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PREPARATION AND TESTING OF THE bERLinPro Gun1.1 CAVITY*

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Abstract

For the bERLinPro energy recovery LINAC, HZB is developing a superconducting 1.4-cell electron gun, which, in its final version, is planned to be capable of continuous-wave (CW) 1.3 GHz operation with 77 pC/bunch. For this purpose a series of three superconducting cavities, denoted as Gun 1.0, Gun 1.1 (both designed for 6 mA) and Gun 2.0 (100 mA) is foreseen. Here the status of the Gun 1.1 cavity is described, including results of the recent vertical testing. Lessons learned from the production and preparation process are summarized, also in order to identify issues critical for the production of Gun 2.0.

CAVITY OVERVIEW

Gun 1.1 (cf. Fig. 1, also [1]) is a 1.3 GHz superconducting niobium radio-frequency (RF) cavity, designed for the initial stage of the bERLinPro operation with up to 6 mA average current. It consists of an elliptical "full" cell, resembling the prominent TESLA/XFEL shape, combined with a so-called "half" cell, which has a length of 0.42·λ/2. In the back wall of the latter a central hole of 11.5 mm diameter is placed to house a replaceable cathode plug. The cathode is supported by a backward pile, thus forming a coaxial set up, which, without additional measures, significantly would drain RF power. This is blocked by a dedicated superconducting "choke" cell (and a specialized pile shape), surrounding the cathode pile and acting as a RF stop-band filter, tunable from the exterior even after tank welding. Two opposing ports for fundamental power couplers of coaxial type are placed in the beam pipe, together with three pick-ups. A fourth pick-up is located on the rear side of the choke cell. All cells are made of niobium with RRR > 300; choke cell and half cell with a large-grain material, full cell, transition and beam pipe out of fine-grain.

MANUFACTURING AND PREPARATION SEQUENCE

In the following the main manufacturing and processing steps done up to now are listed in a chronological manner with brief comments:

- Manufacturing of main groups (separations at equators of full and half cell); unexpected amount of spring back after deep drawing of half cells caused slight exceedance of contour tolerance.
- Trimming and welding of main groups; weld shrinkage at coarse-grain weld at the half cell equator unexpectedly not observed.

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Figure 1: Gun 1.1, mounted in a frame for vertical testing. Beam pipe side downwards, full cell in the picture's center, half cell above. The choke cell is hidden in the cylindrical housing in the upper part.

- First tuning did not reach destination frequency nor field flatness; stopped.
- Chemical processing in four steps; non-trivial acid temperature and flow control, mainly due to the cathode plug hole.
- Accompanying ultrasound wall thickness measurements; coarse grain material shows dependency of thickness readout on grain orientation.
- Backing 700°C for 3 hours after controlled outgassing at 300°C (5 hours).
- Second tuning; demanded frequency shift lowered due to chemistry-caused frequency decrease smaller than expected; material softened in backing. Destination frequency reached, but field in half cell enhanced by 18 % compared to full cell.
- X-ray tomography; second attempt with 600 kV after previous insufficient results with 300 kV.
- High-Pressure-Rinse (HPR) treatment; choke cell not reached by HPR nozzle because of restricted access through the cathode plug hole or the choke cell conus.
- Successful leak check.
- Attaching auxiliary components (antennas, valves, blind flanges) in vendor cleanroom.
- Vertical test at HZB; choke cell pick-up coupling too strong.

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TOMOGRAPHIC INSPECTION

Three-dimensional X-ray-based tomographic was very recently introduced as a cavity inspection technique, to the best of authors knowledge first described in [2]. Because of the complicated tuning and processing history of the Gun 1.1 cavity, it was tested if the inner cavity contour could be measured by such a process. As described in [2], niobium is a least favourable material for X-ray applications because of its strong damping. Using the installations of a commercial vendor (XRAY-Lab, Sachsenheim, Germany, 300 kV tube available at that time) and of Fraunhofer IIS Entwicklungszentrum Röntgentechnik (EZRT), Fürth, (600 kV tube) it was checked, whether this limit could be overcome with high-energy X-ray sources and detector technology, as it is routinely used for high-end industrial tomographic inspections.

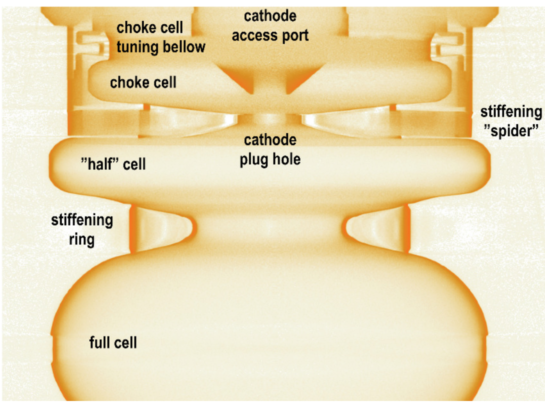

Figure 2: Middle part of the Gun 1.1 cavity's cross section after tuning and processing computed by 3D-tomographic reconstruction.

In Fig. 2 a central cross section of the middle part of the cavity as tomographically reconstructed is shown. Underlying X-ray captures where taken with 587 kV tube voltage, 1.19 mA current, a square detector of 1936 x 1936 pixels, each 200 µm x 200 µm, a source-detector distance of 2500 mm, source-object distance (referred to the axis of object rotation) 1786 mm, resulting in a voxel size of 200 µm·(1786/2500) = 142.9 µm. Since the cavity size exceeded the sensor area, capturing had to be split in three overlapping areas. Obviously most of the inner structures of the cavity are resolved (e.g. stiffening structures between "half" and choke cell, bellow for compensating choke cell tuning) even though several material layers needed to be penetrated. On the other hand, even in the areas of single niobium walls (which had to be passed twice) of ~ 3 mm thickness the tomographic inversion did not resolve the *inner* material contour, whereas the outer shape is pictured with clear contrast in an evaluable manner. The lack of contrast at inner sides made it e.g. impossible to measure the diameter of the cathode plug hole (which was suspected to be widened by an enhanced material loss while chemical etching). Nevertheless inspection of the outer contour revealed significant deformations of the "half" cell due strong tuning deformations, both making the back wall roughly perpendicular to the axis and imposing a circumferential bulb slightly outwards the stiffening rings.

Scale calibration of the voxel size agreed very well with caliper measurements done at the cross sections shown in orange in Fig. 3, worst relative error (found at the uppermost cross section) was $8 \cdot 10^{-4}$. Therefore the outer contour was estimated as reliable and efforts in picture evaluation were undertaken to transfer it for use in CST [3] simulations, assuming undisturbed rotational symmetry (cf. Fig 4).

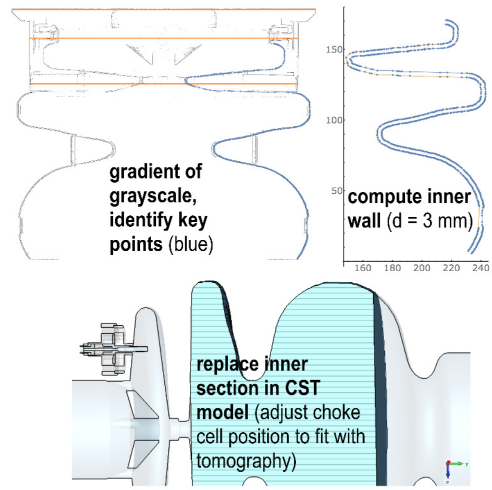

Figure 3: Simplified workflow for the application of tomography data in a CST model used for eigenmode computations.

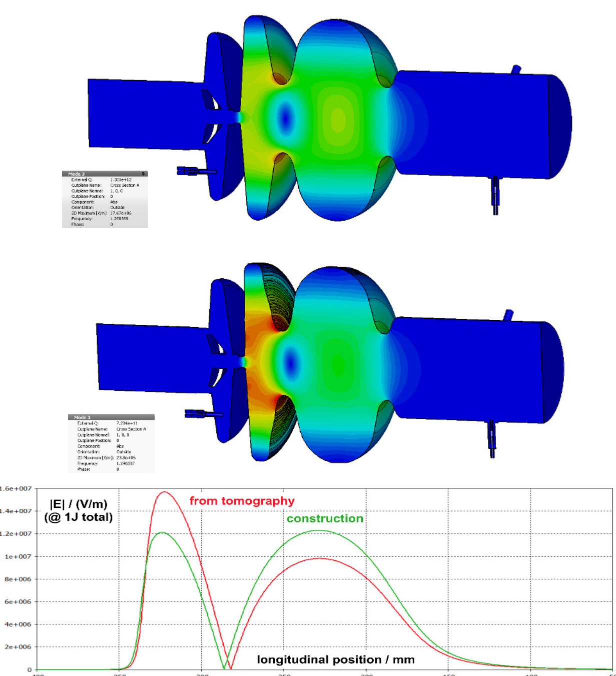

Figure 4: |E| of the accelerating mode, computed for the construction geometry (1298.398 MHz) and using the tomography contour (1296.307 MHz). The model adjusted by tomography results is 2.0 mm shorter than the construction.

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CHEMICAL TREATMENT AND ULTRASOUND WALL THICKNESS MEASUREMENTS

Buffered chemical polish (BCP) was used to treat the inner cavity surface, aiming for in total 200 µm material loss. The narrow shape of both the choke and the half cell, combined with the small diameter of the cathode plug channel gave reason to perform the etching in several steps, carefully monitoring the material loss both by weighting and with an ultrasound thickness gauge. The latter was applied on eight azimuthal (every 45°) times six different, well reproducible height positions (half cell (HC) above and below the equator, full cell (FC) close to the stiffening ring ("high"), above and below the equator and close to the transition ("low"), four to eight samples at every position (cf. Fig. 5). The total material loss taken out of the weight change accumulated to 157.1 µm, the average value of all ultrasonic measurements was found slightly lower with 143.4 µm.

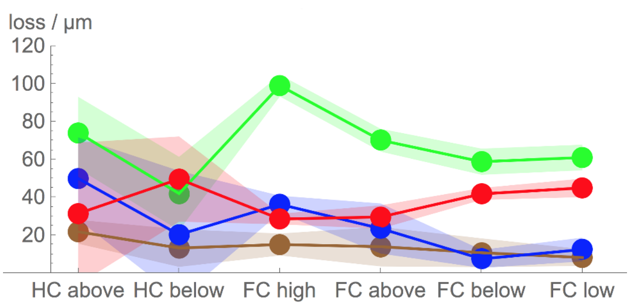

Figure 5: Average wall thickness loss measured with an ultrasound thickness gauge for BCP I to IV, shown in green, brown, blue and red together with an error band of ± one standard deviation. Large error values in the half cell are mainly caused by significantly varying values in neighbouring grains.

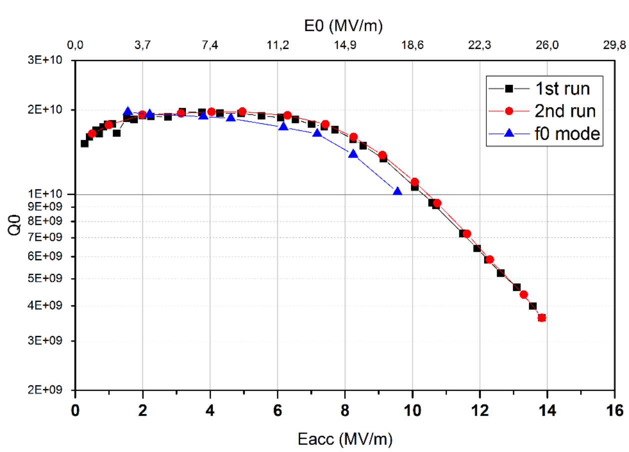

Figure 6: Unloaded Q in dependence of accelerating voltage as found in the vertical test; abscissa values computed from the incident power under the assumption of a flat field distribution.

VERTICAL TEST RESULTS

After cleanroom assembly the cavity was shipped to HZB and tested in a vertical test immersed in liquid helium at 1.8 K. The resulting Q(E)-dependence is shown in Figure 6. The values of the on-axis accelerating electrical field strength Eacc are computed from the incident power under the assumption of a flat field pattern. Since both the final field flatness measurement (bead-pull) after tuning in agreement with the simulation results of the tomographically measured contour strongly indicates a raised field level in the half cell, it is very likely that the peak field strength in the half cell was significantly higher than the abscissa values shown in Fig. 6. The Q(E)-dependence was measured twice for the accelerating mode ("1st run", "2nd run") with a very soft processing in between. Field emission in either case was essentially negligible in either case. Additionally the in-phase ("0"-) mode was measured with very similar results. Furthermore the Lorentz-force detuning slope was found with a value of -7.8 Hz/((MV/m)^2). During the test an unexpectedly strong coupling of the choke cell pick-up was observed (loaded Q < 10^{11}, design 10^{12}); the reason(s) are not fully resolved; possible causes are: –choke cell frequency too high (found 1 MHz above design), –half cell field strength too high because of deformation (strongly indicated), –cathode plug channel being widened too far by chemical etching (tomography very noisy in this area, but also does not exclude), –pick-up antenna too long (possible since numerical dimensioning assumed ideal cavity set-up).

CONCLUSION

The Gun 1.1 cavity was build, processed, tuned, inspected by X-ray tomography and vertically tested. Its performance is not ideal – field flatness was not reached, Q(E) drops faster than expected, the choke cell pick-up is coupled too strongly. It is on the other hand practically unaffected by field emission (so far seen yet), without vacuum issues or other significant deficiencies and operates closely to the destination frequency. The choke cell coupling is adjustable by a shortened pick-up antenna and by a change of choke cell tuning. Those tests are currently under preparation; in case of success the outer LHe tank will be welded next. Flat tuning of such cavities seem to be the most critical issue, as it is not granted that two degrees of freedom (lengths of the two main cells) are sufficient to satisfy both conditions of a correct frequency and a flat field profile; here we gave priority to the first. Tomographic inspection could be rather attractive to capture a full cavity geometry if X-ray sources with even higher photon energy than 600 keV would be accessible.

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