Plasma current ramp-up studies in support of developing fully non-inductive scenarios on NSTX-U

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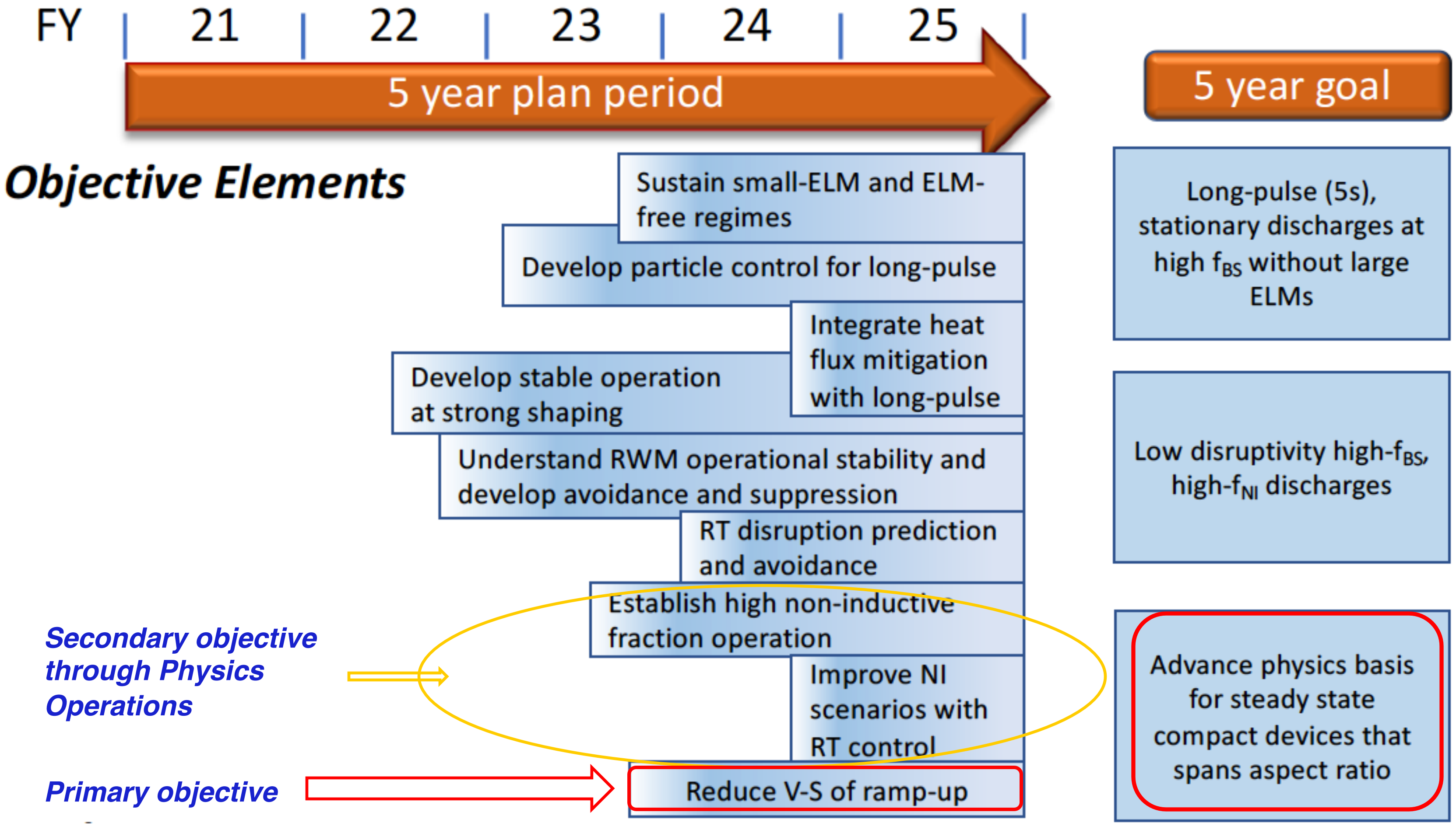
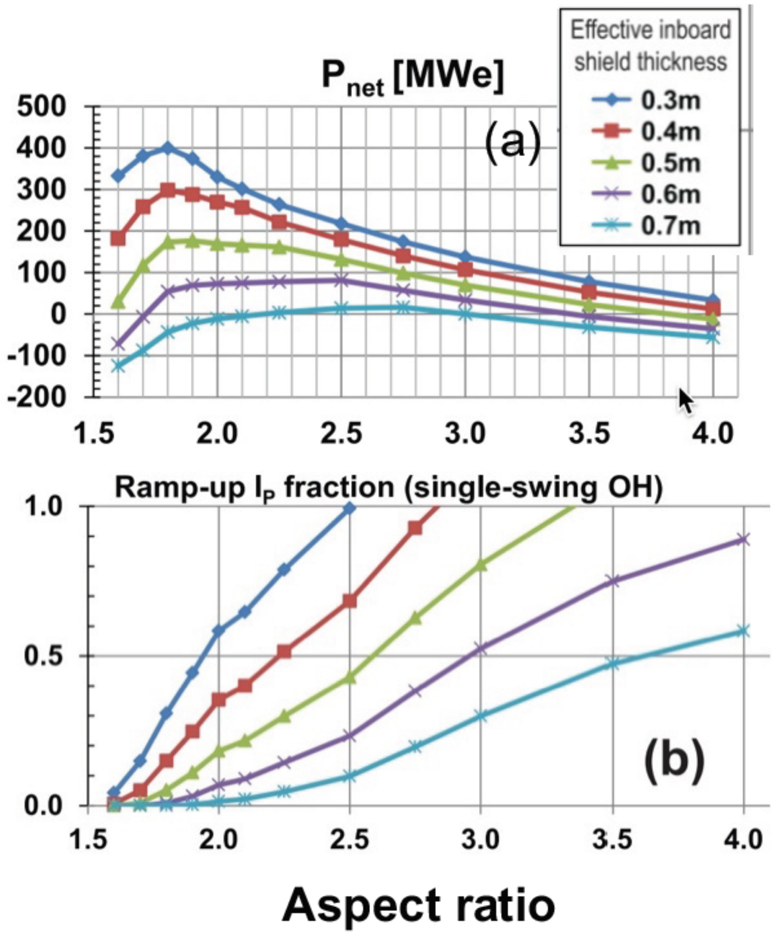
Outline

- Relation to NSTX-U program plan
- Relevance to ST program development
- Objectives of this research activity
  - Background information
  - Overall research plans
  - Summary

2021-2025 Objective 2 Timeline



Addresses Thrust
3.3.3 Reduce V-s consumption of ramp-up



(a) Net electric power and (b) fraction of Ip ramp-up provided by a central solenoid for a R0 = 3m HTS ST/AT pilot plant versus aspect ratio and effective inboard shielding thickness

Years 1-3

- Develop ramp-up scenarios using early HHFW to investigate potential to facilitate low-li and/or low-density ramp-up with savings in the inductive V-s and/or NBI pulse length

Years 4-5

- Optimize low V-s ramp-up that is compatible with fully non-inductive regimes to characterize potential of NBI overdrive and requirements for future non-inductive startup and ramp-up systems

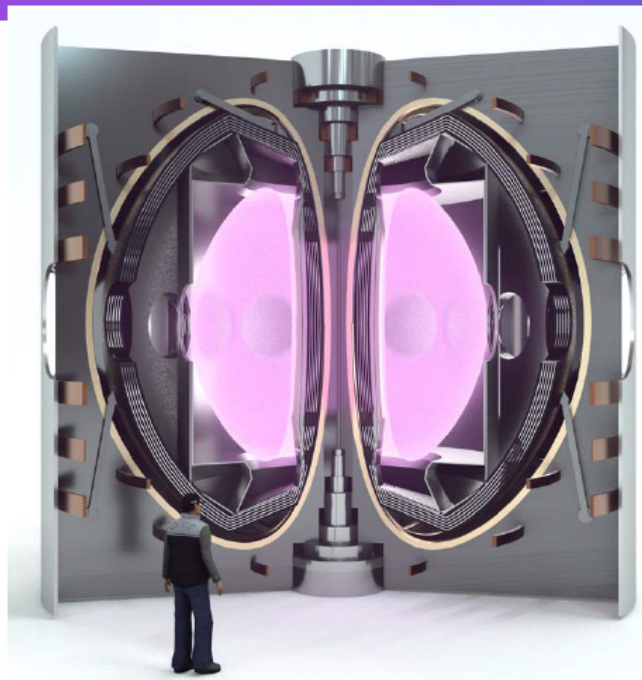
Research activities in this Thrust will focus on the ramp-up phase using HHFW and NBI heating and current drive. The integration of a low V-s ramp-up phase with fully non-inductive scenarios will inform the requirements for future non-solenoidal startup and ramp-up systems that are being advanced through collaborations with Pegasus-III and QUEST.

J.E. Menard et al., NF **56** (2016) 106023

The ST is the Leading Candidate for Fusion Power Commercialization in the United Kingdom

ST-F1: a high field HTS spherical tokamak

tokamak energy
a faster way to fusion



ST-F1 mission:

Demonstrate net fusion energy gain

- Industrial fusion power
- **> 1 GJ** stored magnetic energy
- Plasma volume < 10% of ITER
- Demonstrate non-inductive current drive ⇦ *~ 5 Yrs ?*
- No tritium breeding

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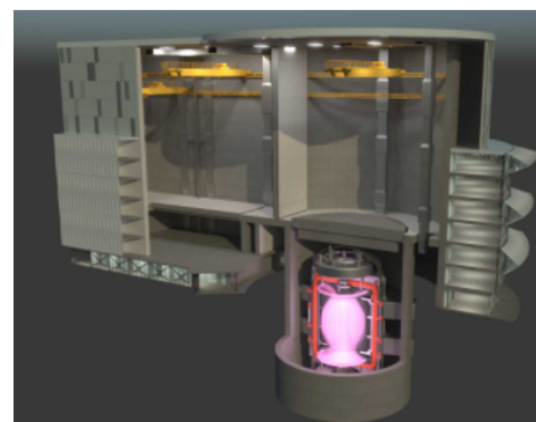
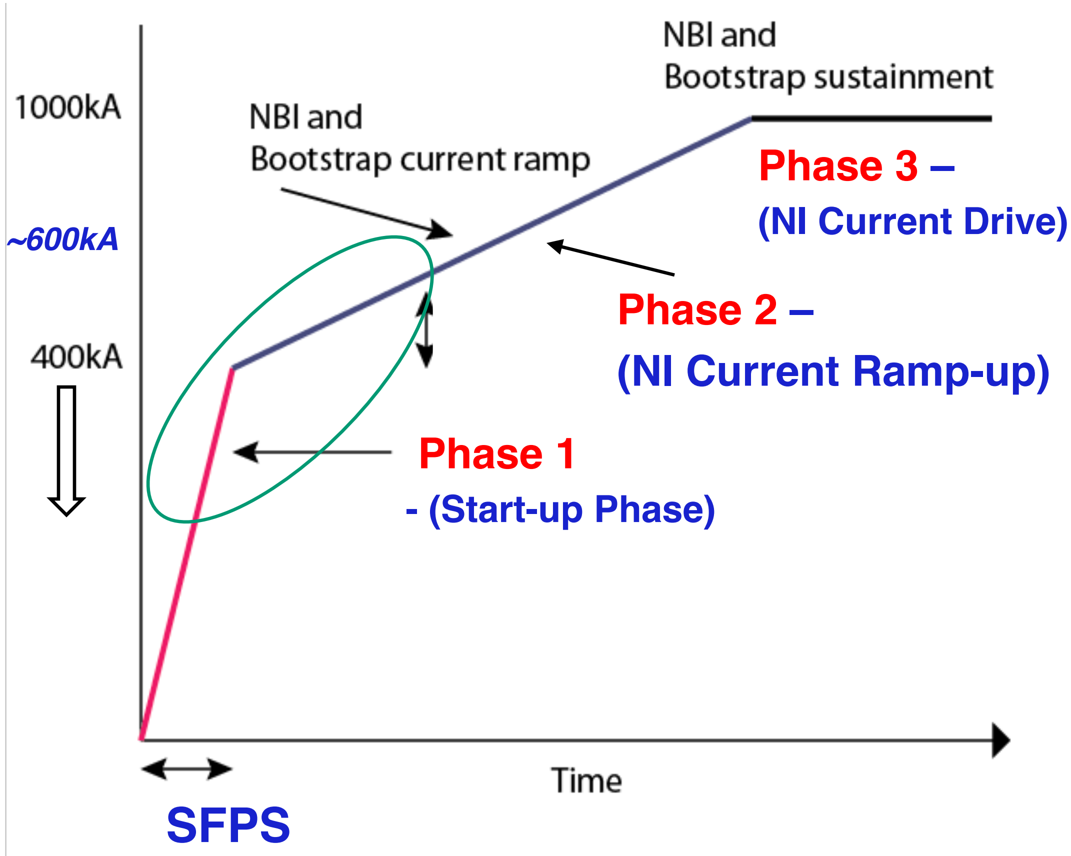
STEP (Spherical Tokamak for Energy Production) is an ambitious programme to design and build a prototype fusion power plant, targeting operations around 2040.



Non-inductive current drive in the ST context has 3 phases

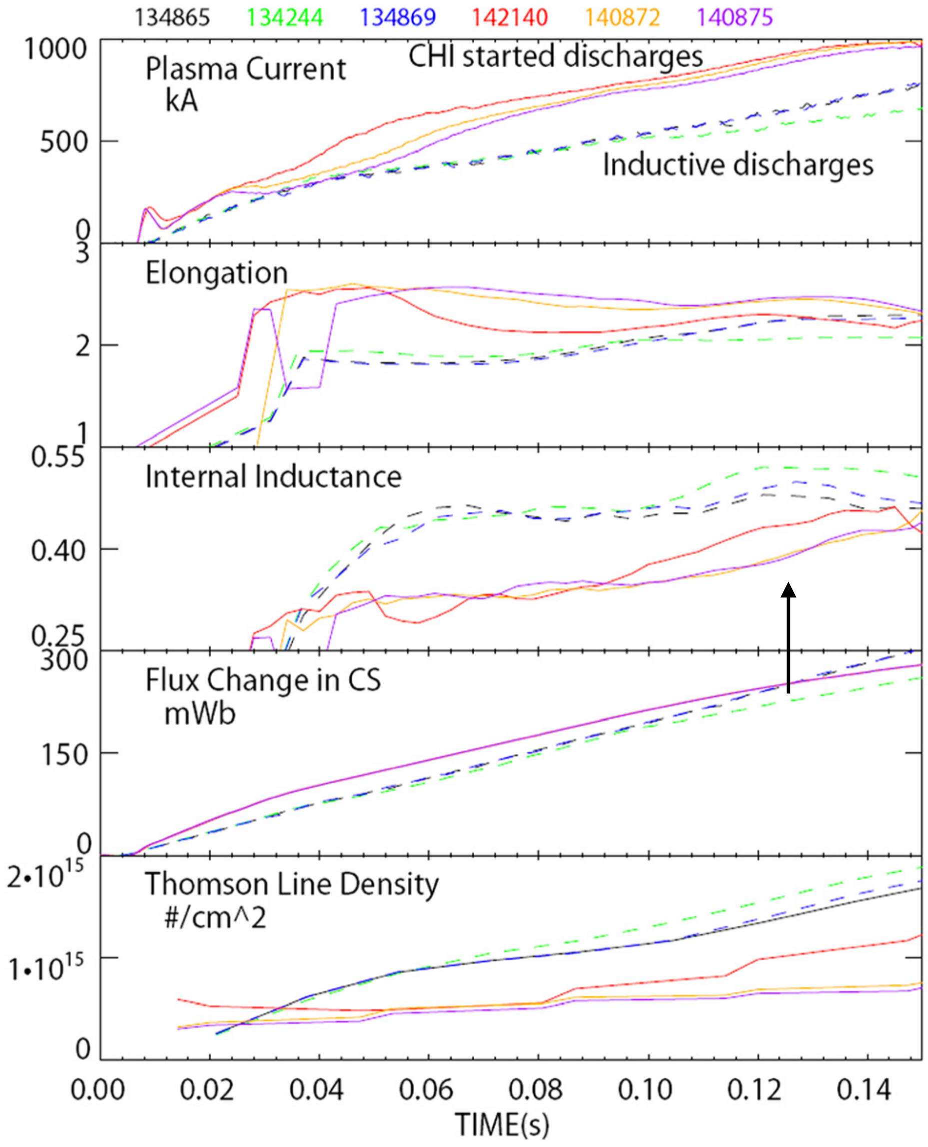
- Start-up / Ramp-up / Sustainment
  - Solenoid-free capability for Phase 1 is being developed on PEGASUS-III (Univ. of Wisconsin), QUEST (Japan), ST-40 (UK)
  - Phase 2 is the most challenging as the current drive method needs to compensate for changing profiles for plasma inductance, density, temperature, and for back EMF induced by the increasing plasma current
  - Higher current start-up in Phase 1 would ease ramp-up requirements during Phase 2



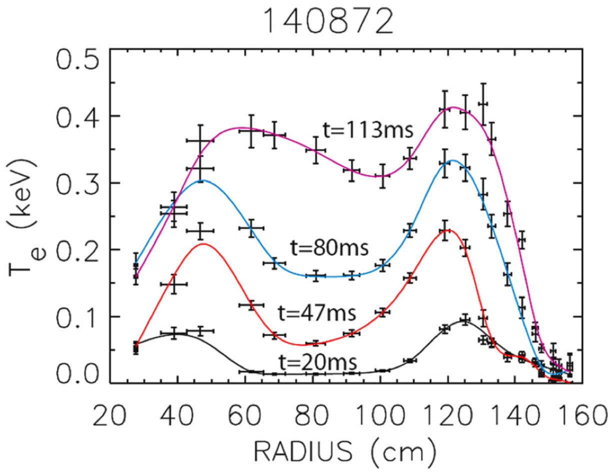
How is flux consumption and non-inductive current ramp-up influenced by the magnitude of the current and plasma parameters in Phase 1?

- Conduct a detailed study of the non-inductive current ramp-up requirements for low-plasma current targets on NSTX-U
  - (1) to understand the minimum required solenoid flux assist for these predominantly non-inductive current ramp-up scenarios,
  - (2) the minimum required solenoid flux to generate these low-current targets in the first place.
- Emphasis is on the early part of the non-inductive current ramp-up, staring from an initial value of 400kA, and the progressively lowering the initial current to ~200kA or lower
- All previous plasmas on NSTX and NSTX-U have relied on a standard inductive target. In this work we will change the initial plasma start-up target and study current ramp-up in these targets using minimal inductive assist

Transient CHI generated plasmas on NSTX with central solenoid assist consumed much less solenoid flux than initial targets that relied solely on the central solenoid start-up

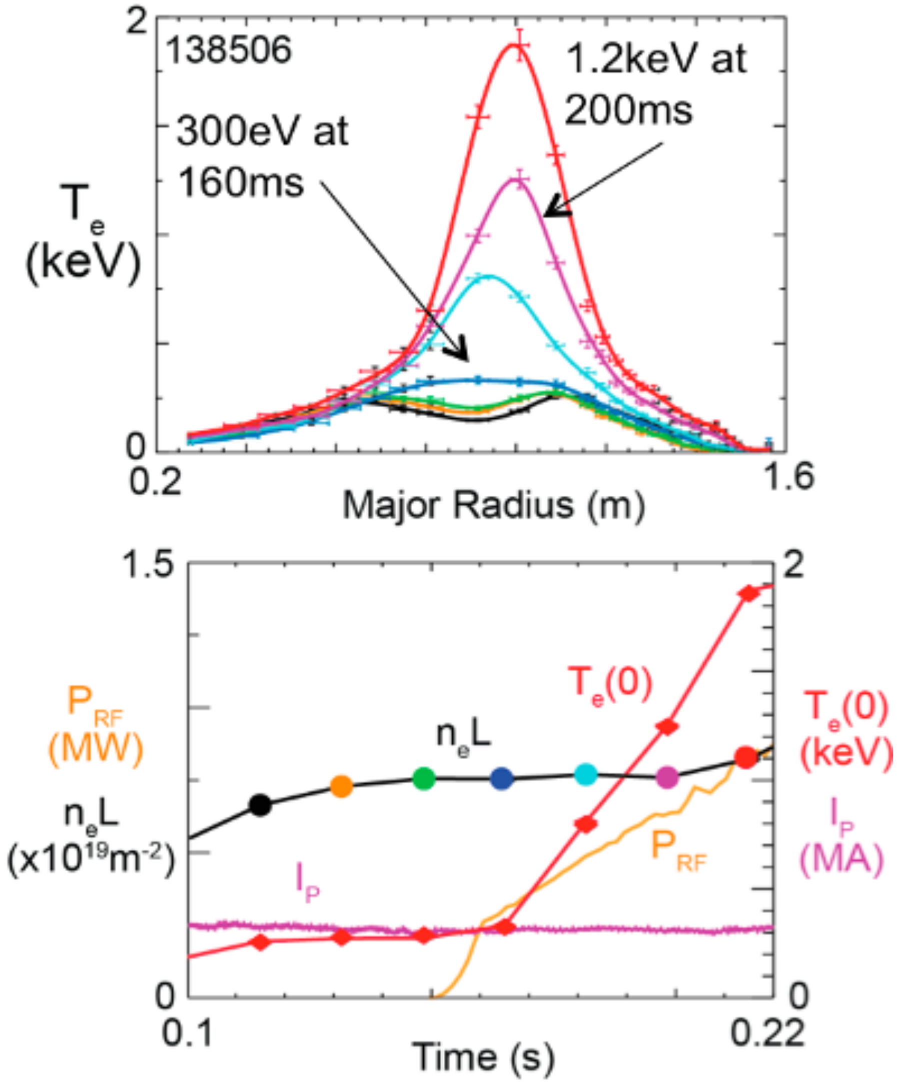


- CHI targets with much less internal plasma inductance (~0.3), and higher plasma elongation than inductive start-up targets have also be similarly coupled to inductive ramp
- Much less electron density and hollow T_e profile



R. Raman, et al., NF **53** (2013) 073017

In NSTX, HHFW has been used to successfully heat a low-current (300 kA) discharge to $T_e(0)$ > 1 keV in less than 40 ms



- Generated over 70% of the plasma current non-inductively, via bootstrap current and direct fast-wave current drive
- Lithium conditioning and good plasma control have shown to improve RF coupling – these capabilities are expected to be much improved on NSTX-U
- These should make very good targets for NI current ramp-up

G. Taylor et al 2012 Phys. Plasmas **19** 042501

General description of planned activities

- It is assumed that it may take two years for the RF system to become reliably operational.

- **YR1-2: Start with inductive targets that have NB assist**: Start with the simplest possible case that was used for plasma current initiation during the 2016 run campaign, with an initial current of 400kA.
  - Extend to zero solenoid pre-charge – (based on CHI plasma ramp-up studies)
  - Flatten the current profile to the extent possible (moving closer to the profiles similar to the CHI targets). Use, both the early application of NBI to slow down the current diffusion to the center and a fast-inductive ramp to increase current driven at lager minor radius.
  - Lower current to 300-200 kA

- **YR3-4: Start with 300-400kA RF Targets:** This portion would be developed with close collaboration with the RF group, with the RF group leading target development starting in YR-1
  - Reduce plasma current to lower levels (200 kA if that is possible).

- **YR5:** These would be the best cases from the above NBI and RF targets, which will be compared and optimized.

Estimated Schedule of Activities

YR-1: N1p, N1z
400kA
standard *li*, n_e, T_e

NBI, Bootstrap CD → 1MA

YR-2: N2p, N2z
400kA
Low *li and* n_e,
High T_e

NBI, Bootstrap CD → 1MA

YR-3: N3p, N3z
300-200kA
Low *li and* n_e,
High T_e
R1p, R1z
300-400kA
High Bootstrap CD

NBI, Bootstrap CD → 1MA

YR-4: R2p, R2z
300-200kA
High Bootstrap CD

NBI, Bootstrap CD,HHFW → 1MA

YR-5:
200-400kA (TBD)
R3
High Bootstrap CD
N4
Low li and n_e, *High* T_e

NBI, Bootstrap CD,HHFW → 1MA

Legend:
N – Predominantly NBI generated target, with solenoid assist
R – predominantly RF generated target, with solenoid assist
z – zero current pre-charge in the solenoid
p – solenoid is pre-charged with 50 to 100% current

- **N1p** 400kA starting discharge from 2016
- **N1z** (extend to *zero solenoid pre-charge*)
- **N2p** and **N2z**: *Flatten the current profile*
- **N3p** and **N3z**: These are lower current versions of targets **N2p** and **N3z**
- **R1p** and **R1z**: These 300 to 400 kA targets using HHFW heating and current drive
- **R2p** and **R2z**: Lower current versions of **R1p** and **R1z**
- Target **N4**: Best cases from the **N1z, p** to **N3z, p.**
- **R3** would be the best case from the RF dominated discharges

Lithium - Boron Comparison

- Start by developing the target and ramp-up conditions using Li coatings. Then early in the subsequent year's run, and before the application of Li, repeat the targets to assess the benefits of Boron to compare to the results obtained using Li during the previous year.

List of key needs or requirements, including on- and off-site person power resources

- Will be working closely with Devon Battaglia and will use available diagnostics, heating and current drive systems that are available
- Support for Li-B systems and gas injection systems from the Boundary Physics group members.
  - The numerous Li and B systems, as well as the numerous gas injection systems for particle control, will be tested and incorporated into the plan in a gradual manner as they become available, and relying on other dedicated XPs that will commission these systems.
  - SGI may prove to particularly useful for early fueling
- Likewise, new start-up scenarios developed as part of this activity will be incorporated into other XPs as needed.
- LRDFIT, TRANSP will be used
- RF Codes for modeling, relevant diagnostics (Thomson, MSE, EFIT, spectroscopy) from collaborating groups

Summary

- Plasma current ramp-up studies in support of developing fully non-inductive scenarios on NSTX-U will contribute to an improved understanding of the minimum solenoid flux needed for predominantly non-inductive current ramp-up of a low-inductance seed current plasma

- These studies will inform us on the solenoid flux capability needed to generate the initial seed plasma current itself

- They will also help define the needed capability from solenoid-free plasma start-up methods being tested at this time within the broader ST program, to inform them of the minimum required seed closed flux current targets, and their parameters such as internal inductance, density, and temperature

General Plan

- The first part of the proposed run-plan to improve our understanding of NBI and HHFW absorption in low-current, low-inductance targets by first generating a sequence of long-pulse targets (of varying parameters) using the central solenoid and then applying neutral beam and HHFW pulses at different energies, and then comparing them to the TRANSP and RF simulations, for establishing the required beam energies and pulses from the six NBI sources, and from the HHFW system to develop the current ramp-up scenarios.

- As NBI would be the primary system for current ramp-up studies, for the initial seed target generation, the High-Harmonic Fast Wave (HHFW) heating system is expected to be the primary means to achieve high-temperature, low density targets, eventually in support of forming a lower inductance plasma.