Chapter 12 -- Diagnostics

A capable array of diagnostics is planned to make the plasma physics measurements necessary to accomplish program goals. The facility will be equipped with an initial set of diagnostics to support shakedown of major machine systems and the first few phases of physics operation: first-plasma, electron-beam mapping of flux surfaces, Ohmic plasma experiments, and initial heating experiments. Experimental results from the initial operating phases will help optimize the selection of upgrade systems and their design characteristics. An implementation plan for upgrade diagnostics has been developed based on experience with other projects for use as a reference for design purposes. It is used in the ongoing design process to set port access requirements and ensure that a feasible solution exists for all required measurements.

During conceptual design, the project emphasis will be on the design of the stellarator core device, including the coils, vacuum vessel, and plasma-facing components. A systematic analysis of the access constraints and tradeoffs for both baseline and upgrade diagnostics will be an important element of the conceptual design activity. Diagnostic considerations have played a prominent role in the preconceptual design development of the NCSX. As a result, a large number of ports (about 87) is provided and many specific diagnostic needs have been taken into account, however the task of providing adequate diagnostic access has only begun. At this stage, the available access is marginal, and providing good diagnostic access will be an important design goal for the conceptual design phase.

As a matter of definition, and based on historical precedent, diagnostic systems as a category include the set of sensors and instrumentation used for general plasma research. It does not include measurement instrumentation used with specific NCSX auxiliary systems. For example, Residual Gas Analyzers and ion gauges are included with the machine vacuum system. Rogowski's to measure coil currents are part of the magnet and power supply systems, *etc*. The exception to this rule for this report is the e-beam and fluorescent mesh instrumentation that is needed for the early field mapping effort on NCSX. This instrumentation is included in the baseline set of diagnostics

12.1 Baseline Diagnostics

The baseline set of research diagnostics represents the minimum component needed to accomplish the initial mission, including first plasma, shakedown of all major machine systems, electron-beam flux surface mapping, Ohmic experiments, and initial heating experiments. Included in this set is the instrumentation needed for e-beam mapping of the magnetic field. The diagnostic systems planned for the first plasma campaign and for field mapping are listed in Table 12-1, along with a summary of machine, infrastructure, and data acquisition interfaces required.

In the current plan, the first run campaign would start with a "first plasma" demonstrating that the machine can create and confine a plasma with all major systems operational. Following this first plasma demonstration, there will be a short campaign to characterize the important global quantities of the plasma. These include the plasma current, the basic equilibrium which yields the stored energy, the radiated power fraction, the line average density, crude measurements of the electron temperature and Z_{eff}, and initial indications of MHD. Following this initial characterization, there will be a campaign to map the magnetic field with an electron beam.

Table 12-1 Baseline Diagnostics and Interfaces

Diagnostic System	comments	rack	window	shutter	valve	vac	digit. channel	Speed S/M/F	frame grabber
Magnetics	100 channels	2					100	M/F	
Visible Cameras	3 cameras	1	3	3					3
Interferometer	single chord	1	1	1			4	M	
UV Spectroscopy	single sightline	1			1	1			1
Visible Spectroscopy	several fibers	1	1	1					1
Visible Filterscopes	3 views,10 fibers	1	3	3			10	M	
SXR Arrays	3 arrays	1			1		60	M/F	
e-Beam Mapping	e-beam probe, screen , CCD	1	2	2	1				2
	total	**9**	**10**	**10**	**3**	**1**	**170**		**5**

The magnetic sensors include a diamagnetic loop, flux loops, Rogowski coils and B-coils which will provide signals to measure the magnetic flux change in the many geometries necessary to determine the internal magnetic field geometry using an equilibrium reconstruction code. Because of the strong shaping in NCSX plasmas, such a magnetic reconstruction can provide important information on profiles of plasma pressure and toroidal current.

A typical magnetic channel consists of a high temperature sensor coil mounted between the carbon first wall and the vacuum vessel with high temperature leads to a vacuum feedthrough. The signal is transmitted via field cables to a junction box and then to an integrator, and finally to a digitizer to provide flux vs time. Many of the signals will also be inputs to the plasma control computer, which will use them to control the coil currents, which determine the plasma size and shape as well as the toroidal plasma current. A detailed analysis to ascertain the optimum number and placement of different sensors will be part of the conceptual design.

Visible camera will be used initially to view all three periods of the plasma with three identical ‘tangential views’. One camera will be moderately fast with a full frame rate of at least 250 Hz to permit viewing of the startup evolution. Because of plans for wall conditioning and bakeout, shutters will be needed to protect the viewing windows from coating. The light from the plasma will be coupled through a viewing lens into a coherent fiber bundle. The fast camera will be located outside of the cryostat and will view the images through an interference filter. The viewing lens and fiber bundle may need cooling to protect them during bakeout. A PC with frame grabber will be used to control the camera, and to capture and store the data. Initially, standard frame rate, compact CCD cameras will be used at the other two locations. Ultimately, there will be dedicated, fast cameras on each of the three views.

An interferometer will be used to monitor the line density on a single line of sight through the core of the plasma during the initial plasma run. A low cost, uncompensated 1 mm microwave system is under consideration, with solid state source and mixer, similar to systems currently in use at DIII-D and Pegasus. The vacuum interface will consist of a quartz window with shutter. Optics will guide the beam through the window to a machined PFC surface on the vessel wall opposite the input port. Refraction may limit usefulness of such a system at high densities due to resulting degradation in the return signal. This effect is dependent on plasma shape and density profile shape, and on the detailed geometry of the beam, the plasma, and the reflecting PFC surface. Once candidate port geometries are defined in the conceptual design phase, ray tracing can be used to quantify the refraction limitations.

A concern with the initial shakedown of any device is unfavorable plasma interaction with the wall leading to the influx of impurities. This can be caused by poor control of the plasma, or by failure of some internal mechanical component, possibly leading to material ablation due to plasma contact. Among the first signs of such problems is an increase in the radiated power. There is also a large increase in specific impurity emission lines, which can help to identify the sources of the problem.

Most of the line radiation is in the vacuum UV and a spectrometer/detector system capable of surveying this region of the spectrum will be purchased to provide these measurements along a single sightline. This system will need a vacuum connection to NCSX, with an interface valve and a dedicated vacuum system. A visible survey spectrometer capable of simultaneously monitoring several lines of sight will also be purchased. This instrument will view the plasma through a quartz or sapphire window for near UV measurements. In addition, it will simultaneously view several quartz fibers relaying light from sightlines at 3 other shuttered windows around NCSX.

At one of these locations there will be lens imaging the plasma onto an array of ~10 large (~1 mm) quartz fibers. The fibers from these windows will be routed to a remote optical table, where interference filter/detector assemblies will be used on selected views to monitor selected impurity lines and H (D) recycling lines with high time resolution. Ultimately, there will be fiber arrays at all three locations.

Internal MHD activity can greatly influence the behavior of the plasma particularly as plasma startup control is first being established. While magnetic coils can detect disturbances that propagate to the plasma edge, a soft x-ray imaging array that spatially resolves x-ray emissivity along a fan array of sightlines with good time response is very useful to detect internal MHD activity. Ultimately a large set of such fan arrays will be needed for tomographic reconstruction of the dynamics of magnetic islands at several toroidal positions. For the first plasma run, a single 16 channel array will be installed.

The proposed array will use a compact, integrated, 16 channel linear AXUV diode array behind a pinhole. Metal foils of known thickness can be used to provide crude energy resolution.

The high sensitivity and speed of these detectors make them ideally suited for fast MHD measurements in the temperature and density range expected for NCSX. It is proposed that these sensors be cooled to enhance sensitivity. The proposed system is similar to those being developed by Johns Hopkins for use on NSTX. They will fit within a reentrant head with a diameter of < 4”, smaller than many of the diagnostic access ports on NCSX.

In addition to detection of MHD activity, this array can provide other data useful for early NCSX operation. Because foils and detectors are absolutely calibrated, using reasonable assumptions about the impurity content of the plasma and comparisons with modeling results, one can put significant constraints on the electron temperature using this diagnostic. This will be valuable, since, at the low TF fields and high densities expected for early NCSX operation, plasmas are overdense for ECE measurements of T_e, and Thomson scattering measurements of T_e will not be available for the first plasma run. In addition, operation of this array without a filter can provide crude measurements of the total radiated power profile. The precision of such measurements is limited due to the non-uniform spectral response of these detectors at low energy.

The field mapping hardware consists of a probe drive with an electron gun at its tip, which can be accurately positioned along a line through the nominal cross-section. The axis of the gun also needs to be adjustable for alignment with the local field. During field mapping the electron beam from the gun will intercept a fluorescent screen as it repeatedly transits the device. The light from the strike points will be imaged by a high resolution CCD camera. Careful metrology will reference screen positions to machine coordinates. Strike points will be compared to expectations of a code, which will compute the beam trajectory for given coil currents. Magnetic island structures will be investigated near reference equilibrium conditions. The influence of trim coil currents will be assessed.

12.2 Schedule for Diagnostics Upgrades

As shakedown of the many NCSX auxiliary systems proceeds, and control of the plasma becomes more routine, attention will shift toward the research goals of NCSX, and progressively more diagnostic capability will be required. Figure 12-1 shows a proposed implementation schedule for diagnostic upgrades, and how this schedule is related to the proposed research campaigns. This schedule will be further refined during the conceptual review process.

Those diagnostics needed for the first plasma campaign are grouped at the top of the list, with development listed as TPC (included in the Total Project Cost for the NCSX Construction Project). The shading specifies estimated duration for the design and installation phase, the debugging phase, and the operating phase of each diagnostic system. It is assumed that there will be approximately 6 months of ‘outage’ time available each year, with in-vessel access, for the installation of diagnostics and other hardware. Many calibration and alignment tasks will also occur during these outages.

As this implementation plan indicates, there is a continuing effort throughout the project to improve diagnostic capability to support program needs. Some of the diagnostics needed for the second run campaign require approximately two years to develop, and so significant effort in these areas is needed at the same time that the baseline diagnostics are being developed and installed.

As a general strategy, diagnostic development will shift from basic monitoring of global quantities and impurities during the first plasma run to local measurements of n_e, T_e, T_i and v_ϕ in the core and edge. In this plan, these local measurements become available during the second half of the ‘Plasma Heating and Transport’ run. More detailed profile information becomes available in the third research run. Diagnostics for measuring MHD activity, fast ion behavior, and edge and divertor characteristics will see a steady improvement in capability. Turbulence measurements become available early at the plasma edge and then in the core toward the end of the plan proposed above.

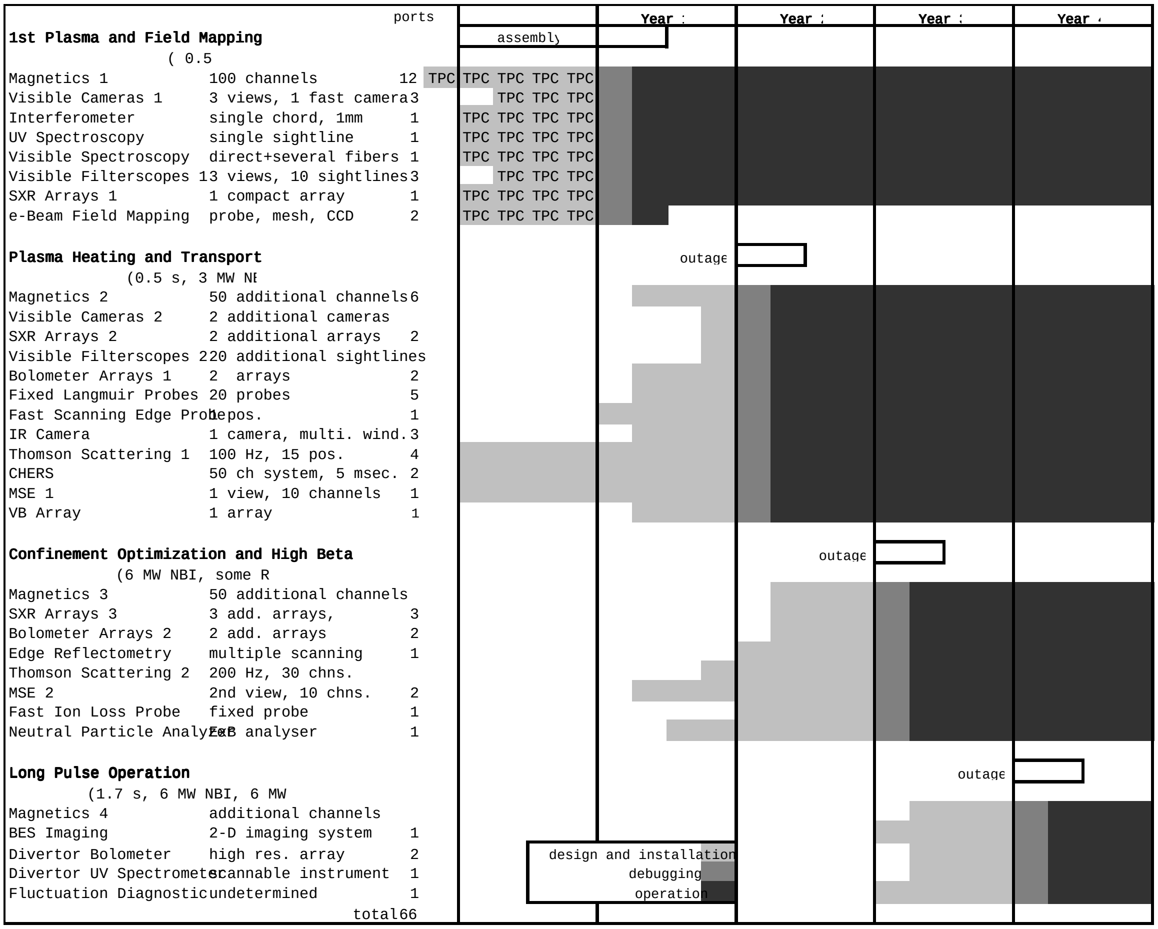

Figure 12-1 Diagnostic Implementation Plan

Since two neutral beam injectors will be operational in the “Plasma Heating and Transport Phase,” it is proposed that beam based spectroscopy be used early on to obtain valuable profile information. A CHarge Exchange Recombination Spectrometer (CHERS) system is proposed to measure T_i and v_ϕ. profiles.

A Motional Stark Effect (MSE) Polarimeter is also proposed to obtain profiles of the internal magnetic field pitch angle. A second MSE system is included later in the plan to permit determination of both E_r and J(r). A diagnostic neutral beam may be needed for these measurements.

Another important profile diagnostic that will be essential for early transport experiments is a Multi-Pulse Thomson Scattering System (MPTS) which provides snap shots of the T_e and n_e profiles along a laser beam.. Similar to systems in use on many devices, the proposed system would utilize high repetition rate (100hz) Nd:YAG lasers and filter polychromator/APD detectors. The system would start with one laser and ~ 15 spatial positions, but it's design would accommodate additional lasers and spatial positions to be added as time and resources permit.

A staged approach is seen for several diagnostics in the plan outline in Figure 12-1. It is envisioned that additional or upgraded magnetics sensors will be added periodically through the life of the project, as experience is gained and as new physics or control needs arise. Multiple sets of SXR arrays for monitoring MHD activity, and bolometer arrays to measure radiated power are similarly staged in the plan.

12.3 Adequacy of NCSX Diagnostic Access

Given the plans outlined above for equipping NCSX with a comprehensive diagnostic set, the adequacy of access available for diagnostics is a legitimate concern. Such access must, in most cases, penetrate the PFC's, the vacuum vessel, the modular coil shells and their supporting plates, and the cryostat. The constraints imposed by these various boundaries severely limit the number and size of diagnostic access ports, and typically place the ports themselves at the end of rather long vacuum extensions. These long extensions pose challenges for diagnostics requiring wide angled views of the plasma.

A systematic analysis of the access constraints and tradeoffs for each diagnostic in Table 12-1, along with a discussion of how well the projected measurement accuracy matches the physics goals of NCSX, are both clearly needed in the conceptual design phase of NCSX. As an example of the geometrical constraints and their impact, consider tomography. In the present design, there are no unobstructed views in a poloidal plane common with any of the six symmetry planes. Tomographic techniques such as multi-camera bolometry and multi-camera soft x-ray arrays benefit from geometrical symmetry to reconstruct profiles. Lack of symmetry means that more cameras will be needed for equivalent spatial resolution in independent reconstructions.

As currently designed, there are 87 ports on NCSX listed in Table 3-6, including the ports used by neutral beams. There will be many other systems requiring port access, for example, feedthroughs for PFC cooling and thermocouples, for gas puffers, for wall conditioning instrumentation such as glow probes and filaments, for current and cooling leads for trim coils, as well as diagnostics. Included in Figure 12-1 is a listing of the number of ports anticipated for each diagnostic in the plan, with a total of 66. Thus, even without consideration of specific geometrical constraints for diagnostics and without any allowance for future diagnostic needs, not to mention the needs of other systems, the port availability is tight, considering the variety of measurements desired.

The only way to get a better feel for the adequacy of access is to begin looking at the needs of specific diagnostic systems. Initial studies have thus far been done for a radial Thomson scattering system, and for the beam-based CHERS systems.

The ideal geometry for the multipulse Thomson scattering system would place the laser beam at the horizontal midplane of the bullet symmetry plane. In this way, one can probe the magnetic axis for all configurations, and the flux surfaces are spread out along the beam, which optimizes the tradeoff between spatial resolution and sensitivity. Unfortunately, this geometry is impossible to achieve in the current design, because this symmetry plane is at the joint between vacuum vessel segments. However, it appears feasible that a modification to the planned port layout could provide small ports (~ 3” dia.) for the laser input and output at the midplane, as shown in Figure 12-2. In this scheme the beam would enter close to the joint on the outside, and exit on the inside on the other side of the joint. Viewing could either be from the large midplane port next to the beam, or from the top on a somewhat smaller port. For efficient design, the viewing port would need to be angled towards the magnetic axis at the symmetry plane, as shown in Figure 12-3.

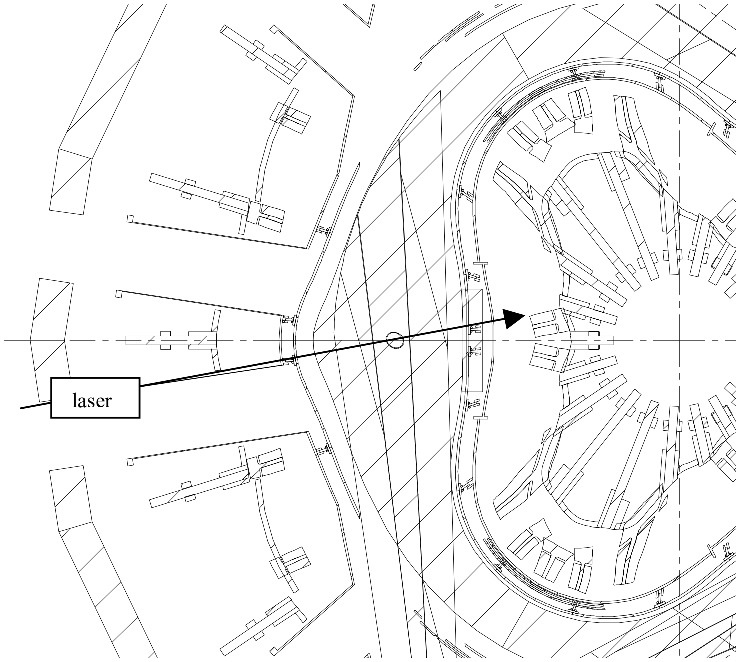

Figure 12-2 Possible path for the Thomson scattering laser

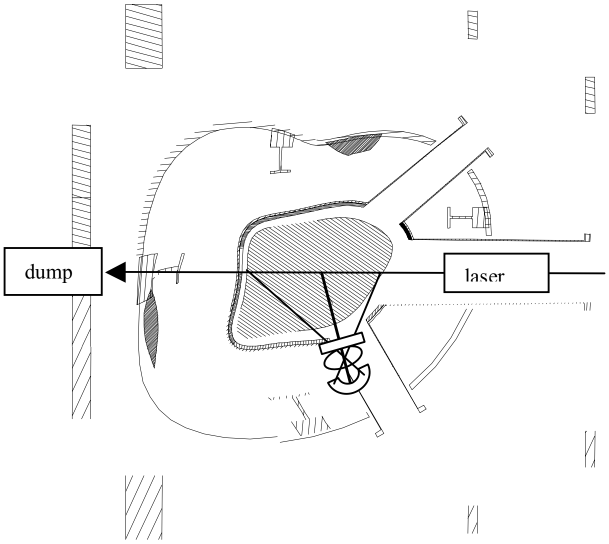

Figure 12-3 Possible viewing geometry for Thomson scattering

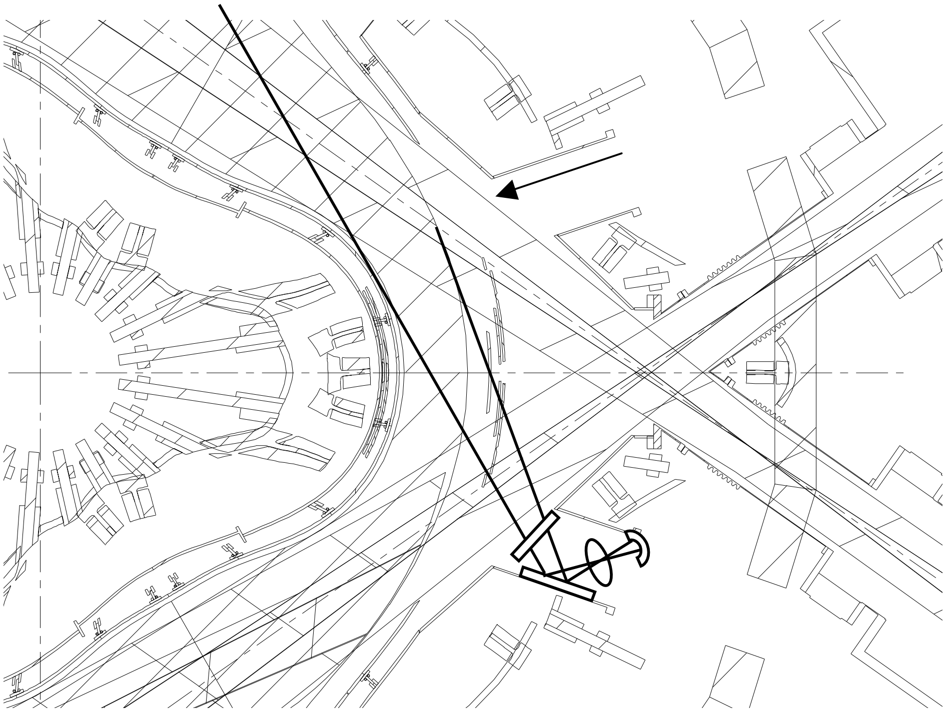

Figure 12-4 Possible viewing geometry for CHERS

Beam based spectroscopy techniques, such as CHarge Exchange Recombination Spectroscopy (CHERS) have traditionally achieved optimum spatial resolution by having sightlines that intercept the beam at points where they are tangent to plasma flux surfaces. This is the case for the sightline in Figure 12-4 at the outer edge of the plasma, if one considers, for the moment, only injecting the bottom right neutral beam. For other sightlines in this geometry, the intersection with the beam spans a large range of flux surfaces. This means that to interpret data from such a view, a spatial inversion will be necessary to derive an ion temperature and toroidal velocity profile. This inversion will likely need input from the calculated equilibrium to account for changes in the flux geometry along the sightline, as well as a calculation of the beam deposition. While such inversions have been done in a tokamak geometry with reasonable precision, uncertainties introduced by the 3-D nature of the NCSX plasma have not been predicted. Note that if one had a diagnostic beam injecting along the arrow shown in the figure, this problem would be much less severe.

The optics shown schematically in Figure 12-4 may have to extend into the path of the beam injecting from the upper right, particularly if it needs to avoid interference with the trim coils or the PFCs in this area. Thus, the choice of beam placement is clearly linked to the spatial constraints of beam-based diagnostics.

As indicated by these initial access considerations for MPTS and CHERS, there are many details to be worked out for each diagnostic, which will strongly affect its ultimate measurement capabilities. The proposed port layout needs modifications to optimize access for these two systems. Such modifications appear feasible for these two cases, provided that sufficient flexibility is maintained in the design process for the various major machine systems to accommodate the modifications. Because it is clear that port allocation will be very tight, the most must be made of each port. The adequacy of the final port configuration will depend critically on the attention given to access needs for specific diagnostics during the NCSX design process.

12.4 Diagnostic Integration Plan

Diagnostic development for NSTX faces significant technical challenges. As described above, the interface between the NCSX device and the associated diagnostics is complex. Adding to the complexity of the access issue is the 3-D nature of the plasma, and the need to probe different toroidal phases. Thermal excursions for diagnostic instrumentation within the cryostat during routine operation and during the plasma facing component (PFC) bakeout will also be an issue. The difficulty of manned access inside the NCSX vacuum vessel will complicate diagnostic installation and calibration. For these and other reasons, as NCSX proceeds from pre-conceptual through detailed design, integration of diagnostics with the other machine components will be an ongoing and critical activity, and it is an explicit component of the project plan.

The proposed research plan for NCSX motivates a relatively aggressive schedule for diagnostic development. As indicated in Figure 12-1, development for several profile diagnostics planned for the first research phase must begin well before the end of the construction project. The diagnostic integration task will give special emphasis to planning for this development.

Opportunities for reuse of diagnostic equipment on NCSX will be considered on a case-by-case basis, weighing reliability and maintainability. As in other machines, the bulk of the costs associated with diagnostics are expended in providing the machine-specific interfaces and infrastructure, and therefore savings associated with component reuse are often relatively insignificant. Current planning assumes no reuse of equipment.

12.5 Opportunities for Collaborations in Diagnostics Development

Diagnostic instrumentation and analysis are specialist's fields, often reflecting the state of the art in physics understanding and technical capability. In addition, the operation of the NCSX device is not directly dependent on the operation of many of the diagnostics. An individual researcher at another institution installing a diagnostic on NCSX needs to know relatively few interface details to mount his diagnostic, and to contribute data quickly to the research program. If a collaborator is not at the site and his diagnostic fails, and is producing no data, other experiments can typically be scheduled to make productive use of the facility until the problem is resolved. Because of these and other factors, diagnostic development and operation is an area with many opportunities for collaborations.

As is the case on other collaborative programs, contributions of particular important measurements on NCSX will open doors of opportunity to the collaborating researcher for notable contributions to the physics of the device. These will typically be driven, in turn, by a wide array of operational, measurement, and analysis tools made available by the entire NCSX research team.