GP12.00105 Initial Physics Operation of NSTX-U*

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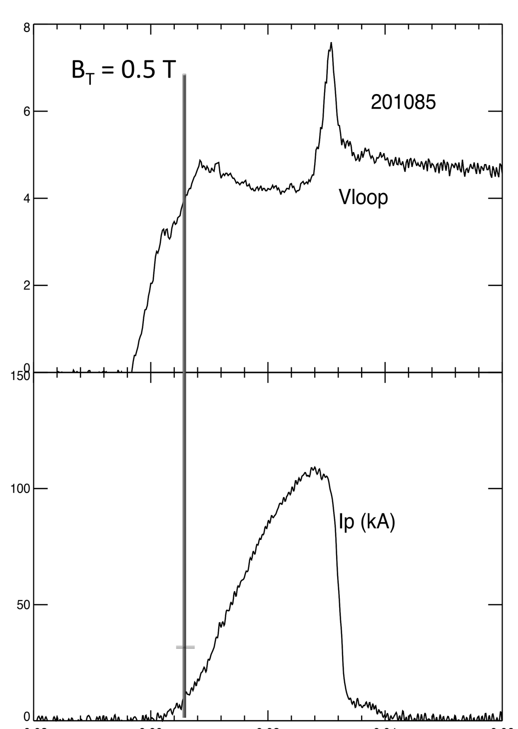
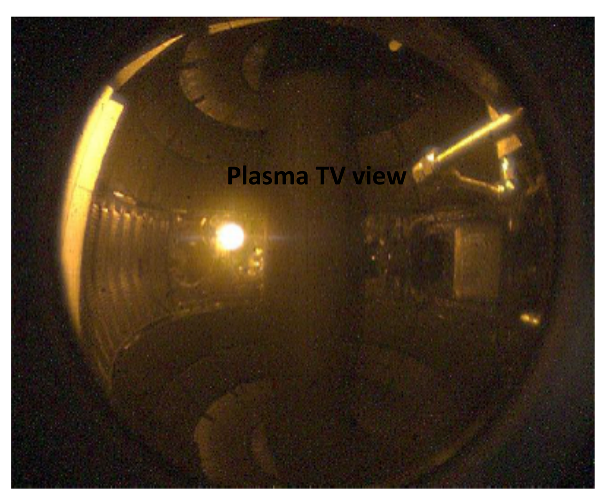
ABSTRACT

The National Spherical Torus Experiment Upgrade (NSTX-U) is an experiment designed to study the physics of Spherical Torus (ST) at about twice the toroidal field and neutral beam injection (NBI) power as NSTX for 5 s. at full parameters. In its initial operational period NSTX-U will limit operation to $B_T \leq .65$ T but the full complement of 6 neutral beam (NB) sources will be available. Three NB sources added during the upgrade inject more tangentially and will be essential to investigate the physics of neutral beam current drive. In NSTX-U, use of a digital real-time plasma control system and the application of wall conditioning techniques will be used to achieve routine operation with good confinement. The wall conditioning techniques include bakeout to over 300°C, helium glow discharge cleaning, boronization of the plasma facing surfaces using deuterated trimethylboron gas in a helium glow discharge and lithium evaporation onto the walls. Auxiliary heating by up to 6 MW of High Harmonic Fast Waves will be available. The operational experience during the plasma commissioning phase will be discussed.

CONSTRUCTION PHASE OF THE NSTX-UPGRADE ENDED WITH THE FIRST DAY OF PLASMA OPERATION ACHIEVED I_p = 120 KA, WELL ABOVE THE 50 KA GOAL





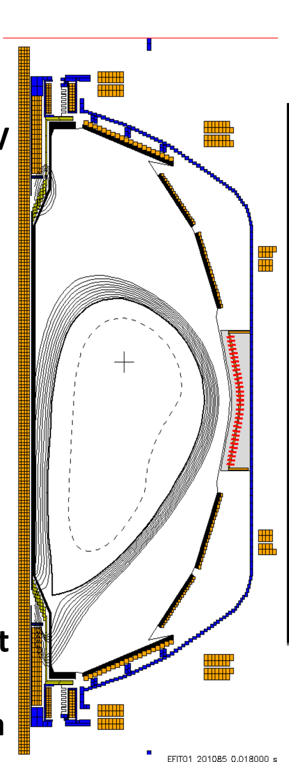
View illuminated by filament shows internal hardware and provides frame of reference for plasma images

EFIT RECONSTRUCTION

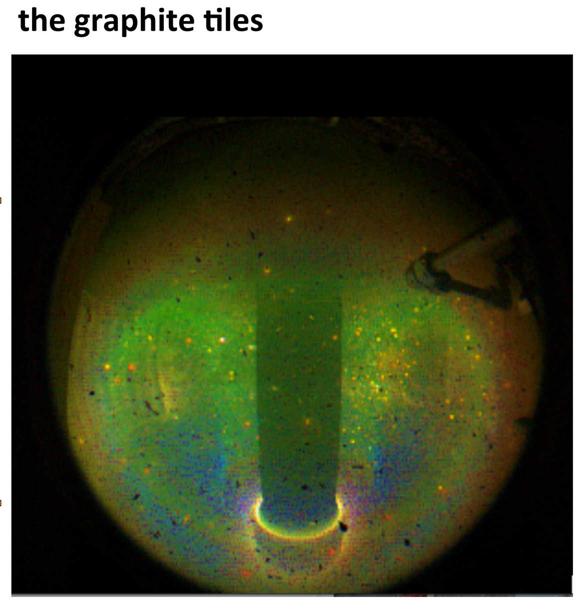
EFIT reconstructions converge to shape and location that agree with Plasma TV images

The convergence is remarkable since I_{vessel}~330 kA at 4 V/turn exceeds the plasma current by a factor of 4

Ip from converged EFIT analysis agrees well with I_p arrived at by taking the difference between a plasma shot and a shot with no gas and the same coil currents



Color plasma TV image at 18 ms shows that Li (green) is predominate impurity The blue light is an indication of the oxygen expected to be present without an extended high temperature bake of the graphite tiles

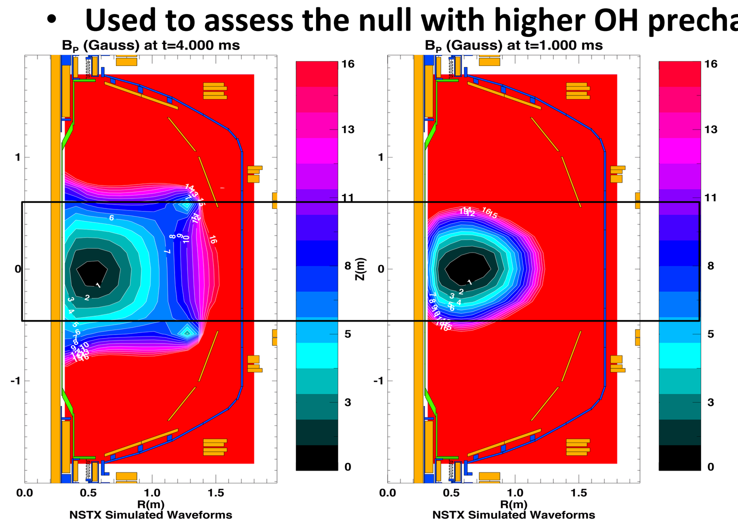


Plasma TV image at 18 ms

*Work supported by U.S.DOE Contract No. *DE-AC02-09CH11466*

DISCUSSION OF START-UP FOR NSTX-U

- NSTX_U has 3X solenoid flux and field as NSTX for the same solenoid current (I_{OH})
- NSTX used its full pre-charge solenoid current of $I_{OH}(0)$ = 24 kA almost exclusively
- NSTX-U at $I_{OH}(0)$ = 8 kA has nearly the same field at start-up as NSTX
  - 8 kA worked well for demonstration plasma
- Biggest difference is larger R for NSTX-U
  - Smaller null area, higher V_{loop} for same E_T, ~ 4 V vs ~ 2 V for NSTX
- For the full flux swing +24/-24 kA it will be more complex
- I_{OH} (0)= 24 kA will require more current from PF3 to create a null
- LRDFIT modeling agrees with measurements for NSTX; CD4 plasma
- Used to assess the null with higher OH precharge



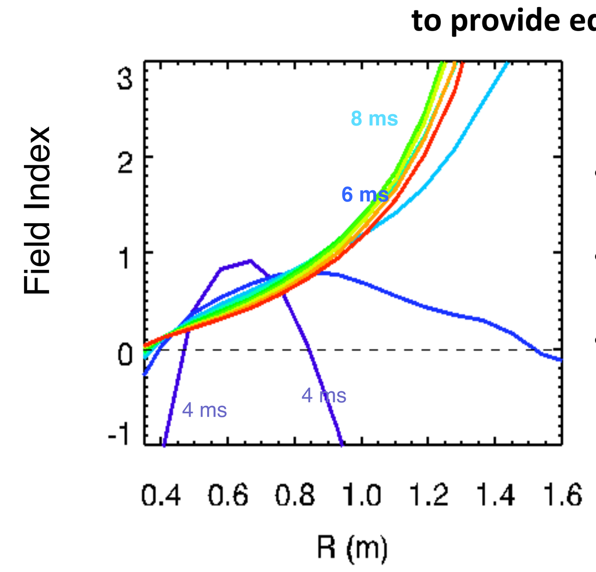
+8 OH precharge   +24 OH precharge

From JET, Tanga, et al

$$\frac{V_{loop} I_{TF}}{R^2 \langle B_\perp \rangle} > 3.14 \frac{\text{V MA}}{\text{m}^2\ \text{G}}$$

R dependence →
NSTX-U requires twice NSTX's V_l for breakdown at same I_{TF}

NSTX-U with $I_{OH}(0)$ = 24 kA; PF3 & PF5 are negative after t=0 to provide equilibrium



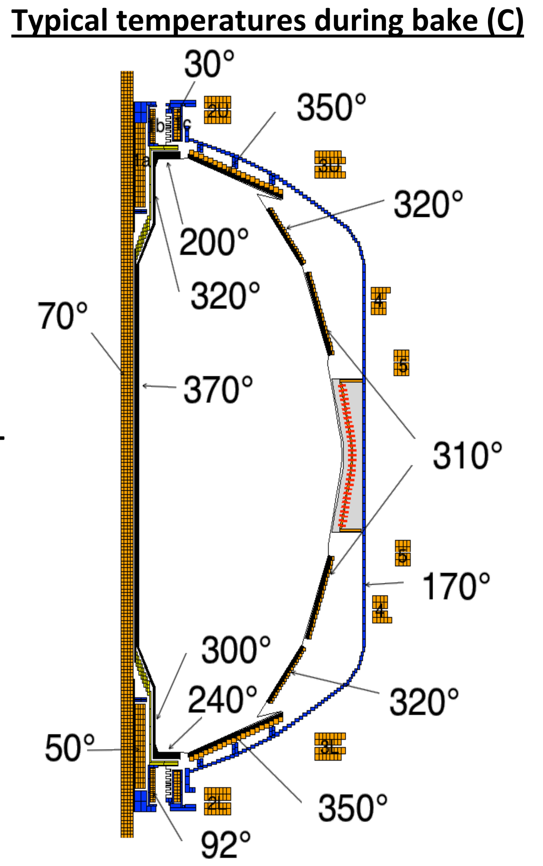
$$n_{decay} = -(R/B_Z)(dB_Z/dR)$$

- PF3 is initially positive to cancel OH fringe field
- Positive I_{PF3} is initially vertically destabilizing
- Will it be necessary to use PF2 or PF4 to enlarge the null or modify the field index at high $I_{OH}(0)$?

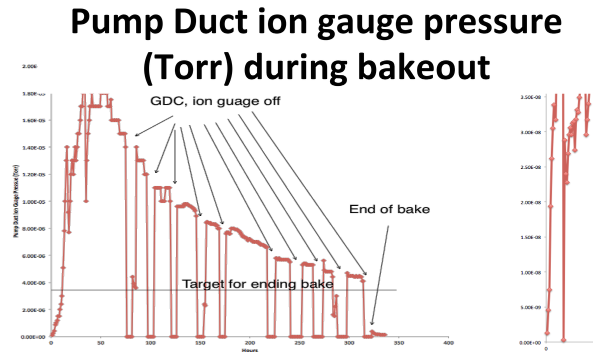
BAKEOUT

- Center stack is heated resistively
- Passive plates and NB armor are heated by hot Helium, outlet temperature 325°C (450°C at source)
- He flow direction was switched part way through bakeout
- Temperatures are thermocouple measurements, typical variation is +/- 20°C
- Performed a few hours of deuterium GDC followed by He GDC on several days
- Target pressure of 3.5e-6 Torr at end of bake is based on NSTX experience.

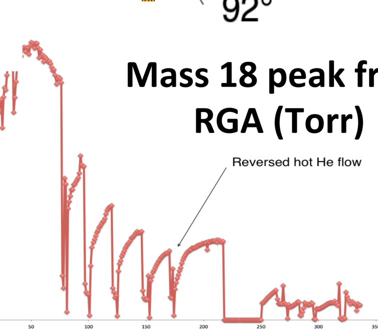
Typical temperatures during bake (C)



Pump Duct ion gauge pressure (Torr) during bakeout



Mass 18 peak from RGA (Torr)

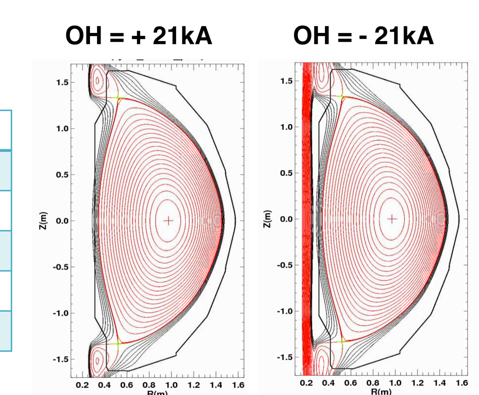


DIFFERING OH(0) → NEED TO ADJUST B_V

- OH fringe field at ± 24 kA is now three times larger
  - Larger impact on PF currents when maintaining a steady shape
  - Fringe field at +24 kA provides enough B_Z to confine a 220 kA plasma
  - PF currents go negative during OH swing to add confining field

Example: low beta, high delta, 1 MA, 0.5 T, DN shape:

	Current in kA			FY16 limits
OH	+ 21	0	- 21	[-21, 21]
PF1A	+ 6.58	+ 6.25	+ 5.92	[0, 15]
PF1C	- 2.62	- 5.70	- 8.78	[-8, 13.5]
PF2	+ 7.98	+ 3.78	- 0.42	[0, 15]
PF3	- 2.88	- 4.33	- 5.77	[-13, 8]
PF5	- 6.97	- 7.66	- 8.35	[-24, 0]



GAP ALGORITHM INCLUDES I_p and I_{OH} TERMs

$$I_{target} = (C_{PF^*} \cdot I_p) + (F_{PF^*} \cdot I_{OH}) + (D_{PF^*} \cdot V_{IN}) + I_{PF^*}$$

- * Indicates the PF coil number
- Only D_{PF3} will be non-zero to correct for vessel currents due to loop voltage

$$E_{PF} = (I_{target} - I_{measured})$$

- The coil current control is handed of to gap control smoothly by use of HGAP* for PF4or5 and PF3

$$E_{PF^*} = (1-H_{GAP^*}) \cdot (I_{target} - I_{measured}) + (H_{GAP^*} E_{GAP^*})$$

- The errors, E's are smoothed and their derivatives taken
- The power supply voltage request is then given by:

$$V_{PF} = (G_{PPF} \cdot E_{PF}) + (GI_{PF} \cdot E_{PF,int}) + (GD_{PF} \cdot E_{PF,der})$$

- The V_{PF}'s are then corrected by their mutuals for dI_{OH}/dt

GAP CONTROL FOR NSTX-U

Flux projection

$$\Delta\Phi = (\Phi_{out} - \Phi_{in}) - 2\pi(R_{out}\Delta_{out}B_{out})$$

Inner flux is FLOHM

Outer flux and B are up/down averaged, also weighted average over selected sensors

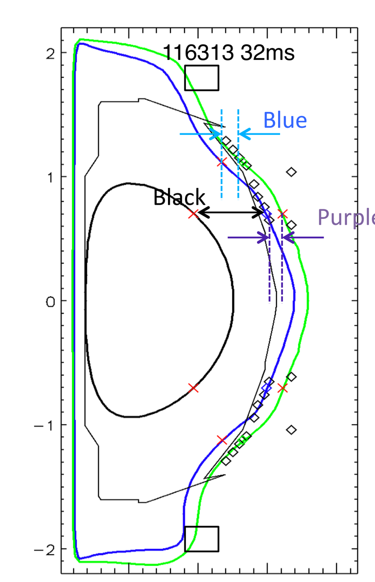
R_{out} is weighted sensor position

Outer gap for PF5 or PF4

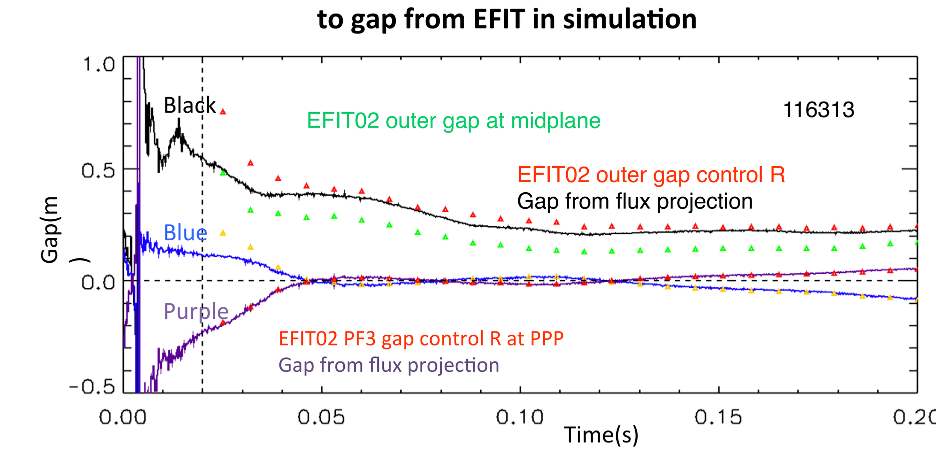
Add PF3 gap option

Removes retuning $CI_p + FI_{OH}$ coeffs for different shapes, conditions

Blue and Green are the flux surfaces passing through PPP and SPP sensors respectively



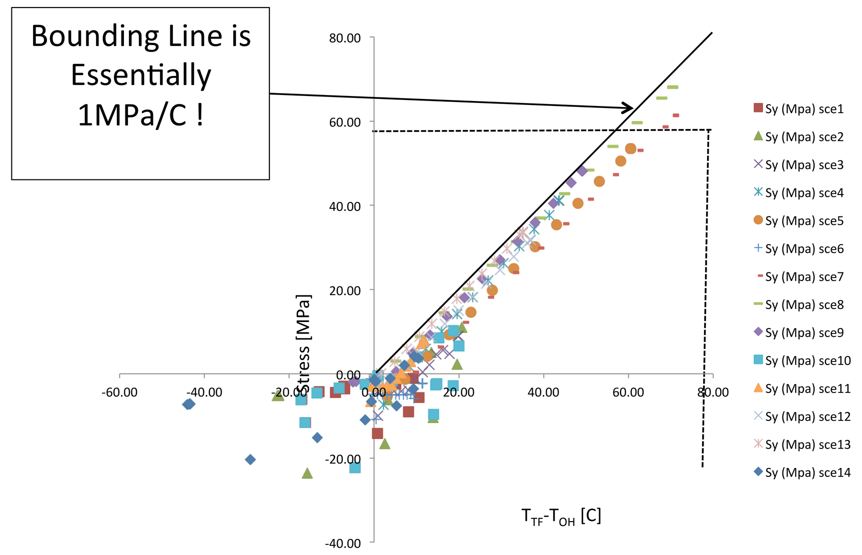
Compare gap derived from flux projection to gap from EFIT in simulation



NSTX-U REQUIRES TEMP(OH) > TEMP(TF)

- The expansion of the TF bundle during operation can stress the lower OH solenoid
  - OH must be at or above the TF temperature to reduce friction and stress

Bounding Line is Essentially 1MPa/C !



Basically, OH expands enough to eliminate the frictional interaction

MUST ADJUST THE OH WAVEFORM SO T_{OH}>T_{TF}

Illustrative Example: 2 MA, 1T, 5 second.

TF Coil:

Current is constant

Temperature is linearly increasing

OH Coil:

Current has a zero-crossing

Temperature has an "S-Shaped" curve.

T limit is 100°C

Options for maintaining T_{TF}<T_{OH}.

Pre-heat the OH coil using currents before the TF turns on.

Control the shape of the OH S-curve by *adjusting the amount of pre-charge*.

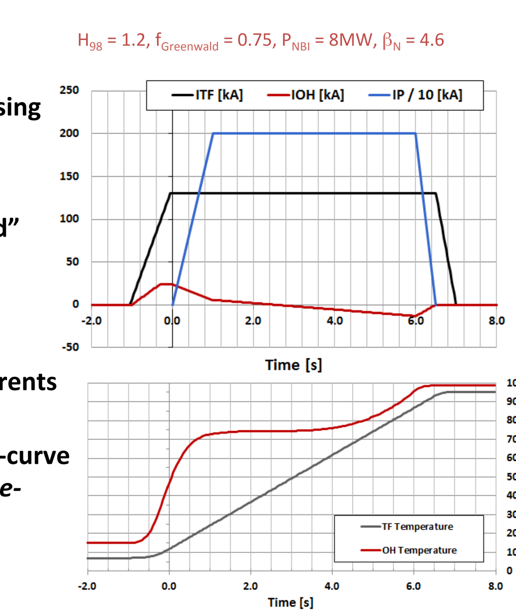
In this example,

Full 24 kA pre-charge

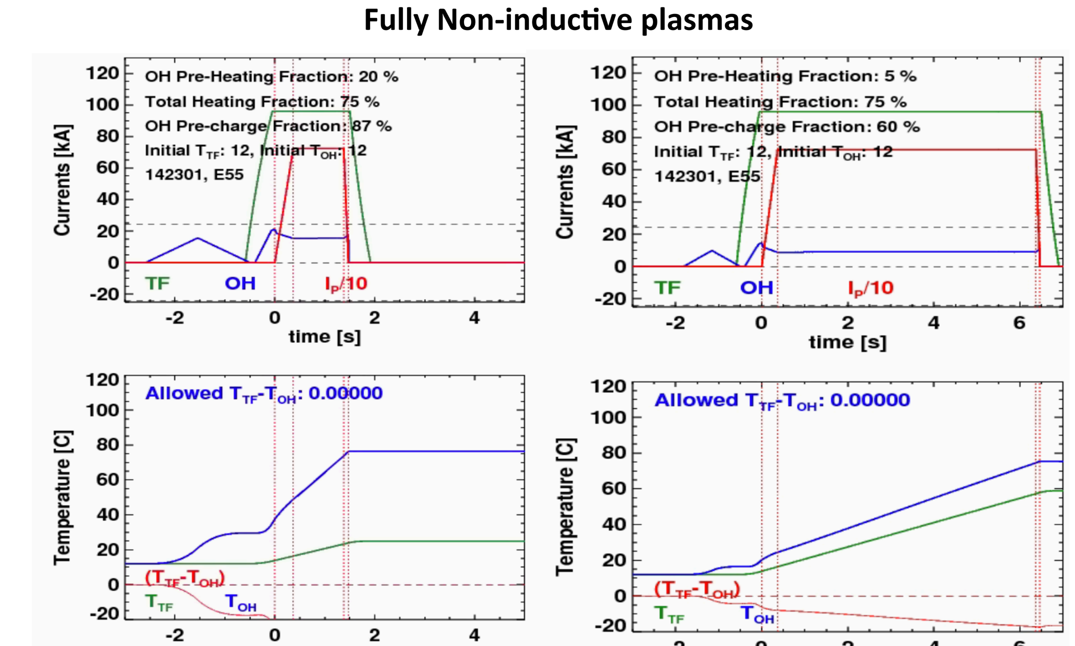
Pre-charge duration is extended to provide heating.

Partially Inductive plasma

H_{98} = 1.2, $f_{Greenwald}$ = 0.75, P_{NBI} = 8MW, β_N = 4.6

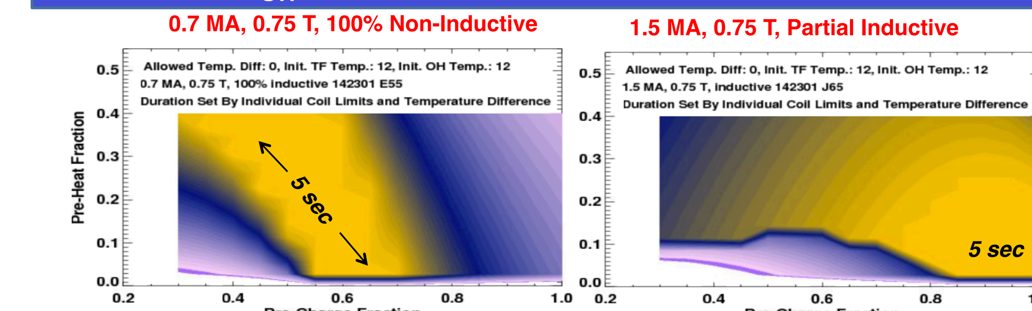


Fully Non-inductive plasmas



SCANS INDICATE 10-20% PRE-HEAT LEVEL $I_{OH}(0)$ DEPENDENT UPON SCENARIO

0.7 MA, 0.75 T, 100% Non-Inductive   1.5 MA, 0.75 T, Partial Inductive



- Pre-Heat Fraction is fraction of I^2t limit of OH coil
- Pre-Charge fraction is $I_{OH}(0)$/24kA

PHYSICS OPERATORS' COURSE*

Plasma break-down, ramp-up and flux consumption
D. Mueller
NSTX-U Physics Ops NBI Overview (Parts 1&2)
Timothy N. Stevenson
Computer Systems, MDSplus, Software Tools for NSTX-U Physics Operators
Bill Davis, Eliot Feibush, Paul Sichta, Greg Tchilinguirian, Gretchen Zimmer
NSTX-U plasma control system
D. A. Gates
CHI and MGI Operations on NSTX-U
R. Raman
NSTX UPGRADE power supply system
Weiguo Que
COE and Machine Operations
Ray Camp
Gas Injection System (GIS)
Devon Battaglia
Navigating the PCS Interface
Devon Battaglia
Equilibrium Magnetics for NSTXUpgrade
S.P. Gerhardt, Clayton Myers, Devon Battaglia, Dan Boyer
3D Fields: Detection and Application
Stefan Gerhardt, Eric Fredrickson, Clayton Myers, Steve Sabbagh, Weiguo Que
NSTX-U Grounding & PCS
J. Lawson
DCPS & Operational constraints
Stefan Gerhardt, Keith Erickson, Ed Lawson, Hans Schneider, Tim Stevenson, Weiguo Que
HHFW Operations on NSTX-U
Joel Hosea
System Identification and Control at NSTX-U
Egemen Kolemen
NSTX / NSTX-U EFIT and RWM Control
S.A. Sabbagh, J.W. Berkery, J.M. Bialek, S.P. Gerhardt, K. Erickson, Y.S. Park, et al.

*The slides from these talks can be found at http://nstx-u.pppl.gov/home They provide a rich resource of material that will be valuable during the NSTX-U campaign. Videos of the talks can be viewed on the internal PPPL website Thanks to all the instructors.

SUMMARY

- Exceeded the target plasma current of 50 kA
- Basic control system working
- EFIT analysis is working well even with vessel current 4 times I_p
- Bakeout completed most of internal graphite to 350°
- Base pressure below 1e-7 Torr
- Enhancements to plasma position and current control tested