FUTURE HIGH-INTENSITY PROTON ACCELERATORS

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Abstract

This paper provides an overview of currently planned high-intensity proton accelerators. While for high energies (>10 GeV) synchrotrons remain the preferred tools to produce high-intensity beams, recent years have seen an impressive development of linac-based lower-energy <8 GeV) high-intensity proton drivers for spallation sources, accelerator driven systems (ADS), production of Radioactive Ion Beams (RIB) and various neutrino applications (beta-beam, superbeam, neutrino factory). This paper discusses the optimum machine types for the various beam requirements and uses a range of projects, which are likely to be realised within the coming decade, to illustrate the different approaches to reach high average beam power with the application-specific time structure. Only machines with a beam power above 100 kW are considered.

INTRODUCTION

High-intensity proton accelerators are characterised by a high time-averaged energy flux per beam cross-section, meaning by high-power beams with small emittances. The smallest emittances can be achieved by full-energy linacs or cyclotrons, as already demonstrated by the LAMPF linac at Los Alamos [1] (1 MW, 0.8 GeV), or the PSI cyclotron (1.2 MW, 0.59 GeV). Rapid Cycling Synchrotrons (RCS) are often proposed for MW beams at energies of a few GeV but one should note that these beam powers have not yet been demonstrated with existing machines. The highest beam power that has been achieved with an RCS in the lower GeV range is 160 kW at 800 MeV at the ISIS [4] spallation neutron source at RAL (UK). For energies above several GeV, high-power beams are exclusively generated by synchrotrons, since linacs become less economical. Examples can be found in the area of neutrino physics, with the NuMI experiment at FNAL (US) [2] operating with 400 kW at 120 GeV, or the CNGS experiment at CERN (Switzerland) operating with 500 kW at 400 GeV.

High-intensity proton machines can be categorised according to their pulse length on target [5], the application of the facility [6], or the repetition rate of the machine [7]. High-energy machines tend to operate at low repetition rates to allow for the cycling periods of a chain of synchrotrons. Typically each synchrotron increases the beam energy by a factor of ten. At lower energies (<1 GeV), high average beam power can only be achieved with high duty cycles or with CW machines such as cyclotrons and CW linacs. In the intermediate energy region, between 1 and 10 GeV cyclotrons are no longer economical and we often encounter a competition between rapid cycling synchrotrons and full-energy linacs. Most of the future projects do not propose repetition rates higher than 100 Hz for synchrotrons or linacs. In the case of synchrotrons the cost of the dipole power supplies becomes too high, while in the case of linacs it is more economical to go to a low-current CW machine. Fixed Field Alternating Gradient (FFAG) machines may be a solution to extend the range of usable repetition rates up to several kHz. However, even if the technology is highly promising, the acceleration of high-intensity proton beams with FFAGs has yet to be demonstrated and it will still take several years for a high-intensity proton FFAG to appear. Figures 1 and 2 summarise the machine choice according to energy range and repetition rate.

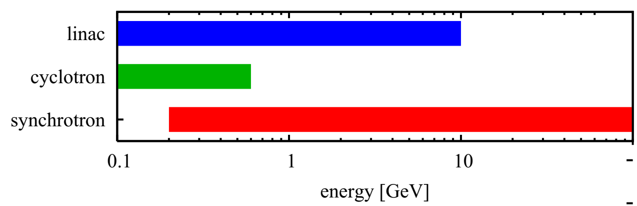

Figure 1: Likely energy range for future high-intensity proton machines.

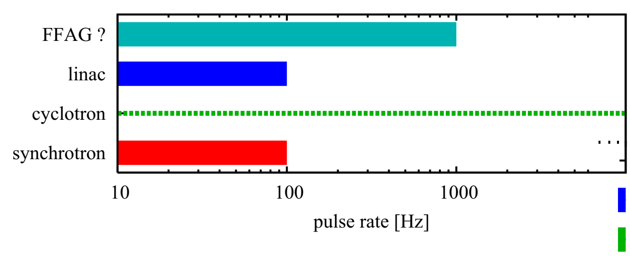

Figure 2: Likely repetition rates for future high-intensity proton machines.

Figure 3 shows a selection of future accelerators with proton beam power values above 100 kW. Most of these machines can be roughly categorised according to the ratio of beam power P (in MW) over energy E (in GeV) and their final beam energy. Up to approximately 10 GeV proposed and existing applications with $P/E >\approx 1$ are almost exclusively driven by linac-based machines (full energy linacs, or linacs together with accumulator/compressor rings), while for energies above 10 GeV most proposals rely on synchrotron-based drivers (linac plus synchrotron).

In the triangular area in Fig. 3, which is characterised by $P/E <\approx 1$ and beam energies below 10 GeV there are competing solution based on linacs and on synchrotrons. Formerly this region was dominated by synchrotrons but due to the advancement of superconducting cavities for $\beta < 1$ there are now more and more linac-based proposals. On the high-energy side we find the LP-SPL at CERN and the 8 GeV linac-based proton driver at FNAL. On the low-energy side there are the RIA/AEBF proposals [9, 10]. A classification according to pulse length on target, which is more closely linked to the application, is given in the following sections.

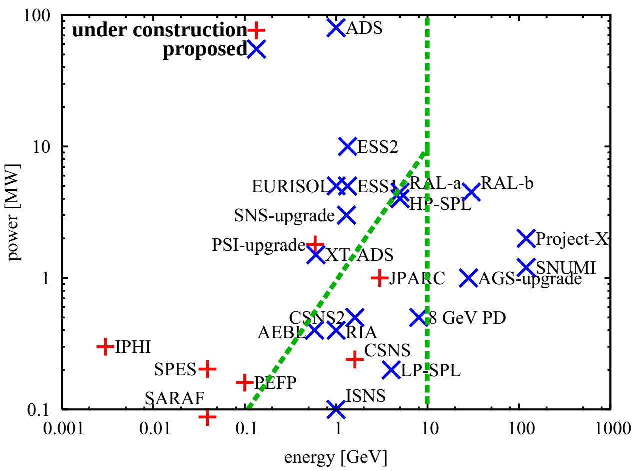

Figure 3: Beam power versus energy for future high-intensity proton machines. The left side (with P/E in [MW/GeV] $>\approx 1$ and $E < 10$ GeV) is dominated by linacs (or linacs + accumulator), while the right side ($E > 10$ GeV) is dominated by synchrotron-based machines (or FFAGs). Within the triangular area both solutions are applicable.

CW OPERATION

High-intensity CW beams are only available from cyclotrons (limited to < 1 GeV) and linacs. These machines are most economical for high beam power at low energy, which is why the beam energy is usually not beyond 1 GeV. They provide beams for "long-pulse" neutron sources, the production of radioactive ion beams and material irradiation. In the coming decades CW linacs are also foreseen to provide beams close to the 100 MW range to be used for the transmutation of nuclear waste. CW machines have the added advantage of high efficiency in terms of power consumption, since for every pulsed machine one pays for the filling time of the cavities, which cannot be used for acceleration. For this reason, when comparisons are made between the power efficiency of pulsed superconducting (SC) and normal conducting (NC) linacs, one must take into account that the filling time is proportional to the quality factor (and inversely proportional to the pulse current), yielding filling time values which can be several orders of magnitude higher in case of SC cavities (in the order of 1 ms) when compared with NC cavities (order of 10 μs).

Proposed cyclotrons for CW operation

A prominent example for a high-power cyclotron is the PSI facility in Switzerland [8], which provides a 1.2 MW proton beam at 590 MeV (proton beam power record!). The high-power beam is used to drive the spallation neutron source SINQ and to generate intense pion and muon beams. Recently an upgrade program has been approved to raise the beam power to 1.8 MW. The upgrade program includes the installation of a new microwave particle source, new buncher cavities (and RF system) for the transport lines at 870 keV and 72 MeV, new resonators for the cyclotron itself, and an upgrade of the target stations. The improvement of the facility has already started and operation at 1.8 MW is expected in the year 2012. The present accelerator layout is shown in Fig. 4.

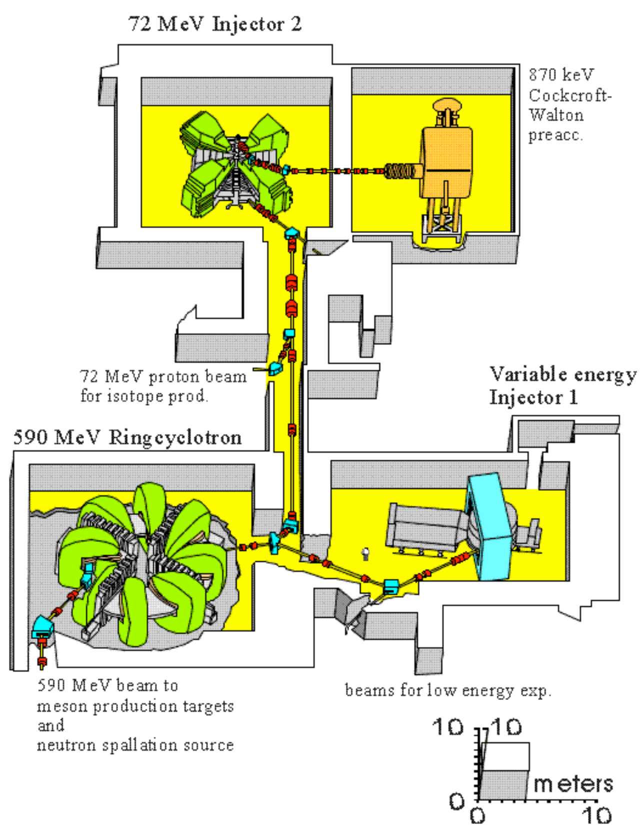

Figure 4: Present layout of the PSI cyclotron chain (source: PSI web-site).

Proposed linacs for CW operation

High-power CW linacs are proposed for the production of radioactive ion beams and for ADS demonstration facilities. Examples for RIB proton drivers are the RIA/AEBL

(US) [9, 10] or EURISOL SC linacs [11, 12] and the European proposal for a demonstration facility for Accelerator Driven Systems (XT-ADS) [13]. The IPHI RFQ [15], which is now under construction at CEA (France) is conceived as a CW injector (100 mA, 3 MeV) suitable for ADS operation. First beam tests are expected in 2008/9. Even though its beam power is slightly below 100 kW (80 kW) it worth mentioning the SARAF facility in Israel [14], which is now under construction and expected to be fully operational in 2010. It consists of a 40 MeV CW linac, producing proton and ion beams for RIB production, nuclear physics, neutron physics and isotope production. For reliability reasons ADS linacs are often composed out of short SC cryo-modules, which allow continued machine operation in the case of cavity failures. For the same reason the low-energy front-ends of ADS linacs (< 50 MeV) are usually duplicated to avoid beam trips in case of source or RF failures in the front-end. Prototyping of suitable ADS cavities (SC CH, NC DTL, SC spoke, SC elliptical) is ongoing but so far none of the proposed facilities is funded.

Even though most proposed proton drivers for RIB production are based on CW linacs, there are also various proposals to use pulsed linacs for this application (e.g. [16]). While CW operation certainly eases the target operation of a multi-megawatt beam, the option of using the same proton driver for RIBs [17] and other applications (such as neutrino physics) in a time sharing mode could significantly reduce the cost for the different physics communities.

LONG-PULSE OPERATION

The front-end of a possible pulsed EURISOL driver is now being constructed at INFN Legnaro (Italy) under the name of SPES [18]. Originally the design was based on a SC linac with a maximum energy of 100 MeV. Recently the design was changed to use a normal conducting pulsed DTL at an energy of 40 MeV (upgradable to 100 MeV). The RFQ design is taken from the TRASCO project [19] and the DTL design is developed in collaboration with the Linac4 project at CERN [20]. The facility aims to produce radioactive ion beams and neutrons by 2013. A similar design to SPES is used for the material irradiation facility PEFP (Proton Engineering Frontier Project) [23], which is now under construction in Korea. This machine consists of a high-duty cycle (24%) front-end (3 MeV RFQ plus DTL up to 20 MeV), and a 2nd DTL section up to 100 MeV, operating with duty cycle of 8%. The layout of the PEFP facility is shown in Fig. 5. The project was launched in 2002 by the Korean government and is now under construction in Gyeongju. The facility is expected to operational in 2012.

Long-pulse proton drivers are linacs without any subsequent circular machines. Typical pulse lengths in sub-ms range are achieved with beam energies between a few MeV and several GeV. Apart from RIB production, long-pulse machines can be used for long-pulse neutron spallation sources (e.g. the proposed long-pulse target of the European Spallation Source (ESS) [21]), material irradiation (as for PEFP) or neutrino physics (e.g. beta-beams [22]).

SHORT-PULSE OPERATION

Short intense pulses (microsecond range) with high average beam power can be produced by synchrotrons or by linacs plus an accumulator ring. For energies above 10 GeV only synchrotrons (or rather chains of synchrotrons) are proposed to produce these pulses, while at lower energies (1 - 10 GeV) there are a number of competing synchrotron-based and linac-based solutions (the same is true for long-pulse operation). For spallation neutron sources one aims at energies below approximately 3 GeV to avoid the efficiency drop of the neutron production rate (number of neutrons/proton beam power). For this reason one either uses a synchrotron-based neutron source at around 3 GeV (1 MW expected beam power as for instance JPARC [25]) or, if higher beam power values are needed, a full-energy linac plus accumulator ring. Examples for the latter approach are the SNS [24] (1 GeV, expected beam power: 1.4 MW), which is in the process of ramping up the beam power, and the proposed ESS [21] facility (1.3 GeV, beam power: 5 MW short pulse plus 5 MW long pulse operation simultaneously).

A synchrotron-based facility in the sub-MW range, which is currently under construction is the Chinese Spallation Neutron Source (CSNS) [5]. In three steps the beam power will be increased from initially 120 kW to 240 kW and finally to 0.5 MW. The 1.6 GeV RCS uses a normal conducting proton linac (DTL) with 81 MeV injection energy, which will then be increased to 134 and 230 MeV in the subsequent upgrades. Figure 6 shows a schematic layout of the facility and indicates the foreseen upgrade plans.

For neutrino factory targets short-pulse (μs range), short bunch operation (ns range) are required, which can be achieved with linacs + accumulator + compressor ring or with synchrotrons that have a final bunch rotation scheme.

The advantage of using a linac plus accumulator ring to produce short pulses is the range of different time structures that can be produced by such a facility. The unmodified linac pulses can be used for long-pulse applications such as radioactive ion beams or long-pulse neutron spallation sources and the short pulses can be used for neutrino physics or short-pulse neutron spallation sources. Especially in view of a staged construction for neutrino physics, a linac-based solution offers unmatched flexibility [26].

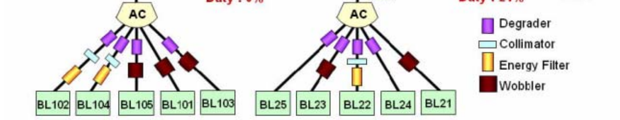

Figure 5: Layout of the PEFP facility (source: [23]).

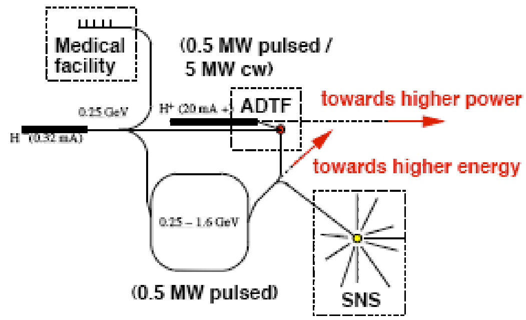

Figure 6: Layout of the CSNS facility indicating the upgrade path (source: [5]).

THE SPL PROJECT AT CERN

As an example for the flexibility of the combination of a linac with accumulator/compressor rings, we present the SPL project at CERN [16, 27], which foresees the following construction stages, matched to a growing number of applications:

1. Construction of Linac4 [20]: the 160 MeV normal conducting front-end of the SPL. This machine has recently been approved and is expected to be operational in 2012. It will replace the present CERN proton linac (50 MeV) and is the first step towards reaching the full luminosity potential of the LHC. The location of Linac4 on the CERN site is such that a straight prolongation of Linac4 is tangential to the SPS (see Fig. 7), with enough space between the two machines to construct the SPL and a new proton synchrotron (PS2), which will replace the aging PS machine. This layout allows to use the Linac4 beam for the commissioning of SPL and PS2, while maintaining the operation of the present LHC proton injector chain (PSB - PS - SPS), thereby minimising any interruption to LHC operation until the new injector chain is fully operational.

2. Low-power SPL (LP-SPL): installation of a 4 GeV superconducting linac, producing 200 kW of beam power with a repetition rate of 2 Hz. Two families of superconducting cavities ($\beta = 0.65$ and $\beta = 1.0$) are used to accelerate the beam to its top energy. This machine forms part of the renovation of the CERN proton injector complex with the goal of the reaching the maximum luminosity for beam collisions in the LHC.

3. High-power SPL (HP-SPL): extension of the LP-SPL to 5 GeV and increase of the repetition rate to 50 Hz, producing 4 MW of proton beam power. In this stage the beam can be used for the production of neutrinos via beta-beams [22] and to drive a pulsed RIB facility like EURISOL.

4. Addition of an accumulator ring: in this configuration the SPL can drive a beta-beam facility and produce a so-called Superbeam at the same time, which is considered to be a promising combination for neutrino physics [28]. The capability to drive a RIB facility and the LHC injector chain remains unchanged.

5. The addition of a compressor ring enables the SPL to produce bunches in the nanosecond range, which are nowadays recommended for a neutrino factory target. In case further target studies prove the need for higher proton energies it seems realistic to extend the SPL to the 10 GeV range. A similar approach is proposed at FNAL in the 8 GeV proton driver project [29]. Energies beyond 10 GeV do not seem practical, since H^- stripping due to magnetic fields and black-body radiation becomes a serious problem [30, 31, 32].

Figure 7: Layout of the SPL on the CERN site.

It should be noted that the optimum energy and time structure for neutrino factory targets has not yet been experimentally determined. In this context the flexibility of a linac-based solution may ease the task of adapting the proton driver time structure to an evolving set of input parameters for a neutrino factory.

The main parameters of Linac4, LP-SPL, and HP-SPL are summarised in Table 1.

Table 1: Parameter list for the machine evolution from Linac4 to HP-SPL.

	Linac4	*LP-SPL*	*HP-SPL*
Energy [GeV]	0.16	4	5
Beam power [MW]	0.005	0.192	> 4
Repetition rate [Hz]	2	2	50
Av. pulse current [mA]	40	20	40
Chopping ratio [%]	65	62	62
Beam pulse [ms]	0.4	1.2	0.4 - 0.6
Beam duty cycle [%]	0.08	0.24	2.0
No. klystrons	19	19+28†	19+57
RF peak power [MW]	24	100	219
Length [m]	80	459	534

† 352 MHz + 704 MHz

RCS VERSUS LINAC

As already mentioned there is often a competition between synchrotron-based and linac-based proton drivers for beam energies between 1 and 10 GeV. The decision for one or the other machine type depends on factors such as the required beam power, the desired time structure and also the experience of the concerned institute with linacs or synchrotrons, respectively. Within the last years two studies have compared the two solutions in terms of performance and cost.

The first one was the FNAL 8 GeV proton driver study II [29] which compared a 8 GeV full-energy superconducting linac with a 600 MeV linac plus an 8 GeV synchrotron. The goal was to achieve initially 0.5 MW beam power and to have the possibility to upgrade the power to 2 MW. It was found that the linac-based solution is approximately 30% more expensive than the synchrotron-based solution. Nevertheless the linac solution was preferred due to: i) its upgrade potential and its adaptability to future proton needs at FNAL, ii) the possibility to construct a test bench for the International Linear Collider (ILC), making use of TESLA-style SC cavities and cryo-modules.

The 2nd study was done this year at CERN to compare the low-power SPL (4 GeV, 0.2 MW) with a rapid cycling synchrotron [33]. Both machines have to provide $1.5 \cdot 10^{14}$ particles per pulse with a 1 Hz repetition rate for a proposed new proton synchrotron (PS2) with 4 GeV injection energy. In accordance with the FNAL study it was found that the linac solution demands a 28% higher initial investment. However, due to its upgrade potential and its expected performance advantages, the linac solution was endorsed by the management and represents now the base line for the planned upgrade of the CERN proton injector chain. The relative merits of each solutions are summarised in Table 2.

Table 2: Relative merits of RCS and SPL options for the injection into the proposed CERN PS2, see [33].

	SPL	*RCS*	*Advantage*
Filling time PS2	0.6 ms	1.3 s	SPL
Time struct. LHC	inherent	different	SPL
Rel. proton rate	2.5	1	SPL
Fixed target phys.	ideal	acceptable	SPL
Ions	acceptable	ideal	RCS
Upgrade potential	high	low	SPL
Relative cost†	1.28	1	RCS

† the relative cost considers only the items that differ between both solutions

SUMMARY

A number of future high-intensity proton accelerators (see Table 3) have been analysed and compared in terms of beam power, pulse length, repetition rate and application. While in some case the choice of the machine is clear there remains an overlap of linac-based and synchrotron-based solution for the energy range of 1 - 10 GeV and $P/E < 1$ (MW/GeV). Most designs are driven by the need for low-loss operation in order to ensure hands-on maintenance of the machine after a few hours of cool-down time. So far linacs and cyclotrons have achieved beam powers in the MW range for energies around 1 GeV. Even though many RCS or FFAG proposals aim for megawatts of beam power in the same energy range, their feasibility still has to be demonstrated. Furthermore linacs offer a high flexibility to adapt the time structure of the beam to changing demands. For energies beyond 10 GeV synchrotrons remain the single machine type able to deliver high-intensity beams for the foreseeable future.

REFERENCES

[1] R.W. Garnett *et al.*, Simulations studies of the LAMPF proton linac, PAC'95, Dallas, Texas, USA.

[2] http://www-numi.fnal.gov/numwork/numiwk.html

[3] http://proj-cngs.web.cern.ch/proj-cngs/

[4] http://www.isis.rl.ac.uk/

[5] J. Wei, S. Fu, and S. Fang, High-power accelerators in China: status and outlook, HB'06, Tsukuba, Japan.

[6] M. Vretenar and R. Garoby, Overview of high intensity linac programs in Europe, LINAC'04, Lübeck, Germany.

[7] W.T. Weng, Comparative study of proton accelerators for high power applications, HB'06, Tsukuba, Japan.

[8] M. Seidel and P.A. Schmelzbach, Upgrade of the PSI cyclotron facility to 1.8 MW, Cyclotrons'07, Giardini Naxos, Italy.

[9] R.C. York, Rare isotope accelerator (RIA) project, SRF'06, Ithaca, New York, USA.

[10] P.N. Ostroumov *et al.*, Accelerators for the Advanced Exotic Beam Facility in the US, PAC'07, Albuquerque, US.

[11] http://www.eurisol.org

[12] J.L. Biarotte, High power CW superconducting linacs for EURISOL and XADS, LINAC'04, Lübeck, Germany.

[13] P. Pierini, The accelerator activities of the EUROTRANS programme, APAC'07, Indore, India.

[14] A. Nagler *et al.*, Status of the SARAF project, LINAC'06, Knoxville, USA.

[15] P-Y. Beauvais, Recent evolutions in the design of the French high intensity proton injector (IPHI), EPAC'04, Lucerne, Switzerland.

[16] F. Gerigk (*Ed.*), Conceptual design of the SPL II, a high-power superconducting H^- linac at CERN, CERN-2006-006.

[17] E. Noah *et al.*, EURISOL target stations operation and implications for its proton linac driver beam, EPAC'06, Edinburgh, UK.

[18] G. Prete (*Ed.*), Technical design for and advanced exotic ion beam facility at LNL, 2007.

[19] A. Pisent *et al.*, The TRASCO-SPES RFQ, Linac'04, Lübeck, Germany.

[20] R. Gerigk and M. Vretenar (*Eds.*), Linac4 technical design report, CERN-AB-2006-084.

[21] http://neutron.neutron-eu.net/n_ess

[22] P. Zucchelli, A novel concept for a $\bar{\nu_e}/\nu_e$ neutrino factory, *Phys. Lett* **B 532** (2002) 166.

[23] B-H. Choi *et al.*, High power proton accelerator in Korea, APAC'07, Indore, India.

[24] S. Henderson *et al.*, Status of the SNS beam power upgrade project, EPAC'06, Edinburgh, UK.

[25] Y. Yamazaki, Approach to a very high intensity beam at J-PARC, HB'06, Tsukuba, Japan.

[26] F. Gerigk and R. Garoby, Operational flexibility of the SPL as proton driver for neutrino and other applications, HB'06, Tsukuba, Japan.

[27] R. Garoby and F. Gerigk, Status of the SPL at CERN, ICANS'07, Dongguan, China.

[28] J.E. Campagne and A. Caze, The θ_{13} and δ_{CP} sensitivities of the SPL-Fréjus project revisited, CERN-NUFACT-NOTE 142 (2004).

[29] G.W. Foster, W. Chou, and E. Malamud (*Eds.*), Proton driver study II, FERMILAB-TM-2169 (2002).

[30] L.R. Scherk, An improved value for the electron affinity of the negative hydrogen ion, *Can. J. Phys.* **57** (1979) 558.

[31] W. Chou *et al.*, 8 GeV H^- ions: transport and injection, PAC'05, Knoxville, USA.

[32] H.C. Bryant and G.H. Herling, Atomic physics with a relativistic H^- beam, *J. Modern Optics* **53** (2006) 45.

[33] R. Garoby *et al.*, Comparison of options for the injector of PS2, CERN-AB-2007-014-PAF.

Table 3: Main parameters of future high-intensity proton accelerators.

machine	E [GeV]	P_{beam} [MW]	f_{rep} [Hz]	I_{av} [mA]	type	application	status
8 GeV PD (FNAL)	8	0.5 - 2	10	0.063	SC linac	neutrinos	proposed
LP-SPL (CERN)	4	0.2	2	0.05	SC linac	LHC upgrade	proposed
HP-SPL (CERN)	5	> 4	50	0.8	SC linac, accumulator	neutrinos, RIB fixed target	proposed
ESS1 (EU)	1.334	5	50	3.75	SC linac	neutrons	proposed
ESS2 (EU)	1.334	10	50	7.5	SC linac, accumulator	neutrons	proposed
SNS2 (ORNL)	1.3	3	60	2.31	SC linac, accumulator	neutrons	proposed
ADS (?)	≈ 1	≈ 80	CW	≈ 80	SC linac	transmutation	proposed
EURISOL (EU)	1	5	CW	5	SC linac	RIB	proposed
XT-ADS (EU)	0.6	1.5	CW	1.5	SC linac	transmutation	proposed
RIA (ANL)	1	0.4	CW	0.4	SC linac	RIB	proposed
AEBL (ANL)	0.58	0.4	CW	0.69	SC linac	RIB	proposed
PEFP (Korea)	0.1	0.16	120, 60	1.6	NC linac	irradiation	construction
SPES (LNL)	0.04	0.2	50	5	NC linac	RIB	construction
SARAF (SOREQ)	0.04	0.08	CW	2	SC linac	RIB	construction
IPHI (CEA)	0.003	0.3	CW	100	RFQ	R&D	construction
PSI upgrade (PSI)	0.59	1.8	CW	3.05	cyclotron	neutrons, muons,	construction
Project X (FNAL)	120	2	0.71	0.0167	8 GeV SC linac, synchr.	neutrinos	proposed
SNUMI (FNAL)	120	1.2	0.75	0.01	upgrade of existing synchr. chain	neutrinos	proposed
AGS upgrade (BNL)	28	1	2.5	0.036	1.5 GeV SC linac, synchr./FFAG	neutrinos, RHIC upgrade	proposed
RAL a (UK)	5-15	4.5	25-50	0.9	180 MeV NC linac, 4 synchr.	neutrinos	proposed
RAL b (UK)	30	4.5	8.3	0.15	180 MeV NC linac, synchr., FFAG	neutrinos	proposed
JPARC (JP)	3	1	25	0.33	600 MeV NC/SC linac, synchr.	neutrons, transmutation	construction
CSNS (CN)	1.6	0.24	25	0.15	134 MeV NC linac, synchrotron	neutrons	construction
CSNS2 (CN)	1.6	0.5	25	0.31	230 MeV NC linac, synchrotron	neutrons	proposed
ISNS (IN)	1	0.1	60	0.1	100 NC linac, synchrotron	neutrons	proposed