

# OVERVIEW OF HIGH INTENSITY LINAC PROGRAMS IN EUROPE

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## Abstract

Recent years have seen a boost in the support by the European Union (EU) of accelerator research in Europe. Provided they coordinate their efforts and define common goals and strategies, laboratories and institutions from the member states can receive a financial support reaching 50% of the total project cost. In the field of High Intensity Linacs, the EU has already supported the EURISOL initiative for nuclear physics, which this year is applying for funding of a Design Study, and the development of linacs for Waste Transmutation. More recently, an initiative for high-energy physics has been approved, which includes a programme for the development of pulsed linac technologies. The coordination and synergy imposed by the EU rules increase the benefit of the allocated resources. Combined with the ongoing internal projects in the partner laboratories, these European initiatives represent a strong effort focussed towards the development of linac technologies.

This paper summarises the requests from the various European communities and gives an overview of linac R&D activities sponsored by the EU, together with some information on parallel national/local projects. The parameter choices as well as the main technical features of the different projects are presented and compared.

## INTRODUCTION

Recent years have seen an increasing worldwide interest in high-intensity linear accelerators for protons and  $H^-$  primarily aimed at the production of intense beams of secondary particles. Secondary beams of scientific interest include:

- Intense neutrino beams for particle physics, produced by the decay of pions, muons or radioactive beta emitters.
- Radioactive ions for nuclear physics, astrophysics and natural science.
- Spallation neutrons as a probe for condensed matter studies or feeding sub-critical reactors for energy production and waste transmutation.

In these applications as “proton drivers”, linacs are attractive with respect to circular accelerators for their capability to operate at high repetition rates, up to CW, with limited current per bunch. For pulsed applications at low duty cycle and high energy (1 GeV and above), they are in competition with Rapid Cycling Synchrotrons, while for CW applications at low energy, they compete with cyclotrons. In the past, linacs have always been considered expensive in comparison to circular accelerators. However, thanks to the recent advances in superconducting RF technology and to the increasing optimisation of linac designs, their energy reach, size and

cost are improving, so that more projects rely on high-energy high-intensity linear accelerators. Moreover, the strict limits on acceptable beam loss required to minimise radiation and allow hands-on maintenance are more easily met in linear machines, less disturbed by harmful beam resonances than circular machines.

## EUROPE AND ACCELERATOR R&D

Any one of these future high energy and high power linacs has such important needs in terms of space and overall infrastructure that it can only be hosted in a large laboratory. With the exception of CERN, the landscape of European accelerator research is rather made-up of a large number of small national laboratories and Universities, with very competent teams, but none having the critical mass required either for a large scale project or for its associated R&D. The basic mission of CERN is for large projects in high energy physics, however its present resources are focused on the construction of the LHC with a very limited support for future options beyond its start-up. Therefore R&D for new European accelerator projects can only be pursued through the collaboration of many different laboratories.

This situation in accelerator research is common to many branches of European science, a fact that is pushing the European Union (EU) commission towards taking a more active role in creating a real European Research Area. In the frame of the 6<sup>th</sup> EU Framework Programme (FP), covering the period 2004-2009, European research institutions are invited to propose Integrated Projects (IP), i.e. a coordinated research programme for a particular topic involving a certain number of EU scientific centres, which establish a common schedule and share their resources and the results of their work. The approved projects can be financially funded up to a maximum of 50% of the total cost (material and personnel). The evaluation is made not only on the scientific case, but also on the level of integration involved in the proposal.

For high intensity proton linacs, the EU has expanded the support already given to pioneering projects in the FP5, by approving the CARE (Coordinated Accelerator Research in Europe) Initiative. The EURISOL and EUROTRANS Design Studies have also been positively evaluated and are expecting approval. In parallel, support for the ADS (Accelerator Driven Systems) activities is continuing through the EURATOM agency of the EU.

It must be stressed that, due to the fierce competition, projects are never funded at the maximum allowed level, the priorities being defined by the EU committees. For example, inside the CARE initiative, the Joint Research Activity (JRA) dedicated to R&D for high-intensity low-energy linacs, has been very positively evaluated but has obtained EU funding for only about 25% of the total

project cost, a value to be compared to the important amount of overhead in handling the meetings and paperwork (periodic reports) required by Brussels. However, the added value of the integrated EU projects comes more from the synergies among the participating laboratories than from the simple financial contribution.

## PARTICLE PHYSICS APPLICATIONS

Particle physics is one of the leading communities pushing for a high-intensity proton facility in Europe, for the production of intense neutrino beams. The recent discovery of neutrino masses has opened new horizons for physics and cosmology, and the new physics of neutrino oscillations is proving extremely rewarding and demands long term experimentation with accelerator neutrinos. Long baseline experiments are in preparation, based on intense beams of neutrinos sent from an accelerator complex to a large underground detector, at distances of hundreds of kilometers.

For the production of neutrino beams orders of magnitude more intense than provided at present facilities, three techniques are presently considered:

- from conventional pion decay (called "Superbeam").
- from the decay of muons, previously accelerated and stored in a decay ring ("Neutrino Factory")
- from the beta decay of radioactive ions, produced in a nuclear physics facility and then accelerated and stored in an accelerator complex ("Beta-beams").

In all three cases, a high power proton driver is needed, with a beam power that has been normalised in the European studies to 4 MW, considered as a (challenging) limit for target technology.

For pion (and muon) production, the intensity of the pion beam is roughly proportional to beam power above a threshold that simulations situate at some 2 GeV, an energy still economically reachable by a linear accelerator. The choice of the proton energy will be strongly influenced by the results of the HARP experiment recently performed at CERN, once its data has been fully exploited [1]. For the Superbeam and Neutrino Factory scenarios, an accumulator and eventually a compressor ring are needed after the high-energy linac. The amount of usable pions being proportional to beam power, alternative scenarios for neutrino production make use of a higher energy proton beam (15-30 GeV) delivered by a cascade of Rapid Cycling Synchrotrons (RCS). Preliminary estimations indicate comparable costs for the Linac/accumulator and the RCS scenarios. While an RCS is ideally suited to concentrate the beam in a small number of short bunches, a high-energy linac provides more flexibility, offering several possible operation modes and upgrade scenarios.

Table 1 compares three European scenarios for particle physics proton drivers with three corresponding US designs and with the highest beam power facilities in operation or close to commissioning.

Table 1: Proton driver parameters

	Linac (MeV)	Ring(s)	Beam Power (MW)	Rep. freq. (Hz)
ISIS	70	800 MeV RCS	$\leq 0.24$	50
SNS	1000	accumulator	1.24	60
JPARC (n)	400	3 GeV RCS	1	25
JPARC (v)	400	50 GeV RCS	0.75	
CERN SPL	2200	accumulator	4	50
CERN RCS	180	2.2 GeV RCS 30 GeV RCS	4	8
RAL	180	2 $\times$ 1.2 GeV RCS 2 $\times$ 5 GeV RCS	4	2 $\times$ 25
FNAL 1	600	8 GeV RCS (+ Main Ring)	1.9	15-0.65
FNAL 2	8000	(+ Main Ring)	2	10
BNL	1200	(+AGS 28 GeV)	1	2.5

### *The Superconducting Proton Linac at CERN*

The Superconducting Proton Linac (SPL) study was started at CERN in 1997, aiming at the construction of a 2.2 GeV linear accelerator using the large inventory of 352 MHz RF (klystrons, waveguides and cavities) recuperated from the LEP machine [2]. The energy of this linac has been chosen in order to fit the needs of a neutrino factory and at the same time to be an improved injector for the CERN Proton Synchrotron (PS), increasing the brightness of its beam by a factor 3. For a neutrino factory, the SPL would feed particles to a 1 km circumference accumulator ring followed by a compressor of the same size, and the 4 MW of beam power would finally be sent onto a target in the form of a 3  $\mu$ s train of 1 ns rms long bunches. For the generation of a neutrino super-beam, the compressor would not be needed. In parallel to the high power operation, the facility could provide via the PS-SPS a beam of very high brightness to the LHC, an essential ingredient of most of the proposed upgrade options for the LHC.

A second Conceptual Design Report of the SPL is in preparation, to be ready by mid-2005. The low energy part will still deliver beam bunched at 352 MHz, but the transition from normal to superconducting cavities will be changed from 120 MeV to 180 MeV. In the superconducting part, state-of-the-art bulk niobium superconducting cavities operating at 704 MHz will be used instead of the aging low-gradient LEP cavities considered in the initial design so that, for the same output energy, the linac will be shorter, or, for a similar length, the energy will be higher. Also being considered is another frequency jump, to a high-energy linac section at 1408 MHz, where even higher gradients could eventually be achieved, with possible synergies with the TESLA developments. The main SPL beam parameters are reported in Table 2 and Fig. 1. In the present CERN plans, the decision of construction is envisaged in 2008. However, the normal-conducting part of the SPL, called Linac4, could already be built between 2007 and 2010, as a replacement to the present injector of the PS Booster.

This would benefit the present users by increasing the intensity and the brightness of the beam provided by the PSB, and the PS could then deliver the “ultimate” beam required by the LHC [3].

Table 2: SPL Parameters (CDR 2)

Ion species	H-	
Kinetic energy	2.2	GeV
Mean current during the pulse	30	mA
Beam duty cycle	6	%
Mean beam power	4	MW
Pulse repetition rate	50	Hz
Beam pulse duration	1.2	ms
Bunch frequency	352.2	MHz
Duty cycle during the pulse	62	%
Normalized rms transv. emittances	0.4	$\pi$ mm mrad
Longitudinal rms emittance	0.3	$\pi$ deg MeV

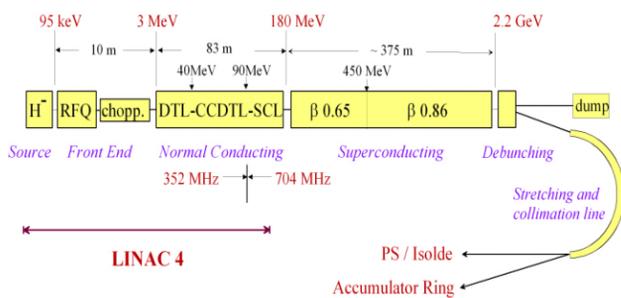


Figure 1: Layout of the SPL (CDR 2).

### NUCLEAR PHYSICS APPLICATIONS

Owing to the increasing interest for the scientific applications of Radioactive Ion Beams (RIB), going well beyond the traditional field of Nuclear Physics, a strong community is advocating the construction in Europe of an RIB facility with an intensity three orders of magnitude higher than the present ones. Such a laboratory could meet the demands of a wide science programme covering solid state physics, biophysics, nuclear astrophysics, studies of fundamental symmetries and interactions, and a full programme on structure and reaction studies of atomic nuclei very far from the valley of beta stability. Two parallel and complementary RIB programs are foreseen in Europe, one based on the in-flight projectile fragmentation around 1 GeV/u, to be pursued at GSI, as part of the FAIR project, and another one based on the Ion Separation on Line (ISOL) method, in another location. The ideal ISOL driver is a high-intensity 1 to 2 GeV proton accelerator, operated in two power levels: around a few hundred kW as a classical ISOL facility or at a few MW when generating radio-active ions by bombardment with spallation neutrons from the target. Instantaneous power deposition in the target is a major concern, and for this reason the beam has to be CW or pulsed at a high repetition rate, 50 Hz being considered as the lowest acceptable value.

### The EURISOL Design Study

The European scientific community working on RIB was present already in the 5<sup>th</sup> FP of EU, and has now submitted the EURISOL Design Study in the frame of the 6<sup>th</sup> FP, aiming at the preparation of a detailed design for an ISOL facility [4]. The baseline EURISOL CW driver (Figure 2) is composed of a 5 MeV front-end based on a proton source and an RFQ, followed by a 352 MHz superconducting section at intermediate energy using Quarter-Wave or Spoke type resonators, and finally by a 704 MHz high energy superconducting section made of elliptical cavities. An additional feature of this design is the capability to accelerate low-mass ions, as required by some experiments.

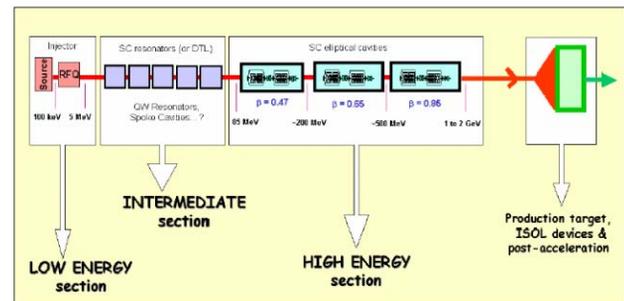


Figure 2: EURISOL layout.

### EURISOL at CERN and the Beta-beams

An interesting option has been recently proposed which shows a remarkable synergy between a neutrino and an RIB facility [5]. Using a single proton driver like the SPL, it is based on an ISOL type facility, providing the radioactive ions needed for nuclear physics and simultaneously producing intense beams of beta emitting ions (<sup>6</sup>He and <sup>18</sup>Ne). These beta emitters are accelerated in a dedicated post-accelerator and then in the existing CERN accelerator complex (PS and SPS). After acceleration in the SPS, they are injected in a storage ring, where their decay produces intense streams of neutrinos at the end of two long straight sections (Figure 3). The analysis of the technological issues of the beta-beam option is one of the work packages in the EURISOL Design Study.

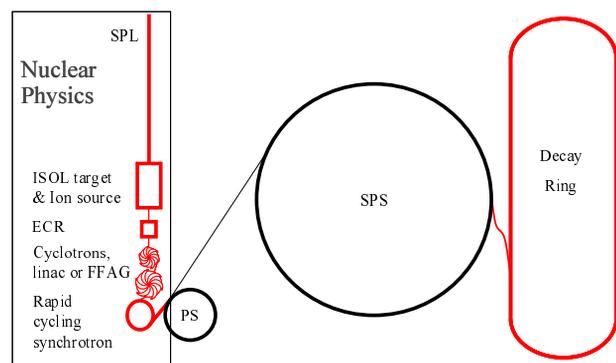


Figure 3: Concept of the beta-beam facility.

### The SPES Programme at INFN-LNL

The SPES machine under construction at INFN Legnaro is a high-intensity proton linac at low energy (20 MeV in the initial stage, 100 MeV final energy), intended to feed an ISOL facility. A 352 MHz CW RFQ for 30 mA current is followed by a superconducting linac made of re-entrant cavities. The machine is designed to be operated at a later stage with deuterons (with a different RFQ), to obtain a larger neutron yield at low energy [6].

## NEUTRON APPLICATIONS

An intense proton beam can be converted into streams of neutrons in a spallation target. The use of neutrons ranges from basic science and condensed matter studies, to feeding sub-critical reactors. European activities are on-going on both fronts, for the ESS and the ADS studies.

### The European Spallation Source (ESS)

An accelerator based Neutron Spallation Source for Europe was the subject of the ESS Study. After the preparation of a detailed proposal, at the beginning of 2003, the partner governments have delayed the decision of construction by 4-5 years and requested the refinement of the technological layout. The new ESS SC reference design (Fig. 4) includes a 1120 MHz superconducting section, starting at 400 MeV energy. The low-energy part is based on two 280 MHz  $H^-$  linacs funnelled at 20 MeV followed by normal-conducting structures at 560 MHz. It includes an innovative fast chopper/collector system, for the double operating mode (short and long pulse, at 5 MW each) that is a unique feature of the ESS [7].

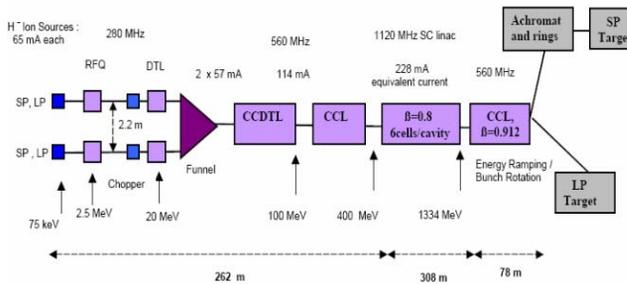


Figure 4: ESS SC reference linac layout.

### Accelerator Driven Systems (ADS)

The preliminary ADS design study funded by EU has recently compared linac and cyclotron layouts for a 600 MeV, 6 mA current CW driver for transmutation, taking into account the high reliability required by ADS systems, with less than 5 beam trips ( $>1$  s) allowed per year. The outcome of the study is that CW superconducting linacs should be chosen for demonstrator and full scale plants, because of their potentiality in terms of availability, reliability and power upgrading capability. Cyclotrons are considered attractive in cost, but at the limit of feasibility for the required parameters, not upgradeable and far less reliable. The PDS-XADS reference layout (Fig. 5) is based on a double front-end

for higher availability, made of a 352 MHz normal-conducting RFQ followed by superconducting structures from the lowest possible energy. Spoke and CH-cavities are considered for the low-beta part of the linac, while the high-energy sections are made of 704 MHz elliptical cavities. The EUROTRANS Integrated project is presently being submitted to the EU, focused mainly on reliability issues and on demonstration experiments.

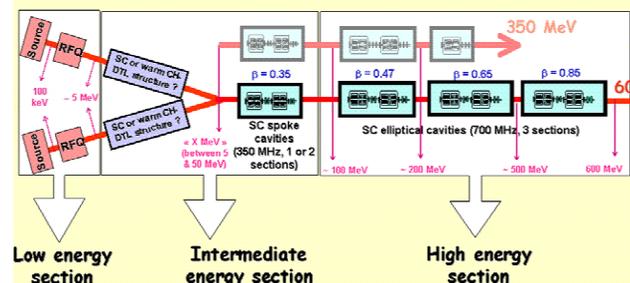


Figure 5: The PDS-XADS reference accelerator layout.

## TECHNOLOGICAL ISSUES

### Front-end

The technological and beam dynamics issues of the front-end (source, RFQ and MEBT) are crucial for a high-intensity linac, and need to be addressed as early as possible, well before the construction of the rest of the linac. The particle distribution is generated in the front-end, and source extraction fields, RFQ multipoles, changes of beam size and focusing period in the MEBT can create harmful halos, which will finally produce losses in the following linac sections. Moreover, the front-end presents many technological challenges, like performance and reliability of the source, power dissipation, field adjustment and coupler design in the RFQ, chopping and collimation in the MEBT. To address these questions two teams in Europe are presently building high-power RFQ's: CEA-CNRS in France and INFN/LNL in Italy. Both RFQ's were originally designed as ADS-type demonstrators, but will be finally used as front-ends for linacs devoted to physics research.

The CEA-CNRS IPHI RFQ is a 100 mA CW RFQ, whose design has been recently revised and the energy, originally 5 MeV, reduced to 3 MeV for this RFQ to be used as injector for the CERN Linac4 and SPL. After a first series of CW tests at Saclay planned in 2006, mainly to assess reliability of an ADS front-end, the RFQ will be sent to CERN in 2007, where it will be installed in a test stand equipped with an  $H^-$  source and a complete MEBT, for extensive beam tests [8]. The LNL RFQ, also conceived for the TRASCO transmutation study, will be now the preliminary injector of the SPES linac at Legnaro. It goes up to 5 MeV with 30 mA of beam current. It is based on a simpler mechanical design than the IPHI RFQ, and should be finished in about the same time [9]. Testing will take place at Legnaro.

### *Superconducting Linac*

Presently, all European high-intensity linac projects include a superconducting high-energy section. The transition energy between normal and superconducting depends on the operation mode and ranges from the 5 MeV of EURISOL (CW, proton and deuteron operation mode requiring individually phased cavities) to the 180 MeV of the SPL and the 400 MeV of the ESS. The frequencies are also standardised for most of the projects to 352 MHz and multiple harmonics, the main reason for this “European” frequency choice being the availability of RF equipment and expertise at this frequency from the old LEP RF system.

The development of 704 MHz low-beta elliptical cavities, as well as of different alternative designs at 352 MHz (spoke, QWR, HWR, re-entrant, etc.) is progressing at several European laboratories. Moreover, some projects are envisaging to push even higher the SC RF frequency (1.4 GHz for the SPL, 1.1 GHz for the ESS) to reduce the size of cavities and cryostats while reaching higher gradients, profiting in this way from the developments made for TESLA.

The instabilities induced by cavity vibrations due to the pulsed mode of operation are being studied, stiffening techniques have been proposed and compensation schemes are under investigation in many laboratories. CERN is testing a prototype high power phase and amplitude modulator intended to facilitate the stabilisation of a string of superconducting cavities fed by a single klystron [10].

### *Beam Dynamics and Halo*

A considerable effort is devoted to beam dynamics calculations and to the study of halo generation and removal. In particular, there is a clear interest in understanding the mechanism of halo formation in the front-end. Realistic distributions from the source are included in the simulations. Modern simulation codes allow calculations with a large number of particles, but in order to have a realistic view of the beam behaviour long end-to-end simulations are needed, either including statistical error distributions for the entire machine, or introducing artificially in the beam an equivalent mismatch to that generated by the error distribution [11].

### **THE HIPPI JOINT RESEARCH ACTIVITY**

In order to address the issues involved in the low-energy part of pulsed high-intensity linacs, the CARE Initiative recently approved by the EU includes the HIPPI (High Intensity Pulsed Proton Injectors) Joint Research Activity, covering the period 2004-2008. The goal of HIPPI is the common development of the technological basis for three proposed new linac injectors, the CERN Linac4, the new 180 MeV linac at RAL and the new GSI proton injector, analyzing jointly the different options and problems for linacs in the energy range between 3 and 200 MeV. HIPPI partners are 9 laboratories from 5 countries: RAL, CEA-Saclay, CERN, FZ-Jülich, GSI,

IAP-Frankfurt, INFN-Milan, IPN-Orsay and LPSC-Grenoble. Inside HIPPI, different technologies are developed in parallel, some in collaboration between laboratories, and some by individual HIPPI members. The results of the development will be jointly analyzed, to come to a common assessment on the technologies and on their applicability to the different linac upgrades.

HIPPI is divided in four technical work packages. The first one will compare four Normal Conducting structures, DTL, H-mode linac, SCL and CCDTL, by building prototypes and scaled models. In this activity three collaborations between CERN and Russian laboratories, that will build prototypes of 352 MHz linac structures to be tested at CERN in 2006, have also been integrated.

The second work package is devoted to the study of superconducting cavities as an alternative to normal-conducting at energies between 90 and 200 MeV. Two different elliptical cavities at  $\beta=0.5$  will be built and tested in a new 704 MHz test stand for 1 MW RF power under preparation at Saclay, aiming for gradients  $>10$  MV/m. In parallel, prototypes of spoke cavity and CH-cavity at 352 MHz will be built and tested.

The third work package will compare two alternative chopper designs and integrates the chopper study into the development and beam testing of the critical MEBT line.

Finally, the fourth work package groups the beam dynamics activities, and aims for a common comparison and assessment of different beam dynamic codes, through extensive simulations and comparison with beam measurements, together with a common development of beam diagnostics.

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