

ENC INTERACTION REGION SEPARATION DIPOLES

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Abstract

The Electron Nucleon Collider (ENC) is proposed as an upgrade of the High Energy Storage Ring of the FAIR. The beams are separated by two dipoles, mounted closely to the interaction point; surrounded by the detectors. Hence these magnets must provide sufficient field quality but be slim to be transparent to the secondary particles. Further these must be air coil magnets due to the detector solenoid field of 2T.

We present the 3D optimised magnet next to a first design of the mechanical restraint structure and a concise description for the field distortion leaking into the detector.

INTRODUCTION

The ENC project is a electron nucleon (proton) collider at rather lower energy [1]. Due to the different charge and direction the Lorentz force acting on the beam particles points into the same direction in a dipole field; but the electron beam will only have a quarter of the energy of the nucleon beam. The interaction region design (IR, see Fig. 1) [2, 3]) uses two dipole for separating the two beams. The space within the detector, available to these dipoles is limited by the following requirements for the secondary beams: particles within an angle of 0 – 5 degree shall be

able to reach the forward spectrometers (EDS and PDS, see Fig. 1) and particles within an angle of 25 – 155 and 175 to 180 degrees shall be not obstructed in their path to the detector. This defined the requirements for the dipole. It's length shall be 0.5 m, the inner bore radius 75 mm and the integral field strength 0.33 Tm. The synchrotron radiation generated by the bending of the electron beam in the dipoles can create an additional continuous heat load on these separation magnets, thus the Nuclotron cable [4] was chosen as it is a good choice for such types of heat loads [5].

INNER DIPOLE 3D DESIGN

The magnet centre is 0.5 m off the intersection point. Only limited space is left between the magnets (0.7 m).

Magnetic field description

The magnets have to fulfil the field quality requirements typical for accelerator magnets while filling as little space as possible as typically required for detector magnets. Classical 2D multipoles

$$\mathbf{B}(z) = \sum_{n=1}^{\infty} C_m \left(\frac{\mathbf{z}}{R_{Ref}} \right)^{n-1} \quad (1)$$

are used and appropriate to describe the magnetic field in the magnet aperture. Here $\mathbf{B}(z) = \mathbf{B}(x + iy) = B_y + iB_x$ with x and y the Cartesian 2D coordinates and $R_{Ref} = 35\text{ mm}$ the reference radius. The higher order harmonics $c_n = b_n + ia_n$ are given by $c_n = \frac{C_n}{C_m} 10^4$, with m the main multipole ($m = 1$ for the dipole). The relative multipoles are presented in units (1 unit = 100 ppm). $b_y(z)$ is defined by $b_y(z) = (B_y(z) - B_y(0)) / B_y$. The multipoles for the 3D Fields were calculated for the fields integrated along the longitudinal coordinate s . Thus the equivalent 2D field is given by

$$B(x, y) = \frac{1}{l_m} \int_{-\infty}^{\infty} B(x, y, s) ds \quad (2)$$

with l_m the foreseen length of the magnet. This integration was done numerically so an integration length of $s = -5\text{ m}$ to $s = 5\text{ m}$ was used.

End field Artifacts

The design, given in [6], was only made for a 2D section. It was clear from the beginning that this design will not satisfy the beam dynamic requirements. Higher order harmonics of 1 percent were found for the integral field.

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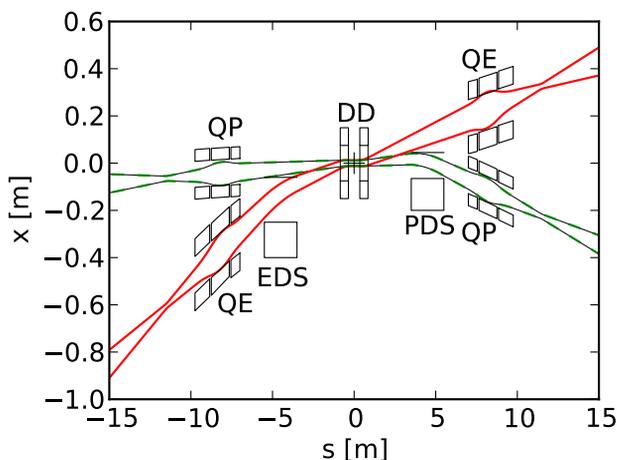


Figure 1: A sketch of the ENC IR region. Red solid line ...electrons, green dashed lines ...protons. large cross ...IP. Magnets: D ...separation dipole, PDS ...spectrometer dipole, EDS ...electron spectrometer dipole; QP ...proton triplet quadrupole, QE ...electron triplet quadrupole

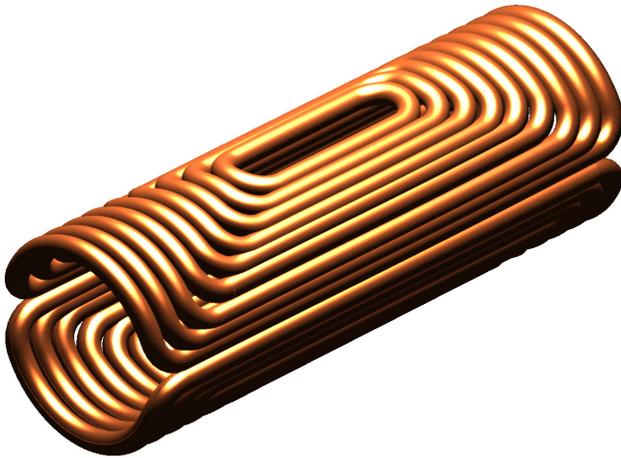


Figure 2: The dipole magnet designed using the high current Nuclotron cable. One can see that the cable thickness and its minimum bending radius will produce a magnet with an inherent 3D field. The length of the magnet is 500 mm and the diameter of its bore 150 mm.

Literature on accelerator magnets gives as a rule of thumb that the lateral field component B_s will be large for a length equivalent to twice the aperture. Therefore one will not expect any 2D field (i.e. $B_s \approx 0$) within these magnets given the bore diameter of 150 mm and the magnet length of 500 mm. Further the length of the coil turns differ significantly (see Fig. 2) due to the diameter of 10 mm of the Nuclotron cable. Therefore the whole 2D/3D magnet design has to be optimised in one step.

For an air coil magnet turns below 30 Degree will produce a positive sextupole and turns above a negative sextupole. The minimum end will typically produce a negative sextupole, and therefore the integral harmonics are optimised varying the length of the cable (see e.g. [7]). This did not work for that magnet as the integrated harmonics had already a large positive sextupole thus the inner windings would require to be longer than the outer windings leading to a at least impractical design.

Optimised 3D field

In a first step different 2D designs were made adding large negative sextupoles. Coil end loops were added to these designs, following the inner bore cylindrical geometry, with a minimum bending radius for the cable of 25 mm, making the coil end as compact as possible. Then the integral field was calculated and its associated harmonics. A central design with a negative sextupole with a relative strength of $c_3 = 5.25\%$ was found to provide a good starting point ($R_{Ref} = 35$ mm).

The final optimisation was performed using the nmsim-plex algorithm as provided by the GNU Scientific Library (GSL) [8] using the angular placement of the central coil windings as optimisation parameter. The result obtained is given in Table 1. This design leaves a sextupole of ≈ -13 units and a dekapole of ≈ -1 unit. The comparison of

Table 1: The harmonics of the IR dipole. 2D denotes the harmonics if the central cross section would be infinitely long. 3D denotes the harmonics as found for the integrated field (i.e. the short lens approximation). The first two lines are given for a design optimised in 2D while the last two lines give a design optimised in 3D.

type	$B_1[T]$	$I[kA]$	b_3	b_5	b_7	b_9	b_{11}
original							
2D	0.66	9.7	0	0	-0.13	0.33	-0.27
3D	0.92	13.6	445.05	18.39	0.94	0.04	-0.21
optimised							
2D	0.85	13.6	-547.3	15.7	0.2	0.6	0.1
3D	0.66	13.6	-13.2	-1.32	-0.08	-0.28	0.02

the former pure 2D design to the design, presented here, optimised for its integral harmonics, indicates that a more current efficient design could be feasible.

The maximum field for the optimised design is found at $x = 0, y = 75, z = 0$ to ≈ 0.98 T, while the field at the inner side of the coil is already considerably lower. The strands, currently procured for the SIS100 dipole, will be measured for their limits. The test of the SIS100 dipole will show which current can be achieved for this high current Nuclotron cable at fields of ≈ 2 T [9]. The maximum field on the conductors is thus estimated to $\sqrt{0.9^2 + 2^2} \approx 2.2$ T due to the field of the Panda solenoid.

All calculations presented here used a pure air coil neglecting the paramagnetism of the superconductor or any other effect of the superconductor.

FORCES ON THE MAGNET

In a pure solenoid field only the components of the vector currents flowing into the x and y direction (see Fig. 1) will create Lorentz forces. The current in the conductors is ≈ 14 kA. Therefore the maximum Lorentz force f_L created by the current and the detector solenoid field of 2T on one conductor, neglecting the field created by the dipole, is 28 kN/m.

So if the geometric axis of the interaction dipole is perfectly aligned to the solenoids direction these forces only occur in the coil head ends but cancel for these windings which are perfectly symmetric, but still add to the total force the magnet support structure must be able to sustain. The Lorentz forces do not cancel out for the currents flowing in horizontal direction (x). One can estimate an upper boundary for this force assuming n wires with a length equivalent to the bore diameter (projection of the largest coil head in the horizontal direction). This total Lorentz force F_L^t on the coil head is given by

$$F_L^t \approx n I_w d_b B = 9 \cdot 14 \cdot 10^3 \cdot 0.15 \approx 38 \text{ kN}, \quad (3)$$

with n the number of turns of the coil, I_w the current in the coil winding and d_b the bore diameter. This force is

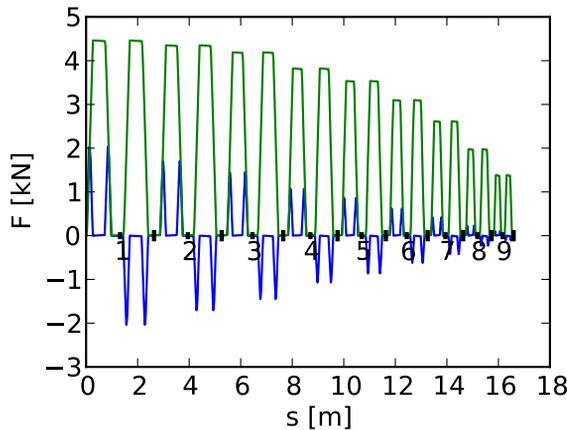


Figure 3: The integrated Lorentz forces created by the detector solenoid (2 T) on the IR separation dipoles (current 14 kA). The independent variable s follows the conductors. The numbers indicate the turn. Its starts from the one closest to the mid plane (first upper, than lower coil), then continues for the next inner conductor. The black lines indicated the end of these double loop and the short ones the end of one part. The numbers show the number of the conductor.

only a rough estimate and cancels over the magnet within the homogeneous area. It shows, however, clearly that the mechanical support structure must be able to sustain:

normal mode The solenoids field is deteriorated due to the magnet. Here the magnet support structure next to its suspension must sustain the forces within the magnet and additional forces due to the deteriorated field

quench of the solenoid The solenoid is also a superconducting magnet. Its field during a quench depends on the origin of quench next to the magnet protection, which can lead to an additional field gradient. In this case different forces can act on the two separation dipole and on the different magnet parts.

The Lorentz force of the solenoidal field on the conductors of the dipoles was calculated (see Fig. 3) and integrated along the line of the conductor. One can see that the forces cancel within the magnet. But if one only takes only a octant of the magnet these forces add up to a total strength of 8.5 kN in the x direction and 15 kN in the y direction. The forces in y create a rotation momentum, while the forces in x only pull on the magnet.

For the Nuclotron cable the superconducting strands are wrapped around the inner helium tube with a certain twist pitch. The projection of the helix on a circle gives an additional force on the strand. This force F_L^N per length l is

$$F_L^T / l \approx \frac{I_w}{n_s} = 0.6\text{N/mm} \quad (4)$$

with I_w and n_s . This force has to be compared to the strength of the pretension applied by the NiCr wire.

CONCLUSION

The short length and large bore of the inner IR dipoles requires a full 3D optimised design to get an acceptable field quality. The chosen reference radius is still larger than the considered beam ($\approx 25\text{ mm}$, $R_{Ref} = 35\text{ mm}$). All current calculations were made for a pure air coil design. Further field quality studies now require taking the paramagnetism of the superconductor next to superconductor effects into account.

The results presented here suffice to estimate the forces on the magnets and make a mechanical layout of their support structure especially when one of the magnets in this system quench (detector solenoid, dipoles) and study their impact on secondary particle beams.

As next steps the dipole magnet reinforcement structure will be designed and the sufficient stiff suspension system together with the required supplies (current and helium) has to be integrated within the detector. The final field calculations and optimisation will then be made including the different materials (vacuum chamber, cryostat, detectors).

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