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ADVANCED DESIGN OF POSITIVE-ION SOURCES FOR NEUTRAL-BEAM APPLICATIONS*

E. F. Marguerat, H. H. Haselton, M. M. Menon, D. E. Schechter,
W. L. Stirling, and C. C. Tsai

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

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Summary

Plasma ion temperatures in the 10-keV range are needed for fusion devices to have net energy production. A proven heating technique in current fusion plasma research is neutral beam injection. For future plasma heating applications in fusion reactors, high power neutral beam injectors could be based on an Advanced Positive Ion System (APIS) incorporating energy recovery to improve system efficiency. The heart of such injectors is the APIS ion source, which is being developed to meet a goal of producing ion beams of ≤200 keV, 100 A, with 10-30-s pulse lengths. In a continuing effort to advance the state of the art and to produce long pulse ion beams, APIS ion sources with grid dimensions of 10 × 25 cm, 13 × 43 cm, and 16 × 48 cm are being developed. In the past year, the 10- × 25-cm ion source has been operated to produce ion beams in excess of 100 keV for many seconds pulse length. An advanced design concept is being pursued with the primary objectives to improve radiation protection, reduce fabrication costs, and simplify maintenance. The source magnetic shield will be designed as a vacuum enclosure to house all source components. The electrical insulation requirements of energy recovery are also considered. Because of the frequent maintenance requirements, the electron emitter assembly will be designed with a remote handling capability. A new accelerator design which incorporates the necessary neutron shielding and associated steering gimbal system is also described.

Introduction

Heating experiments on fusion machines have demonstrated that neutral beam injection is an effective heating technique for fusion devices. Future injection heating experiments will require injectors with a reliability of >90% and with long life, consistent with confinement devices. Such injectors could be based on the Advanced Positive Ion System (APIS) and should be capable of withstanding intense neutron radiation. In applications involving a tritium environment, remote maintenance capabilities will be necessary. The present state-of-the-art technology of neutral beam injectors is reported elsewhere in articles pertaining to the status of heating programs[1] and the development of neutral beam injectors.[2]

In a continuing effort to advance the state of the art in neutral beam injectors and achieve the necessary operating characteristics, the development program for the APIS ion source was initiated with a goal of producing ion beams with energies up to 200 keV, currents up to 100 A, and pulse lengths of many seconds. Testing and evaluation of previous sources[3,4] and extensive development of ion source subcomponents[5,6] have led to the development of a 10- × 25-cm rectangular source[7] and, more recently, a 13- × 43-cm APIS source.[8] A 16- × 48-cm APIS source is now in conceptial design.

Oak Ridge National Laboratory (ORNL) has developed duoPIGatron ion sources which produce ion beams of 5-100 A. These sources, with grid diameters of 7-30 cm, were successfully used on experiments such as ORMAK,[9] PLT,[10] ISX,[11] and PDX,[12] involving pulse lengths in the 50-500-ms range. Based on the operational history of these sources with circular grid geometry, the principal problem areas for extending the pulse length to several seconds involve the electron feed and the accelerator grids. Ways to deal with these problems have been pursued. Recent progress in the electron emitter development has minimized some of the problems related to the electron feed. These developments[13] are described elsewhere in this proceedings.

In order to improve the cooling necessary for adequate thermal and mechanical stability of the grids, a new design has been developed which incorporates rectangular grids. The major advantage of the rectangular design is that it permits coolant flow across the shorter grid dimension and thereby improves the cooling efficiency and grid stability. Conventional techniques of ion source fabrication were used on the previous circular injectors and have been successfully upgraded and applied to the present rectangular APIS ion sources. Following these techniques, components are designed to serve all electrical, vacuum, thermal, and mechanical functions. As a result, many of these components have to be designed to accommodate vacuum seals. Although the rectangular grid design has outstanding advantages over the circular geometry in long pulse performance, it does have a significant cost disadvantage due to increased difficulty in machining rectangular components.

For applications in ignition and reactor devices involving a tritium environment, dual seals will be required on all vacuum joints. In a rectangular geometry, using several such seals will result in a substantial cost increase for the neutral beam injector. For this reason, a new APIS design concept is being pursued. The objectives of the new design concept are cost effectiveness, ease of maintenance, improved radiation protection for sensitive source components, and improvements in operation.

APIS Design Concept

The new rectangular advanced design concept incorporates features of energy recovery[14,15] and provides for remote handling capabilities necessary to maintain the electron emitter. Shown in Figure 1, the concept consists basically of four primary components — electron feed, plasma generator, ion accelerator, and short gas cell. All components are enclosed within a magnetic shield, which protects the source from stray magnetic fields and also serves as the vacuum containment. Therefore, many costly vacuum seals normally required on source components are eliminated. Mechanical and electrical requirements relating to energy recovery[14,15] are concerned

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primarily with the mounting of source components to provide adequate electrical insulation. Figure 1 shows the arrangement of components utilizing the energy recovery features. The plasma generator voltage is boosted to 5-10% of final energy positive with respect to ground and the gas cell is biased negatively to the full accelerating voltage. Such a design concept has been considered in the neutral beam injectors for ISX-C and Zephyr.

Electron Feed

The electron feed[6-8,13,16] should be capable of delivering up to thousands of amperes of current with a corresponding emitting current density of several $A \cdot cm^{-2}$. Operating under such high current density levels adversely affects the life of the electron emitter, either by evaporation or thermal deformation. Therefore, frequent maintenance of the emitter is necessary. By utilizing an isolation valve and sealed emitter housing (Figure 1), replacement of the electron emitter can be accomplished without losing the vacuum integrity of the source even without a conventional valve between the source and beamline box. The convenience and minimum downtime are two of the many advantages which are apparent with this concept. To meet the requirements of reactor applications, adequate dual vacuum seals and an auxiliary vacuum system have been incorporated for returning the emitter to the operating position.

Water cooling of all major feed components is necessary for absorbing the thermal loading resulting from high power, long pulse operation. Coolant supply lines, electrical power, and vacuum lines must be designed with insulated feedthroughs.

Plasma Generator

A plasma generator should be capable of producing a dense plasma of $\sim 10^{12}\ cm^{-3}$ and $\sim 0.3\text{-}A \cdot cm^{-2}$ beam current density uniformly over an active grid area of several hundred square centimeters. Following ORNL source developmental experience, the same type of duoPIGatron rectangular plasma generator now used on the 13- × 43-cm source[8] will be the potential candidate for the advanced source. By using adequate water cooling, the components of the plasma generator are almost entirely free of routine maintenance.

With this design (Figure 1), all components of the generator are mounted to the top plate. Necessary cooling and electrical lines are connected through insulated feedthroughs in this plate. This feature is for the convenience of remote handling whenever maintenance of the ion accelerator is required.

In an efficient neutral beam injector, the gas efficiency should be as high as possible for maximum atomic yield and minimum gas pumping. Hence, the flow of working gas should be directed through the electron feed, plasma generator, ion accelerator, and gas cell with minimum leakage. For successful operation with energy recovery, both the source plasma and the gas cell plasma should be contained within their own housings without leakage. To achieve this, bellows are provided at each end of the accelerator assembly (Figure 1).

Different from that of the 13- × 43-cm source (Figure 2), the advanced arc chamber is designed with the flexibility of changing its cross section. This will provide the freedom of creating a uniform and dense plasma over a desired area for improving efficiency. In addition to the elimination of vacuum flanges, this chamber is constructed with a copper liner which incorporates integral cooling channels under the magnet columns to dissipate the heat generated by the arc current flowing through this cusp area. The magnet columns are utilized to form a multiple line cusp magnetic field for electron containment.[5]

Accelerator Grids

The accelerator grid assembly is used to accelerate the ions generated in the arc chamber. The grid assembly and beam steering gimbal operating at a potential of ~200 kV in the energy recovery mode are isolated electrically from the ground potential of the vacuum enclosure base and from the plasma generator potential of ~20 kV.

The accelerator assembly (Figure 3) consists of the grids, steering gimbal, grid insulators, and metal bellows. Insulated structural posts are provided between the steering gimbal and grid mounting frame for use in isolating each grid operating at different potentials. The grid structure insulators

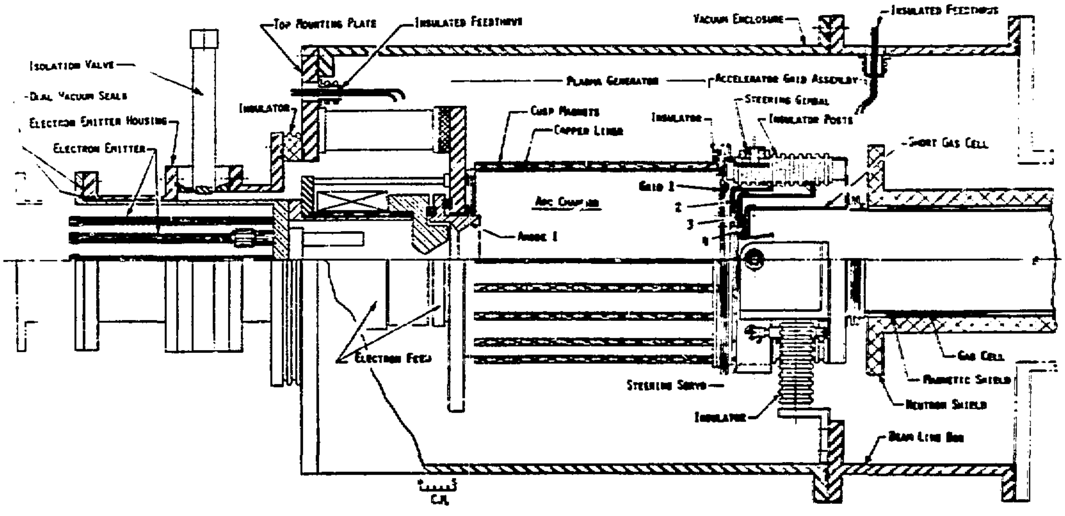

Fig. 1. Advanced positive ion source design concept.

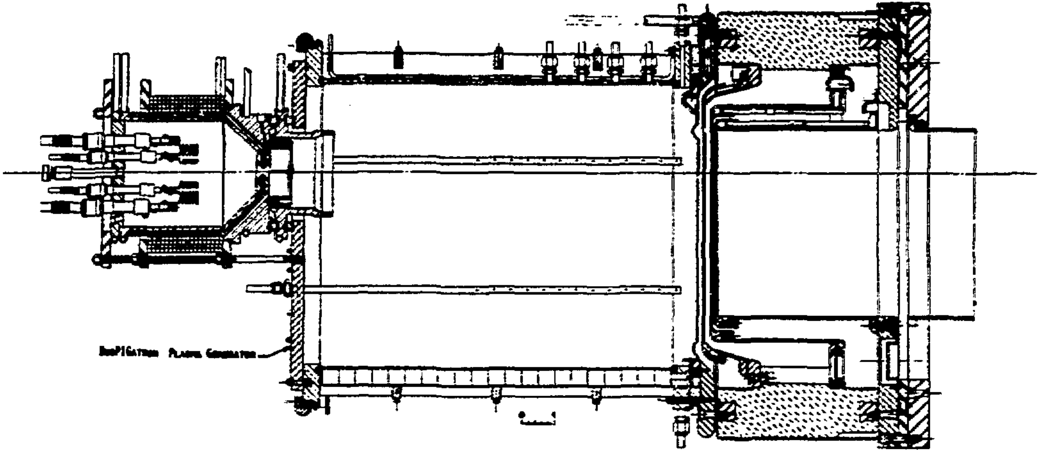

Fig. 2. 13- × 43-cm ion source.

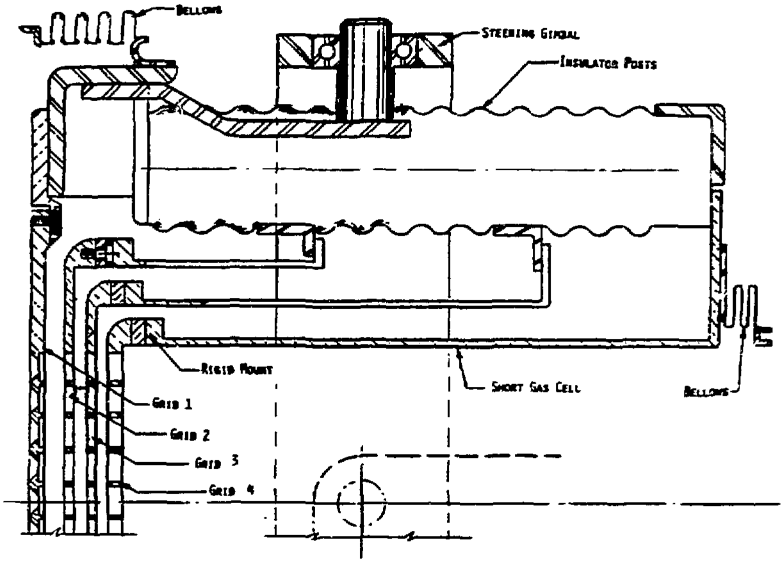

Fig. 3. Accelerator grid assembly.

will be subjected to a significant amount of neutron radiation from deuterium-tritium reactions and, therefore, must be protected with adequate shielding. Radiation studies for TFTR[17] have indicated that with an adequate neutron shield the neutron intensity will be reduced sufficiently to protect the high voltage insulator from scattered neutrons produced in the gas cell adjacent to the accelerator assembly. Other studies[18] have also been conducted to evaluate radiation damage to insulating materials.

In order to precisely align the beam and direct it to the fusion plasma target, a steering gimbal (Figure 3) is provided. This permits both vertical and horizontal steering capability within the limits of ±0.5°. With this design concept, only the accelerator grids are required to have steering capability, thereby reducing considerably the load on the steering control servos. Flexible metal bellows are located at each end of the accelerator assembly to allow the necessary degree of steering and to maintain electrical and vacuum integrity (Figure 1).

The grids have to be cooled with a considerable quantity of high pressure demineralized water to prevent undue thermal deformation, which degrades the optical quality of the beam.[19-21] Thermal and structural analyses[22-24] of previous grid designs have predicted that substantial grid instability will result when restrained grid edges and a limited coolant flow are provided. Difficulties encountered with experiments on previous sources have tended to substantiate this prediction. Results of these analyses and tests have prompted the need to consider possible solutions to this problem and to pursue other grid mounting designs. This advanced design concept has incorporated the necessary improvements in grid stability by providing features of expandable grid edges (Figure 3) at the interface of the grid and rigid mount.[24] This feature permits freedom for expansion, thereby eliminating excessive buckling and deformation of grids. All grids are spherically curved to focus the beam on the plasma target.

A grid design (Figure 4) which has been used on previous sources[4,7] is fabricated from a thin (~2-mm) OFHC copper plate with 1.5-mm-diam cooling tubes furnace brazed into machined grooves. Manufacturing problems associated with this technique exhibit a high failure rate due to plugging of the cooling

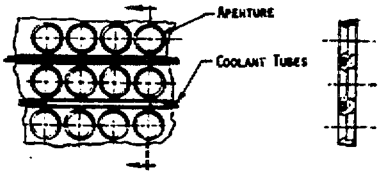

Fig. 4. Typical source grid.

tubes during the brazing process. Difficulty encountered with this process has prompted the need to develop other designs and fabrication techniques which offer greater reliability and easier fabrication. The design for ORNL APIS grids (Figure 5) incorporates the use of cooling channels (0.8 mm wide × 1.5 mm deep) machined into an OFHC copper plate. Channels are filled with a conductive wax and electroformed to the specified plating thickness of ~1 mm. Coolant access holes are drilled into the channels and the wax is melted out. Fabrication is completed by precision drilling of the many apertures to shape, furnace brazing the grid plate to the coolant headers and frame, and press forming to a spherical radius. Finished grids undergo extensive hydro, vacuum, x-ray, and thermal cycle testing to assure quality. Prototype grids fabricated by this technique have operated satisfactorily under preliminary testing.

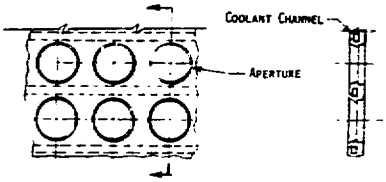

Fig. 5. APIS grid.

Several materials are under consideration for use on ion source grids. Molybdenum and copper are the two most promising candidates for the APIS source and both will be used and evaluated first on the 13- × 43-cm source. Selection for prototype use is a matter of compromise between cost and performance. However, due to the superior voltage holding, secondary emission characteristics, and mechanical strength at elevated temperatures, molybdenum appears to be the more promising. The lower thermal conductivity, higher cost, and greater difficulties in fabrication are some disadvantages associated with the use of molybdenum.

Gas Cell

When operated with the energy recovery system, the neutralizer gas cell (Figure 1) operates at the same potential as the last grid. Insulated from and supported by the beamline box, the gas cell is held in a fixed position and interfaces with the accelerator assembly bellows. Water cooling is provided for removing the heat loading due to the interception of beam particles. Magnetic shielding is incorporated to prevent stray fields from affecting beam transport. In order to improve radiation protection for high voltage insulators, proper neutron shielding around the gas cell adjacent to the accelerator assembly is used.

Conclusion

An alternative ion source design is proposed which offers solutions to some of the potential problem areas of future injectors. The advanced concept exhibits the following design features which satisfy this objective:

- The need for many vacuum tight joints is eliminated due to the use of the combination vacuum enclosure, magnetic shield concept.
- Easier maintenance of the electron emitter is possible with the utilization of an isolation valve for this maintenance.
- Beam steering requirements are simplified due to the accelerator assembly mounting concept.
- Improvement in grid cooling is possible with the rectangular geometry.
- Mechanical stability of the grid is provided by the use of expandable grid mounting.
- The fabrication cost of the source is minimized by utilizing the magnetic shield as the primary vacuum enclosure.
- Vacuum insulation to simplify the design is used for the necessary high voltage holdoff.
- Elimination of a source isolation valve is possible with the use of the remote maintenance valve.

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