RECENT RESULTS IN THE FIELD OF HIGH INTENSITY CW LINAC DEVELOPMENT FOR RIB PRODUCTION

A. Pisent, INFN/LNL, Legnaro, Padova, Italy

Abstract

High Intensity CW Linacs have been proposed as driver accelerators for RIB production in various projects, since they can drive in steady conditions a MW power range target for the production of spallation neutrons that induce fission in a natural uranium target. The necessity to develop a superconducting intermediate energy part with good power conversion efficiency is particularly important for this application, with a relatively low beam current. The second specific requirement of RIB facility drivers, which is also fulfilled by a superconducting intermediate energy linac, is the necessity to keep some flexibility in the species that can be accelerated (deuterons or light ions). In EURISOL RTD project, a 1 GeV 5 mA proton linac has been proposed for this application. In the SPES project, recently approved for its initial phase at LNL, a lower energy proton beam will be used on a solid target. The results of the specific R&D programs in the field of CW RFQ and superconducting low energy linacs will be illustrated. In particular for LNL the status of the RFQ construction and the superconducting cavities prototype tests will be given.

HIGH INTENSITY FOR RIB PRODUCTION

In the last years the availability of new intense radioactive ion beams (RIB) has been recognized as a fundamental tool for future research in Nuclear Physics, and new major facilities have been proposed worldwide (Table 1). By means of RIBs it is possible to study the properties of nuclei that, due to their short life-time, cannot be used as a target. Therefore RIBs allow to extend the knowledge of nuclear structure to exotic compounds and to study conditions that are relevant for the understanding of the early stage of the Universe and for the nucleo-synthesis.

Of the two complementary methods for RIB production, the In Flight (IF) and the ISOL (Isotope Separation On Line), the second one takes directly advantage of the development of cw high intensity linacs.

The basic scheme of an ISOL facility [1] is the following: the primary accelerator beam induces a nuclear reaction in a thick target, producing unstable nuclei. During their short life-time the isotopes evaporate from the target (kept at high temperature), are pumped into an ion source, ionized, extracted, selected by a magnetic spectrometer, accelerated and sent into the experimental apparatus. The RIB intensity actually delivered to the experiments is mainly the product of the primary beam intensity, the cross section of the specific production and the various efficiencies. These efficiencies take into account the particle losses occurred during the effusion from the hot target and the diffusion in the ion source, the nuclei that decay before reaching the experiment and the transmission of the spectrometer and of the reaccelearator. Even if the improvement of the efficiencies and of the ion selectivity of the spectrometer are under many aspect the key points for the success of an ISOL facility, a large flux of primary particles is the initial point.

In Europe the future for the IF method is assured by the GSI project FAIR[2], while for the ISOL method a large group of research institutions, including the major Nuclear Physics laboratories, have joined the EURISOL project, funded by EU, for the determination of the most competitive new generation ISOL facility for Europe. The resulting EURISOL report[3] has been published last year, and more recently the EU has positively evaluated a second stage design work (EURISOL-DS), now in negotiation stage, that includes the funding of prototypes of some critical issues.

Thanks to the complementarity with FAIR, EURISOL is mainly concentrated on the use of a 1 GeV high power proton linac, while the American project RIA, including IF method, considers a lower intensity linac able to accelerate ions up to uranium. For this reason this paper will be centred on European development, even if at present the most performing cw proton beam for RIB production is produced by a cyclotron in America (ISAC at TRIUMF[4]).

In particular in EURISOL design the direct use of a p beam of “moderate” intensity (tenths of mA) on a solid target will allow in most cases to operate at the limit of the target possibility (in terms of power dissipation density) with RIBs intensity much larger than the one available today.

Neutron reach isotopes are instead most efficiently produced by fission reaction with the two targets method: a very high fission rate (exceeding $10^{15}s^{-1}$) can be induced in a depleted uranium carbide target by fast neutrons; the fast neutrons are produced by spallation in a MW class (liquid metal) target.

Therefore, the EURISOL reference facility foresees three 100 kW target stations and one 5 MW target. Correspondently, the linac will have two modes of operation, at 100 μA and at 5 mA. Moreover, the possibility to accelerate light ions with the same driver has been explored; in particular the upgrading of the injectors needed to accelerate ions with A/q=2 up to 500 A MeV and A/q=3 up to 100 A MeV have been considered.

To assure the continuity in RIB research development some new ISOL facilities are proposed in Europe for the next decade (Tab. 2). In EURISOL-DS proposal and in NuPECC Long Range Plan a “EURISOL road map”

Table 1: Main new RIB facilities under discussion worldwide

Location	Driver	Post-accelerator	Fragment separator	Type of facility
Europe: GSI (Germany)	synchrotron, heavy ions: 1.5 A GeV	-	'Super-FRS'	In-Flight
Europe: EURISOL	protons, 1 GeV, 1-5 MW	CW Linac, up to 100 *A* MeV	-	ISOL
USA: RIA Rare Isotope Accelerator	900 MeV protons heavy ions: 400 *A* MeV, 100 kW	Linac up to 8–15 A MeV	4-dipole separator	ISOL, In-Flight
JAPAN: RIKEN RIB Factory	Ring-cyclotrons up to 400 *A* MeV (light ions); up to 150 *A* MeV (heavy ions)	-	3 fragment separators storage & cooler rings	In-Flight

Table 2: New ISOL facilities in EUROPE

Location	RIB Starting Date	Driver	Post-accelerator
SPIRAL-II: GANIL Caen, France	2008	SC linear accelerator LINAG deuterons up to 40 MeV heavy ions up to 15 *A* MeV	cyclotron CIME $K = 265$, 2–25 *A* MeV
MAFF Munich, Germany	2008	reactor 10^{14} *n/cm²*.*sec*	linac up to 7 *A* MeV
SPES Legnaro, Italy	2008 (Initial phase)	SC proton linac 100 *MeV* Initial phase 20 *MeV*	ALPI linac 15-20 *A MeV*
ISOLDE upgrade CERN	2008	PS booster p, 1.4 GeV, 10 μA	linac up to 5 *A* MeV

with the realization of these new facilities on National Laboratory scale is described.

In particular SPIRAL2 [5] at GANIL, using a low frequency (88 MHz) superconducting linac, will explore the production of RIBs with deuteron primary beam, and the double target method, with a fission rate of 10^{13}s^{-1}or more. The facility SPES[6] at LNL will develop a superconducting proton linac (100 MeV, operating at 352.2 MHz) with the same characteristics of the intermediate energy section of EURISOL driver; this proton beam (with a solid converter in Be or ^{13}C and a UC$_X$ target) will also allow to exceed 10^{13} fissions s^{-1}. Both SPIRAL2 and SPES linacs are open to the implementation of a second injector for heavier ions.

PROTON DRIVER

In Fig. 1 the schematic layout of the EURISOL proton linac is shown. Since the main choices are determined by the high energy section, the layout will be described backwards.

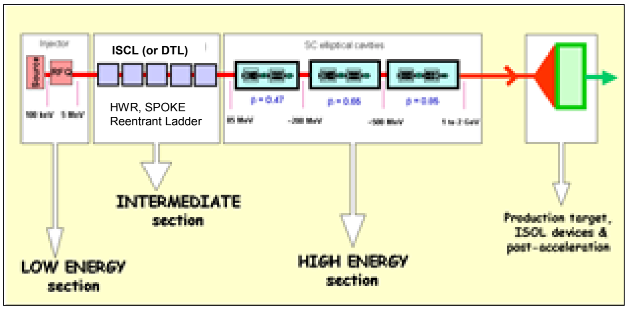

Figure 1: Schematic lay-out of EURISOL proton driver.

Main Linac

The high energy part of the linac will be superconducting as well as established with SNS experience; 704 MHz elliptical cavities with high gradient (above 10 MV/m) can be used. In EURISOL TDR 5-cell cavities are used, with β=0.47, β=0.65 and β=0.85 up to 1 GeV, for a total number of 134 cavities and a linac length of 270 m [3,7]. An intense prototype program for these cavities is under way at CEA-CNRS France and at INFN Italy for RIBs and ADS applications. In Fig 2 a prototype of a β=0.65, 5-cell cavity recently fabricated in France and successfully tested is shown[8]; the β=0.47, 5-cell cavity built in Italy has also exceeded the nominal performances[9].

The superconducting main linac guarantees high gradient, low power consumption and therefore convenient real estate length and power conversion efficiency for this linac which has to work in a wide range of beam currents.

For RIB users the time structure of the primary beam is not a requirement since they see the continuous beam after the effusion from the hot target. It is therefore convenient to build a CW linac since, besides avoiding thermal shocks in the target, the linac operation is simplified due to the absence of Lorenz force detuning in the transient. Moreover, with CW operation the RF power per cavity is minimized (below 50 kW), the couplers can be easily developed and low power RF units can be installed for each cavity, with an important simplification of phase control.

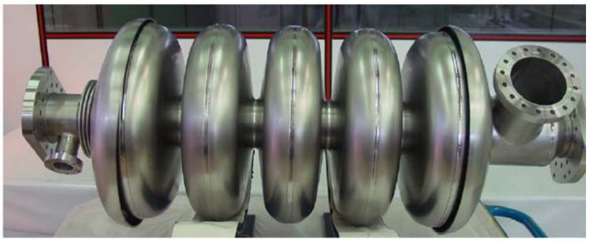

Figure 2: Prototype of a β=0.65, 5-cell cavity fabricated in France.

On the other hand, the analysis done by EURISOL target working group shows that a pulsed linac, with repetition rate higher than 50 Hz, is acceptable for the high power target. As a consequence, if EURISOL shared the driver with other applications (as for example at CERN using SPL), the driver could be pulsed. This also implies that it is preferable that all the superconducting cavities developed for RIB production have the capability to work in pulsed mode.

The Low Energy Linac

The low energy driver linac is based on independently phased superconducting cavities (ISCL) with a capability of 5 mA. The beam current choice is convenient for this linac, since a power level below 15 kW per amplifier can be achieved with solid state technology.

The RFQ Injectors. The front end of the linac delivers a cw beam of 5 mA at 5 MeV. RF ion sources like SILHI and TRIPS are perfectly capable to produce this beam with good emittance and reliability.

The RFQ structure has to operate at 352 MHz, since a lower sub-multiple of 704 MHz would generate a larger longitudinal emittance difficult to be managed in the superconducting linac with a high power beam.

It exists a well established development of cw RFQ for protons at this frequency, with the successful operation of LEDA [5] (100 mA, 6.7 MeV) at LANL and the two European projects IPHI (100 mA, 5 MeV) at CEA-CNRS [10] and TRASCO (30 mA, 5 MeV) at INFN-LNL [11]. These two accelerators, conceived for ADS development, will both be used for fundamental physics (and partly for RIB production).

IPHI RFQ will be built up to 3 MeV (one of the modules has already been brazed) and, after being tested cw at CEA Saclay, it will operate at CERN in pulsed mode as front-end of Linac4[12]. TRASCO RFQ will be used as injector of SPES (two modules have already been brazed) and will be used at full current for interdisciplinary applications.

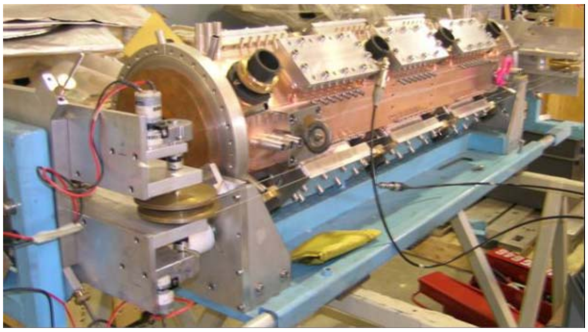

Figure 3: First module of TRASCO RFQ during final RF measurements.

The beam loading in RIB case is rather small (25 kW), in comparison with the power dissipated in the copper (700 kW in TRASCO and more than 1 MW in IPHI) and this makes the RFQ rather inefficient from an energy consumption point of view. Thus a lower intervane voltage structure like TRASCO RFQ suits better since in this case for 30 mA beam current the problems of an RFQ with a beam loading almost negligible with respect to the copper power (150 kW vs 700 kW) has already been faced. In this respect this RFQ is optimized also for 5 mA.

In particular the power dissipation is minimized, a single LEP klystron is used, and the construction procedure is simplified to reduce the costs, at the expenses of a worst control of the non linear components of the focusing field. This last simplification is possible since both for 5 mA and 30 mA the non linear space is not predominant.

From the beam dynamics point of view a 30 mA RFQ can accelerate a 5 mA beam, with virtually full transmission, good emittance and low beam halo parameter [13]. The MEBT has of course to be flexible enough to match the different Twiss parameters. Moreover, in TRASCO RFQ simulations (PARMTEQM) the appearance at low current of a structure with two peaks in the longitudinal phase plane distribution has been observed, due to the very incomplete mixing of the subsequent longitudinal oscillations. This structure survives in the intermediate energy linac (without any dangerous consequences), but its effects in the main linac have still to be investigated.

The possibility to use a superconducting RFQ for this cw low beam loading application has also been taken into consideration. Indeed for these parameters 1% beam losses can correspond to 250 W dissipated in the cryostat at 4.2^0K, a too large number to be managed by the cryogenic system. It is very difficult to envisage beam losses lower than 1% in a RFQ, especially with the mechanical tolerance achievable in a Nb construction, so that unfortunately it will not be possible to use the LNL successful development in SRFQ for this application. On the contrary an SRFQ is very well suited as first element for the reacceleration of RIBs.

Intermediate Energy Superconducting Linac. For the intermediate part of the linac, between 5 and 85 MeV, covered by normal conducting DTL in present linacs, we considered the use of an ISCL; this implies the use of many superconducting cavities evolution of those developed for heavy ion linacs. Proton low beta cavities are under development in many laboratories, starting from the early works more than one decade ago (see for example [14]). In Fig.4 the realized prototypes of some of the cavities considered in EURISOL-TDR are shown (re-entrant[15], half wave coaxial [16]and spoke[17]).

In EURISOL-TDR the normal conducting and superconducting options were compared, showing a similar capital cost but, for the specific application (5 mA cw), a running cost much higher for the normal conducting DTL (about 2M€/year difference).

A key (and not uniquely solved) problem for this kind of structure is the choice of the focusing structure, to allow the efficient use of high performance cavities and the achievement of a high real estate gradient. Typical values for the energy gain per cavity (at $\phi_s=0$) ΔW go from the 0.6 MeV of re-entrant cavities, to 1-1.5 MeV for multi gap structures.

The beam dynamics has to cope with space charge effect and possible single particle and envelope resonances, so that starting with a realistic distribution out of the RFQ the beam quality in the main linac is maintained and beam losses are negligible. A well designed ISCL has to generate a beam quality comparable with a DTL, that has the advantage of a shorter focusing period.

In particular the parametric resonance, occurring when the longitudinal phase advance is about twice the transverse phase advance, must be avoided to preserve beam quality. A more conservative criterion, that takes into account also other low resonances, is $\sigma_{0L} \le \sigma_{0T}$. Moreover the transverse phase advance per period σ_{0T} is limited to $\pi/2$ due to the envelope instability. As a consequence $\sigma_{0L} \le \sigma_{0T} \le \pi/2$ limits the period length L and ΔW, since:

$$\sigma_{0L} = L\sqrt{\frac{eE}{mc^2}\frac{2\pi\sin(-\phi_s)}{\beta^3\gamma^3\lambda}} \approx \sqrt{\frac{n\Delta WL}{\lambda}}\sqrt{\frac{2\pi\sin(-\phi_s)}{mc^2\beta^3\gamma^3}}$$

with E real estate average accelerating field, n number of cavities per period, β and γ relativistic parameters and λ RF wavelength. In other words, the use of a low number of high performance cavities (high ΔW), that is economically advantageous, requires the compactness of the period and of the cavities themselves. These problems are much worst at low energy.

The first consequence is that the use superconducting quadrupoles to be installed inside the cryomodule is almost necessary at low energy (even if the solution with many short cryostats has been considered[17]); secondly the doublet lattice is preferable respect to the FODO lattice, allowing a larger space for cavities during each period (even if 4-gap ladder cavities and FODO lattice can be assembled in a very efficient linac [18]). Finally, very compact cavities in longitudinal direction are needed, even when this has to be compromised with smaller beam bore aperture.

For example in the nominal layout studied for SPES linac between 5 and 10 MeV, 37 re-entrant cavities and 12 superconducting quadrupole doublets are assembled in two long cryostats with a short focusing period (0.7 m in the first cells), and an overall real estate gradient of about 1.3 MV/m [19]. Above 20 MeV HWRs, housed in cylindrical cryostats (similar to ALPI modules) and external normal conducting doublets can be used. The total length of this linac (5-100 MeV) is about 50 m, with full transmission under fair construction error conditions and an rms emittance increase below 10%.

Moreover, a linac of this kind is an open structure, since ions with A/q up to 3 and higher can be accelerated substantially to the same energy per charge unit. The flexibility of this kind of linac allows also to cope with the possible failure of some of the hardware, as studied in details for ADS applications.

Figure 4: Reentrant cavity and HWR (β=0.31) prototypes, developed at LNL, and Spoke cavity (β=0.35) prototypes developed at CNRS Orsay.

PERSPECTIVES

The long range ISOL facility will be on European scale (EURISOL), based on a high intensity linac as driver and a superconducting linac for the reacceleration. The technology of the driver (and of the converter) is common to other applications like spallations sources for Material Science and Nuclear Waste Transmutation, or new High Energy Physics applications, so that synergies are possible and necessary.

There is an intermediate phase with an essential role for National Laboratories, like SPES project at LNL and SPIRAL2 at GANIL.

The first step in Italy will be the construction of the first phase of SPES, SPES-1 in the next five years. This project will be a first significant step in the direction of SPES and EURISOL, a very good test for the high intensity community (ADS), and will be able to serve a community of interdisciplinary physics and medical users.

The specific investment, approved by INFN in Autumn ’03, includes (Fig. 5):

1. the completion and installation of the 5 MeV 30 mA proton injector (TRASCO source and RFQ),
2. the development and construction of the thermal neutron facility ($\geq 10^9$ s^{-1} cm^{-2} thermal neutrons, low gamma and fast neutron contamination) for BNCT

(Boron Neutron Capture Therapy) experimental studies[20,21], based on the 150 kW RFQ beam impinging into a Be target.

3. the development and realization of the superconducting p linac up to 20 MeV, 10mA current, cw.
4. the continuation of the R&D program on RIB production targets, and in particular the rotating converter done in ^{13}C and natural graphite, and the development of UCx fission targets.

It should be noted that with respect to the EURISOL requirements the current accelerated by the superconducting linac has been increased from 5 mA to 10 mA. This allows a better use of the intensity available from the RFQ, and makes the linac development relevant for the other high intensity applications (ADS).

Finally for RIB experiments this opens an additional possibility: a 10 mA 40 MeV proton beam hitting a thick ^{13}C graphite or Be target would produce a neutron flux and a fission rate interesting for experiments. Another possibility under study is the direct use of the proton beam (1 mA 40 MeV) in a thin fission target (some mm), such as leaving the Bragg peak outside. If the R&D on these concepts will be successful, LNL will be able to propose a compact and cost effective RIB source to be coupled to ALPI reaccelerator.

There is therefore an integrated plan for the development of ISOL facilities in Europe, and good perspectives for the implementation of the relative Physics programs.

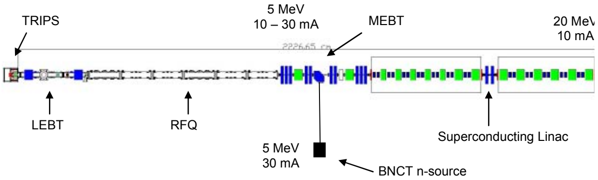

Figure 5: The SPES-1 project layout at LNL-INFN.

AKNOWLEDGMENTS

The author wishes to thank A. Mueller, coordinator of the Driver Accelerator task of EURISOL, G. Fortuna, spoke person of EURISOL-DS and M.H. Moscatello for very informative discussions.

REFERENCES

[1] see for example M. Lindroos “Review of ISOL-Type Radioactive Beam Facility” EPAC 04, Lucerne, in publication.

[2] W. Henning “FAIR-An International Accelerator Facility for Research With Ions and Antiprotons” ibid.

[3] EURISOL report (coordinator J. Vervier) available on line http://www.ganil.fr/eurisol/

[4] P. Schmor “Developments and Future Plans at ISAC/TRIUMF” This conf. p. 306.

[5] M.H. Moscatello this conference and http://www.ganil.fr/research/developments/spiral2/index.html

[6] SPES Technical design report (A. Bracco and A. Pisent editors) LNL-INFN(REP) 181/2002 and http://www.lnl.infn.it/~spes/

[7] J-L. Biarrotte et al. “High Intensity Driver Accelerators For EURISOL” Proc. of EPAC 02, p. 1007

[8] B. Visentin et al “Experimental results on 700 MHz multicell superconducting cavity for proton linac” Proceedings of 2003 PAC, p.1303

[9] A. Bosotti et al. “Rf Tests Of The Beta=0.5 Five Cell TRASCO Cavities” EPAC 04, in publication.

[10] P-Y Beauvais “Recent evolutions in the design of the French High Intensity Proton Injector (IPHI)” EPAC 04, in publication.

[11] A. Pisent, M. Comunian, A. Palmieri, E. Fagotti, G.V. La manna, S. Mathot “The TRASCO-SPES RFQ” this conference.

[12] M. Vretenar et al “Design of The LINAC4, A New Injector for The CERN Booster” these proc. p. 353.

[13] E. Fagotti et al “Characterization of beam parameters and Halo for a High intensity RFQ output under different current regimes” this conference.

[14] J. R. Delayen et al., Nucl. Instr. Meth. B56/57, 1025 (1991).

[15] A. Facco et al “RF testing of the TRASCO Superconducting Reentrant Cavità for High Intensity Proton Beams” proc of EPAC 2002, Paris, 2002.

[16] A. Facco et al. “Construction and testing of the β=0.31, 352 MHz Superconducting Half Wave Resonator for the SPES project” Proceedings of EPAC04, to be published, 2004.

[17] G. Olry et al “Recent Developments on Superconducting β035 and β015 Spoke Cavities at IPN for low and Medium Energy Sections of Proton Linear Accelerators” Proceedings of EPAC04, to be published, 2004.

[18] V. Andreev et al. “Ladder resonator: A novel superconducting structure for the very low beta part of high current linacs” Phys. Rev. ST Accel. Beams 6, 040101 (2003)

[19] E. Fagotti et al.” Beam Dynamics Issues of SPES-1 Linac” this proc. p. 395

[20] Agosteo S., et al. “Advances in the INFN-Legnaro BNCT Project for Skin Melanoma”. Proc. of Int. Physical and Clinical Workshop on BNCT. Candiolo (Torino), February 7, 2001

[21] A. Pisent and J. Esposito “An Accelerator Based BNCT Facility: The Project SPES at INFN Legnaro” Proc of the International Workshop on Neutron Capture Therapy, November 28th, 2003 S. Cataldo, Pisa .