2

H-mode discharges achieved target parameters for H-mode scenario

- 300ms in flattop with …
  - Regular type-I ELMs
  - H factor at or above 1
  - β_N at or above no-wall limit
  - MHD quiescent

- Matched best NSTX performance at I_p = 0.9 MA



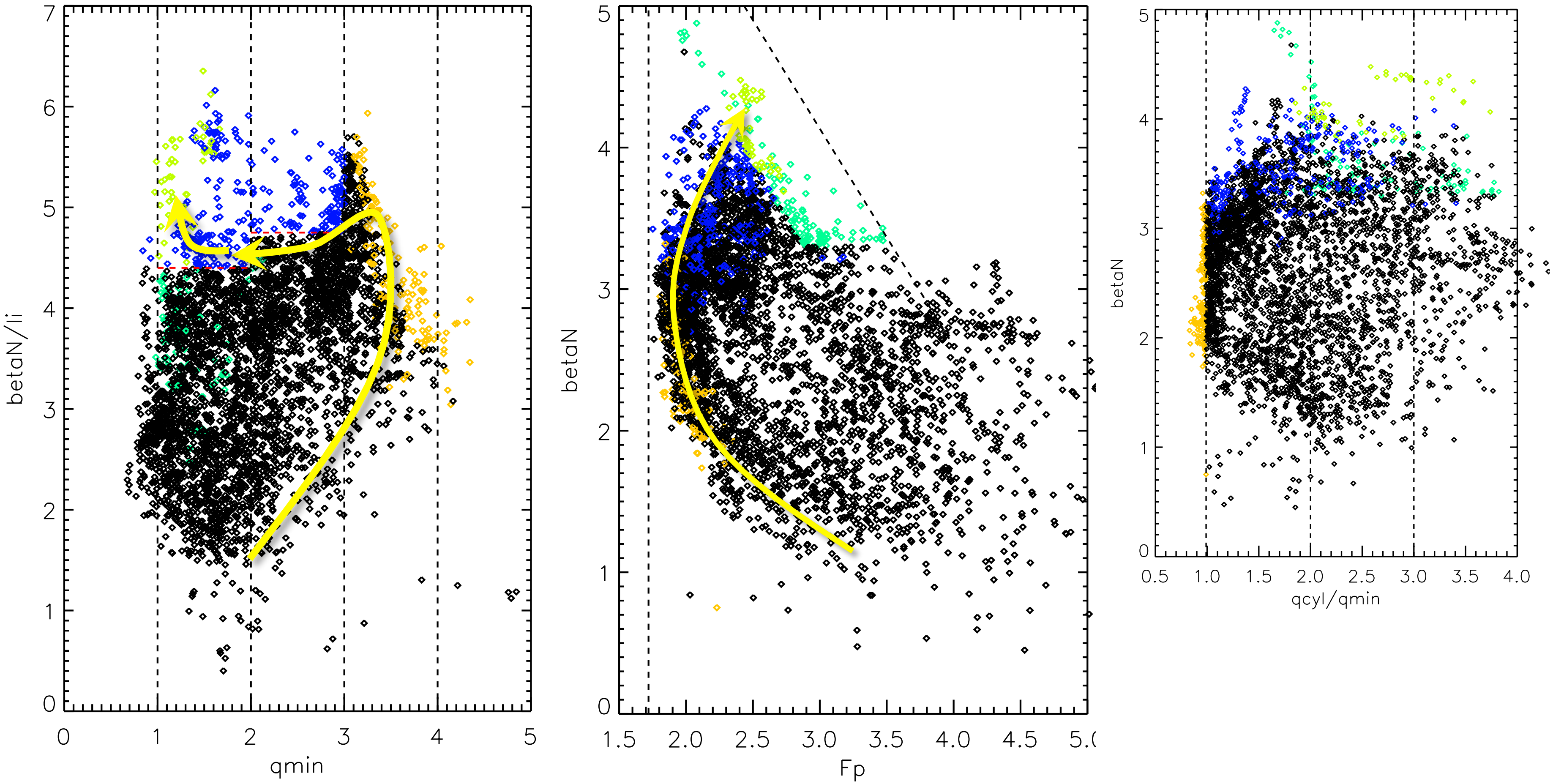


X-point and inner gap control integrated into H-mode scenario in final 3 run weeks

- ISOFLUX control of div coils enhances repeatability of scenarios and enables faster shape development
  - Gain optimization different than low-κ L-mode scenarios
  - Trouble with shot repeatability motivated control development

- H-mode performance from April never recovered
  - Was full-bottle boronization critical to achieving this scenario?
    - Transitioned to 1/4 or 1/5 bottle nightly boronizations after 4/4/16
    - Full-bottle planned for the day following the failure of PF1AU
  - Did the degradation in PF1AU impact the scenario?
    - Coil inductance change started in April and got worse toward June
  - Was the beam energy and mix important?
    - Beams were different every day, mostly going up in voltage

Ongoing analysis: Identify operational limits to guide future scenario development



See Monday Science Talk from June 9, 2016

Ongoing analysis: Examine P_{LH} for NSTX-U

- L-H transitions often occurred at the time of diverting
  - Not conducive to quantifying L-H power threshold

- Small database of discharges that transition in steady conditions following a step in power
  - Preliminary findings …
  - Power threshold is closer to the ITPA P_{LH} scaling developed for conventional-A tokamaks than NSTX
  - Similar density scaling as NSTX and other tokamaks ($n_e^{0.7-1}$)
  - Lowest P_{LH} near balanced DN like NSTX and MAST
  - No strong I_p dependence, lower P_{LH} with reduced V_{loop}
  - P_{LH} does not scale with divertor OII/D_γ ratio
    - We were using this metric to justify mini-boronizations

Summary of H-mode scenario development

- Steady progress in H-mode scenario development during ten weeks of operations
  - Achieved target conditions (H ≥ 1, $\beta_N/\beta_{no\text{-}wall} \geq 1$) and matched best NSTX performance at I_p = 0.9 MA in first six weeks
    - Did not push κ at $l_i < 0.8$ … room to grow
  - Final three run weeks integrated advanced control tools into scenario, but struggled to recover best performance
    - Better bake of inboard divertor, new PF1A coils will help next run

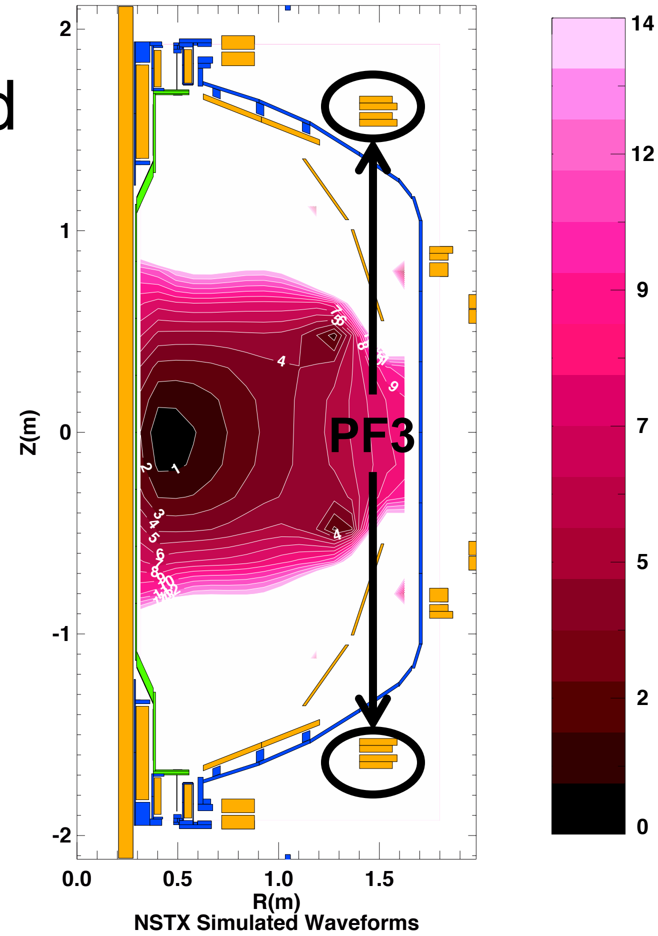
- Progress was driven by improvements in error field correction, plasma control and NBI heating
  - Also, incredible dependability of magnetics, EFIT, MPTS, cameras and filterscopes from day 1
    - And CHERS system when we actually gave Ron the beams he wanted

Backup

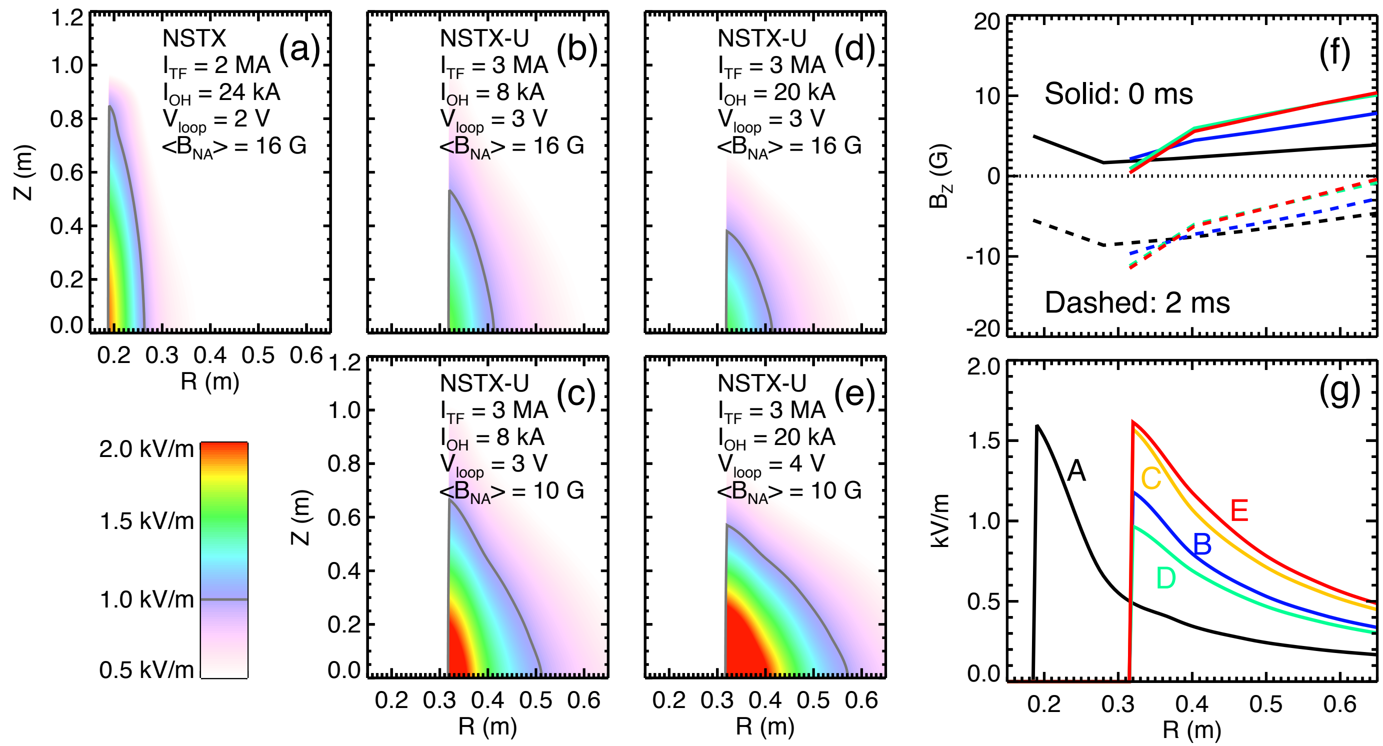
“Startup” is the first 20ms of discharge, producing I_p ~ 150 kA

- Solenoid pre-charged
  - Produces fringe field in vessel
- PF3U and PF3L used to null solenoid fringe field at t = 0
- Vessel pressure ~ 2 x 10^{-5} Torr
- I_{OH} and I_{PF3} ramp to provide V_{loop}
  - Drives breakdown and I_p
  - Induces ~200 kA toroidal eddy currents
- PF3 and PF5 provide equilibrium B_Z following breakdown
  - Need passive radial and vertical stability

Simulated B_p fields at breakdown



LRDFIT calculations provide guidance on I_{OH}, I_{PF3}, I_{PF5} current waveforms in first 20ms



Vertical field evolution

Breakdown metric

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

- I_{OH} and I_{PF3} ramp to provide V_{loop} and field null at t = 0
- I_{PF3} and I_{PF5} provide R and Z position and stability

Putting power on new divertor surfaces requires some “clean up” time