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NSTX

Response to PAC-23 questions

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For the NSTX Research Team

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PAC question #1

a) Just as you have prioritized your “key” hardware upgrades (BES, LLD, HHFW), **what are your “key” run-time/schedule priorities?**

b) Also, what is the interrelationship between your run-time priorities and your “key upgrades”?

Short answers:

a) Gaps in performance/understanding motivate milestones, and milestones receive highest priority for run-time

b) Upgrades support the milestones

More extensive answers are given on subsequent pages

Performance gaps between present and next-step STs motivate operational goals and associated milestones & upgrades

GOALS: reduce n_e, increase NBICD & H-mode confinement, demonstrate start-up/ramp-up

Present high-f_{NICD}	NSTX	NHTX	ST-CTF
A	1.53	1.8	1.5
κ	2.6-2.7	2.8	3.1
β_T	14%	12-16%	18-28%
β_N [%-mT/MA]	5.7	4.5-5	4-6
f_{NICD}	0.65	1.0	1.0
f_{BS}	0.54	0.65-0.75	0.45-0.5
f_{NBICD}	0.11	0.25-0.35	0.5-0.55
f_{GW}	0.8-1.0	0.4-0.5	0.25-0.5
H_{98y2}	1.1	1.3	1.5
Dimensional/Device Parameters:			
Solenoid Capability	Ramp-up + flat-top	Ramp-up to full I_P	No/partial ramp-up
I_P [MA]	0.72	3-3.5	8-10
B_T [T]	0.52	2.0	2.5
R_0 [m]	0.86	1.0	1.2
a [m]	0.56	0.55	0.8
I_P / aB_{T0} [MA/mT]	2.5	2.7-3.2	4-5

Prioritization of performance/understanding gaps

- Priority #1 = Increase & understand beam-driven current
  – NHTX/CTF require full NICD to achieve missions, and NBICD is largest gap

- Priority #2 = Increase & understand H-mode energy confinement
  – ST energy confinement – in particular electron energy confinement - not sufficiently well understood to make extrapolation to next-steps with high confidence (need to better understand underlying physics of scalings)

- Priority #3 = Sustained high β_N ***<u>and</u>*** non-inductive start-up & ramp-up
  (both topics are priority 3)
  – High plasma performance requires sustained β_N near & above no-wall limit
    - Somewhat more important for NHTX which also aims to test reliability of ops. near ideal-wall limit
  – Non-inductive ramp-up essential to ST-CTF, NI start-up also beneficial

Run time/schedule priority will be given to milestones
List below is prioritized based on relative importance of gaps

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- Key upgrades utilized for milestones are shown in (red)
- Note that all milestones below are "high priority", since milestones are allocated as much run-time as is needed (within reason) to achieve their goal

FY2008 Milestones

Joule	Evaluate generation rotation & momentum transport, impact of rotation on stability and confinement	
1.	Couple inductive ramp-up to CHI plasmas	
2.	Study variation and control of heat flux in SOL	
3.	Measure poloidal rotation at low A and compare with theory	(poloidal CHERs)

FY2009 Milestones

Joule	Particle control and hydrogenic fuel retention in tokamaks	(LLD)
1.	Assess non-inductive current drive sources vs. density at high β	(LLD)
2.	Characterize fast-ion redistribution from AE avalanches	(LLD, BES in FY10)
3.	Understand physics of RWM stabilization and control as a function of rotation	

FY2010 Milestones

Joule	TBD – could be additional fast-ion milestone for AE ξ(r,t) in H-mode	(BES)
1.	Study turbulence regimes responsible for ion and electron energy transport	(BES)
2.	Assess pedestal characteristics and ELM stability as a function of ν*	(LLD)
3.	Characterize HHFW heating, CD, and I_P ramp-up in H-mode plasmas	(HHFW)
3.	Assess stability & control of sustained operation near the ideal-wall limit	(LLD, HHFW)

PAC question #2

“At the end of your 3 year campaign, **what are the NSTX performance and/or operational metrics** that will convince the fusion community that you understand ST physics well enough to justify continued research towards a next-step ST device?”

Answer:

See descriptions of performance gaps on next 4 pages, and “Associated performance and understanding metrics for NSTX” bullets for the metrics.

Performance gap #1: Sustained fraction of beam-driven current

- Next-step STs assume 25-50% of I_P will be driven by NBICD
  - Achieve this high fraction of NBICD by operating at low n_e/n_{GW} = 0.3-0.5
    - NBICD efficiency scales as $T_e / n_e \rightarrow 1/n_e^2$ at fixed $\beta \rightarrow$ favors low n_e
  - NSTX H-modes commonly evolve toward $n_e / n_{GW} \rightarrow$ 0.7-1
  - NSTX NBICD fraction $\approx$ 10-15% at high $\beta_N \sim 5$ and $H_{98} \sim 1$ as $n_e / n_{GW} \rightarrow 1$

→NSTX goal is to double or triple sustained NBICD

→NSTX needs 30-50% lower density for $f_{NBICD} \sim 30\%$ → need pump → **LLD** ←

(50% density reduction would be necessary if T_e does not increase at reduced n_e)

- Also expect fast-ion transport from AE avalanches in ST-CTF

→ Assess avalanches at next-step-relevant β_N, H_{98}, n_e/n_{GW} for $\tau \sim 1\tau_{CR}$

To extrapolate → develop predictive capability for avalanches

→Need displacement diagnostic compatible with H-mode → **BES** ←

Initial scoping indicates BES useful diagnostic for AE displacement profile $\xi(r,t)$

- Associated performance and understanding metrics for NSTX for FY08-10:
  - Drive 30% of I_P with NBI at next-step-relevant β_N, H_{98}, n_e/n_{GW} for $\Delta t \sim 1\tau_{CR}$
  - Assess NBICD scaling w/ n_e, predictive capability for J_{NBI} including redistribution

Performance gap #2: Energy confinement in H-mode

- Next-step ST's assume H-mode confinement with H_{98y2} = 1.3-1.5
- On NSTX (and MAST) observe that electron confinement scales nearly linearly with B_T, while ion confinement scales nearly linearly with I_P
  - e-transport is presently dominant loss mechanism, i-transport often near neoclassical
  - These results and scalings differ from conventional aspect ratio
  - Also unclear if these low I_P, B_T scalings are valid at higher I_P, B_T of next-steps
  - → Complete scaling studies at next-step-relevant β_N, **n_e/n_{GW}, ν^*** → **LLD** ←
  - → Understand why scalings are the way they are
  - → Measure wave-numbers responsible for i & e transport → **BES** ←
  - → Use data to determine which modes causing anomalous transport
  - → Determine how transport from measured modes extrapolates to next-steps
- Also need scaling & modeling of pedestal transport & stability vs. ν^*, shape

- Associated performance and understanding metrics for NSTX for FY08-10:
  - Obtain H_{98y2} = 1.2-1.3 at next-step-relevant β_N, f_{BS}, f_{NICD}, n_e/n_{GW} for Δt ~1τ_{CR}
  - Have strong theoretical basis that required level of confinement is achievable

Performance gap #3: Sustained $\beta_N \geq \beta_{N\text{-no-wall}}$ at next-step-ST relevant conditions

- Next-step STs require stable & sustained operation near ideal no-wall limit
  - Would greatly benefit from stable operation above no-wall limit, near ideal-wall limit
- One might assume that with all co-NBI, NHTX/CTF will have sufficient rotation to stabilize RWM, shield out error fields, help stabilize NTMs. But, there are concerns:
  - Even near no-wall limit, likely need active control of RFA, slowly growing RWMs
  - Can't predict what rotation profile (from first principles) will be in next-steps
  - Community still developing experimentally validated theory for RWM critical rotation
  - Collisionality apparently important for RWM critical rotation, next-steps will have lower ν^*
  - NHTX/ST-CTF will potentially operate with $q_{min} > 2$. If low-order rational q surfaces are important in RWM rotation stabilization, critical rotation could increase…
  - Braking torques from mode/EF non-axisymmetric field (NTV) may scale as $1/\nu_i$ → important for sustained/controlled plasma rotation/rotation profile in next-step STs

  → Need to understand physics of RWM stabilization & control as function of rotation
- Generally assume that with $q_{min} > 2$, NTMs will not be problematic
  - Unclear if $q_{min} > 2$ with be optimal q profile for next-step integrated performance
  - NTMs can be triggered by ELMs, and via proximity to ideal-wall limit
  - NTM stability also depends on rotation and error fields

- Associated performance and understanding metrics for NSTX for FY08-10:
  - Operate at β_N far above NW limit (C_β=0.5-0.9) at low n_e / n_{GW}, ν^* for Δt = 1-2τ_{CR}
  - Have strong theoretical understanding of RWM Ω_{crit} & control, NTV, NTM stability

Performance gap #4: Non-inductive start-up+ramp-up for ST-CTF

- ST-CTF requires non-solenoidal I_P ramp-up to 8-10MA
(NHTX has solenoid for ½ swing ramp-up to full I_P, and could also test start-up and ramp-up physics & technology for ST-CTF)

- ST-CTF could have small iron core for ~1MA (estimate) of start-up current
  – Could also use CHI, plasma guns, EBW, VF ramp, or combination for start-up
  – Assume NBICD+BS (and maybe LHCD or EBCD) used for ramp-up to full I_P
  → Need to perform integrated time-dependent modeling to assess feasibility of this

- Already achieved 85% BS fraction during low-I_P (200-300kA) ramp-up experiments with HHFW during 2005-2006
  – Power limited by antenna voltage limits due to low loading at low (early) density
  – Transition to H-mode and ELMs cause HHFW power trips/faults
  → Antenna upgrades + ELM resilience should enable first demonstration of BS current overdrive for ramp-up in an ST → **HHFW** ←
  → HHFW also useful for heating high-β_N, high-f_{BS} integrated scenario → **HHFW** ←

- Associated performance and understanding goals for NSTX for FY08-10:
  – Decouple start-up and ramp-up problems experimentally, and demonstrate:
    - CHI start-up to $I_P \sim$ 300kA, HHFW BS+RF overdrive from 200kA ohmic target → 400kA
  – Understand/model scaling of CHI start-up, HHFW (& NBI) ramp-up for next-steps

PAC question #3

- How to achieve 2010 HHFW goals?

Plan for the NSTX HHFW program to 2010

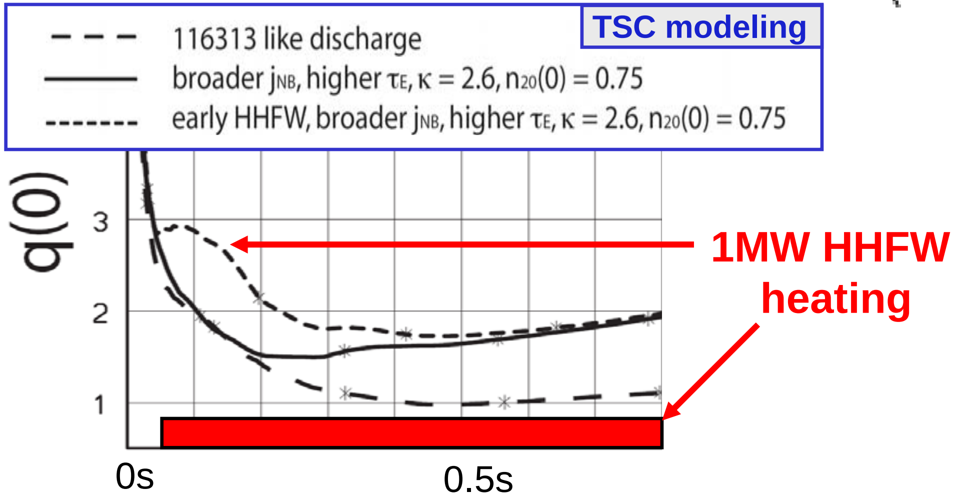
- FY 08 Plan:
  - Extend L-mode coupling physics studies to Deuterium plasma; improve operations w/ NBI
  - Assess effect of Li, and optimize heating efficiency
  - Test -150°C CD phasing (pure spectrum)
  - Begin heating & CD studies in D H-mode plasmas and assess effect of Lithium
  - Finalize ELM resilience system requirement and design
  - Prepare and install double feed antenna system for FY 09 run

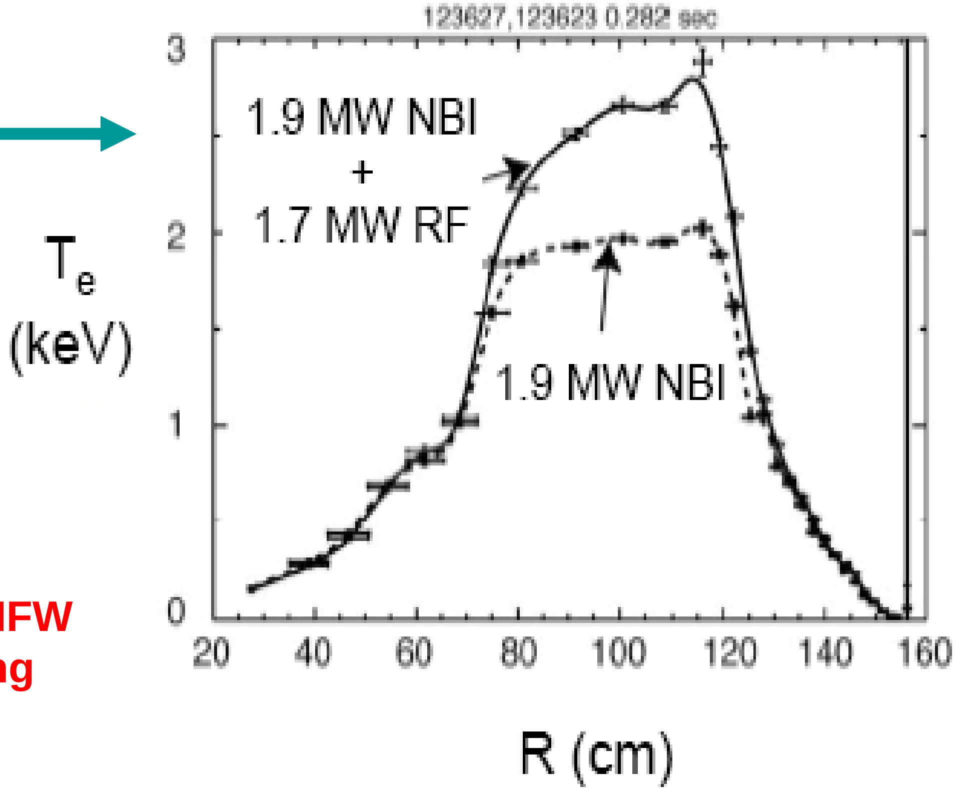
- FY 09 Plan:
  - Assess heating & CD operation with NBI in H-mode plasmas with double feed antenna
  - Optimize HHFW coupling into I_P ramp-up with double feed antenna
  - Test HHFW heating in CHI + OH plasmas

- FY 10 Goal: Characterize HHFW heating and current drive in H-mode plasmas
  - Optimize HHFW heating and CD with NBI H-mode using ELM resilience system
  - Test usefulness of HHFW heating at high-β_N, high-f_{BS} integrated scenario
  - Demonstrate BS current overdrive for ramp-up by HHFW in an ST for the first time
  - Understand/model HHFW ramp-up for next steps
  - Test HHFW heating in CHI + PF-only start up plasmas

Upgraded HHFW will enable assessments of ramp-up and flat-top electron heating in high-performance NBI H-mode scenarios

- 2007: Higher B_T = 0.55kG and $k_{||}$ reduce parasitic surface waves
  - →**Significant e-heating in presence of NBI for first time <u>in L-mode</u>**
- Plan: extend to B_T=5.5kG H-mode
  - – Early HHFW should elevate q



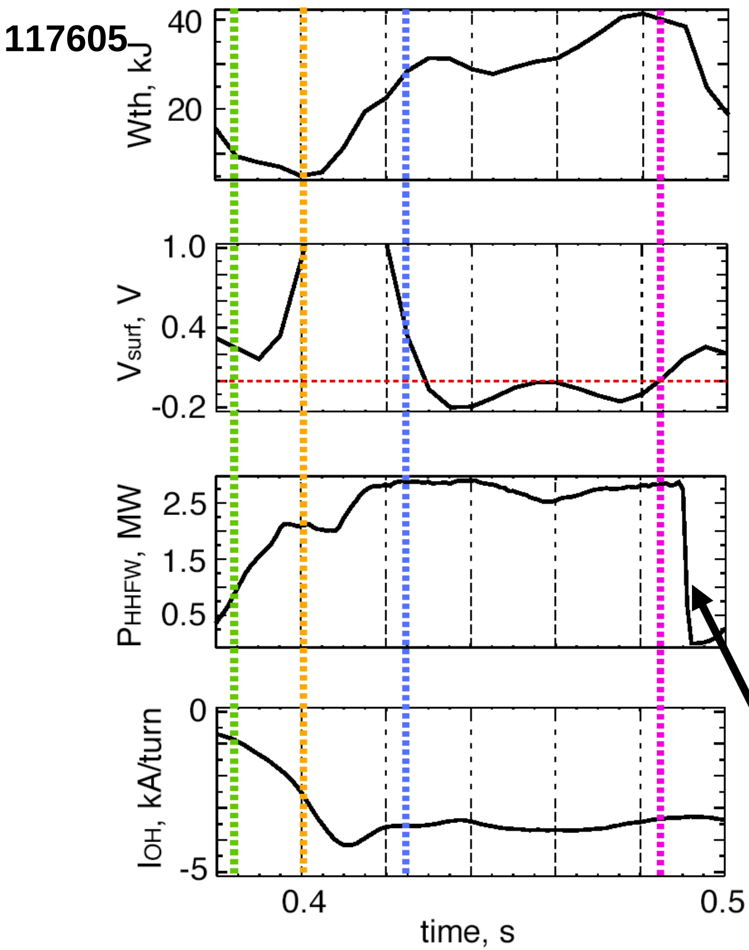


Double-feed antenna for higher P_{RF}, V_{RF} in FY09

Improved matching for ELM-resilience mid-FY10

HHFW experiments at low I_P have shown HHFW heating can induce a high β_P H-mode and drive V_{SURF} and V_{LOOP} → 0

I_P = 250 kA, $k_{||}$ = 14 m^{-1} heating

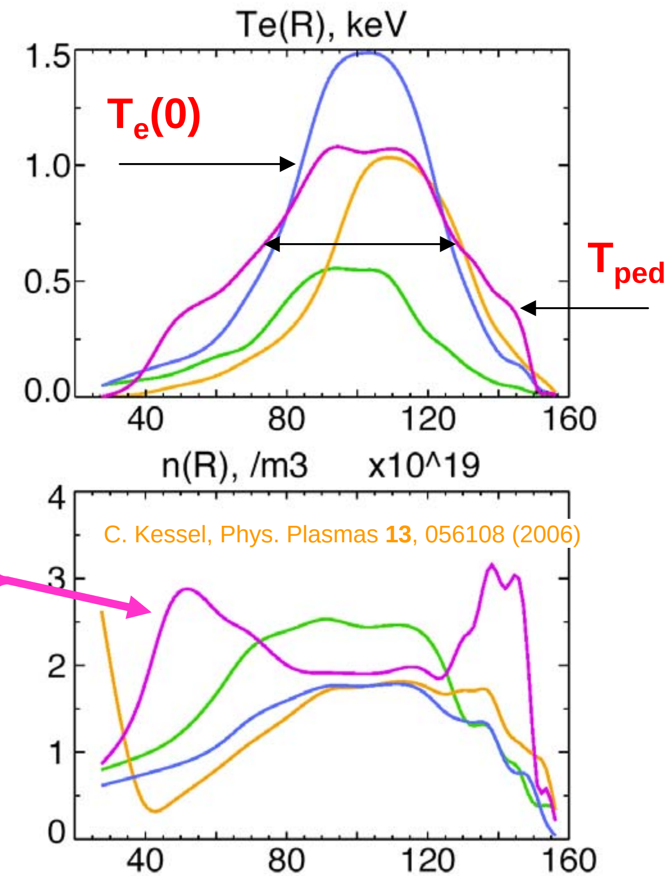


RF power trip caused by ELM

High $T_{ped,}$ broad $T(\rho)$, and "not-too-high" $T_e(0)$ best for non-OH ramp-up

t = 0.385
0.400
0.425
0.485

β_P=1.8
f_{BS}=85%



Need higher RF power & ELM resilience to sustain BS overdrive for ramp-up

PAC question #4

- How to achieve 2010 LLD goals?

Draft plan/ideas for the NSTX lithium program to 2010 (I)

- FY08 Plan – Characterize dual-LITER for n_e control & Li replenishment for LLD-I
  - Proposed experiments:
    - Characterize dual-LITER pumping vs. evap. rate & amount, assess effect on ELMs (FY09 prep)
    - Particle accounting with and without lithium (FY09 prep)
    - Combine with supersonic gas injection to reduce density rate of rise in H-mode
    - Use as tool for preliminary investigation of NBICD efficiency vs. density
  - Key operational questions:
    - Can shot-to-shot reproducibility be maintained with minimal/no He glow
    - If not, use LITER shutters to minimize Li evaporation into He glow
  - Preliminary tests of Li replenishment systems for LLD beyond LITER (if ready)

FY09-10 plans and goals on following page…

Draft plan/ideas for the NSTX lithium program to 2010 (II)

- FY09 Goal: Characterize LLD-1 as a pump (using dual-LITER Li replenishment)
  - Joule Milestone: "Assess particle control and hydrogenic fuel retention in tokamaks"
    - NSTX part of milestone can be achieved with 2-LITER alone – but goal is to use LLD-I also
  - Experimental/operational ideas
    - Perform LITER evaporation rate/amount scans to assess impact on LLD-I pumping performance.
    - Tests of Li replenishment systems for LLD beyond LITER
    - Perform LLD temperature scans (solid Li to liquid Li) to assess if divertor or wall pumping dominates
    - Assess impact of plasma strike-point position, flux expansion, magnetic balance on LLD-I pumping
    - Obtain additional data on NBICD efficiency vs. density
  - Need LLD-I data by April of '09 to make decisions on LLD-II
  - LLD-II possibilities:
    - Remove LLD-I – give up on LLD concept and research for FY10
    - Keep LLD-I as-is, but implement improved Li replenishment systems
    - 2nd Mo-coated Cu plate on inner divertor – requires inboard Li replenishment (could be LITER)
    - Sandia CVD Mo-mesh in tray or more porous Mo-coated plate on outer divertor

- FY10 – Use LLD-II as density/ELM/confinement control tool for physics experiments
  - Characterize core and pedestal transport and stability/ELMs vs. ν^*
  - Assess NBICD and RWM stability vs. density/collisionality at NHTX/CTF levels of n_e/n_{GW}
  - ….

Evaluation of the effect of lithium on core and pedestal relies on new and existing diagnostics

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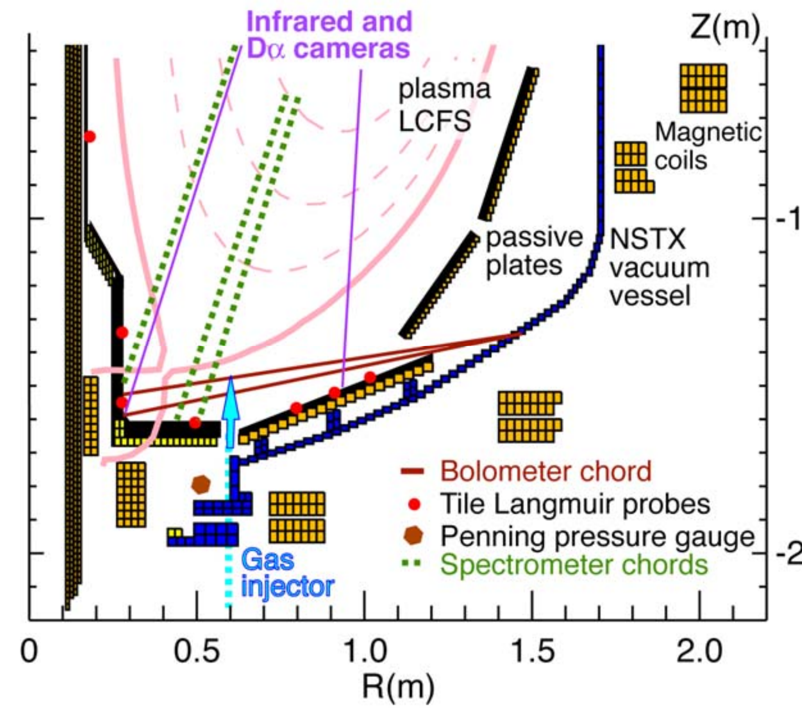
- Correlate global confinement improvement with local transport changes (TRANSP) and pedestal properties (analyze with ELITE)
- Correlate changes in Pedestal properties (Thomson, ChERS) with changes in edge Lithium (ChERS - new capability) and edge carbon (ChERS - existing)
- Correlate changes in pedestal impurities (carbon, Li) with source terms at PFCs (2-D fisheye camera, 1-D CCD cameras with C-I or Li-I filters)
  - Lower priority: study lithium transport in edge/SOL by comparing code calculations with data from other Li charge states
- New diagnostics to assess impact of LLD on divertor
  - Fast IR camera, divertor bolometry
  - Langmuir probe array on diagnostic tile strip
  - Lyman-α arrays for recycling estimates
  - Spectroscopi Penning gauge
  - Local divertor fast pressure gauge
  - Tile embedded fiber thermography

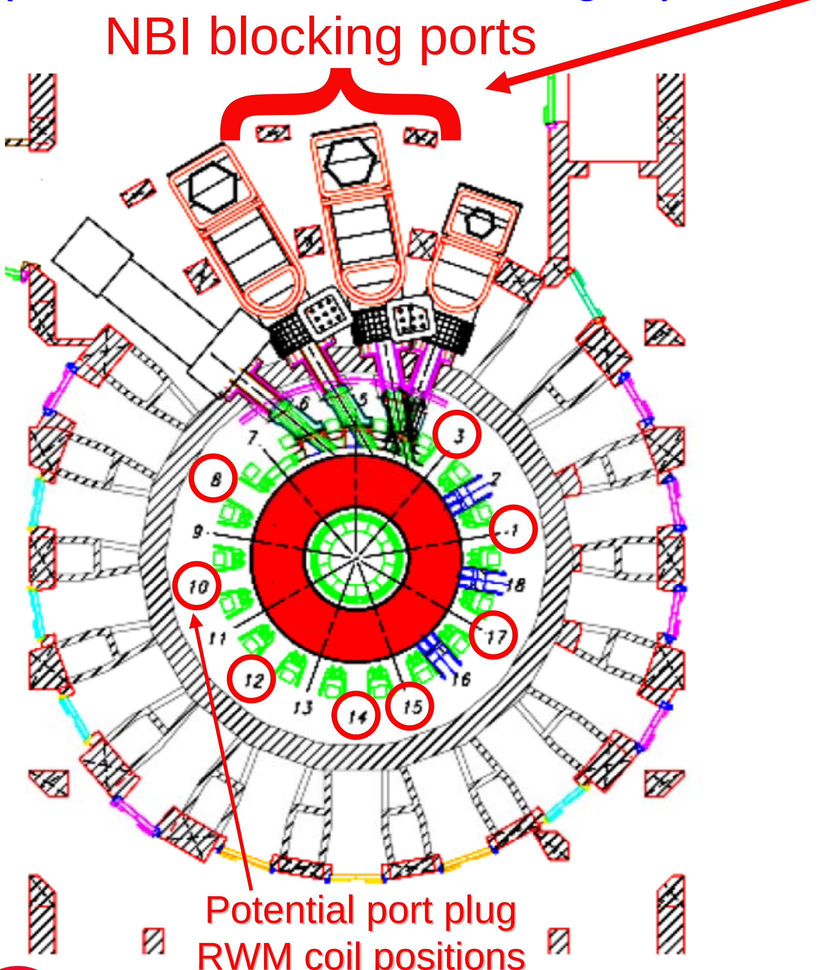


PAC question #5

- Detail of RWM port-plug?

Macro Stability TSG XP802 will assess n = 1 RWM active stabilization using emulation of proposed ITER port plug coils

ITER RWM Port Plug coil proposal
(from DCR document - fig. 2)



- ITER NBI blocks ~ 90° of toroidal angle from RWM coil access
- NSTX RWM coil system will be configured to emulate ITER coil configuration to test stabilization
  - Midplane coils, shielded by conducting structure
  - RWM coil buswork upgraded to allow single coils to be turned off
  - Turn off one and/or two coils (60° or 120° toroidal angle) and determine impact on RWM stabilization / DEFC
- Possible issues
  - lack of toroidal symmetry may lead to n > 1 content – mode might bulge into gap ("mode non-rigidity")