IMPROVED PERFORMANCE OF THE SC LADDER RESONATOR

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Abstract

A novel superconducting (sc) structure, the ladder resonator [1], was proposed to accelerate a high intensity proton beam within the energy range of 5–20 MeV. The first Q-curves were affected by a serious electron-beam welding inconvenience, discovered at a later stage. After repairing the resonator, the Q-values at low field improved by around a factor 5. Present value of the achievable accelerating field is limited by the availability of liquid He, with respect to the time needed to condition field emission (FE) at 4.2 K.

MAIN RESONATOR FEATURES

A superconducting alternative to a normal conducting DTL in the intermediate energy range (β=0.1÷0.2) of CW proton drivers, such as those proposed for RNB facilities, nuclear waste transmutation, spallation neutron sources or neutron irradiation tools, has been proposed.

It consists in few families of independently phased resonators at a frequency of 352.2 MHz covering the energy range 5÷85 MeV, which match the output energy of a normal conducting RFQ and deliver the beam to a spoke or elliptical cavity section covering the 85÷1000 MeV range.

Twelve 4-gap ladders are proposed to cover the range 5÷20 MeV [1]: two families of six ladder cavities each (β_0 = 0.12 and 0.17), housed in two cryostats, are foreseen. Superconducting quadrupoles are located in between ladder cavities. Eight cryostats, with four 2-gap resonators each (either spoke or half-wave resonators [2]), follow the ladder section up to 85 MeV.

Beam dynamics studies with the HALODYN code were made for a 5 mA CW proton beam. Both full transmission and absence of emittance growth up to the 85 MeV were achieved in the simulations.

The need to avoid the parametric resonance, occurring when the longitudinal phase advance (proportional to the square root of the period length L) is twice the transverse one, sets a limit on L and, consequently, suggests to limit the ladder length.

The ladder resonator is a 352.2 MHz 3-parallel-stem cavity built in full Nb, designed to operate at 4.2K. Its stiffening cage and its He vessel are in Ti. The β=0.12 family has been prototyped (fig.1).

A parallel-stem geometry was chosen since it allows rf-currents to flow in the end walls in a similar pattern as in the stems. In these conditions, all the gaps have the same accelerating voltage, without having to increase the length of the outer ones (as it happens on crossed-stem spokes). This design allows this linac section to reach a fairly high real-estate gradient (~2.2 MV/m).

Figure 1: Photo of the ladder resonator prototype.

The price to pay to the compact parallel-stem structure is a lower cell-to-cell coupling of the ladder resonator with respect to crossed-stem spoke resonators. However, an acceptable rf-coupling (1,2%) is achieved by two large coupling holes in each half of the central stem.

Moreover, the parallel-stem arrangement, which concentrates the distribution of the current density on the stem flat areas and on their mirror surfaces on the end-walls, allow the lateral cavity faces to be bolted plates, since the maximum field at their joint is acceptably low (0,18 mT). Such lateral flanges, which were realized in Nb-sputtered Cu, make the resonator BCP and HPWR easier, as well as inspection and repair of the interior volume, with respect to crossed-stem spoke cavities.

Table 1: Calculated RF parameters of the ladder cavity

	COMSOL 3.5 [3]	HFSS 11.1 [4]
RF Coupling	1.2%	1.2%
E_{sp}/E_a	4.0 (±0.6)	3.7 (±0.3)
H_{sp}/E_a [mT/(MV/m)]	9.0	8.8
$H_{s,joint}$ [μT]	182	188
G [Ω]	35.8	36.5
U/E_a^2 [mJ/(MV/m)^2]	38	38
L_{active}	193 mm	

Table 1 shows the relevant parameters of the ladder resonator, calculated with very good agreement by the HFSS [3] and COMSOL [4] codes. The operating field was set to E_a=5.8 MV/m, where the active resonator length in the E_a definition corresponds to the distance between the internal cavity walls.

The average energy gain at the optimum beta, including the TTF, is ΔW~1.03 MeV.

The resonator is mechanically very stiff: calculations with ANSYS [5] show that there are no mechanical vibration modes below 230 Hz [6].

Despite the low rf coupling (1.2%), the field flatness measured at the end of the construction after a rather complex tuning procedure [7] was good: ±3%.

The final value of the resonant frequency at 4.2 K, i.e. 352.22 MHz, is only 20 kHz away from the target value, compatible with the tuning range obtained by pushing/pulling both beam ports by ±0.5 mm (±150 kHz).

CAVITY PERFORMANCE

Multipacting is not an issue for the ladder cavity: residual RFE requires less than 2 h at 4.2K after a few hours treatment at room temperature.

The relevant Q-curves measured on the ladder resonator are shown in fig.2.

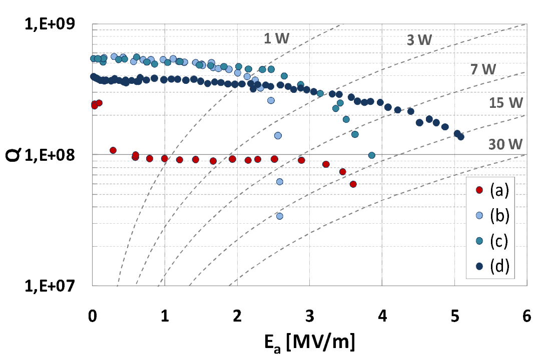

Figure 2: Q-curves of the ladder resonator (see text for explanation).

The first measured Q-curve (curve (a) in fig.2) exhibits a very low Q value. However, internal inspection of the resonator did not show any remarkable defect at that stage: we suspected, therefore, that the low Q was due to the low quality of the Nb/Cu sputtered lateral plates and/or to the bad contact between lateral plates and cavity body. However, after improving both the quality of sputtered lateral plates and the strength of the contact, the Q-curve was nearly the same. Only at this stage did an inspection of the internal surface reveal the rather evident defect, located in a very high field region, shown in fig.3. It had not turned up on previous inspections, as proven by photographic images.

We investigated the defect by means of SEM microscopy: it revealed a groove, around 1 mm wide - 6 mm long and 1 mm deep, the bottom of which was nearly pure Ti (fig.4 and fig.5). This hot spot was a possible reason for the low Q-values of curve (a).

Figure 3: Photo of the Ti defect in the resonator (detail: the portion of Nb wall removed during the repair).

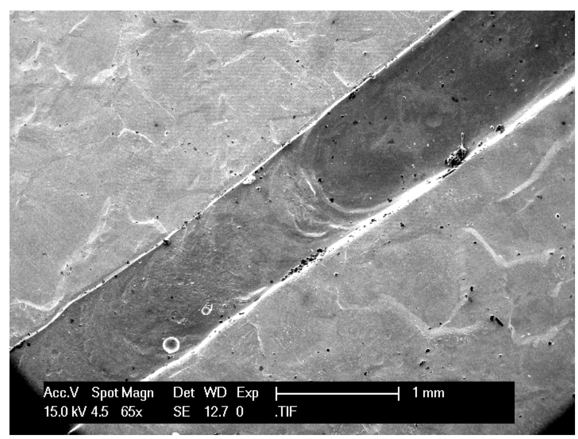

Figure 4: SEM picture of a portion of the defect: the darker part in the groove is titanium.

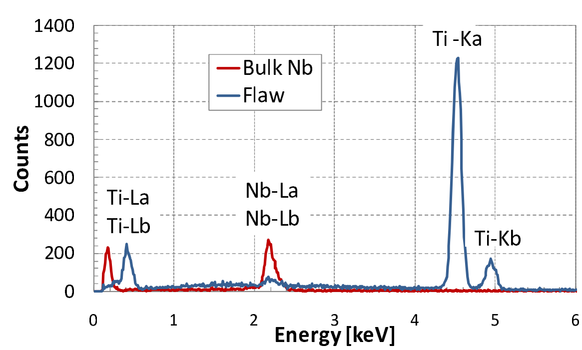

Figure 5: SEM analysis in the center of the groove and just aside it: while the defect is nearly full Ti, the material around the flaw looks unaffected by the welding failure (within SEM resolution limits).

Repair was then undertaken by the welding company. It consisted in opening the Ti box from the outside, removing the ribs behind the defect and taking away – by means of a very thin milling tool – the largest possible area of Nb wall around the flaw, without affecting the EB welds towards stem and end-wall.

Following local chemical etching, the defected area was replaced with high RRR Nb; Ti ribs (with a Nb insert to the resonator wall) were EB-welded to the ladder cavity and TIG-welded among themselves; finally the outer Ti cage was closed again by EB-welding.

Then another 40 μm buffer chemical polishing of the entire resonator was performed.

Figure 6: Completed repair of the EB weld flaw.

After the resonator was repaired (fig. 6), two measurement sessions were conducted, in May and July 2009. The results are shown in curves (b, c) and (d) in fig. 2, respectively.

Curve (b) shows the improvement of the low-field Q-value with respect to curve (a), due to the removal of the Ti flaw. The accelerating field of 3 MV/m was achieved after 2 h of FE conditioning (typically up to 30 W average power, and pulses between 1 and 10% duty cycle).

On curve (c) the improvement on E_a given by another 3 h of FE-conditioning is shown. Then, because of lack of liquid He, the test session was concluded.

In July 2009, the resonator was cooled down again and, after another ~8 h of FE conditioning, curve (d) was measured.

In curve (d), the Q-value is slightly lower than in (b) and (c). The Q_0 measurement is typically affected by the H-field, trapped during the conditioning procedure. Warming up the cavity beyond the transition temperature allows removing the trapped field and provides the good Q-curve. Because of the limited liquid He availability, however, this could not be done in July. Therefore curve (d) is still affected by the trapped field. We are quite confident, therefore, that $4{,}5\times10^8$ is the actual Q_0 value of the ladder resonator at the present stage.

Such a Q_0 value, taking into account the geometric factor (table 1) and the BCS resistance for a 352,2 MHz resonator, is consistent with a residual resistance R_{res}~41 nΩ. A further BCP treatment might reduce R_{res} and improve the Q-curve. Possible additional contributions to the lower-than-expected Q might have been: contamination of the resonator surface, occurred during the warm-up and cool down procedure between May and July, and Q-disease.

Concerning Q-disease, the following must be noted: the cryostat used for these tests was a general purpose one, with which the resonator could not be driven through the temperature region critical region for H migration (140 to 70K) in less than 24 hours: this has most probably induced Q-disease. Thermal treatment at 600K is recommendable before the next test.

In conclusion, the cavity repair improved the low-level Q value by a factor ~5, while the maximum accelerating field achieved was nearly 90% of the design field.

NEXT STEPS

Despite the main reason of the first very poor Q-curve of the ladder resonator was discovered and the resonator repaired, the cavity could not achieve the design specifications (E_a=5.8 MV/m), because of rather strong field emission, which could not be processed within the limits set by the availability of liquid He (250 l to cool down the resonator and 250 l for the FE processing).

We plan therefore:

- to grind mechanically all surfaces were the E-field is relevant (on stems and end-walls);
- to provide a further 20 μm BCP and improve the cleanliness of the assembly procedure after HPWR;
- to apply thermal treatment at 600K so as to cure possible Q-disease
- to increase the available quantity of liquid He on the next shifts.

Once a reasonable Q-curve shall have been achieved, the Lorenz detuning sensitivity of the ladder resonator must be experimentally evaluated.

Following continuing scientific interest and budget availability, slow and fast tuning concepts could be planned , and higher power couplers could be tested.

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REFERENCES

[1] V. Andreev et al., Physical Review Special Topics, Accelerator and Beams, vol.6, 040101 (2003).
[2] M. Kelly, Proc. of HB2006, Tsukuba, Japan, 337.
[3] COMSOL 3.5, distributed by CONSOL Inc., 1 New England Executive Park, Suite 350, Burlington, MA 01803 (USA).
[4] HFSS 11.1, distributed by ANSYS Inc., Southpointe, 275 Technology Drive, Canonsburg, PA 15317, USA
[5] ANSYS Structural, distributed by ANSYS Inc., Southpointe, 275 Technology Drive, Canonsburg, PA 15317, USA.
[6] D. Micheletti, Degree thesis, Dep. Of Mechanical Engineering, University of Padova (I).
[7] A. Palmieri et al., Proc. of EPAC2006, 451.