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COMPACT INTER-UNDULATOR DIAGNOSTIC ASSEMBLY FOR TESSA-515*

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Abstract

Beamline space is a very expensive and highly sought-after commodity, which makes the creation of compact integrated optics and diagnostics extremely valuable. The FAST- GREENS experimental program aims at demonstrating 10% extraction efficiency from a relativistic electron beam using four helical undulators operating in the high gain TESSA regime. The inter-undulator gap needs to be as short as possible (17 cm in the current plans) to maximize the output power. Within this short distance, we needed to fit two focusing quadrupoles, a variable strength phase shifter, a transverse profile monitor consisting of a YAG-OTR combination for co-aligning the electron beam and laser, and an ion pump. By making the quadrupoles tuneable with a variable gradient, in combination with vertical displacement, we can meet the optics requirements of matching the beam transversely to the natural focusing of the undulators. The two quadrupoles in conjunction with the electromagnetic dipole also serve as a phase shifter to realign the radiation and the bunching before each undulator section. This paper will discuss the mechanical design of this inter-undulator break section and its components.

INTRODUCTION

Available beamline space for adequate optics and diagnostics is a struggle for every accelerator layout that aims at efficiency and compactness; the FAST-GREENS experiment planned at the FAST beamline at FNAL is no exception. This experiment aims at demonstrating 10% extraction efficiency from a high brightness electron beam using Tapering Enhanced Stimulated Spontaneous Amplification (TESSA) [1]. It is based on using four tapered helical undulator section having 3.2 cm period and 1 m total length. The setup required the development of a compact multi-purpose break section housing significant number of optical elements and e-beam and radiation diagnostic equipment between each undulator.

For a summary of design parameters for this experiment we refer to Ref. [2].

The TESSA undulator extraction efficiency was found in GENESIS simulations to be highly dependent on the drift length between the undulator sections (Fig. 1) [3]. Even with a phase shifter added to take care of the relative phase between the radiation and the electron bunching, increase in spot size and diffraction affect the output radiation power after each break section.

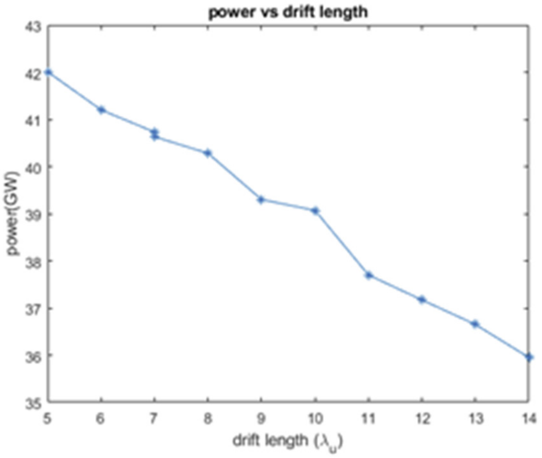

Figure 1: Power output from Genesis Informed Tapering optimized simulation vs. drift length. In this simulation we use four 29-periods-undulator sections, and we varied the drift length between undulators while optimizing the phase shifter. All other parameters, such as the seed laser Rayleigh length and tapering parameters, remain fixed.

Accordingly, special care was given to the design of the very dense inter-undulator break sections (Fig. 2). A strong focusing solution with a permanent magnet-based quadrupole doublet, with 106 mm center-to-center spacing, in between the undulator was adopted. This solution allows to focus the beam to a much smaller average beta function along the interaction than the more traditionally used single quadrupole channel. The implementation of this solution will be a first in high gain FELs and the experience gained from matching in this lattice could be relevant to future upgrades at larger facilities especially for cases where beam

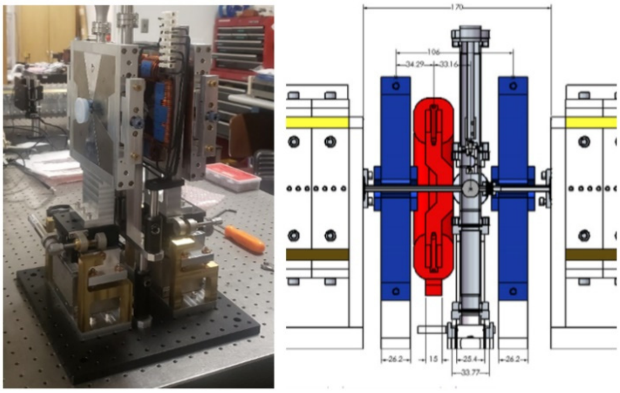

Figure 2: (left) Assembled break section. (right) Model of break section in-situ between undulators shown with size and spacing in mm.

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quality improves and a tighter focusing would be desired to improve the FEL gain [3].

Thus, the available space along the beamline was limited by the center-to-center spacing of two 1-m long helical undulators. One requirement that further complicated the matter was the break section needed to be installed after the undulators were already placed. After several design iterations, the inter-undulator spacing was reduced to 17 cm.

The electron optics components contained within the inter-undulator break section can be seen in Fig. 3 with their specifications listed in Table 1.

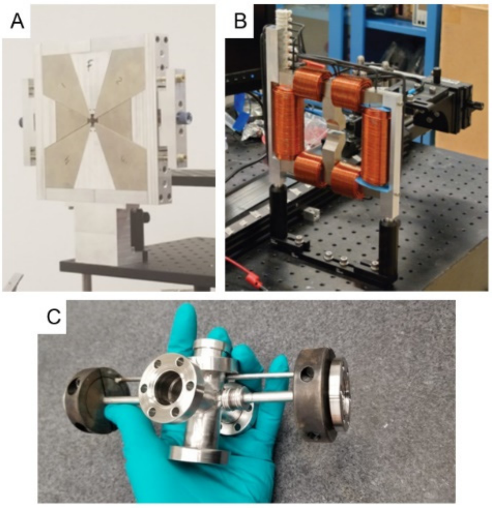

Figure 3: (A) Permanent magnet quadrupole (PMQ), (B) electro-magnetic dipole (EMD), and (C) custom six-way cross chamber with built-in bellows.

Table 1: Break Section Component Specifications

Identification	Eff. Mag. Length	Field
PMQ hybrid quad	30.4 mm	112 T/m
EMD	26.3 mm	0.3 T
PMQ hybrid quad	30.4 mm	112 T/m

In addition, the break section will house an electron beam and radiation diagnostic station. Due to the very small 4.5 mm inner diameter beampipe through each undulator, a small cross with an insertable Yttrium-Aluminum-Garnet (YAG) crystal and Optical Transition Radiation (OTR) foil was added for beam characterization. The chamber that houses this diagnostic station will be pumped on with a 3 L/s ion pump through the bottom port. It has been accepted that conductance through the undulator system will be limited by the size of the undulator beampipes. However, to assist with pumping, a roughing port has also been included on the chamber.

TUNABLE QUADRUPOLE DOUBLET

The TESSA hybrid quadrupole design consists of four steel poles with low carbon content (< 0.06%), and two NdFeB (1.45 T remanence) wedge sectors (Fig. 4). Trapezoidal shaped adjustable shims are used to create a magnetic circuit which can siphon magnetic flux density away from the aperture as the shims are brought in towards the magnet using ¼-100 fine adjustment screws.

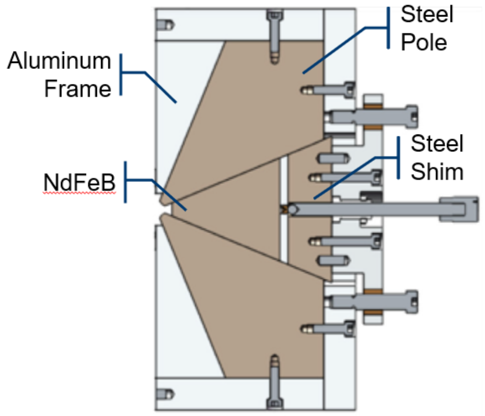

Figure 4: Cut view of half of a tunable PMQ showing material breakdown.

Depending on the gap between the poles of the yoke the target strength of the quadrupole can be adjusted to the needs of the experiment. Matching the 220 MeV beam to the focusing channel set up by the helical undulators and the quadrupole doublet requires a gradient of 112 T/m assuming a magnetic effective length of 30.4 mm and physical length of only 26.2 mm. In Fig. 5 we show RADIA simulation results for the gradient of the quadrupoles as a function of the half-gap. The effective length grows slightly in this interval from 30 mm to 32 mm as we increase the gap. In addition, the shims can be adjusted from 1 mm away to 5 mm away. Our target gap is 4.5 mm where the integrated gradient of the quadrupoles would be tunable from 3 T to 4.5 T. Preliminary measurements showed excellent agreement with the simulation results provided that the residual magnetization of the permanent magnet pieces was reduced to 1.39 T.

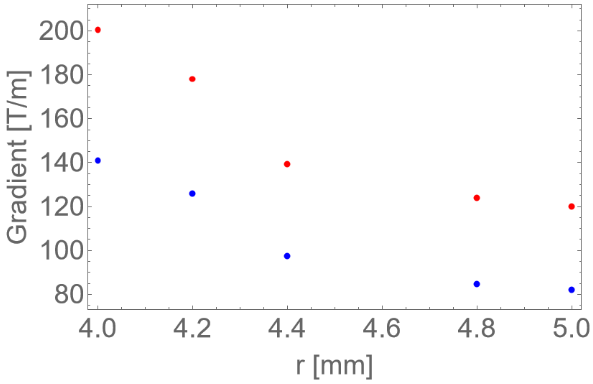

Figure 5: Hybrid quadrupole gradient as a function of the half-gap between the yoke poles. The red and blue dots correspond to the cases where the shims are extracted and inserted all the way respectively.

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PHASE SHIFTER

A phase shifter is also required to compensate for the dephasing between the microbunching and the FEL signal due to the diffraction of radiation [4]. Rather than adding a dedicated section, the idea was to combine the function of the quadrupoles and use them as part of a compact phase shifter design. By displacing them horizontally it is possible, adding an electromagnetic dipole (EMD) to compensate the kicks, to create a small adjustable horizontal orbit bump that can be tuned online to realign the microbunches at the right phase and maximize the extraction efficiency [3]. Remotely controllable XY translation stages were incorporated in the design to shift horizontally the position of each PMQ to provide horizontal trajectory kicks resulting in a tunable phase shifter.

It was important for the dipole to be as close to the center of the quadrupole doublet as possible in order to minimize the required strength. However, challenges came up to achieve the required field resulting in a H-magnet dipole design that would interfere with the flanges for the transverse profile monitor. To avoid this, the design consists of a physical yoke width of only 15 mm and poles that are offset from the center by 10 mm. This allows the poles to be only 8.71 mm offset from the doublet center, as seen in Fig. 6. The remaining offset is due to the position of the profile monitor, which ideally would also be centered be-tween the two PMQs.

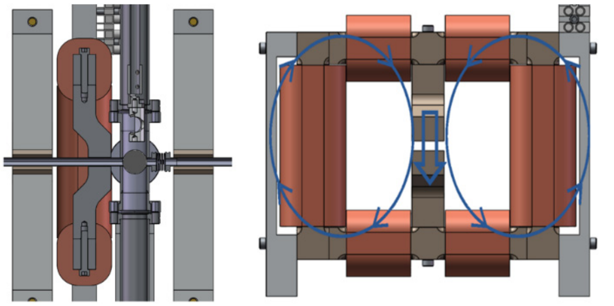

Figure 6: (left) Cut view of EMD showing pole offset. (right) Front view of EMD showing direction of the magnetic field.

The EMD consists of 6 coils, 4 small coils and 2 large coils, wound in series (Fig. 6). It is an atypical H-magnet design as the coils are not wound around the poles, but instead around the body of the magnet. This splitting up of the coils was done to maximize the current and voltage output while minimizing the overall footprint of the magnet. The final EMD has a 0.3 T field with 5 A excitation current.

In the present configuration, a full phase shift of 2π can be obtained by energizing the dipole at 0.3 T and shifting the quadrupoles by 650 and 450 µm respectively resulting in an orbit kick of 140 µm.

BEAM CHARACTERIZATION

Since space was limited, we needed to fit a transverse profile monitor into a ¾” diameter beampipe. This did not allow for a traditional profile monitor with YAG perpendicular to the beam backed by a mirror at 45 degrees. Instead, a custom aluminized YAG was used with 100nm of aluminum deposition on one side. By viewing this aluminized YAG, placed at a 45-degree angle, from both sides we can get the electron beam profile from the YAG side and the radiation profile from the aluminized side.

ACKNOWLEDGEMENTS

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