OVERVIEW OF HIGH INTENSITY ACCELERATOR PROJECTS

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Abstract

This review covers high intensity hadron accelerator projects worldwide, ranging over spallation neutron sources, radioactive ion beams, accelerator driven systems and machines for particle physics, including both existing and proposed facilities. The aim is to compare requirements, explore parameter ranges, identify areas of commonality and highlight how experience in one project can be used to address challenges in others.

INTRODUCTION

The earlier series of ICFA mini-workshops were guided principally by studies of spallation neutron sources and high power proton accelerators. They led to the larger, more formal, HB workshops where the emphasis has considerably widened the spectrum of analysis and application. Different applications impose different requirements in terms of average power and beam energy. These are summarised in Table 1 and show how preferred parameters range from relatively low energy (MeV level), high power, irradiation and ADSR facilities to what might be termed intermediate energies (a few GeV) with slightly lower power (1-5 MW) for spallation sources, and the higher energies (perhaps as high as the 150 GeV of the Fermilab main injector) for particle physics purposes. Individual projects might be arranged into categories as follows:

- **Multi-purpose facilities:** LANSCE (US), J-PARC (Japan), PEFP (Korea), FAIR (GSI)
- **Spallation neutron sources:** SINQ@PSI (Switzerland), ISIS (UK), SNS (US), CSNS (China), ESS (Sweden)
- **Radioactive ion beams (RIB):** FRIB (US), EURISOL (Europe), RIKEN (Japan), SPIRAL2 (France), SPES (Italy), SARAF (Israel) .
- **Secondary beams (Neutrino/muon factories):** Linac4+SPL (CERN), Project-X (US), IDS-NF
- **Irradiation facilities:** IFMIF (Europe/US/Japan) + prototype EVEDA (CEA)
- **Accelerator Driven Systems (ADS):** EUROTRANS (Europe), TRASCO (Italy), ADS (China), MYRRHA (Belgium), ThorEA (UK)

These are plotted on a conventional "Energy Frontier" diagram, indicting how current and energy are balanced to achieve beam power, in Figure 1.

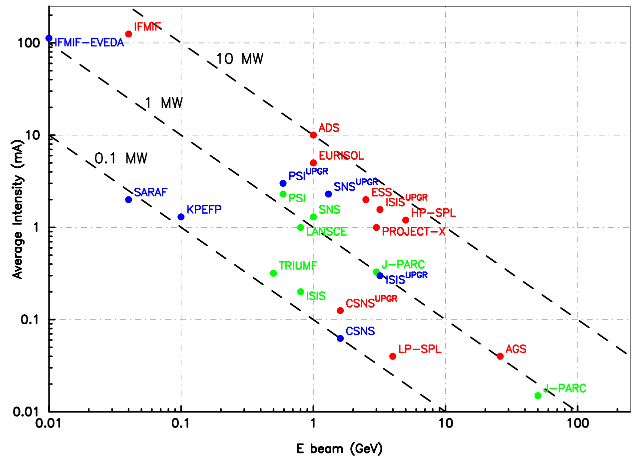

Figure 1: Beam Power Frontier: operating facilities in green, those under construction and upgrades in blue, and proposed new facilities in red.

SPALLATION NEUTRON SOURCES

The **SINQ spallation neutron source** at the Paul Scherrer Institute in Switzerland stands out not only because it is the current leader in terms of beam power but because it is the only spallation facility that operates CW and uses cyclotrons. An 870 keV Cockcroft Walton injector provides protons to a 72 MeV injector cyclotron which in turn feeds a main ring cyclotron taking the beam to 590 MeV. A separate beam line from the injector is used to send $\lesssim 100\,\mu$A to an isotope production facility. The ring cyclotron (Fig. 2) is optimised for high intensity and delivers 2.2 mA of current (1.3 MW) to a spallation neutron production target. Considerable efforts have been made in recent years to improve reliability to above 90% and reduce beam loss to the 10^{-4} level. A new beam intensity record was achieved in 2009 with stable operation at 2.3 mA for several hours [1]. An upgrade programme to 1.8 MW is being implemented with the installation of new resonators in the injector cyclotron and a new 10th harmonic buncher. Completion is planned for 2013. There is great confidence at PSI that the cyclotron concept now represents a viable option for generating high power beams for other applications, including accelerator driven systems (ADS), where very high reliability is in demand.

The new generation of spallation neutron facilities is led by SNS and J-PARC. In contrast to the CW operation of SINQ, **SNS at Oak Ridge, Tennessee**, is the world's most powerful pulsed neutron facility [2]. Based on a 1 GeV

Table 1: Relative Power and Energy Requirements

Application	Note	Power	Energy
Condensed matter studies	Spallation sources	~1-5 MW	~1-3 GeV
Materials irradiation	Neutrons with stripping reaction	2×5 MW	40 MeV
Secondary beams, particle physics	Muons, neutrino production	4 MW	5-15 GeV
RIBS for nuclear & astrophysics	with neutrons	4 MW	~1 GeV
Sub-critical reactors for energy generation and transmutation	MYRRHA demonstrator; thorium cycle	5-10 MW	0.6-1 GeV

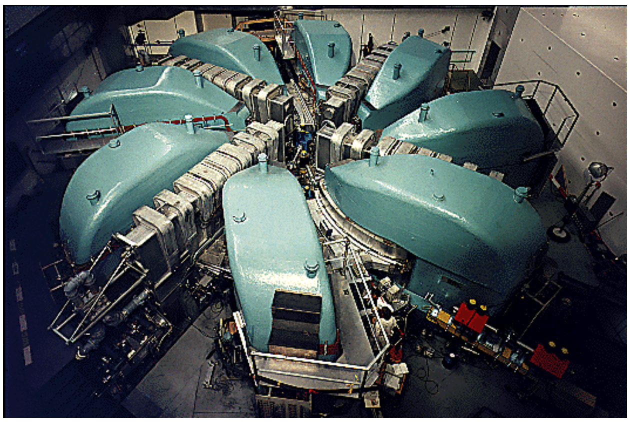

Figure 2: The SINQ sector cyclotron at PSI.

H$^-$ linac and an accumulator ring, SNS began operation in 2006 and now routinely delivers 1 MW of beam power to a mercury target for as much as 5000 hrs per year with 85% availability. 13 neutron scattering instruments are provided for users. Several important principles are incorporated into the design, of which many are accepted features of high power proton drivers:

- A front-end comprising an H$^-$ ion source with an RFQ and a fast beam chopper;
- A 400 MHz normal conducting linac to 186 MeV followed by a superconducting linac at twice the rf frequency;
- Charge exchange injection into an accumulator ring via a carbon stripping foil;
- A complex chicane in the injection line providing horizontal and vertical orbit bumps for transverse distribution painting;
- Operation with uncontrolled beam losses limited to an average of 1 W/m.

At 260 m in length, the SNS linac provides 1 ms, 1 GeV H$^-$ pulses that are converted to protons at entry to the accumulator ring. 1.5×10^{14} protons are accumulated over 1060 injection turns and compressed to 700 ns, whereupon the beam is ejected to the target at a 60 Hz repetition rate. Chopping creates gaps in the linac bunch train that allow for low loss injection into the ring. The idea is to concentrate unavoidable beam loss in regions where it can be properly handled so as to minimise loss in other areas and as far as possible allow hands-on maintenance.

Plans are in place to increase the SNS beam power and availability to its design values of 1.4 MW and 90% over the next two years. The number of instruments is also being increased to 16. Two upgrade projects are in the planning stage. The first is to raise the beam power to 3 MW by increasing the beam energy to 1.3 GeV and the beam current by 60% to 2.3 mA. The second is to add a long pulse target station (for which no accumulation is needed) operating at 20 Hz with pulses interleaved with the current short pulse facility, which would then operate at 40 Hz.

A high power spallation source is also in operation at the **J-PARC facility in Japan**, where neutron production is combined with materials and life sciences facilities, a hadron experimental unit and provision for neutrino beams to the Kamioka detector. In contrast to the SNS, J-PARC uses a lower energy linac to accumulate beam in a rapid cycling synchrotron (RCS) which then accelerates the beam to its final energy for spallation or passes beam to a second synchrotron (the main ring, MR) for high energy experiments. In Phase 1 of the construction programme, a 181 MeV linac was brought into operation with a peak current of 30 mA. After charge exchange injection and accumulation, 0.6 MW of beam power at 25 Hz is provided at the spallation target by the 3 GeV RCS. Once every three seconds a pulse is sent to the MR synchrotron. Following commissioning in 2008, the main ring has been operating at 30 GeV, though the eventual goal is to supply 15 μA of beam current at 50 GeV (0.75 MW) to the hadron and neutrino facilities. Phase 2 is about to commence and new annular coupled accelerating structures will be added to the linac extending its range to 400 MeV. Further plans will add a 400-600 MeV superconducting section to the linac so that the facility can cover nuclear waste transmutation.

In Europe, study of the **European Spallation Source (ESS)** actually pre-dated SNS and to some extent set benchmarks for the final SNS design. Unfortunately, ESS failed to secure funding in its original form as a combined short+long pulse facility. The past two years have however seen rapid developments with the formation of a collaboration of European countries dedicated to the construction of a long pulse facility at Lund in Sweden. In long pulse operation, a linac drives the beam straight into the target; accumulation is unnecessary so a proton, rather than H$^-$, ion source can be used and there is more flexibility in choice of linac current and energy. The proposed design [3] comprises a 2.5 GeV linac operating at

20 Hz and delivering 60 mA of proton beam in 2 ms pulses to a neutron production target at an average beam power of 5 MW. The linac architecture is shown in Fig. 3 and the aim is for reliability $\gtrsim$95%. Expected construction

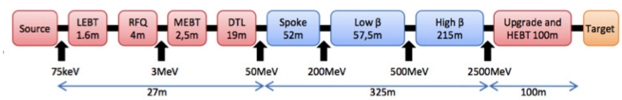

Figure 3: Schematic layout of the proposed ESS linac.

will be during the period 2013-18 with first neutrons due in 2018-19. To date, prototyping has included fabrication and successful testing of two half wave resonators at 325 MHz ($\beta = 0.17, \beta = 0.31$) and two spoke resonators at 325 MHz ($\beta = 0.15, \beta = 0.35$). The cost of the facility is expected to be ∼€1.5 bn, which includes 22 instruments, plus annual operating costs of about €90 m. An upgrade to 7.5 MW will be achieved via progressive increases in ion source current to 75 mA, then 90 mA, and a second target station may later be built with an interleaved 40 Hz mode of operation.

A further spallation facility, due to start construction shortly, is the **Chinese Spallation Neutron Source, CSNS**, at Dongguan in southern China. This is a relatively low power facility, aiming for 100 kW in Phase 1, doubling to 200 kW in Phase 2. The accelerator is based on an H^- Penning source, a 3 MeV RFQ and a drift tube linac (DTL) providing, first 62.5 μA at 80 MeV, and later 125 μA at 132 MeV, to a 1.6 GeV rapid cycling synchrotron operating at 25 Hz. The RFQ has been developed from an earlier ADS study, and use is made of J-PARC rf technology.

The oldest serving of all dedicated spallation sources is **ISIS** at the Rutherford Appleton Laboratory in the UK. After operating for many years at a beam power of 160 kW (200 μA at 50 Hz, 800 MeV), recent developments have seen injector upgrades with installation of an RFQ and incorporation of a dual harmonic rf system to increase the accumulated current in the synchrotron. The increased beam power is linked to operation of an additional, newly constructed, 40 kW, 10 Hz target station. A long-term phased upgrade path is also under study [4] and will see a new H^- linac injecting beam at a higher energy (150-180 MeV) into the ring. Prototyping includes construction and testing of the *Front-End Test Stand (FETS)* – with high current, long life, ion source development, RFQ design and optimisation of a novel idea for a fast beam chopper. The second upgrade phase will involve construction of a new 3.2 GeV synchrotron, taking the beam directly from the original ring and raising beam power to the megawatt level. At a later stage, the old ISIS will be replaced by a new 800 MeV H^- linac at higher current, injecting via charge exchange directly into the 3.2 GeV ring. Theoretical studies suggest that 4-5 MW could be possible.

MULTI-PURPOSE FACILITIES

At **CERN** the present intent is to secure the success of the Large Hadron Collider (LHC) through upgrades to the injector complex. In addition to standard maintenance, upgrades and replacement of component parts, the first major stage is the construction of a new linac, Linac4, to inject into the PS-Booster. Linac4 is an H^- accelerator, with RFQ, chopper, DTL and CCTDL to 102 MeV followed by a π-mode structure to 160 MeV, at an average current of 40 mA [5]. The PS-Booster is being adapted for charge-exchange injection, allowing the accumulation of higher intensities in the rings. Ground breaking took place in September 2008 and the tunnel and surface buildings were delivered in September 2010, exactly two years after commencement.

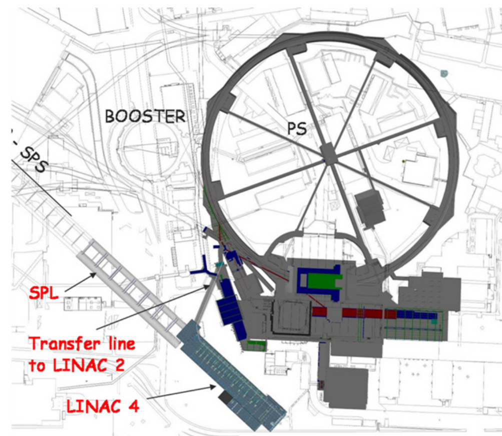

Figure 4: CERN PS and PS-Booster with Linac4 and SPL.

The siting and orientation of Linac4 (Fig. 4) allow for development into the proposed 4-5 GeV Superconducting Proton Linac (SPL), which would eventually inject into a 50 GeV replacement synchrotron for the PS, referred to as PS2. In low-power mode, applications would include ISOLDE and EURISOL (*q.v.*) as well as neutrino physics. A later configuration for high power could provide a multi-megawatt proton facility for future physics needs such as beta-beams, neutrino superbeams and a neutrino factory.

With operation of the Tevatron inexorably drawing to a close, there are proposals at Fermilab for a high power proton facility to support a programme of neutrino and flavour physics over the next two decades, with an eventual upgrade path to a muon collider, possibly by way of a neutrino factory. Provisionally named **Project-X** [6], the multi-megawatt proton source will support the Long Baseline Neutrino Experiment (LBNE) for which a new beam line will be constructed to DUSEL in Lead, South Dakota; there will also be provision for a broad suite of rare decay experiments.

The idea deemed most flexible for Project-X is based around a 3 GeV, 1 mA CW superconducting linac. While most of the beam will be directed to nuclear, kaon and muon experiments, about 10% will be accelerated in either a superconducting RF pulsed linac (5% duty cycle) or a 10 Hz RCS, for injection to the existing Recycler/Main injector for multi-megawatt beams at 60-120 GeV (Fig. 5).

The RCS is not favoured because of its limited upgrade potential, and current work is concentrated on the pulsed linac, for which parameters are 1.3 GHz, 25 MV/m, $\leq$5% duty cycle, 1-30 ms pulse duration. For the muon collider and neutrino factory, new accumulator and compressor rings will be needed, with delay lines and funnelling to combine the beam into a limited number of highly compressed bunches (maximum three) on a pion production target.

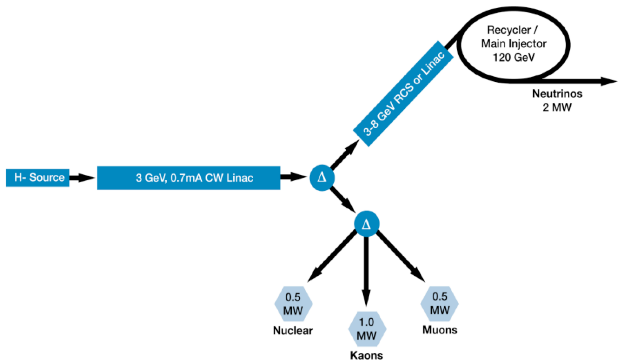

Figure 5: Preferred configuration of the multi-megawatt proton facility Project-X at Fermilab.

For nuclear and hadron research, infra-structure is being provided in the form of **FAIR**, the **Facility for Antiproton and Ion Research** under construction at GSI in Germany. The accelerator complex will provide high intensity beams ranging from antiprotons to uranium ions. The main driver is the 100 Tm SIS100 synchrotron, which will accelerate and deliver ions and protons to converter-targets for radioactive ion beam and antiproton production, to fixed targets, or to a second synchrotron, the SIS300, for acceleration to higher energies. New dedicated storage rings will be provided for in-ring experiments with pre-cooled beams. While existing machines - the UNILAC linear accelerator and the SIS18 ring - will serve as injectors for FAIR, of interest is a new dedicated proton linac, required for the production of the high intensity antiproton beams. This linac will provide 70 MeV, 70 mA protons with 36 μs pulse length at a repetition rate of 4 Hz, and will be the first linac based on coupled H-mode cavities combined with the KONUS beam dynamics. A prototype is shown in Figure 6.

RADIOACTIVE ION BEAM FACILITIES

As FAIR suggests, an interesting and active area of research lies in the development of radioactive ion beams to explore exotic regions of the nuclear chart and push towards the limits of nuclei stability. The RIBs are generated using high power, relatively low energy hadron beams. Two approaches are being developed. In the first RIBs are produced by the fragmentation of projectiles using a thin target. The radioactive nuclei created are separated in flight, producing a high energy beam with potential for good selectivity although the intensity is low. By contrast,

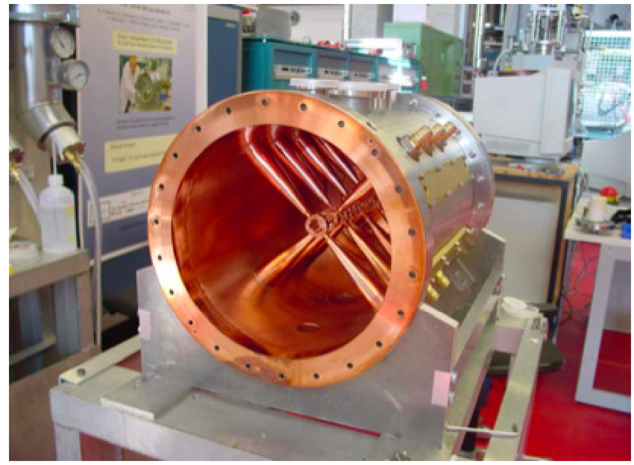

Figure 6: Prototype CH-mode structure for the FAIR proton injector linac.

the ISOL method (Isotope Separation On-line), produces RIBs by spallation, fission or fragmentation reactions with a thick target. The products of the reaction diffuse out of the target, are ionised, separated on-line and then re-accelerated. The resulting secondary beams are very intense, but in this case short-lived nuclei are not reachable.

In Europe the decision of the ESFRI committee has been to focus RIB development on **SPIRAL2**, currently under construction at GANIL in France. The design uses a high power CW superconducting linac to deliver 5 mA deuteron beams at 40 MeV and heavy ion beams up to 14.5 MeV/u (1 mA). The linac has two families of quarter-wave resonators (see Fig. 7) Most of the cavities have been delivered and tested and installation of the cryo-modules is underway. Commissioning should start in mid-2011 [7].

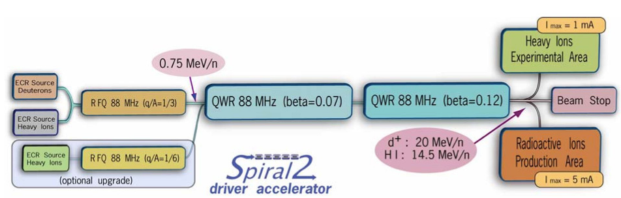

Figure 7: Layout of the SPIRAL2 RIB Facility.

SPIRAL2 is developing a completely new generation of hadron accelerators and will allow constraints imposed by a highly radioactive environment to be tested. However continuation in Europe requires an extensive R&D programme, which is planned in two parts: the high energy fragmentation technique to be studied at FAIR (see above), and the ISOL approach assigned to a collaborative study named **EURISOL**. In EURISOL (Fig. 8) the plan is to accelerate protons up to 1 GeV in a superconducting linac, producing 5 MW of beam power on a neutron converter target. The machine is also capable of accelerating deuterons, ^{3}He and ions up to mass number 40. The beams impinge simultaneously on both a direct target and an indirect target after conversion of protons to neutrons through a loop containing one ton of mercury surrounded by fissile material. Unstable nuclei diffuse out of the target, are ionised and selected, and can be used directly at low energy or re-accelerated by another linac to energies up to 150 MeV per nucleon in order to induce nuclear reactions. There is an active R&D programme into the mercury target and superconducting RF cavities.

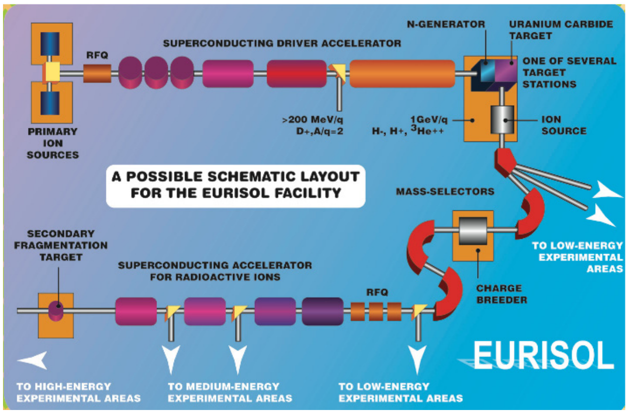

Figure 8: The European ISOL Facility, EURISOL.

In the United States, the policy is to study both fragmentation and ISOL techniques at a single new facility, **FRIB**, to be built at Michigan State University [8]. Approval for this project was given in June 2009, and design and construction will take up to 10 years at a cost of about $600m. Plans are for a superconducting RF driver linac providing 400 kW for all beams. Uranium ions will be accelerated to 200 MeV/u and lighter ions to increasingly higher energy (for example, protons at 600 MeV). There are upgrade possibilities to 400 MeV/u for uranium and to 1 GeV for protons.

IRRADIATION FACILITIES

With the world's energy requirements in mind and the construction of fusion energy test facilities like ITER, a need has been identified for an irradiation tool to quantify the resistance of advanced materials to the extreme, neutron-enriched conditions specific to the reactors of the future. **IFMIF** (the International Fusion Materials Irradiation Facility), whose study is led by CEA-Saclay, comprises two CW accelerators generating 2×125 mA of deuterons at 40 MeV. The combined 10 MW of beam power, directed onto a liquid lithium source, will generate an intense flux of 10^{17}/s neutrons at 14 MeV. This will enable experiments to be carried out to calibrate data from a fission reactor, generate an engineering base of material-specific activation, and support analysis of material for use in safety, maintenance, recycling, decommissioning and waste disposal systems. A pre-cursor of IFMIF, known as IFMIF-EVEDA, is also under development by CEA aimed at constructing a test facility based on a single deuteron accelerator with 125 mA at 9 MeV.

ACCELERATOR-DRIVER SYSTEMS

In a similar context, ADS is a rapidly growing area of research concentrating on the use of accelerators for nuclear waste transmutation and nuclear energy generation using spallation neutron sources. The basic principle is to produce an intense neutron flux from spallation reactions induced by a proton beam on a heavy target. The neutrons are moderated and used to drive a sub-critical blanket, and long-lived nuclear waste can be converted to stable or short-lived isotopes. The idea of using the neutrons to sustain a sub-critical reactor (ADSR) is now recognised as having the potential to replace carbon-free nuclear power stations with a more sustainable, cost-effective and safer form of nuclear power.

The optimum beam energy, beam intensity, and beam shape and profile for ADSR are a compromise between the neutron yield, the target design, He and H production in structure materials, accelerator construction costs and limitations in accelerator technology. Based on information to date, an accelerator complex generating 10 MW of proton beam power at about 1 GeV has been identified. In addition to these accelerator challenges, beam availability must typically be an order of magnitude better than at present to avoid cooling and re-heating of the reactor core, which could lead to structural damage.

The world's first ADS experiment was actually performed at Kyoto University Research Reactor Institute in Japan in March 2009 using a 100 MeV proton beam delivered by an FFAG onto a heavy metal target. A larger-scale test facility has recently been approved by the Belgian Nuclear Research Centre (SCK.CEN) at Mol in Belgium. This envisages a 600 MeV, 2.5 mA CW proton beam and a Pb-Bi eutectic target. Construction is planned to start in 2015 with operation expected in 2020.

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