Progress on PVR Recommendations

September, 2001

The Physics Validation Review panel report included 29 recommendations requiring follow-up by the project. The plan that the project and OFES developed for addressing these recommendations called for a progress report at this time. Since the PVR, the project has been developing tools and conducting design studies with the aim of updating the machine configuration at this time. Since these developments are tightly linked to several of the PVR recommendations, we first summarize the updated machine configuration, and then report progress on the PVR items in the form of a series of attachments, including expanded progress summaries for certain items.

Updated Machine Configuration

This configuration update occurs at a point in time about midway between the March, 2001, Physics Validation Review and the Conceptual Design Review planned for April, 2002. Design efforts since the PVR have resulted in significant design improvements. Better access and more space have been provided for heating, diagnostics, in-vessel hardware, and maintenance, consistent with physics requirements for plasma properties and flexibility. The updated machine configuration consolidates the gains that have been made and will be the basis for the next phase of design development in preparation for the CDR.

The coil design developments since the PVR are summarized in the following table:

	Current Sept., 2001	PVR March, 2001	Comment on current design
Number of modular coils / coil shapes	18 / 3	21 / 4	Lower cost, better access, more consistent with required physics properties and flexibility.
Symmetry planes containing modular coils	none	v = 0	Allows tangential NBI access without extended coil.
Number / location of TF coils	18 / centered on modulars	21 / between modulars.	Better access.
Number of PF coil pairs	5	4	Provides required physics flexibility, Ohmic volt-seconds.

A modified vacuum vessel shape will enlarge the interior volume, including space specifically provided for an inboard radiofrequency wave launcher and a divertor. A modification to accommodate Thomson scattering on the v=1/2 symmetry cross section will be incorporated.

The size (1.4 m major radius) and baseline heating configuration (3 MW of NBI) will be kept the same, as explained in Attachment 1.

The configuration design will continue to evolve as understanding improves. Expected changes include: 1) the modular coil geometry will be perturbed by small displacements to eliminate islands once the design tools are fully tested, 2) coil-to-coil and coil-to vessel spacings will be increased locally to resolve interferences, 3) the vacuum vessel segmentation will be optimized for assembly, and 4) the PFC configuration will be optimized for compatibility with a range of plasma configurations. Nonetheless, the main architecture of NCSX is now established, providing a point of departure for conceptual design development.

Progress in Disposition of PVR Recommendations

While developing the design since the PVR, the project has also made progress in addressing the PVR recommendations, as summarized in the following attachments:

Attachment 1. NCSX Size and Heating Requirements. Addresses recommendations II-2 (machine size) and IV-1 (baseline heating power).

Attachment 2. Stellarator Program Coordination Issues. Addresses recommendations II-1 (3D physics leadership), II-3 and V-2 (reactor studies), II-6 (stellarator interrelationships), V-1 (inclusive management), and V-3 (decision process).

Attachment 3. Progress in NCSX Diagnostic Planning. Addresses recommendations II-5 and IV-8 (physics program-diagnostics linkage), IV-12 (stellarator-secific considerations), and generally integrating diagnostics with the machine.

Attachment 4. PIES Update. Addresses progress on recommendation III-5 (flux surfaces) and generally developing PIES as a design tool.

Attachment 5. NCSX PVR Recommendations Tracking Log. Briefly summarizes plans and current status of all 29 recommendations.

In summary, the project is making steady progress in resolving the issues raised by the PVR committee. The progress to date is commensurate with the overall project schedule and the schedule for closing out the individual PVR recommendations.

Attachment 1. NCSX SIZE AND HEATING REQUIREMENTS

September, 2001

1. Introduction

The choice of the NCSX machine size (major radius) is an important decision that balances project cost with experimental performance. The Physics Validation Review committee expressed a concern that the size is too small, citing examples of parameters considered to be marginal. They also had a concern that critical parameters were being fit to a predefined budget envelope. The committee recommended that the project give continued attention to this issue and carefully justify its choices.

Since the PVR, the project has been working toward a goal of producing an updated machine configuration design that will be the basis for developing the design for the planned April, 2002, Conceptual Design Review (CDR). If a change in the overall size were to be made, now would be the most convenient time to make it. However, increasing the size would certainly raise the project cost above the $65M target (corresponding to $55M in FY-1999 dollars) that the project and PPPL management established. The more attractive course is, if at all possible, to resolve the committee's concerns in ways that do not require enlarging the machine or increasing the project cost. The project is pursuing this course.

Concerns about neutrals penetration and small plasma-to-PFC spacing are being addressed by optimizing the vacuum vessel to allow methods of neutral control. A new design concept has been developed that will significantly increase the interior volume and permit a wider range of PFC options, such as divertor plates and baffles, for neutrals control. Encouraged also by recent successes in W7-AS divertor experiments, the project is now focussing on optimizing the PFC configuration design within the expanded vacuum vessel volume, including compatibility with needed plasma shape flexibility, as its neutral particle control strategy. Even before it had a divertor, the W7-AS experiment had obtained temperatures up to ~2keV (and peak T_e as high as 5keV) with a minimum waist diameter of about 14-17 cm, depending on the configuration. By comparison, the 1.4-m NCSX design has minimum waist diameters of at least 24 cm, providing further reassurance.

With regard to concerns about confinement assumptions, heating power, and neutral beam ion losses, we have reviewed the analyses presented at the PVR for the R = 1.4-m design point. Performance can be measured in terms of the capability to access regimes of simultaneously low collisionality and high beta. In this regard we continue to believe that the 1.4-m design is adequate, though marginal as the committee stated. Rather than enlarging the machine, we have instead pursued approaches that are more attractive from a cost-benefit point of view to boost confidence in the adequacy of the projected performance of the 1.4-m design. One, prospects for neutrals and plasma density control have improved because of W7-AS results and design improvements mentioned above. Two, coil design tools have improved, making it possible to maintain low ripple while improving other design metrics such as access and fabricability. Three, coil and vacuum vessel design improvements have produced better access for both neutral-beam and radiofrequency heating systems, expanding the range of possibilities for heating upgrades beyond the initial 3 MW of NBI.

In summary, the new NCSX machine configuration that is being developed for the CDR is a significant improvement over the PVR design. It is likely that the size-related concerns raised at the PVR will be resolved without increasing the device size or baseline heating power. Given that, increasing the size and cost at this time is not required.

2. Confinement and Heating Power

Confinement analysis is performed to establish requirements that give adequate assurance that the NCSX experiment can achieve the goal of testing the beta limits in a collisionality regime of interest. The calculated beam-orbit losses have been taken into account in the analysis. The main conclusions of this work, which was documented in Sect. 8.2 of the PVR document, are summarized here.

Figure 1b shows that with 3 MW injected and with $H_{ITER\text{-}97P} = 1$ and $H_{ISS\text{-}95} \approx 2.9$, it is possible to reach $\langle\beta\rangle = 3.5\%$ at relatively high collisionality, $\nu_i^* = 1$, or a lower beta $\langle\beta\rangle = 2.7\%$ at moderate collisionality, $\nu_I^* = 0.25$ (the target value). Given the flexibility of the coils to move stability boundaries in beta (confirmed by post-PVR analysis with the latest coil design), the conditions accessible with 3 MW should be enough to complete some tests of beta-limit predictions. These same H factors produce the target $\langle\beta\rangle = 4.0\%$ and collisionality, $\nu_i^* = 0.25$ if the NBI heating power is increased to 6 MW. The design accommodates this possibility as an upgrade. An additional 6 MW of plasma heating can also be accommodated due to a design modification that permits installation of a high-field-side launcher for mode conversion radio-frequency heating. Thus with upgrades the total heating power can be increased to 12 MW. The need and optimum configuration for heating upgrades will be determined by initial results with the baseline 3 MW NBI system.

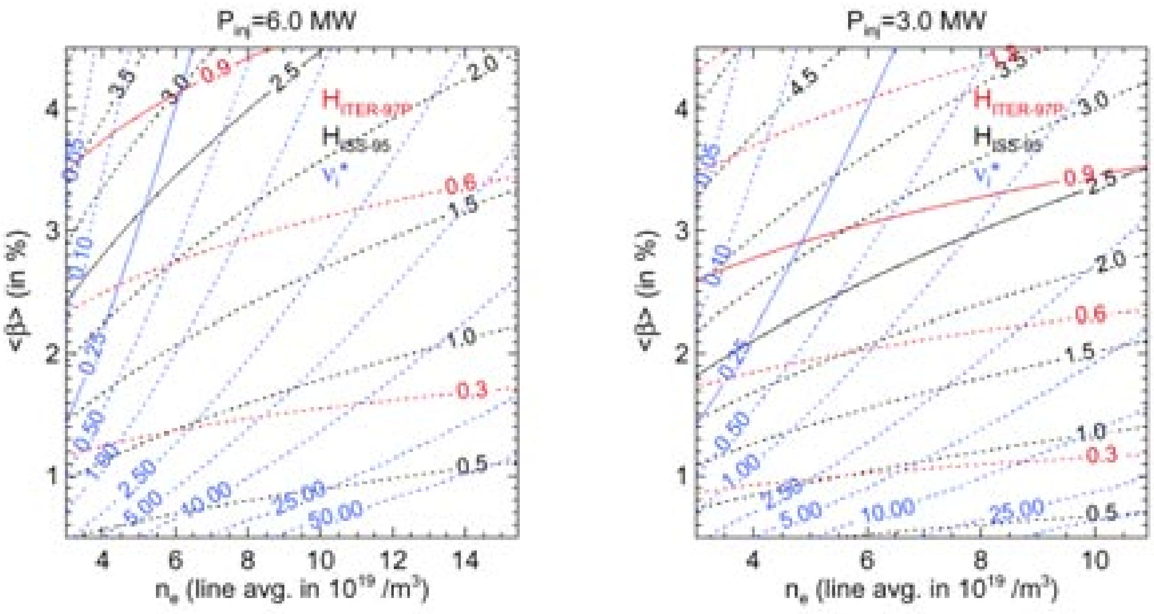

Figure 1. Contours of constant $H_{ITER-97P}$, H_{ISS-95} and collisionality ν*=0.25 for (a)P_{inj} = 6 MW and (b) P_{inj} = 3 MW.

It is important to note that machine size variations are a relatively weak factor in determining the achievable collisionality-beta range at the low end of the magnetic field operating range. Figure 2 shows the effects of machine size and magnetic field variations for two types of density constraint. The H-factors required to reach a given beta with 3 MW or 6 MW of NBI heating are relatively insensitive to size if $B_0 \times R_0$ is kept constant, which approximately corresponds to keeping the neutral-beam orbit loss fraction constant. The benefit of a larger machine would be to reduce the minimum useful magnetic field to a lower value. For the NCSX magnet engineering approach, and for a given coil configuration and temperature rise, the maximum magnetic field is proportional to R. Thus, a larger machine would increase the maximum available magnetic field, increasing plasma performance and extending the range of accessible collisionalities to lower values. The 1.4-m design provides a range of 1.2 to at least 1.7 T in the reference plasma configuration, and at least 2 T in configurations with reduced rotational transform. A determination of whether the upper limit can be raised at this size awaits further analysis that is planned as part of conceptual design preparation.

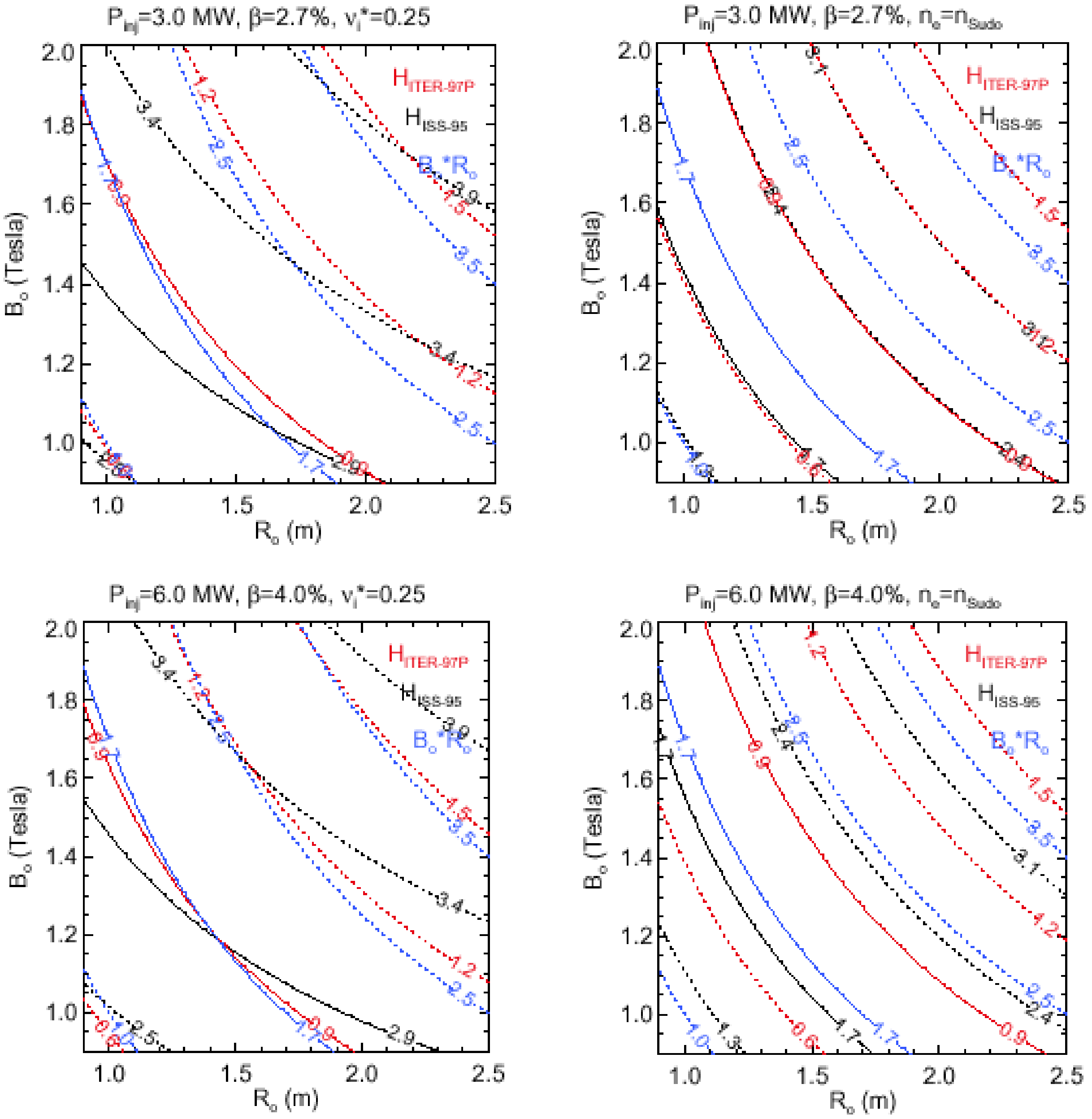

Figure 2. Contours of constant H_{ISS-95}, $H_{ITER-97P}$, and B_0R_0 for constant β, P_{inj} = (a, b) 3 MW and (c, d) 6 MW, and (a, c) constant ν*, and (b, d) Sudo-limited density.

3. Neutral Penetration

An important requirement for the NCSX design is that the neutrals generated at the plasma boundary do not penetrate too far into the plasma discharge for a reasonable range of operating parameters. Deep penetration of the neutrals could lead to an unacceptable energy loss channel and damping of plasma flows. To address this issue the DEGAS 2 code was used to model the neutral penetration, first with recycling occurring at an outboard limiter and then, with the recycling occurring at a divertor baffle. This modeling effort was documented in Sect. 11.8 of the PVR document. Figures 3 and 4 summarize the results. Figure 3 models a neutral source at the outboard mid-plane and in Figure 4 the source is at the banana tips. If the plasma is limited at the midplane, the scale lengths for both the neutral density and the ion source rate in front of the mid-plane limiter are about 0.8 cm. The neutral density at the magnetic axis is roughly 10^{-3} of the peak value for the midplane limiter configuration. For case with the neutral source at the banana tip the neutral density and ionization source at the magnetic axis are effectively equal to zero. Thus, it is very important to ensure that recycling occurs at the banana tips and not the mid-plane. This is the project's design objective.

Neutrals control in NCSX looks promising when compared with the recent experimental results on W7-AS [P. Grigull, EPS 2001]. The W7-AS has only about ~18 cm diameter in the midplane of the bean-shape cross-section (*vs* ≥24 cm in NCSX) and has, nevertheless, achieved excellent plasma performance with the island divertor operation. In particular, density control and plasma collapse which used to be a problem in W7-AS before the installation of the divertor, has been solved due to a combination of recycling control and particle confinement. It appears that the divertor plates and baffles provide the needed neutrals control at the source so that the neutral penetration at the midplane should not be a machine size determinant but careful design of the PFC configuration and location are important for neutral control. We are taking this approach to developing the conceptual design. An initial assessment of the space available for implementing such a divertor on NCSX is encouraging.

It should be kept in mind that neutral penetration in a stellarator, where the narrow waist regions are localized, is much less than in an axisymmetric device with the same minimum waist width. Even before it had a divertor, the W7-AS experiment had obtained temperatures up to ~2keV (and peak T_e as high as 5keV) with a minimum waist diameter of about 14-17 cm, depending on the configuration. By comparison, the 1.4-m NCSX design has minimum waist diameters of at least 24 cm, providing further reassurance.

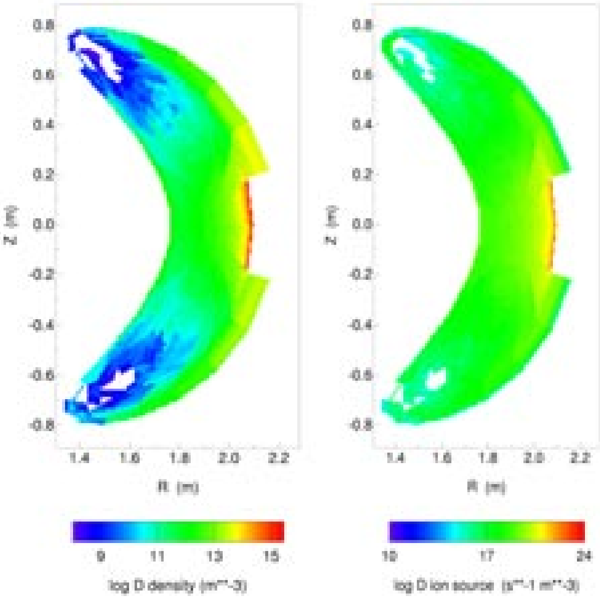

Figure 3. Two-dimensional plots of the log of the neutral atom density and the ion source rate obtained with recycling at an outboard limiter. To facilitate computation of the logarithm, the data were first multiplied by 10^9 and 10^{10}, respectively.

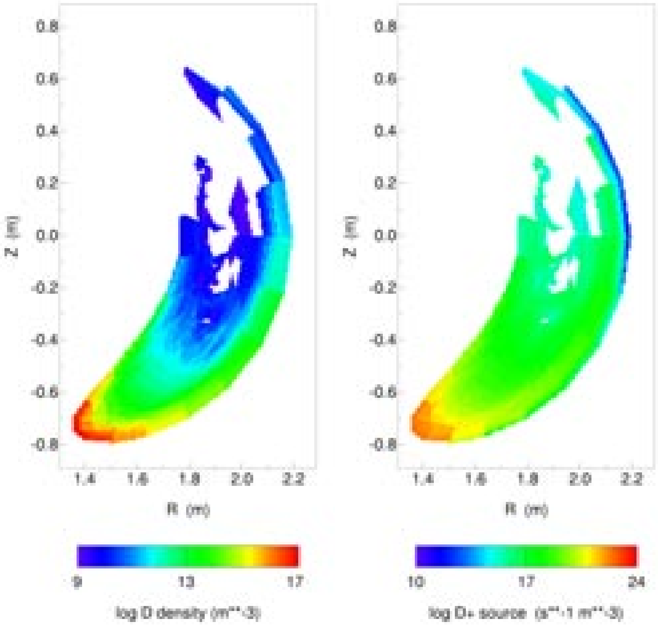

Figure 4. Two-dimensional plots of the log of the neutral atom density and the ion source rate obtained with recycling at lower divertor. To facilitate computation of the logarithm, the data were first multiplied by 10^9 and 10^{10}, respectively.

4. Beam Orbit Confinement

Beam injected ion orbit confinement is generally an issue for experiments the size of NCSX. In addition, the unique shape of NCSX may impact high energy ion orbit characteristics. For this reason orbit analysis has received special attention as part of the NCSX design process. This work is documented in Sect. 7.3 of the PVR documentation.

Figure 5 summarizes the beam ion loss studies. Beam deposition has been modeled using axisymmetric models with the plasma cross-section of the tangency cross-section in the actual geometry. Beam ion dynamics have been modeled using the actual 3D equilibrium and the full collision operator. The loss of injected energy is significant but not prohibitive. The confinement studies have taken these losses into account in projecting operating points. Thus, while a larger machine would increase the operating range in magnetic field and in density (for limiting collisional orbit characteristics), the 1.4-m device is adequate.

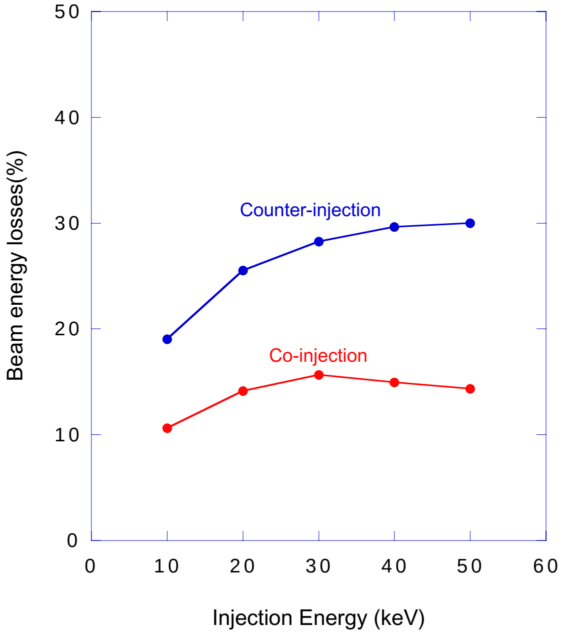

Figure 5. Variation of the beam energy losses with injection energy, including collisions, for a recent machine design point at R_0 = 1.4 m, <B> = 1.23 T, n(0) = 8.5 x 10^{19} m^{-3}, $T_e(0) = T_I(0)$ = 1.58 keV for Hydrogen beams injected into a hydrogen plasma.

5. Access

The overall machine size affects the access for personnel, heating (particularly beam heating) and diagnostics. The status of the access for the NCSX configuration and size are summarized below for each of these areas.

A. Personnel

A discussion of the personnel access is documented in Sect. 3.2.3 of the PVR document. The conclusion outlined there is that the personnel entry access into the vacuum vessel is not limited by the present size of the machine. The primary limitation for entry access are the availability of ports not filled with diagnostics, neutral beams, or trim coils. The solution of the problem of competition for port utilization will be an important design integration focus for the conceptual design.

B. Beam

The neutral beam optics has been modeled for the PBX neutral beams in the NCSX geometry. The modeling uses the measured PBX beam characteristics as input. Front-end cryopumping is provided to eliminate reionization losses in the duct. As a result, it is projected that the full 1.5 MW per beamline will be injected into the torus. The beam “footprint” size is not small compared to the plasma cross section, as shown in Figure 6, but does enclose ~96% of the injected power from the most poorly focussed beam. Quantitative transmission estimates require detailed calculations which have not been done, although they will benefit from the relatively high densities expected in NCSX. The geometrical modeling supports the conclusion that the R = 1.4 machine size is adequate, although marginal and likely to be limited in aiming flexibility.

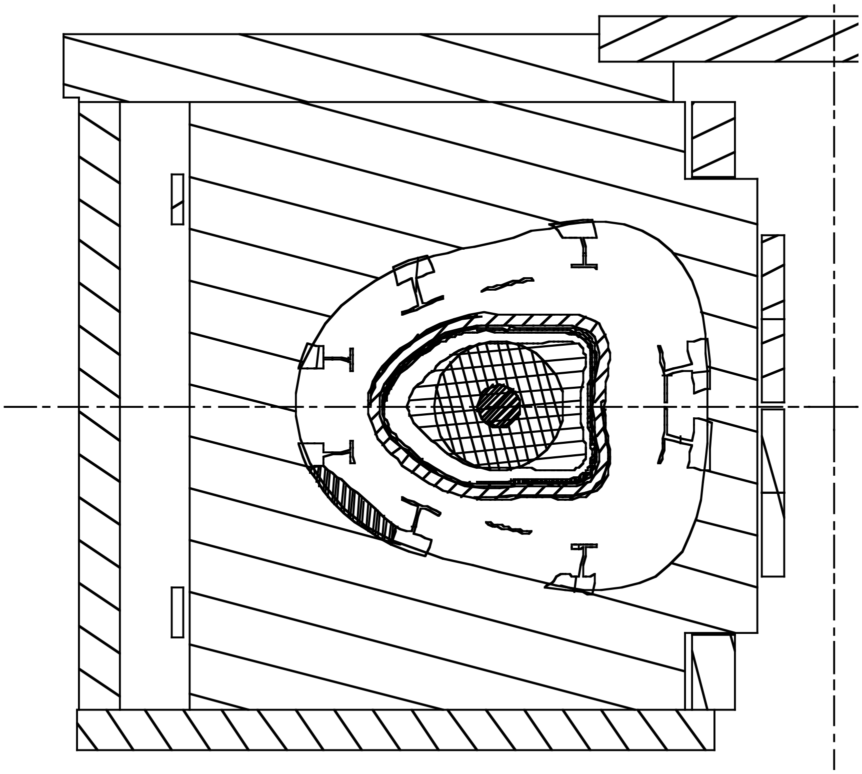

Figure 6. NBI footprint (circles) for the most poorly focussed beam superimposed on the oblate plasma cross section. The larger circle encloses ~96% of the injected power, the smaller circle encloses 47%.

C. Diagnostics

For fusion experiments, factors affecting diagnostic access are the number of ports, port area, duct length, and available sightlines. The specifics of the diagnostics port utilization are provided in Sect. 12.3 of the PVR documentation. For the PVR configuration NCSX has 87 ports with about 66 ports required diagnostics. The assessment at the PVR was that "port availability is tight" for the number of diagnostics required, however the number of ports does not increase with machine size.

It was also noted at the PVR that more detailed diagnostic-specific studies were needed to assess adequacy. Such studies will be done as part of conceptual design, however some important gains in access have already been made. The new 18-coil design is significantly better for diagnostic access than the 21-coil design presented at the PVR. Fewer coils obviously means more space between coils, but more importantly the new design has its TF coils at the same toroidal angles as the modular coils instead of midway in between and it has no coils on symmetry planes. Diagnostic access to symmetry planes, which are the most valuable locations for stellarator diagnostics, is substantially improved as a result of these changes. Also a vacuum vessel design modification has been developed that permits radial access for a Thomson scattering laser beam at the bullet cross section. The same design may also facilitate installation of a diagnostic neutral beam. These improvements have come about through design optimization, not increasing the machine size.

While a larger machine would increase the port area, it would also have the adverse affect of increasing the duct length required to penetrate through the PFC's, vacuum vessel, modular coil shells and the cryostat. Because of these factors increasing the machine size does not obviously improve or degrade diagnostic access.

6. PFC Space

The space available for plasma facing components (PFC) is a weak function of the overall machine size (over the range of reasonable size changes), but strongly dependent on the magnetics design and the space available inside the vacuum vessel. With this in mind we have adopted the strategy of maximizing the space available for plasma scrape-off and PFC's within the constraints of the plasma shape and the coils. For a given coil design, the vacuum vessel volume is limited by the requirement to be able to install the modular coils over the vacuum vessel. Since the PVR, a change from 21 to 18 modular coils and improvements in how the vacuum vessel geometry is generated have made it possible to significantly enlarge the vacuum vessel volume at fixed major radius. While the understanding of the magnetic topology of the plasma edge (over the range of plasma discharges needed for flexibility) and the design of the PFCs will continue to evolve for a period of time, the prospects for having adequate space have greatly improved by these changes to the major components. Based on tokamak and stellerator experience it is expected that the space allocated for the scrape-off and PFC's will be large enough.

7. Summary

The overall machine size impacts the space available for internal hardware, the access for personnel, heating and diagnostics, the neutral penetration to the plasma core and the energy confinement. For those elements related to space availability (i.e. access and PFC space) the present machine size has been shown to be adequate; in fact these elements benefit relatively weakly from increases in the overall machine size. The neutral penetration is most strongly dependent on the location of the source of neutrals. If we avoid limiting surfaces near the narrow plasma cross sections the discharge should not be adversely impacted by neutral penetration. The performance element that is most sensitive to the overall machine size (at fixed heating power) is the useful operating range of magnetic field, which translates into a range of accessible collisionalities. The 1.4-m design provides a range of 1.2 to 1.7 T in the reference plasma configuration. A determination of whether the upper limit can be raised awaits further analysis that is planned as part of conceptual design preparation.

The studies that have been carried out and are summarized in this report show that the NCSX design point is adequate for heating powers somewhere in the range of three to six megawatts. This range of heating powers is dictated by the range of uncertainty in projecting the energy confinement. Based on this assessment it is prudent to begin the heating experiments with a baseline heating power of 3 MW and plan future upgrades of the heating system based on the results from the initial experiments.

Attachment 2. Stellarator Program Coordination Issues

Several of the PVR recommendations (II-1, II-3, II-6, and all of V) addressed the larger stellarator proof-of-principle program, emphasizing 3D plasma physics theory and diagnostics, international collaboration, and stellarator reactor studies in particular. Good coordination and mutual support among the various program elements were recommended, with NCSX seen as having a central role both scientifically and organizationally. In response, the NCSX leadership has been working with the leadership of the other stellarator program elements and involved institutions to move the program forward as a whole and to continuously improve coordination. Some examples of coordination actions taken or planned by the stellarator community since the PVR:

- <u>3D plasma physics theory</u>. A workshop on “Future Directions in Theory of 3D Magnetic Confinement Systems” will be held to develop plans for 3D plasma theory research. It has been scheduled for Jan. 7-9, 2002, at ORNL.

- <u>International Collaboration</u>. Physicists who have been involved in the NCSX design work have begun to shift focus to collaborations with LHD and W7-AS. Topics in which collaborations have started or are being planned include neoclassical transport, anomalous transport, energetic ion physics, MHD equilibrium and stability, and divertors.

- <u>Stellarator reactor studies</u>. Discussions with the ARIES group have produced a preliminary understanding of the approximate cost and possible schedules for an ARIES CS reactor study, and the preparatory work that both the ARIES and stellarator teams would need to do. One constraint on the timing is that stellarator experts who would be needed for a reactor study are still involved in designing experiments.

- <u>Broader management focus</u>. The scope of the NCSX PAC has been broadened to advise on PPPL’s stellarator theory and collaboration activities in addition to NCSX. Stellarator groups outside of PPPL will have the opportunity to make presentations to the NCSX PAC if they wish. The next meeting has been scheduled for November 14-15 at PPPL.

- <u>Support of FESAC / DOE Decision process</u>. The stellarator community presentations to FESAC in May and August explained the program goals; the purpose of each element of the program and their interrelationships, the costs, and the program’s expected benefits to fusion science and energy.

One area that has received little attention in the brief period since the PVR is 3D plasma diagnostics. This will receive more emphasis in the next few months through the NCSX conceptual design effort. Coordination and advancement of the stellarator program will require the sustained efforts of the entire stellarator community leadership. While much remains to be done to follow up on the plans that have been put in place, good progress has been made since the PVR in responding to the recommendations for good stellarator program coordination.

Attachment 3. Progress in NCSX Diagnostic Planning as of September 19, 2001

Comments on diagnostic access for new machine configurations under consideration.

(Important in developing response to Recommendations IV-8 and IV-12)

In the 21 coil configuration with TF coils between modular coils presented at the PVR, diagnostic access was difficult, particularly at symmetry planes. Obviously, the 18 coil option, if it is acceptable, will increase the space available for diagnostic access. Also, centering the TF coils on the modular coils, rather than midway between them, reduces TF coil interference with diagnostic ports and clears space for the diagnostic sensors outside the ports.

This new configuration results in an elimination of coils at the symmetry planes, which makes diagnostic access to these important areas more straightforward. At the bullet symmetry planes, integration of the vacuum vessel joints, the inside RF launch hardware, and the diagnostic views appears feasible. Mike Cole has developed the concept of a short vacuum vessel segment at this symmetry plane providing access for a Thomson scattering input beam tube and inner wall laser dump. Such a short segment for diagnostic access to this important area could also be used by a compact DNB, providing active spectroscopy measurements of the ion temperature and the iota profile.

The configuration changes currently being investigated are, therefore, encouraging from a diagnostic point of view. Design is not yet at the point of having a sufficiently detailed CAD model of the new configuration to permit a systematic reassessment of the adequacy of diagnostic access, or to begin assigning specific ports to various diagnostics. Such work is planned as part of developing the conceptual design in the coming weeks.

Progress in mapping of diagnostic requirements to experimental objectives and program issues.

(Important in developing response to Recommendations II-5 and IV-8)

The link between the diagnostic requirements and the experimental objectives is physical plasma quantities measured. A valuable planning technique used successfully by many projects is to tabulate measured quantities along with diagnostic techniques and several other valuable categories of information. Recently, such tables developed for W7-X were obtained and similar tables for LHD and ITER were requested. Such tables provide a basis for assigning priority for the phasing of diagnostic implementation with the experimental program developed around the project mission. Below are shown examples of table headings and entries. There are 75 row entries of measurement quantities in the W7-X table. These tables are currently being developed for NCSX, and drafts should be available at the NCSX project meeting scheduled for mid-October.

Table of Experimental Studies

Experimental Objective	**Phase within Program**	**Essential Measurements**	**Comments**
transport analysis of ohmic plasmas	2	plasma boundary location conductivity electron temperature profile ion temperature profile radiated power profile Z_{eff} profile	?

Table of Measured Physical Quantities

Quantity Measured	**Parameter Range**	**Plasma Region**	**Accuracy (space/time res.olution)**
Radiated power profile	.05 – 5 watt/cm^3	core	10%, 2 cm, 10msec 30%, 2 cm, 1 msec
Diagnostic Techniques	**Phase of Initial Implementation**	**Comments**	**?**
foil bolometer array AXUV diode array	2 1	For high accuracy For high time response	??

Table of Diagnostic Techniques

Diagnostic Technique	**Primary Reason for Measurement**	**Plasma Region**	**Type of View, # channels**
bolometer array	radiated power profile for power balance	core	2 poloidal arrays, 16 channels each
Phase of Implementation	**Port Allocation**	**Comments**	**Expert Group**
2	??	??	??

Attachment 4. PIES Update

The PIES code is our primary tool for assessing flux-surface quality and ensuring that the design produces good flux-surfaces. Recent work has focussed on improving the speed of convergence of PIES and the flux-surface healing process built upon PIES.

A simple form of preconditioning has been tested in the PIES code and shows promise for a substantial further increase in the speed of the code. The scheme has been developed to address the issue that near-resonant currents are sensitive to small changes in the Jacobian, requiring strong under-relaxation to maintain numerical stability. The new scheme allows stronger under-relaxation to be applied to near-resonant Fourier components of the current than to non-resonant components. A test for the NCSX reference configuration, LI383, obtained convergence in about 60 iterations rather than the several hundred previously needed. An issue for the implementation of a general version of the new scheme is the initialization of the currents. With the Fourier resolution conventionally used in VMEC, near resonant currents are not accurately calculated. Recent VMEC convergence studies at higher resolution show promise for providing sufficiently accurate initialization of the near-resonant currents.

The modification of coil designs (coil-healing) to eliminate islands in the MHD equilibria calculated by PIES is progressing on two fronts. A new method has been developed, named dynamical healing, which adjust the coil geometry at every iteration of PIES to suppress islands. This is being compared with the earlier, named static-healing, which runs PIES a fixed number of iterations (not to convergence) and then adjusts the coils once. Early results include that the dynamical healing method does converge (in that the incremental coil changes go to zero), the converged results appears robust to PIES initialization, and that the static and dynamical healing methods converge to a similar coil set.