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The project SPES at LNL: Accelerator challenges

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Abstract. The Project SPES (study and production of exotic nuclei) aims at the full design of a facility based on a 100 MeV, 1–30 mA CW proton Linac used for production of fission fragments from a uranium like-target by means of a neutron converter. Neutron rich ion species are extracted, selected, further ionized at high charge state, isotopically purified and then accelerated through a superconducting Linac at energies up to 20 MeV/A. SPES represents INFN's effort in view of the construction of the European next generation ISOL-type facility, which is expected to be operative by 2010. A conceptual design report of such a European facility is being prepared with the support of the European Commission. R&D activities, covering the most critical parts of the facility, have been partially started in the last two years, triggered by the French–Italian feasibility study of an accelerator driven system for waste transmutation.

Keywords. Radioactive beams; superconducting Linac; high intensity beams; RFQ.

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1. Introduction

Radioactive beams are known to be an important experimental tool to study nuclear physics and nuclear astrophysics, but also for research in fundamental conservation laws, material science, solid state physics, medical applications [1]. The two main techniques used to produce radioactive beams are the projectile fragmentation (PF) and the so-called isotope selection on line (ISOL) [2]. In both cases the beam intensity that can be obtained is orders of magnitude lower than the one of stable beams, and it is strongly dependent on the kind of isotope selected.

In PF a high-energy ion beam hits a thin target and exotic nuclei are produced in-flight at high charge states. The energy per unit mass of the secondary beam is approximately the same as that of the primary beam; the required isotope being selected and immediately driven to the experimental point. This technique allows to produce a wide variety of beams, including those of very short lifetime isotopes; however, the beam quality is relatively poor after the interaction with the target, and the energy is usually much above the Coulomb barrier value. An example of PF-based facility is FRS at GSI-Darmstadt [3].

In the ISOL technique the primary beam (or secondary neutrons produced by a primary beam) hits a thick target enclosed in an ion source; exotic nuclei, produced at rest in the target bulk, must drift out of the target material into the source volume, where they can be extracted in a low charge state. The beam quality is as high as one of stable beams, and the isotopes can be reaccelerated to the desired energy. The isotope selection is easier than in PF, but there is a longer delay time (of the order of tens of milliseconds) from production to extraction of the beam; this method, thus, is not suitable for very short-lived isotopes. An example of ISOL facility is ISOLDE at CERN [4].

2. International scenario and synergies

Many radioactive beam facilities are already in operation in the world, and many upgrading projects have been started or proposed [5]. Most of them are first generation facilities and consist of a RIB source based on a previously existing accelerator. The beam is used directly after production (PF, e.g the A1200 beam analysis system at NSCL-MSU [6]) or after extraction at low energy (ISOLDE). In second generation machines the radioactive beam is reaccelerated by means of a new dedicated reaccelerator; an example is ISAC at TRIUMF [7]) which recently started delivering reaccelerated beams.

Third generation facilities (e.g. the RIA project in USA [8], EURISOL in Europe [9] and the high intensity proton accelerator facility [10] in Japan) are being designed from the beginning with the aim of RIB production, allowing for much higher beam intensity, variety and quality than previously obtained. Such large facilities will be operative near the end of this decade.

The Legnaro Laboratories are deeply involved in the European project study EURISOL for a third generation RIB facility. The aim is to prepare a conceptual layout, to identify the possible synergies with other major European projects and existing laboratory infrastructures and finally to identify the key technologies involved and the R&D required.

One of the most promising design schemes studied in EURISOL consists of a $\sim$1 GeV, $\sim$ 1.5 mA proton driver, a neutron converter, a ISOL-type RIB ion source, a mass selector, a charge breeder to increase the charge state of the extracted ions, and finally a post-accelerator (Linac and/or cyclotron) capable to reach all beam energies up to 100 MeV/u.

A possible synergy of EURISOL is with the Italian project TRASCO [11] for nuclear waste transmutation by means of a ADS (accelerator driven system). Trasco includes the conceptual design of a 1 GeV–30 mA superconductive proton Linac and the development of critical components of the accelerator. Legnaro Laboratories are in charge of the Linac section up to 100 MeV; this includes the construction of the RFQ and prototyping of the Linac cavities.

3. SPES project overview

A wide variety of experimental utilities (accelerators and detectors) exist at LNL; the ALPI complex, consisting of a Tandem accelerator and a superconducting booster, is used by a large community of nuclear physicists, which is now asking for new experimental tools.

The good tradition in both the fields of nuclear physics, detectors and particle accelerators, the active participation to other radioactive ion beam projects (Eurisol, ISAC-II) as well as the availability of space within the laboratory territory, make LNL an ideal site for

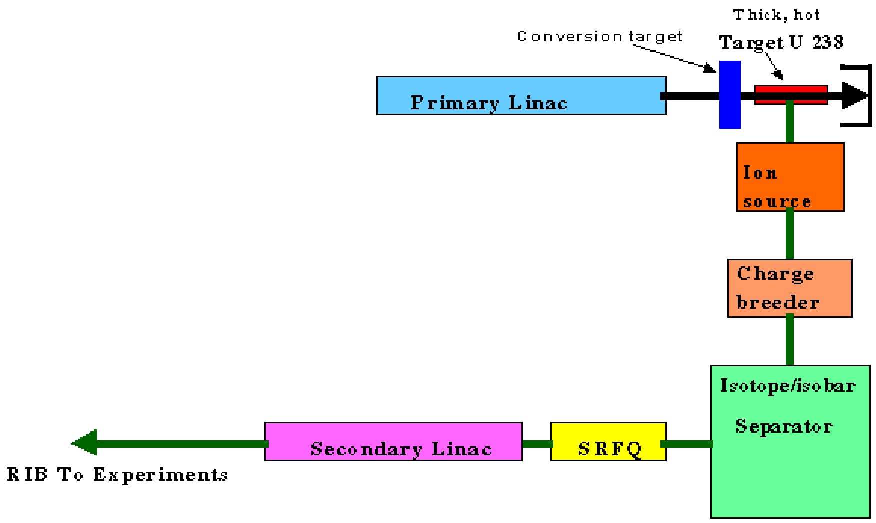

Figure 1. Schematic view of the proposed SPES radioactive beam facility.

a new facility which could take advantage of existing infrastructures. Other communities (solid state physics, material science and medical physics) have also shown interest in a RIB facility.

The SPES project aims to the construction of a radioactive beam facility at Laboratori Nazionali di Legnaro. SPES is the acronym for study and production of exotic species (the word, in the ancient Latin language, means 'hope'), and the first proposal was done in 1999 [12].

A schematic view of the proposed facility is shown in figure 1. The production method is the ISOL technique. The facility consists of a 100 kW, 100 MeV primary proton (or deuteron) beam hitting a neutron converter (a rotating carbon target or a liquid lithium target). Approximately 10^{14} secondary neutrons per second, at an average energy of 7.5 MeV, activate a thick uranium target enclosed into a RIB ion source. The beam can be selected and extracted at low energy, or reaccelerated up to 5–20 MeV/u with the LNL superconducting Linac ALPI [13]. In addition, SPES will provide a neutron source capable of 10^{14} n/s/cm^2.

Because of its structure, SPES could be viewed as a low-energy test bench both for EURISOL and for the TRASCO proton driver.

4. Accelerator issues

The preliminary layout of the SPES facility is shown in figure 2. The driver accelerator resembles very closely the TRASCO scheme (figure 3), with a high intensity proton source, a room temperature, cw RFQ and a independently-phased superconducting Linac (ISCL). The rf frequency is 352 MHz. The TRASCO Linac is designed to accelerate to 100 MeV

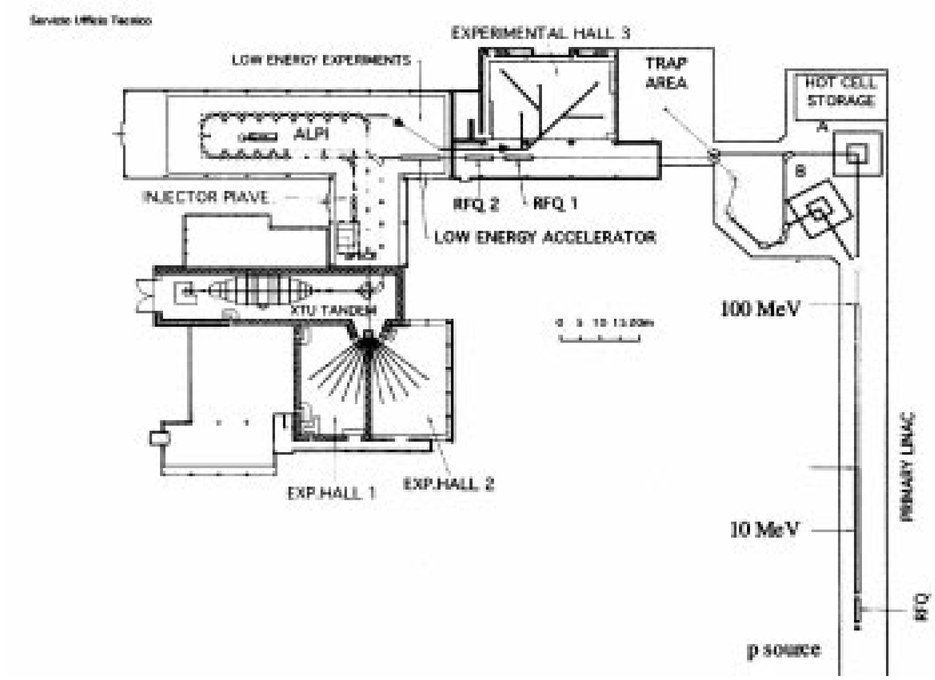

Figure 2. Preliminary SPES layout.

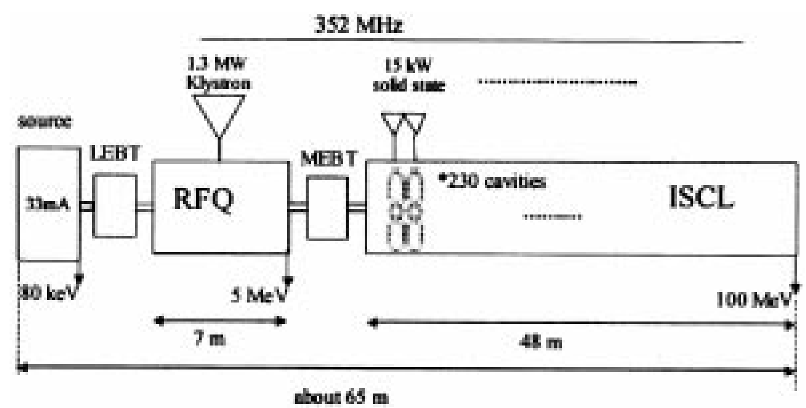

Figure 3. The TRASCO-SPES driver accelerator.

a 30 mA (equivalent to 3 MW power), cw proton beam, with high reliability required by the ADS reactor. The SPES Linac, however, is required to deliver only 100 kW to RIB source, and a scheme accelerating a 30 mA beam up to 10 MeV and 1 mA beam up to 100 MeV is being considered.

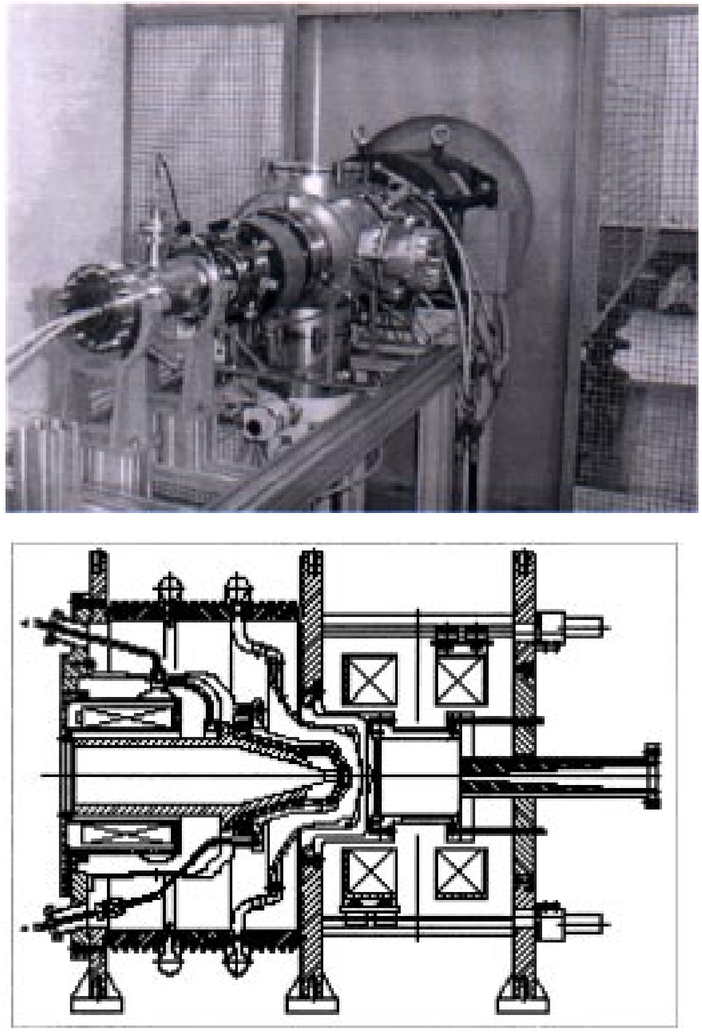

Figure 4. The high intensity proton source TRIPS built in Catania (courtesy of INFN-LNS).

The development of the critical components has started and some prototypes are under construction or commissioning. The parts related to the driver accelerator are being developed in the framework of the TRASCO project and of a French–Italian collaboration on accelerator driven systems.

4.1 *The proton source TRIPS*

This off-resonance microwave discharge source (figure 4), developed by INFN-LNS, Catania [14], is a modified version of the SILHI source operating at CEA/Saclay since four years [15]. SILHI has been run at 80 kV, 77 mA proton beam with a beam emittance of

Table 1. RFQ parameters.

Energy range	0.08–5	MeV
Frequency	352.2	MHz
Proton current	30	MA
Duty factor	100	%
Maximum surface field	33	MV/m (1.8 Kilp.)
Transverse emittance (in/out)	0.2/0.2	mm mrad (r.m.s. norm.)
Emittance L RMS	0.18	MeV deg
RFQ length	7.13	m (8.4 λ)
Intervane voltage	68	kV
Transmission	96	%
Modulation	1–1.94	
Average aperture R_0	0.29–0.32	cm
Synchronous phase	$-90/-29$	deg
Dissipated power SF*1.2	0.579	MW
Quality factor (SF/1.2)	8261	
Beam loading	0.1476	MW
RF power	0.726	MW

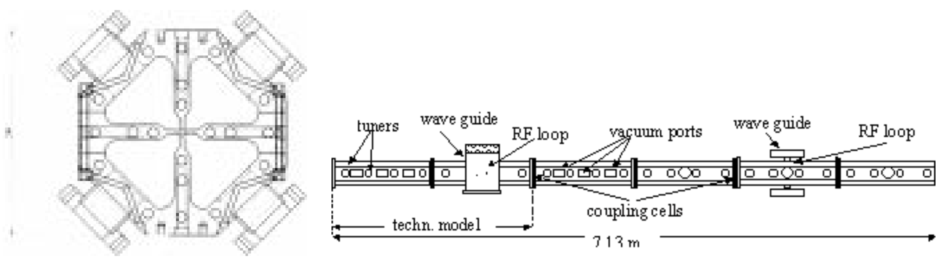

Figure 5. Cross section and schematic layout of the TRASCO RFQ.

0.17 π mm mrad; these performance more than fulfil the TRASCO and SPES requirements. The source TRIPS is presently under commissioning at LNS, Catania. After commissioning the source is planned to be transferred to LNL.

4.2 *The RFQ*

The RFQ [16] has been designed in details within TRASCO research program, and the copper resonator structure is under construction in the Italian industry. It is a high current, cw device able to accelerate 30 mA of protons from 80 keV to 5 MeV with beam losses lower than 4% to prevent copper activation. The total required rf power is 0.726 MW, fed through 4 coupling loops by a single LEP-type klystron with a nominal power of 1.3 MW. The cavity parameters are shown in table 1 and the schematic layout of the RFQ is shown in figure 5. The RFQ, of the four vanes type, is divided in six sections flanged together and its total length is 7.13 m.

The beam dynamics design includes a radial matching section, shaper, gentle buncher and accelerator sections. The average aperture is increased in the last section together with an increased electrode modulation.

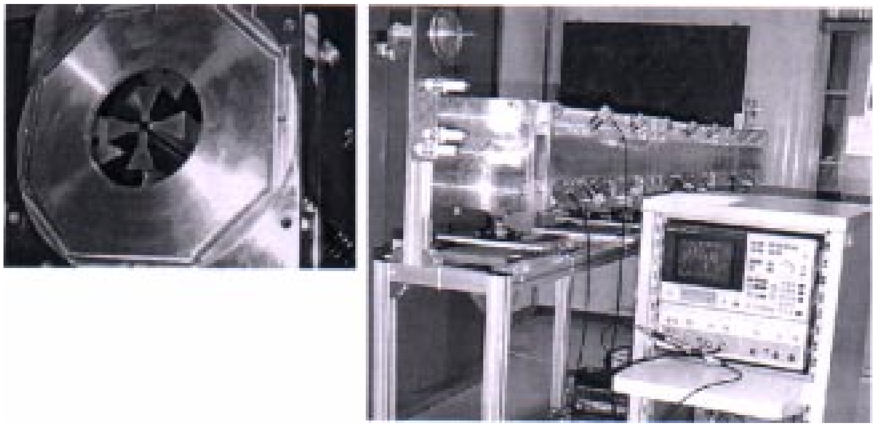

Figure 6. Aluminium RFQ model built for low power rf tests.

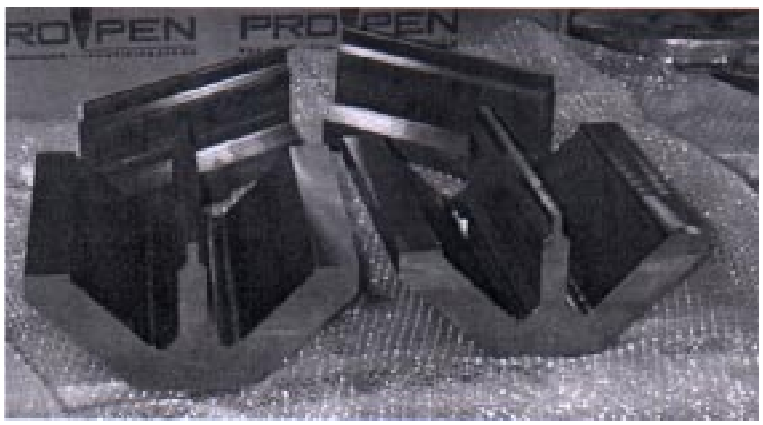

Figure 7. The four solid copper parts to be brazed together to form one rfq section, before milling of the final vane modulation profile.

An extensive optimization of the design parameters has been done to test the tolerances to errors and to minimize emittance growth; a mismatch lower than 6%, a beam misalignment better than 0.25 mm and a source r.m.s. normalized emittance better than 0.23 π mm mrad are required. These figures are consistent with source and LEBT specifications. To test the electromagnetic design of the cavity, a cold aluminum model (figure 6), was built and tested [17]. To achieve an optimum field stability and homogeneity, 96 mechanical tuners are required.

Since one of the main problems to solve in a cw high power cavity is the cooling design for high mechanical stability, effect of mechanical deformations on the electromagnetic field was studied extensively. The total water flow required in operation is about 3000 litres per minute.

The cavity is made of OFE copper; every section is made of 4 parts that have to be brazed together after machining (figure 7). As part of the TRASCO program, the first segment is being manufactured by the Italian company CINEL and will be tested at CERN with full power. The two remaining segments will be built as an extension of this program.

4.3 *The superconducting Linac*

For the SPES proton driver we considered an independently phased superconducting cavity Linac (ISCL) scheme [18], similar to that used for low energy heavy ions in many nuclear physics laboratories like ours; the required beam intensity, however, is many orders of magnitude higher: at 30 mA the rf power load are dominated by the beam, and the beam dynamics is dominated by space charge forces. We checked various superconducting resonators types; we chose the so-called ‘reentrant cavities’, cylindrically symmetric modified pillbox free from dipole components of the transverse electromagnetic field.

One of the advantages of this kind of Linac is its remarkable flexibility; it can be used in cw mode with good efficiency even with different kind of particles, like deuterons. In table 2 we list the main specifications and machine characteristics. An important constraint of the design was the beam reliability required by the TRASCO sub-critical reactor: to meet the ADS needs we imposed that the beam could be fully transmitted also in case of failure of one cavity. The failure of a rf power source appears to be the main reason of shut down in existing Linacs; if the beam survives a single failure, and if the amplifier can be replaced on line in a reasonably short time, the resulting availability of the Linac can be highly improved [19].

For the transverse focusing we have chosen a FODO structure with period $8\beta\lambda$ (figure 8). As the period becomes longer, a larger number of cavities can be installed between the superconducting quadrupoles, and the quadrupoles gradient can be kept constant along the Linac.

Table 2. ISCL Linac parameters.

Energy range		5–100	MeV
Total length		48	M
Synchronous phase		-40	Deg
Average acceleration		1.82	MeV/m
Number of cavities		230	
Cavity bore radius		1.5	cm
Quadrupole gradient		31	T/m
Quad aperture/length		2/5	Cm
Output RMS	Trans. (normalized)	0.42	mm mrad
Emittance	Long.	0.2	MeV deg
Current limit (losses $< 10^{-4}$)		>50	mA
RF dissipation ($R_s = 100$ nΩ) ($R_{\mathrm{BCS}} = 39$ nΩ)		1204	W(@4.5 K)
Beam loading		2.85	MW
RF sys. pwr. cons. ($\eta_{\mathrm{rf}} = 50\%$)		5.7	MW
Static cryo. losses (10 W/m)		480	W
Cryo. sys. cons. ($\eta_{\mathrm{cryo}} = 1/500$)		0.84	MW
Quadrupoles and ancillaries		0.5	MW
Mains power		7.04	MW
Power conversion efficiency		40%	

Table 3. Resonator parameters calculated by means of the code SUPERFISH.

Total length	135	mm
Internal length	80	mm
Bore radius	15	mm
Frequency	352	MHz
U/E_a^2	0.034	J/(MV/m)^2
E_p/E_a	3.05	
H_p/E_a	30.6	Gauss/(MV/m)
$\Gamma = R_s \times Q$	83.9	Ω
$R'_{\rm sh}$ (Cu)	18	MΩ/m
β	≥ 0.1	

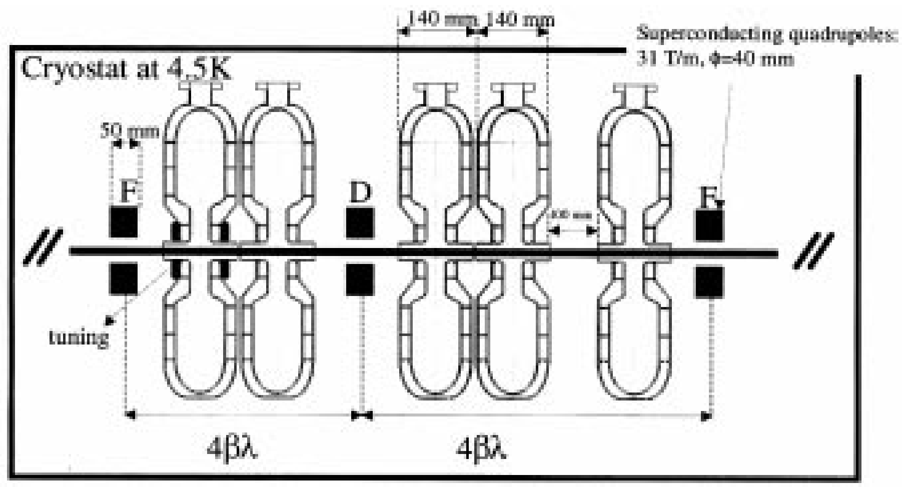

Figure 8. The ISCL structure.

The beam dynamics has been simulated with the code PARMILA using 100 000 macro particles and we did not observe losses up to 50 mA proton beam current. Error studies have been performed, considering various kinds of quadrupoles misalignment and in presence of a cavity failure; the preliminary results show very promising alignment tolerances (of the order of 0.1 mm).

4.4 *Reentrant cavity design*

The first superconductive re-entrant cavities have been developed at Stanford in 1978 [20]. The results of this pioneering work prompted us to develop a resonator suitable for high intensity, low beta proton beam [21]. The single gap allows a large velocity acceptance and the possibility of a 30 mm bore diameter, relatively large considering the low particle velocity and the 352 MHz frequency.

The cavity geometry (figure 9) has been analysed with the SUPERFISH code (table 3). Since the main limitation in low-β superconducting cavities is often determined by the

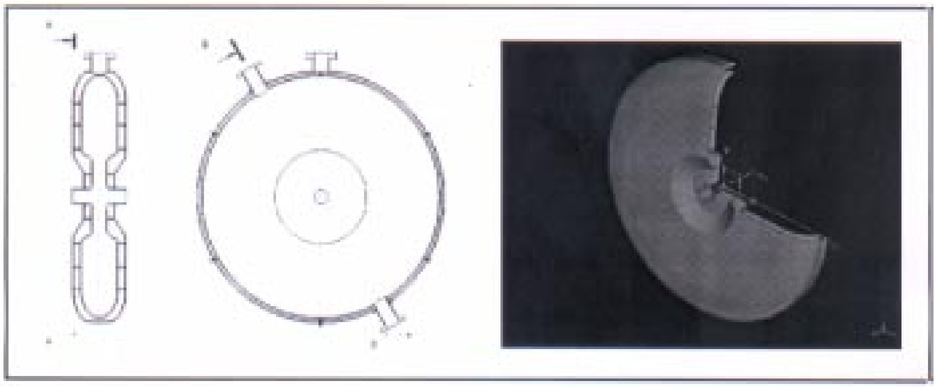

Figure 9. The 352 MHz superconducting reentrant cavity.

maximum achievable surface electric field, related to the onset of field emission, and since our Linac design required relatively low energy gain per cavity, we looked mainly for low surface electric and magnetic field, and short physical dimensions.

The RF power will be fed through an inductive coupler, still under study, located at the resonator equator. Since the strong multipacting is one of the main concerns in these pillbox shaped cavities, the geometry has been optimized by means of the code TWTRAJ [22] for MP simulation. The region where most of the multipacting levels is concentrated, in the 'pillbox' design, is the resonator equator. Electrons originating in high electric field regions drift to the equator and are collected there, building very strong levels with various multiplicities. This region has been properly shaped with an elliptical contour (ratio between axes 1:1.5) and all high field levels have been finally eliminated.

One of the problems we faced in the mechanical design was related to the large force acting on the relatively flat and wide resonator surface. The niobium sheet, 3 mm thick, could not sustain the pressure in the absence of strong reinforcement.

We tackled this problem using a new approach: in our design, the helium vessel is part of the resonator and is welded to the resonator wall so that the net force on the total structure is nearly cancelled. This design allowed us to improve significantly the mechanical stability while keeping a relatively light structure. The liquid helium is fed by gravity through a flange on the top of the resonator and there is no separation between the beam vacuum and the cryostat one.

The tuning is obtained, changing the gap length, by means of a mechanical tuner connected to the external part of the drift tubes. The foreseen cw mode of operation gives a nearly constant radiation pressure on the walls that can be compensated by the tuner. The experimental study of possible mechanical instabilities and of their remedies, however, is one of the aims of this prototype construction. For the design and simulation of the mechanical structure we used the code I-DEAS.

A prototype cavity is under construction and the first testing is foreseen within June 2001.

4.5 *Studies on 2-gap superconducting low beta cavities*

The ISCL design based on reentrant cavities is justified by the constraint of a 0.5 MeV maximum energy gain per cavity; this value is dictated by the requirement of a beam transport without losses, with no change of the Linac operational parameters, even in case of failure of one cavity. Since this requirement is not a necessity in a RIB facility, a cost effective Linac design could be based on 2 gap, high gradient superconducting cavities. The number of resonators would be nearly halved; the Linac overall length and cost could be reduced significantly. 2-gap cavities for a similar application have been first developed at Argonne [23].

The experience acquired by INFN in the development of superconducting quarter wave resonators for low beta heavy ions allow to aim to short cavities able to provide from 1 to 1.5 MeV acceleration [24]. A design of such cavities is shown in figure 10. The 30 mA beam loading per cavity would reach 30–45 kW, value that would require the use of the CERN LEP rf couplers technology. This power range is very well covered by commercial Klystrode rf amplifiers, that combine a very high efficiency, high gain and good linearity characteristics. In the 1 mA case, however, the beam loading would be only 1–1.5 kW; solid state amplifiers would be the natural choice and space charge forces would be negligible in the beam dynamics. R&D on high efficiency, low cost 352 MHz MOSFET amplifiers for accelerator applications started last year at LNL in collaboration with the laboratory LURE at Orsay, and the first 300 W modules have been constructed and successfully tested [25].

The field distribution in the rf gap of a short QWR contains dipole components that could cause beam steering and emittance degradation. Studies are being performed in order to minimize this effect, both by geometrical optimization of the cavity shape [26] and by a properly designed Linac lattice. The dipole field components are absent in half-wave resonators, at the price of a more complicated geometry. HWRs performance is expected to be comparable or even superior to QWRs one.

A prototype of a $\beta = 0.25, 352$ MHz QWR is under construction and it will be tested within spring 2001.

4.6 *The reaccelerator*

The SPES reaccelerator will be the existing superconducting Linac ALPI. To bring the charge-breeded RIB to the ALPI injection energy of 1.2 MeV/u, a new injector is required. This will be a copy of the PIAVE injector [27], under construction at LNL and consisting of 2 superconducting RFQ and 8 low beta quarter wave resonators. Since the radioactive beam source cannot be located in a high voltage platform, as it is in PIAVE, a third superconductive rfq will be required to accelerate the low energy beam extracted from the source to the minimum PIAVE energy of 35 keV/u. A sketch of the PIAVE injector is in figure 11.

Recent achievements in multiple charge state beam transport [28] allow including at least one stripping stage in the reaccelerator, with tolerable or negligible beam intensity losses and significant increase of the Linac efficiency.

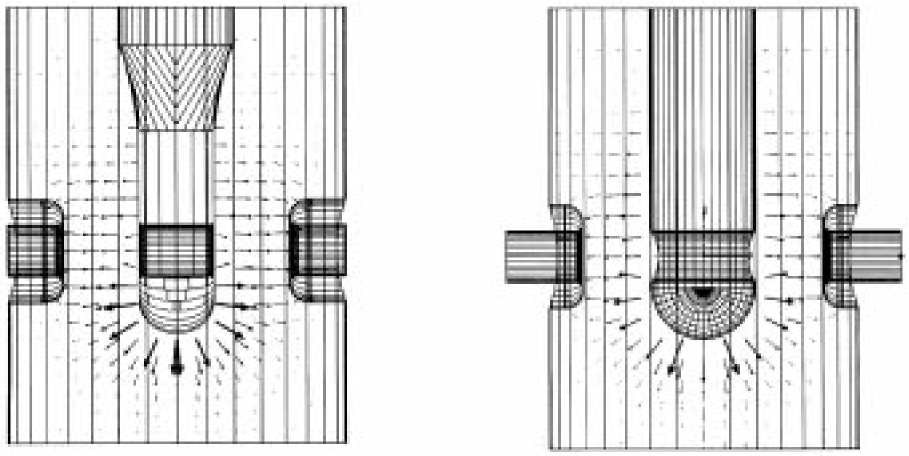

Figure 10. The $\beta = 0.22$ and the $\beta = 0.25$, 352 MHz cavities, of the same family of the 80 MHz cavities developed at LNL.

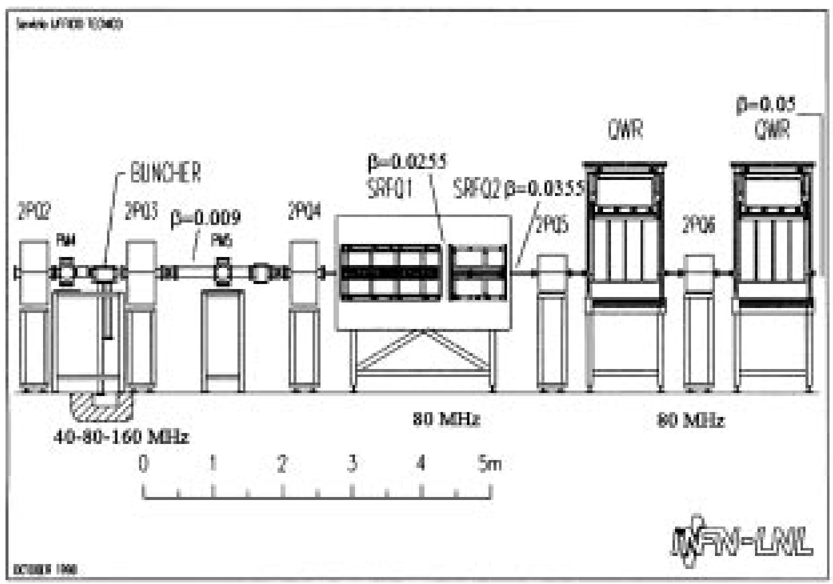

Figure 11. PIAVE superconducting injector layout.

5. RIB source R&D status

A research and development program has started at Legnaro in the field of RIB sources [29]. An ISOL test-bench was set up at the 7 MV CN Van de Graaf (figure 12). A 7 MeV, 3 μA deuteron beam (21 W) on a thick beryllium target gives a neutron yield at

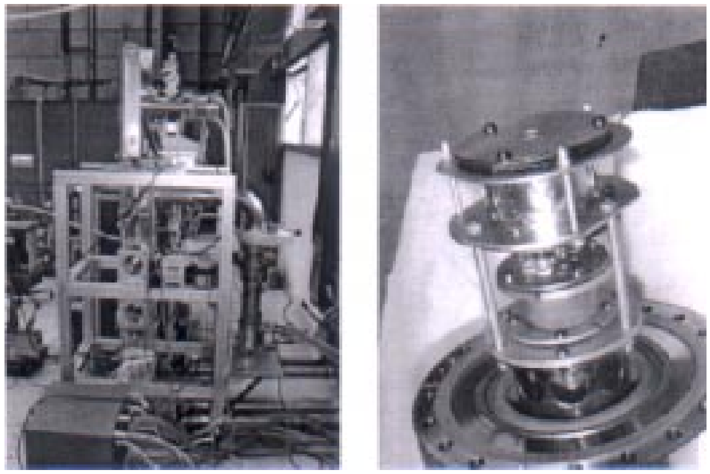

Figure 12. The SPES RIB source test bench and a detail of the source.

$0°$ of 8.5×10^9 n/μA/sr. The secondary neutrons induce fission on a uranium carbide target. Fission fragments produced at rest are extracted, ionized, accelerated to 20 keV and analysed through a mass separator $(\Delta A/A \cong 1/1800)$; isobars of interest are implanted in an aluminized mylar tape and identified off-line. The first experiments showed that the target assembly could withstand temperature in excess of 2000°C, with collection efficiency of isotopes like ^{90,92}Kr, ^{140,142}Xe close to that obtained in other labs in similar experimental conditions.

Monte Carlo simulations (MNCP and MCNPX codes) of the fission fragment production rate in the two target scheme (neutron converter decoupled from the production target) are in progress for different configurations, converter material and proton energies.

6. Summary and conclusions

SPES is a project for a radioactive ion beam facility at LNL. The facility requires challenging developments in accelerator technology for high intensity proton beams and superconducting rf cavities. As a driver, SPES is planned to use a modified version of the 100 MeV high intensity proton Linac designed for the TRASCO project. The reaccelerator will be the existing ALPI Linac that will require a new injector based on three superconducting RFQ resonators. The planned RIB source is based on a neutron converter and a uranium target. The project is presently in the stage of design study and prototyping of critical components.

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