The Design and Fabrication of a Millimeter Wave Linear Accelerator*

Y.W. Kang, G. Waldschmidt, J.J. Song, A. Nassiri, and R.L. Kustom
Argonne National Laboratory, Advanced Photon Source
9700 South Cass Avenue, Argonne, IL 60439

ABSTRACT

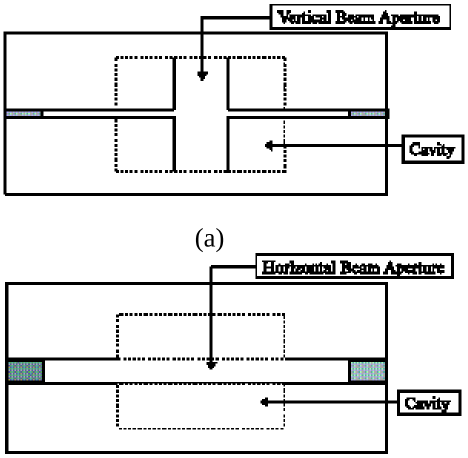
This report examines the feasibility of micro-machining planar millimeter wave cavity structures using a 3-D micromachining process known as LIGA (German acronym for Lithographe, Galvanaformung, and Abformung) or DXRL (Deep X-Ray Lithography). At Argonne National Laboratory, work has been focused on the design and fabrication of a 94-GHz constant-gradient structure, 108 and 120-GHz constant-impedance structures, and a magnetic undulator. Their eventual application would be as part of a linear accelerator, microwave undulator, and FEL. Lately, effort has been made on designing a 94-GHz constant-gradient linear accelerator that achieves proper RF-coupling between cells, efficient cooling for high field gradients, and accurate alignment of the planar cavity structures.

I. INTRODUCTION

Already, submillimeter actuators, motors, and gears are reliably produced using existing micromachining technology. Present methods that are used to create high definition components include UVL (UV-lithography), high energy electron beams, and reactive ion etching. Yet, there exist inherent limitations that prevent their application in the manufacture of exacting devices. For example, UVL has been found to be important in the creation of deep planar structures, but it is unable to maintain tight tolerances. On the other hand, DXRL is capable of producing high aspect ratio structures with a precision of 1.5-10 nm and virtually no runout for a depth of a few hundred microns [1]. This process consists of irradiating a photoresist with synchrotron radiation, chemically etching the resist, and then electroplating the substrate to generate a planar 3-dimensional structure.

Due to DXRL's ability to maintain precise tolerances, it is ideally suited for the manufacture of rf components operating at frequencies between 30-GHz and 300-GHz. At these frequencies, conventional machining is expensive and slight imperfections are difficult to eliminate. As etching and plating technologies have improved to within tolerances of 0.1 μm, DXRL is deemed especially valuable as a dependable, precise process where the potential manufacture of free electron lasers, undulators, wigglers, linear accelerators, and amplifiers is possible.

In 1993 at the inception of the mm-wave linac project, a constant-impedance structure was studied [2]. Since then, the constant-gradient structure has been chosen as a more attractive alternative for the mm-wave linac. It offers greater shunt impedance, and is less sensitive not only to beam breakup and frequency deviations but also to dimensional errors [3]. In addition, it offers uniform power distribution and, consequently, less cooling demands. With reduced cooling requirements, higher power operating conditions may be realized. The remainder of this paper will focus on design considerations concerning the development of a constant-gradient, DXRL-processed mm-wave linear accelerator.



(a)

(b)

Figure 1: Beam Aperture Geometries

II. MILLIMETER WAVE LINEAR ACCELERATOR

Figures 1(a) and 1(b) show cross-sections of two DXRL based accelerating structures. Due to practical considerations, it became necessary to enlarge the beam aperture to ~0.7 mm, as shown in Figure 1, in order to permit reliable passage of the beam. In these structures, cooling will be achieved through an advanced microchannel cooling network on the top and bottom surfaces of the structure, while vacuum pumping will be provided through horizontal slots between the upper and lower halves. Some of the higher order modes (HOMs) will be damped through the vacuum ports.

The alignment of the two planar halves of the accelerating

---

* Work supported by U.S. Department of Energy, Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38.

structure will be achieved using alignment and bonding techniques developed for micromachined electron microscopes [4]. Alignment grooves will be formed into the substrate concurrently with the fabrication of the other cavity features. Then, precision glass fibers will be placed into the grooves to ensure proper alignment. The depth of the cavity cells in each half structure is chosen to form a standard rectangular waveguide aperture at the rf input and output ports. This simplifies testing and measurement of the TE_{10} mode operation, and it lends itself to the inexpensive construction of the final design.

A small tabletop-type linear accelerator which would be combined with a micro-undulator in order to generate x-rays is considered [5]. The goal is to create a structure that requires a minimum number of fabrication steps with DXRL and, at the same time, adequately satisfies the following criteria: vacuum pumping, cooling, field coupling, load matching, and beam dynamics. The main parameters of the accelerating structure for a normal conducting 120-GHz linac are shown in Table I. The accelerating field gradient was tentatively set at 30 MV/m with a 0.1% rf duty cycle until the limits of the design are fully realized. Currently it is believed that the limit on the field gradient may be subject to the cooling ability of the final design.

Table I: 120-GHz Linac Parameters

Parameter	Symbol	Value
Beam Energy	E_b	>50 MeV
Avg. Beam Current	I_b	1 mA
Frequency	f	120-GHz
rf duty cycle		0.001
Field Gradient	E	30 MV/m
Mode of Operation (traveling wave)		$2\pi/3$
Cavity Q		2270
Cavity Shunt Impedance		295 MΩ/m
No. of Cavities	N	84
Structure Length	l	7 cm
RF Power	P	239 kW

Table II shows the comparison of cooling requirements of various accelerator designs at 120-GHz based on analysis with steady state approximation with an assumed 0.1% duty cycle. The required peak rf power for a 30 MV/m field gradient in the constant-gradient structure was estimated to be 239 kW. At this power level, efficient cooling is required to maintain stable and reliable operation. Thermal analysis was done to determine the temperature of the various structures during normal operation. The results are summarized in Table II. In the analysis, the initial temperature was set at 25 ^{o}C with a cooling rate of 10 W/cm^2/^{o}K. If optimized, the actual cooling rate can reach as high as 30 W/cm^2/^{o}K. In Table II, T_{max} denotes the maximum surface temperature inside the cavity.

Table II: Estimated Cavity Cooling and Gradient

Type	Gradient (MV/m)	Peak Power in 1^{st} cell (kW), 0.1% duty cycle	Average heat flux (W/cm^3)	T_{max} (^{o}C)
CI	30	5.7	78.4	43
CG	30	2.6	33	34
CG	45	5.7	76.4	45

CI: Constant Impedance, CG: Constant Gradient

As shown above, a constant-impedance structure dissipates a disproportionate amount of power in the first cell at the input of the structure. This could very likely set the operating power limit of the constant-impedance structure. A constant-gradient structure, on the other hand, has a uniform power dissipation along the length of the structure. For the same field gradient, the dissipated power in a cell in the constant gradient structure becomes lower so that the demand for cooling is less. If the same power is used in the first cell of the constant-gradient structure as in the constant-impedance structure, the field gradient can be ~50% higher.

In addition, if the maximum temperature, T_{max}, was permitted to reach 65 ^{o}C, the field gradient may approach 60 MV/m. A greater T_{max} used in conjunction with a more efficient cooling rate of 30 W/cm^2/^{o}K may produce a field gradient in excess of 100 MV/m.

III. CAVITY STRUCTURE DESIGN

Previously, 108 and 120-GHz constant-impedance linac structures were designed and LIGA structures have been fabricated for the 108-GHz accelerator. However, the frequency has since been shifted to the more practical 94-GHz. This will benefit both the eventual production and the current design process of the linac since a power source and test equipment are commercially available. In addition, the beam dynamics are such that it would be easier to maintain the beam with the required aperture in the larger 94-GHz structure.

The 94-GHz constant-gradient accelerating structure was analyzed for the 2π/3-mode traveling wave with the finite difference time domain code MAFIA using a 3-cell simulation model. The constant-gradient structure can be made by adjusting the iris thicknesses between the cavity cells. The frontal view of this design may be seen in Figure 1(b). Upon further analysis, it was discovered that the Q and shunt impedance degraded excessively over the length of the structure, most noticeably in the cells where the iris thickness was adjusted. Although this design produced the required coupling and beam aperture size, it was found to be insufficient as a good accelerator due to a poor quality factor and shunt impedance.

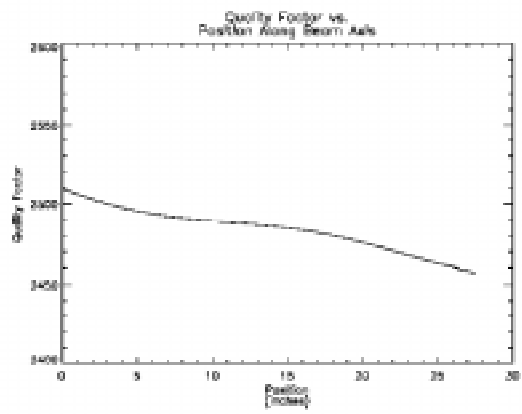


Figure 2: Quality Factor for Constant-Gradient Structure

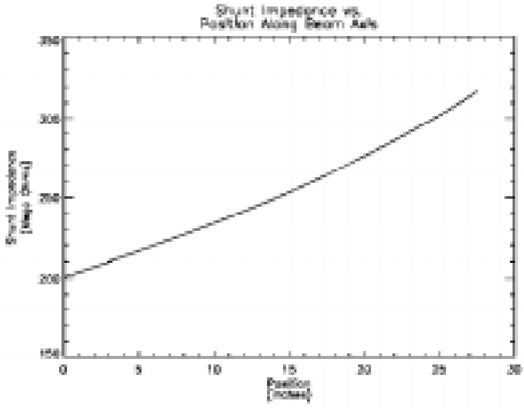


Figure 3:Shunt Impedance for Constant-Gradient Structure

On the other hand, rather than a large horizontal aperture, the desired beam aperture may be achieved by maintaining a minimum horizontal opening and vertical iris cut as shown in Figure 1(a). The proper coupling may be realized by varying the vertical iris cut throughout the length of the structure, thereby eliminating the need for cells with thicker irises. Because of the reduced area for the fields to couple into, a vertical iris cut would produce a greater beam aperture than the horizontal aperture for a given rf coupling.

In addition, the beam aperture shape in Figure 1(a) can reduce the excessive coupling of hybrid modes between cells. The dimensions of the slots and the vertical iris opening are chosen so that hybrid modes will be well separated from the operating frequency of the accelerator, and at the same time the accelerating mode frequency is sufficiently cutoff in the horizontal slots.

For this design, the Q and shunt impedance were found to remain relatively constant over its length as analyzed by MAFIA. Figures 2 and 3 show the behavior of Q and the shunt impedance from the input to the output cell. The optimized 94-GHz structure has 66 accelerating cells with a total length of 7 cm. The 66-cell structure with capacitive matching irises at the input and output coupling cells is shown in Figure 4.

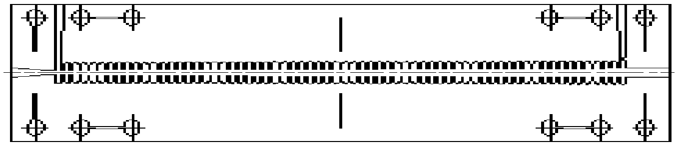
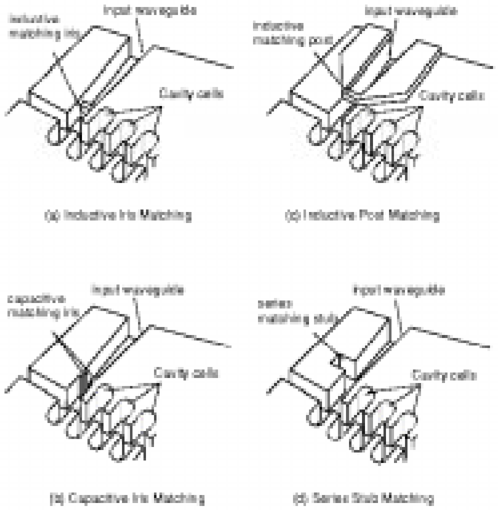


Figure 4. A 94-GHz Constant Gradient Cavity Structure

The input coupler operates as a transition from the rf power source to the accelerating structure and is therefore critical for the rf power transfer. Since a purely resistive, transformer type coupling is not easily achievable, reactive matching must be used as shown in Figure 5. For proper matching, the width of the coupling cell is very nearly a half wavelength. Fabrication with the capacitive iris (b) or waveguide stub (d) can be done with a single layer DXRL exposure, while the inductive iris (a) or the inductive post (c) require multilayer DXRL exposure or other additional microfabrication.



(a) Inductive Iris Matching

(c) Inductive Post Matching

(b) Capacitive Iris Matching

(d) Series Stub Matching

Figure 5: Coupler Designs

IV. FABRICATION

DXRL with hard x-rays from synchrotron radiation allows resists up to 1000 μm thick to be fabricated with sub-micron accuracy. A positive resist, poly-methylmethacrylate (PMMA) is applied to a copper substrate that has a surface flatness of 1.0 μm and smoothness of 0.2 μm over 5 cm [6]. X-ray radiation is irradiated onto the 1.0 mm thick sheet of PMMA through an x-ray mask which is etched with the two dimensional pattern that is being produced. The exposed PMMA is dissolved during chemical development. 99.9% oxygen-free copper is then electroplated to the substrate to create the final structure.

The x-ray mask that is used to irradiate the PMMA is composed of two distinct regions. The first of which consists of a thin membrane which forms the pattern beneath which the PMMA is to be irradiated. The other has a high atomic weight and a high absorption rate of x-ray radiation which shield the underlying PMMA. After irradiation of the PMMA, the area under the thin membrane is dissolved and removed. It is critical that no PMMA located elsewhere is removed. For this reason, investigation continues for chemical developers that optimize this process in order to maintain the necessary tolerance requirements. Figure 6 shows an SEM picture of the regular cells of a 108-GHz constant-impedance structure. Some impurities are evident due to PMMA residues and possibly uneven electroforming during the electroplating process.

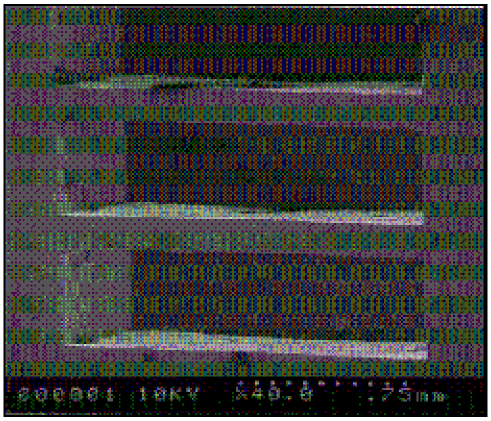


Figure 6: SEM Picture of Cavities

V. FUTURE WORK

Further studies have been planned to lower the frequency of operation to around 60-GHz while incorporating the LIGA processed mm-wave amplifiers on the same wafer as the accelerating structures. At the present time, an x-ray mask for the 94-GHz constant gradient structure is being produced. Once a 108-GHz DXRL processed accelerating structure is fabricated, measurements and high power tests will be performed. The objective will be to characterize the emittance growth of a short-bunch, low-emittance beam as it passes through the small aperture of the mm-wave accelerator, in addition to verifying the rf properties and maximum field gradient in the cavities. Although DXRL technology is making the production of high frequency planar devices economically viable, on-going work is necessary with DXRL to optimize the chemical etching of the resist and to achieve successful electroplating into narrow structures.

VI. ACKNOWLEDGMENT

We are grateful to J. Galayda, division director of the Accelerator Systems Division at ANL for his support and assistance throughout the research. Also, we would like to thank A. Khounsary for data concerning cooling requirements.

VII. REFERENCES

[1] W. Ehrfeld, et al., *Progress in Deep-Etch Synchrotron Radiation Lithography*, Proc. 31st Int. Symp. On Electron, Ion, and Photon Beams, USA, 1987

[2] Y. W. Kang, et.al., *A mm-Wave Planar Microcavity Structure for Electron Linear Accelerator System, Proc. of the 1993 IEEE Particle Accelerator Conference, Vol. 1, pp.549-551*, 1993.

[3] P. M. Lapostolle, A. L. Septier ed., *Linear Accelerators, Chapter B.1.1, North Holland Publishing Co.*, 1970.

[4] A. D. Feinerman, et.al., *Sub-centimeter Micromachined Electron Microscope*, J. Vac. Sci. Technology A, 10(4), 611, 1992.

[5] R. L. Kustom, et al., *Microcavity Structures*, 17th Int. Linac Conference, KEK, 1994.

[6] J. J. Song, et al., *Fabrication of Mm-Wave Undulator/ Linear Accelerator Cavities Suing Deep X-Ray Lithography*, Conference Digest, Synchrotron Radiation Instrumentation, 1995.