

Selected List of Low Energy Beam Transport Facilities for Light-Ion, High-Intensity Accelerators

L.R. Prost[#], Fermilab^{*}, Batavia, IL 60510, USA

***Disclaimer:** This document does not pretend listing all the LEBTs that have been built, operated or designed around the world. It merely gives an overview picture of the technological choices made for light-ion, high-intensity LEBTs, which appeared to be relevant if one would want some background information in the process of designing a similar beam line.*

1 Introduction

The Proton Improvement Plan II (PIP-II) at Fermilab is a program of upgrades to the injection complex^[1]. At its core is the design and construction of an 800-MeV, 2-mA H⁻ CW superconducting linac.

To validate various concepts for the front-end of such machine (i.e. first ~30 MeV), a test accelerator (a.k.a. PXIE) is under construction^[2]. During the design effort, it was useful to look at other facilities to identify peculiarities that the PXIE beam might present. In this instance, we concern ourselves with the design schemes of Low Energy Beam Transport lines (LEBT) only.

PXIE includes a 2 m-long LEBT, which takes an up to 10 mA DC, 30 keV H⁻ beam from the ion source to a Radio-Frequency Quadrupole (RFQ). In the process of searching for the relevant information, it became apparent that merely having a list of machines with similar beam parameters for the front-end would be valuable even before going into the deeper details of each individual design.

2 List of facilities

A survey of some of past, present and future light-ion high-intensity LEBTs around the world, is summarized in Table 1. It includes LEBTs, which are or have been operational as well as some that are or remained at the design stage.

^{*} Operated by Fermi Research Alliance, LLC, under Contract DE-AC02-07CH11359 with the United States Department of Energy

[#] lprost@fnal.gov

Table 1: List of light ion, high intensity accelerator facilities, decommissioned, operating or proposed.

Institution	Accelerator	Ion species	I_{Beam} , mA	E_{Beam} , keV (or keV/u)	Gen. perv. $\times 10^{-3}$ (Eq.1)	Pulse length, ms	Pulse frequency, Hz	LEBT design choice	Operating/Design parameters
RAL	FETS ^[4]	H ⁺	60	35	5.9	2	50	3 solenoids	Operating [*]
CERN	LINAC 4 ^[5,6]	H ⁺	80	45	5.4	0.4	2	2 solenoids	Design [†]
SSC	SSC injector ^[7,8,9]	H ⁺	30	35	3.0	0.007-0.035	10	Electrostatic [#]	Design
LANL	GTA ^[10]	H ⁺	50	35	5.0	2	5	2 solenoids	Operating [‡]
LBNL	AGS pre-injector ^[11]	H ⁺	70	35	6.9	0.45	5	2 solenoids	Operating
DESY	HERA-Linac3 pre-injector ^[12]	H ⁺	20	18	5.4	0.035	<1	2 solenoids	Operating
ESS/INFN-LNS	ESS ^[13,14]	H ⁺	90	75	2.9	2.86	14	2 solenoids	Design
GSI	FAIR proton Linac/SILHI ^[15,16]	H ⁺	100	95	2.2	0.036	4	2 solenoids	Design
KEK/JAEA	J-PARC ^[17,18]	H ⁺	55	50	3.2	0.5	25	2 solenoids	Operating
ORNL	SNS ^[19,20]	H ⁺	50	65	2.0	1	60	2 einzel lenses	Operating
IHEP	CSNS ^[21]	H ⁺	50	50	2.9	500	25	3 solenoids	Operating
FNAL	Linac ^[22]	H ⁺	60	35	5.9	0.145	15	2 solenoids	Operating
INFN-LNL	SPES/TRIPS ^[23,24]	H ⁺	35	80	1.0	DC		2 solenoids	Operating
Soreq NRC	SARAF ^[25,26]	H ⁺ , D ⁺	5	20	1.1 [§]	DC		3 solenoids	Operating
SCK-CEN	MYRRHA/MAX ^[27,28]	H ⁺	5	30	0.6	DC		2 solenoids ^{&}	Design
KAERI	KOMAC ^[29]	H ⁺ /H ⁻	30/3	50	1.7 [§]	DC		2 solenoids	Operating
LANL	LEDA ^[30]	H ⁺	110	75	3.5	DC		2 solenoids	Operating
BARC	LEHIPA ^[31,32]	H ⁺	30	50	1.7	DC		2 solenoids	Design
IMP	C-ADS Injectors ^[33,34,35]	H ⁺	30	35	3.0	DC		2 solenoids	Operating ^{††}
FNAL	PXIE ^[2]	H ⁺	10 ^{**}	30	1.2	DC		3 solenoids	Operating
CEA-Saclay	IFMIF/EVEDA ^[36,37]	D ⁺	140	50	4.1	DC		2 solenoids	Design ^{###}
LBNL	ESQ injector ^[38]	H ⁺	45	100	0.9	DC		Electrostatic quadrupoles	Operating
Goethe University	FRANZ ^[39,40]	H ⁺	50	120	0.8	DC		4 solenoids	Design ^{††}
LANL	LANSCE ^[41]	H ⁺	35	35	3.5	DC		2 solenoids	Design ^{**}
TRIUMF/AES	CDS ^[42,43]	H ⁺	10	40	0.8	DC		1 solenoid	Operating
GANIL	SPIRAL 2 ^[44]	D ⁺	6.5	20	0.7	DC		2 solenoids + quadruplet quads	Design [£]

^{*} at 25 Hz only

[†] parameters demonstrated on a test stand, but not concurrently

[#] normal quadrupoles, helical quadrupoles and einzel lenses were considered. LEBTs with einzel lenses and helical quadrupoles were tested but not to full beam design parameters.

[‡] design was 2% duty factor (measurements only up to 1% duty factor)

[&] evolution from EURISOL injector design, which included 4 solenoids

[§] for H⁺

^{††} at 10 mA only

^{**} max current; 5 mA nominal

^{###} achieved 120 mA DC with H⁺ and 145 mA with D⁺ @ 9.5% duty factor only

^{††} commissioning activities with 3.5 mA, 14 keV He⁺, which corresponds to a generalized perveance of 2.7×10^{-3}

^{**} replacement of the existing Cockroft-Walton based injectors

[£] nominal parameters demonstrated in pulsed mode

3 Discussion

For the range of beam currents (5-140 mA) and energies (20-120 keV) listed here, most designs employ a set of solenoids to transport the beam from the ion source to the next accelerating structure, and it is independent of the beam time structure (i.e. from short pulses to DC). These ‘magnetic’ LEBTs operate in a regime where the beam is highly neutralized, reducing significantly

the potential for emittance growth due to the space charge. Yet, if the beam is pulsed, it gets significantly mismatched during the Space Charge Compensation (SCC) transient, which is often addressed with an additional fast chopping system downstream and/or some limiting apertures.

Very few ‘electrostatic’ LEBTs were found either operational or designed (only 3 identified in the table). They operate in a fully un-neutralized mode by default since the neutralizing particles are swept away by the large electric field of the focusing elements. Thus, it eliminates the difficulties related to the transient time associated with SCC. On the other hand, space charge often limits the maximum transportable beam current and space charge non-linearities may become problematic.

A discussion of pros and cons for both types of LEBTs can be found in Ref. [3]. Below, we suggest using the beam generalized perveance as a figure of merit for comparing the potential for space charge-induced emittance growth between the facilities listed in Table 1 in case of incomplete neutralization.

3.1 *Beam perveance and potential for emittance growth*

The beam current and energy of the facilities listed in Table 1 vary over a fairly wide range of values. Since the magnitude of space charge forces play an important role in the design of the beam line optics, in order to help in making comparisons between the different systems, included in Table 1 is the unit-less parameter called the generalized perveance defined as^[45]:

$$K = \frac{I_{Beam}}{V_{ext}^{3/2}} \cdot \left[\frac{1}{4\pi\epsilon_0(2q/m)^{1/2}} \right] \quad (1)$$

where I_{Beam} is the beam current in Amps, V_{ext} is the ion source extraction voltage in Volts, q is the total electrical charge in Coulombs, m is the mass of the particle in kg and ϵ_0 is the permittivity of vacuum in SI units. Thus, for all the machines listed in Table 1, the beam perveance lies between 6×10^{-4} and 7×10^{-3} . Generally speaking, the beam perveance sets a practical limit for un-neutralized transport where lumped focusing is no longer possible because the space charge forces cause the beam to diverge too fast between consecutive lenses. A practical estimate of what this limit may be, can be derived (e.g.: following Ref. [46] Section 3) and is found to be $\sim 1.2 \times 10^{-2}$, almost an order of magnitude above any of the values listed in Table 1 for which un-neutralized transport was realized, the largest being 2×10^{-3} for Oak Ridge National Laboratory’s Neutron Spallation Source.

The practical limitation associated with a large beam perveance just mentioned is not necessarily what makes the realization of space charge dominated transport often unattractive. Instead, this is the potential for emittance growth associated with large tune depression concurrent with the imperfections of a real beam and machine even in the linear regime. An analytical formulation for the simplest model of continuous focusing and paraxial approximation is given and discussed in some detail in Ref. [47]. While there are other components that determine the evolution of the emittance in any accelerator, the predominance of LEBTs employing a neutralization scheme shows the importance given to the possibility of emittance growth due to space charge in the design of a beam transport line.

3.2 *Number of focusing elements*

There are many details that go into the design of a LEBT, well beyond the discussion of the preceding section, which merely illustrates how some basic parameters (such as beam energy and beam current) may set some limits to what is theoretically and practically achievable. On the other

hand, Table 1 clearly indicates that solenoid focusing has been and still is the most common choice for LEBTs around the world (with the most notable exception of the SNS front-end). From a theoretical point of view, only 2 free parameters are necessary to match the Twiss functions (α , β) of the beam produced by an ion source to those required at the entrance of a RFQ or another accelerating structure. For instance, in a single solenoid configuration, these 2 parameters are the solenoid current (i.e. focusing strength) and the solenoid position, given that the beam line geometry and the ion source parameters are fixed. That was the choice made by TRIUMF/AES for their Contraband Detection System (CDS) injector. However, the most common choice for a magnetic LEBT is to use 2 solenoids in order to be able to accommodate various tunes of the ion source.

Then, the choice of adding more focusing elements appears to be mainly dictated by auxiliary considerations often associated with other requirements for the LEBT. For instance, the beam line might include a bend and/or a chopping system, which in turn might require the beam to have specific parameters at its entrance. This is often accommodated with one more solenoid (for a total of 3), but for example, for FRANZ at the Goethe University in Frankfurt, it was decided to have 2 solenoids before and 2 solenoids after a complex E×B chopping system. For PXIE, a 3-solenoid LEBT has been chosen to accommodate a bending magnet and a robust chopper. Adding more focusing elements might also be required when the LEBT has to accommodate multiple ion species in a common beam line (e.g.: SPIRAL 2 at GANIL, which employs quadruplet quads in addition to solenoids)

3.3 *PXIE LEBT*

The PXIE LEBT design choices are discussed in some detail in Ref [46]. One of its peculiarities is the fact that the beam transport is space charge dominated, by design, over the last ~1m before the RFQ. The PXIE beam perveance is one of the lowest listed in Table 1, making it relatively easy to focus even without any neutralization. Also, the PXIE LEBT transport scheme assumes that the transition between neutralized transport and space charge dominated transport occurs where the beam transverse distribution is close to being uniform, hence limiting the potential for emittance growth due to relaxation into a thermal equilibrium. Scraping of the tail particles to limit non-linear space charge forces is also part of the scheme.

4 Conclusion

A list of LEBTs for light ion, high intensity accelerator facilities has been compiled. Most designs employ a transport scheme with at least 2 solenoids and high degrees of beam neutralization, although details of the beam lines may vary significantly. While solely based on the value of the generalized perveance space charge-dominated transport is not precluded, the overwhelming use of a neutralized transport scheme suggests that the potential for emittance growth due to relatively large tune depressions concurrent with non-ideal, non-stationary particle distributions and phase-space distortions due to space charge non-linearities are prime considerations in the design of Low Energy Beam Transport lines.

5 Acknowledgement

The author is grateful to A. Shemyakin for his critiques and guidance, as well as for his suggestion to write such a document.

6 References

- [1] S. D. Holmes et al., *PIP-II Status and Strategy*, Proc. of IPAC2015, Richmond, VA, USA (2015) THPF116, pp. 3982-3985, ISBN: 978-3-95450-168-7; and *PIP-II Reference Design Report* (2015), <http://pip2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1>
- [2] A. Shemyakin et al., *Status of the Warm Front End of PXIE*, Proc. of LINAC2014, Geneva, Switzerland, (2014) THPP056
- [3] Chauvin et al., *Source and Injector Design for Intense Light Ion Beams Including Space Charge Neutralisation*, Proc. of LINAC2010, Tsukuba, Japan (2010) TH302
- [4] C. Gabor et al., *H Beam Transport Experiments in a Solenoid Low Energy Beam Transport*, Rev. Sci. Instrum. **83**, 02B719 (2012); doi: 10.1063/1.3678656
- [5] F. Gerigk, M. Vretenar, editors, *Linac4 Technical Design Report*, CERN-AB-2006-084 ABP/RF (2006) <http://cds.cern.ch/record/1004186/files/ab-2006-084.pdf>
- [6] M. Vretenar et al., *Status and Plans for Linac4 Installation and Commissioning*, Proc. of IPAC2014, Dresden, Germany (2014) THPME048
- [7] Deepak Raparia, *HESQ, a Low Energy Beam Transport for the SSC Linac*, Proc. of LINAC1990, Albuquerque, NM, USA (1990) 405
- [8] S.K. Guharay et al., *Compact ESQ System for Transport and Focusing of H Beam from Ion Source to RRQ*, Proc. of LINAC1992, Ottawa, ON, Canada (1992) TU4-16
- [9] K. Saatdatmand, *H Ion Source and LEBT Activities at SSCL*, Nucl. Instrum. Meth. Phys. Res. B **79** (1993) 365
- [10] O.R. Sander, et al., *Commissioning the GTA Accelerator*, Proc. of LINAC1992, Ottawa, ON, Canada (1992) WE1-01
- [11] J. G. Alessi et al., *Performance of the New AGS RFQ Preinjector*, Proc. of PAC1989, Chicago, IL, USA (1989) 999; BNL-41841
- [12] L. Criegee et al., *The 50 MeV H Linear Accelerator for HERA: LINAC3 Collaboration*, Rev. Sci. Instrum. **62**, 867 (1991) <http://dx.doi.org/10.1063/1.1142023>
- [13] L. Celona et al., *Design Issues of the Proton Source for the ESS Facility*, Proc. of LINAC2012, Tel-Aviv, Israel (2012) THPB076
- [14] L. Celona et al., *A High Intensity Proton Source for the European Spallation Source Facility*, Proc. of IPAC2015, Richmond, VA, USA (2015) WEPWA010
- [15] L. Groening et al., *The 70 MeV Proton Linac for the Facility for Antiproton and Ion Research FAIR*, Proc. of LINAC2006, Knoxville, TN, USA (2006) MOP061
- [16] R. Brodhage et al., *Status of the FAIR Proton Linac*, Proc. of IPAC2015, Richmond, VA, USA (2015) THPF011
- [17] Y. Yamazaki, Editor-in-Chief, *Accelerator Technical Design Report for J-PARC*, March 2003, Parameter list: <http://hadron.kek.jp/~accelerator/TDA/tdr2003/chap10/10.1.pdf>
- [18] Y. Liu, *Front-end, Linac Upgrade, and Commissioning of J-PARC*, ICFA mini-Workshop on Beam Commissioning for High Intensity Accelerators, Dongguan, China (2015) <http://indico.ihep.ac.cn/event/4749/session/1/contribution/3/material/slides/0.pdf>
- [19] S. Henderson, originator, *SNS Parameters List*, June 2005, SNS 100000000-PL0001-R13 http://sns.gov/media/pubs/pdf/sns_parameters_list_june05.pdf
- [20] J.W. Staples et al., *The SNS Front-End Accelerator Systems*, Proc. of PAC1998, Chicago, IL, USA (1998) MO4056
- [21] H. Ouyang, *Beam Commissioning of CSNS Front End*, ICFA mini-Workshop on Beam Commissioning for High Intensity Accelerators, Dongguan, China (2015) <http://indico.ihep.ac.cn/event/4749/session/1/contribution/4/material/slides/0.pdf>

- [22] D. S. Bollinger, *H⁻ Ion Source Development for the FNAL 750keV Injector Upgrade*, FERMILAB-CONF-12-476-AD, January 2013, arXiv:1301.7691v1 [physics.acc-ph] <http://arxiv.org/abs/1301.7691>
- [23] G. Ciavola et al., *The TRASCO High Current Proton Source and its LEBT*, Proc. of LINAC2002, Gyeongju, Korea (2002) 674
- [24] E. Fagotti et al., *Design of the SPES-1 LEBT*, Proc. of LINAC2004, Lübeck, Germany (2004) MOP17
- [25] L. Weissman et al., *SARAF Phase I Linac Operation in 2013-2014*, 2015 JINST **10** T10004 <http://iopscience.iop.org/article/10.1088/1748-0221/10/10/T10004/pdf>
- [26] A. Kreisel, *SARAF Phase-I Beam Operation Status*, Proc. of LINAC2014, Geneva, Switzerland, (2014) WEIOB02
- [27] D. Vandeplassche, L. Medeiros Romao, J.-L. Biarrotte, H. Podlech, *MAX Project Final Report*, August 2014 http://ipnwww.in2p3.fr/MAX/images/stories/freedownloads/MAX_Deliverable_1.5_final_free_download.pdf
- [28] R. Salemme et al., *Design Progress of the MYRRHA Low Energy Beam Line*, Proc. of LINAC2014, Geneva, Switzerland, (2014) MOPP137
- [29] B. H. Choi et al., *Development of the Low Energy Accelerator for KOMAC*, Proc. of LINAC2000, Monterey, CA, USA (2000) TUD21
- [30] J. Sherman et al., *Status Report on a DC 130 mA, 75 keV Proton Injector*, Rev. Sci. Instrum. **69**, 1003 (1998) <http://dx.doi.org/10.1063/1.1148706>
- [31] R. Pande et al., *Design & Development of LEBT for LEHIPA Project*, Proc. of InPAC2011, New Delhi, India (2011) 146
- [32] R. Pande et al., *A LEBT for the 400 keV RFQ based Neutron Generator at BARC*, Proc. of InPAC2011, New Delhi, India (2011) 148
- [33] Y. He et al., *The Conceptual Design of Injector II of ADS in China*, Proc. of IPAC2011, San Sebastián, Spain (2011) WEPS053
- [34] Z. Wang, *10-mA Proton Beam Commissioning of Demo Facility of C-ADS Injector II*, ICFA mini-Workshop on Beam Commissioning for High Intensity Accelerators, Dongguan, China (2015) <http://indico.ihep.ac.cn/event/4749/session/1/contribution/5/material/slides/0.pdf>
- [35] F. Yan, *Front End Commissioning for China-ADS Injector-I Test Facility*, ICFA mini-Workshop on Beam Commissioning for High Intensity Accelerators, Dongguan, China (2015) <http://indico.ihep.ac.cn/event/4749/session/1/contribution/6/material/slides/0.pdf>
- [36] N. Chauvin et al., *Final Design of the IFMIF/EVEDA Low Energy Beam Transport Line*, Proc. of PAC2009, Vancouver, BC, Canada (2009) TH5PFP004
- [37] G. Pruneri, *7th LIPAc Technical Meeting*, IFMIF Newline Article Online, June 03, 2015, <http://www.ifmif.org/?p=603>
- [38] O. A. Anderson et al., *Application of Electrostatic LEBT to High Energy Accelerators*, Proc. of EPAC1990, Nice, France (1990) 1288
- [39] P. P. Schneider et al., *Beam Dynamics in the LEBT for FRANZ*, Proc. of IPAC2014, Dresden, Germany (2014) THPME014
- [40] C. Wiesner, *Chopping and Transport of Low-Energy Ion Beams for FRANZ*, FNAL Accelerator and Technology Seminar, March 17, 2015, FNAL Beams-doc-4791-v3 https://beamdocs.fnal.gov/AD/DocDB/0047/004791/003/APT_2015-03-17_Wiesner_upload.pdf

- [41] Y.K. Batygin et al., *Design of Low Energy Beam Transport for New LANSCE H⁺ Injector*, Nucl. Instrum. Methods in Phys. A **753** (2014) 1-8
- [42] M. F. Reusch and D. L. Bruhwiler, *End-to-End Particle Simulations of a 1.76 MeV Electrostatic Proton Linac for Contraband Detection*, Proc. of LINAC1996, Geneva, Switzerland (1996) 358
- [43] S. T. Melnychuk et al., *Operating Characteristics of a High Current Electrostatic Accelerator for a Contraband Detection System*, Proc. of PAC1999, New York, NY, USA (1999) 587
- [44] J.-L. Biarrotte, P. Bertrand and D. Uriot, *Beam Dynamics Studies for the SPIRAL-2 Project*, Proc. of EPAC2006, Edinburgh, Scotland (2006) WEPCH007
- [45] M. Reiser, *Theory and Design of Charged Particle Beams*, John Wiley & Sons, Inc. (1994) p197 Eq. (4.28)
- [46] A. Shemyakin and L. Prost, *Scheme for Low Energy Beam Transport with a non-neutralized section*, FERMILAB-TM-2599-AD (2015)
- [47] M. Reiser, *Theory and Design of Charged Particle Beams*, John Wiley & Sons, Inc. (1994) p470 and onward