Preprint of paper presented at the 1990 Linear Accelerator Conference. Albuquerque, NM, Sept. 1990.

REVIEW OF NEGATIVE HYDROGEN ION SOURCES

Charles W. Schmidt
Fermi National Accelerator Laboratory*
Batavia, Illinois 60540

Abstract

In the early seventies, significant discoveries for H⁻ ion sources were made at Novosibirsk. These and many improvements which followed have led to useful accelerator sources. With these sources charge-exchange injection into circular accelerators has become desirable and routine. This paper reviews the major developments leading to practical H⁻ sources. Different types and variations of these sources with some basic physics and operation will be described. The operating parameters and beam characteristics of these sources will be given.

Introduction

The usefulness of negative hydrogen ions has been recognized for several decades for a variety of purposes. Early Tandem Van de Graaff Accelerators used proton sources followed by an attachment canal to produce several hundred microamps of H⁻ ions.[1] The H⁻ ions were accelerated to a high potential, stripped to protons and accelerated to ground, gaining an energy of twice the potential.[2] Soon after, H⁻ ions were used with cyclotrons so extraction could be achieved by stripping to neutrals or protons. Penning type sources which fit within the Dees produced five milliamps of H⁻ current.[3]

Linear accelerators have long been used as proton injectors to synchrotrons. It was recognized early that H⁻ ions would be useful for charge-exchange injection into circular accelerators.[2] Intensity and reliability of H⁻ sources limited this possibility until the seventies when H⁻ injection was accomplished at the Argonne ZGS.[4] At that time H⁻ ions were achieved using a proton source with a charge-exchange cell.[5]

The next major step in H⁻ source development occurred in the Soviet Union at Novosibirsk. There, improved geometries and the addition of cesium produced intense sources with an output of several Amperes per square centimeter of aperture.[6] Geometries of both the Penning and magnetron forms were studied. These sources have become known as surface-plasma sources (SPS).

The Soviet work was adopted in the U.S. at Brookhaven to produce high current sources for neutral beam injectors for the confinement fusion program.[7] At Los Alamos the Penning geometry was studied to produce an accelerator source of high current and duty factor.[8] At Fermilab the research magnetron of the Brookhaven group was redesigned into an operational source for pulsed applications with good current and low duty factor.[9] Significant improvements to this source design at Fermilab [10] and Brookhaven [11] have made the magnetron a highly useful H⁻ source for many linacs used as synchrotron injectors.[10-13] The Penning sources have been useful in high-duty and high-brightness applications.[14,15]

While the magnetron and Penning sources were being pursued for accelerators, a large potentially d.c. multicusp surface-plasma source originated at Berkeley for the fusion program.[16] Modified versions of this source were studied and used for accelerators.[17,18]

Parallel to the SPS effort, a French group at Ecole Polytechnique near Paris vigorously pursued obtaining H⁻ ions from a hydrogen plasma.[19] This effort, which has led to the volume source, is being studied at several laboratories.[20,21]

* Operated by the Universities Research Association under contract with the U.S. Department of Energy

This paper will deal primarily with the modern surface-plasma and volume-process sources useful or anticipated for accelerators such as linacs. These sources can produce reliable pulsed H⁻ beams from ≈10 to 100 mA with normalized emittances of 0.2 to 2 π mm-mr for 90% of the beam.

Where emittances are in other than 90% values, the given emittance will be quoted and a value for 90%, assuming a Gaussian distribution, will be given in brackets for reference to other sources. [$\varepsilon_{(90)} / \varepsilon_{(rms)} = 4.6$, $\varepsilon_{(90)} / \varepsilon_{(95)} = 0.77$].

Basic Principles

Surface-Plasma Sources

The surface-plasma sources all produce H⁻ ions by the interaction of energetic plasma particles with a surface (Fig. 1). These particles, having energies of several tens to several hundred eV, are produced in a plasma near the surface. This surface is typically a cathode electrode. The incident particles may be protons, ionized hydrogen molecules, heaver positive ions, such as cesium, or energetic neutral atoms or molecules that may occur in the plasma. Upon striking the surface they may desorb hydrogen atoms which can leave the surface in several states, occasionally as an H⁻ ion. Also, protons or neutral hydrogen may reflect from the surface and acquire sufficient electrons to become an H⁻ ion. To improve the possibility that H⁻ ions will leave the surface and not lose electrons, cesium is added to the source to partially cover the surface and lower its work-function. As cesium covers the surface, typically tungsten or molybdenum, the work-function decreases from above 4.5 eV to ≈1.8 eV at 0.6 of a monolayer of cesium and then rises to about 2 eV for one monolayer or greater of cesium. To minimize the work-function and maximize the H⁻ yield the cesium feed is controlled. Cesium also ionizes easily to produce electrons and ions in the plasma improving the source stability. After formation the H⁻ ions pass through the plasma to the anode aperture and are extracted. Some ions incur collisions in the plasma and are lost or destroyed. Others may charge-exchange with neutral hydrogen atoms to form thermal H⁻ ions. These thermal ions are the basis for a brighter beam in some sources. Since the polarity is appropriate to extract negative ions, electrons are also extracted from the source and must be dealt with.

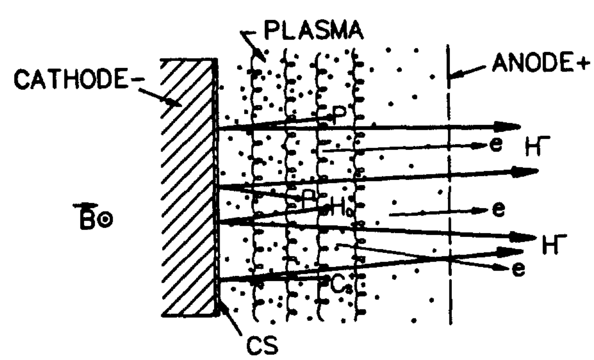


Fig. 1. Surface-plasma production of H⁻ ions.

Volume Sources

In volume sources, H⁻ ion formation relies on the greatly increased cross-section for the dissociative-attachment reaction when molecules are excited to high vibrational states. During collisions with walls or energetic electrons (>5 eV), hydrogen molecules are excited to high vibrational states (v">6). For such molecules the cross-section for the dissociative-attachment reaction, $e + H_2(v") \rightarrow H^- + H$, $e \leq 1$ eV, increases more than five decades for v"=6 and continues to rise for higher states.[22] Although the destruction reactions: neutralization ($H^- + H^+ \rightarrow H + H$), associative detachment ($H^- + H \rightarrow H_2 + e$), etc.; can be serious, the increased production due to high vibrational states can give a significant population of H^- ions in the plasma.

The source therefore takes on the geometry of a two region chamber [22] (Fig. 2). The first region contains a broad range of electrons emitted from hot cathodes or filaments. Here energetic electrons and wall collisions create high molecular vibrational states: $e + H_2(v"=0) \rightarrow e + H_2(v")$, $e > 5$ eV. The second region is separated from the first by a magnetic filter so only low energy electrons (≤ 1 eV) can pass along with molecular hydrogen in various states. In the second region H^- ions are more readily created than destroyed forming a significant fraction of the plasma from which they are extracted. To extract the H^- ions with minimum electrons, a magnetic filter is again used at the extraction region.

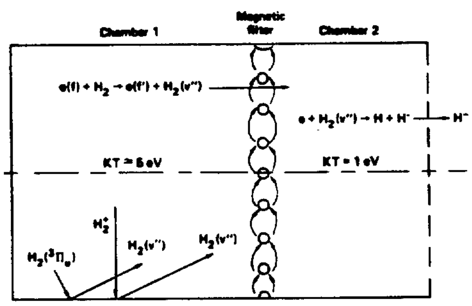


Fig. 2. Volume production of H^- ions.

Surface-Plasma Sources

Three basic geometries of H^- surface-plasma sources have been built for accelerators: magnetron, Penning and multicusp sources. The magnetron tends to be a low-duty-factor source and has been used with several linacs as injectors to synchrotrons. The Penning source can operate at much higher duty, possibly d.c. and tends to produce the brightest beam. It has been used on high duty-factor linacs and for stringent beam requirements. The multicusp source has its best application as a high-current, large-aperture d.c. source useful for neutral beam fusion injectors. It has been used on high duty-factor linacs. A discussion of these sources will show their typical operating characteristics and differences.

Magnetron H^- Source

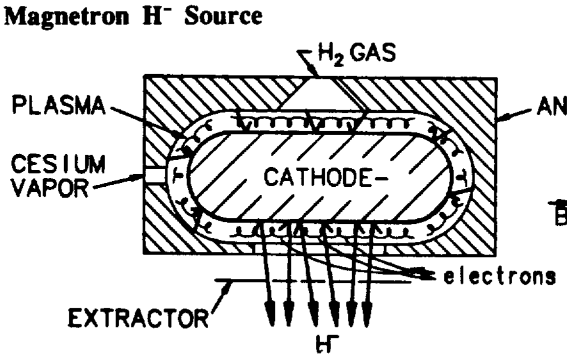


Fig. 3. Basic magnetron source configuration.

The magnetron source (Fig. 3) consists of a central oval cathode, the active surface, surrounded by an anode. A magnetic field passes through the source parallel to the cathode axis, perpendicular to the anode-cathode electrical field. This ExB configuration is highly efficient at confining electrons and producing dense plasmas. Ions and energetic particles from the plasma strike the cathode and reflect or desorb hydrogen atoms producing H^- ions. The H^- ions go through the plasma to the anode gaining energy and where possible pass through the anode aperture to be accelerated through the extractor. In this source the anode-cathode gap is small, typically 1 mm, to avoid significant destruction of the H^- ions while traveling through the plasma. Nevertheless, some ions are lost or charge-exchange with neutral thermal atoms: $H^-(\text{fast}) + H(\text{slow}) \rightarrow H(\text{fast}) + H^-(\text{slow})$. These thermal ions can be extracted to form a beam of greater brightness. In the magnetron, energetic ions are extracted at low pressure (≈400 mTorr) where the source normally operates. At high pressure, low-energy ions dominate, but the gas consumption is large.

Hydrogen gas is introduced in the rear of the source by a closely connected pulsed gas valve. Since these sources are small and operate at low duty factor, the small volume allows the gas to be pulsed into the source to minimize vacuum requirements.[23] Cesium is obtained by heating metallic cesium in an oven at 150-200°C.[23] All parts of the cesium supply system must be maintained above the oven temperature to prevent condensation of the cesium. The vapors enter the source and coat the cathode surface. The cesium usage is <1 mg/hr. In operation the source operates at 350 to 450°C for good surface conditioning and sufficient cesium ions in the plasma. Heating of the source comes from the plasma arc power plus a small external heater if needed.[10] The plasma power, passive cooling and permissible source temperature limit this source to low-duty operation.

To increase the ions passing through the anode aperture, the cathode is curved to give focusing from the cathode to the anode.[24] With slit apertures the curving is a groove on the cathode parallel to the aperture. In the newer magnetrons circular apertures and extraction geometries are used and the cathode is dimpled behind the anode aperture.[11] These changes have reduced the arc current, increased the beam current and improved the beam optics.

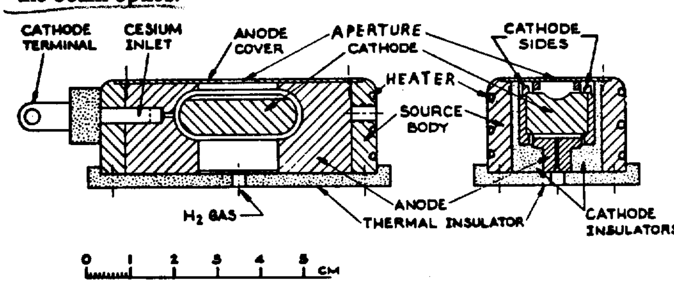


Fig. 4. The Fermilab H^- magnetron source.

Operating magnetron sources produce a beam current of ≥50 mA. In the Fermilab source [9] (Fig. 4) the beam is extracted at an energy of 18 keV from a 1-mm x 10-mm aperture. This large asymmetry creates a stronger space charge force in the narrow or perpendicular direction to the slit than in the parallel direction. To compensate for this difference and obtain a nearly circular beam, a 90°-bending magnet with a radius of 8 cm and a gradient index, $n = -rdB/Bdr \approx 1$, is used after the extractor. This magnet has pole extensions to provide the source field. Following the bending magnet, the beam enters the primary accelerating column and is accelerated to 750 keV (Fig. 5). At 750 keV the normalized emittance for 90% of the beam is $\varepsilon_{n\ \text{horz}\ (90)} = 0.9\ \pi$ mm-mr, $\varepsilon_{n\ \text{vert}\ (90)} = 1.5\ \pi$ mm-mr.

The Brookhaven source operates with a circular extraction geometry sized to produce >50 mA and extracts at 35 keV.[11] There is no bending magnet following the source. This arrangement produces a circular beam with emittance in both planes of $\varepsilon_{n\ (90)} = 1.1\ \pi$ mm-mr. The circular beam is matched to an RFQ by a 2-meter magnetic-focusing line (Fig. 6). The RFQ accelerates the beam to 750 keV.

Accession Number: 4903

Publication Date: Sep 01, 1990

Title: Review of Negative Hydrogen Ion Sources (preprint)

Personal Author: Schmidt, C.W.

Corporate Author Or Publisher: Fermi National Accelerator Laboratory, Batavia, IL 60540

Comments on Document: Preprint of paper presented at the 1990 Linear Accelerator Conference, Albuquerque, NM, Sept. 1990

Descriptors, Keywords: Negative Hydrogen Ion Accelerator Particle Beam Physics

Pages: 00005

Cataloged Date: Feb 22, 1994

Document Type: HC

Number of Copies In Library: 000001

Record ID: 28662

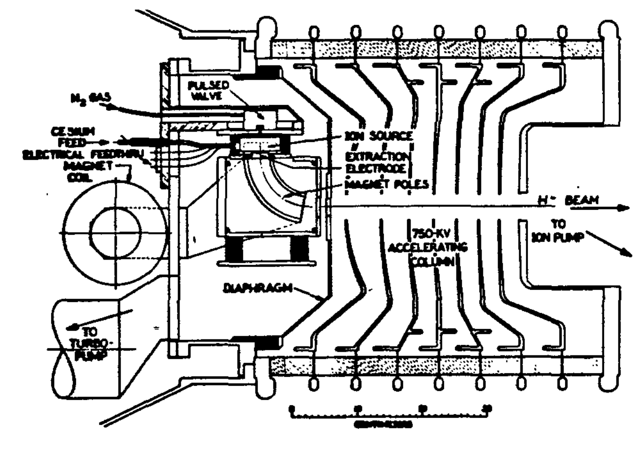


Fig. 5. The Fermilab H⁻ 750-keV preaccelerator.

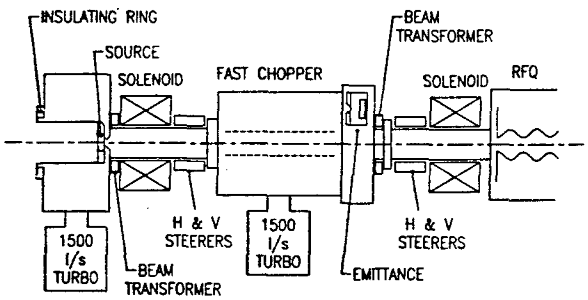


Fig. 6. The Brookhaven H⁻ source and transport line.

The magnetron source has been only used for pulsed operation at low duty factor. At Fermilab the beam-pulse width is up to 66 μs at a repetition rate of 15 Hz.[10] Brookhaven uses a 600-μs beam pulsed at 5 Hz [25] and Argonne operates at 30 Hz with 90-μs pulse width.[12] DESY uses even lower duty for the HERA injector [13] and pulses the source arc between beam pulses to maintain source temperature.

Lifetimes for the source range from four to six months at Fermilab to about one year between changes at Argonne. Failures occur due to erosion of the cathode and the buildup of erosion products in the source. The piezoelectric pulsed gas valve is an occasional cause of early breakdown. Auto fuel injectors have recently been used for gas valves with good success.[26]

The magnetron, originally developed by the Novosibirsk group, is referred to as the planotron source in Soviet literature. A modification has produced the semiplanotron. The semiplanotron [27] (Fig. 7) is similar to the planotron but uses only the front portion where the plasma is produced.

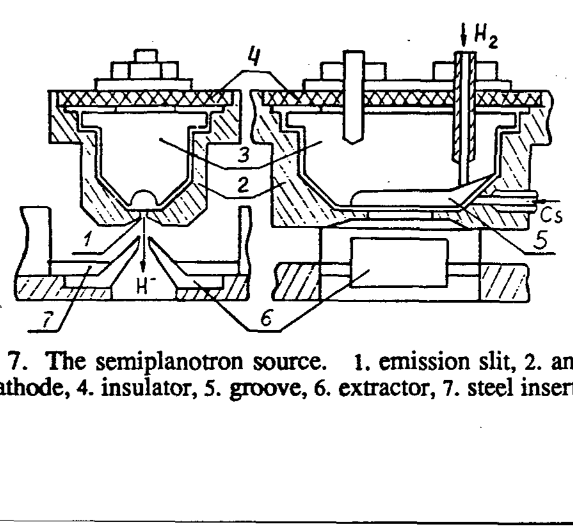


Fig. 7. The semiplanotron source. 1. emission slit, 2. anode, 3. cathode, 4. insulator, 5. groove, 6. extractor, 7. steel inserts.

Penning H⁻ Source

The Penning source geometry (Fig. 8) resembles a right circular cylinder as an anode with isolated caps at each end of the cylinder which are the cathodes. A magnetic field passes through the source parallel to the anode axis. In this arrangement the electric and magnetic fields are parallel. Electrons created in the source oscillate from cathode to cathode, trapped in the magnetic field lines, to produce a dense plasma. Positive ions from the plasma are accelerated into the cathode and, as in the magnetron, produce primary H⁻ ions coming from the cathode surfaces. Cesium is added to the source to lower the surface work-function and increase the H⁻ yield.

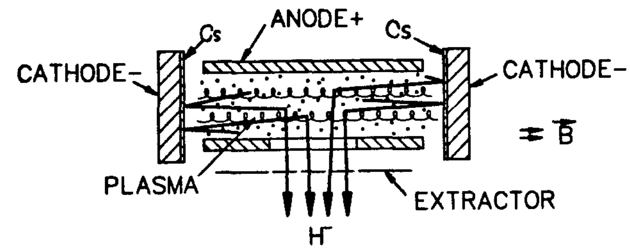


Fig. 8. Basic Penning source geometry.

In the Penning source, ions are extracted from an opening in the anode wall. Because of the aperture orientation it is difficult for the primary H⁻ ions to pass favorably through the opening. To obtain a useful beam, primary H⁻ ions must charge-exchange with thermal hydrogen atoms, H⁻(fast) + H(slow) → H(fast) + H⁻(slow), to form slow H⁻ ions which can migrate to the aperture and be extracted. As in the magnetron, slit apertures of large asymmetry are used for the Penning source and strong-focusing bending magnets are used to handle the beam forces. Circular apertures are also being used with minimum bending to give higher quality beams.[28]

Beam currents of 50 to 100 mA is typical for Penning sources in operation or under study. Since the cathodes are accessible they can be cooled or rotated to produce sources of high duty factor and possibly d.c. operation. Because the ions leaving the source originate from thermal atoms their transverse energy is low and small emittance is typical of the Penning source. The Los Alamos sources [28] (Fig. 9) produce bright beams to 100 mA with a normalized rms emittance at ≈29 keV of $\varepsilon_{n\,(rms)} \approx 0.05\,\pi$ mm-mr, [$\varepsilon_{n\,(90)} \approx 0.23\,\pi$ mm-mr].

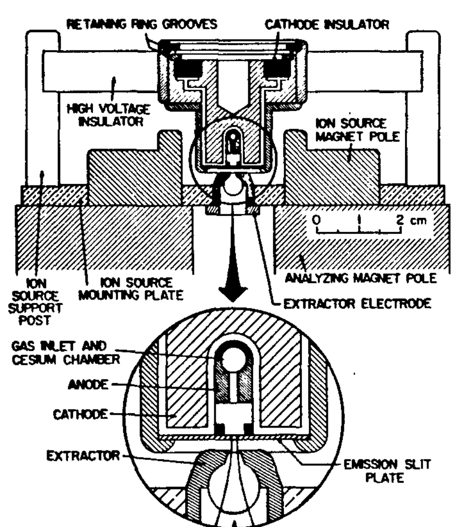


Fig. 9. A Los Alamos H⁻ Penning source.

Multicusp Surface-plasma Source

The multicusp surface-plasma source [16] (Fig. 10) is a large-volume low-pressure source that can operate at high duty factor. The source chamber is typically a cylinder of large diameter (≈20 cm) with alternating polarity magnetic dipoles on the outer surface to produce cusp magnetic fields inside. The chamber, usually the end plates, contain feedthrus for filaments in the source. Near the center of the chamber is the H^- production surface or converter. Opposite the converter surface is an opening in the chamber wall for extracting the H^- ions. In operation the filaments supply electrons to ionize the gas (pressure ≈1 mTorr) and create a plasma. The cusp field minimizes the electron loss to the walls and confines the plasma to the center of the chamber near the converter. Ions created in the plasma strike the converter surface which is biased negative with respect to the plasma. H^- ions formed on the converter surface are accelerated through the plasma region and into the extractor. As in other SPS, cesium is injected into the source to lower the converter surface work-function and increase the H^- yield. Negative ions reaching the extractor leave the source for further acceleration. Most electrons which would accompany the ions through the extractor are repelled by a magnetic filter made of dipole permanent magnets at the extraction aperture.

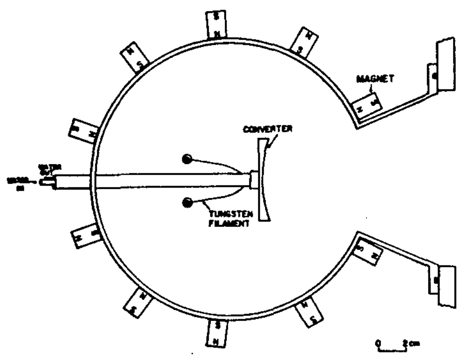


Fig. 10. Basic multicusp surface-plasma source.

Multicusp accelerator sources (Fig. 11) have been built at LAMPF and KEK. LAMPF developed a 20-mA source that is capable of long term operation at 10% duty factor (800-µs pulses at 120 Hz).[17] The normalized emittance for 95% of the beam is $\varepsilon_{n\,(95)} = 0.8\ \pi$ mm-mr, [$\varepsilon_{n\,(90)} \approx 0.6\ \pi$ mm-mr]. At KEK a multicusp source has operated on the 12-GeV synchrotron.[18] The source produced 15-20 mA of H^- beam with pulses of 200 µs at 20 Hz. The normalized emittance after acceleration to 750 keV is $\varepsilon_{n\,(90)} = 1.8 - 2.1\ \pi$ mm-mr. This source used lanthanum hexaboride (LaB_6) cathodes that ran cooler and survived longer than tungsten filaments. As a result the cesium consumption was lower, operation was more stable and lifetime much longer (>2500 hours) than previous sources.

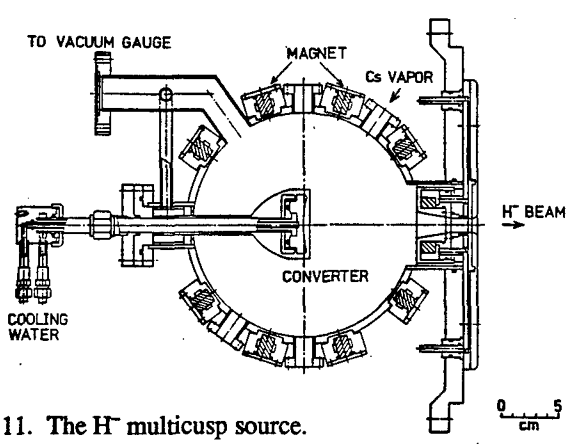


Fig. 11. The H^- multicusp source.

Volume Source

The volume source (Fig. 12) is another "large" source similar to the multicusp. The plasma is usually contained in a cylindrical chamber surrounded with permanent dipole magnets that form cusps and fields to confine the electrons of different energies. The rear or outer regions of the chamber contain filaments biased to create electrons of sufficient energy (E>5 ev) to excite hydrogen molecules to high vibrational states. The second region, separated from the first by a magnetic field, is located near the extraction aperture. This field prevents energetic electrons (E>1 ev) from entering the second region and destroying the H^- ions once produced. In this region the collision of slow electrons with excited hydrogen molecules produces H^- ions. Good operation is very sensitive to the dimensions and conditions in this region. At the extraction aperture another magnetic filter passes the H^- ions and hopefully excludes the electrons.

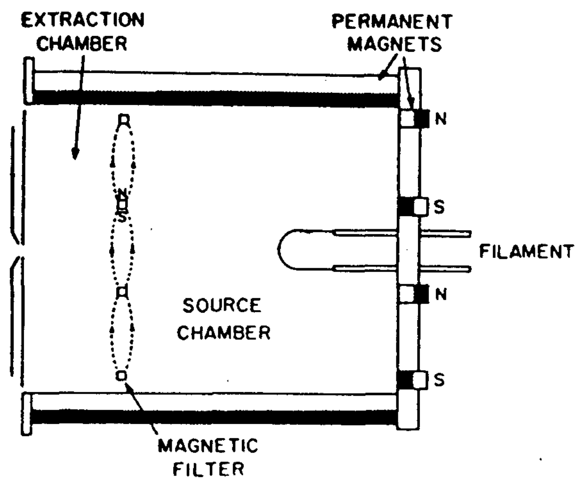


Fig. 12. Basic H^- volume source.

Several volume sources are in use or under study. TRIUMF uses a low-current (≈1 mA) volume source.[29] The normalized emittance is $\varepsilon_{n\,(90)} = 0.15\ \pi$ mm-mr. The source has good electron suppression with e/H^- as low as one.

Brookhaven has achieved 30 mA of H^- with 750 mA of electrons from a 1-cm^2-aperture volume source [30] (Fig. 13). With higher arc current the source pressure increases from 5 to 15 mTorr for optimum output. For a 21-mA beam the normalized emittance at 90% is $\varepsilon_{n\,(90)} \approx 0.94\ \pi$ mm-mr. Considerable work is still being done on the source.

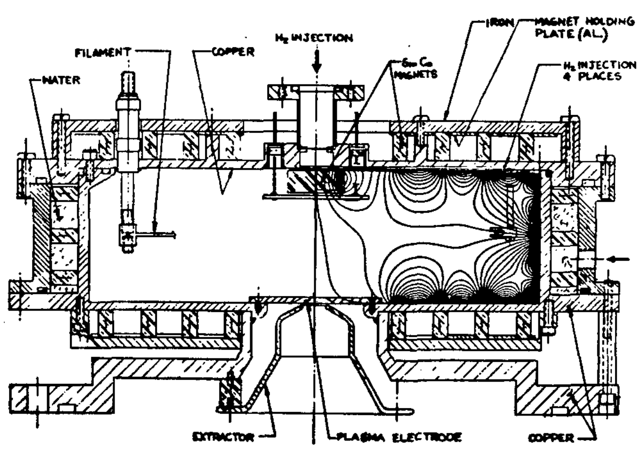


Fig. 13. The Brookhaven H^- volume source.

At Los Alamos, a volume source[20] has produced 10 mA with a normalized rms emittance of $\varepsilon_{n\,(rms)} = 0.08\,\pi$ mm-mr, [$\varepsilon_{n\,(90)} \approx 0.37\,\pi$ mm-mr]. The aperture was 6.3-mm diameter and the source operated at pressures of 2 to 20 mTorr.

At Berkeley, cesium has been added to a volume source with significant improvement.[31] At high currents the H^- output increased fivefold exceeding current densities of 250 mA/cm^2 with reduced e/H^- ratios. At high cesium levels, where extraction breakdowns occurred, the output exceeded 1 A/cm^2. Using an extractor of seven apertures (each 0.7 mm diam inside a 2.26 mm diam circle), 33 mA of H^- was extracted with an e/H^- of 20. At present the tungsten filaments limit the source lifetime. LaB_6 filaments should be a great improvement. To remove the filaments and improve the lifetime, the Berkeley group has been developing an rf driven volume source.[32]

Summary

H^- ion sources are still very new and there is much research and improvement to be done in this area. Each application has a unique set of requirements for the source and among the existing sources a great many applications can be met. Typically the accelerator usage has stressed duty factor, reliability, lifetime, gas consumption, intensity and emittance. Most modern sources have the intensity for linear accelerators (20 to 100 mA). For emittance or brightness the Penning or possibly the volume source is best with the magnetron being acceptable for general uses. The magnetron is presently good only for low duty-factor operation (<0.3%) in contrast to the other sources which have high duty factor capability and may achieve continuous operation. Lifetime is often dependent on the duty factor of the source and for low-duty usage the lifetime can be many months to a year as witnessed by operating magnetrons. The multicusp SPS has achieved many thousand hours running at high duty-factor operation using LaB_6 cathodes. The Penning source does operate many days at high duty factor and may do better with cathode improvements. Presently the largest operational experience has been with the magnetron and its reliability is very good. The multicusp SPS has also shown reliable operation. The other sources have not had the same operational experience.

For small sources the gas consumption depends on the operation. At low duty-factor operation the gas can be pulsed into the source so the consumption per a pulse is simply the volume times the pressure. Fortunately in these sources the volume is small since the pressure is relatively high (<2 cc, >100 mTorr). For larger and high duty factor or d.c. operation the pressure and anode aperture determine the gas flow. For the multicusp SPS and the volume source the aperture is large but the pressure is low ($\approx$1 cm^2, 0.1-10 mTorr).

Cesium usage is typically about one milligram per hour or less for the cesium sources. Even though these sources may exist just before high voltage-gradient devices, additional sparking has not been a problem. In some cases refrigerated surfaces have been used before the accelerator while in others there has been little more than a meter or less transport line to minimize cesium contamination.

Many ideas look good and work fine on the test bench even under simulated operational conditions but the real operational proof for lifetime, reliability and other qualities can be determined only under running conditions. In operation, the daily fine adjustments done on a test bench are often not possible, and less then experienced operators must be able to keep it running. This is the real test of an ion source. Of course, the reliability of a source is not just the device from which the ions emerge. There are many support devices - vacuum, gas, cesium and cooling systems, power supplies, monitoring, controls, etc.- all which must operate reliably in the source environment.

References

In addition to the references cited, the Proceedings of the International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams contain much detailed information on H^- ion sources. Five symposia have been held at Brookhaven. These Proceedings are published as:
First Symposium (1977) BNL 50727,
Second Symposium (1980) BNL 51304,
Third Symposium (1983) AIP Conf. Proc. 111,
Fourth Symposium (1986) AIP Conf. Proc. 158,
Fifth Symposium (1989) AIP Conf. Proc. 210, in print.
Likewise the book by A. T. Forrester, *Large Ion Beams,* (Wiley-Interscience, New York, 1988) has an excellent chapter on H^- sources.

1. R. P. Bastide, N. B. Brooks, A. B. Wittkower, P. H. Rose, K.H. Purser, IEEE Trans. Nuc. Sci. NS-12 V.3 (1965) 775.
2. Luis W. Alvarez, Rev. Sci. Inst. 22 (1951) 705.
3. K. W. Ehlers, Nuc. Inst. Meth. 32 (1965) 309.
4. C. W. Potts, IEEE Trans. Nuc. Sci. NS-24 (1977) 1385.
5. John A. Fasolo, IEEE Trans. Nuc. Sci. NS-24 (1977) 1597.
6. Yu. I. Belchenko, G. I. Dimov, V. G. Dudnikov, Proc. 2nd Sym. on Ion Sources and Formation of Ion Beams, Berkeley, LBL-3399 (1974) VIII-1.
7. K. Prelec, Th. Sluyters, M. Grossman, IEEE Trans. Nuc. Sci. NS-24 (1977) 1521.
8. Paul W. Allison, IEEE Trans. Nuc. Sci. NS-24 (1977) 1594.
9. Charles W. Schmidt, Cyril D. Curtis, IEEE Trans. Nuc. Sci. NS-26 (1979) 4120.
10. C. W. Schmidt, C. D. Curtis, AIP Conf. Proc. 158 p. 425.
11. James G. Alessi, AIP Conf. Proc. 158 p. 419.
12. V. Stipp, A. DeWitt, J. Madsen, IEEE Trans. Nucl. Sci. NS-30 (1983) 2743.
13. H. S. Zhang, G.-G. Winter, H. Krause, N. Shirm, I. Tessmann, DESY HERA 87-04, February, 1987.
14. Paul Allison, Joseph D. Sherman, AIP Conf. Proc. 111 p. 511.
15. P. E. Gear, R. Sidlow, Proc. 2nd Int. Conf. Low-Energy Ion Beams, Bath 1980: Inst. Phys. Conf. 54 (1980) 284.
16. K. N. Leung, K. W. Ehlers, Rev. Sci. Instr. 53(6), (1982) 30.
17. Ralph R. Stevens,Jr., Rob L. York, John McConnell, Robert Kandarian, 1984 Linear Accel. Conf., Seeheim, Germany, GSI-84-11, (1984) 226.
18. Y. Mori, A. Takagi, K. Ikegami, S. Fukumoto, AIP Conf. Proc. 158 p. 378.
19. M. Bacal, E. Nicolopoulou, H. J. Doucet, BNL 50727 p.26.
20. Ralph R. Stevens,Jr., R. L. York, K. N. Leung, K. W. Ehlers, AIP Conf. Proc. 158 p. 271.
21. K. Prelec, IEEE Particle Accelerator Conference, 89CH2669-0, Chicago, (1989), 340.
22. J. R. Hiskes, AIP Conf. Proc. 158 p. 2.
23. C. W. Schmidt, C. D. Curtis, BNL 50727, p. 123.
24. J. G. Alessi, Th. Sluyters, Rev. Sci. Instr. 51(12), (1980) 1630.
25. Richard L. Witkover, AIP Conf. Proc. 111 p. 398.
26. J. G. Alessi, J. M. Brennan, A. Kponou, Rev. Sci. Instr. 61(1), (1990) 625.
27. Yu. I. Belchenko, V. I. Davydenko, G. E. Derevyankin, G. I. Dimov, V. G. Dudnikov, I. I. Morosov, G.V. Roslyakov, A. L. Schabalin, Rev. Sci. Instr. 61(1), (1990) 378.
28. H. Vernon Smith,Jr., Joseph D. Sherman, Paul Allison, 1988 Linear Accel. Conf., Newport News, Va., CEBAF-Report-89-001, (June, 1989) 164.
29. D. H. Yuan, R. Baartman, K. R. Kendall, M. McDonald, D. R. Mosscrop, P. W. Schmor, AIP Conf. Proc. 158 p. 346.
30. K. Prelec, J. G. Alessi, Rev. Sci. Instr. 61(1), (1990) 415.
31. K. N. Leung, C. A. Hauck, W. B. Kunkel, S. R. Walther, Rev. Sci. Instr. 60(4), (1989) 531.
32. K. Leung, LBL, Private communication. Soon to be published.

COMPONENTS FOR CW RFQ'S*

T. Tran-Ngoc, G.E. McMichael, G.M. Arbique and F.P. Adams
AECL Research, Chalk River Laboratories
Chalk River, Ontario, Canada, K0J 1J0

Abstract

Many components have been designed and tested in cw operation using the RFQ1 accelerator structure as a test bed. Improved VCR's (vane-coupling-rings) have been in service for over a year with no sign of deterioration. Dynamic tuners were developed and performed flawlessly at cw power levels approaching 8 W/cm^2. Recently, the design of the drive loop has been modified after some problems were encountered in operation. Calculation of the field enhancement at the end of the vane showed that the racetrack-shaped gasket, which makes the rf and vacuum joint between the tank and the vane, withstands a factor of 5 higher power density than expected.

Introduction

The RFQ1, a 75 mA cw proton accelerator, has been used as a test bed for developments aimed at building a firm technological base for the design of cw RFQ's. Components such as rf drive loops, slug tuners, vane-coupling-rings (VCR's), rf and vacuum joints have been designed, tested and improved.[1] The design features of these components, their recent performance in testing and operation, and design improvements, will be discussed in this paper.

RF Drive Loop

The drive loop, shown in Fig. 1, is mounted in one of the four centre ports of the RFQ. The inner and outer conductors of the drive loop are water cooled. The vacuum window is an air-cooled ceramic (99.9% alumina) cylinder. Mechanical clamps engage split rings seated in grooves near the ends of the ceramic cylinder to compress O-rings and make the vacuum seals. This type of removable joint permits easy disassembly of the loop for inspection or servicing.

The loop conductor is cooled by the main assembly cooling circuit. The loop body, sized to compensate for the open volume of the port, maintains the correct rf field balance and frequency for the tank.[2]

The original loop design operated without any major problems for about 2 years at cw power levels up to 175 kW. However, after a 2-month shutdown, attempts to recondition the RFQ were unsuccessful and excessive arcing was observed in the drive loop. Upon disassembly of the loop, the section of the ceramic cylinder facing the tapered portion of the inner conductor was found to be heavily coated with copper (about 0.03 mm thick) which had sputtered from the neighbouring copper surfaces on the inner and outer conductors. The loop was refurbished by grinding and cleaning the inside of the ceramic cylinder and smoothing the eroded copper surfaces.

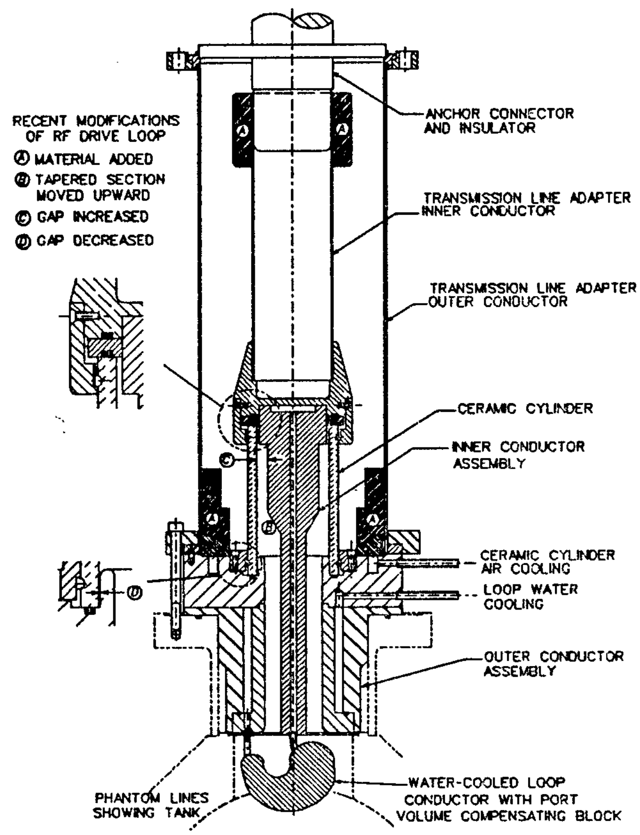
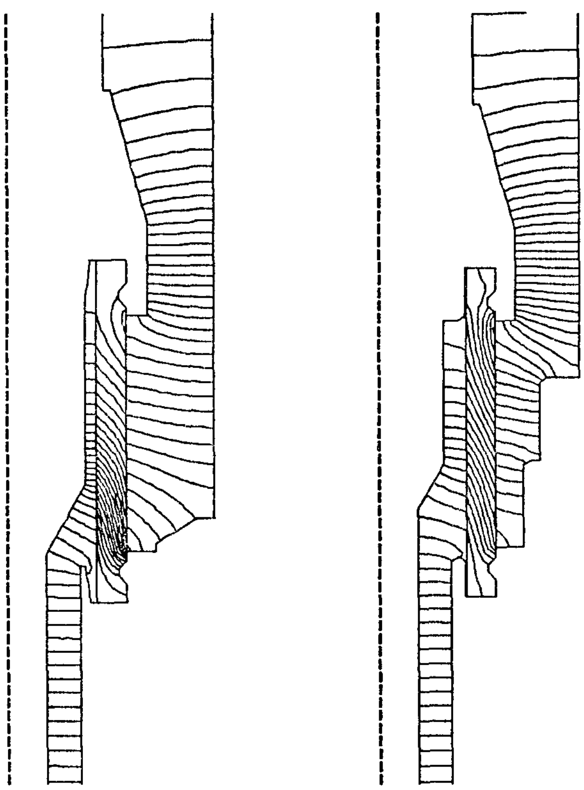


Fig. 1. RFQ1 drive loop

When the loop was re-installed, only a few tens of watts could be delivered to the RFQ. Much higher power could be delivered without vacuum in the RFQ, indicating that multipactoring was the likely cause of the problem. The ceramic cylinder was coated with chromic-oxide to reduce secondary electron emission, but no improvement was observed. The ends of the RFQ were then opened for a thorough cleaning of the interior surfaces in the region of the end tuners and VCR's. It was then possible to break through the multipactoring levels, and a tank power of about 100 kW (80% of normal operating level) was reached before a large vacuum leak developed in the loop after more arcing. The ceramic had fractured, presumably due to thermal shock in the region where copper had again sputtered on the inner surface. The geometry of the loop conductors in this region was then modified in an attempt to decrease the field intensity. This changed the pattern of copper plating and erosion, but did not prevent the arcing or eventual destruction of the ceramic.

*This work was partially supported by Los Alamos National Laboratory under contract No. 9-X5D-7842D-1.

Most recently, the loop was modeled using the new code SEAFISH, a SUPERFISH-like code able to compute complex-valued travelling-wave rf field distributions and VSWR's.[3] The calculations showed an electric field concentration at the end of the ceramic cylinder where fracturing occurred (see Fig. 2a). They also indicated that the modifications highlighted in Fig. 1 would improve the design by: (i) giving a more uniform rf field distribution through the ceramic (see Fig. 2b), which would reduce the field stress by a factor of 2; (ii) improving the match of the loop (from a VSWR of 1.66 to 1.07) ; and (iii) eliminating standing waves between the ceramic and the loop termination. A loop with these modifications is presently being tested on RFQ1.



(a) (b)

Fig. 2. Rf field distribution in the gap between inner and outer conductors and through the wall of the ceramic window a) before modification b) after modification

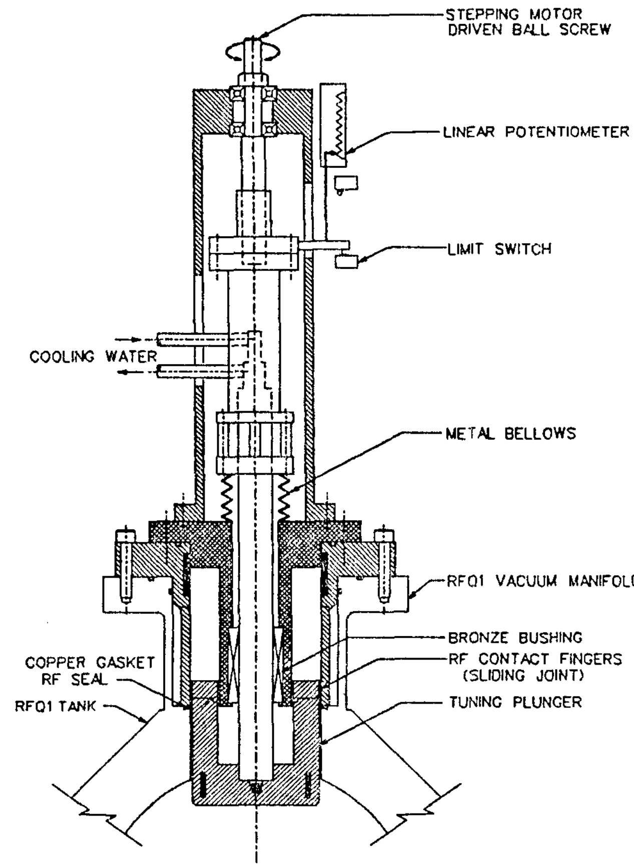


Fig. 3. RFQ1 dynamic tuner

Dynamic Tuners

One static plug-tuner is mounted in the RFQ1 centre-port directly opposite to the rf drive loop and 2 motor-driven plug-tuners (see Fig. 3) are installed in the adjacent ports. The tuning plunger diameter and the plunger-to-tank gap are 96.4 mm and 1.0 mm, respectively. The design mechanical stroke and speed of the dynamic tuners are $\pm$ 20 mm and 2.5 mm/s, respectively.

Figure "H" contact fingers are used at the plunger sliding joint. The fingers are cooled by direct conduction to the outer cylinder and plunger. Water channels in the outer cylinder and a coaxial flow circuit in the centre shaft of the tuner provide good cooling of all parts exposed to significant rf heating. A bronze bushing, located close to the front end of the tuner, keeps the various moving parts concentric and assures uniform compression of the sliding contact fingers. The surfaces that they contact are made of solid OFHC copper to provide good electrical conductivity. Stainless steel walls on the cavity behind the contacts attenuate any rf field that may leak past the joint. A metal bellows, remote from rf fields, forms the flexible vacuum barrier.

Positioning of the tuning plunger is by a ball nut and screw, directly driven by a stepping motor. A motion control indexer-module, a linear-potentiometer, limit-switches and a fail-safe brake are the critical components of the position control system.

During commissioning, insertions to 9.6 mm and retractions to 7.6 mm, from a position flush with the tank wall, were tested. Moved in tandem, the 2 tuners changed the tank frequency by 625 kHz. Moved in opposition (one inserted, the other retracted) a dipole field of up to 10% was introduced. The tuners performed flawlessly up to cw power levels approaching 8 W/cm^2 (1.6 Kilpatrick vane tip fields). The tuner moved smoothly under high power, with no indication of sparking. Visual inspection of disassembled components after the tests revealed no sign of damage.

VCR's

A pair of VCR's are used at each end of the RFQ1 vanes to suppress dipole components in the RFQ field.[1] These are made of 6.3 mm OFHC copper tubes, which are water cooled by bypassing the flow from cooling channels on the connected vanes. The water-to-vacuum joints are soft-soldered to allow easy removal, and we had problems with the solder melting during the first year of operation. Since then, the VCR design has been improved by: (i) increasing the joint diameter to decrease the current density; (ii) using a tin-silver solder (Mattisol-E) instead of the lower-temperature, 50/50 tin-lead solder; (iii) copper-plating the soldered joints (using a brush-plating technique) to lower surface resistance; and (iv) increasing the VCR to end-tuner-post gap to decrease the current due to the capacitance coupling. The improved VCR joints have been in service for over a year with no sign of deterioration.

RFQ1 "Racetrack" Seals

Racetrack-shaped gaskets, made from 1.5 mm thick OFHC copper, are compressed against sealing edges at the bottom of the vanes and on the tank, to make rf and vacuum joints.[4] They are cooled by conduction to cooling channels in the vanes, tank and clamps. Overheating of the gasket at the end of the vane is still a factor limiting the cw operating power on RFQ1. Recent MAFIA calculations have confirmed that overheating is due to field enhancement in the vane-end region, which was not accounted for in the original cooling design of the tank and vanes. The predicted power density at the bottom-end corner of the vane and on adjacent surfaces of the copper gasket is a factor of 5 higher than anticipated in the original design. The racetrack-shaped gaskets have thus proven they are able to withstand much higher temperatures and thermal gradients than expected.

Since replacement of the vane seals in early 1989, there has been only a minor vacuum leak at the high-energy end of one of the vanes. Torquing the three bolts nearest the end of the vane an additional 5% cured the leak and there have been no reoccurrences in the past year.

Discussion And Conclusions

RFQ1 has proven to be a valuable test bed for high-power cw RFQ components. Detailed designs for dynamic tuners, rf drive loops, VCR's and racetrack-shaped copper seals have been developed, tested and improved for cw operation up to 150 kW, 10% above design power. Although recent problems with the operation of the drive loop have interrupted operation of the facility, we are gaining a better understanding of this critical component and are establishing the utility of the SEAFISH code for rf component design and analysis.

Acknowledgments

Special acknowledgment to R.M. Hutcheon, J.C. Brown and J.Y. Sheikh for their support in rf design, to M.S. de Jong for his support in rf computer simulation, to E.C. Douglas for his assistance in mechanical design, to L.F. Birney, A.D. Davidson and B.H. Smith, who assembled, tested, and maintain the facility, and to the staff in the Accelerator Physics machine shop who built, repaired and modified the components.

References

1) G.E. McMichael, G.M. Arbique, J.C. Brown, B.G. Chidley, R.M. Hutcheon, M.S. de Jong and J.Y. Sheikh, "Exploring the Beam Parameter Space of a CW RFQ Proton Accelerator", Proc. 1989 IEEE Part. Acc. Conf., 2, 980, 1989.

2) B.G. Chidley, G.M. Arbique, R.M. Hutcheon, G.E. McMicheal and J.Y. Sheikh, "RF Tuning and Initial CW Operation of RFQ1", European Particle Accelerator Conference, Rome, Italy, June 1988.

3) M.S. de Jong, private communication.

4) G.E. McMichael, B.G. Chidley, R.M. Hutcheon and T. Tran-Ngoc, "RFQ1 Fabrication and Low Power RF Tuning", Proc. 1987 IEEE Part. Acc. Conf., 3, 1875 (1987).

HIGH POWER RF AMPLIFIERS FOR ACCELERATOR APPLICATIONS: THE LARGE ORBIT GYROTRON AND THE HIGH CURRENT, SPACE CHARGE ENHANCED RELATIVISTIC KLYSTRON

R. M. Stringfield, M. V. Fazio, D. G. Rickel, T. J. T. Kwan, A. L. Peratt, J. Kinross-Wright, F. W. Van Haaften, R. F. Hoeberling, R. Faehl, B. Carlsten, W. W. Destler*, and L. B. Warner
Los Alamos National Laboratory,
Accelerator Technology Division,
MS H851, Los Alamos, New Mexico, 87545

ABSTRACT

Los Alamos is investigating a number of high power microwave (HPM) sources for their potential to power advanced accelerators. Included in this investigation are the large orbit gyrotron amplifier and oscillator (LOG) and the relativistic klystron amplifier (RKA). LOG amplifier development is newly underway. Electron beam power levels of 3 GW, 70 ns duration, are planned, with anticipated conversion efficiencies into RF on the order of 20 percent. Ongoing investigations on this device include experimental improvement of the electron beam optics (to allow injection of a suitable fraction of the electron beam born in the gun into the amplifier structure), and computational studies of resonator design and RF extraction. Recent RKA studies have operated at electron beam powers into the device of 1.35 GW in microsecond duration pulses. The device has yielded modulated electron beam power approaching 300 MW using 3-5 kW of RF input drive. RF powers extracted into waveguide have been up to 70 MW, suggesting that more power is available from the device than we have converted to-date in the extractor. We have examined several aspects of operation, including beam bunching phenomena and RF power extraction techniques. In addition, investigations of the amplifier gain as a function of input drive, electron beam parameters (energy, current, and position in the device) and axial magnetic field strength also have been explored. The effect of ions formed during device operation also has been considered.

Introduction

Los Alamos has been investigating novel high power RF sources for the past eight years. Included in this research have been various vircator designs, magnetron-like designs (including the large orbit gyrotron (LOG), and the magnetically insulated line oscillator), and most recently, the relativistic klystron amplifier (RKA). Of these, the large orbit gyrotron, operated as an amplifier, and the RKA appear to us to offer the most promise as RF drivers for future improvements in particle accelerator design.

The Large Orbit Gyrotron

During the past three years we have investigated the large orbit gyrotron experimentally as an oscillator operated at a frequency of 2 GHz[1,2]. These results have encouraged us to begin, during the ongoing year, the initial work we hope will lead to an amplifier based upon the LOG's basic operating principles. The LOG amplifier is attractive for linear collider applications, since it requires relatively modest applied magnetic field requirements, only a few hundred gauss, since it operates at a harmonic of the cyclotron frequency. It can operate at frequencies of 15 GHz or more with these small magnetic fields. RF breakdown problems should be relatively small, as well, since the electrons move to smaller orbits, away from the walls of the device, as they convert their energy into microwaves. Hence electron bombardment of the walls, which can lead to breakdown, is relatively modest.

The oscillator we recently investigated is depicted in Figure 1. The device is powered by a

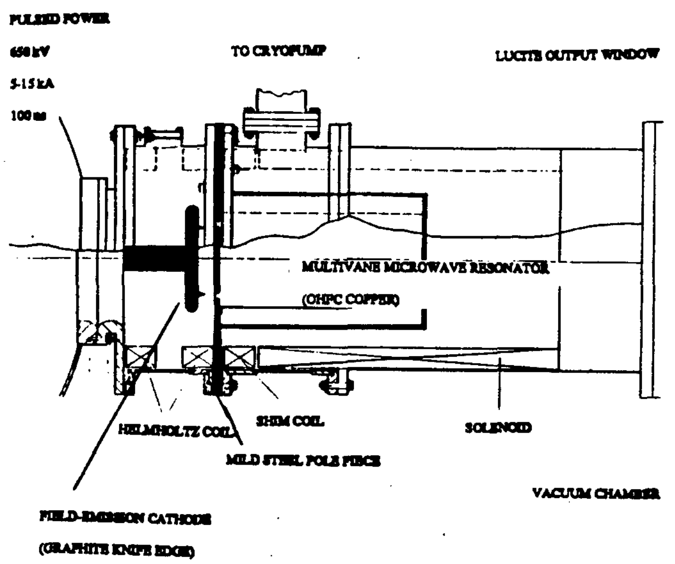


Figure 1. Cutaway drawing of the LOG oscillator experiment.

Marx-Blumlein pulser operated at 650-700 kV, 6 kA, for pulse lengths of 70 ns FWHM duration. RF power was radiated out of the device axially into a chamber lined with microwave absorber. RF radiated into the chamber was monitored with waveguide receivers, either standard gain horns or waveguide stubs. The signals were then coupled to coaxial cable and RF power was measured with crystal detectors. Heterodyning circuits monitored the frequency.

The device operates as follows. A 12.5 cm diameter annular electron beam is formed in an axial magnetic field having a magnitude of 500-800 gauss. An annular aperture at the anode plane is situated in a cusp-shaped magnetic field formed by opposing magnetic fields. The fields are formed by two oppositely wound coils which surround the diode and the RF resonator region downstream of the anode. The cusp shape is enhanced by a 2 cm mild steel plate at the anode, which concentrates the region of magnetic field transition between regions of axial and radial field direction such that the cusp is predominantly within the thickness of the steel. The beam enters the cusp after it has been accelerated in the diode. There the beam acquires a rotational velocity component which is axis encircling, while still retaining a component of axial velocity. Thus the beam spirals in the resonator downstream, with a pitch angle given by the ratio of rotational velocity to the axial velocity. For a sufficiently large magnetic field, all of the axial velocity acquired in the diode can be converted into rotational motion, and the beam will not propagate downstream, but instead, reflect back into the diode. For these experiments, this ratio of rotational velocity to axial velocity, designated α, had a value in the range of 1.5 to 1.7.

Azimuthal bunching of the electron beam occurs through the negative mass instability. A periodically varying boundary along the circumference of the resonator serves to bunch the beam with a periodicity such that it interacts with the resonator, converting beam energy to RF standing wave energy in the cavity.

A representative RF output pulse from the device operating at 2 GHz is shown in Figure 2. A spatial map of power radiated from the device into the absorber-lined chamber is shown in Figure 3. Of the total electron beam power available, 500 MW injected into the resonator. The total power radiated from the device, within the solid angle monitored by this measurement, was 35 MW. This result corresponds to a conversion efficiency from electron beam power to microwave power of 7 percent. Only a portion of the total power radiated by the device was measured by this spatial scan, since the power was not zero in the wings of the measurement, far off axis. We were prevented from moving the receiving antenna to larger radial positions by physical barriers in the chamber. Hence the true efficiency in this experiment may be larger than that cited here. Further efficiency improvement may be achieved by increasing the ratio of rotational electron beam energy to axial beam energy in the resonator region. For this experiment, the ratio was 2-3. Values for this ratio as high as 6-8 should be achievable, providing more available rotational beam energy from which to extract. Measuring all of the currently generated RF, combined with increases in the fraction of rotational beam energy, should increase the efficiency to as much as 20 percent.

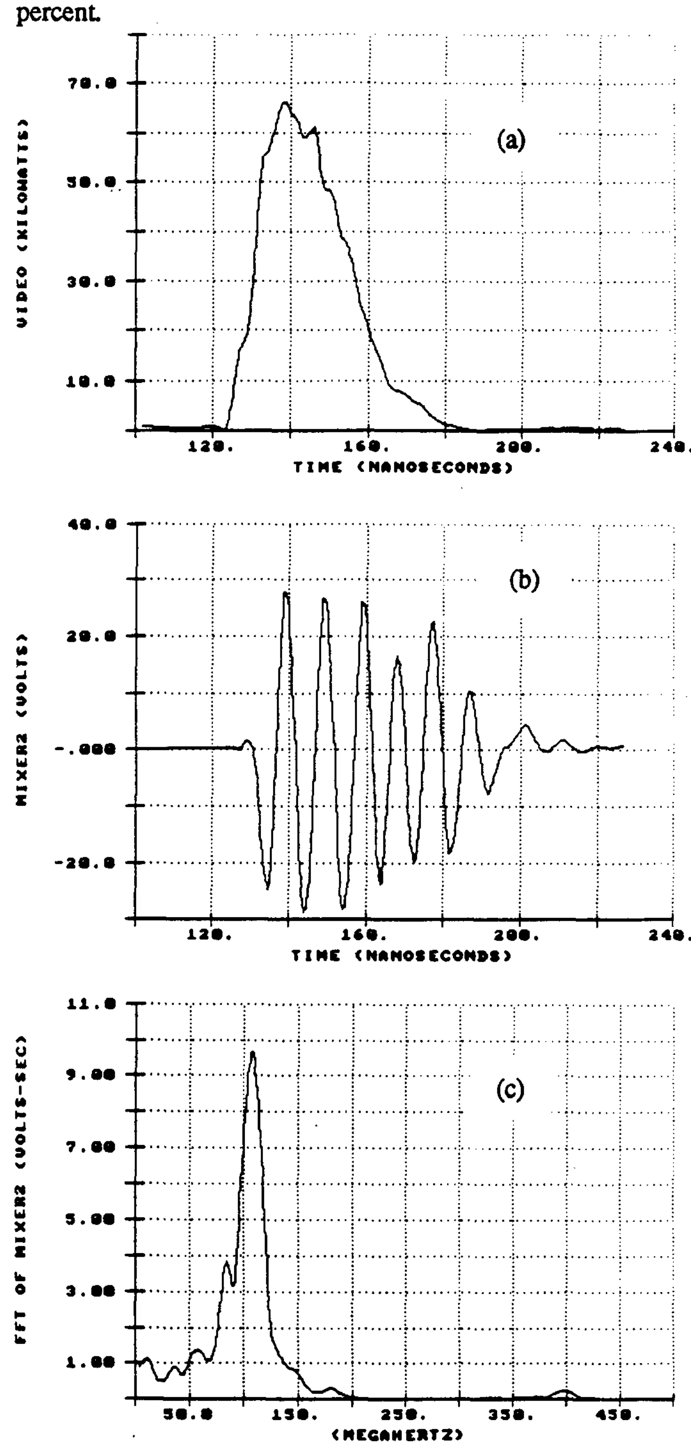


Figure 2. Sample RF data for the LOG oscillator, shot 2136. a) is a detected signal received over an effective area of 65 cm^2. b) is the frequency downconverted RF signal with a 1.90 GHz local oscillator frequency. c) is the fast Fourier transform of the downconverted signal.

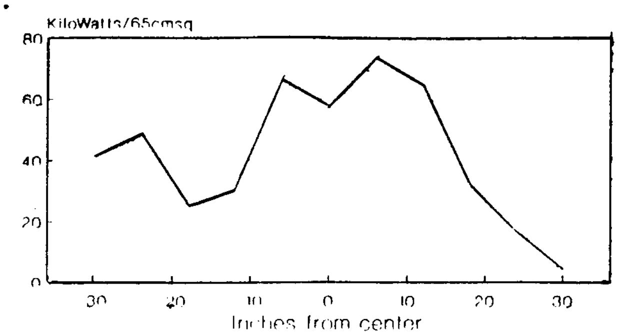


Figure 3. Radial position scan of the power received by a waveguide stub antenna. The asymmetry is caused by the resonator having a three vane azimuthal periodicity. The left half of the pattern is azimuthally aligned with a resonator vane, the right side is aligned with the position of the smooth wall connecting adjacent resonator vanes.

Our initial step in developing an amplifier has been to examine methods of increasing the current fraction injected into the resonator from the diode, and to properly position the higher current in the interaction space. Computational modelling has been performed with the particle-in-cell code ISIS. Modelling has indicated that increasing the fraction of diode current injected into the resonator as a rotating beam and establishing a final rotating beam diameter of 12.5 cm can be achieved by launching the beam from a 2 mm thick annular cathode having a diameter of 14 cm. Care must be taken to launch the beam such that radial oscillations (zeroth harmonic cyclotron frequency) in the beam motion as it travels down the resonator are not generated. Such a condition was found computationally to be achieved by placing the emission annulus on a conical equipotential surface, having an angle of 22.5^{o} with respect to the direction normal to the axis of symmetry. Experiments are now underway to test these computational predictions. The control of the beam trajectory as a function of cathode equipotential angle, electron energy, and ratio of rotational velocity to axial velocity are among the beam injection parameters being examined.

We are computationally investigating approaches to the design of the LOG amplifier. One approach, a two stage device, is shown in Figure 4. The device consists of a preliminary RF input stage which initiates electron beam bunching, and a final RF output stage in which the fully bunched electron beam generates a strong RF standing wave in an output resonant cavity. These stages constitute discrete, separate entities, separated by a beam transport section in which the bunching of the rotating electron beam develops to a maximum prior to entering the RF output section. The two stage design offers the flexibility to separately optimize the RF input and output sections of the device.

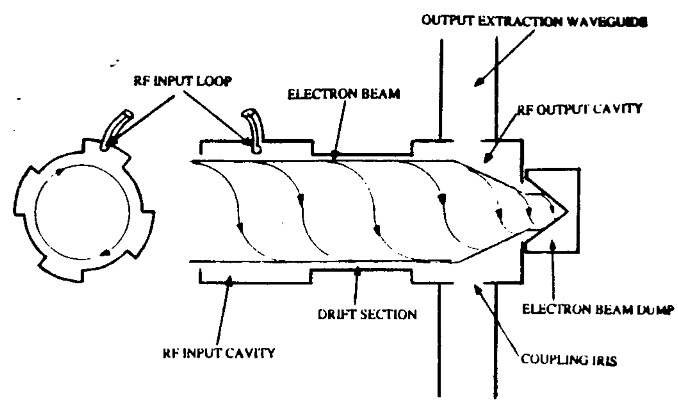


Figure 4. Conceptual arrangement of a LOG amplifier configuration.

In one configuration under consideration, the first stage consists of an azimuthally periodic wall boundary in a resonant cavity with cylindrical symmetry. RF is injected by a loop or iris coupler into this structure. The standing wave energy stored in this cavity velocity modulates the rotating electron beam. The RF is contained in this structure by designing the cavity to be beyond cutoff for axial RF propagation. The beam, now with an azimuthal velocity modulation, is transported by the axial magnetic field through a smooth, cylindrical section where azimuthal spatial bunching of the beam develops due to the velocity modulation. Adjustment of the length of this drift section will optimize the degree of spatial bunching achieved at the end of the transport. Downstream of the transport section the beam enters a second periodic wall structure which converts the rotating, spatially bunched, beam energy into RF standing wave energy. This energy is then coupled into waveguide through either an axial or side extraction coupler. A mode converter would pipe the output RF into an array of rectangular waveguides. Evaluation of amplifier approaches is ongoing, with initial hardware designs expected to be completed in the summer, 1991.

The Relativistic Klystron Amplifier

One of the most promising concepts that we have begun to investigate experimentally at Los Alamos is the high current relativistic klystron amplifier (RKA) pioneered by M. Friedman and co-workers at the Naval Research Laboratory[3]. This RKA, as tested by Friedman, has produced several gigawatts of power with 40% efficiency at 1.3 GHz in a 100 ns long pulse on a single shot basis. Peak electron beam currents of 13 kA at 1.3 GHz have been produced. We have identified the high current relativistic klystron as a very promising source that has exhibited very good performance in a very limited parameter space. We currently are engaged in a modest effort to extend the performance envelope of this device from a 100 ns to a 1 µs pulse length, and eventually to repetitively pulsed operation at these very high power levels. The attraction of this device for accelerator applications, aside from amplifier operation, is its demonstrated high efficiency of 40%, even without energy recovery schemes being applied.

The present work has progressed well and the relativistic klystron amplifier shown in Figure 5 is being tested.

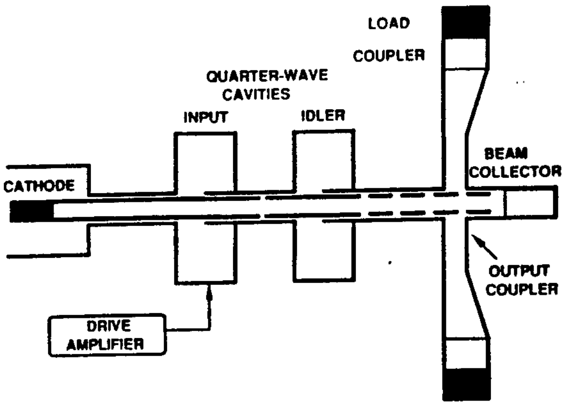


Figure 5. Los Alamos relativistic amplifier.

This device consists of a field emission diode producing a hollow beam that passes through the coaxial quarter-wave input cavity and idler cavity, and on to the rectangular waveguide output coupler. For RF beam modulation measurements the output coupler is replaced on the beam line with a beam pipe containing a linear array of B-dot loops. So far we have produced a modulated electron beam for one microsecond with a voltage of 350 kV, and a peak RF current of 0.9 kA after the second cavity. In some cases we have observed beam modulation in excess of 2 microseconds. The dc beam current is about 3 kA giving approximately a 30% beam modulation. The component of beam power at the microwave drive frequency (1.3 GHz) is approximately 350 MW. The RF drive level is 5 kW which will result in a gain of 42 dB if one can extract this power with an efficiency of 25% (a conservative estimate). Efforts to extract this power into the waveguide coupler are underway.

Figure 6 shows the frequency down-converted mixer (IF) signal from a calibrated B-dot probe located on the beam pipe after the second cavity. This signal indicates the RF current modulation on the beam which lasts for 900 ns.

The performance of the RKA can be enhanced significantly with several experimental modifications. More input RF drive power should result in greater output power. The diode must be adjusted for optimal beam diameter and more efficient current injection into the device. Very careful design is needed for a one microsecond device because a number of phenomena that can be ignored on a 100 ns-time-

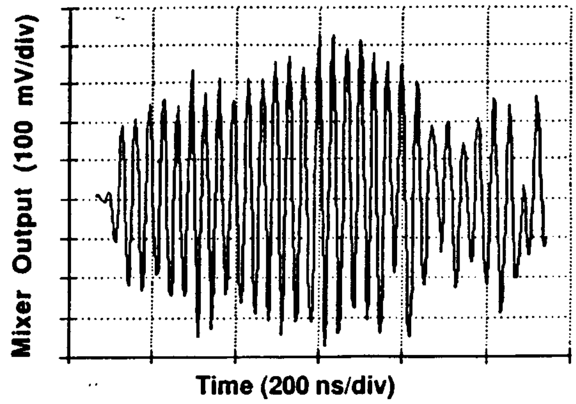


Figure 6. Frequency downconverted (IF) mixer signal from B-dot probe located downstream of RKA idler cavity showing RF current modulation on the electron beam.

scale cannot be ignored when the longer, microsecond timescale is required. For example, the formation of a plasma can have a deleterious effect on beam quality and the production of microwave energy. The electron beam, striking a surface inside the device can create a plasma which can migrate several cm per μs to interfere with the electron beam dynamics and microwave production. Therefore carefully controlling the beam quality is essential for successful operation of the RKA. A relatively thin annular beam is needed, streaming at a controllable radius in the beam pipe, with minimal oscillation in the radial dimension. Because the axial electric fields in the cavity gaps are highest at the radius corresponding to the beam pipe wall, the highest gain is obtained with the beam operating as close to the wall as possible, consistent with the constraint that the beam current density be large enough to approach the space charge limit. The downside of operating the beam close to the wall is that a few stray electrons can strike surfaces creating plasma and inducing high voltage breakdown. Part of the effort will involve determining the tradeoff between radius, gain, and the pulse stability on the microsecond time scale.

Pulsed Power

The availability of the BANSHEE pulsed power modulator currently driving the RKA makes possible high power microwave source development in a relatively unexplored pulse length regime. BANSHEE, which is described in detail elsewhere[4], is designed to deliver a 1 μs pulse at 1 MV and 10 kA at a 5 Hz repetition rate. The rep-rate capability is essential over the long term, because RF conditioning of the microwave tubes will be necessary to achieve reliable high power operation on the microsecond time scale. RF conditioning has historically been proven to be a necessity for reliable operation of high power microwave tubes and RF cavity accelerating structures.

Summary

Work on a large orbit gyrotron amplifier has recently begun. Computational modelling of improved electron gun designs has been performed to increase the fraction of the diode current entering the microwave tube, and to achieve improved beam placement in the tube as well. Electron injection experiments are now underway. Preliminary designs for an amplifier now are being considered. The relativistic klystron amplifier is in the initial stages of experimentation, and has achieved to date 900 ns of bunched beam with a peak current of 0.9 kA. Efforts to extract this power into rectangular waveguide are in progress. The RKA has been designed with future repetitive operation in mind, when the BANSHEE pulser has been fully qualified for rep-rate operation.

Acknowledgements

This work was supported by Los Alamos National Laboratory Program Development and Internally Sponsored Research, under the auspices of the United States Department of Energy.

References

1. W. W. Destler, et al, "High-power microwave generation from large-orbit devices," IEEE Trans. on Plasma Science **16** (2), April 1988, p. 71.

2. Y. Y. Lau and L. R. Barnett, "Theory of a low magnetic field gyrotron (gyromagnetron)," Int. J. of Infrared and Millimeter Waves **3** (5), 1982, p. 619.

3. M. Friedman, et al, "Externally modulated intense relativistic electron beams," J. Appl. Phys. **64** (2), 1 Oct. 1988, p. 3353.

4. F. W. Van Haaften, et al, "A high-voltage, high-current electron beam modulator for microwave source development," presented at the Fifth National Conf. on High Power Microwave Technology, West Point, New York, May, 1990, to be published.

* Electrical Engineering Department, University of Maryland, College Park, MD.