STUDY OF A SPOKE CAVITY FOR LOW-BETA APPLICATIONS

G.Olry*, J.L. Biarrotte, H.Saugnac, J.Lesrel, Institut de Physique Nucléaire (IPN), Orsay, France

Abstract

Since a few years, intensive studies have been developed on SC cavities (for instance, spoke-type or re-entrant cavities) for their use as accelerating structures in the low energy part of high power proton or ions accelerators (typically from 5 to 100 MeV). Within the framework of the EURISOL (EURopean Isotope Separation On-Line) & XADS (eXperimental Accelerator Driven System) European accelerators projects, IPN Orsay decided to plan a R&D program on low-beta spoke-type cavities.

In the major part of this paper, we report on the optimization of the geometry of a β=0.35, 2 gap spoke cavity, aiming at achieving good electromagnetic parameters (i.e. lowest E_{pk}/E_{acc} and B_{pk}/E_{acc}). A mechanical study is also presented, as well as a preliminary design of a proton spoke Linac (12-85 MeV) composed of β=0.18 and β=0.35, 2 gap cavities.

1 INTRODUCTION

Based on the hopeful RF test of the first spoke prototype cavity [1], R&D programs on spoke-type cavities have been developed in various laboratories within the framework of several accelerators projects [2-4]. The latest low temperature tests performed on ANL (Argonne National Laboratory) spoke cavity have confirmed these good RF performances (i.e. E_{acc}>12 MeV/m and Q_0>2.10^9 at 4 K) [5-6]. In the near future, integration of such cavities into the low energy part of a proton Linac [7-9] (let's say between 5 and 100 MeV) instead of classic warm devices (i.e. DTL, CCDTL ...) represents an exciting challenge with regard to many providing advantages: efficiency (almost 100% RF power into the beam), reliability (large beam tubes = higher safety margin for structures activation) and flexibility (independent RF power sources).

Being aware of the real potential of such cavities, we have started studying spoke cavities for XADS accelerator type.

2 SPOKE DESIGN

Before doing the electromagnetic cavity optimization, several parameters have been chosen in order to match XADS general requirements:

- 352.2 MHz frequency (i.e. IPHI-RFQ frequency)
- β_g=0.35 (transition with 704.4 MHz, β_g=0.47 elliptical cavities)
- 2-gap (higher energy acceptance as compared to multi-gap structures)
- Beam tube aperture of 6 cm (≥10 times the rms beam diameter)

Optimization and final RF parameters calculations have been performed using MAFIA [10]. Of course, the main goal of the study was to lower electric and magnetic peak surface fields.

Note that to be consistent with previous simulations already done [11-12], we used the same conventional definitions: gap-center to gap-center distance ($g=\beta_g\lambda/2$) and overall cavity length without beam tubes ($L_{cav}=2/3\beta_g\lambda$).

2.1 Geometry optimization

First calculations were done using a simple pillbox in order to estimate the effect of the spoke to end walls distance (we used a cylindrical spoke). We made the spoke diameter D increase while the cavity length was fixed (L_{cav}=30 cm). As illustrated in Figure 1, there is an identical optimum value for both E_{pk}/E_{acc} and B_{pk}/E_{acc} ratios: D/L_{cav}=0.33.

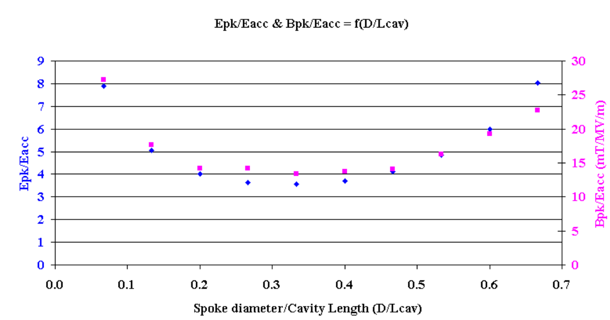


Figure 1: E_{pk}/E_{acc} and B_{pk}/E_{acc} as a function of spoke diameter to cavity length ratio.

Secondly, we optimized the spoke itself using cylindrical, elliptical and racetrack shapes. Minimum B_{pk}/E_{acc} value was found using the cylindrical shape (i.e. lower of about 30%) whereas there was no such large difference between each E_{pk}/E_{acc} minimum values (for instance, the minimum value using racetrack shape was 10% higher than the cylindrical one). On the other hand, an increase of the transit time factor was observed using both elliptical and racetrack shapes. Consequently, the spoke base (i.e. the region of the spoke to outer cavity wall transition) must be cylindrical while the spoke center (i.e. the aperture region) must be elliptical or like racetrack type. At this point, we had to take into account

*olry@ipno.in2p3.fr

the feasibility and the production cost of the cavity. Obviously, the spoke fabrication will be cheaper if we design it for deep-drawing technique (i.e. just by squeezing the center part of the spoke) instead of carved it in a bulk Niobium bar. In this case, racetrack shape is the good one. Moreover, it makes the spoke design easier because once we have defined its thickness and its width, we directly have the spoke base diameter.

Therefore, we have the overall shape of the spoke. Complementary calculations have been performed on the racetrack shape (i.e. by changing width and height) and on the cylindrical shape (i.e. by changing the spoke base length). None significative changes were observed. Finally, we changed the cavity diameter in order to match the 352.2 MHz frequency. Table 1 summarizes the major dimensions of the cavity. Figure 2 shows a cross-section a the half cavity and figure 3 a 3D plot (including the RF pickup ports).

Table 1: Major dimensions of the cavity

Overall cavity length (L_{cav})	200 mm
Gap-center to gap-center length (g)	150 mm
Spoke thickness at beam hole aperture ($t=0.33* L_{cav}$)	67 mm
Spoke width at beam hole aperture	147 mm
Spoke diameter at base	118 mm
Top cavity length (L_{top}=3*Spoke diameter at base)	354 mm
Cavity diameter	420 mm

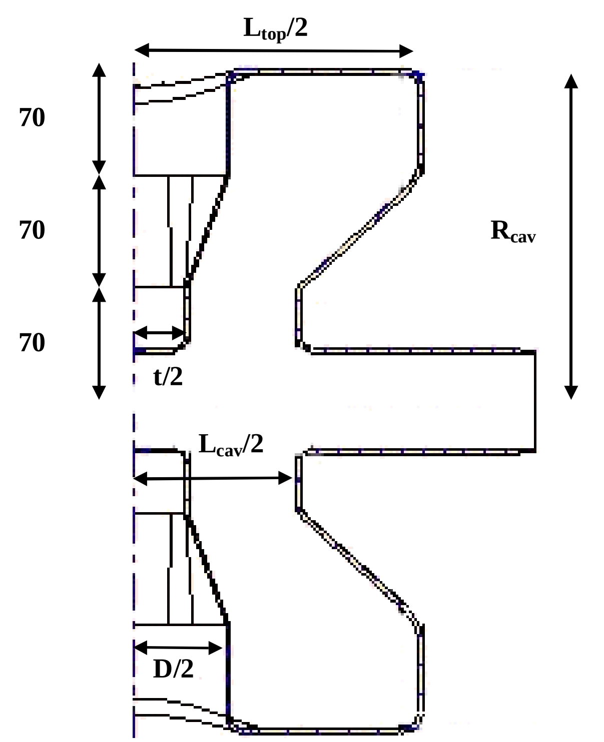


Figure 2: Cross-section of the half spoke cavity (dimensions in mm)

2.2 RF parameters

Calculation of RF parameters (see Table 2) has been performed using 4000000 mesh points (i.e. mesh size about 1.4 mm). Accelerating electric field E_{acc} is scaled with the overall cavity length L_{cav}.

Table 2: RF parameters of the cavity

Q_0 at 2K (R_{res}=10 nΩ)	8.7 10^9
Geometrical factor (Ω)	97
E_{pk}/E_{acc}	3.10
B_{pk}/E_{acc} (mT/MV/m)	8.51

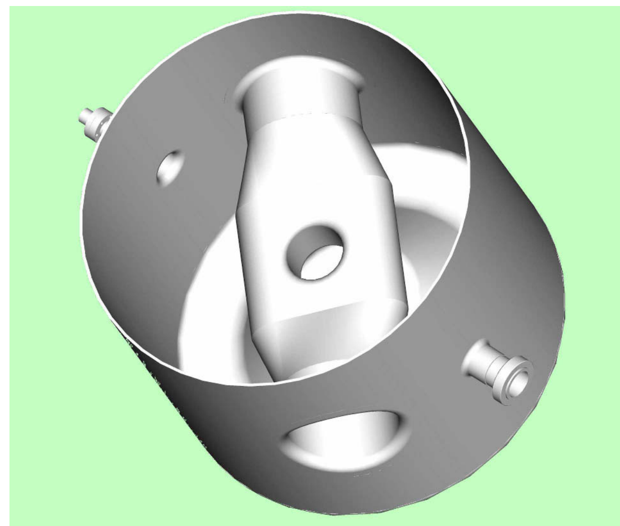


Figure 3: 3D representation of the optimized cavity shape designed using CAD software Pro-engineer [13].

3 MECHANICAL STUDY

Based on the spoke geometry designed using MAFIA, we started a preliminary structural analysis. Design of the cavity (without spoke to outer cavity wall and spoke to beam hole rounded transitions) and calculations have been performed with ACORD_CP software [14]. Material properties of Niobium used are: density=8560 kg/m^3, Young's modulus=107000 MPa and Poisson ratio=0.359.

3.1 Stresses and displacements under external pressure

Numerical runs were performed with the cavity (3 mm thick) subjected to an external pressure of 2 Bars while both end beam tubes were fixed. According to the first results, additional external supports on both end walls (see Fig. 4) must be used in order to keep the maximum stress lower than the yield strength σ of Niobium (i.e. σ=50 MPa at T=300 K). Consequently, we stiffened each cavity end wall using 8 Nb supports (3 mm thick too) located into the re-entrant part (i.e. they are fixed both on cavity end wall and beam tube).

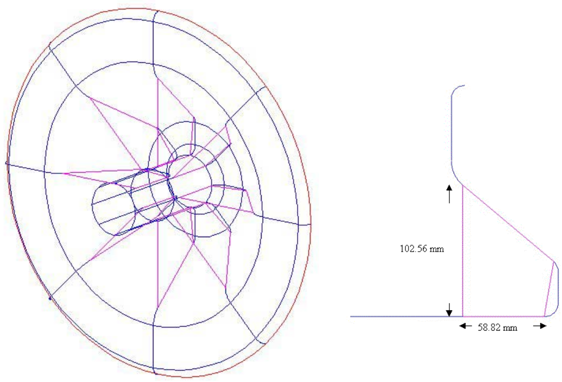


Figure 4: Left part, location of the 8 supports (in pink) & right part, dimensions of a support.

Stiffening resulted in an important decrease of peak Von Mises stresses (by a factor of 8) and peak displacements (by a factor of 10) as illustrated in Table 3. Peak Von Mises stresses are located on: spoke to outer cavity wall transition, spoke to beam hole transition and beam tubes and end wall to supports transition. Peak displacements are only located on end walls.

Table 3: Von Mises stress and displacements under 2 Bars external pressure (boundaries conditions: beam end tubes fixed)

	Without supports	With supports
Peak Von Mises stress (MPa)	386	49
Peak displacements (mm)	1.03	0.109

Note that shape and locations of the stiffening supports are the first we used. So, they are not precisely designed and may be changed in case of fabrication problems or new improvements in calculations. Moreover, we did not perform calculations on tuning sensitivity which may lead to modifications.

3.2 Spring stiffness and mechanical vibrations

We performed complementary calculations of the equivalent spring stiffness of the cavity by pushing both end beam tubes until reaching 50 MPa. The corresponding peak displacement of each beam tubes was 0.5 mm and the spring stiffness value obtained 3000 N/mm. Such a low value seems to make the tuning system design easier. We have to notice also that end walls deviate as a whole which let us foresee a good sensibility for tuning (see Fig. 5).

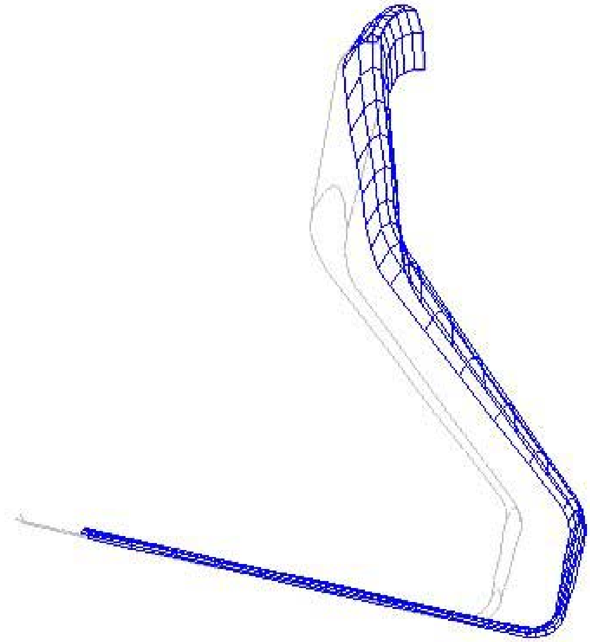


Figure 5: Displaced end wall (blue shape) as compared to undisturbed shape (in grey).

Preliminary calculations of the mechanical vibrations modes were performed by fixing both end beam tubes. Results indicate that the lowest frequency is around 93 Hz (torsion mode). Further analyses are planed to complete this study.

4 PRELIMINARY LINAC LAYOUT

A preliminary design of a low-β SC proton linac using spoke cavities has been achieved, based on the following considerations:

- use of 352.2 MHz 2-gap spoke cavities which represent an easier technological challenge for fabrication than multi-gap ones (+ higher energy acceptance).
- working with conservative values for the peak surface fields in the cavities and the synchronous phase ($E_{pk} \leq 25$ MV/m, $\varphi \leq -30°$).

In the XADS [15] and/or the EURISOL [16] context, this spoke section aims at covering the “intermediate” part of the proton linac, between the end of the injector and the beginning of the high energy section using elliptical superconducting cavities. One can show that this energy range can be covered with only 2 different spoke cavity types. In the following, we will discuss the case of a 20 mA spoke line covering the energy range from 12 MeV (output energy of the Saclay RFQ + DTL IPHI injector [17]) up to 85 MeV (input energy of the β=0.47 704.4 MHz SC cavities section [18]).

A first linac optimization was done by minimizing the linac length and the total number of cavities while keeping the zero-current longitudinal phase advance per lattice below 80°. This led to the choice of the two following types of spoke resonators (see Fig. 6):

- Section 1 (12-26 MeV): β=0.18 cavities, 2 cavities per focusing lattice.
- Section 2 (26-85 MeV): β=0.35 cavities, 3 cavities per focusing lattice.

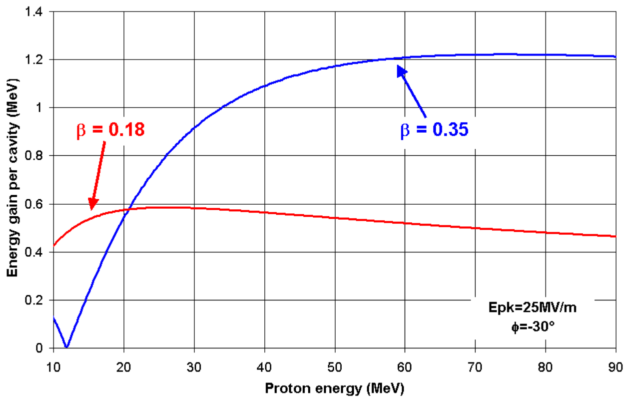


Figure 6: Energy gain per cavity along the 12-85 MeV spoke linac (2-gap cavities, E_{pk}=25 MV/m, φ =-30°).

One of the most crucial points in this linac design is to provide a good matching with the previous DTL, where the focusing lattice is very short (< 30 cm) and the phase advance per meter values are very high. That's why we tried here to minimize as far as possible the length of the first spoke lattice, and to gradually increase the lattice length through the beginning of section 1 (see Fig. 7). This approach allows to take full advantage of the high accelerating gradients available with our SC spoke cavities, even at low energy. On the other hand, this choice leads to a 9.5 meters long cryomodule #1 (see Fig. 8) which may be difficult to handle during the linac assembly.

Another approach would consist in taking a longer focusing lattice (here 1.9 m) from the very beginning so as to obtain a simpler and single cryomodule design in the whole section 1. This approach, proposed in the AAA program [8], implies to lower the accelerating fields in the first section, leading to a higher overall linac length.

Our spoke linac design is also based on the following considerations:

- focusing is provided by SC quadrupoles inserted inside the cryomodules; gradients are kept below 40 T/m along the whole linac.
- the synchronous phase is ramped at the beginning of section 1 from –50° to –30° for a better longitudinal capture of the beam.
- the emittance growth is minimized keeping the zero-current transverse phase advance per focusing lattice near 80°, while staying below the envelope stability at 90°. The zero-current transverse and longitudinal phase advances per unit length are kept as smooth as possible (see Fig. 9) to try to decrease the sensitivity to beam current variations.
- the matching between sections is done maintaining equal values of the longitudinal and transverse phase advances per unit length at each side of the transition; this is done by synchronous phase and quadrupole fields adjustments.
- beam specifications at the entrance of the linac are taken from the IPHI output (transverse emittance: 0.25 π.mm.mrad norm.rms, longitudinal emittance: 0.47 π.mm.mrad norm.rms, 0-current longitudinal phase advance: 70°/m).

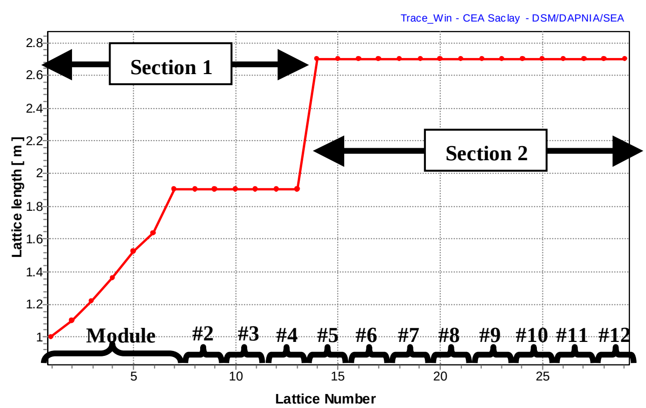
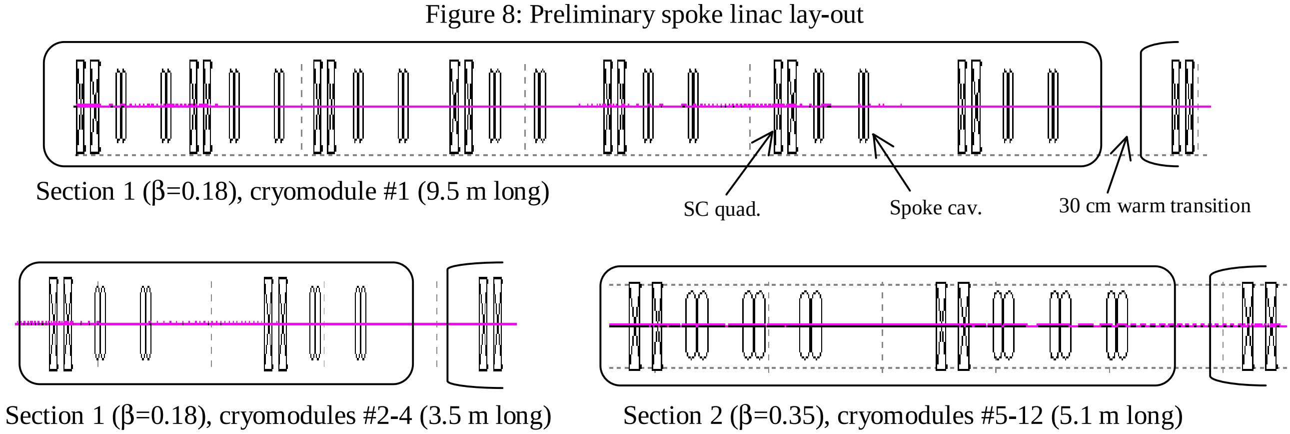


Figure 7: Focusing lattice length evolution.

Figure 8: Preliminary spoke linac lay-out



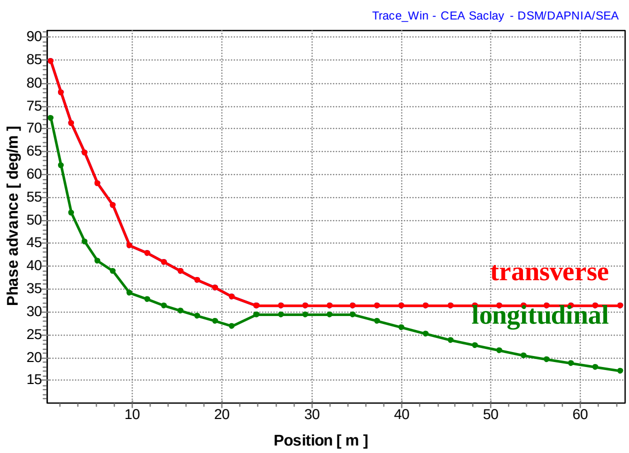


Figure 9: Zero-current phase advances as a function of linac length.

Beam dynamics calculations were performed using codes developed at CEA Saclay (GenLin, TraceWin, Partran) by N.Pichoff and D.Uriot [19]. These simulations include space charge effects and non linear effects in gaps; Partran simulations were run with 10.000 particles. Note that these first simulations do not include error studies.

The main results are reported on Figures 10 & 11, showing no beam losses and a transverse emittance growth of less than 5%. Table 4 summarizes the main characteristics of our preliminary spoke linac.

Table 4: Spoke linac main parameters (352.2 MHz, 2-gap cavities, 20 mA proton beam)

	Section 1	Section 2
Geometrical β	0.18	0.35
Cavity length (cm)	10.2	20.0
Aperture diameter (cm)	5	6
Number of cavities / focusing lattice	2	3
Focusing lattice length (m)	1.0 to 1.9	2.7
Cryomodule length (m)	#1: 9.5 #2 to 4: 3.5	5.1
Nb cavities	26	48
Total length (m)	21.5	43.5
Energy range (MeV)	12 to 26	26 to 85
Synchronous phase (°)	-50 to -30	-30
Accelerating field (MV/m)	5.6 to 7.0	4.4 to 8.5
Energy gain /cavity (MeV)	0.36 to 0.60	0.68 to 1.40
RF power / cavity (kW)	7.2 to 12.0	13.5 to 28.0
Quad. length (cm)	7.5	10
Quad. gradient (T/m)	35 to 28	18 to 30
Max. rms beam diameter (mm)	4.5	5

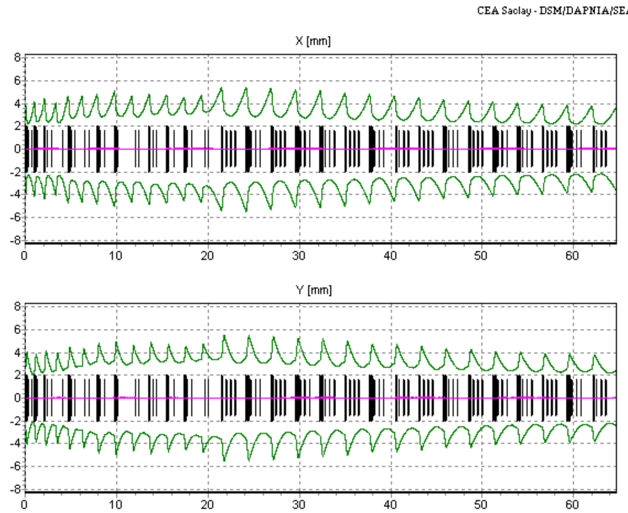


Figure 10: Maximum beam envelope as a function of linac length.

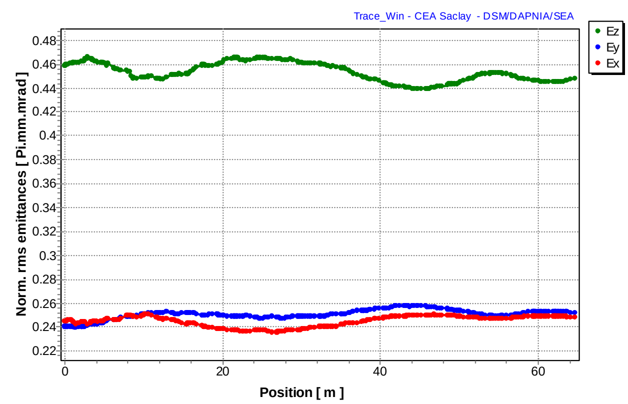


Figure 11: Emittances as a function of linac length.

Further studies are going on at IPN Orsay in order to precise and optimize this preliminary spoke linac design: decrease of the entrance energy at 5 MeV (IPHI RFQ output) replacing the β=0.18 section by a β=0.15 section, precise matching with the previous DTL or RFQ (and with the high energy section), possible use of SC solenoids instead of SC quadrupoles at low energy, cryomodule design, coupler design, operating temperature (4 K or 2 K), capability to accelerate heavy ions…

However that may be, these first results already give us some confidence in the feasibility of such a spoke linac. A comparative study has been started to compare this kind of linac with a DTL-like warm structure; a first analysis shows that, for the same order of length and investment cost, the spoke linac alternative shows great advantages in terms of reliability (with the use of small independent RF generators), of safety (beam tube apertures 4 times higher than in DTL structures), of flexibility (easy power adjustments, large particle-type acceptance), and of course in terms of efficiency, since, thanks to superconductivity, about 3 M€ per year is saved for operating cost (for a 20 mA proton beam linac).

5 CONCLUSION AND PERSPECTIVES

The optimization of the β_g=0.35 spoke cavity geometry is now achieved. After finishing the mechanical calculations and fixing the shape of the stiffeners, we planed to produce a first prototype in copper before the end of the year in order to control the fabrication procedure. A first niobium prototype will be built in March 2002 with low RRR sheets. In parallel, the study of a new vertical cryostat for testing the cavity (internal diameter=800 mm) is going on. Before 2003, the construction of 3 other cavity prototypes (β=0.35 & β=0.18 or 0.15) is planned, aiming at the fabrication of a whole spoke cryomodule before 2005 to be tested under beam with the Orsay Tandem and with IPHI. Note that a collaboration for the conception and fabrication of the focusing SC elements is currently under progress.

6 ACKNOWLEDGMENTS

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