

SRF DEVELOPMENTS FOR ION ACCELERATION

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Abstract

This paper gives an overview of the recent Superconducting Radio Frequency developments on low and medium beta resonators, including Quarter-Wave Resonator, Half-Wave Resonator, Spoke and CH-type cavities, for ion accelerators.

We will describe the work done for the upgrade of some existing facilities, as well as the on-going developments on cavities for new projects.

INTRODUCTION

SRF cavities (mainly low beta QWRs) are operating for many years in heavy-ions boosters [1-2]. Their successful operation leads to their integration into most of the new developments for ion acceleration: on existing facilities, such as ISAC-II, ATLAS or PIAVE-ALPI, and new facilities under construction like SARAF and SPIRAL2. Moreover, each driver of the future large-scale accelerators (HINS, FRIB in USA and EURISOL, EUROTRANS in Europe, for example) includes SRF low and medium beta cavities.

QWRs (and HWRS in a lesser extent) are mainly used for existing facilities upgrades and new facilities because of the need of a wide velocity acceptance in order to boost various ion species. Typical range of betas is from 0.001 to 0.15 and voltage gain per cavity around 1 MV.

Spoke resonators and CH-type cavities are studied in the frame of larger SC linacs for which, their multi-gap structure is a real advantage.

UPGRADE OF EXISTING ION ACCELERATORS – UNDER CONSTRUCTION

TRIUMF/ISAC-II

The ISAC-II superconducting linac is currently delivering beams since 2007. It boosts ion energy by 20 MV, thanks to 20 bulk Niobium QWRs housed in 5 cryomodules. The extension of that linac (called “Phase 2”) has started since one year and should end up, by the end of 2009, to the addition of twenty new 141 MHz, “high beta 0.11”, QWRs [3]. One can note that, besides the beta and frequency values, the inner conductor geometry has been modified (i.e. new “donut” shape) [SRF2007].

A local company, PAVAC, was chosen for the prototyping development and the series production. They built, at first, two copper models to test fabrication, assembly sequence and frequency tuning procedure then, two bulk Niobium prototypes (see photograph in Fig. 1). Final frequency of both cavities was well within 10 kHz

of goal, demonstrating a good reproducibility of the fabrication.

Buffered Chemical Polishing (BCP) and High Pressure Water Rinsing (HPWR) were done in-house, at Triumf. Both resonators exceeded the ISAC-II specifications (Fig. 1) [4].

The 6 first cavities should be delivered at the end of October 2008.

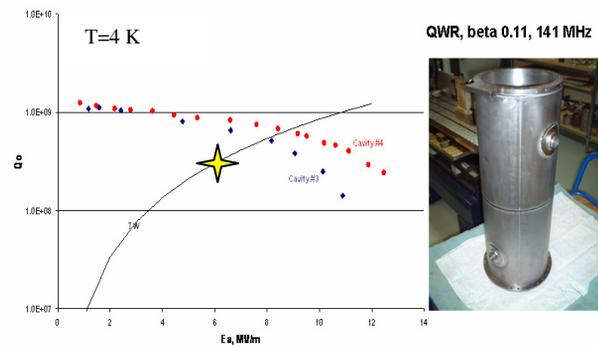


Figure 1: Vertical cold test results of the two first QWR prototypes. Yellow star: ISAC-II, phase 2 specifications.

ANL/ATLAS

This upgrade calls for a total voltage boost between 12 and 14 MV (depending on ion species) thanks to the replacement of an “old” cryomodule by a new one. It will house seven 109 MHz, beta 0.14, QWRs made of bulk Niobium [5]. Cavities have been already qualified in vertical cold tests, giving a 25% higher average accelerating gradient than the design goal (Fig. 2). Details about the cavities’ fabrication and preparation can be found in [6].

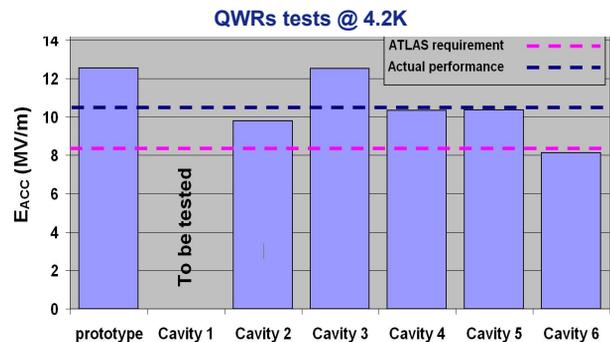


Figure 2: Vertical cold test results of the QWRs composing the new cryomodule for the ATLAS upgrade.

The cryomodule is currently under assembly in the ANL clean room. Its completion is foreseen by the end of 2008 and then, it shall be moved into the ATLAS tunnel.

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INFN-Legnano/PIAVE-ALPI

The upgrade of the low-beta section of the superconducting linac PIAVE-ALPI will aim at a total voltage gain of about 10 MV, thanks to the addition of a new cryomodule (housing 4 new 80 MHz, beta 0.047, QWRs) and, among other things, replacements of RF amplifiers and couplers (see details in [7]).

The first resonator has been tested with its new tuning system (modified ISAC-II type which gives wider tuning range) and meets the specifications (Fig. 3) [8]. The second one is still under testing as they met some problems with the coupling antenna (preliminary results give a good Q₀ but a quench at 5.5 MV/m [9]). Remaining two cavities are waiting for testing.

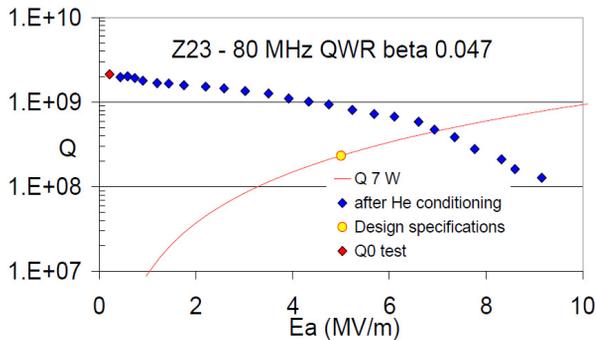


Figure 3: Vertical cold test results (T=4K) of the first QWR for the PIAVE-ALPI upgrade.

New cryostat should be operating in a couple of months while beginning for one year, the upgrade of the “old” cryomodules.

IUAC New Delhi

Ion beams were successfully accelerates, by end of 2007, through the first superconducting linac module composed of 8 bulk Niobium QWRs (beta 0.08, 97 MHz) [10].

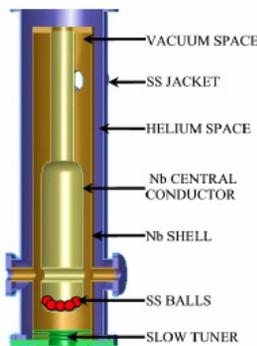


Figure 4: Stainless Steel balls (in red) inserted inside the inner conductor to damp mechanical vibrations.

However, some problems occurred while operating the cavities: lower accelerating gradient than expected, perturbations because of microphonics or leaks located near the tuning system. Important efforts were done to get

rid of these problems. For example, Stainless Steel balls were inserted inside the inner conductor for reducing the perturbations due to microphonics (Fig. 4) and the fixture of the tuning system was changed to avoid leaks [11].

Now, these modifications are implemented for the 16 QWRs of the 2 next modules which are currently under fabrication at IUAC. They have developed all the necessary facilities to produce (EB welding machine) and prepare SC cavities (EP, HPWR and furnace for heat treatment).

UPGRADE OF EXISTING ION ACCELERATORS – CAVITY DESIGN & PROTOTYPING

MSU-NSCL/Re-Accelerator

A SC linac with 3 new cryomodules is proposed for the acceleration of ion beams up to a maximum energy of 3 MeV/u [12]. The cryomodules will house bulk niobium 80.5 MHz QWRs with beta of 0.041 and 0.085.

Two prototypes have been fabricated (one of each beta) in a close collaboration with INFN-Legnano, and successfully tested at MSU in vertical cryostat [13-14]. Fig. 5 shows very good results of the beta 0.041 resonator with probably the highest peak surface electric field ever achieved in a QWR. The cavity preparation was done at MSU (BCP and HPWR).

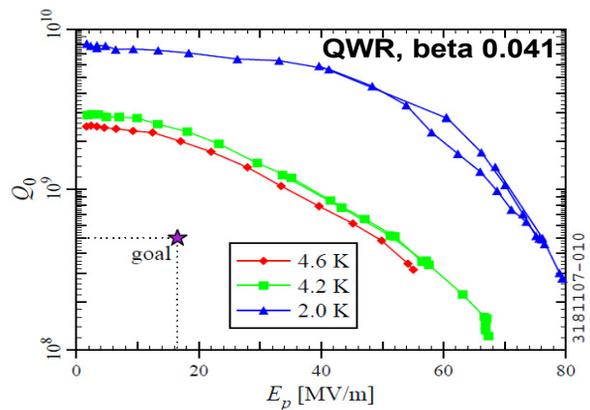


Figure 5: Vertical cold test results of the beta 0.041 QWR for the Re-Accelerator.

In parallel, a prototype cryomodule housing a beta 0.085 QWR cavity and a 322 MHz, beta 0.285, HWR, together with two focusing elements (one SC Quadrupole and one SC solenoid) has been assembled [15].

CERN/HIE-ISOLDE

The energy upgrade of the REX-ISOLDE linac is an important part of the HIE-ISOLDE project at CERN [16]. This upgrade aims at a final energy of 10 MeV/u (= total boost of 37 MV) and will be realized in 2 stages:

- Stage 1: addition of 2 modules, housing 5 QWRs, beta 0.12, 101 MHz each, to get a final energy of 5.5 MeV/u.

- Stage 2: Reaching 10 MeV/u by adding 10 QWRs, beta 0.075, 101 MHz and 5 more QWRs, beta 0.12, 101 MHz.

“Classical well proven” technologies have been chosen for the cryomodule and QWR designs: common vacuum and Nb/Cu sputtered technology (Fig. 6) [17].

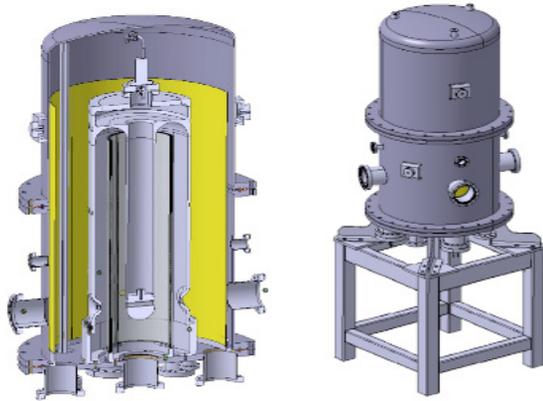


Figure 6: Sputtering chamber.

One copper model of the beta 0.075 resonator is currently under construction at CERN and should be completed by the end of October 2008.

NEW FACILITIES – UNDER CONSTRUCTION

SOREQ/SARAF

The SARAF “Phase 1” SC linac is getting close to the end after one year of commissioning [18]. Last element to be commissioned is the Prototype Superconducting Module (PSM) which hosts six 176 MHz, beta 0.09, bulk Niobium HWRs. Final expected energies are 4 MeV for protons and 5.2 MeV for deuterons beams.

While vertical tests performed at ACCEL showed that all cavities complied with the specifications ($Q_0 > 5 \cdot 10^8$ for $E_{pk} = 25$ MV/m), Q values of some cavities were much lower during the “off-line” PSM operation because of strong field emission. Nevertheless, as it is illustrated in Fig. 7, the average accelerating gradient is good and exceeds by 20% the design value (i.e. $\langle E_a \rangle = 5$ MV/m).

location	Cavity name	vertical Test			10/2007 PSM Test			03/2008 PSM Test	
		max field [MV/m]	losses at 25 MV/m [W]	Q at 25 MV/m	max field [MV/m]	losses at 25 MV/m [W]	Q at 25 MV/m	losses at 25 MV/m [W]	Q at 25 MV/m
HWR1	LB-2	40	7.3	6.0E+08	30	6.3	7.0E+08	6	8.00E+08
HWR2	LB-3	43	7.3	6.0E+08	28	31.4	1.4E+08	9	5.00E+08
HWR3	LB-5	33	6.3	7.0E+08	32	22.0	2.0E+08	24	2.00E+08
HWR4	LB-7	46	6.3	7.0E+08	29	22.0	2.0E+08	39	2.00E+08
HWR5	LB-4	36	5.5	8.0E+08	31	11.0	4.0E+08	13	4.00E+08
HWR6	LB-6	38	7.3	6.0E+08	29	14.7	3.0E+08	42	1.00E+08
	sum	40.0			107.3			133	

Figure 7: Cold test results of the 6 beta 0.09, HWRs in the PSM [19].

Some cavities also suffered from ponderomotive oscillations (coupling between Lorentz Forces and

Helium pressure fluctuations) while E_{pk} was getting close to 16 MV/m. The phenomenon is now identified and piezo-tuners will be used to compensate this frequency detuning. Microphonics measurements were also performed and did not show up additional problems [18].

The PSM is now “on-line”, ready to accelerate its first beam.

GANIL/SPIRAL2

Major components of the SPIRAL2 SC linac are presently under construction [20] and among these; the two series of “low-beta” and “high-beta” resonators (88 MHz, QWRs made of bulk Niobium of two different betas 0.07 and 0.12).

Prototypes and qualifying cavities have been already tested in vertical cryostat and met the design specifications (results of beta 0.12 QWRs in Fig. 8) [21], excepted for the qualifying beta 0.07 cavity which low Q_0 value is not yet understood [22].

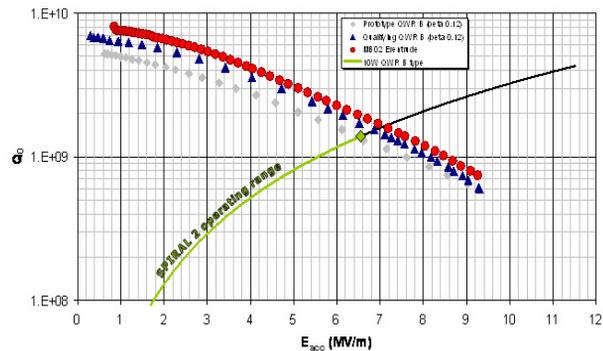


Figure 8: Vertical cold tests results of the beta 0.12 QWRs. Curves: Purple diamonds - prototype, blue triangles - qualifying cavity and red circles - 1st series cavity.

The qualifying cavity has been set in its cryomodule and should be tested with its tuning system and RF power coupler in October 2008. The series fabrication of the two first beta 0.07 has started and delivery is expected in March 2009.

Series fabrication by ACCEL of the 16 “high beta 0.12” resonators is currently progress. The 3 first cavities have been delivered and one already tested with success (vertical cold results are presented in Fig. 8). This cavity and the qualifying one will be tested in cryomodule with their power coupler and tuning system. Last results of the tuning system by SC plunger used for beta 0.12 cavities are detailed in [23].

NEW FACILITIES – CAVITY DESIGN & PROTOTYPING

Fermilab/HINS

A SC linac with 325 MHz Single-Spoke (SSR) and Triple-Spoke resonators (TSR) is proposed to accelerate H⁺ from 10 MeV to 400 MeV [24].

Two SSR with beta 0.22 have been fabricated (one by Zanon SpA, the other by Roark) and two more are presently under fabrication by the Inter University Accelerator Center in new-Delhi. The cavity produced by Zanon has been prepared in the ANL facility and tested at Fermilab. As shown Figure 9, a maximum gradient of 18 MV/m was reached (i.e. the highest E_a in a spoke cavity nowadays, see following Table 1). See more details in [25].

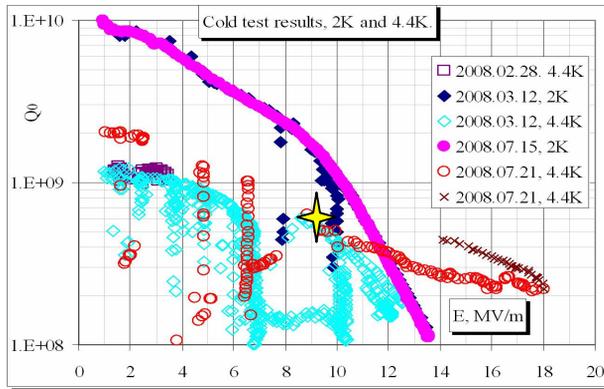


Figure 9: Vertical cold test results of the beta 0.22 Single-Spoke prototype.

INFN-Legnaro & IPN Orsay/EURISOL

176 MHz, beta 0.15, HWRs and 352 MHz, beta 0.30, triple-spoke cavities are proposed for, respectively, the low and medium beta sections of the EURISOL driver [26]. HWR specified operating gradient is 5.5 MV/m and 8 MV/m for the spoke cavity.

The HWR design made by INFN-Legnaro and the Spoke cavity design made by IPN Orsay are finished (see Fig. 10) and the prototypes fabrication should begin in 2009. Both cavities are made of bulk niobium.

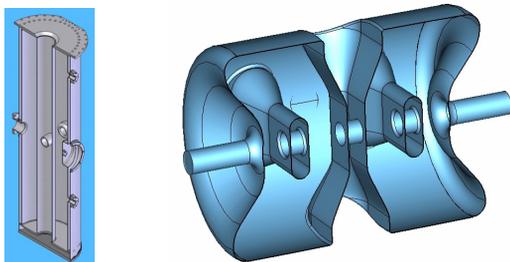


Figure 10: 176 MHz, beta 0.15, HWR (left) and 352 MHz, beta 0.30, Triple-Spoke cavity (right) for the EURISOL driver.

The RF tuning of the HWR will be done by cup deformation whereas a new RF tuning system by SC plunger will be tested with the triple-spoke cavity

IAP-Frankfurt & IPN Orsay/EUROTRANS

Two different types of SC cavities (both operating at 352 MHz) are proposed for the proton driver of EUROTRANS between 5 MeV and 50 MeV.

- a beta 0.10, multi-gap, CH cavity between 5 and 17 MeV designed by IAP-Frankfurt..
- a beta 0.35, Single-Spoke resonator between 17 MeV up to 50 MeV designed by IPN Orsay.

A prototype of 19-gap, CH cavity has been successfully tested in vertical cryostat: E_a max of 7 MV/m, limited by field emission, for a design goal of 4 MV/m [27]. The cavity is now equipped with a tuning system and wait for a cold test in a refurbished horizontal cryostat. A new prototype, with 7 gaps, has been recently designed and should be fabricated in 2009.

Tests in horizontal cryostat are going on with the Single-Spoke beta 0.15. Piezo-tuners have been set on the tuning system and first test gave good results: expected sensitivity (100 Hz/ μ m) and good reproducibility of the full stroke (Fig. 11). A new version of the digital Low Level RF system is under fabrication. It will be used, together with the piezo-tuners tuning system, to get a frequency regulation.

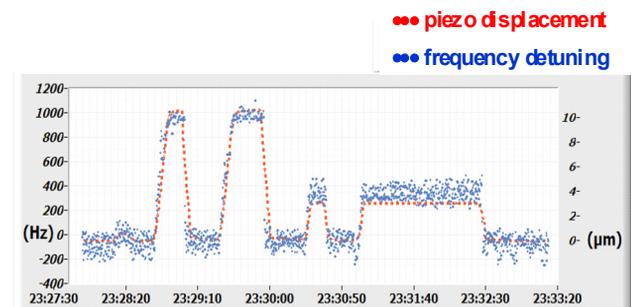


Figure 11: Frequency variation (blue dots) while moving the piezo-tuner (red dots).

“ALL-AROUND-THE-WORLD” SPOKE COLD TESTS RESULTS

The table 1 summarizes the vertical test results of existing Spoke-type cavities at 4.2 K. One shall note that the accelerating gradient E_a is normalized with the following definition:

$$E_a = n\beta\lambda/2 \tag{1}$$

with n the number of gaps.

Taking apart cavity performances below 5 MV/m, the mean values of E_a , E_{pk} and B_{pk} are, respectively, 8.3 MV/m, 40 MV/m and 100 mT.

ACKNOWLEDGEMENTS

The author would like to address many thanks to: B. Laxdal, L. Ristori, M.P. Kelly, W. Hartung, M. Doleans, R. Toelle, E. Zaplatin, A. Facco, I. Mardor, D. Berkovits, J. Rodnizki, H. Podlech, M. Pasini, H. Saugnac and P. Bosland.

Table 1: RF performances of existing Spoke-type cavities at 4.2 K.

Lab	Type	Frequency [MHz]	Optimal beta (name)	Ea [MV/m]	Epk [MV/m]	Bpk [mT]	Voltage [MV]
IPN Orsay	Single	352	0.20	4.77	32	69	0.82
	Single	352	0.36	8.14	38	104	2.49
ANL	Single	855	0.28	4.40	24	56	0.26
	Single	345	0.29	8.75	40	106	2.21
	Single	345	0.40	7.02	44	117	2.44
	Double	345	0.40	8.60	40	79	4.49
	Triple	345	0.50	7.65	28	88	6.65
	Triple	345	0.62	7.94	31	95	8.70
FZ-Juelich	Triple	760	0.20	8.63	42.8	87.2	1.36
LANL	Single	350	0.21 (EZ01)	7.50	38	100	1.35
	Single	350	0.21 (EZ02)	7.22	37	96	1.30
Fermilab	Single	325	0.21 (SSR1-01)	12.00	69.5	112.5	2.43

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