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PROGRESS REPORT ON ZERO GRADIENT SYNCHROTRON H⁻ SOURCE DEVELOPMENT*

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Summary

The operational reliability required of an H^- source for direct or booster injection into a proton synchrotron has been demonstrated during several recent tests of Booster I, the developmental booster for the Zero Gradient Synchrotron (ZGS); the minimum pulsed design current of 4 mA at 50 MeV was obtained for the first time during a recent test of direct H^- injection into the ZGS. On the basis of these results and anticipated further improvements in the source, preparations are being made for the permanent installation of a stripper in the ZGS for the conversion of H^- to H^+. Direct H^- injection will become the normal mode of operation, with the 50 MeV beam going to the booster and ZING, an intense neutron generator, in the interval between ZGS pulses. The planned effort through July 31, 1975, calls for an operational tandem-acceleration sequential charge exchange source yielding a 50 MeV H^- current of ~ 8 mA. In this source, a low density hydrogen target will serve as a space charge neutralizer and a buffer between the positive ion source and a sodium-vapor charge exchange cell receiving the H^+, H^0, and H^- output from the hydrogen cell. This effort will require a relatively small and conservative extrapolation within the confines of the present state of the art. If it is entirely successful, the 50 MeV H^- current will exceed the requirement for direct injection into the ZGS by a factor of two and the initial requirement of 6-8 mA of 50 MeV H^- for Booster II, the operational booster, and ZING will have been met. To meet the anticipated future needs of Booster II and ZING, a further extrapolation of a pioneering nature will be required; its goal will be a single-component H^- current of 50 mA out of the source and ~ 20 mA of H^- at 50 MeV, pulsed at a continuous 30 Hz rate.

Introduction

As was reported at the Second Symposium on Ion Sources and Formation of Beams,[1] the first of two short-term objectives of the H^- source development program for the ZGS was met when the operational reliability required of an H^- source for direct or booster injection into a proton synchrotron was demonstrated, for the first time anywhere, during the January-February 1974 test of Booster I.[2,3] During this test, the beam was pulsed at 4-10 Hz rates for a total of ~ 1.7×10^7 pulses. This is equivalent to 46 days of continuous operation at the normal booster-ZGS duty cycle of 15 pulses at a 30 Hz rate once every 3.5 s. The second objective was met (marginally) last September when the minimum design current of 4 mA at 50 MeV was obtained for the first time during a test of direct injection into the ZGS.

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On the basis of these results and anticipated further improvements which are expected to provide sufficient extra current to compensate for normal tuning errors and drifts, preparations are being made for the permanent installation of a stripper in the ZGS for the conversion of H^- to H^+. Direct H^- injection will then become the normal mode of operation. The 50 MeV H^- beam will also be used for injection into the booster and ZING in the intervals between ZGS pulses. Booster development will then proceed independently of ZGS operations and the high energy physics research program.

The geometry of the tandem acceleration source used for the test of direct H^- injection into the ZGS is described and discussed in detail in ref. 1. For the present discussion, the schematic diagram of Fig. 1 will suffice. The field of the M-2 coil mounted over the small diameter section of the charge exchange cell opposes the field produced by the source magnet and the mild steel intermediate electrode of a duoplasmatron in which the arc plasma extends from the cathode to a nonmagnetic stainless steel source grid on the far side of a split OFHC anode. (A chopper wheel sandwiched between the anode segments pulses the H_2 outflow from the intermediate electrode at a 30 Hz rate.) This coil can be used to produce a magnetic cusp in the vicinity of the plasma boundary from which ions are extracted or to otherwise shape the field.

The performance of the cusped field source, work in progress, and the planned future effort will be discussed in the following sections.

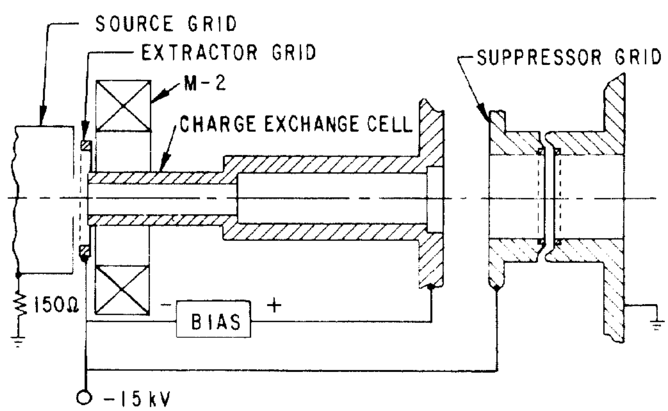

Fig. 1 Schematic of the H^- Section of the Cusped Field Source of Ref. 1

Performance of the Cusped Field Source

The maximum usable beam which can be extracted from the source plasma is expected to scale as $n_o W_{90}^2$ where n_o is the on-axis plasma density and W_{90} is the full width at 90% of maximum of the radial plasma density distribution in the vicinity of the sheath from which ions are extracted. For the geometry used in the January-February 1974 run, with source parameters adjusted to the values which produced the highest 50 MeV current and a Langmuir probe located in the plane normally occupied by the extractor grid, a value of 0.69 cm was measured for W_{90}. This is only 54% of the design value for the initial beam diameter.

The cusped field source is the culmination of a series of changes (discussed in ref. 1) in the discharge geometry and the magnetic field distribution. W_{90} has not been measured for this geometry, which differs necessarily from the makeshift geometry used to obtain a cusped field during probe studies of the plasma. (In the makeshift assembly, the field shaping coil was wound on an insulator which normally connects the source and extractor grid holders; for the probe measurements, a 2 in long diagnostic chamber was interposed between the source grid holder and the insulator.) For this assembly, W_{90} increased from 0.61 cm with M-2 off to 1.02 cm with the magnet adjusted to form a cusp in the plane of travel of the Langmuir probe. n_0 was ~ 3 times higher than it had been in the January-February run.

Fabrication of the cusped field source was completed just prior to the start of the August-September 1974 booster run. The source was installed in the 750 kV terminal after a single bench test lasting about 4 h. During this test, with the beam pulsing at a 5 Hz rate, a 30 keV current of 15.4 mA peak, 12.9 mA average was obtained for pulses of 220 μs duration. The current is measured after a magnetic analysis which removes heavy ions from the beam but does not resolve the H^- components derived from H^+, H_2^+, and H_3^+. The currents cited above are a factor of 2 higher than those obtained with the geometry of the January-February 1974 run. As noted above, the 50 MeV H^- current is also about a factor of 2 higher.

During the August-September run, there was no remote link to M-2, which was set at the value used in the bench test. When the source was returned to the test stand after the run and more operating experience was gained with this geometry, it was found that M-2 has a smaller effect than was previously assumed. With careful tuning, ~ 20% more beam was obtained with a cusp than without it. It is now clear that most of the factor-of-2 increase in current over the previous geometry is due to changes other than the addition of the field shaping magnet.

The source was reinstalled in the 750 kV terminal in the first week of February 1975. It began to deliver beam to the ZGS on February 11 and to the booster on February 17. Early in the run, scheduled to end on March 17, the M-2 power supply was destroyed by an arc-down. The loss of M-2 has not made a noticeable difference in the 50 MeV H^- current obtained during routine operation, with all elements from the source to the high energy end of the linac running unattended. During such "hands-off" operation, the current is apt to be at least 20-30% lower than it would be with constant tuning of all elements.

Emittance Measurements

Several years ago,[4] an attempt was made to obtain emittance measurements on the 30 keV beam with a single slit followed by an array of strip collectors whose amplified signals are processed by an on-line computer as at Fermilab.[5] The attempt failed because of poor signal-to-noise ratios, and the SPEM (slit programmed emittance measurement) gear was shelved so that full time could be devoted to the more urgent problems of reliability and beam intensity.

Several months ago, the gear was dusted off and checked out and debugged by H. R. Hiddleston and R. A. Sanders, who then used it to obtain horizontal emittance measurements on the 30 keV beam. They obtained a phase space area, divided by π, of 19 mrad cm. This gives a normalized emittance of 0.15 mrad cm, with an uncertainty of 20-25%.[6] The vertical emittance has not yet been measured but is expected to be significantly lower because the parallel ribbons of the extractor grid are vertical; beam scattering due to field perturbations is worse in the horizontal plane. Although the slit- and segmented-collector method of measuring emittance is used at accelerator laboratories for beam energies of 750 keV or higher, the present measurements are the first that we know of for typical ion source beam energies.

At this time, signal processing and display are being done without a computer, as at Brookhaven.[7] A link from the computer to the H^- lab is being considered.

Results of an Attempt to Eliminate the H^- Gap Grids

The suppressor and grounded grids of Fig. 1 are used to eliminate the focussing action of the H^- accelerating gap. Removal of the grids has been considered for some time as a means of improving source reliability. Although it is more than adequate for booster or direct injection into the ZGS, source life is still uncomfortably short for continuous operation at the present injection rate of 15 Hz for ZING.

Figure 2 shows two geometries in which the grounded grid has been eliminated. In Fig. 2a, the suppressor grid has been moved to a location where it does not disturb the field of the gap lens. The lens was designed to be as weak as possible without excessive reduction of the inside diameter of the first electrode. For the geometry of Fig. 2, this diameter is 1.750 in; the inside diameter of the second electrode is 2.625 in.

The optical constants for this lens can be determined from Spangenberg's curves.[8] For the H^- component derived from H^+, which doubles its energy in going through the lens, the focal length f_2 and the mid-focal length F_2 are ~ 44 in. For the H^- component from H_2^+, which triples its energy, $f_2 \simeq 17.5$ in and $F_2 \simeq 12$ in. For the H^- component derived from H_3^+, which quadruples its energy, $f_2 \simeq 10.5$ in and $F_2 \simeq 7$ in.

With the suppressor grid tied to the extractor grid and electrode 1 tied to the charge exchange cell and bias +, loading on the extractor power supply was so

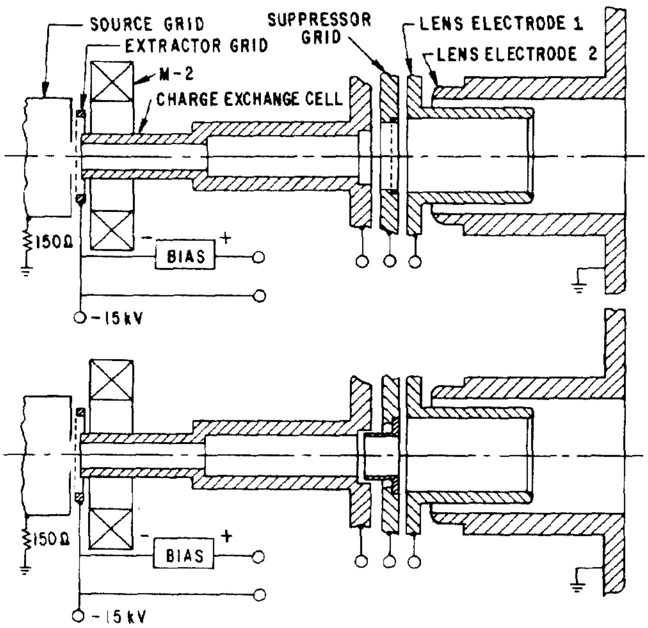

Fig. 2 Two Gridless H$^-$ Gap Geometries Tested as Possible Substitutes for the Geometry of Fig. 1

severe that the voltage could not be raised above 6 kV. When the suppressor grid, electrode 1, and the charge exchange cell were all tied to bias +, loading decreased but the H$^-$ current was limited to about 33% of that obtained with the reference geometry of Fig. 1. The optimum bias voltage was zero.

When the grid of Fig. 2a was removed and replaced with the cylinder of Fig. 2b, a current within 10% of that produced by the reference geometry was obtained. In this case, the charge exchange cell was connected to bias + and the suppressor grid and electrode 1 were tied to the extractor grid. The largest beam current was obtained with zero bias.

On the basis of these results, it was assumed that the geometry of Fig. 2b would perform as well and perhaps better than the reference geometry. However during two days of operation in the 750 kV terminal, this geometry gave a factor of 2 less 50 MeV beam for the booster than the reference geometry of Fig. 1. At the same time, the x-ray level in the vicinity of the preaccelerator was several times higher.

During the two days that this geometry was installed, the total time spent tuning for maximum 50 MeV beam amounted to an hour or so. Since the beam was being used by the booster and ZING and beam users do not appreciate wild excursions in intensity, there were no radical departures from the tune used with the reference geometry.

With the new geometry removed, a question remains as to whether a radically different and better tune exists; but even if a better tune had been found, the source would probably have been removed because of the excessively high x-ray level. The source of the electrons causing the x-rays is not known with certainty. Transmission of energetic electrons from the source, through a solenoidal lens, a collimating aperture, and two electrostatic quadrupoles to the 750 kV accelerating gap has not been measured or calculated; it is believed to be quite small. Secondary electrons and free electrons from ionization of residual gas in the vicinity of the quadrupoles would be collected by the positive electrodes. Secondary electrons due to incorrectly focussed off-energy ions striking the beam pipe between the quadrupole housing and the accelerating gap can reach the gap and are probably responsible for most of the x-rays. Measures will have to be taken to collect as many of these secondary electrons as possible before they reach the accelerating gap.

H$^-$ Stripping by Electrons

For the reference geometry of Fig. 1, which stops electrons going toward the suppressor grid when it is biased but does not efficiently force the electrons back into the charge exchange cell, the optimum bias voltage of $\approx$ 100 V gives a large reduction in extractor power supply loading, thus permitting the achievement of higher extraction voltage which, in turn, can result in a higher beam current. For the geometries of Fig. 2, the largest beam currents were obtained with zero bias voltage, i. e., with nothing to prevent the loss of electrons from the charge exchange cell. This suggests that the process $e + H^- \rightarrow H + 2e$ is causing a significant loss of H$^-$ beam. The cross section for this loss process, $\sim 4.4 \times 10^{-15}$ cm^2 at 15 keV, is an order of magnitude larger than the sum of the stripping cross sections for H$^-$ in hydrogen gas. Thus electron buildup in the charge exchange cell can reduce the equilibrium yield of H$^-$ and some sort of control of the electron density in the cell is called for.

Before the geometry of Fig. 2b was removed from the 750 kV terminal, the charge exchange cell and electrode 1 were tied to the extractor grid; the suppressor grid was connected to bias +. With the bias at zero, the beam measured on a Faraday cup at the entrance to the linac decayed exponentially over a period of ~ 50 μs from an initial value of 3 mA to a constant value of 2 mA. When the bias was raised to some optimum but unknown value (readout not calibrated), the initial beam value was 4 mA and the current decreased linearly to 1 mA over the pulse period of ~ 200 μs. This linear decay suggests the possibility of a power supply loading problem.

When source testing is resumed, a modified charge exchange cell will be used to study H$^-$ stripping by electrons. In this cell, a longitudinally split cylinder will be mounted in the large diameter section of the charge exchange cell. The two halves of the cylinder will be biased in various ways to increase or decrease the electron density in the cell, and the effects of these variations in density on the H$^-$ beam current will be determined. The desirability of tailoring the electron distribution from one end of the charge exchange cell to the other with a more complicated set of biased electrodes will then be considered.

Sequential Charge Exchange Source

The planned effort through July 31, 1975, calls for an operational tandem-acceleration sequential charge exchange source yielding a 50 MeV H^- current of ~ 8 mA. In this source, a low density hydrogen target will serve as a space charge neutralizer and a buffer between the positive ion source and a sodium-vapor charge exchange cell receiving the H^+, H^o, and H^- output of the hydrogen cell.

For a given source geometry and plasma composition, the maximum yield of H^- is proportional to $\eta(V_b)V_a^{3/2}$. This quantity is plotted as a function of V_a and V_b, for hydrogen and sodium targets, in Fig. 3, where η, V_a, and V_b are defined.

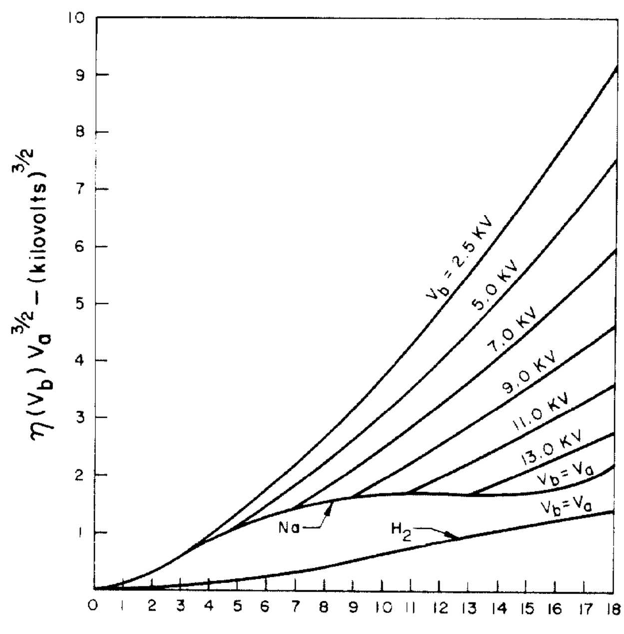

Fig. 3 Relative H^- beam current as a function of accelerating (extraction) voltage V_a and beam voltage V_b for a beam accelerated to energy $E_a = eV_a$ and then decelerated to energy $E_b = eV_b$. η, a function of V_b, is the conversion efficiency for the process $H^+ \rightarrow H^-$.

Achievement of a factor of 5 or 6 increase in current over the value presently obtained in hydrogen is necessary to satisfy the anticipated future need of a 20 mA, 50 MeV beam for Booster II and ZING. Figure 3 shows that this increase could, in principle, be obtained by extraction of positive ions with a voltage of ~ 15 kV, to exploit the $V^{3/2}$ dependence of beam current on extraction voltage, and then deceleration of the beam to ~ 2.5 keV, the optimum energy for $H^+ \rightarrow H^-$ in sodium. In practice, this may prove to be extremely difficult, if not impossible. The problem is to slow the beam down by a large factor without losing it to a wall because it is too highly convergent or divergent after slowing down.

In the absence of charge exchange, Brillouin flow[9] could be used to guide the positive ions through the hydrogen and sodium cells; however, with the charge state of each particle changing at least once, magnetic confinement would not be effective for any reasonably sized cell and the emittance of any beam that emerged from the sodium cell would be larger than that of the entering beam.

There is evidence that the standard three-electrode accel-decel geometries used at various CTR laboratories cannot be used to give a factor of 5 or 6 increase in current.[10] However, deceleration from 15 keV to 13 keV with a standard accel-decel geometry should not present any difficulties and could give the factor of 2 increase required to achieve the near-term goal of an operational source yielding an 8 mA, 50 MeV beam.

Further deceleration, to 10 or 11 keV, may require a small departure from the standard geometry but can give a factor of 3 increase over the yield in hydrogen. The approach to obtaining as large a gain as possible by the accel-decel method will be to use a standard electrode geometry as the point of departure for an effort to devise, with the aid of a computer, more complicated geometries which will permit the use of larger ratios of extraction voltage to finalbeam voltage.

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