HIGH INTENSITY PROTON SOURCES

A. Facco, INFN- Laboratori Nazionali di Legnaro, I-35020 Legnaro (Padova) Italy

Abstract

Since the start of the Spallation Neutron Source project, the field of high intensity (in the mA range and above) proton linacs based on superconducting resonators is living a time of great interest. A large variety of possible applications (nuclear waste transmutation, spallation neutron production, energy amplifier, radioactive ion production, neutrino factories, etc.) prompted many studies and proposals of new machines with final energy ranging typically from a few tens of MeV to about 1 GeV; high power requirements and reliability issues introduced new kinds of problems in linac and resonators design. A "zoo" of different superconducting cavity types, often evolved either from the electron or from the heavy ion SRF technology, is growing to cover the many different proposed applications, and triggering development in related high power couplers and fast tuners. During the last few years, high gradient resonators have been successfully prototyped in the full range of interesting beam energy, down to beta=0.1. The trend is to extend the SC sections of high current proton linacs to very low beta, taking advantage of the large acceptance of short cavities in order to increase linac reliability and, in some cases, to allow acceleration of deuteron beams. The construction of new, superconducting high intensity proton linacs is foreseen in the next future.

INTRODUCTION

High Intensity Proton Sources (HIPS), in an extended definition, consist of accelerators able to deliver proton beams at intensity of several mA, at energy usually between 50 and 2000 MeV. Special issues of such machines are the presence of high beam power, space-charge dominated non relativistic beams with possible halo formation, accelerating structures for nearly every β [1]. Typical requirements are low beam losses (anyhow <1W/m to avoid excess of activation), high reliability and, in some cases (ADS systems), absence of beam interruptions longer than 0.3 s [2]. Although cyclotrons could reach the performance up to a few mA, only linacs are presently competitive in the high current range; modern HIPS usually include a superconducting section delivering a large part of the beam power.

HIPS have a wide range of application as drivers in spallation neutron sources, radioactive beam facilities, sub-critical reactors for nuclear waste transmutation; as injectors for proton synchrotrons for high energy physics and neutrino factories; as drivers in industrial applications like radioisotopes production for medical use. Some of these activities can have a significant impact not only in fundamental research but also in everyday life.

HIPS STRUCTURE

Even if no HIPS exists yet, a consolidated scheme of such machine exists (figure 1). This includes a normal conducting (NC) injector and an RFQ ($\beta\leq0.1$), made of superconducting elliptical cavities, a low- and intermediate-energy section ($\sim0.1\leq\beta\leq0.5$) containing the normal to superconducting transition, and a superconducting (SC) high energy section. Efficiency, gradient and aperture are larger in SC cavities than in NC ones, and they allow a more flexible and modular design. Moreover, the excellent vacuum of cryostats reduces the stripping probability in H^- accelerators, resulting in lower beam losses. This is widely accepted for elliptical multi-cell cavities at $\beta\geq0.5$; below this value, other kinds of geometries are required (typically 2-gap spoke cavities) and NC structures (DTL, SDTL, CCDTL) can be still competitive, especially for pulsed operation.

Short, low-β SC cavities, however, can give other advantages. They have wide velocity acceptance, allowing acceleration of different A/q beams (e.g. protons and deuterons). They can allow a cavity-fault tolerant linac, as required in ADS systems: this can be obtained, in the longitudinal phase space, if the energy gain per cavity is lower than the energy width of the bucket [3]. Moreover, high gradient and large number of accelerating gaps cannot be completely utilized at low velocity due to rf defocusing [4]. This calls for short structures.

The optimum NC-SC transition energy, thus, depends on the linac parameters (beam current, time structure, and reliability requirements).

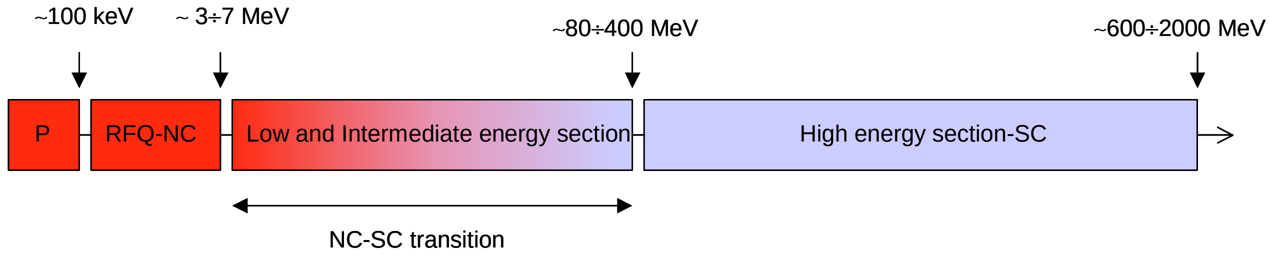

Figure 1: Schematic layout of a high intensity proton linac.

HIPS SC CAVITY TECHNOLOGY

High-β SC conducting cavities are an evolution of electron cavities, the main difference being the cell length. Many laboratories have developed successful prototypes [5][6][7][8][9][10] and 81 resonators are presently being produced for the SNS project in Oak Ridge [11]. This can be regarded as a mature technology.

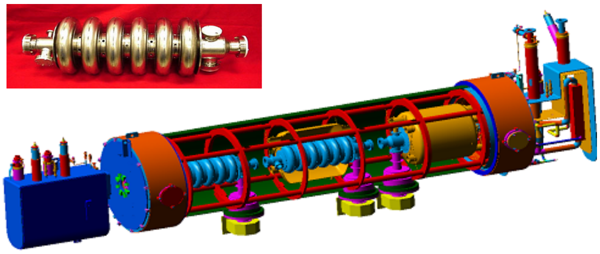

Figure 2: SNS β=0.61 cavity and cryomodule scheme.

Low-β cavities have their origin in heavy ion linac ones, the main differences coming from the high current requirements of the former (rf couplers, aperture, etc.). Even if significant overlap exists between the two fields, the RFQ requirements of high current proton linacs allow only resonators working above 160 MHz (typically 352), while in heavy ion linacs lower frequencies are preferred below β=0.2 (see, e.g., [43]). Also, larger rf coupling required for high current make cavity control easier.

type	Low-β (~0.1¸0.5)	High-β (~0.5¸0.9)
# cells	1÷19 (typ. 2)	4÷9
f (MHz)	160 ÷352	352 ÷972
Operating T	4.2 K	2.2 K
Coupler	≤200 kW cw	≤2 MW pulsed, ≤500 kW cw
Aperture	30 ÷ 60 mm	80 ÷100 mm
Design E_a	5÷8 MV/m	6÷13 MV/m

Table 1: Typical parameters of SC cavities for high intensity proton linacs.

The possibility of overcoming multipacting and reaching high gradient has been demonstrated in low-β cavities with 1, 2 and 3 accelerating gap (reentrant and spoke types). Development of suitable rf couplers and tuners, however, is not concluded yet.

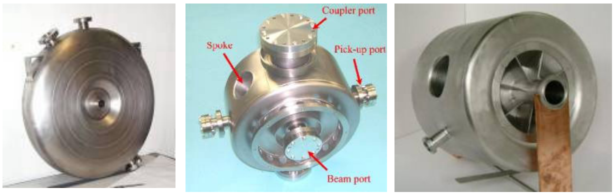

Figure 3: 352 MHz cavities. From left: β>0.1 reentrant (LNL) [12], β=0.2 Spoke (LANL) [13], and β=0.35 Spoke (IPNO) [14].

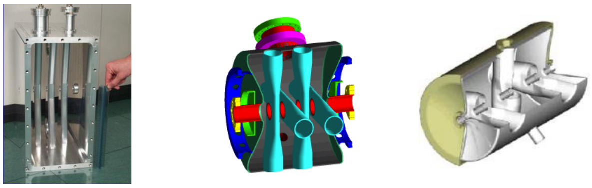

Figure 4: 4- and 5-gap resonators. From left: 352 MHz, β=0.12 Ladder (LNL) [15], β=0.2 Spoke (LANL) [2], and β=0.5 Spoke (ANL) [16].

Resonators with more than 3 gaps are under development in many laboratories, with the aim of increasing the real-estate gradient while reducing the number of cavities and rf systems. Wide velocity acceptance is not needed if only protons are being accelerated; however, linacs with fixed velocity profile require all cavities in operation and do not allow fault tolerance, especially at very low-β.

Multi-gap resonators (up to 19 gap) that should allow building extremely compact superconducting linacs are being studied and first prototypes are under construction. Multipacting, mechanical stability, rf mode separation are major issues to be explored in these cavities. To prevent the possibility of building up excess of rf defocusing, the KONUS beam dynamics based on 0° synchronous phase acceleration must be used.

Figure 5: β=0.1 CH structures under development at the University of Frankfurt: (left) model of the 352 MHz, 19-gap [17] and (right) sketch of the 174 MHz, 16-gap [18] resonators.

Coaxial half-wave resonators are used in the frequency interval between 160 and 352 MHz, where neither quarter-wave ones (due to excess of beam steering) nor spokes cavities (do to excessively large size) can be used conveniently. This geometry is characterized by relatively lower shunt impedance (about 30%) compared to the previous ones, but its symmetry can lead to rather good mechanical stability, suitable for pulsed operation.

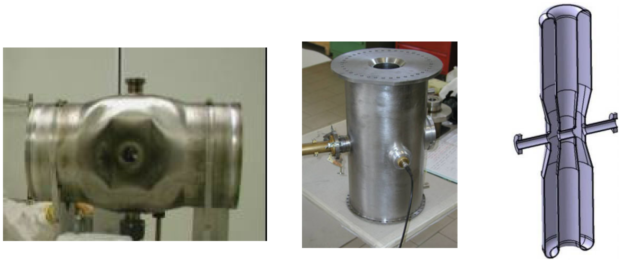

Figure 6: Half wave resonators. From left: β=0.28, 322 MHz (MSU) [19]; β=0.31, 352 MHz (LNL) [20]; β=0.12, 160 MHz (KFZ Juelich) [21].

Linac	E_{in}/ E_{out} MeV	I_{peak} mA	duty cycle %	Rep. rate Hz	N.cavities (N. types)	rf freq. MHz	Notes	Status
SNS (USA)	187 / 1000	26	6.25	60	81 (2)	805	H-	Operation 2006
ESS (EU)	200 / 1330	114	6	50	137 (2)	704	H-, p	Proposal
CONCERT (EU)	200 / 1330	114	6	50	137 (2)	704	H-,p	Proj. Study (closed)
J-PARK phase II (J)	400 / 600	30	1.25	25	22 (1)	972	H-	R&D
APT (USA)	211 / 1030	100	100	CW	242 (2)	700	p	Proj. Study (closed)
ADTF H.E. (USA)	109 / 600	13	100	CW	133 (2)	700	p	Proposal; R&D
XADS H.E. (EU)	95 / 600	10	100	CW	88 (3)	700	p	Proj. Study, R&D
TRASCO H.E. (I)	100 / 1000	30	100	CW	124 (3)	704	p	Proj. Study, R&D
EURISOL H.E. (EU)	85 / 1000	5	100	CW	134 (3)	700	p	Proj. Study, R&D
SPL-CERN (EU)	120 / 2200	22	14	50	202 (3)	352	H-	Proposal, R&D
KOMAC (Korea)	100 / 1000	20	100	CW	90 (3)	700	p	Proposal, R&D
FNAL 8 GeV (USA)	87 / 8000	25	1	10	384 (4)	805/1207.5	H-, p	Proposal
AGS upgr. (USA)	200/1200	28	0.18	2.5	92 (3)	805/1610	p	Proposal
ADTF L.E. (USA)	6.4 / 109	13	100	CW	128 (3)	350	p	Proposal; R&D
XADS L.E. (EU)	5 / 95	10	100	CW	96 (2)	350	p	Proj. Study; R&D
TRASCO L.E. (I)	5 / 100	30	100	CW	230 (1)	352	p	Proj. Study (closed)
SPES (I)	5 / 100	3	100	CW	113 (3)	352	p,A/q=3	Proposal; R&D
COSY INJ (GER)	2.5 / 52	2	0.1	2	44 (2)	160/320	H-, D-	Proposal; R&D
SARAF (Israel)	1.5 / 40	2	100	CW	48 (2)	176	p, d	Operation 2008

Table 2: Superconducting High Intensity Proton Sources proposed worldwide

HIGH INTENSITY SUPERCONDUCTING PROTON LINAC PROJECTS

Many High Intensity SC Proton Linac (HISPL) feasibility studies and R&D, involving a large number of researchers, have been done worldwide during the last decade; some of them resulted in real proposals for a facility construction and one (SNS) has started. A second one (SARAF) is funded, and it is in a phase of technology demonstration.

HISPL in USA

SNS -The Spallation Neutron Source at Oak Ridge [22], presently the leading accelerator project in USA, will be the world's most powerful neutron scattering facility, and the first HISPL that will come into operation [23]. SNS is being constructed by six DOE laboratories (ANL, BNL, JLAB, LBNL, LANL and ORNL) and will cost 1.4 Billion USD. The facility includes a 1 GeV HISPL, a compressor ring and a liquid mercury target where a high flux of neutrons is produced; neutrons are immediately slowed down by means of degraders, and sent to experimental points.

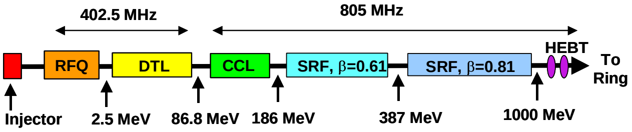

Figure 7: SNS linac scheme

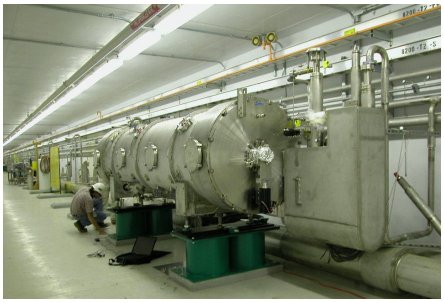

Figure 8: The first β=0.61 cryostat installed in the SNS beam line.

A special requirement of the SNS beam is time structure, in order to allow energy tagging of neutrons by means of time of flight measurements. The linac is pulsed at 60 Hz and produce 1 ms bunches, further compressed below 1 µs by the compressor ring. The current within the linac bunches is 26 mA and the total power at the target is 1.4 MW.

The linac is normal conducting up to 161 MeV and includes DTL and CCL structures. The SC section includes β=0.61 and β=0.81 six-cell cavities developed at JLAB, equipped with piezoelectric actuators to compensate for expected Lorenz force detuning in pulsed operation. Each one is powered by a 550 kW klystron; HOM couplers, although probably not critical, have been implemented too. The first production cavities have shown performance exceeding the design requirements, and cryostat installation on the beam line has started. SNS will be in operation from 2006. Its construction assesses the superiority of the superconducting technology at $\beta > 0.5$.

ADTF -The Accelerator Demonstration Test Facility at LANL is the project of an ADS system for nuclear waste transmutation [2]. It consists of a 13 mA, 600 MeV cw proton accelerator coupled to a sub-critical reactor; a second extraction line leads to a tritium production target as foreseen in the previous APT project at LANL [24]. The ADTF linac is all superconducting above 6.4 MeV and uses spoke cavities and 5-cell elliptical cavities [6]. A special requirement is reliability, which must prevent uncontrolled beam interruptions longer than 0.3 seconds. Most of the linac technology, including injector, RFQ and superconducting modules, had been previously developed for ATP. Recent results are the $\beta=0.2$ spoke cavities [13] with large aperture (50 mm) (see Fig. 3) and rf coupler (200 kW cw) integrated in the cavity design. The ADTF construction, not yet funded, must follow the completion of the sub-critical reactor design; the estimated construction time after approval is 10 years. The estimated cost is 1.5 Billion USD.

type	RFQ	SC Spoke			SC Elliptical	
f, MHz	350	350	350	350	700	700
n. gap	-	2	2	3	5	5
β_0	-	0.175	0.2	0.34	0.5	0.64
E, MeV	6.4	14	40	104	211	600

Table 3: ADTF linac resonator types

FNAL 8GeV Linac- The construction of a "Multi-mission 8 GeV Injector Linac" at Fermilab has been recently proposed [25]. The linac should include "well established" technologies of SNS and RIA up to 1.2 GeV, and TESLA modules from 1.2 to 8 GeV. The linac could accelerate protons, H- ions for injection in the FNAL main injector ring, electrons and positrons. Various applications are foreseen, including neutrino super beam, X-Free Electron Laser, and upgrading of the Tevatron beam quality. The proton beam parameters are very similar to the SNS ones, at a lower repetition rate (25 mA, 1 ms bunches at 10 Hz). The final average beam power, due to the higher final energy, would reach 2 MW. Cost: 370 Million USD.

BNAL AGS upgrade- The upgrading by one order of magnitude of the AGS beam power, thus reaching 1 MW, was recently proposed at BNAL [26]. This can be obtained by means of a 1GeV superconducting linac bypassing the present 1.5 GeV booster, increasing beam current and repetition rate. The existing 200 MeV, room temperature linac injector would be preserved. The new linac would utilize the SNS technology at 805 MHz up to 400 MeV, and the frequency would be doubled from 400 to 1200 MeV by scaling the cavity dimensions. The beam characteristics (28 ma, 0.7 ms pulses) would be similar to the SNS ones but the repetition rate would be lower (2.5 Hz to match the AGS frequency). The main aim of the project is production of neutrino beams to be sent to underground laboratories. Cost: 100 Million USD.

HISPL in EUROPE

XADS – XADS is a 12 M€ program, funded in large part by the European Community, for the study of a ADS system for nuclear waste transmutation. The program is lead by 25 partner laboratories and institutions, and the studies include a 600 MeV, 10 mA cw proton linac [27]. The cavity technology was mainly developed in France, Germany and Italy in previous national projects. As ADS, the high reliability (no beam interruptions longer than 1 s) is an important requirement and fault tolerance techniques are one of the development subjects. The linac is superconducting above 100 MeV, with 98 5- and 6-cell cavities [8] (see Figure 9).

Two possible options, NC and SC, are still opened for

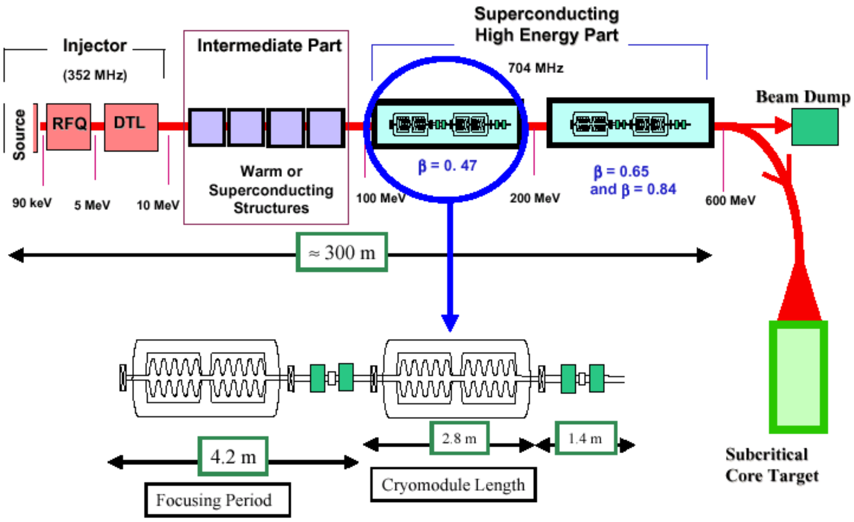

Figure 9: Schematic layout of the XADS linac

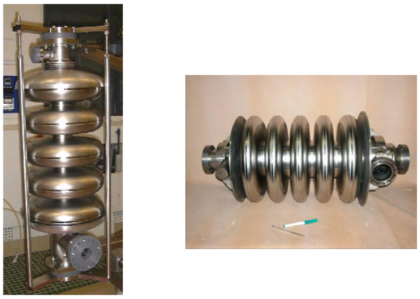

Figure 10: (left) XADS 700 MHz, β=0.65 cavity (IPN Orsay) and β=0.5 cavity (INFN Milano).

the low- and intermediate-β section between 10 and 100 MeV; the SC one [28] is based on Spoke cavities developed at IPN Orsay (figure 3). The main frequency is 350 MHz. The project is presently entering a phase of prototyping of complete linac cryomodules and critical components.

EURISOL Driver - The project for a European readioactive beam facility EURISOL [29], studied by a large community involving most of the European nuclear physics laboratories, foresees a 1 GeV, 5 mA cw proton linac. The 5 MW beam is needed to produce, directly on a Uranium target or via a neutron converter, a high flux of radioactive ions by means of isol-type techniques; the radioactive ion beam is then re-accelerated up to about 100 MeV/u by a superconducting linac. The Proton Driver baseline design is superconducting above 85 MeV and the high-β section is similar to the XADS one; two possible SC design schemes are under study for the low- and intermediate-β section up to 85 MeV [30]: one based on Spoke cavities and one with reentrant (or ladder) cavities and HWRs.

SPES at LNL - The SPES project at Legnaro (Fig. 11) is a reduced version of EURISOL, with a 100 MeV, 3mA cw proton driver (with possible upgrade to deuterons and A/q=3 ions) and isol RIB source [31].

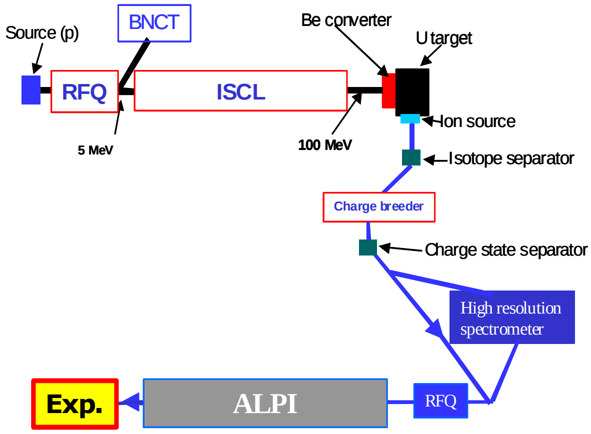

Figure 11: Layout of the SPES RIB facility project at LNL

The post-accelerator should be the existing superconducting linac, properly upgraded with a new low energy injector. The driver is made of a 5 MeV RFQ, a 5-20 MeV low-β section of reentrant [12] or ladder [15] cavities, and an intermediate β section made of coaxial HWRs [20]. Cavity prototyping and RFQ construction are in an advanced stage. In the first phase, the RFQ will be used to produce a large neutron flux at 5 MeV for skin melanoma treatment in a BNCT facility.

ESS – The European Spallation Source is a 1.5 Billion Euro project for a neutron facility with 10 MW beam on two targets [32]. The performance would exceed by one order of magnitude the ones of SNS in a 10 years construction program. The H^- linac, NC up to 186 MeV, would resemble the XADS one from 186 to 1384 MeV; the huge current specifications, 114 mA, would require funnelling of two injection lines and two rf couplers per resonator. A complex beam time structure (2 pulses of 0.5 ms at 50 Hz and 1 pulse of 2 ms at 16.6 Hz) is required to feed the Long Pulse target and the Compressor Ring-Short Pulse target, respectively. ESS is supported by 20 institutions that hope for the project approval and funding in 5 years.

SPL at CERN – CERN is studying a 2.2 GeV superconducting proton linac for neutrino production (Super Beam or Beta Beam) and radioactive beam production (ISOLDE or EURISOL) [33]. The present design of the superconducting section, which starts at 120 MeV, is based on 352 MHz cavities housed in the LEP cryostats now available after the dismounting of the ring. The high-β section (383÷2200 MeV) can be made with CuNb sputtered resonators, an evolution of the LEP ones with 5 cells instead of 4. This choice, although increasing the linac length in comparison with the XADS 700 MHz design, allows significant reduction in cryomodules cost.

The beam, 13 mA pulsed at 50 Hz with 14% duty cycle, has an average power of 4 MW.

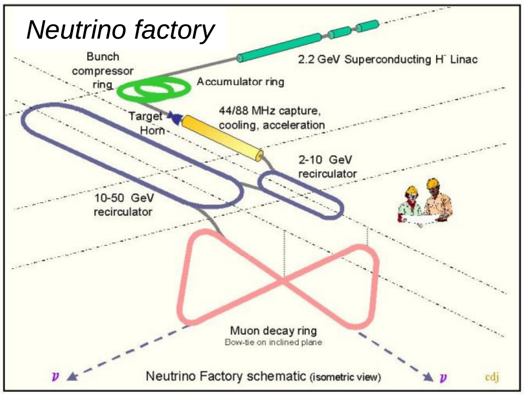

Figure 12: The proposed neutrino factory at CERN, based on muon decay. A facility based on ion β-decay (beta beam) was also proposed [42].

COSY Injector –A new injector for the Cooler Synchrotron at FZJ Juelich has been proposed, requiring 50 MeV, 2 mA polarized proton and deuteron beams in 0.5 ms pulses at 2 Hz [34]. The tight space available, and the wide velocity acceptance required, could be fit by a superconducting linac made of 44 HWRs working at 8 MV/m [21]. The cavity frequencies are 160 and 320 MHz. After the proposal, the project was suspended for two years but the design and R&D work is continuing to prototype the cryomodules.

IFMIF linac – A very high current deuteron (extendable to protons) low-β linac is being studied by GSI and IAP Frankfurt for the International Fusion Material Irradiation Facility [35]. The beam is sent to a Li target for production of a high neutron flux. According to the design, a linac made of a NC injector and 4 multi-gap, 174 MHz SC resonators will accelerate a 125 mA beam from 5 to 40 MeV in only 8.2 am. Resonator prototypes are under construction.

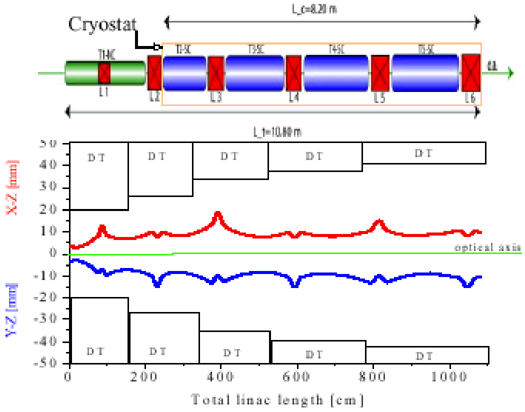

Figure 13: Sketch of the IFMIF linac [35].

HISPL in ASIA

JPARK – The JAERI-KEK joint project JPARK for a multi task facility is under construction [36]. The project is based on a 400 MeV NC linac and two synchrotrons delivery beam up to 50 GeV for particle physics, nuclear physics, material science, life science, nuclear technology.

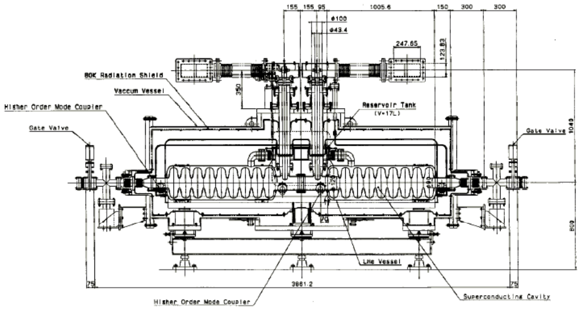

Figure 14: Sketch of the JPARK cryomodule

The facility will be operating in 2007. In a second phase, a superconducting linac from 400 to 600 MeV should be constructed for ADS applications [37]. The linac is based on 972 MHz, 9-cell resonators with β=0.72 developed at KEK . A 30 mA beam, pulsed at 25 Hz with 1.5% duty cycle, will be accelerated by 11 cryomodules containing 2 cavities each. Rf couplers have been tested up to the pulsed power of 2.2 MW.

KOMAK KAERI – South Korea is building a multi-purpose 1 GeV, 20 mA cw accelerator complex for basic research, waste transmutation, medical therapy and industrial applications [38]. The project was funded up to 100 MeV; a SC linac section, from 100 to 1000 MeV, is planned after 2008.

Indian ADS Program –India, being rich of Thorium resources, is interested in development of ADS systems for nuclear energy production using Thorium fuel. In this framework a multitask facility, including an ADS and a neutron spallation source, will be built at CAT Indore [39]. In the long term a 1 GeV, 10 mA SC linac will be required. In the next 5 years India will develop different technologies for a 100 MeV linac. CAT is studying a superconducting design based on 352 MHz reentrant cavities [40].

SARAF at SOREQ – The Israeli laboratory SOREQ started a project for the construction of a facility for production of medical radioisotopes. SOREQ has commissioned a "turn-key", 40 MeV wide-β linac to the company ACCEL [41]. The linac, which will provide 2 mA cw of proton and deuteron beam, will be based on 48 HWRs working at 176 MHz and superconducting solenoids. The facility will be operating in 2008.

CONCLUSIONS

The field of Superconducting High Intensity Proton Sources is more active than ever, with many laboratories involved. SNS in an advanced stage of construction, other projects are starting and new proposals are coming for new applications. High beam power and reliability requirements brought new kinds of problems that required a new approach in accelerator design for ADS applications. The high-β linac technology is mature and well established; the low- and intermediate-β one still presents a few different competing schemes. Beam dynamics studies and cavity development are steadily evolving and R&D will require significant effort in the next years.

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