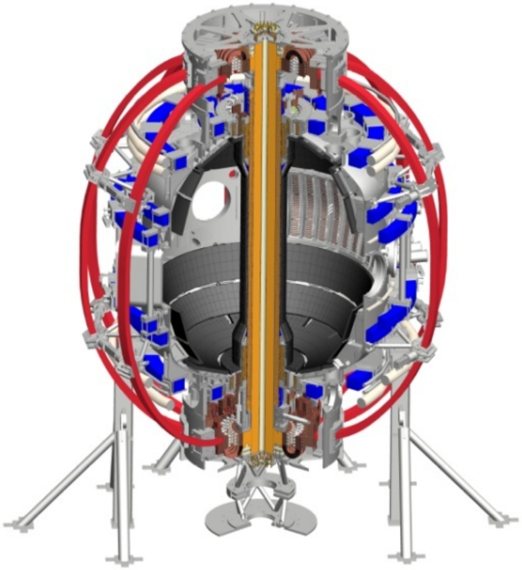
Advanced Scenarios and Control (ASC) Progress and Plans

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
Old Dominion
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

Stefan Gerhardt
E. Kolemen
and the NSTX Research Team

NSTX-U PAC 31
B318, PPPL
April 18th, 2012



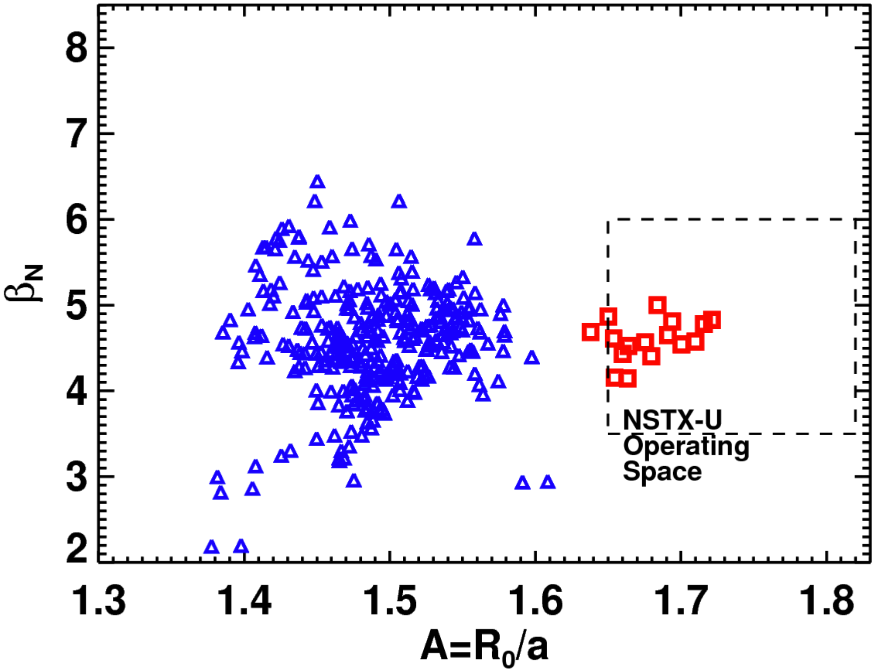
Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

ASC Research Targets Integrated, Steady-State Scenario Needs for FNSF/CTF and ITER

A steady state CTF/FNST must:

- Have full current drive with acceptable recirculating power.
  - Research program exploring a range of β_N with 100% non-inductive CD.
- Control the divertor heat flux to be within acceptable material limits.
  - Research program in divertor control.
- Simultaneously optimize confinement and passive disruption avoidance.
  - Research program on the optimization and control of the boundary shape, rotation and current profiles.
- Detect and respond to disruptions and off-normal events.
  - Research program in disruption detection and soft-shutdowns.

NSTX Operational Space: β_N vs κ
$>1\tau_E$ average for each point

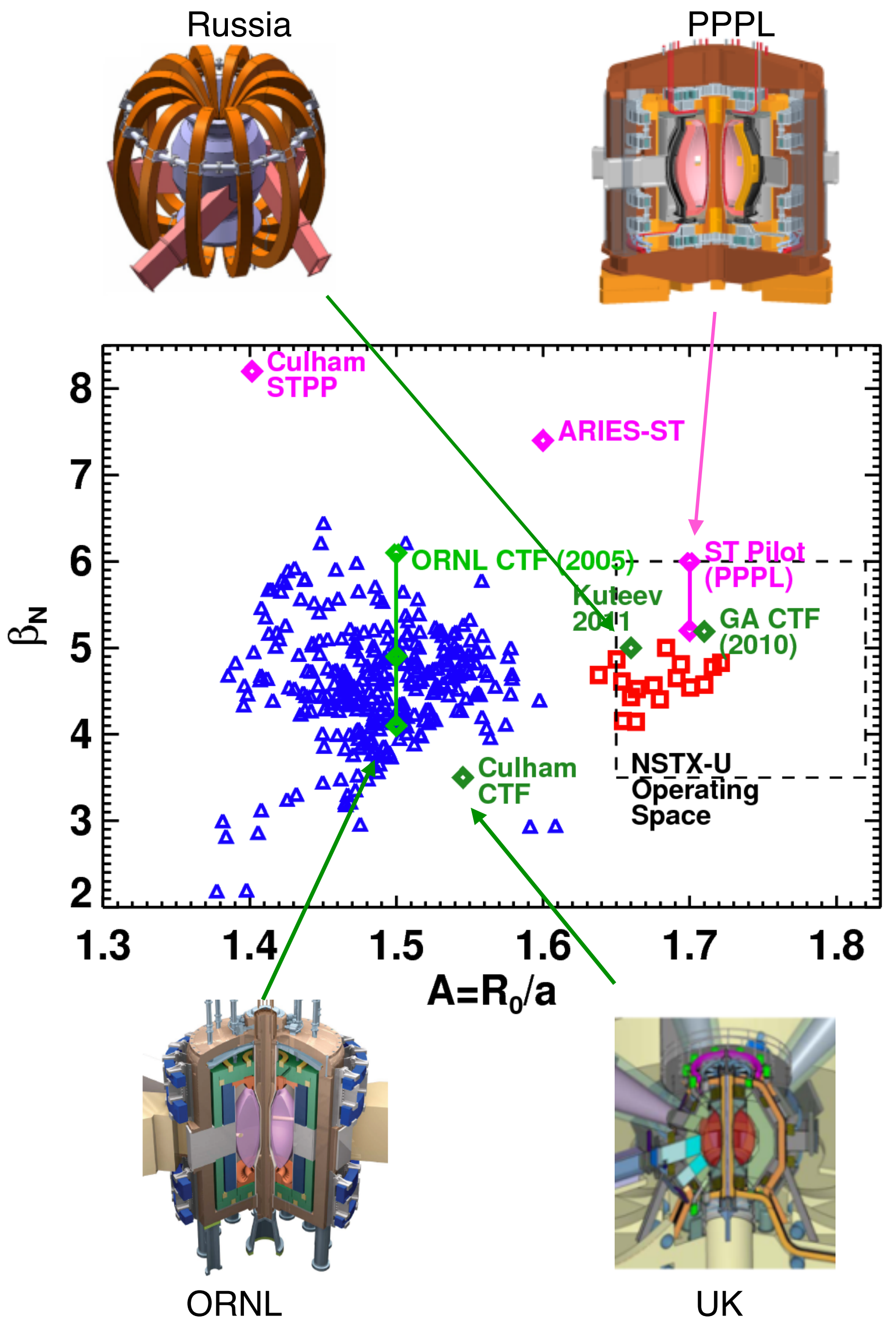


Conventional NSTX Operating Space
High-A Experiment During FY-11 Run

ASC Research Targets Integrated, Steady-State Scenario Needs for FNSF/CTF and ITER

A steady state CTF/FNST must:

- Have full current drive with acceptable recirculating power.
  - Research program exploring a range of β_N with 100% non-inductive CD.
- Control the divertor heat flux to be within acceptable material limits.
  - Research program in divertor control.
- Simultaneously optimize confinement and passive disruption avoidance.
  - Research program on the optimization and control of the boundary shape, rotation and current profiles.
- Detect and respond to disruptions and off-normal events.
  - Research program in disruption detection and soft-shutdowns.



Outline

- Recent activities in the ASC TSG.
  - Scenario modeling for NSTX-U with free boundary TRANSP
  - Progress in axisymmetric control development
  - Disruption detection
- ASC research plans for NSTX-U
  - 1: Scenario development
  - 2: Axisymmetric control development
  - 3: Event handling
  - 4: Scenario optimization for next step devices

Proposed ASC Elements of the NSTX-U 5-Year Plan

- Summary

Outline

- Recent activities in the ASC TSG.
  - Scenario modeling for NSTX-U with free boundary TRANSP
  - Progress in axisymmetric control development
  - Disruption detection
- ASC research plans for NSTX-U
  - 1: Scenario development
  - 2: Axisymmetric control development
  - 3: Event handling
  - 4: Scenario optimization for next step devices

Proposed ASC Elements of the NSTX-U 5-Year Plan

- Summary

We Have Extended the NSTX-Upgrade Scenario Modeling Using Free-Boundary TRANSP

PAC29-7
PAC29-41

- Variations considered:
  - Beam configuration & boundary shapes
  - Confinement level & profile shapes
  - Z_{eff} (=2 in most simulations)
  - Anomalous fast ion diffusion
- Used free-boundary capability in TRANSP
- Allow the current profile to fully equilibrate
- Profiles:
  - Use neoclassical theory to predict the ion temperature
  - Scaled experimental T_e profiles to achieve a $H_{98y,2}$=1, or H_{ST}=1.
  - n_e profile scaled from experiment to give desired f_{GW}.
- Studied many types of scenarios:
  - High current
  - Full non-inductive
  - Very long pulse
  - High β_T.

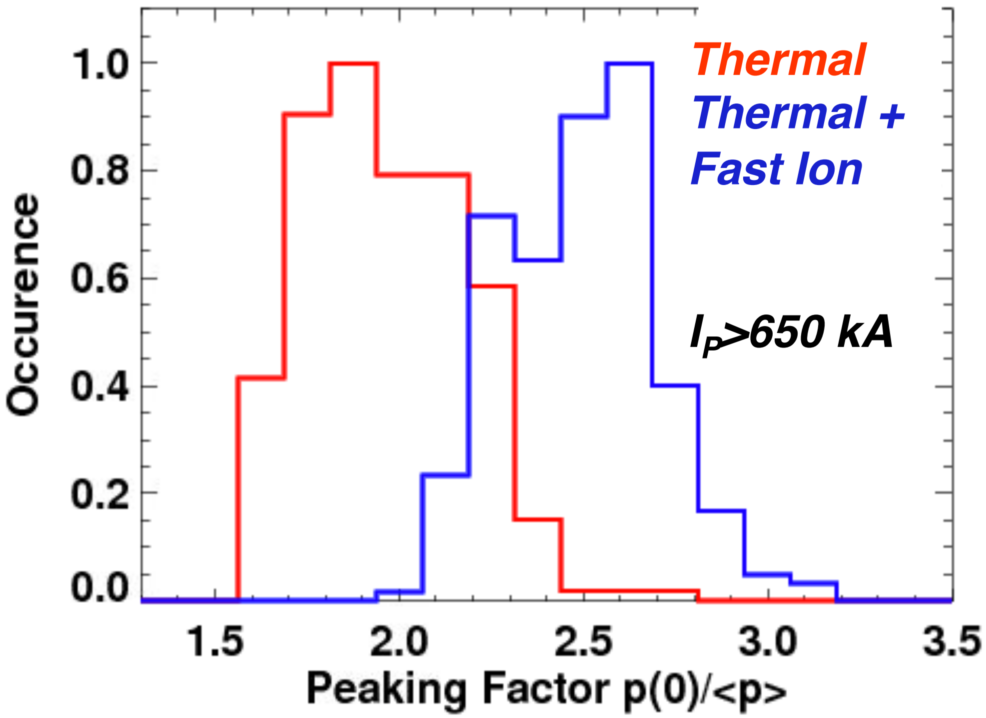
Under review at Nuclear Fusion

Profile Peaking Over the Range Observed in NSTX Results in ~35% Variation in q_{min} and l_i

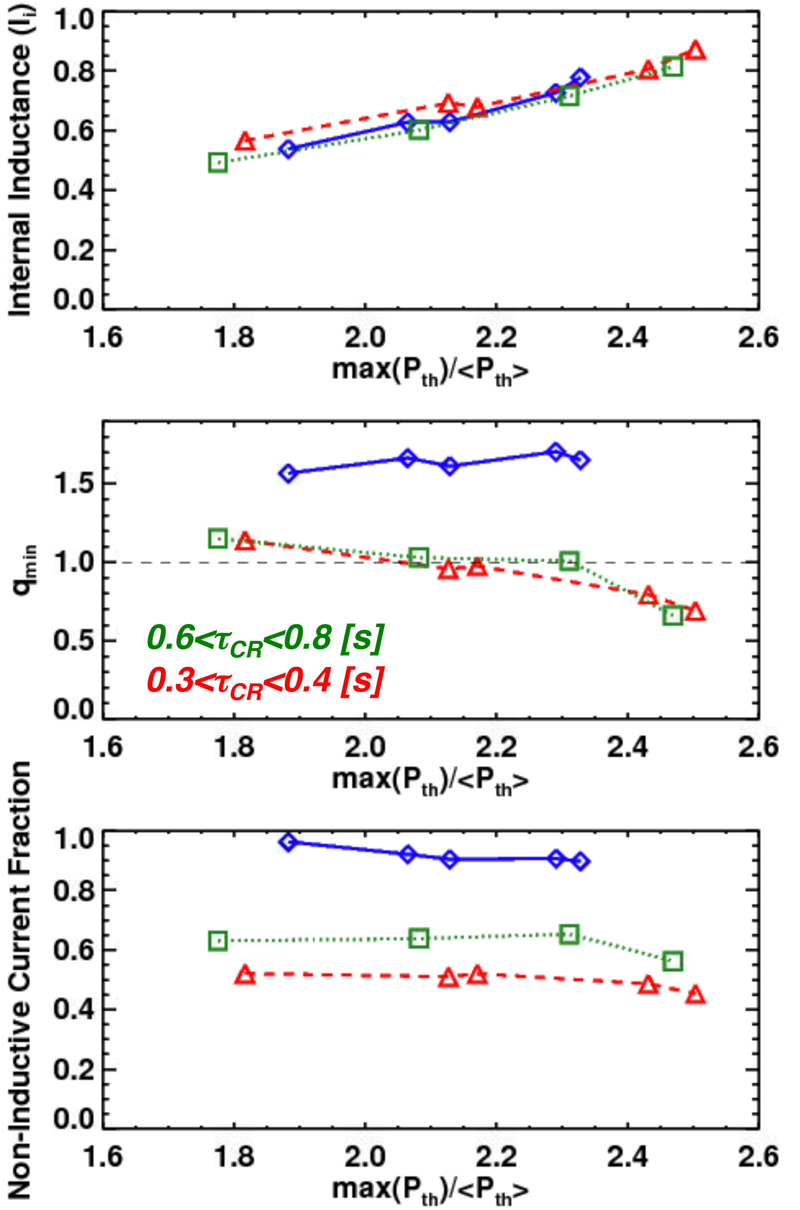
PAC29-7

1.0 MA, 1.0 T, P_{inj}=12.6 MW, near non-inductive
1.6 MA, 1.0 T, P_{inj}=10.2 MW, partial inductive
1.2 MA, 0.55 T, P_{inj}=12.4 MW, high β_T
All: f_{GW}=0.7, $H_{98y,2}$=1

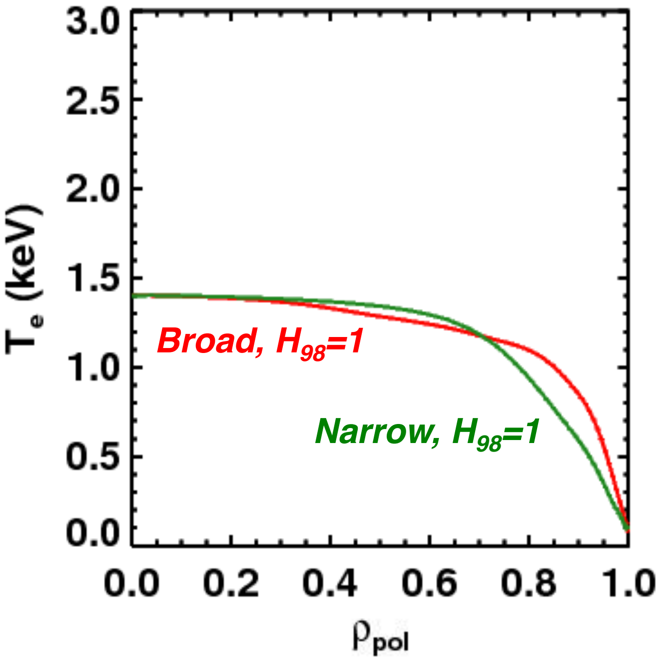
Peaking Factors in NSTX High-Performance Database

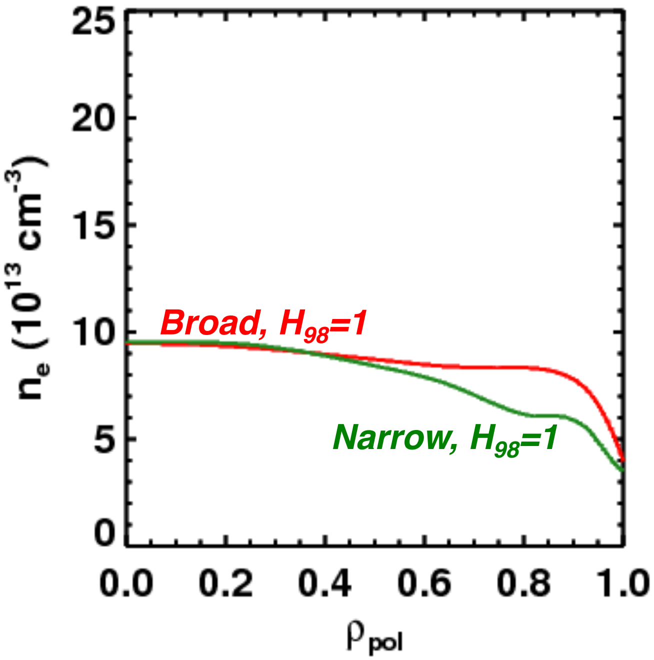


Scan of Thermal Pressure Peaking to Accommodate Different ELM Regimes and Core Peaking



We Anticipate The Non-Inductive Current Level at B_T=1.0 T and P_{inj}=12.6 MW To Be Between ~900 & ~1300 kA

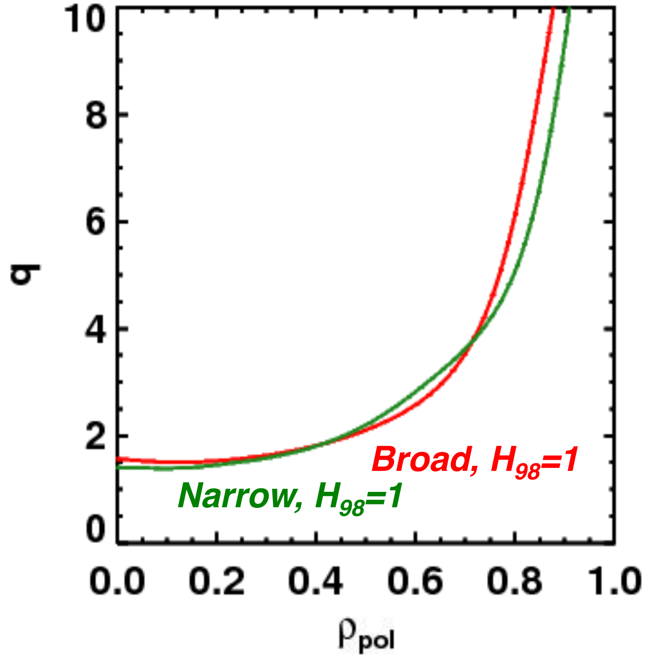




Dashed: ITER-98 confinement scaling

$$\tau_{98y,2} \propto I_P^{0.93} B_T^{0.15} \overline{n}_e^{0.41} P_{Loss}^{-0.69}$$

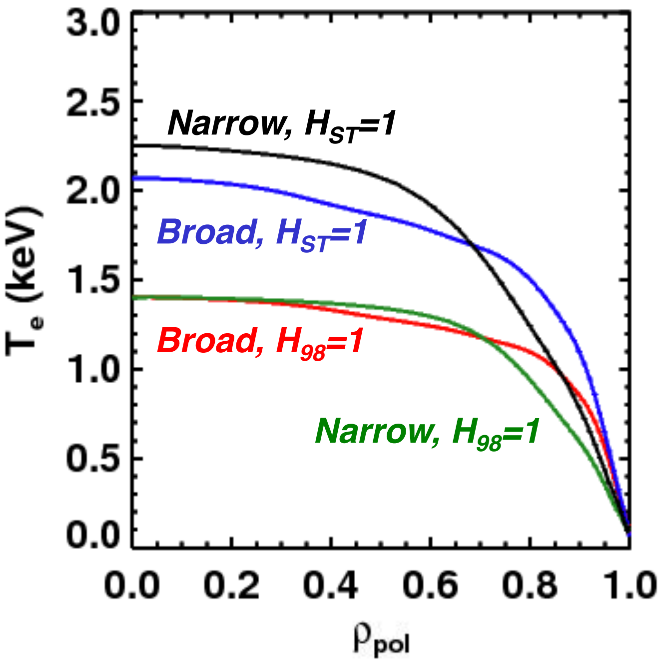
PAC29-7
PAC29-41

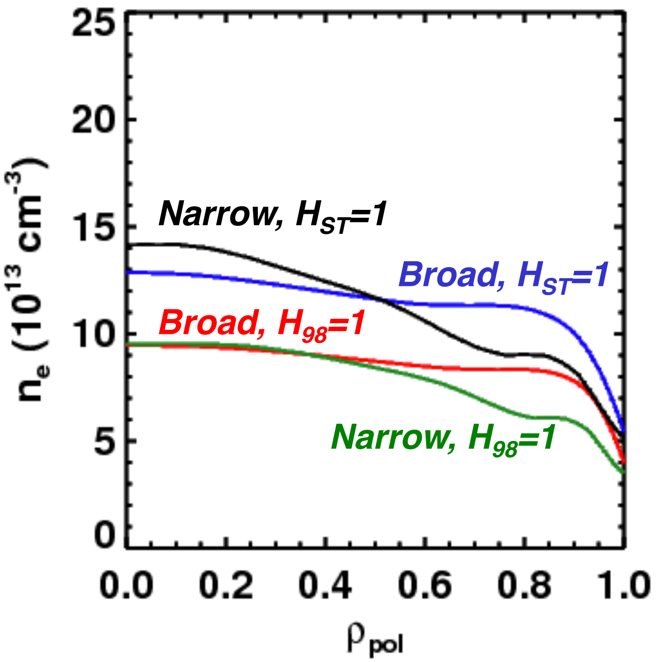


- **Fix: 1.0T, P_{inj}=12.6 MW, f_{GW}=0.72**
- **Fix: A=1.75, κ=2.8**
- Find the non-inductive current level for 2 confinement and 2 profile assumptions…*yields 4 different projections.*

Confinement	Profiles	I_P [kA]	β_N	q_{min}
H_{98}=1	Broad	975	4.34	1.5
H_{98}=1	Narrow	875	4.87	1.4

We Anticipate The Non-Inductive Current Level at B_T=1.0 T and P_{inj}=12.6 MW To Be Between ~900 & ~1300 kA





Dashed: ITER-98 confinement scaling

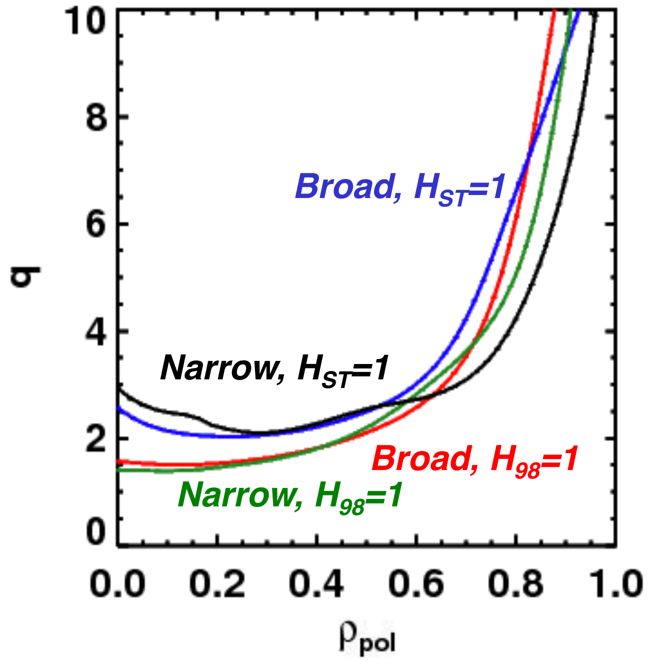
$$\tau_{98y,2} \propto I_P^{0.93} B_T^{0.15} \overline{n}_e^{0.41} P_{Loss}^{-0.69}$$

Solid: ST confinement scaling

$$\tau_{ST} \propto I_P^{0.57} B_T^{1.08} \overline{n}_e^{0.44} P_{Loss}^{-0.73}$$

(S. Kaye, NF 2005)

PAC29-7
PAC29-41



- **Fix: 1.0T, P_{inj}=12.6 MW, f_{GW}=0.72**
- **Fix: A=1.75, κ=2.8**
- Find the non-inductive current level for 2 confinement and 2 profile assumptions…*yields 4 different projections.*

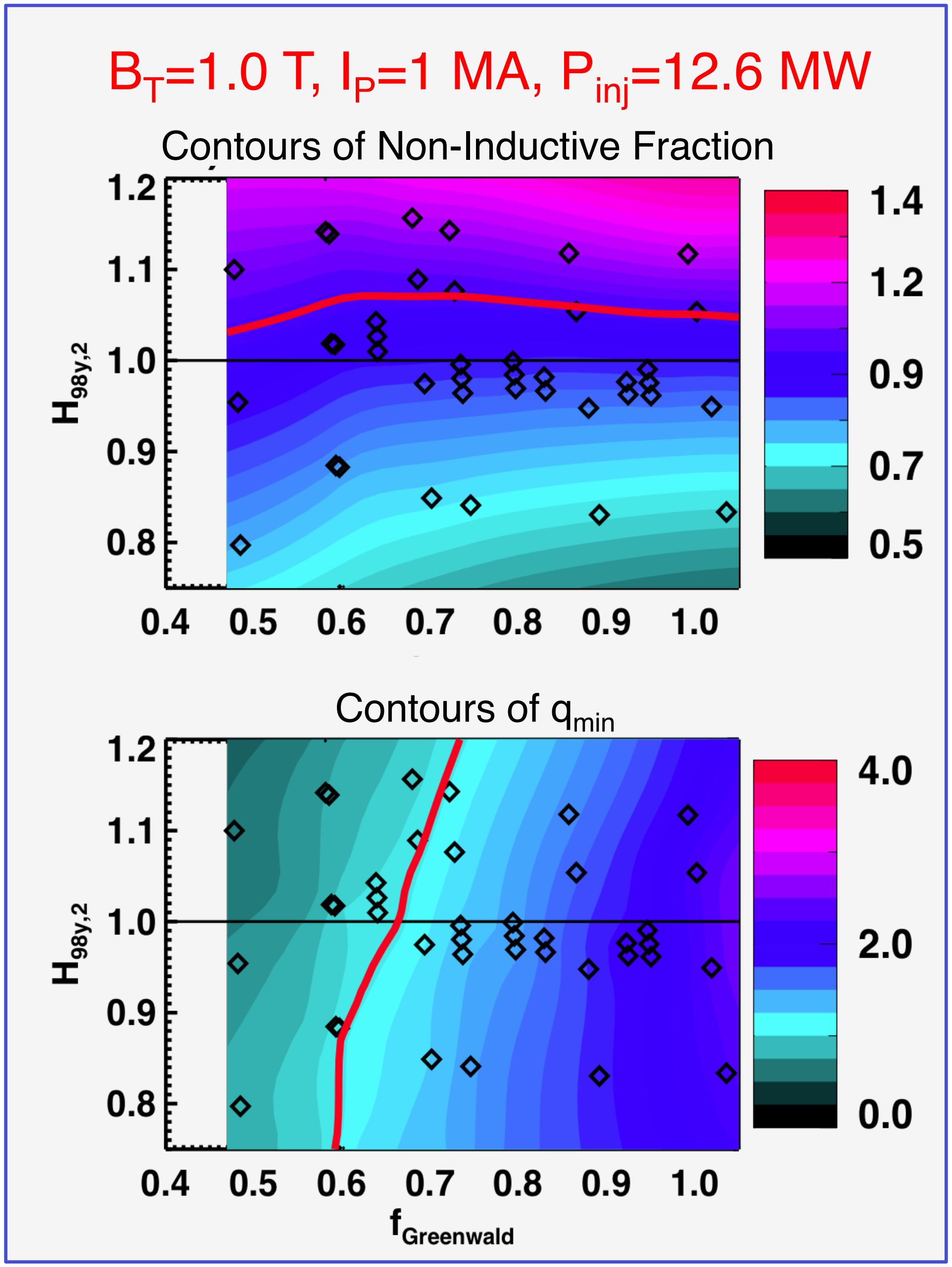
Confinement	Profiles	I_P [kA]	β_N	q_{min}
H_{98}=1	Broad	975	4.34	1.5
H_{ST}=1	Broad	1325	5.32	2.0
H_{98}=1	Narrow	875	4.87	1.4
H_{ST}=1	Narrow	1300	5.97	2.1

Non-Inductive Operating Points Projected Over a Range of Toroidal Fields, Densities, and Confinement Levels

Projected Non-Inductive Current Levels for κ~2.85, A~1.75, f_{GW}=0.7

B_T [T]	P_{inj} [MW]	I_P [MA]
0.75	6.8	0.6-0.8
0.75	8.4	0.7-0.85
1.0	10.2	0.8-1.2
1.0	12.6	0.9-1.3
1.0	15.6	1.0-1.5

- From GTS (ITG) & GTC-Neo (neoclassical):
  - $\chi_{i,ITG}/\chi_{i,Neo}$~$10^{-2}$
  - Assumption of neoclassical ion thermal transport should be valid.



Outline

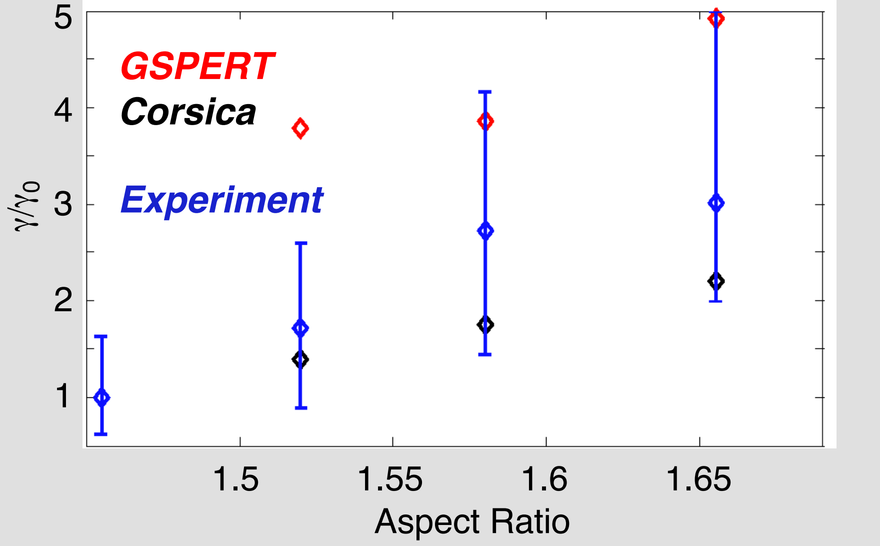
- Recent activities in the ASC TSG.
  - Scenario modeling for NSTX-U with free boundary TRANSP
  - Progress in axisymmetric control development
  - Disruption detection
- ASC research plans for NSTX-U
  - 1: Control development
  - 2: Event handling
  - 3: Scenario optimization for next step devices
- Summary

Proposed ASC Elements of the NSTX-U 5-Year Plan

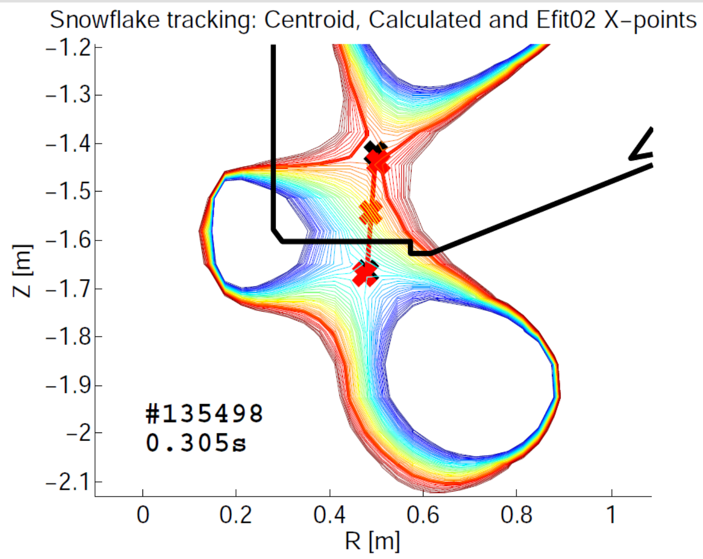
Progress in Boundary and Divertor Control

- Improvements to our vertical control measurements and modeling:
  - Begun to compare measured growth rates to theoretical predictions (Corsica and GSPERT).
  - Improved plasma position observer (more flux loops).
  - RWM coils for n=0 control.
- Smoothed transition between shape control phases.
  - Eliminate transients due to integral error resets.
- Began to develop algorithm for snowflake divertor control (PPPL, GA, LLNL Collaboration).

Vertical Growth Rates vs. Aspect Ratio



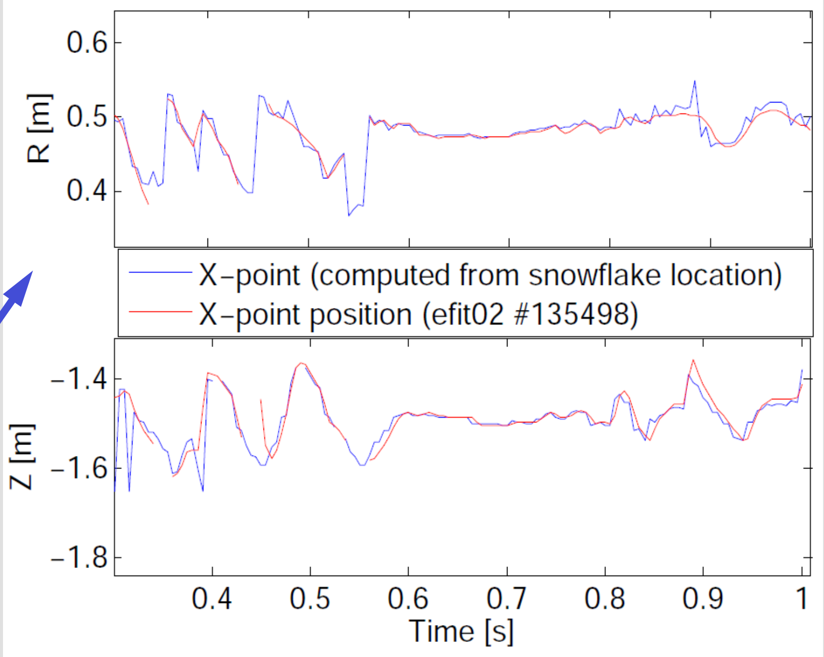
Examples of X-point finding via. G.-S. expansion algorithm



In Space

In Time

Milestone R14-3

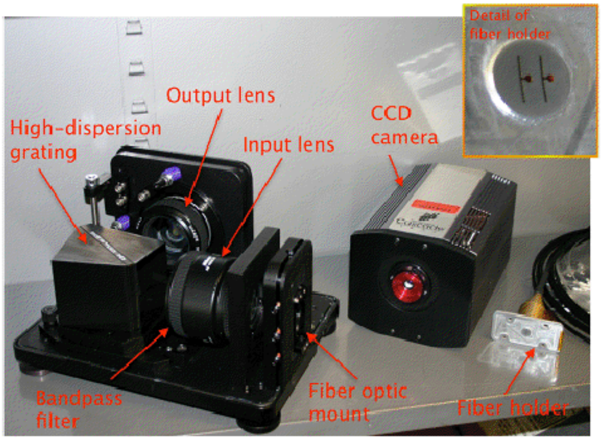


NSTX-U is Ramping Up Development of Realtime Profile Diagnostics For Profile Control

PAC29-5f

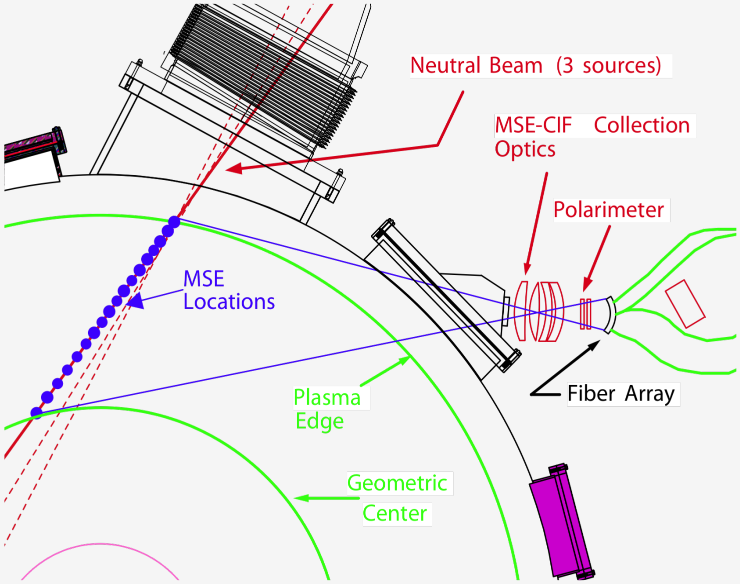
- Realtime rotation diagnostic has been developed.
  - Critical achievement for rotation control plans.
- Four radii spanning core to edge.
  - Radial location optimized for best resolution of the profile.
- Readout and non-linear fitting demonstrated at 1 kHz.
  - Instrument can supplement normal CHERS with high time resolution physics studies

Camera hardware for rtV_ϕ



- Realtime MSE has been funded in collaboration with Nova Photonics.
  - Is the fundamental rtEFIT constraint for q-profile control.

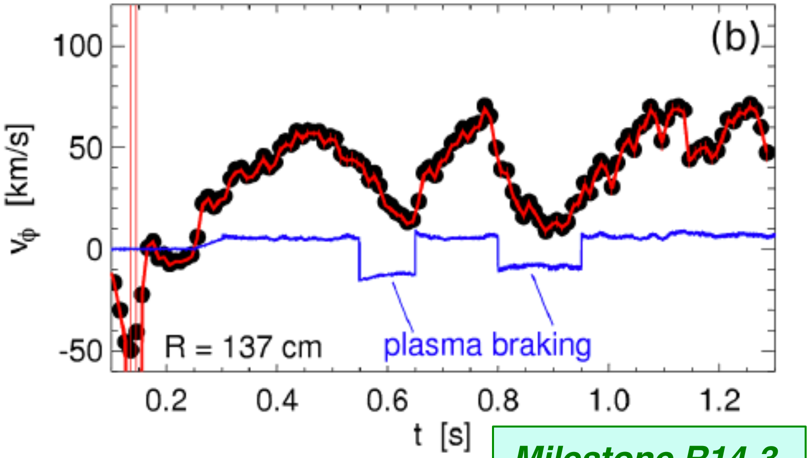
Arrangement of the NSTX MSE system (CIF)



Comparison of CHERS analysis.

Standard offline code

Fast realtime code



Milestone R14-3

Outline

- Recent activities in the ASC TSG.
  - Scenario modeling for NSTX-U with free boundary TRANSP
  - Progress in axisymmetric control development
  - Disruption detection
- ASC research plans for NSTX-U
  - 1: Scenario development
  - 2: Axisymmetric control development
  - 3: Event handling
  - 4: Scenario optimization for next step devices

Proposed ASC Elements of the NSTX-U 5-Year Plan

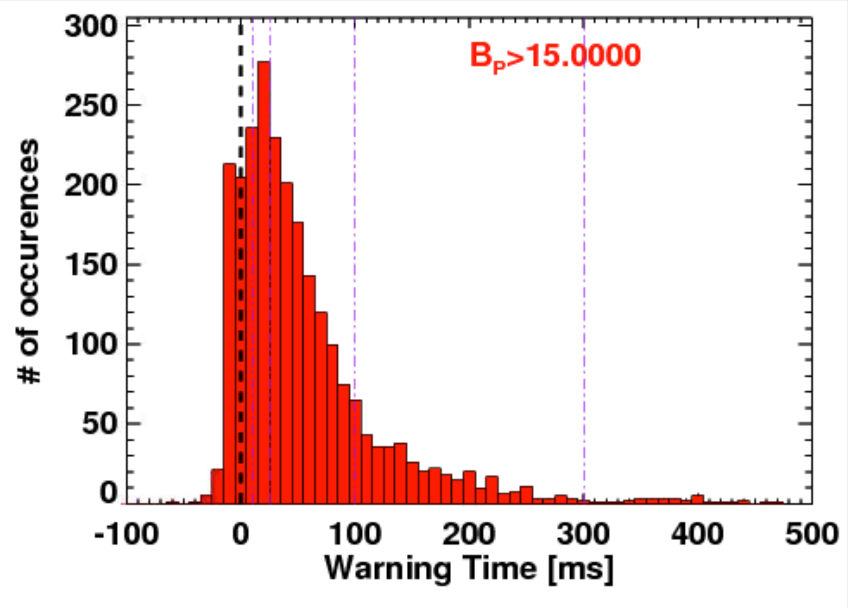
- Summary

Disruption Detection Studies Show That No Single Diagnostic Can Predict All Disruptions

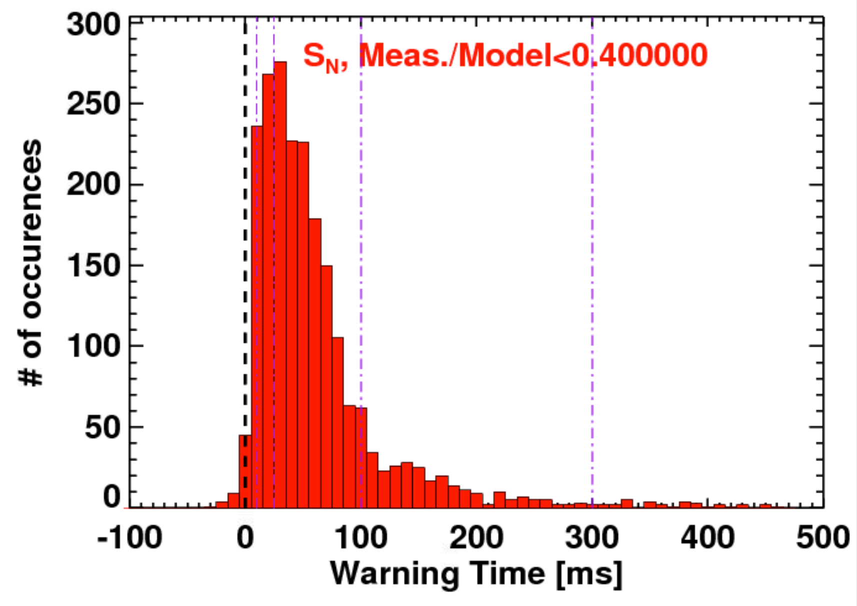
- Examined >20 different signals that might be used for disruption prediction.
  - Rotation, confinement, rotating MHD, RWMs and locked-modes, q*, β_N, f_{GW}, P_{rad}/P_{tot},…
- For each signal, define limits beyond which disruptions become likely.
  - Use physics based predictions of signals if possible.

Milestone R13-4

Example #1: In-Vessel n=1 RWM sensors
Instantaneous values >~15 G indicative of imminent disruption.

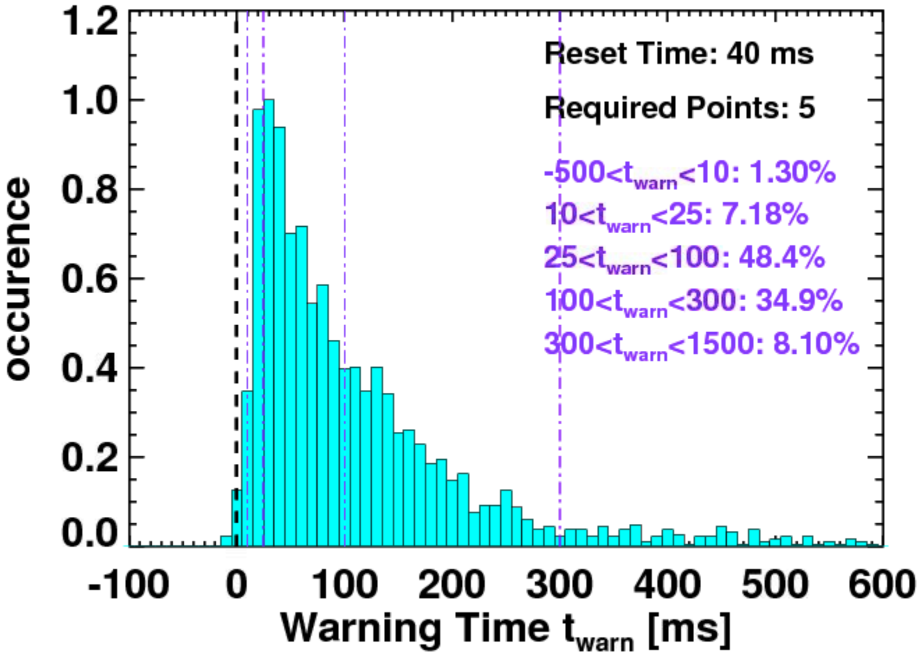


Example #2: Neutron Emission
Predict the neutron rate using a 0D slowing-down model
Measured/Model ratios <~0.4 indicative of imminent disruptions



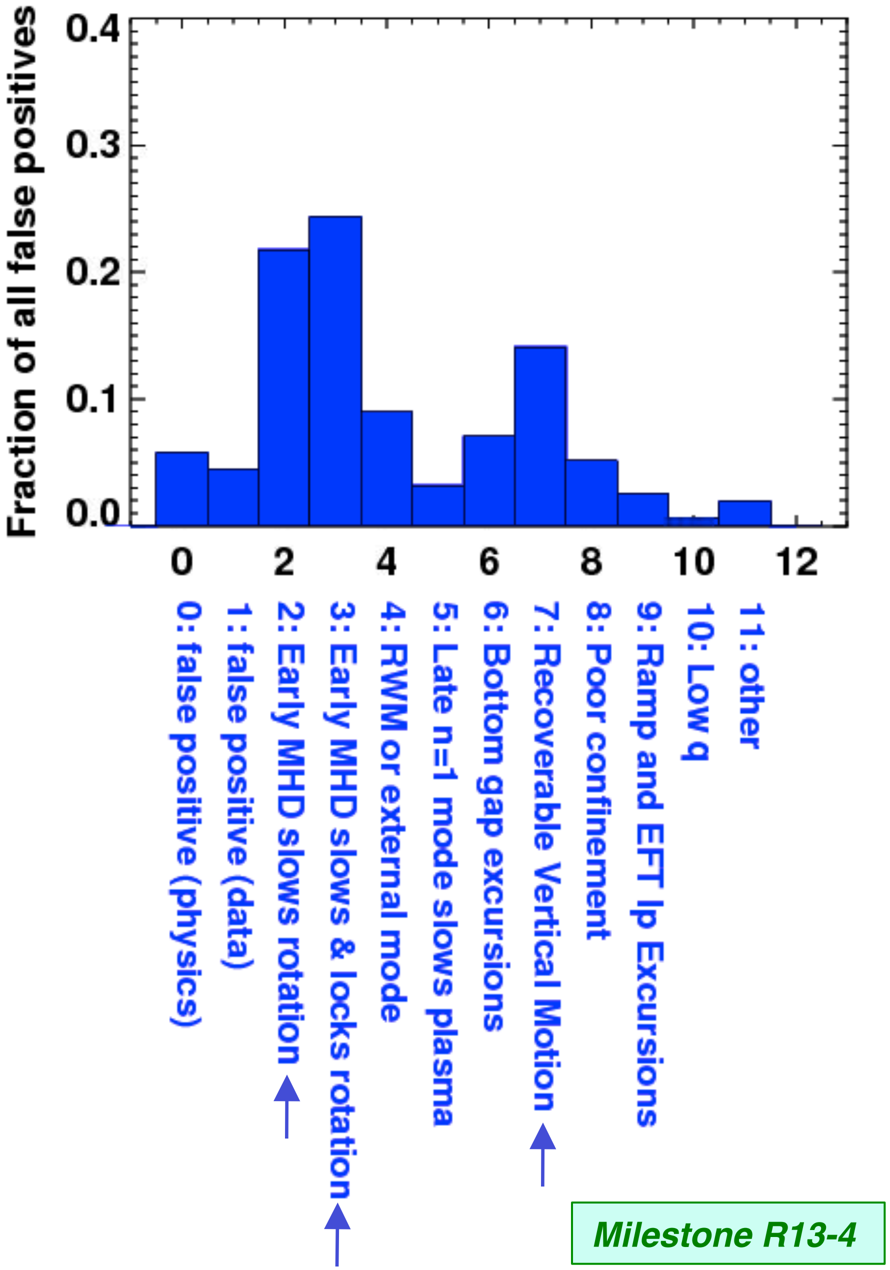
Simple Predictor Can Predict Disruptions With High Probability of Success

- Predictor based on combinations of threshold based tests.
  - Multiple thresholds for each test.
  - No machine learning
- Produces a very low missed disruption rate.



- Most false positives are due to “near disruptive” events.
- If tuned for a missed disruption fraction of 2%, then false positive rate is only 6%.

Physics Origins of “False Positives”



Milestone R13-4

Outline

- Recent activities in the ASC TSG.
  - Scenario modeling for NSTX-U with free boundary TRANSP
  - Progress in axisymmetric control development
  - Disruption detection
- ASC research plans for NSTX-U
  - 1: Scenario development
  - 2: Axisymmetric control development
  - 3: Event handling
  - 4: Scenario optimization for next step devices

Proposed ASC Elements of the NSTX-U 5-Year Plan

- Summary

Research plan is cross-cutting with essentially all other TSGs
Collaboration is implied through the plan.

Thrust 1: Many ASC Activities in Preparation for NSTX-U Operations

PAC29-6

- Major upgrade of the control computer underway.
  - 64 bit, 16 processor machine running true realtime LINUX.
- Must upgrade PCS code to utilize NSTX-U hardware upgrades
  - Additional divertor coils
  - Three new NB sources.
  - New inner-vessel magnetic constraints on rtEFIT
- New realtime profile diagnostics are to be incorporated.
- Keeping operations and control skills fresh through collaboration.
  - PCS control development on KSTAR and DIII-D
  - Physics operations assistance on KSTAR and EAST
- Year 1 capabilities will already vastly exceed those from NSTX
  - 90 kV operation from all 6 sources.
  - Initial operations at B_T=0.55-0.65 T, for up to 5 s.
    - Push toward 0.75T by the end of the campaign.
    - Plasma currents up to 1400-1500 kA
  - Up-down symmetric divertors w/ three coils each.
    - Facilitate early start on upper/lower snowflake development

PAC29-6

Thrust 1: Pursue 100% Non-Inductive Current at Progressively Higher I_P and B_T

PAC29-7
PAC29-41

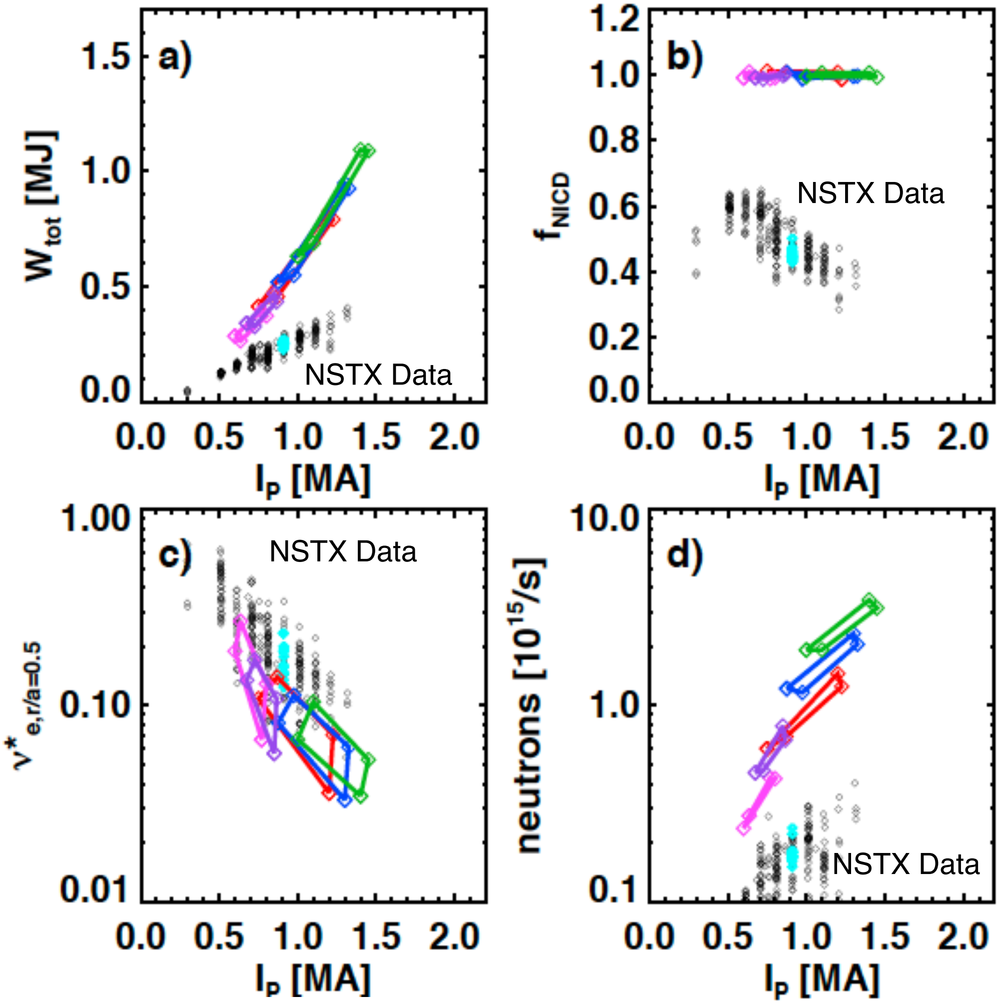
years	B_T [T]	Current Goal [kA]	Duration Goal
1	0.75	~600-800	A few τ_E
2	0.75-1.0	~600-800	1-2 τ_R
3-5	1	800-1300	Up to 4.5 s at lower I_P

- Lower currents mean that high heat fluxes are unlikely to impede research.

Incremental Funding: Accelerate testing of 100% non-inductive current drive for FNSF.

TRANSP Projections for 100% Non-Inductive Scenarios

Each polygon for a given engineering configuration, multiple profile and confinement assumptions



6x80 kV, B_T=1 T
6x90 kV, B_T=1 T
6x100 kV, B_T=1 T

4x80 kV, B_T=0.75 T
4x90 kV, B_T=0.75 T

End of year 1 target

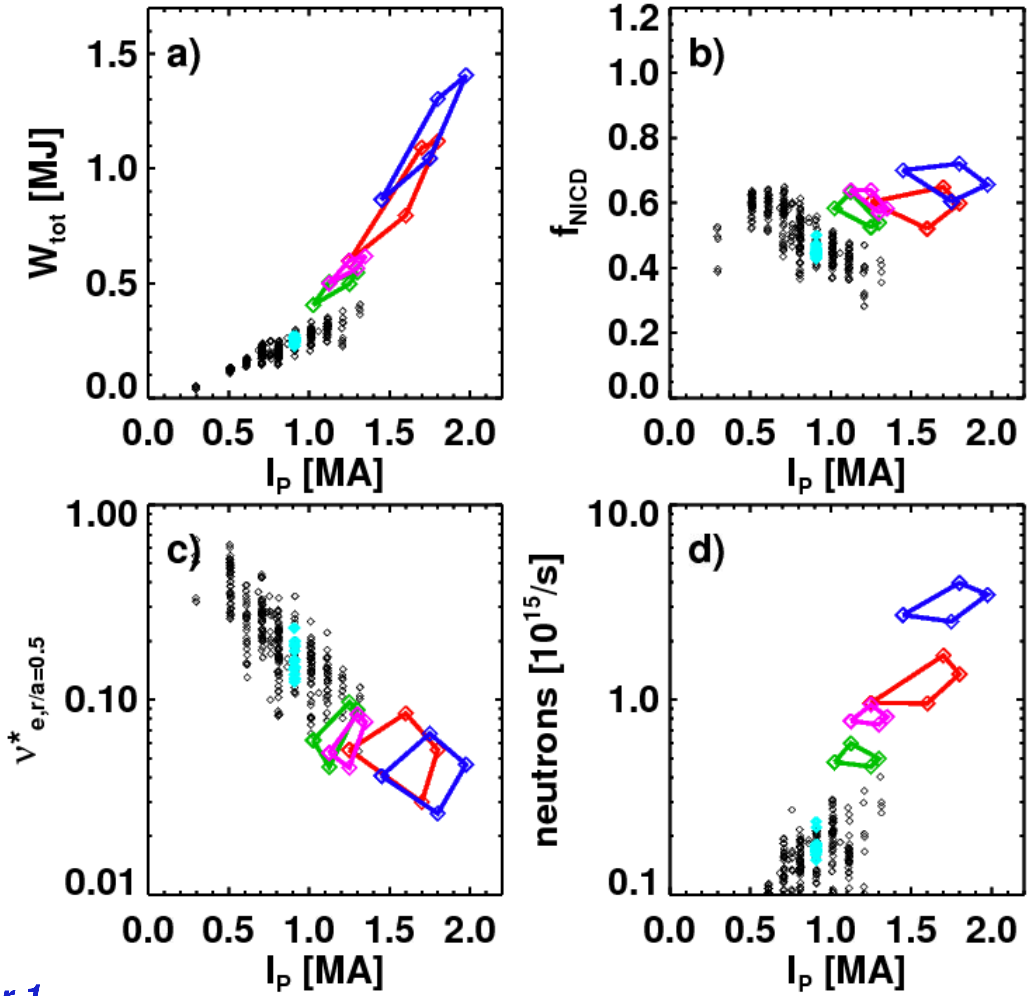
Thrust 1: Develop Long-Pulse Partial Inductive Operation Up to 2 MA with High Power

PAC29-6

PAC29-7

- Two types of partial inductive operation:
  - High-I_P operation supports collisionality scaling and divertor heat flux studies.

Parameters For Partial Inductive NSTX-U Scenarios with ***Relaxed 1.1<q_{min}<1.2*** & Heating Duration < 5 sec



All: f_{GW}=0.7, 1.1<q_{min}<1.2

6x80 kV, B_T=1 T, 15 cm outer gap

6x100 kV, B_T=1 T, 15 cm outer gap

4x80 kV, B_T=0.75 T, 15 cm outer gap

4x90 kV, B_T=0.75 T, 15 cm outer gap

End of year 1 target

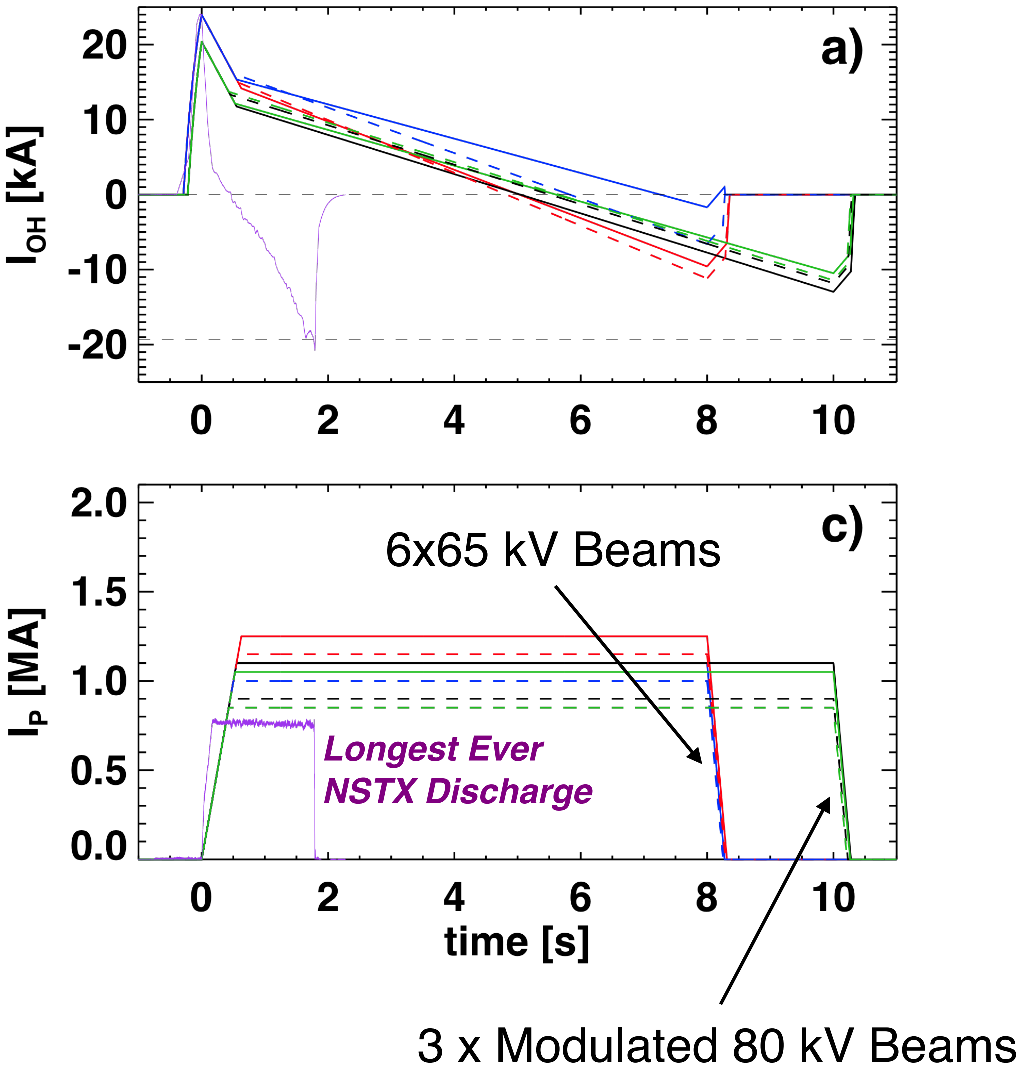
Thrust 1: Develop Long-Pulse Partial Inductive Operation Up to 2 MA with High Power

PAC29-6 **PAC29-7**

- Two types of partial inductive operation:
  - High-I_P operation supports collisionality scaling and divertor heat flux studies.
  - Long pulse operation for particle retention and disruptivity reduction studies.
- Years 1 & 2: Re-optimize startup for reduced fuelling at I_P=1200-1500 kA.
  - Goal: Enhance utility of Li pumping by reducing the early gas load.
- Years 3-5: Performance Extension
  - Discharges up to 2 MA for 5 seconds.
  - Long pulse at ~1 MA for up to 10 seconds
- High-I_P development is connected to progress on heat flux mitigation.

B_T=0.75 T, ***8-10 Second Discharge*** Scenarios Limited by q_{min}>1.1 or OH Coil I^2t

2 Confinement and 2 Profile Assumptions



6x65 kV Beams

Longest Ever NSTX Discharge

3 x Modulated 80 kV Beams

Thrust 2: Axisymmetric Divertor Control Likely Required for High-Current Operation

PAC29-6

- Outage:
  - Collaborate on snowflake divertor physics and control experiments at DIII-D.
  - Implement control algorithms for new divertor coils, including snowflakes.
- Years 1 & 2:
  - Develop upper/lower snowflake control at higher current.
  - Assess schemes for dual X-point control using new divertor coils.
  - Assess magnetic balance control in the presence of 4 X-points.
  - Document heat flux reductions compared to standard DN.
  - Assess impact of limited Moly. coverage on scenarios.
- Years 3-5:
  - Utilize cryopump and divertor upgrades to control density in long pulse scenarios.
  - Years 3-5: Pending progress in BP TSG, begin implementation of closed loop radiative divertor control.

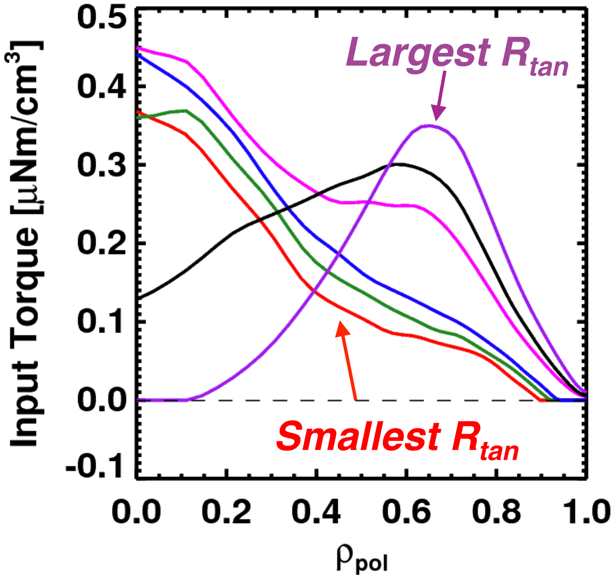
Thrust 2: Current and Rotation Profile Control Will Be Developed for Stability and Confinement Optimization

- Profile control philosophy:
  - Torque from NBI & 3D fields for rotation.

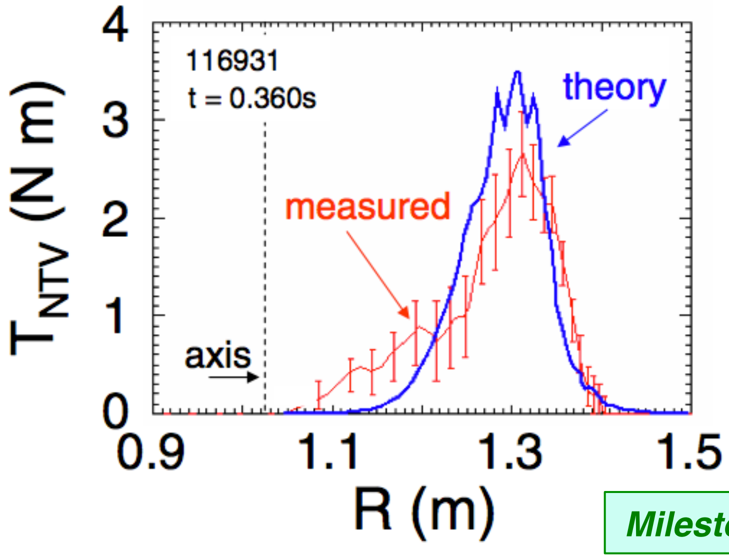
PAC29-7

Rotation Profile Actuators

Torque Profiles From 6 Different NB Sources



Measured and Calculated NTV Torque Profiles



Milestone R14-3

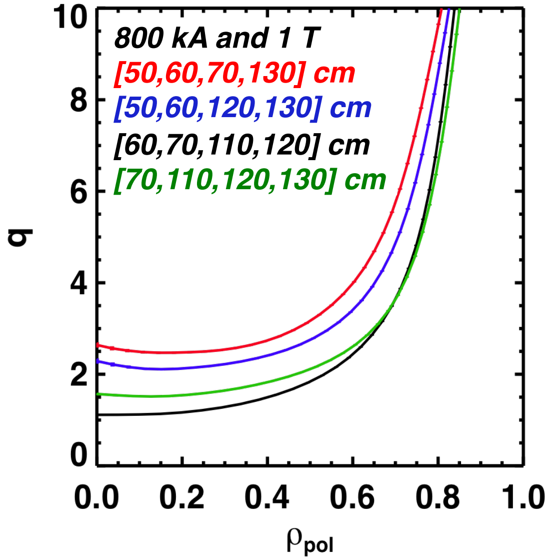
Thrust 2: Current and Rotation Profile Control Will Be Developed for Stability and Confinement Optimization

- Profile control philosophy:
  - Torque from NBI & 3D fields for rotation.
  - Variations in the beam source selection and outer gap for the q profile.

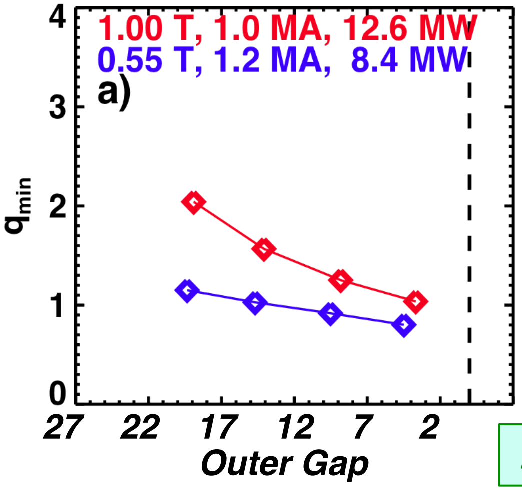
PAC29-7

q-Profile Actuators

Variations in Beam Sources
800 kA Partial Inductive



Variations in Outer Gap



Milestone R14-3

Thrust 2: Current and Rotation Profile Control Will Be Developed for Stability and Confinement Optimization

- Profile control philosophy:

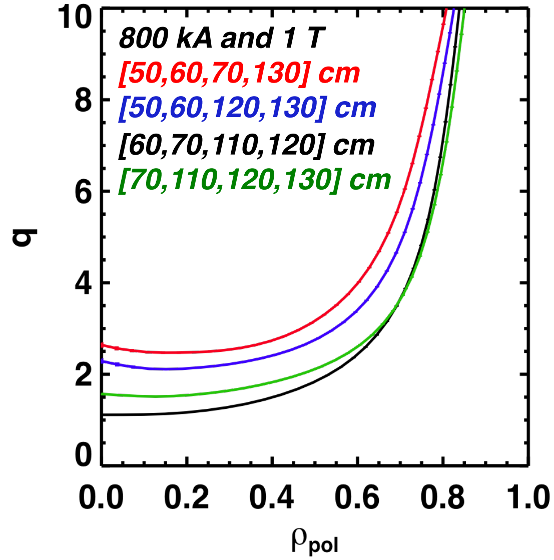
PAC29-7

  - Torque from NBI & 3D fields for rotation.
  - Variations in the beam source selection and outer gap for the q profile.
- Plans for model-based profile control
  - Outage: Progress by collaboration…
    - E. Schuster at Lehigh for NSTX-U profile control, E. Kolemen at GA for 2 years.
  - Years 1 & 2
    - Test rotation control using NB 3D field torque.
    - Feed forward test ability of different beam combinations to modify the q-profile.
    - Install and commission rtMSE and implement as constraint in rtEFIT.
  - Years 2-4: Test current profile control
  - Years 4-5:
    - Utilize NCC coil for better NTV control
    - Study feasibility of combined control.

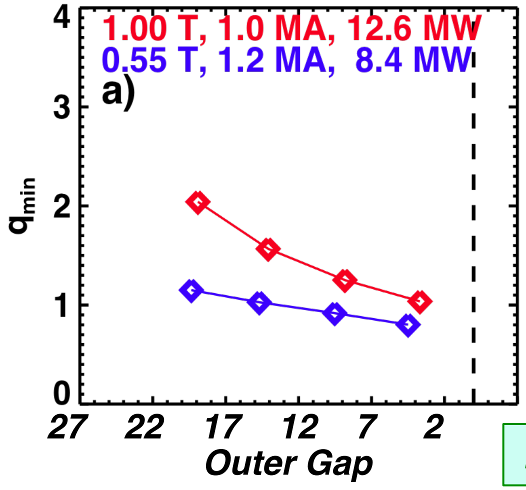
Incremental Funding: Accelerate testing of large R_{tan} NBCD for current profile control.

q-Profile Actuators

Variations in Beam Sources
800 kA Partial Inductive



Variations in Outer Gap



Milestone R14-3

Thrust 3: Disruption Avoidance and Off-Normal Event Handling Will be Studied

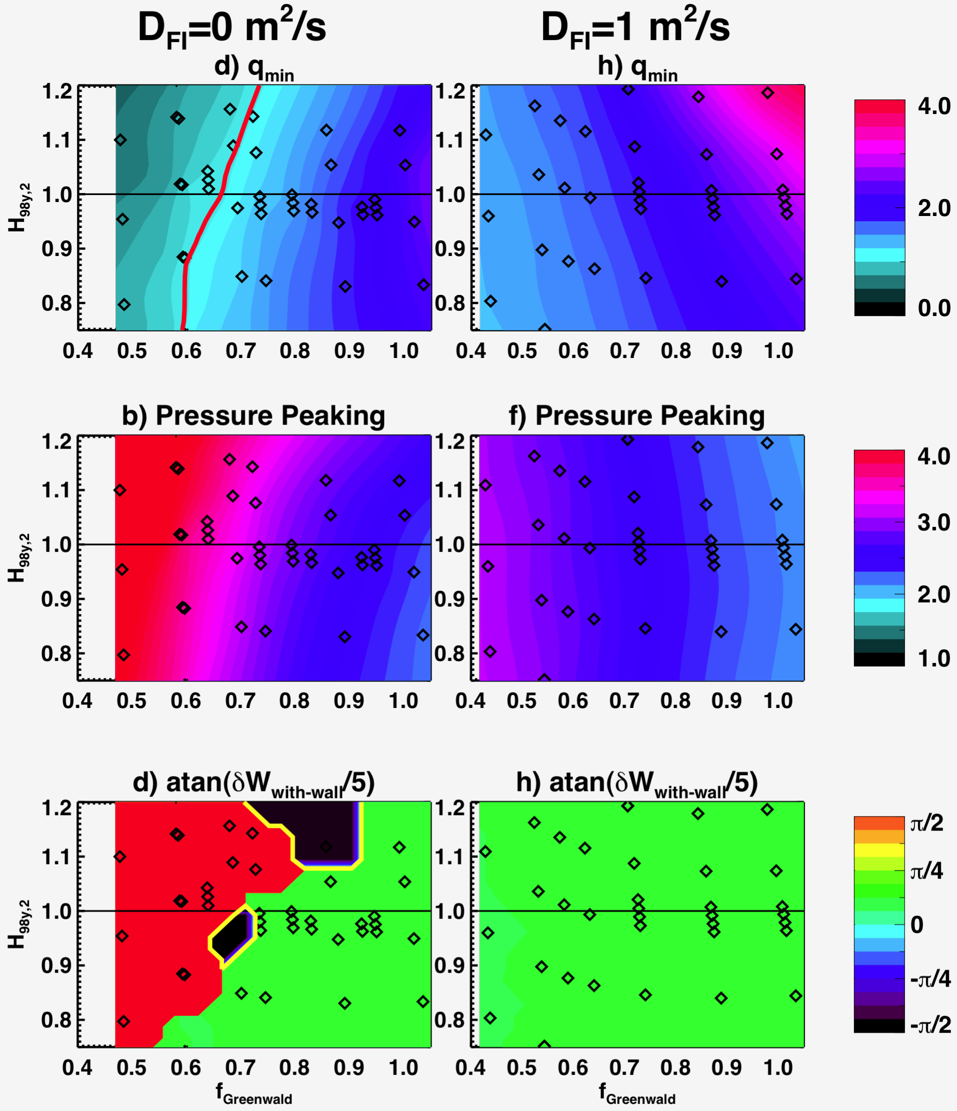
- There are good reasons to avoid high-energy/current disruptions in NSTX-U.
  - Avoid stressing mechanical components, compromising lithium coatings, or potentially damaging metal PFCs.
  - Develop the basis for disruption free operation in next-step STs & FNSF, help with the ITER disruption avoidance needs.
- Outage:
  - Use NSTX data to develop an optimal disruption detector.
  - Determine realtime data requirements.
- Years 1 & 2:
  - Implement basic detector in PCS, and design architecture of control response.
    - Incorporate data from new “Digital Coil Protection System”.
  - Assess accuracy of predictor for NSTX-U disruptions, and refine as necessary.
  - Do initial tests of automated rampdowns.
- Years 3-5
  - Add additional realtime diagnostics for improved detection fidelity.
  - Optimize rampdowns for different types of alarms.
  - Incorporate closed loop MGI if it appears promising.

Thrust 4: Explore Optimal Scenarios for Next Step STs

- Study optimal profiles for high confinement and good stability.
  - Years 3-4: Optimization of the current profile for best confinement and core n=1 stability.
  - Years 3-5: Explore alternative optimal scenarios, such as EPH or w/ ITBs.
- Study the conditions for classical beam current drive
  - Years 1-2: Study what parameters determine when *AE modes lead to anomalies in the fast ion diffusion and NBCD.
  - Years 3-5: Determine if anomalous diffusion be used for scenario optimization.
- Explore & validate integrated models for projections to FNSF.
  - Years 1-2: Compare NBCD & q-profile predictions from integrated codes to NSTX-U.
  - Years 3-5: Use knowledge to project scenarios to ST FNSF devices.

PAC29-7

1 T, 1 MA, 12.6 MW, Near Non-Inductive Scenario



Red: Internal Modes Unstable *Green: stable*

Blue/Black: External modes unstable

NSTX-U ASC Research is Supporting NSTX-Upgrade Needs While Developing the Knowledge Base for Next-Step STs

- Recent progress
  - Developed an extensive database of free boundary TRANSP simulations for a large range of NSTX-U scenarios.
    - Being used for studies of boundary physics, energetic particle and global stability, and transport and turbulence.
  - Made progress in X-point tracking and snowflake divertor control.
  - Developed new realtime diagnostics
  - Developed disruption detection algorithms.
- Comprehensive ASC research plan for NSTX-U is being developed with four main thrusts:
  - High performance scenario development
  - Axisymmetric control
  - Event handling and disruption avoidance
  - Scenario optimization for next-step STs

Backup

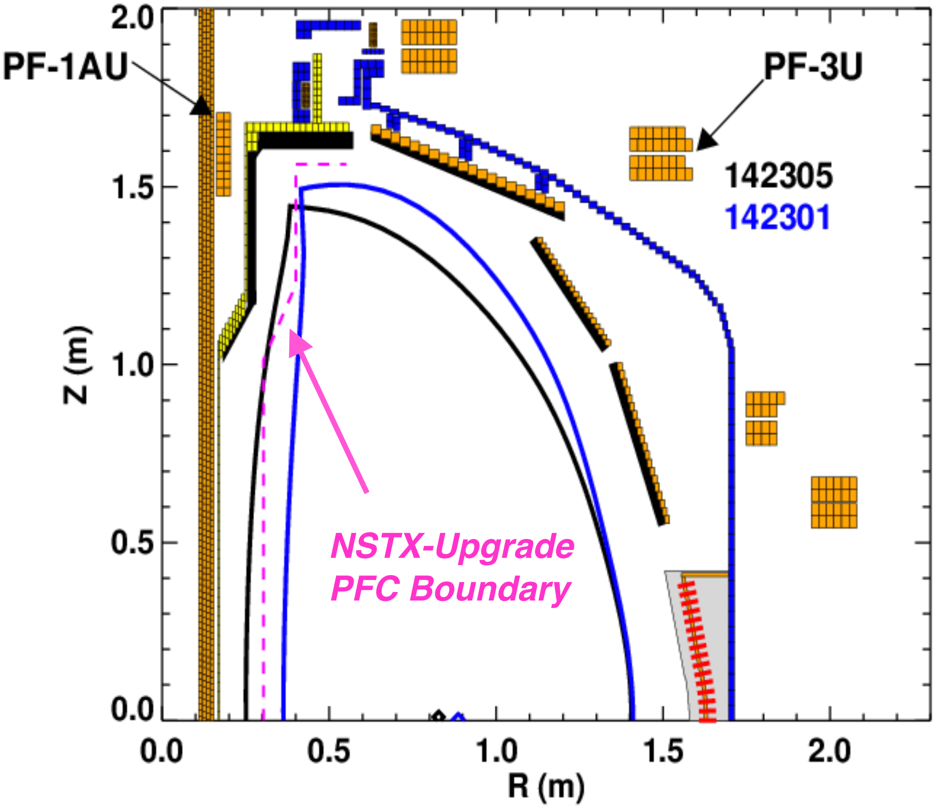
ASC-Related Collaboration Activities

- D. Mueller assisting with KSTAR and EAST operations.
- E. Kolemen relocated to GA for DIII-D control development work.
  - Presently working on realtime steerable ECCD mirrors.
- NTV physics
  - NSTX continuing long-time collaboration on NTV physics w/ CU.
  - QH-mode and EFC experiments in DIII-D
- Rotation and Current Profile Control:
  - Collaboration with E. Schuster of Lehigh University and CU.
  - E. Kolemen at DIII-D will participate in profile control experiments.

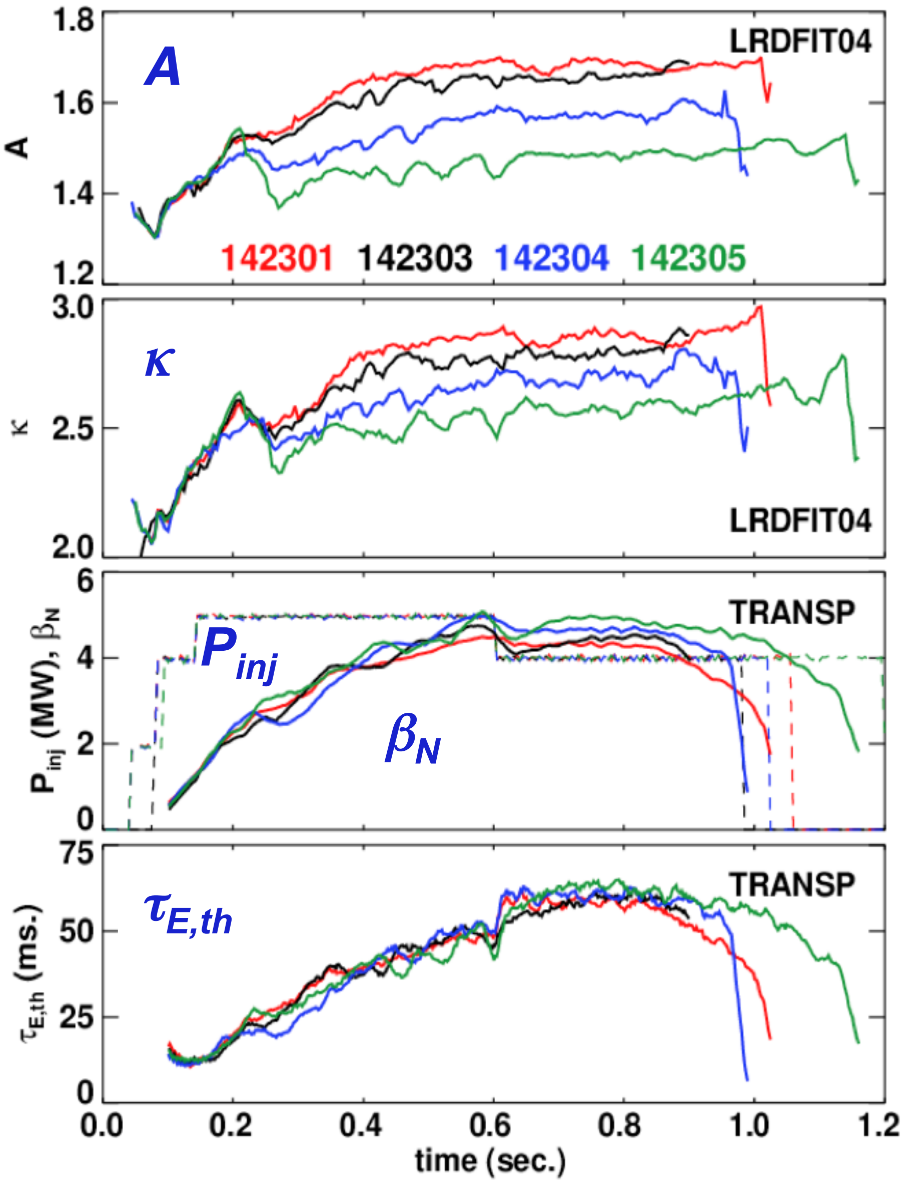
Potential NSTX Contributions to the FY-13 JRT

- Dynamics and characteristics of type-V regimes
  - Demonstration that transient heat loads scale appropriately to FNST/ITER.
  - Exploration of the shaping/collisionality/β regime for accessibility.
- Dynamics of low-level ‘EHOs’ observed in NSTX.
  - EHOs observed in both type-V ELM and lithiumized ELM-free plasmas.
    - Are these the same modes?
  - Developing strategies to actively drive these modes.
- Search for I-mode in the NSTX database.
  - For instance, more careful examination of the reversed-B_T campaign in 2009, high X-point cases with favorable grad-B orientation.
- Study effect of 3D fields on particle transport.
  - Start with “ELM-let” experiments in 2010, expand to other discharges.
- Other: Compare EPH to VH? NTV support using IPEC.

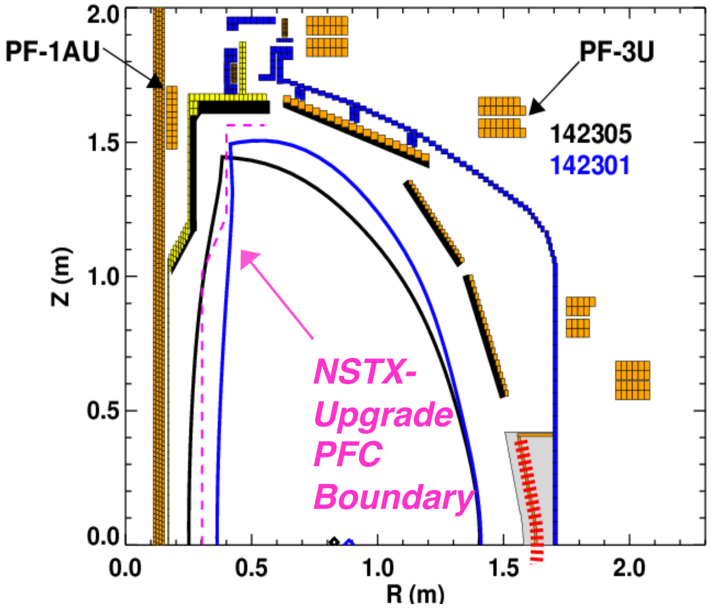
Reminder: NSTX Discharges Have Matched the Aspect Ratio and Elongation of NSTX-Upgrade Without Performance Degradation



Performance Characteristics vs. Aspect Ratio

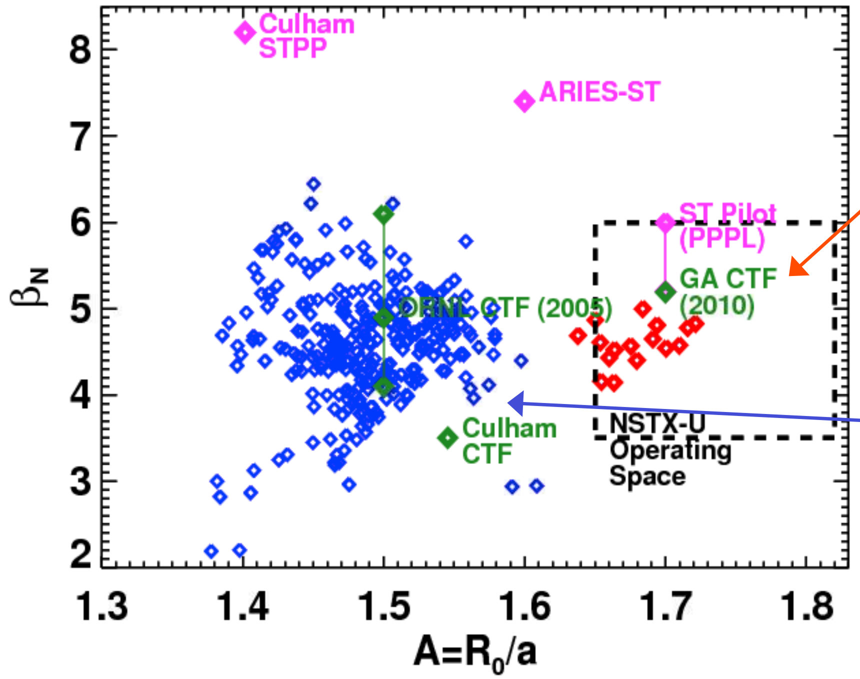


Reminder: NSTX Discharges Have Matched Many Important Equilibrium and Stability Parameters with Next Step Device



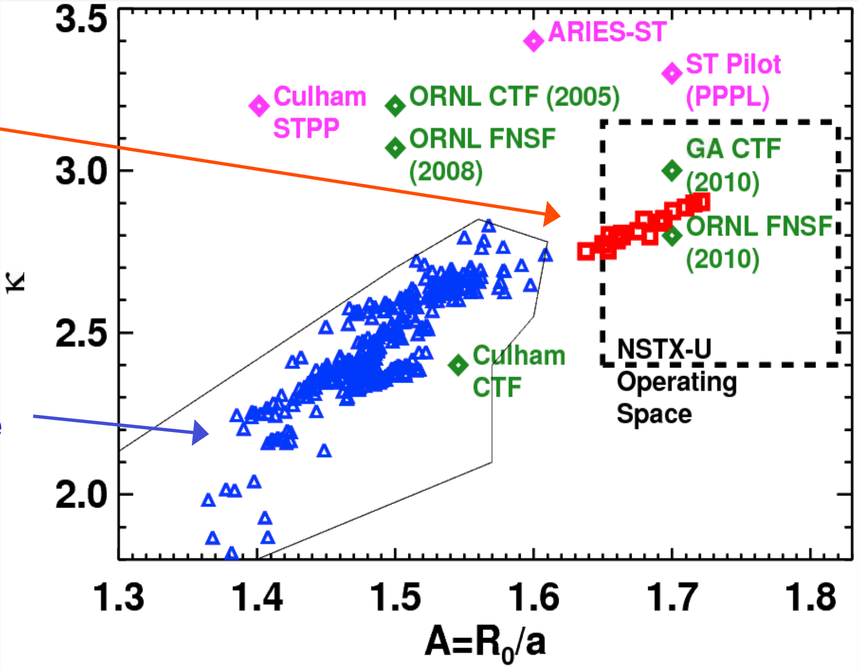
- XP during the FY2011 run develop high performance plasmas at NSTX-U aspect ratio

NSTX results (Low & High A) compared to
Pilot plants and power plants
Nuclear component testing



High-A Experiment (l_i~0.5)

Standard NSTX Operating Space ($0.5<l_i<0.8$)

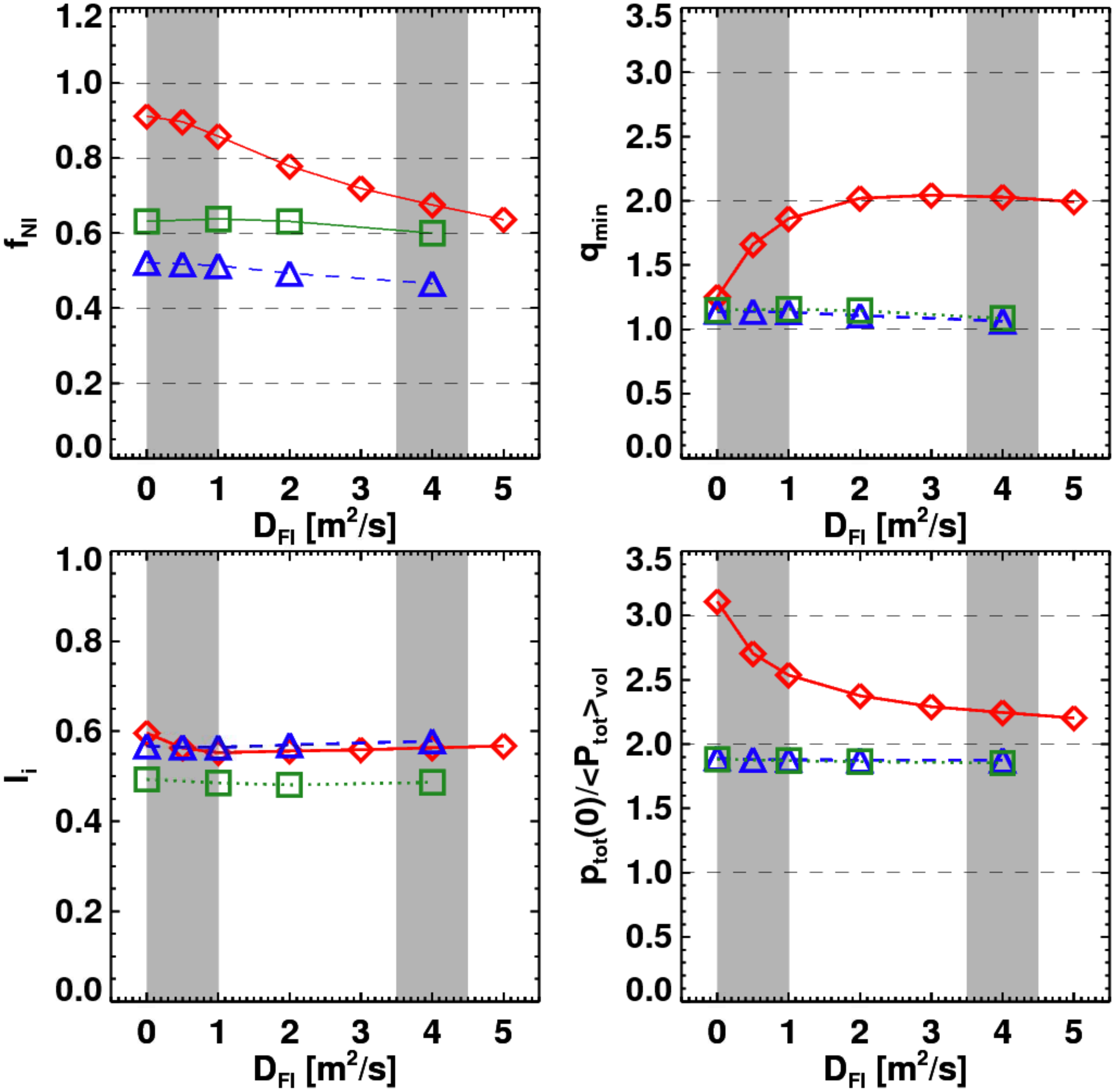


Small Amounts of Fast Ion Diffusion Reduce Non-Inductive Fraction…

PAC29-7

1.0 MA, 1.0 T, P_{inj}=12.6, near non-inductive
1.6 MA, 1.0 T, P_{inj}=10.2 MW, partial inductive
1.2 MA, 0.55 T, P_{inj}=8.4 MW, high β_T
All: f_{GW}=0.7, H_{98}=1

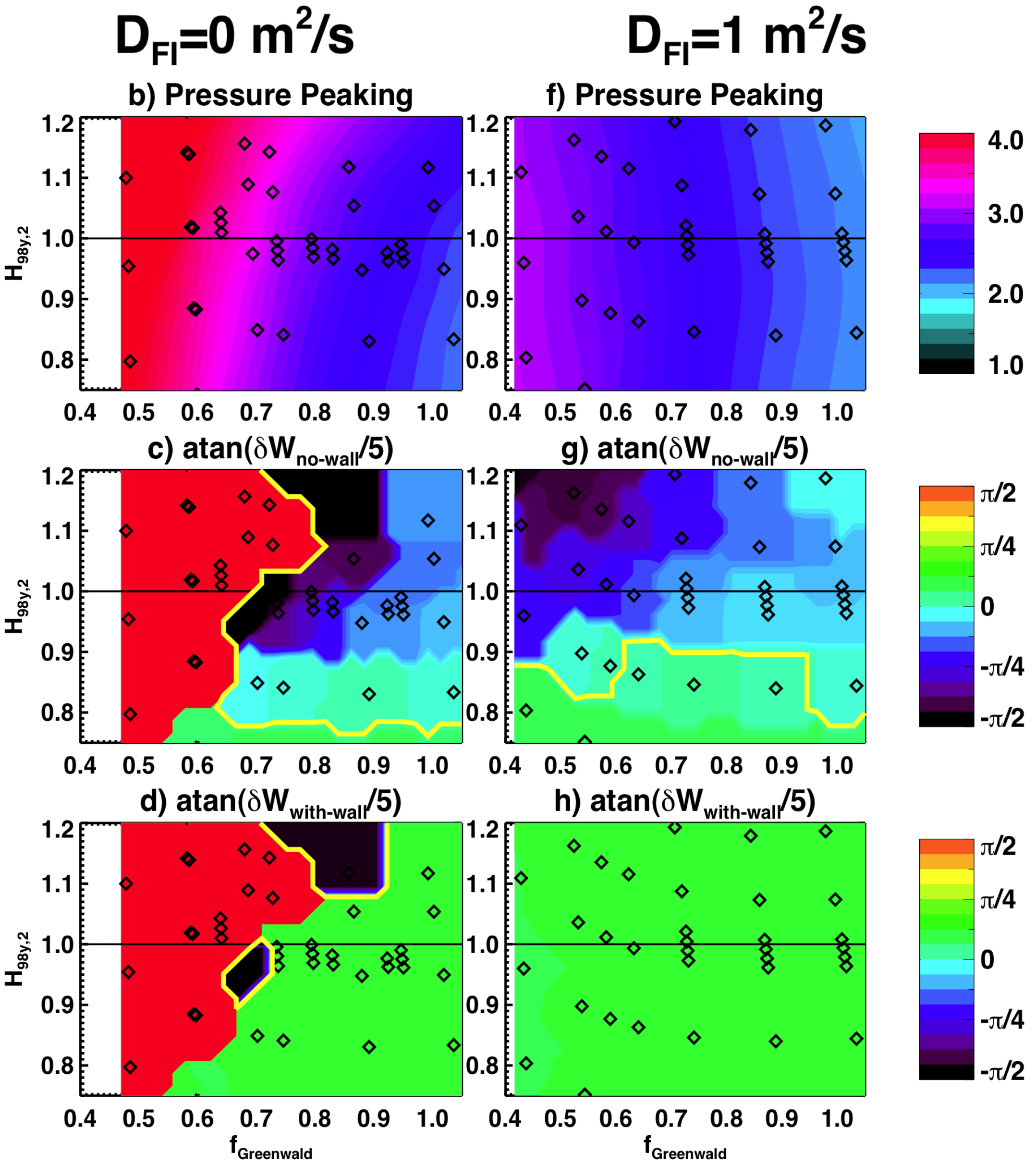
- Result from PAC-29:
  - In MHD free H-modes, bound $0<D_{FI}<\sim1$ m^2/s
  - Large sequence of TAE avalanches yields time average $D_{FI}\sim4$ m^2/s
- For scenarios with smaller beam current drive, the effect of D_{FI} up to ~4 is irrelevant.
- For scenarios with larger beam current drive, D_{FI} ~1 already has a strong effect.
  - Lowers the non-inductive fraction.
  - Lowers the pressure peaking.
  - Raises q_{min} (less central NBCD)



Small Amounts of Fast Ion Diffusion Reduce Non-Inductive Fraction …But Improve Stability

PAC29-7

- Consider the nearly 100% non-inductive scenario at 1.0 MA, 1.0T, and P_{inj}=12.6 MW
    - H_{98}=1.06 yields f_{NI}~1
- Consider D_{FI}=0 &1 m^2/s.
- Small fast ion diffusion results in:
    - Reduced pressure peaking, and increased q_{min}, at lower density.
    - Improved external mode stability.
    - Elimination of internal modes due to low-q.
- When combined with a conducting wall, the space is stable to all n=1 modes.
    - See MS talk for RWM stability calculations



Red: Internal Modes Unstable *Green: stable*

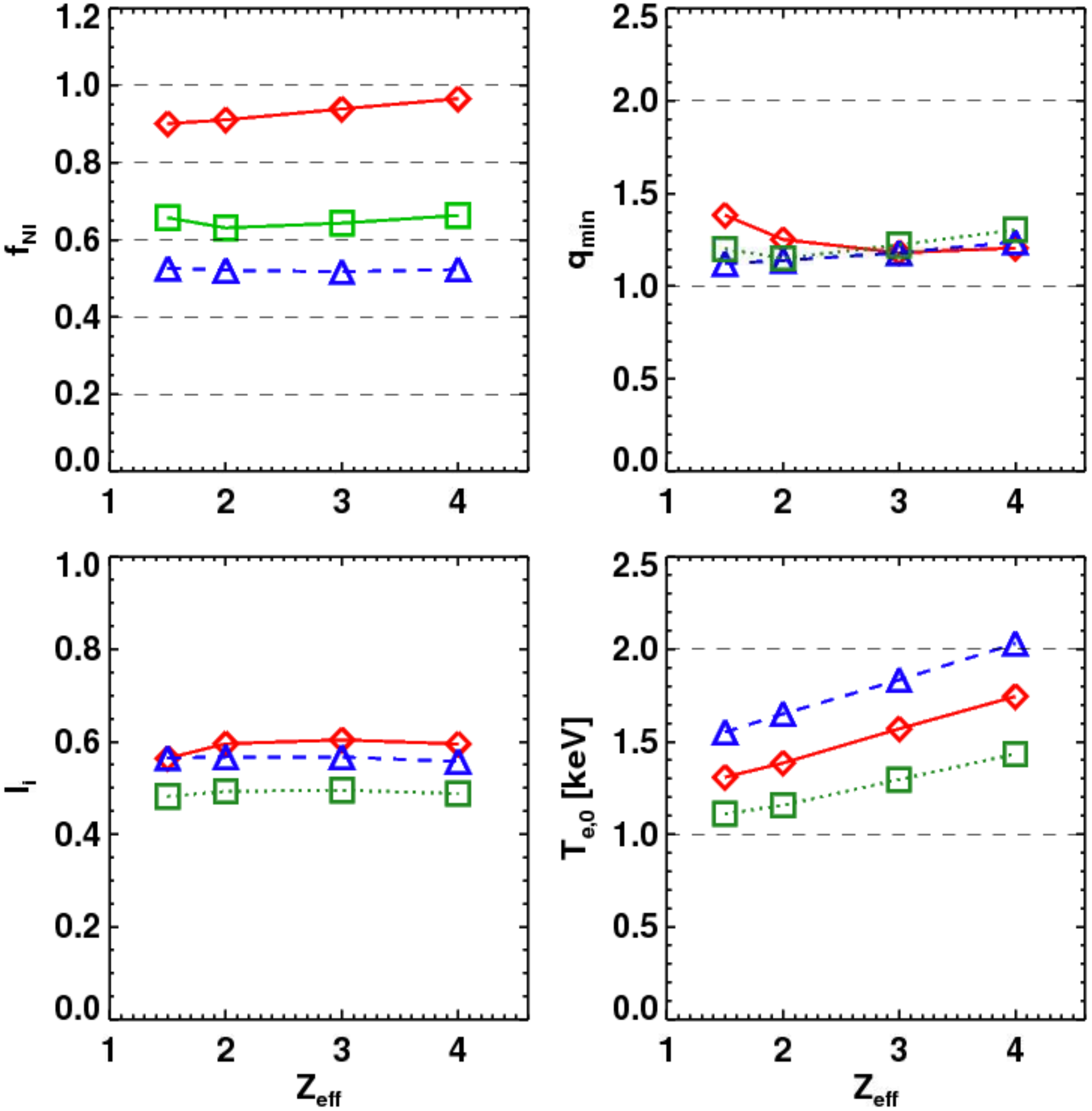
Blue/Black: External modes unstable

Scenario Goals Can be Met over a Range of Z_{eff}, Provided Confinement is Maintained

PAC29-7

- Li H-modes, even w/ small ELMs and controlled density, tend to have Z_{eff}~3.
- Increasing Z_{eff} with fixed T_e reduces non-inductive fraction.
- Increased Z_{eff}, with fixed H_{98}, results in very little change.
  - H_{98}~1 confinement (or better) observed in lithiated H-modes over a range of Z_{eff}.
- The electron confinement is a critical variable in determining the scenario performance.

1.0 MA, 1.0 T, P_{inj}=12.6, near non-inductive
1.6 MA, 1.0 T, P_{inj}=10.2 MW, partial inductive
1.2 MA, 0.55 T, P_{inj}=8.4 MW, high β_T
All: f_{GW}=0.7, H_{98}=1



Discharges Up to 10 s in Duration May Ultimately Be Possible Using Modulated 1st and 2nd NBI

PAC29-7

Modulation of 6 Beams To Produce Minimal q_{min} Variation