HIGH-INTENSITY PROTON SC LINAC USING SPOKE CAVITIES

J-L. Biarrotte*, J-L. Coacolo, J. Lesrel, G. Olry, CNRS/IN2P3, IPN Orsay, France

Abstract

This paper describes the studies going on at IPN-Orsay concerning the conception and the design of a superconducting proton linac using spoke cavities. Different linac concepts from 5 MeV up to 80–100 MeV have been investigated, mainly based on beam dynamics studies, and especially caring about reliability and safety aspects. The study leads to a final proposal of a high-intensity proton linac using spoke cavities, that could be proposed in the frame of the XADS project.

1 INTRODUCTION

Superconducting cavities have been recently considered as a very promising technical solution for a use as accelerating devices in the intermediate section of high-intensity proton linear accelerators [1,2,3]. As a matter of fact, comparative studies show that the use of superconducting cavities in this energy range, from 5 MeV up to 80–100 MeV, should provide many advantages compared with classical room-temperature structures: while the investment cost and the overall length for both solutions seem to be of the same order, the AC power consumption is much lower using SC cavities, that makes a huge difference in the operating cost; the savings are estimated to be in the order of 3 M€/year for a 10-mA CW proton beam (see section 2.4). Moreover, the superconducting solution gives higher safety (larger beam tubes), and has great potential in terms of reliability and flexibility thanks to its independently-powered structures. Considering the great potential of such a solution, IPN Orsay has started a R&D program on very low-β SCRF resonators, and in particular on spoke-type cavities which appear to be one of the most promising structures for this application. This R&D program is closely linked with the 5th EU Framework since this spoke solution is proposed in the frame of the two main European projects foreseeing the use of a high-power proton linac: the EURISOL project [3], aiming to the preliminary design of the next-generation European ISOL facility, and the PDS-XADS project [4], aiming to the demonstration of the feasibility of an ADS for waste transmutation.

2 SPOKE LINAC DESIGN

This spoke linac design is based on the following specifications:

- Energy range from 5 MeV (RFQ output) up to 80–100 MeV (high energy section input).
- Operation at 352.2 MHz and 4 K.
- Use of 2-gap SC spoke cavities, which have large energy acceptance, and remain quite easy to fabricate as compared with multi-gap structures.

2.1 Reliability aspects

A major part of this study has been done within the frame of the XADS project. The main technical specifications for this proton accelerator are the following [4]: 10-mA maximum beam intensity, 600–800-MeV maximum proton energy, and operation with less than 10 beam trips per year, to limit as much as possible the number of thermal shocks in the spallation target and the core. This last point means that extremely high reliability is required for this project, posing new challenges in the accelerator field. In this context, accelerator experts from the PDS-XADS accelerator study group (WP3) are being converging [5] towards the solution of a whole-superconducting linac from 5 MeV, composed with independently-phased superconducting devices, running in the CW operation mode, and carefully designed to match the reliability requirement. In this sense, the choice of the spoke technology for the intermediate-energy section appears to be a good choice, since spoke cavities show interesting specificities with some potential in terms of reliability and safety: very large beam aperture, good mechanical stability, and negligible steering effects. Moreover, one has to keep in mind that comfortable margins have to be taken in account during the linac design, so as to ensure both a reliable operation of the accelerating structures and of RF components, and a high robustness of the focusing design.

2.2 Accelerating structures

A preliminary optimisation of the linac shows that only two different β-values are needed to cover the required energy range: β=0.15 spoke cavities are used from 5 MeV up to 18 MeV, and β=0.35 cavities from 18 MeV up to 80 or 100 MeV. The cavity design optimisation has been done for each β-value [6,7], so as to minimise the peak surface fields in the cavities during operation (E_{pk}<25 MV/m), while reaching good RF and mechanical properties, and keeping large beam apertures.

2.3 Focusing design

In order to obtain a focusing design as fault-tolerant as possible, the following choices have been made:

- Superconducting focusing elements are used to minimise the lattices' length, ensuring a certain continuity between the RFQ and the high-energy section.
- The synchronous phase is ramped from - 45° to - 30° in the first focusing lattices for a good longitudinal capture of the beam.
- The emittance growth is minimised keeping the zero-current phase advances per focusing lattice below the envelope stability at 90° (see Fig. 1), that

* biarrott@ipno.in2p3.fr

leads to upper limits for the energy gain per focusing lattice and the beam size. Longitudinal and transverse phase advances never cross, so as to avoid any resonant collective instabilities that could imply some emittance exchange between the longitudinal and transverse planes.

- The phase advance per meter is kept continuous through the linac to have a good matching between the structures, to decrease the sensitivity to current variations, and to minimise the halo formation.

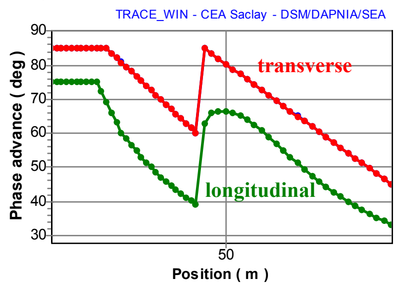

Figure 1: Evolution of the phase advance per lattice.

Concerning the choice of the focusing elements, SC solenoids and SC quadrupole doublets have been considered. No significant difference was found between the two solutions concerning the beam dynamics performances, both for matched and mismatched configurations. We finally chose the quadrupole doublets solution, for which the focusing in the two transverse directions are dissociated, whereas they are coupled in the solenoid case. This choice should allow a better control of the beam, especially for the beam matching between the different accelerating sections, and should improve the robustness of the focusing design.

2.4 Linac architecture

Different philosophies have been investigated for the conception of the linac architecture (see Fig. 2). The first one (1) consists in using long and compact cryomodules with short focusing lattices. This approach is very attractive because it leads to a very short linac, but the main drawback is that the lattice length continuity is broken at each warm transition between modules: a specific beam matching is required at each transition, that could induce some "weak points" as far as the robustness of the focusing design is concerned. For this reason, the second approach (2), which consists in keeping the lattice length continuity in the whole linac, was preferred. This solution leads obviously to an increased overall length of the linac, but it may be the price to pay to ensure a fault-tolerant focusing design. Moreover, the cryomodules are very simple, that could be an argument in terms of reliability and flexibility. Finally, a third philosophy (3) would consist in shortening the very first lattices of the spoke section, so as to smoothen as much as possible the transition with the previous RFQ, in which the focusing lattice is very short. But this approach, which had been detailed in our previous spoke linac design [8], was not retained here, because the gain in terms of beam stability was not so obvious, while the handling of such a complicated first module may have some negative impact on the flexibility and the reliability of the whole linac.

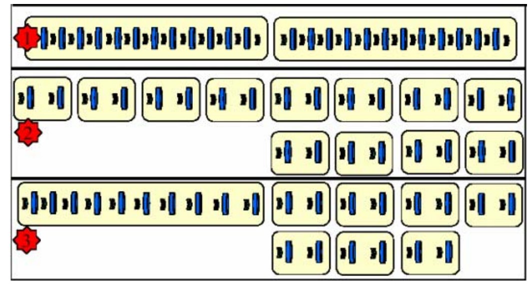

Figure 2: Different linac architecture philosophies.

2.4 Accelerator layout

The final proposed 5–80 MeV linac is composed of 84 spoke cavities, for an overall length of 91 metres. The main characteristics of the linac, including a preliminary cost estimate, are summarised in Table 1. More information about the technical design of the cryomodules can be found in [7].

Table 1: Layout of the 5 MeV–80 MeV spoke linac.

Beam intensity: 10 mA CW	**β=0.15 section**	**β=0.35 section**
Energy range (MeV)	5 – 18	18 – 80
# Cavities	30	54
# Cavities per focusing lattice	1	2
Focusing lattice length (m)	1.32	1.90
# Cavities per cryomodule	2	4
Synchronous phase	- 45° to - 30°	- 30°
Energy gain per real meter (MeV/m)	0.12 – 0.42	0.50 – 1.47
Beam loading RF power (kW/cavity)	1.6 – 5.6	5.5 – 14.0
Quadrupole gradient (T/m)	18 – 24	25 – 36
Beam aperture (mm)	50	60
Max. rms beam diameter (mm)	5.2	4.4
Overall length (m)	40 *(DTL: ~10)*	51 *(DTL: ~54)*
Preliminary cost estimate (M€) - without buildings & contengencies	9.7 *(DTL: ~5.2)*	17.1 *(DTL: ~18.2)*
Preliminary electricity cost estimate (M€/year)	0.12 *(DTL: ~0.7)*	0.55 *(DTL: ~3.3)*

3 BEAM DYNAMICS SIMULATIONS

Beam dynamics simulations have been performed using codes developed at CEA Saclay (GenLin, TraceWin, Partran). The calculations include space charge effects (PicNic routine), and multi-particle simulations are done using 10,000 particles. In all cases, we use the IPHI RFQ exit beam distribution as the input beam for the spoke linac; the normalized rms emittance is 0.27 π.mm.mrad in the transverse phase plane, and 0.39 π.mm.mrad in the longitudinal plane. The matching between the two spoke sections is achieved adjusting slightly the cavity phase and the quadrupole gradients at each side of the transition.

3.1 Matching with the RFQ

One of the most crucial points in this study is the matching with the previous RFQ section. One can show that a good matching can be achieved simply adding a β=0.15 spoke module between the RFQ and the spoke linac; in this additional module, the 2 spoke cavities are used at 90° synchronous phase for bunching. The advantage of such a solution is that no specific matching section is needed. Simulations show (see Fig. 3) that the beam envelope remains quite smooth at the transition.

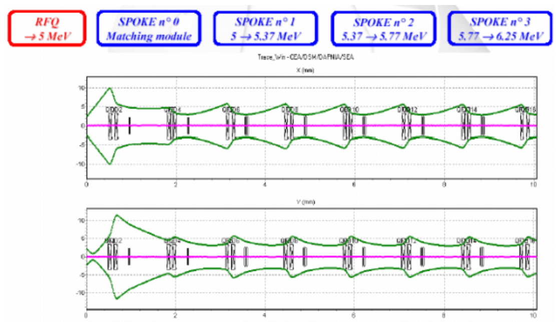

Figure 3: Matching with the RFQ.

3.2 Simulation results

In the case of a matched beam, the simulation results show very smooth envelopes, and an emittance growth below 5% (see Fig. 4). The main part of this emittance increase is due to the unavoidable discontinuity of the phase advance at the transition with the RFQ at 5 MeV. A smooth halo is noticeable at the linac exit, but it can be shown that this halo is produced inside the RFQ before injection in the spoke line.

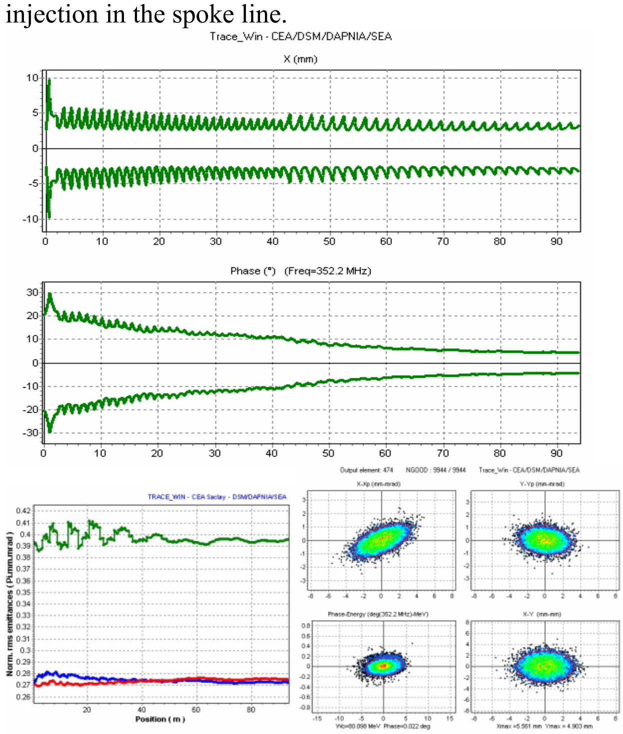

Figure 4: Simulation results for a matched beam: real beam envelopes, rms emittance evolution, and beam distribution at the linac exit (80 MeV).

3.3 Fault scenarios

One of the main issues of this study was to design a highly-reliable linac; in this context, the analysis of possible fault scenarios is a crucial point. Some first simulations indicate that our design is quite fault-tolerant, both in the case of mismatched beams, and in the case of failures of components. Figure 5 shows for example the case where a β=0.15 cavity fails: the longitudinal emittance immediately doubles, but the beam envelope remains quite regular, and no beam loss is encountered.

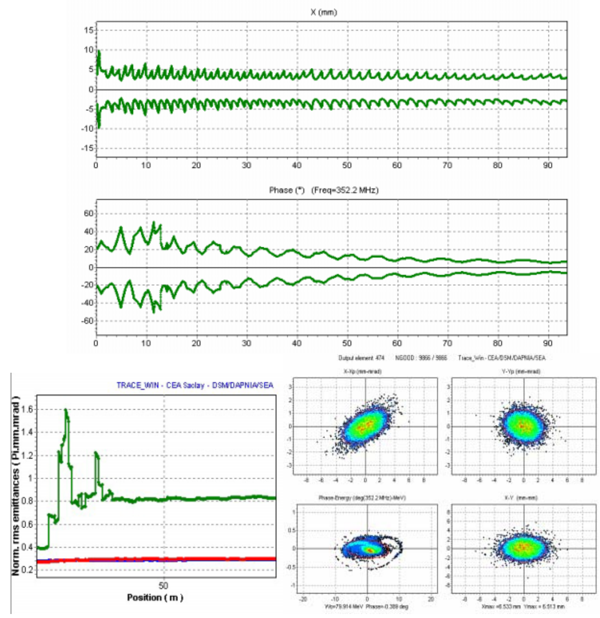

Figure 5: Simulation results: failure of a β=0.15 cavity.

4 CONCLUSION & PERSPECTIVES

The design of a 5–80 MeV high-intensity proton linac using spoke cavities is proposed, that could be applied to projects like EURISOL or XADS. This design has been made taking in account the very high reliability required by the XADS project. In this sense, a thorough campaign for fault scenarios has started, caring especially about the transitions both with the RFQ and with the β=0.47 704 MHz section; the aim is to reach a final design where the failure of most of the components can be accepted.

5 REFERENCES

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