Questions from PAC-35 – Day 1

1. What is "administrative limit" for total energy input into NSTX-U?

2. Please provide a chart versus time showing the tasks and required device/diagnostic capabilities for the first year, including requirements for the conditioning strategy. (Alternative: please describe the process required to develop such a chart.)

3. Please briefly summarize the university collaborations that are currently underway on the NSTX-U project, including a short descriptor of the nature of the research and the people involved, i.e., number of PhD-track students, postdocs, research staff.

4. Please briefly summarize the areas of theoretical research that are *not* included in the NSTX-Theory Partnership, especially those areas that might have been terminated as a result of the Partnership

Response to Question 1 - Executive Summary
(What is "administrative limit" for total energy input into NSTX-U?)

- Beams have energy limits. For six sources:
  - 80 kV -> 5 sec, 1.7 MW/source, 6 sources -> 51 MJ
  - 95 kV -> 2 sec, 2.5 MW/source, 6 sources -> 30 MJ
  - Limits handled by numerous timing systems at the source control consoles
- Vessel is ultimately qualified for 70 MJ total (14 MW x 5 seconds).
  - Assumes cooling water flowing on both inner and outer vessel, and that the *inner horizontal target is limited to 5 MW/m^2*.
- Cooling $H_2$0 on casing behind inner horizontal target implemented from Day 0.
- Beam armor has dual interlocks on the plasma current.
  - Armor designed to take full power without failing
    - Designed for [10.3 MW, 5 sec] or [15 MW, 1 sec]
    - CFCs, ATJ, Poco
- NSTX achieved: 600 second cycle with 8 MJ, no active vessel cooling
- NSTX-U will run on 15-20 minute cycle initially
  - Administrative limit on the pulse length in the commissioning phase will easily keep us in the envelope demonstrated on NSTX.
  - Monitor IR camera data and TCs post-shot.
- We do not have plans to interlock the discharge against TC or IR TV measurements during the first campaign.
- We have active plans, in many TSGs, to address peak heat flux mitigation.

See backup for more details

Response to Question #2 - Highest Level Schedule

2014					2015								
Aug.	Sept	Oct	Nov	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.
Upgrade Construction					CD-4	Bake	Comm.		Research Operations				

Implementation Schedule for Diagnostics

2014					2015								
Aug.	Sept	Oct	Nov	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.

Upgrade Construction | CD-4 | Bake | Comm. | Research Operations

General In-Vessel Diagnostic Work

Neutron Calibrations

- Most Basic Magnetics
- Plasma TV

MPTS Rayleigh/Raman Scattering

- Complete magnetics for equilibrium reconstruction (…and EFIT!)
- Fast Mirnovs & mode spectrograms
- MPTS
- Neturon Detectors
- Filter scopes

- IR TV
- RWM sensors (locked modes…)
- Visible, EUV, SXR spectroscopy
- Toroidal CHERS
- MSE-CIF
- Bolometry

Envelope of Experiments Grows as Diagnostic Systems Become Available

This will allow a good TRANSP run! We can do important experiments!

Many other diagnostics will be commissioned during this phase as well…

New
Modified
Unchanged

MPTS = Multi-Pulse Thomson Scattering

Implementation Schedule for Conditioning/Fuelling Techniques

2014					2015								
Aug.	Sept	Oct	Nov	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.

Upgrade Construction | CD-4 | Bake | Comm. | Research Operations

- Glow Discharge System
- Resistive Bake of the CS

Hot Helium Bake of the Outer Vessel and C PFCs
(+ resistive bake of the CS)

Boronization (and are starting to work on it now.)

Lithium Evaporators for Research + General Conditioning
Timing determined by:

- Physics goals
  - Have we got a good baseline on boronized conditions?
  - can we diagnose/optimize the B->Li transition?
- Confidence that no vents will be necessary.
- Technician and engineer resources.
- Desire to limit the total Li inventory.

Timing of Li introduction ultimately determined by discussions between run coordinator, TSG leaders, engineering, NSTX-U program management.

- *Supersonic gas injection (SGI) commissioning*

- Granule Injector for Dedicated XPs
- FIReTIP realtime interferometry
- ELM Pacing with 3D fields

New
Modified
Unchanged

Stretch Goals
Density Feedback
Upward Evaporators (more likely FY16 run)

Implementation Schedule for Control Code/Hardware

2014					2015								
Aug.	Sept	Oct	Nov	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.

Upgrade Construction | CD-4 | Bake | Comm. | Research Operations

Rectifier Testing

- DCPS
- Basic Power Supply Control

Basic gas delivery

- I_P control
- Flux-projection shape control
- Vertical position control
- HFS and LFS gas delivery

rtEFIT
Vertical Position control upgrades

RWM control & DEFC
ISOFLUX shape control
Supersonic Gas Injection
CHI and HHFW commissioning

Physics Algorithms (not priority order)

- β_N+l_i control
- Multiple X-point tracking & SFD control
- Automated rampdowns
- Realtime toroidal rotation and MSE
- Divertor gas injection and MGI

New
Modified
Unchanged

Implementation Schedule for Control Code/Hardware

2014					2015								
Aug.	Sept	Oct	Nov	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.
Upgrade Construction					CD-4		Bake	Comm.	Research Operations				
	Rectifier Testing												

- DCPS
- Basic Power Supply Control

Basic gas delivery

Note on baseline fueling plan:
NSTX system had 1/8" OD long fueling tube on the HFS
(~600 ms decay time, ½ of discharge)
NSTX-U system uses ¼" OD tubes
(faster pump-out, fuelling over shorter fraction of discharge).
Also have large diameter tubes near the "shoulders".

HFS improvement + SGI + new Boronization will be explored in early FY-15 research

- I_P control
- Flux-projection shape control
- Vertical position control
- HFS and LFS gas delivery

rtEFIT
Vertical Position control upgrades

RWM control & DEFC
ISOFLUX shape control
Supersonic Gas Injection
CHI and HHFW commissioning

Physics Algorithms (not priority order)
- β_N+l_i control
- Multiple X-point tracking & SFD control
- Automated rampdowns
- Realtime toroidal rotation and MSE
- Divertor gas injection and MGI

New
Modified
Unchanged

Response to Question 3

Source	PI	Institution	Topic	Staff (# people, not FTEs)	Post-docs	PhD students
FES Science/non-diag	Sabbagh, Steve	Columbia University	Study of MHD Stability, Active Mode Control, and Disruption Avoidance in NSTX-U	4		Co-advising Imene Ghouri
FES Diagnostic	Boeglin, Werner	Florida International U	A Fast Fusion Proton Diagnostic for NSTX	1		2
FES Diagnostic	Stutman, Dan	Johns Hopkins U	Soft X-Ray Measurements of Transport and MHD Activity in the Core and Edge NSTX Plasma	2	1	
NSTX-U Direct	Schuster, Euginio	Lehigh University	Current profile control development for NSTX-U	1	1	2
FES Science/non-diag	Ram, Abhay and Bonoli, Paul	MIT	Propagation and Damping of High Harmonic Fast Waves and Electron Cyclotron Waves in the NSTX-U Device.	3		
NSTX-U Direct	White, Anne	MIT	Electron gyro-scale turbulence and high-k scattering interpretation	1		1
PPPL Direct (LDRD)	Koel, Bruce	Princeton University - Chemistry	Surface science studies - supporting high-Z and lithium PFC development	1	3	4
NSTX-U Direct	Rowley, Clancy	Princeton University - MAE	Plasma control development for NSTX-U (rotation profile control)	1		1
PU / Other funding	Bhattacharjee, A.	Princeton University - Astrophysics Dept	Co-head of NSTX-U / theory partnership, CHI modelling for NSTX-U (Fatima Ebrahimi)	2		
NSTX-U Direct	Kaita R, Jaworski M	Princeton University - PPPL/NSTX-U	High-temperature erosion and local redeposition of low-Z materials, global material transport with OEDGE+WallDYN, MAPP on LTX for NSTX-U, lithium leak detection			5
FES Science + Diagnostic	J.P. Allain, J.P.	U Illinois	Upgrade of the Materials Analysis Particle Probe (MAPP-U) to Decipher the Impact of Lithium-Based Surfaces on NSTX-U Plasma Behavior + elucidating thin-film lithium coatings on graphite and high Z metals including role of boron and also high temperatures	1	1	3
FES Science + Diagnostic	Wirth, Brian	U Tennessee Knoxville	Diagnostics and Modeling in Support of Boundary Physics Research on NSTX Upgrade + Unraveling the material migration and surface evolution in NSTX-U tokamak through integrated diagnostics and computational simulation	1	2	
FES Science/non-diag	Raman, Roger	U Washington	Solenoid Free Plasma Start-up Using Coaxial Helicity Injection and Subsequent Non-inductive Current Ramp-up Studies on NSTX-U	3		2
FES Science/non-diag	Raman, Roger	U Washington	Disruption mitigation studies on NSTX-U using rapid impurity delivery systems			1
FES Science/non-diag	Fonck, Ray	U Wisconsin	Local Helicity Injection for Non-Solenoidal Startup in NSTX-U	2		1
FES Diagnostic	McKee, George	U Wisconsin	Investigating the characteristics and behavior of long-wavelength turbulence and other instabilities in the ST [with an advanced optical diagnostic, Beam Emission Spectroscopy]	2		1
FES Science/non-diag	Schmitz, Oliver	U Wisconsin	Control of neutral fueling and helium exhaust in NSTX-Upgrade plasmas by three-dimensional magnetic control fields	3		2
FES Diagnostic	Luhmann, Jr. N.C.	UC Davis	FIR Density Monitoring, Feedback Control and Fluctuation Diagnostics for NSTX	2	1	3
FES Science + Diagnostic	Heidbrink, William	UC Irvine	Fast-Ion D-Alpha Diagnostic for NSTX + Beam-ion studies in NSTX-U	2		1
FES Science/non-diag	Crocker, Neal	UCLA	Develop a predictive capability for compressional and global Alfvén eigenmodes in NSTX-U and advance understanding of the associated electron thermal transport	1		1
FES Diagnostic	Peebles, Tony	UCLA	Cross-Cutting Research Studies on NSTX-U (Multi-channel (16) reflectometry installation, 288GHz mid-plane polarimeter)	3		1
				36	9	31

Question 4a: Briefly summarize the areas of theoretical research that might have been terminated as a result of the Partnership

Assumption: Enough funds to support the additional 2.5 Theory + 1.0 CPPG

- **Steve Jardin** (M3D-C^1): less work on
  - Sawtooth studies on DIIID, CMOD, and ASDEX-U
  - M3D-C1 code modifications to include kinetic effects
- **C.S. Chang et al.** (XGC0, XGC1): less work on
  - Gyrokinetic impurity transport in SOL and pedestal (development)
  - Gyrokinetic study of L-H transition
- **Elena Belova** (CAE/KAW): less work for Tri Alpha (FRC)
- **Edward Startsev** (implementing e-m effects in GTS): less work on HEDP
- **Weixing Wang** (GTS core transport studies): less work DIII-D core transport
- **Josh Breslau** (VDE simulations): stopped working on innovative stellarator coil design
- **Roscoe White** (energetic ion transport by *AE modes): less work on density limit disruptions
- **Amitava Bhattacharjee** (helped establish Partnership): delayed greatly finishing review paper on sawtooth physics with Ian Chapman and Hyeon Park

AB: "working with the NSTX team often produces synergisms in which the whole becomes larger than the sum of the parts."

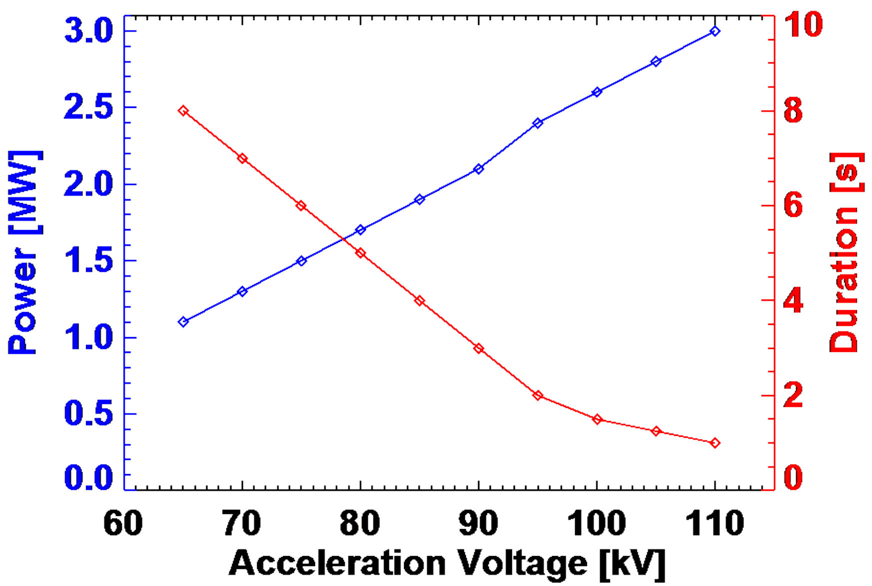
Question 4b: What NSTX-related Theory work is being done outside the NSTX-U/Theory Partnership?

- **NTV Physics** (NTVTOK, IPECs/POCA): Columbia U., NSTX-U
- **Kinetic stabilization of IWM, RWM**: NSTX-U, Columbia Univ.
- **Development of reduced model for fast ion transport**: NSTX-U
- **Transport model validation** (RLW, TGLF, MMM): NSTX-U, GA, Lehigh U.
- **Core gyrokinetic studies, including momentum transport** (GYRO, GTS, GS2, GEM, GKW): NSTX-U, U. Colorado, U. Bayreuth
- **Impurity transport** (MIST/STRAHL): Johns Hopkins U.
- **SOL transport physics, including blobs** (UEDGE, SOLPS, SOLT): LLNL, Lodestar
- **Pedestal physics** (XGC0,1, ELITE, GS2/GYRO, gyrokinetic edge model development): NSTX-U, GA, ORNL, PPPL Theory
- **Materials modeling**: U. Tenn, U. Illinois
- **FW & EBW physics** (AORSA, TORIC, GENRAY, CQL3D): ORNL, NSTX-U, MIT, CompX
- **CHI/reconnection modeling** (NIMROD): LLNL, U. Wisc.

Backup for Question 1

Heating System Limitations from the GRD

- Beam duration is limited by low cycle fatigue on the primary energy ion dump.
  - 5 seconds: 6*1.7 MW =10.2 MW total power from 6 sources



  - Note: Upgrades to hypervapotrons, as envisioned for TPX, would eliminate this issue.
  - Limits enforced by source operators (administratively) and numerous timing systems.
- The HHFW system is assumed to create 4 MW of power for 5 seconds

Vessel is Qualified for 70 MJ on a 20 Minute Cycle

- Vessel power balance assumed 14 MW for 5 s.
  - is 70 MJ
  - NSTXU-CALC-11-01-00
- Assumed that
  - DN plasma
  - ~40% of the power ends up on the horizontal targets
    - For an assumed power loading of ***5 MW/m^2 on average***.
  - 1200 s rep rate = 20 min
  - The CS and outer vessel are actively cooled between shots
    - Capability is new on the CS to buffer the coils from the plasma thermal loads
    - We have had this capability on the outer vessel for bake-out.
- Under these assumptions, the tile surfaces go toward ~1000 C at the end of the pulse, but
  - the vessel/casing are maintained without boiling the water in any location.
  - The vessel system is qualified for 70 MJ

However, the Peak Heat Flux May Prove Problematic…

- Limit #1: Thermal stresses in target tiles can exceed ATJ graphite limits.
  - Inner horizontal target tiles qualified for 5 sec operation at Q_{ave}=5 MW/m², Q_{Pk}=8.0 MW/m²
- Limit #2: Desire to avoid tile surface temperatures exceeding T_{max}~1200 C.
  - Due to enhanced sublimation.
- Conservative assumption: $\lambda_q = 0.92 I_P^{-1.6}$ $\quad Q_{Pk} = \dfrac{P_{heat} f_{div} \sin(\theta)}{2\pi R \lambda_q f_{exp}}$ $\quad Q_{ave} = 0.63 Q_{Pk}$

100% NI

	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/m²]	Time to T_{max} [s]	Q_{Pk} [MW/m²]	Time to T_{max} [s]
Long Pulse	0.75	10.2	5.0	6	12.6		
	1.5	10.2	5.0	18	1.4		
	2.0	10.2	5.0	28	0.5		
Highest Power	1.5	15.6	1.5	27	0.6		
	2.0	15.6	1.5	43	0.25		

However, the Peak Heat Flux May Prove Problematic… Unless it is Mitigated

- Limit #1: 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, Q_{Pk}=8.0 MW/m^2
- Limit #2: Desire to avoid tile surface temperatures exceeding T_{max}~1200 C.
  - Due to enhanced sublimation.
- Conservative assumption: $\lambda_q = 0.92 I_P^{-1.6}$ $\quad Q_{Pk} = \dfrac{P_{heat} f_{div} \sin(\theta)}{2\pi R \lambda_q f_{exp}}$ $\quad Q_{ave} = 0.63 Q_{Pk}$
- Primary solutions: Broadening the heat channel (f_{exp}) via the snowflake divertor
  Increasing the fraction of radiated power (decreasing f_{div})

100% NI

	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]
Long Pulse	0.75	10.2	5.0	6	12.6	1.5	200
Long Pulse	1.5	10.2	5.0	18	1.4	4.5	22
Long Pulse	2.0	10.2	5.0	28	0.5	7	8.7
Highest Power	1.5	15.6	1.5	27	0.6	7	9.3
Highest Power	2.0	15.6	1.5	43	0.25	11	4.0

These Observations Motivate the Strong Desire to Mitigate the *Peak* Heat Flux

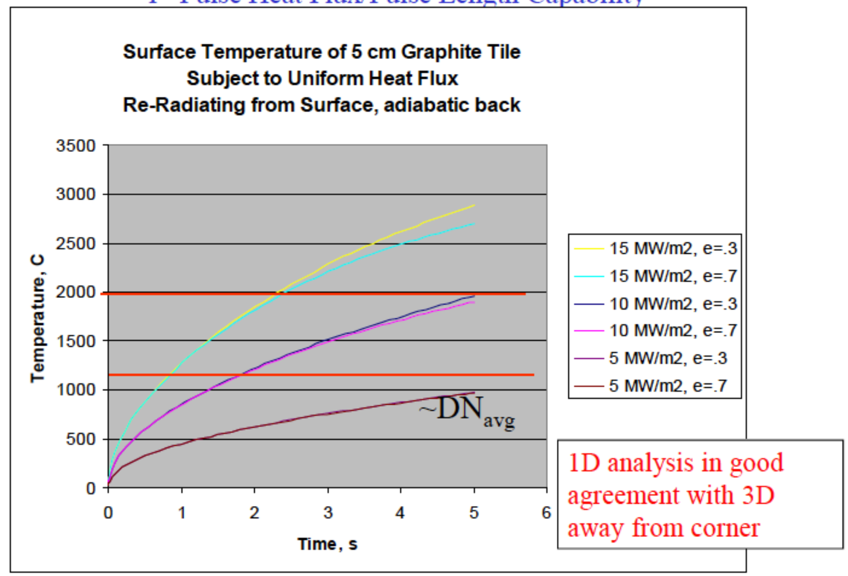
- Collaborations…
  - LLNL and PPPL members of the NSTX-U team collaborating on snowflake divertor research on DIII-D.
    - Physics, control,…
  - PPPL members of the NSTX-U team active in radiative divertor control at DIII-D.
- Engineering Analysis…
  - Mike Jaworski and I have been working with analysis division to assess the impact of more realistic heat flux profiles on tile thermal stresses.
- Infrastructure…
  - NSTX-U has more divertor coils in order to optimize the divertor geometry.
  - Installing high-throughput divertor gas systems to control the director radiation.
  - Comprehensive system if IR cameras to asses surface temperatures
    - ORNL collaboration.
- Plans…
  - Heat flux mitigation figures prominently in the plans/goals for ASC, Boundary Physics, and Materials/PFC TSGs.

Criterion For Heat Flux Limits

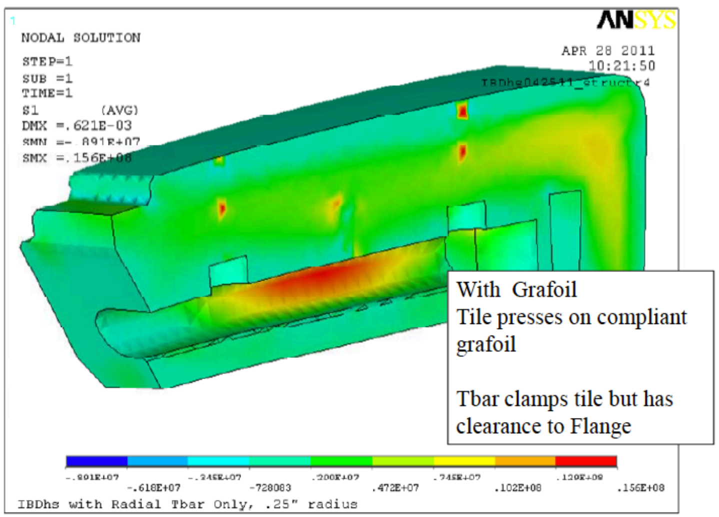
- Calibrate expression for tile surface temperature against engineering models:
  - $T_{surf}=CQ_{ave}t^{1/2}$
  - Use T_{surf}=1000 C, t=5 s, Q_{avg}=5 MW/m^2.
    - Derive C~90 Cm^2/MWs$^{1/2}$
- Derive heat flux Q from simple scalings:

$$Q_{peak} = \frac{P_{heat} f_{div} \sin(\theta)}{2\pi R \lambda_q f_{exp}} \qquad \lambda_q = 0.92 I_P^{-1.6}$$

1st Pulse Heat Flux/Pulse Length Capability



11 Single pulse without ratcheting with ATJ Graphite



Summary of Tile Thermal Structural Response					
	Heat Flux for 5s	Ratcheted Temperature	Peak Tensile Principal Stress, S1	Peak Compress Principal Stress, S3	Max Deflection
	mw/m2	C	MPa		mm
IBDhs, surface	5.0	1062	15.6	-58.0	0.6
Hot Spot at Corner		1512			
IBDvs, surface	1.6	425	7.0	-16.3	0.1
Hot Spot at Hole		560			
CSAS, surface	1.6	327	8.2	-10.7	0.2
Hot Spot at Hole		417			
CSFW	0.2	260	1.6	-6.5	0.01