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A 50-MeV mm-Wave Electron Linear Accelerator System for Production of Tunable Short Wavelength Synchrotron Radiation*

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Abstract

The Advanced Photon Source (APS) at Argonne in collaboration with the University of Illinois at Chicago and the University of Wisconsin at Madison is developing a new millimeter wavelength, 50-MeV electron linear accelerator system for production of coherent tunable wavelength synchroton radiation. Modern micromachining techniques based on deep etch x-ray lithography, LIGA [1] (Lithografie, Galvanoformung, Abformung), capable of producing high-aspect ratio structures are being considered for the fabrication of the accelerating components.

Introduction

In recent years, microfabrication technology has sufficiently developed to produce working miniature-size devices on silicon wafer [1]. Based on this technology, a 50-MeV compact linear accelerator is used as a design goal for developing the technology which would result in, if successful, the production of x-ray radiation with tunable wavelengths in the range of 2-10 Å. The linac consists of an rf electron gun operating at 30 GHz, a double-sided muffin-tin structure for acceleration of relativistic electrons at 120 GHz [2], and a microwave undulator for the production of x-ray radiation. The linac is 4.95 meters long and is made of sixty-six 7.5-cm-long unit cell accelerating structures placed end to end. The rf design requires locating the unit cell structures 0.3 mm above and below the beam path. This requires vertical and horizontal stacking of LIGA substrates [3]. This paper will describe the design of the linac components and report on the beam transport calculations, rf measurements of a 12-GHz scale model, and fabrication processes. A schematic layout of the linac is shown in Figure 1 and the main parameters are given in Table 1.

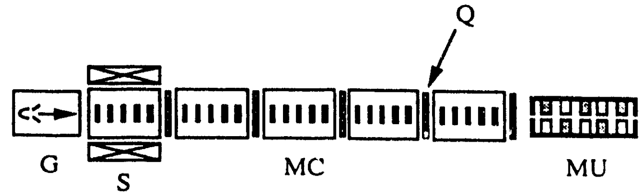

Figure 1
A schematic of the mm-wave linac layout.
G: rf gun, MC: muffin-tin cavity, S: solenoid,
Q: quadrupole, MU: microwave undulator.

Table 1
mm-wave linac parameters.

Energy	E	50	MeV
Beam current	I	1	mA
Normalized emittance	ϵ_n	1	$\pi mm - mrad$
Field gradient	E	10	MV/m
Beam pulse length	τ_p	1	μsec
Operating frequency	f	120	GHz
Energy spread	ΔE	±0.1%	
Duty factor	DF	1%	

Design Analysis

A. Electron Source

Conventional DC guns followed by rf bunchers have reached their limitations in providing low emittance beam (high beam brightness) and do not meet the requirements for this application. For the mm-wave linac, a 30-GHz thermionic rf gun based on the modified version of the SSRL rf gun (2856 MHz) [4] is proposed. This rf gun consists of $3\frac{1}{2}$ cells with side-coupled cavities [5]. The operating mode at 30 GHz is chosen to be $\frac{\pi}{2}$. The length of a full cell of the structure is one-half the free-space wavelength of 30 GHz:

$$L = \frac{\lambda}{2} = \frac{c}{2f}, \quad (1)$$

where L is the periodic length of the structure and λ = 1.0 cm. A complete design analysis of this gun is underway and will be reported in a separate paper.

B. Accelerating Structure

A double-sided muffin-tin planar structure is well suited for using microfabrication techniques like LIGA [1]. The operating frequency being considered is 120 GHz (λ = 2.5 mm). This open structure's main advantages are its ease of pumping and its low higher-order modes which may be damped using the side opening slots. Figure 2 is a cross sectional view of the muffin-tin accelerating cavity. Since heat dissipation in a structure of this size is an important factor, a traveling wave (TW) mode of operation was chosen over a standing wave mode (SW) which has higher average heat dissipation. A TW $\frac{2\pi}{3}$ mode of operation

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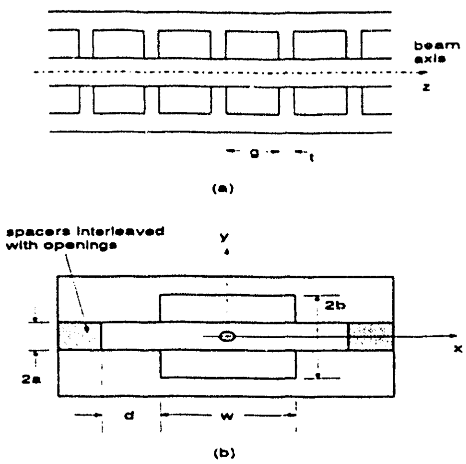


Figure 2
The double-sided muffin-tin structure.
a) longitudinal b) transverse cut. All dimensions in mm.
$a = 0.3, b = 0.9, w = 1.8, d = 0.8, g = 0.633, t = 0.2$

Table 2
Muffin-tin cavity RF parameters.

Frequency	f	120	GHz
Shunt impedance	r_o	312	$M\Omega/m$
Quality factor	Q	2160	
Operating mode	TW	$2\pi/3$	
Group velocity	v_g	0.043 $\times c$	
Attenuation	α	13.5	m^{-1}
Accel. gradient	E	10	MV/m
Peak power	P	29.1	kW

gives the highest shunt impedance.The MAFIA code [6] was used to study the rf properties of this structure. The main parameters of the muffin-tin structure are summarized in Table 2. More details on the cavity design can be found in Ref. [7] A 12-GHz copper scale model (7 cells) was fabricated to measure and identify various modes of the muffin-tin structure. The modes were determined by passing a small metallic object through the center of the structure along the beam axis and measuring the resonant frequency shift (field perturbation method). A Hewlett Packard 8510 network analyzer was used to take measurements. The results are given in the dispersion diagram in Figure 3.

C. Beam Dynamics

A double-sided muffin-tin structure, unlike the cylindrical accelerating structures, does not possess axial symmetry. Thus, there is a strong defocusing force in one of the transverse planes (the y-plane in Figure 2) which causes beam blowup at low beam energy. At high beam energies, this defocusing force is mainly cancelled by the focusing

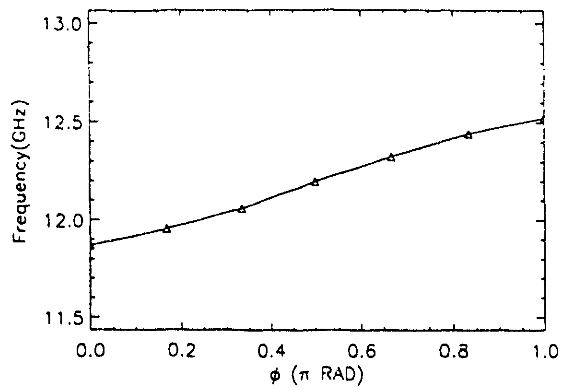


Figure 3
Dispersion curve of the 12-GHz muffin-tin structure.

force in the other transverse plane (the x-plane in Figure 2). The electromagnetic fields in the muffin-tin structure were obtained by solving the Helmholtz equation. The z-component of electric field satisfies

$$[\nabla^2 + k_0^2]E_z = 0 \tag{2}$$

where $k_0 = \frac{\omega}{c}$. Applying the boundary conditions (Figure 2), the z-component of electric field is

$$E_z = E_{z0} \cos(k_x x) \cosh(k_y y) \cos(k_z z - \omega t - \phi_0) \tag{3}$$

where

$$k_x^2 + k_y^2 + k_z^2 = k_0^2 \tag{4}$$

and k_x, k_y, and k_z are the propagation wave numbers. Other components of the electromagnetic fields are obtained by solving Maxwell's equations. To study the beam transport in the mm-wave linac, a particle tracking computer code, **elegant** [8] was used. The tracking was done by providing the electromagnetic field distributions with appropriate boundary conditions in the muffin-tin cavity [9] and performing numerical integration of the equations of motion. The initial input beam parameters to **elegant** are the rms beam sizes and the energy spread of the rf gun. The geometry used for simulation is shown in Figure 1. In these simulations we assume an accelerating field gradient of 10 MeV/m is provided to the muffin-tin structure and all the beamline components are aligned with respect to the beam axis. The space charge effects are neglected in these simulations since the beam energy at the exit of the rf gun is 2.5 MeV for an average beam current of 1 mA. The tracking results for 400 particles indicate that without solenoidal focusing at low energy (up to 5 MeV), the maximum beam envelope size exceeds the accelerating structure aperture and significant beam loss will occur. A solenoidal field of 1.5 Tesla around the first section of the accelerating structure is sufficient to confine the maximum beam size within the aperture (see Figure 4). After the first section, electrons emerge with energy of approximately 10 MeV and a simple FODO array with electromagnetic quadrupoles is

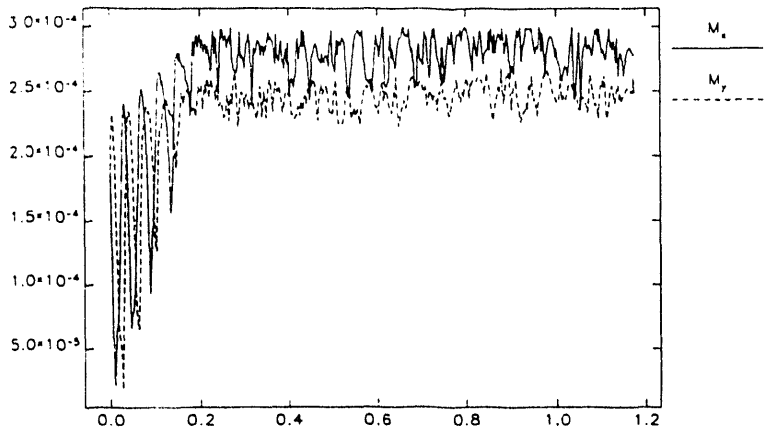


Figure 4
Electron beam size in the first section of the mm-wave linac.

used for focusing. The beam transport efficiency from the rf gun to the end of the mm-wave linac is greater than 90%.

D. Thermal Analysis

Thermal loading caused by rf power losses in the accelerating structure is a major concern for miniature-size devices such as a muffin-tin structure. Proper cooling of the structure is required to avoid thermal stresses and provide thermal stability. A thermal analysis of mm-wave structure was done [10] to find the cooling requirements under various thermal loads. The finite difference electromagnetic code MAFIA was used to model one-eighth of the muffin-tin cavity and to obtain the exact tangential magnetic field distribution on the cavity walls. The thermal behavior of one-eighth of the copper cavity was modeled using the ANSYS finite element package [11]. Simulation results show that in a pulse mode operation with 1% duty cycle and an average heat flux of 40 W/cm^2, the maximum temperature at the top of the center of the iris exceeds 100°C when using conventional cooling techniques. The use of a silicon microchannel heat exchanger with a cooling rate of 10 W/cm^2-K reduces the maximum temperature rise at the iris to 35°C with respect to the heat exchanger. The calculated temperature distribution is shown in Figure 5.

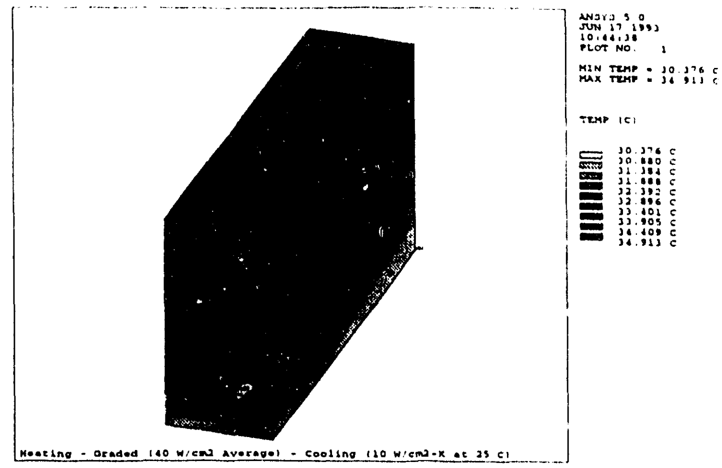


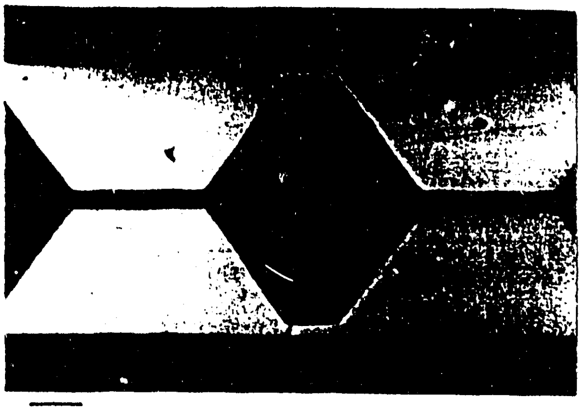
Figure 5
Temperature distribution in one-eighth of the cavity.

FABRICATION

The assembly and characterization of a 4.95-meter-long mm-wave linac presents an interesting fabrication challenge. The new microfabrication technique, LIGA, uses synchrotron radiation to expose high-aspect ratio features in poly(methyl methacrylate) (PMMA). Metal is electroplated into those areas of the PMMA exposed by the x-ray beam and then removed with a developer. LIGA can produce one half of a waveguide section that is approximately 600 μm deep, 1 cm wide, and 7.5 cm long. Vertical stacking [3] is required to assemble the two halves of the waveguide to fully enclose the beam. Three techniques have been considered to accomplish the vertical stacking: optical fibers in silicon v-grooves, fibers in electroplated rectangular grooves, and placing LIGA-generated pegs in LIGA-defined square holes. The first technique has achieved the required accuracy (Figures 6 and 7). In this method, a silicon wafer is covered with a nitride layer and a thin electroplating base. Rectangular openings are made in these layers prior to spinning on a thick layer of PMMA. After aligning the x-ray mask to these openings, the PMMA is exposed and developed and metal is electroplated into the PMMA openings. The PMMA is stripped and the wafer is anisotropically etched forming v-grooves that hold optical fibers to space the bottom and top sections of the waveguide. In the second method, rectangular grooves are generated in the LIGA process which eliminates the initial etch in the first method. The last method involves a "bunk bed" construction with electroplated posts placed into matching holes.

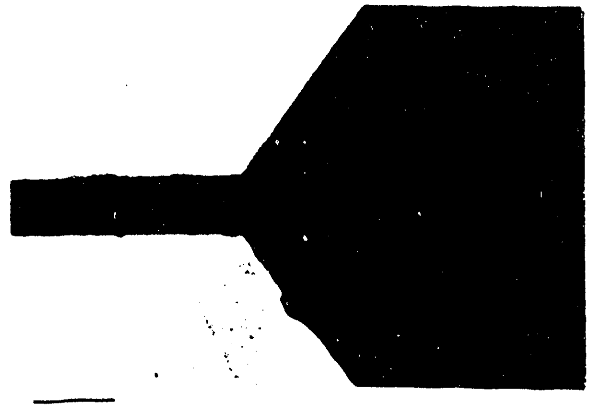
Horizontal stacking is required to assemble sixty-six 7.5-cm-long structures into a 4.95-meter accelerator. This method involves constructing a two-layer "brick wall" with vertical stacking. Substrates are staggered as they are stacked to extend the structure horizontally. Each substrate overhangs the previous one by half its length, or 3.75 cm.

In order to achieve efficient coupling between fields and electrons all structural dimensions must be controlled with a 0.1% accuracy. To verify the alignment of the actual die sets used within the final waveguide, a non-destructive characterization of the alignment accuracy is being developed [12]. This method involves using three capacitor bridge circuits and an accompanying set of etched optical windows to determine the relative die plane orientation and center of mass position. The balanced capacitive circuits will extract three scalar values to form a relative surface normal vector for the upper die with respect to the lower one, while the pair of optical alignment features will allow measurement of the relative horizontal offset and



100 μm

Figure 6
The alignment of the two silicon die, separated by a uniform gap of 37 μm, was achieved by anodically bonding 484 μm diameter glass capillaries to etched v-grooves.



50 μm

Figure 7
Close-up of two v-groove edges demonstrates that the alignment is better than 1 μm.

orientation. The system thereby determines the six spatial parameters necessary to evaluate the alignment success for each module of the system.

Summary

A 50-MeV mm-wave linac based on micromachining techniques is proposed. In this paper, we described various components of the linac. The 30-GHz rf gun can provide an electron beam of 1 mA and 2.5 MeV/c with small emittances. Double-sided muffin-tin structures are well suited for mm-wave frequencies and microfabrication techniques. A traveling wave mode with $2\pi/3$ phase advance per cell with an accelerating gradient of 10 MeV/m is adequate. The fabrication challenges are the assembly of sixty-six unit cell (each 7.5 cm) structures and maintaining dimensional accuracy of 0.1% or better. The alignment accuracy is measured by using a three-capacitor bridge circuits method. To overcome the thermal heat load problems, silicon microchannel cooling devices are incorporated into the accelerating cavity design. Thermal calculations show that a moderate 10 W/cm^2-K is sufficient to keep the maximum temperature rise in the center of the cavity iris below 35°C. Finally, beam dynamics simulations show that a 1-mA electron beam from the rf gun can be successfully accelerated through the mm-wave linac with a transport efficiency of greater than 90%. Further works are in progress to improve the design parameters of the linac.

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