Steady-State Position Control for the Tokamak Physics Experiment (TPX)

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1. Introduction

The TPX Diagnostics Description Document (TPX DDD:WBS 62) provided high-level descriptions and requirements for diagnostic systems. In particular in the area of Plasma Control:

"Plasma Control An array of magnetic diagnostics shall be provided to measure the plasma and vacuum vessel currents, the radial and vertical plasma position, and the plasma shape with time resolution and accuracy sufficient to satisfy the associated control and operational requirements."

The primary problem addressed in this study is how to achieve the control and operational requirements in true steady-state, not just for 1000 second pulses. Solutions to this problem (for they should be multiple and redundant) will probably have to be engineered into the initial design of TPX. (However, the TPX DDD said "at the present time such steady-state magnetic capability is not included in the baseline diagnostic set for TPX.")

Whether or not magnetic measurements are directly used as the fundamental position sensing technique in steady-state, magnetic probes will be used on TPX for interim control and fluctuating field measurements. With the long (fusion) experience with "fluxmeters" using integrating electrical circuits (both passive, active, and in software) and the accuracy on short times they can achieve, an array of such integrated probes will certainly be used on TPX. The "zero point" of such fluxmeters can then be periodically set in time by comparison to some other DC or steady-state position sensing technique. In between such "set times" the magnetic data can be used in the normal, familiar fashion to provide instantaneous equilibrium information.

The problem of steady-state position control then comes down to finding a technique (or redundant set of techniques) that can periodically determine the equilibrium to sufficient accuracy to "set" the fluxmeters.

1.1 Determination of the Magnetic Equilibrium

Given the external measurements of the magnetic field, computer codes are routinely used to determine the equilibrium of the tokamak discharge[1,2]. What will be needed on TPX is a computer code that, given some information, computes the equilibrium and then determine what the magnetic field should be at the fluxmeters. The information might be the magnetic field measured by some special set of magnetic detectors accurate in steady-state; or the information might be contained in an image of the plasma, or the location of some region of high density gradient.

For the record, thorough reviews of MHD equilibrium calculations and use of magnetic information are found in Tatsuoki Takeda and Shinji Tokuda, “Computation of MHD Equilibrium of Tokamak Plasma,” J. Comp. Physics **93** (1991) 1, and Bastiaan J. Braams, “The Interpretation of Tokamak Magnetic Diagnostics,” Plasma Phys. Controlled Fusion **33** (1991) 715 (see Refs. 1 and 2).

What is the expected duration of such a computation? This would determine the period between “set times” of the fluxmeters. “A typical kinetic/magnetic full equilibrium reconstruction, with a model fast beam pressure such as in the examples given, requires about 7 min of CPU time on a VAX-8650 using a 65 x 65 (R,Z) grid with a relative equilibrium convergent error of less than 10^{-4}”.[3] “The code developed can produce a full equilibrium reconstruction in 25 s on a Cray computer.”[4] Extrapolating computing capability for TPX to the year 2000 would imply the calculations could be done in 25/8 seconds (computing power doubling every two years). Fortunately we may not need to do a “full equilibrium” calculation in real-time, but just compute the boundary surface. Presently state-of-the-art appears to be to calculate the equilibria ahead of time, and then use a “predetermined linear mapping” and linear matrix algebra to do control.[5]

1.2 Criteria of choice

What are the design criteria that the technique (or redundant techniques) need to satisfy in the TPX design? The TPX DDD specified for Plasma Position and Shape generally 5 mm accuracy in radius and X-point positioning, and 2.5 mm up-down positioning. In addition the sensors providing this accuracy must be:

As insensitive to neutron irradiation as possible

Able to survive and operate at hot (300 ^{o}C) temperatures, and in some cases function at cryogenic temperatures (4 ^{o}K).

Must withstand disruption transients and fault-mode quenching of superconducting magnet coils.

“Simple and cheap”: strong expectation of lasting lifetime of experiment.

“Modular”: If some components fail, system can still achieve accuracy needed.

These criteria will be applied below in making recommendations.

2. Magnetic Methods

Based on previous experience in the fusion program[6], the most likely techniques for sensing the position of the plasma equilibrium are to measure the magnetic field. The initial problem is that standard probes or "fluxmeters" measure the *change* of the flux through the probe and not the absolute value, and require integration in time. While such integration may work out to the initial 1000 second operation of TPX, it cannot be straightforwardly extrapolated to steady-state. A further complication, even under the <1000 second scenario, is that the toroidal field in TPX will be on long before the plasma is initiated, since the TF (indeed, most all coils) in TPX are superconducting.

Nevertheless, there *are* methods of measuring DC magnetic fields, some of which might be applicable to the conditions of TPX. Methods of measuring the magnetic field both external and internal to the plasma are considered.

2.1 Methods of External Magnetic Field Measurement

The following review of methods of external DC magnetic field measurements draws largely from the review[7] "DC and low-frequency magnetic measuring techniques" by P. J. Flanders and C. D. Graham Jr. of the University of Pennsylvania, *Rev. Prog. Phys.* **56** (1993) 431. Quotations from that review are typeset "in this font." Also included are other ideas picked up in a literature search using the Science Citation Index (on CD-ROM) covering the last decade.

2.1.1 Fixed Magnetic pickup coils: Electronic integrators

"A coil subjected to a changing magnetic field ... generates a voltage proportional to the time derivative of the magnetic flux. Integration of this voltage gives a signal proportional to the change in flux. The instrument that performs this integration is called a fluxmeter."

"When connected to an input resistor R_i and a feedback capacitor C_i ... the output voltage E_0 is ...

$$E_0 = \frac{\Delta BAN}{R_i C_i} \times 10^{-8}$$

where ΔB is the change in the flux density in gauss, A the cross-sectional area of the test coil, and N is the number of turns."

A typical magnetic coil and integrating circuit is shown schematically in **Figure 1**. Different coil sizes, shapes, and mountings on the tokamak are used in short-pulse machines to accomplish a variety of tasks[8], including:

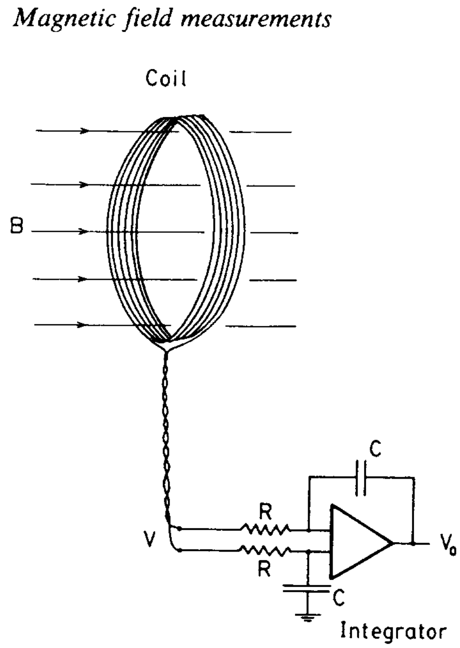

Figure 1: Schematic of typical magnetic coil & integrator (*from I. Hutchinson's book Plasma Diagnostics, 1987)*

2.1.1.1 ***Rogowski Coils***

These coils measure a time-changing current (typically the toroidal current in a tokamak), when wound around a current carrying conductor (plasma or wire). The coil is usually a helically wound solenoid, with a return center conductor so that the coil has no net loop around the plasma, and is usually encased in a Faraday shield to avoid electrostatic pickup. The detector is shown schematically in Figure 2 on the next page. A negative gain amplifier with gain G can be employed to extend the RC time by a factor of (1+G). The component sensitive to radiation and heat damage is the insulator, and the failure mode is an arc breakdown, which would typically result in destruction of the coil.

2.1.1.2 ***Voltage/Flux Loops***

These coils are typically one-turn loops which measure the time-rate of change of the poloidal flux, from which one can infer the toroidal loop voltage. A typical tokamak has at least an inner and outer loop, or a multiply-redundant set of these coils.

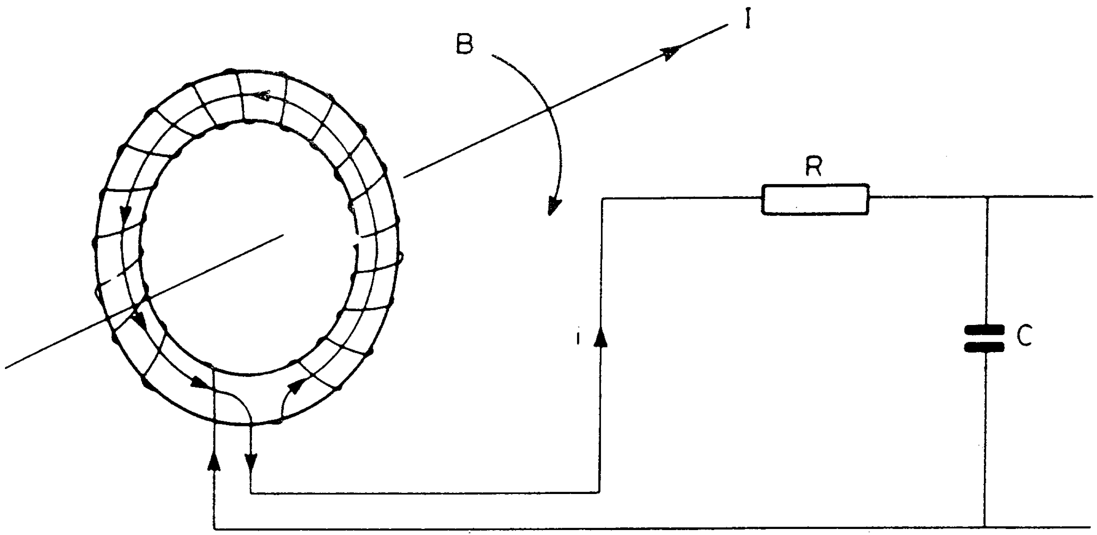

Figure 2: Rogowski coil to measure plasma current ***(from P. E. Stott, Varenna School on Plasma Diagnostics, 1982)***

2.1.1.3 ***Magnetic Probes & Position Coils***

These coils are typically small area loops which sense the time changing local poloidal or radial magnetic fields, and are used to determine the plasma position and shape. Moments of the current distribution are obtained by partial Rogowski coils, wound with a packing density to select particular Fourier components.

2.1.1.4 ***Diamagnetic Loops***

Diamagnetic loops measure the time changing part of the toroidal flux, contained within a poloidal cross-section, and are usually wound the “short-way” around the tokamak. They provide a measure of the average plasma beta. Alignment is critical for these coils, and pickup due to motion of the coil set from vessel displacements is problematic. **We do not have a way to measure the diamagnetically excluded flux in steady-state with external-to-the plasma measurements**. Schematically the coil is shown in Figure 3, also from Stott[8].

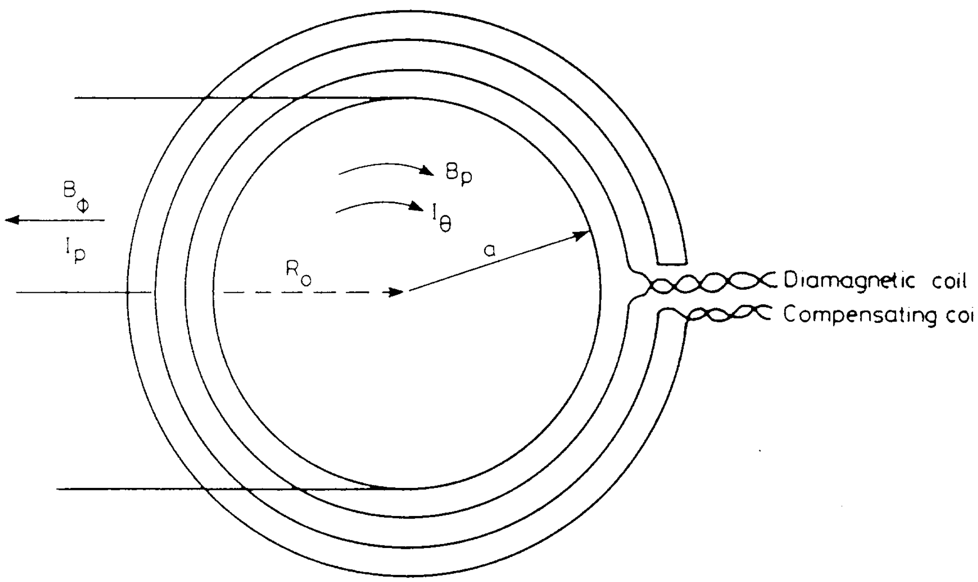

Figure 3: Simple diamagnetic loop ***(from P. E. Stott, Varenna School on Plasma Diagnostics, 1982)***

TPX is planning on using "standard flux-loops", as have all previous tokamaks, for pulses of less than 1000 second duration. Based on Tore-Supra claims of low-drift long pulse integrators, it is believed that this approach will work out to pulse lengths of 1000 seconds. *In all cases, the integrating time is of order* $R_i C_i$. . Making the integration time long reduces the sensitivity, or if active gain is employed, increases the problems with long-term drift stability.Long-pulse analog integration techniques, probably adequate for TPX, have also been demonstrated in the laboratory at JET[9]

2.1.2 **Vibrating or Rotating magnetometer**

Rather than have the magnetic flux change through a fixed probe, it is conceptually possible to move the probe through a fixed field and measure the resulting induced voltage. "The frequency and amplitude of the sample motion must be maintained constant during the measurement". Such moving probes are immediately complicated and subject to mechanical failure. A key question is the length of time such a probe could operate reliably between preventative maintenance intervals, especially in hard to reach places around the tokamak vacuum vessel.

2.1.3 **A Hall probe**

Hall probes apply a DC voltage across a conductor and then measure the ExB current perpendicular to the voltage and the magnetic field. A number of commercial vendors are available (including LakeShore, Micro Instruments, etc). Probe heads typical cost a few hundred dollars each, and require a controller to measure the current and/or voltage. Multiplexing of probes from one controller is possible for TPX timescales. Five digit accuracy for DC magnetic fields is typical, and different probe heads work in up to 300 kG fields.

Hall probes have been used by the TRIAM-1M tokamak[10] for discharges of more than one hour duration. Two probes are used for in-out, and two for up-down position control. They are mounted on water-cooled copper fingers which are encased in a thin stainless steel vacuum jackets near the circular plasma cross-section boundary.

A minor difficulty with the Hall probes is that they are sensitive to temperature changes, and so should be compensated for with *in-situ* thermocouple measurements. In TPX an additional major concern would be slow drifts and increased noise due to long-term damage from nuclear radiation. According to information provided by Jeff Dierker (LakeShore Cryogenics, Inc), LakeShore manufactures Hall probes out of doped (majority electron carrier) indium arsenide. The most highly doped material (referred to as “HST”) is the least sensitive to temperature changes (30-50 ppm/^{o}K) and the most “radiation hard”. It has the following radiation characteristics:

Table 1: Effects of Irradiation on InAs Hall Probe

Type of Radiation[11]	**Effect on Hall Probe**
Gamma	little effect
Protons	up to 10 Mrad changes sensitivity by less than 0.5%
Neutrons	(>0.1 MeV, 10^{15} n/cm^2) causes a 3-5% decrease in sensitivity.

At a DD neutron rate of $3x10^{16}$ n/sec, then the surface dose of neutrons could be $4x10^{13}$ n/cm^2 for one 1000 second pulse. The sensitivity of the Hall probes would be affected within 20 discharges or so, which is to say in a few weeks to a month of high-power, full-duration TPX operation. Checking tables in a report[12] “Radiation Hardening of Diagnostics for Fusion Reactors”, GA-A16614, by J. F. Baur, et al., Dec. 1981, indicates that the radiation threshhold for “significant damage” to a Hall effect sensor is in the range of 10^{16} to 10^{19} neutrons/cm^2, which is optimistically higher than the data from LakeShore.

2.1.4 **Force method (DC gradient)**

"The force on a magnetized sample located in a field gradient can be used to determine the magnitude of the magnetic moment of the sample. This is a venerable technique, known sometimes as the Faraday method and sometimes as the Curie method... The relevant equation may be written as:

$$F_z = M\frac{dH}{dz}$$

where F_z is the force in the z direction, M is the magnetic moment of the sample, and dH/dz is the field gradient."[13] Turning this technique around, given a sample of known magnetic moment and a way to measure the force on in the field gradient can be determined.

We don't need to measure the gradient of the field for the TPX problem. This is thus an unnecessary complication.

2.1.5 **Magnetostriction**

"Magnetostriction refers to any dimensional changes which take place when a material is subjected to a magnetic field[14]."

"The standard technique for measuring magnetostriction requires a very stable temperature since variations in T induce apparent strains due to the temperature dependence of the gauge resistance and to thermal expansion. A way to separate these apparent strains from the magnetostrictive effects is to rotate either the sample of the magnetic field at a constant angular frequency Ω so that the magnetostrictive effects are detected at harmonics of Ω."[15]

Again, sample rotation, as with rotating a fluxmeter, is complicating. Furthermore, the temperature sensitivity of these techniques may be very problematical. One might need yet another primary standard for calibrating these sensors on a given day.

2.1.6 **Lorentz Force on Fiber-Optics**

A fairly recent technique[16] involves measuring the change in length of a fiber using fiber-optic interferometry. Such a magnetometer, under development by Fusion Physics & Technology company[17], is an inexpensive device that responds to magnetic flux density $\Im B \Im$, directly. It has a frequency response limited to a hundred Hertz or so, and a claimed accuracy of 0.0001%, while able to span a dynamic range of 5 orders of magnitude. The fiber path length changes as a result of JxB force resulting from a known current which bows the fiber locally. Using one interferometer, and multi-plexed currents in successive coated segments of one fiber, the field components perpendicular to the fiber at multiple positions could be measured on a rapid timescale (of order 100 msec). By orienting segments of the same (or different) fiber in three orthogonal directions, all magnetic field components can be measured.

Darkening of the fibers due to neutron damage should be minimized by operating the fibers at high temperatures, a la JET, and in the near IR wavelength region (to minimize color-center scattering). One could imagine a jacketed tube going around the torus in poloidal direction which would contain the fiber, with multiple wire leads (and hence multiple sensors), but using only one laser for fiber interferometry. The multiple sensor points would each measure the magnetic field perpendicular to the fiber, so each measurement would be a mixture of two field components. Other sets of sleeves could go around the torus in the toroidal direction to measure B_θ and B_R. Because the laser is very bright, a large amount of darkening could be tolerated if necessary.

2.1.7 **Torque magnetometer**

"Under equilibrium conditions, when the magnetization in a material does not align with the applied magnetic field vector, a torque on the sample results which is a measure of the magnetic anisotropy energy. The basic function of a torque magnetometer is to measure the magnitude of the torque on a specimen located in a uniform magnetic field as a function of the angle between a particular axis of the sample and field."

Again, moving parts seem to argue against primary use on TPX. Also, long-term changes in the magnetization of a sample could lead to drift in the measurement.

2.1.8 **Gas Turbine**

"The field induces a retarding torque [in the turbine rotating about an axis perpendicular to the field] which decreases the rotor frequency [due to an] eddy current torque $kf\sigma\ B^2$ ... where k is a constant that depends on sample geometry and B is the total flux in the sample [and f is the rotor frequency and σ the conductivity.]"

Once again, something moving/rotating.

2.1.9 **Galvanomagnetic Devices**

The following is *not* from Flanders and Graham: "Agrawal and Swami (1981)[18] have shown that the static I-V characteristics of an unijunction transistor [sic] (UJT) is modified in a magnetic field. If this UJT forms part of a relaxation oscillator, then the magnetic field would change the frequency of the oscillator (which is a function of peak point voltage and valley point voltage)."[19] Such solid-state electronics may suffer dramatically over the lifetime of TPX from neutron damage.

2.1.10 **Faraday Rotation External to Plasma**

The Faraday rotation of polarized light passing through a medium subjected to a magnetic field causes a rotation of the plane of polarization of the light. This has been used in fusion devices to measure both the magnetic fields internal and external to the plasma. When used with a laser beam in a fiber which encompasses the torus outside of the plasma, relying on the Verdet constant of a special twisted fiber, one has a "fiber-optic" Rogowski coil. The advantages over a normal Rogowski coil are that it measures B, not dB/dt, and it has no electrical insulation difficulties. The disadvantages are possible radiation damage to the fiber, and that strain and temperature changes in the fiber can also create/or change the linear birefringence "signal component." The use of a twisted core fiber has been pioneered by Jahoda and Foreman[20] to reduce these effects. Alternatively, Ren & Robert[21] from Lausanne use time multiplexing of two different states of polarization at the input of the fiber, thereby making the Faraday rotation measurement independent of the linear birefringence of the fiber. These techniques are quite simple, and cost-effective for true steady-state measurements, but have only been demonstrated for short pulse operation on plasma devices. Fiber survivability against bakeout temperatures of 300-350 ^{o}C would not be a problem, and indeed should be possible up to 500 ^{o}C. In order to use high temperature "annealing" of the fibers to eliminate radiation damage, an operating temperature of 400 ^{o}C is needed.

2.1.11 **SQUID Magnetometers**

Superconducting quantum interference device (SQUID) magnetometers measure the voltage induced by quantized flux jumps at a narrow neck in a strip of superconducting material,when the magnetic field changes[22]. They are available from a variety of vendors[23], and can use either liquid helium (4 ^{o}K, niobium) or liquid nitrogen (77 ^{o}K, high temp superconductors) coolants for the probe element. They can be compact and very sensitive, but do not generally have a wide dynamic range (of B field) before quenching of the superconductor occurs. The heads must be designed with sufficient normal conductor braiding to act as a “shunt” for the fields expected. In a large background field (*i.e.*, the toroidal field), it might be necessary to first bring the field up, and then “freeze-in” the field by cooling the sensor after the TF is applied. Since the TF will “always” be on for TPX, this should be feasible, but might require local heating of each cooled sensor. Three-element sensors on each head are possible, to obtain all three field components. Radiation damage to the superconductors is a concern, in a similar manner to the superconducting coils for TPX. Generally speaking, SQUID’s are too sensitive for magnetic fusion applications.

2.1.12 **Nuclear Magnetic Resonance**

The technique of nuclear magnetic resonance can be used in "reverse", to determine the total local magnetic field strength. A frequency-scanned RF pulse which applies a rotating magnetic filed to a known sample (ie, protons in water) is used to determine an unknown (larger) "static" magnetic field. The frequency value of the nuclear magnetic moment is about 76 MHz per Tesla, so for TPX one would need to scan in the range of 200-400 MHz. This could be done rapidly with a short (broadband) RF pulse, in an inverse-Fourier transform type of NMR spectrometer. In contrast to laboratory situations where the magnetic field and temperature are precisely controlled, the environment on TPX would be problematic. It is conceivable that a pair (or more) of sensors (RF pickup coils) could allow determination of the spin axis, and hence field direction. We have not identified a manufacturer of compact (also cheap?) NMR equipment. At first glance, this technique may be robust, and should not be ruled out for eventual reactor applications.

2.2 Measurements of the Internal Magnetic Field

DC measurements of the internal magnetic field could also be used to constrain the magnetic equilibrium and reset the integrators on the fluxmeters. An excellent review can be found[24] in H. Soltwisch, “Current Density Measurements in Tokamak Devices,” Plasma Phys. Controlled Fusion **34** (1992) 1669. Many of these techniques suffer from accuracy (in both magnitude and space) as well as possibly precision over months of operation, and they are considered unlikely to meet the detailed requirements of the position for TPX. However, their use can significantly improve the equilibrium reconstructions of limited magnetic data.[25]

2.2.1 Faraday Rotation to measure B(r) and n(r)

Faraday rotation of polarized laser beams passing through the plasma, measures the change in polarization angle which is proportional to $\int n\vec{B} \bullet d\vec{l}$ along the laser path. This technique has been used on TEXTOR[26], TFTR[27], MTX[28], and other plasma devices (ZT-40M & JET). Even with a 10-chord polarimeter for simple feedback control, it is not widely seen as being high enough resolution for position control. If limited spatial resolution were deemed sufficient, the main difficulty will be one of access, mode quality, and vibration effects associated with TPX's geometry and long pulse length.

It is conceptually possible to have a multi-fan approach, and use quasi-optical waveguide horns (for 100 micron radiation) near the plasma. However, required retroreflectors would have to be mounted on internal vessel structures (rather than supported by an external "vibration-less" space-frame. The resulting vibrations during a 1000 second to steady-state pulse **must be compensated**, presumably with a two-color scheme. This is a much more serious complication than encountered in short-pulse machines. In fact, it is qualitatively similar to the integrator drift problem faced by standard magnetic loops......it is a long time before you get to see the post-shot baselevel of the signal.

In order to unfold the magnetic signal, one usually uses chordal density information obtained by so-called "simultaneous" interferometry from the same polarimeter setup. In every such system to-date, miscounting of fringes is a problem, especially in the face of pellet injection, or rapid plasma transients. Then, in addition, there are false signals due to vibrations of the interferometry/polarimeter, and occasional "hiccups" of the source laser (it changes longitudinal or transverse modes in the FIR or CO_2 cavities).

The spatial resolution of an FIR Polarimeter is typically a few cm in the transverse direction to the laser beam, but has no resolving power along the beam. Time resolution can be in the 100 microsecond to 10 millisecond range. As a diagnostic for standard short-pulse plasmas (0.1 to 20 second duration), there is no question that this approach offers value in determining the internal magnetic field. It is a sophisticated, proven (although not widespread due to it's complexity and finicky nature of the available FIR sources) diagnostic.

2.2.2 Motional Stark Effect (MSE)

Motional Stark Effect (MSE) has been developed as an effective internal magnetic field diagnostic on tokamaks with neutral beams[29,30], and should certainly be fielded on TPX. It uses the known velocity of hydrogenic neutral beams and the measured Stark polarization from the vxB electric field of Balmer transitions to determine the local magnetic field B at the intersection of the neutral beam and the spectroscopic view. However, while the pre-eminent internal magnetic field diagnostic in hot plasmas, MSE does not feature the spatial resolution or accuracy needed for TPX position control by itself. Data from it will be very useful as a constraint on equilibrium modeling.

2.2.3 Microwave Emission (ECE)

It has been suggested that crossed sight-line correlation of the broadband thermal fluctuations in the electron cyclotron radiation could be used to measure the local magnetic field[31]. Accuracy of 1 part in 10^3 is claimed, with 10 msec time resolution for 5 Tesla fields or higher. This electron cyclotron band emission measurement has not been experimentally demonstrated in a tokamak. It uses only metallic components in the vicinity of the plasma, and requires relatively small angular access. A major drawback is that it depends on accurate electron density and temperature information to unfold the B field. Experience on TFTR has shown that less than few centimeter accuracy in the kinetic pressure profiles are themselves very difficult to achieve.

From TPX DDD: “there has been discussion of current profile determination via use of O and X-mode reflectometry[32], where the O-mode cutoff depends solely on density and the X-mode cutoff depends on both density and magnetic field.”

3. Imaging Techniques

By imaging the edge or core plasma with plasma light emission in the desired wavelength band, usually with a “tangential” view, one can in principle determine the plasma position. If soft x-rays are imaged, then the core plasma position can be determined, while if lower energy photons are observed, the plasma edge can be located. Since positioning accuracy of a few mm is desired, the imaging system must have a correspondingly large number of pixels. Many pixels implies a long readout time. Consequently, an imaging device could be envisioned which would periodically be used to calculate the plasma position during a long period where the plasma is not moved, and “reset” the drift on standard, high time-resolution, magnetics signals every 1- 10 seconds.

In order to deconvolve the plasma shape from the line-integrated image, one must have a model of the plasma. Spurious light which contributes to the image, such as Marfes, ELMs, and divertor light must be averaged out, or taken into account. Particular slices, corresponding to specific vertical and horizontal moments could be analyzed rapidly, and other regions of the image near the X-point position separately fit with the goal of determining the X-point position. It is well-known that visible spectrum film images of the divertor region specifically "show" the shape of magnetic field lines near the X-point (as in ASDEX or Alcator C-Mod), although a detailed comparison of positions from these images to the magnetics determined position has not been done to our knowledge.

3.1 Visible & Bolometric Images

Visible imagery is planned for TPX. By selecting appropriate line filters, the plasma X-point can be imaged in CIII light (for example) from a tangential view. This could provide a near real-time monitor of the X-point position. An analysis algorithm to deal with ELMs and Marfes would have to be developed. Visible light imagery will by necessity be useful only for locating the plasma edge. Problems associated with chordal measurements and Abel-type inversions are still present. Local asymmetries (tile hot-spots, RF-antennae shields, etc) will also exist in the data.

An imaging bolometer could also provide similar data, but covering a wider spectral band, which should view more deeply into the plasma.

Rather than tangential imaging, tomographic reconstruction from vertical slices could be tried. Efforts to date[33] only achieved 1 cm out of 17 cm minor radius accuracy.

3.2 Soft X-Ray Images

A tangential-view soft x-ray imaging camera has been employed on PBX-M[34] to make low-resolution measurements of the highly-shaped PBX-M plasma. The 128x128 pixel image was reduced to a 32x32 array for image analysis[35], and for inversion purposes the plasma was assumed to be toroidally symmetric. Then a maximum entropy algorithm was used in combination with external magnetics information to map the internal magnetic structure of the plasma. Spatial resolution was necessarily limited on PBX-M as they were trying for relatively fast time response. Similar pixel resolution was achieved on COMPASS-C[36]. On TPX a longer integration time would allow more pixels to be left in the analysis both because of more signal per pixel and more time to do the computational inversion. Survival of the intensifier due to radiation damage in a close-in position (for a wide field-of-view) is problematic, as is operation of the intensifier electronics in the strong magnetic field near the tokamak. These problems are difficult but not unsolvable.

3.3 Hard X-Ray Images

Hard X-ray imaging is especially relevant to determine core magnetics geometry if lower-hybrid current drive is employed. The resulting high energy electrons produce an easily detectable bremsstrahlung radiation, which has been used on PBX-M[37] for moderate resolution plasma-shape determination.

K. Ida from NIFS in Japan has proposed a high resolution 2D X-ray camera for real time plasma position control in the steady-state tokamak[38]. He suggests using a fiber bundle coupled to a slow-readout 512x512 element cooled-CCD with 12-bit dynamic range, in conjunction with a thin NaI converter for 50-100 keV x-rays. The frame rate is variable from 16 frames/second to 1 frame per hour. For slow feedback (10 Hz) control the plasma position information is provided by the imaging. Three computer CPU's are suggested: one to acquire the images, one to calculate the horizontal position, and one to calculate the vertical position. This technique should be directly applicable to TPX. A primary concern would be the influence of neutrons on the x-ray converter phosphors, or of neutron fluorescence in the imaging bundle. It is easy to imagine an even higher resolution system for TPX in the next 5-year period, with 1024x1024 or even 2048x2048 pixel elements. The images need only be stored transiently for long enough to process the desired position and shaping moments. Spatial resolution of 1-2 mm should be achievable, especially if readouts every second or so give adequate temporal information to reset standard integrator offsets.

4. Other Techniques

4.1 Finding peaks or centroids from discrete data

There are a variety of diagnostics that measure what are supposed to be flux-surface quantities (like temperature or density; however, certainly in the case of density there is much present controversy about asymmetries in the density on flux surfaces). However, typical tokamak diagnostics tend to have finite spatial resolution, and not particularly great spatial accuracy. Figure 4 shows the analyzed position of the peak of electron and ion temperature, electron density, and neutron emission from several different diagnostics (interferometry (RMIRI), Thomson scattering (RTETV), CHERS (RTI), electron cyclotron emission (RECE), and neutron collimator (RG)) for a common data set of discharges on TFTR plotted versus the position of the magnetic axis determined from magnetic loops.[39] Not only is there typically several centimeter disagreement between diagnostics, but finite resolution of the diagnostics leads to several centimeter variations of a single diagnostic as the plasma moves. This clearly illustrates the difficulty of using most plasma diagnostics to determine plasma position with millimeter accuracy.

Higher accuracy in relative position sensitivity has been achieved by moving the plasma across the field of view of a diagnostic. Such "jogs" could be programmed on TPX every few seconds or so; however, such movement may affect coupling to RF antennas and be difficult considering the constrained geometry of the deep TPX divertors.

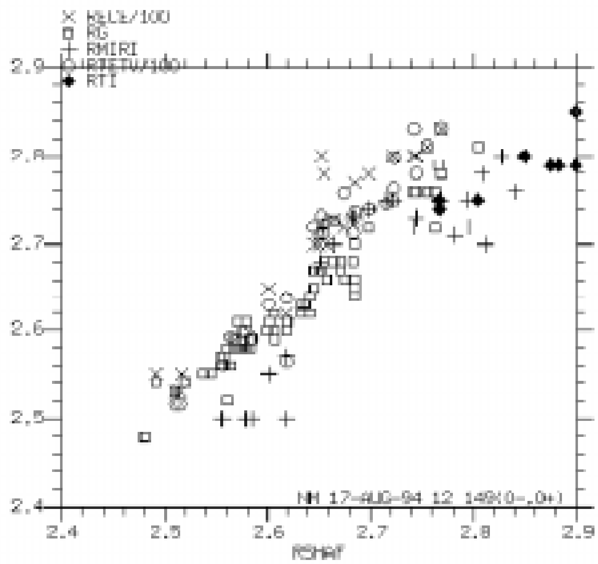

Figure 4: Position of profile peak (location of Shafranov shifted axis) from various TFTR diagnostics vs estimated position of magnetic axis from magnetic diagnostics

4.2 Balancing Heat Loads

As an engineering position control technique in a reactor, it has been suggested to monitor the heat loads on tile surfaces through platinum thermocouples which monitor the coolant temperature from tile sections or belts. While this is a "reactive" technique, and it has a relatively slow (1-10 second) time constant, due to coolant flow issues, it is simple. Certainly tile temperatures will be monitored at key stike-point and inner armor positions, as well as at protective limiters on RF antennaes in TPX. This information could be incorporated into a position control algorithm. However, it is exactly this problem of excess plasma heat hitting components that the position control is trying to avoid.[40]

4.3 **RF Antenna Coupling**

The outside midplane position may be essentially controlled by adjusting the plasma edge density to optimally couple RF power to the plasma. This can be done in principle by feedback control of the reflected ICRF or LH power, to provide a signal to the plasma vertical field magnet supplies. Some information from antenna (or antenna shields) surface temperature may also be of use in this algorithm. It would also be possible, although maybe not necessary, to perform the same task with a continuous density measurement in the edge (either interferometry or reflectometry).

5. Summary

We have identified a host of truly steady-state magnetic field measurement techniques. All have differing strengths and weaknesses. Common themes running throughout these techniques are questions of reliability, stability, and ruggedness, especially given the fact of relatively difficult mounting constraints. Achieving adequate sensitivity is generally not a problem. In almost every case, the steady-state technique is more complex than a simple pickup coil and passive integrator. We have a bias against techniques with moving parts, although it has been pointed out that a speedometer cable usually works just fine for 10 year periods!

Because we envision the steady-state measurement as providing the capability to "reset" the standard magnetic loop integrator drifts, fast time response is not a requirement for the steady-state techniques (although several techniques are quite fast). In some cases (the Rogowski for example) could be outside the "thick" vacuum vessel. This would presumably make their replacement easier (outside of the nuclear boundary). However, a well-designed set of Hall-probe modules could be envisioned to go in vacuum, but protected from direct plasma exposure by thin stainless shields. Measurements associated with the highly-shaped plasma in the divertor require sensors close-in to the divertor. Issues associated with maintaining alignment accuracy are the same for steady-state techniques, as for the standard magnetic set.

We have not identified a suitable replacement for diamagnetic loops, which effectively perform an "integral measurement". Even assuming that Hall probes can measure all three field components, they are still effectively a point measurement, do not measure the flux excluded from the plasma interior. Similarly, there is no steady-state equivalent of the "loop voltage" monitor, but fortunately it isn't needed, since in principle, there is no steady-state loop voltage, and the normal B-dot probes work fine for transients!

A collection of the diagnostics discussed in this paper is summarized in Table 2 on the next page. Specific time and space constraints depend in most cases on the desired accuracy of the measurement, and the number of sensors deployed on the machine. This is also related to the minimum size of the sensor, which usually sets the spatial averaging distance (or area).

Table 2(a): Steady-State Position Control (via external magnetic methods)

Diagnostic	Ref	Tested ?	Spatial Accuracy	Temporal Accuracy	Reliability	Radiation Hardness	Comments
Fixed Coil Flux loops	6,7	Yes	Depends on number and size of detectors	Depends on area, # of turns, sensitivity desired.	Standard	limited by insulation	limited by integrator drifts
Moving probe	7	No	"	Depends on rotation speed or vibration frequency.	Unknown	limited by insulation	maintenance issues
Hall Probe	9	Yes	"	fast	no moving parts	limited by bulk damage to sensor	Temperature drift can be easily compensated.
Curie Method	7	No	"	slow (reponse necessary to "weigh a sample") ?	uses magnetization force on a sample with known magnetic moment	magnetization of sample may change with heat or radiation damage	measures gradient of the magnetic field
Magnetostriction	7	No	"	medium	rotating/moving pieces, temperature and strain sensitive	depends on sample construction	Good temperature stability required.
Lorentz Force (Fiber Optic)	15	No, needs tokamak test	1-2 cm, Measures field perp to fiber	100 millisec easily achievable	Probably good, decladding of fiber must be tested.	Laser allows tolerance to fiber darkening. Elevated temperature ok.	Multiple measurement points can be multiplexed along one fiber. Lock-in techniques can be used
Torque Magnetometer	7	No	------	------	moving parts, changes in magnetization.	Depends on materials selected	Assumes uniform magnetic field in sample reqion.
Gas Turbine	7	No	Size of turbine	10 millisec	Spinning rotor, bearings	Good	Force required to keep turbine spinning at constant speed.
Unijunction Transistor	17	No	2 mm	100 microseconds	Compact, no moving parts,	Poor, damage to silicon junction	Temperature compensation required.
Fiber-Optic Faraday Rotation	18	Yes	Integral measurement	10-50 msec	no moving parts	Darkening of Fiber, change in Verdet constants	Responds to total B inside of fiber loop. Twisted core fiber to eliminate strain effects.
NMR		No	point measurement	1 second (?) or less	Complex RF equipment	Insulators, detector survival	Magnitude of field
SQUID Magnetometer	21	No	point measurement	0.1-1 second	Limited operating range. Cryogenic.	Superconductor	Excess field must be shunted to prevent quenching. Almost too sensitive for fusion work.

Table 2(b): Methods for measuring internal magnetic fields

Diagnostic	Ref	Tested ?	Spatial Accuracy	Temporal Accuracy	Reliability	Radiation Hardness	Comments
Internal Faraday Rotation	22-26	Yes, for short times only	Chordal. Measures 2 cm ⊥ to laser beam	100 microsecond	FIR source mode hopping, vibrations, coating of windows	limited by window damage. Detectors must be shielded.	Access to plasma is problematic. Laser stability and mechanical vibrations of mirror structures is a problem on long timescales
Motional Stark Effect	27	Yes, for short times only	"point" measurement 2 cm	10-100 millisecond	Requires neutral beam	windows , fibers, & insulators	No intrinsic problems for steady state. Spatial access limitations to plasma.
Microwave Emission	29	No	"Point" measurement 2 cm	fast	Unknown. Current drive could affect measurement	Waveguide components are tough. Vacuum window a minor problem	Requires crossed sightline access, and sensitive, wide-band detectors. Needs proof-of-principle demonstration.
High Resolution Tangential Imaging	32,36	Yes, low resolution tests only	limited by "fuzziness" of plasma, inversion of chordal measurement.	100 millisecond to 10's of seconds	Unknown, affected by plasma transients. Proper spectral region important.	Windows, fibers, x-ray converters, intensifiers	Wide variety of wavelength choices (visible to hard x-ray). Useful for edge plasma definition, X-point position, and as LHW current drive monitor.

6. Recommendations

1) We feel that TPX will in fact become a test-bed for steady-state techniques (of all types). The TPX project should encourage new steady-state measurements through the SBIR and STTR processes, and go so far as to plan for their eventual field-testing through a reentrant outboard midplane region where "test" probes of various type could be inserted. Examples of test devices could be a rotating flux loop or an NMR apparatus.

2) Even though Hall probes are eventually subject to radiation damage, they should be incorporated at some level from Day 1. They will work just fine in the hydrogen phase of operation, and we may see a better (more radiation-hard) technology available in the next 5-years. Some radiation testing of Hall probes should be done on TFTR. One could argue that they will never work on a reactor (from a radiation damage point of view), so why test them on TPX if other techniques are available.

3) A Fiber-Optic Rogowski loop for total current measurement is proven, straightforward, and would be essentially immune to radiation damage if run at elevated temperature, as shown for fibers in general on JET and TFTR. The fiber-optic Rogowski is a high-benefit, and relatively low-cost item that should be allowed for at the earliest possible stage. The material's Verdet constant will most likely be temperature dependent, so the temperature will need to be monitored.

4) It may be impractical to station a steady-state "backup" technique at each conventional magnetic loop position (in order to "reset" its integrator). Consequently the overall imaging techniques which provide a global measure of plasma position to be compared to a real-time "EFIT" calculation will be necessary. Gross plasma shape information can be obtained from imaging, but it is of necessity complicated by line of sight integration, even for a high-resolution image. A diagnostics requirement for the tangential visible imaging system(s) on TPX should be the capability of high-resolution, long-integration, wide-dynamic range picture acquisition, to support its use for steady-state position and shape control.

5) Effort should be made to build a real-time equilibrium code (boundary determination) capability with 1 second clock-time between runs.

Finally, the prospects for truly steady-state operation provide a new development direction for so-called “standard” plasma diagnostics. The problems with magnetic sensors in steady-state are only the first wrinkle to appear in the fielding of all diagnostics on TPX.

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