SPIRAL 2 : A HIGH INTENSITY DEUTERON AND ION LINEAR ACCELERATOR FOR EXOTIC BEAM PRODUCTION

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Abstract

Based on the "LINAG Phase 1" conceptual design [1], a two years detailed study on a ISOL-type facility for the production of high intensity exotic beams, named SPIRAL2, has been launched. The rare isotope beams are produced via the fission process, with the aim of 10^{13} fissions/s at least, induced either by fast neutrons from a C converter in a UCx target or by direct bombardment of fissile material. The driver, with an acceleration potential of 40 MV, has to be upgradeable and versatile: it will accelerate deuterons (5 mA) and A/q=3 ions (1 mA) and even heavier ions in a later stage. It consists in high-performance ECR sources, an RFQ cavity and independent phase superconducting resonators.

The primary beam is transferred towards the production system, including converter, target and ion source. The exotic beam can be directly used in a low energy experimental area or is accelerated by the existing CIME cyclotron after increase of its charge-state by means of an ECR charge booster. The selection of the parameters as well as the technology result from an optimisation of the linac. Systematic beam dynamics calculations with space charge forces, 3-D field maps and alignment errors to check the robustness of the design and the very low loss rate all along the linac are in progress.

INTRODUCTION

In order to extend the study of the structure of nuclei far from stability to medium-mass nuclei at GANIL, a two-year detailed design study on an ISOL-type facility, named SPIRAL 2, has been launched. As the final intensities of RIB's will define the areas of the nuclear chart that will be accessible to experiments, high intensity primary beams as well as various production methods are needed. The production method of the rare isotope beams is based on a variation of the ISOL method by resorting to the fission process induced either by fast neutrons from a C converter in a UCx target, with the aim of producing more than 10^{13} fissions/s, or by direct bombardment of fissile material. Different types of ion source will be coupled to the target depending on their ionisation efficiency for the selected radioactive element. The isotopes will be bred to higher charge state for proper post-acceleration up to 6 MeV/u in the existing CIME cyclotron. In addition, the acceleration of heavy ion beams of high intensity, thanks to the forthcoming generation of ECR ion sources, will allow users to do fusion-evaporation physics. The driver, with an acceleration potential of 40 MV will accelerate 5 mA deuterons, 1 mA ions of mass-to-charge ratio A/q=3 and even higher A/q ions in a later stage (up to 6).

DRIVER LAYOUT

Due to the high beam power (200 kW) and to its modularity, the linac solution was chosen. As it must accelerate light ions (deuteron) and heavier ions of A/q=6, the linac was optimised in energy for A/q=3 ions. Moreover, the energy range of the driver for the heavy ions must be very flexible and extend from ~ 15 MeV/u to very low energies, as low as ~1 MeV/u. The main linac parameters are given in Table 1.

Table 1 : Main linac parameters

	A/q = 2	A/q =3
E_{in} [keV/u]	20	20
E_{out} [MeV/u]	20	14.5
$\varepsilon_{\perp}$ rms [π.mm.mrad]	0.2	0.4
ε_z rms [π.deg.MeV]	0.05	0.12
Intensity [mA]	5	1

Figure 1 shows the schematic layout of the driver. A first injector includes two ECR sources for deuterons and A/q = 3 ions, the associated Low-Energy Beam Transfers (LEBT) followed by a common RFQ cavity. A second injector for injecting the higher A/q ions beam is planned to run into the Medium-Energy Beam Transfer (MEBT). The beam is then accelerated up to a total energy larger than 40 MeV by an Independently Phased Superconducting Linac, providing a safe cw operation and high flexibility in the acceleration of different ion species and charge-to-mass ratios.

Ion sources

In order to avoid severe reduction of the beam intensity by using stripping foils at intermediate energies, one takes advantage of the continuous progress of high charge state ECR sources. The 5 mA deuteron beam will be produced either from a downgraded version of the high intensity SILHI source [2] (replacement of e.m. magnets by permanent magnets and modification of the extraction system) or from an improved version of the micro-phoenix source [3]. For the A/q=3 ions, the state-of-the-art in ECR sources gives 1 mA $_{18}O^{6+}$ and 0.2 mA $_{36}Ar.^{12+}$. High confinement fields (B_r ~ 2-3 T) and high frequency (f > 28 GHz) are required to increase the ion beam currents. Two options, based respectively on a fully superconducting ECR source and on a combination of permanent and high temperature superconducting magnets, are expected to start in 2004 in the framework of an european research program, named "Ion Sources for Intense Beams of Heavy Ions" (ISIBHI).

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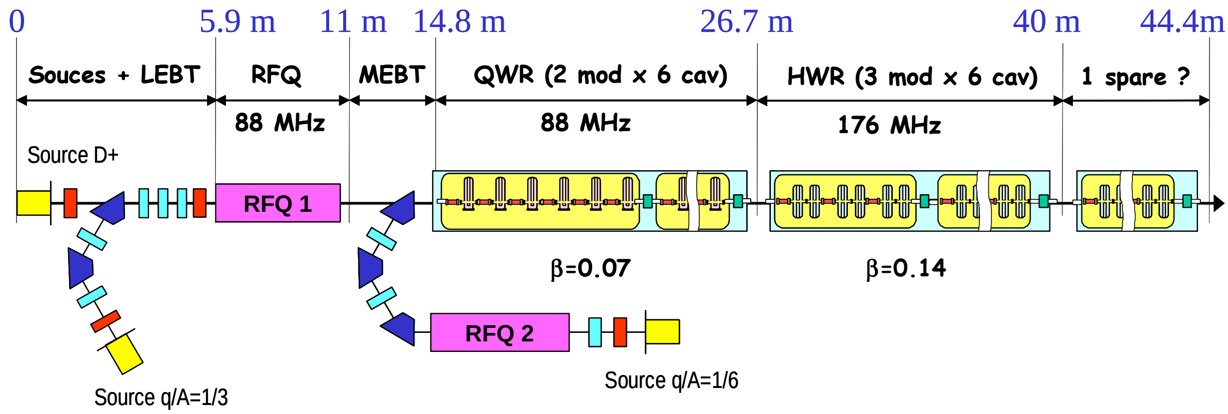

Figure 1 : Architecture of the SPIRAL 2 Linac

Frequency choice

On the one hand a low rf frequency at the linac front end offers a suitable longitudinal acceptance for the slow heavy ion beam, on the other hand a high rf frequency is preferred because of the more compact and consequently cheaper accelerating structures. As a tradeoff, a frequency jump at intermediate energy is generally chosen. Different frequency scenarii have then been studied:

- 88 MHz for the whole linac
- 88/176 MHz for the low/high energy part
- 176 MHz for the whole linac

Two types of superconducting cavities have been considered: Quarter-Wave Resonators (QWR) and Half-Wave Resonators (HWR). The former is quite convenient at low frequency whereas the latter is too bulky at low frequency but avoids the "steering effect" that can be detrimental for light particles [4]. The two-frequency scheme was finally chosen: the whole linac at 176 MHz leads to the highest number of resonators and the highest power consumption in the RFQ and jeopardizes the acceleration of heavy ions; the whole linac at 88 MHz gives the largest cavity aperture over beam size ratio but the too big diameters make the fabrication of resonators and cryostats tricky.

RFQ cavity

A high RFQ transmission is required (lower than 3% beam loss with all combined errors) to allow for hands on maintenance. Different technologies at 88 MHz were studied: the 4-vane type gives a safe cw operation even for a high electrode voltage (greater than 100 kV) and the highest transmission but a simplified mechanical design has to be found to compete with usually cheaper 4-rod or IH type RFQs. An only mechanically assembled cavity without brazing or welding and made from a simple copper tube is proposed. RF joints can be used because of the low power density (< 6 W/cm^2) and of the moderate magnetic fields (< 2500 A/m). Figure 2 shows the main parameters of the RFQ. The construction takes into account the non constant voltage and R_0 profile, the tolerances of 1% on the voltage law and of one tenth of mm on the vane tips displacement. One variant that introduces coupling windows in the vanes, also called "split-coaxial RFQ", thus reducing up to two times the external diameter, has not been retained because the peak power density is larger and the added complexity of the assembling makes the cost very similar.

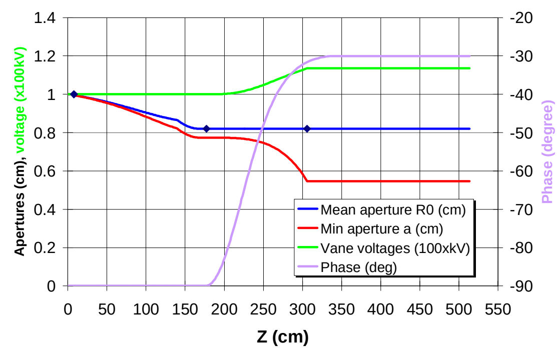

Figure 2 : Main RFQ parameters

The length of the RFQ is between 5 and 6.5 m, corresponding respectively to 0.75 and 1.0 MeV/u and will be determined by the results of start-to-end multi-particle simulations including all realistic errors.

Resonators and cryostats

Two resonator families that differ in geometric β and frequency are used. The β-values were optimised to give the shortest linac with a minimum number of resonators. The assumed accelerating field is 8 MV/m. The resulting linac comprises a total of 30 resonators and is composed of 2 modules of six β=0.07 resonators at 88 MHz and 3 modules of six β=0.14 resonators at 176 MHz. A slot is left at the end of the linac to allow for the installation of an additional 6-cavity module if the field of 8 MV/m could not be reached but decreased as low as 6.5 MV/m.

The shape of the resonators was first optimised to achieve the lowest peak fields. For example, the lowest electric and magnetic fields for the QWR type are obtained by enlarging the curvature radius of the drift tube and the stem diameter, respectively. The final geometry gives peak fields over accelerating field ratios of $E_{pk}/E_{acc} \sim 5$ and $B_{pk}/E_{acc} \sim 10$ mT/MV/m. An accelerating field of 8 MV/m leads to $E_{pk} \approx 40$ MV/m and $Bpk \approx 80$ mT, which should be achieved without too much effort by using the well-tried methods developed in the last ten years (high pressure rinsing, high purity niobium, clean conditions...). Besides, a conical shape of the stem and a rounded shape at the top improve the stiffening of the cavity. Figure 3 shows the geometries of both QWR and HWR types. Last, a slight modification of the wall at the beam ports location of the QWR will cancel the "steering effect" if beam dynamics calculations show that this effect is too strong.

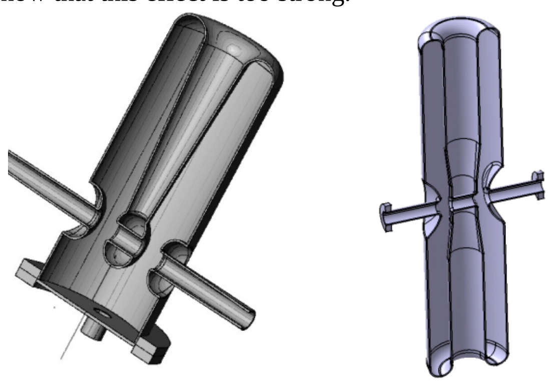

Figure 3 : QWR and HWR geometries

Up to now conservative values of spacing between the different components (bellows, flanges, cold-warm transition, etc) have been assumed. More attention will be paid to the reduction of these distances if the present cryostat length (~5 m) and inter-tank spacing are too large from the beam dynamics point of view.

LOW LEVEL RF

As a Low Level RF (LLRF) system is required for different types of accelerating structures (RFQ, QWR and HWR) fed by tube or solid-state amplifiers, the flexibility offered by digital systems makes them ideal candidates.

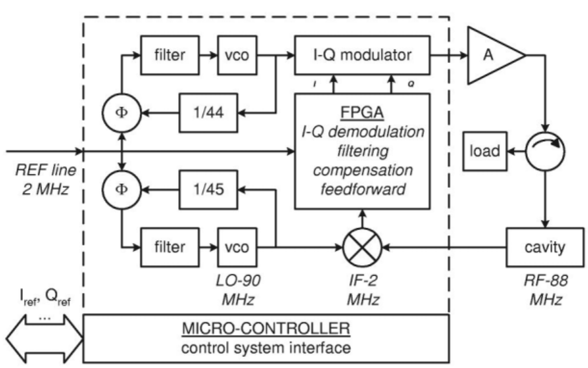

Figure 4 : Block diagram of the LLRF system.

A common hardware design (Figure 4) with a high integration level in a fast programmable logic chip (FPGA) will provide high performances in terms of noise and reliability and at a lower cost for manufacturing and maintenance. The reference signal of 2 MHz is sampled with the IF signal to provide a 4-quadrant I-Q demodulation. The dynamic compensation of the feedback loops, as well as an eventual feedforward, are implemented as IR filters in the same FPGA.

BEAM DYNAMICS

Two essential rules must be respected to avoid dilution and beam loss: the phase advance per lattice period must be lower than 90° and the beam must be carefully matched in all planes (longitudinal and transverse) between tanks. This statement favours a large number of cavities per tank and led to choose 6 cavities per cryostat. The focussing is ensured by solenoids instead of quadrupoles because the sensitivity to misalignments and the cost are lower but care must be paid to the tilt of the solenoids. The axial field is kept low enough (lower than 8 T) in order to use a classical technology of NbTi for the superconducting coils. Figure 5 shows for example the phase advance per cell and the beam power per cavity for a 5 mA deuteron beam and a maximum accelerating field of 8 MV/m. Detailed calculations are presented in [5,6]. The next step will be devoted to systematic start-to-end simulations including 3-D field maps and correction of beam steering induced by QWRs and alignment errors.

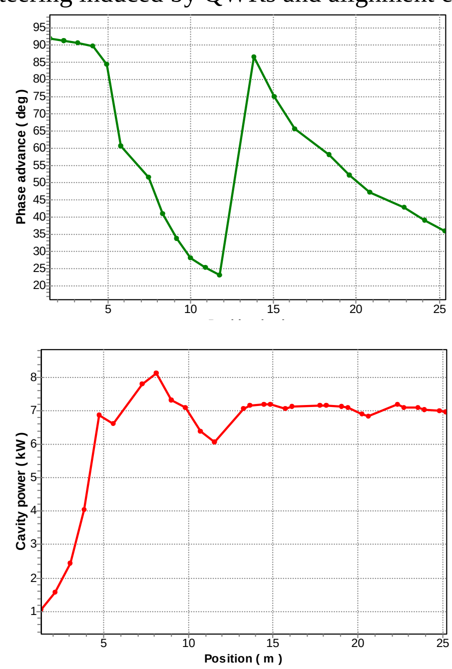

Figure 5 : Phase advance / cell (top) and beam power / cavity (bottom) along the SC linac for the D^+ beam.

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