ION SOURCE AND ACCELERATOR DEVELOPMENT FOR THE LLL 14-MeV NEUTRON SOURCE FACILITY[a]

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Summary

The ion source, acceleration tube, and beam transport system for the Lawrence Livermore Laboratory (LLL) T(d,n) ^{3}He neutron sources are described. To produce 4 x 10^{13} n/s, a 150-mA D^+ beam at 400 keV is required. A 17-aperture version of the reflex-arc MATS-III ion source is under test for this use. To simplify the acceleration tube and beam transport design, a 90° double-focusing magnet is to be used to separate the D^+ component from molecular beam components. Emittance measurements on the resulting D^+ beam are given. A four-gap, uniform-field acceleration column has been designed. Beam trajectory calculations for the acceleration column and transport system are presented. Design concepts will be tested on a prototype accelerator scheduled to operate in mid-1977.

Introduction

A new, intense, 14-MeV neutron source facility[1] is now under construction at LLL for fusion reactor material studies and possible cancer therapy applications. This D-T neutron source utilizes a 400-keV D^+ beam to bombard a T-loaded, high-speed rotating target. This follows the approach of an existing neutron source facility at LLL known as RTNS-I (Rotating Target Neutron Source), which produces up to 6 x 10^{12} n/s with a 20-mA D^+ beam at 400 keV. The first phase of the new RTNS-II facility calls for a dc 150-mA D^+ beam at 400 keV for an expected yield of 4 x 10^{13} n/s; an upgrade to 400 mA for a yield of ∿10^{14} n/s is planned. A schematic layout of the ion source and accelerator sections of one of the two accelerators for this facility is shown in Fig. 1. This paper describes the ion source and accelerator part of this facility. The details of the rotating target will not be covered here other than to note that to handle the ∿60-kW power load on the ∿1-cm^2 target spot without a prohibitive heating transient and loss of T requires changing from the present 23-cm-diam., 1100-rpm target to a 50-cm-diam., 5000-rpm version that includes special integral water cooling channels. Typical operating lifetimes for the T-loaded targets (until decay to 70% of initial yield) are expected to be ∿100 h. The maximum power density which the target can withstand limits the peak flux to 1.5 x 10^{13} n/cm^2 · s for the present Ti $T_{1.8}$ target material.

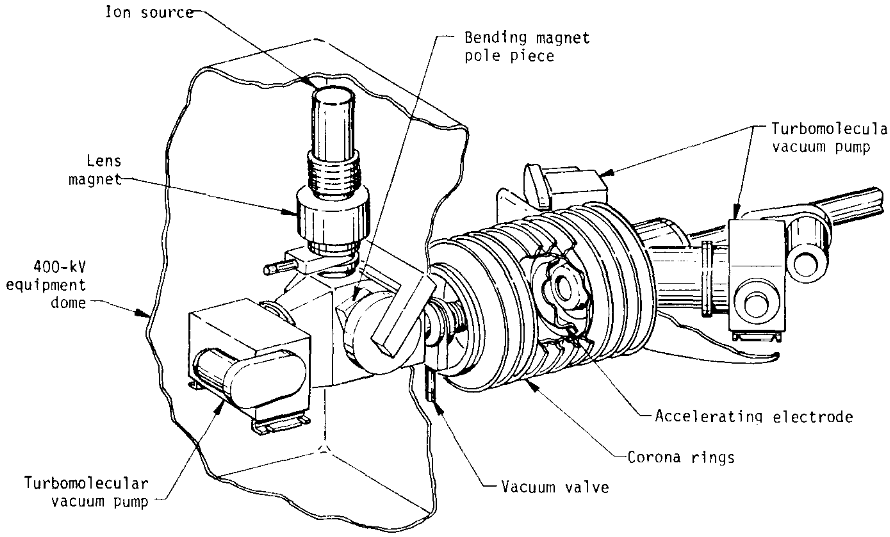

Figure 1: Ion source and acceleration tube sections of RTNS-II.

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Ion Sources

The ion source for the first phase of this accelerator application has the requirement of dc operation that will yield a minimum of 150-mA D^+ with an acceptable normalized emittance $\lesssim$ 0.4 mrad-cm [$\varepsilon_n \equiv$ area $(r,r')\ \beta\gamma/\pi$]. Several ion sources seemed capable of being scaled to meet these requirements. However, because only the MATS-III reflex-arc ion source[2] appeared presently operational up to the desired 400-mA dc range, it was adopted for final development and testing for this application. As originally developed for neutral-beam injection into the controlled fusion Baseball II experiment,[3] the 63-aperture, 6.0-cm-diam. beam MATS-III source was capable of total beam of ∿1-A dc at 20 kV. For the 150-mA D^+ beam requirement, the MATS-III source extraction plate was masked down to an 3.3-cm-diam. array of 17 4.1-mm-diam. apertures with a 0.25-mm-thick Mo mask on the plasma side of the extraction electrode. Source tests were performed in the test stand geometry shown in Fig. 2 that includes a 90° double-focusing magnet designed[4] to separate the desired D^+ beam from molecular components. Use of only the D^+ component arises partially from the severe reduction in target life-time if the target is bombarded with a mixed atomic and molecular beam and partially from the desire to simplify beam transport and focusing.

The principal ion source parameters of interest are the dc beam output, the usable pure-D^+ beam after separation, and the D^+ beam emittance. Here, performance will be described for the 17-aperture version.

In addition to basic measurements needed for this application, work has been continued on several areas where improvement appeared desirable. Among these are a higher fraction of D^+ available, a higher gas efficiency, a lower normalized emittance, and improved component lifetime. As backup to the multiple-aperture source, development work has continued on scaling up a duoplasmatron source for higher output and dc operation, and on a single-aperture version of the MATS-III reflex arc dubbed SARA (Single Aperture Reflex Arc). The SARA source (shown schematically in Fig. 3) is also described here because of several possible advantages including a relatively rugged, simple, extraction-electrode system and an unusually low beam emittance. However, production of a 150-mA D^+ beam with a single, ∿2-cm-diam. aperture would require extraction at > 40 kV and would present some disadvantages for the present application. For comparison, the typical operating parameters for the MATS-III-17-aperture source and SARA sources are given in Table I, with a lens magnet for beam focus and a 90° magnet for species separation. Neither source has yet been optimized for gas efficiency. Tests to date have been limited to $\leq$ 20-kV by the test stand power supply.

The species measurements quoted here involve an analysis of the total beam with a 90° separation magnet designed for nearly symmetric double focusing. The system appears to yield a good beam for $P > 10^{-5}$ Torr at the conjugate focus ∿127 cm from

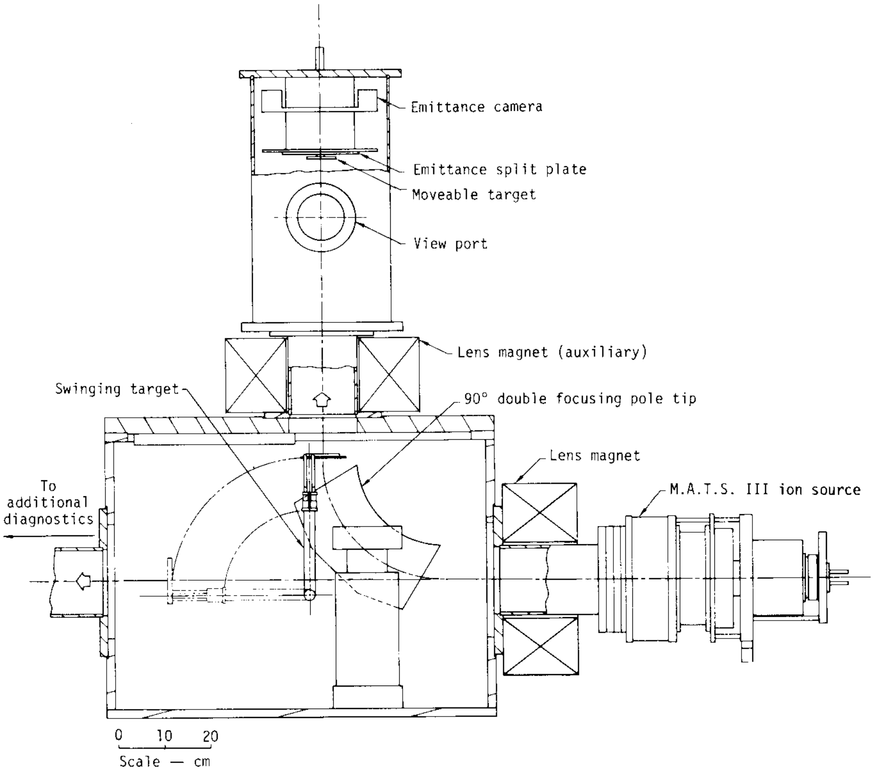

Figure 2: The 20-kV test stand for ion source development.

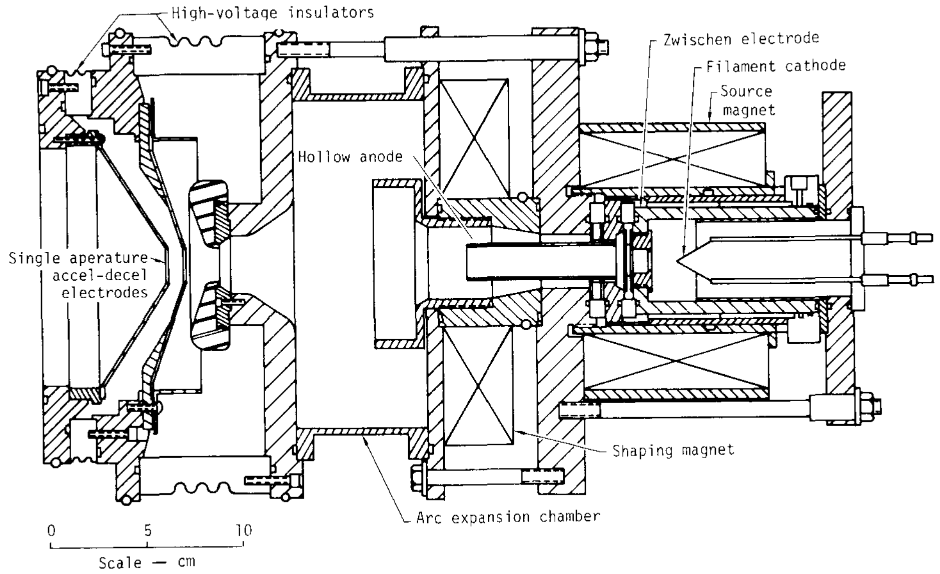

Figure 3: SARA ion source assembly.

TABLE I

TYPICAL ION SOURCE OPERATING PARAMETERS

	Source	
	15-kV, 17-Aper. MATS-III	20-kV SARA
Gas flow (D_2), STP	$\sim$12-15 cm^3/min	$\sim$8-10 cm^3/min
Arc current	25-35 A	14-20 A
Arc voltage	60-120 V	50-100 V
Drain current/extraction/voltage	400 mA, 15 kV	100-120 mA, 20 kV
I (100-cm^2 target at 1.5 m)	350-380 mA	80-100 mA
$f_c(D^+)$ charged beam fraction D^+	60-70%	75-83%
f_0 total energetic beam fractional neutral	15-25%	8-11%
Normalized D^+ emittances (at 10 kV)	$\sim$0.1 mrad cm	$\sim$0.02 mrad cm

the source, but the evaluation of the system optics and the degree of space-charge neutralization are still in progress. To date, the specially shaped pole tips have only been used with a small-area magnetic yoke (in the 20-kV test stand) which permits 90° deflection only for D^+ up to 10 kV (or 20-kV H^+).

Previous measurements of the ion species composition generally were made using a relatively small sample of the beam on axis and often tended to yield a somewhat high and hence misleading D^+ charged-beam fraction. The study here with a swinging target to intercept the various components of the total charged beam indicates a substantial variation in $f_c(D^+)$ with extracted beam radius: from $\sim$50% for a 6-cm-diam., 63-aperture system, to $\sim$65% for a 3.3-cm-diam., 17-aperture system, and to $\sim$80% for a 2-cm-diam., single-aperture system. In general $f_c(D^+) \gtrsim f_c(H^+)$ for all source conditions tested. To attain the $f_c(D^+)$ values given above required a hot anode (arc heated to $\sim$2000 K) and extensive use of thin, 0.25-mm Mo heat shields as liners throughout the arc chamber. To explore the other extreme, the normal hot Mo anode was replaceed by a water-cooled Cu anode ring placed near the extraction aperture plate. In this mode of operation, the $f_c(D^+)$ was reduced to 10-20% with a correspondingly high $f_c(D_2{}^+)$. In addition, it was noted during tests with the 17-aperture system that a fresh, heavy-oxide cathode coating had an apparently catalytic effect, that is, it tended to temporarily enhance $f_c(D^+)$ to as high as 90%, but provided no useful increase in the D^+ current. Predissociation of the input D_2 gas was also tried with an auxiliary W oven; however, there was little effect beyond that attained with the hot Mo liner system, implying that the species equilibrium is still dominated by some wall recombination process.

The normalized emittance ε_n was measured for the 90° emittance camera location shown in Fig. 2. The multiple-slit camera required a 1- to 10-s exposure to attain a readable level of visual damage on a strip of polymer plastic used as a film roll. The measurements quoted here are only for the plane of deflection, and because they suffer from remanent beamlet structure in the multiple-aperture case, require averaging several scans from densitometer readout. Use of a multiple-lens magnet, 90° double-focusing system also introduces beam crossover and aberration problems unless special care is taken with the beam focus adjustment. More refined emittance measurements that are planned at higher beam currents on a 50-kV test stand, 90° deflection magnet system, will include a measurement in the plane orthogonal to the 90° deflection. The very low value of the SARA emittance is taken to imply a relatively uniform plasma density, ion temperatures of only ∿1 eV (within ± 1 cm of the axis) and a minimum of aberration in the semi-Pierce extraction geometry shown in Fig. 3.

Accelerator Design and Beam Envelope Studies

The electrode structure chosen to accelerate the emergent D^+ beam to a total of ∿400 keV is a relatively large-aperture, nearly uniform moderate-gradient (∿20 kV/cm) column design as shown in Fig. 4. This tube design was selected as a compromise among several conflicting requirements. To minimize beam expansion due to space charge, the acceleration to full energy should occur in the shortest possible length; i.e., the highest gradient consistent with reliable operation should be used. However, the extent to which the high gradients possible in pulsed operation at low-duty cycles could be sustained in dc operation was not clear. The electric field has thus been set at a value approximately half that used in pulsed injectors. Secondly, although the space-charge expansion can be compensated by the $z^{4/3}$ variation of potential used in Pierce structures, use of this technique would require electrodes reaching close to the beam and would produce proper field configuration only for a single current value. Because the neutron source strength must be easily variable, the acceleration column must tolerate a reasonable range of input current. Other requirements are re-entrant electrodes to shield the ceramic insulators and water cooling of the outer electrodes to remove energy deposited by stray beam striking the electrodes. The ceramic envelope has been made in several sections to allow for easy replacement or modification of electrodes or ceramic sections. Inner field-shaping electrodes are Mo; intermediate connecting electrodes are Cu with Cr plating; and the outer electrodes that are vacuum brazed to the ceramic insulators are Cu. An acceleration column of this design is now in fabrication for testing with H_2^+ beam on a prototype accelerator scheduled for completion in July 1977.

Computer studies have been used as an extensive tool to check the electrode design. The JASON code[5] was used to insure acceptable vacuum fields, and the TRACE code was used for D^+ beam-envelope studies as a function of beam voltage, beam current, input beam emittance, and fractional space-charge neutralization of the exit beam.

A typical set of trajectory traces is shown in Fig. 5. The beam current for this case was a 150-mA, 5-cm-diam. D^+ beam that diverged at 1°. The image point of the 90° separation magnet is located 10 cm before the first gap, i.e., where space-charge effects become important. Space-charge expansion of the beam is compensated for by the strong lens effect at the tube entrance. As the injected beam current is decreased, the beam diameter is reduced to decrease the lens effect. Ray-tracing runs indicate that for currents from 30-150 mA, beams exiting the tube will be parallel or slightly convergent. The 50-kV test stand which duplicates the optical layout of all terminal components will be used to determine the limits to which the source can be matched to the tube.

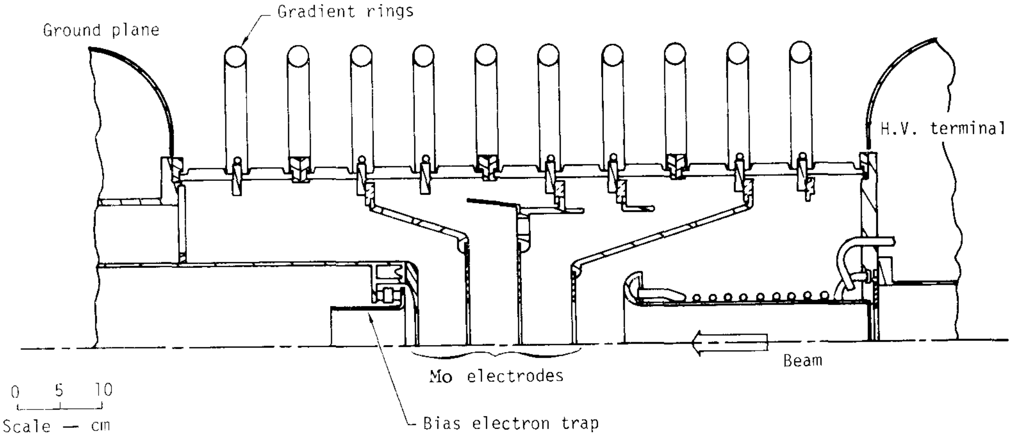

Figure 4: Accelerator column assembly.

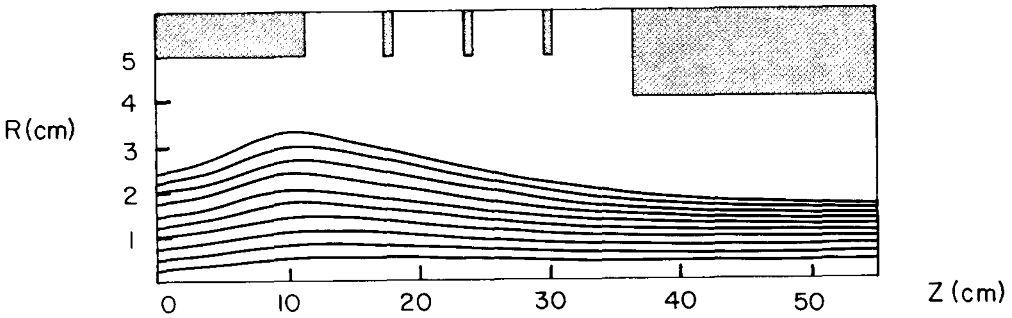

Figure 5: TRACE code trajectory calculations (note the differences in vertical and horizontal scales and that the beam enters from the left side).

Serious problems which remain to be investigated with the prototype accelerator are the effects of beam density variations due to both the multiple-aperture structure and to ion-source noise. These variations will affect both the beam focus and the extent to which the beam can be considered space-charged neutralized in the post-acceleration drift space.

Beam Transport System

Transport of the 400-keV beam from the accelerator ∿6 m to the target will be done with a system utilizing 10-cm-aperture, quadrupole triplet lenses. The major uncertainty in design of this system is the extent of neutralization of the beam. If the beam is assumed to be fully neutralized, then a 1-cm FWHM beam spot can be produced with elements having fields of ≤1600 G at the surface. Up to ∿20% residual space charge on the beam can be compensated by raising the field strength to 2000 G, well within the limits of the elements selected.

A tentative layout of components was done with the statistical transport code SPEAM, which allows variable space charge on the beam. This three-triplet system was then optimized using TRANSPORT in a search mode. The sensitivity of the beam spot size to variations in energy was acceptable, with a 1% change in beam energy causing only a 5% change in the area of the beam spot on target. The final design of the transport system will depend upon the beam parameters measured on the prototype accelerator.

Acknowledgments

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DISCUSSION

C.D. Curtis, FNAL: Were both quoted emittances for beams after bending magnets?

Osher: Yes, but at the lower beam levels required by the 10 keV D^+ limitation of the 90° bending magnet in the test stand.