PRELIMINARY FEASIBILITY STUDY ON 1.1 – 2.2 T RAMPING DIPOLES FOR DAFNE2

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Abstract

DAΦNE $e^+ - e^-$ collider ring can, in principle, be upgraded up to about 2 GeV c.m. energy without any changes in the machine layout, apart from the substitution, in the main rings, of the dipole magnets, the splitters and few quads. This paper deals with the feasibility of the realization of the required dipoles, taking into account the new magnetic field requirement, the mechanical constraints due to the present layout of DAΦNE and the eventuality to ramp the magnet from lower field. Two different approaches are considered: to modify the present geometry of the dipoles and to use high performance magnetic materials in the core.

INTRODUCTION

DAΦNE team is investigating the opportunity to increase the energy of the beams in the machine up to neutron-antineutron threshold (about 2 GeV c.m.) [1].

To do this, the modification in the machine can be limited to the:

- Substitution of the present 16 1.2 T dipoles of the main rings with new ones with higher maximum magnetic field, eventually with the possibility to ramp the magnet from the present nominal field
- Substitution of the 4 splitter magnets
- Substitution of the low-beta quadrupoles in the 2nd interaction region (IR2)

Almost all of the rest of the DAΦNE hardware (e.g. other magnets, vacuum chamber, injection system, RF system, feedback…) can be still used in the new machine.

The main problem of this upgrade comes from the dipole design: saving the present vacuum chamber leads to the necessity to realize magnets with the same bending angle and (almost) the same bending radius of the DAΦNE dipoles. Increasing the beam energy keeping constant the bending radius implies an increase of the magnetic field, which can be reached either with superconducting magnets or with resistive dipoles. Different reasons brought us to choose to study the second hypothesis.

DAΦNE DIPOLES

In the DAΦNE main rings there are 16 dipoles, 8 in the electron ring and 8 in the positron one (see Fig. 1). Each ring has two sections, the *long* section and the *short* section [2,3].

All the dipoles are C–shaped magnets with the same bending radius. Half of them are sector-like, and the others are parallel end shape. Dipoles in the *long* section have a bending angle greater than the ones in the *short* section.

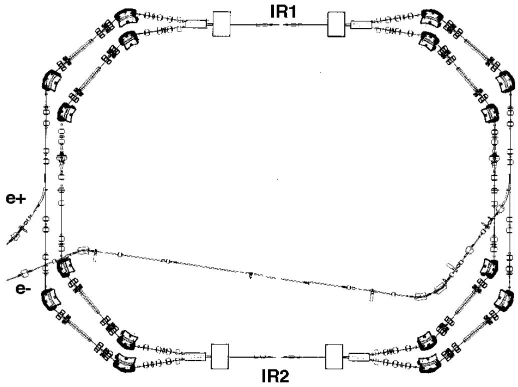

Figure 1: DAΦNE Main Rings Layout

The main parameters of the magnets are listed in Table 1. They are valid for both the sector-like and the parallel end shape dipoles.

Ring Section	*long*	*short*
Nominal Field	1.21 T	
Bending Radius	1.400 m	
Bending Angle	49.5°	40.5°
Gap Height	75.6 mm	
Magnetic Length	1.210 m	0.990 m
Good Field Region	± 30 mm	
Field Quality	$\pm 1.5 \times 10^{-4}$	
Current Density	2.5 A/mm^2	

Table 1: DAΦNE dipole main characteristics

NEW DESIGN AND CONSTRAINTS

We based the dipole design starting from the constraint that the present layout imposes to us.

The main constriction is to maintain the DAΦNE vacuum chamber. This implies constraints on minimum gap and on the mechanical length. At present the gap is 75.6 mm, although it is possible to lower it down to 70 mm removing the vacuum chamber thermal insulation, that it is no longer required. In the following we will consider this last value.

Keeping DAΦNE vacuum chamber also should impose the same bending angle and bending radius of the present dipoles. However, it is possible to slightly modify the particle trajectory in the bending sections in order to

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increase the radius up to 1.53 m. It helps us to lower the required magnetic field.

This trajectory adjustment can be done modifying the magnets dimension and shape, in order to fill all the available space on the vacuum chamber; in this way all the dipoles become sector-like.

Unfortunately, these modifications make the installation of the new magnets much more complicated. In fact, it is not possible to put the magnet directly around the vacuum chamber from the lateral side. End plates of the magnet have to be installed after that main core had placed on site.

From the equation

$$E\,(\text{GeV}) = 0.3\,B(\text{T})\,\rho(\text{m}), \tag{1}$$

if we consider electron (or positron) with energy of 1.02 GeV and a bending radius of ρ = 1.53 m, we get a required field B of 2.22 T. This means that, using iron magnet, the pole shoes will be fully saturated.

Also, due to the effects of the strong field, the good field region cannot be as large as the present one. In this paper a value of ±20 mm is considered.

The main requirements about the new dipole are summarized in Table 2.

Ring Section	*Long*	*Short*
Beam Energy	0.51 to 1.02 GeV	
$B\rho$	1.7 to 3.4 T m	
Magnetic Field	1.1 to 2.2 T	
Bending Radius	1.530 m	
Bending Angle	49.5°	40.5°
Gap Height	70 mm	
Good Field Region	± 20 mm	

Table 2: New Dipole Requirements

In the next sections the 2-D simulations are described. Two different design strategies are considered: first, the reshape of the present dipoles using the same iron. Second, the opportunity of using high performance material has been considered.

IRON DIPOLES

Due to the high field requested in the gap, it is necessary to increase the dimension of the magnets, in order to reduce the saturation, at least in the iron yoke and in the leg. However, there are some limitations in the overall dimension of the magnets. As it can be seen in Fig. 1, some of the dipoles are very close each others, especially near the interaction region.

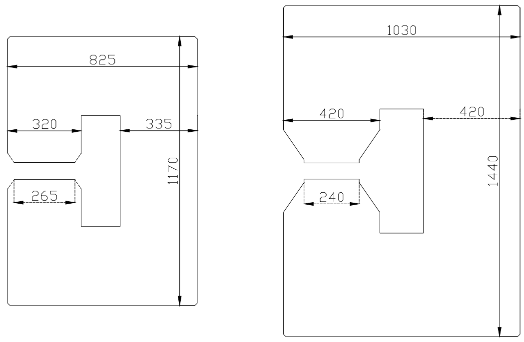

Figure 2: Iron dipole profile chosen in the simulations (right) compared with DAΦNE dipoles profile (left)

In Fig. 2 the dipole profile chosen for the simulations in comparison to the DAΦNE dipole profile are shown (drawings *are* in scale). Also the coil profile area is increased, and the poles are reshaped to optimize the field in the gap. In particular, the pole tips are shaped to get the best field quality in the range of beam energy considered (from the present energy of 0.51 GeV up to 1.02 GeV). The material chosen for the yoke is the Magnetil, the same of the DAΦNE dipoles.

Simulation results

Two-dimensional simulations are made with POISSON SUPERFISH finite element method code.

Different simulations have been made in the range of fields 1.1 – 2.2 T. The main results are:

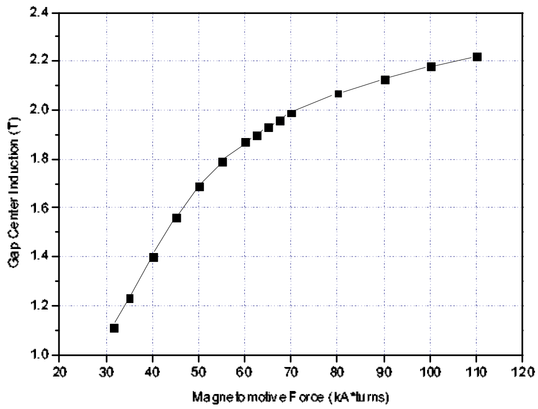

Figure 3: Induction in the gap center versus magnetomotive force.

- the magnetomotive force ranges from 31.5 to 110 kA*turns (see Fig. 3). Consequently, with a given coil surface area of 3.24×10^4 mm^2 and a typical filling factor of 0.55, the current density in the coils ranges from 1.8 to 6.2 A/mm^2;
- at the higher fields not just the pole tips, but also the iron yoke is saturated. This leads to

strong stray fields (500 G at 1 m off the beam axis in the 2.2 T case) and to relevant power loss;

- the field quality shows its better value (4.5 $\times 10^{-5}$ in a good field region of ±20 mm) at an intermediate field, but it rises to about 9×10^{-4} at the ends of the range (Fig. 4). As the ramping field range can be lowered (i.e. starting the ramp from a field higher than 1.1 T), these values can be improved, reshaping the pole tips.

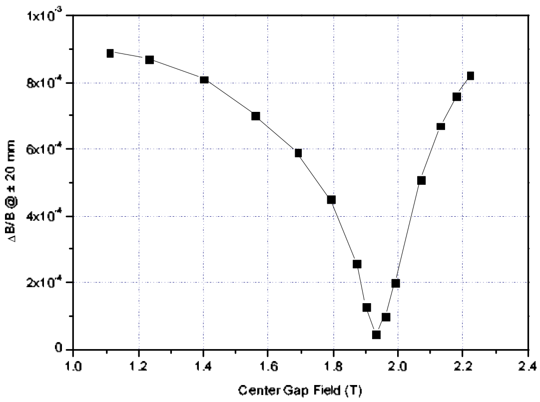

Figure 4: Field quality at different induction values.

As an example of the field profile in the transverse axis of the dipole, the vertical component B_y of the field is shown in Fig. 5. $X = 0$ cm corresponds to the beam axis.

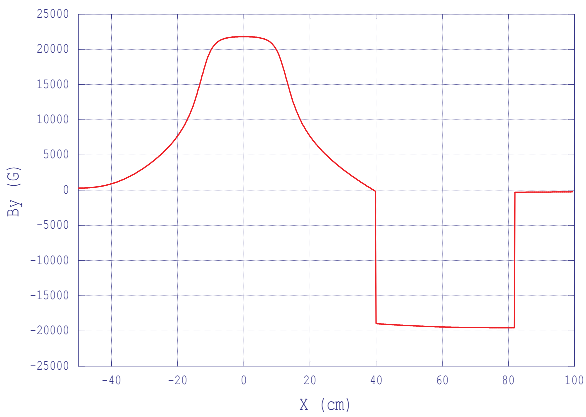

Figure 5: Output of Poisson on X axis for B_y. $H = 100$ kA*turns.

In conclusion, these preliminary simulations show that it is, in principle, possible to realize iron magnets with the required specifications, but it is very hard to do. Also, there are at the moment some open points: effects of stray fields and fringing fields (this last point needs three-dimensional simulation), and finally mechanical complexity of the installation.

This brings us to try other ways to investigate the matter, such as consider changing some parameters. A possibility is to use other materials than iron. In the next section a design where the yoke is realized with two different materials is described.

HIGH MAGNETIC SATURATION MATERIALS

High performance materials opportunities have been explored in order to obtain higher fields saving magnetomotive force and volume.

Special high temperature Iron-Cobalt-Vanadiun alloys, with about 50% of Co, sometimes named Permendur, at the moment represent the commercial soft magnetic materials with the highest saturation induction: up to 2.4 T with respect to 2.15 T of pure Iron (ARMCO®). These alloys are produced with small differences in the composition and different denomination by manufacturers.

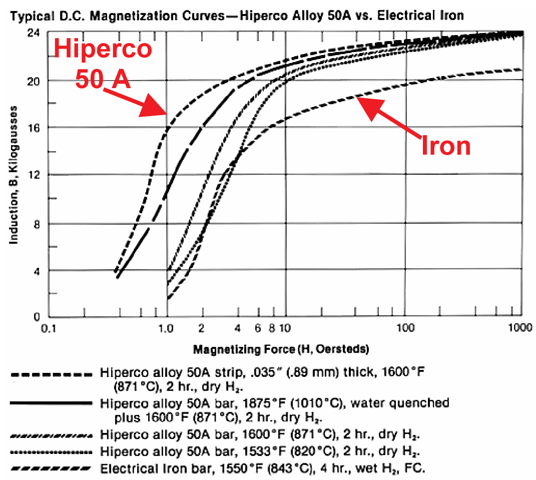

Figure 6: Hiperco and Steel DC Magnetization Curves.

Hiperco® is a registered trademark of Carpenter Technology [4] (Fig. 6) Vacoflux® of Vacuumshmelze Gmbh [5]. This specialty is forged in bars, wires and also in strip. It has been taken into account in the form of strip, respectively as Vacoflux® 50 and Hiperco® Alloy 50A.

These alloys have been used primarily for magnetic cores in electrical equipment requiring high permeability at high magnetic flux densities such as high flux density pole-shoes of alternators, electromagnets, magnetic lenses, needle printers, relays, motors and actuators with high torques and forces.

In the following simulations of the dipoles, Hiperco® Alloy 50A characteristics have been adopted. This alloy (49% Cobalt, 2% Vanadium, 0.05% silicon and trace of Carbon, iron balance) shows high magnetic saturation (24 kilogauss), high D.C. maximum permeability, low D.C. coercive force, and low A.C. core loss.

Fig. 7 shows the relative permeability of Hiperco® 50A vs. induction compared with Magnetil® [6], the high performance silicon-steel currently used in DAΦNE dipoles.

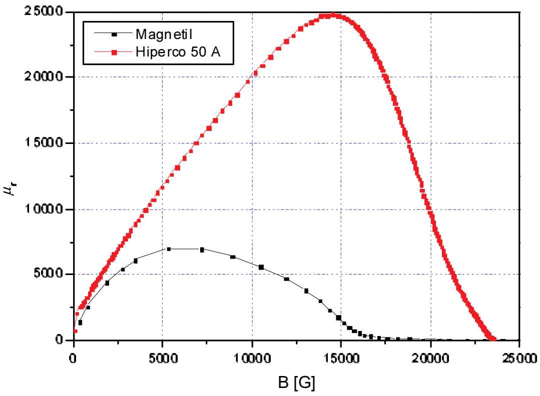

Figure 7: Hiperco® 50 A and Magnetil® relative permeability μ_r.

COMPOUND DIPOLES

Due to the high cost of Co-Fe alloys, a compound magnetic core with only the pole of this material has been evaluated. In this case the yoke is made of electric steel. The aim is to make a flux concentrator having an high flux density in the gap and a limited one in the yoke.

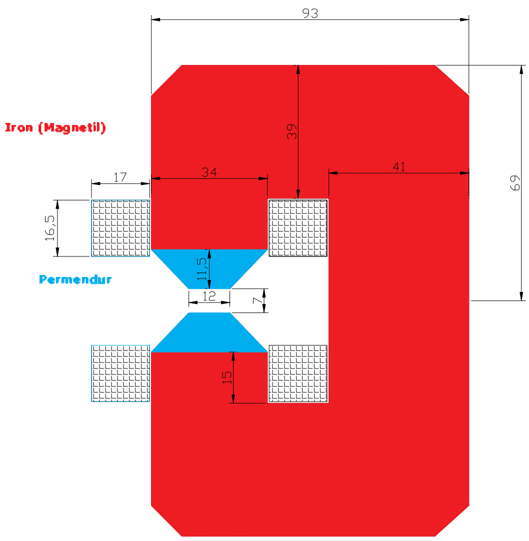

Figure 8: Sketched cross section of the compound magnet (dimensions are in cm).

Bi-dimensional FEM analysis has been made using POISSON and Maxwell 2D. Electrical laminated steel Magnetil® has been used for the yoke. Tip poles have been simulated with the magnetic properties of Hiperco alloy 50A of Carpenter Ltd. On both regions a stacking factor of 0.97 has been taken into account.

Several tentative outlines have been worked out in order to optimize the ratio between Hiperco and Iron volume, starting from the DAΦNE dipole overall dimension. A bit larger core with respect to DAΦNE original dipole has been assumed in order to reduce MMF and stray fields.

Fig. 8 shows the dimension of a section of the magnet with a good compromise between the maximum induction in the center of the gap and the volume of Hiperco.

The simulation results are shown in Fig. 9 and 10 with a magnetomotive force of 90 kA* turns.

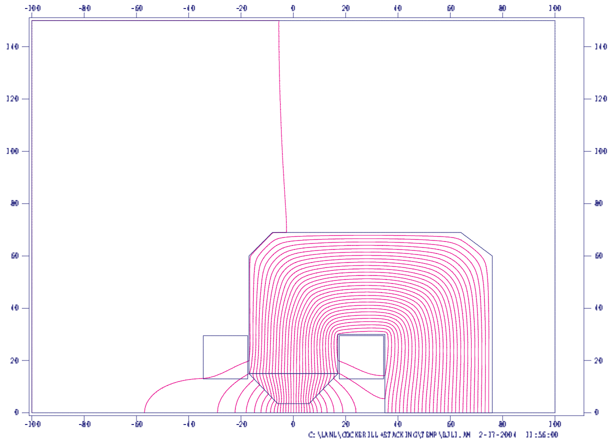

Figure 9: Magnetic flux lines generated with Poisson @ 90 kA*turns.

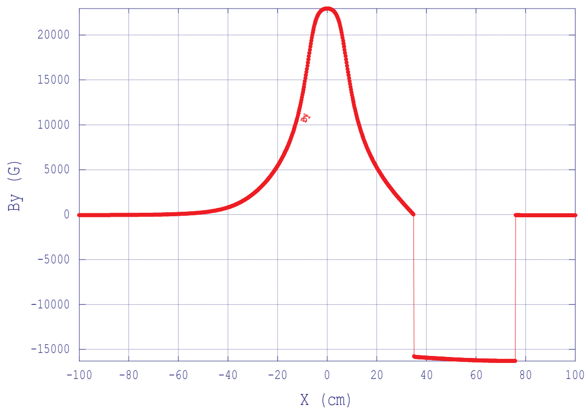

Figure 10: Output of Poisson on X axis for B_y. H = 90 kA*turns.

The geometry of the core has been optimized in order to achieve the same saturation level in the steel and in the Hiperco region. Once defined the starting geometry several simulations have been performed at different currents.

Flux densities versus magnetomotive force are plotted in Fig. 11, where B_o represents the field in the center of the gap, B_{fe} the average value in the iron core, B_{max_fe} the maximum flux density in iron and B_{tip} the value in the center of the Hiperco region. The plot shows that the maximum cost-effective magnetomotive force of this configuration is about 90 kA*turns, that can produce a field in the center of the gap of 2.29 T.

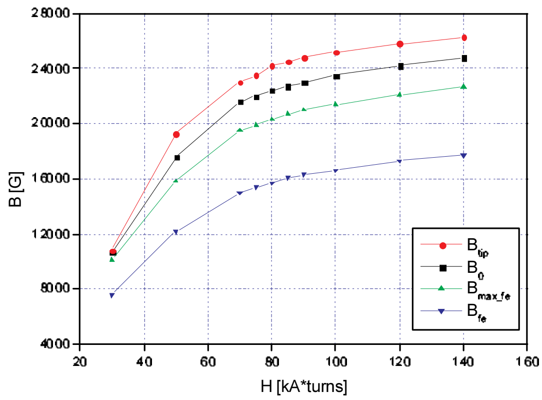

Figure 11: Induction in the gap (B_0), compared with max values in Iron region (B_{max_fe}), Hiperco® pole tip (B_{tip}) and in the Iron (B_{fe}), versus magnetomotive force.

Using this working point Steel and Hiperco are not yet fully saturated and stray fields are limited, as it shown in fig.12. Increasing current above the saturation point produces a limited induction gain with relevant power loss and stray fields.

As expected, with the flat pole used in these preliminary simulations field quality results are very poor because pole shaping optimisation is not yet performed. Field quality is less than 1.7×10^{-2} in the good field region of ± 30 mm (Fig. 13).

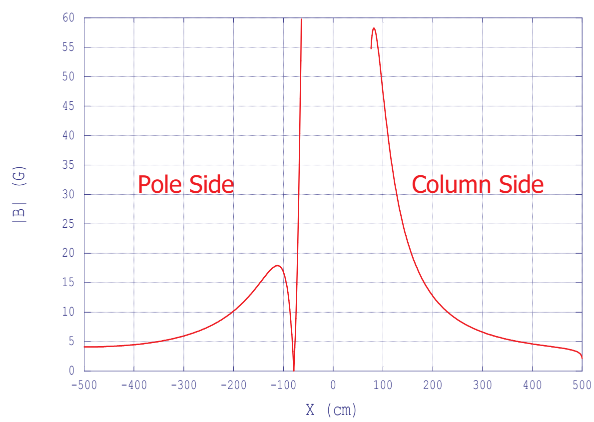

Figure 12: Fringing fields decays on pole and column side @ 90 kA.

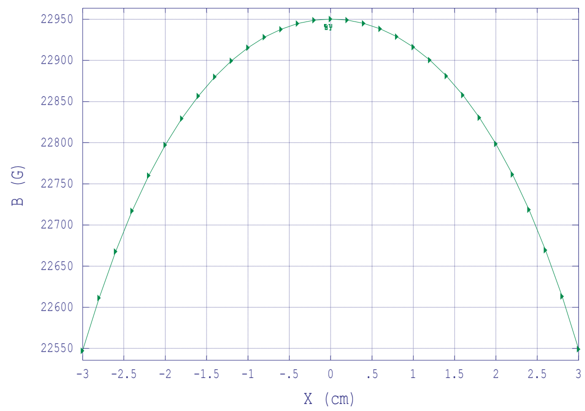

Figure 13: Flux density in the gap @90 kA.

Assuming the same wire and the same number of turns used for the DAΦNE Dipole coils (144 turns), the considered working point has a current of 625 A, a current density of 6 A/mm^2 and power loss of 467 kW per ring. This means that the new dipoles fit with the existing power supplies and cables with consistent cost saving.

Table 3 resumes material quantities and power loss.

	Dipole Type		Total DAFNE2
	Long	Short	
Bending angle [deg]	49.5	40.5	
Volume [m^3]			
Steel	1.33	1.13	19.67
Permendur	0.07	0.06	1.00
Copper	0.10	0.09	1.50
Weight [kg]			
Steel	10517	8879	155171
Permendur	549	464	8102
Copper	878	763	13126
Tot Type	11944	10106	176398
Power [kW]	63	54	935

Table 3: Weight and Power loss

Some different sketches with different ratio Hiperco/Iron volume have been investigated in order to evaluate the Permendur zone contribution.

Table 4 compares the results obtained at 90 kA using the same core section with increased use of the alloy. Value of these comparisons is limited because dimension of yoke and leg are not optimised with the modified materials.

Part of Permendur	*% of Permendur Volume*	*Bo [T]*
None - All Magnetil	0.0	2.12
Pole tip (fig. 8)	4.7	2.30
Pole tip+ 5 cm of pole	7.7	2.31
Pole tip+ 15 cm of pole	13.8	2.37
All the magnet	100.0	2.46

Table 4: Flux density in the gap from cores with increasing percentage of Permendur at the same MMF (I=90 kA).

Cost evaluation

The overall cost is dominated by Cobalt-Iron alloy, whose rough material cost is evaluated around 120 €/kg. To estimate the cost, the total extra cost of the Hiperco of about 1000 k€ has to be added to the revaluated cost of DAΦNE dipoles.

Extra costs are balanced by the saving in the supply system.

CONCLUSIONS

This preliminary 2D study shows that a Steel/Iron Cobalt dipole with similar dimension of existing ones could reach 2.3 T with reasonable current and stray fields.

1.02 GeV of energy, that means 2.2 T of dipole field, could be reached with these new magnets with 75 kA and doesn't involve additional changing in the layout.

1.06 GeV could be considered as the maximum energy that can be reached with this geometry. Some more gain could be obtained increasing the content of Hiperco, as shown in tab. 4.

More simulations have to be done to define the pole profile in order to obtain acceptable field quality.

3D modelling has to be done in order to validate the 2D simulations and define the magnetic length.

The construction of a prototype of the magnet has is strongly recommended.

ACKNOWLEDGEMENTS

We warmly acknowledge Claudio Sanelli for his helpful suggestions.

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