704 MHZ SUPERCONDUCTING CAVITIES FOR A HIGH INTENSITY PROTON ACCELERATOR

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Abstract

The Hybrid program has been recently started in France in order to explore nuclear waste transmutation technology, based on a spallation neutron source driven by a high-intensity proton linear accelerator. The study of the high-energy section of this accelerator (Superconducting Accelerator for Hybrid) has begun : it aims at developing 704 MHz superconducting radiofrequency (SCRF) cavities for the two different beta sections (β=0.47 and β=0.65). A single-cell (β=0.65) SCRF cavity has been designed by CEA Saclay, and built in industry (CERCA). Mechanical stiffness was analyzed at IPN Orsay. The first cryogenic tests have been performed, showing excellent RF performance. The Qo value was as high as 7.10^{10}, indicating extremely low RF losses. The accelerating field went up to 26MV/m, exceeding by more than a factor of two the design point of 10 MV/m.

1 INTRODUCTION

The Hybrid program has been recently started by CEA in order to explore nuclear waste transmutation technology, based on a spallation neutron source driven by a high-intensity proton linear accelerator [1]. The study of the high-energy section of this accelerator (>85MeV) has begun, with the ASH project proposal (Superconducting Accelerator for Hybrid). The work is done within the frame of a large collaboration between CEA/Saclay, CNRS/Orsay, and other laboratories like INFN/Milano.

One of the main point in ASH high-energy section study is the development of radiofrequency cavities. Elliptical superconducting radiofrequency (SCRF) cavities were chosen, because of their high efficiency and the possibility of running at higher gradient fields than in classical copper cavities.

The goals for ASH cavities study are :

- reach a quality factor exceeding $Qo=8.10^9$.
- work with a maximum surface peak magnetic field Bpk=75mT.

2 HIGH ENERGY SECTION DESIGN

The high energy section has an operating frequency of 704.4MHz [1]. A linac cost optimization with the number of cells per cavity as a parameter leads to the choice of 5-cells cavities (figure 1).

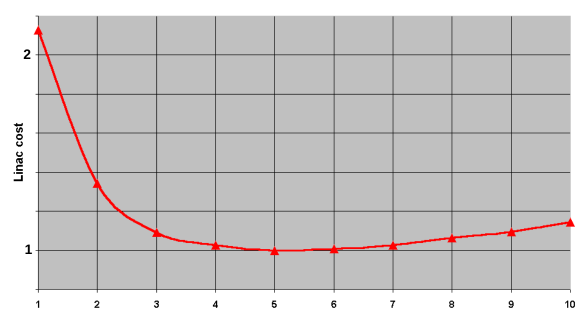

figure 1 : linac cost (arbitrary units) as a function of the number of cells per cavity

After a calculation of the accelerating fields Eacc, the high energy section of the linac is divided in 2 different β-sections (β=0.47 and β=0.65). These values are chosen so as to accelerate all the particles (ε>85MeV) with a good efficiency ($Eacc \geq 80\% Eacc_{max}$). As a matter of fact, in a cavity with a given geometrical β, only the particles with an energy between the « minimum working energy » and the « maximum working energy » will be « well accelerated » (figure 2).

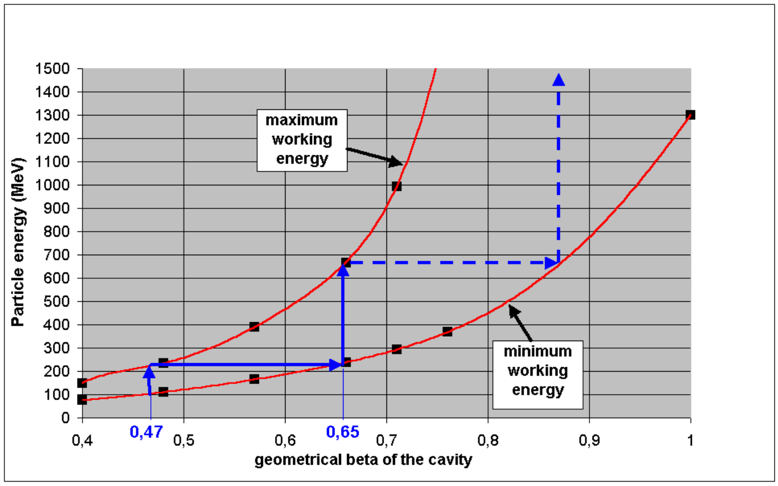

figure 2 : choice of the cavities β values

3 CAVITY DESIGN

The cavity design results of an optimization taking in account the electromagnetic characteristics and the mechanical properties. This design should also ensure that there will be no multipactoring.

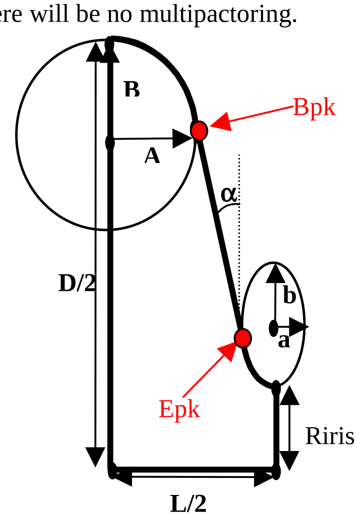

figure 3 : reference geometry for the cavity shape.

RF optimization was made with a collaboration between INFN Milano and CEA Saclay, using Superfish and Urmel codes. Castem and Ansys simulations for mechanical stiffness were made in Orsay and Milano.

This study leads to the choice of bulk niobium cavities, with an elliptical iris, a circular or elliptical equator (depending on the β), a value of the angle α high enough to insure good rinsing and avoid multipactoring. The beam tube aperture is more than 20 times the beam size, and allows a cell-to-cell coupling of around 1%. A scheme of the cavity geometry is shown in figure 3. Note that the end cells have been modified in order to achieve field compensation. Note also that the beam tube diameter on the right side is large enough to insure a good coupling between the cavity and the power coupler.

The geometric parameters of the 5-cell cavities are reported in table 1.

	β=0.47			β=0.65		
	left end cell	inner cell	right end cell	left end cell	inner cell	Right end cell
L/2 (mm)	50.0	50.0	50.0	70.0	70.0	70.0
D/2 (mm)	187.0	187.0	187.0	186.4	186.4	186.4
A (mm)	33.0	33.6	36.6	45.1	45.1	53.0
B (mm)	56.0	53.8	36.6	49.6	45.1	53.0
a (mm)	8.0	7.9	6.7	12.2	12.1	11.4
b (mm)	10.4	10.3	8.7	15.9	15.8	14.8
α (°)	5.98	5.5	4.84	8.85	8.5	5.6
Riris (mm)	40.0	40.0	65.0	45.0	45.0	65.0
Nb thickness (mm)	4 (with stiffening)			4 (no stiffening)		

table 1 : geometric parameters of ASH 5-cell cavities.

In table 2 are reported the main electromagnetic characteristics of the two structures : the geometry factor G, the r/Q value, the ratio between the peak electric field on the cavity surface with respect to the accelerating field, the ratio between the peak magnetic field with respect to the accelerating field, and the cell-to-cell coupling.

	β=0.47	β=0.65
G *(Ω)*	**152.7**	**194.1**
$(r/Q)_{ref}$ *(Ω)*	**79.5**	**157.5**
$Epk/Eacc_{ref}$	**3.58**	**2.61**
$Bpk/Eacc_{ref}$ *(mT/MeV/m)*	**5.88**	**4.88**
Cell to cell coupling (%)	**1.2**	**1.0**

table 2 : electromagnetic characteristics of ASH 5-cell cavities

Note that r/Q is here given by :

$$r/Q = \frac{(Eacc.Lacc)^2}{2\omega W}$$

where W is the stored energy in the cavity, ω the pulsation of the wave, and Lacc the accelerating length of the cavity.

Note also that Eacc varies with the particle speed (figure 4) : $Eacc_{ref}$, $(r/Q)_{ref}$, $Epk/Eacc_{ref}$ and $Bpk/Eacc_{ref}$ are given for a reference particle speed of v=β.c. For particles having different energies, these values are corrected using a coefficient f such as:

$$Eacc=f.Eacc_{ref}$$
$$(r/Q)=f^2.(r/Q)_{ref}$$
$$(Epk/Eacc)=(1/f).(Epk/Eacc)_{ref}$$
$$(Bpk/Eacc)=(1/f).(Bpk/Eacc)_{ref}$$

(- f values are given in table 3 -)

Energy (MeV)	β=0.47	β=0.65
80	0.440	
100	0.785	
125	1	
150	**1.053**	
200	0.935	0.622
250	0.745	0.870
308		1
350		**1.030**
500		0.960
700		0.800
1000		0.625

table 3 : corrected coefficient f for different energies

For the « demonstrator » project, the maximum surface magnetic field value is safely limited to 50mT. The corresponding accelerating field is then less than 8.6 MeV/m in the (β=0.47) section, and less than 9.1MeV/m in the (β=0.65) section (figure 4).

In the futur accelerator for the prototype project, the maximum surface magnetic field will be extended to 75mT. The working accelerating field will be less than 12.1 MeV/m in the (β=0.47) section, and less than 11.4MeV/m in the (β=0.65) section.

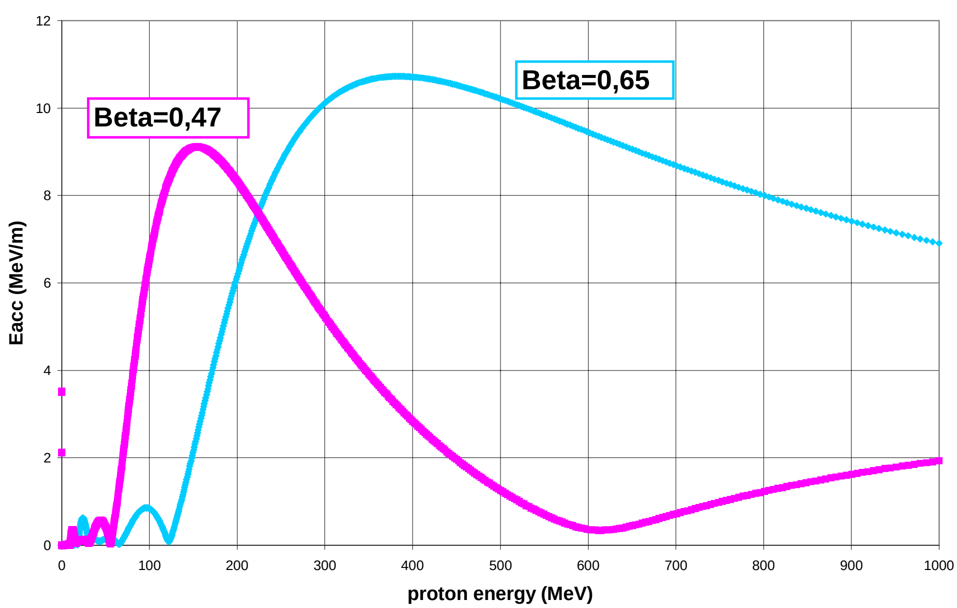

figure 4 : ASH cavities accelerating field, normalized to Bpk=50mT.

4 CAVITY FABRICATION AND PREPARATION

As the (β=0.65) section represents the most important part of the linac, focussing is directed towards the fabrication of (β=0.65) cavities. Two (β=0.65) single-cell cavities namely A101 and A102 were fabricated. A101 was build with niobium sheets with a low residual resistance ratio (RRR=30), and was destinated to preliminary tests. For A102 (figure 5), niobium sheets with a RRR of more than 200 were used, supplied by Wah-Chang Company, USA.
The fabrication of these cavities was done in french industry : spinning of the half-cells by Bonitempo, and electron beam welding at CERCA at the iris and the equator.
The preparation before the cryogenic test was done in Saclay, and consisted in :
- RF measurements at room temperature.
- a chemical surface treatment of around 100µm, based on the use of a 1:1:2 mixture of fluoridric acid, nitric acid and phosphoric acid.
- a high pressure rinsing with ultra-pure water and a final preparation in a class 100 clean room.

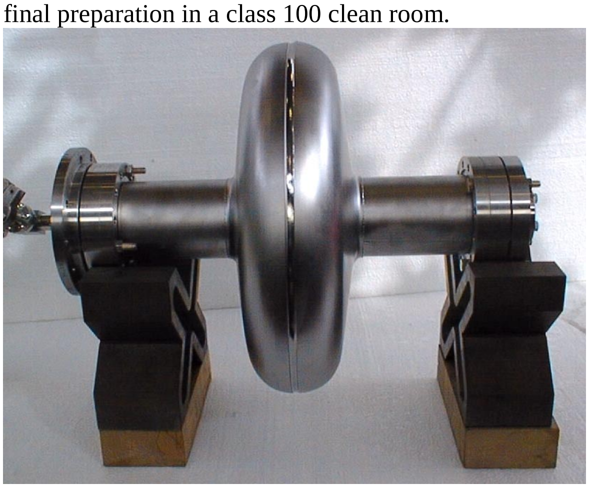

figure 5 : A102 single-cell cavity

5 RESULTS

The test facility is installed in the Saclay site. The cavity was tested in a vertical cryostat, and the cooling was made very rapidly, in order to avoid the 100K effect [2]. The cryostat has a very good magnetic shielding, with a residual static magnetic field less than 5mG. Before the high field experiments, the fundamental resonant frequency mode was measured : 699.73MHz at 300K, 700.83MHz at 4.2K, and 701.30MHz at 1.7K.
RF measurements have been first made at 4.2K : field was limited by the available amplificator power, and an accelerating field of 9.5MeV/m was obtained without any field emission. At 1.7K, an accelerating field of 26MeV/m was obtained, corresponding to a peak magnetic field of more than 120mT, with a few electron emission over 23MeV/m, and without any quench. Excellent Qo value was obtained , exceeding 5.10^{10} up to 15MeV/m (figure 6).
Measurements were done at different temperatures. A change in the Qo slope is obtained at the phase transition of liquid helium (HeI / HeII) (figure 7). It shows that, for a good cooling, SCRF cavities will have to work below the λ-transition (2.17K).

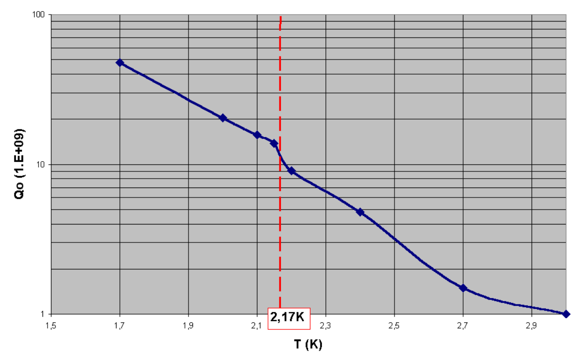

figure 7 : Qo value as a function of the temperature for an accelerating field of 15MeV/m (note the change in slope at the λ-transition)

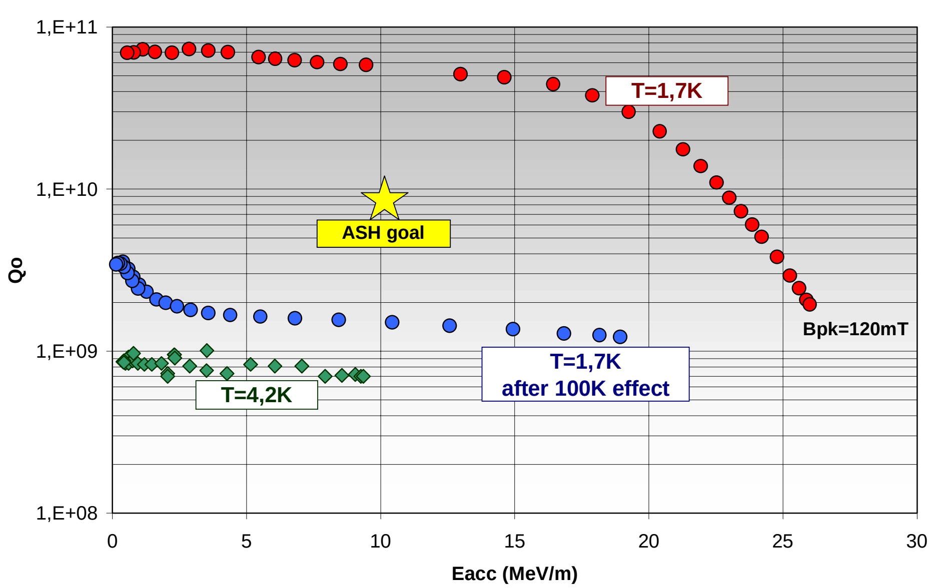

figure 6 :
Qo values of A102 before heat treatment (test1)

In order to study the 100K effect, A102 stayed 2 hours between 125K and 135K, and was cooled down to 1.7K. An important degradation of the Qo value was observed (cryogenic losses were more than 10 times higher).

To avoid this 100K effect, a heat treatment of the cavity (2h, 800°C) was achieved . A new cryogenic test showed that this unwanted effect has disappeared (figure 8). This heat treatment will have to be performed on all cavities before installation in the cryomodule.

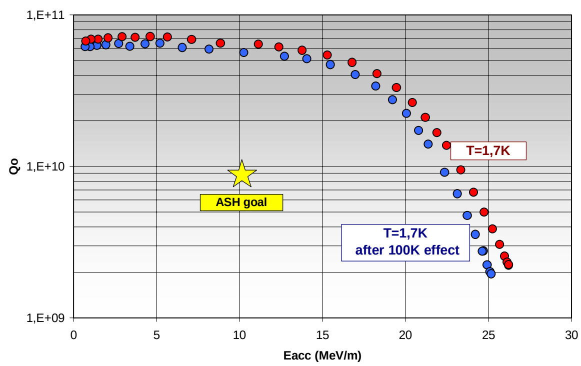

figure 8 : Qo values of A102 after heat treatment (test2).

The temperature dependance of the surface resistance of the cavity was measured for an acccelerating field of 1MeV/m. Figure 9 shows the result of the measurements. The residual resistance was evaluated to 2.5nΩ.

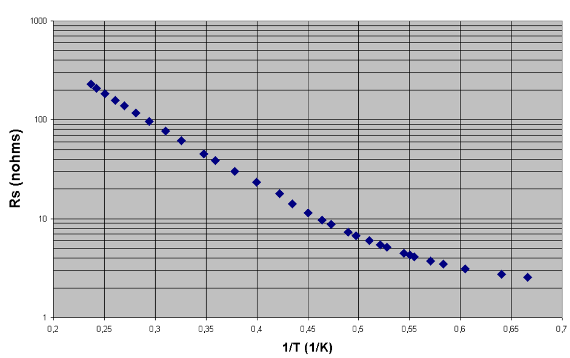

figure 9 : surface resistance as a function of 1/T for an accelerating field of 1MeV/m.

Finally, the variation of the resonant frequency due to the Lorentz force as a function of the accelerating field was evaluated to be 16Hz/(MV/m)² for a completely free cavity (figure 10).

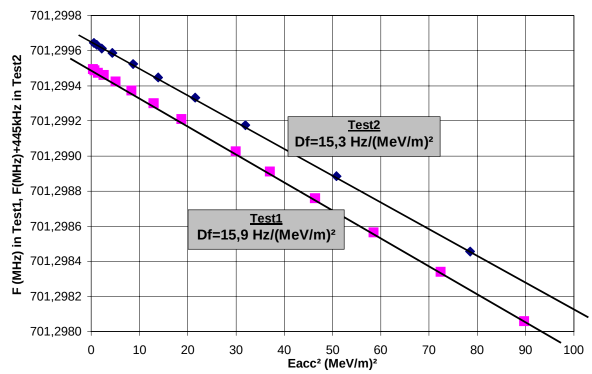

figure 10 : frequency shift due to Lorentz forces (T=1.7K).

6 MECHANICAL MEASUREMENTS

Deformation measurements under vacuum have been made on A102, based on a system using deformation comparators with a sensibility of 10µm, keeping one end of the cavity fixed, and the other one free. A good agreement was observed between these measurements and Castem simulations.

The maximum stress observed is about 40MPa (under 2bars), below the elastic limit (70MPa) (figure 11).

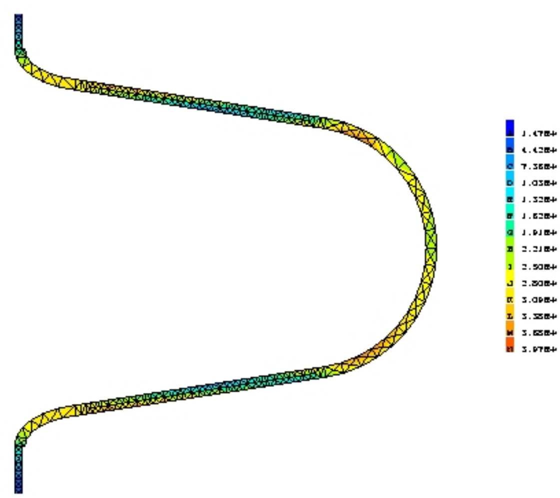

figure 11 : Castem calculation of stress on cavity A102 (5mm thickness) under 2bars (maximum stress=39.7MPa).

Note that A102, for safety reasons, was made with 5mm thick niobium. After optimisation (figure 12), and with the idea to keep the stress below 50MPa (under 2bars), a niobium thickness of 4mm, corresponding to a maximal stress of 42MPa under 2bars, is clearly sufficient.

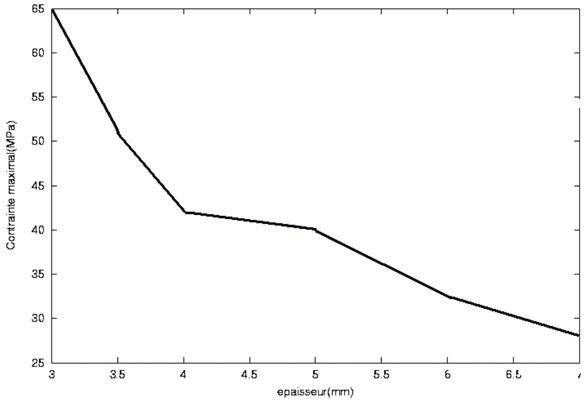

figure 12 : maximal stress (under 2 bars) as a function of Nb thickness

Some calculations have also been made for the 5-cell cavity optimization with Castem and Ansys. A good agreement was found between the 2 codes.
This study leads to the choice of a niobium thickness of 4mm without any stiffening in the case of (β=0.65) cavity (figure 13), and 4mm with stiffening at the iris in the case of (β=0.47) cavity.

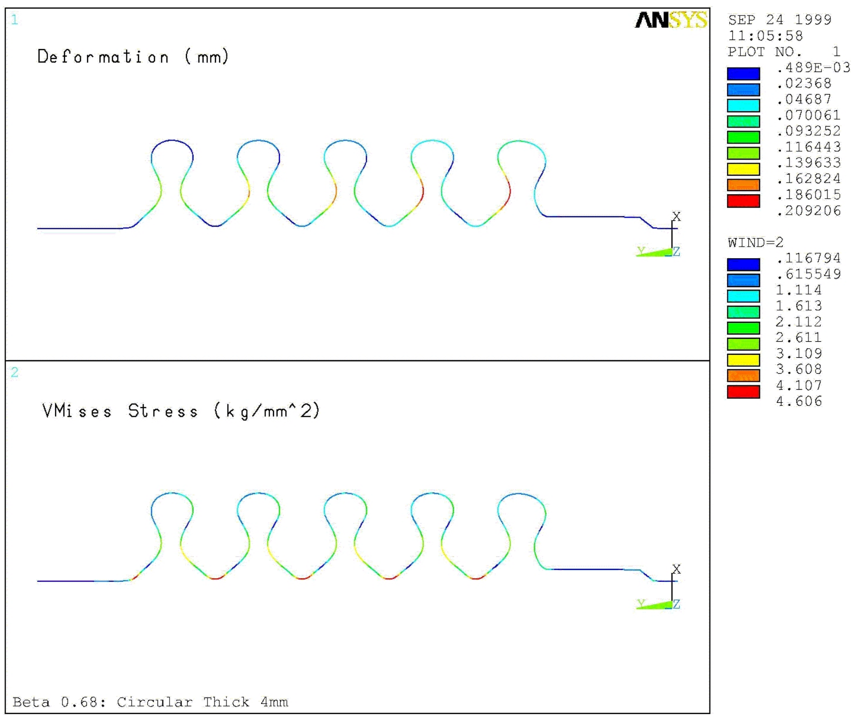

figure 13 : Ansys calculation of stress on β=0.65 5-cell cavity (under 2bars) (Maximum stress = 46MPa)

7 CONCLUSION

We have fabricated and tested a 700MHz niobium cavity for proton accelerator with a (β=0.65). Excellent performance was obtained (26MV/m), exceeding by more a factor of 2 the design value (10MV/m). These results give more confidence in the options chosen for the superconducting part of the accelerator. They also indicate additional margins in the accelerating parameters, opening tracks for future improvements. The R&D work for SCRF cavities will continue, with the fabrication of another (β=0.65) single-cell cavity (with its power and HOM ports) to confirm A102 excellent performance, followed with the fabrication of two (β=0.47) single-cell cavities and one (β=0.65) 5-cells cavity. A great effort is made to improve the fabrication procedures and the surface treatment in the view of an industrial production.

REFERENCES

[1] H. Safa, « Superconducting Proton Linac for Waste Transmutation », these proceedings.
[2] B. Bonin, R.W. Röth, « Q-degradation of Niobium Cavities due to Hydrogen Contamination », Proceedings of the 5th Workshop on RF Superconductivity, Hambourg, Germany, p.210 (1991).