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MAGNETIC BUNCH COMPRESSION FOR A COMPACT INVERSE COMPTON SOURCE

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Abstract

A compact electron accelerator suitable for inverse Compton source applications is in design at the Center for Accelerator Science (CAS) at Old Dominion University (ODU). Here we discuss two options for transverse magnetic bunch compression and final focus, each involving a 4-dipole s-chicane with M_{56} tunable over a range of 1.5-2.0m with independent tuning of the final focus to an interaction point β*=5mm. One design has no net bending, while the other has net bending of 90 degrees and is suitable for compact corner placement.

INTRODUCTION

There is significant interest in X-ray sources beyond those available at large third-generation, lab-based synchrotron light sources. Medical phase imaging, and industrial applications have been developed that have motivated development of compact light sources based on inverse Compton scattering (ICS) [1] that provide single beamline operation at a cost of about $10-15M. A compact ICS source is in design at the ODU CAS with an X-ray energy of up to 12 keV, flux of approximately 1.6×10^{14} photon/sec, and average brilliance of 1.5×10^{15} $\mathrm{photon/(s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%BW)}$ [2].

This project consists of an optimized 500 MHz superconducting electron gun, 4K 500 MHz superconducting spoke cavity linac [3], and a bunch compressor to provide a short, high-brightness electron bunch to collide with an incoming laser beam to produce inverse Compton scattered photons. The electron beam requirements are shown in Table 1. The bunch length requirement of a few ps and energy spread requirement of 3×10^{-4} indicate the need for small longitudinal emittance (<7 eV-m) and well-corrected bunch compression. A practical system will also have tunable M_{56} to optimize the scattered photon beam.

Table 1: Electron Beam Parameters at Collision

Parameter	Value	Units
Energy	25	MeV
Bunch charge	10	pC
Repetition rate	100	MHz
Average current	1	mA
Normalized emittance	0.1	mm·mrad
$\alpha^*_{x,y}$, $\beta^*_{x,y}$	0, 5	-, mm
FWHM bunch length	3.0 (0.9)	psec (mm)
RMS energy spread	7.5	keV

DESIGN PHILOSOPHY

Traditionally dispersion-free chicanes are used for magnetic bunch compression, with $M_{56} < 0$ and $T_{566} > 0$[4]. However, these chicanes are not very compact and cancel dispersion only to odd orders. M_{56} tunability is also directly connected to the chicane transverse dimension, and so is limited.

For a compact design with tunable M_{56}, we have been investigating 4-dipole s-chicanes that alternate the bending directions of the center dipoles. A chicane of this type was investigated for the final bunch compressor of TTF-FEL [5]. S-shaped compressors are dispersion free to all orders, have greater M_{56} tunability, and can be wrapped in on themselves with large central bend angles to be made compact. As described in [5], M_{56} is tunable by adjusting the central dipole angle.

Initial designs considered combining quadrupoles in the compressor with quadrupoles outside the compressor to tune the final focus. However, the aggressiveness of the design final focusing to $\beta^* = 5$mm is best handled with a separate independent low-beta focus section. This sacrifices some small measure of compactness of the design, but greatly improves the orthogonality of tuning knobs for achromaticity, M_{56}, final focusing, and upstream matching. The linac design for this ICS suggests that a reasonable range for M_{56} tuning is 1.5-2.0m.

A typical s-shaped chicane compressor ensures achromaticity by having a net horizontal phase advance of 2π, with a pair of symmetrically-placed horizontal focusing quadrupoles to tune achromaticity and a vertical focusing quadrupole at the center symmetry point to control vertical betas. Here the compact design pushes us towards stronger focusing, and we investigate two designs: one with net 3π phase advance and a net 90° bend for corner use, and one with net 4π phase advance for larger dispersion and M_{56} lever arm. M_{56} is tunable for both designs by adjusting the center symmetric bend angles and rematching achromaticity and final focus.

DESIGNS AND RESULTS

We use elegant from the APS for lattice design, optimization, and particle tracking, including simulation of short quadrupole end effects as described in the next section. Each lattice has three quadrupoles in two symmetric families between the center dipoles. For a given central

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Table 2: 3π Bunch Compressor Parameters

Parameter	**Value**	**Units**
Final β_x,β_y	0.005	m
Final α_x,α_y	$< 10^{-8}$	-
Maximum β	≈ 85.8	m
M_{56}	1.498	m
Floor Dimensions	3×4	m
Dipole Lengths	0.8,1.0,0.8,1.0	m
Dipole Bend Angles	70,-115,-115,70	°
Max Quadrupole Gradient	≈ 9.5	T/m
Quadrupole Length	0.1	m

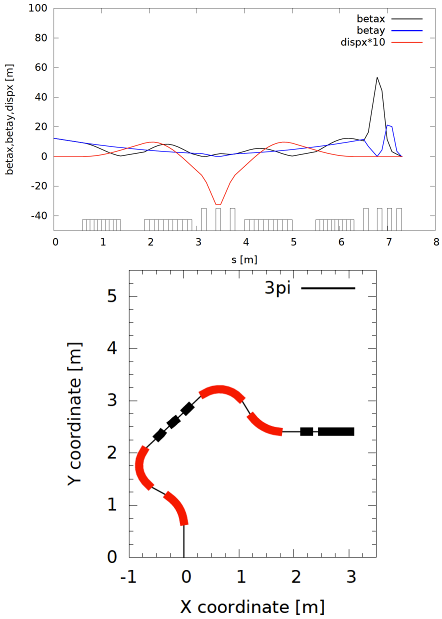

Figure 1: 3π bunch compressor optics and floor plan.

dipole bend angle (and hence M_{56}),

- The pair of symmetric quadrupoles are tuned to make the compressor achromatic.
- The center quadrupole is tuned to control vertical beam size entering the final focus section.
- The final focus is retuned to match collision IP conditions of $\beta^*_{x,y} = 5\text{mm}$ and $\alpha^*_{x,y} = 0$.

In both designs, peak beam sizes are well-controlled, and chromatic effects of the final focus are minimal, indicating no need for nonlinear corrections that would otherwise distort the transverse phase space. Neither design includes sextupoles to control T_{566} as of present, though their inclusion should be straightforward at high dispersion locations in the bunch compressor to control longitudinal distribution linearity [9].

3π Compressor

The first compressor, denoted ”3π”, has a total dispersion phase advance of 3π and a net bending of 90°, making it suitable for a compact corner design. Four quadrupoles are used in the final focus. The floor layout and the transverse optics are shown in Fig. 1, and relevant parameters are shown in Table 2. The compressor fits in a 3.5×4m area, and in these conditions is tuned for $M_{56} = 1.498$m. Note that for this compressor, the first and fourth dipoles bend in the same direction to provide the dispersion cancellation and overall bend.

Table 3: 4π Bunch Compressor Parameters

Parameter	**Value**	**Units**
Final β_x,β_y	0.005	m
Final α_x,α_y	$< 10^{-8}$	-
Maximum β	$\approx$29.5	m
M_{56}	1.4	m
Floor Dimensions	2×4.3	m
Dipole Lengths	0.35,1.134,1.134,0.35	m
Dipole Bend Angles	40,-175,175,-40	°
Max Quadrupole Gradient	≈ 9.15	T/m
Quadrupole Length	0.1	m

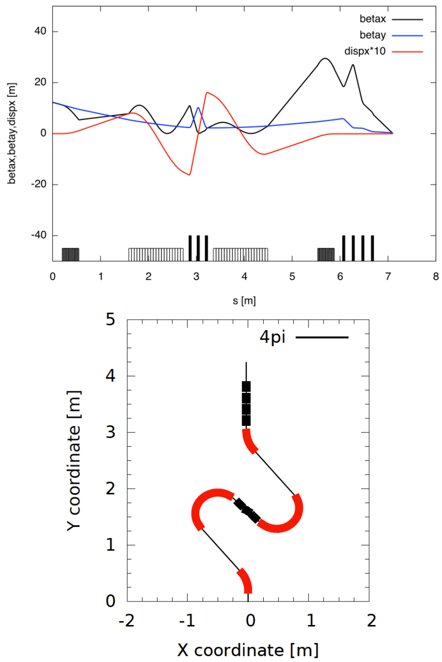

Figure 2: 4π bunch compressor optics and floor plan.

4π Compressor

The second compressor, denoted ”4π”, has a total dispersion phase advance of 4π and no net bending; it is more transversely compact than the 3π design. three quadrupoles are used in the final focus. The floor layout and the transverse optics are shown in Fig. 2 and relevant parameters are shown in Table 3. The compressor fits in a 2.0×4m area, and in these conditions is tuned for $M_{56} = 1.4$m. Additional quadrupoles may be added in the outside drifts for extra optics control.

QUADRUPOLE CONSIDERATIONS

Fringe Fields

Since the quadrupoles in this design are comparatively short, we investigated the effect of inclusion of fringe fields on the transport and matching. Considering the fringe field to be symmetric on both ends, we used the single parameter Enge function [6] to calculate the required integrals for elegant to calculate the final beta functions with effects from the fringe fields from the quadrupoles. Elegant requires the normalized quadrupole fringe field $\tilde{k}(s)$ to be normalized [7], so using the field profile shown in Fig. 3 we found the Enge coefficient a_1=4.6.

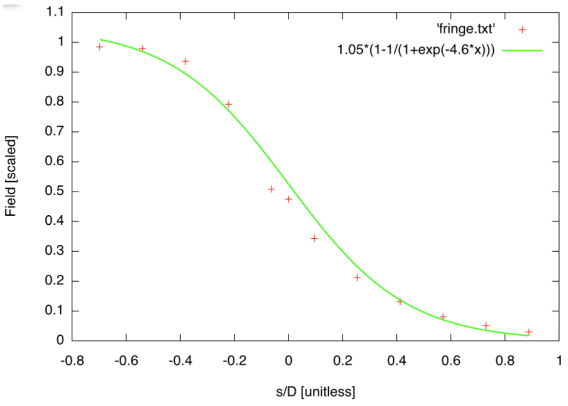

Figure 3: Fit of normalized fringe field for typical compressor quadrupole design.

Design Availability

The quadrupoles in both designs are typically 10 cm long with an exception of the focusing quartet of 4π compressor, which are 15 cm long, with a maximum field gradient of nearly 10 T/m. Some parameters for various quadrupoles used in these design are shown in Table 4.

With the design beam pipe diameter, these parameters match those of commercially available quadrupoles such as those from RadiaBeam. The air-cooled diamond quadrupole BEMQD-01-155-245 [8] is such a magnet which is close to the required dimensions while having a max gradient of 12 T/m.

Table 4: Quadrupole Data

Parameter	Value(range)	Units
Bore	0.04	m
Magnetic Field Gradient	2.5-9.7	T/m
Length	10	cm
Total Current (NI)	434-1684	A
Conductor cross-section (air-cooled)	4.3-16.84	cm^2
Conductor cross-section (water-cooled)	0.43-1.684	cm^2

Table 5: RadiaBeam Diamond Quadrupole

Parameter	Value	Units
Bore	0.0394	m
Max field gradient	12	T/m
Magnetic length	~9.74	cm
Total current (NI)	1940.4	A-turns

FUTURE DIRECTIONS

Further optimization work on the bunch compressors will focus on tunability, chromatic compensation in the final focus, and T_{566} nonlinear longitudinal focusing to correct longitudinal bunch distortion from the linac. T_{566} should be straightforward to independently control to first order with the inclusion of sextupoles at high dispersion locations in the bunch compressor [9]. Beam dynamics will follow those in [10]. Plans of adding an upstream matching block between the linac and the compressor are in consideration

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