DESIGN OF OCTUPOLE CHANNEL FOR INTEGRABLE OPTICS TEST ACCELERATOR

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Abstract

We present the design of octupole channel for Integrable Optics Test Accelerator (IOTA). IOTA is a test accelerator at Fermilab, aimed to conduct research towards high-intensity machines. One of the goals of the project is to demonstrate high nonlinear betatron tune shifts while retaining large dynamic aperture in a realistic accelerator design. At the first stage the tune shift will be attained with a special channel of octupoles, which creates a variable octupole potential over a 1.8m length. The channel consists of 18 identical air-cooled octupole magnets. The magnets feature a simple low-cost design, while meeting the requirements on maximum gradient – up to 1.4 kG/cm^3, and field quality – strength of harmonics below 1%. Numerical simulations show that the channel is capable of producing a nonlinear tune shift of 0.08 without restriction of dynamic aperture of the ring.

QUASI-INTEGRABLE OPTICS AT IOTA

Integrable Optics Test Accelerator is a relatively small research storage ring with the circumference of 40 m. It will operate with short bunches of 150 MeV electrons injected from the FAST linac [1], and later with 2.5 MeV protons from a recommissioned HINS RFQ [2]. The ring has a flexible linear optics to allow for a variety of physics experiments [3], including nonlinear integrable optics, the concept of which is described in [4].

The ring setup for nonlinear optics consists of two 1.8m-long sections for nonlinear magnets with equal beta-functions and zero dispersion for nonlinear magnets, and the so called T-inserts with transfer matrices of thin axially symmetric lenses between these sections (Figure 1). The nonlinear magnets create a potential, which can be described in normalized coordinates as:

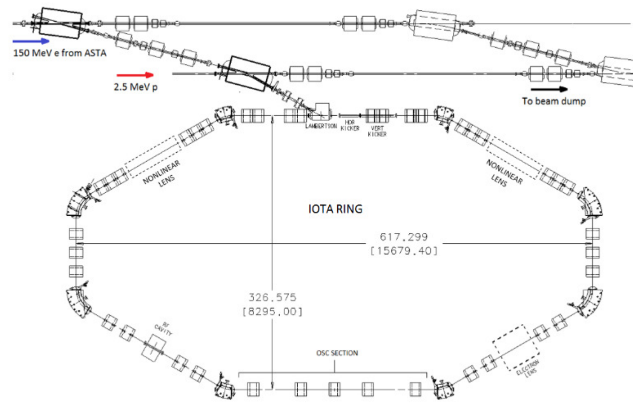

Figure 1: IOTA, configuration for nonlinear optics.

strength as $\beta(s)^{-3}$. Then the resulting Hamiltonian:

$$H = \frac{1}{2}(x^2 + y^2 + p_x^2 + p_y^2) + \frac{2t}{3c^2}(x^4 - 6x^2y^2 + y^4) \quad (1)$$

is independent of longitudinal coordinate s and thus it is an invariant of motion. 6D numerical simulations predict that in this "quasi-integrable" case one will be able to achieve a betatron tune shift of up to 0.08 (Fig. 3). Table 1 summarizes the main parameters of IOTA.

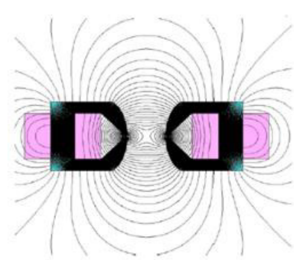

Figure 2: Magnetic field lines inside IOTA nonlinear magnets [3].

$$U(x,y) = t \cdot \mathrm{Re}\left[(x+iy)^2 + \frac{2}{3c^2}(x+iy)^4 + \frac{8}{15c^4}(x+iy)^6 + \frac{16}{35c^6}(x+iy)^8 + \ldots\right], \quad (2)$$

where t and c are parameters. For IOTA nonlinear magnets $c^2 = 0.01$ cm.

Figure 2 depicts magnetic field lines inside the magnet. It has two points of singularity at $x = \pm c$, making its design, manufacturing, and testing challenging [5]. Because of that at the first stage a set of conventional octupole magnets will be used to approximate the nonlinear potential (1), since the octupole term in is the lowest order term in (1) that creates a nonlinear tune spread. To create this potential one needs to scale octupole

The channel will have 18 conventional air-cooled octupole magnets, powered in pairs by 15V/2A DC power supplies. Distribution of octupole gradient through the channel is described by

$$\frac{\partial^3 B}{\partial x^3} = \frac{16t}{c^2}\frac{B\rho}{\beta(s)^3} \quad (3)$$

and is shown in Fig. 4. In the experiment the octupole strength will be varied from 0 to t = 0.5 in (2), or 1.4 kG/cm^3. Simulations showed that raising the gradient

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beyond that leads to decrease of the dynamic aperture. Field errors at the level of 10% are tolerable – they do not distort the dynamics significantly.

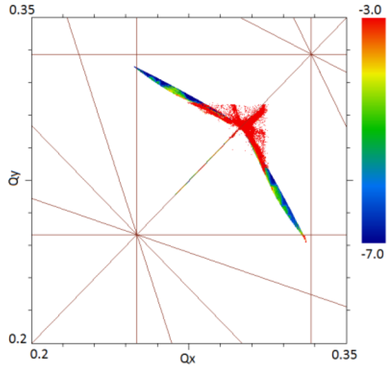

Figure 3: Frequency Map Analysis shows an attainable tune spread of 0.08 [6]. Resonant lines depicted in brown.

Table 1: Parameters of IOTA Ring for Electron Operation

Electron energy	150 MeV
Ring circumference	40 m
Length of NL magnets	1.8 m
Phase advance per NL section	0.3
Synchrotron damping time	~1 sec
Equilibrium RMS beam size	0.1 mm
Chromaticity: x, y	-10, -7
RF harmonic number	4
Bunch length	10 cm
Tunes: x, y, s	5.3, 5.3, $5 \cdot 10^{-4}$
Max tune shift with octupoles	0.08 [6]

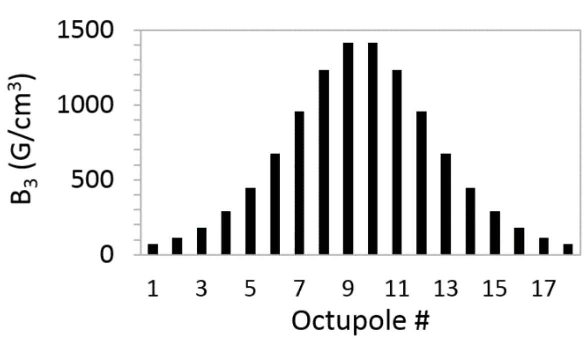

Figure 4: Distribution of octupole strength in the channel; strength parameter t = 0.5.

DESIGN

The design goal was to provide a simple low-cost solution for the channel. Figure 5 shows a drawing of the octupole and Table 2 summarizes its main specifications. The round yoke of the magnet is manufactured from a piece of steel tube. Pole assemblies slide into grooves in the yoke and held in place with two bolts. Pole tips are fixed with two aluminum "crowns" on both ends of the magnet. This allows to achieve the precision of positioning of the tips of 0.5 mm. Physical aperture of the magnets is 28 mm, which is higher than that of the special nonlinear magnet. This will allow to use a standard 1-inch round beam pipe.

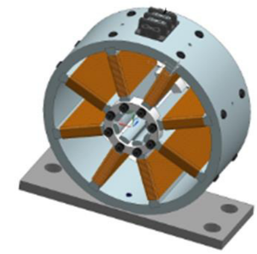

Figure 5: 3D model of IOTA octupole.

Each coil has 88 turns of # 14 AWG square copper wire in 4 layers. The wires are coated with HAPT 200 coating. This type of coating allows to safely bake the assembly at 130 C, which is necessary for achieving the desired vacuum in the machine.

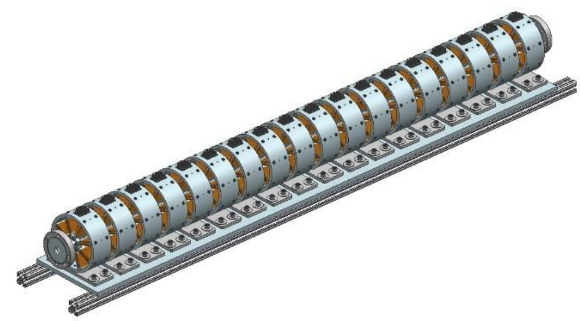

Figure 6: IOTA octupole channel.

The octupoles will sit on a dedicated girder (Fig. 6) with distance between the centers of the adjacent magnets being 10 cm. The girder provides three points of support for each magnet, allowing to fully adjust their positions in 3D.

Table 2: Requirement Specification

Spacing between octupoles	10 cm, between centers
Physical length	7 cm
Aperture	28 mm
Integrated current	176 A-turns
Coil current	Up to 2 A
Number of coil turns	88 in 4 layers
Voltage drop per pole	≤ 0.625 V
Voltage drop per magnet	≤ 5 V (poles in series)
Bake temperature	130 C
Power consumption	≤ 10 W per magnet
Max octupole gradient	1.4 kG/cm^3
Field quality at 10 mm	0.1 or better
Magnetic length	7.5 cm

MAGNETIC SIMULATION

Magnetic field simulations were performed in Comsol Multiphysics® suite to check the field magnitude, its quality, and magnetic length. Figure 7 depicts the distribution of magnetic field in the transverse crosssection of the magnet. The resulting field is close to the design cubic dependence, with the discrepancy being within a couple percent throughout the aperture of the beam pipe. At 10 mm the discrepancy is insignificant: less than 10 G, which satisfies the required quality of the field.

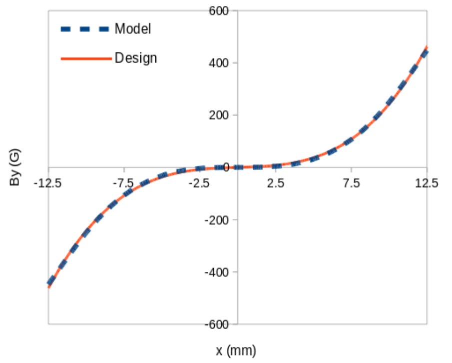

Figure 7: Simulated magnetic field follows the desired cubic dependence.

Figure 8 shows the field strength at 10 mm off the center as a function of longitudinal position. Maximum field at flattop is 250 G, corresponding to the octupole gradient of 1.5 kG/cm^3. The simulations yield a magnetic length of 7.6 cm, which is close to the design value.

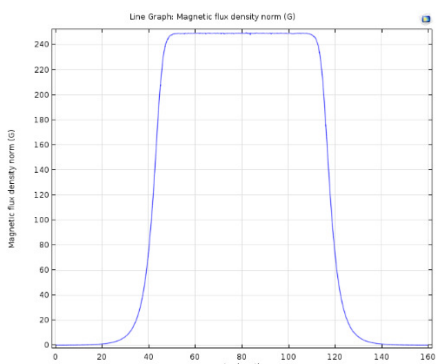

Figure 8: Field strength at 10 mm.

TEST RESULTS

A prototype magnet has been tested at Fermilab's Technical Division test magnet facility. Magnetic and thermal measurements have been performed.

During thermal measurements at room temperature the surface of the magnet stayed below 31 C at full current of 2A. Field quality measurement was made with a 25 mm rotating probe. A centering correction has been applied which forces the sextupole field component to zero (a non-zero sextupole is assumed to stem from being off-center in the octupole field – the so-called 'feed-down' correction), and digital bucking of the fundamental fields using several probe signals has been used to mitigate effects of vibrations during rotation.

The integrated strength of the octupole at 8.5 mm (2/3 of the 12.7 mm radius of the vacuum chamber) was 0.001406 T-m at the current of 2 A. The harmonics were measured to be less than 1% for all orders (Fig. 9), with the largest terms being n=6 (i.e. 12-pole – the first allowed harmonic of quadrupole symmetric magnet) and n=12 (the 24 pole – first allowed term of an octupole magnet). Thus, the prototype magnet meets the field quality requirements.

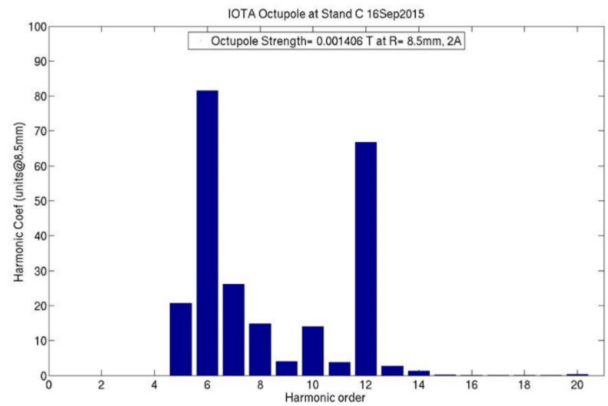

Figure 9: Integrated strength of harmonics relative to octupole field is less than 1% (100 units).

CONCLUSION

We have designed an octupole channel for IOTA. The channel will serve for the first stage of experiments with nonlinear integrable optics. It consists of 18 octupoles that create a varying potential over 1.8 m length. The design of the octupoles satisfies the requirements on sufficient strength – octupole gradient up to 1.4 kG/cm^3, field quality – strength of harmonics below 1%, and physical aperture – 28 mm. The design is also relatively simple, allowing to reduce the manufacturing costs.

A magnetic simulation has been done to confirm the requirement specification and then a prototype magnet has been assembled. It has been thermally and magnetically tested at Fermilab's test magnet facility and has confirmed the design parameters. The full octupole channel is going to be assembled at the IOTA facility later this year.

ACKNOWLEDGEMENT

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