Large Momentum Acceptance Superconducting Magnets for High Energy Physics Accelerators

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Introduction

Accelerator beamlines with large momentum acceptance preserve beam quality over a range of beam energies with static field in the accelerator magnets. For High Energy Physics (HEP), this approach shows promise to (1) increase the intensity of proton accelerators by reducing or eliminating the need for magnet ramping, and (2) enable the transport of beams with large momentum spread. Superconducting magnets are uniquely suited for the design of large momentum acceptance beamlines for these applications. In addition to producing fields much higher than the ~2 T saturation point limiting iron-dominated magnets, the coil-dominated nature of superconducting magnets gives flexibility for producing complex and combined-multipole fields. Coupling of magnet design and beam dynamics codes with multi-objective optimizers allows for not only achieving a very large momentum acceptance, but also integrating the required focusing, phase shifting, and/or higher order corrections required by different applications.

Background

Magnet technology for large momentum acceptance applications has been largely driven by the needs of fixed-field alternating gradient (FFAG) accelerators, fragment separators, and ion therapy [1-4]. Recently at LBNL, two large momentum acceptance superconducting magnet designs were developed for proton therapy as part of the HEP Accelerator Stewardship program. These designs show promise for broad application within HEP. The first is a combined function magnet, based on the alternating gradient canted-cosine-theta (AG-CCT) design. A modular winding approach is used to produce overlapping dipole, quadrupole, and sextupole fields all within the bore of a single, large aperture, curved magnet [5,6]. In addition, the quadrupole fields change along the length of this magnet with five alternating focusing and de-focusing sections. This design achieved a 20 % momentum acceptance which resulted in an order of magnitude reduction in magnet ramp rate to match beam energy changes during treatment. In addition, the beam spot size and shape at the patient location was precisely controlled by optimization of quadrupole and sextupole fields. The AG-CCT has also been studied for transport and energy selection of ion beams from laser plasma accelerators where initial spread in beam energy is large [7].

A second approach, using a combination of nonlinear bending magnets with even larger momentum acceptance, was developed in which the gantry accepts the full range of proton treatment energies (70-220 MeV) with fixed field in the superconducting magnets [8]. In this design, the magnetic profile within the magnets is highly nonlinear, and was optimized by integrating the magnet design with beam dynamics simulation tools in COSY INFINITY. First steps have been taken to extend this approach to higher energies relevant for the Intensity Frontier, with optimization of nonlinear magnets for large momentum acceptance and phase shifting in a 500 MeV to 2 GeV recirculating proton linac [9]. For this study, the beam dynamics code IMPACT [10] was also utilized, allowing for simulation of space charge effects and other challenging beam dynamics.

Fixed-Field Superconducting Magnets for High Intensity Proton Drivers

High intensity, GeV level proton accelerators are an enabling technology for neutrino physics experiments. To support such experiments, a staged upgrade of the Fermilab accelerator complex is in progress with the ultimate goal of supplying 2.4 MW beam power for the LBNF/DUNE neutrino program. Beyond the current phase of this project (PIP-II), both novel, rapid cycling synchrotrons and SRF linacs are being studied to reach the ultimate beam power target [11-15]. Another promising option proposed is the recirculating proton linac (RPL) [16-18]. This accelerator uses several re-circulating sections to accelerate the protons up to the final energy, allowing for high intensity CW operation (similar to a linac), and also more efficient use of expensive SRF cavities due to being multi-pass (similar to a synchrotron). Recirculating accelerators have been built and operated for electrons, but for protons have the unique challenge of more pronounced phase slippage in the desired energy range. The design of magnetic phase shifters to overcome this are challenged by (1) the need for high magnetic field due to the large magnetic rigidity of the proton beam at GeV energy, and (2) the need for very large momentum acceptance to enable fixed-field transport of multiple beam energies at once.

An LDRD-funded program has taken the first steps towards demonstrating fixed-field superconducting magnets can be designed to meet the challenges of the RPL. For different phase shifting sections in a 500 MeV to 2 GeV recirculating proton linac, preliminary superconducting magnet designs were optimized to produce a fixed, non-linear field profile which satisfies the phase shifting conditions for all the recirculating energies [9]. This required coupling of magnet design and beam dynamics tools to global optimizers, allowing for optimization of the non-linear field shape in the magnet to satisfy accelerator beam requirements. These studies are continuing, with the additional goal of also providing the correct beam focusing and performing a full tracking through the accelerator including space charge and non-linear effects. As initial accelerator and magnet designs are finalized, magnet prototype testing will become critical in order to demonstrate the feasibility and performance of the design, ultimately taking a large step forward in determining the feasibility of the RPL as a cost-saving option for future high intensity proton accelerators.

The AG-CCT for Large Momentum Acceptance Synchrotrons and Beamlines

The AG-CCT design can produce combinations of field harmonics (dipole, quadrupole, sextupole, etc.) which are constant or alternating along the length of the magnet. This flexibility lends itself to many HEP accelerator applications and also broader use within DOE. For superconducting synchrotrons, the AG-CCT shows promise to precisely control beam behavior (using combined-function fields) while reducing magnet ramp rate (through large momentum acceptance). For laser-based acceleration of ions, an initial study showed a beamline of AG-CCT superconducting magnets can transport ions with energy selection over a range of +/- 12% from 10 to 200 MeV/u. Finally, this approach is flexible to produce high-field fragment separators and spectrometers desired for nuclear physics.

Detailed studies are needed to quantify the perceived advantages and set magnet metrics for the various applications. Demonstration of the magnet technology through prototype testing is also critical. Initial results from this process are promising, with a first set of curved Nb-Ti dipole layers with 290 mm aperture and 0.9 m bend radius reaching their design field [6]. The next step is fabrication and test of a full AG-CCT system, which combines alternating quadrupole and dipole layers. Finally, continued development integrating CCT-specific magnet design tools with beam dynamics codes (such as COSY INFINITY) is crucial. This work connects magnet winding shape to beam behavior including full 3D field effects [5], allowing for efficient, simultaneous optimization of the accelerator layout and superconducting magnet coils for a broad range of applications.

References

[1] R. Barlow, et. al., "EMMA—The world's first non-scaling FFAG", *Nucl. Instrum. Methods Phys. Res. A*, Vol. 624, Iss. 1, Pg 1-19, 2010. [https://doi.org/10.1016/j.nima.2010.08.109]

[2] D. Trbojevic, R. Gupta, B. Parker, E. Keil, A.M. Sessler "Superconducting non-scaling FFAG gantry for carbon/proton cancer therapy", *2007 IEEE Particle Accelerator Conference (PAC)*, 2007. [https://doi.org/10.1109/PAC.2007.4440714]

[3] Toshiyuki Kubo, "In-flight RI beam separator BigRIPS at RIKEN and elsewhere in Japan", *Nuclear Instruments and Methods in Physics Research B,* Vol. 204, Pg. 97–113, 2003 [https://doi.org/10.1016/S0168-583X(02)01896-7]

[4] A. Gerbershagen, D. Meer, J. Schippers, and M. Seidel, "A novel beam optics concept in a particle therapy gantry utilizing the advantages of superconducting magnets", Z. Med. Phys., ol. 26, no. 3, p. 10664,2016, [https://doi.org/10.1016/j.zemedi.2016.03.006]

[5] W. Wan, L. Brouwer, S. Caspi, S. Prestemon, A. Gerbershagen, J.M. Schippers, and D. Robin, "Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries", *Phys. Rev. ST Accel. Beams*, Vol 18, 103501 (2015). [https://doi.org/10.1103/PhysRevSTAB.18.103501]

[6] L. Brouwer, S. Caspi, K. Edwards, A. Godeke, R. Hafalia, A. Hodgkinson, A. Huggins, C. Myers, S. Myers, M. Schillo, J. Taylor, M. Turqueti, X. Wang, W. Wan, and S. Prestemon, March 2020, "Design and test of a curved superconducting dipole magnet for proton therapy", *Nucl. Instrum. Methods Phys. Res. A*, [https://doi.org/10.1016/j.nima.2020.163414]

[7] Q. Ji, S. Bulanov, S. Steinke, T. Schenkel, E. H. Esarey, W. P. Leemans, "Design of a compact ion beam transport system for the BELLA Ion accelerator", *Proceedings of IPAC2016, Busan, Korea*, THPMR004, 2016. [https://doi.org/10.18429/JACoW-IPAC2016-THPMR004]

[8] L. Brouwer, A. Huggins, W. Wan, "An achromatic gantry for proton therapy with fixed-field superconducting magnets", *International Journal of Modern Physics A*, Vol 34, 1942023, 2019. [https://doi.org/10.1142/S0217751X19420235]

[9] J. Qiang, L. Brouwer, S. Prestemon, A Phase Shifter for Multi-Pass Recirculating Proton LINAC, *Proceedings of IPAC2019, Melbourne, Austrailia*, MOPRB103, 802-805, 2019 [https://doi.org/10.18429/JACoW-IPAC2019-MOPRB103]

[10] J. Qiang, S. M. Lidia, R. D. Ryne, C. Limborg-Deprey, "Three-dimensional quasistatic model for high brightness beam dynamics simulation", *Phys. Rev. ST Accel. Beams*, Vol 9, 044204, 2006. [https://doi.org/10.1103/PhysRevSTAB.9.044204]

[11] Vladimir Shiltsev, "Improvement Plans of Fermilab's Proton Accelerator Complex", *J. Phys.: Conf. Ser.* Vol 888, 012043, 2017 [https://doi.org/10.1088%2F1742-6596%2F888%2F1%2F012043]

[12] J. Eldred, V. Lebedev, and A. Valishev. "Rapid-Cycling Synchrotron for Multi-Megawatt Proton Facility at Fermilab", *Journal of Instrumentation*, Vol 14, P0702, 2019 [https://doi.org/10.1088/1748-0221/14/07/P07021]

[13] V. Danilov and S. Nagaitsev, "Nonlinear accelerator lattices with one and two analytic invariants", *Phys. Rev. ST Accel. Beams*, Vol 13, 084002, 2010 [https://doi.org/10.1103/PhysRevSTAB.13.084002]

[14] S. Antipov et al., "IOTA (Integrable Optics Test Accelerator): facility and experimental beam physics Program", *Journal of Instrumentation*, Vol 12, T03002, 2017 [https://doi.org/10.1088%2F1748-0221%2F12%2F03%2Ft03002]

[15] K. Ruisard, "Design of a Nonlinear Quasi-Integrable Lattice for Resonance Suppression at the University of Maryland Electron Ring", Ph.D. thesis, Phys. Dept., University of Maryland, College Park, Maryland, United States, 2018.

[16] J. Qiang, "Wide energy bandwidth accelerating cavities," Nuclear Instruments & Methods in Physics Research A, 795, p. 77 (2015). [https://doi.org/10.1016/j.nima.2015.05.056]

[17] K. Hwang and J. Qiang, "Beam Dynamics Simulation of a Double Pass Proton Linear Accelerator", *Phys. Rev. Accel. Beams*, 040401 (2017). [https://doi.org/10.1103/PhysRevAccelBeams.20.040401]

[18] Y. Tao, J. Qiang, K. Hwang, "Overtaking collision effects in a cw double-pass proton linac", *Phys. Rev. Accel. Beams*, Vol 20, 124202, 2019. [https://doi.org/10.1103/PhysRevAccelBeams.20.124202]