OBJECTIVES OF THE MAGNETIC MEASUREMENTS ON STELLARATOR NCSX

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INTRODUCTION

The destruction of magnetic surfaces and creation of islands is caused by perturbations of the magnetic field. They lead to appearance of additional field components (ΔB_R [1] , ΔB_v [2] etc.) that have to get canceled.

The most prominent sources of perturbations are:

- Inaccurate coils manufacturing ($\Delta a_h/a_h$ [3] $\leq 1.10^{-2}$; $\Delta R/R_o$ [4] (ellipticity) $\leq 1.10^{-3}$ etc.);
- Inaccurate relative location of coils (d_n - the angle between the planes of TFC[5] and SC[6], for instance, $\alpha_n \leq$ (10' - 15')
  relative displacement (noncoaxial) of coils is $\Delta x/R_o \leq 1.10^{-3}$ etc.);
- Current carrying wires (leads), junctions and etc.;
- - magnetic permeability of metallic parts.

Our proposals associated with Magnetic Measurements (MM) are described in this report.

There are 2 steps in performing MM:

Step I (PMM)

Preliminary MM (PMM) only for TF of the PBX device.

Step II (FMM)

Final MM (FMM) of the magnetic field of NCSX stellarator.

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[1] ΔB_R - radial component of the flux density B
[2] ΔB_v - vertical component of the B
[3] a - minor radius of the Helical Winding (HW)
[4] R_o - major radius of the HW
[5] TFC - Toroidal Field Coils
[6] SC - Saddle Coils

A. Step I (PMM)

DISCUSSION ON ONE OF THE POSSIBLE PROGRAMS OF RESEARCH AND CORRECTION OF MAGNETIC FIELD CREATED BY EXISTING TF AND PF COILS OF THE PBX DEVICE (MAGNETIC MEASUREMENTS)

I. INTRODUCTION

1. Reason for taking magnetic measurements (MM)

Magnetic measurements on the PBX device should be taken within the next few months - before completion of Saddle Coils (SC) and the new Polodial Field Coils (PFC) and before the disassembling of the Vacuum Vessel (VV) has begun.

The reason for taking these measurements are as follows:

- Expeditious gathering of information about those elements of the PBX device which will be used in NCSX;
- Research of toroidal magnetic field (TMF), including preliminary compensation of observed (detected) perturbations;
- Determination of geometrical basis for positioning SC, the new PFC, Liner and apparatus (instruments) for final MM.

2. Possible ways to compensate perturbations

Let us present some ideas in this regard, based on the experience in taking MM on torsatron U-3M (Figures 1, 2, 4, 5, 6, and 11) and stellarator U-1 (Figure 3).

a) As shown on Figures 4a and 4b, compensation of the radial (ΔB_R) and vertical (ΔB) components ($\Delta B_R/Bo$ [7] = −0.55%; ΔB / B_o = 1.38%) of magnetic field, averaged along the toroidal axes and produced by perturbations only, may lead to significant improvement of the magnetic configuration.

b) However, this compensation is insufficient, because many kinds of perturbations cause big magnetic islands (MI) to form on magnetic surfaces (MS), even where ΔB_R and ΔB are compensated. Perturbations with a small number of perturbations periods ("n") are most dangerous (for instance, where n=1 four big islands form on MS with the angle t = n/m = 1/4 - (See Figures 5 and 6).

Two kinds of perturbations are shown on Figures 5 and 6 as examples:

- No. 1: Equatorial planes of the helical (HW) and compensating (CW) windings (See Figure 1) are positioned at 12′ angle (α_n = = 12') to one another (Figure 5).
- No. 2: Vertical axes of those windings (HW and CW) with a relative shift (eccentricity) $\Delta X/R_o = 1.10^{-3}$ (Figure 6). (n/m = 1/4).

It is necessary to lay a foundation for compensation of the aforesaid types of perturbations on the early stages of PBX toroidal field research. To this end, the geometry of the toroidal flux will be determined with regard to some basis, by way of experiment. Probably, the outboard of the VV may be used as such basis.

[7] B_o - flux density on the toroidal axes

Further, it will be necessary to adjust the new elements of the device (SC, Liner and etc.) to the aforesaid basis. In doing this, the value of "α_n" and "x" must not exceed the allowed tolerances.

II. PROPOSED PROGRAM OF PRELIMINARY MAGNETIC MEASUREMENTS

Main stages of the program are as follows:

II.1. Development and utilization of various methods of taking MM as applied to the PBX/NCSX device.

II.2. Detection of "surprises" (troubleshooting). Unfortunately, many new devices contain a number of surprises.

II.3. Taking measurements of components of the magnetic field by the "Magnetic Resonance" (MR) method.

II.4. Determination of TFC, PFC and VV positions with regard to each other.

II.5. Gathering of integral data on the value of magnetic permeability (M) of metallic parts and its saturation depending on the averaged value of toroidal field
Detection of M - anomaly points.

II.6. Creation of a preliminary field correction method by means of additional field components (ΔB_R and ΔB) generated by currents in the PFC.

• About the Additional Correction Windings (ACW) for compensation of possible errors of the TF (for example, SC used in tokamak D-IIID). It is possible that ACW will not be necessary in Step I. ACW in which case they will be used for Step II.

II.7. Determination of shape and dimensions of the magnetic flux cross-section and limited by the Liner (L). Correction and optimization of the flux shape.

III. DISCUSSION OF THE PROGRAM

Let us describe briefly the contents of some of the aforementioned stages.

1. <u>On methods of magnetic measurements (See II.1.).</u>

It is necessary to improve and to utilize a number of methods[8] and design apparatus for measuring: components of magnetic field ("MR" - method), trajectories of force lines (FLMF) and the shape of flux (CF)[2] ("Single-and multiple-passage" measuring methods of low-energy electron beams (EB) and a luminescent probe (LP) will be used). (See Appendix I). Let us mention the advantages of this method - visual observation of brightness of EB in a neon atmosphere (EBV). In this case, the electron gun (EG) emits beams in both directions and the brightness of many passages of the electron beam can be observed.

Let us also mention some specifics of the measurements related to the LP method (Figure 7). The electron gun is a mobile emitter (E) (Figures 2 and 7) screened by a grounded anode (its outer diameter is ~1.5 mm). The screen has an aperture (its diameter is ~1.0mm) for the formation of a beam of electrons. The LP probe is a grounded metal rod of 1.5mm in diameter and covered with luminofor. Both the gun E and the probe LP are fastened to their mobile device which allows to scan the cross-section = const (Figure 7).

The maximum area of the measured cross-section is limited by a circumference, the radius of which is equal to a_e [3] (Figure 7).

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[8] In this case the experience in taking measurements on U-1 [9], U -3M[3] and other stellarators will be used (See "References")

[9] a_e is the length of the mobile part of E or LP. Center of rotation "O" may be installed on the toroidal axes (R_o = 1.5m) and can move to both sides of the axes (see Figure 7).

2. Several methods may be used to determine (measure) the position of TFC, PFC and VV with respect to each other (See II.4):

   - By means of correct geometric measurements (for instance, taken by laser);
   - By means of electron beams (method LP), etc. (for a detailed discussion, see Section III, p. 1, 3 and 4).

3. Preliminary correction of the toroidal field (See II.3 and II.6).

   Let us mention the main stages in taking these measurements:

   a) Based on the results of calculations and measurements of the TF components, data will be gathered on the position of the toroidal magnetic axes[10];

   b) Mobile guns (E) and probes (LP) will be put into four windows (Figure 7):

      - guns (E) and probes (LP) will be put into W2 and W4;
      - one probe (LP) will be put into each W1 and W3.

   c) The position of central magnetic force line (CFL-see Figure 8.a) will be measured on one passage (Prior to that, the shift of the beam, produced by the field of Earth and toroidal drift, will be compensated).

[10] The position of this axes is determined by the radius of the circumference (R_o = 1.48m) on which the averaged TF equal 1.0T (B = 1.0T).

4. Detection and compensation of perturbations (See II.6 and II.7)

Let us conditionally divide perturbations into "Integral" and "Local" categories:

a) Integral perturbations (IP) (See II.6).

Those perturbations which cause the formation of new averaged components of TF (ΔB_R and ΔB) fall into this category. These components cause deflections of the force line ("ΔX" and "ΔY" - see Figure 8) after one revolution. A number of factors causing the formation of these components ΔB_R and ΔB can be identified.

Let us examine a possible way to compensate integral deflections of the FL, by means of an example, where one of the TFC is inclined and turned (Figure 8). For convenience, let us examine the behavior of one - central force line (CFL), which approximately coincides with the position of the toroidal axes, define above.

If the aforesaid perturbations are present, after its passing of one revolution, CFL deflects from its original position (Figure 8, "ΔX" and "ΔY"). These deflections may be easily compensated through the use of a pair of PFC, which create a field with components ($-\Delta B_R$) and ($-\Delta B$)

In this event, CFL is a closed, single revolution (ΔX=O, ΔY=O. See Figure 8.a, p.b).

The event of closed CFL may be detected using probes and guns and observing beams gleaming in neon. Before compensation, a beam revolving (making multiple revolutions) inside VV may be observed. As the compensating field grows, the radial distance between neighbor

"revolutions" decreases. At the moment of full compensation, only one closed radiant ring can be seen. The position of this ring, that is, the position of CFL, may be used afterwards, for example, to correct the position of SC with respect to TFC.

The correction may cause a virtually total liquidation on possible shift (ΔX) and incline (d_n) of these elements of magnetic system.

As a basis for geometrical measurements, the outboard of VV, on which the probes and guns are installed, may be used. Their coordination mechanisms allow to determine with sufficient accuracy the coordinates of CFL with respect to VV.

However, the aforesaid radiant ring (CFI) is not smooth. Rather, it is deformed at the point of perturbation (see Figure 8.a., p.b). Let us define this perturbations as local ones.

b. Local perturbations (LP) (See II.7)

After compensation of integral perturbations, it is necessary to use E and P to determine points of local perturbations. Perturbations related to the M anomaly and etc. also fall into this category.

Further, it is necessary to try various methods in order to compensate them (such methods are not discussed in detail here). However, it may be the case that, as a practical matter, some kinds of these perturbations cannot be compensated completely[11]. As a result, the deflection of force lines from the projected trajectories will remain at the LP point (Figure 8.c., p.3). That may cause a decrease of the cross-section of the flux (Figure 8.c, p.4) permeating some limiting mechanical apparatus, such as the Liner. Figure 8.c shows as an example such decrease of the cross-section of the flux permeating a Liner of circular cross-section.

[11]Let us point out that kinds of local perturbations are not too dangerous to the structure of magnetic surfaces.

In the NCSX device the Liner will be of a sophisticated shape (Figure 9). To determine the shape of the flux permeating the Liner, it is proposed to use the discrete equivalent "Pseudo-Liner" consisting of four deformed rings (Figure 10). These rings match the shape of the solid Liner of the NCSX device.

5. Determination of perturbations related to permeability (M) (See II.5).

There may be a case that some elements, such as the support system, the coils case and VV, made of stainless steel (SS), have values of $M > 1$. That may cause perturbations of the magnetic field. To detect, record and compensate initially[12] these perturbations, the method of determination of CFL described in Section III.4.a may be used. For this experiment, it is necessary to determine the dependency of deflections of CFL ("ΔX" and "ΔY").upon the value of the toroidal magnetic field B within of $0.1T \leq B \leq 0.7T$ range. Let us point out that the value of is saturated in fields B=(0.2-0.4)T.

[12]Moreover, the resonance method is used to determine the impact of M . The essence of this method (see Figure 11) is as follows: first magnetic surfaces (MS) are created, where profile of dependency of the angle t upon the radius of MS has resonance values t (for example, t = n/m = 1/4 - see Figure 11). That causes the formation of

islands. As the value of B changes, the position of resonance values t and the size of the islands also change. The value of M is determined based on this change.

B. Step II

- The study will be done of the magnetic surfaces (MS) created separately by Helical Winding (HW) and Saddle Coils (SC);

- Another study will be done on MS created by HW and SC together;

- There is a possibility of utilizing the ACW;

- There is a suggestion of using two types of beam “Probe” methods.

I. INVESTIGATION OF PARAMETERS OF MAGNETIC SURFACES (MS) CREATED BY AMS[7] IN CONJUNCTION WITH TFC AND PFC.

1. Refinement of beam, "resonant" method of magnetic measurements (BRMM). With help of AMS[13] one could create MS with adjustable parameters. The value of angle t should have a resonance[14] value on the profile t ($t=f(r)$). For instance, t = n/m=1/3 (resonance of third sort and t = n/m 1/4 (resonance of fourth sort). This lays a foundation for measurements of occurring magnetic islands and understanding of sources of magnetic field perturbations. The toroidal field on the circular axis of the torus (B_o) should vary in the range $0.1 \leq B_o \leq 0.7T$.
2. Creation of MS and refinement of methods for parameter correction and perturbation cancellation.
3. Investigation of MS and perturbation cancellation caused by:
   a. value of M ;
   b. feeders (electrical connecting leads)
   c. inaccurate in manufacturing and relative location of TFC, PFC, AMS etc.

II. INVESTIGATION OF MS, CREATED BY SADDLE COILS (SC) IN CONJUNCTION WITH TFC AND PFC (AND IN THE PRESENCE OF AMS AND A LINER).

1. Investigation and correction of toroidal flux shape (created by TFC) as when the flux is located inside the liner (a correction of the liner location is necessary).
2. Investigation of magnetic surfaces parameters in different regimes and cancellation of perturbation due to Stellarator magnetic field.
3. Refinement of different regimes for the Stellarator NCSX magnetic system as a whole.

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[13] AMS-Additional Magnetic System. At present, it is not clear whether AMS is going to be built along Saddle Coils (SC) and the liner or separately or independently.

[14] Note, that the resonant method of measurement of MS parameters is most sensitive and precise.

C. Schedule of performing the Magnetic Measurement

a) "The Draft of Construction Schedule of NCSX" shows that PMM should be prepared and performed during the year (Oct. 98 - Sept. 98):

- DSGN/Apparatus/Assembling and Adjusting - 8 months (Oct. 98 - May 99)

- PMM - 4 months (June 99 - Sept. 99)

b) Time estimated of preparation of the experiment (Table 1) shows that 23 man-months are required for developing, manufacturing and "ready-to-use" adjustment of the apparatus and equipment for performing the MM by "LP" method and 6 man-months (additional) - by "T" method.

On principle, the possibility to order some parts of the equipment in the Institute of Plasma Physics of National Science Center "Kharkov Institute of Physics and Technology" can be envisaged. In this Institute, the experience was accumulated in measurements of magnetic surfaces on stellarator-type machines with different methods in use. In particular, the method of the luminescent probe was used for investigation of magnetic surfaces on 1=3 torsatron Uragan-3M and 1=2 torsatron Uragan-2M (see Ref.[3]-[5].

Table 1. Time estimated for different stages of preparation of the experiment on measuring the characteristics of magnetic surfaces

Object	time for preparation the draft project, man-month	time for preparation the technical project man-month	time for manufacturing, man month	time for assembli and adjusting man-month	total time
Electron gun with system of transfer	0.25	0.25	0.5x2=1.0	0.5	2.0
Power supply for movemer of the electron emitter	0.25	0.25	0.5x2=1.0	0.5	2.0
Power supply for movemer of the luminescent rod	0.25	0.25	1.0x2=2.0	0.25	2.75
System of movable luminescent rod	0.75	1.25	4.0x2=8.0	1.25	13.0
Pseudoliner with system of transfer	0.25	0.25	0.5x4=2.0	0.5	3.0
The program providing experiment and program o information treatment					2.0
TOTAL	1.75	2.25	14.0	3.0	23.0

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TOTAL (“LP”) METHOD): 23.0 MAN-MONTHS