ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR33

PRELIMINARY TESTS FOR THE DIFFUSION BONDING OF HIGH GRADIENT CRYOGENIC RADIO-FREQUENCY CAVITIES *

F. Bosco†, A. Fukasawa, B. Naranjo, G. Lawler,
J. Rosenzweig, University of California Los Angeles, Los Angeles (CA), USA
A. Mostacci, Sapienza University of Rome, Rome, Italy
B. Spataro, Frascati National Laboratories (INFN-LNF), Frascati, Italy
C. Pennington, J. Maxson, Cornell University, Ithaca (NY), USA
E. Simakov, Los Alamos National Laboratories, Los Alamos (NM), USA
P. Carriere, Radiabeam Technologies, Los Angeles (CA), USA
O. Camacho, S. Tantawi, Stanford National Accelerator Laboratory, Menlo Park (CA), USA

Abstract

High field radio frequency (RF) accelerating structures are an essential component of modern linear accelerators (linacs) with applications in photon production and ultrafast electron diffraction. Most advanced designs favor compact, high shunt impedance structures in order to minimize the size and cost of the machines as well as the power consumption. However, breakdown phenomena constitute an intrinsic limitation to high field operation which ultimately affects the performance of a given structure requiring dedicated tests. The introduction of a recent design based on cryogenic distributed coupling structures working at C-band (~6 GHz) allows to increase the shunt impedance by use of alternative distribution schemes for the RF power while mitigating the breakdowns thanks to the low temperature. In this paper we introduce the plan for high field and breakdown tests envisioned for a simple two-cell version of the aforementioned structure. Moreover, we discuss the joining procedure proposed to unify the two fabricated halves of such a structure and relying on the diffusion bonding technique which constitutes an attractive alternative to the brazing approach.

INTRODUCTION

RF copper structures constitute a widely established tool for the acceleration of charged particles and have been extensively used over the last decades. In particular, RF linacs favor the use of high gradient accelerating cavities in order to achieve the target energies while reducing the footprint of the machine. The development of such a technology led to the thrive of several type of linac-driven facilities for photon production, high energy physics, radiotherapy and industrial applications [1–3]. Such a strong scientific motivation led to remarkable improvements in the design and optimization of RF structures increasing their *shunt impedance* [4] however breakdown phenomena constitute the intrinsic limitation for the maximum electric field a structure can support. Recent experimental results discussed in [5, 6] have shown that the breakdown rate is mitigated in cryogenic (~45-77 K) normal conductive copper structures. Cryogenic temperatures increase, in addition, the conductivity with a positive impact on the shunt impedance of the accelerating structure which can be further enhanced by a proper choice of the topology for the unit-cell cavity. This concept was fully exploited in [7] where the RF power is distributed in the cells by a guiding manifold enlarging the parameter space available for the optimization. Due to such advantages, cryogenic distributed coupling structures are the foundation of modern linac and photo-injector designs for free electron lasers (FELs) [8, 9], linear colliders [10] and very high energy electron (VHEE) linacs [11]. In the context of a collaboration among the author's institutions a two-cell prototype of distributed coupling linac was realized in C-band (5.712 GHz) in order to perform high field and breakdown tests at cryogenic temperatures. The 2-cell structure is shown in Fig. 1. The piece was manufactured in two halves by the company G-ZERO and two possible alternatives were considered for the join: brazing and diffusion bonding. While the discussion concerning which method should be employed is still open with a slight preference for brazing, we decided to perform preliminary diffusion bonding experiments in order to understand the advantages and the limitations of such a technique.

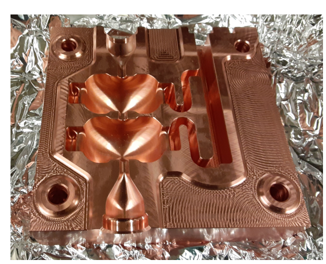


Figure 1: Two-cell distributed coupling structure for high field tests (also shown in [9]).

Diffusion bonding is a solid-state bonding procedure wherein the atoms of two adjacent metallic surfaces intersperse themselves over time due to diffusion effects [12]. The migration of such atoms is regulated by the evolution of their concentration $\varphi(\mathbf{r}, t)$ as described by Fick's law for diffusion [13]

$$\frac{\partial \varphi}{\partial t} = D\nabla^2\varphi \tag{1}$$

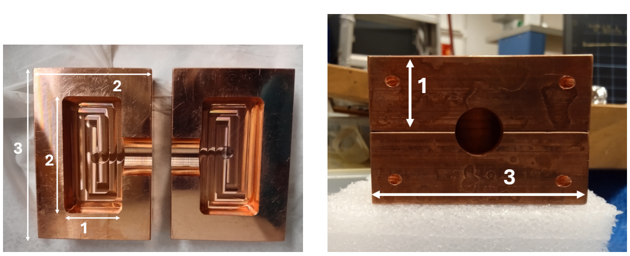
* This work is supported by DARPA under Contract N.HR001120C0072, by DOE Contract DE-SC0009914 and DE-SC0020409, by the National Science Foundation Grant N.PHY-1549132 Center from Bright Beams.
† fboscophysics.ucla.edu

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR33

where the rate of diffusion, or *diffusivity*, D becomes larger at high temperatures reducing, in turn, the joining time. Unlike brazing, diffusion bonding does not require a filler metal between the joining surfaces which avoids potentially dangerous residues contaminating the actual cavity. The latter is a motivation to explore the advantages of diffusion bonding for the realization of RF cavities. In this paper we describe the on campus setup utilized at UCLA for the realization of diffusion bonded structures. In particular we discuss the results obtained for the first experimental sample we tested which is used as an indicator to investigate the capabilities of our infrastructure.

METHODOLOGY

The initial step for obtaining reliable results with the diffusion bonding technique is to establish a working procedure that is compatible with the available infrastructure. Accordingly, we started investigating copper samples with simplified geometry in order to perform an arbitrary number of intermediate tests and understand the capabilities and efficacy of the onsite setup at UCLA. The first structure that we tested is shown in Fig. 2. The sample was manufactured by UCLA's machine shop and consists of two pieces of $3 \times 2 \times 1$ cube inches of bulk copper. Each side contains a $2 \times 1 \times 1/3$ cube inches rectangular cavity which is coupled to the exterior by means of a cylindrical pipe of 1/3 in radius. Though being extremely simplified, the test sample allows to observe and study some of the challenges that a more complicated design would introduce. As an example, the reader can notice the fine groove engraved on the top and bottom surfaces of the cavity which is meant to measure the ability of preserving smaller features in the bonding process. In the following we discuss in details the "recipe" we applied to our sample from the preparation treatment to the bake-out. Part of the procedure described in [14] was used as a reference.



(a) Structure halves. (b) Side view.

Figure 2: Sample structure. All measurements are in inches.

Surface Cleaning

The sample was prepared applying the following cleaning procedure. A citric acid bath allows to remove the oxidized layer that naturally develops when metals are exposed to air environment. Thus, we soaked the copper pieces in a 50 % solution of citric acid for 4 hours. Afterwards, we rinsed the sample with tap water and made a final rinse with distilled water wiping off any excess with a soft tissue. The structure was then stored under mild vacuum (~ 100 Torr) to prevent further oxidation.

Clamping and Pressure

In order to realize an effective bond the joining surfaces need to be held at a strong contact pressure. For our first test we investigated the efficacy of a moderately tight clamping system made of two parallel steel plates ($5 \times 4 \times 3/8$ cubic inches) held together by four 3 in long and 1/4 in wide bolts in the corners. The clamping structure holding the sample is shown in Fig. 3. The torque applied to each bolt, measured by use of a torque wrench, is equal to 98.3 Nm. The value of the corresponding axial force can be calculated by the conversion formula

$$T = KFd \tag{2}$$

where d is the diameter of the bolt and $K = 0.2$ for steel. The latter can be used to estimate the force applied on the contact surface and hence the contact pressure which is approximately 6.6 MPa. For comparison, the contact pressure in [14] is ~ 30 MPa. Nevertheless, as the coefficient of thermal expansion (CTE) for copper is greater than for steel, the expected pressure at the contact surface is further enhanced during the bake-out.

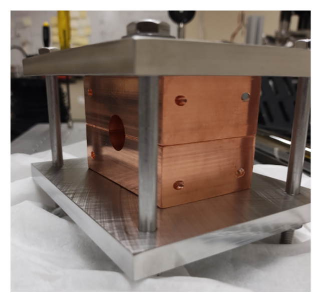


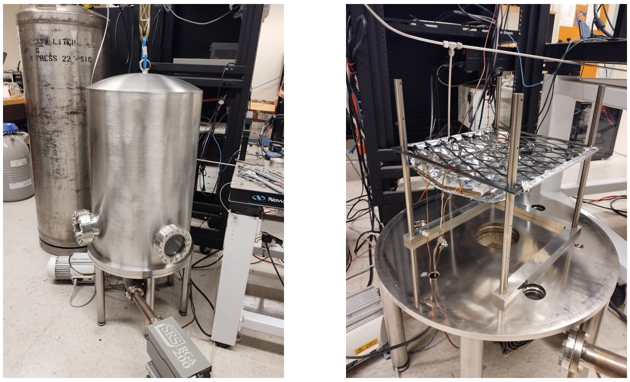
Figure 3: Clamping system applying pressure on the test structure.

Baking

The setup utilized to bake the sample is shown in Fig. 4. The oven and the ancillary equipment constitute a custom system assembled by one of the authors (B.N.) and can be operated on campus. The picture shows the vacuum chamber (~113 l) and the electric current driven heating element therein. A thermocoupler is in contact with the heating grid such that a feedback loop can be used to control the temperature in the oven by varying the duty cycle of the current pulses. Additionally, a residual gas analyzer (RGA) is installed in order to monitor the composition of the outgas products during the bake-out.

The sample was placed on top of the heating grid and covered with three layers of aluminum foils to keep the heat uniform and localized in the neighboring volume. The chamber was then closed and pumped down to a pressure of ~ 10^{-8} Torr. Heat was then applied by delivering DC current

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR33

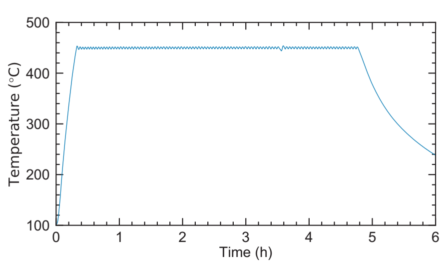


(a) Vacuum chamber. (b) Heating elements.

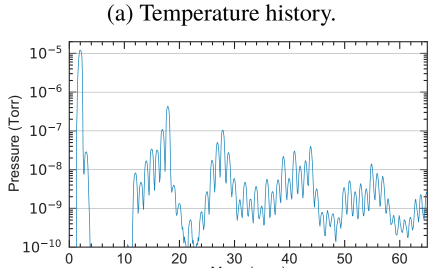
Figure 4: Oven setup and heating elements.

pulses with 50 % duty cycle and ramping the temperature up to the target value of 450 degrees Celsius.

The temperature recorded in the oven is shown in Fig. 5a where it is possible to notice a warm up phase, a ~4.5 hours long flat top phase where most of the bonding occurs and a final warm down phase. For comparison, in [14] bonding times are typically 2 hours however we are expecting a longer process due to the smaller applied pressure. Figure 5b shows the RGA spectrum after 1 hour where it is possible to notice a strong presence of hydrogen (atomic mass unit, amu = 2). The latter is expelled by the stainless steel plates creating a reducing atmosphere that helps keeping the copper free of oxide. The other contributions are given by the following components: water (H_2O, amu = 18), carbon monoxide (CO, amu = 28) and carbon dioxide (CO_2, amu = 44).



(a) Temperature history.



(b) RGA spectrum at t=1h, *i.e.* 450 degrees Celsius.

Figure 5: Temperature recorded during the baking and snapshot of the RGA spectrum after 1 hour.

RESULTS

The sample after the treatment described above is shown in Fig. 6. Even though the original gap is still visible the the two halves form now a single structure. The sample is thus effectively bonded.

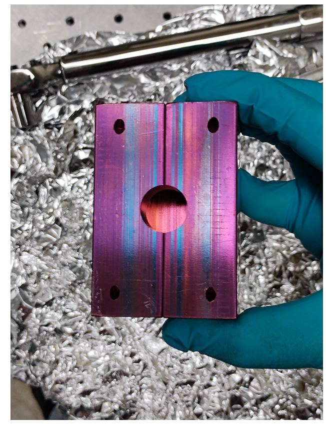


Figure 6: Sample after the diffusion bonding experiment.

Different criteria can be adopted to evaluate the quality of the bonding. At the time of writing we were not able to perform such tests but we planned a list of features that can be investigated in order to provide a complete characterization of the sample as well as the effectiveness of the sealing.

- Evaluate the RF seal by measuring the reflection coefficient of the cavity
- Evaluate the vacuum seal by attaching a flange and pumping down the structure
- Evaluate the mechanical strength by applying stresses of increasing pull with a stepper motor
- Identify damages with post-mortem SEM analysis

CONCLUSION

In this paper we introduced the plan for high field and breakdown tests for C-band distributed coupling cryo-RF cavities. We observed that the manufacture and joining of such structures are crucial and require dedicated studies. Therefore we have started the investigation of diffusion bonding methods that can be pursued with the on campus resources at UCLA. In particular, a first sample structure was realized and the applied methodology was discussed in details. It is expected that the experience matured from the first experiment will instruct the following iterations improving the quality of the bonding while keeping the overall setup relatively simple and inexpensive.

REFERENCES

[1] L. Faillace *et al.*, "Status of compact inverse compton sources in Italy: BriXS and STAR," in *Advances in Laboratory-based X-Ray Sources, Optics, and Applications VII*, International Society for Optics and Photonics, vol. 11110, 2019, p. 1 111 005.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR33

[2] V. Shiltsev and F. Zimmermann, "Modern and future colliders," *Rev. Mod. Phys.*, vol. 93, p. 015 006, 2021. doi:10.1103/RevModPhys.93.015006

[3] L. Faillace *et al.*, "Perspectives in linear accelerator for flash vhee: Study of a compact c-band system," *Physica Medica*, vol. 104, pp. 149–159, 2022. doi:10.1016/j.ejmp.2022.10.018

[4] T. P. Wangler, *RF Linear Accelerators*. J. Wiley & Sons, 2008.

[5] A. D. Cahill, J. B. Rosenzweig, V. A. Dolgashev, Z. Li, S. G. Tantawi, and S. Weathersby, "Rf losses in a high gradient cryogenic copper cavity," *Phys. Rev. Accel. Beams*, vol. 21, p. 061 301, 6 2018. doi:10.1103/PhysRevAccelBeams.21.061301

[6] A. D. Cahill, J. B. Rosenzweig, V. A. Dolgashev, S. G. Tantawi, and S. Weathersby, "High gradient experiments with X-band cryogenic copper accelerating cavities," *Phys. Rev. Accel. Beams*, vol. 21, p. 102 002, 10 2018. doi:10.1103/PhysRevAccelBeams.21.102002

[7] S. Tantawi, M. Nasr, Z. Li, C. Limborg, and P. Borchard, "Design and demonstration of a distributed-coupling linear accelerator structure," *Phys. Rev. Accel. Beams*, vol. 23, no. 9, p. 092 001, 2020.

[8] J. B. Rosenzweig *et al.*, "An ultra-compact x-ray free-electron laser," *New Journal of Physics*, vol. 22, no. 9, p. 093 067, 2020. doi:10.1088/1367-2630/abb16c

[9] J. Rosenzweig *et al.*, "A high-flux compact x-ray free-electron laser for next-generation chip metrology needs," *Instruments*, 2024. https://api.semanticscholar.org/CorpusID:268178214

[10] M. Bai *et al.*, *C^3: A "cool" route to the higgs boson and beyond*, 2021.

[11] P. G. Maxim, S. G. Tantawi, and B. W. Loo, "Phaser: A platform for clinical translation of flash cancer radiotherapy," *Radiotherapy and Oncology*, vol. 139, pp. 28–33, 2019, FLASH radiotherapy International Workshop. doi:10.1016/j.radonc.2019.05.005

[12] A. I. H. Committee, *Welding Fundamentals and Processes*. ASM International, 1990.

[13] A. Fick, "Ueber diffusion," *Annalen der Physik*, vol. 170, no. 1, pp. 59–86, 1855. doi:10.1002/andp.18551700105

[14] C. Zhao, F. Li, Y. Chen, Y. Huang, and Z. Wang, "Joining of oxygen-free high-conductivity cu to cucrzr by direct diffusion bonding without using an interlayer at low temperature," *Fusion Engineering and Design*, vol. 151, p. 111 400, 2020. doi:10.1016/j.fusengdes.2019.111400