NSTX-U

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Analysis of vertical stability limits and vertical displacement event behavior on NSTX-U

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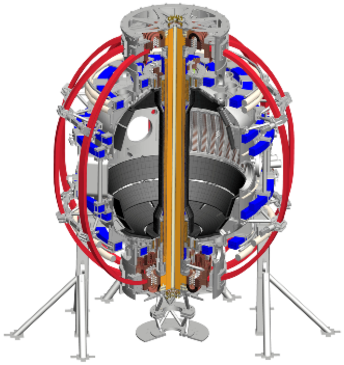
PPPL



Overview

- Optimization of vertical control on NSTX-U is critical to achieving high performance
  - High elongation improves beta limits, increases bootstrap current
  - Oscillation-free control improves confinement and diagnostic quality
  - NSTX-U operates at increased aspect ratio
- Improvements to the control system were made for the last campaign
  - Was able to realize elongation vs. l_i operating space similar to NSTX but at higher aspect ratio
  - Shots typically evolved to high l_i, limiting achievable elongation
- To study control limits, a database of VDEs and vertical oscillations on NSTX and NSTX-U was generated
  - Specific attention paid to oscillations in ramp-up phase
- Results provide guidance for future work:
  - Ramp-up optimization
  - Scenario development
  - Control system improvements

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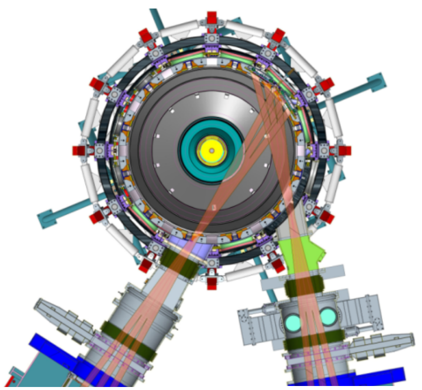
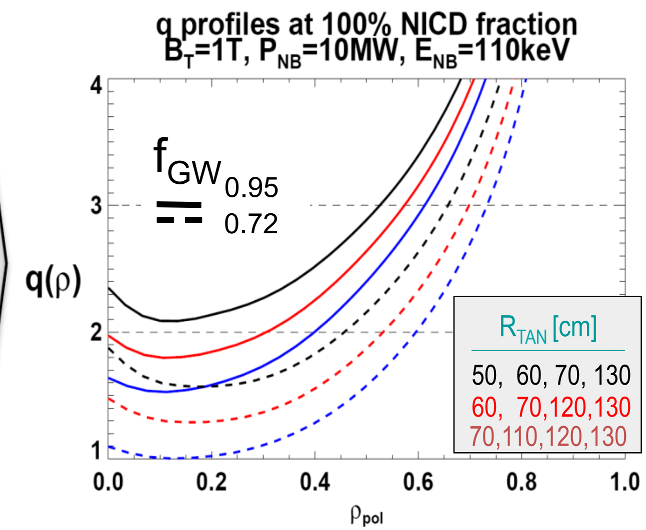
NSTX-U improves controllability and brings about new control requirements

- **New opportunities** to use feedback control to optimize performance as a result of:
  - Longer pulse length, increased toroidal field, increased heating and current drive
- **Advanced control** will be **necessary** for achieving many operational goals, e.g.,
  - Non-inductive scenarios, snowflake divertor, rotation control, current profile control

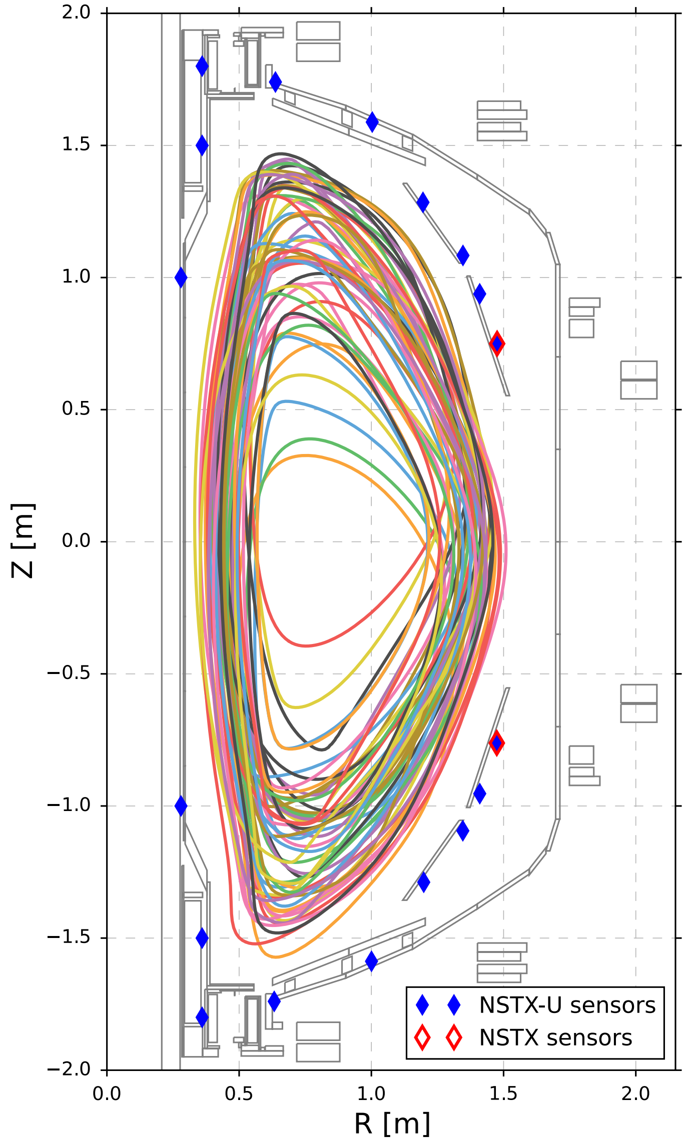


Present NBI New 2^{nd} NBI

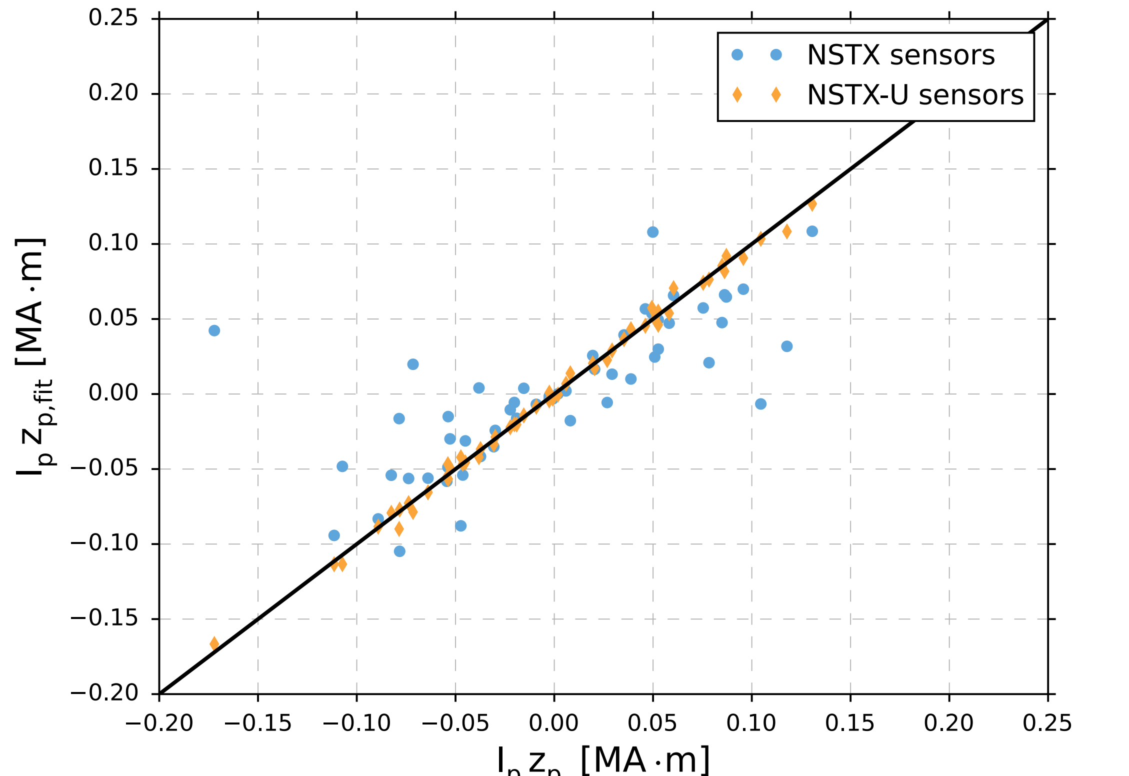
- ➢ 2x higher CD efficiency from larger tangency radius R_{TAN}
- ➢ 100% non-inductive CD with core q(r) profile controllable by:
  - NBI tangency radius
  - Plasma density, position



Additional voltage differences improve estimation of vertical position

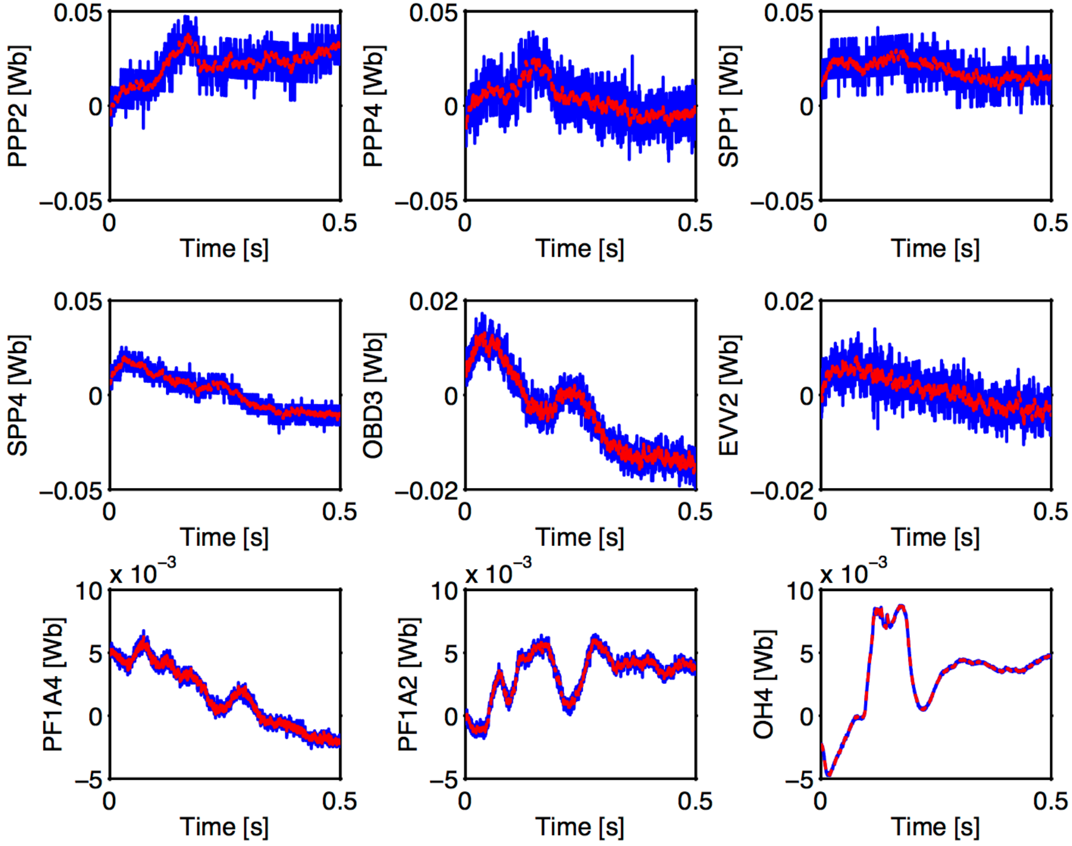


- ~60 NSTX-U equilibria generated with ISOLVER free boundary code
- Flux loop weights determined by least squares fit to IpZp
- Optimal weights will be established based on EFIT reconstructions of experimental discharges

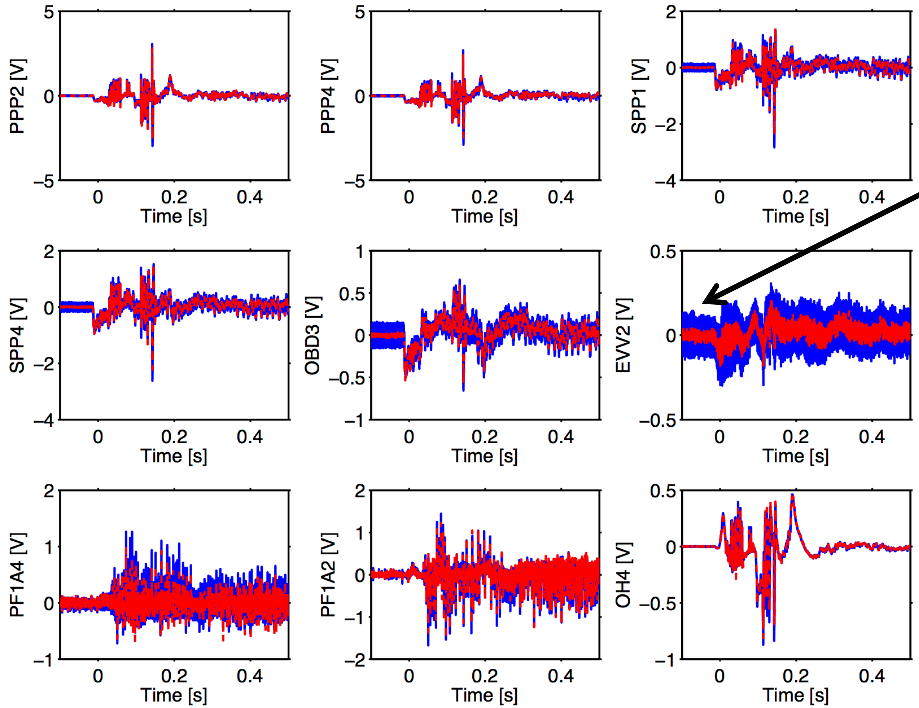


Kalman filtering used to improve noisy, low signal-to-noise flux differences

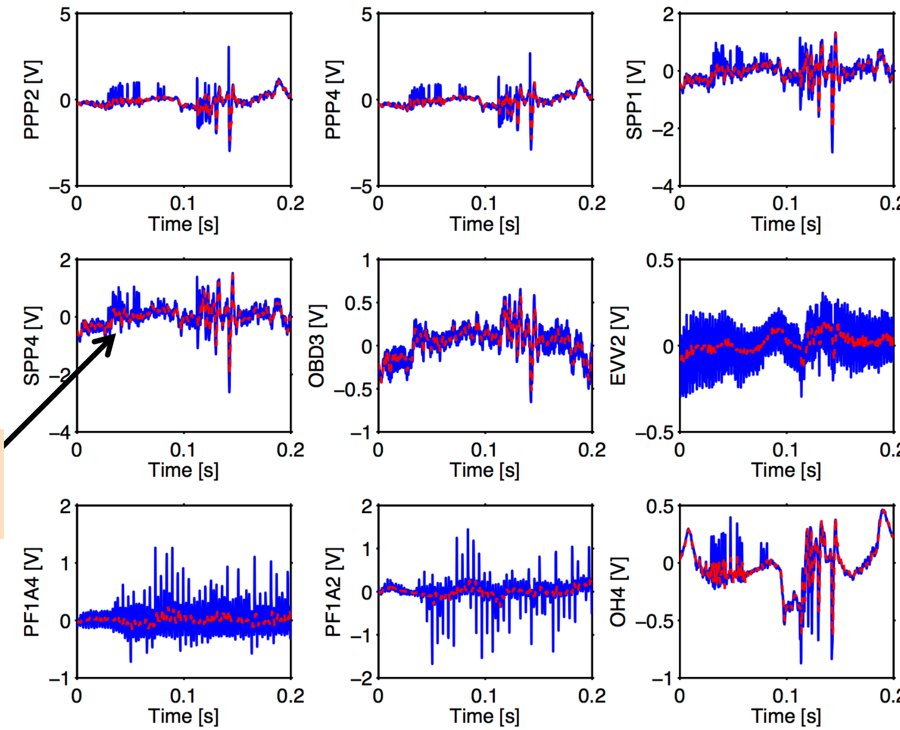
- Voltage differences are hardware differenced, but flux loops are differenced in software
- For small plasma motion, the differences are near the digitizer resolution
- Could integrate voltages digitally in PCS, but would miss fast transients
- Kalman filter weights integrated voltages and noisy measurements to obtain a smoothed estimate of the flux difference



Notch and median filtering added to remove power supply ripple and MHD events

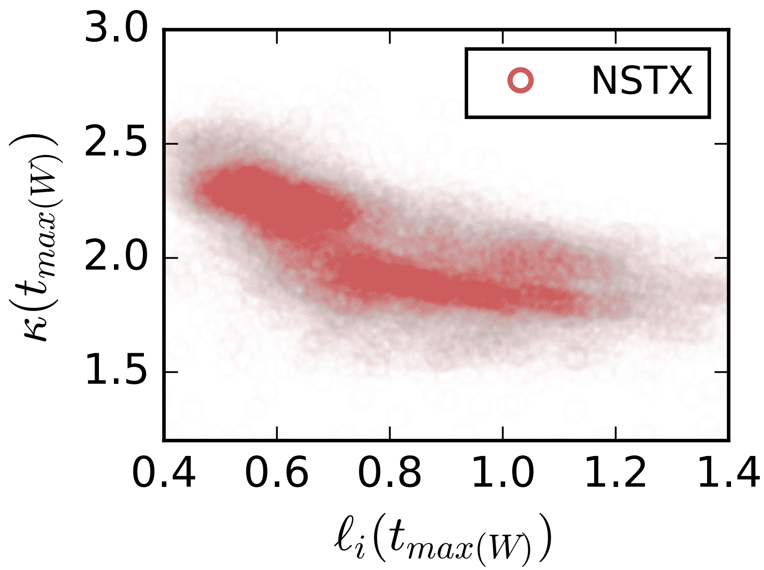


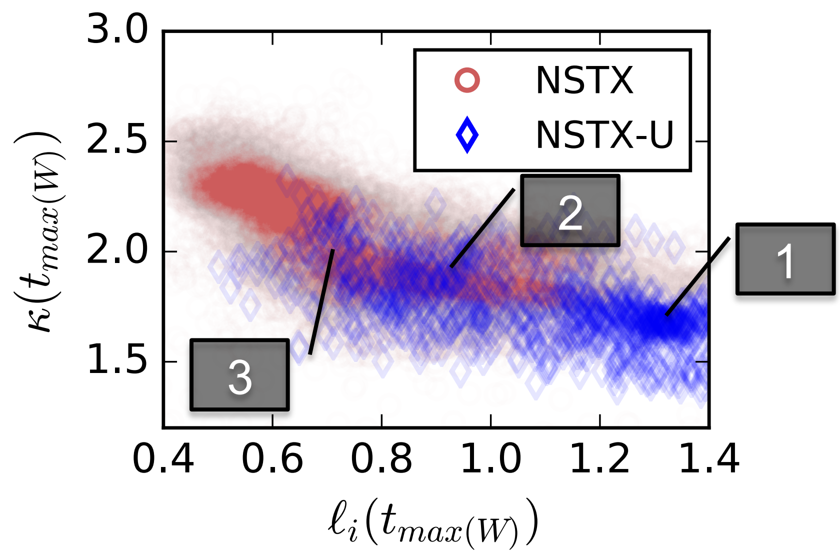
Notch at ~360Hz and ~720Hz removes power supply ripple and harmonic



Median filter removes noise spikes on sensors caused by MHD events during ramp-up

At time of maximum stored energy, NSTX-U operated in elongation vs. li space similar to NSTX

- Database of achieved elongation at time of maximum stored energy
- 



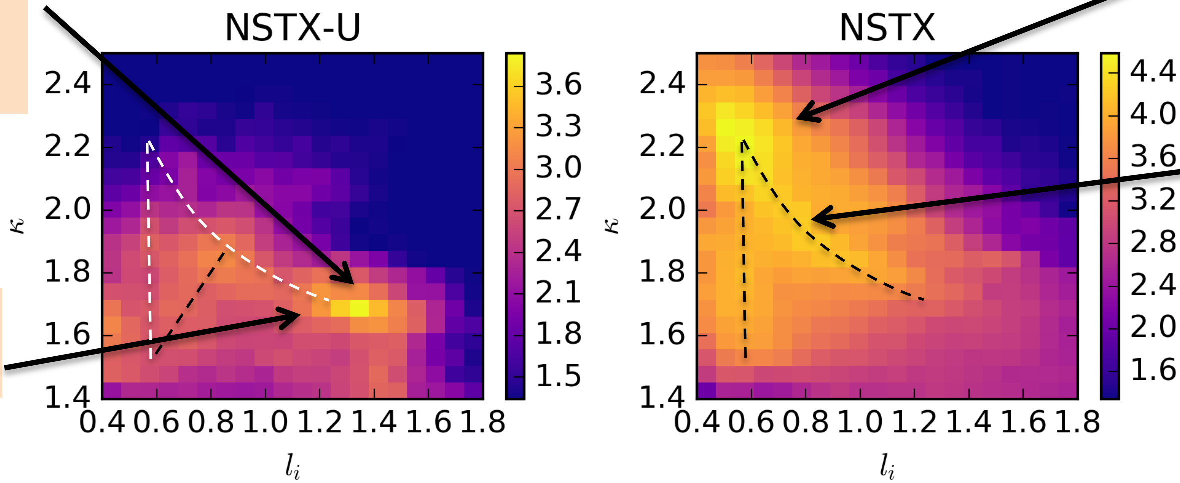
1. Extended NSTX trends to higher internal inductance
2. Similar elongation at mid-range internal inductance
3. Occasionally reached higher elongation, low li space

Comparing all EFIT01 slices for NSTX and NSTX-U: operated along similar paths, but NSTX achieved high elongation early

Log scale histogram of all EFIT01 slices

High-l_i L-mode fiducial used in commissioning

Typical NSTX low-l_i H-mode

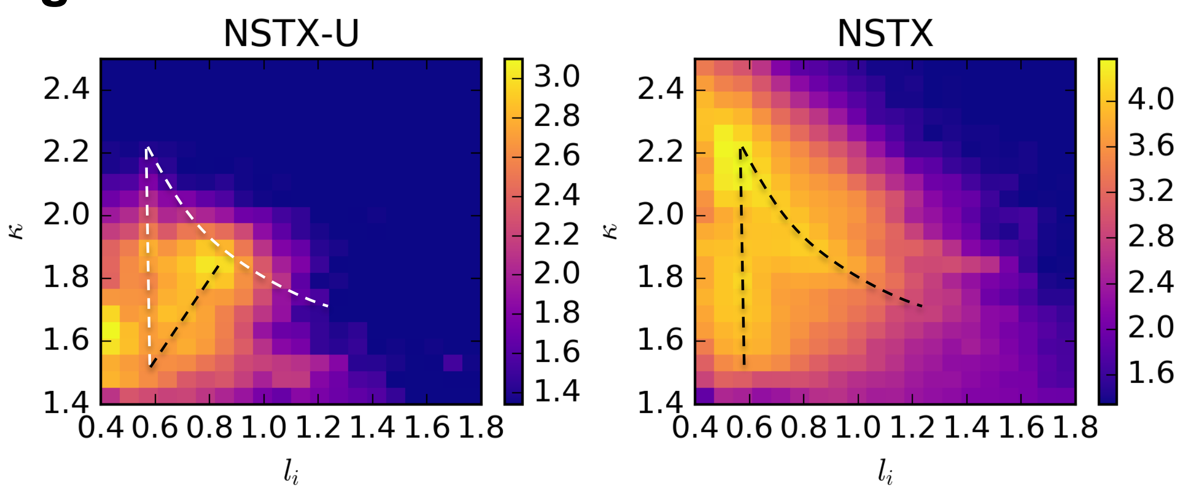


Continued NSTX trend at higher l_i

Most frequent NSTX operation along these lines

Log scale histogram of all EFIT01 slices for t<0.3s

NSTX-U typically had low l_i early, but low elongation

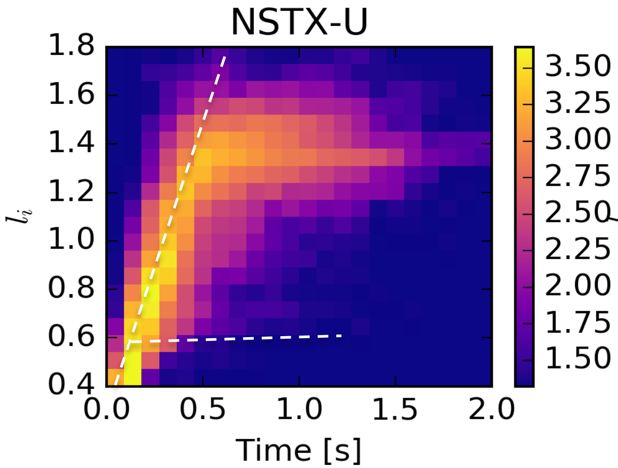


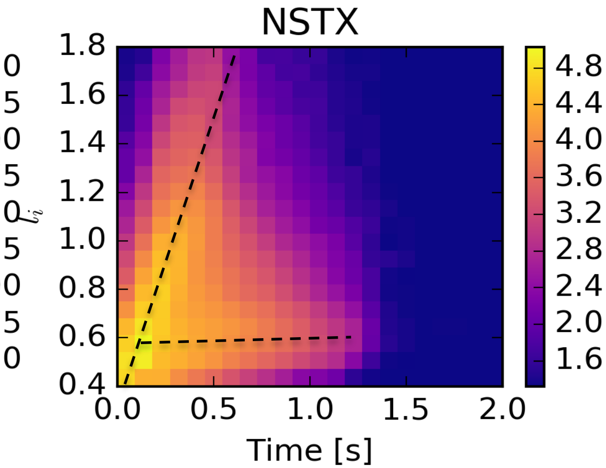
NSTX reached final elongation and l_i early on

Longest NSTX H-mode shots occurred at low li and high elongation; NSTX-U exceeded these shots in L-mode despite operating at high li, low elongation

Log scale histogram of l_i vs. time for all EFIT01 slices

NSTX-U achieved pulse lengths far exceeding NSTX even at high l_i





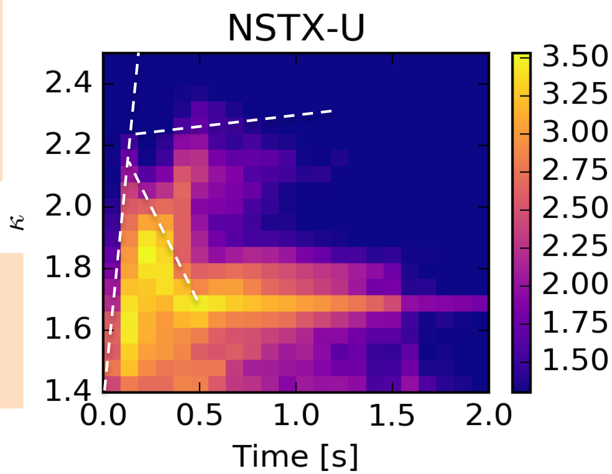
l_i ramp rate in L-mode is similar for NSTX-U and NSTX

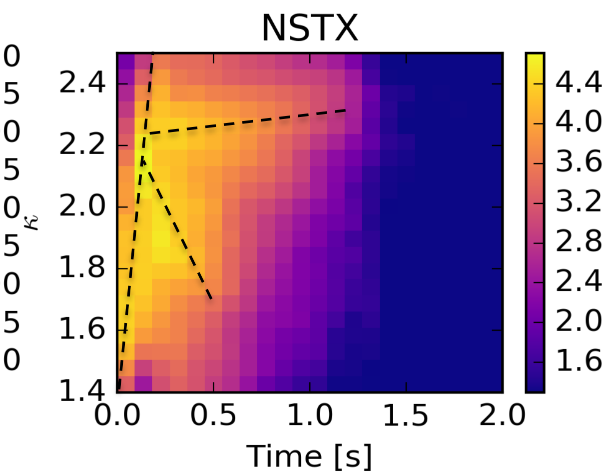
Longest NSTX pulse lengths occur at low l_i, maintained by higher H-mode temperature

Log scale histogram of elongation vs. time for all EFIT01 slices

NSTX-U elongation low early, ramped toward target

κ reduced in L-mode for vertical stability at high l_i

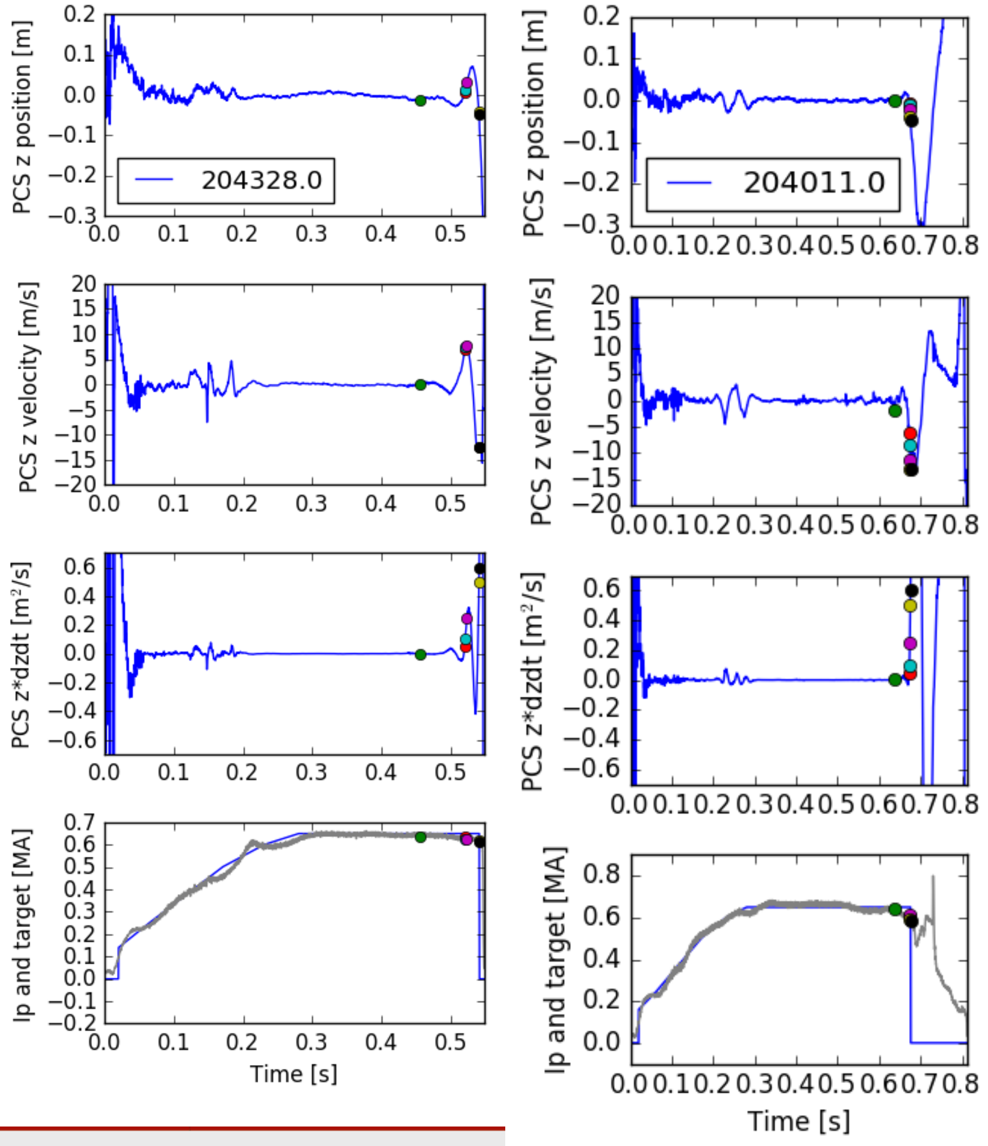




NSTX reached high elongation early, then three common trajectories

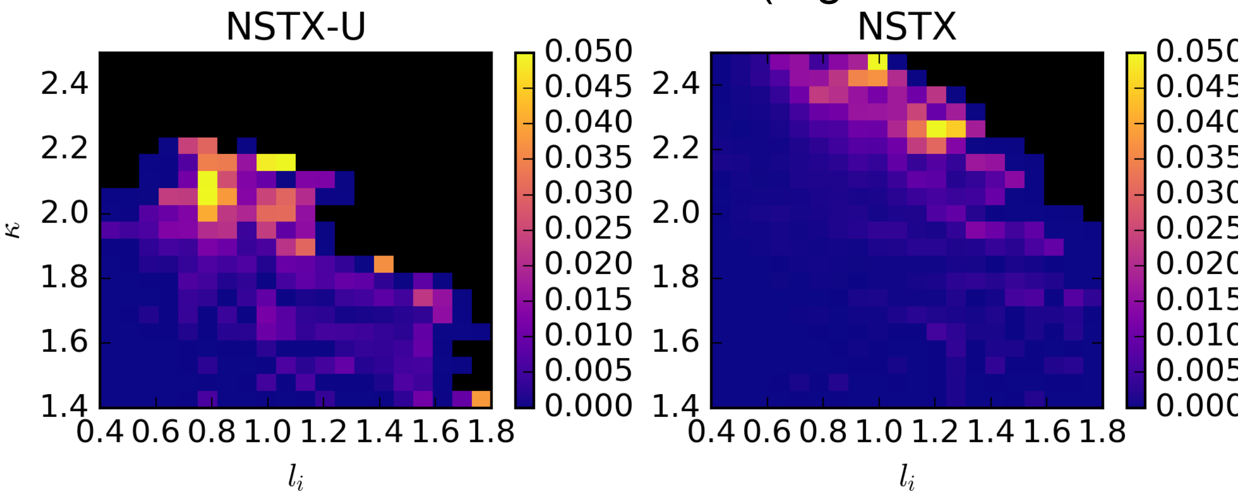
Database of VDE times generated to assess limits and triggers for VDEs

- Shots analyzed for times of vertical excursions and recovery
  - Last excursion without a recovery is flagged
  - Times that vertical motion exceeds thresholds are flagged
  - Also detects spikes in plasma current that occur during VDE to help distinguish between 'pure VDEs' and other disruptions



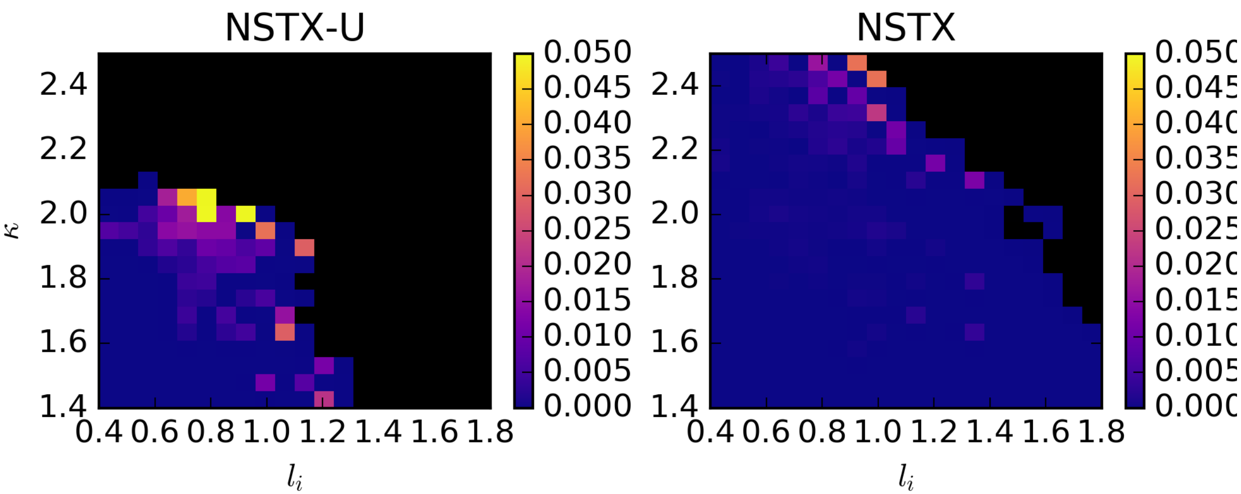
Probability of VDE higher at lower elongation for NSTX-U

#VDEs/#slices for all EFIT01 slices (regions with <30 slices colored black)



- Highest VDE probability along a line in κ vs. l_i space for NSTX
- High probability of VDEs in ramp-up for NSTX-U
    - More on this later…

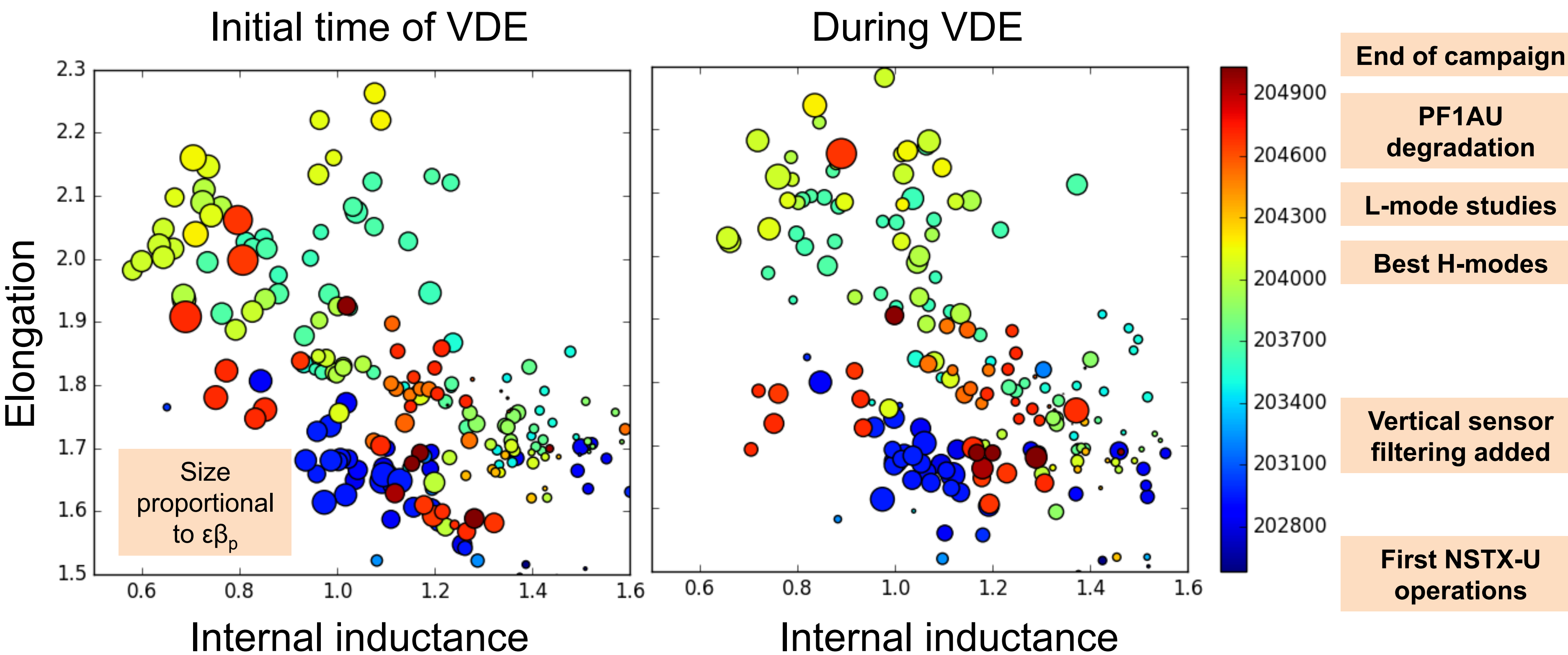
#VDEs/#slices for all EFIT01 slices for t<0.3s (regions with <30 slices colored black)



Caveats:

- Much smaller data set for NSTX-U
- NSTX-U shots dominated by
    - control commissioning,
    - error field identification experiments,
    - ramp-up optimization experiments

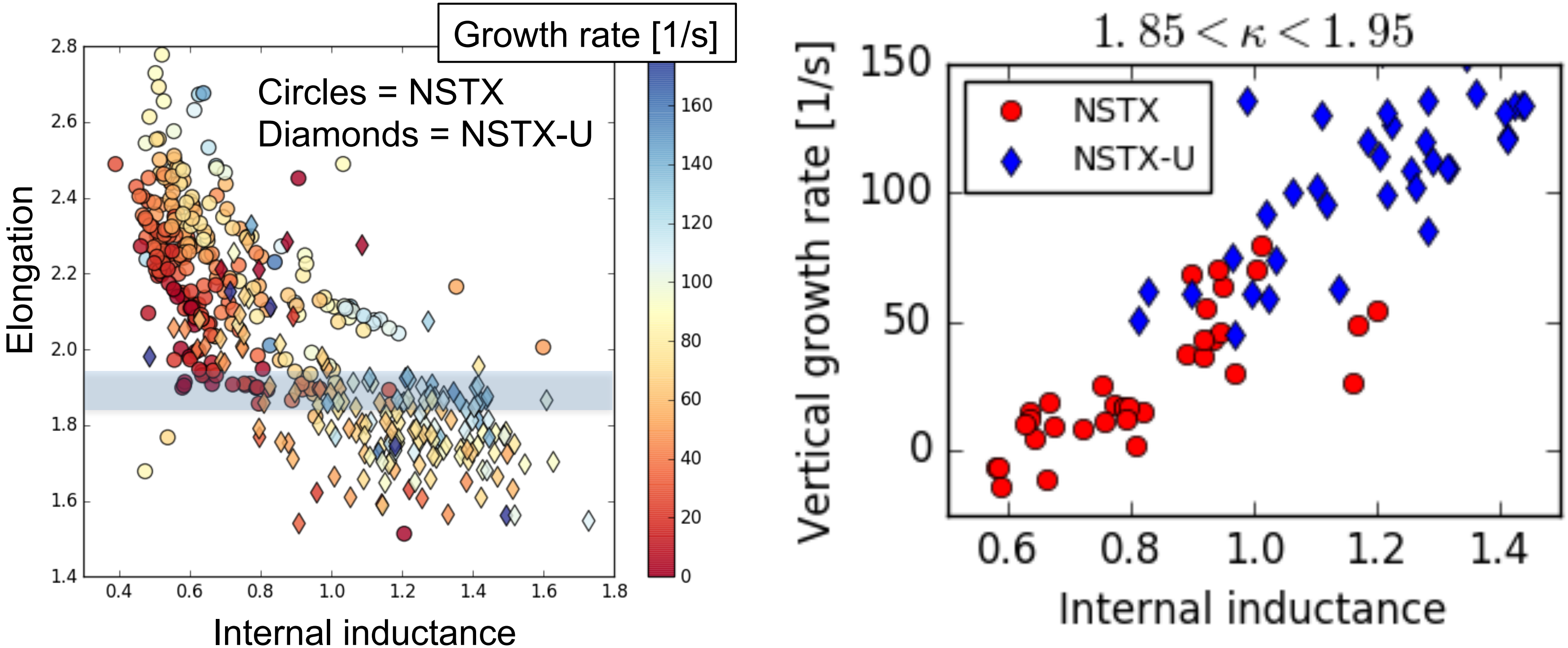
Elongation vs. l_i at the time of VDEs for NSTX-U illustrates increase in VDE limit as campaign progressed



- High elongation shots typically seem to move toward higher l_i during VDE
  - Likely caused by H-L back transition
  - Results in increased growth rate, challenging control

Growth rate calculations will guide projection of limits to planned scenarios

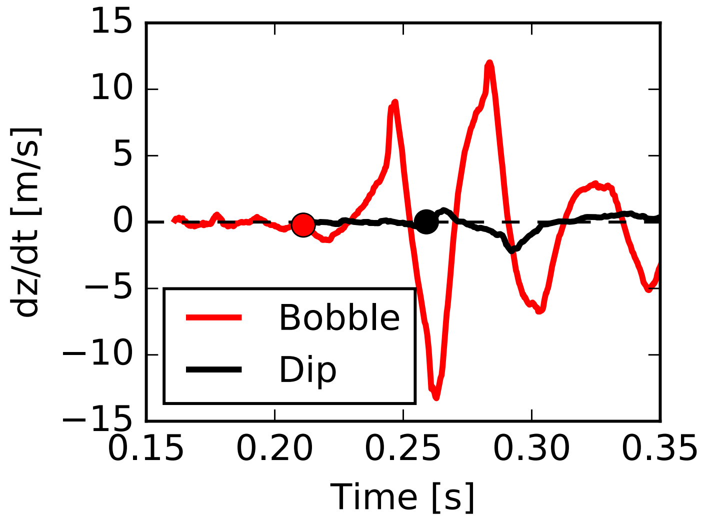
- Using ISOLVER to calculate open loop vertical growth rate [Menard]
- Calculations done at a time just before each VDE in the database



- Maximum growth rates for NSTX-U and NSTX similar, maybe slightly higher for NSTX-U
- Many ‘VDEs’ occur below the limit for both devices
  - some at very low growth rate

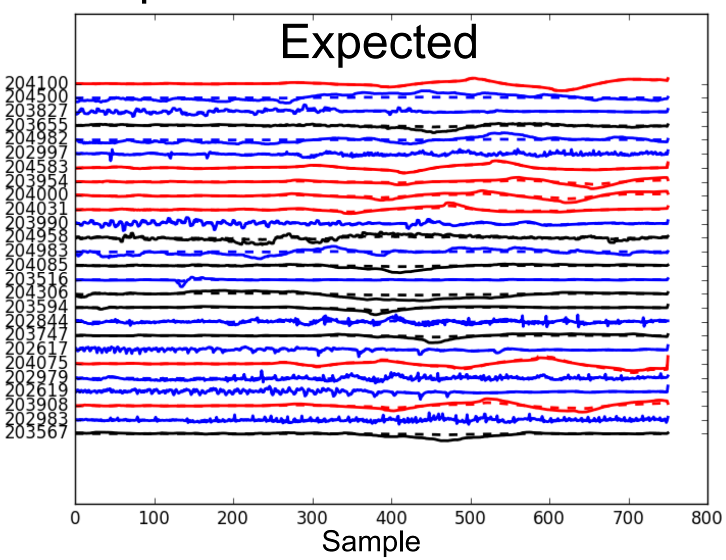
Database of vertical motion at time of diverting, used to classify of behavior

- Clustering used to look for typical behaviors at time of diverting
- Two main classes of oscillations ➔

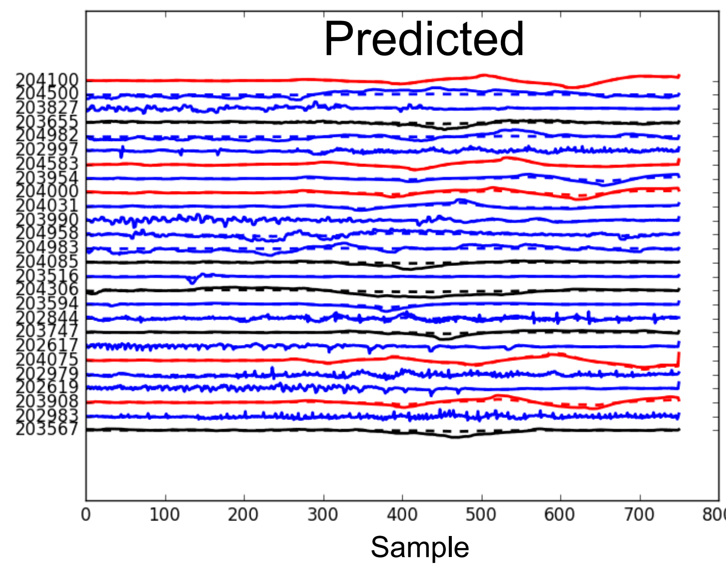


- Machine learning to automatically classify entire run into ‘bobbles’, ‘dips’ or other behaviors
- Used to explore parameter regimes and root causes

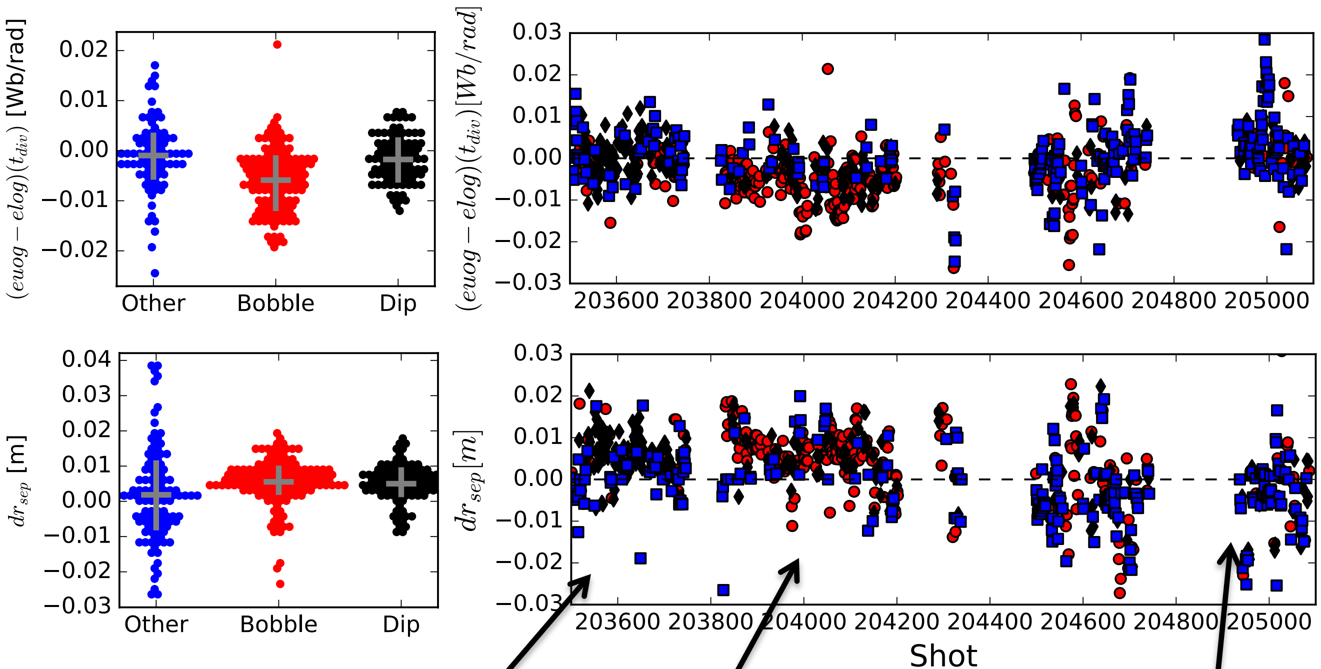
Classifier performance on validation data set:



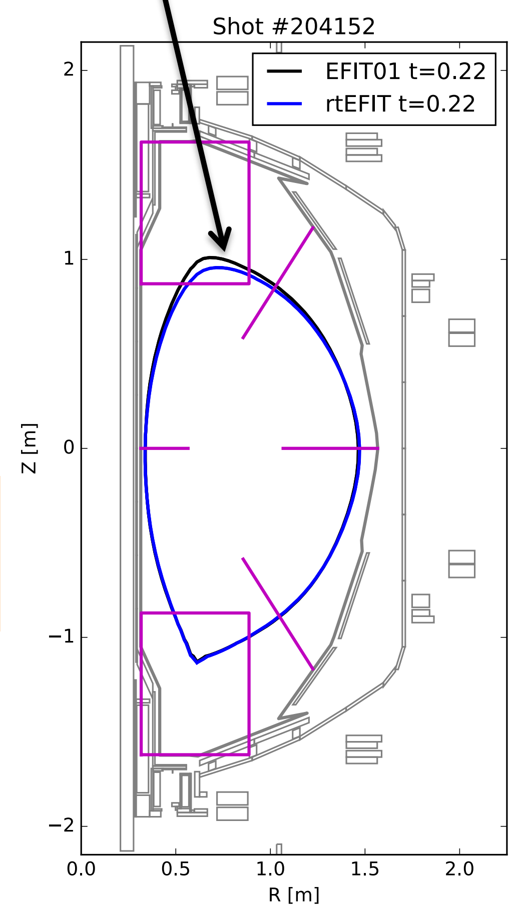
Bobble
Dip
Other



Shots with large oscillations typically had positive drsep and up-down asymmetry in shape control errors



Comparison of rtEFIT and EFIT01 boundary at time of diverting

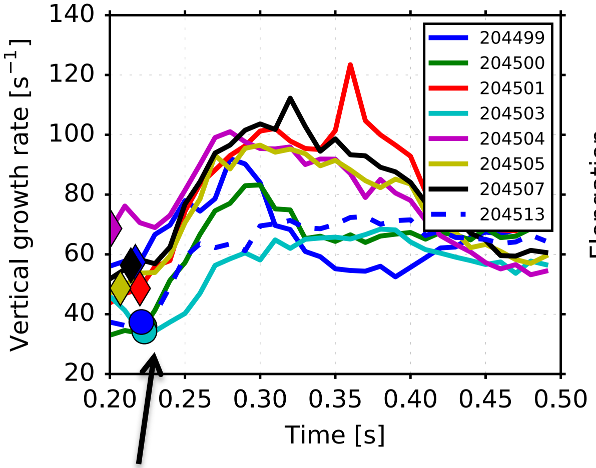


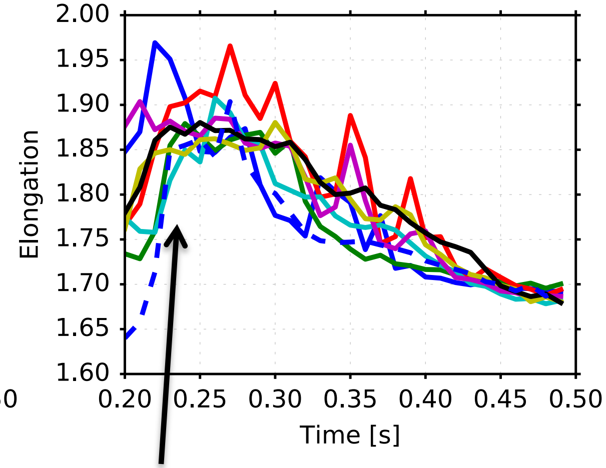
Small error asymmetry but positive drsep early – more dips

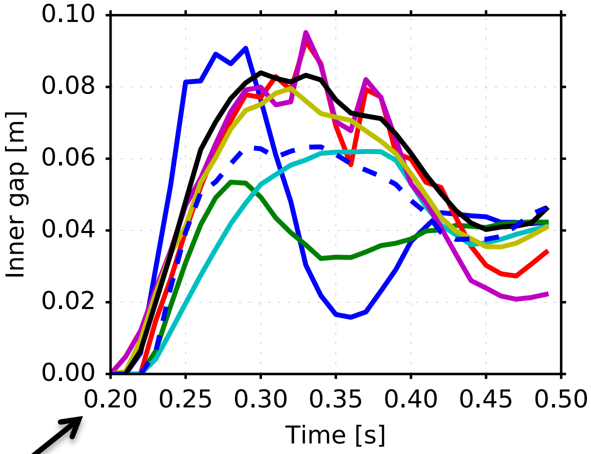
Smaller error, lower drsep decreased likelihood of bobbles

Bobbles most frequent during phase of campaign when both criteria were met

Vertical growth rate typically increased rapidly at time of diverting due to rapid increase in inner gap size



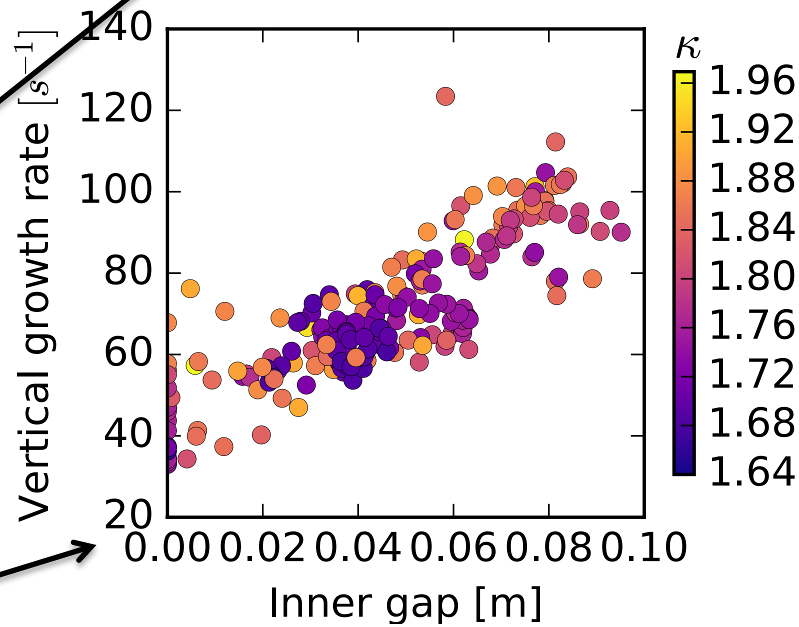




Time of diverting indicated by diamonds for shots with oscillations, circles for shots without.

Elongation is increasing at time of diverting

Inner gap increased quickly to ensure plasma diverted

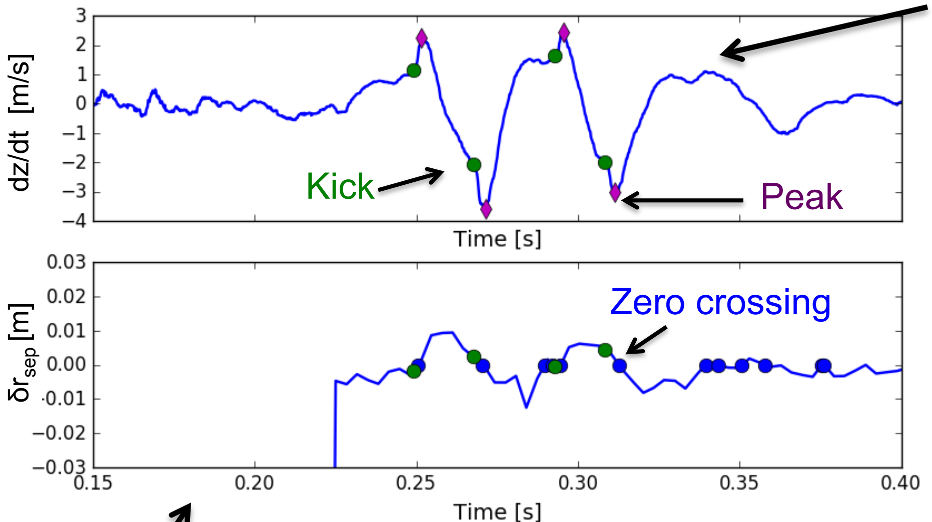


Growth rate is strongly dependent on inner gap in these shots

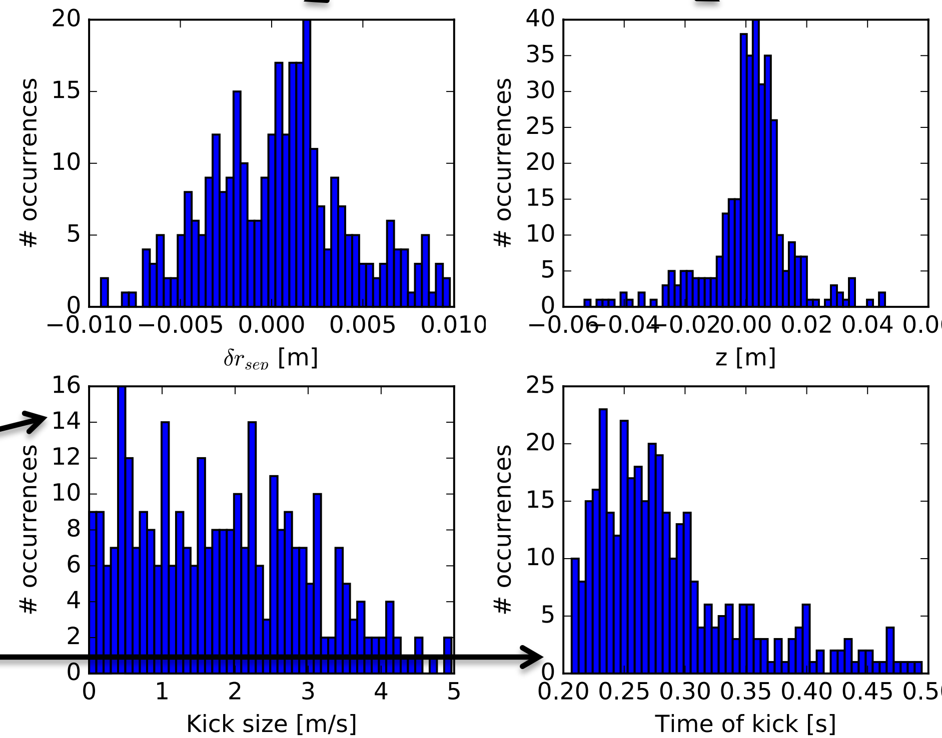
Oscillations appear to be sustained by ‘kicks’

Kick size decreases later in shot

Kicks typically occur at or just above drsep=0, z=0.



Abrupt vertical motion near maximum velocity in oscillations, near zero crossings in drsep

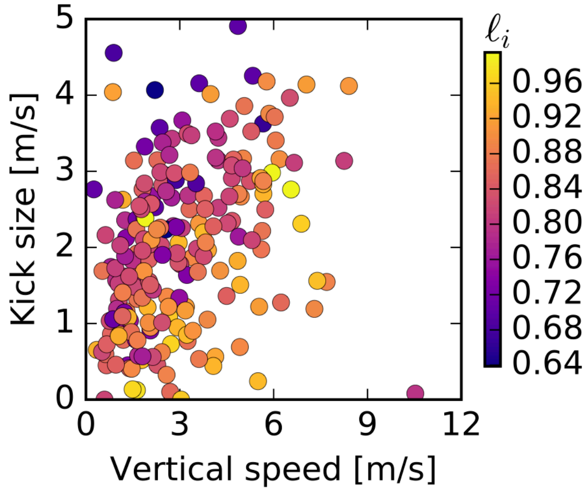


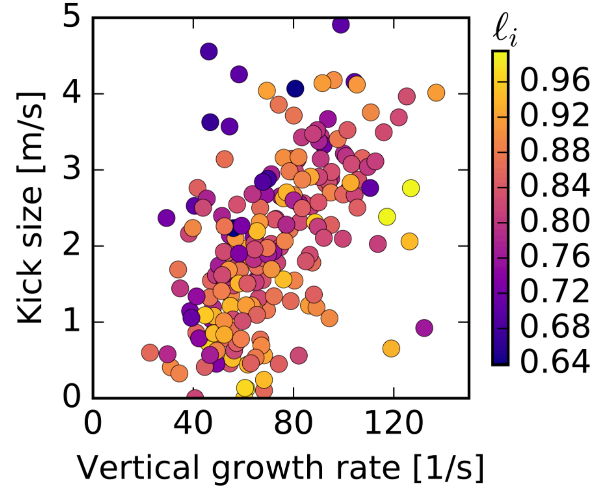
Kick size is broadly distributed below 3m/s

Kicks occur most often before t=0.3s

Size of kicks varies with vertical growth rate, vertical motion, and equilibrium

Kick size dependence on vertical speed at time of kick decreases as li increases

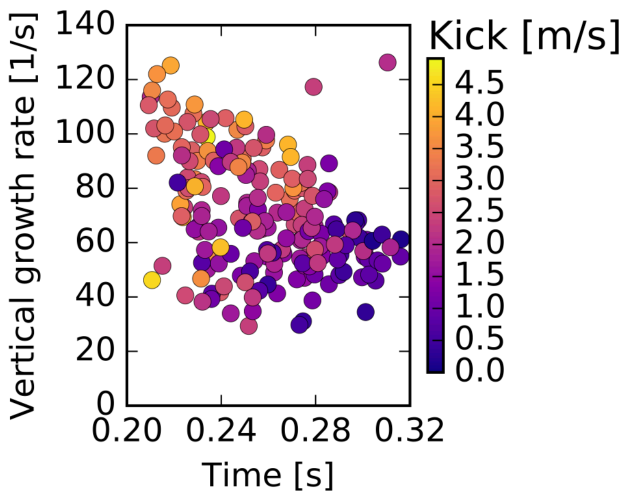


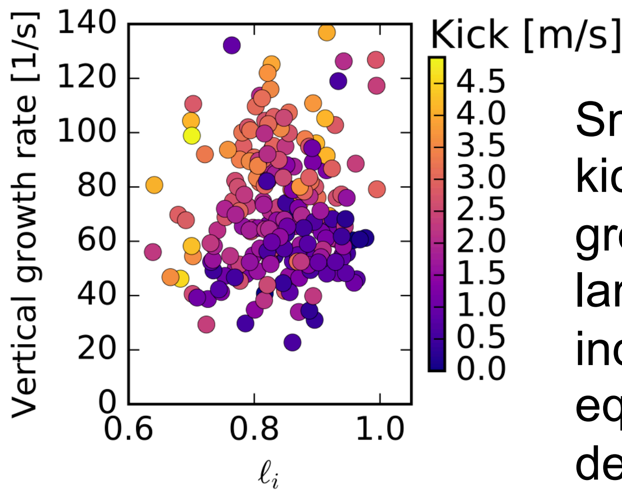


Kick size dependent on vertical growth rate

Vertical growth rate typically higher early

For same growth rate, kick size is larger early

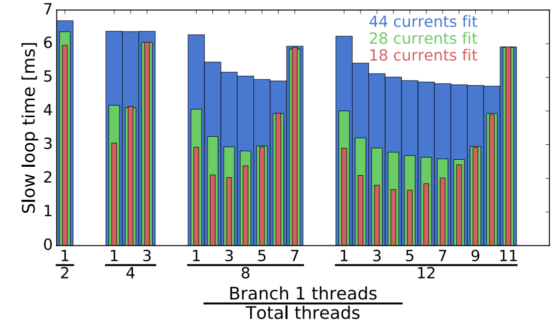


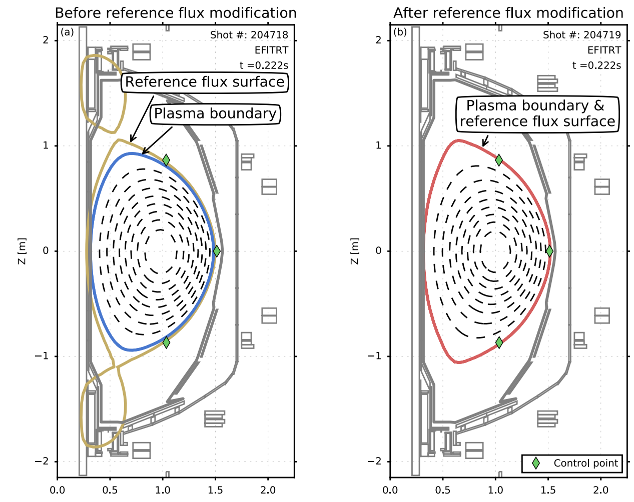


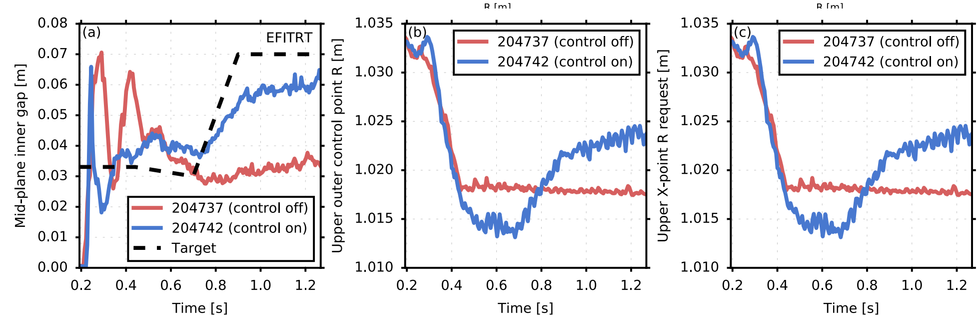
Smallest kicks at low growth rate, large li. May indicate equilibrium dependence

Upgrades made to control algorithms will eliminate or reduce severity of the potential causes of oscillations

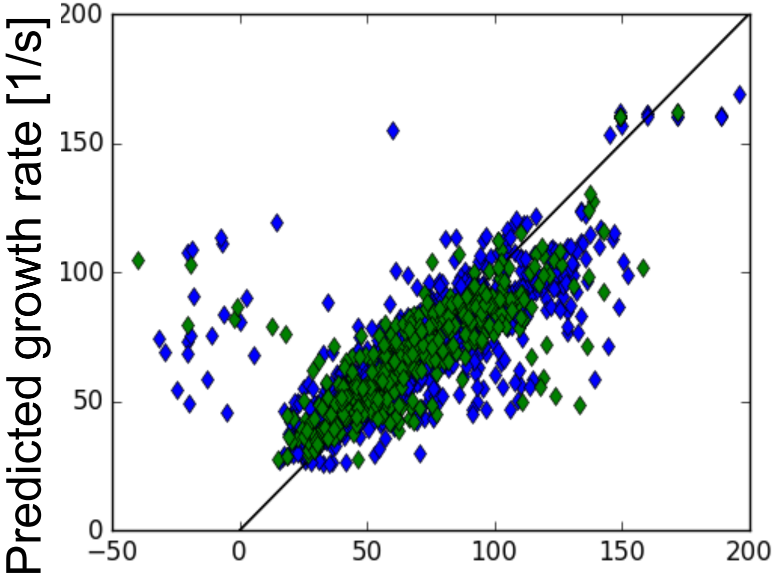
- Multi-threading of rtEFIT
  - Enable faster reconstruction and/or vessel current fitting
- Automatic selection of reference flux in ISOFLUX algorithm
  - Switch between limiter and X-point flux as boundary reference
  - Avoid need for transition between separate algorithms
- Inner gap control
  - Automatically adjust X-point targets to control inner gap size
  - Avoid overshoot and associated high vertical growth rates







Neural network trained on growth rate calculations, can be used to study trends or adjust shape to avoid VDEs



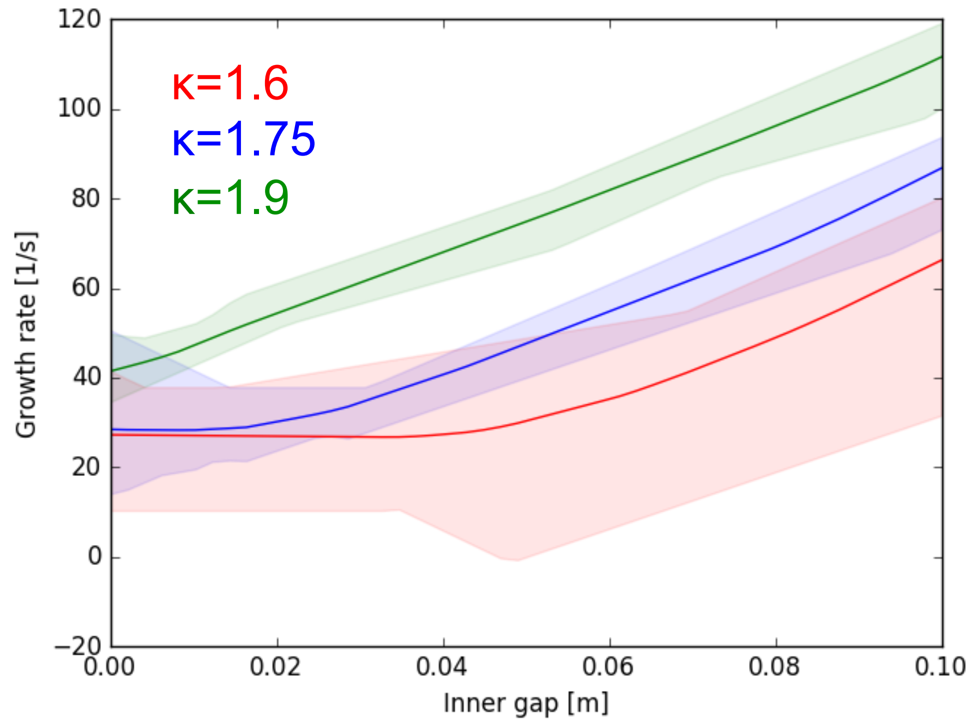
Calculated growth rate [1/s]

- Provides some guidance in designing target equilibrium

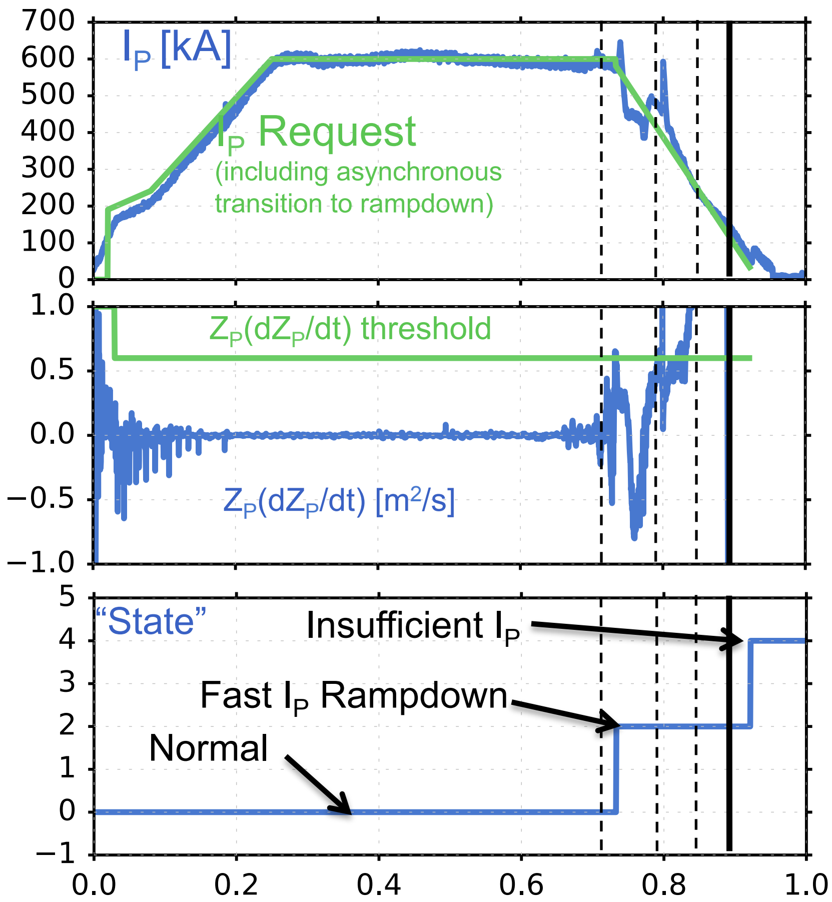
- Planning to fit to probability of VDE to provide real-time indicator likelihood of loss of control

- Working on improving the fit...
- Multiple NN used to provide sense of uncertainty

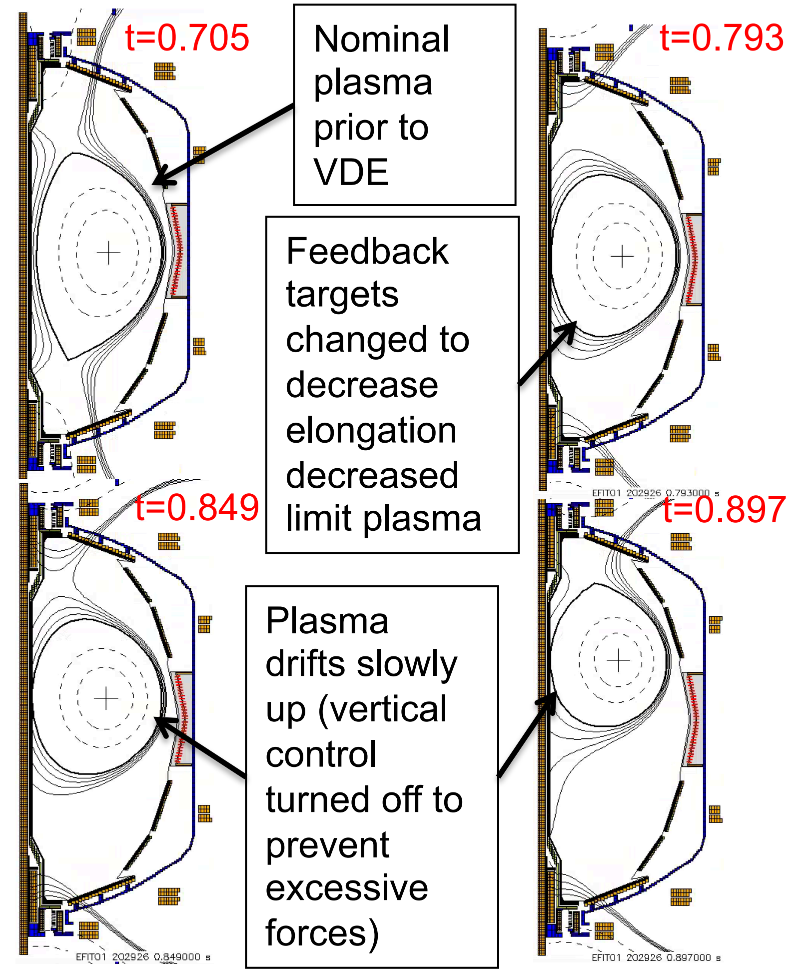
l_i=0.8, β_p=0.2, I_p=650k,z=0, outer gap: 0.05m



State-machine-based shutdown handler was used to end shots when VDE detected - future version planned to end or alter shot when approaching VDE limits



- Plasma control system detects loss of control
  - OH near max current
  - Vertical oscillations exceed threshold
  - ABS (I_p - $I_{p\ request}$) too large
  - Locked mode detected



- Feedback control switches to new "states" that attempt to gently end the discharge

Conclusions and outlook

- Improvements to vertical control helped achieve an operating space similar to NSTX, now at higher aspect ratio
  - However, NSTX-U typically operated at high l_i
- Database of VDEs generated to assess elongation limits
- Largest difficulty for vertical control was around time of diverting
- Large oscillations seem to be initiated by motion near the time of diverting and sustained by kicks
  - Improvement to ISOFLUX removes need for algorithm transitions near time of diverting
  - Multi-threading of rtEFIT should improve reconstruction near time of diverting
  - Inner gap control will reduce overshoot and associate high growth rate
  - Oscillations sustained by growth rate and equilibrium dependent ‘kicks’
    - Modeling underway to find a suitable equilibrium that is less sensitive
- Model of growth rate and VDE probability planned for use in real-time VDE avoidance algorithm

Vertical control challenges during ramp-up often occurred near time of diverting and transitioning to H-mode

Improvements to vertical control system helped achieve elongation vs. l_i at peak stored energy similar to NSTX at higher aspect ratio

PCS upgrades and modeling work aim to avoid oscillations and VDEs in the next campaign