Preliminary Study of the High Temperature Superconducting Solution for 2GeV CW FFAG Magnet

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Introduction

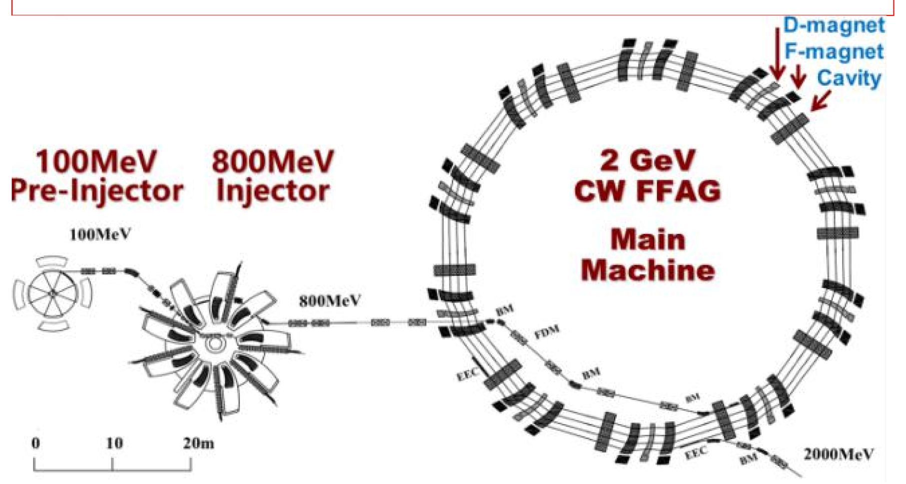
Proton beam with an average power of 5MW-10MW have important applications in particle physics towards the intensity frontier, as well as in the advanced energy, and material science. The fixed field alternating gradient (FFAG) accelerator combines the advantages of existing accelerators, which has a higher limitation of beam energy than high power cyclotron and has a higher beam-to-grid efficiency than existing high power linac and synchrotron, thus is considered as a good candidate for high power proton machine. By utilizing the strong focusing and large acceptance features of FFAG in the theoretical framework of the fixed field and fixed frequency of isochronous cyclotron, a 2GeV/6MW continue wave FFAG design has been proposed in China Institute of Atomic Energy (CIAE). Due to the beam loss of high power proton beams, the resulting high radiation will deposit a large amount of radiation dose and head load on the SC magnet. As the high temperature superconductors (HTS) have a much larger thermal margin due to high critical temperature (> 90 K) and high upper critical field (> 100 T) than the traditional low temperature superconductors, and have been also considered have the lower overall construction costs and power consumption than the conventional magnet, currently the HTS magnet is the favorable solution for the 2GeV FFAG magnet design. In this paper, the lattice design along with the requirements on the F-D-F magnet of the 2GeV FFAG design is briefly introduced first. Then, the design of the F-D-F magnet is outlined. And the details of the HTS coil design utilizing ReBCO conductor and operating at ~30 K is also included.

Conclusions

A 2GeV/6MW CW FFAG is proposed by CIAE to meet the requirements on the cost and energy effective solution for multi-MW high power proton production. The HTS magnet is prefered for the F-D-F magnets of the proposed FFAG due to its radiation resistant and thermal stable properties. Promising results of isochronism and tune have been obtained by using analytical field model and a genetic-based multi-objective optimization algorithm. The design of the F-D-F HTS magnet shows that stray field in angular direction need to be taken care of carefully. As the superconducting magnet technology using 2nd generation HTS for accelerator is still under development world wide, an R&D project for 1/4 scale HTS defocusing magnet has been initiated recently at CIAE to develop HTS coil winding, fixing, quench detection and protection technologies, especially for HTS coil with concave shape.

Introduction

The layout of the circular accelerator complex with a 100 MeV pre-injector, a 800 MeV injector and a 10 FDF cell CW FFAG

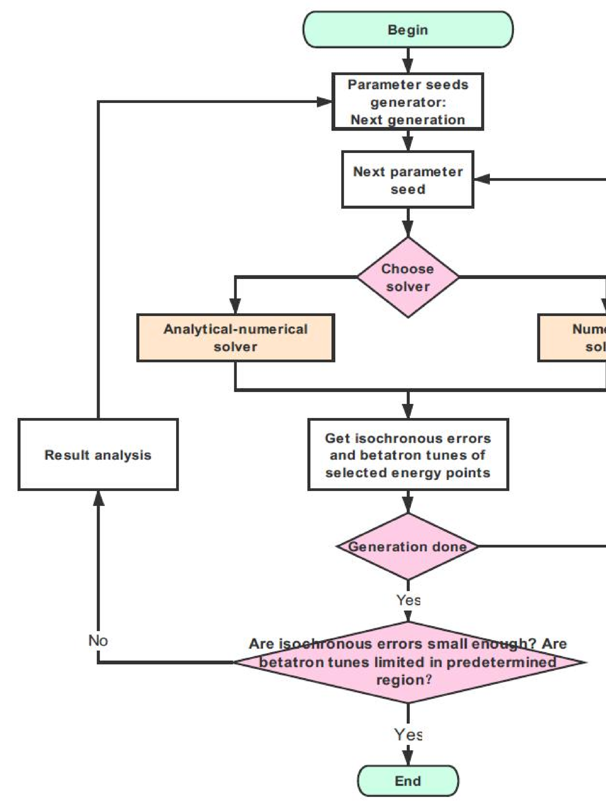


The FermiLab researcher reported the energy efficiency of the three operational accelerators with the highest beam power world wide. The energy efficiency of the PSI ring cyclotron is about 3 times of the other types which draw the same conclusion as Dr Y. Ishi that the isochronous accelerator is a good technical route due to its high power efficiency and high cost effectiveness to produce high average proton beam, if it can break through the energy limitation of 1GeV. Based on the basic FFAG idea, a high power circular accelerator complex consists of a 100 MeV pre-injector cyclotron, a 800 MeV injector ring cyclotron and a 10 FDF cell 2 GeV CW FFAG, is under development at CIAE.

Lattice design

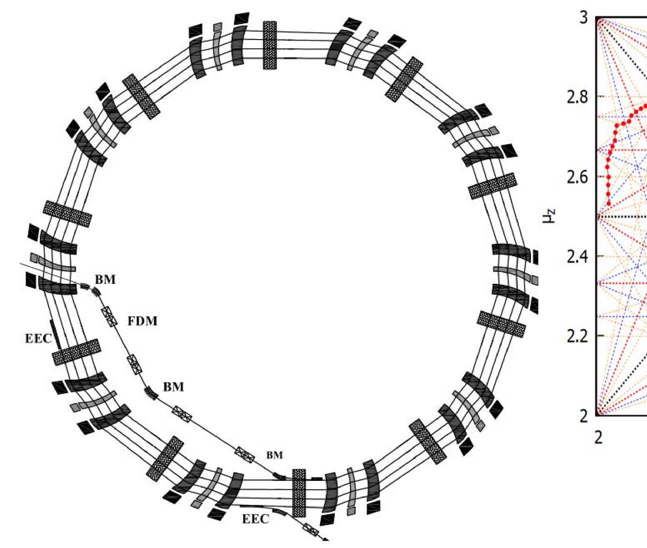
Design method

The challenge of isochronous FFAG lattice design is to maintain the isochronism up to 2 GeV and optimize the tune for resonance crossing. A genetic-based multi-objective optimization algorithm andthe analytical magnetic field fitted by high-order polynomial is used. Spiral angle of F and D magnet change with radius and the angular width of F and D magnet increase monotonically with radius.

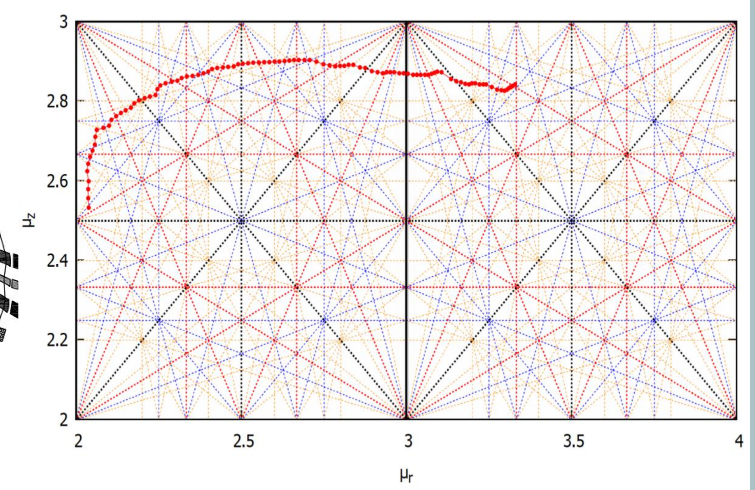


Lattice design results

Ten "FODO-like" periodic cells, which contain two bending (focusing) magnets and one reverse bending (defocusing) magnet, make up the whole FFAG lattice ring. The tune is also calculated



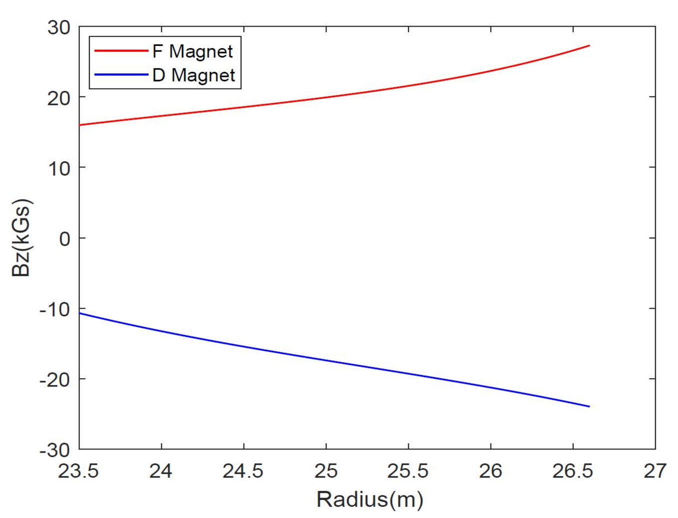
The layout of the 2GeV FFAG



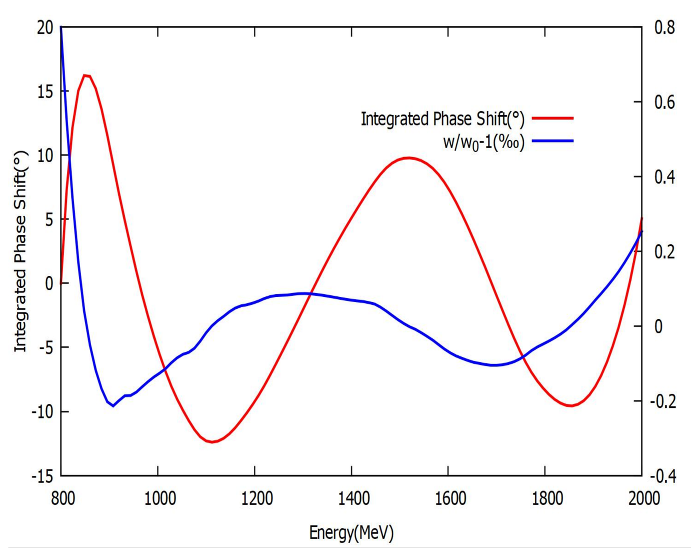
The tune diagram of 2GeV FFAG using analytical magnetic field

Magnetic field requirements

The average magnetic field of the F and D magnets are calculated from the analytical magnetic field. And the integrated phase shift is well controlled within ±15° .



The average magnetic field of F magnet varies from 1.5 T to 2.7 T, and the D magneti varies from 1.0 T to 2.4 T.

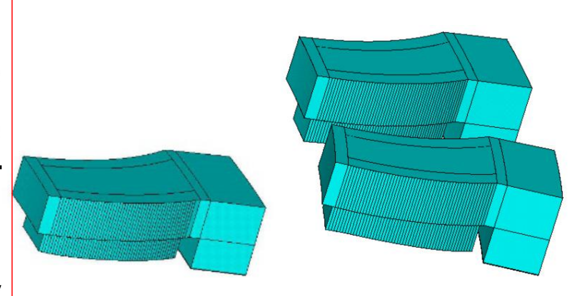


The integrated phase shift is well controlled within ±15° .

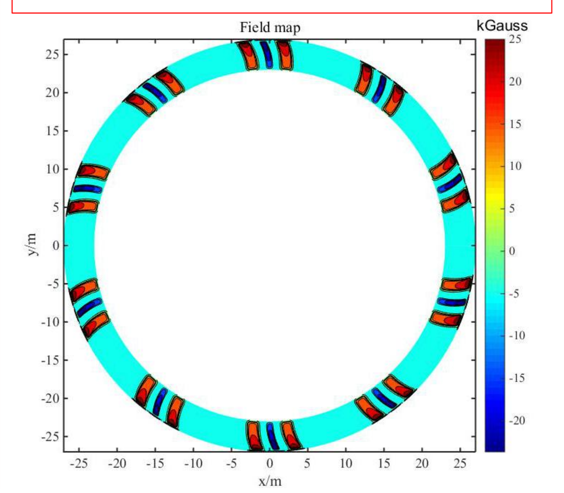
Design of the F-D-F HTS magnet

The magnetic field in the extraction radius of 2 GeV in defocusing magnet and the focusing magnet are ~-2.4 T and ~2.7 T respectively, which have already exceeded the saturation field of pure iron (~2.14 T). As the 2 GeV FFAG is designed to operate at high power, the 2nd generation REBCO superconducting magnet solution with both radiation resistant and thermal stable properties is preferred.

The FEM Model of D and F magnets



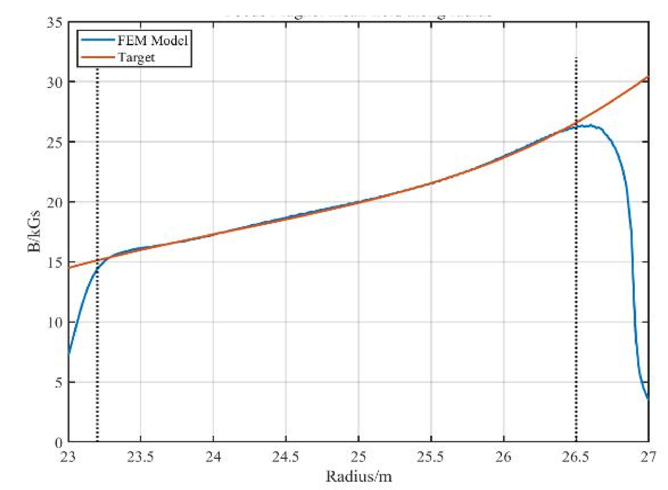
The contour plot of the field map from FEM model.

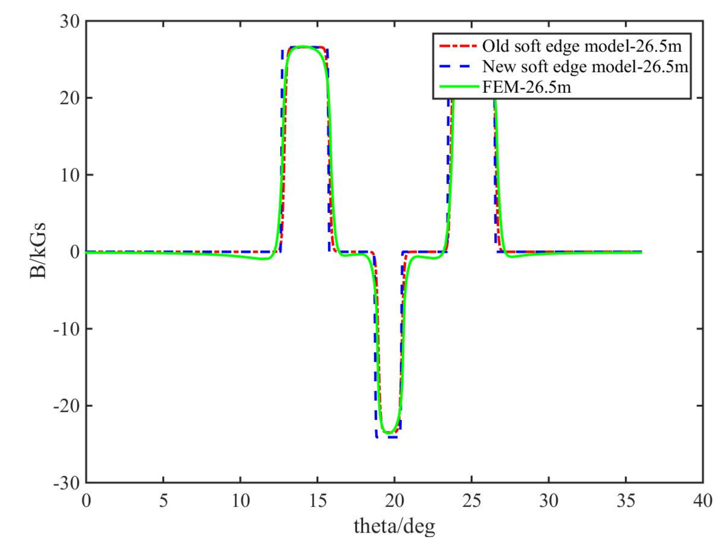


In current version of the magnet design, the pole gap distance of the defocusing and the focusing magnets can be fitted as 5th order of polynomials, i.e., n=5 in the following equations, which is too complicated and may introduce unexpected field errors during machining. Considering we have successful experiences in designing and machining of pole gap fitted with 2nd order (elliptical) polynomials in our 100 MeV cyclotron, and also considering the required 3rd order polynomial of magnetic field, n=3 will be used in the further magnet pole gap design.

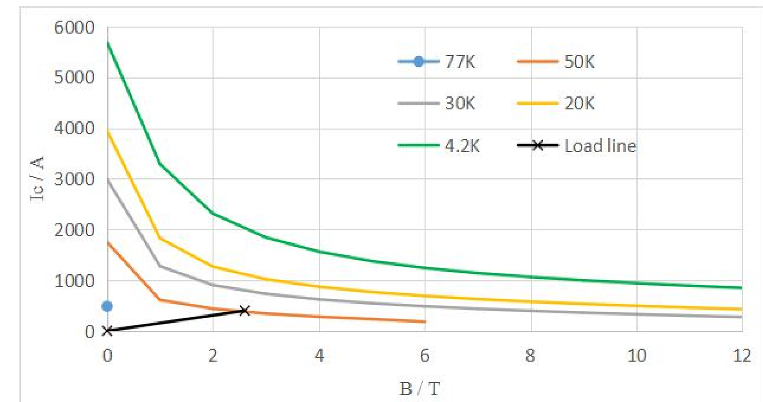
$$g_{k(k=d,f)} = a_{k,0} + \sum_{i=1}^{n} a_{k,i} r^{i}$$

Pole gap varies along radius.





Radial and angular distribution of the magnetic field



Using the Ic value of ReBCO wire of 10 mm width, operation current 400 A @ 2.65 T, 30K, about 50% of Ic.

Summary of the preliminary design parameters of the defocusing magnet and focusing magnet.

Item	Defocusing magnet	Focusing magnet
Radial length of pole	3.78 m	3.78 m
Average azimuthal length of pole	~1.44 m	~1.84 m
Total weight	~316 t	~486 t
Total Ampere turns	264000 AT	646000 AT
Turn No.	660	660
Total length of HTS wires	~14 km	~37 km

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