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Publication Date

1994-10-01

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LBL-36347
CONF-9410233
UC-404

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

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Part 1: Workshop Summary
Lawrence Berkeley Laboratory
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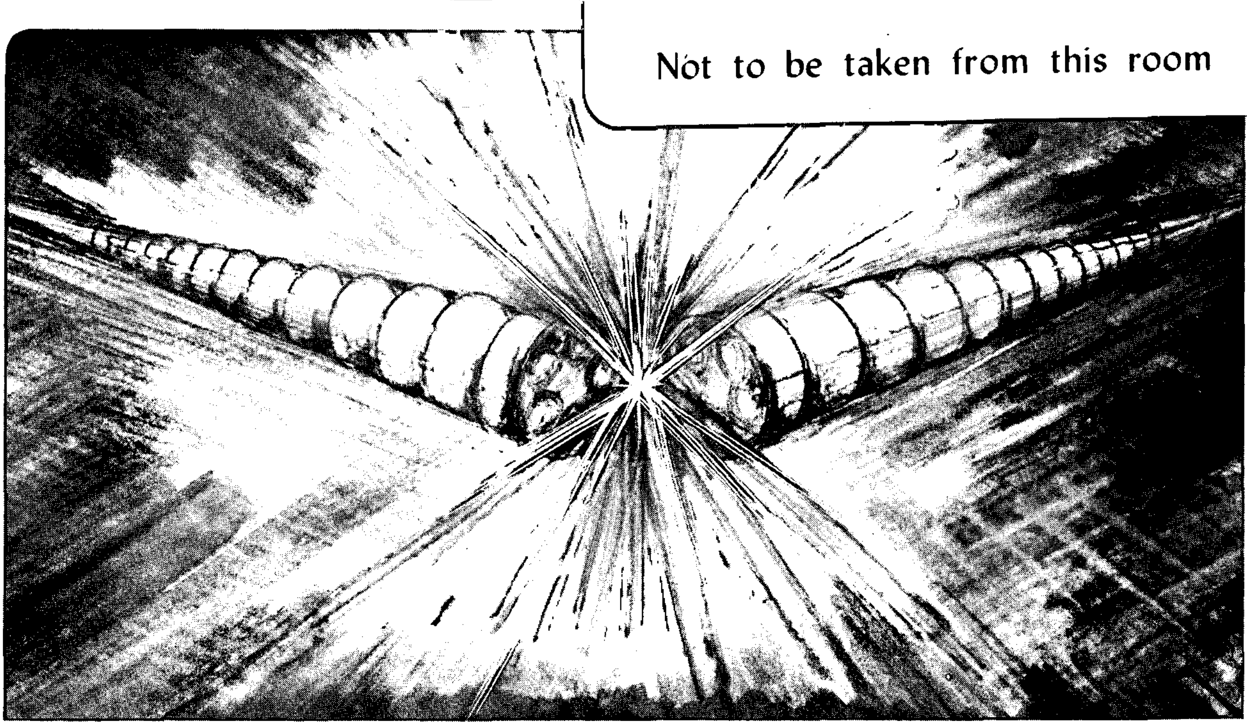
L. Schroeder, K.-N. Leung, and J. Alonso, Editors

October 1994



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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Proceedings of the Workshop on Ion Source Issues Relevant to a Pulsed Spallation Neutron Source:

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Editors: Lee Schroeder, Ka-Ngo Leung and Jose Alonso

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This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Workshop on Ion Source Issues Relevant to a Pulsed Spallation Neutron Source

EXECUTIVE SUMMARY

The workshop reviewed the ion-source requirements for high-power accelerator-driven spallation neutron facilities, and the performance of existing ion sources. Table I summarizes these required performance levels for existing and planned neutron facilities. Of note is that proposals for new facilities in the 1- to 5-MW range call for a widely differing set of ion-source requirements. For example, the source peak current requirements vary from 40 mA to 150 mA, while the duty factor ranges from 1% to 9%. Much of the workshop discussion centered on the state-of-the-art of negative hydrogen ion source (H^-) technology and the present experience with Penning and volume sources. In addition, other ion source technologies, for positive ions or CW applications were reviewed. Some of these sources have been operational at existing accelerator complexes and some are in the source-development stage on test stands. Table II summarizes demonstrated performance of the various sources discussed. An assessment was then performed of the match between requirements for proposed PSS scenarios and demonstrated source performance.

The workshop identified that out of the several types of sources, the Penning source and the volume source are potential candidate technologies suitable for the pulsed spallation scenarios currently under consideration. We noted that the optimum performance of the ISIS Penning source meets the minimum requirements for IPNS-II, the ANL 1-MW proposal. For the other proposed configurations, no existing source performance can satisfy all requirements simultaneously. Further development of source performance is required for all of the proposals, with the IPNS-II proposal requiring the least source development and the 5-MW and LANSCE-II proposals requiring the most source development.

The R&D items required to support each proposal were discussed in some depth, noting the close relationship and coupling between the ion source, LEBT, chopping, and matching into the first stage of acceleration (most probably an RFQ). Of great importance is demonstration of operational reliability and reproducibility, as well as ease of operation and maintenance.

To develop and demonstrate all these characteristics we strongly recommend the initiation of a relevant R&D program. One option we developed is to construct a flexible, integrated test bench suitable for testing both Penning and volume sources, as well as different LEBT configurations and chopping techniques. Once optimized, this line could become the front end of the new pulsed neutron source. Estimates of costs and schedules for such a test bench and its associated program are summarized in Tables III and IV.

Status of Ion Source Requirements and Performance for a Pulsed Spallation Neutron Source

1. Introduction

Ion source performance has been identified as one of the critical areas that will ultimately determine the on-target power that will be achieved in an accelerator-based pulsed spallation neutron source (PSS). Our order of work was to first describe the ion source requirements foreseen for each of the leading concepts of a PSS, then to list the presently-achieved performance of operating ion sources. A comparison of these two tables can identify possible fits of ion sources technology to specific projects, and also point to areas of deficiency in particular ion source technologies that should be targeted for R&D activities.

2. Source Requirements

Seven facilities and projects were described during the Workshop, specific ion source performance requirements for each were identified and tabulated. These numbers were accepted as presented by the various contributors. An eighth project, AUSTRON, was added after the Workshop, based on data provided by project director Meinhard Regler.

2.1 ISIS - Rutherford Appleton Laboratory, UK (Charles Planner)

The ISIS facility, currently the world's leading pulsed spallation source, has been producing neutrons since December 1984. Now, typically 140 kW (170-microamperes average current at 800 MeV) are delivered to a single target station. Excellent reliability is now the norm of operation. A Penning H^- source delivers 35-mA pulses about 0.25-msec long to the 70-MeV linac. Multiturn injection through a stripper brings beam into the rapid cycling (50-Hz) synchrotron where it is accelerated to 800 MeV. Beam is extracted by means of a kicker and delivered to the target.

2.2 SINQ - Paul Scherrer Institute, Villigen, Switzerland (Miguel Olivo)

The PSI cyclotron complex has been a leading facility for pion and muon physics for many years. A major addition to this facility will be the spallation neutron source SINQ, which is nearing completion. SINQ is a continuous neutron source to provide thermal and cold neutrons for condensed matter research. With proton currents in the region of 1 mA, intensities will be comparable to those at present reactor neutron sources. Noteworthy is that following upgrading of the main Ring Cyclotron 50-MHz RF system (now nearing completion), the accelerator systems will be capable of delivering 1.5 mA to the pion targets and around 0.5-MW of beam power (0.9 mA at 570 MeV) to the SINQ target.

A PSI-Culham bucket source with 60-kV extraction delivers 12-mA of steady-state H^+ current. After collimation in the 60-keV LEBT and passing through an 810-kV acceleration column, a 9-mA proton current at 870 keV is delivered to the Injector Cyclotron through a MEBT. Strong bunching in this MEBT and beam collimation in the central region of this cyclotron results in a CW-current of 1.5 mA. This is accelerated to 72 MeV and transported (at present about 1 mA) to the Ring Cyclotron for final acceleration to 590 MeV. Beam transmission after the collimation in the central region of the Injector Cyclotron is better than 99.9%. About 0.9 mA will reach the SINQ target after the 1.5 mA beam traverses the intermediate targets and has been cleaned up by the beam scrapers. This current can be increased to 1.2 mA, largely through changes in the thickness of the pion targets. The research program at SINQ will begin in 1996.

2.3 ESS - European Spallation Source study (Horst Klein, University of Frankfurt)

Current scenario for ESS calls for two H^- sources each delivering 70 mA in 1.45-msec pulses at a 50 Hz rate to a full-energy (1.334-GeV) linac system. A funneling system allows two RFQs to feed the main linac string operating at twice the RFQ frequency, doubling the beam current. Output peak current from the linac will be 100 mA, average current is 3.8 mA, leading to a total beam power of 5 MW. Two rings will accumulate beam, capturing $\approx$ 1000 turns by charge-change, using foil stripping (taking care to minimize the Lorentz stripping of any excited states of unstripped H° exiting the foil). The rings will compress the bunches, and kick them out to two targets, one operating at 10 Hz, the other at 40 Hz. Great care will be taken to assure an absolute minimum of beam loss throughout the acceleration, bunching and transport.

2.4 ETA (BTA) - Engineering Test Accelerator (Basic Technology Accelerator) - JAERI (Hidetomo Oguri)

The scenario presented for a high-current, multi-purpose accelerator would find applications in transmutation, meson production, neutron spallation, radioactive-beam production and basic nuclear physics research. The ultimate goal is a 1.5-GeV linac system with an average proton current of 10 mA; implementation is through a staged approach involving first an "R&D Stage" to include a test-stand delivering 2-MeV H^+ beams at 100-mA peak (10% duty factor). The second stage (BTA) would use the test stand as a front end and add linac capability to 10 MeV. The final stage would complete the linac structure to the full 1.5-GeV beam energy. The R&D stage is now operating, at full design specifications. Implementation of the neutron spallation application would require accumulator rings injected by stripping H^- beams. While the H^+ source is now operating at full design value, development of a comparable H^- source must take place for this application.

2.5 LANSCE II - Los Alamos (Andy Jason)

The 1 MW Los Alamos proposal calls for using the existing LAMPF 800-MeV side-coupled linac structure, but will replace the first sections with a new RFQ-DTL combination. Accumulation and compression is accomplished in a full-energy compression ring that accepts a 1.2-ms H^--beam pulse having 30-mA peak current. Two targets will be fed at 20 Hz and 40 Hz respectively. It should be noted that the positive-ion beam power available from LAMPF today is 1 MW; the new front-end structures will provide the improvements in negative-ion beam quality required for minimizing loss during accumulation and compression. An eventual extension to 5 MW will be accomplished through funneling in the front end, and increasing the linac energy to 2 GeV. A 1-MW, long-pulse mode that uses direct impingement of an 800-MeV proton beam on a target is also under study.

2.6 IPNS Upgrade - Argonne (Yanglai Cho)

The ZGS tunnel will be used to house a 2 GeV rapid-cycling (30 Hz) synchrotron. A new 400-MeV linac will provide ≈0.5-msec pulses of ≈50-mA H^- beams to the synchrotron, carefully chopped to allow maximum efficiency of capture into an established RF bucket. Two target stations will be provided. The 1 MW of beam power is achieved by asking for the highest possible synchrotron energy, while keeping performance demands on the ion source within the current state of the art. The relatively low repetition rate (30 Hz) is responsive to the community's need for long flight-paths for slow neutrons for accurate TOF determinations.

2.7 The Brookhaven PSNS Proposal (Jim Alessi)

BNL proposes to use a pair of 3.6-GeV, 30-Hz rapid-cycling synchrotrons to deliver 60 pulses per second to two target stations. The linac system (operating at 60 Hz) will feed 450-microsecond, 100-mA peak current, 600-MeV pulses of H^- ions to the synchrotrons. Total power on target is 5 MW. Peak current required from the ion source is 150 mA; this high number being based on very conservative assumptions for both the chopping duty factor and the charge-exchange multiturn injection process. Further beam dynamics studies of multiturn injection are in progress.

2.8 AUSTRON - Austrian study (Meinhard Regler)

A single 1.6-GeV, 25-Hz synchrotron will be fed by one 130-MeV H^- DTL (Drift Tube Linac). 50-mA pulses of 200-microsecond duration are required from the source. For a total beam power of 200 kW, this configuration is a conservative extension of the ISIS scenario. An upgrade to 400 kW is accomplished through increasing the repetition rate to 50 Hz, and changing the source output by doubling the peak current but halving the pulse length. Plans are to build a second synchrotron on the site, fed by the same linac, to deliver 400-MeV/amu light-ion beams for medical applications.

3. Ion Source Performance Requirements Matrix

Table 1 is a compilation of ion source requirements for the various operating and proposed facilities. An explanation of the columns is given below.

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. Note the relationship between peak current and duty factor, a rough indicator of power dissipated in the source. 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, and in sources where suppression of electrons extracted with the negative hydrogen ions is a problem. In several options the source is closely coupled to an accelerating column, mitigating the low-beta beam transport issue.

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 again 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 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. This duty factor will in general be lower than the fraction of time the arc is on, again owing to the "overhead" time required to stabilize the source plasma for good quality beam.

Emittance: The figure quoted relates to the normalized emittance (measured emittance times beta-gamma) for the contour containing the brightest 90% (or 100%) 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.

Comments: This column identifies one or two parameters that are important considerations in each proposal or facility, that relate to source performance requirements.

Table I

Ion Source and LEBT Performance Requirements

Facility	Ion +/-	I_{peak} (mA)	Extract Voltage (kV)	Beam Pulse length (ms)	Rep rate (Hz)	Duty Factor (%)	ε_{norm} (mm-mrad)	Comments
ISIS 160 kW	-	35	18	0.25	50	1.2%	3π (y) 2π (x) (100%)	Would like better reproducibility of source performance after source changes Emittance measured at base of 665 keV Cockcroft-Walton.
SINQ 700 kW	+	12	60	CW	CW	100%	0.2π (90%)	Required performance achieved in present operation
ESS 5 MW	-	70	55	1.4 / 2.0	50	7 / 10%	0.3π (90%)	Moderate peak current, High duty factor
ETA (BTA) 15 MW	+ (-)	120 "	100 "	1 "	100 "	10% "	0.5π (100%)	Positive ion performance demonstrated. Brightness for negative ions must be developed
LANSCE II 1 MW	-	40	100	1.4	60 pps (120)	8.6% (17.2%)	0.9π (90%)	Low peak current, High duty factor (120 Hz if 60 pps doesn't work)
IPNS II 1 MW	-	44 - 67	35	0.5 - 0.33	30	1.5 / 1%	$<1\pi$ (100%)	Most conservative source performance. Requirements: <10% flatness <5% repeatability
BNL 5 MW	-	150	50	0.45	60	3%	1π (90%)	High beam current, Moderate duty factor
AUSTRON 200 kW	-	50	70	0.2	25	0.5%	0.4π (100%)	Conservative parameters

4. Present Source Performance

Workshop participants presented data on the actual 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 the previous section. The organization of this material is via technology, with a clear division between sources required for pulsed H^- scenarios and others such as CW H^+ and H^-, or pulsed H^+ applications. Within the pulsed H^- category, Penning sources are discussed first, followed by magnetron and surface sources, and then volume H^- sources. Although not directly applicable to current PSS design concepts, CW and positive ion sources were also discussed, as techniques developed for these sources can have direct bearing on the pulsed high-current negative ion sources.

4.1 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.

4.1.1 LANL Penning sources

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.

4.1.2 ISIS Penning source

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 sub-harmonics of this to meet proton beam intensity requirements of accelerator or experiment tuning.

4.1.3 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 a solid base for the successful development of 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.

4.2 Magnetron sources at BNL and FNAL

The magnetron surface plasma source is capable of producing 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. The source has 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 it is used at very low duty factors (<0.5%). The power efficiency of this source is excellent (50 mA/kW), and one would be able to deliver 70-100 mA at up to 3% duty factor with engineering required only on the extraction system. The 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. Another problem with this type source is the relatively noisy beam current, which may preclude its being used in any of the proposals due to resultant emittance growth and beam loss.

4.3 Budker Planotron (Magnetron) and Semi-Planotron sources (Gennady Derevyankin, via Charles Planner, Vadim Dudnikov)

Both the Planotron (Magnetron) and Semi-planotron ion sources have been developed and studied at the Budker Institute. These sources have a lower brightness than the Penning source, having emittances typically greater than 1.0 π mm-mrad. The Planotron is considered an unlikely candidate for high duty-cycle operation, because of the difficulty of arranging effective cooling for the cathode. It has only been developed for experimental studies; developments for accelerator applications have concentrated on the Semi-planotron.

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.

4.4 Surface-production source

The Multicusp Converter Source, used to produce H^- ions for LAMPF, has been on-line for many years and reliably produces 20 mA at 12% duty factor with an availability of greater than 95%. This source is an LBL converter source; it 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 the present low brightness precludes its use until this parameter can be improved.

4.5 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.

4.5.1 Toroidal Geometry

The BNL Toroidal Volume H^- Source has a novel conically 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. Filaments are placed around edges of 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.

4.5.2 RF-Driven Multi-cusp Geometry

Sources based on an LBL design are currently being operated at LBL, 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 on power supplies and not on inherent source characteristics. The SSC source has operated (at 0.1% duty factor) with 60 mA pulses for 7 consecutive days, as well as intermittently (one shift per day) for a total of 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, S.A.E.S.) 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.

Development activities at Frankfurt are underway, an RF-driven volume source is in its initial testing stages.

4.6 Positive Ion sources

While not directly applicable to any of the pulsed spallation source designs discussed during the Workshop, positive ion sources are in demand for related applications. Volume sources seem to be the leading technology in this area. Duoplasmatrons, the mainstay for high-brightness, high-current applications in the 60's and 70's, are still in use today, but enhancing their performance beyond existing levels is not seen as an immediate possibility. The LAMPF duoplasmatron is listed as a representative example; other sources perform at about the same levels. High-brightness positive-ion volume sources have been run in a wide range of configurations, from CW at modest current levels for cyclotron injection (e.g. the PSI source, operating at 12 mA of proton current) to pulsed at quite high currents (the 140 mA, 10% duty factor JAERI source). The PSI filament-driven Culham-type source has demonstrated excellent reliability, as well as stability and reproducibility of operation, both short-term and long-term. This is critical for high current facilities, where variations in beam parameters will lead to activation problems caused by losses during acceleration. The RF-driven Grumman and LBL sources share a common design; extensive work by Grumman on antenna lifetime in the CW mode will no doubt carry over into the high-current pulsed mode of operation. Although the JAERI source currently operates at 10% duty factor, the design goal is for CW operation at 120 mA with the same emittance.

Microwave-driven sources are beginning to appear. Los Alamos has taken over the Chalk River source, designed for their CW RFQ project. This source is now running at LANL, and has just undergone a 170-hour lifetime test, operating in CW mode at a current level of 60 mA. Availability during this test, after initial bake-in, was around 95%.

4.7 Negative-ion CW sources

TRIUMF is operating numerous CW negative-ion Volume cusp sources for use in cyclotrons. Negative ions are useful in cyclotrons in that extremely efficient extraction is possible by stripping at the outer radius (different energy beams are obtained by moving the extractor foil to an inner radius). Most of these sources are filament-driven, and operate at currents from 1 mA (for the main TRIUMF cyclotron), to 5 mA (a 30 MeV isotope-producing cyclotron), to 12 mA (in development on a 1 MeV test stand). A microwave-driven source is under development now, although current levels are somewhat low for the present, this source is offering attractive benefits in long-term stability and efficiency of operation.

The TRIUMF sources run continously for up to six weeks without a filament change on the 30 MeV industrial cyclotron. This isotope-producing cyclotron has been in commercial operation for over 4 years and the ion source and extraction system shows only very slight effects from beam erosion. The average currents for this ion source are not too diferent from the requirements of the PSS. This is also true for the average power dissipated within the source, due to the electron beam which must be eliminated. Therefore the TRIUMF source stands as an example that the engineering problems assosiated with the electron beam and thermal effects are solvable for the average power levels needed for PSS operation. There are of course stress, sparking and perhaps other effects which are unique to pulsed operation that must be addressed.

5. Source Performance Tables

Table II lists measured performance characteristics of the various sources presented at the Workshop. The ordering of this table follows the discussions above. Column headings are similar to those described for Table I above, with the exception that the normalized emittance measured is generally that of the beam as it emerges from the source. To assess source performance with PSS requirements will require, as stated earlier, an evaluation of the LEBT (Low Energy Beam Transport) system that is used to transport the beam from the source to the first acceleration element. (Critical aspects of the transport system design are discussed in a following section.)

The Table is divided into two sections, Table II-a lists H^- sources tested in pulsed operation. The peak current listed is specifically for the H^- component of the extracted beam. Note, the ISIS Penning source is close-coupled to the accelerating column, so effectively has no LEBT. The emittance measurement for this source is performed at the ground end of this column, so includes the effect of this first stage of acceleration. Table II-b lists sources that are not operated in the pulsed H^- mode, and so are not specifically suited for the current proposals for a PSS. These sources produce either positive ions, or negative ions and operate in the CW mode. The latter are designed for cyclotron injection. Positive-ion peak currents quoted are the H^+ fraction of the total current, the proton yield, if known, is listed in the comments column.

Table II - a

Demonstrated Ion Source Performance FOR PULSED H^- APPLICATIONS

Source Type	I_{peak} (mA)	Extract Voltage (kV)	Arc Pulse length (ms)	Beam Pulse length (ms)	Rep rate (Hz)	Arc Duty Factor (%)	e/H	ε_{norm} (mm-mrad)	Comments
Penning 4X LANL (2.6 mm)	63	35	2.3	2.0	10	2.3	≈1	0.06π (rms) 0.3π (90%)	2.6 mm extraction aperture
Penning 4X LANL (5.4 mm)	150	23	1.1	0.6	5	0.5	≈1	0.2π (rms) 0.9π (90%)	5.4 mm extraction aperture
Penning 8X LANL (2.6 mm)	40	25	1.2	0.6	5	0.6	≈1	0.06π (rms) 0.32π (90%)	
Penning ISIS	35	18	0.5	.25	50	2.5	<1	$3\pi(y)/2\pi(x)$ (≈100%)	≈21 days MTBF Emittance measured at base of 665 keV Cockcroft-Walton
Penning Budker	100	20	0.25	0.25	100	2.5	1-2	$0.1\pi/1.0\pi$ (90%)	0.5 x 10 mm slit > 300 hr lifetime
Magnetron BNL	70-100	35	0.7	0.65	5	0.35	<1	1.2π (90%)	Higher noise level
Semi-Planotron Budker	100	20	0.25	0.25	50	1.25	1-2	$0.2\pi/1.0\pi$ (90%)	0.5 x 10 mm slit Not cooled
Surface (LAMPF) LANL	20	80	1		120	12		0.13π (rms) 0.8π (95%)	Cs ≈38 days MTBF

Table II - a

Demonstrated Ion Source Performance FOR PULSED H^- APPLICATIONS

Source Type	I_{peak} (mA)	Extract Voltage (kV)	Arc Pulse length (ms)	Beam Pulse length (ms)	Rep rate (Hz)	Arc Duty Factor (%)	e/H	ε_{norm} (mm-mrad)	Comments
Volume: Toroidal BNL	50 (max)		1.5				≈1	0.07π (rms) 0.32π (90%)	ε meas at 13 mA
Volume: Toroidal LANL	18 8	80 80	0.8 0.8		120 120	10 10	≈2 ≈2	Not meas 0.3π (95%)	40 mA/cm^2 current density 20 mA/cm^2
Volume: RF LBL	40						≈10	0.6π (?)	SAES Cs collar
Volume: RF Grumman	80 65	35 "	0.3 1		10 "	0.3 1	≈10 "	Not meas 0.15π (rms)	SAES Cs collar Temp-controlled collar 40-days operation
Volume: RF SSC	60-109	35	0.1		10	0.1	10-2	0.12π (rms)	SAES Cs collar ≥77 mA available for extended periods with no noticeable wear

Table II - b

Demonstrated Ion Source Performance, CW and Positive Ion

Source Type	Ion +/-	I_{peak} (mA) (protons)	Extract Voltage (kV)	Arc Pulse length (ms)	Rep rate (Hz)	Arc Duty Factor (%)	ε_{norm} (mm-mrad)	Comments
Volume PSI	+	20	60	CW	CW	100	0.3π (90%)	Modified (by PSI) Culham Filament (W) ≈33% proton yield
Volume LBL	+	60						RF ≈80% proton yield
Volume Grumman	+	44	42	CW	CW	100		RF ≈55% proton yield
Volume JAERI	+	140	100	1	100	10	0.5π (90%)	Filament 85% proton yield
Volume LANL	+	60	47	CW	CW	100		Microwave ≈200 hr longevity test 75% proton yield
Duoplasmatron LANL	+	30	35	1	120	12	0.065π (rms)	Run to 45 ma at 6% DF Directly interfaced to 750 kV column
Volume TRIUMF	-	12	25	CW	CW	100	0.3π (4 rms)	Filament (Ta) e/H ≈ 5
Volume TRIUMF	-	1.6	25	3	60	20	0.3π (4 rms)	Microwave Good lifetime

6. 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.

6.1 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 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 probably adequate to achieve compensation.
- Magnetic transport elements are called for; electrostatic elements will not allow the buildup of the requisite ion density for neutralization
- Operation of a space-charge compensated beamline is very convenient, no worries about voltage-holding or sparking from the electrostatic elements.
- Beam will be lost due to stripping in the gas, although this is not terribly 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, leading to difficulties in calculating beam envelopes due to transitions into and out of neutralized regions, and emittance growth will occur at each transition.
- The pulsed nature of the beam is a problem in that 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 electrostatic elements 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.

6.2 Electrostatic LEBT

The Frankfurt and LBL 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 some advantages for the PSS application.

7. Chopping

Injecting high current pulses into rings presents some 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 all of the rings we are considering will occur well above the Coulomb barrier, 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.

Chopping is done with one of two goals in mind:

- 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 will employ this for injection into its rapid-cycling synchrotron.

- The LANSCE II 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.

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 plates above and below the beam, traveling at the same speed as the particles. Thus the same particle in the bunch will see the rising electric field and be deflected, giving rise to sharp fronts. Beam is deflected, then stopped on a collimator that transmits the undeflected beam.

7.1 LEBT (35 - 100 keV) chopping

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 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 their chopper to the post-RFQ (750 keV) transport line.

7.2 MEBT (≈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 their main problem 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 for the present LAMPF PSR beam is also done at 750 keV.

7.3 Chopping in the ion source

Several studies at LANL 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.

7.4 Conclusions on Chopping

The consensus was that while chopping beam at the source would not meet the stated requirements, doing so 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.

This work is still in early stages of development, much R&D is still required.

8. R&D Necessary for Development of Ion Sources for a 1-5 MW PSS

(Jim Alessi, Horst Klein, Rob York, Vernon Smith)

In the following, we will concentrate on the cesiated volume and Penning H^- sources, since they appear to be the leading candidates for a PSS. The Penning source always requires cesium, and only a cesiated volume source can meet the PSS requirements. There is no ion source development required for ISIS, since their Penning source now meets their needs quite satisfactorily. In addition, 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. The required development effort to meet these specifications is small, though, and is not viewed as a major technological challenge. Therefore, the remainder of this section will focus on the R&D 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.

There are some R&D issues that are common to both type sources. Both have significant questions concerning lifetime. In the case of the Penning source, the issue is cathode erosion, while for the volume source it's 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 flat current pulse (possibly within 1%) is important to avoid particle losses in high duty factor machines. At the required pulse widths, both sources must still demonstrate such flatness. 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.

8.1 R&D Issues Specific to the Penning Source

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.

8.2 R&D Issues Specific to the Volume Source

At the lower current requirements of the ESS and LANSCE II proposals, a demonstration of operation at the required duty factors is needed. Achieving the 150 mA requirement of the BNL proposal with a volume source would require some development. For all proposals, work should continue on reducing the electron-to-H^- ratio, and on improving lifetime and reliability.

8.3 System Related 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. There are two options for the LEBT, electrostatic focusing of an uncompensated beam, or magnetic focusing of a space charge compensated beam. Although magnetic transport has been used quite often, we feel that it is important to demonstrate the performance of both types of systems at these high currents. 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.

It will be necessary to build up at least one test bench in which the ion source and LEBT can be studied. It is suggested that if only one is constructed, this test bench should be suitable for testing both Penning and volume sources, as well as both electrostatic and magnetic LEBT configurations. Issues such as alignment, exit emittance, stability, and long term performance of the integrated system can be addressed on this test bench. Later on, the first RFQ could be added to measure transmission and emittance growth. Development of diagnostics for these high power beams can be performed as well. Finally, beam chopping, either before or after the RFQ, could be studied. Ultimately, one would end up with a fully-functional front end which, if desired, could be directly incorporated into the PSS construction project.

The rationale for such a test program is straightforward. Experience has shown that there are problems in transferring laboratory test results of ion source performance to the demanding requirements of any front-line research accelerator, most particularly a user-oriented high-intensity spallation neutron source where high reliability is of prime concern.

An ion source must first demonstrate that it can simultaneously meet all the required parameters: current, emittance, pulse length, pulse repetition rate, etc. Existing source technologies are capable of meeting many of these parameters, however meeting them all simultaneously, and demonstrating acceptable lifetime while operating in this extreme mode is a step beyond today's technologies. Thus, the first goal of the test program is to develop sources engineered to meet all the stated requirements.

The source must then operate, while meeting these performance requirements, with a constancy and reliability, over an acceptable period of time. Constancy and stability 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 (can not 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." Testing the source integrated into the "accelerator system" is important because there are source issues relating to extracting ion and electron currents, beam transport and matching to the RFQ.

9. Estimate for Costs and Schedules for Constructing a Test Bench, and Conducting a Suitable Test Program (Andrew Jason)

The following is presented as a model for effort and resources needed to assemble and operate a suitable test bench that could accomplish all of the above-stated R&D goals. This model was not widely discussed during the Workshop, but is based on LANL's extensive experience in conducting exactly this kind of program. Further study is needed to provide more focus and to better establish goals for a suitable R&D program, and to develop the most cost-effective plan for addressing the development needs.

The comprehensive R&D program modeled here assumes development and testing of the ion source alone first, and then further testing on an integrated test system (ITS). The end product will be a prototype front end (nominally 3 MeV) that may, in full or in part be used as the front end of the actual accelerator . This cautious approach, namely the development of the front end that can meet full system specifications, is suggested because of the higher perceived risk in the low-energy part of the system and because it may well fit in, both technically and cost-wise, with total system integration. The scenario incorporates workshop discussions for component needs, and assumes that three possible chopping methods are developed (in-source, low-velocity (LEBT), and high-velocity (HEBT) transport lines).

Certain assumptions are made as to the current state-of-the-art (well-formed ideas that can immediately specify a prototype design), the desired product-confidence level to be obtained in development (assumed high), and final product format. A source prechopper and two types of chopping (pre- and post-RFQ) are assumed; the study is sufficiently modular so that any changes can be readily dealt with. Within these assumptions, a standard deviation of 20% for the accuracy of the estimates. Very little in the way of existing infrastructure is assumed; the existence of an ion source lab with test facilities, electronics, etc. can effect appreciable savings in time, materials and services. Savings for scenarios that require "no source development" will be appreciable but not overwhelmingly so, since integration and reliability work are still important.

A 3-month 1-FTE (for specific definition of the term "FTE" see footnote below Table III) initial effort defines the approach. Several parallel paths then go into an immediate start (some with appreciable float). The critical path is defined by ion source development; an 8-mo. prototype design and an 8-mo. prototype construction period is begun for both the volume (V) and Penning (P) sources in parallel. Simultaneously, a test stand for dual testing is begun. Upon completion of the sources, a testing program of 1.2 yrs duration is begun. A prechopper program is also merged with the testing. After this time, the source is assumed to meet requirements and have experienced substantial reliability testing and modifications. It is now ready for integration with the remainder of the system. This is done on the ITS that was begun at the project start. At this point, the choice between P and V may have been made or dual development continued. The rationale for developing an ITS separately from the dual-source test stand includes timing considerations, an acknowledgement of the specialized nature of a source-only stand, and the possiblility of iterative development of the integrated system and sources.

At project start, the Low Energy Beam Transport line (LEBT) is also begun with conceptual design and construction. It may be tested on the ITS earlier than completion of the source, using an auxillary source. Design and construction, requiring 2 yrs, of an RFQ has also begun and is integrated with the source-LEBT combination on the ITS. Finally, the High Energy Beam Transport line (HEBT), including a possible high-energy chopper, is added to the ITS. The HEBT includes the chopper and beam stop, three quad-triplet assemblies, three rf-cavities, and a section for matching to the DTL.

Table III summarizes effort required, elapsed time, and M&S (materials and services) costs for conducting a single test-bench program at one Laboratory. Table IV presents a Flow Diagram for this program, identifying total time flow and critical-path items for this particular model of the test-bench implementation.

TABLE III - Effort Table for a Test Bench Program

	Time, FTE's, M&S
A. Approach study	0.25 yr, 1.0 FTE
B. Development and facility construction	
1. Source	
-Design (8 mo) and Construct (8 mo) Penning- and Volume-Source Prototype	1.3 yr, 5.0 FTE, 400 k$
-Design and Construct dual test stand	1.5 yr, 3.0 FTE, 750 k$
-Conduct prechopper study	1.0 yr, 2.0 FTE, 200 k$
-Develop Sources	1.2 yr, 4.5 FTE, 200 k$
2. LEBT Development	
-Study LEBT & LE Chopper	0.5 yr, 1.0 FTE
-Construct LEBT & LE Chopper*	1.0 yr, 3.5 FTE, 800 k$
3. Integrated Test Stand (ITS)	
-Design and Construct ITS	1.0 yr, 4.0 FTE, 1.5 M$
4. Radio Frequency Quadrupole	
-Design and construct RFQ prototype	2.0 yr, 5.0 FTE, 5.0 M$
5. HEBT	
-Design and construct HEBT w/ chopper*	2.0 yr, 4.0 FTE, 4.0 M$
C. Integration	
1. Source and LEBT tests on ITS	0.5 yr, 3.0 FTE, 500 k$
2. Add RFQ, test, and develop	0.5 yr, 3.0 FTE, 500 k$
3. Add HEBT, test, and develop	0.5 yr, 3.0 FTE, 500 k$

*Includes pulsed-power development

TABLE III - Continued

Totals:

Time	4.5 yr (along critical path)
Manpower	41.5 FTE (distinction between skills not explicitly made - mixture of physicist, EE, ME, electronic & mechanical technician required. Source, diagnostics, pulsed-power, vacuum, magnet skills needed.)
Materials & Services	14.4 M$ Includes capital equipment, shop fabrication

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*The term FTE (Full-Time Equivalent) is used to mean man years, e.g., 2 people working 1/2 time for one year constitutes one FTE. At this level of estimate no explicit distinction is made between tech and staff FTEs.

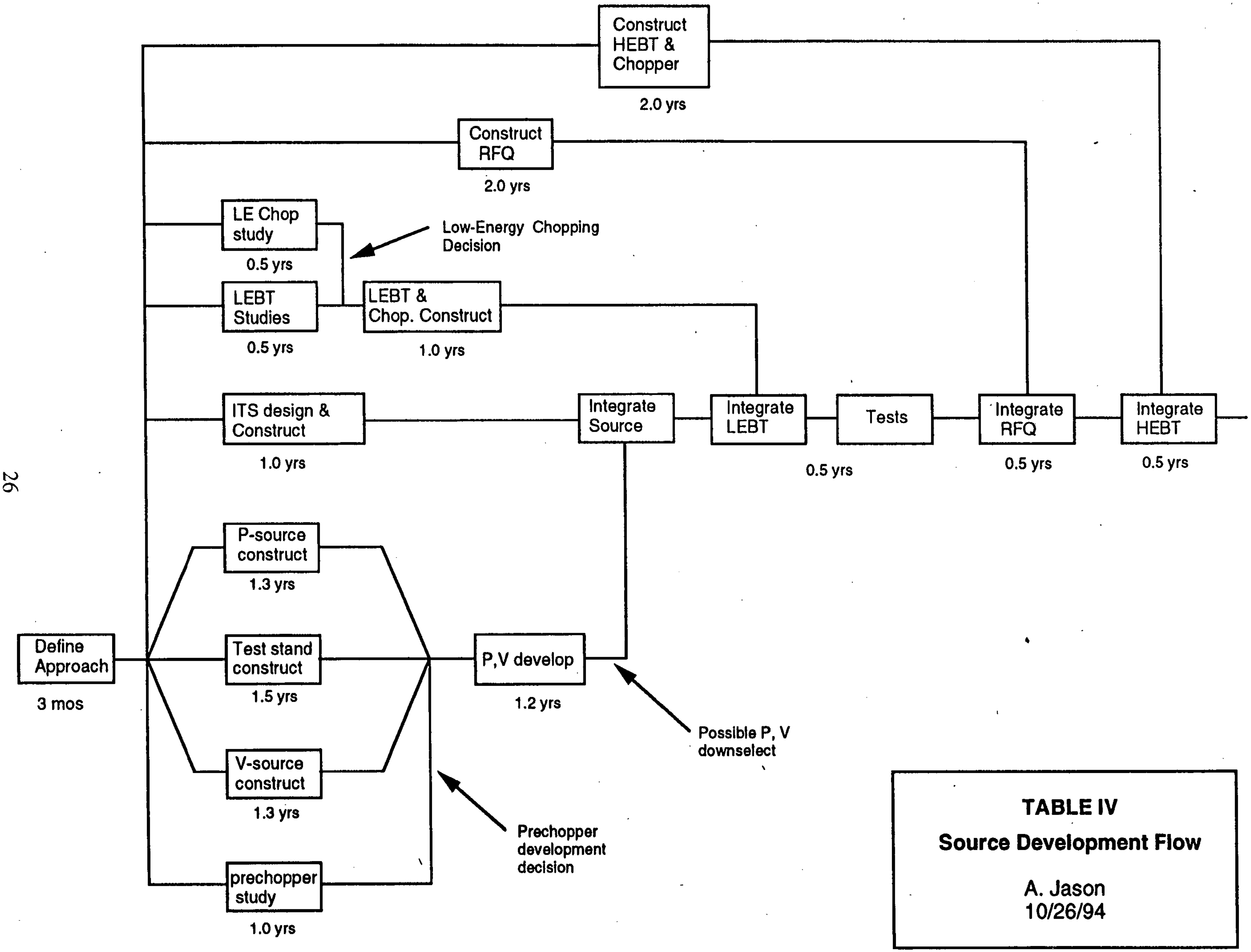

TABLE IV

Source Development Flow

A. Jason
10/26/94

10. SUMMARY: Conclusions/Recommendations

The workshop reviewed the ion-source requirements for high-power accelerator-driven spallation neutron facilities, and the performance of existing ion sources. Table I summarizes these required performance levels for existing and planned neutron facilities. Of note is that proposals for new facilities in the 1- to 5-MW range call for a widely differing set of ion-source requirements. For example, the source peak current requirements vary from 40 mA to 150 mA, while the duty factor ranges from 1% to 9%. Much of the workshop discussion centered on the state-of-the-art of negative hydrogen ion source (H^-) technology and the present experience with Penning and volume sources. However, other ion source technologies, for positive ions or CW applications were also reviewed. Some of these sources have been operational at existing accelerator complexes and some are in the source-development stage on test stands. Table II summarizes demonstrated performance of the various sources discussed. An assessment was then performed of the match between requirements for proposed PSS scenarios and demonstrated source performance, and goals for an R&D program were outlined for ion source development in cases for which it is required.

The workshop identified that out of the several types of sources, the Penning source and the volume source are potential candidate technologies suitable for the pulsed spallation scenarios currently under consideration. We noted that the optimum performance of the ISIS Penning source meets the minimum requirements for IPNS-II. For the other proposed configurations, no existing source performance can satisfy all requirements simultaneously. Further development of source performance is required for all of the proposals, with the IPNS-II proposal requiring the least source development and the 5-MW and LANSCE-II proposals requiring the most source development.

The R&D items required to support each proposal were discussed in some depth, noting the close relationship and coupling between the ion source, LEBT, chopping, and matching into the first stage of acceleration (most probably an RFQ). Of great importance is demonstration of operational reliability and reproducibility, as well as ease of operation and maintenance.

We strongly recommend the launching of an R&D program to address all these issues. Several alternatives exist for conducting such a program. Without doubt the best, though also the most expensive, is the scenario presented above for an integrated test bench with sufficient flexibility to test different sources, LEBTs and overall system performance up to an energy of around 3 MeV. Alternatively, a priori decisions of technology can be made, and a more focused test stand designed to develop the approach and components selected. Although most probably sporting a lower price tag, this approach also carries technical risk in that possibly promising technologies are not followed, and options available for solving problems encountered will be more limited.

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