

Fabrication and High-Power Testing of Welded Accelerating Structures

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On behalf of the INFN-LNF/SLAC collaboration

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Outline



- Novel clamping technique for high-gradient accelerating structures^{*, #}
- Welded single-cell X-Band structures:
 - Electron Beam (EB) Welding
 - Tungsten Inert Gas (TIG) Welding
- High-Gradient RF Tests of Welded X-band Accelerating Cavities^{\$}
 - Cavities Autopsy
 - Test results

First useful welded structures with operational gradients beyond 100 MV/m

- Design and Fabrication of a welded X-Band accelerating structure made of two halves.
- Application to W-Band.

* V.A. Dolgashev, L. Faillace, B. Spataro and R. Bonifazi, *"Innovative compact braze-free accelerating cavity"*, Journal of Instrumentation JINST 13, no. 09 (2018): P09017.

V.A. Dolgashev, L. Faillace, Y. Higashi, A. Marcelli, B. Spataro and R. Bonifazi, "Materials and technological processes for High-Gradient accelerating structures: new results from mechanical tests of an innovative braze-free cavity", Journal of Instrumentation. 2020 Jan 27;15(01): P01029.

\$ Paper submitted for publication in Physical Review Special Topics – Accelerators and Beams.

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Motivation



High-gradient linacs are sought for various applications, from high-energy physics, industry and medicine, and require novel accelerating structures which are compact, robust and cost-effective.

- We want to avoid high temperature processing of the cavities to benefit from superior high gradient performance of hard copper alloys.
- Electron Beam Welding (EBW) and Tungsten Inert Gas (TIG) processes allow us to build practical, multi-cell structures out of hard copper alloys.
- Costs reductions no need for use of vacuum or hydrogen furnaces, and in case of TIG welding, no need for expensive Electron Beam Welders.
- This study is the result of a continuous, decade-long collaboration involving the SLAC, INFN-LNF and KEK.
- The full study of building practical structures made of hard materials includes several developments (joining techniques, surface processing compatible with this techniques and corresponding materials, etc.)

First step of this process: viability of novel joining techniques.

This work was made possible by the efforts of SLAC's V.A. Dolgashev, S. Tantawi, E. Nanni, J. Eichner, C. Yoneda, A. Haase, C. Pearson, J. Van Pelt, B. Weatherford, and staff of TID

In close collaboration with B. Spataro INFN-LNF and Comeb srl, Italy Luigi Faillace (INFN-LNF)

Vacuum RF breakdown - "state of the art"



- Experimental results with hard copper cavities, conducted at SLAC, CERN and KEK have shown that hard materials sustain higher accelerating gradients for the same breakdown rate;
- We practically can predict performance of heat-treated soft copper X-band (11.424 GHz) structures from drawings.
 - Peak pulse heating to be good predictor of breakdown rate in simple, disk-loaded-waveguide type geometries.
 - "Modified Poynting vector" (Sc) is a practical predictor of breakdown rate in more complex geometries.
- Motivated by correlation of peak pulse heating and breakdown rate we study hard copper alloys and methods of building practical structures out of them.
 - We found hard Cu and hard CuAg have better performance than soft heat-treated copper.
- Typical gradients in S-band linacs ~20 MV/m, in superconducting linacs ~30 MV/m. We are pushing beyond 100 MV/m with record of 200 MV/m (hard CuAg).
- Breakdown study in cryo normal conducting structures. As for now, such accelerating structures hold the absolute record for X-band accelerating cavities, ~250 MV/m gradient (0.5 GV/m peak at surface) at 10⁻³/pulse/m breakdown probability.
- Breakdown physics in 100 GHz and 200 GHz structures*.

*Othman, Mohamed A. K. et al., *"Experimental demonstration of externally driven millimeter-wave particle accelerator structure"*, Appl. Phys. Lett. 117, 073502 (2020); <u>https://doi.org/10.1063/5.0011397</u>

First Activity on X-Band accelerating structures DEMETRA experiment at INFN-LNF

















Braze-Free Cavity – Construction and Clamping System





Braze-Free Cavity – Construction and Clamping System



Main RF parameters of the structure normalized to 100 MV/m accelerating gradient.

Parameter	Value
Resonant frequency, f [GHz]	11.424
Stored energy [J]	0.153
Quality factor Q	8590
Shunt impedance $[M\Omega/m]$	102.894
H_{max} [MA/m]	0.29
E_{max} [MV/m]	203.1
Power loss per cell [MW]	1.275
$a [\mathrm{mm}]$	2.75
a/λ	0.105
$H_{max}Z_0/E_{acc}$	1.093
t [mm]	2
Iris ellipticity	1.385
Phase advance per cell [deg.]	180





V. Dolgashev, L. Faillace, B. Spataro, and R. Bonifazi, Innovative compact braze-free accelerating cavity, Journal of Instrumentation 13 (09), P09017.

Braze-Free Cavity – Construction and Clamping System





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Cavity Assembly Procedure

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Parts of the structure before final assembly



Side View

Knife edge – (RF contact)

- 1. Special hollow screws;
- 2. Channels for pumping the secondary vacuum chamber;
- 3. Primary RF chamber.



- 1. Special stainless-steel screws;
- 2. Gas pumping channels;
- 3. Primary RF Vacuum chamber;
- 4. Tuning holes;
- 5. Teeth for welding;
- 6. Input RF flange.



Welding Process



TIG cavity

Tungsten Inert Gas welded Single Cell Standing Wave structure, 1C-SW-A2.75-T2.0-TIG-Cu-Frascati-#1



EBW cavity

Electron Beam Welded Single Cell Standing Wave structure, 1C-SW-A2.75-T2.0-EBW-Cu-Frascati-#1

SLAC-INFN/LNF-Comeb

(1) Welding joints, (2) input RF flange, (3) downstream Conflat vacuum flange, (4) Conflat flange for pumping the secondary vacuum chamber.

Setup prototype for Temperature Monitoring during TIG Welding







Thermocouples wiring

- Tooth thickness is proportional to welding current: lower electric current, smaller tooth;
- Optimal compromise: lowest electric current, mechanically stable welding (robustness) and no signs of oxidations.

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TIG Welding electric current set up 140 A [welder readout, effective value 117 A]



 Temperature of cavity surfaces always BELOW copper annealing temperature (~590 °C) for all trials;

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- Argon was flushed at all times to avoid copper oxidation;
 - All tested samples were visually examined: we chose the welding current and speed with NO signs of oxidation observed!



Installation inside the lead-box at SLAC



The TIG structure installed inside the lead box at SLAC.

Experimental setup:

- (1) 1C-SW-A2.75-T2.0-TIG-Cu-Frascati-#1 cavity,
- (2) TM₀₁ mode launcher,
- (3) Coaxial cables to the current monitors,
- (4) Port for secondary vacuum,
- (5) High-vacuum ion pumps.



Courtesy of V. Dolgashev, SLAC

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Processing History (quick premise)

- 1. EBW cavity high-power testing was limited by arcing in the mode launcher;
- 2. EBW performance was not limited by the structure itself (as see during cavity autopsy) but arcing in the mode launcher;
- 3. Mode launcher was reconditioned and ready for the TIG cavity;
- 4. TIG cavity was successfully high-power tested.

Courtesy of V. Dolgashev, SLAC

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







- Hard copper EBW structure has a gradient of about 90 MV/m has a gradient at breakdown rate 10⁻³/pulse/meter;
- Hard copper TIG welded structure has a gradient of 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 both soft and hard copper.

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Pulse length dependence of breakdown probability of EBW welded hard copper structure, shaped pulse with 100 ns, 200 ns, and 400 ns flat part, all breakdowns





- Peak pulse heating is a surprisingly good predictor of the breakdowns rate;
- The hard copper EBW structure did not reach its ultimate performance, so this data is a snapshot of metal surface state;
- Likely cause: multipacting in RF input power mode launcher.

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- Neither peak surface fields nor peak pulse heating are good predictors of the breakdown performance;
- The breakdown rate depends more on peak fields at short pulses;
- At longer pulses, it depends more on peak pulse heating.

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EBW cavity after high-power tests







Low RF breakdown activity in middle cell, as expected.

EBW cavity was not fully conditioned due to limitations of mode launcher.





No oxidation observed inside the primary chamber, on the high-field surfaces!

TIG cavity after high-power tests







High RF breakdown activity in middle cell, as expected.

Oxidation inside the secondary vacuum chamber (as expected during the TIG process)

No oxidation observed inside the primary chamber, on the highfield surfaces!



Autopsy of 1C-SW-A2.75-T2.0-EBW-Cu-Frascati-#1

Central high field cell



- The middle cell has evidence of the heaviest arcing.
- Few isolated locations that have large concentrations of arc pits (high Electric field areas), which are typically observed in these type of structures.
- SEM images showed the cells were not chemically etched with standard procedure developed for brazed structures.





High Magnetic field area shows contamination but no signs of RF pulsed heating damage.

10 µm



Cell RF compression seal area looks good

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Autopsy of 1C-SW-A2.75-T2.0-TIG-Cu-Frascati-#1



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- As expected, the middle cell has evidence of the heaviest arcing
- The electric field areas have many scattered small arc pits, which is typical for these type of structures.



The high magnetic field areas appear unaffected > (typical for hard copper structures).

Some pits are seen at high magnification, but they are probably not RF related.



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"Hard" Split - Open structure: X-Band cavity made of two halves





On-axis electric field profile of the operating $\underline{\pi}$ mode

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"Hard" Split - Open structure: Clamping

Same goal as single-cell cavity:

Building practical multi-cell structures made out of hard copper alloys.

The two cavity halves are aligned clamped together by means of a malefemale matching surface.

Clamping is obtained with stainless-steel screws.

The structure is eventually TIG welded on the outer surface









"Hard" Split - Open structure: Low-power testing





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• On-going studies for application in W-band structures with INFN-LNS Luigi Faillace (INFN-LNF)

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Conclusions



- We developed an innovative approach for the cell-to-cell clamping, by means of special screws. Istitute Nazionale
- Two braze-free X-Band (11.424 GHz) structures, clamped with this approach, were welded avoiding high temperature processing, thus preserving the hardness of the metal.
 - 1. The EBW structure was successfully constructed and characterized at low-power. The structure did not reach its ultimate performance, due to multipacting in the input RF power mode launcher. However, it demonstrated an accelerating gradient of 90 MV/m at a breakdown rate of 10⁻³/pulse/meter using a shaped pulse with a 150 ns flat part.
 - 2. The TIG welded structure was successfully constructed and high power tested. The cavity performance showed about a 150 MV/m accelerating gradient at a breakdown rate of 10⁻³/pulse/meter using a shaped pulse with a 150 ns flat part.
- The autopsy of both structures reinforced our experience of the importance of pre-assembly chemical etching but showed no RF-related damage in cell-to-cell joints.
- This is the first important step to validate our approach of structure construction and building practical multi-cell structures made out of hard copper alloys. This technique is suitable for fabricating meter long structures.
- This is first useful welded structures with operational gradients beyond 100 MV/m!
- Our innovative clamping technique is also suitable for smaller dimensions, i.e. W-Band accelerating structures.
- Same idea was used for an X-band structure made of two halves which was TIG welded, low-power tested and ready for high-power tests.

Thank you very much for your attention!

Special Thanks for the efforts of SLAC's group for the High-Power Testing:

V.A. Dolgashev, S. Tantawi, E. Nanni, J. Eichner, C. Yoneda, A. Haase, C. Pearson, J. Van Pelt, B. Weatherford, and staff of TID

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