COMPACT-TWO-OCTAVE-SPANNING PERPENDICULAR KICKER OF MeV ELECTRONS BASED ON A CUBIC MAGNET DIPOLE ARRAY

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Abstract

New compact particle acceleration structures, including but not limited to plasma, THz and direct laser driven accelerators, have in common that they cover a wide energy range of potential final energies and often show a large energy spread. Moreover, they may initially have a rather large emittance. To analyse the energy range of a single shot and/or to deflect the beam to safely dump the electrons away from an end-station requires an electron kicker covering a large energy range. Here, we present a magnetic dipole structure based on a 2D Halbach array. For the current experimental test accelerator in AXSIS, an electron beam in the energy range from 4 to 20 MeV is deflected by 90 degree and energetically dispersed. In direct contrast to a simple magnetic dipole, an array of cubic magnet blocks with tailored magnetization directions allows a focusing of the beam for both longitudinal and transverse directions at 90-degree bend. An genetic algorithm optimizes the magnetic field array to the predefined deflection angle and divergence. The modular array structure, in combination with the algorithm enables a simple exchange of magnets to adapt for different beam parameters.

INTRODUCTION

X-ray light sources based on large-scale linear accelerators (LINAC's), known as Free Electron Lasers have made a tremendous impact to the scientific community due to their ability to produce ultrashort (femtosecond) and ultrabright pulses that allow single shot diffractive imaging before the sample is altered.

Tremendous effort is currently put into the development of significantly more compact LINAC's by replacing the RF acceleration with plasma, THz or direct laser-driven structures. The benefits are, besides the more attractive size and costs, the potential to generate even shorter pulses in the attosecond regime. One side effect of the more compact LINAC design is that the radiation safety becomes more challenging. The electron beam and its secondary radiation is supposed to be blocked before the x-ray end station that is by design concepts only a few meters away from its generation point to maintain: a short pulse duration (lateral focussing), a good transverse focussing and to improve the overall stability. e.g., for the case of the THz powered accelerator AXSIS [1] at DESY, the entire accelerator including the experimental end-station is placed on a 10 m long granite block to circumvent any auxiliary vibrations. The area on the granite is then separated into an accelerator lab and an x-ray hutch with different radiation safety measures. Thus, the electron beam needs to be bent significantly away from the x-ray hutch by a single compact device.

Additional complexity comes from the fact that the possible beam parameters in terms of safety of these test accelerators using new acceleration techniques have to be considered to have a large energy spread and relatively large emittance as long as experimental results of these parameters are unknown.

DESIGN REQUIREMTS

The aforementioned conditions motivated us to design a bending magnet for the electron beam at 90 degrees. This way, the secondary radiation of the beam dump will stay in the accelerator lab and no direct radiation will hit the divider wall to the x-ray hutch. The challenge is that a full energy spectrum up to the maximum energy of 20 MeV has to be considered. This fixed full energy range, the compact design requirement and safety considerations all favour a permeant magnet kicker over an electromagnetic one.

A simple dipole with an exit surface of 45 degree with respect to the incident beam is a good starting point since the higher energies will propagate longer in the effective field such that all of the electrons do close to a quarter circle (90 degree) bend only limited by fringe fields, Fig. 1.

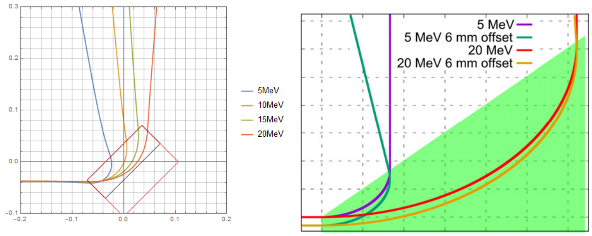

Figure 1: A dipole magnet at 45 degree with the correct field will result in about a quarter circle (90 degree) bending. However, this is very sensitive to offsets.

However, the potential divergence as well as offsets of the beam will result in different emission angles for both, within the plane of curvature and out of plane. This out-of-plane component is of particular importance since the high-energy electrons might hit the magnet and cause radiation damage, i.e., demagnetize it.

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2D DIPOLE ARRAY

In the following, a method of using a 2D array of magnetic cubes with varying magnetic orientations was used to solve the dipole configuration by a genetic algorithm in MATHEMATICA using the RADIA package for magnetic simulations [2]. Different generations of solutions are discussed.

Automatically Found Solution on Angles

Figure 2 shows the initial result for a 7x7 array of 20 mm magnets of a strength of 1.32with 21 mm spacing. The dipole structure has a gap of 20 mm. The simulation is performed for an energy range from 5 to 20 MeV and a spatial 3x3 beam array separated by 3 mm each.

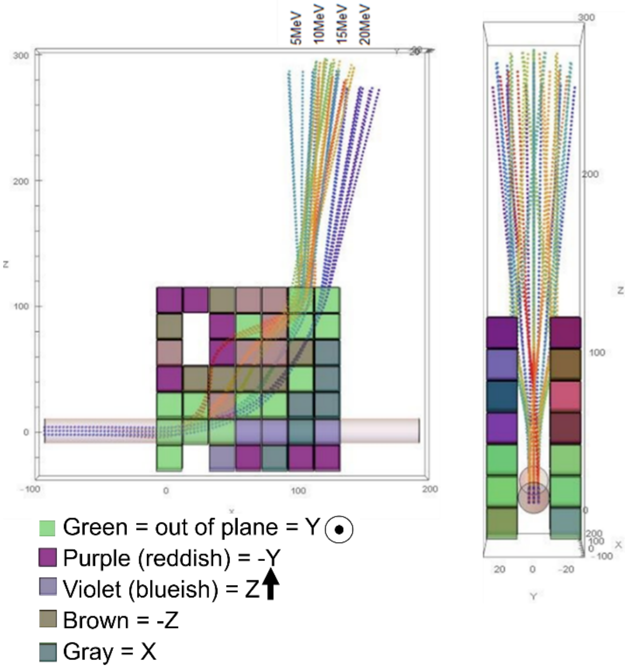

Figure 2: Initial solution by the evolutionary algorithm and legend of the different magnet orientations.

In the bending plane, the initial result is very satisfying. All the energies are not only bent close to 90 degrees, but in addition, they are also close to each other in position, convenient for a beam dump to be placed. However, for the out-of-plane components, it can be seen that the beam is deflected into the magnets. The initial optimization condition of this algorithm was simply the exit angle of the individual beam such that the position was not an optimization parameter.

Manually Altered Array

Figure 3 shows a manually predefined result before running it through the automatic algorithm. The concept of a Halbach array is to enhance the field by closing the magnetic field lines as much as possible. In this application, this is done best by an inverted magnetic field in the right bottom corner (purple) and enhancing the bending by adding a Z component as long as the electron trajectory is dominant in X direction (bottom edge) and adding an X component for the upward pointing (Z) trajectory. This alignment of the magnets was used as the input orientation for the genetic algorithm which only had to find the right alignment in the upper left corner to bend all (the lower) energies by (not more than) 90 degree.

As can be seen in the out of plane propagation on the right, the trajectories here do not hit the magnets any more. In fact, the ones most outward are the intermediate energies with green and yellow colour that have one magnet less in height such that they will not come close to the magnets.

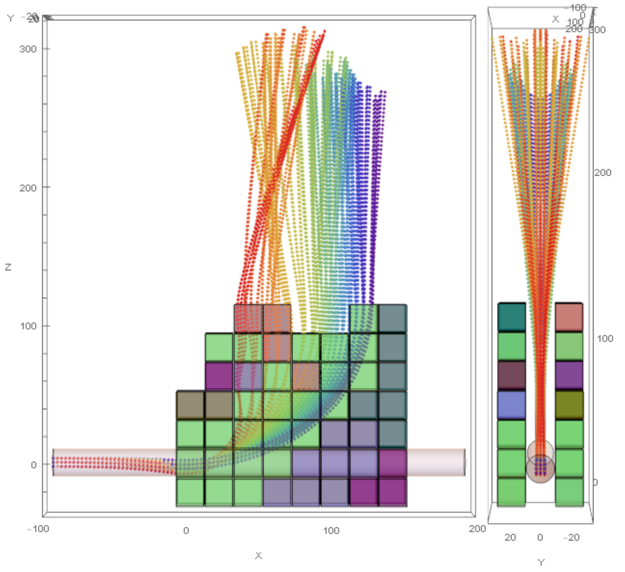

Figure 3: Modified 8x7 dipole array, plotted for energies from 4 to 20 MeV in steps of 1 MeV and again for a spatial 3x3 beam array separated by 3 mm each.

Contribution of Lower Energies

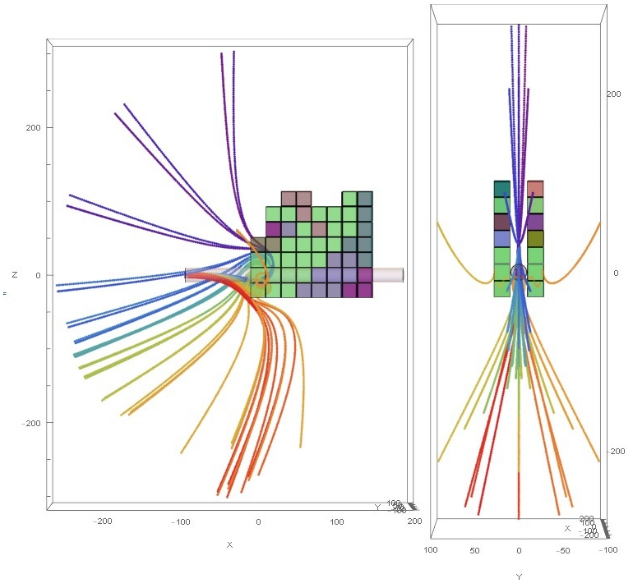

Figure 4: Propagation of electrons from 0.5 to 3.5 MeV.

So far, the energies below 4 MeV have been ignored because their penetration depth is low enough that any secondary radiation of them will be blocked by the lead wall between accelerator and x-ray hutch. However, when looking at their propagation in Figure 4, the low energy

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electrons are deflected downwards and the higher energy electrons are going up such that there is indeed an intermediate energy range around 1.5 MeV where the electrons start to spiral inside the array, Figure 4. This will result them in demagnetizing some magnets of the array. Thus, another solution has to be found once more.

Spectrometer Like Focussing

The final solution is to implement some magnets with -Z orientation (brown) above the initial bending of the beam. This further enhances the bending, in particular for low energies. The remarkable side effect as evident in Fig. 5 is a focusing of the beam for both, an offset of the beam and beam divergence. This is even more surprising as the electron beam in a magnetic field is typically most offset at 90 degree bent for different initial angles, see Fig. 6 in [3].

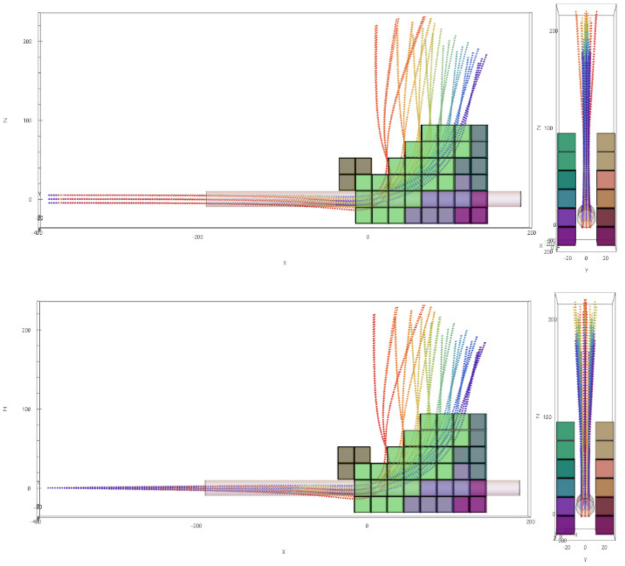

Figure 5: Final design of the dipole shown for beam offset (top) and beam divergence (bottom). In both cases each energy is pretty much focussed on the same point.

DESIGN AND ASSEMBLY

The final parameters used for the expected beam at AXSIS are beam deflection by (close to) 90 degree from 4 to 20 MeV with 20 mm cube magnets of 1.38 T in a 9x7 array with 21 mm spacing and a 22 mm gap. The maximum acceptable beam divergence is 7.5 mrad for a focal distance of 80 cm or with 20 cm distance and 6 mm beam offset (3x3 aray) an additional 3 mrad of beam divergence are still acceptable. This last example already results in a nominal width in the diagonal of 25.46 mm. The assembly then included a test assembly of 3D printed array pushing the magnets down with a stamp and fixing the in place with a rod. The final design uses an aluminium frame with an iron magnetic shielding at the entrance.

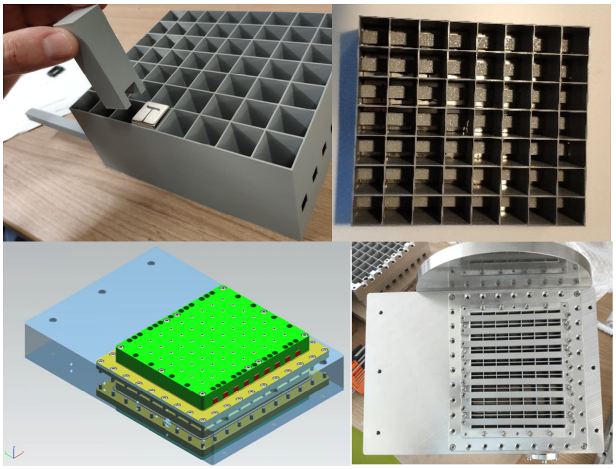

Figure 6: (top) test assembly of the magnet array with 3D printed plastic structure. (bottom) CAD design and image of the final assembly including a Fe shielding plate at the entrance and a 15 cm beam dump out of Al.

CONCLUSION

In summary, a method for a compact permanent magnet safety dipole was presented for more than 2 octaves of energy. The flexibility to modify this this array allows an easy adaption to other applications. The focussing by the additional magnets in –Z direction needs to be emphasized. This allows the dipole to be used without further focussing optics and thus being more compact. The fact that both deviations, beam divergence and beam offset is focussed onto about the same position for a 90-degree bend comes at a surprise and makes this tool perfect for the application of a high-resolution (single-shot) spectrometer by accumulating a large beam distribution at the entrance without the need of additional focussing or entrance slit apertures or a highly efficient monochromator as required in [4].

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