PROGRESS ON A COMPACT ACCELERATOR DESIGN FOR A COMPTON LIGHT SOURCE*

K. Deitrick[1†], J.R. Delayen[1,2], B.R.P. Gamage[1], G.A. Krafft[1,2], T. Satogata[1,2]
[1] Center for Accelerator Science, Old Dominion University, Norfolk VA, 23529, USA
[2] Thomas Jefferson National Accelerator Facility, Newport News VA, 23606, USA

Abstract

A compact Compton light source using an electron linear accelerator is in design at the Center for Accelerator Science at Old Dominion University and Jefferson Lab. We report on the current design, including beam properties through the entire system based on a full end-to-end simulation, compare current specifications to design goals, and target areas for improvement.

INTRODUCTION

Compton Light Source

At present, there is a high level of interest in an inverse Compton light source with a compact floor plan due to the wide variety of applications such a system could facilitate. To this end, a preliminary design was developed and presented, with the necessary electron beam and resulting x-ray beam properties shown in Table 1 [1].

Table 1: Electron Beam Parameters at Collision, Compton Source Parameters

Parameter	Value	Units
Energy	25	MeV
Bunch charge	10	pC
Repetition Rate	100	MHz
Average current	1	mA
Normalized ϵ_{rms}	0.1	mm-mrad
$\beta_{x,y}$	5	mm
FWHM bunch length	3.0 (0.9)	psec (mm)
RMS energy spread	7.5	keV
X-ray energy	Up to 12	keV
Photons/crossing	1.6×10^6	
Flux	1.6×10^{14}	photon/sec
Average brilliance	1.5×10^{15}	photons/(sec-mm^2-mrad^2-0.1% BW)

Simulation Tools

A number of accelerator codes were used to develop an end-to-end simulation. CST Microwave Studio© (CST) is an electromagnetic (EM) field solver [2]. SUPERFISH is also an EM field solver, provided the geometry is cylindrically symmetic, developed by Los Alamos [3]. The tracking through the accelerating section was performed by ASTRA (A Space-charge TRacking Algorithm), which tracks particles through user-defined external fields [4]. Space charge was taken into account throughout, and the image charge due to the cathode was included within the gun.

After emerging from the linac, the beam dynamics were calculated by `elegant` [5]. Translating the final bunch produced by ASTRA into the SDDS format required by `elegant` was done by a specific function provided within the package for that purpose.

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† kdeit001@odu.edu

ACCELERATION

Electron Gun

The electron gun is a 500 MHz superconducting RF (SRF) quarter-wave design, originally based on the shape proposed by Harris et al. [6]. The design is highly reentrant in order to mitigate the growth of the transverse normalized emittance due to space charge. In order to remove a surface tangential discontinuity near the cathode, the design was slightly altered. The RF properties of the altered design are presented in Table 2 [7].

Table 2: RF Properties of the 500 MHz Quarter Wave Electron gun at $E_{\text{acc}} = 1$ MV/m

Parameter	Value	Units
Frequency of accelerating mode	499.3	MHz
λ/4	150	mm
Design β	0.95	
Stored energy	44	mJ
QR_s	83.5	Ω
R/Q	154	Ω
Peak electric surface field (E_P)	3.67	MV/m
Peak magnetic surface field (B_P)	6.64	mT
E_P/B_P	1.81	mT/(MV/m)

In order to study the beam dynamics of a bunch, the EM fields of the gun calculate by SUPERFISH were exported and translated into the format required by ASTRA. A 10 pC bunch consisting of 2000 electrons with a plateau longitudinal distribution of length 24 ps, σ_r of 0.5 mm, and negligible initial emittance or transverse momentum was generated and tracked by ASTRA through the gun. Both the space charge of the bunch and the mirror-image contribution of the cathode were included in this simulation. The properties of the beam after the exit of the gun (15 cm from the surface of the cathode) are shown in the top section of Table 3.

Table 3: Beam Properties After Exiting Gun (top) and the Linac (bottom), as Simulated by ASTRA

Parameter	Value	Units
E_{kin}	1.55	MeV
Energy spread	0.526	keV
$\sigma_{x,y}$	0.477, 0.477	mm
Normalized RMS $\epsilon_{x,y}$	0.12, 0.12	mm-mrad
E	25.02	MeV
RMS Energy spread	31.09	keV
σ_z	2.1 (7.0)	mm (psec)
$\sigma_{x,y}$	0.511, 0.482	mm
Normalized RMS $\epsilon_{x,y}$	0.16, 0.15	mm-mrad
$\alpha_{x,y}$	2.34, -0.591	
$\beta_{x,y}$	82.1, 75.5	m

Linear Accelerator

As before, the linear accelerator (linac) consists of four 500 MHz double-spoke high-velocity accelerating cavities to bring the beam up to the required energy. The EM fields were calculated by CST, before being translated into the format required by ASTRA. The bunch previously produced by ASTRA after traversing the gun was then tracked by ASTRA through the linac, continuing to take space charge into account.

In order to produce the roundest possible beam, the design takes advantage of the quadrupole-like effects of the spoke cavities [8]. This means as the bunch travels down the beam line after exiting the gun, the first spoke of each cavity that the bunch traverses is orthogonal to its predecessor. In essence, the first four spokes (in two cavities) are oriented as follows: (horizontal, vertical) (vertical, horizontal).

In order to chirp the bunch for compression, the last two cavities of the linac are run off-crest at 6.5° each. The properties of the beam emerging from the linac are shown in the bottom section of Table 3, with the transverse phase spaces shown in the top row of Fig. 1.

MATCHING

While the beam properties are fairly reasonable, the transverse phase spaces resemble bowties more than ellipses. In order to correct this, a solenoid was placed after the linac. The resulting phase spaces are the bottom row in Fig. 1. While this does benefit the phase space, it increases the magnitude of x' and y' $\ni$ $x' \equiv \frac{p_x}{p}$ with a similar definition of y'. As the emittance increases as the maximum magnetic field of the solenoid does, the strength of the solenoid is balanced between the increase in emittance and the decrease of bowtie resemblance.

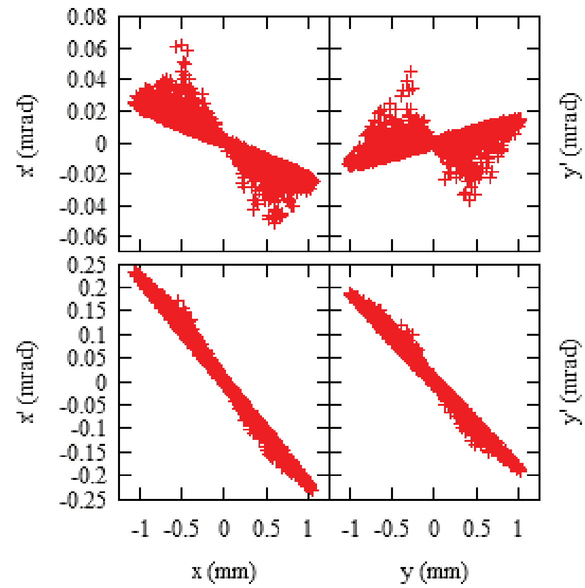

Figure 1: Transverse phase spaces after the linac (top) and the solenoid (bottom).

In order to make $\alpha_x = \alpha_y$, a quadrupole was placed downstream of the solenoid after a drift. The beam properties after both the solenoid and the quadrupole are in Table 4.

Table 4: Beam Parameters After (1) the Solenoid and (2) the Quadrupole, as Simulated by `elegant`

Parameter	(1)	(2)	Units
Normalized RMS $\epsilon_{x,y}$	0.19, 0.18	0.19, 0.18	mm-mrad
$\sigma_{x,y}$	0.50, 0.47	0.38, 0.39	mm
$\beta_{x,y}$	65, 61	38, 39	m
$\alpha_{x,y}$	15, 12	10, 10	

BUNCH COMPRESSION

As has been previously reported, there exist two possible designs for a bunch compressor. Both are four dipole s-chicanes, with a symmetric set of three quadrupoles in the center of the dipoles and a final focusing section after the dipoles. One has a net phase advance of 3π, while the other has a net phase advance of 4π [9]. The parameters for both bunch compressors are presented in Table 5. Given that the sign of the M_{56} values are opposite for the two designs, the necessary chirp is in different directions for each, though the magnitude of the chirp is the same.

Demonstrating the ability to tune the M_{56} of these designs is shown by adjusting the bend angles for the inner pair of dipoles. The bunch has been tracked through altered lattices where only the inner dipole bend angles have been adjusted. A comparison of the resulting compression for both the 3π and 4π compressor are shown in Fig. 2.

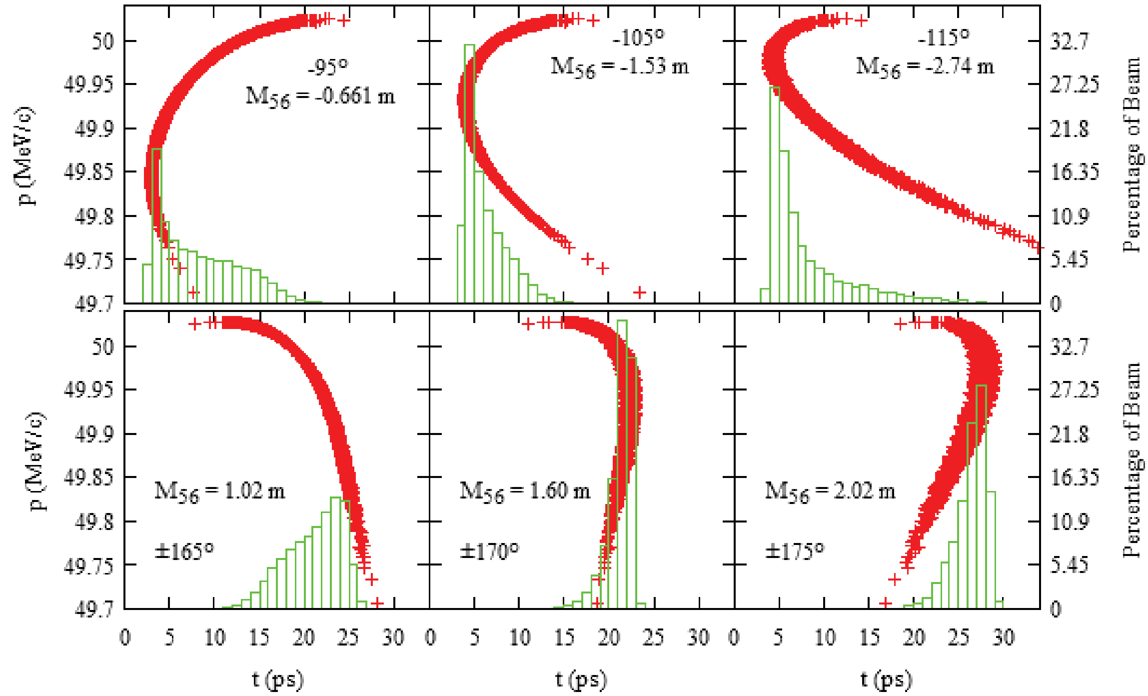

Figure 2: Comparison of M_{56} due to bend angle of inner dipole pair and the resulting compression for 3π (top) and 4π (bottom) compressors. Longitudinal density is shown by histogram.

Table 5: Bunch Compressor Parameters for the 3π and 4π Designs

Parameter	Value	Units
Final $\beta_{x,y}$	5, 3	mm
M_{56}	-1.53	m
Dipole lengths	0.8, 0.8, 0.8, 0.8	m
Dipole bend angles	60, -105, -105, 60	°
Final $\beta_{x,y}$	4, 8	mm
M_{56}	1.60	m
Dipole lengths	0.35, 1.1, 1.1, 0.35	m
Dipole bend angles	40, -170, 170, -40	°

FURTHER WORK

Given the results previously presented and the parameter goals initially stated in Table 1, we believe that a feasible design is possible. It should be emphasized that we have not applied emiitance compensation yet in the gun region, and still achieve beam parameters close to those required. At present, the two parameters of most concern are the transverse normalized emittance and the RMS energy spread. As the transverse emittance comes out of the gun already higher than the desired value, it needs to be improved by another optimization of the gun. In order to meet the desired energy spread, it may be necessary to decrease the bunch length off of the cathode. As this adjustment will certainly have an impact on the space charge fields within the gun, and thus the emittance, careful calculation and optimization of the beam dynamics will be needed.

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