NSTX-U

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Advanced Scenarios and Control Overview

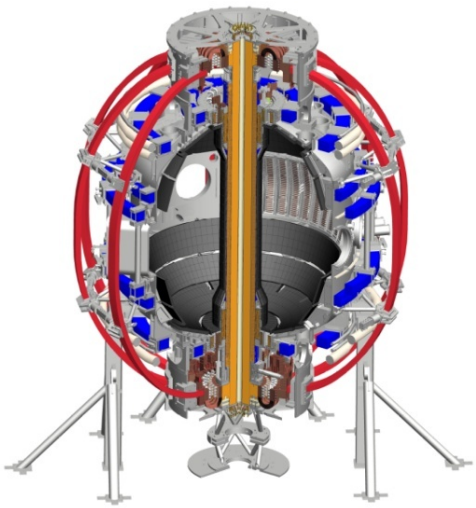
Status and Plans for NSTX-U Research Operations

Stefan Gerhardt

and the NSTX Research Team

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
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

NSTX-U PAC 35
B318, PPPL
6/11/2014



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

Advanced Scenarios and Control Group Goals

ASC Programmatic Goal From The 5 Year Plan:
Develop the basis for integrated, steady-state operation and axisymmetric control for next-step STs, while helping resolve key scenario and control issues for ITER

ASC Operational Goal From The 5 Year Plan:
Establish stationary, 100% non-inductive operation, and partial inductive operation up to I_P=2 MA, for 5 seconds over a wide range of Greenwald fractions, collisionalities, and β values

This talk will focus on research and operations aspect in FY14-FY16 targeting these goals

Outline
(organized chronologically)

- FY-14 control research to support milestones and five year plan research
- Research operations preparations
- Scenario and control research activities for the first 2 years of operations
  - Long-Pulse and High Current Scenarios
  - Non-Inductive Scenarios
  - Profile Control Research
  - Heat Flux Control
  - Disruption Avoidance
  - NBCD Studies

Modeling of non-inductive start-up/ramp-up discussed in talk by F. Poli.

Outline
(organized chronologically)

- FY-14 control research to support milestones and five year plan research

R14-3 Milestone

Develop advanced axisymmetric control techniques in sustained high performance plasmas

Supports five year plan thrust 2 goals

Current Profile Control

Dan Boyer (ORISE Fellow) and E. Schuster Group (Lehigh U.)

Rotation Control

Collaboration with PU Mechanical and Aerospace Engineering

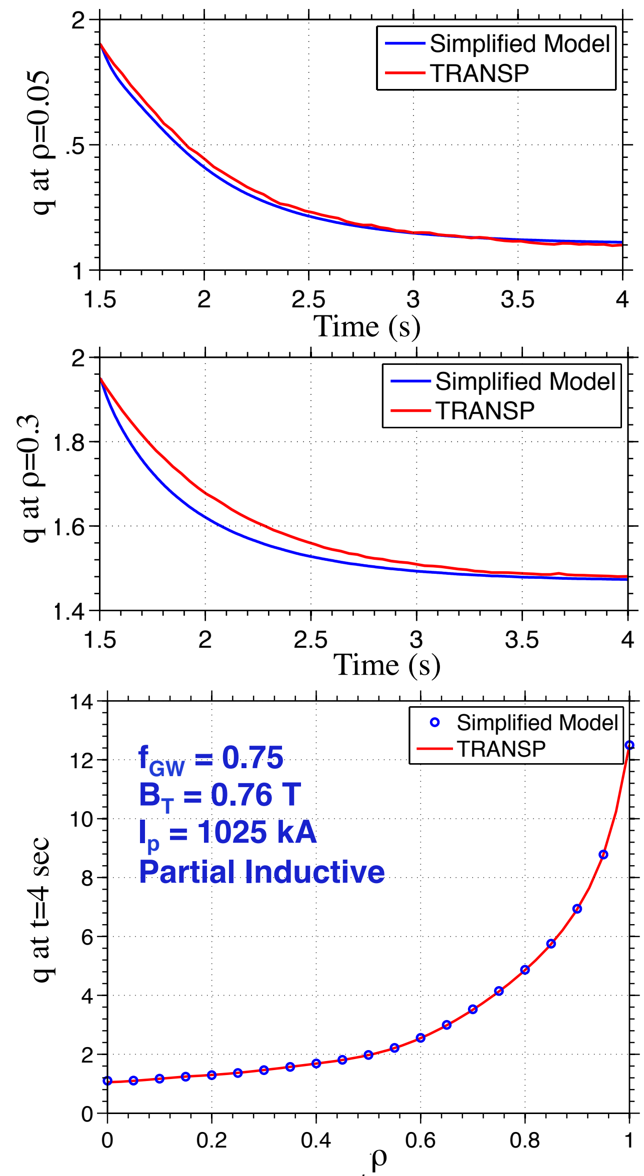
Primary effort by I. Goumiri (graduate student)

TRANSP is the Primary Tool for Full-Physics Modeling

Running code with an “expert file” that allows it to be used as a virtual experiment

Reduced Model For Current Profile Evolutions Will Guide Profile Control Design

- Control-oriented dynamic model based on magnetic diffusion equation
  - Fixed model parameter profile shapes; magnitudes scale with global parameters
    - Electron density and temperature, resistivity, non-inductive current drive, bootstrap current
  - Fixed magnetic geometry assumed
- Used to design dynamic observer for profile estimation
  - Improves real-time measurement quality (denoise, account for non-converged rtEFITs)
  - Enables preliminary control experiments prior to real-time MSE
- Reduced further for control design
  - Linearized around operating point to obtain state-space model for modern control design
- Process similar to that used in successful q-profile control at DIII-D

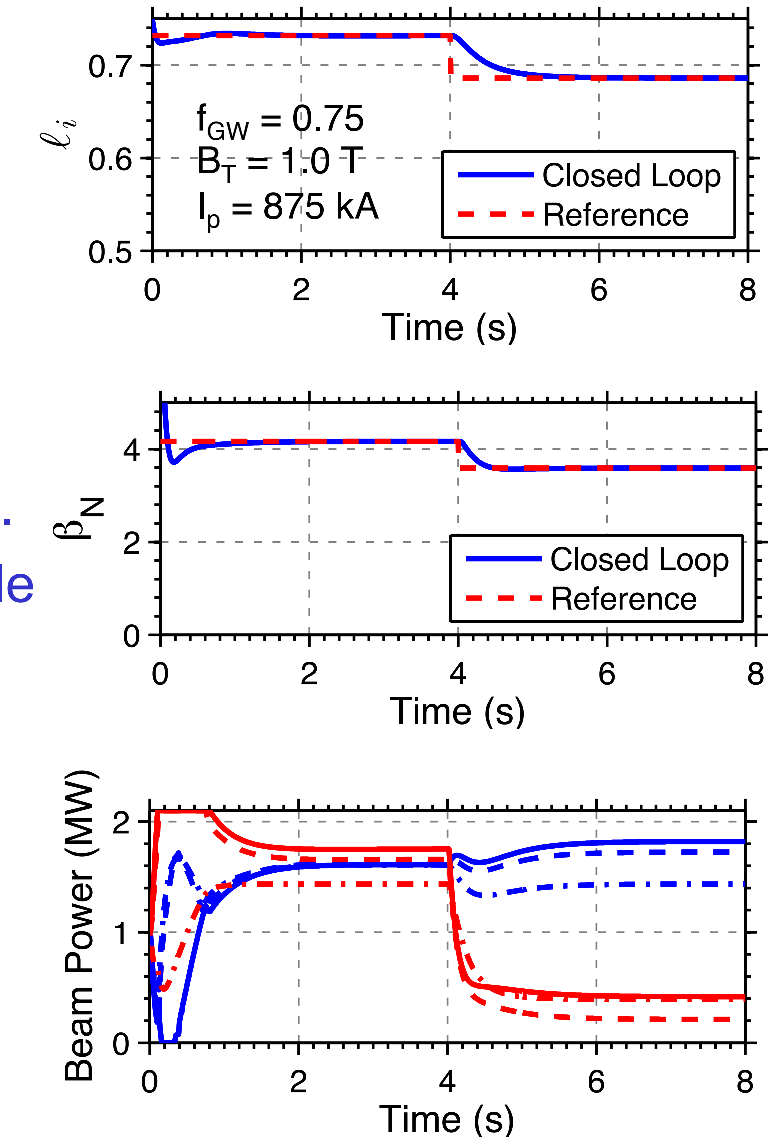


R14-3

Dan Boyer, ORISE + Lehigh U. Control Collaboration

First Use of Model is For Combined β_N & l_i Controller

- Optimal control, considering six individual beams as feedback actuators
- Plans for FY14
  - Validate profile estimation scheme using NSTX data.
  - Explore controllable range of variation.
  - Design controllers for beta and q profile
    - Simulate in TRANSP using expert file
    - Incorporate additional feedback actuators (density, outer gap, I_p)
  - Prepare PCS algorithms for:
    - β_N & l_i
    - β_N & q



R14-3

Dan Boyer, ORISE + Lehigh U. Control Collaboration

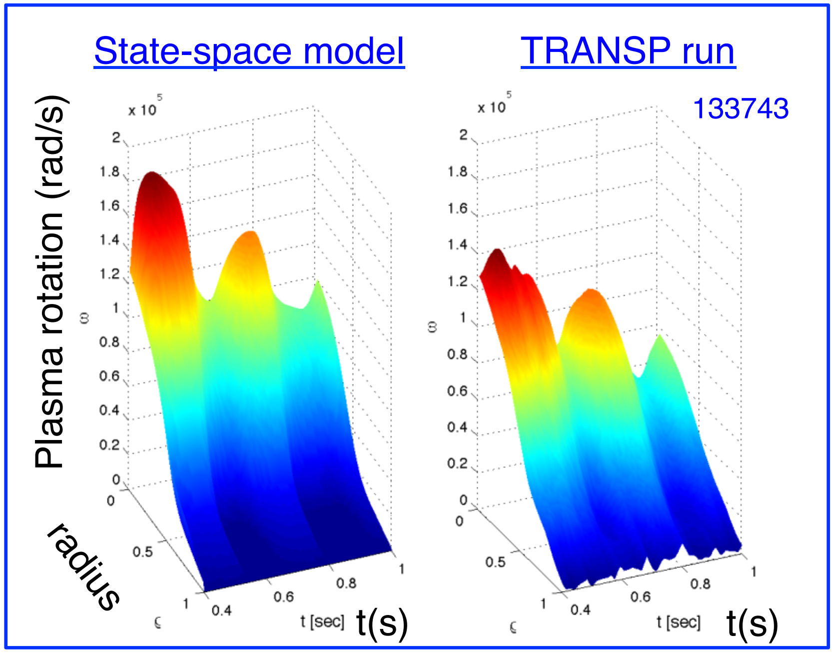
Non-resonant Neoclassical Toroidal Viscosity (NTV) physics will be used for the first time in rotation feedback control

- Momentum force balance – ω_ϕ decomposed into Bessel function states

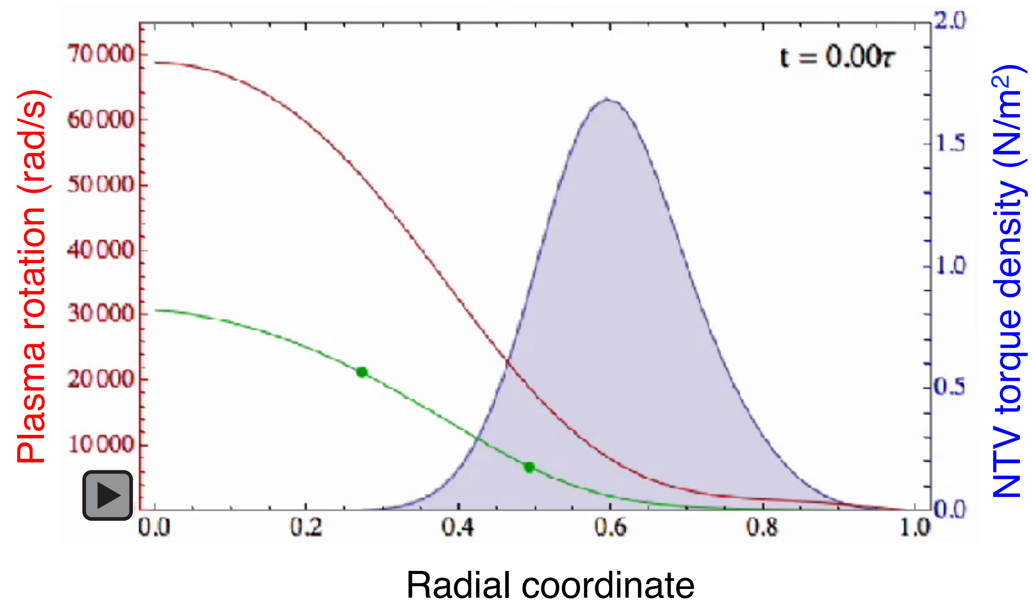
$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle \left(R \nabla \rho \right)^2 \right\rangle \frac{\partial \omega}{\partial \rho} \right] + T_{NBI} + T_{NTV}$$

- NTV torque:

$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2} \right) g\left(\delta B(\rho) \right) \left[I_{coil}{}^2 \omega \right]$$ (non-linear)

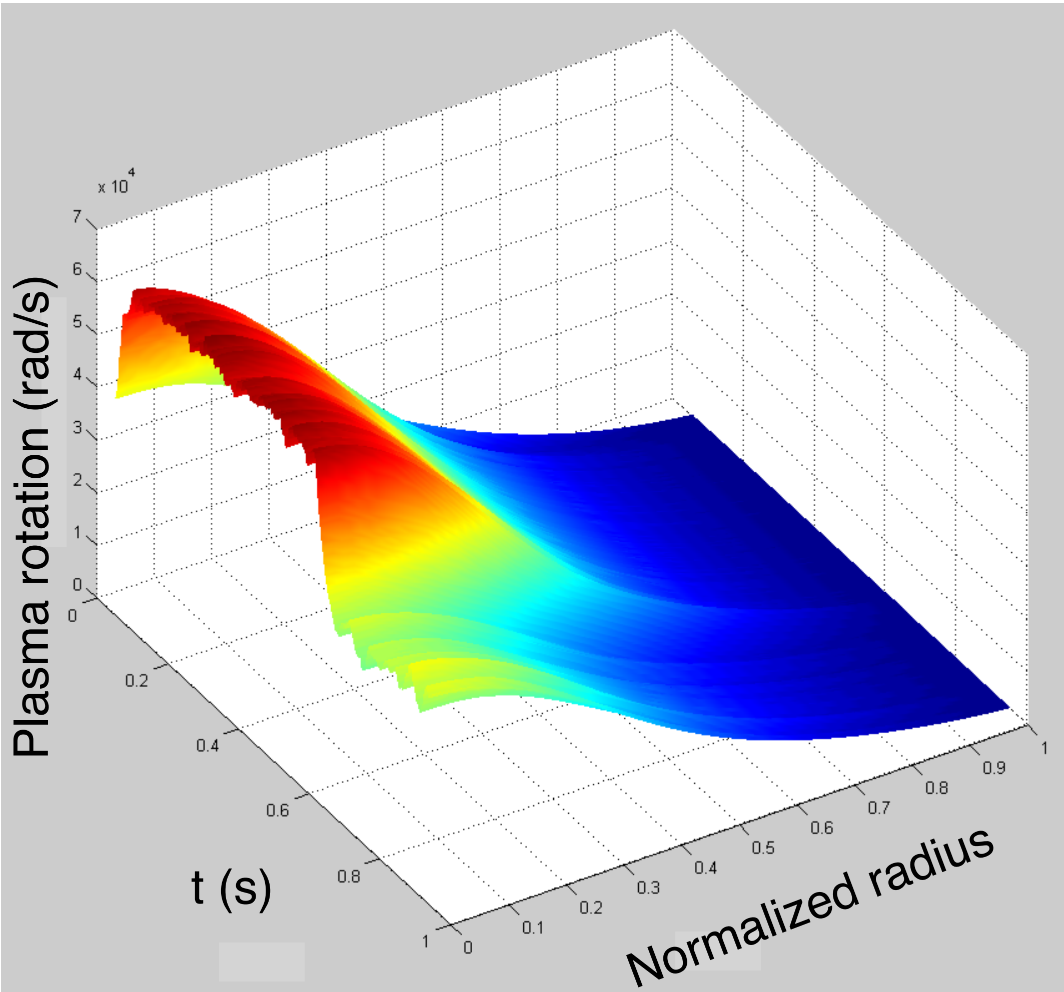


Feedback using NTV: "n=3" $\delta B(\rho)$ spectrum

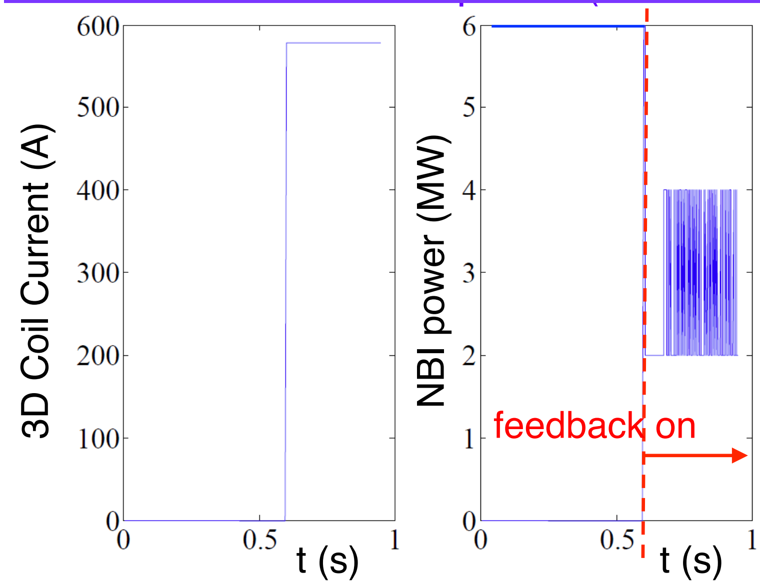


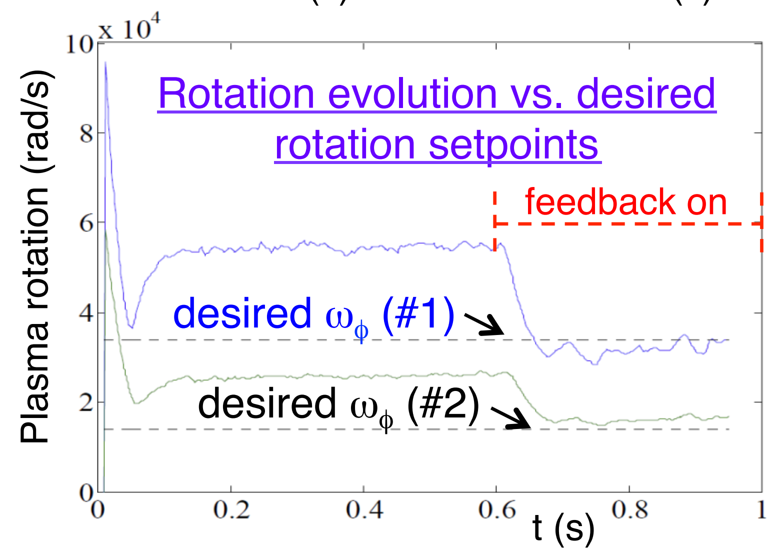
I. Goumiri (PU), S.A. Sabbagh (Columbia U.), D.A. Gates, S.P. Gerhardt (PPPL)

Plasma rotation control has been demonstrated for the first time with TRANSP using NBI and NTV actuators



3D coil current and NBI power (actuators)





- This case uses pre-programmed 3D coil current and NBI feedback

Outline

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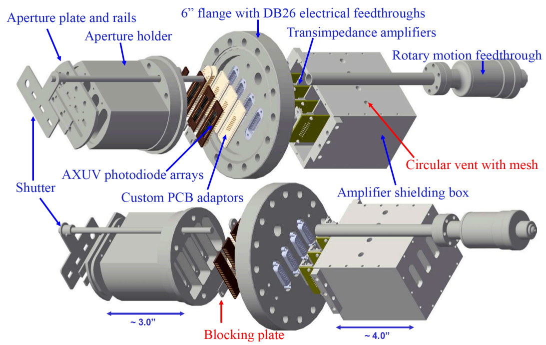
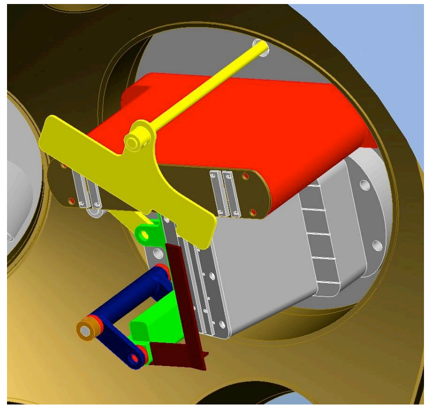
Operations Team Making Great Progress in Preparing the Facility for Research: Diagnostics

New SSNPAs

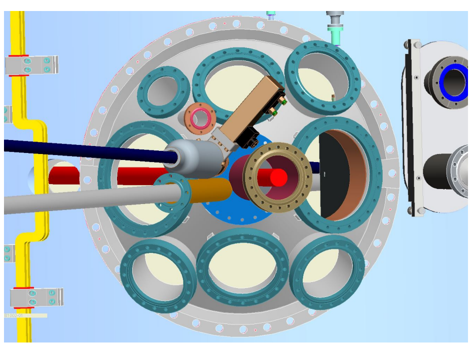


Combined Bolometer and ME-USXR Diagnostic

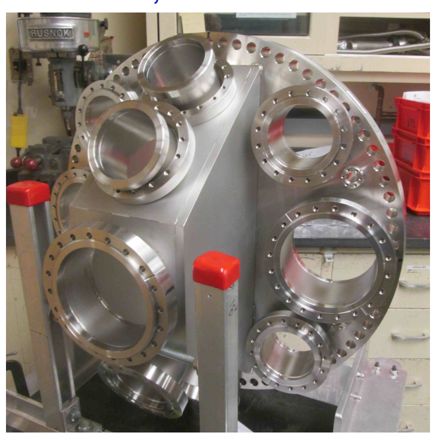


- CHERS, FIDA, MSE systems reinstalled and undergoing calibration
- MPTS Upgrade on-track to support first research operations in March
- New 17 channel Langmuir probe arrays in each of upper and lower divertors
- MAPP probe has been fit-up to check for interferences with NSTX-U infrastructure
- sFLIP rebuilt to accommodate new port

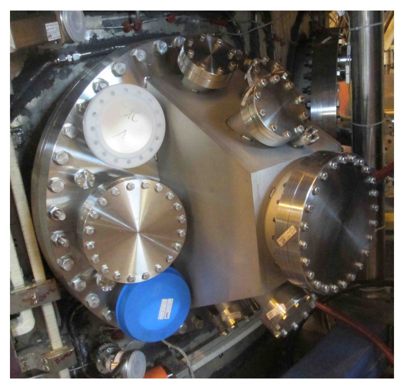
Bay G "cerberus"
FIReTIP interferometer, High-K Scattering, VB diagnostic
(Note: FIReTIP will be the primary measurement for density control)



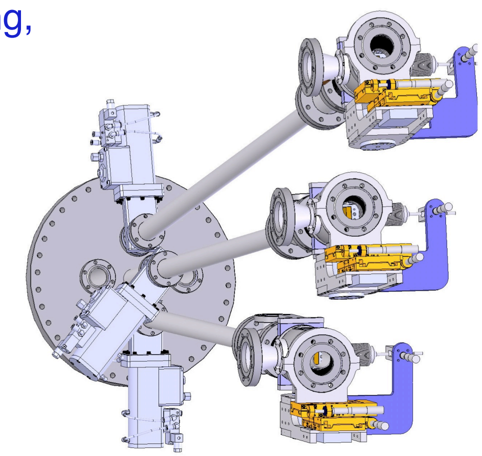
Bay J
UT-K and Divertor Spectrometers, Upward LITER, UCLA Reflectometer and Polarimeter, SGI, RF Probe.



Bay I
XCS, TGS, IR & Visible Cameras, SSNPA, Plasma TV, Microwave Imaging, QMB, Bolometers



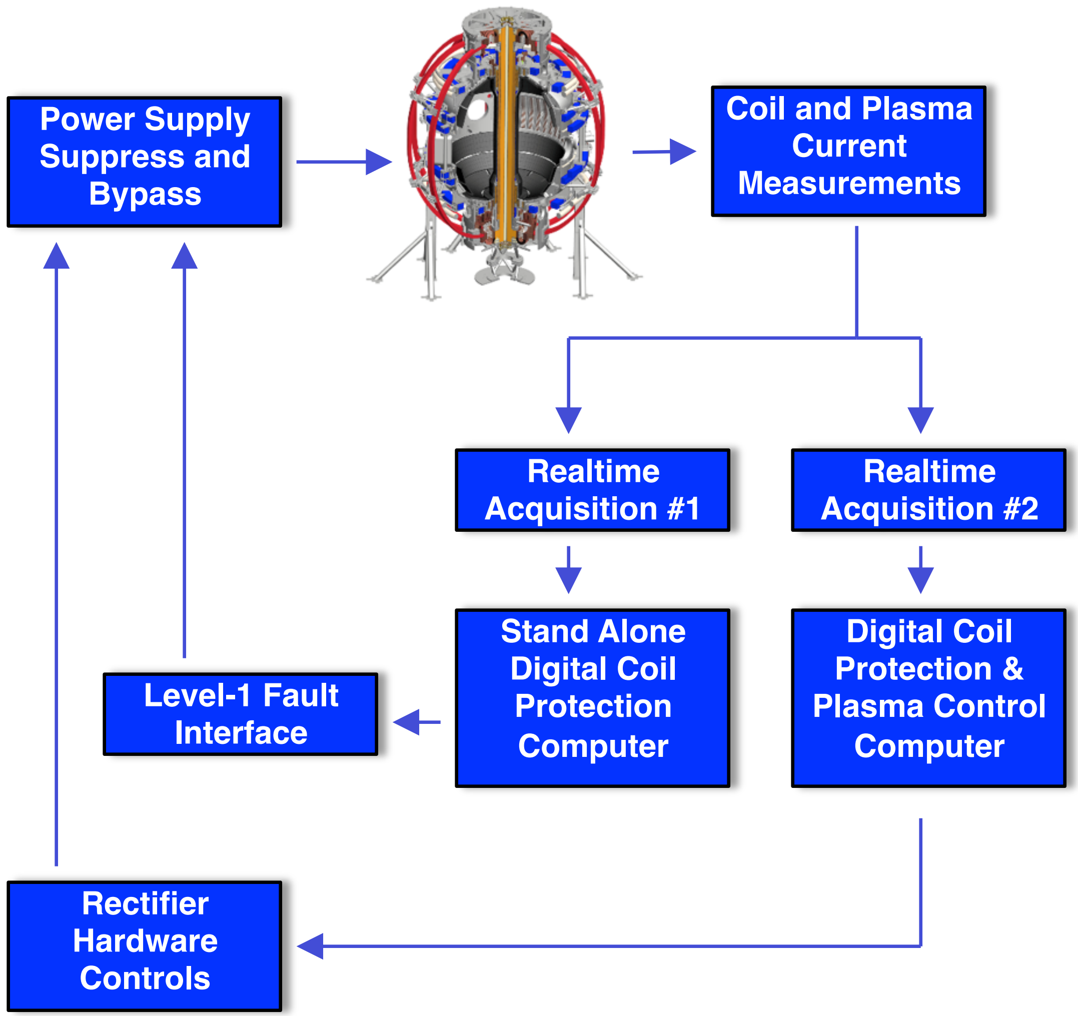
Bay K
XEUS, LoWEUS, MonaLISA EUV and USXR spectrometers



Operations Team Making Great Progress in Preparing the Facility for Research: Boundary Physics Operations

<table>
<tr><td>Radiative Divertor Studies</td><td colspan="2">• Two new high-throughput gas delivery systems in the lower divertor.
• If attractive, can be easily duplicated at other locations and in upper divertor</td></tr>
<tr><td>Fuelling and Density Control</td><td colspan="2">• All gas valves will be under PCS control
• Allowing SGI to be used for density feedback
• Divertor injectors for radiation control</td></tr>
<tr><td>Boronization</td><td colspan="2">• New engineer with extensive experience in hazardous gas handling recently hired.
• Anticipate that a new boronization system will be available for research operations</td></tr>
<tr><td>Lithium Evaporators (LITERs)</td><td>• Evaporators carefully stored during the outage.
• New lab being developed for LITER filling & maintenance</td><td rowspan="2">• Lithium chemist hired to oversee the safe and efficient deployment of these technologies.</td></tr>
<tr><td>Granule Injectors for NSTX</td><td>• Use UIUC technique for making granules under mineral oil.
• New injector almost assembled</td></tr>
</table>

New Digital System Provides Comprehensive Coil Protection



- **Protects the NSTX-U coils and mechanical structure against electromagnetic loads**
- **Computes forces and stresses in realtime based on reduced models of the full mechanical structure**
- **Redundant systems**
- **Full commissioning system will be a key part of early operations**

“DCPS” software testing is being performed right now

Plan for a Smooth Transition from Construction to Research Operations

NSTX-U ISTP, Commissioning, and Startup will follow a similar process as NSTX initial commissioning and startup from February 1999.

Pre-operational test of subsystem s (PTP'S) → *Activity Certification Committee (ACC) review* → *PU Operational Readiness Assessments (ORA)* → *Integrated system test procedure (ISTP) (per OP-NSTX-02 rev 14)* → *CD-4 Construction Project Complete* → *Final Preparation for Research Campaign*

Activity Certification Committee (ACC)

- representatives from PPPL Engineering, Research, Safety, and the DOE Princeton Area Office,
- review newly installed subsystems before commissioning.
- System reviews are performed at completion of construction activities.

Operational Readiness Assessment (ORA)

- Led by the Princeton University,
- external committee review based on ACC and QA Audit reports, on site visits, before start-up.

Safety Certificates allowing Power and then Plasma Operation issued following recommendations of the ORA.

Provisional Schedule for the FY15 Research Campaign

October 2014				November 2014				December 2014					January 2015				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
											Holliday						
Upgrade Project (CS Installation, TF Flex. Connections & Lead Extensions, NB Conditioning, Rectifier Commissioning, Pump-down and Leak Check)													CS Bake, GDC	ISTP	CD-4	Facility Work While Under Vacuum	

February 2015				March 2015					April 2015				May 2015			
18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
	MPTS Rayleigh Raman	Bake Out				ISTP	Commisioning				1	1	Maint.	1	1	1

June 2015					July 2015				August 2015				September 2015					Total
35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	
Maint.	1	1	1.1	Maint.	1.1	1.1	1.1	1.1	Maint.	1.1	1.1	1.1	1.1	1.1	vent	Outage (Calibrations, Inspections, Upgrades)		18

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Data Acquisition Commissioning for Diagnostics
Ex-Vessel Diagnostic Installations
Gas Delivery System Final Checks
Magnetics Debugging
Beamline #1 Final Checks

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Magnetic Calibrations
MSE Calibrations
CHERS Calibrations
Boronization

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Commissioning

I_p<=1.0 MA, B_T<=0.5

- Breakdown and current ramp scenarios
- EFIT & rtEFIT Reconstructions
- Shape & position control
- Reliable H-mode
- Diagnostic operations
- DCPS under plasma operations

Boronizaton +He GDC for PFCs

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Boronizaton +He GDC for PFCs

<u>Research Operations</u>

LITERs when the operational status allows and physics program desires
Continued discharge, control, and diagnostic commissioning

18 Run Weeks with Contingency

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Strategy for Achieving Full NSTX-U Parameters

After CD-4, the plasma operation could quickly access new ST regimes

	NSTX (Max.)	FY 2015 NSTX-U Operations	FY 2016 NSTX-U Operations	FY 2017 NSTX-U Operations	Ultimate Goal
I_P [MA]	1.2	~1.6	2.0	2.0	2.0
B_T [T]	0.55	~0.8	1.0	1.0	1.0
Allowed TF I^2t [MA^2s]	7.3	80	120	160	160
Longest I_P Flat-Top at max. I^2t, I_P, and B_T [s]	~0.4	~3.5	~3	5	5

- 1st year goal: operating points with forces up to ½ the way between NSTX and NSTX-U, ½ the design-point heating of any coil
  - Will permit up to ~5 second operation at B_T~0.65
- 2nd year goal: Full field and current, but still limiting the coil heating
  - Will revisit year 2 parameters once year 1 data has been accumulated
- 3rd year goal: Full capability

Repair of the motor generator weld cracks to finsh in July 2014, facilitated by incremental funding in FY14

Operation Tools for Density & Impurity Control

Years 1 & 2 of ops.: Examine Wall Conditioning, Fueling, and ELM Pacing

Boronized PFC Studies

- Plan to start NSTX-U operations with TMB.
- Utilize regimes with natural ELMs to control impurity accumulation
- Between-shot He glow for wall conditioning
- Deuterium inventory likely to rise throughout the discharge

Lithiated PFC Studies

- High-τ_E, ELM-free regimes w/ Li conditioning
- Pulsed 3D fields or lithium granules for ELM pacing to provide impurity control
- Deuterium inventory likely well controlled, but unclear if target Z_{eff}~2 can be achieved

Both Scenarios: Realtime Density Measurements via FIReTIP
Supersonic Gas Inj. for Density Control

Out Years: Utilize Cryo-pumping and Partial NCC

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    } Thrust #1 of 5YP
  - Profile Control Research
  - Heat Flux Control
    } Thrust #2 of 5YP
  - Disruption Avoidance } Thrust #3 of 5YP
  - NBCD Studies } Thrust #4 of 5YP

Modeling of non-inductive start-up/ramp-up discussed in talk by F. Poli.

Profile Control Will Be Developed to Support Scenario Development and Optimization

- Plans for FY14
  - Finalize observer/controller designs for β_N+l_i, β_N+q
  - Extend rotation control design to NSTX-U beams sources
- Plans for FY15
  - Validate NBCD predictions
    - Described in three more slides
  - Measurements:
    - Complete realtime V_ϕ measurements
    - Test realtime MSE measurements
  - Implement current profile observer in PCS
  - First β_N+l_i control studies
  - Finalize rotation control design and begin implementation
- Plans for FY16
  - Begin closed loop rotation control experiments
  - Begin implementation of MSE constraint in rtEFIT for improved reconstruction.
    - Make first assessment of β_N+q_{min} control if possible

Supports Milestones R14-3, 15-3, 16-4

Research Will Focus on Optimizing the 100% Non-Inductive Operating Point

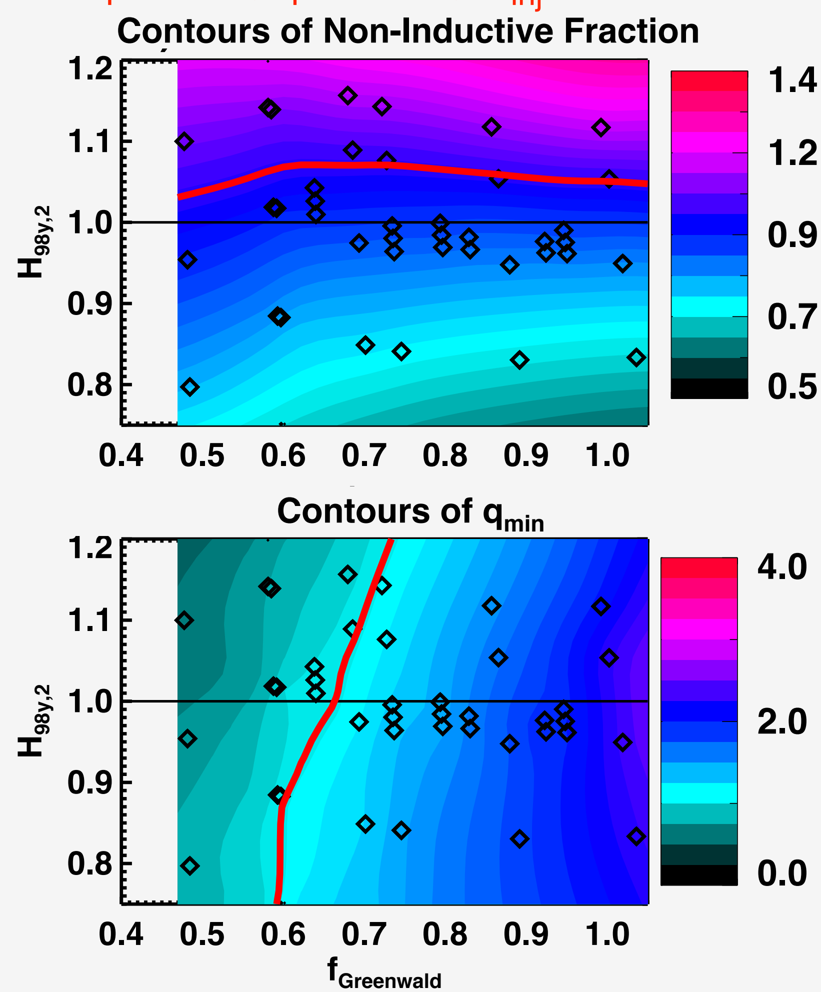
- Fully relaxed non-inductive operating points have been explored with free-boundary TRANSP calculations

R16-4

Research Timeline for 100% Non-Inductive Scenarios

Operation Year	B_T [T]	Current Goal [kA]	Duration Goal
2015	0.75	~600-800	A few τ_E
2016	0.75-1.0	~600-1000	1-2 τ_R
Out-Years	1	800-1300	Up to 4.5 s at lower I_P

- These scenarios, obtained at first with an inductive ramp-up, will provide a target for non-inductive ramp-up studies
- See talk by F. Poli



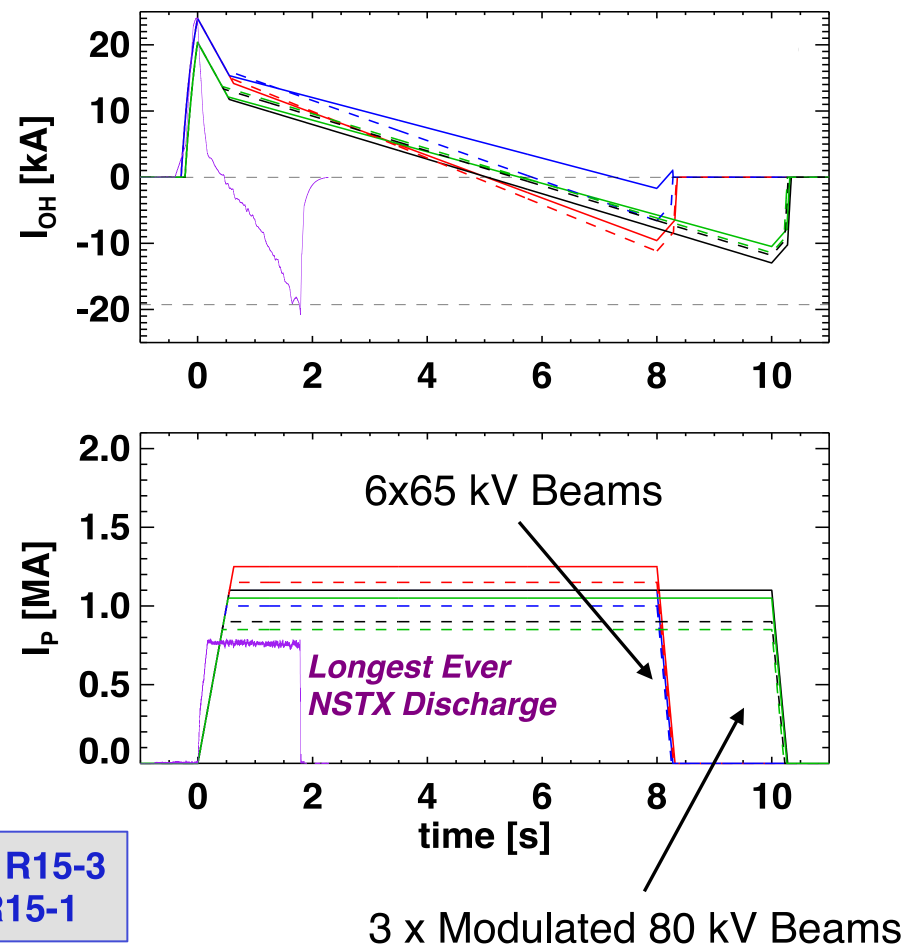
S.P. Gerhardt, et al, Nuclear Fusion 52 083020 (2012)

ASC Group Will Develop High-Current and Long Pulse Scenarios For Physics Exploration

- Two types of partial inductive operation:
  - High-I_P operation for low collisionality and divertor heat flux studies
  - Long pulse for particle retention and disruptivity studies
- FY15: Re-optimize startup for reduced fueling and low collisionality.
  - Optimize fueling, ramp-rate, error field correction, torque input.
- FY16: Develop longer pulse and higher current operations.
  - Learn to run the 2MA scenarios within the DCPS operating envelope.
  - Assess long-pulse operations within the pumping and particle control tools available.
- High-I_P & long pulse development will be connected to progress in:
  - Particle Control
  - Heat flux mitigation

Addresses milestone R15-3
Supports milestone R15-1

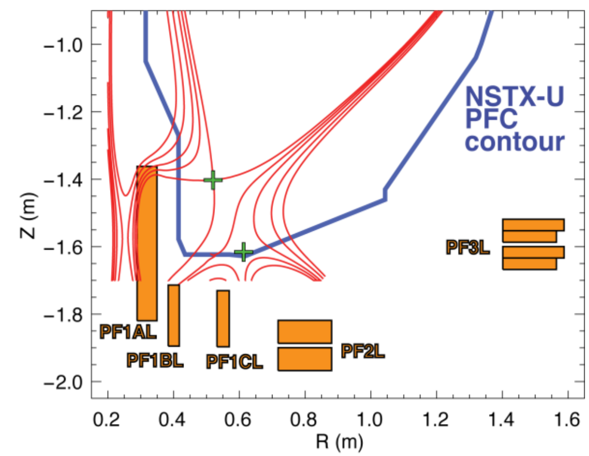
B_T=0.75 T, ***8-10 Second Discharge***
Scenarios Limited by q_{min}>1.1 or OH Coil I^2t
2 Confinement and 2 Profile Assumptions



Snowflake Geometry and/or Divertor Radiation Will Be Developed to Support High-Current Operation

- Roughly speaking, exceeding 1.5 MA and 10 MW will require strong divertor radiation or large flux expansion.
  - See backup slides.
- Physics of these techniques to be covered in Boundary Physics talk
- Control development plans

Snowflake Divertor in NSTX-U
Increases divertor volume and flux expansion.



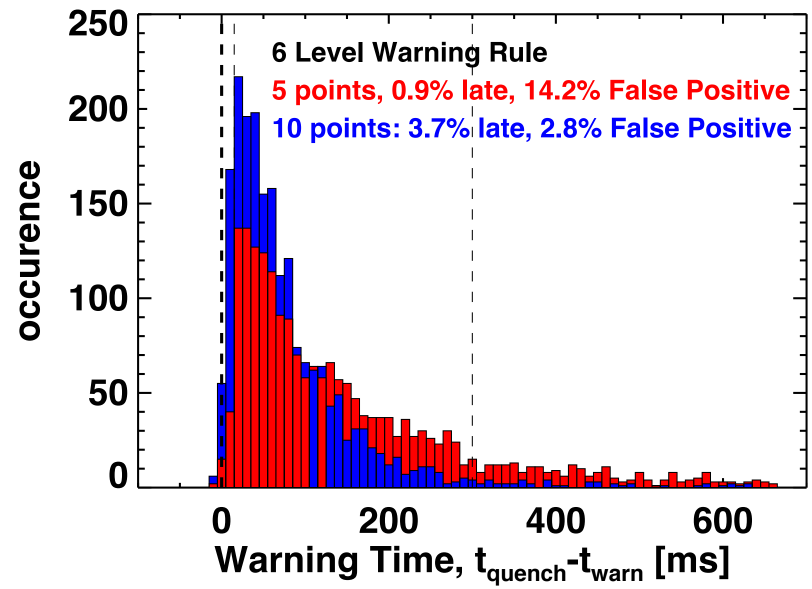
– FY15 research:
  - Bring rtEFIT, ISOFLUX and strikepoint control back online
  - Implement dual X-point tracking software and make first tests of snowflake divertor control
  - Develop realtime density measurement with FIReTIP interferometer
  - Off-line development of diagnostics relevant for radiative divertor control

– FY16 research
  - Finish tuning of snowflake divertor controller
  - Assess magnetic balance control in the presence of 4 X-points
  - Develop the realtime measurements for divertor radiation control
  - Commission density control with FIReTIP and SGI

Supports Milestone R16-1

Disruption Avoidance Via Soft Landing Will be Developed

- Disruption detection algorithms have been developed using NSTX data
  - Compare diagnostic data to thresholds & assign "penalty points" when thresholds are exceeded
  - Sum the "penalty points", and declare a warning when the point total exceeds a given threshold
- Provides a foundation for disruption detection in NSTX-U
- FY15 Research Plan
  - Implement basic detector in PCS, and design architecture of control response
  - Assess accuracy of predictor for NSTX-U disruptions, and refine as necessary
  - Do initial tests of predefined automated rampdowns
- FY16 Research Plan
  - Do first closed loop testing of soft landing algorithms
  - Refine disruption detector algorithm



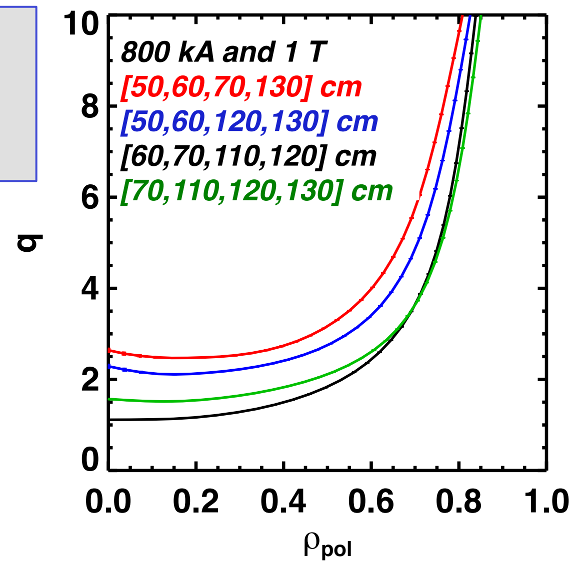
S.P. Gerhardt, et al., Nuclear Fusion **53**, 063021 (2013)

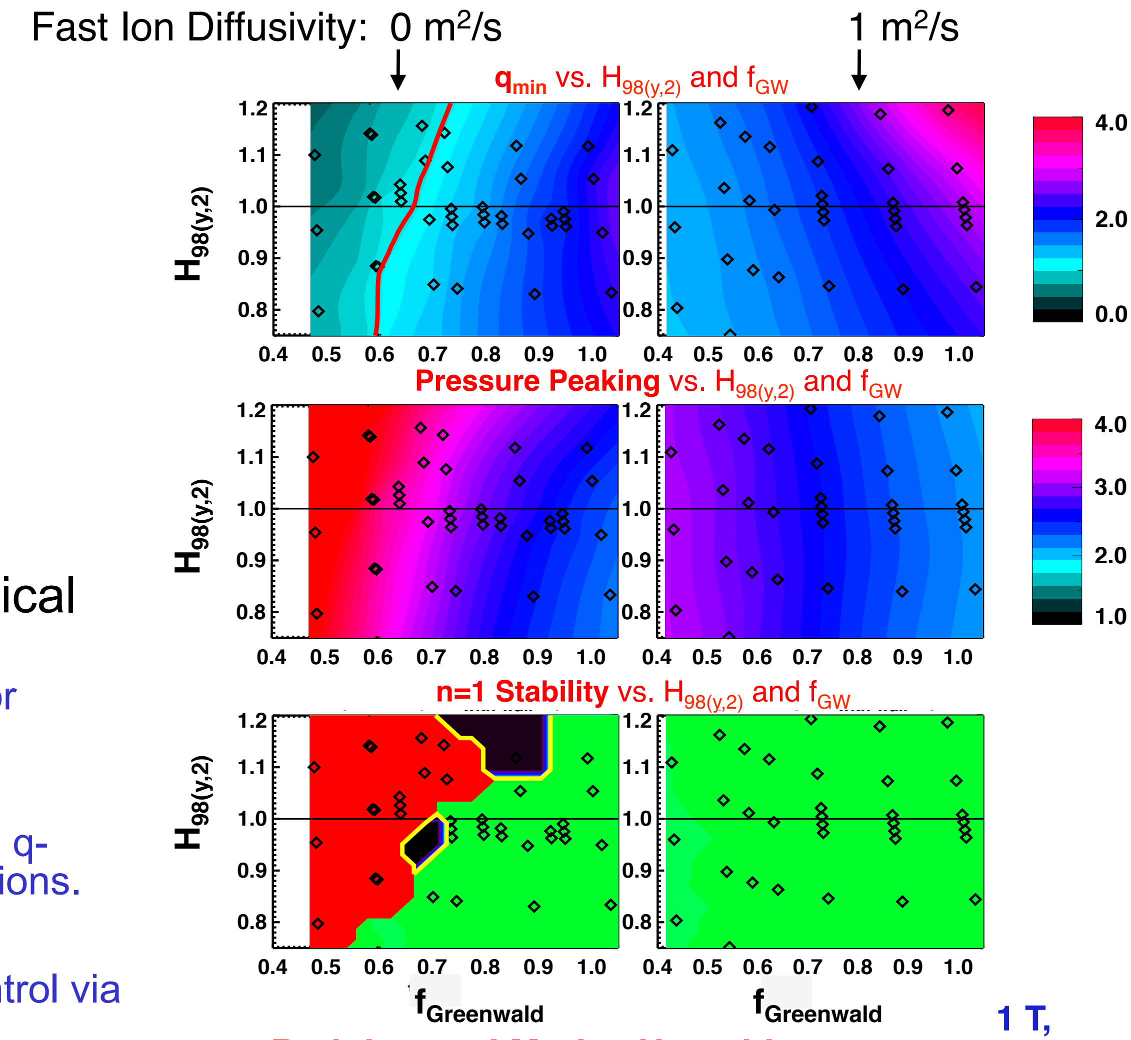
Connections to MS TSG:
- n>=1 control, including disruption avoidance scenarios, covered by MS TSG.
- MGI physics covered by MS TSG

Supports 2016 JRT

Optimization of Beam Current Drive Will Be Addressed

Milestone R15-2, 2015 JRT, R16-4





Red: Internal Modes Unstable
Green: stable
Black: External modes unstable

1 T,
1 MA
12.6 MW

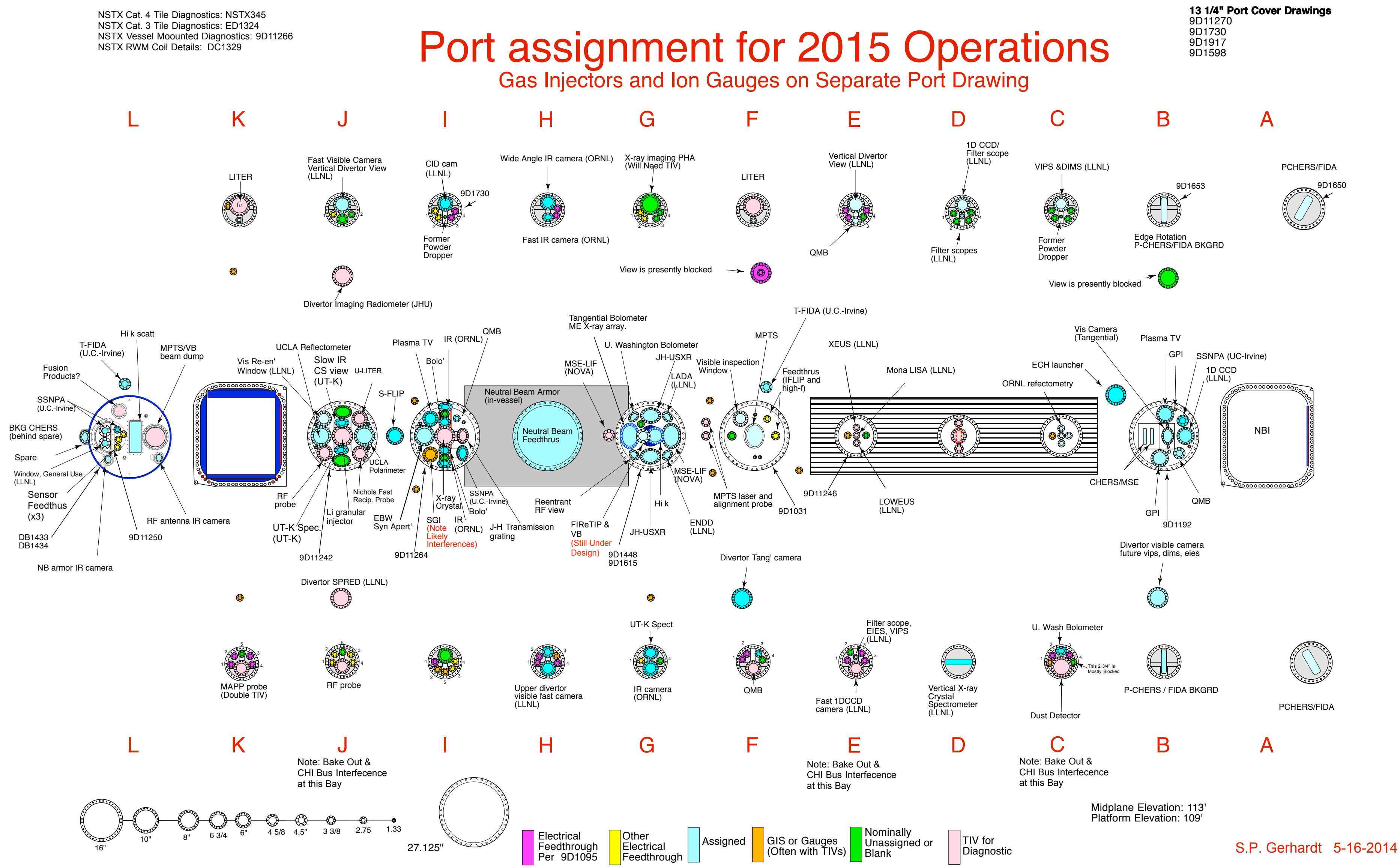
- Study the conditions for classical beam current drive
  - Can anomalous diffusion be used for scenario optimization?
- FY15 Research
  - Verity the expected variations of the q-profile with different beam combinations.
- FY16 Research
  - Continue verification of q-profile control via NBCD
  - Begin to assess if fast ion redistribution can help to elevate q_{min}.

Summary

- Making excellent progress in developing profile control schemes for NSTX-U
  - Efforts led by Lehigh U., ORISE post-doc and PU graduate student with PPPL, CU, & GA support
- Developing the operational tools and plans for a successful research campaign in FY15
- Research plan has been formulated to support the FY15 & 16 high-priority goals
  - Discharge development
  - Scenario control
  - Disruption avoidance

Backup

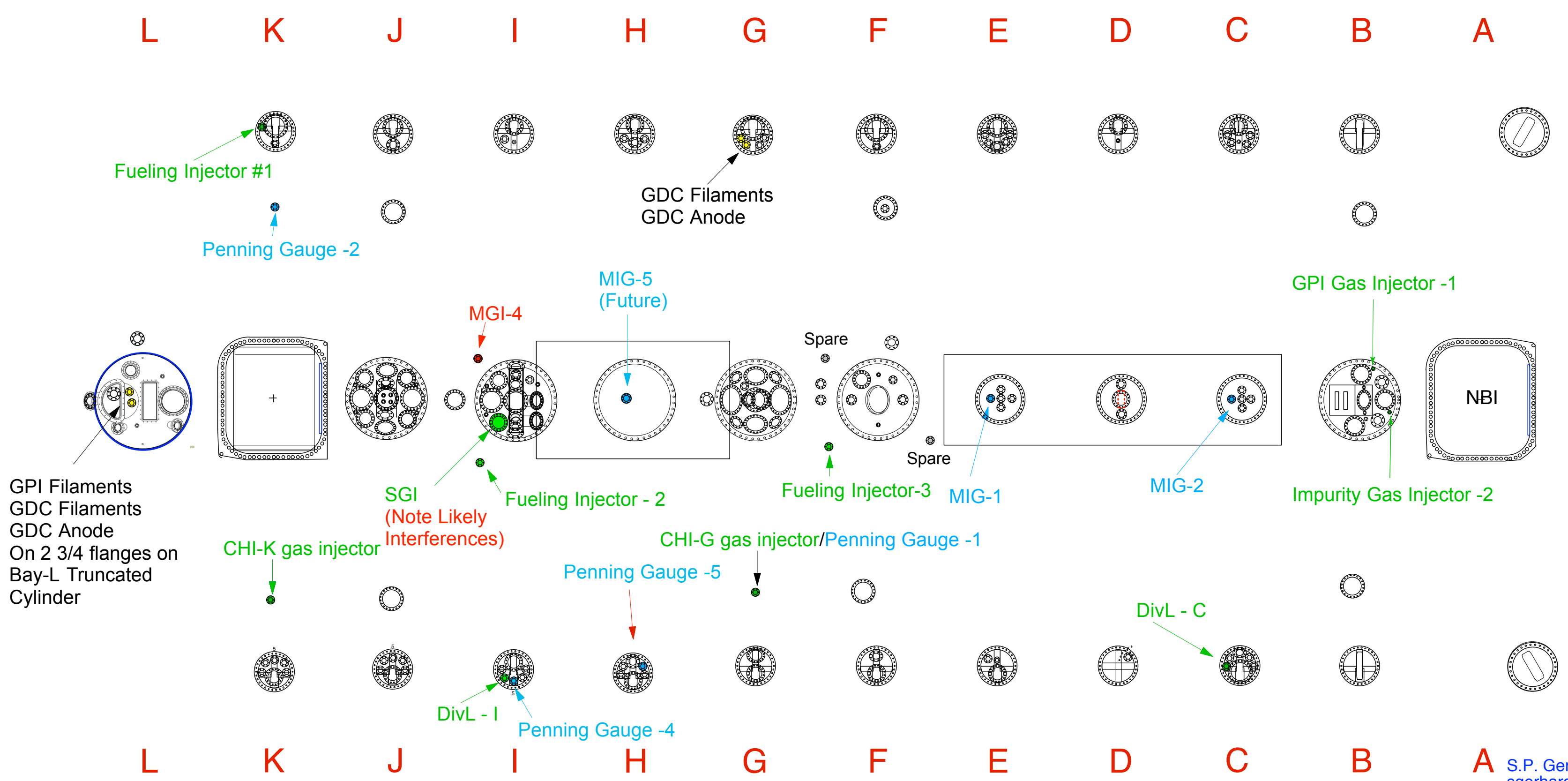
Complete Port Allocation



Gas Delivery System Layout

Port Assignment for FY 2015 (Pressure measurement, gas delivery, GDC)

Many Port Cover Details Are Incorrect...See Diagnostic Drawing



S.P. Gerhardt
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5-16-2014

Gauges and Injectors on Inner Vessel (see ED1324)

MGI #1: Lower 180 Degree Organ Pipe
MGI #2: Lower 15 Degree Organ Pipe
MGI #3: Upper 345 Degree Organ Pipe
Penning #3: Lower 240 Degree Organ Pipe

CS-Mid-125: 0.125" tube, Bay C
CS-Mid-250: 0.25" tube, Bay I
CS-Shoulder-125: 0.125" tube, Bay D
CS-Shoulder-250: 0.25" tube, Bay J

Gauges onTVPS Pumping Ducts :

Ion Gauge -1
Ion Gauge-2
Capacitance Manometer 1 (1 Torr)
Capacitance Manometer 2 (10 Torr)
Capacitance Manometer 3 (1000 Torr)
MIG-4 (On Duct)
MIG-3 (On Bay K Spool Piece Flange, midplane)

Definitions

MGI - Massive Gas Injector
MIG - Micro Ion Gauge
DivU - Upper Divertor injector
DivL- Lower Divertor injector

GPI - Gas Puff Imaging
CHI - Co-axial Helicity Injection
SGI - Super Sonic Gas Injector
Penning Gauge

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

- Free-Boundary TRANSP calculations of NSTX-U operations points.
  - See: S.P. Gerhardt, et al, Nuclear Fusion **52** 083020 (2013)

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]	Heating Duration [s]
0.75	6.8	0.6-0.8	5
0.75	8.4	0.7-0.85	3
1.0	10.2	0.8-1.2	5
1.0	12.6	0.9-1.3	3
1.0	15.6	1.0-1.5	1.5

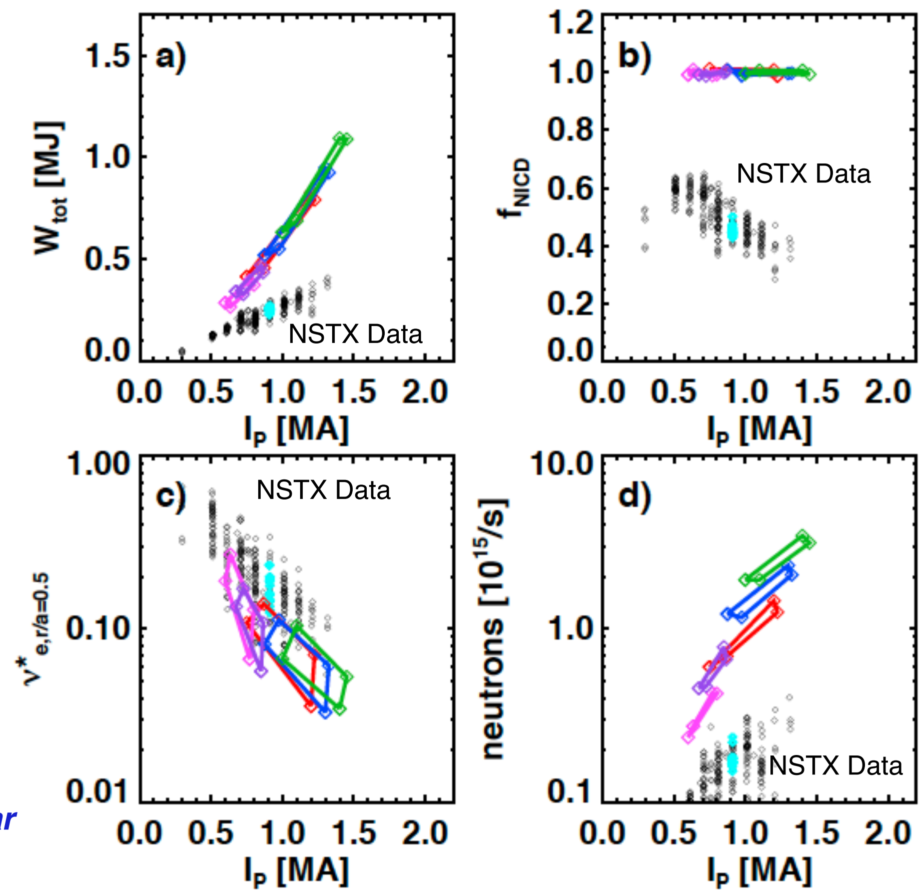
6x80 kV, B_T=1 T
6x90 kV, B_T=1 T
6x100 kV, B_T=1 T

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

End of year 1 target

TRANSP Projections for 100% Non-Inductive Scenarios

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



Simplified Current Profile Evolution Model

Magnetic Diffusion Equation:

$$\frac{\partial \psi}{\partial t} = \frac{\eta(T_e)}{\mu_0 \rho_b^2 \hat{F}^2} \frac{1}{\hat{\rho}} \frac{\partial}{\partial \hat{\rho}} \left(\hat{\rho} \hat{F} \hat{G} \hat{H} \frac{\partial \psi}{\partial \hat{\rho}} \right) + R_0 \hat{H} \eta(T_e) \frac{< \bar{j}_{NI} \cdot \bar{B} >}{B_{\phi,0}} + \frac{\dot{\rho}_b \hat{\rho}}{\rho_b} \frac{\partial \psi}{\partial \hat{\rho}}$$

$$\left. \frac{\partial \psi}{\partial \hat{\rho}} \right|_{\hat{\rho}=0} = 0, \qquad \left. \frac{\partial \psi}{\partial \hat{\rho}} \right|_{\hat{\rho}=1} = -\frac{\mu_0}{2\pi} \frac{R_0}{\left. \hat{G} \right|_{\hat{\rho}=1} \left. \hat{H} \right|_{\hat{\rho}=1}} I(t)$$

Scenario Oriented Parameter Models:

Electron Density:

$$n_e(\hat{\rho}, t) = n_e^{profile}(\hat{\rho}) n_0(t)$$

Electron Temperature:

$$T_e(\hat{\rho}, t) = T_e^{profile} \frac{I(t)\sqrt{P_{tot}(t)}}{n_0(t)}$$

Resistivity:

$$\eta(\hat{\rho}, t) = \frac{k_\eta^{prof}(\hat{\rho}) Z_{eff}}{T_e^{3/2}(\hat{\rho}, t)}$$

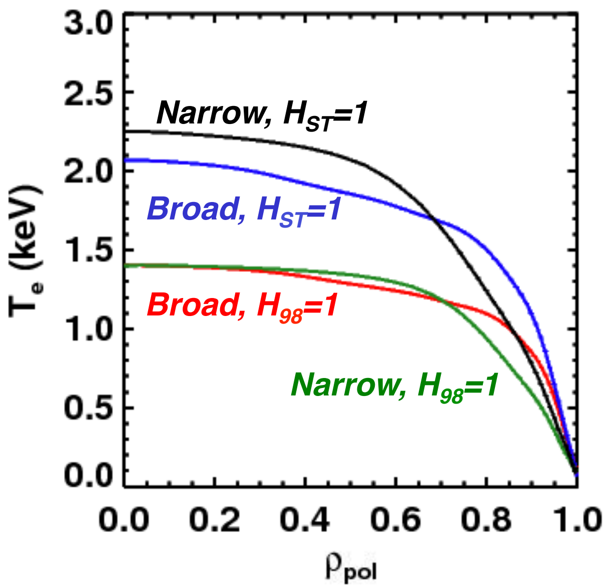
Bootstrap Current:

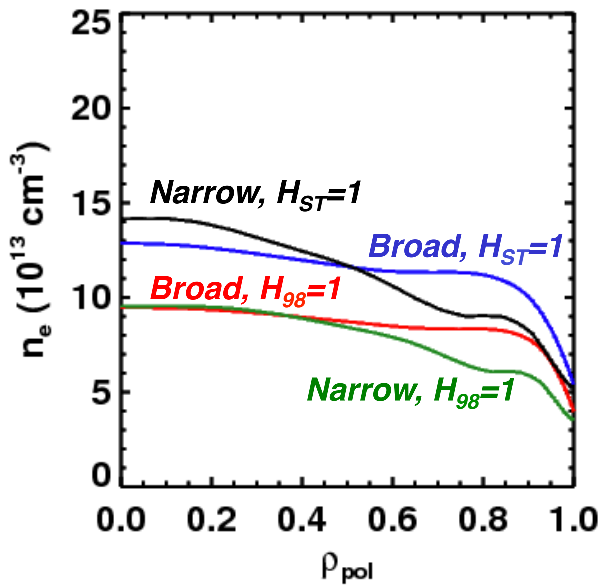
$$\frac{< \bar{j}_{bs} \cdot \bar{B} >}{B_{\phi,0}} = I(t)\sqrt{P_{tot}(t)} k_{bs}^{prof}(\hat{\rho}) \left(\frac{\partial \psi(t)}{\partial \hat{\rho}} \right)^{-1}$$

Beam Driven Current:

$$\frac{< \bar{j}_k \cdot \bar{B} >}{B_{\phi,0}} = j_k^{profile}(\hat{\rho}) \left(\frac{I\sqrt{P_{tot}}}{n_0(t)} \right)^{\alpha_{CD}} \frac{P_k(t)}{n_0^{\beta_{CD}}(t)}$$

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

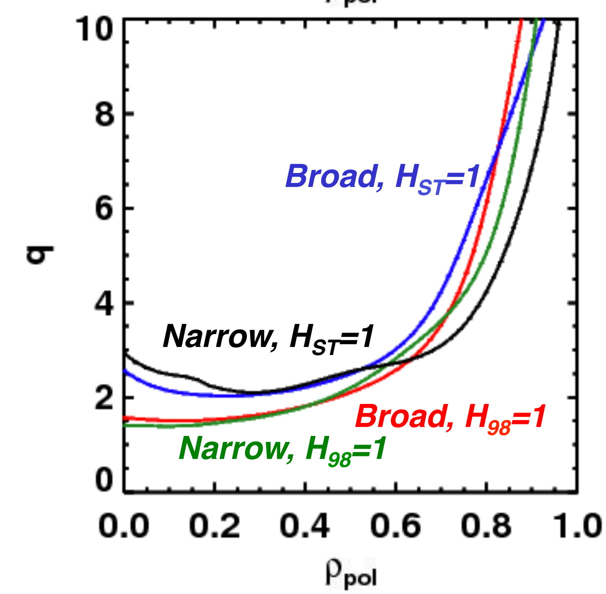




Dashed: ITER-98 confinement scaling

Solid: ST confinement scaling

(S. Kaye, NF 2006)



- **Fix: 1.0T, P_{inj}=12.6 MW, f_{GW}=0.72**
- **Fix: A=1.75, κ=2.8**
- Determine 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

Full Utilization of the NSTX-U Will Require Heat Flux Mitigation Solutions

- Thermal stresses in target tiles can exceed ATJ graphite limits.
  - Inner horizontal target tiles qualified for 5 sec operation at Q_{ave}=5 MW/m^2
- Desire to avoid tile surface temperatures exceeding T_{max}~1200 C.
- Conservative assumption: $\lambda_q = 0.92 I_P^{-1.6}$ $\quad Q_{Pk} = \frac{P_{heat} f_{div}}{2\pi R \lambda_q f_{exp} \sin(\theta)}$ $\quad Q_{ave} = 0.63 Q_{Pk}$
- Primary solutions: Broadening the heat channel (f_{exp}) via the snowflake divertor
  Increasing the fraction of radiated power (decreasing f_{div})

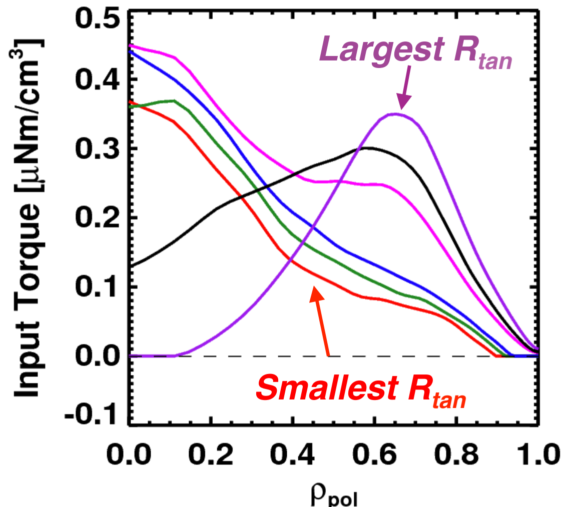
Discharge Parameters			Worst-Case Standard DN Divertor f_{exp}=15 & f_{div}=0.4		f_{exp}=60 & f_{div}=0.4 or f_{exp}=15 & f_{div}=0.1	
I_P [MA]	P_{inj} [MW]	Heating Duration [s]	Q_{Pk} [MW/m^2]	Time to T_{max} [s]	Q_{Pk} [MW/m^2]	Time to T_{max} [s]
0.75	10.2	5.0	6	12.6	1.5	200
1.5	10.2	5.0	18	1.4	4.5	22
2.0	10.2	5.0	28	0.5	7	8.7
1.5	15.6	1.5	27	0.6	7	9.3
2.0	15.6	1.5	43	0.25	11	4.0

NSTX-U Will Have Significant Actuators For Profile Control Studies

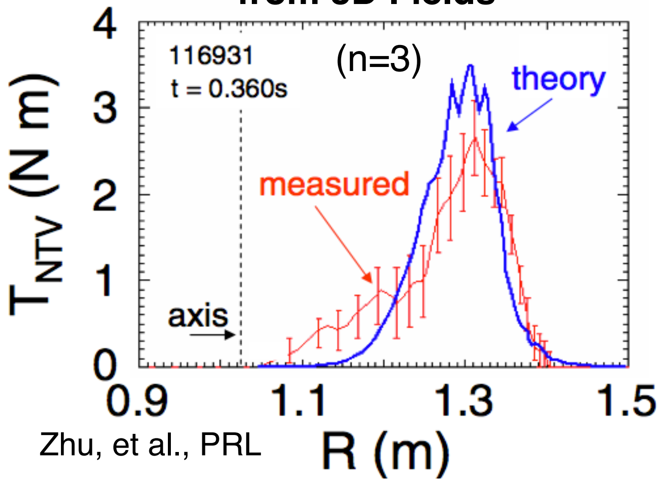
Thrust #2

Rotation Profile Actuators

Torque Profiles From 6 Different NB Sources



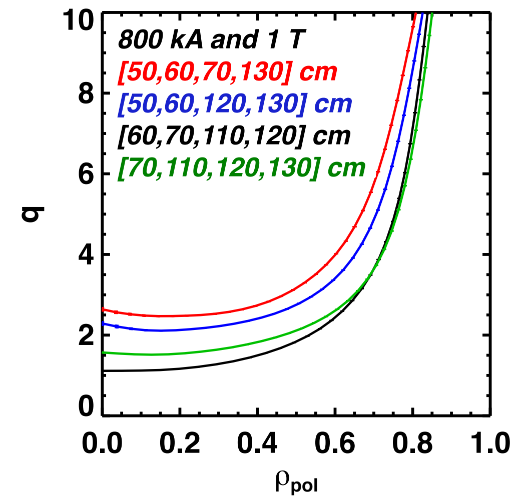
Measured and Calculated Torque Profiles from 3D Fields



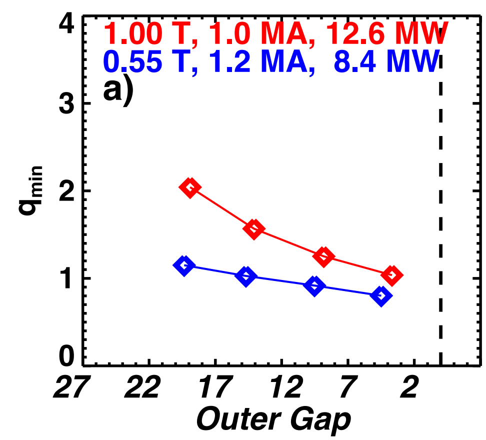
Zhu, et al., PRL

q-Profile Actuators

Variations in Beam Sources
800 kA Partial Inductive, 87% < f_{NI} < 100%

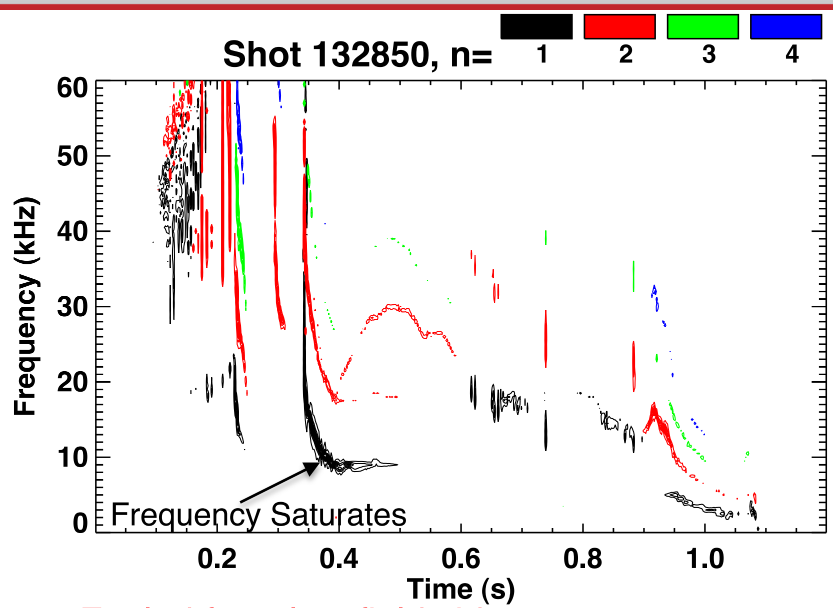


Variations in Outer Gap



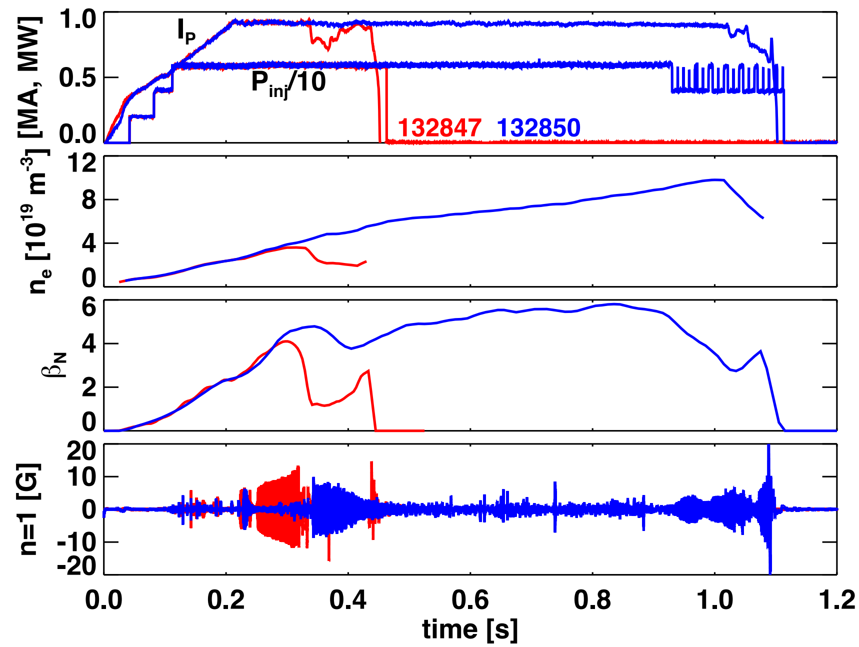
Milestone R14-3

Optimizing the Early Discharge Evolution Will Play an Important Role in Achieving Low Collisionality at High-Current



132847: Fueled from low-field side

132850: Fueled from both low- and high- field sides



- Timing and magnitude of fueling has profound impact on discharge evolution, will be optimized in NSTX-U.
  - Will slower I_P ramps w/ larger solenoid facilitate reduced fueling?
  - Will improved solenoid design and reduced error fields improve lower-density startup.
  - Will the extra torque from the new beams reduce prevalence of locking?

Milestone R14-1