Development of X-band high gradient structures and CuAg alloys

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Abstract

High energy physics experiments using particle accelerators as well as industrial and medical applications are continuously seeking more compact, robust and cheaper accelerating structures. As of today, stable operating gradients, exceeding 100 MV/m, have been demonstrated by the SLAC group in the X-Band (11.424 GHz). These experiments show that hard structures, fabricated without high-temperature processes, achieve a better high gradient performance in terms of accelerating gradients. Therefore, we present an innovative and compact type of accelerating cavity that avoids any high-temperature processes like brazing or diffusion bonding. All cells are joined together by means of specifically designed and proprietary screws which ensure good vacuum and RF contacts. Two three-cell standing-wave accelerating structures, designed to operate in the pi-mode at 11.424 GHz, have been successfully built and cold tested. In order to guarantee a vacuum envelope and mechanically robust assembly, we used the Electron Beam Welding (EBW) and the Tungsten Inert Gas (TIG) processes. This work has been carried out within a large international collaboration between LNF, SLAC and KEK for the development of X-Band accelerating cavities using "hard structure"technology. A preliminary temperature and stress tests during the welding process is shown. The high power RF tests have been performed at SLAC by achieving excellent results.

Introduction

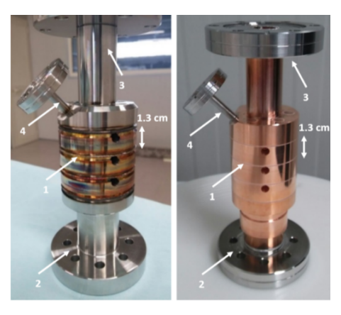
- There is a strong demand for accelerating structures able to achieve higher gradients and more compact footprints for the next generation of linear accelerators [1], for research, industrial and medical applications[2, 3]. The project presented herein is the result of a continuous, decade-long collaboration involving INFN in Italy, SLAC in the U.S.A, and KEK in Japan.
- Accelerating cavities are usually made of many single cells bonded together. The most common bonding techniques, used worldwide, are high-temperature brazing and diffusion bonding. The brazing and the diffusion bonding are performed inside a high-temperature furnace. The first process involves the melting of copper alloys which bond together the metallic surfaces of adjacent cells. In the second one, the melting occurs directly at the contact surfaces.
- These high-temperature processes require high-level skills and are often unsuccessful in the production of cavities suitable for high RF power operation, as it is well-known in the accelerator community. Many are the risks of both brazing and diffusion bonding which could lead to either a failure of the process itself or damage to the structure or both. For example, if the brazing alloy is not properly placed, small pockets with air can remain around the filler regions causing virtual leaks [4] which are sources of trapped gas into the ultra-high vacuum volume or if the furnace has a vacuum issue it can cause the structure inside to oxidize.
- Another reason to avoid the high-temperature bonding processes is the possibility to achieve higher accelerating gradients with hard un-annealed copper-alloy structures. Recent experiments [3, 5] have demonstrated that structures made out of hard copper alloys can achieve higher accelerating gradients with lower RF breakdown rates (BDR) with respect to the high-temperature treated ones.
- Furthermore, the brazing or diffusion bonding costs are also an issue since dedicated fixture, filler materials and furnace time, just to mention a few, need to be accounted for. The improvement in high gradient performance and the cost of high-temperature bonding led us to the invention proposed in this paper.
- In this work, we show the design and mechanical tests of an innovative cost-effective 3-cell accelerating X-band cavity realized without using the high-temperature bonding processes. The accelerating structure, made out of hard copper material, will be consequently employed for high-gradient tests as well as the study of the physics of RF breakdown.
- The structures were successfully high power tested at SLAC. RF high power tests were successful results.

Braze-free "Squeeze-cavity"

Solid model, one-half of the braze-free 3-cell cavity: 1. High-gradient cells, RF vacuum chamber; 2. Special screws for clamping; 3. Input RF flange 4. secondary vacuum chamber; 5. Vacuum flange for the secondary vacuum chamber; 6. Downstream vacuum flange; 7. Water cooling pipe.

In figure above, it is shown the solid model of the 3-cell accelerating X-band structure, that we call the "Squeeze cavity", showing our proposed clamping system which is achieved by means of special and proprietary screws (2). Thanks to this innovative approach, it is possible to obtain perfect RF contacts between the cells and the desired quality factor without using any high-temperature bonding process. Two vacuum regions or chambers are present in the structure. The primary RF vacuum chamber (1) is the volume inside the high-gradient accelerating cells, where the RF power builds up the electromagnetic field. This chamber is connected to a vacuum pump through the input circular RF flange and the circular downstream vacuum flange (3 and 6). The secondary vacuum chamber (4) serves two important purposes: 1) it prevents any virtual air pockets, created between cells clamped together, from leaking gas into the primary vacuum chamber; 2) it reduces the risk of contamination of the primary chamber caused by the welding process performed on the outer surfaces of the cavity [6].

Tungsten Inert Gas (TIG) welding process VS. Electron Beam Welding (EBW) process

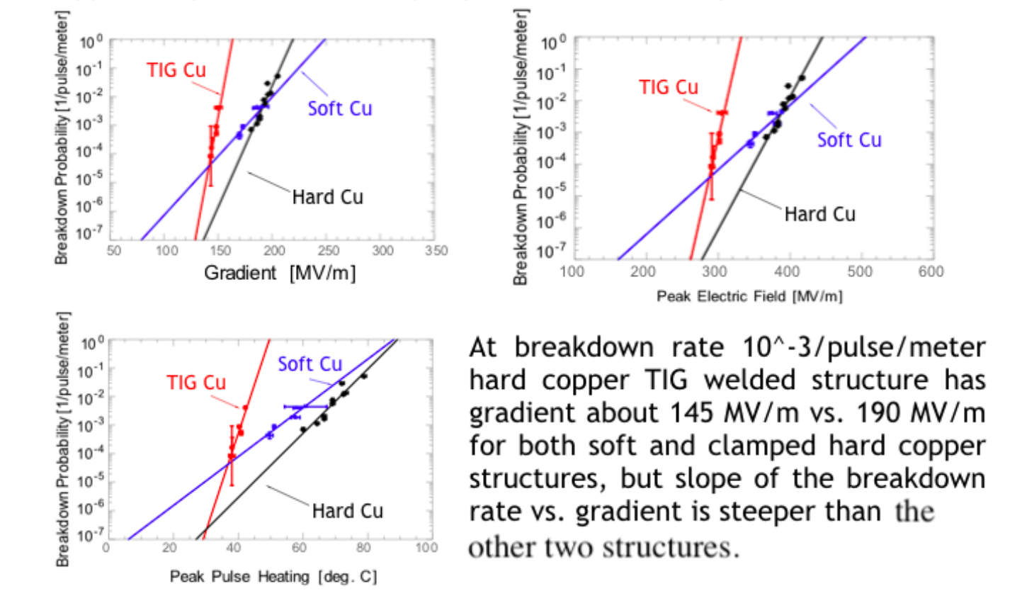


Left, 3-cell cavity after TIG welding. Right, 3-cell cavity after electron beam welding. 1. Welding joints; 2. Input RF flange; 3. Downstream vacuum flange; 4. Circular flange for pumping the secondary vacuum chamber. Geometrically, the primary vacuum envelope in both structures are identical. Each cell is individually connected to the other by means of stainless steel screws that hold them tightly together. They both have a primary RF vacuum chamber, i.e. the volume where the electromagnetic field will resonate, and a secondary vacuum chamber, while they differ in the welding procedures. The welding joints are also shown [7].

High power experimental tests

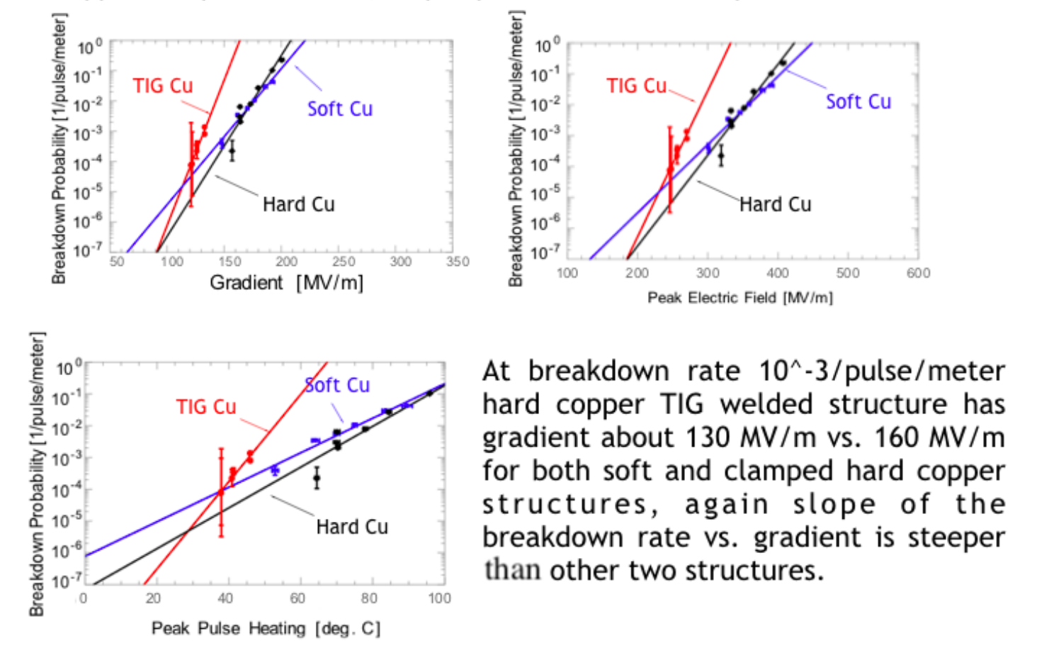
- Structure was successfully constructed and high power tested which validated the TIG welding approach toward building full scale multi-cell low cost linacs.
- Slope of the breakdown rate vs. gradient is steeper then soft copper structures and close to that of CuAg structures.
- Likely, at short pulses, the breakdown ratedepends more on peak fields, and at longer pulses non peak pulse heating.

Comparison of performance of TIG welded hard copper structure with soft and hard copper clamped structures, shaped pulse with 150 ns flat part



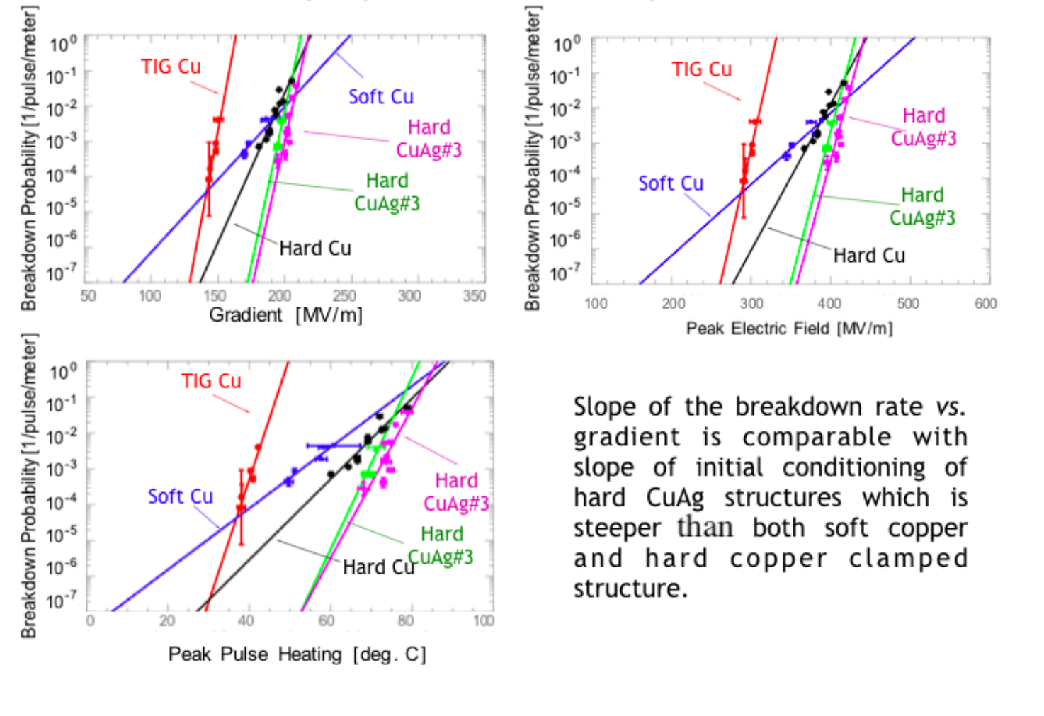
At breakdown rate 10^-3/pulse/meter hard copper TIG welded structure has gradient about 145 MV/m vs. 190 MV/m for both soft and clamped hard copper structures, but slope of the breakdown rate vs. gradient is steeper than the other two structures.

Comparison of performance of TIG welded hard copper structure with soft and hard copper clamped structures, shaped pulse with 400 ns flat part



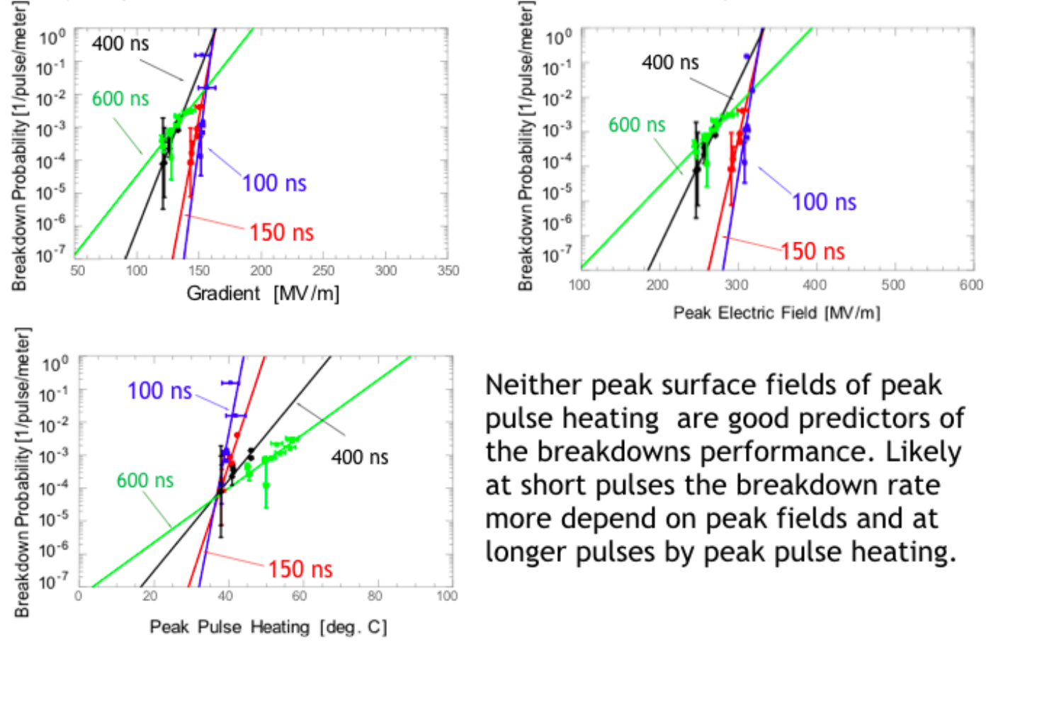
At breakdown rate 10^-3/pulse/meter hard copper TIG welded structure has gradient about 130 MV/m vs. 160 MV/m for both soft and clamped hard copper structures, again slope of the breakdown rate vs. gradient is steeper than other two structures.

Comparison of performance of TIG welded hard copper structure with soft and hard copper clamped structures and two clamped hard CuAg structures, shaped pulse with 150 ns flat part



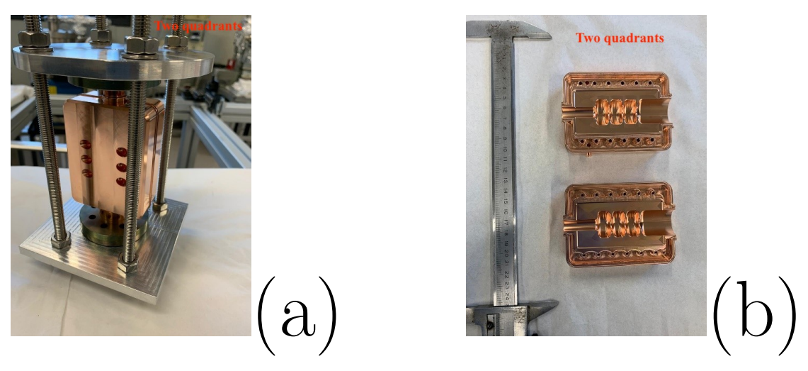
Slope of the breakdown rate *vs.* gradient is comparable with slope of initial conditioning of hard CuAg structures which is steeper than both soft copper and hard copper clamped structure.

Pulse length dependence of breakdowns probability of TIG welded hard copper (1C-SW-A2 .75 -T2 .0- TIG-Cu- Frascati-#1_6May2019) structure, shaped pulse with 100 ns, 150 ns, 400 and 600 ns flat part



Neither peak surface fields of peak pulse heating are good predictors of the breakdowns performance. Likely at short pulses the breakdown rate more depend on peak fields and at longer pulses by peak pulse heating.

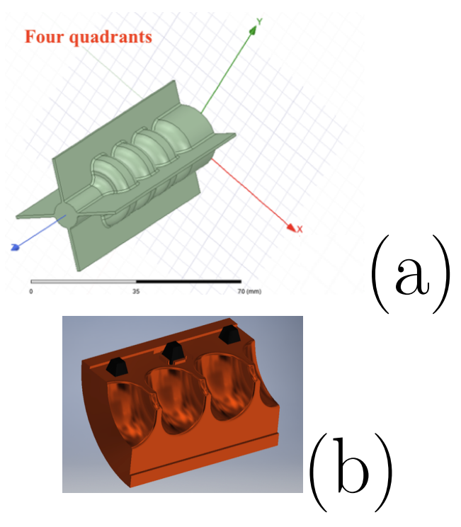
Comparison between mode frequencies and quality factors for the closed structure and two-half structure



Mode	Frequency [MHz] (Two Halves)	Frequency [MHz] (Closed Structure)	Quality Factor (Q) (Two Halves)	Quality Factor (Q) (Closed Structure)
0	10,749	10,760	10,520	10,615
$\pi/2$	10,979	10,984	10,213	10,306
π	11,418	11,420	10,512	10,610

Picture of the two halves structure under test. (a) clamped structure for low-power tests; (b) two halves of the machining [8]. In this Table, we report frequencies and quality factors of the resonant modes, obtained from simulations, for the split open structure in comparison with the same cavity designed with the conventional "closed" approach. The frequency separation between the π-$\pi/2$ and $\pi/2$-0 modes is about 440 MHz and 230 MHz, respectively, in the case of the two halves structure, while it is equal to about 435 MHz and 225 MHz for the closed one. The two-halves structure cell-to-cell coupling coefficient is estimated to be 6.1% , while the one for the other structure is 6%. In addition, we observe a quality factor Q reduction of the modes by increasing the quadrant, as it is expected to be. The structure material is Cu/Ag alloy.

Four quadrants X-Band structure



a) 3D model of the four quadrants X-Band structure b) one quarter of the four quadrants structure for wakefields damping. This structure will be fabricated considering Cu/Ag material within this year and it will be tested at high power at SLAC.

Conclusions

- We have proposed here an innovative approach for cell-to-cell clamping, by means of special custom screws, which avoids high-temperature brazing or diffusion bonding. The choice for working with hard structures which are not high temperature treated is justified by decade-long studies performed in National Labs world-wide (e.g. SLAC, KEK) that showed a better high-gradient performance with respect to high-temperature treated cavities.
- The first two prototypes were vacuum tight and tested at low RF power. The clamping mechanics permits to obtain ultra-high vacuum level (< 1E-12 Torr), sufficient for high-gradient operation. We decided, for these first two prototypes, to proceed to the welding of the outer surfaces of the cavity by using the EBW and TIG processes, in order to assure a steady vacuum envelope and more robust mechanical assembly.
- The primary purpose of this project is a study of high gradient performance of structures joined in a novel way using special screws. By creating a secondary vacuum chamber and welding the structure to seal the vacuum envelope, we created a robust way to ensure vacuum integrity. The study of feasibility of clamped-only structure will be done in the next steps, once the high gradient performance of the current two structures is verified.
- Both structures have already been tested at high RF power at SLAC (National Accelerator Laboratory in California, U.S.A) [9] by giving very interesting results which will be discussed in a dedicated forthcoming paper.
- It will be conducted an intense investigation to optimize the Cu/Ag alloy as a function of Ag concentration in order to increase the breakdown threshold.

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References

[1] M. Ferrario et al., "EuPRAXIA@$SPARC_LAB$ Design study towards a compact FEL facility at LNF", submitted *Nucl. Instrum. Meth. (2018)* [arXiv:1801.08717].

[2] A. Grudiev, S. Calatroni and W. Wuensch, "New local field quantity describing the high gradient limit of accelerating structures", *Phys. Rev. ST Accel. Beams 12 (2009) 102001.*

[3] V.A. Dolgashev, S.G. Tantawi, A.D. Yeremian, Y. Higashi and B. Spataro, "Status of high power tests of normal conducting single-cell standing wave structures", in *Proceedings of the IPAC 2010, Kyoto, Japan, 23-28 May 2010, pp. 3810-3812* (and references therein).

[4] https://www.mtm-inc.com/av-20100312-vacuum-chamber-design-what-is-a-virtual-leak.html.

[5] V.A. Dolgashev, "High Gradient, X-Band and above, Metallic RF structures", talk given at the *2nd European Advanced Accelerator Concepts Workshop, La Biodola, Isola d'Elba, Italy, 13-19 September 2015.*

[6] Dolgashev, V.; Faillace, L.; Spataro, B.; Tantawi, S.; Bonifazi, R. High-Gradient RF Tests of Welded X-band Accelerating Cavities. *Phys. Rev. Accel. Beams* **2021**, *24*, 081002.

[7] Dolgashev, V. A., et al. "Innovative compact braze-free accelerating cavity. "*Journal of Instrumentation 13.09 (2018): P09017.*

[8] Spataro, Bruno, et al. "A Hard Copper Open X-Band RF Accelerating Structure Made by Two Halves."Instruments 6.1 (2022): 5.

[9] V.Dolgahev,"Building and High Power Testing Welded Accelerating Structures ", *presentation at HG2019 workshop, June 10-14,2019,Chamonix (FR)*