North American Particle Acc. Conf. NAPAC2019, Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-THYBB3

COMPACT 1 MeV ELECTRON ACCELERATOR

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Abstract

The cost of accelerating structures in modern medical accelerators and industrial linacs is substantial. This comes as no surprise, as the accelerating waveguide is comprised of a set of diamond-turned copper resonators brazed together. Such a multistep manufacturing process is not only expensive, but also prone to manufacturing errors, which decrease the production yield. In the big picture, the cost of the accelerating waveguide precludes the use of accelerators as a replacement option for radioactive sources. Here we present a new low-cost brazeless electron accelerating structure assembled from two copper plates fastened to each face of an additional stainless-steel plate. This additional plate, possessing a machined knife-edge on each face, is designed to bite into the copper plates, thus providing vacuum inside the entire system. The designed X-band 1 MeV structure consists of eight different length cells and accelerates field-emitted electrons from a copper cathode. The structure is fed by a 9 GHz magnetron which produces 240 kW, 1 µs pulses. The average gradient is as high as 10.6 MV/m and maximum surface fields do not exceed 23 MV/m.

INTRODUCTION

Brazeless accelerator design considered here assumes replacement of brazed joints with stainless-steel – copper RF and vacuum joints. Typically brazeless assembly relies on a stainless-steel part with knife edge biting into a copper part, i.e. stainless-steel is inevitably a part of the microwave structure. To alleviate microwave losses associated with stainless-steel, it was originally proposed to plate the stainless-steel part with copper. While this approach had been proven effective at low gradients, the long-term stability of the plating, especially at ultra-high microwave power has yet to be verified. This brazeless split block design eliminates this concern completely. In this assembly, the stainless-steel knife-edge connection occurs outside of the microwave volume.

ACCELERATING STRUCTURE DESIGN

The choice of acceleration structure design is a multiparametric task. It is, as usual, a trade-off between price and complexity of fabrication and tuning. In our case, deciding factors were the split block dimensions and available RF power source. These limitations lead us to develop a standing wave (SW) disk loaded accelerating structure in X-band frequency range (powered by radar pulsed magnetron).

The 8-cell 9.4 GHz accelerating cavity (see Fig. 1) provides a 1 MeV energy gain for a low-energy 20 keV electron beam, utilizing around 200 kW RF power. The main accelerator parameters are presented in Table 1. Due to variable beam velocity, each cell is of different length and radius, but maintains a fixed aperture of 10 mm. The input iris (3 mm radius) collimates the low-energy beam. Waveguide dump, located in the last cell of the coupler, symmetrizes accelerating field and reduces transverse components kick.

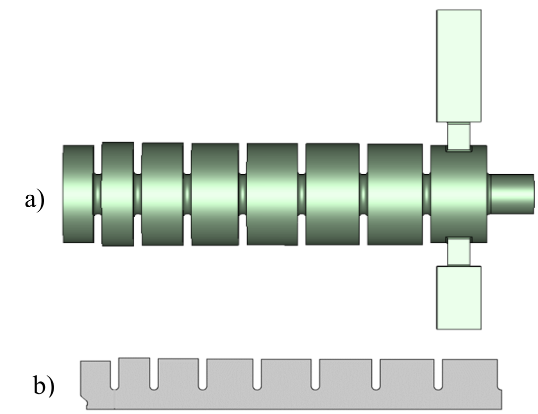

Figure 1: 8 cell SW accelerating cavity design with input waveguide coupler and waveguide dump: a) 3D model; b) accelerating cell's shape.

Electric field map in 3D (CST Studio 2018 [1]) simulation and energy gain vs input accelerating field phase are shown in Fig. 2 and Fig. 3, respectively.

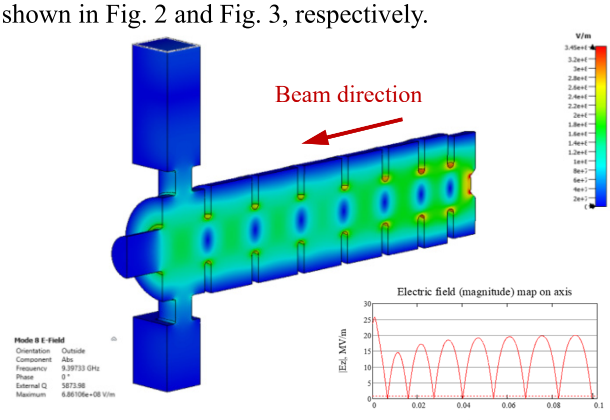

Figure 2: The π mode electric field map in the 8-cell 9.4 GHz accelerating cavity.

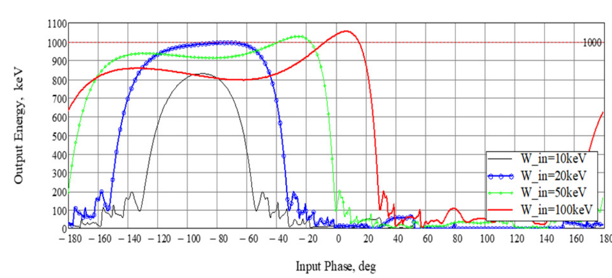

Figure 3: Energy gain vs initial accelerating field phase and input beam energy.

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Non-flat accelerating field distribution (see Fig. 2) is led by optimization of particle capture (peak in the first cell) and maximization of total shunt impedance (field gain from 2nd to last cell). With 200 kW input RF power 10.6 MV/m accelerating gradient is expected.

Table 1: Main 1 MeV Accelerator Parameters

Operation frequency	9430 MHz
RF source	Magnetron
RF power	203 kW
Peak surface electric field	23 MV/m
Accelerating cavity length	111 mm
Shunt impedance	4.7 MOhm
Input beam energy	20 keV
Output beam energy	1 MeV

The present cavity design does not consist of a cooling system because using radar X-band magnetron can provide around 3 W of average RF power (240 kW, 1 µs pulse duration, 10 Hz repletion rate). Pulsed heating will be negligible in this case, < 1°K. Although, brazeless design allows for the addition of cooling channels and cooling ribs. The beam focusing system is designed to be implemented outside of the cavity. This system includes at least one solenoid in addition to X and Y steering magnets.

ENGINEERING DESIGN AND FABRICATION

Split block geometry has recently become a technology of high interest for X-band accelerators, with SLAC and CLIC leading the development of state of the art 100MV/m+ gradient split block structures [2, 3]. The reason for this breakthrough is purely technological: novel 5-axis CNC machines now achieve tolerances and the surface feature complexity required for accelerating waveguides. It is quite appropriate to slice accelerating waveguides along the z-direction, because wall currents are all in the z-direction. These two halves can be combined by brazing, e-beam welding, diffusion bonding and other methods. Euclid Techlabs has developed the brazeless split block accelerating structure illustrated in Fig. 4.

The brazeless split block contains a large stainless-steel part that wraps around the cooper pieces, with conflat flanges on the sides of beam inlet and outlet in addition to the two knife edges on the top and bottom. This part is being pressed by the two copper plates, each with half of the accelerating structure milled out in them. The two knife edges on the stainless-steel part seal vacuum on each corresponding half (Fig. 4). Fabricated parts are shown in Fig. 4 c) and d). Knife-edge joints can be sealed only once. In less demanding cases, vacuum seal can be provided by a Viton gasket. In this configuration, it is possible to assemble – disassemble multiple times. This is important for maintenance and troubleshooting an accelerating waveguide.

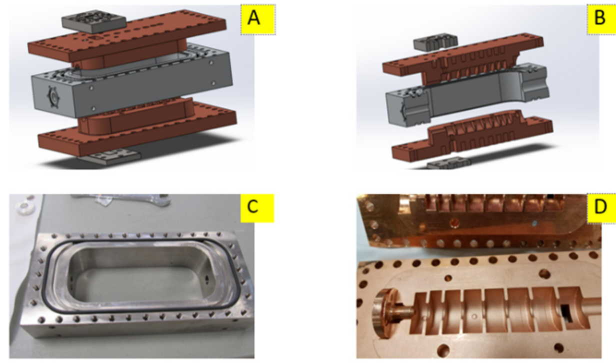

Figure 4: Brazeless split block engineering. A) Brazeless split block – knife loaded stainless-steel middle is being pressed by two copper halves. B) Brazeless split block – cut away view. C) Stainless-Steel block fabricated. D) Two copper RF halves.

TUNING AND TESTING

The brazeless cavity tuning is inherently easier compared to regular brazed iris loaded accelerating section. Accessibility of all inner elements (see Fig. 4) allows full control of each cell's frequencies and intercell coupling. The results of a bench test are shown in Fig. 5.

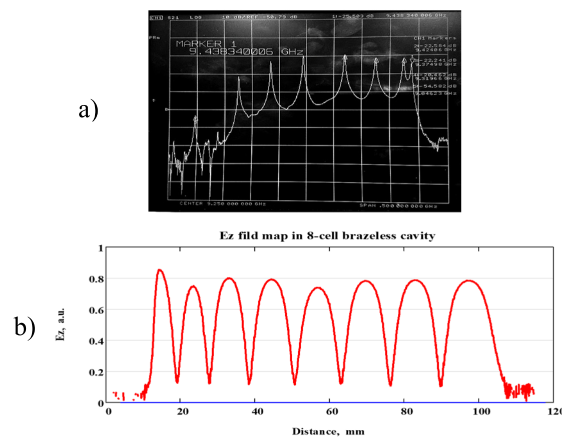

Figure 5: 8-cell brazeless cavity tuning results: a) resonance frequency spectrum; b) accelerating field bead pull measurement.

After fine tuning of the accelerating field balance, we conducted vacuum and high-power tests. The fully assembled structure was evacuated down to 1.2×10^{-7} Torr with the original conflat assembly and 4×10^{-7} Torr with Viton gaskets. The split block cavity was not baked. Next we used a 240 kW X-band magnetron and vacuum RF window to power the 9.4 GHz cavity. Conditioning the brazeless did not require a long time. No issues with multipacting or field emission inside the accelerating cavity did not occur up to the maximum feeding power.

For complete testing of the brazeless accelerating cavity we developed and fabricated a 20 keV electron beam source (Fig. 6). The diode like DC gun, based on electron microscope cathode and grounded anode grid, provides up to 25 kV energy and 250 µA beam current in the CW or pulse regime.

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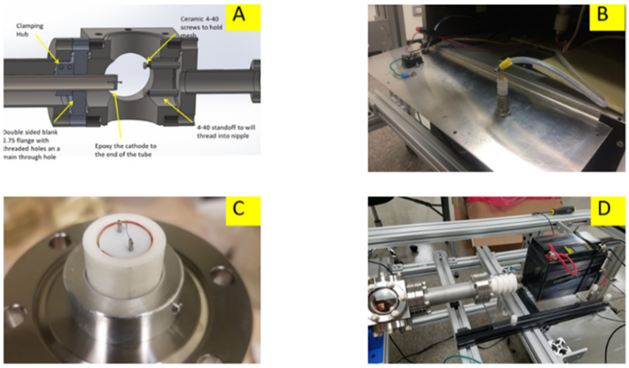

Figure 6: DC gun engineering. A) Overall layout. B) Modulator high voltage feedthrough. C) Gun packaging. D) DC gun stand assembly with floating battery for filament heating (safety cage removed).

When working with RF power the magnetron modulator could be used as a high-voltage source for the DC gun (see Fig. 6B). The RF power driver could run at a maximum rate of 10 Hz, making the duty cycle of the accelerator of just 10^{-5}. For this reason, it was important to test the data acquisition system to ensure the 1 MeV beam register at such a low repetition rate. Euclid Techlabs developed a microwave resonator detuning sensor that proved itself to be most sensitive. The fact that it measures peak power, allows it to have a large signal to noise ratio (see Fig. 7) while other methods like faraday cup or fluorescence have weak responses.

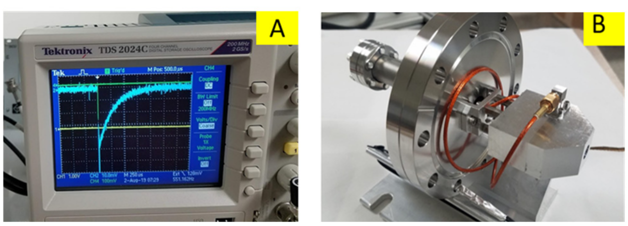

Figure 7: Accelerated beam signal on beam halo monitor: A) low beam current (< 50μA pulse, 10^{-5} duty factor) signal; B) beam halo monitor with silicon sensor inside.

Now, we are preparing more detailed measurements of the accelerated beam parameters. A spectrometer magnet dipole with vacuum chamber has already been developed and fabricated. The next steps are installation of sensitive beam current monitors and calibration of the spectrometer magnet.

SUMMARY

This brazeless technology appears increasingly more attractive for low and for high energy linacs. In our case, the 1 MeV linac was developed, fabricated and tuned over an extremely short time and with an incredibly low budget. Despite the highly affordable fabrication cost, a more convenient and diverse tuning procedure allowed for us to achieve our desired results.

The prior established fabrication technology prevented a true brazeless structure from being fabricated [4], since the copper plating of stainless-steel has not been proven stable at high-power. This means brazeless accelerating structures can be used for higher gradient and intensity linacs.

ACKNOWLEDGEMENT

This project was supported by DOE Small Business Innovative Research phase I grant DE-SC0017749.

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