CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC – Note – 1135

THE ZEPTO DIPOLE: ZERO POWER TUNEABLE OPTICS FOR CLIC

Alexander Bainbridge[2], James Clarke[2], Norbert Collomb[2], Bainbridge Shepherd[2],
Michele Modena[1]

[1]CERN, Geneva, Switzerland
[2]STFC Daresbury Laboratory, UK

Abstract

The proposed Compact Linear Collider is an entirely normal-conducting machine planned to employ a Drive Beam Decelerator which will decelerate an electron beam from 2.4 GeV to 240 MeV. This structure features a series of turn-around loops that will require a large number of dipole magnets which would be subject to prohibitive power requirements if operated as resistive electromagnets. STFC and CERN have collaborated to design and construct a novel tuneable permanent magnet dipole to solve this issue. A scaled down prototype is currently under construction and is due to be tested at STFC Daresbury Laboratory.

8th International Particle Accelerator Conference, Copenhagen, Denmark, 14 - 19 May 2017

Geneva, Switzerland
18 May 2017

THE ZEPTO DIPOLE: ZERO POWER TUNEABLE OPTICS FOR CLIC

A.R. Bainbridge[†], J.A. Clarke, N.A. Collomb, B.J.A. Shepherd, STFC Daresbury Laboratory, UK
M. Modena, CERN, Geneva

Abstract

The proposed Compact Linear Collider is an entirely normal-conducting machine planned to employ a Drive Beam Decelerator which will decelerate an electron beam from 2.4 GeV to 240 MeV. This structure features a series of turn-around loops that will require a large number of dipole magnets which would be subject to prohibitive power requirements if operated as resistive electromagnets. STFC and CERN have collaborated to design and construct a novel tuneable permanent magnet dipole to solve this issue. A scaled down prototype is currently under construction and is due to be tested at STFC Daresbury Laboratory.

INTRODUCTION

The Compact Linear Collider (CLIC) is an ambitious project lead by CERN to design a 3 TeV linear electron-positron collider. The proposed design utilises a novel two-beam acceleration scheme [1], in which a drive beam is first conventionally accelerated to 2.4 GeV before entering the Drive Beam Decelerator (DBD). The DBD's contain deceleration structures reducing the drive beam energy from 2.4 to 0.24 GeV with the excess energy being utilised to accelerate the main beam to 1.5 TeV.

The planned structure of the DBD complex requires that the drive beams will have an initial trajectory opposite to the main beam. The drive beam bunches must therefore be brought into the decelerator structure via a series of 180º Turn-Around Loops (TAL's). The TAL's are located in 800 m intervals along the main linacs. Further to this there is a long (1216 m, 228º) TAL running from the combiner rings into the DBD complex, and each main beam passes through 1944 m, 180º TAL before entering the main linac. The CLIC design therefore calls for a large number of strong dipole magnets with a significant power requirement.

To combat the high power requirements of CLIC the ZEPTO (Zero Power Tuneable Optics) project has been conceived by collaboration between STFC and CERN. The purpose of this project is to design and construct novel prototype accelerator magnets based on blocks of Permanent Magnet (PM) material instead of normal electromagnet induction. Whilst PM based accelerator magnets have been employed before, they are typically only used where the field requirements are static or where very small adjustments are required [2], though the potential for larger tuning ranges has attracted previous attention [3]. The ZEPTO project aims to grant power saving PM systems the same versatility as electromagnets by building systems where the induction may be changed by moving the PM blocks, whilst maintaining field quality and homogeneity.

The ZEPTO project has previously resulted in the successful design and construction of two permanent magnet quadrupoles, high strength [4] and low strength [5] version. Both variants of these magnets were first simulated using OPERA-3D [6], before being built and tested at STFC Daresbury Laboratory, and between them cover the full range needed to replace the entire sequence of 41,848 quadrupoles in the DBD complex resulting in an expected power saving of 17MW from electrical resistance alone. Directly following on from this success the collaboration has now developed a prototype dipole based on similar principles.

The present design of the DBD complex calls for a total of 576 dipoles. Each has an effective length of 1.5 m and a flux density of 1.6 T. The CLIC team has estimated that each of these magnets will dissipate 21.6 kW (for a total power consumption of 12.4 MW) if operated as conventional resistive electromagnets. This does not include the power requirements of the magnet water cooling system or extraction of heat from the accelerator tunnel, which is likely to be limited to an average of 150 W/m. These magnets have been identified as the primary candidates for replacement by the ZEPTO dipole. Also of interest are a family of 184 DBD dipoles with similar parameters but a larger gap (42 kW per magnet, 7.7 MW total), and 666 main beam TAL dipoles (L=1.5 m, B=0.5 T) with an estimated total consumption of 2.5 MW.

MAGNET DESIGN

Several design options were considered using techniques such as sliding PM blocks, rotating radial PM's and moving sections of yokes. A design of balanced benefits was chosen based on prior experience with the low strength quadrupole prototype, which uses a single rectangular PM block between a pair of steel arms which form the yoke. This design, shown in figure 1, is analogous to a traditional C-dipole in which the PM forms the return arm of the yoke. The field in the gap may then be adjusted by horizontally sliding the PM block away from the beam pipe. The PM is not in direct contact with the steel to facilitate easy motion.

This design allows the flux density to be adjusted without altering the magnet gap. This overcomes the fact that for a given pole width the field homogeneity is related to the gap, avoiding the need for an unreasonably wide pole to maintain homogeneity at large-gap/low-flux. Homogeneity is instead determined by careful design of the pole shims and requires careful management of saturation as the PM changes position. Sliding the PM

---

* Work supported by funding from CERN & STFC

[†] email address alex.bainbridge@stfc.ac.uk

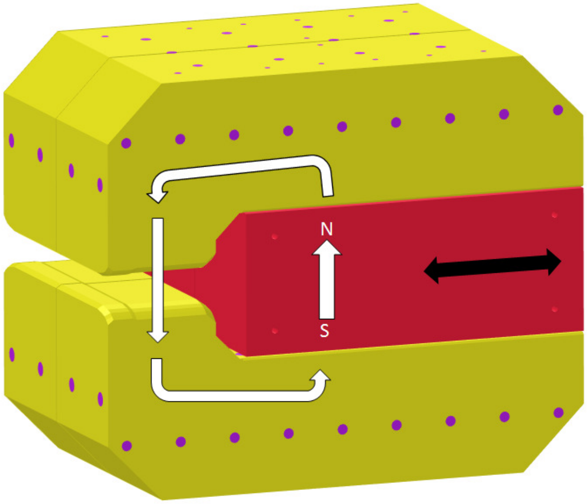

Figure 1: An OPERA-3D representation of the dipole design. Magnetic steel is shown in yellow, non-magnetic steel in purple and the PM in red. The magnetic circuit is illustrated in white and the motion of the PM in black.

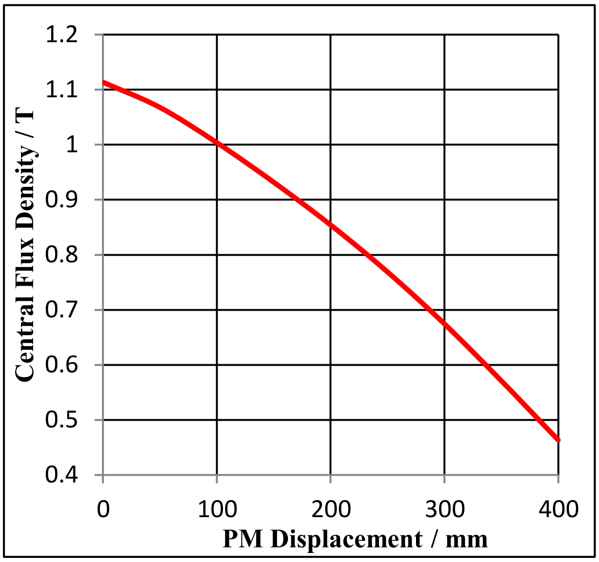

Figure 2: Predicted magnetic flux density at the geometric center of the magnet as a function of block displacement.

horizontally also requires less force than pulling the yoke apart.

The prototype has a target peak field of 1.1 T over a length of 400mm with a 40 mm gap with a 100%-50% tuning range. The PM block (which has been successfully constructed) is 500x400x200 mm of sintered NdFeB with a max Br of 1.41 Tesla. It was anticipated that this design may make achieving a highly homogenous integrated field difficult and so the target homogeneity was reduced from the CLIC target of 0.01% absolute and 0.1% integrated over 40x40 mm to only 0.1% integrated over 30x30 mm.

Simulations predict that the peak field in the magnet gap will exceed the 1.1 T target with the block fully inserted. Retracting the block changes the central field in a slightly non-linear fashion, as shown in figure 2. This is more noticeable at high field due to small areas of saturation in the steel. Moving the block by 400 mm results in a central field of 0.46 T. The 50% tuning mark occurring at approximately 355 mm displacement. The prototype is therefore being constructed with a motion system designed to accommodate a 400 mm stroke to ensure that the entire tuning range is covered. The required stroke could potentially be reduced by introducing a secondary magnetic circuit for the PM to retreat into, this also complicates the magnetic forces and engineering so is not included in the first prototype.

The C-dipole design with all PM material on one side of the beam prevents good homogeneity of the integrated field using conventional shim designs. As the bunch approaches the magnet (and again shortly after it exits the magnet) the bending field is slightly stronger on the side of the bunch closest to the PM. This is countered by using an asymmetric pole shape; on the pole side nearest the PM a roll-off reduces the field strength and on the opposite side a shim increases it, with the poles flat and parallel over the diameter of the beam pipe. This results in a slightly imbalanced field inside the magnet itself which opposes the imbalance on approach and exit, leading to

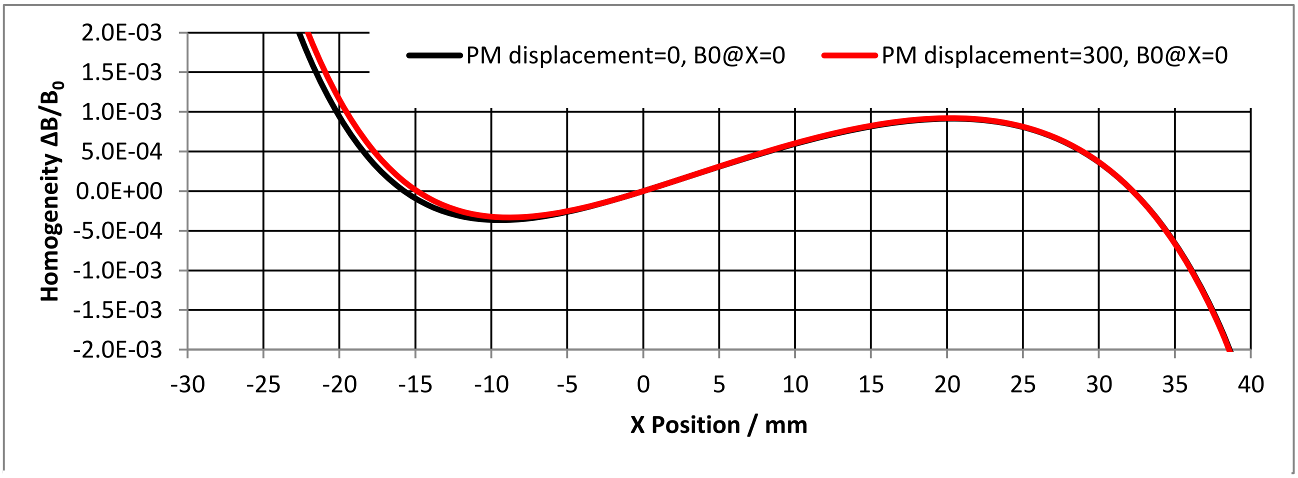

Figure 3: Predicted integrated field homogeneity of the proposed magnet design. X=0 is the geometric center of the gap. Black= magnet fully inserted and red=retracted 300 mm with B_0 chosen as the integrated field at X=0.

acceptable homogeneity of the integrated field between ±∞.

The predicted homogeneity of the integrated field is shown in figure 3. The current pole design allows the 0.1% requirement to be met from X= -22 to +34 mm from the beam axis. This is highly encouraging considering that the target was only to achieve this to ±15 mm. This homogeneity is well preserved as the block moves; balancing pole shape with saturation makes homogeneity relatively independent of PM block position.

MAGNETIC FORCES & ENGINEERING

The magnetic forces arising from having such a large PM block so close to the steel poles represent a significant engineering challenge. The gap between the PM block and the steel pole, necessary to facilitate motion, is nominally 2mm and must be kept constant as the PM block moves. The force across the magnet gap is also significant, as the yoke consists of two separate pieces strong support is required to maintain separation.

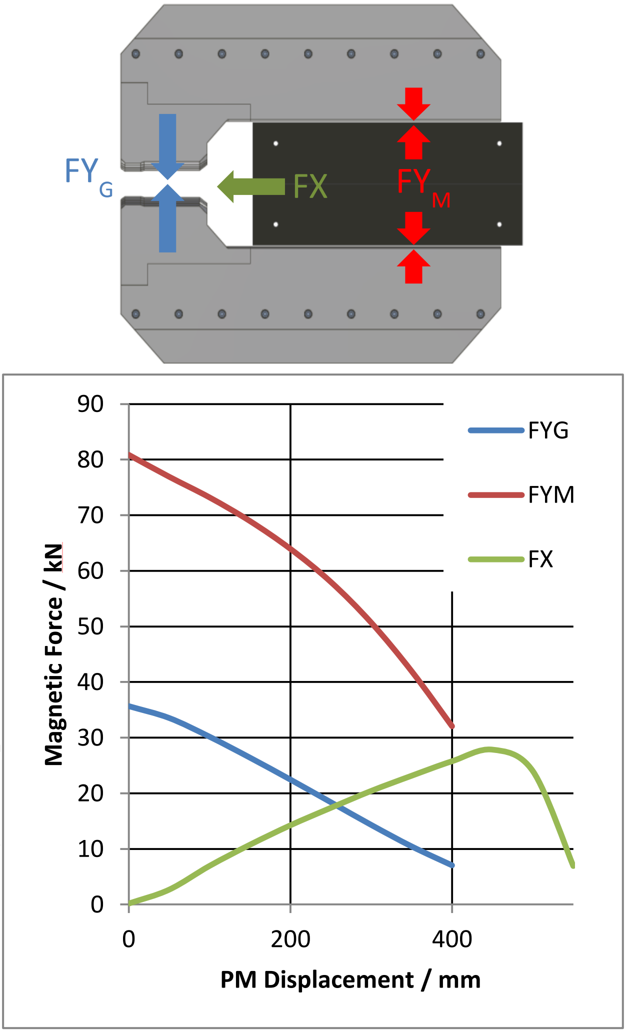

Figure 4: Significant predicted magnetic forces across all gaps in the proposed design.

The actions of the forces and their predicted values are shown in figure 4. The vertical force (FY_M) between the PM block and the steel is countered by aluminium extensions to the pole pieces (not shown) which are then locked a fixed distance apart by a back plate which houses the motion system. Rails are mounted on the poles between which a carriage sits containing the PM block, keeping it central. The carriage frame provides support against the vertical forces as it slides on bearings along the rails. The peak of FY_M occurs with the PM fully inserted, approximately 81 kN for each of the 2 pole pieces.

The force across the main magnet gap (FY_G) is supported by 3 adjustable titanium support pillars. These forces, and their central point of action, are strongly dependent on the position of the PM block. The peak of FY_G is approximately 36 kN, again at full insertion of the PM.

The PM block is also subject to a strong horizontal force (FX) which always acts in the direction of the magnet gap and varies strongly. This force is modelled past the maximum stroke for initial insertion of the PM block and is predicted to peak at 28 kN during insertion and at 26 kN at the position of maximum stroke. To move the block accurately a motion system has been designed employing a step-servo motor with a pair of low range gearboxes giving a 60-1 reduction. The carriage is linked to the gearboxes by a pair of ball screws. It is expected that this system will move and hold the PM block at any point of the stroke with a maximum accumulated error of 3.75 µm over the entire range.

The magnet prototype is currently under construction. The PM block was delivered by Vacuumschmelze, and the magnet steel and aluminium backing components have been finished in house at STFC Daresbury. We are currently in the process of centering the magnetic block within the poles and locking components in place against the magnetic forces. The motion system will shortly be tested. The dipole performance will then be assessed against simulation be means of Hall probe mapping, integrated field measurements via stretched wire and harmonic assessments via rotating coil.

CONCLUSIONS

A new type of adjustable permanent magnet dipole with a 50% tuning range has been designed by collaboration between STFC and CERN. This magnet presents an opportunity for large scale energy savings in new accelerator projects. Mechanical and magnetic modelling is complete and a prototype is currently under construction and is due to be tested at STFC Daresbury Laboratory.

REFERENCES

[1] M. Aicheler *et al.*, “A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report”, CERN, 2012.

[2] J. Citadini *et al.*, "Sirius-A 3 GeV Electron Storage Ring Based on Permanent Magnets," *IEEE Transactions on*

Applied Superconductivity, vol. 22, no. 3, pp. 4004404-4004404, June 2012.

[3] T. Watanabe *et al.*, “Magnetic-Field Variable Permanent Dipole Magnet For Future Light Sources”, *Proc. 5th Int. Particle Accelerator Conf. (IPAC’14)*, Dresden, Germany, June 2014, paper TUPRO092, pp. 1253-1255.

[4] B. J. A. Shepherd *et al.*, “Tunable High-Gradient Permanent Magnet Quadrupoles”, *Journal of Instrumentation,* Vol 9, T11006, 2014.

[5] B. J. A. Shepherd *et al.*, “Design And Measurement Of A Low-Energy Tunable Permanent Magnet Quadrupole Prototype”, *Proc. 5th Int. Particle Accelerator Conf. (IPAC’14)*, Dresden, Germany, June 2014, paper TUPRO113, pp. 1316-1318.

[6] OPERA Finite element magnetic modelling software, from Cobham (Vector Fields): `www.operafea.com`