DESIGN AND COMMISSIONING OF CHASMAN-GREEN DOUBLE BEND ACHROMAT LATTICE LINEAR TRANSPORT LINE AT THE UNIVERSITY OF HAWAI'I MKV ACCELERATOR FACILITY*

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Abstract

The design of the Double Bend Achromat (DBA) lattice was originally motivated by the desire to increase the brightness of a synchrotron ring by storing a low emittance electron beam [1]. Alternating the direction of the bends in the DBA lattice turns the ring into a linear transport line, which has advantages over the straight transport lines typically used in linac FEL's. The dipoles in the DBA cells provide synchrotron images of the electron beam, a real-time non-destructive diagnostic during operation. As in circular machines, sections between DBA cells provide a low-emittance dispersion free beam for insertion devices such as FEL's and inverse Compton backscattering sources. This paper describes an example linear DBA, which has been designed and commissioned as part of the MkV 40 MeV electron accelerator facility at the University of Hawaii.

INTRODUCTION

The University of Hawai'i (UH) MkV Linear Accelerator facility and Free Electron Laser (FEL) Lab utilizes a thermionic LaB_6 cathode electron source in a microwave gun injector followed by a single section of traveling wave S-Band linear accelerator to produce a ∼200 mA average macro-pulse current 40 MeV electron beam. This beam drives a hybrid NdFeB planar undulator and Michelson interferometer phase-locked resonator based infrared FEL. Constructed on UH campus and occupying roughly one-third of the first floor of the physics department, the accelerator beamline was commissioned by 2009 and the lab produced first laser light in 2010; current experiments are focused on demonstration of inverse Compton x-ray photon production via FEL laser output and electron beam collision. A pico-second resolution x-ray detector and multi-gigabit per second sampling electronics are also being developed in parallel by collaborators in the University of Hawai'i Instrumentation Development Lab (IDLab) for measurement of the resulting micro-bunch x-ray train.

The electron beam transport system configuration for these experiments requires strong focusing to achieve small transverse size of the e-beam (and similarly so for the optical beam used in the collision) in order to achieve optimum x-ray flux. This transport system is known as the Diagnostic Chicane (DC) and delivers the beam from the accelerator to the FEL and also contains the inverse Compton interaction point. Traditional interrupting beam diagnostic instruments are included, such as insertable optical transition radiation (OTR) screens along the beamline and a wire scanner beam profilometer [2] at the inverse Compton interaction point. Stripline beam position monitors (BPM's) [3] and optical synchrotron radiation imaging of the e-beam are included to provide real-time non-destructive transverse and longitudinal information.

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MOTIVATION

In electron beam transport systems containing many bends, the intrinsic momentum spread of the beam can lead to unacceptable beam growth due to dispersion in dipole magnets. The Diagnostic Chicane is such a system, containing ten individual dipole magnets purchased from RadiaBeam Technologies [4]. The design was inspired by the double-bend achromat, first proposed by Renate Chasman and G. Kenneth Green [1] for the bright circulating beam required for the National Synchrotron Light Source at Brookhaven National Laboratory. The DBA has become a fundamental component of lattice design for many modern synchrotron and storage rings built afterwards, such as ESRF (France) and HiSOR (Japan) [5], as well as APS (Argone) and SOR (Japan) [6].

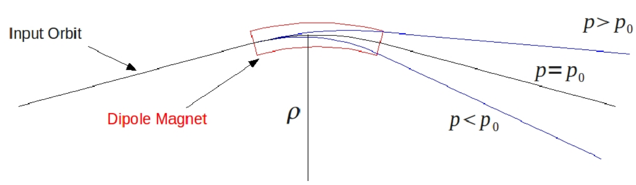

Figure 1: Dispersion induced by bending magnet. Electrons exit dipole separated from design orbit according to differing momenta.

This transport lattice provides cells having zero dispersion function, reserved for experiments and electron beam focusing for envelope matching between cells. These dispersion free portions alternate with cells containing dipole magnets and non-zero dispersion. The bends provide a means for physically separating the optical synchrotron radiation emitted by electrons as they traverse the dipole magnets, which is used for obtaining real-time transverse images.

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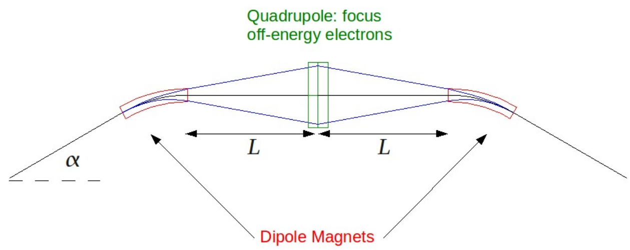

Figure 2: Dispersion correction by quadrupole magnet. Electrons of all momenta exit second dipole on design orbit.

SYSTEM DESIGN

The original model proposed by Chasman and Green used a single quadrupole placed at the center of the drift section separating two identical dipoles. As the beam travels through the first bend, particles having a momentum $p \neq p_0$, where p_0 is the momentum of the design orbit, exit the dipole magnet off-axis and off-angle (see Fig. 1). This leads to a beam expansion, horizontal separation of electrons according to their energy, and an effective growth in the beam's emittance. The quadrupole located at the symmetry point of the cell midway between the dipoles, is operated such that it is focusing in the bend plane, and when set correctly, re-images the off-energy electrons back onto the design orbit at the exit of the second dipole (see Fig. 2). The DBA cell is a key tool for compensating for the dispersion induced by bending magnets.

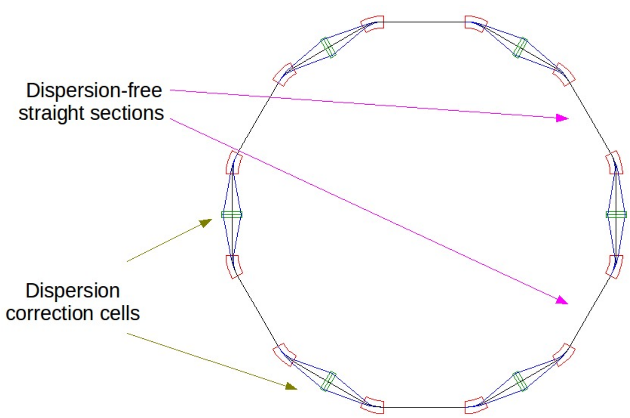

Figure 3: Chasman-Green DBA lattice for traditional ring configuration.

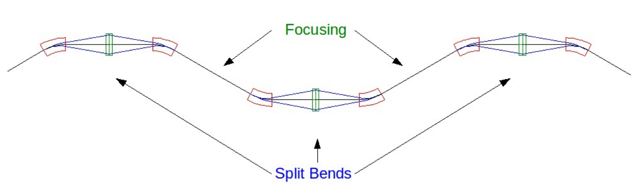

Figure 4: Chasman-Green DBA lattice for UH linear transport Diagnostic Chicane adaptation.

The momentum dependence of the transport system can be characterized by the dispersion vector $\mathbf{D}$, which tracks a particle that has a fractional momentum difference of $\delta \equiv \frac{p-p_0}{p_0} = 1$. In the language of general first order transport [7, 8], the 6-D dispersion vector is given by $\mathbf{D} = (D_x, D'_x, 0, 0, 0, 1) \equiv (D, D', 1)$, neglecting path length differences and assuming only horizontal bending. In this case [5, 6], the components of the dispersion vector obey the inhomogeneous differential equation:

$$D''(s) + \frac{1}{\rho^2} D(s) = \frac{1}{\rho} \tag{1}$$

where s is the longitudinal coordinate, ρ is the bend radius, and corresponding total deflection angle $\alpha = s/\rho$. If the dispersion function and its derivative are zero at the entrance of a bending magnet, at the output of the bend these functions are given by:

$$D_{out} = \rho(1 - \cos\alpha) \tag{2}$$

$$D'_{out} = \sin\alpha \tag{3}$$

which are determined completely by the geometry of the bend.

In the drift separating the first dipole and the central quadrupole, the dispersion ray travels at an angle from the design orbit of $\theta = D'_{out}$. From the symmetry of the system, the quadrupole must deflect this ray by an angle $\Delta\theta = -2D'_{out}$. This is the condition for the dispersion ray to exit the second dipole along the design orbit. For a thin-lens, the required focal length f for a given drift length L between the dipole exit and the quadrupole center is:

$$f = \frac{\rho(1 - \cos\alpha) + L\sin\alpha}{2\sin\alpha} \tag{4}$$

For small bending angles, this reduces to [6]:

$$f \approx \frac{L_{bend}}{4} + \frac{L}{2} \tag{5}$$

with L_{bend} the arc-length in the dipole.

Although first developed for circular machines where all the bends are in the same direction and have a sum of 360°, the analysis is equally valid in the case of alternating bends as in a chicane. Figure 5 shows the dispersion function and its derivative for the Diagnostic Chicane. The qualitative difference between this plot and a similar plot for a synchrotron ring is that the sign of the dispersion alternates with each Double Bend Achromat section.

The bend angles and drift lengths of the DBA sections of the DC are determined by many factors, including the orientation angle of the focusing sections, the availability of space in the lab, and the as-built x-ray extraction hole bored through the radiation shielding. With the geometry for the Diagnostic Chicane determined by these constraints, the dispersion correcting quadrupole focal lengths (and hence gradients and drive currents) can be calculated by equation (4). Alternatively, the quadrupole gradient can be found using the exact version of equation (4), as calculated by simulation software package PBOLab [9] using TRANSPORT

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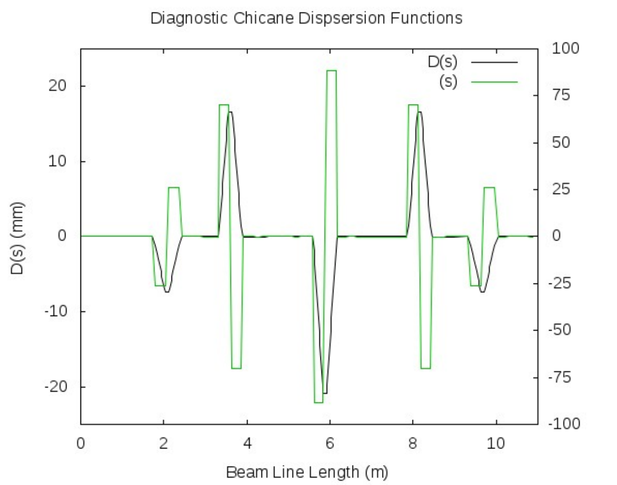

Figure 5: TRANSPORT simulation results of Diagnostic Chicane dispersion function and derivative.

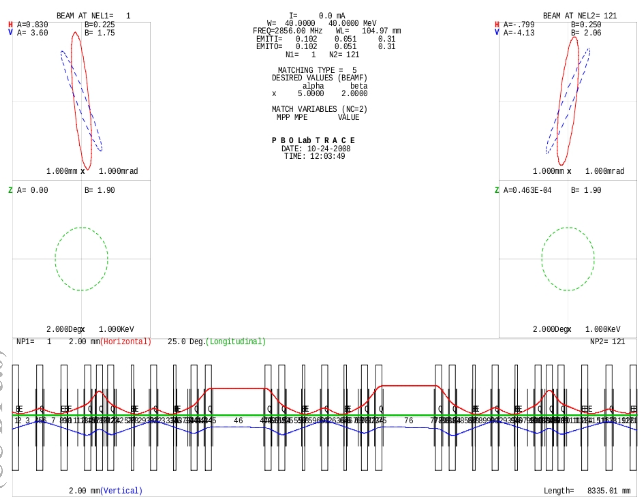

Figure 6: Examples of quadrupole triplet and doublet pair focusing schemes in Diagnostic Chicane, red trace is the horizontal envelope; the blue trace is the vertical envelope.

[10] and Trace3D [11] computation modules. In this case both quadrupole and dipole magnetic fields are represented without introducing either of the thin-lens or small angle approximations. The results are shown in Fig. 5.

Beam focusing is left for the dispersion-free sections between the DBA cells, which are known as the "focusing" sections. These focusing sections match the beam from one DBA cell to the next. Two simple quadrupole configurations for providing this match are the quadrupole triplet and the quadrupole doublet pair. An example of each of these is shown in Fig. 6. The beamline in this simulation starts at the input to the DC beginning with a DBA cell. The first and last focusing sections use a pair of quadrupole triplets and the second and third focusing sections use pairs of doublets.

SUMMARY

To summarize, the Chasman-Green Double Bend Achromat has been incorporated into and adapted for an alternating chicane beamline, inspired by the original synchrotron ring application. Simulations show the desired properties of sections for dispersion correction and dispersion free sections for beam focusing. Two simple focal schemes are shown to provide a match between the split-bends for beam transport through the Diagnostic Chicane. The system has been operational since commissioning in 2009.

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REFERENCES

[1] Renate Chasman and G. Kenneth Green, "Preliminary Design of a Dedicated Synchrotron Radiation Facility," IEEE Transactions on Nuclear Science, NS22(3):1765-1767, June 1975

[2] M. R. Hadmack, et al. "Scanning Wire Beam Position Monitor for Alignment of a High-Brightness Inverse-Compton X-ray Source," in Preparation

[3] B. T. Jacobson, M. R. Hadmack, J. M. J. Madey, P. Niknejadi, "Modular Logarithmic Amplifier Beam Position Monitor Readout System at the University of Hawai'i," MOPA17, IBIC Conf. Proc. (2012)

[4] RadiaBeam Technologies, www.radiabeam.com, Santa Monica, CA 90404

[5] Klaus Wille, "The Physics of Particle Accelerators: an Introduction," Oxford University Press Inc., 2000

[6] S. Y. Lee, "Accelerator Physics," World Scientific Publishing Co. Pte. Ltd., 2004

[7] Karl L. Brown, "A First- and Second-Order Matrix Theory for the Design of Beam Transport Systems and Charged Particle Spectrometers," 1982, SLAC-75, Revision 4

[8] Karl L. Brown, "First- and Second-Order Charged Particle Optics," 1984, SLAC-PUB-3381

[9] AccelSoft Inc., "PBO Lab 2.0 (Particle Beam Optics Laboratory) User Manual"

[10] D. C. Carey, K. L. Brown, F. Rothacker, "Third-Order TRANSPORT with MAD Input: A Computer Program for Designing Charged Particle Beam Transport Systems," SLAC-R-530 or Fermilab-Pub-98-310, 1998

[11] K. Crandall, D. Rusthoi, "TRACE 3-D Documentation," Third Edition, LA-UR-97-886, 1997

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