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A high-resolution X-ray imaging crystal spectrometer, whose instrumental concept was thoroughly tested on NSTX and Alcator C-Mod, is presently being designed for LHD. The instrument will record spatially resolved spectra of helium-like Ar^{16+} and provide ion temperature profiles with spatial and temporal resolutions of 1 cm and > 10 ms which are obtained by a tomographic inversion of the spectral data, using the stellarator equilibrium reconstruction codes, STELLOPT and PIES. Since the spectrometer will be equipped with radiation hardened, high count rate, PILATUS detectors, it is expected to be operational for all experimental conditions on LHD, which include plasmas of high density and plasmas with auxiliary RF and neutral-beam heating. The special design features required by the magnetic field structure at LHD will be described.

I. Introduction.

The recent introduction of x-ray imaging crystal spectrometers, which record spatially resolved spectra from highly charged ions of medium-Z elements from argon through tungsten, has facilitated the measurement of ion-temperature profiles and profiles of the toroidal rotation velocity in tokamak plasmas with high spatial and temporal resolutions of $\geq$ 1 cm and $\geq$ 10 ms for almost all experimental conditions [1-4]. By contrast, the widely used charge exchange recombination spectroscopy [5-7] requires the injection of energetic hydrogen or deuterium beams, and its applicability is further restricted: (1) if as on Alcator C-Mod and ITER the electron density and electron temperature are so high and/or the plasma dimensions so large that neutral beams cannot penetrate to the core of the plasma; (2) if as on EAST and KSTAR, which are tokamaks with superconducting magnetic field coils, a plasma discharge lasts for several minutes and it is not feasible to inject a neutral beam for the full duration of a plasma to make ion temperature measurements; and (3) if the injection of a neutral beam would perturb a certain experimental investigation, as for instance, the study of intrinsic plasma rotation without external momentum input, RF-heating and lower-hybrid current drive. The latter conditions are also relevant for the Large Helical Device (LHD), a stellarator of large dimensions with superconducting coils, long plasma pulses of several minutes, densities in the range from 10^{19} to 10^{20} m^{-3}, and electron temperatures up to 10 keV [8 - 10]. For these reasons, an x-ray imaging crystal spectrometer will be installed on LHD in order to measure ion temperature profiles for the various experimental conditions. This spectrometer is presently being designed, as part of a NIFS/PPPL collaboration agreement, which also includes theoretical support for the data analysis with the stellarator equilibrium reconstruction codes, STELLOPT and PIES [11-15]. The x-ray imaging crystal spectrometer will record spectra of helium-like argon with a spatial resolution of about 1 cm in a direction perpendicular to the equatorial plane and 6 cm in the toroidal direction; the time resolution will be $\geq$ 10 ms. To meet these design criteria for a stellarator geometry, certain instrumental modifications are necessary, which are described in this paper. Spectra of helium-like argon are presently observed on LHD with a standard, single-chord, Johann-type x-ray crystal spectrometer [16]. The experience gained from the operation of this instrument provided guided our design of the present, multi-chord, x-ray imaging crystal spectrometer.

II. Objectives

The objectives the above mentioned PPPL/NIFS collaboration are twofold:

The first objective is to provide an instrument for the measurement of ion temperature profiles in LHD plasmas with a spatial resolution of 1 cm and temporal resolution $\geq$ 10 ms, using the spectra of helium-like argon, which are now routinely observed with a single-chord Johann crystal spectrometer [16, 17]. An example of the helium-like argon spectra, which have been obtained with the present x-ray crystal spectrometer on LHD, is shown in Fig. 1. This spectrum covers the wavelength range from 3.94 to 4.00 Å and consists of the main helium-like lines w, x, y, and z, and the numerous $n \geq 2$ satellites [18, 19]. Because of experimental constraints imposed by the stellarator geometry, which are explained in the following section, the new multi-chord instrument will only record the small part of this spectrum, which includes the resonance line w and the associated nearby $n \geq 3$ dielectronic satellites. Thus, it will still be possible to measure, in addition to the ion temperature profile (which will be determined from the Doppler width of the resonance line w) also the profile of the electron temperature from the satellite-to-resonance-line ratios.

The second objective is to provide theoretical support for the data analysis, using stellarator equilibrium reconstruction codes STELLOPT and PIES. Figure 2 shows, as an example, results from an equilibrium reconstruction of the W7AS stellarator. To obtain the reconstruction, the STELLOPT reconstruction code [11, 12] was first used to obtain an equilibrium reconstruction assuming nested flux surfaces. The resulting equilibrium solution was used as the starting point for the calculation with the PIES code [13], which does not assume good flux surfaces. The reconstructed pressure and current profiles from the STELLOPT calculation were used in the PIES equilibrium. The PIES equilibrium reconstruction will be improved to use the diagnostic signals directly, and to calculate reconstructed pressure and current profiles that give an optimal fit to the diagnostic data. Synthetic diagnostics will be incorporated in the PIES code for this purpose. Thus, for the spectrometer, the chord-integrated experimental data will be simulated by integrating over the theoretically predicted local values. The simulated data will be compared with the actual data, and the pressure and current profiles will be constructed to give a best fit to the data, including that from the spectrometer. As a first step, however, it will be desirable to initially use tomographically inverted data.

III. Layout of the x-ray imaging crystal spectrometer for LHD

The constraints imposed by the peculiar geometry and magnetic field configuration of LHD require modifications of the spectrometer design that is commonly used for tokamaks. As shown in Fig. 3, the spectrometer consists of a spherically bent crystal and a two-dimensional position-sensitive detector, which are arranged in a Johann configuration [20]. X-rays of a certain wavelength λ, which are emitted from the plasma and reflected by the crystal with a Bragg angle θ according to the Bragg condition, form a point image in the detector plane at the point P. Because of the astigmatism of the spherically bent crystal, these rays seem to emanate from a *sagittal* line source at B_s. For the preferred experimental arrangement of the crystal and detector, which is shown in Fig. 3, this *sagittal* line source is parallel to the toroidal magnetic field. The astigmatism is then of no concern due to the fact that the electron density and electron temperature and thus the x-ray emissivity are uniform along the toroidal magnetic field. Since the ray pattern is symmetric with respect to rotations about the axis OC, one obtains a one-dimensional image of the plasma on the detector, with spatial resolution perpendicular to the toroidal magnetic field. The design of an x-ray imaging crystal spectrometer for LHD is, however, more challenging and complicated due to the fact that, in contrast to tokamaks, the magnetic field varies rapidly with the toroidal angle Φ. In fact, there are only a few locations around the torus, where the magnetic field has a predominant toroidal component. These locations are the most appropriate locations for the installation of an x-ray imaging crystal spectrometer. However, the spectrometer must still be designed in such a way that the *sagittal* line source is compatible with the scale length of the magnetic field variations. As can be inferred from Fig. 3, the extension of the *sagittal* line source is determined by the width of the crystal and the Bragg angle θ. The distances of the *sagittal* line source and the point-image at P from the crystal are $b_s = -R \bullet \frac{\sin(\theta)}{\cos(2\theta)}$ and $p = R \bullet \sin(\theta)$, respectively, where R is the radius of curvature of the crystal. The new x-ray imaging crystal spectrometer will be installed on the equatorial port, AL01-07, at the end of the LHD pump duct, where the magnetic field has a predominant toroidal component over a scale length of 60 to 120 mm and where the plasma cross-section has an elliptical shape with a major half axis in the equatorial plane of about 1500 mm and a minor half axis perpendicular to the equatorial plane of about 500 mm - see Fig 4. The fact that the minor half axis is perpendicular to the equatorial plane has the beneficial effect that a minimum number of detectors is needed to obtain a de-magnified one-dimensional image of the whole plasma. Port, AL01-07, is equipped with a 12" gate valve, which is at a distance of 19811 mm from the center of LHD and. In order to avoid interferences with other diagnostics on neighboring ports the crystal will be placed at a distance of 3079 mm from this gate valve. Since the center of the plasma is at a distance of 3750 mm from the center of LHD – see Fig. 4, it follows that the crystal is at a distance of $d_{cp} = 19140mm$ from the center of the plasma. In order to place the *sagittal* line source as close as possible to the center of the plasma and to assure that the length of the *sagittal* line source will be compatible with the above-mentioned scale length, $l_s < 120mm$, for magnetic field variations, the spectrometer will be equipped with a spherically bent 110-quartz crystal with a radius of curvature $R = 6124mm$, a width of $w = 40mm$, and height of $h = 100mm$. Since the 2d-spacing for this crystal cut is $2d = 4.91304 \AA$ and since the wavelength for the resonance line w of helium-like argon is $\lambda = 3.9494 \AA$, this line will be observed at a Bragg angle of $\theta = 53.50°$. As a result, we obtain the instrumental parameters which are listed in Table I. Due to the fact that the de-magnification of the plasma image in the detector plane is 0.257 (see Table I), it will possible to record a 1 m high plasma on three Pilatus II detector modules. Each of the Pilatus II detector modules has a sensitive area of 83.8 x 33.5 mm^2, which consists of 94,965 pixels with a pixel seize of 172 x 172 μm^2. The 83.8 mm long dimension will be used for the display of spatial information, and the wavelength will be displayed on the 33.5 mm short dimension. The wavelength dispersion in the detector plane is $5.97 \bullet 10^{-4} \frac{\AA}{mm}$, so that the observed spectral range extends from 3.94 to 3.96 Å. This spectral range includes the resonance line w and the $n \geq 3$ satellites - see Fig. 1. The trace of the spectral lines in the detector plane will be slightly curved. For instance, the trace of the resonance line w can be described by an ellipse with the major and minor half axes $a = 8050mm$ and $b = 5415mm$, respectively.

The Pilatus II detector modules are based on the modern CMOS hybrid-pixel technology [21, 22]. Very important features are the high single-photon count rate capability 2 MHz per pixel and low neutron response. These detector modules are radiation hardened and have been tested with neutron fluences up to $10^{14}$and 10^{15} neutrons/cm^{2}s^1. Shielding of these detectors is not required on present facilities like NSTX, where the background due to neutrons and gammas of the order of 200 counts per pixel and second is negligible against the typical x-ray counts of 10^4 photons per pixel and second. Based on the experience gained with the existing crystal spectrometer on LHD, it should be possible to obtain typical count rates of 10^4 photons/per pixel and second.

The layout of the spectrometer is shown in Fig. 5. The crystal housing is connected to the 12" gate valve on port, AL01-07, by approximately 3 m long tubing, with diameters varying from 10" at the gate valve to 8" at the crystal housing. Similarly, the crystal housing is connected to the detector housing by approximately 5 m long tubing with diameters varying from 8" at the crystal housing to 14" at the detector. The crystal chamber is separated from the LHD vacuum vessel by a 75 μ thick beryllium window with a rectangular aperture of 3" x 5 ". This beryllium window is mounted inside an 8" zero-length adapter flange, which is installed on the crystal housing. The dimensions of the beryllium window, gate valve, and tubing are such that each crystal element has unimpeded views of the whole plasma and the three Pilatus detectors. The crystal chamber will be evacuated by a roughing pump to about 10^{-3} Torr to avoid the attenuation of the 3 keV x-rays in air. The Pilatus II detectors will be operated in vacuum: They will be turned on for the short period of a plasma discharge and turned off for cooling between discharges.

In summary, an x-ray imaging crystal spectrometer for measurements the ion and electron temperature profiles on LHD with a spatial resolution of 1. 5 cm and temporal resolution > 10 ms is being designed. This spectrometer will be constructed and tested at PPPL in 2010; and it will be installed on LHD in April 2011. The measured ion and electron temperature profiles will be compared with predictions from equilibrium reconstruction codes.

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Table I: Instrumental parameters for the LHD x-ray imaging crystal spectrometer

Distance between crystal and plasma core:	$d_{cp} = 19140mm$d
Distance between crystal and *sagittal* line source:	$b_s = 16838mm$
Length of *sagittal* line source: (This condition can always be satisfied by covering the crystal laterally, reducing its width.)	$l_s < 120mm$
Distance between crystal and detector plane:	$p = 4923mm$
Spatial resolution in the plasma in the vertical direction:	$\Delta z = h \bullet \frac{d_{cp} - b_s}{b_s} = 14mm$
Spatial resolution in the horizontal direction:	$\Delta y = l_s < 120mm$
De-magnification of the plasma image in the detector plane:	$DM = \frac{p}{d_{cp}} = 0.257$

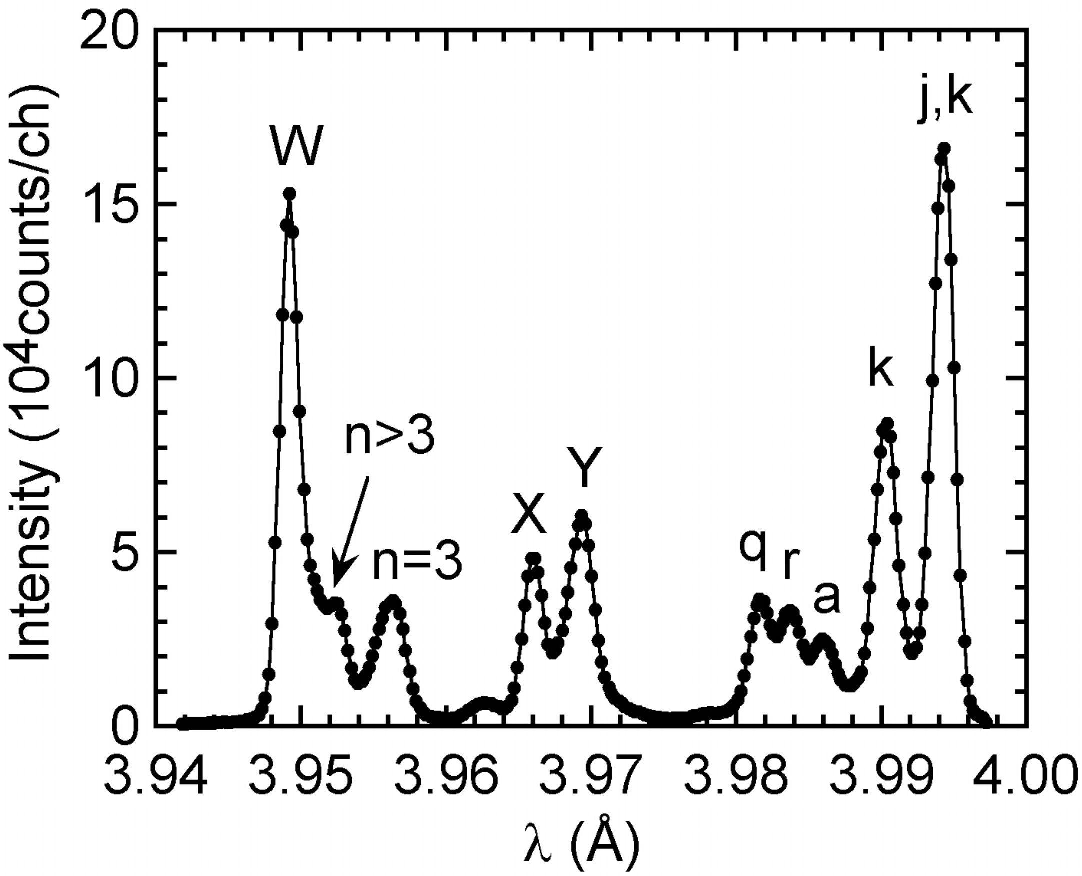

Figure 1: Spectrum from existing single-chord Johann crystal spectrometer on LHD

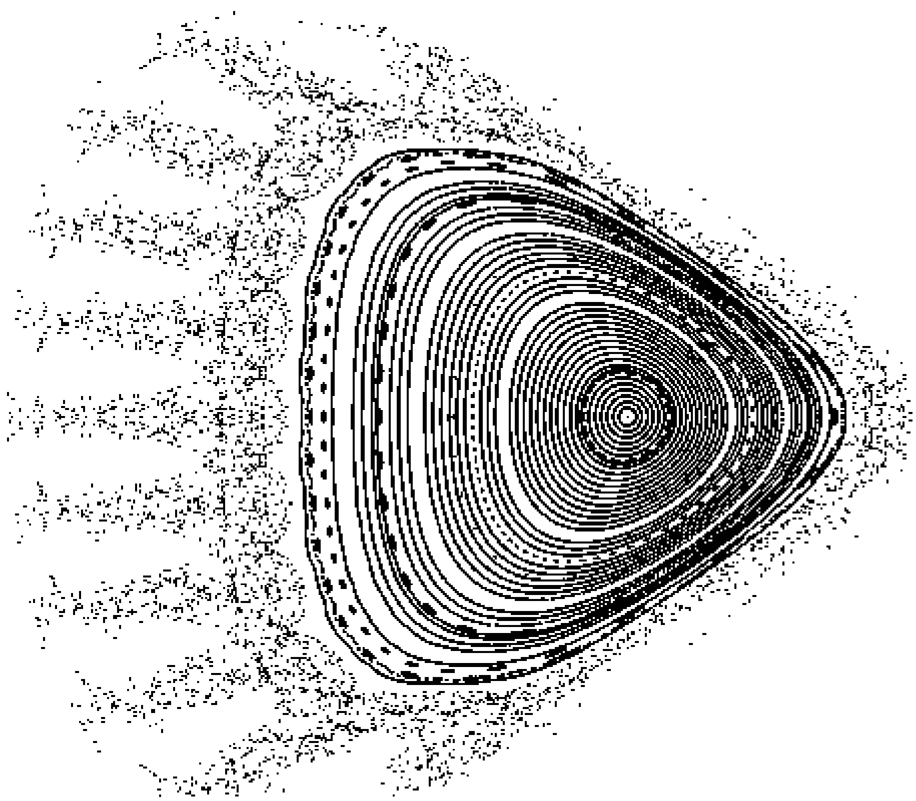

Figure 2: Poincare plot for a reconstructed equilibrium of the W7AS stellarator.

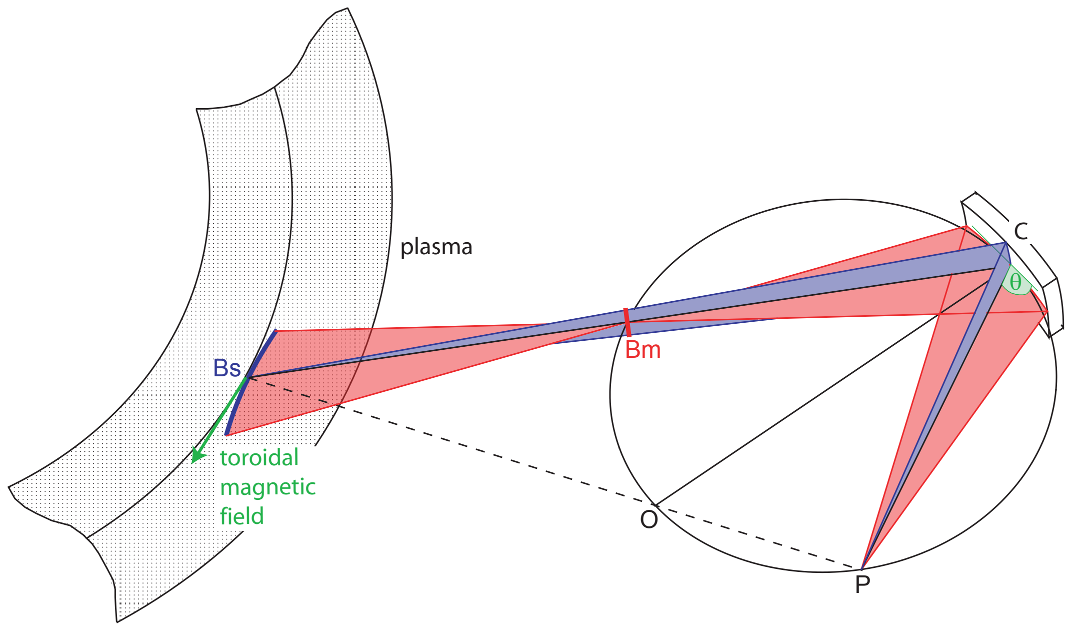

Figure 3: Principal arrangement of an x-ray imaging crystal spectrometer on tokamaks and stellarators.

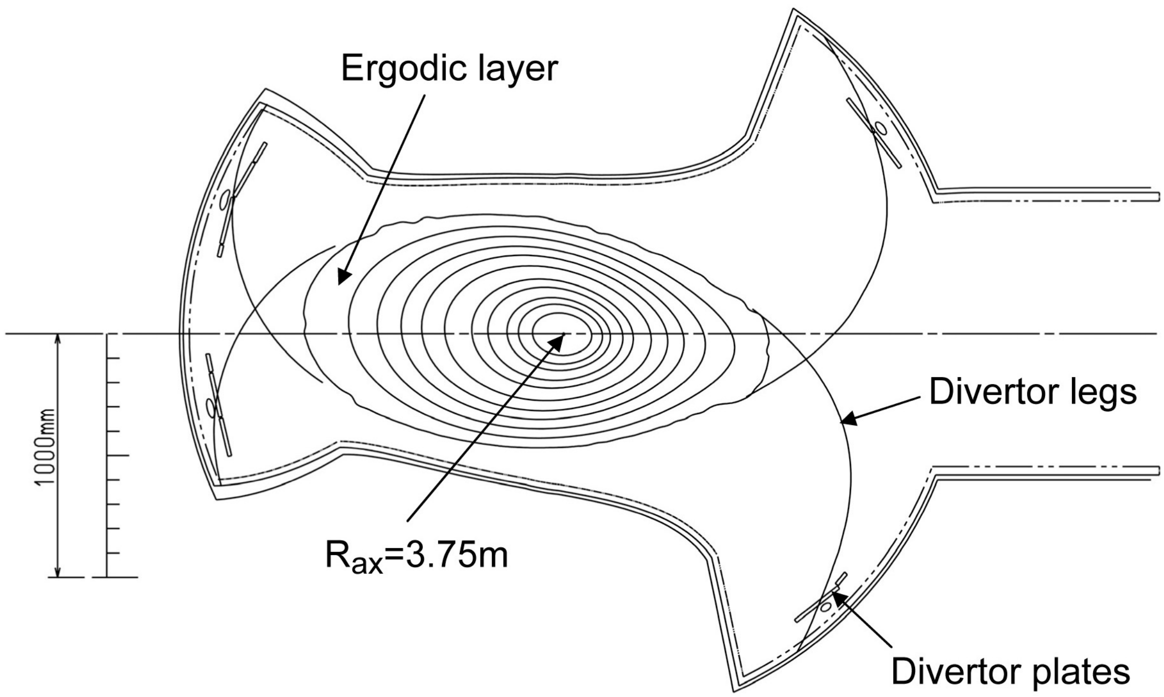

Fig. 4: plasma cross-section at LHD port AL01-07

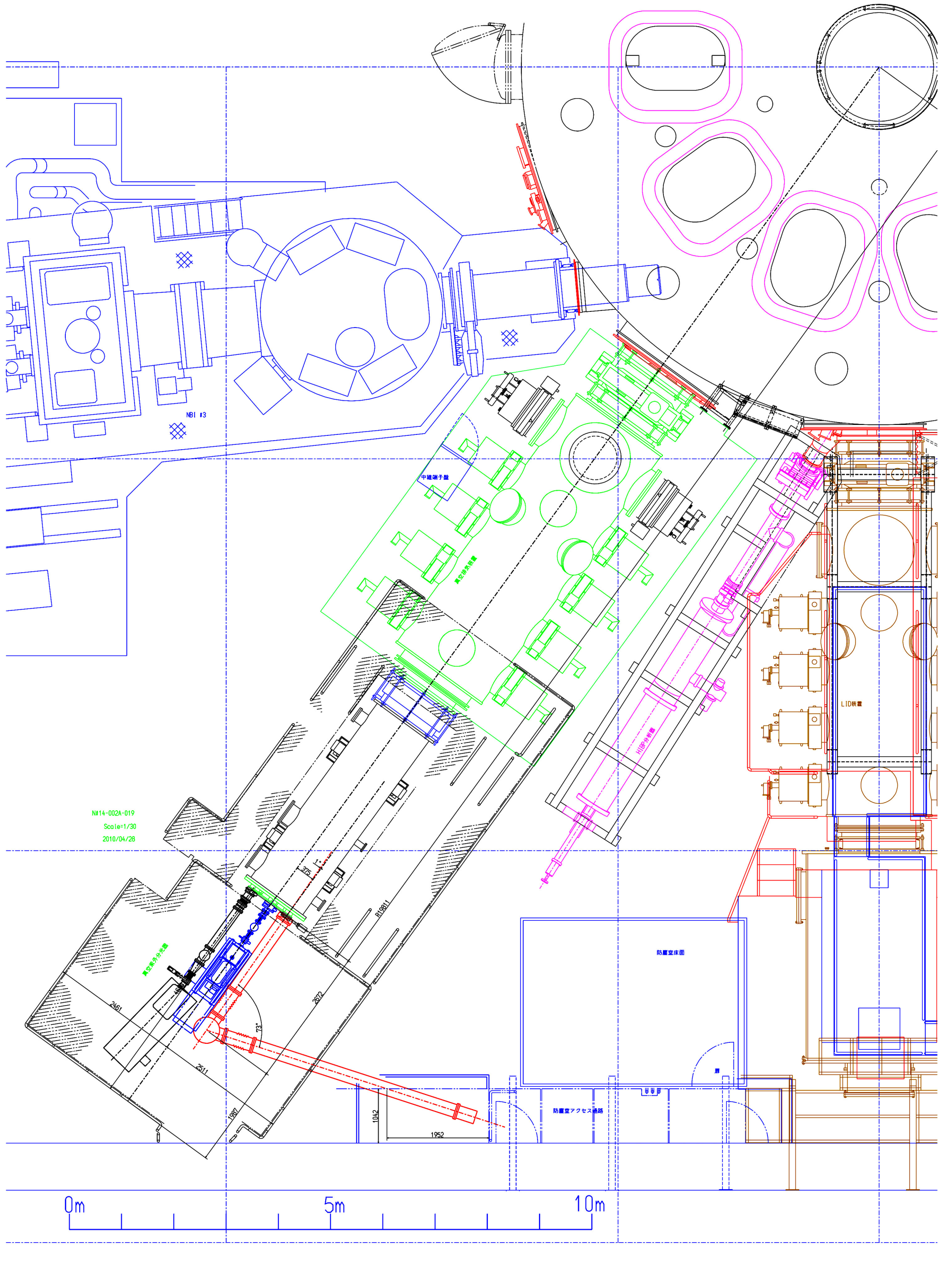

Fig. 5: Layout of X-ray imaging crystal spectrometer for LHD

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