Making of the NSTX Facility*

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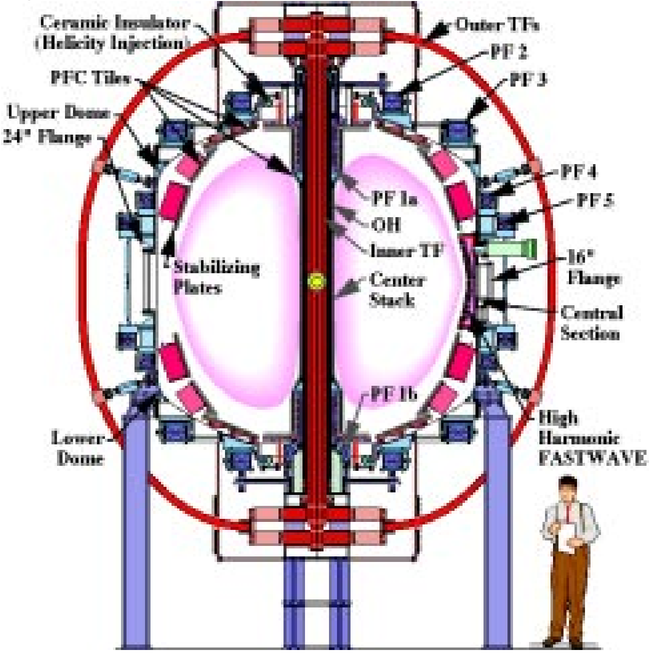
Abstract – The NSTX (National Spherical Torus Experiment) facility located at Princeton Plasma Physics Laboratory is the newest national fusion science experimental facility for the restructured US Fusion Energy Science Program. The NSTX project was approved in FY 97 as the first proof-of-principle national fusion facility dedicated to the spherical torus research. On Feb. 15, 1999, fhe first plasma was achieved 10 weeks ahead of schedule. The project was completed on budget and with an outstanding safety record. This paper gives an overview of the NSTX facility construction and the initial plasma operations.

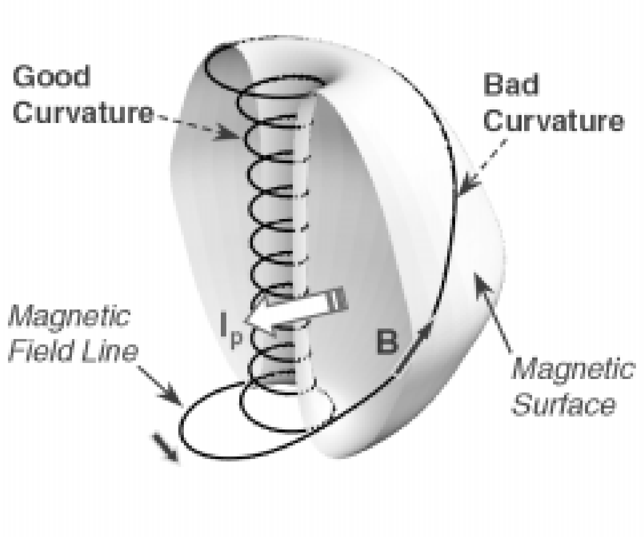
I. INTRODUCTION

The National Spherical Torus Experiment (NSTX) is a national fusion science facility whose mission is to establish the fusion physics principles of the innovative spherical torus (ST) concept [1]. The cross section of the NSTX device is shown in Fig. 1 [2]. NSTX is a major component of the restructured U.S. Fusion Energy Sciences Program, which is intended to innovate in confinement concepts and to find a cost-effective route to an attractive fusion power source. NSTX will advance fusion plasma science in a new regime that promises very high beta, good confinement, efficient noninductive startup and current drive, and dispersed divertor fluxes. In November 1998, DOE selected the initial members of the NSTX National Research Team, comprising researchers from 13 fusion institutions. The NSTX facility was completed in FY 99 and is now well into the Research Operations phase. The NSTX National Research Team is investigating ST plasma physics principles over much wider parameter ranges than previously investigated [3-5].

Fig. 1. A schematic of the NSTX device cross-section.



II. WHY ST?



A schematic of ST configuration is shown in Fig. 2.

Fig. 2. ST Configuration

It is seen from Fig. 2 that the ST combines a short field line length of bad curvature and high pitch angle toward the outboard plasma edge with a long field line length of good curvature and low pitch angle toward the inboard plasma edge. In other words, the favorable inner region of ST is high-q tokamak-like, dominated by the toroidal field, and the unfavorable outer region is CT (Compact Toroid)-like, with a strong poloidal field component. A consequence of dominant good field line curvature is MHD stability at high plasma pressure in reduced magnetic field (i.e., high β). This enhancement in β by reducing the aspect ratio in moderate to high-q toroidal configurations has been identified for some time in the tokamak. The aspiration of order-unity β without relying on an applied toroidal field has been an overarching goal of the CT research. A broad range of encouraging advances has been made recently in the exploration of the spherical torus (ST) concept. These include the experimental data from the pioneering experiments such as CDX-U [3], HIT-II [4] and START [5], theoretical predictions [6], attractive devices projected for near-term fusion energy development such as the Volumetric Neutron Source (VNS) [7], and future applications such as the power plants [8]. As a result ST research has gained broad support and interest in the U.S. and world fusion communities. Active national and international collaborations with the world ST community including the newly commissioned PEGASUS (University of Wisconsin), MAST (Culham, England) and GLOBUS-M (St. Petersburg, Russia) devices will complement and broaden the base in ST physics studies.

III. NSTX RESEARCH PROGRAM

The mission of the National Spherical Torus Experiment (NSTX) [9] is to investigate the physics principles of:

- Non-inductive start-up, current sustainment and profile control,
- Confinement and transport,
- Pressure limits and self-driven currents,
- Stability and disruption resilience, and
- Scrape-off layers and divertors;

in a low-aspect-ratio (spherical) torus as a plasma confinement innovation. These principles are to be investigated in scientifically interesting regimes characterized by:

- High average β_T (up to 40 %),
- High pressure gradient driven current fraction (up to 70 %),
- Fully relaxed, non-inductively sustained current profile,
- Collisionless plasmas with high temperature and densities, and
- Low aspect ratio as low as 1.26 and plasma elongation as high as 2.0.

The physics outcome of the NSTX research program is relevant to near-term applications such as burning plasma experiment and the VNS, and future applications such as the pilot and power plants.

IV. NSTX CONSTRUCTION PROJECT

The NSTX Facility Construction Project was officially approved in Oct. 1996 after the Alternate Concepts Panel Review under the FESAC (Fusion Energy Sciences Advisory Committee) Scientific Issues Subcommittee. FESAC concluded that the ST concept is ready to proceed to the Proof-of-Principle level research. NSTX is a national research facility located at PPPL, and to occupy a central role in "innovation in confinement concepts, focused on finding a cost-effective route to an attractive fusion power source." The NSTX project goal was to build a world-class proof-of-principle ST facility within the TPC (Total Project Cost) of \$ 23.86 M and to start the research operations in FY 99 within three years of the project start. To accomplish these rather challenging project objectives the NSTX Project Team was formed comprising four institutions, PPPL, Oak Ridge National Laboratory (ORNL, Columbia University, and University of Washington: PPPL was to be responsible for the design, fabrication, and operation of the NSTX facility, ORNL was to provide the NSTX Program Director and physics and engineering design on rf (radio-frequency) systems in collaboration with the OFES Enabling Technology Division [10] and the plasma facing components [11], the University of Washington was to lead the physics design of the Coaxial Helicity Injection (CHI) system [4], and the Columbia University team was to provide the MHD based physics support for NSTX.

V. NSTX DESIGN ACTIVITY

The device design is clearly the most highly leveraged activity in the entire construction project. Obviously, a good design will lead to ease of construction, operation, maintenance, and upgrading. The NSTX physics design team through modeling calculations issued the physics design requirements [12] in accordance with the NSTX Research Program Mission. The NSTX engineering design team then went on to work on the engineering design to meet the physics design requirements. The engineering design team consisted of experienced engineers who typically had decades of fusion design experience including TFTR, BPX, TPX, and ITER. The NSTX project also received much needed help from the fusion community. The NSTX project partners are the primary example. A number of technical reviews were conducted including community experts from the major fusion facilities such as DIII-D, C-Mod and START/MAST. The reviews yielded a number of design improvements, which turned out to be crucial for the success of the Project. The design of demountable center stack was an example of the design innovation by the NSTX engineering team. The center stack being the most critical component of the whole device was designed and reviewed most intensely. The demountable center stack facilitates the construction, maintenance and/or upgrading of the device. This feature was fully utilized during the outage after the First Plasma to install additional in-vessel hardware. The use of a special insulation tape developed for ITER for the inner TF bundle (to provide sufficient shear strength against the torsional force of OH) is a good example of benefit realized from the ongoing technology R&D in the fusion program. The present NSTX device design therefore is a product of about two years of intense community-wide design effort. It should be mentioned that there was about three years of physics design work by the PPPL-ORNL team prior to the Project start. Based on the device construction and initial device performance data, it appears that the NSTX design indeed belongs to the "good design" category.

VI. FAVORABLE FACTORS FOR NSTX

After the shut down of the TFTR operations in 1997, the D-site facility became available for NSTX. While the NSTX construction TPC budget is less that $24M, the project was able to take advantage of over $100 M worth of relatively modern site credits from TFTR. These included power supplies, a well-shielded and spacious Test Cell, utilities such as deionized water-cooling and AC power systems, and the plasma heating and current drive systems. The experienced technical staff with decades of hands-on experience on TFTR and other fusion facilities are of course the most important resource for the facility construction. In addition, strong involvement of the PPPL laboratory support functions including ES&H, Procurement, and QA/QC were crucial. The PPPL Critical Lift Team performed a large number of challenging lifts with a perfect record. The credit also goes to the PPPL management, the OFES and DOE NSTX Managers who were very supportive and responsive to the Project needs. Other important help the Project received was the utilization of the DCMC (Defense Contractor Management Command) to monitor the progress on the component manufacturing at remote facilities including the one in Finland where much of the NSTX copper conductor material was manufactured.

VII. PF 5 COILS AND REDESIGN OF PFCS

Even as the device construction was proceeding, there were a number of design changes that took place as more physics calculations were performed. Perhaps the most challenging one was the addition of the PF 5 coils. In the spring of 1998 during the midst of component fabrication, the Columbia University and PPPL researchers showed that the base poloidal field (PF) coil sets (PF 1 to PF4 which were from S-1 Spheromak Device) was not adequate for the NSTX research goal. The plasma stability calculations showed that a plasma produced with the original poloidal coil set is more prone to plasma pressure instabilities than an ideal shape case, which resulted in significant plasma performance degradations. The only practical remedy was to add an extra set of PF coils of larger diameter (PF 5) to the original sets. Beside the extra cost for the coil set, the new coil set needed to be manufactured in time for the outer TF assembly. If delayed, it would impact the entire project schedule. If the installation was postponed, it would be time consuming and costly since the outer TF coils and all the diagnostics and heating systems connected to the outer vacuum vessel would have to be disassembled. These constraints meant only about four months were available for the design and construction of PF5 coils. The NSTX Project Team responded to the challenge. The new PF coil set was indeed designed and manufactured in four months and installed just in time for the device assembly. The new coil set introduced changes in the plasma outer boundary, which necessitated the redesign of the outer passive plate structure as well as HHFW antennas. While such design changes are often unavoidable, the project success is influenced significantly as to how well it can minimize such mid-stream design changes.

VIII. ES&H ISSUES

The personnel, facility, and environmental safety issues were very important part of the NSTX Project. A single mishap in any one of these important areas could easily cripple a project. The NSTX Project benefited greatly from the laboratory's ES&H (Environment, Safety & Health) Division, which provided assistance in the ES&H related issues. In the early phase of the NSTX Project, the Environmental Assessment was performed, and the Project was able to obtain FONSI (Findings Of No Significant Impacts) from the State of New Jersey and DOE. In terms of personnel and device safety, the Project prepared SAD (Safety Assessment Document) which included Failure Modes & Effects Analyses (FMEAs). About one year prior to the NSTX First Plasma operations the laboratory formed the Activity Certification Committee (ACC), which included the DOE PG (Princeton Group) staff as participating members. The ACC reports to the Executive Safety Board chaired by Laboratory Deputy Director. The ACC's main function is to review the safety and readiness for starting the NSTX facility operation. The ACC met regularly and performed numerous site visits and reviewed NSTX documents and procedures including the SAD. The ACC recommendations indeed resulted in many safety related improvements. From the Project side, the importance of personnel safety was particularly stressed at all levels. A dedicated safety inspector was brought in during the construction period. In the area of training, the NSTX Project developed a training matrix which is a table of training requirement for each job function. Much of the training program and procedures developed for TFTR have been adopted by NSTX. Indeed, the Integrated Safety Management (ISM) philosophy was practiced throughout the NSTX team and the laboratory. As a result, the NSTX construction was completed with exemplary safety record, and the NSTX Project received the 1998 State of New Jersey Governor's award for safety.

IX. NSTX CENTRAL INSTRUMENTATION AND CONTROL

While the NSTX Project utilized much of the available site credit, one area of significant departure from the existing system was the Central Instrumentation and Control (I&C) system. Since much of the TFTR Central I&C was nearly 20 years old, it was decided to purchase new computer hardware. The former TFTR Control Room was converted in the NSTX Control Room by eliminating much of the old instrumentation racks and cables. New computer hardware for system control and data acquisition systems was installed along with an optical fiber based network. Almost all the technical computer software being used on NSTX was developed by the US science community. NSTX decided to bring in the MDS-PLUS data acquisition software developed by the C-Mod at MIT. MDS-PLUS was later incorporated into the DIII-D system. The common data acquisition platform not only reduced the implementation cost for NSTX but also improved the data sharing capability among the major US fusion facilities. NSTX also obtained the EPICS (Experimental Physics and Industrial Control System) software for the engineering system control from Argonne National Laboratory. For plasma real time control, NSTX installed DIII-D's Plasma Control Software in collaboration with General Atomics (GA). For the plasma reconstruction, the Columbia team brought the EFIT plasma equilibrium reconstruction code developed on DIII-D. In fact the utilization of those already largely developed software was a crucial element in getting the NSTX facility commissioned on schedule and on budget. It also enabled NSTX to move quickly toward the modern plasma operations such as the real time plasma control and the remote collaboration capabilities. Indeed, the NSTX plasma is now run by the real time plasma control system and the NSTX Control Room is being remotely accessed by the off-site NSTX Team members.

X. EARLY FIRST PLASMA

By the spring of 1998, it was becoming clear that the projected cost to completion was rapidly approaching the TPC target. Fortunately, most of the component fabrication activities needed for the first plasma were progressing quite well. In order to insure the on-budget construction project completion, it was decided to start the first plasma operations early in February 1999 well ahead of the April 30 1999 DOE Milestone. The early plasma would provide very important data for the engineering and research team while reducing cost. In order for this to happen, the device components needed to arrive on time and the device assembly must proceed smoothly. Quite remarkably, all the needed components arrived just in time and the device assembly went even better than expected. The vacuum vessel and the center stack were transported into the NSTX Test Cell in early Oct. 98. The device assembly started in mid-Oct. and the center stack was installed in early November. The vacuum vessel was pumped down for the first time in mid-November and easily passed the vacuum leak check. The device assembly was largely completed in mid-Dec. 98 with installation of the outer TF coils. During the month of Jan. 1999, the utilities were hooked up to the device and various PTPs (Preoperation Test Procedures) were performed. After the successful PPPL Safety and DOE Operations Readiness Assessment reviews in early Feb, permission for the first plasma was officially given by PPPL on Feb. 11. For the First Plasma operations, it was decided to limit the toroidal field (TF) to 2 kG (design value of 6 kG), the Ohmic Heating coil current to 18 kA single swing (design value of 24 kA double swing) and the PF coil currents to 10 kA (design value of 20 kA). On Feb. 12, the Los Alamos Fast Camera observed the first "flash" of ohmic plasma (about 20 kA of plasma current). It was rather remarkable that a fusion device as complex as NSTX obtained an Ohmic plasma on being turned on for the first time. It should be noted that due to the continuous vacuum vessel and flanges, when the Ohmic heating (OH) is applied, the toroidal eddy current of over 200 kA typically flows in the vacuum vessel structures. Such wall currents can cause significant vertical fields, which could prevent OH plasma initiation. The NSTX design team was able to predict quite precisely what kind of waveforms were needed on various poloidal coil magnets to produce desired null-field during the OH initiation. Another important factor of the success was the NSTX power system reliability. The power supplies have been improved over the years on TFTR for operational reliability. On Feb. 15, the plasma current quickly exceeded the DOE Level I Milestone of 50 kA ohmic current ten weeks ahead of schedule. Within the following two days of plasma operations, the plasma current reached 300 kA level, which is close to the predicted value for the OH flux used. (See Fig. 4)

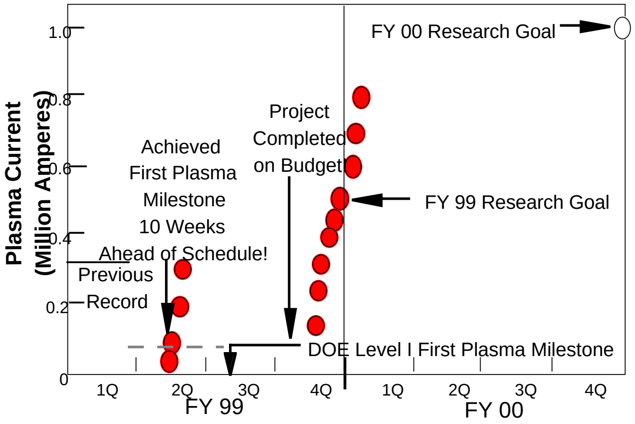


Fig. 4. Progress of the NSTX plasma operation

It should be noted that the newly formed NSTX National Research Team played a crucial role from the start. The Los Alamos Team brought the fast visible camera to capture the plasma evolution, which was a useful tool in bringing the plasma current to 300 kA in just two days, guiding the poloidal field waveform programming. The EFIT reconstruction of the first plasma was also successfully carried out by the Columbia University team using the magnetic data.

The First Plasma Operations confirmed the basic device operational readiness in terms of power supplies and other utilities. While the device magnets were not energized to the full capability, it gave the engineering team some level of confidence that the device was indeed designed and constructed correctly. The EPICS and MDS-PLUS software platforms performed extremely well. On Feb. 26 1999, Energy Secretary Richardson visited the laboratory and dedicated the NSTX facility, noting that the NSTX device was built on cost and on schedule.

XI. COMPLETION OF NSTX CONSTRUCTION

After the First Plasma Operations, the NSTX construction team went back to work to install the rest of the TPC items not covered by the First Plasma Operations. The main items were in-vessel hardware including the passive/outer divertor plates, HHFW antennas, and CHI ceramic insulators. In order to facilitate the in-vessel hardware installation, the center stack was pulled out of the device. With the center stack out of way, it was much easier to work inside the vacuum vessel for installation. The overhead crane was used to transport heavy components and equipment through the resulting large 42" diameter "hole". Also very importantly, in parallel, the installation of PFCs and sensors on the Center Stack proceeded while the work was done inside the vessel. The amount of effort to remove and reinstall the center stack was estimated to be only about 6-8 manweeks.

During the installation of the passive plates, a new calculation result indicated the need to change the design of the passive plates jumpers. A passive plate jumper is U-shaped copper bus electrically connecting the passive plates toroidally. It is designed to be flexible to accommodate the movement due to the thermal growth of the passive plates during bakeout. Although the passive plates are supported by stainless steel structure, it was assumed that the conductive copper jumper would insure the current in the passive plates to flow predominantly in the copper jumpers not through the stainless steel support structure. The 3-D eddy currents calculations (SPARK code) by the Columbia team however showed that sizable currents can actually flow in the stainless steel support structure resulting in non-axisymmetric n=1 eddy currents induced in the vacuum vessel and the passive plates. The n=1 eddy currents induce non-axisymmetric n=1 vertical fields of as much as 100 gauss near the plasma boundary, which could cause a severe problem in plasma stability and position control. While there was cost and schedule pressure, the project decided to make a proper correction to the 44 jumper elements prior to the installation. The project was able to successfully complete all of the TPC tasks on budget on July 9, 1999.

XII. RESTART OF NSTX PLASMA OPERATIONS

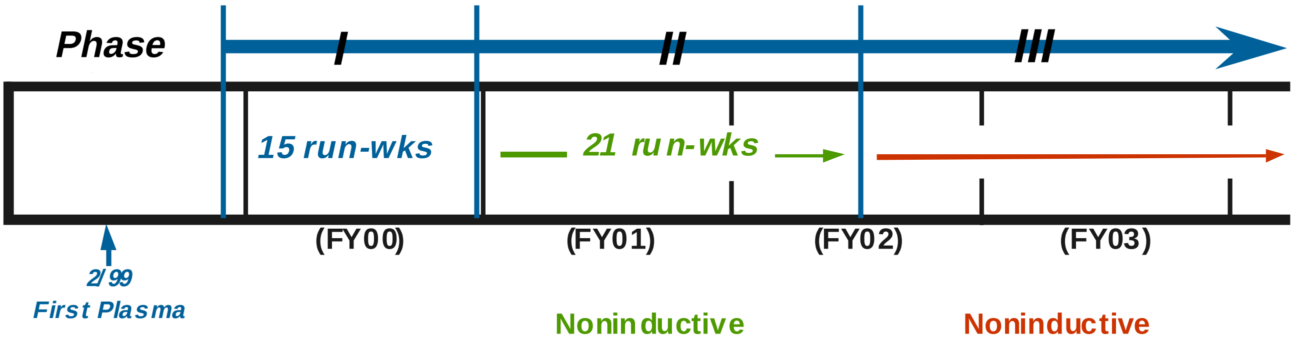
The NSTX plasma operation restarted on Sept. 1, 1999. There was a question as to how well and how quickly plasma operation could come up with the newly installed additional in-vessel components such as the passive plates and graphite tiles (over 2500 tiles). Also installed were 12 HHFW antennas and CHI ceramic insulators. For the restart of the plasma operation, the toroidal field was increased to 3 kG, which is the nominal field for the 1 MA operation. The poloidal field coils were tested to full 20 kA. The OH double swing at 18 kA was also tested for the first time. Again, the OH plasma started on the first attempt. It only took several plasma shots to reach the 320-kA to exceed the previous ST plasma current record. With the double swing OH operation (with 75% available flux), the plasma current ramped up to 800 kA in a short time as shown in Fig. 3. It appears that 1 MA operation is indeed feasible with the full available flux.

An electron cyclotron preionization (ECP) system, which is a refurbished klystron unit, brought to NSTX by the ORNL team. The 18 GHz unit is capable of delivering 30 kW of ECP power for 100 msec. The ECP also worked from the start very reliably. It created a vertically uniform plasma sheet at the electron cyclotron resonant layer which is about R = 42 cm for the nominal 3 kG toroidal field. The ECP makes the OH plasma initiation less sensitive to error fields, enhancing the operational flexibility. Another potential utilization of ECP is the Coaxial Helicity Injection (CHI). The ECP will create initial plasmas needed for CHI breakdown. The error field problem is likely to be more severe for the CHI initiation than the regular OH discharges.

Key to the achievement of recent plasma operations was the implementation of the real time plasma control system in collaboration with GA. The Skybolt I computer system was able to feedback control on the plasma radial and vertical positions as well as the plasma current. The highest current of 0.8 MA was in fact obtained with the current ramp control using the real time plasma control system. The control system was also able to create single null and double null diverted discharges with plasma elongation up to $\kappa = 2.4$.

XIII. FUTURE RESEARCH PLAN

The NSTX Research Program is outlined in Fig. 4. In the near term, the HHFW plasma heating and CHI non-inductive plasma initiation are the two main experimental topics in addition to the ohmic heating discharge optimization. The device plans to run until December 1999. The NBI (Neutral Beam Injector) related opening would take place in January to June of Year 2000. The plasma operations will resume in July 2000 and the NBI operation (5 MW) will start in October 2000. The HHFW heating and current drive power is scheduled to be increased to the 6 MW level, and the CHI plasma start up to demonstrate the non-inductive startup current of up to 500 kA. With HHFW, NBI, and CHI tools in place, the Phase II research starting in FY 2001 will assess the high beta regimes consistent with the no-wall beta limit of about 25 %. The bootstrap current fraction is relatively modest 40%. In the longer term, the project plans to reconfigure the passive stabilizing plate jumpers for the plasma kink stabilization. This wall stabilization of kink is essential for the attainment of the high beta (40%)/high bootstrap fraction (70%) discharges aimed in the Phase III Research. Much of the needed data should be available from the on-going tokamak experiments (e.g., DIII-D and HBT-EP) for the NSTX decision point in 2001.



	Inductive	Noninductive Assisted	Noninductive Sustained
Toroidal Beta, β_T		≤ 25% (no-wall limit)	≤ 40% (wall stabilized)
Bootstrap Current		≤ 40% (no-wall limit)	≤ 70% (wall stabilized)
Current	≤ 0.5 MA	≤ 1 MA	~ 1 MA
Pulse	≤ 0.5 s	≤ 1 s	≤ 5 s
HHFW Power	≤ 4 MW	~ 6 MW	~ 6 MW
NBI Power		≤ 5 MW	~ 5 MW
ECH Power	~ 30 kW	≤ 0.4 MW (incremental)	~ 0.4 MW
CHI Startup	≤ 0.2 MA	≤ 0.5 MA	~ 0.5 MA
Measure	$T_e(r)$, $n_e(r)$	j(r), $T_i(r)$, flow, edge	**turbulence**

Fig. 4. NSTX National Research Program Plan

Another important upgrade item is a new center stack to increase the device/plasma performance and to investigate ARIES ST-like higher elongation plasmas which has higher beta (50%) and higher bootstrap current fraction (90%). The new center stack is capable of 1 T operation with longer pulse length. The center stack is larger in diameter so the aspect ratio will be increased from 1.26 to 1.4 – 1.5 range (more typical of the ARIES –ST regime). The plasma elongation κ can be increased to the 2.5 – 3.0 range from the present κ = 2. Due to the larger OH coil size, the OH flux can be increased by a factor of 2, which should enable the plasma operation to be eventually extended toward 2-3 MA range.

I. CONCLUSIONS

In conclusion, the NSTX Construction was successfully completed with the First Plasma Milestone achieved 10 weeks ahead of schedule and the TPC tasks completed on budget. This was possible because of the relatively modern site credit of over $100M and the experienced personnel at PPPL and at the collaborating institutions. The NSTX National Team consists of researchers from 14 institutions, who are working very well. The plasma operation in a short period reached very close to the device design value of 1MA (0.8 MA achieved). The real time plasma control system is now producing plasmas with various configurations (inner wall imited, double null diverted, and single null diverted) and various elongations (κ = 1.5 – 2.3). The success of the project can be attributed to the effective and constructive teamwork among the multi-institutional participants.

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