PROGRESS AND TRENDS IN SCRF CAVITIES FOR FUTURE ACCELERATORS

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Abstract

Tremendous progress have been achieved since ten years on superconducting radiofrequency (SCRF) accelerating cavities mainly driven by the requirements of nuclear and particle physics machines. SCRF cavities are used either for their extremely high Q (very low RF losses) in the case of Continuous Wave (CW) or long pulsed operation (nuclear physics) or for their high gradients breaking the high-energy frontier within reasonable lengths (colliders for particle physics). Since a few years, a new trend is showing up worldwide for the use of SCRF cavities in high power proton projects. Typically, these multi-MW machines are aiming at energies ranging from 200 to 2000 MeV with beam currents of tens of mA. Operating both in CW (or long pulsed) and at high fields, SCRF cavities offer for these particular application additional advantages like large bore openings and flexibility. Non relativistic particles may also require a new structure shape, intermediate between electron type and heavy ions type structures. This class of accelerator leads to many different applications, like neutron spallation source, nuclear waste transmutation, neutrino physics (through muon production) and radioactive ion beams.

1 INTRODUCTION

Since the first application at Stanford [**1**] in the 70's, many laboratories have been involved in the SCRF cavity business. From rings (Cornell, CERN, DESY, KEK) to recirculating linacs (CEBAF, Darmstadt), from heavy ion boosters (Argonne, Legnaro, Saclay) to B-factories (KEK), finally to linacs (TTF/TESLA) and FEL applications, basic fundamental physics was the driving force for R&D development. While still valid, this statement is now slightly shifting with the explosion since a few years of new projects based on medium energy protons (from 200MeV up to 2 GeV). A typical layout of this kind of machine is shown in figure 1.

Many applications are based on this accelerator type like the spallation neutron sources (SNS, ESS), radioactive ion beams (RIA, Eurisol), tritium production (APT), nuclear waste transmutation (ATW, Hybrid demonstrator) or muon and neutrino factories. Depending on the application, the requirements may vary. For pulsed neutron sources, cost is a major issue and performance (high field, low Q_0) is important together with availability. RF control and Lorentz force detuning will be the major concern. For an ATW type running in a CW mode, reliability will be the most important issue (operation in fault condition [**2**]) because of the stringent requirement of extremely low number of beam trips on the target. Focusing is then directed towards high CW power couplers. While for RIA, R&D work should emphasis very low beta cavities and microphonics reduction.

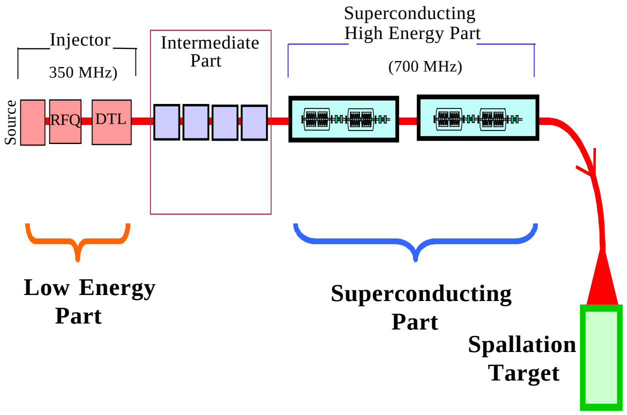

Figure 1: Layout of a typical proton linear accelerator

The use of SCRF cavities offers many advantages. Due to the very low losses, a significant part of the operating cost is saved, especially in CW accelerators [**3**]. Moreover, less RF power sources are needed, making additional savings upon the investment costs. Besides these definite economical advantages, technical issues equally favor the superconducting option. Large beam tube openings help to dramatically reduce the threat of activation induced by beam halo. As a matter of fact, zero beam loss is expected even for high current beam [**4**]. Secondly, the length of the high-energy part is about three times shorter. Finally, independent short superconducting structures will allow more flexibility. For example, the beam power can be easily changed while maintaining a fairly high efficiency. The only drawback is the use of cryogenics, but this technology is now quite well mastered on several large machines.

2 STATE OF THE ART

2.1 *Surface Resistance (Rs)*

Losses in the cavity are related to the overall surface resistance, which is the sum of the theoretical BCS resistance, plus an additional term called “residual resistance”. Fundamental studies have identified the many different contributions to this residual term [**5**]. This issue is now considered as almost fully understood and residual resistances as low as 0.2 nΩ ($Q_0 > 2.10^{11}$) were experimentally obtained on real large area cavities.

2.2 *Field Emission (FE)*

Electron emission may occur on metallic surfaces whenever a very high electric field is applied. This phenomenon is a severe limitation for SCRF cavities as the Q value drops exponentially with field. Fundamental studies have been successfully conducted in many labs leading to the protrusion on protrusion model [**6**,**7**,**8**,**9**]. Providing the use of high pressure rinsing (HPR) [**10**] and extremely careful cleanliness during the preparation, cavities mounted in a clean room can sustain peak electric fields exceeding 80 MV/m with no sign of FE. However, FE is still a technological challenge as there are some practical difficulties to completely eliminate particle contamination on real structures with large areas involved and a few big opening ports (power coupler, other couplers, beam pipe connections).

2.3 *High Gradient (Quench)*

One major limitation for increasing the field in SCRF cavities is the thermo-magnetic breakdown called “quench”. This is a surface magnetic peak field limit at which a transition from the superconducting state to the normal state occurs. The theoretical limit is given by the superheating field (190 mT for Nb at 2 K) [**11**]. Experimentally, quenches were observed at much lower fields (50 mT) primarily due to the presence of tiny defects in the material. The use of high RRR niobium [**12**,**13**] and the heat treatment purification process [**14**,**15**] strongly improved the performance (up to 130 mT). Then, recently, chemistry has been identified as playing an important role [**16**]. The electropolishing technique used by KEK [**17**] is now enabling to achieve fields exceeding 170 mT, closely approaching the theoretical limit. KEK results are now confirmed by the DESY/CERN/Saclay collaboration on electropolished single-cells [**18**]. In laboratory tests, the state-of-the-art of accelerating field is now in the 40 MV/m range (fig. 2). However, electropolishing is difficult to perform on large area cavities and R&D to improve performance of standard chemistry is underway [16].

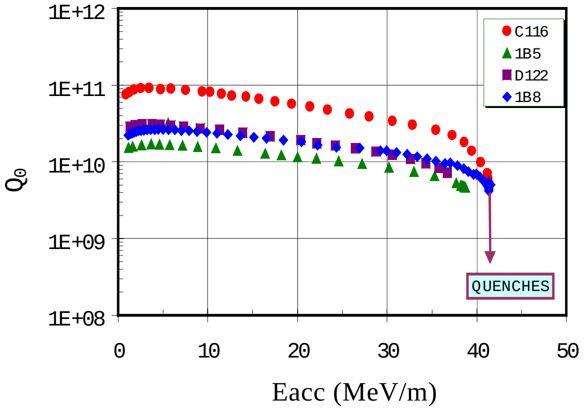

Figure 2: Results obtained on electropolished single-cell cavities in the DESY/CERN/Saclay collaboration.

2.4 *Q_0 drop at high field*

Anomalous (non-quadratic) losses appeared when a cavity was submitted to surface fields exceeding 100 mT, thus rapidly limiting the performance [**5**]. Recent experiments are now bringing some light on the mechanism of this Q degradation at high fields. Baking the cavity at moderate temperatures (80 to 150°C) reduces the effect [**19**]. This clearly suggests a diffusion process. Analysis of oxygen diffusion in the bulk, reducing the oxygen concentration on the surface, at the expense of a slight degradation in the first 10 to 50 nm is consistent with the experimental observations (fig. 3). The surface resistance at T = 4.2 K is reduced (in the BCS regime, the lower the RRR, the lower Rs).

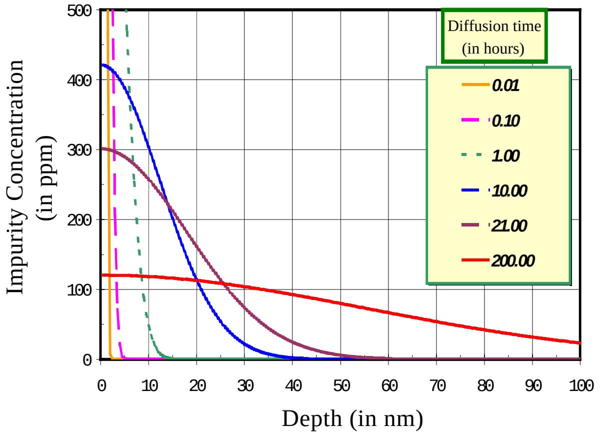

Figure 3: Diffusion profile of oxygen in niobium at a temperature of 120°C and different time duration

Moreover, sub-oxides and oxygen content measurements by surface analysis made at Saclay confirm this hypothesis and will be reported elsewhere. Assuming the oxygen diffusion process is correct, a maximum baking time is evaluated for each given temperature (fig. 4). Exceeding this duration would result in a quench deterioration due to the surface RRR decrease.

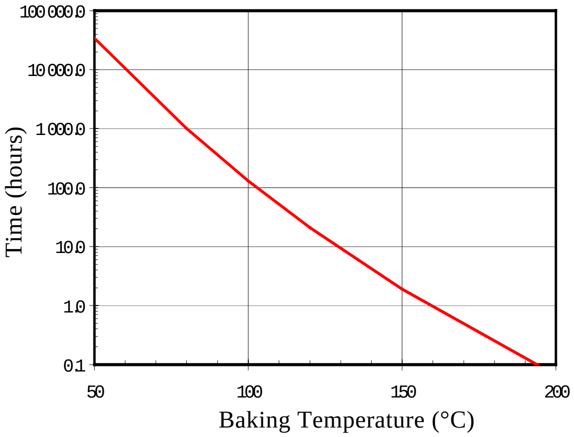

Figure 4: Baking time as a function of temperature.

2.5 *Multipactor*

Severe multipactor may limit the cavity accelerating field well below the quench field. Elliptical electron cavities have been designed to reduce the multipactor burden. But multipacting is geometry related and can be favored upon squeezing the shape to account for non-relativistic protons. Cavity tests results obtained at Saclay on 3 different geometry having the same frequency 700 MHz and the same β=0.65 seem to confirm that statement. A new electron trajectory code developed at Saclay support these experimental results [**20**].

2.6 *Main Coupler*

A coupler is needed to feed the RF into the cavity. It is an important issue, mainly when dealing with high power in CW mode. A few years ago, producing a 200 kW power coupler was considered as technically challenging. Nowadays, many labs have started R&D work on high power main couplers for SCRF cavities and progress is readily achieved. Cornell and KEK have demonstrated more than 300 kW transferred to the beam on real machines. CERN has designed a 400 kW power coupler for LHC and LANL power coupler exceeded 1 MW CW on a room temperature test stand. The remaining problems are the ceramic window (one should avoid cold windows and shield them from the beam), condensed gases and multipactor bands. In CW operation, the power coupler is considered as a critical part because its failure may condition the reliability of the whole accelerator.

2.7 *Higher order Modes (HOM)*

This is a very serious problem for circular machines where higher order modes can be excited and enhanced at each turn under resonance conditions [**21**]. In linear machines, the problem is quite different as the beam passes only once through each cavity. A HOM may build up in the very unlikely event that its frequency happens to be exactly a multiple of the bunch frequency. Adding HOM couplers will heavily damp the HOM modes, enlarging the bandwidth. Careful analysis shows that the probability of occurrence of HOM build-up is extremely low in a superconducting linac. The main coupler will provide enough damping of the HOMs that there is no need for specific couplers (figure 5). Moreover, HOM couplers will enhance HOM excitations, increasing the power losses. A detailed analysis of this study will be reported elsewhere.

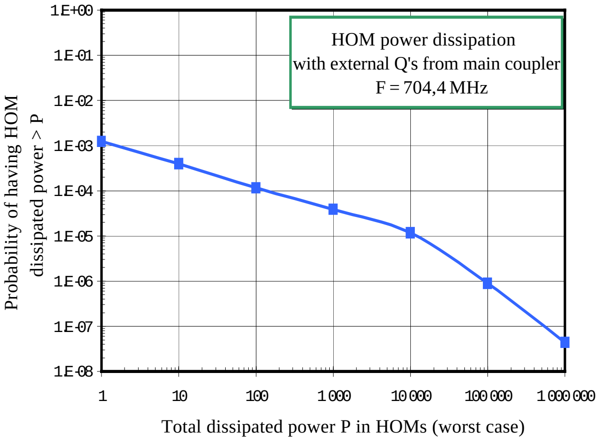

Figure 5: Expected probability of power loss in HOMs. It actually is so low that HOM couplers are unnecessary.

2.8 *Stiffening*

Mechanical stiffening of the cavity is required mainly for low frequency cavities whenever the induced yield stress exceeds the elastic limit of niobium (30 to 80 MPa, depending on the heat treatment). Maximum stress will be applied when the cavity is evacuated and cool down is launched. Due to the helium evaporation, the cavity may have to sustain an equivalent over-pressure exceeding 1.5 bar. Under normal operation, the cavity is cold (Young modulus is then much higher than at room temperature) and the helium pressure is less than 1 bar. Usually, mechanical stiffening is ensured using a thick enough niobium wall.

2.9 *Lorentz Force Detuning*

If the cavity is operated in a pulsed mode, additional mechanical stiffening is required. The electromagnetic field pressure exerted on the cavity wall will induce a resonance frequency change. The cavity sensitivity is determined by the Lorentz coefficient $k = \left(\Delta f / E_{acc}^2\right)$ in Hz/(MV/m)^2. Although quite small (Hz to kHz range), this shift, known as the Lorentz force detuning, can put the resonance out of reach of the phase lock loop system. This is a major issue for pulsed operation at very high gradients (TESLA) or for superconducting structures having high Lorentz coefficient like low beta cavities.

2.10 Microphonics

External mechanical vibrations will also translate into resonance frequency vibrations that cannot be compensated for using only the mechanical tuner. Experimentally, frequency variations of a few Hz are generated by microphonics, which is usually very small compared to the cavity bandwidth (300 Hz to 3 kHz). But when the beam loading is small (case of very low current beams like in heavy ions machines), microphonics can be the main source of additional RF power. Specific cryomodule and cavity design is then required to take in account the microphonics damping [**22**].

3 FUTURE TRENDS

3.1 Material

Niobium is still the best material for SCRF cavities, despite many attempts to replace it with other higher critical temperature materials. Thin films suffer from grain boundaries losses [**23**] and the RF critical field of niobium is one of the highest known [**24**]. Moreover, Nb is a metal having a fairly good workability. Approaching the theoretical limits, the breakthrough over 200 mT will definitely require the use of another superconducting material. A15 compounds are probably the most promising ones (Nb_3Sn [**25**] or Nb_3Al). Critical temperatures in the 20 K region allow operation at atmospheric boiling helium (4.5 K), thus saving both in the cryogenic plant and in operation costs.

3.2 Geometry and Shape

Considering the multipactor issue, careful design of the cavity shape is required for obtaining good performance. For non-relativistic beams, elliptically shaped cavities are still effective down to β=0.47. Lower β will ask for a new cavity geometry, derived from the heavy ion structures ($\lambda/2$, $\lambda/4$ [**26**], spoke [**27**], re-entrant [**28**], split rings [**29**], H-mode [**30**]…). The β=0.15-0.4 range look mostly attractive for both the proton and the radioactive ion accelerators and cavity effort should be directed towards developing an optimized shape for that application.

3.3 Stiffening

A new stiffening scheme under study is the plasma copper spraying onto a bulk niobium cavity [**31**]. This simple (and potentially cheap) technique may provide enough mechanical stiffening without a too severe deterioration of the thermal resistance. Preliminary results obtained on single-cells are quite promising.

3.4 RF Control

Due to the very sharp resonance, SCRF cavities require extremely good RF control in frequency, phase and amplitude. The digital control used for TTF with a feed forward compensation [**32**] is a significant improvement. Adding a fast piezoelectric for fine tuning in addition to the coarse (and low) mechanical tuner is a good idea that can lead to a much better control, primarily for a pulsed operation. This could ultimately relieve the burden of stiffening required to cope with Lorentz force detuning [See 2.9].

3.5 Main Couplers

Fundamental power couplers are of primary importance and many labs are now investing more R&D effort in this field [**33**,**34**,**35**]. The future trend is of course to try to increase even more the power capability (1 MW CW is a fairly challenging goal). Reducing the conditioning time needed to process the coupler (due to vacuum degassing and multipacting) is also a practical issue for accelerators.

3.6 Cost Reduction

Cost reduction is a major issue for linear accelerators. While not a primary concern for proton accelerators, cavity cost is very important in future 30-km long colliders (like TESLA). Niobium metallurgy has been extensively studied in order to find a cheaper way to produce cavities. Hydroforming [**36**,**37**], spinning [**38**] and other exotic forming techniques avoiding the electron beam welding have been investigated [**39**] with some very relative success. Yet, no convincing new fabrication technique has been industrially applied. A lot of effort have been also devoted to niobium thin films at CERN [**40**] but the performance, while improving, is still significantly lower than bulk material.

4 CONCLUSION

Superconducting RF cavities have now reached a mature state and the time for application has come. Experimental results on bulk niobium cavities are approaching the very fundamental limits of the material (B_{pk} = 190 mT, Q = 2.10^{11}). Another material should be investigated if a higher accelerating field (or a higher working temperature) is required. However, R&D is still active in many technological issues related to the integration in a real cryomodule: Field emission, power coupler, stiffening and tuners are examples where additional work is needed to fully take benefit of SCRF performance in actual accelerators. Reproducibility and reliability are also major challenges to address.

A very serious push in the SCRF field is given today by high power proton linacs [**41**]. As an example, the SNS project [**42**] have recently decided to change its baseline linac design. Even though the accelerator duty cycle is relatively low (6%), the use of superconducting RF cavities was considered as more attractive.

REFERENCES

1 C. Lyneis & al., "The Stanford superconducting recyclotron", IEEE Trans. On Nucl. Sci., NS-26, 3, PAC (1979) p. 3246

2 N. Pichoff & H. Safa, "Reliability of Superconducting Cavities in a High Power Proton Linac", these proceedings, EPAC 2000, Vienna, Austria

3 H. Safa, " Superconducting Proton Linac for Waste Transmutation ", 9th Workshop on RF Superconductivity, Santa Fe, USA, [1999]

4 G. Lawrence and T. Wangler, "Integrated NC/SC high power proton linac for the APT project", PAC97 proc., p. 1156, Vancouver, Canada [1997]

5 H. Safa, "High gradients in SCRF cavities", Particle Accelerators, Vol. 60, p. 219 [1998]

6 D. Moffat & al., Particle Accelerators, 40 (1992) 85

7 R. Noer, 6th Workshop on RF Superconductivity, CEBAF, Newport News, USA, [1993] 236

8 M. Jimenez & al., J. Phys. D: Appl. Phys., 27 (1994) 1038

9 J. Tan, "Field Emission studies at Saclay and Orsay", 7th Workshop on RF Superconductivity, Gif-sur-Yvette, France, [1995] 105

10 P. Bernard & al., 3rd EPAC, Berlin, Germany, (1992) 1269

11 G. Muller, “Superconducting niobium in high RF magnetic fields”, 3rd Workshop on RF Superconductivity, Argonne, Ill., USA [Sept. 1987], p.331

12 H. Padamsee, "The technology of Nb production and purification", 2nd Workshop on RF Superconductivity, CERN, Geneva, Switzerland (1984) p. 339

13 H. Safa, “Influence of the RRR of niobium on the RF properties of superconducting cavities”, Advances in Cryogenic Engineering, Vol. 43, (1998)

14 P. Kneisel, J. Less Common Metals, *139* (1988) 179

15 H. Safa & al., "Advances in the purification of niobium by solid-state gettering with titanium", Journal of Alloys and Compounds, 232 (1996) p. 281-288

16 C. Antoine, "Alternative approaches for Nb superconducting cavities surface treatment", 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

17 K. Saito & al., "Superiority of electropolishing over chemical polishing on high gradients", 8th Workshop on RF Superconductivity, Padova, Italy, [1997] p. 795

18 L. Lilje & al, "Electropolishing and in-situ baking of 1.3 GHz niobium cavities", 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

19 B. Visentin & al., 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

20 G. Devanz, "A 2D multipactor simulation code for RF components and accelerating cavities", these proceedings, EPAC 2000, Vienna, Austria

21 M. Serio & al., 5th EPAC, Sitges, Spain (1996) 148

22 A. Facco, "Mechanical mode damping in superconducting low β resonators", 8th Workshop on RF Superconductivity, Padova, Italy, [1997] p. 685

23 B. Bonin, H. Safa, “Power Dissipation at high fields in granular RF superconductivity ”, Superconductor Science & Technology, 4 (1991), p. 257-261

24 T. Hays, 8th Workshop on RF Superconductivity, Padova, Italy, (1997) p.789

25 G. Müller & al., 5th EPAC, Sitges, Spain (1996) 2085

26 K. Shepard, "Development of very low velocity superconducting linac", PAC, Washington, USA (1987) p. 1812

27 J. Delayen & al., Linac Conference, Ottawa, Canada, (1992) 695

28 P.H. Ceperly & al., "Superconducting re-entrant cavities for heavy ion linacs", IEEE Trans. Nucl. Sci., NS-22, 3, (1975) 1153

29 K. Shepard & al., IEEE Trans. On Nucl. Sci., NS-22, (1975) p. 1179

30 U. Ratzinger, GSI Darmstadt, these proceedings, EPAC 2000, Vienna, Austria

31 S. Bousson & al., “An Alternative Scheme for Stiffening SRF Cavities by Plasma Spraying”, PAC Conference, New York, USA (1999), p. 919

32 S. Simrock, "Advances in RF control for high gradients", 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

33 W.B. Haynes, "High power coaxial coupler design and testing", 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

34 H.P. Kindermann, "The variable power coupler for the LHC superconducting cavities", 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

35 G. Devanz & al., "Preliminary design of a 704 MHz power coupler for a high intensity proton linear accelerator", these proceedings, EPAC 2000, Vienna, Austria

36 H. Kaiser, "Advances at DESY in hydroforming of TESLA cavities", 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

37 C. Antoine, "Hydroforming at CEA Saclay", 8th Workshop on RF Superconductivity, Padova, Italy, [1997] p. 598

38 V. Palmieri, "Spinning of TESLA-type cavities", 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

39 V. Palmieri, "Seamless Cavities", 8th Workshop on RF Superconductivity, Padova, Italy, [1997] p. 553

40 P. Darriulat, "Superconducting niobium films for RF cavities", EPAC98, Stockholm, Sweden, (1998) p. 179

41 K.C.D. Chan & al., "Review of superconducting RF technology for high power proton linacs", 9th Workshop on RF Superconductivity, Santa Fe, USA, (1999)

42 Y. Cho, "Preliminary Design Report : SCRF linac for SNS", SNS report, SNS-SRF-99-101, (Dec. 1999)