NSTX-U

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

R17-5 Q3 Review: Analysis and modeling of current ramp-up dynamics on NSTX and NSTX-U

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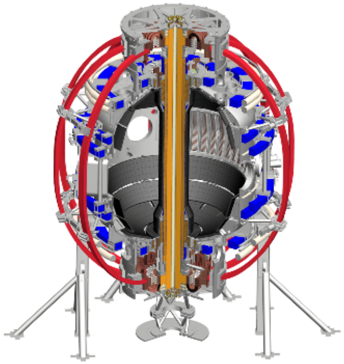
on behalf of the ASC TSG

FY2017 Q3 Research Milestone Status
May 25, 2017

PPPL



R(17-5): Analysis & modeling of current ramp-up dynamics

- Evaluate elongation limits during ramp-up phase using data and calculations
  - What factors limit the elongation before, during and after diverting?
  - Identify growth rate of vertical instability to predict controllability of high-κ shapes
- Establish the dependence of the L-H transition on density, plasma shape, etc. to inform modeling of threshold criteria and scenario targets
- Perform stability analysis of experimental and modeled discharges to identify MHD limits during ramp-up
- Prepare for R18-6: establish TOKSYS framework for testing and optimizing control
- Prepare for R18-6: begin TRANSP analysis of ramp-up phase

Action items from March 31rst meeting

- Carry out TRANSP simulations of early-H-mode ramp-ups, then play with H-mode timing, heating, etc. to begin to understand and predict ramp-up evolution - try to get initial simulations during next few months.
  - Simulation of NSTX ramp up is underway to test / refine TRANSP assumptions and models.
  - This work not explicitly mentioned in FY17 milestone, will produce great results for FY18.
- Complete engineering model of NSTX-U power-supplies to characterize controllability and control power requirements for vertical control of 2MA shots
  - Simulink model of switching power supplies is progressing
  - Comparison to more comprehensive power supply models should occur in the near future

Plans for FY17 Q3 (as stated in Q2)

- Create vertical stability probability relationship (disruptivity) from the NSTX database, compare to NSTX-U results
  - Slides follow
- Extend NSTX-U growth rate calculations to higher κ shapes
  - Defer to Q4
- Continue to investigate 'The Bobble' at time of diverting
  - Slides follow
- Identify subset of discharges where TRANSP runs would help identify P_{LH}
  - Defer to Q4
- Perform stability analysis of experimental and modeled discharges to identify MHD limits during ramp-up
  - Defer to Q4
- Continue debugging TOKSYS and incorporate GS solver (GSEVOLVE)
  - Slides follow
  - GA is supporting debugging activity

Ongoing activities studying vertical control limits in ramp-up and flat-top

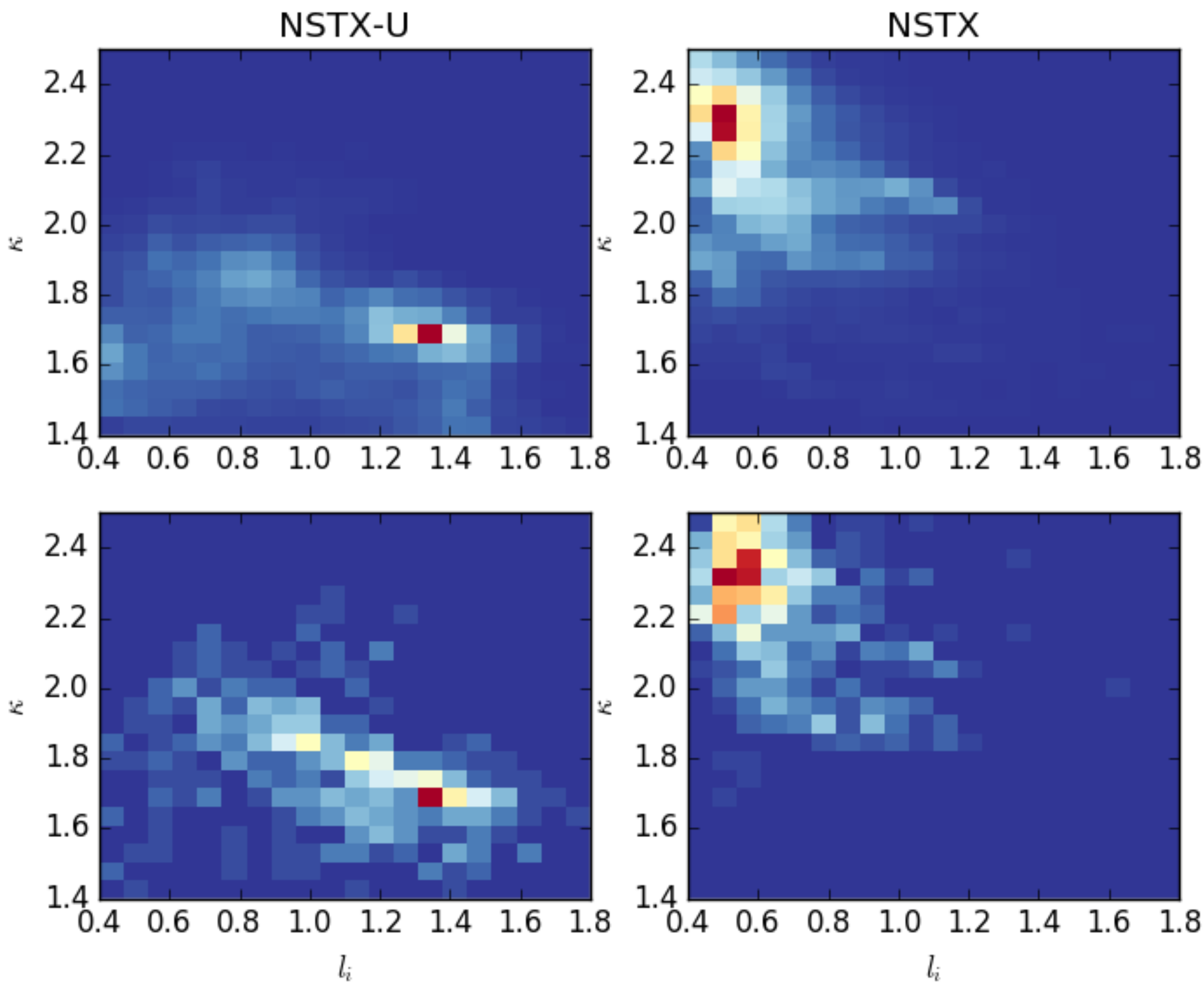
- Exploration of disruptivity and stability boundaries
  - Database of VDE times on NSTX-U and NSTX generated
  - Working on removing shots that disrupted due to other initial causes ➔ will be working with DECAF team
  - Growth rate calculations at start of VDE using ISOLVER
    - Defining empirical disruptivity in terms of growth rate should allow for extrapolating stability boundary to planned future equilibria

- Database of vertical motion at time of diverting
  - Classification of different behaviors
  - Working to identify cause and understand contributing factors to severity of undesirable behaviors, e.g., the ‘bobble’

Histograms of NSTX/NSTX-U equilibrium operating space and VDEs

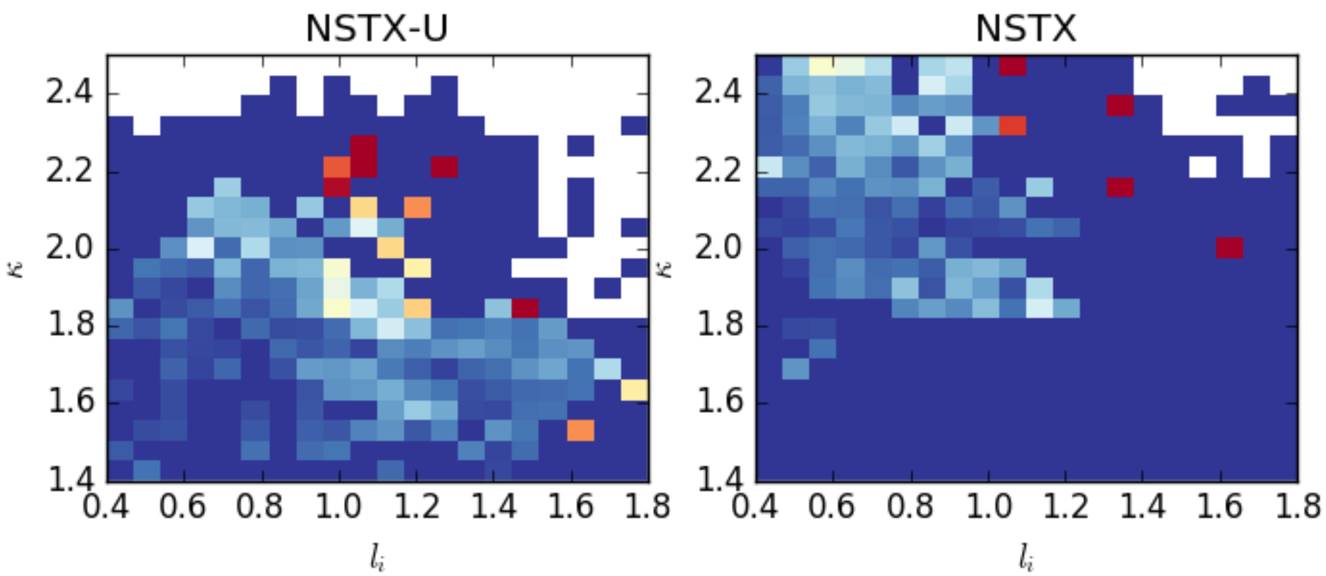
Number of EFIT01 slices:
All NSTX-U shots,
NSTX shots > 140000

Number of VDEs:
All NSTX-U shots,
NSTX shots > 140000,
Only VDEs that start in flattop phase



Database will be used to examine disruptivity of plasma scenarios

Disruptivity:
Number of VDEs/
Number of EFIT01 slices

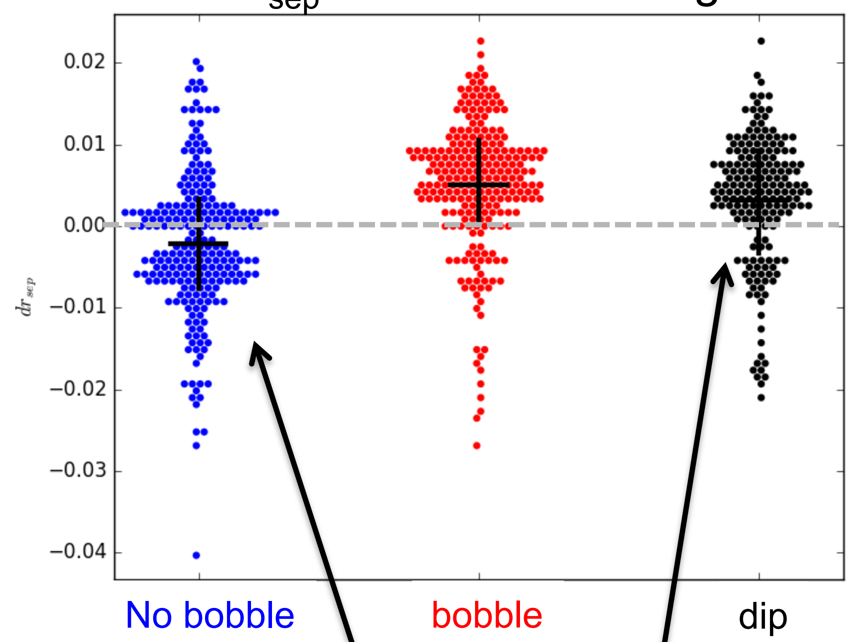


- Plans
  - Extend NSTX analysis to include all shots
  - Include additional equilibrium parameters in histograms
  - Work with DECAF team to exclude VDEs triggered by other disruptions
  - Fit disruptivity to equilibrium parameters, map to growth rate

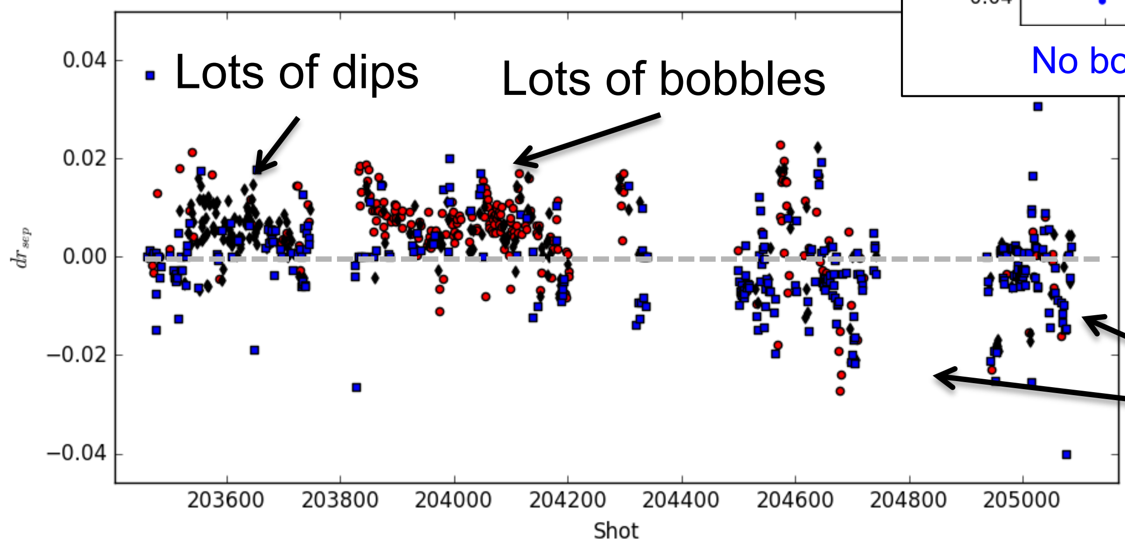
Database of oscillations around time of diverting (the 'bobble') provides insight into root cause

- Bobble appears to occur most frequently in a range of shots with positive dr_{sep} at time of diverting

dr_{sep} at time of diverting



dr_{sep} at time of diverting



Negative dr_{sep} favors no bobble or small bobble (dip)

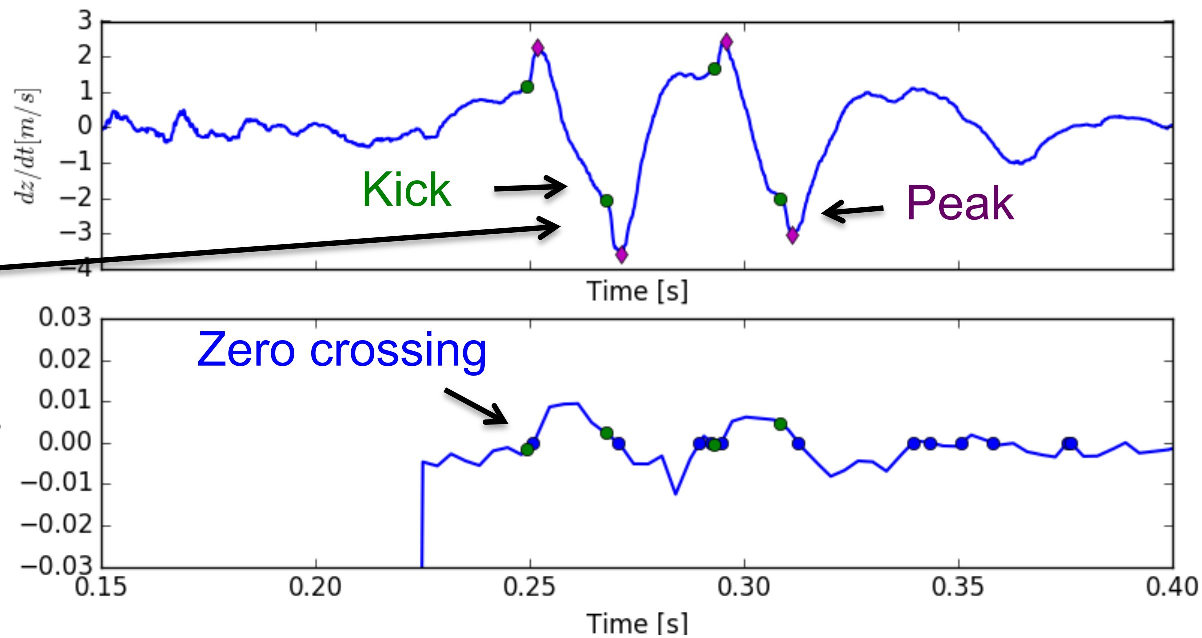
Oscillations between USN and LSN could be driven by control response

- Appears to be sustained by rapid plasma motion at time of crossing $dr_{sep}=0$
- Bobble may be initiated by shape control errors when transitioning between ISOFLUX phases
  - Efforts to improve/remove transitions seemed to help during campaign
- Plan to model transitions and the effect of dr_{sep} zero crossings in TOKSYS
  - Modify transition logic and control gains to reduce or avoid bobble

dz/dt [m/s]

Looking into what parameters determine size of kick

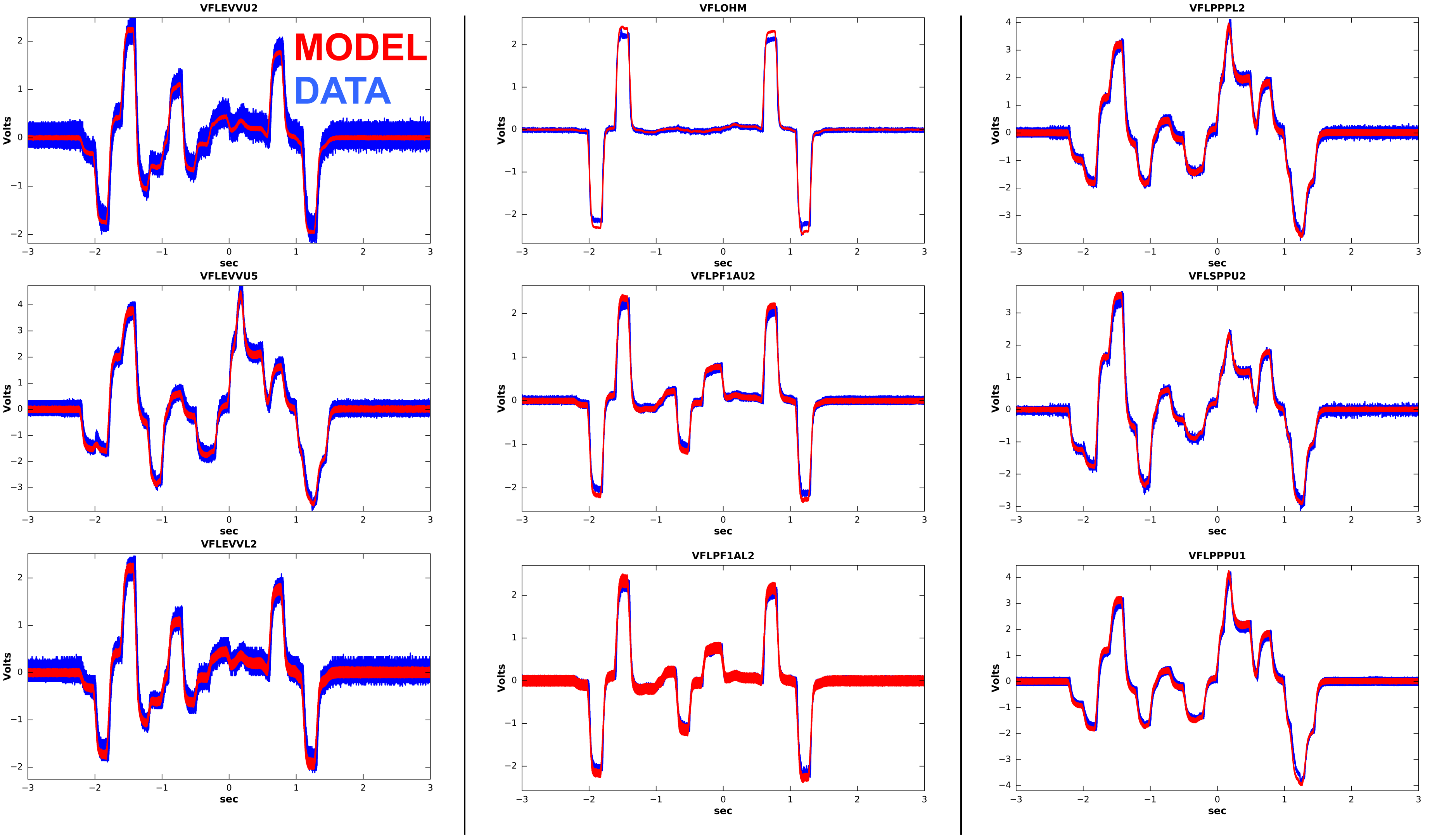
dr_{sep} [m]



Overview of TokSys framework development in Q3

- Coupled LR circuit model for coils and passive conductors (vacuum model)
  - Vacuum model fully-validated against NSTX-U coils-only shots
- Linear plasma response models developed
  - Validation in progress
- Framework developed for simulating ISOFLUX shape control and tuning controller gains
  - Nonlinear plasma simulation called GSEVOLVE in-development *(Anders Welander, General Atomics)*
- Simulink-to-PCS link demonstrated (Simserver)

Vacuum model and synthetic magnetic signals in good agreement with NSTX-U data



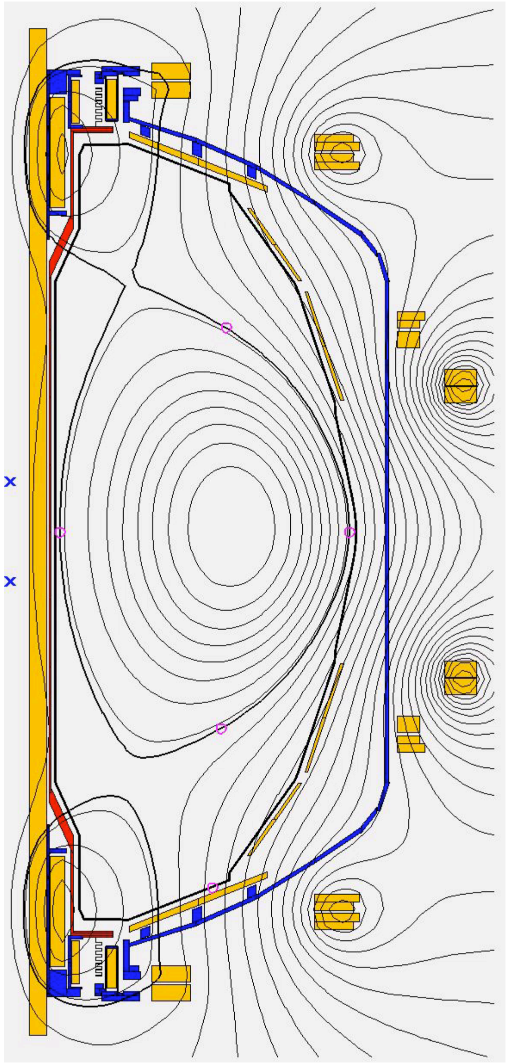
Vacuum vessel *Centerstack* *Passive plates*

Linear plasma response model has been developed and applied to shape control testing

- Linear simulation tool has been developed in Simulink for control design
  - Validated vacuum model
  - Plasma response linearized around an equilibrium

- Tool has been used for testing several algorithms
  - ISOFLUX shape control
    - Tuning of PID gains for ISOFLUX segment errors
    - Strike point control demo (right)
  - Snowflake control

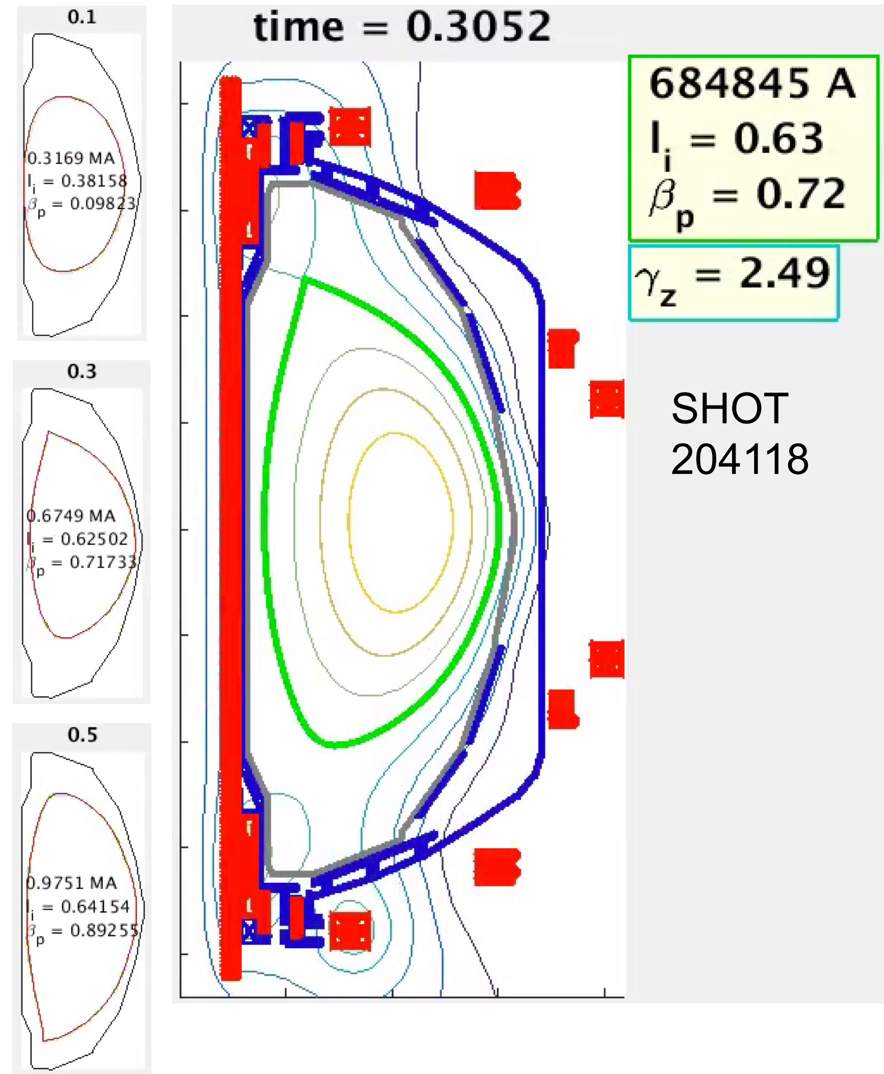
- Simulation tool can be used for development and optimization of shape control algorithms
  - MIMO shape control
  - Advanced divertor control
  - …



Nonlinear plasma simulation GSEVOLVE is under development

A. Welander

- Implemented in Simulink
- Simulink module which solves the Grad-Shafranov equation
  - Inputs: PF coil power supply voltages, model for heating and current drive
  - Outputs: PF coil currents, magnetic diagnostic signals
- Capable of simulating an entire NSTX-U discharge
  - shot 204118 (right)
- Enables test of control algorithms in dynamic phases, such as ramp-up



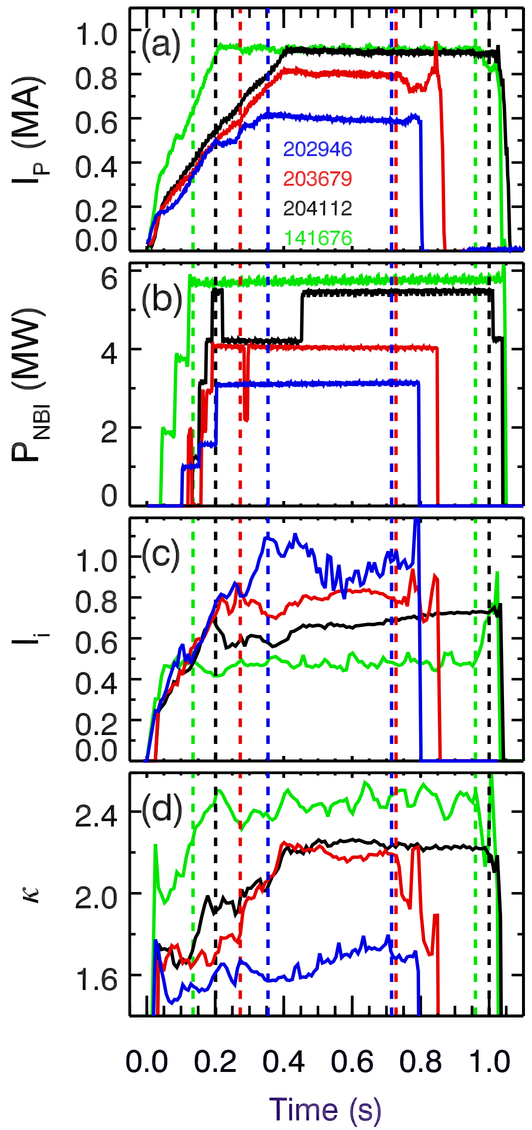
Plans for Q4

- Extend NSTX-U growth rate calculations to higher κ shapes
- Perform TRANSP runs that would help identify P_{LH} scaling with plasma parameters
- Perform stability analysis of experimental and modeled discharges to identify MHD limits during ramp-up
- Refine disruptivity analysis by examining dependence with other plasma parameters

Backup

H-mode flattop performance depends on the I_p ramp-up

- **NSTX fiducial** had L-H transition before 150ms
  - $l_i \sim 0.5$, $\kappa \sim 2.4$ with P_{NBI} = 5.8 MW
- NSTX-U: progress in obtaining early L-H transition, higher I_p and κ
  - **202946 → 203679 → 204112**
  - Enabled by increase in P_{NBI}, improvements in shape control, EFC
- Access to higher I_p (> 1.6 MA) and κ (> 2.4) requires further ramp-up development during next run

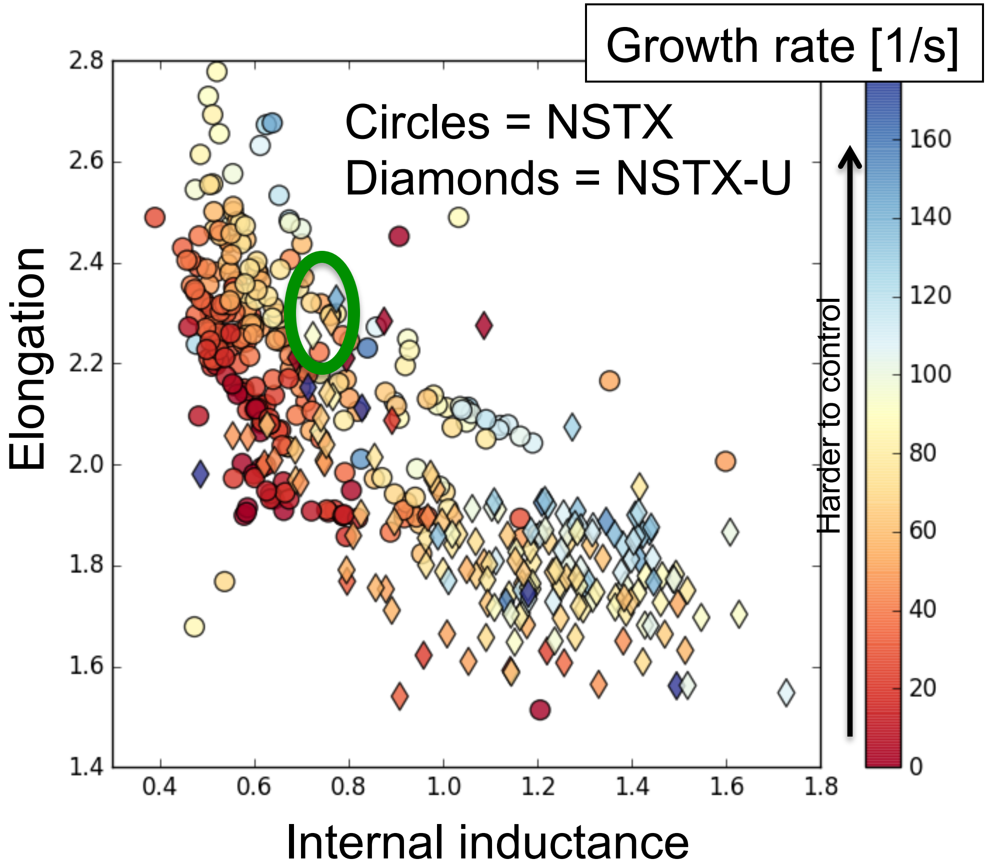


Growth rate calculations will allow projection of NSTX-U limits to lower l_i

- Calculations within ISOLVER quantify open loop vertical growth rate [Menard]
  – Evaluate growth rate just prior to VDE time

- Maximum growth rates for NSTX-U and NSTX are similar
  – Good! Suggests we can do as well as NSTX at low l_i

- Many 'VDEs' occur below limit ~ 140 1/s
  – Probably have different triggers, e.g., locked modes
  – Will refine filtering of VDE database (DECAF)



Database of L-H transitions and corresponding L-mode shots

- Identify important dependences of L-H transition power threshold to guide modeling and experiments

- Most shots are very dynamic around L-H transition
  - Transitioning from limited to diverted
  - Large dI_p/dt and dW/dt during ramp-up
    - $P_{LH} = \xi P_{NBI} + P_{OH} - dW/dt$
  - Many shape parameters (gapin, d_{rsep}) not stationary

- Created a database of L-H and L-mode times
  - NBI efficiency presently computed using simple model benchmarked against BEAST data for all L-mode times
    - Will need to run TRANSP runs for subset of interest to really quantify P_{LH}
  - Most useful result (so far) has been identifying range in parameters that preferentially excludes L-mode dataset

Dataset confirms experimental observation that d_{rsep} and V_{surf} influence P_{LH}

- Dataset of 68 L-H times and 101 L-mode times
  - L-H in a limited shape are excluded

- If the dataset is restricted by …
  - $n_e > 1.2 \times 10^{19}$ m^{-3}
  - $0.7 < V_{surf} < 1.2$
    - Minimum P_{LH} near V_{surf} = 0.95 V
    - Surprising to see P_{LH} increase below V_{surf} = 1V
  - $-0.4 < d_{rsep} < 0.8$
    - L-H seemed to favor USN ?
    - Minimum P_{LH} near d_{rsep} = +0.2

- 5 L-mode (5%) and 43 (63%) L-H times remain in constrained dataset
  - Most of L-H times removed had $P_{LH} > 3 \times$ minimum P_{LH}