SUPERCONDUCTING RF TECHNOLOGY FOR PROTON AND ION ACCELERATORS

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Abstract

The worldwide status of superconducting RF cavities and cryomodules for low velocity ion and proton particles is reviewed, with emphasis on the construction and tests of prototypes. A number of different multi-cell structures at a range of operating frequencies have been successfully realized. This review will cover the progress of several facilities under construction or being proposed.

COAXIAL CAVITIES EVOLUTION

Historically the low velocity ion acceleration is the realm of superconducting quarter wave resonators (QWR) as used on ATLAS at ANL [1] or ALPI at INFN Legnaro[2]. The evolution of the technology from the simple cylindrical cavity shapes to more complex RF designs has been driven by the increase in beam currents, beam apertures and a step up in the specification of accelerating voltages. In order to cope with the higher peak fields, the cavity preparation procedures used for elliptical cavities are widely adopted for the QWRs. A separate vacuum for the cavity is generally adopted to prevent contamination when cavities are installed in cryomodules.

The evolution of the use of QWRs from low beam intensity to higher currents is reflected in a shift in the main efforts to improve the technology. In a low intensity application the frequency sensitivity of the cavity to external perturbation is predominant since the loaded bandwidth of the resonator is narrow. Most effort is then concentrated on how to minimize these microphonics either by mechanically damping the mechanical resonances, actively tuning the cavity using fast piezo electric tuners, or by electronically overcoming this at the expense of RF power injected in the cavity. The VCX system initially developed at ANL is an example of the later [3]. Increasing the cavity bandwidth by over-coupling at the expense of RF power is a frequently adopted solution. At higher beams intensities in the mA range for recent projects like SPIRAL2 [4] or SARAF [5], the resonator bandwidth is of the order of 100 Hz. In this case it is expected that cavities can be operated without mechanical dampers of fast tuners. In the case of the IFMIF superconducting linac [6], the beam intensity is 125 mA. The microphonics are not a issue but coupling the RF power to the cavity become the driver in the cavity design.

LOW VELOCITY IONS LINACS

ANL Atlas Upgrades

The Atlas accelerator is currently going through upgrades to expand its capabilities [7]. The energy upgrade was carried out by adding one cryomodule containing 7 β=0.15 QWRs [8]. The intensity upgrade sees the replacement of three split-ring resonator modules by a single cryomodule containing 7 72 MHz QRWs with a β of 0.077. The goal is to obtain a voltage of 17.5 MV in the reduced space of 5.2 m. In order to achieve this high real estate gradient, the RF design includes all the most advanced features, including a conical shape of the resonator outer conductor to minimize further Bpk/Eacc ratio, separate vacuum, fully welded structure [9]. Electropolishing is carried out on low beta resonators since the 80's at ANL. First, separate parts were deeply etched separately, then welded together. The process evolved in 2009 with open pre-assembled QWRs being polished. The bottom plate was etched separately then welded to main cavity body. A new electropolishing device has been developed to achieve the operation on fully welded cavities using 4 access ports in the cavity [10]. Water is circulated in the helium vessel of the cavity in order to control the temperature of the EP mixture. A β= 0.077 cavity polished with this new system for 12 hours (150 µm removal) reached Eacc=13 MV/m and a low residual resistance of 1nΩ was measured [11]. Both a variable 4 kW power coupler and a fast piezo tuner are being developed for the 72 MHz QWRs [12].

TRIUMF ISAC-II

The SRF linac ISAC-II[13] consists in 40 QWRs split in three families as shown in table 1.

Table1: ISAC QWR Families

β	Frequency [MHz]	Cryomodules
0.057	106	2 of 4 cavities
0.072	106	3 of 4 cavities
0.11	141.44	2 of 6 + 1 of 8 cavities

Their design is an evolution from ALPI-Piave proven design, keeping the same RF design principle with resonator shape as close as possible from a simple coaxial line geometry, a common vacuum between cavity and cryomodule, and the built-in stem mechanical damper [14]. A new cavity tuning plate and tuning system has been developed for the ISAC QWRs, using a flexible bottom plate with extended stroke, thanks to an optimized slotted geometry [15]. The first 20 cavity are online since 2006, and the installation of the high beta modules was

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completed in 2011. The full 40MV linac has been commissioned with beam since then [16]. The reported problems during operation were linked to disruption in He delivery which would lead to flux trapping in the cavities, forcing the modules to be warmed up, then conditioned for low field multipactor activity[17] before resuming beam operation. The performance reduction of some QWRs of the last cryomodule is also investigated [18].

MSU RεA and FRIB

The Facility for Rare Isotope Beams (FRIB) will use a high power SRF linac delivering stable ion from hydrogen to uranium to a target for RIB production by fragmentation [19]. A total of 112 QWRs at 80.5 MHz and 229 half wave resonators (HWR) at 322 MHz is needed to provide a beam power up to 400 kW. The linac will be operated in CW mode at 2 K to benefit from the 4 fold reduction in RF losses and increased He pressure stability compared to the 4.2 K alternative.

The development of low-β SRF cavities at MSU has already gone through several generations of QWRs. The RεA re-accelerator running at 4.2 K hosts the first stages of cryomodule development with the latest versions of these cavities as part of its first stage RεA3 [20]. The first module in operation is the rebuncher module comprising 80.5 MHz β=0.041. The design is an evolution from Legnaro type of cavities [21]. Most important changes are the separate vacuum, toroidal top cap formed from Nb sheets, and the bottom plate equipped with a slotted tuning plate based on the design introduced for ISAC-II. The next QWR stage consists in β=0.085 cavities. One module containing these cavities is installed in RεA. The first versions of these QWRs experienced thermal instability in the bottom plate area. This is often the case for cavities with dismountable bottom plate and separate vacuum, because this area concentrates challenges: the plate is not directly cooled by He, and has to be electrically connected to the main cavity body using a RF gasket. The last generation of prototypes benefit from a re-design of the bottom part of the QWRs. The RF coupler ports were moved to the cavity side to reduce heat load, and the cavity was lengthened which further reduces RF dissipation. This modified design displays excellent results obtaining E_{pk}=58 MV/m and B_{pk}=130 mT in vertical test at 2 K [22].

The FRIB β=0.29 HWRs see evolutions from their first version of 2002[23], mainly to decrease Bpk/Eacc and improve its mechanical stability. Prototypes will be available in 2012. Two prototypes of the β=0.53 HWRs have reached the FRIB specification of V_{acc}=3.7 MV and $Q_0=10^{10}$ and are being assembled in a test cryomodule [24].

HIGH INTENSITY ION LINACS

GANIL Spiral-2

Spiral 2 is a RIB facility to be installed in Ganil Caen. In its first phase it will produce radioactive ions with the ISOL method from a 5 mA, 20 MeV deuteron beam. The superconducting part of the linac consists in two families of 88 MHz QWRs running at 4.2 K [25]. Conventional quadrupoles are used for transverse focusing between each low β=0.07 cavities and every other cavity in the case of the β=0.12 section. This departs from most SRF ion linac designs which use SC solenoids and top-loaded cryomodules. The cryomodules design is strongly influenced by the short longitudinal space available between quadrupoles. The cavity specifications are a gradient of 6.5 MV with a maximum dissipation of 10 W. This lead to RF optimization in view of reduced peak fields. The choice of separate vacuum technology was also made.

The low β cavities (CEA-Saclay) have a removable bottom end in order to ease the preparation phases. This end plate where the input coupler port is located was initially made out of Nb and cooled by conduction. It was changed for a copper version after experiencing difficulties to keep its temperature below 9.2 K. The cold tuning system is installed in the beam tube region and acts through the stainless steel He vessel by squeezing the cavity in the direction orthogonal to the beam. All stainless steel mechanical parts including the gear box are operating at the cavity temperature. One side of the cavity is allowed to move freely during cooldown to prevent plastic deformation of the QWR due to a large difference in cooling and shrinkage rates of the cavity and the tuner. Once the cavity is at operating temperature, the tuner can be engaged to squeeze the cavity and increase the resonant frequency [26].To date, all the 12 cavities have been manufactured and 6 have been tested in vertical cryostat reaching E_{acc} values up to 12 MV/m and two cryomodules have been tested.

The mechanical design of the high β cavities (IPNO) is different from the low βs. The cavity is fully welded. Two ports at the top and two at the bottom give an access for all preparation stages including high pressure rinsing. The He vessel is made from Ti and like the low beta does not include the bottom part of the resonator where the power coupler is connected. The tuning system is the first of the kind to be used in a SRF cavity: a superconducting plunger is used in one of the cavity access port in the upper magnetic region. Another fixed plunger allows to adjust the central RF frequency during assembly [27].

The 16 β=0.12 cavities have been manufactured and tested in vertical cryostat showing very reproducible results and low losses (4W) at nominal E_{acc} [28].

SOREQ SARAF

The high intensity accelerator SARAF is a light ion 2 mA accelerator with an output energy up to 40 MeV [29]. In its first stage, it includes a 176 MHz β=0.09 HWR cryomodule housing 6 cavities and 3solenoids. This is the first HWR module to accelerate a high intensity beam. Early problems of strong field emission have been cured using helium processing. After initial operation in pulsed mode at low duty cycle, a CW proton beam of

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1mA was accelerated from 1.5 to 3.07 MeV in the HWR module [30]. As reported in [31], the the performance of the cavities are limited by mechanical stability problems including a high pressure sensitivity of -60 Hz/mbar, high Lorentz detuning coefficient leading to ponderomotive oscillations. Improvements in the control of the piezo tuner are underway. This, combined with an upgrade of the RF power available for each resonator from 2 kW to 4 kW should improve the situation. The next phase of the SRF linac construction consist in adding 5 higher energy modules. The RF design of the new β=0.13 HWRs has started.

IFMIF

The International Fusion Materials Irradiation Facility (IFMIF) uses two 125 mA 40 MeV CW SRF deuteron linacs to produce neutrons needed for the investigation of fusion materials. Two families of HWRs at β=0.094 and 0.16 accelerate the beam from 5 MeV to 40 MeV. The first cryomodule hosting 8 low-β 176 MHz cavities and 8 solenoids is under study at CEA-Saclay. The power couplers for this first module are designed with the 200 kW power specification needed for the high-β HWRs. Their design is based on a single disk window [32]. Due to the size of the couplers, they are installed in vertical position below cavities. Since the coupling port is in the mid-plane of the resonators, the later are installed in horizontal position in the module [33]. The tuning system is based on a capacitive SC plunger located opposite to the coupler port [34]. Two prototypes have been manufactured and are being tested in vertical cryostat. The first tests without the plunger tuner were plagued by multipactor in the plunger port. A subsequent test with the tuner in place was limited by an early quench whose origin is under investigation.

HIGH INTENSITY PROTON LINACS

Introduction

The architecture of most H+/H- linac planed or in construction using SRF technology consists in a room temperature injector providing beam for a series of SRF cavities grouped into β families. One of the most important design choices for such machine is the energy at which this ”warm-to-cold” transition is operated. Spoke resonators which have been developed in a growing number of laboratories have yet to be actually tested with a beam, but the increase of their performance in the recent years make them a sensible alternative to room temperature structures [35]. The medium-β elliptical multicell cavities have been tested in test cryomodules down to β=0.47 both in CW [36] and in pulsed mode [37]. Going to lower β with elliptical multicell cavities would be possible at the expense of performance in terms of achievable gradient and complicated mechanical stiffening needed to overcome the lack of mechanical stability of flatter cavities.

SNS

The Spallation Neutron Source is the first high power H^- linac to make use of the SRF technology [38]. Since the start of beam commissioning in 2006, it has proven elliptical multicell cavities cryomodules with β<1 could be operated with high reliability once the initial problems linked to parasitic phenomena in the cavities have been understood. The acceleration from 190 MeV to 1 GeV is provided by β=0.61 and 0.81 805 MHz cavities at a nominal temperature of 2.1 K. Many important facts have been learned from the SNS operation of the linac[39]: the limitation of cryomodule performance due to field emission, the possibility to accelerate the beam with cavities turned off, thanks to the flexibility of independently phased cavities. The reliability of components has been challenged: problems with multipactor and detuning of HOM couplers lead to the decision to remove them gradually, but power couplers considered as critical devices operated without flaws[40]. The proposed power upgrade plan is to use the empty space between the end of the SC linac and the HEBT to install new modules in order to reach the energy of 1.3 GeV, and simultaneously increase the beam current from 26 to 42 mA [41].

CERN SPL

CERN is studying a 5GeV pulsed proton linac using 5-cell β=0.65 and β=1 elliptical cavities at 704 MHz operating at a gradient of 19 and 25 MV/m respectively [42]. The RF and mechanical design aiming at minimising the Lorentz detuning is described in [43,44] and makes use of a Ti helium vessel with a common design for the medium and high β cavities. CERN is also studying a stainless steel He tank version of the β=1 cavity [45] aiming for the integration in a 4-cavity prototype cryomodule, which will be used to test the concept of using the power couplers as a cavity support [46]. The cryomodules are of the segmented type. Other developments are carried out on power couplers. A pair of couplers of the KEK-SNS type was designed and tested up to 1 MW on a room temperature test stand and in a cryostat at Saclay [47]. New coupler prototypes have been manufactured at CERN with a design derived from LHC and SPS ceramic windows [48] and will be tested in the coming months. Piezo tuner and field stabilisation developments and tests are also going on [37].

ESS

The European spallation source will be constructed in Lund, Sweden. The design of the 2.5 GeV 50 mA pulsed proton linac make full use of the SRF technology, including a spoke resonator section starting at a beam energy of 50 MeV [49]. The 2011 layout of the 2 K superconducting linac is shown on table 2:

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Table 2: ESS SRF Linac Layout

type	β_g	Frequency [MHz]	Cryomodules
Double spoke	0.57	352	14 of 2 cavities
5-cell elliptical	0.70	704.42	16 of 4 cavities
5-cell elliptical	0.90	704.42	15 of 8 cavities

The respective accelerating gradients of the three cavity types are 8, 15 and 18 MV/m. The nominal power rating for the fundamental couplers is 900 kW, with a duty cycle close to 5%. A 30% operational margin has been defined for these power couplers, leading to a maximum admissible input power of 1.2 MW. A number of European laboratories have started working in 2011 in view of producing a technical design report at the end of 2012. Prototypes of the spoke cavities and the high β elliptical will be tested in the same time frame. The design of the later [50] is making use of the latest developments on cavities, coupler and tuners carried out for the SPL.

FNAL Project-X

The high energy project of FNAL also relies on spoke resonators for the lower energy part of the SC linac to accelerate the beam from 2.5 to 160 MeV. The CW linac accelerates 1 mA of H^- to 3 GeV. Thanks to a combination of choppers and pulsed dipole, the 3 GeV beam can be distributed to several experiments or a pulsed 8 GeV 1.3 GHz linac used as the injector for a high energy ring. The cavities types are listed in table 3.

Table 3: Project-X SC Cavities

type	β_g	Frequency [MHz]	Cryomodules
Single spoke	0.11	325	1 of 18 cavities
Single spoke	0.22	325	2 of 10 cavities
Single spoke	0.4	325	4 of 10 cavities
5-cell elliptical	0.61	650	6 of 6 cavities
5-cell elliptical	0.90	650	20 of 8 cavities
9-cell elliptical	1	1300	28 of 8 cavities

A very active development has taken place which lead to breakthrough results on single spoke resonator achieved gradients. A majority of prototypes around the world have reached Eacc values of 8 MV/m (using the normalisation corresponding to L_{acc} per gap of βλ/2)[35]. At FNAL, E_{acc}=21 MV/m was obtained on a β=0.11 single spoke resonator [51,52]. The design of the spoke cryomodule is also progressing. The 650 MHz cavities are at the prototyping stage and recently results have been obtained on β=0.61 single cell etched by BCP. Gradients between 16 and 19 MV/m have been obtained in 2 K dewar tests [53]. The 650 MHz elliptical cavities cryomodule design is underway, and relies on a cryogenic an vacuum segmentation determined by a maximum 2K load of 250 W per unit, still using the mechanical design of ILC/XFEL modules [54].

ADS

Linacs for accelerator driven system have the highest requirements in terms of reliability, typically about 10 trips per 3 month period. Several R&D programs have been launched to assess the feasibility of SC linac with these ambitious goals. The 600 MeV, 4 mA CW proton linac MYRRHA is the demonstrator in Europe [55]. It relies on a dual injector arrangement for fault tolerance. SRF cavities are used starting at 5 MeV with SC CH cavities. The main linac is based on the combination of 352 MHz β=0.35 spokes resonators and two families of 5-cell 704 MHz elliptical cavities at β=0.47 and 0.65. Prototypes of spokes and elliptical resonators have been build and tested in previous programs [56-58].

The Chinese CIADS 10 mA 1.5 GeV project [59] will use 350 MHz spoke resonators at β=0.12, 0.21 and 0.4 followed by two families of 650 MHz elliptical cavities. An alternative for one of the dual injectors part consists in using 162.5 MHz HWRs instead of the lower beta spokes. Single spoke resonators at β=0.2 and 450 MHz are also developed at PKU in another context [60].

ADS program in India (IADS) is also planning to use spoke and elliptical cavities at 325 and 650 MHz [61].

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