NCSX Engineering Design Document

Design Description
Diagnostic Systems (WBS 3)

NCSX CDR

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Table of Contents

Table of Figures

Tables

1 DESIGN REQUIREMENTS AND CONSTRAINTS

The diagnostic systems provide the detailed measurements of the plasma parameters that are critical to the research goals of NCSX. For example, the spatial profiles of electron temperature and density are fundamental inputs needed for nearly all of the envisioned research topics. These systems typically include state-of-the-art instrumentation detecting light or particles from the plasma or plasma facing components, and the supporting interface hardware that provides the required views. The requirements for measurements are derived from the NCSX research program. Table 1 lists the research topics in various phases of the program, along with the required plasma measurements which need to be added as the program advances in maturity. Also listed are the proposed diagnostic techniques added at each phase to make these measurements.

The diagnostics which are part of the NCSX Project are those needed to verify that the core device has met its engineering goals. These are the diagnostic systems listed in Phases 1 and 2 – the Initial Operation Phase and the Field Mapping Phase. However, it is important to consider the full complement of diagnostics needed for the research mission, in order to insure that the diagnostic implementation is consistent with the design of the core machine in the context of various technical constraints. Most of the conceptual design effort in the diagnostic area has addressed this important issue.

The most serious of the technical constraints are spatial constraints. Inside the vessel, for example, there is a gap with a minimum distance of 5 cm between the first wall of the PFCs and the inner vessel wall. Magnetic sensors and leads must fit in this gap along with the PFCs and associated supporting and heating hardware. Compact soft x-ray arrays for tomography must also be located in this gap. There are also various geometrical constraints between diagnostic sightlines, the vacuum vessel, and the PFCs. Another important spatial constraint, which affects the device as well as the diagnostic designs, is the requirement for manned, in-vessel access for installation and maintenance activities. These constraints appear workable in the current design.

Outside the vessel there are also spatial constraints affecting diagnostics. The gap between the outer vessel wall and the modular coils is very tight in some areas, and magnetic sensors may be needed in these areas. In order to achieve needed views, some diagnostics may require space within the cryostat boundary. Space on the platform and on the floor of the NCSX cell will be needed for a large number of diagnostic equipment racks and other diagnostic components. At this point in the design, it appears that these constraints can also be satisfied.

The most serious spatial constraints occur at the vacuum boundary. Diagnostic port extensions need to be positioned between modular coils and associated support structures at locations where they will not interfere with the TF coils or TF supports as they extend out through the cryostat. In the design of the core machine, diagnostic access was given a high priority, and there are several examples of how this consideration affected the design direction. The 18 TF coil design, which places the TF coils over the average toroidal position of the modular coils, resulted in better diagnostic access, relative to previous TF configurations. The vacuum vessel was modified to provide access for a Thomson scattering laser or compact DNB to the oblate plasma cross-section (v=1/2), to take advantage of the spreading of the flux surfaces at this location. A third example is the conformal cryostat, designed so that the outer panels are modular, and thus can be custom fitted to optimize diagnostic access.

Viewing concepts for a few diagnostics have been completed, and will be presented later in this section. The overall adequacy of diagnostic access is difficult to assess with confidence, until such concepts have been completed for the full diagnostic complement. This has not been done. Such assessments will require more detailed definition of the interface between the diagnostic port extensions and the PFCs. Similarly, more detailed definition of the interface between the port extensions and the cryostat are needed. These activities will be carried out during the preliminary design phase. From the first-order perspective of considering simply the number of ports, there are 75 port extensions of various sizes available for diagnostics on NCSX. Many of these ports are large enough to accommodate multiple diagnostics. Table 2 shows the proposed diagnostics and an estimate of the number of ports needed. At this level of consideration, port access appears adequate. Table 2 also lists other vacuum interface estimates, including the expectations regarding the number of windows/shutters, the numbers of electrical and mechanical vacuum feedthroughs, and the number of vacuum torus interface valves (TIVs).

Table 1 Research Topics, Essential Measurements, and Diagnostics Requirements

research topic	essential new measurements	new diagnostics
1. Initial Operation		
initiate plasma: exercise coil set	plasma current	plasma current Roqowskis
Ip >25 kA	conductivity	flux loops
checkout vacuum diagnostics	plasma position	saddle loops
checkout magnetic diagnostics	total stored energy	B-dot probes
initial wall conditioning		diamagnetic loop
	plasma/wall imaging	fast visible cameras
	line integrated density	1 mm interferometer
2. Field Line Mapping		
map flux surfaces	vacuum flux surfaces	e-beam probe
verify iota and QA	variable energy trace particles	fluorescent rod probe
		high dynamic range CCD
3. Initial Ohmic		
initial plasma control, plasma evolution control	electron density profiles	multichord FIR interf./ polarim.
global confinement & scaling, effect of 3D shaping	electron temperature profiles	Thomson scattering
density limit & mechanisms	radiated power profiles	core foil bolometer array
study of Te and ne profiles.	magetic axis position	compact SXR arrays
vertical stability	low (m,n) MHD (<100kHz)	
current-driven kink stability	flux surface topology	
effect of low-order rat. surf. on flux-surface topology	impurity species	visible spectrometer
initial study of effect of trim coils, both signs	impurity concentration	abs. UV spectroscopy
effect of contact location on plasma edge & recycling	Zeff	filtered 1D CCD camera
initial attempts to control plasma contact location	hydrogen recycling	visible filterscopes
4. Initial Aux. Heating		
plasma control with NB heating and CD		diagnostic neutral beam
test of kink & balooning stability at moderate beta	ion temperature profile	toroidal CHERS
effect of shaping on MHD stability	toroidal rotation profile	
initial study of Alfvenic modes w/ NB ions	poloidal rotation profile	poloidal CHERS
confinement scaling w/ iota, B, …	radial electric field	MSE polarimeter
local transport measurements, perturb. meas.	iota profile	
test of quasi-symmetry on confinement and transport	fast ion loss	fast ion loss probe
density limits and control with heating	ion energy distribution	neutral particle analyser
use of trim coils to minimize rotation damping	neutron flux	epithermal neutron detector
blip measurements of fast ion conf. and slowing down	first wall surface temperature	compact IR cameras
initial attempts to obtain enhance confinement regimes	high frequency MHD(<5Mhz)	high frequency Mirnov coils
pressure effects on surface quality		fast tang. x-ray pinhole camera
controlled study of neoclassical tearing using trim coils		enhanced x-ray tomography
wall coatings with aux. heating	SOL tmperature and density	moveable Langmuir probe
edge and exhaust charact. with aux. heating	neutral pressure	neutral pressure gauges
attempts to control wall neutral influx		
wall biasing effects on confinement		
5. Confinement & beta push		
stability tests at beta >~ 4%	edge/div. radiated power profile	divertor foil bolometer arrays
detailed study of beta limit scaling	divertor recycling	divertor filtered CCD cameras
detailed studies of beta limiting mechanisms	edge temp. and dens. prof.	fast scanning edge probe
disruption-free operating region at high beta	divertor target surface temp.	fast IR camera
active mapping of Alfvenic mode stability (with antenna)		divertor thermocouples
enh. conf.: H-mode, hot ion modes, RI mode, pellets	core helium density	He CHERS system (with DNB)
enhanced confinement, rotation effects	target Te, ne	plate mounted Langmuir probes
scaling of local transport and confinement	divertor impurity concentration	divertor UV spectroscopy
turbulence studies	core density fluct. amp. & spec	fluctuation diagnostics TBD
scaling of power or other thresholds for enh. conf.		
ICRF wave propagation and damping (possible)		
perturbative RF measurements of transport (possible)		
divertor operation optimized for power handling		
trace helium exhaust and confinement		
scaling of power to divertor		
control of high beta plasmas and their evolution		
6. Long Pulse		
long pulse plasma evolution control	more detailed divertor profiles	divertor Thomson scattering
equilibration of current profile		divertor diagnostics (TBD)
beta limits with ~ equilibrated profiles		
edge studies (3nd generation wall)		
long-pulse power and particle exhaust w/ div. pumping		
compatibility of high conf., high beta, and div. ops		

Table 2 Estimated Diagnostic Interfaces

DIAGNOSTIC	DESCRIPTION	WBS	CHAN	SPEED	PORT	WIND SHUT	ELEC FDTH	MECH FDTH	TIV	RACK
1. Initial Operation										
magnetics	100 sensors + integrators, etc	31	100	100 kHz	12		200			3
visible cameras	3 cameras (1 fast) with filters	361	3	frm grb	3	3		3		1
1 mm interferometer	with inner wall reflector	350	2	200 kHz	1	1		1		1
2. Field Mapping										
e-beam probe	retractable, radially scanning	38	4	10 kHz	1		6	2	1	0.5
fluorescent rod probe	retractable, pivoting	38	4	10 kHz	1		2	2	1	0.5
high dynamic range CCD	standard frame rate	38	2	frm grb	1	2		2		0.5
3. Ohmic										
Thomson scattering	ultimate 60 spatial ch., 100 Hz	351	100	500 MHz	2	2		2		4
multich. FIR interf./ polarim.	# chords, λ, geometry TBD	356	24	100 kHz	1	2		2		4
compact SXR arrays	3 arrays of 16 channels	341	48	200 kHz	1		48	3		1
core foil bolometer array	16 channel array	334	16	10 kHz	1		32	1		0.5
visible spectrometer	multichan., survey instrument	331	1	frm grb	1	1		1		1
abs. UV spectroscopy	vac. UV survey instrument	332	1	frm grb	1				1	1
filtered 1D CCD camera	single view	333	1	frm grb	1	1		1		0.5
visible filterscopes	several sightlines	335	6	100 khz	3	3		3		0.5
4. Initial Aux. Heating										
additional magnetics	add 50 varied sensors & integ.	31	50	100 kHz	6		100			2
diagnostic neutral beam	50 kV, 6 amps neutrals, 6 cm	352	10	10 kHz	1				1	3
MSE polarimeter	uses DNB, midplane view	353	20	10 kHz	1	1		1		2
toroidal CHERS	uses DNB, midplane view	354	2	frm grb	1	2		2		1
poloidal CHERS	uses DNB, vertical view	355	2	frm grb	2	2		2		1
enhanced x-ray tomography	additional 8 compact SXR arrays	341	128	200 kHz	3		128			2
fast tang. x-ray camera	uses unused beam port	343	1	frm grb	1			2	1	1
fast ion loss probe	geometry TBD	322	1	frm grb	1	1	10			1
neutral particle analyser	geometry TBD	321	50	50 kHz	1		?	?	1	2
epithermal neutron detector		323	1	10 kHz						0.5
high frequency Mirnov coils	6 larger TFTR style coils	342	6	5 MHz	3		12			0.5
compact IR camera	no periscope, standard speed	364	1	frm grb	2	2		2		0.5
neutral pressure gauges	midplane and banana tips	363	4	10 kHz	2		4			0.5
moveable Langmuir probe	moveable between shots	362	6	200 khz	1		8	2	1	1
5. Conf. and Beta Push										
divertor foil bol. arrays	2 crossed, 16 channel arrays	335	16	10 kHz	2		64	2		1
divertor filtered CCD camera	view TBD	338	1	frm grb	1	1		1		0.5
fast IR camera	needs periscope	365	1	frm grb	1	1		1		0.5
fast scanning edge probe	outer midplane, v = ?	367	6	100 kHz	1				1	2
He CHERS system	uses DNB	357	1	frm grb	1	1		1		1
plate Langmuir probes	array of fixed probes	366	10	.1 ms	1		32			2
divertor thermocouples	instrumented divertor tiles	368	30	1 Hz	3		64			1
divertor UV spectroscopy	dedicated divertor view	336	1	frm grb	1				1	1
fluctuation diagnostic	TBD	371	4	TBD	2	1		1		2
6. Long Pulse										
divertor Thomson scattering	100 Hz, 18 spatial ch.	369	30	500 MHz	2	2		2		3
divertor diagnostics	TBD		24	TBD	2		12			3
	total		**718**		**72**	**29**	**722**	**42**	**9**	**54**

In addition to the tight space constraints between diagnostics and other machine components, there are other technical constraints that are challenging. Many of the diagnostic systems will need re-entrant front-end components located near the plasma. These components may be subjected to large thermal excursions during bakeout or cryostat cool down. It is likely, in some cases, that diagnostic component cooling/heating will be needed. The lengths of the re-entrant front end may be considerable, and difficulties maintaining precise alignment will grow with increasing length. The magnetic field strength at the re-entrant front end could be large, since this location will be adjacent to modular coils. Thus, the design of the diagnostic front-end needs to be sensitive to eddy current forces.

A typical diagnostic system consists of several component parts. There is the front-end collection system, which may be a magnetic sensor, a particle collector, or a lens system collecting light from the plasma. This collector must be supported on a mount, which may need to accommodate adjustable alignment of the system. There is typically a relay system of fiber optic or copper cables that carry the signals from the collectors to the signal conditioning components, which are generally located in equipment racks near the machine, to avoid the noise and expense introduced by long relay cables. In the case of systems utilizing components sensitive to x-rays, gammas or neutrons, the signals may need to be optically relayed to areas just outside the cell shield wall.

Space needs to be reserved around the core machine for these racks. Table 2 gives an estimate for the number of racks required. The high-bay area currently planned for NCSX has adequate space for such racks, provided supporting subsystems that can be conveniently positioned further from the machine are so located. Currently, there are five rooms on the west side, adjacent to the outside of the radiation shield, reserved for diagnostic systems that are sensitive to radiation.

WBS 3 is responsible for the basic diagnostic system components. These include sensors, collection systems and associated support structures, sensor cables, and signal conditioning hardware and racks. There are several critical areas of diagnostic support which are the responsibility of other WBS elements. These tasks have been planned and budgeted in the WBS elements listed below, including both project and upgrade components:

- Port extensions and their interface with the vacuum vessel and cryostat - WBS 1
- Interface between port extensions and PFCs - WBS 1
- Junction boxes near the machine where sensor cables join field cables - WBS 4
- Field cables which join sensor cables to racks, and associated cable trays - WBS 4
- AC power to racks, rack grounding and isolation - WBS 4
- Modular data acquisition and control system, including timing and triggering, standard digitizers, control modules, and associated crates and computers, with software (nonstandard digitizers covered in WBS 3) - WBS 5
- Platform around machine - WBS 61
- Remote control of view port shutters for between shot GDC - WBS 231

An estimate of the projected number and speed of data acquisition channels, and the number of view port windows and shutters is also given in Table 2.

Each diagnostic system must be designed to satisfy specific measurement requirements. These requirements can be described in terms of the range of the plasma parameter being measured, the desired accuracy, and the spatial and temporal resolution required to permit the experimental investigation of the various research topics. Table 3 is a preliminary listing of such requirements. At this point, these requirements should be viewed as design goals for the diagnostics, and the values listed may evolve as more consideration is given in matching the measurement needs to the experimental program. Quantitative confirmation that these goals can be met in the case of a specific diagnostic will be part of the preliminary design for that diagnostic system.

Table 3 Preliminary Measurement Requirements

MEASUREMENT	RANGE	RESOLUTION		ACCURACY	DIAGNOSTIC TECHNIQUE
1. Initial Operation					
plasma current	1-400 kA	1 ms	integral	1% + 0.1KA	Rogowski coils
conductivity		1 ms	integral	1%	flux loops + Ip
plasma boundary position and shape	??	5 ms		2.0 cm on gap	magnetics + 3-D EFIT
total stored energy	10 kJ - 500 kJ	1 ms	integral	10 kJ	diamagnetic loop
visible image of plasma/wall	2 views	2 ms	0.5 cm		video cameras with optional filters
fast visible image of plasma/wall	1 view	0.1 ms	2 cm		fast video camera
line integrated density	1018 -5x1020 m-2	1 ms	integral	5-10%	1 mm interferometer
2. Field Mapping					
vacuum flux surfaces	v = ? plane	10 ms	0.2 cm	0.2 cm	e-beam probe + fluorescent rod/screen probe + high dyn. range CCD camera
3. Ohmic					
core electron density profile	5xl0l8-5xl02O m-3 with inversion	.01 ms	10-15 cm with inv.	1 fringe	multichord FIR interferometer/ polarimeter
core electron temperature profile	0.05-3.0 keV full profile	10 ms	1 cm	5%	Thomson scattering
core electron density profile	5xl0l8-5xl02O m-3	10 ms	2 cm	5%	Thomson scattering
core radiated power profile	0-30 w/cm3 with inversion	1 ms	integral	15%	core foil bolometer array
low (m,n) MHD modes, ST, disrupt.		100 kHz	3 cm with inv?	10%	multiple compact SXR arrays
magnetic axis position	v = 0 plane	.01 ms		1.0 cm	comp. SXR arrays + 3-D EFIT
magnetic axis position	v = 1/2 plane	.01 ms		1.0 cm	Thomson scattering
impurity identification	200 - 1000 nm	1 ms	integral	0.1 nm	visible spectrometer
impurity concentration	10 - 150 nm	5 ms	integral	0.1 nm	abs. UV spectroscopy
Zeff profile	1-10	5 ms	3 cm with inversion	20%	use Thomson scattering system
hydrogen recycling	several sightlines	1 ms	integral	10%	filtered 1D CCD camera
4. Initial Aux. Heating					
magnetic axis position	v = 1/2 plane	5 ms		2.0 cm	DNB + MSE polarimeter + 3-D EFIT
higher (m,n) MHD modes		100 kHz		10%	additional multiple compact SXR arrays
flux surface topology		2 ms		5%	tangential, 2-D, x-ray pinhole camera + 3-D EFIT
ion temperature profile	0.1-3 keV	5 ms	2 cm	5%	DNB + toroidal CHERS
toroidal rotation profile	10 - 200 km/sec	5 ms	2 cm	5%	DNB + toroidal CHERS
poloidal rotation profile	10 - 200 km/sec	5 ms	5 cm	10%	DNB + poloidal CHERS
iota profile	0.1 - 1.0	5 ms	2 cm	5%	DNB + MSE polarimeter + 3-D EFIT
fast ion loss	.01 -10 mA/cm2	0.1 ms	integral	20%	fast ion loss probe
ion energy distribution	5-100 keV	0.1 ms	integral	5%	netral particle analyser
neutron flux		0.1 ms	integral	10%	epithermal neutron detector
high frequency MHD(<5Mhz)		5 MHz		5%	high frequency Mirnov coils
first wall surface temperature	20° C - 3000° C	30 ms	1 cm	1%	compact IR camera
SOL electron temp. and density	0.5-100 eV 5xl0l7-5xl019 m-3	.1 ms	0.5 cm	10%	moveable Langmuir probe
edge neutral pressure	0 - 10 mtorr	10 ms		5%	gauges at midplane and banana tips
5. Conf. & Beta Push					
divertor radiated power profile	0-100 w/cm3 with inversion	1 ms	integral	15%	divertor foil bolometer arrays
divertor plate temperature	20° C - 3000° C	1 ms	0.5 cm	1%	fast IR camera
core density fluctuation amplitude	dn/n > 10-4	100 kHz	2 cm	10%	fluctuation diagnostic TBD
edge electron density and temp. profiles	outer midplane	.1 ms	0.5 cm	10%	fast scanning edge probe
core helium density	(10-1 - 10-4) ne	5 ms	2 cm	20%	DNB + He CHERS system
divertor target surface temperature	20° C - 3000° C	1 sec	5 cm	1%	divertor thermocouples
target Te, ne	1 - 100 eV 1xl0l9-1xl021 m-3	.1 ms	2 cm	10%	plate mounted Langmuir probes
divertor recycling	2-D imaging	30 ms	0.5 cm	10%	divetor filtered CCD camera
divertor impurity conc., flows	200 - 1000 nm	1 ms	integral	0.1 nm	divertor UV spectroscopy
6. Long Pulse					
divertor electron temp. profiles	1.0-300 eV profile	10 ms	0.5 cm	5%	divertor Thomson scattering
divertor electron density profiles	1xl0l8-5xl02O m-3 profile	10 ms	0.5 cm	5%	divertor Thomson scattering

2 DESIGN DESCRIPTION AND PERFORMANCE

This section contains more details on the design elements for the diagnostics for Phases 1 and 2, which are funded as part of the NCSX Fabrication Project. A similar short description will be given for certain critical diagnostics in Phases 3 and 4 that will be funded under the NCSX Program. Optimizing the integration of these critical diagnostics may require modifications in the design of the vacuum vessel and/or the port extensions.

Diagnostic Integration - As the preliminary design of the core machine continues, it is important to continue the integration of diagnostics into the device with higher levels of definition. For example, developing sightline concepts for the full array of planned diagnostics may point to the need for slight modifications in the diagnostic port extensions. Another example is the further definition of space needs for in-vessel sensors, and the integration of these sensors into the PFCs and associated support structures. The allocation of port space between diagnostics and other auxiliary systems is another important part of this integration effort.

Magnetics - The magnetic sensors include diamagnetic loops, 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 diagnostic 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 electrical feedthrough. The signal is transmitted via field cables a junction box and then to an integrator, and finally to a digitizer to provide flux versus 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.

There is little experience with feedback control of the evolution of a 3-D stellarator plasma. As part of the preliminary design, detailed modeling is planned to ascertain the optimum number, type, and placement of the sensors needed for equilibrium reconstruction and control. The computational tools development needed to perform this analysis will be funded by the NCSX program, collaborating with other stellarator groups and building on existing tools. Rough estimates indicate that approximately 100 sensors of several different types will be required initially.

Visible Cameras - Visible cameras will be used initially to view the plasma with three reentrant, wide-angle views. The cameras will be moderately fast with a full frame rate of at least 1 kHz 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 cameras will be located outside of the cryostat and will view the images through an interference filter. The viewing lenses and fiber bundles may need cooling to protect them during bakeout. A PC with frame grabber will be used to control the cameras, and to capture and store the data.

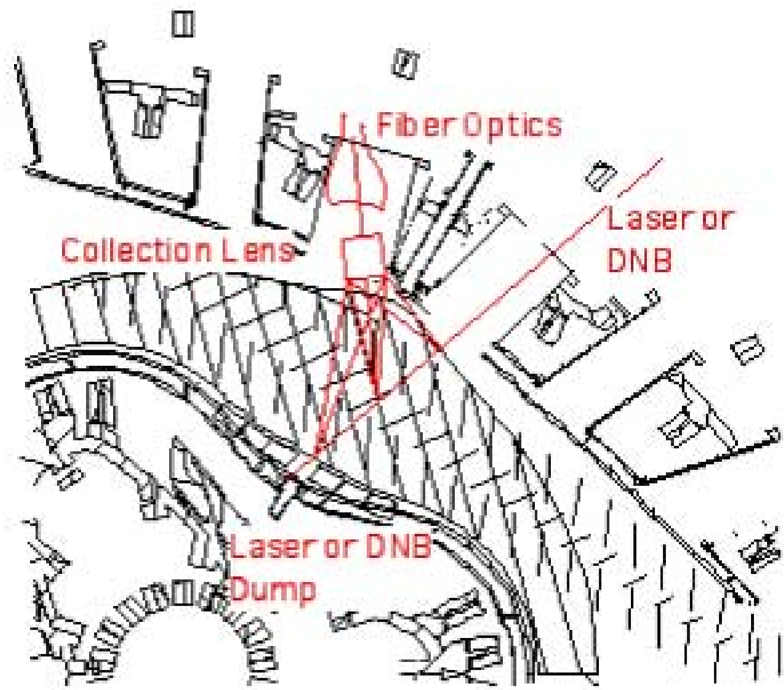
1 mm Interferometer - An interferometer will be used to monitor the line density on a single line of sight through the core of the plasma during the initial plasma run. A low cost, uncompensated 1 mm microwave system is under consideration, with solid state source and mixer, similar to systems currently 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. In the long term plan, this diagnostic is intended to provide a normalization to the density profile determined by Thomson scattering, and therefore the beam path needs a geometry that matches the laser beam.

Field Mapping - 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 an array of phosphor-coated fiber optics as it repeatedly transits the device. The light from the strike points will be collected by the vacuum-compatible optical fibers and relayed to a fast readout, high dynamic range CCD camera. Careful metrology will reference the array 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 at reference vacuum configurations. In later phases, the influence of trim coil currents will be assessed.

The following short concept descriptions are for diagnostic systems that are not part of the NCSX project, however, they are included because access compatibility issues will likely influence the design of the core device, particularly the details of the port extensions.

Thomson Scattering - Because of the moderate density and relatively low magnetic field on NCSX, it will not be possible to use conventional ECE techniques for measuring $T_e(R,t)$. Thus Thomson scattering will be a key diagnostic, providing both $T_e(R,t)$ and $n_e(R,t)$. The current concept for this diagnostic uses a Nd:YAG laser system with a laser repetition rate of 100 Hz (possibly using 2-50 Hz lasers). Twenty filter polychromators will be used with 4 spectral channels each. Light from 3 positions in the plasma will be relayed via 3 different fiber optic bundle lengths to each polychromator. Fast transient recorders (4x20 = 80 channels at 1 Gs/s) will resolve the three time-multiplexed signals from the APD detectors. In this way a 60 point spatial profile will be recorded for each laser pulse, with a spatial resolution of ~ 1 cm. In the current concept, the laser is fired near radially at the midplane of the v=1/2 plane to a dump on the inner wall, as shown in Figure 1.

Figure 1 Concept for Viewing Geometry for Thomson Scattering (using laser) and Active Spectroscopy (using diagnostic neutral beam)

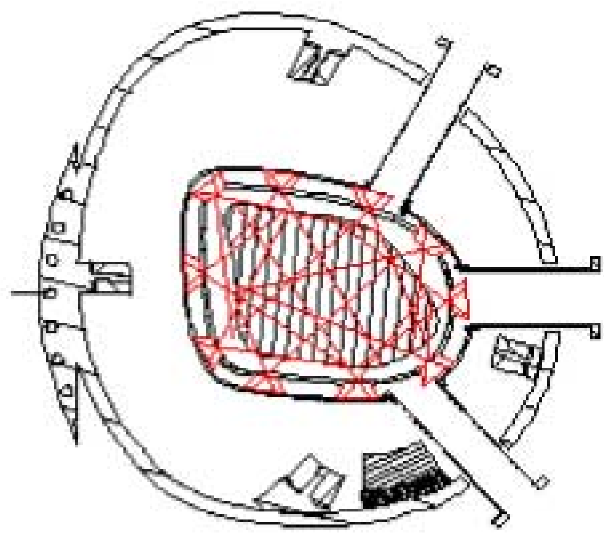


Active Spectroscopy - The NCSX heating beams inject nearly parallel to flux surfaces. Because of the large beam cross-section, this means that viewing the intersection of the beam with the core plasma region from any position results in sightlines that cross many flux surfaces, and hence poor spatial resolution. In principal, information from many views from different angles could be inverted to regain localization, this would be very difficult in the 3-D geometry of NCSX.

A diagnostic neutral beam (DNB) with a compact cross-section, injected as shown in Fig. 2.3.2.1, could be used for profile measurements of T_I and v_ϕ with a CHERS system viewing carbon charge exchange emission and an iota with a MSE polarimeter system viewing D_{α} emission. Ideally such a beam would have an energy of 50 keV/amu, a neutral current > 50 mA/cm^2, a diameter of < 6 cm, and a pulse length of ~ 500 msec.

Compact Soft X-Ray Arrays - X-ray tomography using a large number of sightlines in multiple fan arrays is a powerful technique for investigating MHD mode structure, and thereby the topology of equilibrium flux surfaces. Such arrays have been used on both tokamaks and stellarators, typically with extensive coverage in one or two poloidal cross-sections. In order to achieve such coverage on NCSX, it will be necessary to install compact arrays inside the vacuum vessel, between the first wall and the vacuum vessel. One example of such an implementation is shown in Figure 2.

Figure 2 Viewing Concept for Compact In-vessel Soft X-ray Arrays



Currently, there is not a design available for the array module that is compact enough to fit within the 50 mm space constraint between the first wall and the inner vacuum vessel wall. It may be necessary to enlarge the vessel in this region to accommodate realistic SXR array sizes. Using available technology, a minimum clearance of ~ 110 mm would be needed. It would be preferable to do this in a section near the oblate cross-section (v=1/2) such as that in Figure 2, to take advantage of the larger absolute island sizes at this location.

3 DESIGN BASIS

There are two distinct components of the diagnostics design. The first is the diagnostic implementation plan. The basis for this plan is past experience on similar scale devices such as NSTX. It was assumed that the range of research topics and the pace of the research will be similar to that on NSTX, and that, compared to that machine, a similar number of diagnostics of similar complexity will be needed for NCSX.

The second design component is the collection of concepts for specific diagnostics. For some diagnostics in the Project, like visible cameras and 1 mm interferometer, the concepts are straightforward extensions of past experience on machines like NSTX. However, in other cases, such as magnetics and field mapping, the NCSX requirements dictate development of new tools or new techniques.

In the case of magnetics, we assume that the sensor types are similar to those currently in use on other fusion devices. However, selection of the optimum sensor types and optimum locations will be done in the preliminary design phase using numerical optimization techniques based on calculations of 3-D equilibria and their interactions feedback systems actuating model coil sets. Space constraints, temperature constraints, vacuum material constraints and signal processing needs for the magnetic diagnostics should not, however, be strongly affected by this optimization.

The field mapping effort is also in need of further definition of design requirements, before engineering concepts have a firm basis. More work is needed to model the vacuum configurations to be probed, the necessity of probing more than one toroidal position in the field period, the necessity of probing evolving vacuum configurations, and the necessity of diagnosing configurations with cryogens in the coils. At this stage, we assume that a spatial resolution requirement of a few mm over the full cross-section at one toroidal position, with a time resolution of 30 msec. This represents a significant increase in both spatial and temporal resolution over previous systems. We also assume that a vacuum vent will not be needed to deploy this diagnostic.

4 DESIGN IMPLEMENTATION

Implementation of the designs for diagnostics is a straightforward extension of capability at PPPL and in the broader US fusion community. As is the case on NSTX, participation by the broader community in diagnosing this device is an essential part of the NCSX program. The organizational structure and funding process forthese diagnostic collaborations is not yet defined.

The diagnostic plan assumes that new diagnostic components will be procured or fabricated. Plasma diagnostic instrumentation benefits greatly from rapidly evolving sensor and data acquisition technologies. Diagnostic designs should seek to take advantage of the progress toward more sensitive, compact measurement devices.

In most cases, diagnostic system components will be assembled and tested on a laboratory bench prior to assembly on NCSX. For example, a magnetic pickup coil will be wound, have leads attached, be vacuum prepped, and be tested in the lab, before delivery for field installation. Optical systems will also be pre-assembled and characterized prior to installation on the machine. Once installed, diagnostic components typically will have more tests done. For magnetics, this might include resistance and polarity tests. For optical diagnostics this would include alignments and calibrations, as well as shutter tests. Alignments will likely involve the use of a measurement arm or laser ranger, to locate sightlines relative to machine benchmarks. Manned entry into the vessel will be necessary for a variety of diagnostic installation and maintenance tasks.

5 RELIABILITY, MAINTAINABILITY, AND SAFETY

The requirements for diagnostic reliability and redundancy vary according to the impact of failure. For example, an in-vessel sensor or a shutter needs to be more reliable than a component external to the cryostat, since repair of in-vessel components would involve venting the vessel, or worse, vessel manned entry. Ex-cryostat repairs could be accomplished when the Test Cell is next available for entry. Access for ex-vessel repairs for magnetic sensors located between the vessel and the modular coils will be very difficult once the machine is assembled, and therefore high reliability and redundancy will be designed into these components.

The three most common hazards faced in installing and operating diagnostic systems are fall hazards, high voltage hazards, and laser eye hazards. Diagnostic designs will include engineered safeguards to minimize these and other hazards.

6 COST, SCHEDULE, AND RISK MANAGEMENT

Table 4 is a summary of estimated costs for the diagnostic activities in the NCSX Fabrication Project. The total cost is estimated to be $2425K in year of expenditure dollars with an overall contingency of 28.8%.

The cost for Magnetic Diagnostics (WBS 31) is $880K. Cost drivers for the magnetics task include the:

- large number of sensors (~ 100),
- need to modify existing custom designs for the high temperature, vacuum compatible sensors,
- need to design mounts for many unique geometries with differing spatial constraints,
- careful documentation of sensor location and wiring, and
- fabrication of large number of integrators.

Existing designs for sensors in machines like NSTX can likely be modified, assuming space constraints do not become more severe. There is some possibility that some sensor development may be needed. The results of the planned optimization of sensor number, type, and location are not in hand. Largely for the latter reason, a sizable contingency is justified for this activity.

The cost of Edge and Divertor Diagnostics (WBS 36) is $296K. This cost element includes visible cameras. The visible camera job covers the work needed for three re-entrant, shuttered, wide-angle views. It also includes three re-entrant, cooled optical heads with lenses, coherent fiber bundles, fast framing CCD cameras with magnetic shielding, and control electronics and PCs. Contingency is justified because of the technical risk in the reentrant views and optical assemblies and because this is a top-down estimate.

The cost of Profile Diagnostics (WBS 35) is $210K. This cost element includes a 1 mm interferometer. It is classified as a profile diagnostic, because, in the long term, it will be used to normalize density profiles measured with Thomson scattering. The 1 mm interferometer task involves the design and construction of the window with shutter, a reflector on the inside wall, procurement of various microwave components, including a source, and the beam optics and associated stable support structure. Contingency for this top-down estimate is based on the expectation that existing concepts can be adapted for this system, with some uncertainty in the difficulty of providing a stable support structure.

The cost of Electron Beam (EB) Mapping Diagnostics (WBS 38) is $524K. Concepts are being explored which could offer considerable enhancements over past approaches, improving spatial and temporal resolution. Design requirements are not fully defined. Some development and prototyping is probably needed. A large contingency is justified at this early stage of concept development.

The cost of Diagnostics Integration (WBS 39) is $514K. This cost is a top-down estimate based on experience at PPPL with diagnostics for similar scale devices in the tokamak and ST configuration. The main responsibility is to interact with machine designers to facilitate diagnostic access adequate to carry out the research mission of NCSX. The contingency is based on the fact that we have little direct experience with stellarators, with cryostat interfacing, or with highly re-entrant assemblies. Also we expect that the preliminary measurement requirements listed in Table 3 will evolve during the machine design.

Table 4 Diagnostics Systems (WBS 3) Costs

Total Estimated Cost (K$)							3 Total
		31 Total	35 Total	36 Total	38 Total	39 Total	
Manufacturing Development	Labor/Other						
	M&S						
	Total						
Design (Title I & II)	Labor/Other	225	69	90	168	514	1066
	M&S						
	Total	225	69	90	168	514	1066
Fabrication/Assembly (incl Title III)	Labor/Other	359	99	117	174		750
	M&S	296	43	89	182		609
	Total	655	142	206	356		1359
Installation/test	Labor/Other						
	M&S						
	Total						
Grand Total		880	210	296	524	514	2425

The schedule for implementing the Diagnostic Systems (WBS 3) may be seen in the **Project Master Schedule**, provided as part of the Conceptual Design Report**.** Title II for diagnostic systems will generally be completed in FY06. Fabrication, installation, and testing will occur in parallel with machine assembly during the nine months preceding first plasma in mid-FY07.

Most of the diagnostics are not part of the Fabrication Project and will be installed after first plasma in time for when they are needed in the experimental program. The strategy for scheduling diagnostic implementation begins with basic monitoring of global quantities and impurities and local measurements of n_e and T_e during the Ohmic Phase. In the Initial Auxiliary Heating Phase, more detailed profile information for T_i, v_ϕ , and iota will become available. Diagnostics for measuring MHD activity, fast ion behavior, and edge and divertor characteristics will see a steady improvement in capability. Core turbulence measurements become available toward the end of the proposed plan. Table 5 shows an implementation spread over many years of roughly level funding for diagnostics upgrades, currently estimated at ~$2.5M/yr.

Diagnostic Systems are composed of many individual diagnostics. Technical, cost, and schedule risks are minimized by:

- Providing a large number of ports with areas and view angles appropriate for measurement requirements,
- Locating diagnostics where they can be readily accessed,
- Providing high reliability and redundant measurements for diagnostics that cannot be readily accessed,
- Providing diagnostics integration concurrently with the design of the stellarator core (in some cases, long before the preliminary design of the individual diagnostic needs to be initiated),
- Applying diagnostic designs already proven on other machines,
- Drawing on the capabilities of the whole US fusion community instead of just PPPL/ORNL,
- Staging the diagnostics implementation to benefit from rapidly evolving sensor and data acquisition technologies, and
- Assembling and testing diagnostic components prior to installation on NCSX.

Table 5 Preliminary Diagnostic Implementation Plan

DIAGNOSTIC	03	04	05	06	07	08	09	10	11	12
diagnostic integration	.05	.25	.30	.30	.10					
1. Initial Operation										
magnetics	.05	.05	.05	.40	.45					
1 mm interferometer				.70	.30					
visible cameras				.70	.30					
2. Field Mapping										
e-beam mapping			.05	.60	.35					
3. Ohmic										
Thomson scattering				.35	.20	.20	.25			
multich. FIR interf./ polarim.				.10	.60	.30				
compact SXR arrays				.40	.40	.20				
core foil bolometer array					.50	.50				
visible spectrometer				.30	.30	.40				
abs. UV spectroscopy				.30	.30	.40				
filtered 1D CCD camera				.30	.30	.40				
visible filterscopes				.30	.70					
4. Initial Aux. Heating										
additional magnetics						.50	.50			
diagnostic neutral beam				.10	.60	.30				
MSE polarimeter						.10	.60	.30		
toroidal CHERS				.10	.60	.30				
poloidal CHERS						.10	.60	.30		
enhanced x-ray tomography						.50	.50			
fast tang. x-ray camera								.50	.50	
fast ion loss probe								.60	.40	
neutral particle analyser							.10	.60	.30	
epithermal neutron detector							1.00			
high frequency Mirnov coils							1.00			
compact IR camera								.50	.50	
neutral pressure gauges							1.00			
moveable Langmuir probe								.50	.50	
5. Conf. and Beta Push										
divertor foil bol. arrays								.50	.50	
divertor filtered CCD camera								.50	.50	
fast IR camera								1.00		
fast scanning edge probe									.50	.50
He CHERS system									.50	.50
plate mount Langmuir probes									.50	.50
divertor thermocouples									.50	.50
divertor UV spectroscopy									.50	.50
fluctuation diagnostic									.30	.70
6. Long Pulse										
divertor Thomson scattering									.20	.80