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A NEW INTERACTION REGION DESIGN FOR THE SUPER-B FACTORY*

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Abstract

A final focus magnet design that uses super-ferric magnets is introduced for the Super*B* interaction region. The baseline design has air-core super-conducting quadrupoles. This idea instead uses super-conducting wire in an iron yoke. The iron is in the shape of a Panofsky quadrupole and this allows two quadrupoles to be side-by-side with no intervening iron as long as the gradients of the two quads are equal. This feature allows us to move in as close as possible to the collision point and minimize the beta functions in the interaction region. The super-ferric design has advantages as well as drawbacks and we will discuss these in the paper.

INTRODUCTION

The Super*B* accelerator design [1, 2] uses high-current (~1-2 A), very low emittance (~2 nm-rad in x and ~5 pm-rad in y) beams with a crabbed waist crossing angle scheme (allowing β_y^* values of ~0.2 mm) to achieve a design luminosity of 1×10^{36} cm^{-2}s^{-1}. This is at least 50 times higher than current B-factories. Present heavy flavour data samples are; 0.5 ab^{-1} for the BaBar detector and 1 ab^{-1} for KEKB. The Super*B* accelerator plans to deliver 15 ab^{-1} over a 10 yr period. This will generate a large enough data sample of B meson decays to enable a search for new physics with a mass reach in the several TeV range, matching and, in some cases, even exceeding the LHC. Getting these low emittance beams into and out of collision with the very small design β^* values is one of the more important aspects of the accelerator design.

THE INTERACTION REGION DESIGN

Baseline Design

The baseline interaction region (IR) design is described in more detail in [3]. We summarize here some of the important features. We have a series of 7 permanent magnet (PM) quadrupole slices located on the low-energy beam (LEB) in front of a cryostat containing two sets of twin super-conducting (SC) quadrupoles. The SC magnets are air-core magnets wound in a helical fashion to minimize the space needed for the conductors. The twin magnets are side-by-side and the windings of each magnet are designed so as to cancel the external fields produced by the neighboring quad. Table 1 lists some of the machine parameters of this design and Table 2 lists the magnet parameters. Table 1 shows a β_y^* that is lower for the LEB than for the high-energy beam (HEB). This was the reason the PM slices were added only to the LEB.

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Table 1: Some machine parameters important for the IR.

Parameter	HEB	LEB
Energy (GeV)	7.0	4.0
Current (A)	2	2
β_x^* (mm)	35	20
β_y^* (mm)	0.21	0.37
Emittance x (nm-rad)	2.8	1.6
Emittance y (pm-rad)	7	4
Crossing angle (mrad)	60	

Table 2: Magnet parameters of the baseline IR design.

Magnet	Z (m)	G (T/cm)
PM slices (2 cm each)	0.36-0.50	-(0.80-1.00)
QD0 LEB	0.58-0.98	-0.52
QD0 HEB	0.58-0.98	-1.19
QF1 LEB	1.6-1.9	0.40
QF1 HEB	1.6-1.9	0.72

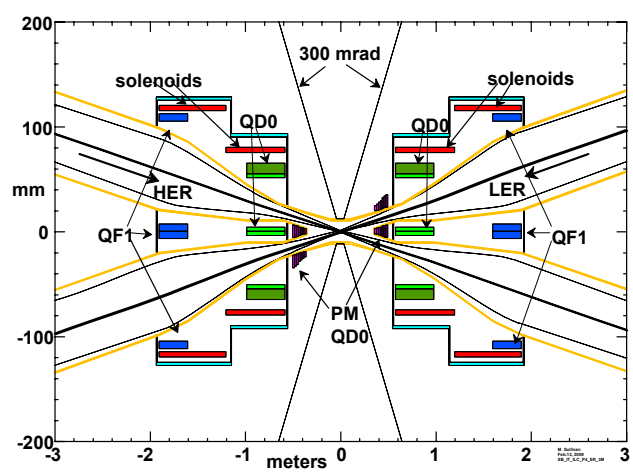

Figure 1 Drawing of the baseline design of the Super*B* interaction region as of June 2009.

Super-Ferric Idea and IR Design Evolution

One of the difficulties of the above design is that the SC quads have fairly high field strengths (especially the twin quad section for the HEB). In addition, the difference in field strengths between the LEB and the HEB in the twin QD0, although possible to do in the air-core design, were making the overall design still more difficult. Since then, a new idea has come forward (from P. Vobly of BINP) to use Panofsky style quadrupoles in place of the air-core quads. These magnets would have a Vanadium Permendur steel alloy frame about which the coils would be wound. The Panofsky design can have a very thin profile and two magnets can be set side-by-side. In addition, the flux through the central section of iron cancels, in this case, allowing us to actually remove the

iron from between the two beams as long as the gradients of the two quads are equal. The coils would still be super-conducting and hence all of the cryostat requirements would be the same. Fig. 1 shows an example of a twin super-ferric quadrupole design.

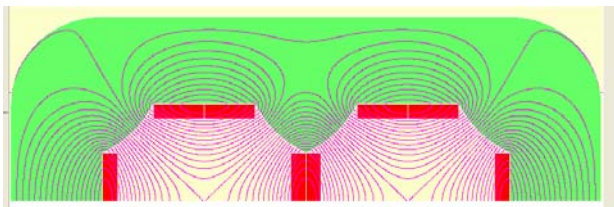

Figure 1. Example of a Panofsky style twin quadrupole. Notice that there is no iron between the quads. One can also see that the magnets are self-shielding. The iron thickness in this drawing is very conservative. We should be able reduce the iron thickness by at least a factor of 2 and perhaps by as much as a factor of 4.

This idea has many attractive features. One is that the design and construction of these magnets would be significantly easier than the air-core design. Another is that the magnets are generally self-shielding. Yet another advantage is that the quadrupoles can be aligned with the beam axis. However, there are a couple of drawbacks. The first is that the twin quads have to have the same gradient or else we have to make room between the beams to insert some amount of iron between the twin magnets. Second, the maximum allowed gradient, set by the saturation curve of the iron, is about 1.8 T. Vobly proposed 2 T as a limit but we need to be able to increase the gradient about 10% in order to scan the center-of-mass energy above the 4S resonance hence the lower limit of 1.8 T. A way around both of these problems is to add a second Panofsky style quad to the HEB behind the QD0 magnet. This magnet would continue the vertical focusing of QD0 for the HEB and give us the needed integrated strength to control the HEB beta functions. This then allows us to make gradients in the twin QD0 magnet equal and keep the gradient strength below the upper limit of 1.8 T by increasing the effective length of the HEB QD0. This second QD0 for the HEB does not need a partner quad on the LEB because of the self-shielding aspect of the Panofsky design. This same idea can be used on the QF1 magnet which is also a twin magnet.

This approach looked promising. However, the field strengths were still getting high and consequently we either had to back up the magnets from the interaction point (IP) or we had to lengthen the magnets in order to keep below the 1.8 T limit. This can rapidly lead into more difficulties as either backing up the magnets and/or lengthening these magnets increases the beam size in these magnets which forces an increase in the magnet aperture which, in turn, forces a decrease in the magnet gradient in order to stay below our upper limit of 1.8 T.

In this same time frame the accelerator design was evolving and modifications to the beta functions at the IP led to a more balanced set of β* values. Table 3 shows the new machine parameters.

Table 3: Some parameters from the improved machine design used in the newer IR design.

Parameter	HEB	LEB
Energy (GeV)	6.7	4.1
Current (A)	2	2
β_x^* (mm)	32	26
β_y^* (mm)	0.21	0.25
Emittance x (nm-rad)	2.5	2.0
Emittance y (pm-rad)	6.2	5
Crossing angle (mrad)	66	

Permanent Magnet Redesign

Rebalancing the IP beta functions suggested that we should re-evaluate the permanent magnet design. It was clearly not optimal and perhaps we could improve the PM part of the design by being more aggressive in adding magnetic material. We increased the opening angle between the beams from 60 mrads to 66 mrads with this in mind. We also decreased the size of the beam pipes under the PMs from a 7 mm radius to a 6 mm radius. In addition, we shortened the z length of the PM slices and increased the number of slices in order to further increase the amount of magnetic material. We also added two magnetic slices inboard of the split beam pipe. These slices are shared (both beams go through them) and hence we obtain small beam deflections from these shared PM slices that further increase the beam separation. We also chose a slightly higher remnant field (1.34 T) for the material which means we are using Neodymium-Boron-Iron material. This remnant field value is not the highest possible so we have some conservatism in the design to account for packing fraction and mechanical support. One final change was to orient the slices along the beam axis which keeps them perpendicular to the beam and reduces entrance angle aberrations. These changes allowed us to significantly increase the focusing strength of the PM part of the design. In addition, we were able to move most of the PM focusing over to the HEB thereby reducing the required strength of the QD0 magnet for the HEB and making the gradients for the two QD0 magnets more naturally equal. The result is the design shown in Figure 2 and in Table 4.

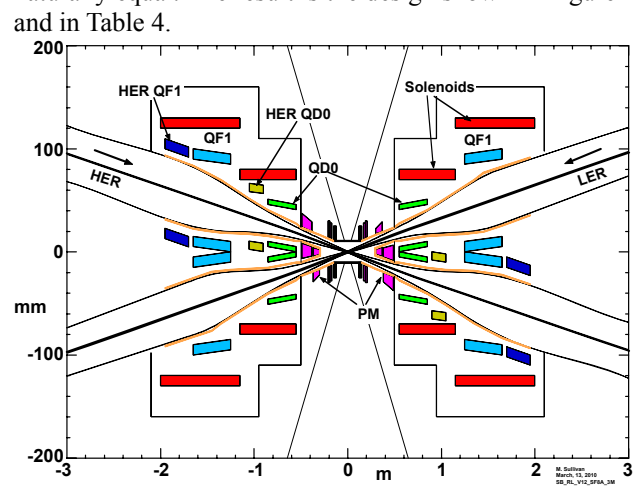

Figure 2. Drawing of the improved IR design with the Panofsky style quadrupoles. The improved PM design is also shown. Note the extra quadrupoles on the HEB. Note also that the quads are generally more aligned with the beams.

Table 4: Magnet parameters of the improved IR design.

Magnet	Beam	IP (m)	L (m)	G (T/cm)
QD0SA	both	0.017	0.02	-1.076
QD0SB	both	0.019	0.02	-0.994
QDPA	LEB	0.30	0.01	-1.392
QDPB	LEB	0.31	0.01	-1.473
QDPC	LEB	0.32	0.01	-1.547
QDPD	LEB	0.33	0.01	-1.616
QDPE	LEB	0.34	0.01	-1.680
QDPF	LEB	0.35	0.01	-1.740
QDPG	LEB	0.36	0.01	-1.796
QDPI	HEB	0.38	0.01	-1.899
QDPJ	HEB	0.39	0.01	-1.945
QDPK	HEB	0.40	0.01	-1.989
QDPL	HEB	0.41	0.01	-2.030
QDPM	HEB	0.42	0.01	-2.070
QDPN	HEB	0.43	0.01	-2.107
QDPO	HEB	0.44	0.01	-2.142
QDPP	HEB	0.45	0.01	-2.175
QDPQ	HEB	0.46	0.01	-2.207
QDPR	HEB	0.47	0.01	-2.238
QDPS	HEB	0.48	0.01	-2.266
QD0 (twin)	both	0.55	0.30	-0.938
QD0H	HEB	0.90	0.15	-0.707
QF1 (twin)	both	1.25	0.40	0.407
QF1H	HEB	1.70	0.25	0.381

The new design has improved flexibility over our baseline design. We are able to adjust the LEB magnets and then compensate for the effect the change has on the HEB (that comes through the twin magnets) by adjusting the HEB only quadrupoles. In a similar fashion, we can adjust the HEB only quadrupole magnets to change the HEB and not affect the LEB. One can see that most of the gradients of the magnets are smaller, especially the highest gradient magnet (the HEB half of the QD0 twin) which is lower by 20%. The twin air-core magnet design can also be used in this newer configuration. The air-core magnets should be able to replace the twin Panofsky style quads and we can continue to maintain the flexibility of the new design.

Holmium

We have recently become aware of the fact that there exists a whole series of rare-earth elements that exhibit large magnetic moments. The element with the largest magnetic moment of all is Holmium. It is also interesting in that this metal becomes ferromagnetic at temperatures below 20° K. This element has a magnetization curve in excess of 3.8 T [4, 5]. If we use this metal for the Panofsky style quads then we can either reduce the thickness of the metal and still be able to generate the desired field gradient or we can try a design with the same metal thickness as the vanadium permendur design but with shorter magnets in z and with higher field gradients. We decided on this latter choice. We chose a maximum field of 3.2 T for the design. The shorter magnets move magnet centers closer to the IP thereby lowering the maximum β values. Table 5 summarizes the maximum β values for the three designs.

Table 5: Beta function values of several design options. The vanadium permendur and air-core designs use the same z space for the twin magnets and hence have the same maximum beta function values.

	LEB		HEB	
Design	IP	Max. β	IP	Max. β
	x/y (mm)	x/y (m)	x/y (mm)	x/y (m)
Baseline	35/0.21	414/2193	20/0.37	580/1970
Van. Per.	32/0.21	309/1424	26/0.25	490/1208
Air-core	32/0.21	309/1424	26/0.25	490/1208
Holmium	32/0.21	221/1300	26/0.25	328/1111

SUMMARY

The interaction region design of the Super*B* accelerator has significantly improved. A large part of the improvement is due to the new machine parameters of more balanced β_y^* values and a larger beam crossing angle. These changes evolved over the last year and caused us to re-evaluate the permanent magnet (PM) aspect of the IR design. We found that by making several changes to the PM design we were able to significantly increase the magnetic strength of the PM part, thus reducing the strengths of the super-conducting (SC) parts of the final focus system. This improved the feasibility of the SC part of the baseline design as well as open up the possibility of using Panofsky style quadrupoles instead of air-core quads. The idea of Panofsky style quadrupoles has also allowed us to add extra quadrupole magnets to the high-energy beam final focus system without introducing unwanted external fields on the nearby low-energy beam. This increases the flexibility of the design by further decoupling the two beam lines. The overall design now looks very promising.

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