PAC-33 Questions – Day 2

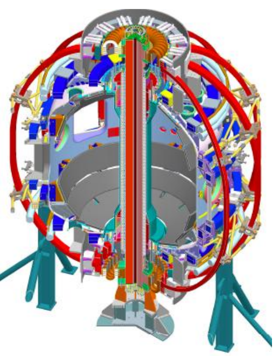
- What would it take from budget and scheduling standpoint to implement full high-Z wall coverage during 5 year plan. Consider both base 5YP and incremental. What is high-level programmatic impact?
- NSTX-U Program response summary:
  - Achieving full high-Z coverage with 5YP base budget is possible, but eliminates most other important topical science upgrade options and delays critical ST-specific research – we view this as unacceptable
  - Achieving full high-Z coverage with <u>5YP incremental</u> budget is possible and could be done mid-5YP, and also allows for good diagnostic coverage for high-Z+Li+divertor, while also providing critical ST-development tools such as ECH, plasma guns, NCC

5 year plan tools with 5YP base funding
(FY2012 + 2.5% inflation)

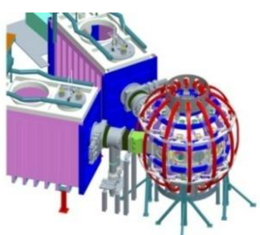
2014	2015	2016	2017	2018

Upgrade Outage | **1.5 → 2 MA, 1s → 5s**

New center-stack



2nd NBI



Start-up and Ramp-up
- Upgraded CHI for ~0.5MA
- Up to 0.5 MA plasma gun
- ECH/EBW 1MW

Boundary Physics
- Lower divertor cryo-pump

Materials and PFCs
- High-Z tile row on lower OBD
- High-Z tile row on cryo-baffle
- Lower high-Z divertor

Liquid metals / lithium
- Li granule injector
- Upward LiTER
- LLD using bakeable cryo-baffle

MHD
- MGI disruption mitigation
- Partial NCC
- Enhanced MHD sensors

Transport & Turbulence
- δB polarimetry
- High k_θ

Waves and Energetic Particles
- HHFW limiter upgrade
- 1 coil AE antenna
- 4 coil AE antenna

Scenarios and Control
Establish control of:
- Snowflake
- $\bar{n}_e$
- Rotation
- q_{min}
- Divertor P_{rad}

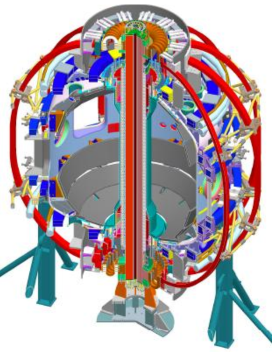
- Cryo-pump, high-Z tile row on cryo-baffle, and partial NCC would be installed in-vessel during ~1 year outage between FY2016 and FY2017
  - NSTX-U would operate 1st half of FY2016 and 2nd half of FY2017

5 year plan tools with 5YP base funding w/ early high-Z

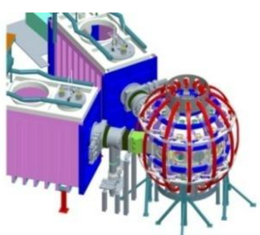
(FY2012 + 2.5% inflation)

	2014	2015	2016	2017	2018
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			

New center-stack



2nd NBI



Start-up and Ramp-up	Upgraded CHI for ~0.5MA
Boundary Physics	Lower divertor cryo-pump
Materials and PFCs	High-Z tile row on lower OBD; All high-Z PFCs
Liquid metals / lithium	Li granule injector; Upward LiTER
MHD	MGI disruption mitigation
Transport & Turbulence	δB polarimetry; High k_θ
Waves and Energetic Particles	1 coil AE antenna; 4 coil AE antenna
Scenarios and Control	Establish control of: Snowflake, $\bar{n}_e$, Divertor P_{rad}, Rotation, q_{min}

- Cryo-pump + full high-Z coverage would be installed in-vessel during ~1 year outage between FY2017 and FY2018
  - NSTX-U would operate 1st half of FY2017 and 2nd half of FY2018

- Performing cryo and high-Z conversion in single outage is most time/cost-effective
- Requires ~3 years to accumulate resources to implement cryo and full high-Z conversion
- Could accelerate full high-Z by 1 year if cryo delayed1-2 years
- No ECH, plasma guns, partial NCC, enhanced MHD sensors, or HHFW modifications

5 year plan tools with 5YP incremental funding w/ early high-Z

1.1 × (FY2012 + 2.5% inflation)

2014	2015	2016	2017	2018

Upgrade Outage | **1.5 → 2 MA, 1s → 5s**

- Cryo-pump + full high-Z coverage would be installed in-vessel during ~1 year outage between FY2016 and FY2017
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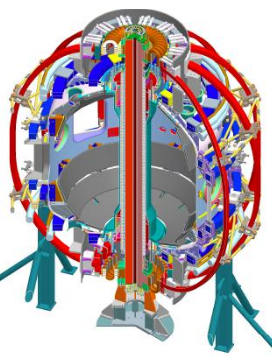
New center-stack



Start-up and Ramp-up: Upgraded CHI for ~0.5MA; up to 1 MA plasma gun; 1 MW ECH/EBW

Boundary Physics: Lower divertor cryo-pump; Divertor Thomson

Materials and PFCs: High-Z tile row on lower OBD; All high-Z PFCs; Diagnostics for high-Z wall studies

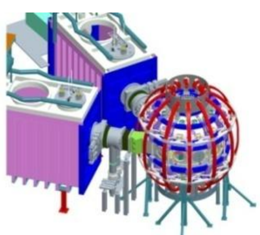
Liquid metals / lithium: Li granule injector; Upward LiTER; LLD using bakeable cryo-baffle

MHD: MGI disruption mitigation; Partial NCC; NCC SPA upgrade; Enhanced MHD sensors

Transport & Turbulence: δB polarimetry; High k_θ

Waves and Energetic Particles: 1 coil AE antenna; 4 coil AE antenna

Scenarios and Control: Establish control of: Snowflake, $\bar{n}_e$, Divertor P_{rad}, Rotation, q_{min}; Control integration, optimization



2nd NBI

- Divertor Thomson and high-Z diagnostics included
- 1MW ECH instead of 2MW
- Partial NCC instead of full (but includes SPA upgrade)
- Flowing Li module could be substituted for plasma gun or SPA upgrade
- No intermediate-k turbulence
- No HHFW modifications or fast-ion diagnostics for high density

Several high-Z PFC fabrication concepts will be developed in parallel w/lab studies; demonstrated readiness affects pacing

- High heat flux regions (strike-point regions)
  - TZM or W lamellae, or TZM tiles (if workable)
- Intermediate heat flux regions (cryo-baffles, CS midplane)
  - TZM tiles or TZM/W lamellae
- Low heat flux regions (passive plates, CS off-midplane)
  - W-coated graphite
- Additional pulse-length extension (10-20s) at high power (~15MW) would require actively-cooled divertor PFCs

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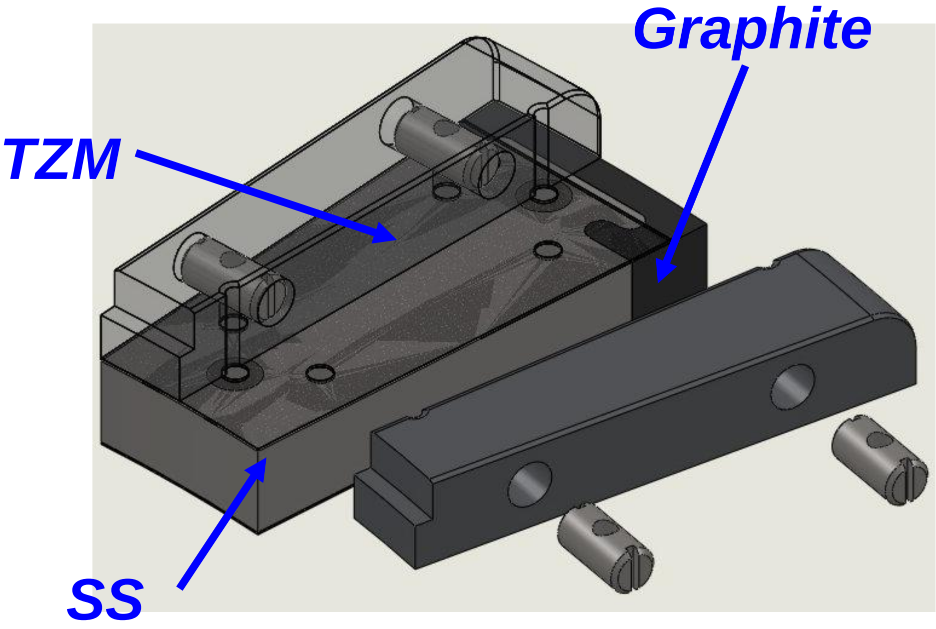
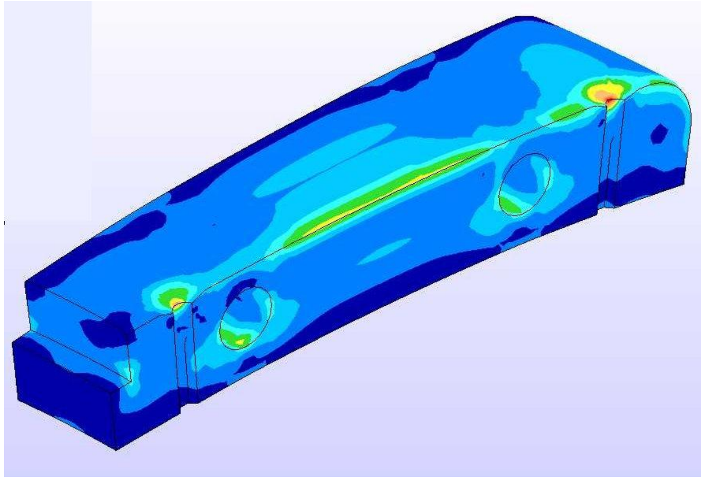
FY2011 tile design

- Design developed for FY2011 run campaign, inboard horizontal divertor (next to CHI)
- Split-top molybdenum to reduce eddy-current forces (NSTX design points)
- 2MW/m^2 for 2s average surface heat flux expected to be acceptable for avoiding fatigue limits of TZM



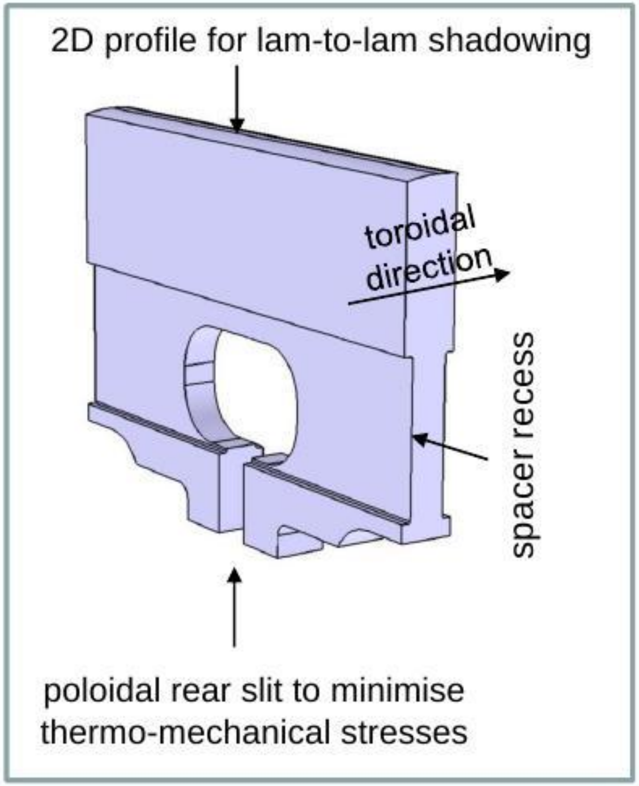


Thermo-mechanical stress

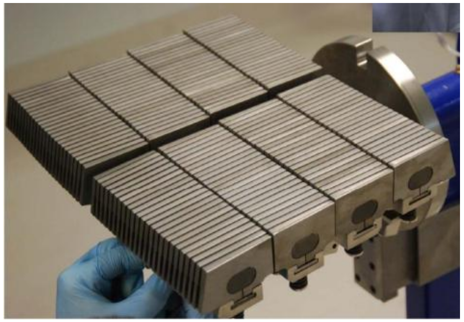
R. Woods Mo-tile FDR

Lamellae used on JET and CMOD divertors

- Designed for 7MW/m^2 (uniform) for <10s (60MJ/m^2 total energy deposition)
- Lamellae depth determines thermal reservoir
- Cuts in toroidal and poloidal directions minimize eddy-currents and thermo-mechanical stress
- Complex shaping used to eliminate leading-edge effects

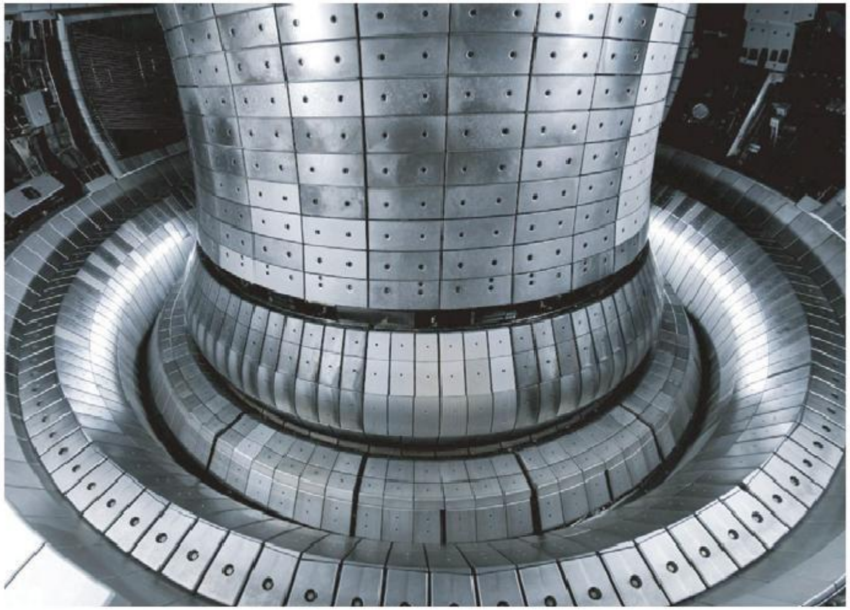


Ph. Mertens, 13th PFMC, 2011



Coatings of graphite substrates

- ASDEX converted machine to tungsten with the use of coatings
- Wall components coated with ~4 μm
- Divertor targets coated with ~200 μm
  - Despite extensive tests, still delaminated under peak heat fluxes >10MW/m^2
  - Switch in coating technologies due to repeated delaminations
  - Necessitated radiative divertor development



Neu, Phys. Scr. 2009.

Initial thoughts without rigorous engineering assessment of concepts

- NSTX-U parameters will make bulk tiles difficult to implement
  - Bulk-tile difficult to reduce thermal stresses and maintain thermal capacity
  - Lamellae seem to offer all the appropriate features
  - Not considering actively cooled targets (yet)

- Low-heat flux areas can probably use coatings
  - Assuming already fabricated ATJ to be used
  - Some batch testing recommended to ensure any CTE mismatch not "life-threatening"

Possible NSTX-U high-Z development plan

- FY 13 – Perform more rigorous engineering assessment of lamellae vs. bulk-tile for NSTX-U conditions (much of this would likely require ~1 FTE engineer, ~0.5 FTE designer/drafting + some tech time per year)
  - Identify coating technology (e.g. PVD vs. VPS) for use on ATJ tiles
  - Identify heat-flux facility for cyclic testing
- FY 14 – Fabricate prototype PFC tile for thermal testing at suitable facility
  - Test small lots of coated samples
  - Test PFC prototype
- FY 15 – Determine PFC interfacing issues with existing mounting hardware – final designs, procurements
  - Begin scenario development to control PFC energy deposition
  - PFC prototype testing to failure to establish absolute limits
- FY 16 – fabrication installation
  - Complete scenario development for high-Z protection
- FY 17 – operation with all high-Z

M&P diagnostic needs for high-Z upgrade on accelerated/incremental schedule

- M&P program written against baseline funding and consistent diagnostic set
  - Diagnostics consistent, PFCs transition
  - Expected modest implementation in first 5 years.
- With aggressive transition to high-Z walls the following would be advantageous
  - Expanded coverage of first-wall elements (passive plates) with particle sensors (probes) and spectroscopic coverage
  - Ensure core x-ray spectrometers are ready for operations to support high-Z transport studies and core accumulation

Acceleration to All Metal PFCs Will Result In Modifications to the Scenario/Control Research and Likely Accessible Scenarios (slide 1)

- PFC integration/protection issues would become a primary recipient of control & scenario development resources.
  - Radiative divertor realtime diagnostic and control research would become high priority…likely comparable to SFD.
  - Automated discharge shutdown methods would get higher priority.
    - But likely less emphasis on more theoretical/abstract aspects of disruption PAM.
  - May be necessary to develop realtime hot-spot detection, similar to IR system on JET (visible cameras w/ filters for IR).
    - If so, major control effort needed for realtime processing and interlocking.
  - Program shift would likely take resources from other scenario research topics
    - Rotation control, 100% non-inductive development, NBCD studies would be de-emphasized compared to present plan.

Acceleration to All Metal PFCs Will Result In Modifications to the Scenario/Control Research and Likely Accessible Scenarios (2)

- Scenario impacts are hard to predict a-priori, but may include:
  - Radiative divertor may result in edge cooling, more peaked thermal pressure profile. If so…
    - Will result in higher-l_i, may cause more issues for vertical stability, reduced shaping flexibility.
    - Will lower q_{min} for otherwise similar parameters, making plasmas more susceptible to core n=1 modes.
  - Remains unclear that the f_{GW}=0.35, I_P=2.0 MW, P_{inj}~10 MW cases will be accessible, due to requirement of higher divertor density for PFC protection.
    - May eliminate the x10 reduction in collisionality compared to NSTX, even with cryo-pump.
  - Low flux-expansion shapes will be restricted to quite low currents and heating powers.
    - If flux-expansions greater than ~20 are required for higher I_p and B_T, then the low-δ shapes are practically eliminated.
  - If tiles are shaped to eliminate leading edges, then reversed B_T is excluded. Except if I_P is revered as well (counter-injection!!!).

Acceleration to All Metal PFCs Will Result In Modifications to the Scenario/Control Research and Likely Accessible Scenarios (3)

- Scenario impacts are hard to predict a-priori, but may include:
  - Need to develop new diagnostic methods.
    - CHERS on other spectral lines (is this possible???)
    - More complicated impurity accounting for core Z_{eff} measurements.
    - Better spectroscopy for core and edge high-Z materials.
  - If high-Z PFCs result in current quenches faster than projected from NSTX data, then maximum I_P allowed may be restricted.
    - Note, slow current quenches in JET with low-Z Be wall.
  - If disruptions become problematic, then will require substantial modifications to run planning.
    - Many present experiments in MS/ASC would be restricted to lower values of parameters, as they are prone to disruption.
    - More experienced individuals would have to be present for experiments, with more physics operator discretion to say “no”.
      - NSTX would likely be a far less friendly environment for new/young experimenters.