NSTX-U

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NSTX-U 5YP upgrade element impact and prioritization discussion + Q&A

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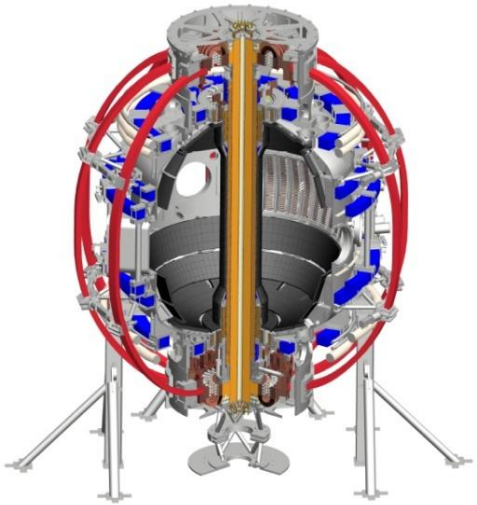
NSTX-U 5YP Status Meeting
Control Room Annex
January 11, 2013



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5 research thrusts / high-level goals for 5 year plan
(from last PAC Q&A, modified to emphasize ST needs)

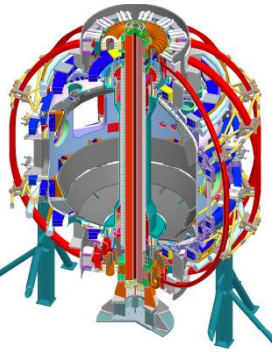
- Demonstrate 100% non-inductive current at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
- Access reduced ν^* and high β combined with ability to vary q & rotation to dramatically extend ST plasma understanding
- Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation w/ small/no solenoid
- Develop and utilize high flux expansion divertor magnetic configuration for heat flux mitigation
- Assess high-Z PFCs + flowing liquid lithium to develop high-duty-factor integrated PFC/PMI solution for FNSF, beyond

10 year plan goals with ~10-15% incremental funding

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Upgrade Outage | **Establish ST physics, scenarios** | **Integrate long-pulse + PMI solutions**

New center-stack



2nd NBI

Start-up and Ramp-up
- Increase CHI closed-flux current
- Understand plasma gun start-up at increased device size / major radius
- Develop/understand ECH/EBW H&CD for ST
- Increase/extend ramp-up heating and off-axis current-drive for advanced scenarios

Boundary Physics
- Establish main-ion density and ν^* control
- Understand snowflake divertor performance
- Investigate high-Z first-wall erosion, migration, particle sources & sinks

Materials and PFCs
- Assess high-Z divertor PFC impact and performance
- Assess high-Z first-wall
- Assess impact of high-temperature first-wall

Liquid metals / lithium
- Establish low impurities / Z_{eff} , assess increased Li coverage, replenishment
- Test flowing liquid metal for heat-flux mitigation, surface replenishment
- Assess flowing LM PFC with full toroidal coverage

MHD
- Extend disruption and RWM detection, develop disruption mitigation techniques
- Enhance non-axisymmetric field spectrum and capabilities for control of: RWM, EF, RMP, rotation, NTM, EP

Transport & Turbulence
- Understand ES and EM turbulence at high β, low ν^*, emphasizing e-transport
- Extend wave-number coverage of turbulence measurements

Waves and Energetic Particles
- Support plasma start-up, assess effectiveness of fast-wave in NBI H-modes
- Prototype driving edge-harmonic oscillations (EHOs) and/or *AE
- Drive and control EHO and/or *AE modes

Scenarios and Control
- Demonstrate full non-inductive, high I_P & P_{AUX} operation Control: boundary, β, divertor heat flux, Ω & q profiles
- Assess integrated control of long-pulse / high-performance

U.S. FNSF conceptual design including aspect ratio and divertor optimization

Budget considerations / constraints

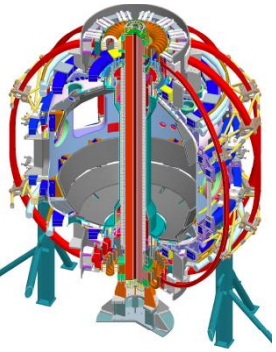
- Actual out-year budget is uncertain (and always is)
- FES provided guidance to assume 2 scenarios:
  - Base: essentially FY12 budget + inflation
  - Incremental: FY12 budget + 10% + inflation
- Significant resources for post-Upgrade upgrades only begin to appear after NSTX-U Project is complete in FY2014
  - Base profile for FY14-18: 0.5-2M, 2.4, 6.3, 6.5, 6.6 → 22M total
  - Incremental for FY14-18: 4.6, 4.7, 8.7, 9, 9.2M → 36M total
- Plan has to roughly match profile and total amount
- Estimates of cost of proposed upgrades are guesstimated based on previous experience, and have large uncertainties
- More detailed engineering analysis of cost & schedule must also wait for resources – hopefully late FY13 / early FY14

10 year plan tools with ~10-15% incremental funding

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Upgrade Outage | **1.5 → 2 MA, 1s → 5s** | **Metallic PFCs, 5s → 10-20s**

New center-stack



2nd NBI

Start-up and Ramp-up
- 0.3-0.5 MA CHI
- 0.5-1 MA CHI
- 0.2-0.4 MA plasma gun
- up to 1 MA plasma gun
- ECH/EBW
- 1MW → 2 MW
- Extend NBI duration or implement 2-4 MW off-axis EBW H&CD

Boundary Physics
- Lower divertor cryo-pump
- Divertor Thomson
- Diagnostics for high-Z wall studies

Materials and PFCs
- Mo/W PFCs on cryo-baffle
- Lower Mo/W divertor
- U + L Mo/W divertors
- All High-Z PFCs
- Hot high-Z FW PFCs using bake-out system

Liquid metals / lithium
- Li granule injector
- Upward LiTER
- Flowing Li divertor or limiter module
- Full toroidal flowing Li divertor

MHD
- MGI disruption mitigation
- Enhanced MHD sensors
- Partial NCC
- Full NCC
- NCC SPA upgrade

Transport & Turbulence
- High k_θ
- δB polarimetry
- DBS, PCI, or other intermediate-k

Waves and Energetic Particles
- HHFW limiter upgrade
- 1 coil AE antenna
- 4 coil AE antenna
- Test HHFW straps to excite EHO
- High-power AE antenna

Scenarios and Control
- Establish control of:
  - Snowflake
  - Rotation
  - q_{min}
  - Divertor P_{rad}
- Control integration, optimization
- Control integration, optimization with long-pulse and full metal wall

U.S. FNSF conceptual design including aspect ratio and divertor optimization

Example ranking of 5YP upgrade tool impact

		Programmatic impact			Impact from cross-linkage or utility to TSG											
		Importance to assessing next-step ST viability	Important ITER physics/ops contribution	Uniqueness for ST or in world program	MHD	T&T	BP	Mats & PFCs	EP	RF	SU & RU	ASC	Impact score	Resources required ($M)	Impact / cost	Impact / sqrt(cost)
18	Control: snowflake, rotation, qmin, Prad	1	1	0.5	1	1	1	1	1	1	1	1	10.5	2.0	5.3	7.4
4	Cryo-pump	2			1	1	1	1	1	1	1	1	10.0	4.0	2.5	5.0
3	ECH / EBW - 1MW	2		1	1	1				1	1	1	8.0	3.5	2.3	4.3
12	Partial NCC coils		1	0.5	1	1	1		1			1	6.5	2.0	3.3	4.6
13	NCC coils		1	0.5	1	1	1		1			1	6.5	4.0	1.6	3.3
1	CHI upgrades	2		1	1						1	1	6.0	1.0	6.0	6.0
14	High k-theta	1	1	1		1	1		1				6.0	1.0	6.0	6.0
2	Plasma guns	2		1	1						1	1	6.0	1.5	4.0	4.9
16	HHFW limiter upgrade	1				1			1	1	1	1	6.0	2.0	3.0	4.2
11	Enhanced MHD sensors		1	0.5	1		1				1	1	5.5	0.5	11.0	7.8
8	Upward LiTER			0.5	1	1	1	1				1	5.5	1.0	5.5	5.5
15	Polarimetry	1	1	0.5	1	1			1				5.5	1.0	5.5	5.5
6	High-Z divertor PFCs	1	0.5	0.5			1	1			1		5.0	2.0	2.5	3.5
17	HHFW straps for EHO		1	1	1		1			1			5.0	2.5	2.0	3.2
7	Li granule injector		1	0.5			1	1				1	4.5	0.5	9.0	6.4
10	MGI disruption mitigation	1	1	0.5	1							1	4.5	0.5	9.0	6.4
5	Divertor Thomson	1	1	0.5			1	1					4.5	3.5	1.3	2.4
9	Flowing Li divertor module			1			1	1				1	4.0	2.5	1.6	2.5

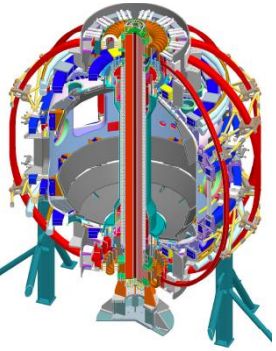
Example ranking of 5YP upgrade tool impact / cost

		Programmatic impact			Impact from cross-linkage or utility to TSG											
		Importance to assessing next-step ST viability	Important ITER physics/ops contribution	Uniqueness for ST or in world program	MHD	T&T	BP	Mats & PFCs	EP	RF	SU & RU	ASC	Impact score	Resources required ($M)	Impact / cost	Impact / sqrt(cost)
11	Enhanced MHD sensors		1	0.5	1		1				1	1	5.5	0.5	11.0	7.8
7	Li granule injector		1	0.5			1	1				1	4.5	0.5	9.0	6.4
10	MGI disruption mitigation	1	1	0.5	1							1	4.5	0.5	9.0	6.4
1	CHI upgrades	2		1	1						1	1	6.0	1.0	6.0	6.0
14	High k-theta	1	1	1		1	1		1				6.0	1.0	6.0	6.0
8	Upward LiTER			0.5	1	1	1	1				1	5.5	1.0	5.5	5.5
15	Polarimetry	1	1	0.5	1	1			1				5.5	1.0	5.5	5.5
18	Control: snowflake, rotation, qmin, Prad	1	1	0.5	1	1	1	1	1	1	1	1	10.5	2.0	5.3	7.4
2	Plasma guns	2		1	1						1	1	6.0	1.5	4.0	4.9
12	Partial NCC coils		1	0.5	1	1	1		1			1	6.5	2.0	3.3	4.6
16	HHFW limiter upgrade	1				1			1	1	1	1	6.0	2.0	3.0	4.2
4	Cryo-pump	2			1	1	1	1	1	1	1	1	10.0	4.0	2.5	5.0
6	High-Z divertor PFCs	1	0.5	0.5			1	1			1		5.0	2.0	2.5	3.5
3	ECH / EBW - 1MW	2		1	1	1				1	1	1	8.0	3.5	2.3	4.3
17	HHFW straps for EHO		1	1	1		1			1			5.0	2.5	2.0	3.2
13	NCC coils		1	0.5	1	1	1		1			1	6.5	4.0	1.6	3.3
9	Flowing Li divertor module			1			1	1				1	4.0	2.5	1.6	2.5
5	Divertor Thomson	1	1	0.5			1	1					4.5	3.5	1.3	2.4

Example ranking of 5YP upgrade tool impact / SQRT(cost)
(JEM's favored approach…)

		Programmatic impact			Impact from cross-linkage or utility to TSG											
		Importance to assessing next-step ST viability	Important ITER physics/ops contribution	Uniqueness for ST or in world program	MHD	T&T	BP	Mats & PFCs	EP	RF	SU & RU	ASC	Impact score	Resources required ($M)	Impact / cost	Impact / sqrt(cost)
11	Enhanced MHD sensors		1	0.5	1		1				1	1	5.5	0.5	11.0	7.8
18	Control: snowflake, rotation, qmin, Prad	1	1	0.5	1	1	1	1	1	1	1	1	10.5	2.0	5.3	7.4
7	Li granule injector		1	0.5			1	1				1	4.5	0.5	9.0	6.4
10	MGI disruption mitigation	1	1	0.5	1							1	4.5	0.5	9.0	6.4
1	CHI upgrades	2		1	1						1	1	6.0	1.0	6.0	6.0
14	High k-theta	1	1	1		1	1		1				6.0	1.0	6.0	6.0
8	Upward LiTER			0.5	1	1	1	1				1	5.5	1.0	5.5	5.5
15	Polarimetry	1	1	0.5	1	1			1				5.5	1.0	5.5	5.5
4	Cryo-pump	2			1	1	1	1	1	1	1	1	10.0	4.0	2.5	5.0
2	Plasma guns	2		1	1						1	1	6.0	1.5	4.0	4.9
12	Partial NCC coils		1	0.5	1	1	1		1			1	6.5	2.0	3.3	4.6
3	ECH / EBW - 1MW	2		1	1	1				1	1	1	8.0	3.5	2.3	4.3
16	HHFW limiter upgrade	1				1			1	1	1	1	6.0	2.0	3.0	4.2
6	High-Z divertor PFCs	1	0.5	0.5			1	1			1		5.0	2.0	2.5	3.5
13	NCC coils		1	0.5	1	1	1		1			1	6.5	4.0	1.6	3.3
17	HHFW straps for EHO		1	1	1		1			1			5.0	2.5	2.0	3.2
9	Flowing Li divertor module			1			1	1				1	4.0	2.5	1.6	2.5
5	Divertor Thomson	1	1	0.5			1	1					4.5	3.5	1.3	2.4

5 year plan tools with base funding

	2014	2015	2016	2017	2018
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
New center-stack					
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			Mo/W PFCs on cryo-baffle		
Liquid metals / lithium		Li granule injector		Upward LiTER	
2nd NBI					
MHD		MGI disruption mitigation		Enhanced MHD sensors	Partial NCC
Transport & Turbulence		High k_θ		δB polarimetry	
Waves and Energetic Particles		HHFW limiter upgrade; 1 coil AE antenna		4 coil AE antenna	
Scenarios and Control		Establish control of: Snowflake	Rotation	q_{min}	Divertor P_{rad}

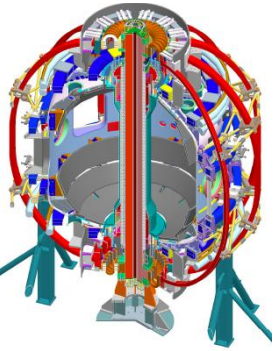
Contingencies / decision points

- These make planning complex - 5YP gets complicated fast
- But need to think these through and show some of these in intro chapter and program/facility overviews.
- Example: NCC has strong physics impact, but is expensive.
  - Need to look for ways to reduce cost and/or stage implementation
  - Simplistically, partial NCC of 6-12 coils (vs. full 24) buys ~1 year, $2M
  - Can also look for other upgrades that may not be needed…
- Other "expensive" upgrades to consider whether essential:
  - HHFW limiter: if we only use for (or is only useful for) start-up studies, it is possible limiter upgrade won't be needed
    - Will base this on heating results from first 1-2 run years
  - ECH heating: don't need if HHFW and/or NBI quickly heat and ramp-up CHI/low-Ip plasma to high current (appears pretty unlikely)
  - Cryo-pump: if new lithium tools rapidly give us density and impurity reduction and control (past history is anti-demonstration of this)
    - JEM opinion: NSTX-U should develop advanced scenarios that don't require Li, if for no other reason than to quantify the performance differences

Example alternative 5 year plan tools with base funding (no MHD sensor or HHFW limiter upgrade)

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		Mo/W PFCs on cryo-baffle	Lower Mo/W divertor	
Liquid metals / lithium	Li granule injector	Upward LiTER		
MHD	MGI disruption mitigation	Partial NCC	Full NCC	
Transport & Turbulence	High k_θ	δB polarimetry		
Waves and Energetic Particles	1 coil AE antenna	4 coil AE antenna		
Scenarios and Control	Establish control of: Snowflake	Rotation	q_{min}	Divertor P_{rad}

Can only afford 1 of these → possible decision point, etc, etc

Response to questions collected by Stan

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1. Need plan for Mo/W divertor tiles

- This will be topic for next Friday's meeting – stay tuned!!!
  - Builds on several previous meetings
- Timelines shown on baseline and incremental viewgraphs
- Present assumptions:
  - High heat flux regions (i.e. divertors, maybe CS midplane) will be solid high-Z. Other PFCs eventually will be graphite with high-Z coatings
  - Leaning towards cryo on the bottom
    - Most divertor diagnostics located/view here
    - Concern over need to flip BT for same H-mode threshold for USN
    - BES and tFIDA designed for standard B-field pitch
  - Would put row of high-Z tiles on cryo-baffle (i.e. lower outer divertor) at radius where incident heat-flux is acceptable/safe
  - Move strike-point onto high-Z for testing w/ or w/o Li (like LLD)
  - Compare solid and liquid Li vs. cryo for pumping, C vs high-Z
  - Increase high-Z coverage pending results from baffle PFC tests
  - Bakeable cryo-baffle might enable high-Z PFC temperature scans for Li

2. Timing of control goals in Base Plan (Chap. 1, Fig. 1.2.3)

- Why does qmin control come so late (rtMSE is being worked on now)
  - JEM timelines moved this a bit earlier to be consistent with ASC timelines
  - rt-EFIT “ready” to accept pitch angle data once available, but MSE reconstructions can be challenging offline, we have no experience with this in real-time EFIT, and it will take time to develop and optimize the algorithm for controlling the beam source, modulation, other parameters

- In general, why are the goals in series (and in that particular order), why not in parallel?
  - Order now more consistent with SPG’s ASC timelines
  - Series is over-simplification, and work will go on in parallel
  - Plan timeline Figure is meant to represent roughly which items will come first, and that each item will take time, and delivering 1 major new control capability per year is reasonable goal.
  - See ASC chapter for much more definitive timeline

3. Are gas valves for divertor impurity injection in Base Plan?

- Think so – see Stefan/Roger for when these will be available
- JEM did not include because they are not major upgrades

4. Need for a timeline for installation of all funded diagnostics (PPPL & collaborator)

- **Master diagnostic list/plan is known action item for Masa**
- Decision on single-sightline NPA
  - JEM and MO question the benefit vs. cost (and floor-space) of re-installing it, so generally view as low priority, but EP TSG asking for it – not presently in plan
- DBS appears in Base Plan, but it is presently not funded (UCLA waiting to hear about proposal)
  - This diagnostic was not funded in recent innovative diagnostic solicitation
  - But in recent discussions, UCLA will likely re-propose this during next NSTX-U diagnostic solicitation – call this a "possible collaborator proposal" if you wish to reference it all, but cannot promise this
- Boeglin diagnostic (fusion products) to be tested on MAST
  - Who will fund installation on NSTX if we want it? Should not be considered as part of Base Plan until funding identified
    - Presently no PPPL plans to fund it, FIU might re-propose (don't know)
    - Can't really count on it, but if it works on MAST, we could reconsider
- Is X-ray crystal spectrometer funded?
  - NSTX-U does not have plans to procure XCS, but PPPL owns several (including on C-Mod), so if/when C-Mod or LHD is not operating, could bring to NSTX-U? (to be run by Luis D-A). Higher initial priority for Luis for NSTX-U will be core and divertor bolometry.

5. How to handle unfunded items

- **There will be opportunity for collaborators to list plans/proposal items in Appendix of 5YP. This can be referenced in the main text if desired.**
  - **But,** availability cannot be guaranteed beyond present grant cycle of collaborator plan in question
- CT injector?
  - No plans (again) to implement this during 5YP (sorry Roger)
- Electromagnetic particle injector (EPI) (is this funded?), Can EPI be used for impurity transport experiments?
  - Roger is leading this effort, developing it this year – likely to propose during next NSTX-U solicitation
  - Cost appears to be modest, and this research is high priority for ITER disruption mitigation material delivery, so if funded, NSTX-U will certainly support
  - Ask Roger about EPI for impurity delivery

6. AE antenna: HHFW straps too extended to be useful for this purpose

- Need something dedicated: use prototype (is this funded for Yr 1?)
- AE antenna not described in Chap. 10
- Need clarification on whether amplifier is funded

- AE coils now in Chapter 10

- JEM: Now have correct / more up-to-date info for 5YP
  - Having coils this early is based on stated low/modest cost – subject to change
  - Need additional (engineering) analysis to insure can withstand Upgrade disruptions
    - Need to minimize additional operational risk – especially during 1st run year
  - Will try to have 4 TAE antenna coils installed for before 1st plasma is technically sound and resources are available.
  - But plan/promise to be ready with 4 coils for physics experiments in Year 2

7. Cryo-pump: need decision on where and when

- This will also be topic for next Friday's meeting
- If in upper, how effective would it be with LSN ops (normal TF)?
  - Not very effective – but depends on DRSEP – designing to pump (enough) with balanced DND
  - Does DIII-D have any experience with this?
    - Many years – see the literature on particle and power exhaust vs. DRSEP
- If upper and reversed Bt for USN ops, lose GPI and BES
  - Large negative impact on T&T, EP, MHD, BP, etc. research plans
    - Agree – this is major reason why considering lower cryo
- If lower, probably useless for CHI
  - Not sure pumping CHI plasma is a goal, but it does raise the question about whether CHI plasma formation would be adversely impacted by cryo….
- Decision should not be made based on a possibility of a liquid metal limiter/divertor module as incremental, nor should it be based on the next 5 year plan
  - Opinion duly noted
- If location not decided upon before PAC/5 YR plan review, how to handle in Research Plan (see "9")
  - A plan will be decided upon before PAC/5 YR plan – even if by "executive order"
  - Have been several productive meetings on this already – very close to a decision
  - Can always change the plan later if better/different logic for plan is found

8. Significant impact of Nat. Lab funding decisions on collaborator involvement

- Affects diagnostics, manpower, etc
- Still waiting to hear
- How to handle (assume funding)?

- JEM: Difficult to answer, but would advise to assume you will get much (but likely not all) of what you ask for
  - Collaborator support funding has been very stable (good news), but also hasn't increased much over the years →
  - Use previous proposal success as a guide
  - Will likely need to change 5YP details once decisions are known
  - Should be doable in time for written plan due April 1, 2013

9. Conceptual question

- How specific should Research Plans/Thrusts be if decisions on base/incremental capabilities still need to be made (e.g., cryo/Mo tiles/NCC/….)
  - We will make the decisions on these by end of January (before dry-runs), and may review/change at least 1 more time based on PAC comments
- Can goals be vague, just pointing to general research issues?
  - Not really (but depends on the topic). We are asking for substantial resources and need to justify with sufficient detail why research plans should be funded
- Is it ok to state that more specific decisions on capabilities that will be made later will lead to a refinement of the research plan details?
  - When things are uncertain or conditional, much better to think through and describe the contingencies or decision points in some detail so it is clear the plan is well thought out
  - All that said, it is understood the plan will be far less knowable in the out-years
  - Most important thing is to do good/relevant science along the way, but remember NSTX-U will be evaluated mid-term on progress toward 5YP goals
    - → Goals and plans for first 2-3 years should be pretty specific

10. Desire good reference page for each diagnostic

- Technical description, location, etc.
- General resource – longer term task

- Best we will likely have is in Masa's chapter 10

- There is also: http://nstx-u.pppl.gov/diagnostics
  - Will gladly accept volunteers to help update this
  - Outage is good opportunity to better document NSTX-U capabilities

Questions on incrementals (1)

1. How much should incremental funding be split among hardware capabilities, people, run time
    1. Up to each specific situation (yes!)
        1. JEM: Incremental run-time might increase from 10-14 run-weeks per year to 18-22 (approximate)
        2. If/when budgets increase, could consider hiring a few more people
2. How much should research based on incrementals be emphasized
    1. Example: MHD heavy reliance on NCC (even with incremental, this comes late)
        1. JEM: Have tried to get more NCC in the plan by staging the capability and considering contingencies and decision points
    2. Support and backing from PAC/5YR plan review committee would be good, but even with this, incremental funding likely NOT to appear
        1. JEM: True - emphasis should be on base: base needs to be compelling by itself, and increment should make the plan substantially stronger

Questions on incrementals (2)

1. Plan for plasma guns
    1. Need to badger the Badgers for details
    2. JEM: Badger badgering has begun, details by end of January (?)
2. What is plan for EC?
    1. Is 1 MW tube purchased?
        1. YES – most likely from Japan/Tsukuba
    2. Does the upgrade to 2 MW require 2nd tube?
        1. Depends on tube development – they are working toward 2MW tube
    3. Is steerable (or not) mirror included in upgrade to 2 MW?
        1. MO: will have some between-shot (or run day?) steering capability (TBD)
        2. R&D required due to larger mirror at lower f to have real-time steering
        3. Steerable mirror (and a 2nd gyrotron) contingent on decent EBW heating → next FYP
        4. ECH heating of CHI target doesn't require steerable mirror
3. HHFW limiter vs EHO/AE
    1. AE is now separate system – no usage of HHFW straps
    2. Using HHFW for EHO depends on whether HHFW heating is effective/routine in NSTX-U
        1. Need more team discussion of decision points for limiter and change-over to EHO
        2. Lithium granule injector is main-line ELM/particle transport tool to be tested during this 5YP