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ERROR FIELD CONSIDERATIONS FOR BPX

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ERROR FIELD CONSIDERATIONS FOR BPX

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<u>Abstract</u>: Irregularities in the position of poloidal and/or toroidal field coils in tokamaks produce resonant toroidal asymmetries in the vacuum magnetic fields. Otherwise stable tokamak discharges become non-linearly unstable to disruptive locked modes when subjected to low level error fields [1]. Because of the field errors, magnetic islands are produced which would not otherwise occur in tearing mode stable configurations; a concomitant reduction of the total confinement can result [2]. Poloidal and toroidal asymmetries arise in the heat flux to the divertor target [3].

The field errors from perturbed BPX coils are used in a field line tracing code of the BPX equilibrium to study these deleterious effects. Limits on coil irregularities for device design and fabrication are computed along with possible correcting coils for reducing such field errors.

Introduction

The term "error field" is used for the toroidally asymmetric field resulting from "as-designed" poloidal or toroidal field coils, *i.e.*, from coil feeds, turn-to-turn jogs, layer-to-layer transitions, *etc.*, or "as-built" coils, *i.e.*, coils fabricated with shape variations from as-designed or mounted with shifts and/or tilts from the nominal as-designed location. For the engineering design and fabrication of BPX (Burning Plasma Experiment), physics must provide tolerances on error fields from as-designed and as-built irregularities. The optimum performance of a tokamak, avoiding disruptions, maximizing confinement and minimizing divertor target hot spots, may depend on keeping field errors below a tolerable level.

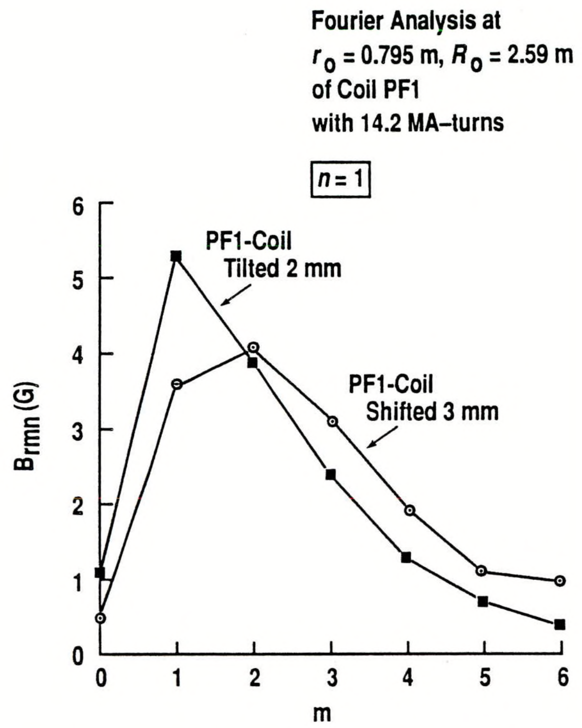

Fig. 2. Fourier analysis of the helical, radial field error components of coil PF1 shifted or tilted.

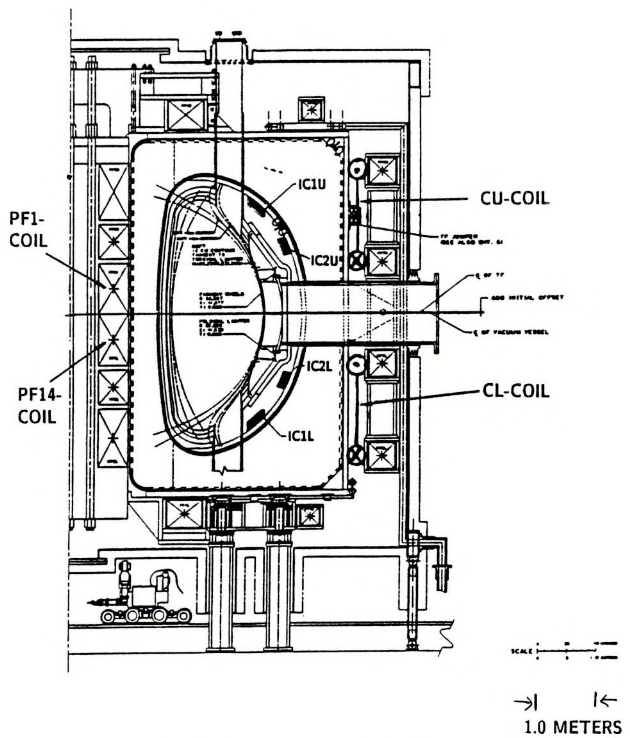

Fig. 1. Cross-section of BPX.

Sources of Error Fields

The cross-section of BPX with its 14 poloidal field (PF) coils and one of 18 toroidal field (B) coils is shown in Fig. 1; the major radius R is 2.59 m and the minor radius a is 0.795 m. Near the end of a 11.8 MA plasma current, 9 T discharge, coils PF1 and PF14 will have, by far, the largest PF coil currents with 14.2 MA-turns. Irregularities in PF1 or PF14 could be a shift and/or tilt of the coil from concentricity with the toroidal field. A double harmonic series is used to represent the asymmetric field of a perturbed coil [1]. Examples of the spectra of an irregular PF1–coil are shown in Fig. 2 for PF1 shifted horizontally by $\Delta_S = 3$ mm or tilted vertically by $\Delta_T = 2$ mm; the Fourier analysis of toroidal mode $n = 1$ versus poloidal mode m is done on a torus of minor radius 0.795 m, major radius 2.59 m.

Other PF–coils carry much less current and have correspondingly lower error fields from similar shifts or tilts. Irregularities in the toroidal field coil shape and/or location can also be of concern; a 3 mm horizontal shift of one of the 18 B–coils, for example, produces a $m = 2$, $n = 1$ relative error field of $B_{r21}/B_T = 3.0 \times 10^{-5}$ or $B_{r21} = 2.7$ G at $B_T = 9$ T.

Field Line Tracing with Error Fields

The field errors are added to a representation of the axisymmetric equilibrium field of BPX for $I_p = 11.8$ MA, $B_T = 9$ T, $a = 0.795$ m, $R_0 = 2.95$ m, elongation $\kappa \approx 2$ with a double-null divertor (DND) configuration. Unperturbed surfaces are shown in Fig. 3(a) with, from inside to out, $q = 1, 2, 3$ and the separatrix; the surfaces are from a Poincaré plot of punctures every 360° toroidally for a total of 150 toroidal revolutions. Adding the error field from PF1 shifted 3 mm, breaks the surfaces into narrow islands of full width $\Delta_{mn} \approx 1 \sim 2$ cm each (no plasma response used) and makes the separatrix indistinct if not ergodic [see Fig. 3(b)].

The field lines in the separatrix region lead heat and particles coming out of the core to the top and bottom divertor targets; the tangling of these field lines is made evident by starting selected lines at the top divertor target at the same toroidal angle and following them back to determine where they came from. This is shown in Figs. 4(a) and 4(b), without and with PF1 shifted. Without field errors [Fig. 4(a)], all lines at the outside top divertor ceiling connect to the bottom divertor floor; with field errors [Fig. 4(b)], some lines (which ones vary toroidally) connect to "quasi-closed" interior flux surfaces and can be subject to enhanced heat flux. Divertor hot spots may result.

Physics Limits on Error Fields

Stability

Locked modes occur in a variety of tokamaks and are a precursor of disruption [1]. The locked mode $n = 1$ field is oriented to the phase of the externally applied error field. Otherwise, stable discharges with no locked modes can become non-linearly unstable and disrupt when subjected to modest relative helical $m = 2$, $n = 1$ radial error.

The theory of tearing modes in a rotating plasma driven non-linearly unstable by external resonant perturbation is consisent with experiments in existing tokamaks such as DIII–D and COMPASS-C [6]. Extrapolating from DIII–D to avoid locked modes in BPX, the resonant $n = 1$ error fields should be kept below

$$\frac{B_{rm1}}{B_T}\Big|_{r=a} \leq 8 \times 10^{-5} \left(\frac{f}{\text{kHz}}\right)^{4/3} \left(\frac{\bar{n}}{10^{20}\ \text{m}^{-3}}\right)^{2/3} , \quad (1)$$

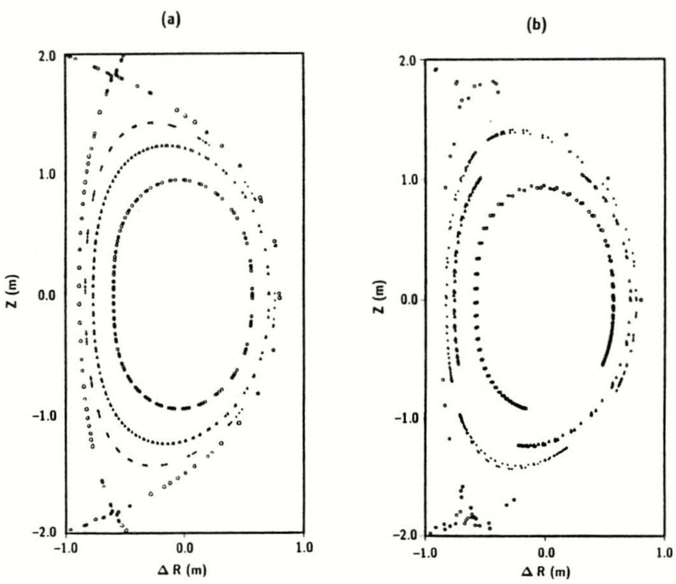

Fig. 3. (a) Poincaré puncture plot every 360° of field lines followed 150 times around toroidally for an unperturbed, 11.8 MA, 9 T BPX configuration; surfaces are $q = 1, 2, 3$ and the separatrix. (b) Same as (a) but with perturbation by a 3 mm shift of coil PF1 with 14.2 MA-turns.

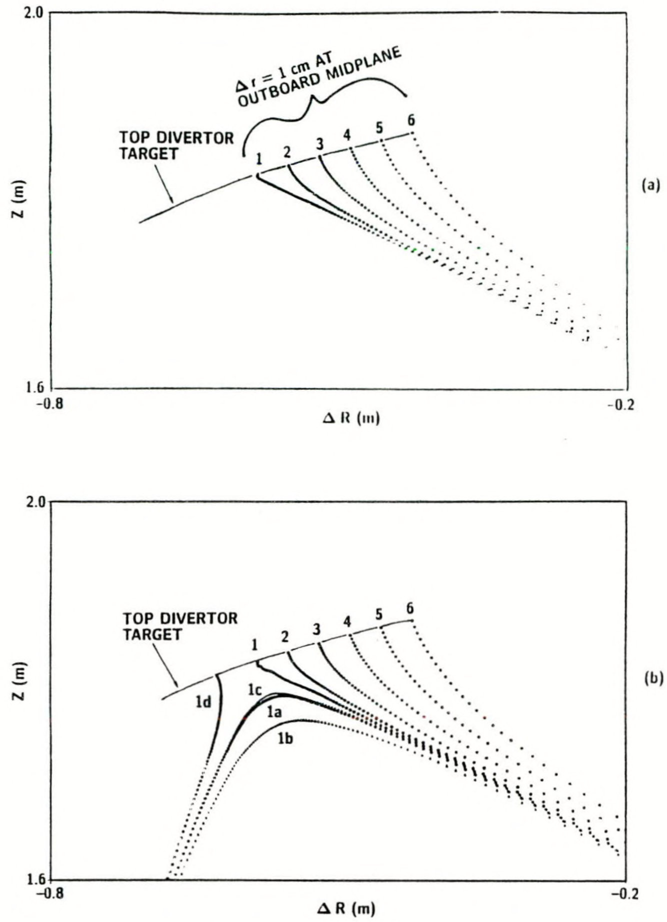

Fig. 4. (a) Tracing of unperturbed field lines which start at the top divertor target. (b) Same as (b) but with coil PF1 shifted 3 mm.

where $m = 1$, 2, or 3, the helical radial field is evaluated at $r = a$ and f is the toroidal plasma rotation frequency at $q = m/1$ for the m^{th} mode. In the ohmic heated phase of BPX, one expects that the frequency will be about the electron diamagnetic drift frequency calculated to be 1 kHz. **Thus at full field and current, before supplementary heating and with $f = 1$ kHz and $\bar{n} = 1 \times 10^{20}$ m^{-3} for example, the $n = 1$ relative resonant error field components should be kept below 8×10^{-5} to avoid locked modes.**

Confinement

Error fields can produce islands which "short-circuit" the temperature profile and reduce the effective size of the plasma and, thus, the total confinement [2,5]. **The proposed criterion for error fields is that they do not reduce confinement time by more than 5%.**

$$\frac{\Delta \tau}{\tau} \leq -0.05 = -\sum_{mn} 4 \left(\frac{r_{mn}}{a}\right)^3 \frac{\Delta'_{mn}}{a} . \quad (2)$$

where r_{mn} is the radius of the $q = m/n$ resonance and Δ'_{mn} is the full width of the $q = m/n$ error field island, including the response of the rotating plasma. As an example, for $n = 1$, $m = 1, 2, 3$ relative error field of 8×10^{-5} just satisfying stability from Eq. (1) at $f = 1$ kHz and $\bar{n} = 1 \times 10^{20}$ m^{-3}, and with q at the 95% flux surface of 3.2, one estimates $r_{11}/a \approx 0.50$,

$r_{21}/a \approx 0.80$ and $r_{31}/a \approx 0.95$. With no plasma response $\Delta_{11} \approx 2.6$ cm, $\Delta_{21} \approx 2.9$ cm and $\Delta_{31} \approx 3.4$ cm which would give $\Delta\tau/\tau \approx -0.23$ with no plasma response and $\Delta\tau/\tau \approx -0.02$ with a factor of 100 shielding of the error fields for a rotating plasma [6]. Thus, whether or not modest error fields make a "tolerable" reduction in τ of 5% or less, depends on the response of the rotating plasma.

Criteria for asymmetry of divertor heat loading

1. **Toroidal Variation of Field Angle at the Divertor.** If the heat flux coming out of the core is uniform toroidally, then the error field causes a toroidal variation in the field $\vec{B} \cdot \vec{n}$ normal to the divertor target which should produce a **toroidal variation in the heat flux Q of no more than $\pm 5\%$.**

$$\frac{\Delta Q}{Q} \approx \frac{\Delta\psi}{\psi} \leq \pm 0.05 \quad , \tag{3}$$

where $\psi = \tan^{-1}(\vec{B} \cdot \vec{n}/B_T)$ is the angle between the field line and the divertor surface. For BPX, a 9 mm shift of PF1 is required to violate this criterion.

2. **Asymmetry in Heat Flux out of Core.** Field errors create poloidal and toroidal asymmetries in the heat flux by destroying otherwise closed flux surfaces [3]. Some strike points on the target which are outside the unperturbed separatrix connect to interior "quasi-closed" flux surfaces when field errors are added; the separatrix becomes ill-defined and varies toroidally. **In order to avoid "hot spots" on the divertor, the radial layer Δr @ $\theta = 0°$ from tangling by field errors should be kept to no more than the heat flux scrapeoff length λ_q.** Extensive field line tracing with PF1 shifted by 9 mm for example, produces a tangled layer of $\Delta r \approx 4$ mm compared to predicted λ_q of 7 mm.

RMS Limits on Coil Irregularities

Assuming, for example, a limit of $B_{r21}/B_T = 8 \times 10^{-5}$ for the total $m = 2$, $n = 1$ field error allowable, the shifts and tilts of PF1 and PF14 and shifts of the 18 B–coils will be the dominant "as-built" sources of error field. Assuming random shifts and tilts and assigning equal weight to the sum of PF1 and PF14 as to all 18 B–coils, the allowable rms tolerances on coil positioning are

- $|\Delta_S| \leq 1.8$ mm for PF–coils.
- $|\Delta_T| \leq 1.3$ mm for PF–coils.
- $|\Delta_S| \leq 1.3$ mm for B–coils.

Error fields from other coils and irregularities, when properly weighted, would reduce the above rms tolerances further.

An Error Field Correcting Coil for BPX

As locating all PF and B–coils to $1 \sim 2$ mm accuracy may be very difficult, an error field correcting coil, "C–coil," is under consideration for BPX. (See also J.T. Scoville and R.J. La Haye, "Design of a Coil to Correct Magnetic Field Errors on the DIII–D Tokamak," to be presented at this 14th Fus. Eng. Conf.) As BPX is to be toroidally divided into sextants, the C–coil lends itself to 6 upper and 6 lower 56° wide coils as shown in Fig. 5 (see also Fig. 1). Pairs 180° opposite toroidally are to be run in series with equal and opposite currents to make odd n, principally

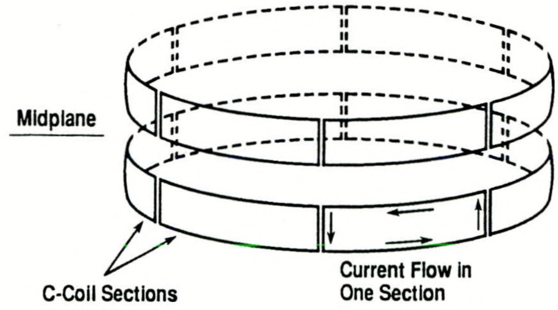

Fig. 5. Layout of proposed BPX error field correction coil, "the C–coil;" each segment can have different current.

$n = 1$. For a given error field source, PF1 titled by 2 mm at $\phi = 0°$, as an example, it is straightforward to work out the six independent C–coil pair currents to cancel any two $n = 1$ m-modes: the error field spectra with and without correction of the $m = 2$, $n = 1$ and $m = 1$, $n = 1$ modes are shown in Fig. 6. The C–coil currents needed are modest. An alternate algorithm in which $\sum B^2_{rmn}$ for $n = 1$ error fields are minimized may be more attractive. Knowledge of all field errors and their vector sum will be needed to determine the actual C–coil currents needed to bring error fields below tolerable values for optimal performance of BPX.

Acknowledgment

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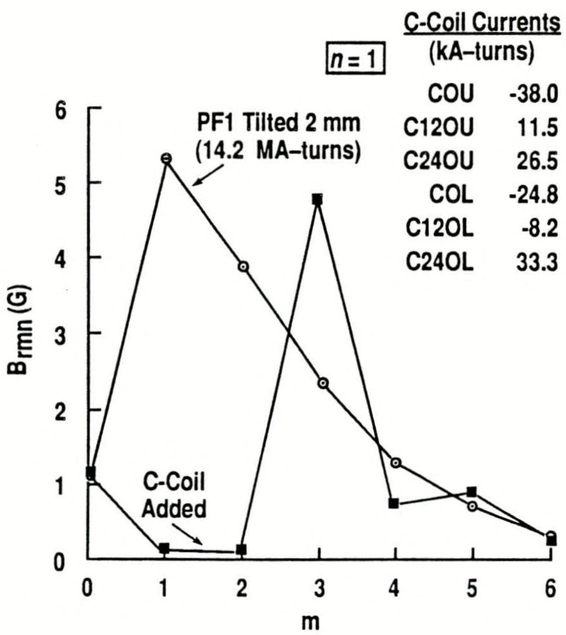

Fig. 6. Error field spectra of 2 mm tilted PF1–coil with and without correction of $m = 2$, $n = 1$ and $m = 1$, $n = 1$ modes by the C–coil.

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