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IN-VACUUM LAMBERTSON SEPTUM FOR SPEAR3 LOW EMITTANCE INJECTION*

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Abstract

A new in-vacuum Lambertson septum magnet is being designed for the SPEAR3 storage ring, intended to replace the existing septum to allow injection into a new lower emittance operation mode for SPEAR3. The new septum design is constrained to fit in the same length and have the same bend angle as the existing injection septum, so as to minimize changes to surrounding storage ring and transfer line components, while also meeting stringent requirements on the stored beam leakage field. This has led to a design using Vanadium Permendur alloy for the septum pole pieces, with shaping of the inner profile of the stored beam channel to minimize the leakage fields indicated in 2D and 3D magnetic simulations.

INTRODUCTION

The SPEAR3 storage ring at SLAC is a third generation synchrotron light source, constructed in 2003 with a circumference of 234.1 m and nominal beam energy of 3 GeV [1, 2]. Since 2007, SPEAR3 has been operated with ε_x = 10 nm emittance, but preparations have been made in recent years [3] to allow ε_x < 7 nm operation[1], which will increase the x-ray brightness provided to user beamlines.

Injection Requirements

To inject from the booster into SPEAR3 with the lower emittance lattice, the distance between the kicked stored beam[2] and the injected beam must be lowered to ~7 mm to be within the dynamic aperture of the new lattice.

The present injection layout is shown in Fig. 1 below, where the transfer line comes in from above at a 8.792° angle, offset 32 mm to the inside of the nominal stored beam path. A Lambertson-type septum magnet bends the injected beam into the storage ring plane while the stored beam passes through its shielded vacuum chamber. This magnet has a total wall thickness of 6.3 mm, meaning that a new septum with decreased wall thickness is needed.

Specifying the septum wall to ≤ 2.5 mm, all of which must be ferromagnetic material, leads to the new septum magnet having one of its poles fully inside vacuum, with a zero field-channel cut through for the stored beam.

The other main challenge for the new magnet design is that the leakage field in the stored beam channel should meet the same set of requirements as for insertion devices for SPEAR3 [4], corresponding to ±1 G local field flatness, which is a very strict, especially considering that the bending field on the other side of the septum wall is 1.3 T.

THE NEW SEPTUM MAGNET DESIGN

The new design keeps the Fig. 1 layout essentially intact, keeping the bend angle and vertex the same, and the magnet effective length/field strength about the same as for the old septum. Main parameters are listed in Table 1.

2D and 3D magnetic Finite Element Analysis has been used to optimize the magnet geometry to meet the leakage field requirements, followed by iteration between magnetic and vacuum/mechanical design, which is currently in progress. A 2D simulation of the present design, of a cross section import from the 3D cad model, is shown in Fig. 2.

The general layout of the new septum was established in earlier design efforts [5], including features like the split back return yoke (see Fig. 2), which reduces sensitivity to variations between top and bottom yoke parts, ie reduces vertical (B_y) leakage fields caused by top/bottom return flux imbalance, and the trim coil (shown in Fig. 2), which can cancel out return flux imbalances.

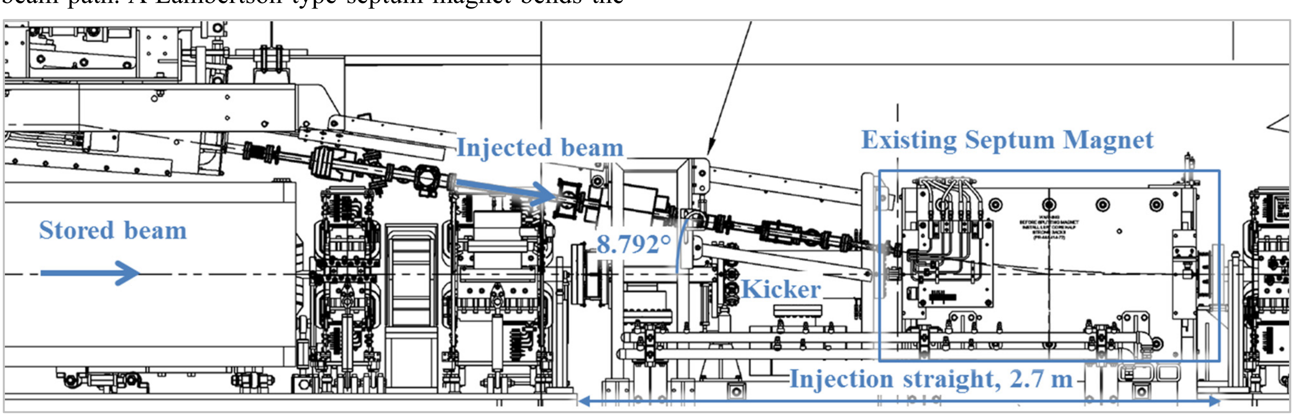

Figure 1: Present SPEAR3 injection straight, drawing view from storage ring inside with septum location indicated.[3]

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[1] By running the existing storage ring magnets at new current set values.
[2] SPEAR3 is injected using a 3-kicker bump with K2 located directly upstream of the septum.
[3] From drawing no. LO-444-414-00.

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Table 1: Magnet Design Parameters for the new Septum

Parameter	Value	Unit
Bend angle	8.792	°
Pole gap	11	mm
Injected beam nom. B_x	-1.316	T
Bend radius	7.608	m
Main coil [4], nominal I	288	A
yoke material	1010 steel	
stored beam pole material	Hiperco 50A [5]	

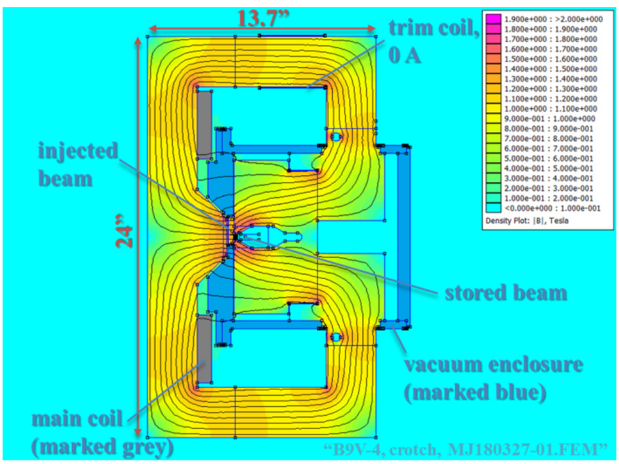

Figure 2: FEMM [6] 2D field distribution in magnet cross section at NI = 12096 A. The color scale goes from 0-2 T.

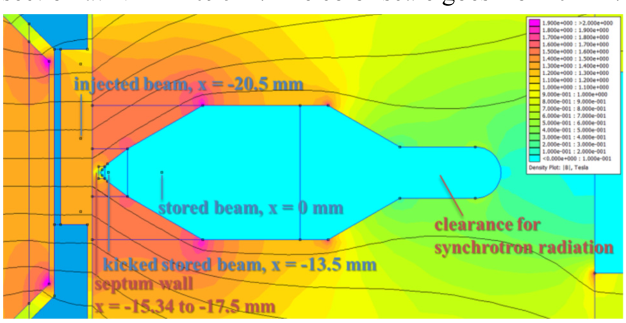

Figure 3: Close up of Fig. 2, stored beam channel, with specified [4] beam positions indicated.[6]

In general for Lambertson septa, the B_x leakage field depends on the pole gap field and the wall permeability at this field level as $B_x \approx B/\mu_r$ [7], suggesting that the septum wall should be made of high μ_r material. Our FEA indicates that B_x right inside the septum wall follows this rule, independent of the stored beam channel shape[7], but that the $B_x(x)$ profile from there onward depends on the shape.

Consequently, the stored beam channel shape shown in Fig. 3 has been optimized using the height, slope and nose shape as free parameters to meet the leakage field flatness requirement, expressed as $|\int B_x(x)dz|$ non-linear terms < 40+75*|x| Gcm [4]. The resulting $B_x(x)$ shown in Fig. 4 have residuals from linear fits < 0.5 G, fully within the [4] spec., which corresponds to ±1.3 G at x = -15 mm.

[4] Using the existing septum spare coil, drawing no. SA-444-414-16.
[5] A VP-type alloy, ® of Carpenter Technology Corp, Reading PA, USA
[6] Inj. beam x is +11.5 mm from present location, meaning that the last part of transfer line will need to be re-aligned +11.5 mm for the new septum.
[7] As long as the material near the septum wall isn't saturated.

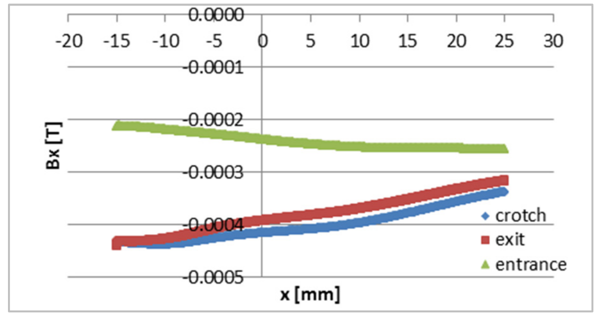

Figure 4: 2D simulation data, stored beam channel $B_x(x)$ from the Fig. 2 file (crotch) and two more cross sections from the Fig. 5 model at different longitudinal positions.[8]

The material choice for the stored beam pole pieces is based on repeat FEA with different B(H) data, indicating that Vanadium Permendur-type alloys meet the requirements with small variations in the critical leakage field flatness. Both high peak μ_r and high saturation level are needed, so it is crucial that the real septum wall material is not degraded compared to the B(H) in the simulations.

MECHANICAL DESIGN

Key features of the present design, shown in Fig. 5 are:

- Stored beam pole pieces, 8x 5.68" long, are inserted through upstream 14" CF flange and their fasteners are accessed through the side pump ports.
- Split back return yoke is realized by 4x welded stainless spacers.
- Vacuum enclosure is formed by welding stainless plates to split back yoke 1010 pieces – the design is leak-checkable and repairable.

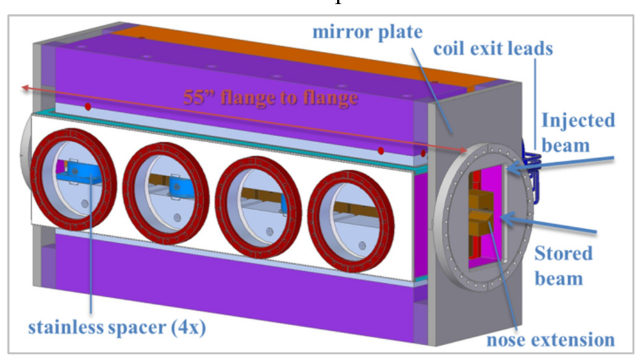

Figure 5: Septum magnet 3D cad model dated 3/16/2018.

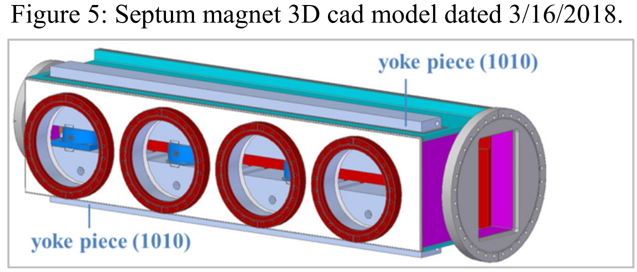

Figure 6: Same model, showing vacuum chamber only.[9]

[8] The leakage field for the "entrance" cross section is lower due to the pole gap field between the legs of the Y-pole being lower (cf. fig. 7).
[9] Downstream side has bellows and RF-fingers similar to the old septum.

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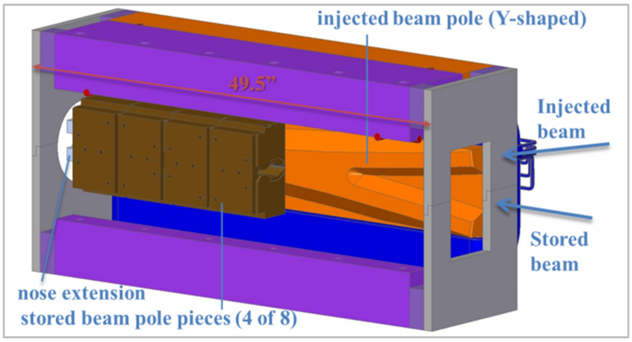

Figure 7: Same, with chamber and 4/8 pole pieces hidden.

With the 1010 yoke pieces Ni plated and the Hiperco 50A pole pieces Cu plated, analytical estimates indicate that 4x 750 l/s TSP's on the side ports will allow reaching the required < 1E-9 Torr pressure through the stored beam channel for this design.

3D SIMULATION RESULTS

A 3D model of the present design, created by importing the Fig. 5 cad model, is shown in Fig. 8. Due to the mirror plate openings for the vacuum chamber, there are unshielded fields at the ends, as seen in Fig. 9. These end fields are mainly dipole, so the resulting $\int B_x(x)dz$ profile (in Fig. 10) is still as flat as the 2D, meeting all the [4] requirements. It can be noted that this is after optimizing the end regions in 3D (ie. 2D FEA only is not enough).

Furthermore, 3D sensitivity studies have indicated that longitudinal gaps between pole pieces, vertical shifts and cut-outs for RF-fingers and pump ports are not critical for magnetic results, leaving freedom for the mech. design.

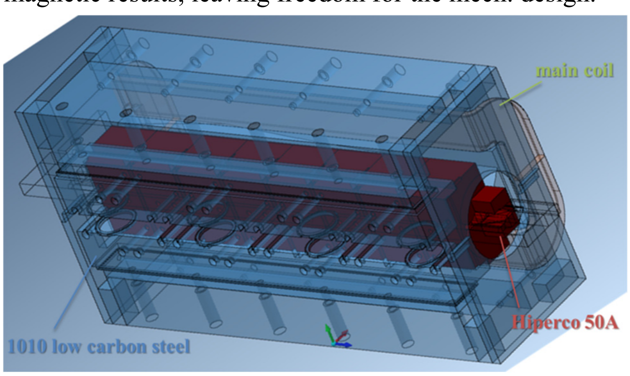

Figure 8: MagNet [8] 3D model.

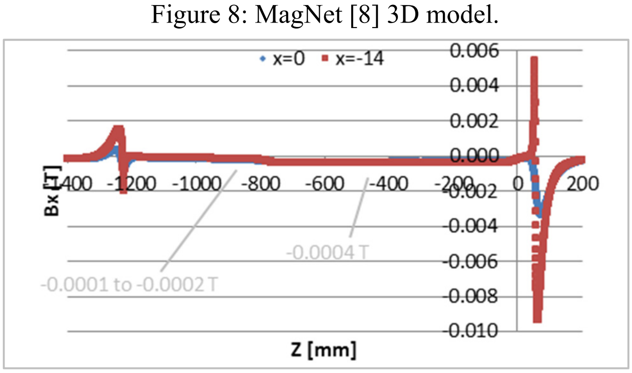

Figure 9: 3D simulation data, B_x leakage field through the stored beam channel from the Fig. 8 model. B_x levels within the bulk of the magnet agree with 2D (cf. Fig 4).

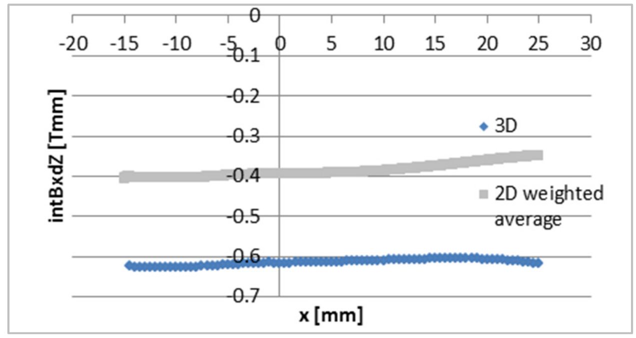

Figure 10: 3D simulation data from the Fig. 8 model, $B_x(x)$ integrated through stored beam channel, plotted together with weighted average of the Fig. 4 2D $B_x(x)$.

PROTOTYPE PLAN

In 3D simulations of a full length magnet with just a 10" long stored beam pole piece present, this pole piece has the same leakage field through its center as when the full length of pole pieces are present, suggesting the possibility of verifying the leakage fields without building the full magnet. Our current plan is to fabricate 3x 5.68" long pole pieces as follows:

1) Saw or water jet cut 3x blanks from as-received Hiperco 50A plate.
2) Rough machine to within 1/8" of final dimensions.
3) Heat treat per manufacturer's recipe, 4h at 865°C.
4) EDM to final dimensions.
5) Cu plating (tentative).

These pole pieces will then be mounted in a bolt-up version of the magnet (without vacuum details) and the leakage fields will be characterized by Hall probe.

CONCLUSIONS

The 3D magnetic FEA indicate that the present design is meeting the strict leakage field requirements. Comparisons between different 2D and 3D codes (MagNet 2D/3D, FEMM, Opera-3d) made for earlier versions of the design suggest that the simulations themselves are accurate. The main uncertainty lies in whether the material parameters used as input for the simulations, the B(H) data, is accurate. Or to put it another way, whether the intended processing/machining steps will result in the material having the magnetic properties it should have.

Other uncertainties are how flat we'll be able to get the split back yoke mating surfaces after welding, and how high the sensitivity to top/bottom return flux imbalances will be in reality. While 2D sensitivity FEA has indicated that asymmetric gaps between yoke parts of > 0.05 mm can be tolerated (leakage B_x and B_y flatness still within spec, and can be fully cancelled with trim coil.), 3D FEA indicates this sensitivity is 2x-3x higher than in 2D, as magnetic flux will move in z direction to adjacent pole pieces, driving more flux through the septum wall region.

If the measured leakage fields for the prototype agrees with simulations we will consider at least the B(H) data as verified and proceed to fabricate the pole pieces for the actual septum magnet by the same procedure.

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