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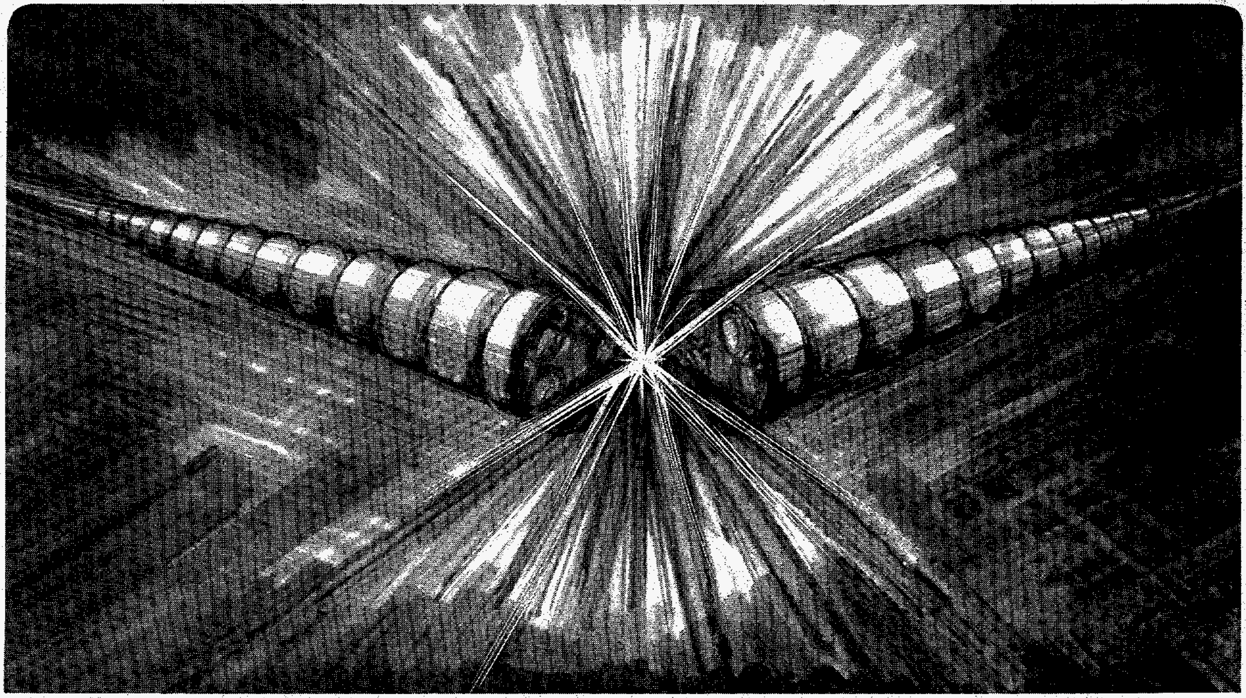

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Ion Source Requirements for Pulsed Spallation Neutron Sources

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Abstract. The neutron scattering community has endorsed the need for a high-power (1 to 5 MW) accelerator-driven source of neutrons for materials research. Properly configured, the accelerator could produce very short (sub-microsecond) bursts of cold neutrons, said time structure offering advantages over the continuous flux from a reactor for a large class of experiments. The recent cancellation of the ANS reactor project has increased the urgency to develop a comprehensive strategy based on the best technological scenarios. Studies to date have built on the experience from ISIS (the 160 kW source in the UK), and call for a high-current (approx. 100 mA peak) H^- source-linac combination injecting into one or more accumulator rings in which beam may be further accelerated. The 1 to 5 GeV proton beam is extracted in a single turn and brought to the target-moderator stations. The high current, high duty-factor, high brightness and high reliability required of the ion source present a very large challenge to the ion source community. A workshop held in Berkeley in October 1994, analyzed in detail the source requirements for proposed accelerator scenarios, the present performance capabilities of different H^- source technologies, and identified necessary R&D efforts to bridge the gap.

INTRODUCTION

Slow neutrons are in many ways an analog to x-rays for materials-science applications. In the energy regime where neutron wavelengths are of the order of an Angstrom (tens of milli-electron volts), diffraction and scattering of neutrons gives crystalline structure and composition information of materials studied. Because of greater penetration than x-rays, as well as sensitivity to light elements (particularly hydrogen), and to magnetic properties of materials, experiments with neutrons give information often not obtainable with x-rays. As a consequence, the materials-science community continues to express a strong interest in high-intensity neutron facilities. Traditionally, reactors have been used, but because of the difficulty in obtaining neutron beams of well-defined energy (and the large flux loss in the monochromatizing process), experiments are difficult to perform, and often require inordinately long exposure times and much patience.

Accelerators as a source of neutrons can bring a new dimension to the picture. By striking a suitable target with a sharp pulse of high-energy protons, neutrons can be produced that all emerge from the target-moderator assemblies at a well-defined time. Thus time-of-flight can be used to determine the energy of neutrons probing the test sample, with significantly increased data rates for certain classes of experiments. (It should be noted that accelerator-produced pulsed-neutron beams are not the panacea for the entire field, there is still a large body of experimental techniques that are better suited to continuous neutron beams, resulting in two equally-strong and complementary research communities.)

Characteristics of a Pulsed Spallation Neutron Source

Working backwards from the experimental station, we describe the components of a typical accelerator-based pulsed spallation source. To produce the required neutron beams, moderators are placed close to the target in a carefully designed configuration to maximize the collection and thermalization of the MeV-energy neutrons produced in the target. Angstrom-wavelength neutrons (2-100 meV energy) emerge from room-temperature moderators, while beams optimized for longer wavelength require cryogenic (liquid hydrogen or deuterium) moderators. Considering that these are placed in close proximity to the target in which several megawatts of beam power are being deposited, the engineering challenges are not to be underestimated.

Optimization of neutron production via spallation reactions indicates use of proton beams with energies between 500-MeV and 3-GeV striking thick heavy targets. Uranium is the most copious producer of neutrons, but faces more severe materials lifetime and integrity problems. Tantalum and Tungsten targets are often used as well.

The thermalization process typically requires several microseconds, so to achieve a sharp "start" time for the neutron time-of-flight measurements, the accelerator pulse need not be much shorter than about one microsecond. This is well suited to a kicker in a ring that extracts all the beam in a single turn. Neutron velocities down the long beam channels indicates the pulse repetition rate should be between 20 and 60 Hz, to avoid possible pulse-overlap problems.

Putting all these data together, we can specify the configuration of the accelerator needed to produce the requisite beams. A high-current, high-brightness ion source produces a beam of H- ions that are accelerated in a linac, in a pulse typically 1 millisecond long. This pulse is accumulated in a ring by means of stripping injection. This type of injection, namely changing the charge from H- to H+ is the only way known today to stack the 1000 or so turns into the ring without unacceptable beam losses. If needed, (i.e. unless the ions are accelerated in the linac to their full energy) the ring accelerates the beam, then the beam is deflected out of the ring by means of a fast-kicker magnet in a single turn (a bunch no longer than a few 100 nanoseconds), and sent to the target. Although there is a wide variation in parameters between the various existing and proposed facilities, the above description can be applied to each one of them.

Existing Pulsed Spallation Neutron Sources

Four facilities are running today dedicated to research with pulsed neutron beams. The KENS facility at KEK, Japan, takes unused pulses from the 20 Hz 500 MeV rapid-cycling Booster for the Proton Synchrotron. It has operated since 1980 at a power level of 2.5 kW on target. IPNS, at Argonne, uses 450 MeV protons from a rapid-cycling synchrotron. Operating since 1981 this facility is dedicated exclusively to neutron research. The single target operating at 7.5 kW

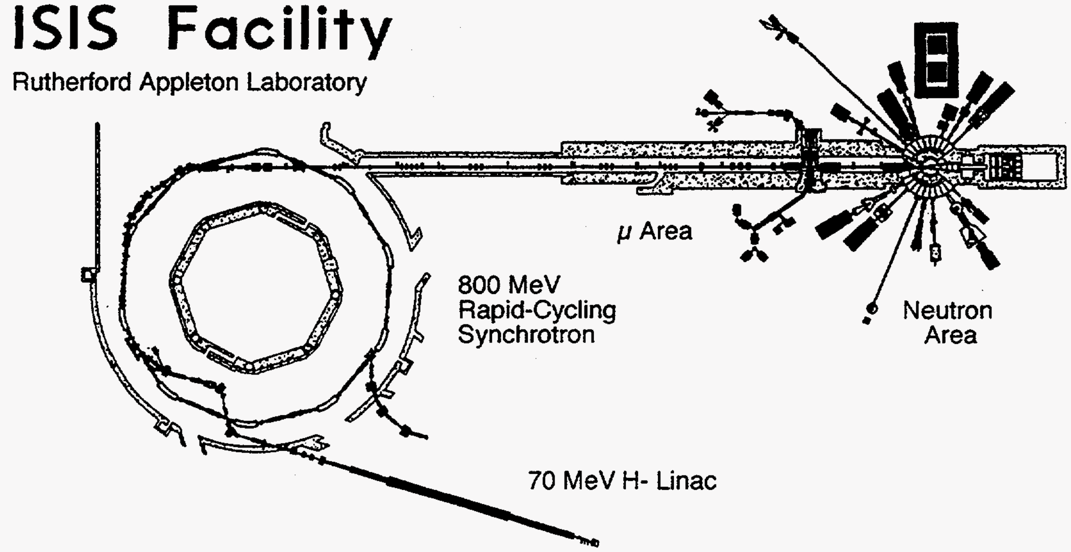

FIGURE 1. Layout of ISIS Facility at the Rutherford Appleton Laboratory, UK. It is the world's most intense pulsed spallation neutron source.

feeds 12 neutron beamlines. The LANSCE ring at Los Alamos accumulates beam from the LAMPF linac at 800 MeV and delivers bunches (without further acceleration) at a 20 Hz rate to a target station. Beam power on target is around 48 kW, up to 16 experiments are fed. It has been in operation since 1985. Also coming on-line in 1985 was ISIS, at the Rutherford Appleton Laboratory (UK). It is currently the world's most powerful Pulsed Spallation Neutron Source, with a beam power on target of 160 kW. Figure 1 shows a schematic layout of this facility, with its 70 MeV linac feeding the 50 Hz, 800 MeV RCS (rapid-cycling synchrotron). Beam is fed to a single target, which provides neutrons for around 14 different experimental stations.

Proposals for New Facilities

To meet the community requests for new facilities with significantly higher neutron fluxes, several proposals have been prepared. The accepted goal is between 1 and 5 MW of beam power on target; 1 MW is viewed as being about at the limit of today's technology, while 5 MW would be closer to producing the most desirable neutron flux rates. IPNS-II (1), upgrades the Argonne facility to the 1 MW level with new accelerators and target areas, built in the same ZGS Hall housing the currently-operating facility. LANSCE-II (2) operates off of LAMPF, which would receive a new front end to provide better beam quality and higher intensities, and would feed a new accumulator ring (or rings) and new target stations. Beam powers of 1 to 5 MW would be possible. Brookhaven has developed a "green-field" 5-MW design (3). In Europe, the 5-MW ESS (European Spallation Source) (4) is being studied, while a full conceptual design for AUSTRON (5) has been developed, a 250 kW modest extrapolation from ISIS, is currently seeking construction funding from the Austrian government. The Paul Scherrer Institute, in Switzerland is converting the backstop from its 590 MeV high-current cyclotron into a neutron target, and although accelerator-based, SINQ (6), as this 1-MW facility is called, will offer continuous and not pulsed neutron beams. This facility will be a direct replacement for the research reactor at PSI which has recently shut down. It is expected to be on line in a few months. JAERI, in Japan, is planning a large project called ETA (7), based on a high-current linac with both H$^+$ and H$^-$ capabilities. The former would be developed into transmutation and waste-burning applications, while the latter would feed rings for a PSS. With the exception of SINQ, all these facilities are based on the usual formula of negative hydrogen sources feeding linacs and rings. Each proposal, however, optimizes its design in slightly different directions, leading to somewhat different requirements for ion sources and accelerators. These will be detailed below.

ION SOURCE REQUIREMENTS

As part of a DOE-funded study of issues related to the next-generation spallation source, a workshop was held at LBNL in October of 1994 to evaluate relevant ion source requirements, and to assess the capabilities of present-day ion source technologies (8,9). A gathering of 31 representatives from 19 Laboratories, this workshop collected essentially all the major players in the field of high-current negative-hydrogen sources. Data and comments provided in this paper is derived from information presented and developed at this workshop.

TABLE 1. Ion Source Requirements

Facility	**Ion** H+/-	I_{peak} (mA)	**Extract Voltage** (kV)	**Beam Pulse length** (ms)	**Rep rate** (Hz)	**Duty Factor** (%)	ε_{norm} (mm-mrad) (90%)
ISIS 160 kW	-	35	18	0.25	50	1.2%	3 π (y) 2 π(x)
SINQ 700 kW	+	12	60	CW	CW	100%	0.2π
ESS 5 MW	-	70	55	1.4 / 2.0	50	7 / 10%	0.3π
ETA (BTA) 15 MW	+ (-)	120 120	100 100	1 1	100 100	10% 10%	0.5π
LANSCE II 1 MW	-	40	100	1.4	60 pps (120)	8.6% (17.2%)	0.9π
IPNS II 1 MW	-	44 - 67	35	0.5 - 0.33	30	1.5 / 1%	<1π
BNL 5 MW	-	150	50	0.45	60	3%	1π
AUSTRON 200 kW	-	50	70	0.2	25	0.5%	0.4π

Table 1 is a compilation of ion source requirements for the various operating and proposed facilities that have been described above. Column descriptions follow.

Ion. The ion species required from the ion source. The main reason for H$^-$ ions is to allow for multiturn injection into a synchrotron or accumulator ring via the stripping process, allowing increasing of phase-space density while preserving total emittance to the greatest degree possible. SINQ and ETA do not require negative ions, although an upgrade scenario for ETA (specifically for a pulsed spallation source) will use an accumulator ring and will require H^- ions.

I(peak). The peak current from the ion source, measured (or extrapolated back to) a point just following the extractor aperture. The SINQ source, operating in steady-state, has a much lower current level, but total power dissipation is comparable to the higher current, low duty-factor sources.

Extraction Voltage. This parameter is important in LEBT design. It provides a trade-off between voltage-holding capability and high-current beam transport.

Pulse Length. The pulse length quoted is the duration of the beam pulse extracted from the source. It will be shorter than the arc pulse, because of time required for start-up and fall-off of the arc, and the need to allow the arc plasma conditions to stabilize so the beam pulse is uniform and quiet. For example, the ISIS Penning source extracts beam for around 250 μsec, but the total arc pulse varies from 400 to 650 μsec. The first 100-200 μsec of the arc pulse are required to achieve stability. While the beam pulse width directly relates to the total power delivered to the neutron production target, the arc pulse length is an important parameter in establishing the total power dissipated in the source, affecting cooling requirements, as well as lifetime and reliability of the source operation. An important point in source evaluation, then, is how close the beam pulse width can actually be made to the arc width.

Repetition Rate. This parameter relates to the total power dissipated in the source. Here the ratio of arc length to beam pulse length is important, in a higher rep rate operation more of the source power will be used as "overhead" in preparing for the beam pulse.

Duty Factor. As quoted, this relates to the total fraction of time that usable beam is emerging from the source.

Emittance. The figure quoted relates to the normalized emittance (measured emittance times beta-gamma) for the contour containing the brightest 90% of the beam. It is the area of the ellipse that will contain this 90% contour. (Note, ellipse area is the product of the semi-major (a) and semi-minor (b) axes times π, the numbers usually quoted are $(a * b)\ \pi$.) Often times, aberrations will cause skewing of the emittance, but the quantity that is relevant is the actual acceptance of the first stage of acceleration (in most cases an RFQ), this acceptance is best described by an ellipse. The emittance quoted is for the beam as it enters this first acceleration stage, so includes not only the inherent source emittance but also the effects of the transport system from source to this first stage. Throughout the Workshop the strong coupling between the source and the LEBT was emphasized many times, the need for demonstrating performance of the front end must include both of these components.

PRESENT-DAY ION SOURCE PERFORMANCE

Workshop participants presented data on the demonstrated performance of their ion sources, some in test-stands, while others in actual operational conditions. Emphasis was on comparing these performance figures with the requirements for PSS facilities identified in Table 1. Table 2 summarizes these data for the pulsed H^- sources presented. Although CW and H^+ sources were also discussed at the Workshop, these will not be included in this report for the sake of brevity.

TABLE 2. Measured Ion Source Performance. Peak current is H^- component, e/H is the ratio of measured electron current to H^- current. Arc DF (Duty Factor) is the percentage of time the arc is on.

Source Type	I_{peak} (mA)	**Extract Volts** (kV)	**Arc Pulse** (ms)	**Beam Pulse** (ms)	**Rep rate** (Hz)	**Arc DF** (%)	**e/H**	ε_{norm} (mm-mrad) (90%)
Penning 4X LANL (2.6 mm)	63	35	2.3	2.0	10	2.3	≈1	0.3π
Penning 4X LANL (5.4 mm)	150	23	1.1	0.6	5	0.5	≈1	0.9π
Penning 8X LANL (2.6 mm)	40	25	1.2	0.6	5	0.6	≈1	0.3π
Penning ISIS	35	18	0.5	.25	50	2.5	<1	3π / 2π (x) (y)
Penning Budker	100	20	0.25	0.25	100	2.5	1-2	0.1π / 1.0π (x) (y)
Magnetron BNL	70-100	35	0.7	0.65	5	0.35	<1	1.2π
Semi-Planotron Budker	100	20	0.25	0.25	50	1.25	1-2	0.2π / 1.0π (x) (y)
Surface (LAMPF) LANL	20	80	1		120	12		0.8π
Volume: Toroidal BNL	50 (max)		1.5				≈1	0.3π
Volume: Toroidal LANL	18 8	80 80	0.8 0.8		120 120	10 10	≈2 ≈2	Not meas 0.3π
Volume: RF LBNL	40						≈10	0.6π
Volume: RF Grumman	80 65	35 35	0.3 1		10 10	0.3 1	≈10 ≈10	Not meas 0.6π
Volume: RF SSC	60-109	35	0.1		10	0.1	10-2	0.6π

Penning Sources

Penning H^- sources have a good track record in an operational environment, with ISIS being the primary example. As a result, Penning technology is perhaps somewhat more mature than that of the volume source. Penning sources require no filaments or RF antennas in the plasma. Beam quality and current are very good. Electron - to - H^- ratio is very good, typically ≈1/1. Peak operation requires cesium which has been provided by an oven. Temperature regulation to ensure optimum

Cs concentration is important. The discharge requires time to quiet down after the arc is struck, lengthening the duty cycle specifications for the source. Obtaining peak performance requires careful tuning. Lifetimes in operational conditions have been very good, typically three weeks of continuous performance.

LANL Penning sources (Vernon Smith, Ralph Stevens, Rob York). The Los Alamos versions of the Penning surface-plasma source, the 4X and the 8X sources (operated on the GTA and on test stands), have larger discharge chambers than Dudnikov's original (the "1X source"). The larger sources have lower particle fluxes striking the electrodes (the source walls), resulting in reduced cathode erosion and improved reproducibility and stability. The 4X and the 8X sources both produce the H^- current (40 mA) within the 90% normalized emittance (0.9 π mm mrad) required for the 1 MW version of LANSCE II. By opening the aperture of the extractor from 2.6 mm to 5.4 mm diameter, the 4X source has also produced the 150 mA, 0.9 π mm mrad H^- beam current and emittance required by the Brookhaven pulsed spallation neutron source design.

ISIS Penning source (Charles Planner, Reginald Sidlow). Excellent reliability, with an average 21-day MTBF (mean time between failures), is the primary hallmark of this source. This has been achieved through engineering improvements and experience in obtaining optimum operating conditions. New sources are generally capable of producing between 40 and 50 mA, but are detuned to 35, significantly increasing reliability. Cathode temperature (hence beam stability and output level) is regulated partly by varying the arc pulse length. During the first ≈100 µsec after the arc is struck, the source produces noisy beam, tuning to ensure quiet beam requires careful adjustment of source parameters, primarily affecting the Cs environment. The arc is operated at a constant 50-Hz rep rate (to maintain constant environmental conditions), while the extractor may be pulsed at subharmonics of this to meet proton beam intensity requirements of accelerator or experiment tuning.

Budker Penning source (Gennady Derevyankin, via Charles Planner). This is a fully studied and engineered source for accelerator application. The present source has a slit aperture, and as developed for the Moscow Kaon Factory at Troitsk delivers a high-brightness 100-mA beam at 2.5% duty-factor and pulse-repetition-rate of 100 Hz for operational periods greater than 300 hours. The lifetime is limited by sputtering produced by backstreaming positive ions accelerated in the extraction gap. This lifetime may be significantly improved by designing a suitable three-electrode extraction configuration to trap the positive ions in the extraction region. The low ion temperature (< 1 eV), high emission current density (> 2 A/cm^2), high ion beam current (100 mA) and high duty factor (> 2%) of this source provide confidence that this technology could eventually produce a source with an ion beam current of 100-150 mA, emittance (90%) < 0.1 π mm-mrad, duty factor ≈ 10% and lifetime of about 1000 hours.

Magnetron Sources

BNL and FNAL magnetron surface plasma sources (James Alessi, BNL). These sources produce currents high enough to meet the requirements of any of the PSS proposals, but the emittance would be larger than that from either the Penning or volume H^- sources. These sources have been used very successfully for more than 10 years on the high energy accelerators at BNL and FNAL, and can operate continuously for 6 months, although at very low duty factors (<0.5%). The power efficiency of this source is excellent (50 mA/kW), however the source-geometry is such that providing adequate cooling for the cathode is a problem. With suitable engineering, expectations are that one might be able to design a source capable of 70-100 mA at up to 3% duty factor. Such a source would probably be able to meet the requirements of the IPNS II proposal, but it could meet the BNL requirements only if the emittance requirement was relaxed. The ESS and LANSCE II proposals, requiring higher duty factor and low emittance, would be very difficult to achieve with the magnetron source. A problem with this type source is that operating parameters for reliability and high current cause the source to run in a regime where beam noise is (perhaps unacceptably) high. Such noise introduces emittance-growth and beam-loss problems in subsequent transport and acceleration stages.

Budker Planotron and Semi-Planotron sources (Gennady Derevyankin, Vadim Dudnikov). Both the Planotron and Semi-planotron ion sources have been developed and studied at the Budker Institute. These magnetron-type sources have a lower brightness than the Penning source, having emittances typically greater than 1.0 π mm-mrad. The Planotron design is quite similar to the BNL and FNAL sources (whose original design in fact came from this Budker group), and shares the cathode-cooling impediment to long duty-cycle operation. A more promising new development, the Semi-Planotron can be cooled more easily and should be more suitable for high duty-cycle operation. It has the attractive feature that it is 5-to-7 times more efficient than the Penning configuration at discharge currents in the range of 20-30 A but at higher discharge currents (≈100 A) its efficiency approaches that of the Penning source. This source has operated at 100 mA ion beam current, 1.25 % duty factor and 50 Hz pulse repetition rate, but has not yet been tested to gain any substantive lifetime experience. There is a worry in this respect associated with the unclosed drift of the discharge plasma. Source lifetime may be limited by the accumulation at the ends of the drift path of products from cathode-sputtering, causing a short circuit in the discharge region.

Surface-Production Sources

LANL Multicusp Converter Source (Rob York, LANL). This source, used to produce H^- ions for LAMPF, has been on-line for many years and reliably delivers 20 mA at 12% duty factor with an availability of greater than 95%. This source, based on the LBNL converter source concept, utilizes a cusp-field plasma confinement geometry and employs a cesiated converter-electrode to produce the negative ions. The beam emittance is determined by the geometry of the converter and emission-aperture system and can be made any desired value by appropriate choice of size and spacing for these electrodes. The beam brightness, however, is limited by the sputter ion temperature at the converter. The requirements for high current and low emittance needed for most of the PSS applications makes the use of this source marginal in these applications. Further development of this source concept using RF drive instead of filaments could possibly result in brighter beams, an idea that should be pursued. The high gas efficiency and low electron contamination make this source very attractive from an operational point of view, but present low brightness performance precludes its consideration for high-current application until this parameter can be improved.

Volume Sources

Volume sources offer many attractive features for high-current, bright-beam applications, although as of yet there is not much long-term operational experience for sources running in the mode anticipated for the PSS. They produce an inherently quieter plasma than other sources, and seem to be significantly easier to operate than other sources. Indications are that they can be run to longer duty factors with few problems, and have potentially better Cs management strategies. Modest currents of H^- ions (suitable for some applications, but not for present PSS scenarios) can be produced without Cs, however, without Cs the e/H^- ratios are very unfavorable (as high as 10 or 20 to 1). Introduction of a controlled amount of Cs increases the ion current typically a factor of 2 or 3, but more importantly has the effect of suppressing the electron current, so the e/H^- ratio for an optimized source approaches unity. Sources are operated either with a filament or with RF or microwaves to generate the plasma. Filament lifetime is an issue, as is the lifetime of the RF antenna which is exposed to the plasma.

Toroidal Geometry (James Alessi). The BNL Toroidal Volume H^- Source has a novel conic-shaped filter field, and without cesium it has typically produced currents of up to 35 mA, with an electron-to-H^- ratio of 2-5. It does not have a transverse magnetic field (the field is axially symmetric), which may be an advantage in terms of minimizing emittance growth while dumping the electrons in the extraction channel. Filaments are placed around the edges of the source, minimizing exposure to plasma thus enhancing filament lifetime. Only low duty factor versions of this source have been built at BNL, but a high duty factor source of this type is now being tested at LANL. Tests at LANL using this type of source show that there is no deterioration in source performance up to a 10% duty factor.

RF-Driven Multi-cusp Geometry (Ka-Ngo Leung, Luke Perkins, LBNL; Kourosh Saadatmand, SSCL; Steven Melnychuk, Alan Todd, Grumman). Sources based on an LBNL design are currently being operated at LBNL, SSCL and Grumman. Best RF antenna lifetime is obtained with a porcelain-coated copper tube. Good currents at modest duty cycles have been obtained on these test stands, although limits have been due to power supplies and not on inherent source characteristics. The SSC source has operated continuously (at 0.1% duty factor) with 60 mA pulses for 7 consecutive days, as well as intermittently (one shift per day) for another 52 days. Although much of this 52-day period was devoted to different tests, H^- currents in excess of 100 mA were obtained several times. A base performance current of at least 77 mA was achievable any time the source was specifically tuned to optimize current output. At the end of this extended test period, no degradation of source components was observed. During these tests, e/H^- ratios equal to 1 were achieved for short periods of time (a few hours). Cs dispensing was done with "SAES" strips (named after their Italian manufacturer) mounted on the electron suppression collar guarding the exit aperture. These dispensers allow optimized H^- production with an extremely small amount of Cs. At the end of the tests it was observed that only a small amount of the Cs available had actually been used. Triggering the plasma was done with a starter filament, or with a quartz flash-lamp. Using a starter allows more freedom in setting source parameters.

LOW ENERGY BEAM TRANSPORT (LEBT)

Beam transport from source to first stage of acceleration can be accomplished either with a series of magnetic lenses or with electrostatic elements. Both techniques have been used successfully, however a design decision for the PSS application is not straightforward. Two factors enter into this decision: space-charge compensation and beam chopping.

Space-Charge Compensated LEBT with Magnetic Elements

For the high-current, high brightness beams, mitigation of space-charge forces by means of compensation is an attractive option. The Frankfurt group (Joachim Pozimski) presented its studies of the compensation process, pointing out that although good results can be expected with a compensation scheme, the processes involved are not completely understood. Some of their observations:

- Pressures in the beamline of the order of 10^{-5} torr are generally adequate to achieve compensation.
- For space-charge compensation, magnetic transport elements are required; electrostatic elements will not allow the buildup of the requisite ion density for neutralization
- Beam will be lost due to stripping in the gas, although this is not very significant. (Typical transmission is 95%.)
- The presence of electric fields, at the source extractor and at the front end of the RFQ will prevent the buildup of space-charge neutralizing ions in these regions, leading to difficulties in calculating beam envelopes due to transitions into and out of neutralized regions. Emittance growth will occur at each transition.
- The pulsed nature of the beam is a problem with negative ions, in that significant time is required to build up the compensating charge (of the order of 100 μsec). Compensation works better in a CW beam. Thus beam characteristics through the LEBT are different between the front end and the main body of the beam pulse. Longer pulse widths are needed, with cleanup collimators.
- Chopping, which is normally performed with pulsed electric fields will again cause loss, or at least distortion of the distribution of space-charge compensating ions, and create complications in the predictions for beam envelopes and phase-space densities.

Electrostatic LEBT

The Frankfurt (Margit Sarstedt) and LBNL (John Staples, Chun-Fai Chan) groups have studied electrostatic transport systems, in which no space-charge neutralization occurs. Emittance preservation is more of a problem, and requires maintaining larger beam diameters to minimize space-charge forces, however such larger apertures lead to greater lens aberrations. Nonetheless, good transport solutions are possible. Fields are high, and care must be taken to prevent breakdown, particularly in the presence of high beam and electron currents during pulsing. The problem is exacerbated by the potential presence of Cs contamination which reduces the work function on contaminated surfaces, lowering breakdown voltages. In spite of these problems, it appears that electrostatic transport systems might offer significant advantages for the PSS application.

Beam Chopping

Injecting high current pulses into rings presents novel challenges to minimize beam loss at high energies. In earlier days one flooded the ring with particles, those conforming to the acceptance of the ring were captured and the rest were lost. As transfer into the high-energy rings occurs well above the threshold for nuclear reactions, beam loss leads directly to activation and neutron production. At the high intensities we are dealing with even the loss of a small fraction of the beam can have serious consequences for the overall facility design and operation. The problem can be mitigated with beam chopping, which can take one of two forms:

- Injection into an RF-on condition, so beam drops directly into a well-established bucket. This prevents loss normally associated with adiabatic capture when RF is turned on after or during the injection process. IPNS II (Yang-Lai Cho) will employ this for injection into its rapid-cycling synchrotron. The KEK Booster currently uses chopping (in the ion source) for this purpose.
- The LANSCE II (Vernon Smith) compression ring accepts beam at 800 MeV with a pulse-train of 235 nsec of beam off and 436 nsec of beam on. This stores particles in about 2/3 of the ring, the hole being required for turn-on time of the extraction kicker when the beam is ejected for transport to the neutron-production target. The specification for LANSCE II is that the hole should contain less than one part in 10^4 of beam. This level of beam suppression can be quite a challenge. In addition, rise and fall times should be less than 20 nsec.

Traveling Wave Choppers

Both the Brookhaven AGS and LAMPF have developed traveling-wave chopping systems. This device injects a high-voltage pulse that moves down a series of narrow plates above and below the beam, traveling at the same speed as the particles. Thus the same particle in the bunch will see the high electric field and be deflected, giving rise to sharp fronts. Beam is deflected, then stopped on a collimator that transmits the undeflected beam.

LEBT (35 - 100 keV) chopping (James Alessi). BNL has studied the effect of a chopper on a space-charge neutralized beam at 35 keV for the beam-shaping required for injection into the AGS Booster. During the time the chopping voltage is on the neutralizing gas ions migrate in the opposite direction from the beam, displacing the effective charge cloud by an amount sufficient to cause deleterious effects on the beam distribution during the chopper-off time period. The BNL system, constrained by the 35 keV beam energy, was quite noticeably affected by this, but the LANSCE II (100 keV) design parameters should be more favorable in this respect. Both lines utilize two solenoids for beam focusing, the LANSCE II design is based on a tune solution assuming partial neutralization through the chopper area, which is located directly between the two solenoids. Because of unfavorable results at 35 keV, BNL moved its chopper to the post-RFQ (750 keV) transport line.

MEBT ($\approx$750 keV) chopping. By moving to the medium energy transport line, BNL has been able to successfully use the chopping concept for injection into the Booster. The MEBT no longer requires space-charge neutralization, eliminating the problem encountered with low-velocity chopping. Deflection angles are smaller for the same chopper length and field, but transport distances are longer allowing the same level of rejection of unwanted beam. Note that the chopping of the present beam for LANSCE is also done at 750 keV.

Ion Source Chopping

Several studies at LANL (Ralph Stevens) have attempted to the turn beam on and off at the source (by means of biasing the plasma and collar electrodes) to meet the chopping specification. While it is feasible, the results have indicated that this method cannot be used as the sole chopping technique. In general, turn-on and -off times have been slower than the required 20 nsec (volume sources were the best, but still slow); beam-current modulation was not sufficient, the sources could not be totally turned off (90% beam suppression was about the best achieved). Nonetheless, further work is being done, and is expected to substantially improve ion-source chopping. Similar results have been reported by KEK: 90% suppression of their Penning source current could be achieved, with turn-on and -off times comparable to those reported by LANL.

Conclusions on Chopping

It is clear that while chopping beam at the source will not meet the stated requirements, source-chopping would still be useful in conjunction with either a LEBT or a MEBT chopper. The fine time-edge definition and floor-suppression would be provided by the traveling-wave chopper, but modulating the source current in synchronization would help to reduce heat loads on scrapers, as well as reduce the number of stray particles during the time the beam is being dumped.

REQUIRED R&D PROGRAM

While very good performance is now achieved with negative ion sources and low energy transport systems, meeting all the specifications for a Pulsed Spallation Source is still somewhat beyond the state-of-the-art. These requirements are not viewed as beyond what is achievable, but a well-developed R&D program is necessary to bring technology to the proper state of readiness for this project.

Ion Source R&D Issues

The cesiated volume and Penning H^- sources currently appear to be the leading candidates for the PSS. Note that the existing ISIS Penning source comes close to meeting the IPNS II requirements; fully meeting the pulse-width and duty-factor specifications, but falling short in the beam-current, emittance and repeatability areas. More of a challenge is meeting the needs of ESS and LANSCE II, both requiring intermediate current, high duty-factor sources, and the BNL 5-MW proposal that requires a high current, intermediate duty-factor source.

The emittance requirements are similar for all three proposals, and will probably not be a problem. The Penning source has demonstrated that it can reach the desired emittance at the current required for all three proposals, but achieving the duty factor will take development. In the case of the volume source, the duty factor requirement is probably not an issue, but demonstrating the required current and emittance simultaneously will take development, particularly for the BNL scenario.

The most significant R&D issue for the Penning source is duty factor. The required pulse lengths and repetition rates have both been demonstrated, but not simultaneously. The 3% duty factor requirement of the BNL proposal requires some development, but significant re-engineering will be required to reach the 7-9% duty factors of the other proposals. On the other hand, beam noise is more likely to be an issue in the high-current, low-velocity LEBT called for in the BNL proposal.

Duty factor is probably less of an issue for the volume source. However, achieving the required brightness, and demonstrating operational lifetime and reliability are definitely issues. Volume sources do not yet have the operational track-record of Penning sources, they have yet to supply beams to operating accelerators. In addition, work should continue on reducing the electron-to-H^- ratio in volume sources.

The lifetime question is in fact common to both source types In the case of the Penning source, the issue is cathode erosion, while for the volume source it is the filament or antenna life. Another common issue is the extraction system design, particularly concerning the dumping of electrons. This becomes more important as the duty factor is increased. Power removal and the preservation of beam quality are important considerations here.

A uniform current pulse (possibly within 1%) is important to avoid particle losses in high current machines. At the required pulse widths, both sources must still demonstrate such flatness, although volume sources appear to be inherently quieter. Gas loading is another issue common to both sources, particularly its impact on the extraction system. In this regard, operation with a higher plasma density allows one to use smaller extraction holes. Finally, careful control of cesium delivery to optimize H^- and minimize LEBT contamination will also be important in both cases, although experience generally shows that it is not as much of a problem as is sometimes perceived.

There have been preliminary attempts to pre-chop the beam within both types of ion sources. It seems unlikely that the required 20 nanosecond rise and fall times, and the required level of beam modulation, can be achieved at the source. However, pre-chopping at the 90% modulation level may still be useful to ease the burden on the downstream chopper.

LEBT R&D Issues

The ion source, extraction, and low energy beam transport (LEBT) must be considered as one integrated system. The LEBT design must be done carefully in order to avoid emittance growth. The two options for the LEBT: electrostatic or magnetic focusing should both be developed. Special problems for the electrostatic transport are controlling aberrations, and voltage-holding at these high currents and duty factors in the presence of cesium. In addition, the subject of beam steering has not been studied so far. In magnetic transport with solenoids, overcompensation of the beam is important in order to avoid instabilities, and achieving proper matching into the RFQ to ensure high-efficiency transport.

LEBT work must also integrate chopping stages, and investigation of the effect of choppers on space-charge compensation and emittance of the transmitted beam.

System Related R&D Issues

To conduct these tests it will be necessary to construct a flexible test stand, suitable for both Penning and volume source research, as well as different LEBT designs, and chopping schemes. The goals of the testing program will not only be to demonstrate required beam specifications, but also engineering performance levels of repeatability and reliability that are so necessary for an efficient user-oriented research facility. Constancy, stability and reproducibility of operation are critical. The tuning of the accelerators and compressor rings proposed for the next generation spallation sources will be restrictive with respect to intensity (one cannot afford to lose beam because of subsequent radiation damage and activation of components). To minimize the need for retuning after an ion source change it is important to obtain reproducibility in ion source performance for a number of sources. This requires detailed considerations of quality control in manufacture and engineering design for self-alignment of components, assemblies and integration into the accelerator system.

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REFERENCES

1 Cho, Y. (ed), *IPNS Upgrade: A Feasibility Study,* Argonne National Laboratory, ANL-95/13, April 1995.

2 Pynn, R. (ed), *Next-Generation Spallation Neutron Source*, Los Alamos National Laboratory, LA-UR-93-4440, January 1993.

3 van Steenbergen, A. (ed), *5 MW Pulsed Spallation Neutron Source: Preconceptual Design Study,* Brookhaven National Laboratory, BNL-60678, June 1994.

4 Gardner, I.S.K., Lengeler, and H., Rees, G.H. (eds), *Outline Design of the European Spallation Neutron Source*, ESS 95-30-M, September 1995.

5 Bryant, P., Regler, M., and Schuster, M., *AUSTRON Feasibility Study*, AUSTRON Planning Office, Vienna, Austria, November 1994.

6 Bauer, G.S., *A New Large Facility for Research at PSI: The Spallation Neutron Source SINQ,* Paul Scherrer Institute, Villigen, Switzerland, October 1994.

7 Oguri, H., Okumura Y., and Mizumoto, M., "Requirements for the Ion Source Performance of the ETA," in *Proceedings of the Workshop on Ion Source Issues Relevant to a Pulsed Spallation Neutron Source*: *Part 2 "Workshop Presentations* LBL-36347, October 1994, section I.5.

8 Schroeder, L.S., Leung, K-N., and Alonso, J., *Proceedings of the Workshop on Ion Source Issues Relevant to a Pulsed Spallation Neutron Source, Part 1, Workshop Summary and Part 2, Workshop Presentations*, LBL-36347, October 1994.

9 Alonso, J., "High-Current Negative-Ion Sources for Pulsed Spallation Neutron Sources, LBNL Workshop, October 1994", in *Proceedings of the Sixth International Conference on Ion Sources*, Reviews of Scientific Instruments, February 1996.