XI. DIAGNOSTICS

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The primary mission of the BPX is to study the physics of D-T burning plasmas, that is, discharges in which most or all of the power arises from fusion alpha particles. To assess the physical processes involved in this unique set of conditions, it will be necessary to measure not only the standard plasma parameters, density, temperature, magnetohydrodynamic (MHD) phenomena, impurity concentrations and transport, magnetic properties, and fluctuation activity, but also a new set of phenomena associated with the behavior of the alpha particles themselves. In particular, we want information about the alpha–particle birth rate, the prompt alpha loss rate, transport and slowing down of the confined alphas, and on the buildup or exhaust of the thermalized alpha "ash." The effects of the alpha population on the background plasma, including Alfvén modes and alpha-driven sawteeth, will need to be measured. In addition, we require diagnostics suitable for assessing the performance of the radio-frequency (RF) heating and for the unique divertor design where the thermal load is spread over the divertor plate surfaces by slow movement of the separatrix.

The measurement capabilities for plasma control, confinement physics, fluctuation/wave activity, divertor/edge plasmas, and fusion product measurements required to accomplish the BPX mission are given in the BPX General Requirements Document. A preliminary list of diagnostic techniques to provide this measurement capability is given in Table 11.1. Information is presented below on the types of measurements as well as the range, resolution, accuracy, and so forth that have been adopted as guidelines for the design of the diagnostics, which are described in more detail in the BPX Diagnostics Systems Description Document. There is, of course, some overlap since some measurement methods give information on several plasma quantities, and some quantities can be measured by different methods. The detailed requirements, given in Tables 11.2 through 11.12 in terms of the principal plasma parameters to be measured, will be useful to establish the diagnostic requirements for BPX. These values derive partly from operational experience of the diagnostic experts and partly from specification by the physics group, and may require considerable iteration during the course of the BPX design.

A plan view of the BPX cell is given in Fig. 11.1, showing the diagnostics that require significant floor space. These include the infrared interferometer (bay A), diagnostic neutral beam (bay B), ultraviolet survey spectrometer (bay I), X-ray crystal spectrometer and X-ray photometer (bay J), and Thomson scattering (bay K). Space is allocated on three sides around the perimeter of the experimental cells for instrumentation, electronics, computer workstations, and other facilities that are required to support operation of the diagnostic systems. In addition, the basement area beneath the machine (not shown) contains several diagnostics, including spectrometers and collimator arrays for neutron and gamma diagnostics.

The most severe constraints on the diagnostic systems for BPX are imposed by the high-radiation environment that is inherent in the mission of the device. The impact of the radiation environment on the diagnostic systems occurs at several levels. First, the transient interaction of the neutron and gamma flux with optical or electronic components can lead to spurious signals or noise, which, if not considered in the design, could contaminate the data or render the diagnostic useless during the tokamak pulse. Second, the cumulative dose can cause permanent degradation or damage to diagnostics components, leading to changes in calibration or system failure. Third, catastophic failure may occur in extreme cases, for example, shattering of an optical window leading to loss of tokamak vacuum. An extensive diagnostic R&D program that has been developed to address these issues is described in the Diagnostic Systems Description Document.

Additional diagnostic constraints arise from the small number of full–field discharges (3000) envisioned for the operation. The latter situation dictates that a maximum amount of information be obtained on each shot, including spatial profiles and temporal evolution of relevant quantities. The BPX design provides diagnostic and heating access with twelve 46 cm × 102 cm horizontal ports, thirty-six smaller, circular horizontal ports (10.2- and 17.8-cm diameters), and twelve sets of "obround" ports (44 cm long by 6 to 17 cm wide). Nevertheless, the available port access restricts the number of diagnostics that can be employed at a given time, and therefore, a prudent selection of diagnostic redundancy in determination of any given parameter is required. Such redundancy is typically found to be valuable in tokamak experiments because different physical processes are often involved in the measurements being compared. Spurious effects can occasionally render a single measurement unreliable, for example, when a mildly nonthermal distribution function affects the apparent electron temperarture determined by cyclotron emission, or when a high local density (MARFE) influences or prevents the determination of integrated density by interferometry. Cross checking of data may be of particular importance in the case of BPX where some uncertainty in calibration due to radiation effects can be expected, and phenomena not previously encountered in tokamak operation may introduce spurious results or interference with standard diagnostics.

To compensate for the above constraints on BPX diagnostics, the approach adopted for the development of diagnostics incorporates certain general requirements. First, proven methods will be used where possible, and the diagnostics must be fully tested prior to installation, including fabrication of mockups to validate compliance with remote handling needs. As mentioned earlier, an extensive R&D program has been developed to address "unproven" diagnostic issues. All diagnostics will be installed and commissioned prior to significant activation of the machine, so that hands-on modifications can be carried out. An exception to this guideline is envisioned for certain fusion product diagnostics that require significant D-D or D-T operation for proper checkout. Modifications or replacement of diagnostics after significant activation has occurred must be done by remote-handling equipment.

As discussed in Chap. XII, the operation of BPX may be considered to consist of a preburn phase and a burning plasma phase. The object of the preliminary preburn phase of operation will be to qualify the tokamak subsystems, including diagnostics, and verify the physics necessary to ensure efficient exploration of the burning plasma regime. Qualification of operating procedures, such as current rampup, position and shape control, fueling and particle control, etc., will require monitoring of profile information, MHD activity, impurity transport, edge plasma parameters, pellet penetration and ablation rate, and extensive heat load measurements, which may not be possible in later operation. Determination of divertor performance will entail the use of specific edge plasma and divertor region diagnostics, including spectroscopic and perhaps probe measurements of impurity and neutral behavior.

Verification of the confinement physics is an essential aspect of the preburn operating program. For this purpose, detailed measurements of plasma profiles and power deposition will be required. In addition, measurements of fluctuation spectra, MHD activity, etc., will be important in understanding, and perhaps modifying, the observed transport. The same sort of information will be required to study the analogous physical processes under alpha heating, so virtually all of the same diagnostic systems must operate during the burning plasma phase as well.

During the main portions of the operation, devoted to burning plasma studies, the parameters of primary interest will be associated with the alpha–particle effects. Diagnostics that measure properties of the alpha particles themselves can be tested on nonburning plasma either by looking at low-Q driven D-T discharges or by use of ICRF to generate high–energy ^{3}He populations. These diagnostics will have to be on–line and tested prior to full D-T operation. The study of transport effects in alpha–heated plasmas represents a major portion of the program. The data required for evaluation of the transport consists of profiles of the plasma energy and particle content, together with characterization of the relevant sources, including the alpha-particle birth rate, losses, and slowing down. Determination of the underlying physics will require capability for measuring microturbulence and MHD activity, as well as the ability to conduct scaling studies and parameter scans.

TABLE 11.1

BPX PRELIMINARY DIAGNOSTIC LIST

Parameter	Technique	Applica-bility	Comments/Issues
Plasma position and shape Current and total energy content	Magnetics	√	Need to establish that suitable materials are available.
Electron Density Profiles	Transmission Interferometry	√	Partial profile due to limited access. Horizontal system needs wall mirrors.
	Thomson Scattering	√	Midplane LIDAR system proposed. Powerful and accurate technique but requires development of radiation resistant windows and mirrors. For density measurement absolute calibration is also required.
	Reflectometry	√	Concern is whether the density profile can be measured routinely in the presence of cut-offs and density fluctuations.
Electron Temperature Profiles	Thomson Scattering	√	See above.
	Electron Cyclotron Emission	√	Limitations can arise from harmonic overlap and interference from non-thermal emission.
Ion Temperature Profiles	Neutral Particle	x	Edge measurement due to high density. Requires the development of detectors compatible with intense neutron irradiation and high energy diagnostic neutral beams.
	X-Ray Crystal Spectroscopy	√	Requires development of radiation resistant crystals and may require high Z seeding of plasma.
	Charge Exchange Recombination Spectroscopy	√	Requires development of radiation optical components, fibres etc., and high energy diagnostic neutral beams.
	Neutron Diagnostics	√	Suitable calibration methods and neutron spectrometers need further development
Radiated Power	Bolometry	*	Requires development of radiation resistant bolometer and demands wide angle of view

√ Probably applicable after suitable development
* Needs extensive development
x Unlikely to be applicable

BPX PRELIMINARY DIAGNOSTIC LIST

Parameter	Technique	Applica-bility	Comments/Issues
Impurity Identification and Densities	Visible and Near UV Spectroscopy	√	Development of radiation resistant optical components (windows, mirrors, light-guides) required.
	VUV Spectroscopy	√	See above
	X-Ray Spectroscopy	*	See above
	Visible Bremmsstrahlung	√	See above. Tangential view is highly desirable, but difficult due to port access.
	Visible Filterscopes	√	See above
Fluctuations and MHD Instabilities	Magnetics	√	Mirnov loops, lock-mode coils
	Soft X-ray	x	Detector survival is the major problem.
	Neutrons	√	Probably shares neutron collimator.
	Electron Cyclotron Emission	√	Grating polychromator is most suitable for high frequencies (>100 kHz)
	Reflectometry	√	See above.
	Milli-meter Wave Scattering	*	Requires development of ~200 GHz, high power sources.
Edge Plasma Divertor and First Wall	Langmuir Probes	*	Design must be integrated with first-wall structure.
	ECE	√	Range of plasma conditions is likely to be limited.
	Reflectometry	√	Should provide information on density fluctuations but measurements of density profile are uncertain.
	Visible Spectroscopy	*	Needs radiation-hardened components.
	Plasma/IR Imaging	√	Radiation resistant reflective optics are required.
	Edge Probes	√	Should be possible but with limited diagnostic capability.

√ Probably applicable after suitable development
* Needs extensive development
x Unlikely to be applicable

BPX PRELIMINARY DIAGNOSTIC LIST

Parameter	Technique	Applica-bility	Comments/Issues
	Faraday Rotation	√	Measurement of current density on axis may be possible: limited number of sight-lines.
	Thomson Scattering	*	Very difficult due to available port access.
Plasma Current Density	Zeeman Splitting Spectrograph/ Lithium Pellet	*	Yet to be demonstrated, requires pellet injector development and visible optics.
	Motional Stark Effect	*	Requires hydrogen beam (~800 keV)
Neutrons and Fusion Products	Neutron Flux	√	Development work is required on calibration of epithermal neutron detectors.
	Neutron Collimator	√	Development work is required on calibration and detectors.
	Neutron Activation	√	Need to select isotopes with long half-life and develop methods of calibration.
	Fusion Gamma	√	Shares neutron collimator.
Alpha Source	Neutron Collimator	√	See above.
Escaping Alphas	Particle Detector	*	Requires development of radiation hard detectors compatible with thermal environment.
Confined Alphas	Collective Thomson Scattering	*	R&D development required. Needs source at $\lambda \sim 200\ \mu m$.
	Carbon Pellets	*	R&D development required.
	Charge Exchange Recombination Spectroscopy	*	Requires high energy He diagnostic neutral beam.
	Hard X-ray monitors	√	Mounted on center cell walls.
	Vacuum gauges	√	Need fast gauges in divertor throat region
Miscellaneous	Residual Gas Analyzer	√	Redundant systems required.
	Glow Discharge Probes	√	Multiple locations.

√ Probably applicable after suitable development
* Needs extensive development
x Unlikely to be applicable

Table 11.2. Plasma Position and Shape

Position/Shape	Time Resolution	Rate of Change	Accuracy
R_{in}, R_{out}	1 ms (10 to 100 μs)*	100 cm/s	0.5 cm (5 to 10 cm)*
R_x, Z_x	1 ms (10 to 100 μs)*	100 cm/s	0.5 cm (5 to 10 cm)*
Z_c	1 ms (10 to 100 μs)*	100 cm/s	0.25 cm (5 to 10 cm)*

* For disruptions and other fast phenomena.

Here, R_{in} and R_{out} are the midplane positions of the inboard and outboard separatrix, respectively; R_x and Z_x are coordinates of the X-points, and Z_c is the vertical shift of the plasma center. The plasma position and shape measurements will be used in the control of the plasma equilibrium using the relevant poloidal field coils. The accuracy specification above is for absolute position. Relative position should be known on the slow time scale to much better accuracy. The overall shape of the outermost closed flux surface must be known to ± 1 cm at all points. The measurements will be made using a variety of magnetic probes. Infrared views of divertor plate surface temperatures, divertor thermocouples and neutron camera will also give data about up-down asymmetry.

Table 11.3. Plasma Current

Current Range	Time Resolution	Rate of Change	Accuracy
0.1 to 11.8 MA	1 ms†	5×10^6 A $\cdot$ s^{-1}	1%
	10 to 100 μs*	$< 4 \times 10^9$ A $\cdot$ s^{-1} *	~ 30%

† For normal operation.
* At current quench at a disruption.

The total plasma current measurement will be done by Rogowski coils and will be used in the feedback control. The halo currents that flow to the first-wall tiles during a disruption will be measured by instrumenting selected support members with Rogowski coils. The vacuum vessel currents will be measured as well using external Rogowski loops.

Table 11.4. Displaced Toroidal Flux (Plasma Beta)

Beta Range	Time Resolution	Sensitivity	Accuracy
$0.01 < \beta_p < 3$	1 ms 10 μs*	1 mWb $\cdot$ s^{-1}	1 part in 10^5

* At thermal quench of a disruption, edge-localized modes, and other fast events.

Beta will be measured by diamagnetic loop and derived from kinetic measurements.

Table 11.5. Electron Density

	Density Range	Spatial Resolution	Time Resolution	Accuracy
Core	1×10^{19} to 1×10^{21} m^{-3}	2 cm	1 ms	10%
Edge*	1×10^{17} to 3×10^{20} m^{-3}	3 mm	1 ms	10%
Divertor†	1×10^{19} to 1×10^{21} m^{-3}	1 cm	10 ms	10%

* Also applies to the X-point.

† Adjusted for a 14:1 expansion from the edge scrape-off layer (scrape-off width ~5 mm) to the divertor plate.

The line integral density will be used for the control of the fueling; it is also probable that a density profile measurement should be available for input to burn control. The system must have sufficient speed that it will be able to follow the density rise from pellet injection.

Three methods are being considered to provide the necessary information. These are LIDAR Thomson scattering with repetition rate ≤20 Hz, interferometry, and reflectometry.

Table 11.6. Electron Temperature

	Temperature Range	Spatial Resolution	Time Resolution	Accuracy
Core	0.5 to 40 keV	2 cm	1 ms†	10%
Edge	5 to 1000 eV	3 mm	1 ms	10%
Divertorr	5 to 300 eV	1 cm	10 ms	10%

† Better resolution is required for fluctuation measurements.

The electron temperature may be used as in an interlock for launching of the fueling pellets. Profile measurement may be used in the heating and burn control.

The selected methods are LIDAR Thomson scattering with the laser pulsing as rapidly as 20 Hz and electron cyclotron emission. Langmuir probes are required for the edge region. The X-point region may require development of new diagnostic methods, for example, electron cyclotron absorption (ECA).

Table 11.7. Ion Temperature

	Temperature Range	Spatial Resolution	Time Resolution	Accuracy
Core	0.5 to 50 keV	8 cm	1 to 10 ms	10%
Edge	5 to 1000 eV	3 to 5 cm	1 to 10 ms	10%

The central ion temperature may be used for burn control. The preferred measurement methods are neutron spectroscopy and flux measurement for the central region and charge-exchange recombination spectroscopy for the full profile. (Requires a modulated diagnostic hydrogen beam with preliminary parameters estimated to be 300 keV, 10 A. Note that a helium diagnostic beam is required for charge-exchange recombination spectroscopy of "thermalized" alphas.) Visible spectroscopy is required for the ion temperature and flow in the divertor region.

Table 11.8. Impurities and Radiated Power

Parameter	Time Resolution	Spatial Resolution	Accuracy
Z_{eff}	1 ms	8 cm	20%
Low-Z impurities	50 ms	18 cm	20% †
High-Z impurities	50 ms	8 cm	20% †
Total radiation	10 ms*	8 cm	20%
n_d/n_t	50 ms	-	20%
n_{He}/n_d	50 ms	-	20%

† The numbers presented are dependent on the quantities of impurities present.

* 10 μs for fast disruptions

The ratio n_d/n_t could be required as a fueling control signal. Visible bremsstrahlung detection will provide information on the Z_{eff}; visible spectrometers and a crystal X-ray spectrometer will provide data on low-Z and high-Z impurities, respectively. Bolometer arrays will measure the radiated power. The ratios of n_d/n_t will be provided spectroscopically and/or via charge-exchange neutral particle analysis at the edge and by neutron spectroscopy in the core. The helium "ash" will be detected by a charge-exchange recombination spectrometer (with its associated diagnostic beam). Exhaust gas analysis will provide overall particle balance information, including a shot-by-shot assessment of tritium retention.

Table 11.9. $q_\psi(r)$ (Plasma Current Density)

Range of q	Spatial Resolution	Time Resolution	Accuracy
$0.6 < q_\psi(r) < 5$	8 cm	100 ms	10%

The preferred methods are spectroscopic measurement of the motional Stark effect, making use of the same diagnostic beam as that required for ion temperature measurement, and Faraday rotation using the interferometer sightlines.

Table 11.10. Fusion Products

Parameter	Parameter Range	Time Resolution	Accuracy
Neutron flux	1×10^{11} to 1×10^{21} n/s	1 to 10 ms	15% (10% rel.)
Fusion power	1 to 1×10^3 MW	100 ms	15% (10% rel.)
Neutron fluence	Many activation locations		10%
Alpha source	$a/10$ spatial resolution	10 ms	~3%
D-^{3}He rate	$a/10$ spatial resolution	100 ms	10%
Escaping alpha arrays		10 ms	10 to 20%†
Confined alphas	$1 < E_\alpha < 3.5$ MeV	1 to 10 ms	10 to 20%

† Integrated absolute alpha power loss.

The total neutron flux that gives the total fusion power will be used for fusion power regulation. Various neutron detectors will be used for the measurement of the neutron flux and fluence and to quantify the source region. A gamma-detection system will provide the D-^{3}He reaction rate and will supplement the neutron measurements. Escaping alpha-particle studies are planned utilizing scintillators on movable probes or integrated wall samples. New diagnostics must be developed (gyrotron scattering and carbon pellet are examples) for the high-energy confined particles. Charge-exchange recombination spectroscopy (with the associated diagnostic neutral beam) will be used for the slowing down confined particles.

Table 11.11. Fluctuations

Parameter	Maximum Frequency	Spatial Resolution	Accuracy
MHD	0.5 to 1000 kHz	8 cm (for T_e, T_i)	10%
Edge MHD	0.5 to 1000 kHz	–	30%
n_e fluctuations	0.5 to 1000 kHz	8 cm	10%

Magnetohydrodyamic fluctuations will be measured by internal magnetic coils, by electron cyclotron emission detection, and by neutron systems. Information on density fluctuations will be obtained by reflectometry. D_α filterscopes will be used for edge light fluctuations (ELMs).

Table 11.12. Edge, Divertor, and First Wall

Parameter	Requirement
Surface temperature	$T \geq 350°C$, ≤ 1 cm resolution, 10 ms rise time
Residual gas analysis	One on each duct, differentially pumped for GDC
Total/partial pressure measurement	$\approx 10^{-3}$ to 10^{-9} Torr, ≈ 100 ms response

The surface temperature of the first wall and of the divertor plates will be measured at a number of locations using infrared detectors. Pressure and partial pressure will be measured in a pumping duct and close to the vacuum vessel.

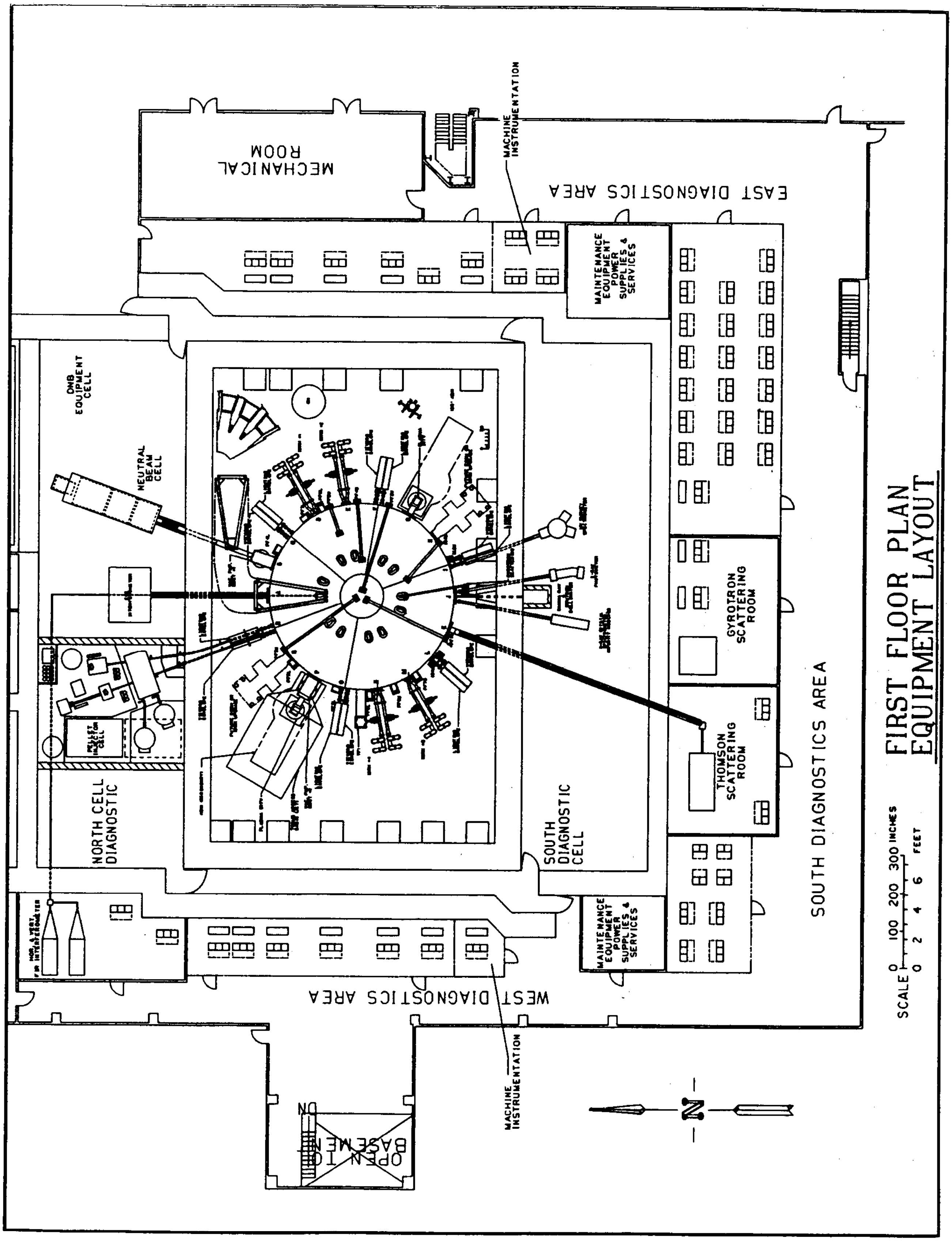

Fig. 11.1. Diagnostic layout on BPX.