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INEXPENSIVE BRAZELESS ACCELERATOR PROTOTYPE

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Abstract

A simple, inexpensive way to manufacture a standard radio frequency (RF) driven particle accelerator is presented. The simplification comes from two innovations: utilization of LCLS gun type RF design to avoid an expensive brazing process and copper plating of stainless steel that further reduces manufacturing cost. This is realized by a special structure design where accelerating structure cells are made out of copper plated stainless steel with knife edges and structure irises - copper disks acts also as gaskets for vacuum and RF seal. Besides the reduced cost, brazeless assembly allows integration of effective cooling and magnet optics elements into accelerator cells. Here we report on manufacturing and testing of brazeless accelerator prototype.

INTRODUCTION

One of the main drivers for the cost of an accelerator is the production of the copper accelerating structure, which requires the turning of several individual copper cells, and then brazing them together into a high-vacuum assembly. Brazing is an expensive process that is prone to errors that reduce the production yield, driving up the cost of making the structure.

In the quest for low emittance and reduced dark current, following the design of the BNL/SLAC/UCLA gun [1], many RF electron guns adopted a design in which the whole back wall of the gun is a replaceable cathode [2, 3]. After several iterations, the LCLS gun solution with a shallow sloped knife edge at the RF joint, followed by a vacuum joint, provided a brazeless breakdown-free joint for high gradient operation. An important point about the RF joint knife edge is that it is made out of stainless steel, and copper plated on the inside [3].

In a recent development, a complete electron gun structure was proposed in a brazeless design [4]. The key is a special gasket design. Copper parts of the structure are used to crush an annealed and slightly softer copper gasket. In a sense, the complexity of the brazing step is replaced by a rather complex mechanical design. The intended gain of such a design is not cost reduction, but the potential for improved high gradient operation, since thermal heating in a brazing cycle is believed to reduce the copper breakdown strength.

Euclid Techlabs proposes a revolutionary brazeless accelerating structure [5] made out of copper-plated stainless-steel or tungsten cells, with copper irises serving as gaskets for the vacuum and RF seals. Eliminating the brazing step and using stainless-steel components reduce the cost compared to the fabrication of conventional copper structures. The brazeless design also allows the addition of cooling channels and embedded focusing magnets for performance optimization. In addition, embedding the focusing or steering elements allows for a small bore, lower current coil, providing for a significant size and weight reduction.

ACCELERATING STRUCTURE DESIGN

For a proof of principle structure production it was decided to design a standing-wave accelerating waveguide for electron energy gain from 100 keV to 1 MeV. The input energy is rather high, and was chosen to simplify the design work for the prototype, so that the full structure could be built and tested in short period of time. The goal for this initial structure was to test vacuum properties and run a high power test, in order to observe how resilient the copper plating process is.

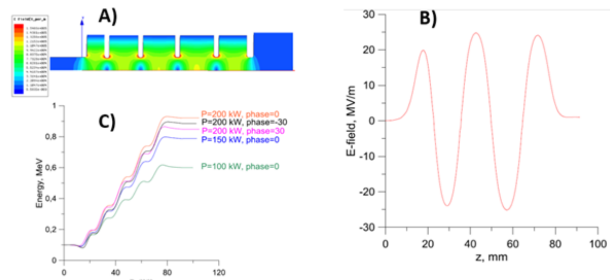

Figure 1: A) z-component of RF electric field. B) field distribution along z. C) energy gain simulations for various input power.

We chose π-mode cavity operation at 9.3 GHz frequency, and selected a 5-cell cavity. Beam energy gain for a few different power points and input phases is shown on Fig. 1. At this moment, we haven't optimized particle capture, beam loading, etc., focusing solely on production technology. Once the technology is proven, all these practical things can be implemented in the same way it is done for standard accelerator waveguide designs. With 200 kW input RF power 12 MV/m accelerating gradient is expected. Pulsed heating is negligible in this case, < 1K.

The cavity coupler was designed with a geometry compatible with the brazeless fabrication method (Fig. 2 and Fig. 3). The coupling tuning is done with an oversized coupling iris – gasket and a step inside of the coupler body. The beam is to be injected from right to left in Fig. 2. Cells elongate as electrons gain energy and become faster. The last cell looks shorter, but effectively has an appropriate length due to fringe fields.

ENGINEERING DESIGN

Engineering and fabrication was the central part of this work. The standing-wave cavity design shown in Figure 2 was implemented in engineering a brazeless assembly

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design (Fig. 3). We present here a novel design for an accelerating structure that does not require a brazing step. In a sense, it is evolutionary from the LCLS gun, and applied here to the design of iris-loaded accelerating structures. The key engineering design innovation is that the gasket of the RF and vacuum joint is a part of the resonator assembly, namely the iris. We further refer to it as iris-gasket in the text. We use stainless steel flanges that act as the resonator body, or cells in the accelerating structure. We will refer to them as flange-cells further in the text. Just like in the LCLS gun, stainless steel-cells are copper-plated, to provide the best RF performance. From the standpoint of RF design, the resulting structure is fully equivalent to a brazed all-copper accelerating structure. Remarkably, the complexity of the proposed assembly is not much different from the reliable and inexpensive conflat flange technology. The flange-cell is a stainless-steel part with a knife edge similar to that in the LCLS gun. The copper gasket-iris is indeed very similar to a blank conflat flange gasket. Conflat gaskets are stamped and, being a beamline commodity item, are cheap. For high gradient operation, one may elect to machine the copper gaskets, which will modestly increase the price. However, for industrial gradients of 20–40 MV/m, it may be possible to do away with stamped gaskets, bringing the price further down.

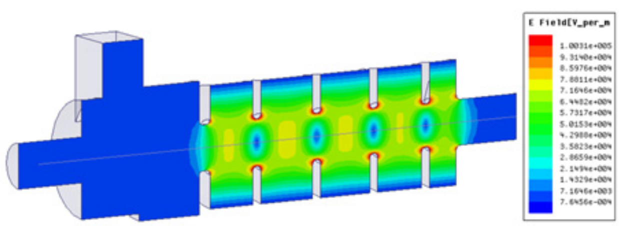

Figure 2: Simulation of coupler and structure (Ez-field).

FABRICATION AND COLD TEST

The stainless-steel parts were machined (Fig. 4), and we performed initial cold test measurements and diameter adjustments. We used honing (polishing) of the inner diameter to control its dimensions to within a few microns. After diameter adjustment, we copper plated the stainless-steel parts with about a 10-micron copper layer (Fig. 4). Engineering design was done with consideration of the ~10 micron copper plated layer.

We were able to cold test the assembly at every step of the way. The initial stainless-steel cell-flange assembly with copper iris-gaskets was measured for transmission (S_{21}) (Fig. 5, Left, orange trace) into a zero-coupled antenna placed at the exit of the structure (Fig. 5, Right). As expected, the quality factors of the 5 resonances were rather low ~ 1000. After copper plating, the quality factors of the resonances (Fig. 5, Left, green trace) became close to the values from simulations (~5000). The frequencies are shifted because the gaskets were under-compressed. This will not present a problem for high power tests, since we utilize a frequency – tunable magnetron. Other than this frequency shift, the structure behaves as if it were fully made of copper and brazed together.

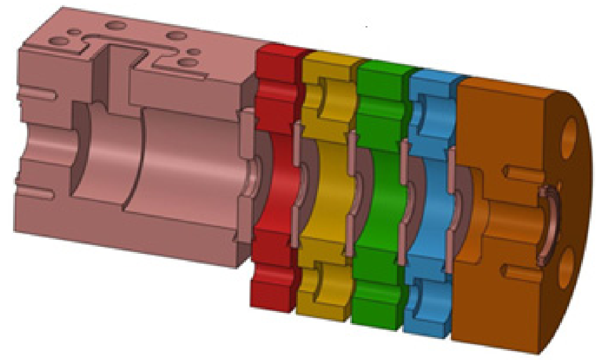

Figure 3: Brazeless assembly engineering.

HIGH POWER TEST

Due to the extremely fast fabrication of the vacuum-tight cavity, we had time for a high power test. The fully assembled structure was pumped down to 1.9×10^{-7} Torr (Fig. 6). We used a 220 kW X-band magnetron to power the 9.3 GHz cavity (Fig. 6). To monitor the magnetron frequency, we mixed the signal with a local oscillator (running at a frequency close to that of the magnetron), and read out the down-converted signal with a 200 MHz scope.

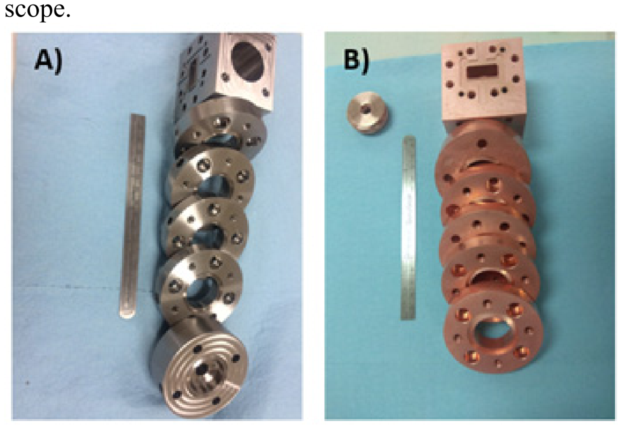

Figure 4: Brazeless assembly manufacturing. A) Stainless steel parts. B) Copper plated parts

Then, we tuned the magnetron frequency to the frequency of the π-mode of the cavity. Reflection from the cavity is measured with a power diode. We changed the RF distribution system to gradually condition the cavity to high power. The structure was conditioned with 200,000 pulses at 50 kW of input power, followed by 100,000 pulses at 75 kW and 220,000 pulses at 200 kW. Several breakdown events occurred during conditioning, when the RF pulse was shortened by reflection from the cavity. However normal operation of the cavity immediately recovered. In the end, we could run for a day at full power without breakdown events.

After high power tests, we disassembled the structure – a true testament to the flexibility of the brazeless design. We inspected the copper plating and did not observe any delamination. The copper gasket–irises were also

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inspected closely, and one damage spot was found near the knife edge mark. This damage was associated with a possible multipactor event.

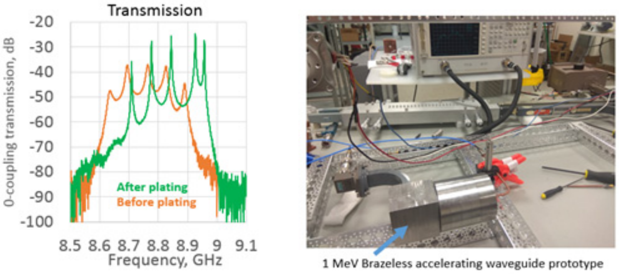

Figure 5: Left: Transmission (S21) measurement before and after plating. Right: Network analyzer measurement of the structure before plating

SUMMARY

In our experience, this was the fastest accelerating structure development, from design to high power testing, that we have ever carried out, and with the smallest budget. A vacuum tight, tuned and high power–ready structure was fabricated in several weeks. The structure was conditioned to 200 kW input power, which was equivalent to a 12 MV/m accelerating gradient.

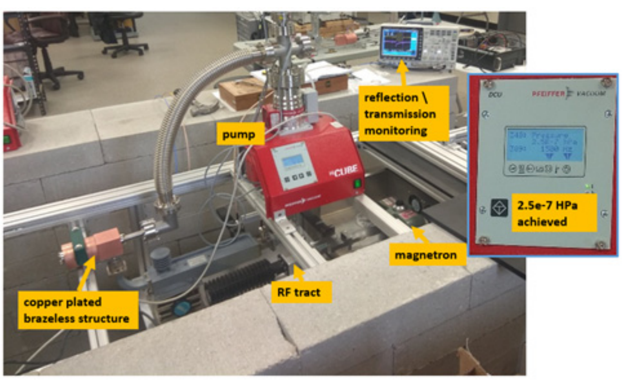

Figure 6: High power test setup with key components identified.

After high power testing, the structure was disassembled and no damage to the copper plating was observed. Minor damage occurred on one of the copper gasket–irises, which most likely can be eliminated through higher quality fabrication. This technology is ready for ~10 MV/m gradient accelerating structure production. The cost of the accelerating waveguide will be a record low ~ $10K. It is highly intriguing to find out how far this technology can be pushed in terms of accelerating gradient. The weak spot of the technology is the copper plating on stainless-steel cells, which fortunately experience a lower field strength. The field is highest at the irises, which are produced from solid copper, and can be fabricated with the surface roughness required for ultra-high gradient operation.

ACKNOWLEDGEMENT

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