COMPACT ACCELERATOR DESIGN FOR A COMPTON LIGHT SOURCE*

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Abstract

A compact electron accelerator suitable for Compton source applications is in design at the Center for Accelerator Science at Old Dominion University and Jefferson Lab. The design includes a KE=1.55 MeV low-emittance, optimized superconducting electron gun; a 23.45 MeV linac with multi-spoke 4.2 K superconducting cavities; and transport that combines magnetic longitudinal bunch compressor and transverse final focus. We report on the initial designs of each element, including end to end simulations with ASTRA and elegant, and expected beam parameters.

INTRODUCTION

A Compton source is essentially a lepton-photon collider. The total number of source photons produced per bunch crossing N_x is

$$N_x = \frac{N_e N_\gamma \sigma_T}{2\pi\sqrt{\sigma_{e,x}^2+\sigma_{\gamma,x}^2}\sqrt{\sigma_{e,y}^2+\sigma_{\gamma,y}^2}} \quad (1)$$

where N_e is the number of electrons per bunch, N_γ is the number of photons per bunch, $\sigma_T \equiv 8\pi r_e^2/3$ is the Thomson cross section, r_e is the classical electron radius, and sigmas are transverse RMS electron and photon beam sizes at the interaction point. This assumes that the electron bunch length is smaller than transverse beta functions to ignore hourglass effects. The flux of photons produced is $F = fN_x$ where f is the collision repetition frequency; multiply by 1.5×10^{-3} to obtain the flux into a 0.1% bandwidth in the forward direction [1].

Usually for FEL applications, the required source emittance is defined by the diffraction limit, $\epsilon < \lambda/(4\pi)$, where λ is the wavelength of the emitted radiation. This condition usually cannot be achieved in Compton sources with lower beam energy and correspondingly larger RMS emittances. The brightness of the source in the non-diffraction limited mode of operation is $B = F/(4\pi^2\epsilon_x\epsilon_y)$. Therefore minimum electron beam transverse emittance is desirable to obtain maximum photon brightness.

Longitudinally, minimized energy smearing of the forward flux compared to the total bandwidth requires that the compressed beam energy spread be less than 0.03%. At E =25 MeV this translates to 7.5 keV.

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Table 1: Electron Beam Parameters at Collision, Optical Cavity Parameters, and Compton Source Parameters

Parameter	Value	Units
Energy	25	MeV
Bunch charge	10	pC
Repetition rate	100	MHz
Average current	1	mA
Normalized emittance	0.1	mm·mrad
$\beta_{x,y}$	5	mm
FWHM bunch length	3.0 (0.9)	psec (mm)
RMS energy spread	7.5	keV
Wavelength	1 (1.24)	μm (eV)
Circulating Power	1	MW
N_γ, Photons/bunch	5×10^{16}	
Spot size	3.2	μm
X-ray energy	Up to 12	keV
Photons/crossing, N_x	1.6×10^6	
Flux, F	1.6×10^{14}	photon/sec
Average brilliance	1.5×10^{15}	$\frac{\text{photon}}{\text{s·mm}^2\text{·mrad}^2\text{·0.1\%BW}}$

These requirements are reasonably close to that achievable from an SRF gun and injector system [2]. This guides us towards a set of self-consistent design goal parameters listed in Table 1.

ELECTRON GUN

We started with a quarter-wave gun developed and tested by Harris et al. [3] for the gun geometrical design. This is a highly reentrant cavity, with a length o(λ/4), where λ is the longest resonant wavelength of the cavity. A 500 MHz RF frequency was chosen for compactness. Further design and optimization was performed with CST Microwave Studio© 2012 (CST) [4].

We tracked particles using ASTRA [5], using RF fields from CST. We tracked 2000 electrons with total bunch charge of 10 pC, in a can-shape distribution including space-charge effects for 0.15 m, well beyond the gun exit. A convex-shaped cathode reentrance nosecone geometry was optimized to give a minimally divergent or convergent beam at gun exit. Over various parameter scans in CST, this cavity performed better than the other geometries in terms of low surface fields and high shunt impedance.

Fig. 1 shows the preliminary design based on initial parameter sweeps. This is a reentrant cavity with a spherical inward curvature on the beam exit face, and a convex cathode aperture. Table 2 presents the cavity's geometrical parameters and RF properties. RF parameters were calculated by scaling electric and magnetic field values from CST, given the kinetic energy gain output from ASTRA.

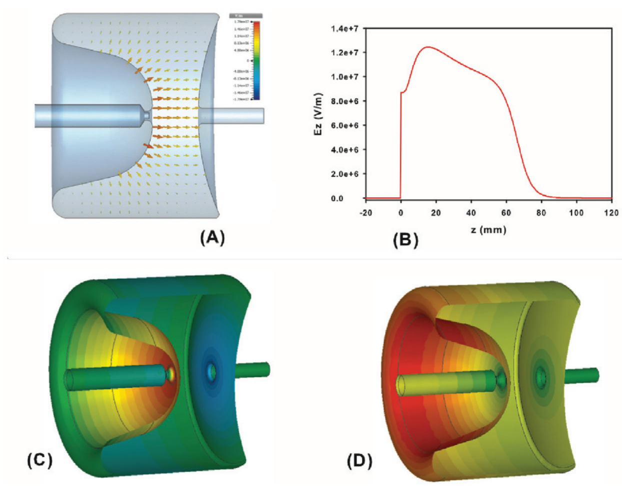

Figure 1: Preliminary design of a 500 MHz quarter wave electron gun. (A) Longitudinal cross section and electric field within the cavity at 1 J (B) Accelerating electric field profile along beam axis; (C) Surface electric field; (D) Surface magnetic field.

Table 2: Cavity and RF Properties of the 500 MHz Quarter Wave Electron Gun at $E_{\mathrm{acc}} = 1$ MV/m and Reference Length $\beta\lambda/4$, and ASTRA Tracking Results at $z = 0.15$ m

Parameter	Value	Units
Frequency of accelerating mode	500.0	MHz
Frequency of nearest mode	504.3	MHz
Design β	1	
$\lambda/4$	150	mm
Cavity length	221.5	mm
Cavity radius	133.9	mm
Cavity gap	60	mm
Beamport aperture radius	10	mm
Average kinetic energy gain	1.55	MeV
Accelerating voltage ($V^{\star}_{\mathrm{acc}}$)	1.55	MV
Peak electric field ($E^{\star}_{\mathrm{p}}$)	5.59	MV/m
Peak magnetic field ($B^{\star}_{\mathrm{p}}$)	10.4	mT
$(B^{\star}_{\mathrm{p}})/(E^{\star}_{\mathrm{p}})$	1.86	mT/(MV/m)
Geometrical factor, G	89.5	Ω
$(R/Q) \times G$	1.01×10^4	Ω^2
Energy content ($U^{\star}$)	160	mJ
Dissipated power (at $Q_0 = 10^9$)	80	W
Average kinetic energy	1.554	MeV
Energy spread	0.4727	keV
Transverse beam emittances x, y	0.0632,0.0683	π mm-mrad
Correlated divergence x, y	0.831,0.833	mrad
Longitudinal beam emittance z	0.857	π keV-mm

MULTI-SPOKE LINAC RF CAVITIES

Multi-spoke cavities have not been used for $\beta \approx 1$ electron acceleration. We are investigating their use for a compact light source since they have smaller transverse cross section than similar-frequency elliptical cavities, and power and HOM couplers can be attached directly to the outer conductor. Our design goal was to minimize peak fields for a given gradient while maximizing shunt impedance, to lower microphonic requirements, keep cavities as compact as possible, and permit (less expensive) 4.2 K operation at 500 MHz.

Competing frequency and field requirements led to a double-spoke cavity design with spoke broadening near the cavity outer conductor. Table 3 presents some of the physical and RF properties of an optimized cavity design. Fig. 2 shows the peak surface electric and magnetic fields.

Table 3: Cavity and RF Parameters, 500 MHz, $\beta_0 = 1$, $E_{\mathrm{acc}} = 1$ MV/m, and $R_s = 107$ nΩ

Parameter	Value	Units
Frequency of accelerating mode	500.0	MHz
Frequency of nearest mode	507.1	MHz
Cavity diameter	416.4	mm
Iris-to-iris length	725	mm
Cavity length	805	mm
Reference length [(3/2)$\beta_0\lambda$]	900	mm
Aperture diameter	50	mm
Energy Gain at β_0	900	kV
R/Q	675	Ω
QR_s	174	Ω
(R/Q)*QR_s	1.2×10^5	Ω^2
E_p/E_{acc}	3.7	-
B_p/E_{acc}	7.6	mT/(MV/m)
B_p/E_p	2.05	mT/(MV/m)
Energy Content	0.38	J
Power Dissipation	0.87	W

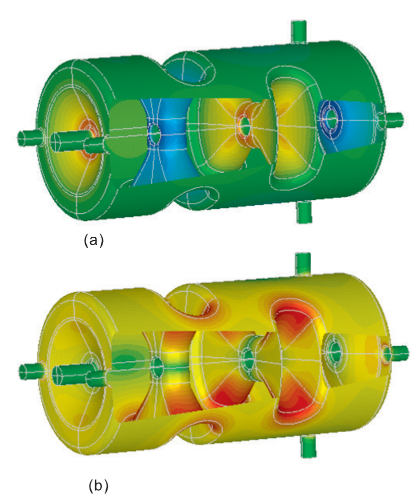

Figure 2: (a) Surface electric field and (b) surface magnetic field for the 500 MHz $\beta = 1$ double spoke cavity.

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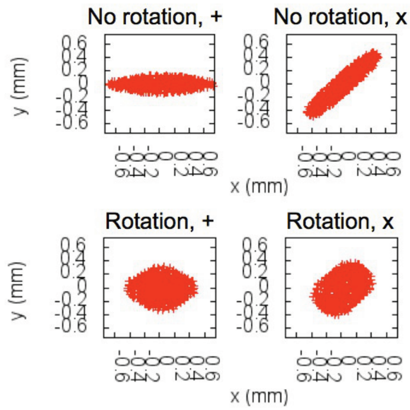

Figure 3: Spoke cavity orientation effects on beam distribution at end of linac. “+” and “x” are spoke orientations. “Rotation” alternates spoke orientation by 90° between successive cavities, while “No rotation” does not. Nearly round uncoupled beam is provided by the “Rotation +” configuration.

LINAC MODELING

The linac consists of four double spoke cavities, with the first three run on crest and the last run $\sim 10^\circ$ off crest to provide a (z, δ) chirp of $\sim 0.5\ \mathrm{m}^{-1}$. We investigated four combinations of cavity spoke orientations to provide nearly round uncoupled beam at the end of the linac; see Fig. 3. This beam ellipse matches $\beta_{x,y} = 12.3$m and $\alpha_{x,y} = 2.7$.

Space charge transport simulations with ASTRA conclude that this configuration can transport the desired transverse emittances with a beam KE=1.55 MeV at the end of the gun and entrance to the first linac cavity, which are spaced by 10 cm. No additional space charge compensation is needed in this region to achieve normalized transverse RMS emittances of 0.1 mm-mrad at the exit of the linac. Residual transverse nonlinearity seen in the final beam distribution (Fig. 4) is under investigation.

BUNCH COMPRESSION AND FOCUS

Bunch compression is performed magnetically in a symmetric achromatic Z-chicane that includes 4π of dispersion oscillation. This is followed by a triplet final focus section to $\beta_{x,y} = 5$mm. Chicane M_{56} is tunable over a range of 1.5-2m with central dipole bend angles, and a symmetric pair of quadrupoles enforces achromatic constraints. β_y entering final focus is controlled independently by a quadrupole at the central $\eta_x = 0$m crossing. This configuration permits straightforward independent tuning of achromaticity, M_{56}, and $\beta^\star_{x,y}$. The layout and optics of this compressor are shown in Fig. 5.

We are also considering alpha magnet bunch compression after the gun, but it is likely that space charge and transverse emittance considerations will preclude this approach from meeting transverse emittance requirements. An alternative bunch compressor with a 3π dispersion oscillation and net 90° bend is also being considered for a compact corner design.

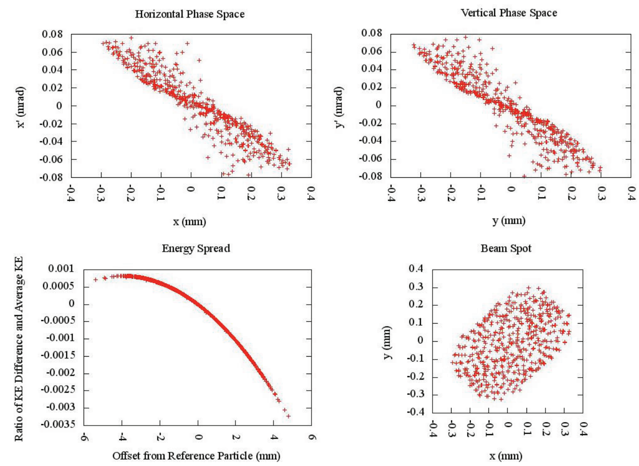

Figure 4: Beam distribution at linac exit, E=25 MeV.

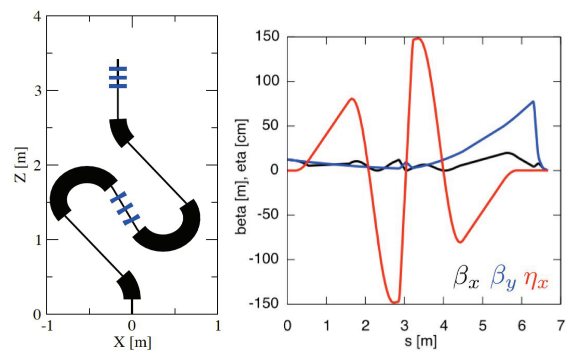

Figure 5: Magnetic bunch compressor footprint (left) and optics (right). The compressor fits within a 2.0m×3.5m space, and provides large dispersion for sextupole chromatic and T_{566} control.

FUTURE PLANS

Initial component optimizations have been performed, and we have developed a functional end-to-end simulation. Our next primary goal is to optimize the integrated performance, particularly concentrating on longitudinal emittance improvement and chromatic corrections. This includes evaluation of nonlinear transverse spoke cavity fields.

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