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Development of a cryogenic APPLE CPMUE15 at BESSY II

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Abstract. Building on the innovative design of the In-Vacuum APPLE IVUE32, a design for a 15mm period cryogenic elliptical undulator (CPMUE15) is proposed. The undulator is to be developed under the ATHENA collaboration. Initially designed to provide a radiator for the SINBAD facility at DESY, a comparison is made for a design to provide an Afterburner device for FLASH1.

1. Background

As part of the ATHENA collaboration [1], Helmholtz-Zentrum Berlin are building two insertion devices. The first is an in-vacuum APPLE II device to be installed in BESSY II [2], and the second is a cryogenic APPLE device.

The original plan was to install the second device in the LUX Plasma FEL demonstrator [3], where paired with the 15mm period CPMU FROSTY, the device would act as a proof-of-principle demonstrator for a plasma driven FEL. A fundamental scaling parameter for the FEL interaction is the dimensionless Pierce parameter, ρ. A measure of the efficiency of the FEL process, the Pierce parameter relates the peak power of the emitted radiation, P, to the electron beam power, P_{beam}: $P=\rho*P_{beam}$. It is proportional to the undulator decoupling factor f_b, which is 1 for helical undulators and less than 1 for other types of undulators. As a result, the helical undulators have a higher peak power and a short gain length. The primary specification of this device was a 15mm period length, to match the existing FROSTY undulator, and an aperture of 2mm, to achieve a K-parameter of 2.11 in all modes. A change of circumstances means that the second device will actually be targeted as an afterburner for the FLASH1 beamline at DESY[4]. Again, the primary specification is indicative of a 15mm period device, although with a relaxed minimum aperture of 6mm.

The selection of minimum aperture has significant ramifications on the design of a magnet array for a cryogenic APPLE, and this will be explored below.

2. Impact on magnetic field profile

A strong requirement for insertion devices is to have a uniform magnetic field profile transverse to the electron beam axis. The split nature of the upper and lower rows of APPLE II devices introduces a discontinuity in the driving field, such that manifests in a high order multipole on axis. For longer period out of vacuum devices, such as the 56 mm period shown in figure 1, this discontinuity is far enough away from the device axis, that the effects are smoothed on the beam axis. However as the gap approaches in-vacuum scales of 6-4 mm for storage rings, or even 2mm for some FEL applications, the inhomogeneity of the on axis field can become very noticeable.

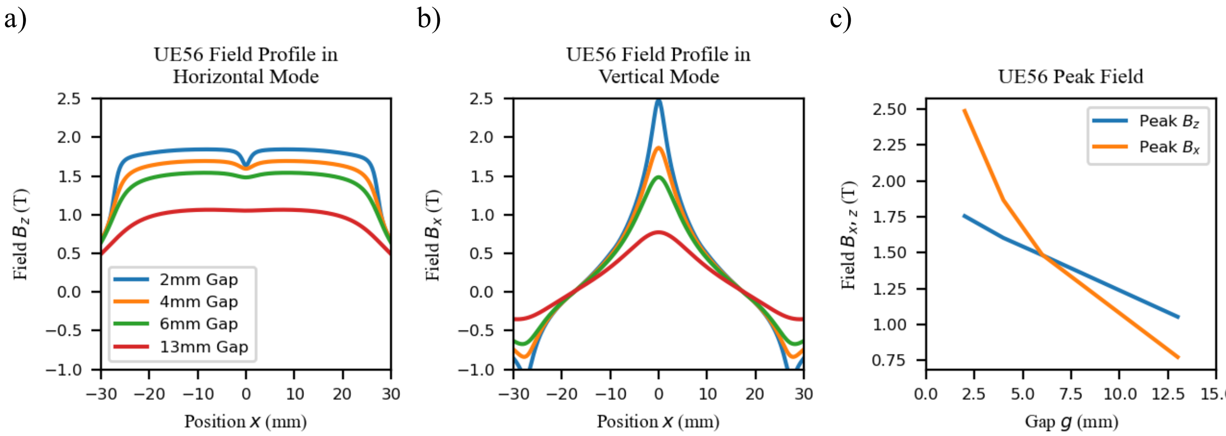

Figure 1. Field profile of a 56 mm period length out of vacuum APPLE II undulator in a) horizontal and b) vertical polarisation modes, and the c) peak field of each mode with undulator gap.

The increasingly sharply peaked on-axis fields have several impacts.

i) For a 100 µm wide electron beam, the electrons in the bunch will no longer see the same field. This will cause a smearing of the undulator radiation peak.

ii) The 'efficiency' of the magnet array decreases in horizontal polarization modes, and drops from >98% of an equivalent linear device at large gaps, to about 88% for a gap of 2mm.

iii) The relative 'efficiency' of the APPLE II device increases for vertical polarization modes.

iv) The positional requirements of the magnets in the array become much more stringent, as at low gaps a fixed absolute variation of the magnet block position correlates to a much larger relative variation. This has significant ramifications for the eventual achievable phase error of the device.

The central dip in the B_z field of an APPLE II undulator can be corrected, and even inverted, by rotating the easy axis of the vertical magnets in the Halbach array through an angle M_φ in the XZ plane. The impact of M_φ is mostly seen at the smallest gaps, but the dip in B_z seen above is recovered for all gaps, as seen in a 15 mm period cryogenic model in figure 2.

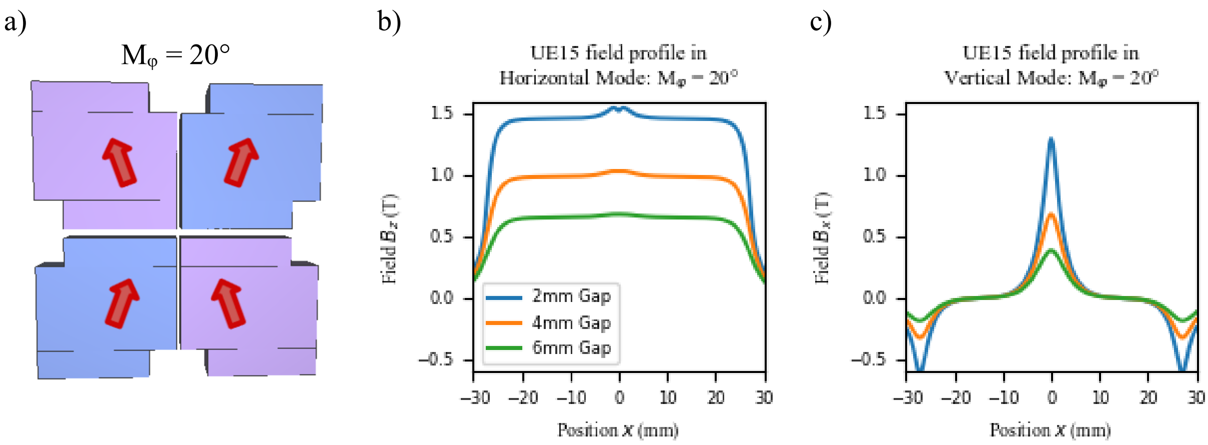

Figure 2. a) An illustration of easy axis rotation of vertical magnets and the impact on b) horizontal and c) vertical polarisation modes of a 15 mm period cryogenic APPLE undulator.

In addition to the transverse field profiles of small gap APPLE devices, the on-axis field must also be treated carefully. The high ratio of undulator period length to minimum gap can reduce and flatten the peak of the on-axis field. This flattening was simulated for a 15mm period device at a magnetic gap of 2.2 mm. By increasing the number of magnets per period in the Halbach array, N_H, to 6, the peak field of the device was recovered in both horizontal and vertical polarisation modes (figure 3).

3. Reducing Magnet Load

As FELs are not recirculating machines that need to deal with orbit disturbances during injection cycles, it is no longer necessary to have a good field region up to ±40 mm. Instead the limiting factor for on-axis peak field is magnet block size. It is possible to reduce functional magnet size down to 15 mm x 15 mm before on-axis peak field is significantly degraded at 2.2 mm gap (figure 3).

a) b)

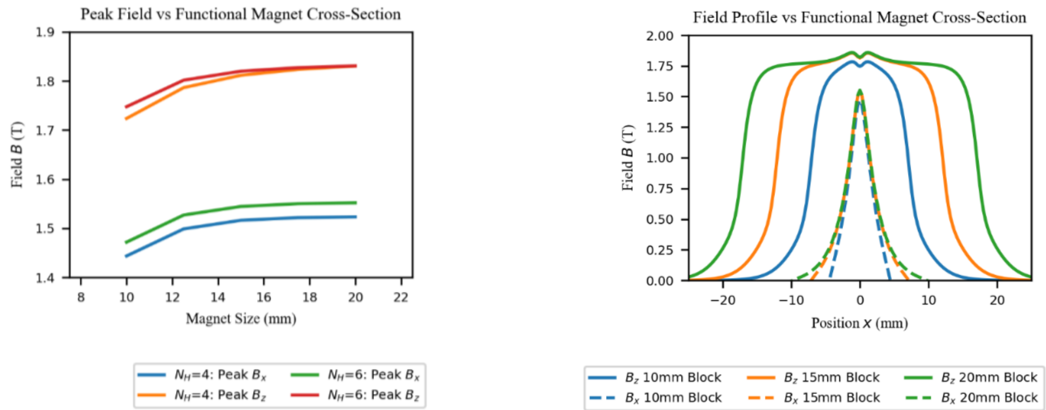

Figure 3. The impact on a) device peak field and b) field profile for different size magnet blocks.

A magnetic force compensation scheme developed by J Bahrdt [2] offers a solution to overcome the large forces generated between neighbouring arrays in an APPLE II device, using additional magnet arrays offset longitudinally with a phase of π. The compensation scheme continues to work for the very low gap geometry; that is, for a rotated M_φ and a Halbach number N_H of 6. The vertical forces are reduced by a factor 10, and the transverse forces by a factor of three (figure 4b), allowing a support structure of the necessary stiffness and stability to be realised through a vacuum chamber. Further work is ongoing to understand the difference between the two directions.

a) b)

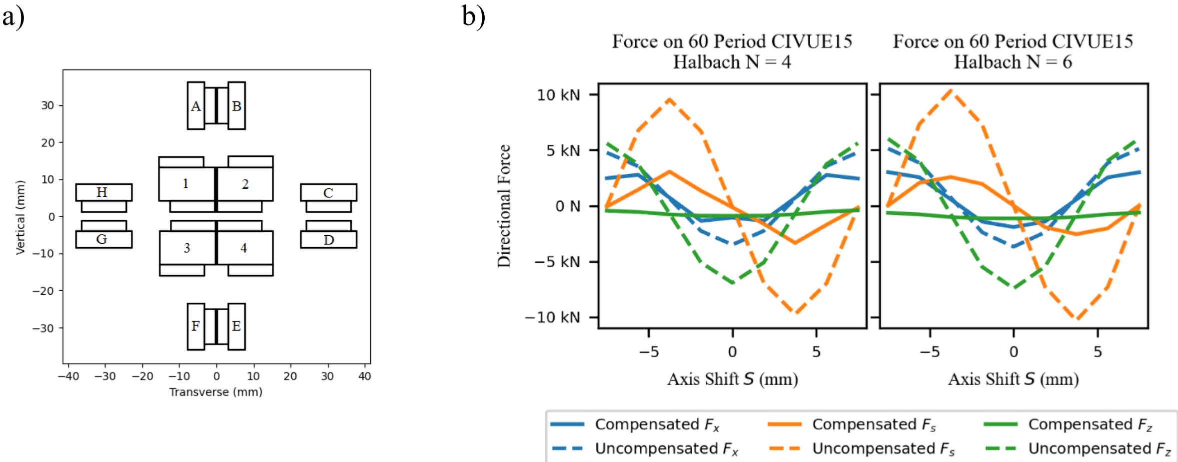

Figure 4. a) The cross section of the compensation scheme of the cryogenic undulator, with functional magnet rows 1-4 and compensation magnet rows A-H. b) The force on the girder carrying magnet row 1 with and without a magnetic force compensation scheme.

4. Mechanical Considerations

The very small size of the magnets for the 2 mm aperture device, being approximately 2.5 mm deep, presents a large challenge for securing the magnet blocks. To overcome this, it is planned to fix the magnets together in half-period packets prior to magnetisation. Although pre-gluing unmagnetised magnet pairs for APPLE II devices is routine for HZB, where the easy axes of magnetisation for N_H = 4 array are separated by 90 °, the wider angular separation of easy axes of 120° in a triplet packet of an N_H = 6 array requires study to determine if the magnets can be well magnetised.

Investigations are underway to determine if the magnets can be satisfactorily magnetised in two pulses at an angle of ±10° to ± 20° off the easy axis of the central magnet in the packet (figure 5). First results indicate that the glued packet is able to be magnetised with an angular accuracy of better than 2°. Further study is planned to determine if the individual components of the triplet pack are satisfactorily accurately magnetised.

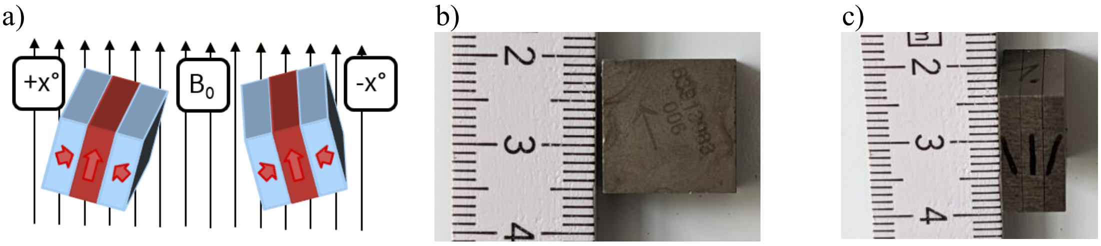

Figure 5. a) An illustration of how the triplet magnet assembly can be magnetised using two magnetising pulses. b) and c) views of a trial magnet assembly.

5. Cryogenic solutions

In order to maximise the on-axis field of the device, it is proposed to use a cryogenic grade of PrFeB material such as VACODYM T130. This material exhibits increased remanence of 30% at temperatures of 80K, and as such, the device will need to be cryogenically cooled.

There are two primary means of achieving cryogenic temperatures below 100 K: closed circuit liquid nitrogen cryocoolers, and Gifford-McMahon compressed helium coldheads. Liquid Nitrogen cryocoolers allow for an order of magnitude more cooling power at 80K than Gifford-McMahon coldheads, and are often used to cool CPMUs such as that installed at BESSY II [5]. The initial brief for the cryogenic APPLE was for installation in a very confined vault with limited ventilation possibilities, precluding the use of liquid nitrogen cryocoolers on safety grounds. However the location of the device as an afterburner should allow for the use of this traditional solution.

6. Conclusion

Work has started on the magnetic design of an small-gap APPLE style undulator, making use of cryogenic grade magnet materials. Initial work has focused on the several optimisations to the magnetic array required for a very low aperture 2 mm device suited to be a radiator for a plasma wakefield accelerator driven FEL, and for the optimisations required for a more relaxed 6 mm aperture afterburner device.

For a very low gap device of period length 15 mm, and a magnetic gap of 2.2 mm, the magnetic array design is fairly complicated. The optimised device has an M_φ of 20°, and each period is an N_H = 6 Halbach array. When the minimum gap requirement is relaxed to 6 mm, on axis field improvements are still seen for M_φ of 20°, however a Halbach array with N_H = 4 is sufficient.

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