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by

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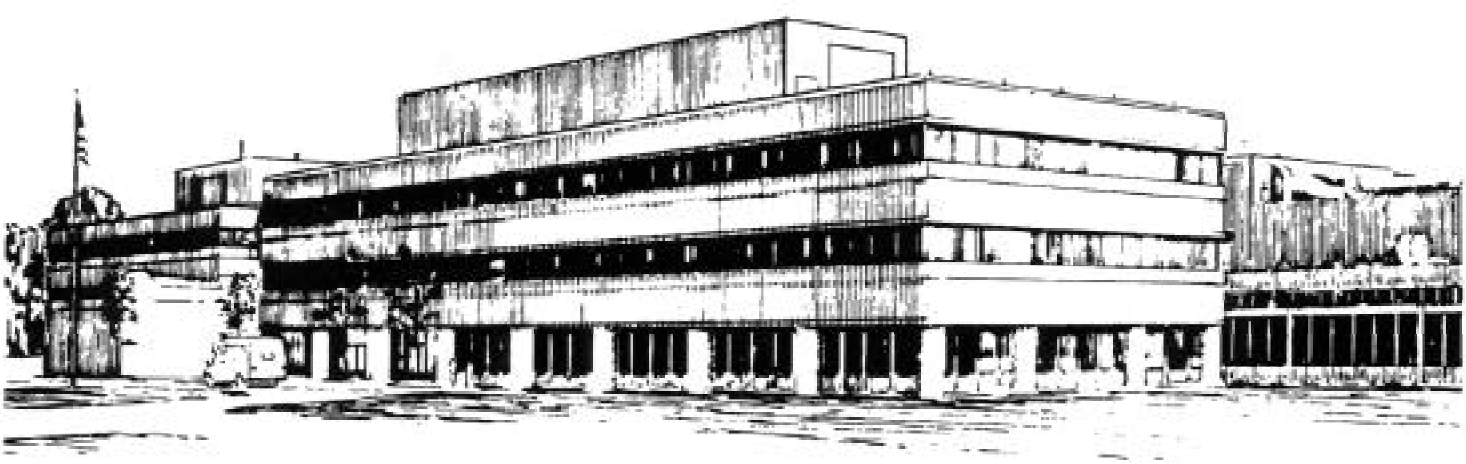

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Abstract The negative ion neutral beam system now operating on JT-60U was the first application of negative ion technology to the production of beams of high current and power for conversion to neutral beams, and has successfully demonstrated the feasibility of negative ion beam heating systems for ITER and future tokamak reactors [1, 2]. It also demonstrated significant electron heating[3] and high current drive efficiency in JT-60U[4]. Because this was such a large advance in the state of the art with respect to all system parameters, many new physical processes appeared during the earlier phases of the beam injection experiments. We have explored the physical mechanisms responsible for these processes, and implemented solutions for some of them, in particular excessive beam stripping, the secular dependence of the arc and beam parameters, and nonuniformity of the plasma illuminating the beam extraction grid. This has reduced the percentage of beam heat loading on the downstream grids by roughly a third, and permitted longer beam pulses at higher powers. Progress is being made in improving the negative ion current density, and in coping with the sensitivity of the cesium in the ion sources to oxidation by tiny air or water leaks, and the cathode operation is being altered.

1. Introduction

During initial operations of the JT-60U negative ion system, the beam pulse length, power, and operating voltage were all somewhat less than was desired. While this condition arose from a number of processes, they all Manifest themselves as excessive heating of the accelerator and ground grids of the ion sources due to interception of the grids by energetic divergent beam particles. These grids were receiving roughly three times the fractional heat load from the beams that their cooling was designed to handle (in the case of the ground grid a load fraction of as much as 15% of the accelerated power, versus an expectation of less than 5%). This in turn limited the beam parameters which could be achieved without high voltage breakdowns in the grids. Several of the principal phenomena arise from the characteristics of large area sources, and thus had been less apparent in smaller ones. This paper discusses measures taken to address these phenomena.

2. Beam Stripping

One cause of the heavy grid interception was excessive stripping of the negative ions in their passage through the grid structure. Prematurely neutralized ions did not experience the full set of electrostatic lenses, leaving some energetic neutrals lodged on very divergent trajectories. Since beam ions were neutralized after passing through differing lengths of the accelerating field, some of them had energies lower than the nominal accelerating voltage, producing a lower energy continuum in the beam. The stripping was found to arise from a steeply increasing pressure in the source and accelerator as a function of time, which occurred as a consequence of the long vacuum time constant of the gas feed system. While it was not immediately feasible to change the geometric characteristics that gave rise to this behavior, it was possible to change the gas pulse timing to allow the gas to equilibrate before the arc, which in turn allowed a lower gas throughput to be used. After this improvement, a

Doppler shift measurement revealed that essentially all of the beam power transmitted to JT-60U was at the full acceleration energy.

3. Secular Dependence of Arc and Beam Parameters

After the sharp time dependence of the source and accelerator pressure was corrected, a strong secular dependence still persisted in nearly all of the source parameters, including the arc voltage and current, the extraction current, the extraction grid bias current, and the fraction of co-extracted electrons in the beam. In particular, the arc impedance was declining significantly, which in turn reflected a change in arc characteristics, and consequently a time dependence in the extractable negative ion current density. This led to time-varying divergence in the beam, which increased the average grid interception. It was found that the time required for the arc to equilibrate in negative ion sources of this sort is very long, and that the early operation had been done during the long turn-on transient. This problem was also corrected, so that the source plasma characteristics are equilibrated by the inception of beam extraction. This was accomplished by increasing the time the arc was on prior to beam extraction. The period required for equilibration was a decreasing function of arc and filament power, with 1.5 to 2.0 seconds being sufficient for most conditions, as opposed to the 0.5 second of arc prior to beam extraction which had been used during early operations.

Recently, further control over the secular dependence of the arc has been implemented with a filament control system which allows the programming of eight different values of the filament heating current at different times during the arc and beam pulse. This facilitates stable operation for longer pulses. It also results in lower average filament temperatures than was previously the case, reducing the evaporation of tungsten, and also the incidence of unipolar arcs which erode the filament. It is expected that this will increase filament lifetime, and reduce cesium burial on the source surfaces.

4. Spatial Non-Uniformity of the Ion Source Plasma

A strong spatial non-uniformity in the source plasma persisted even in the equilibrated arc, and this in turn led to a non-uniformity in the local negative ion current density extracted from different areas of the source grids. Since the same voltage gradients are applied over the whole area of the grids, local variations in current density result in mismatches between the radially outward force of the beam space charge and the radially inward electrostatic focussing field, and cause position-dependent divergence growth.

A number of diagnostic techniques revealed a consistent view of the non-uniformity, including a beam scanning calorimeter, the ratios of the arc currents flowing through the spatially distributed filament groups, the sharpness of reverse-accelerated beamlet burn marks on the back wall of the source, the relative temperatures of the vertically arrayed sectors of the plasma grid, and, more recently, Langmuir probes.

Figure 1 shows the negative ion beam profile measured by a scanning calorimeter located about three meters downstream of the ground grid of the uppermost of the two negative ion sources. This distance is still in the near field of these large, 24 meter focal length sources, so the beam uniformity is a measure of the corresponding extractable negative ion current density illuminating the source plasma grid. It is apparent that there is some short scale length non-uniformity, both across the narrow dimension of the source, and also in terms of local clumping which may be related to the discrete array of filament groups. However, the dominant inhomogeneity lies along the vertical direction, with the density declining by several tens of percent in the lower part of the source.

In attempting to determine the driving mechanism for this vertical non-uniformity, all parameters within the sources were scanned, and those which could be reversed (such as the plasma grid magnetic field) were also reversed. The non-uniformity was largely unchanged by any of these variations, leading to the supposition that it is probably driven at least in part by the one parameter that could not be reversed: the direction of arc current flow through the filaments and into the plasma. This produces a linked magnetic field flowing the length of the source which is the net field produced by the arc current flowing through the filaments. Unlike the magnetic field produced by the filament heating current, the magnetic field from the arc is not self-canceling. The potential for this causing non-uniformity is greater for sources with large long extraction areas than for this source's smaller predecessors

Figure 2 shows the arc current distribution among the eight filament groups for typical conditions when the series resistors all have values of 100 milliohms. When the filaments are run in the space-charge limited mode, which was the case through most of the JT-60U beam operations, the current flowing through each group and across the cathode sheaths acts as a relative measure of the local plasma density, much like a reverse Langmuir probe. For similar reasons, plasma non-uniformity may tend to be self reinforcing in the vicinity of space-charge limited cathode sheaths, since higher local density permits larger electron current flow, yielding greater ionization. Figure 2 demonstrates that the presence or absence of cesium in the source makes little difference in the non-uniformity.

Figure 3 displays typical ion saturation current and electron density profiles for the Langmuir probes, with characteristic non-uniformity similar to that shown by the filament group currents and the scanning calorimeter. As shown, varying the magnitude of the current flowing through the plasma grid which produces a magnetic filter field does not significantly alter the shape of the nonuniformity.

We also measured the temperatures of the five vertically arrayed plasma grid segments. The plasma grid is uncooled except by edge conduction, and is heated by the local plasma discharge and the radiation from the filaments. The fact that the lowest segment is typically sharply cooler than the others reflects the lower plasma density in this region, consistent with the other diagnostics. This lower temperature in turn results in over-accumulation of cesium on this segment, raising the electron work function above the optimum, and presumably reducing local negative ion production.

A number of techniques have been implemented to correct the non-uniformity in these sources. The most successful involved installing resistors whose value could be changed independently in the circuit for each of the eight filament groups, and, in addition, masking about 19% of the grid area to avoid extracting divergent beamlets from remaining areas of lower plasma density. The non-uniformity was also decreased when the source was operated at lower pressure. Figure 4 shows the large improvement in uniformity obtained by reducing the arc series resistors of the lowest two filament groups from 100 milliohms to 50 and 25 milliohms. This particular configuration had the disadvantage that the current through the changed filament groups rose too high during longer pulses. This is now being further optimized through the use of the time-dependent filament heating current programming, and by increasing the base resistance to 150 milliohms.

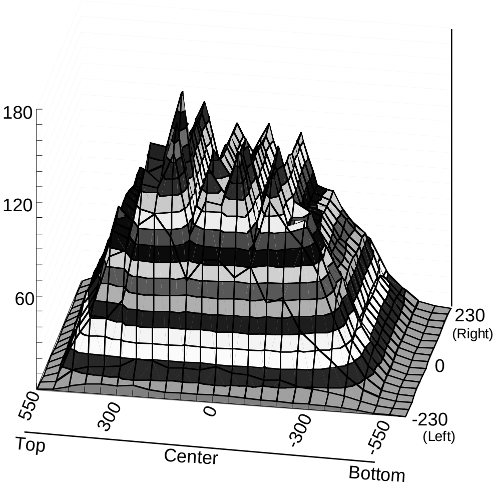

FIG. 1: Negative ion beam profile

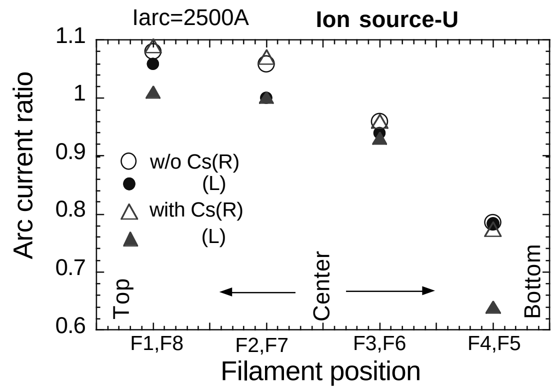

FIG 2: Arc current distribution in source

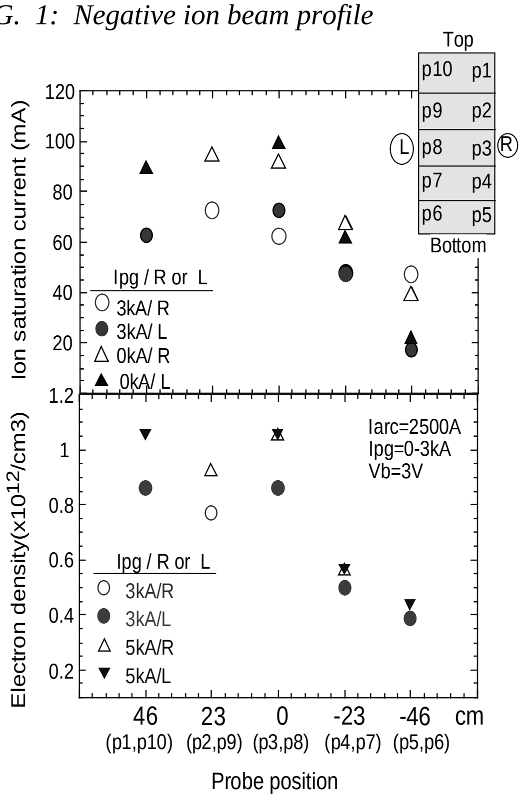

Fig. 3: Ion saturation current and electron density showing the same general top-down decline as exhibited by the arc current distribution in figure 2. Changing the magnetic field produced by the plasma grid current does not affect shape of the distribution.

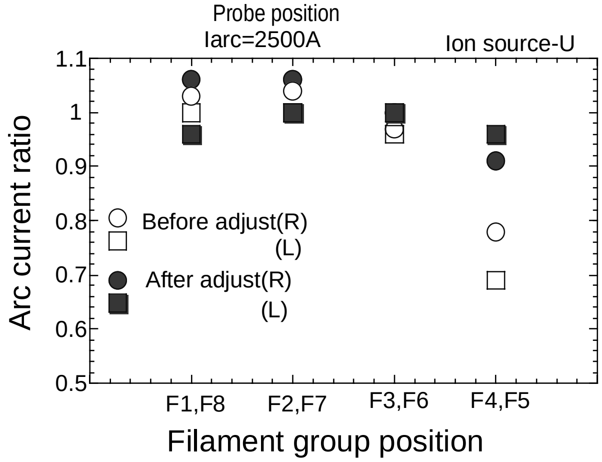

Fig. 4: Distribution of arc current among the eight filament groups, showing the large improvement in uniformity obtained after changing the series resistors to groups 4 and 5 in the bottom of the source from 100 milliohms to 25 and 50.

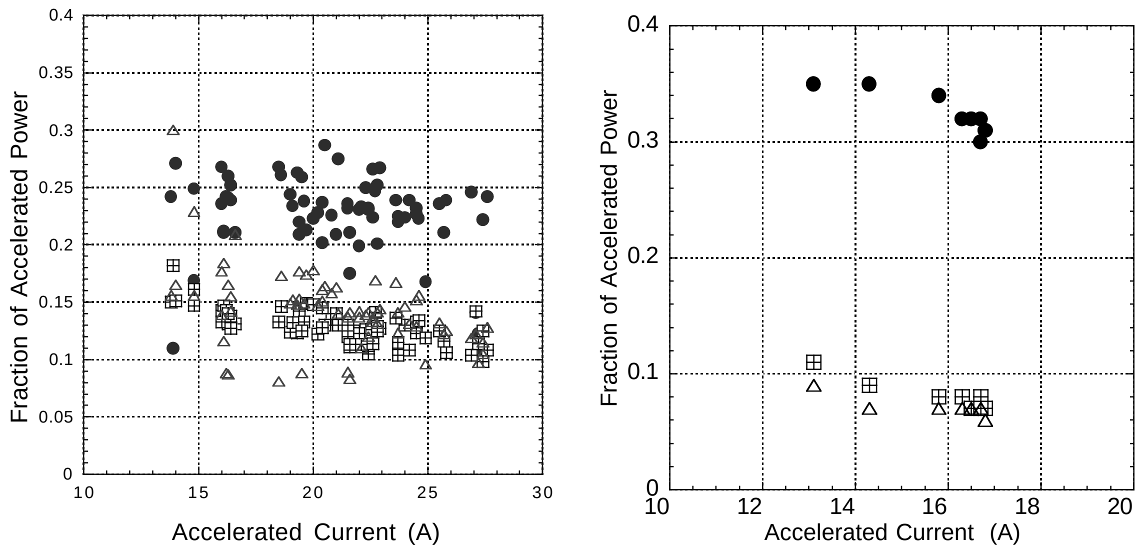

Figure 5: Fraction of accelerated power striking calorimeter (closed circles), ground grid (boxes), and second accelerator grid (triangles) before (left) and after (right) improvements described.

5. Negative Ion Current Density

The negative ion current density is often reduced by oxidation of the cesium in the source from air or water leaks. This limits the acceleration voltage which can be used, since the beam current density must balance the applied radial electric field component. A very large system like the JT-60U negative ion beamline is more susceptible to leaks than were previous generations of small sources and test stands Improvements to the vacuum and gas systems are reducing the potential for leaks.

There is some optimum arc discharge voltage for producing extractable negative ions. When the cathodes are run in space charge limited mode, the control over the arc impedance, and thus the discharge voltage, is limited. The addition of the filament heating programming control has allowed operation recently with emission limited cathodes, permitting control of the arc impedance and some corresponding improvement in transmitted negative ion power.

6. Conclusion

This study clarified the role of various physical processes which appear more prominently in large scale cesiated ion sources, and it thus contributed to improved beam performance on JT-60U. Figure 5 shows a comparison of the fractional accelerated power being deposited on the second accelerator and ground grids at the beginning and end of this work, and also the fractional portion transmitted to the calorimeter. The acceleration efficiency of D has increased from 55% to 74%, and to 80% with H. The maximum injected deuterium power so far achieved as a result of these improvements is 5.2 MW at 350 keV for 0.77 sec [5], and the maximum pulse length is 2.0 sec at 4.0 MW and 360 keV.

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[3] T. Oikawa et. al. , Proc. 17th Int. Con. on Fus. Energy, Yokohama Oct. 1998.
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