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Exploitation and development of particle beams at Culham Laboratory (invited)

T. S. Green

(Euratom/UKAEA Fusion Association) Culham Laboratory, Abingdon, Oxon, United Kingdom

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Particle beams have been developed at the Culham Laboratory for many years, mainly for application to the production of high-temperature plasmas. These developments included demonstration of fundamental plasma physics such as particle trapping, heating, and current drive coupled to continuous advances in the physics and technology of ion beam production and transport. This work reached its zenith in production of multimegawatt high-proton fraction sources for the neutral beam injectors for JET. A new initiative is now coming for the development of negative ion based injectors. This wide ranging base of physics and technology provided a springboard for exploitation of beams in areas other than fusion. The last few years have seen increasing R and D at Culham in areas such as space, defense, surface treatment, and implantation. The applications have ranged from beams of H^+ or H^- to Xe^+, from currents of less than 1 mA to currents of amperes and from energies of 50 eV to energies of hundreds of kilovolts. This paper describes some examples of these activities and relates them to the physics and technology base. Future areas of interest are also discussed.

INTRODUCTION

The production of ion beams was often considered a necessary evil in the design and operation of particle accelerators. However, the development of sources for isotope separators and subsequently ion implanters brought the subject into a new perspective.[1] This was further enhanced by the fusion research community's growing need for energetic neutral particle beams and Culham Laboratory established a program of ion beam development over 20 years ago. This research and development have resulted in several important physics demonstrations on the one hand, and a continuous development in physics and technology of plasma sources, accelerator design, and beam transport on the other. In particular, the magnetic multipole (or bucket) ion source was developed as a work-horse ion source for hydrogen and inert gases.

High-power beams, as needed for injectors, must have low divergence and good beam quality. This has led to major improvements in beam optics of the accelerators in closely packed multiple arrays.

The design principles of both sources and accelerators have been carried over to other applications. In the 1970s, Culham developed a Kaufman-type ion source as a potential ion thruster for space propulsion. The growing market for spacecraft on a commercial scale has led to reassessment of the need for such propulsion units and a rebirth in the UK of the development of a xenon ion thruster.

With this new activity, Culham Laboratory began to find more applications for its particle beam technology outside of the fusion field. While some of these were direct extrapolations in key technologies (e.g., 200-keV accelerator design), others required the development of new ion sources and accelerators and a reevaluation of some aspects of beam transport. In the following sections, the author briefly reviews the history of beam development and application in the fusion field, then describes some of the more recent exploitations of beam systems.

I. ION BEAMS FOR FUSION

The first use of ion beams for fusion research at Culham was to fill a magnetic mirror machine. These early sources were based on duopigatrons and used single-aperture extraction systems. The need for higher currents and better system control led to two parallel efforts in ion source design and beam optics studies.

A. Source development

Via a single discharge volume (hence called a monopigatron) the Culham group studied some of the basic properties of sources based on ionization by electrons emitted from hot filaments.[2] At that time, magnetic multipole sources were introduced at Culham[3] based on the plasma confinement systems developed by McKenzie.[4] From these sources, the Culham group has developed a magnetic multipole source for use in the JET injectors[5] as shown in Fig. 1. Operated in hydrogen it yields 60 A of ions. A modified version has also been developed by KFA Julich in collaboration with Culham to deliver 80 A.

The concept of this type of source is relatively simple. The magnetic multipoles create a short-range magnetic field with a rather low field strength (<5 G) throughout most of the source volume. Thus, electrons emitted from the hot cathodes can be contained magnetically; yet provide uniform ionization throughout most of the source volume. The ions so formed are partially confined and most impact on the plane of the extraction electrode with nearly uniform illumination.

The theory of ionization referred to above shows that the ionization efficiency is a function of gas pressure as shown in Fig. 2, in a way that depends on the electron containment time. However, there is a limit to the value of containment time that can be achieved because the magnetic confinement cannot be perfect. If it were, no cold electrons would flow to the anode and the current circuit from cathode

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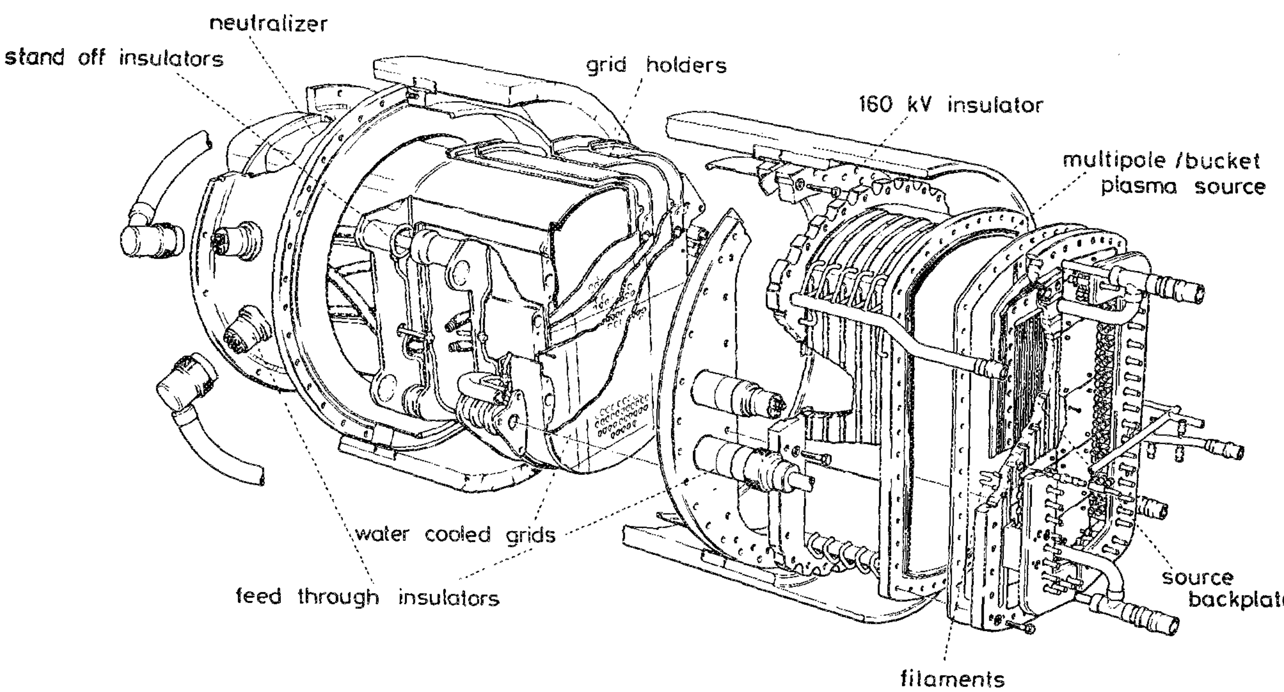

FIG. 1. Schematic diagram of 80 kV, 60 A, hydrogen ion injector for JET

to anode would not be closed. When magnetic multipoles have been made with too little loss to the anode, the plasma potential has inverted and the source has shown instabilities[6,7] (so-called mode flipping).

Sources have been optimized empirically in hydrogen, but one should note that for other gases, there may be a better optimization since the maximum allowable electron containment time is proportional to the transit time of ions in the source and hence to the square root of the atomic mass.

A major requirement for neutral injectors in JET was the maximization of power in the full energy H^0 component deriving from neutralization of H^+ rather than the molecular ions. Achievement of high H^+ fractions from the magnetic multipole source became a key issue, resolved by adapting the concept of a magnetic filter developed at Berkeley.[8] To make this as a retrofit to the JET sources, it was necessary to use a so-called virtual filter achieved by modification of the externally mounted magnets (Fig. 3).

This type of filter has been shown to modify the electron energy distribution and create two separate volumes: one with energetic ionizing electrons and warm plasma electrons; the other with only cool plasma electrons.[9] There are still conflicting evidences and views on the reasons for the enhanced H^+ yield. On the other hand, there is now wide

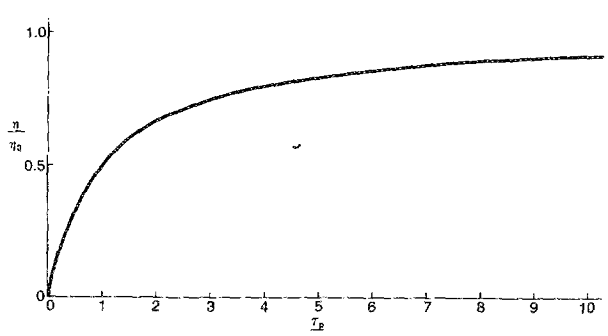

FIG. 2. Plasma source efficiency as a function of electron containment time. η = No. of ions produced per primary electron, η_0 = value of η at infinite containment time, τ_p = containment time of primary electrons, τ_0 = ionization time constant, ■ = [gas density x ionization rate coefficient]$^{-1}$.

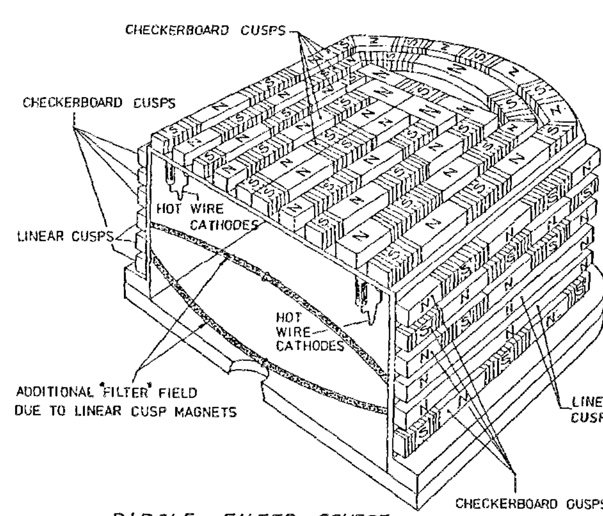

FIG. 3. Schematic diagram of magnetic multipole ion source with virtual magnetic filter.

agreement that such tandem plasmas are suitable for the production of negative ions,[10–12] and this had led Culham to develop such sources as a possible basis for neutral injection in next generation tokamaks such as NET.

Figure 4 shows the current of H^- extracted from a single aperture in a plasma source based on the JET H^+ sources.

B. Beam optics

The ion source designed for JET was based on multiaperture electrodes with ~200 mA of H^+ per aperture at 80 kV. This is a high perveance, and was selected as a balance between the desire for higher current densities that are achievable in these sources and limits set by the influence of perveance on beam quality, by beam-gas collision in the accelerator, and by voltage hold off. By suitable optimization of aperture geometry, Holmes[13] produced a beam with good divergence (0.4°). We should note that the data on beam optics obtained in the fusion field apply to a narrow part of parameter space in terms of current, voltage, and dimensions. Some limitations in extrapolation of these data are discussed below.

II. SPACE APPLICATIONS

A. Ion thrusters

As noted in the Introduction, Culham (in collaboration with the, then, Royal Aircraft Establishment at Farnborough) developed a small ion thruster operating in mercury during the 1970s. This work stopped when it appeared that there was no near-term commercial application. However, this situation changed over the past few years with the evolution toward larger, more powerful, and longer lived spacecraft. In addition, the change has been made from mercury to xenon, a fuel more compatible with spacecraft. Consequently, with a now-perceived application for thrusters, the Royal Aerospace Establishment at Farnborough placed a contract with Culham to carry out an experimental evaluation of a 10-cm beam diameter thruster operating in xenon, and an assessment of the advantages of using such a large thruster for station keeping on large multiton communication satellites.

The thruster is shown in Fig. 5; it is of the type known as a Kaufman thruster. Electrons from a hollow cathode ionize the propellant and form a plasma, from which ions are accelerated through two closely spaced grids containing multiapertures. The grids are typically spaced by 0.75 mm, and have apertures of 0.25 mm diameter, and a geometric transparency of 73%. The specified thrust for this system is 25 mN, achieved with approximately 450 mA at a beam voltage of 1.1 kV. The system is very flexible and has a wide performance range, having recently been operated at thrust levels in excess of 70 mN.

A second experimental thruster with a beam diameter of 25 cm has recently been operated up to 260 mN, with beam currents up to 3.3 A at beam voltages of 2.2 kV. While the performance of the thruster is capable of further improvement by, for example, modified plasma generator design, this is not a major issue. Lifetime and reliability of the thin accelerating grids are more critical.

B. Other studies

Space is a subject that involves many disciplines. It is interesting that several of these exist side by side at Culham, affording an excellent opportunity to carry out research and development to industry, Ministry of Defence, Royal Aerospace Establishment, British National Space Centre, and European Space Agency.

As an example, Culham recently won an ESA contract in collaboration with University College London, the Norwegian Defence Research Establishment, and the Technical

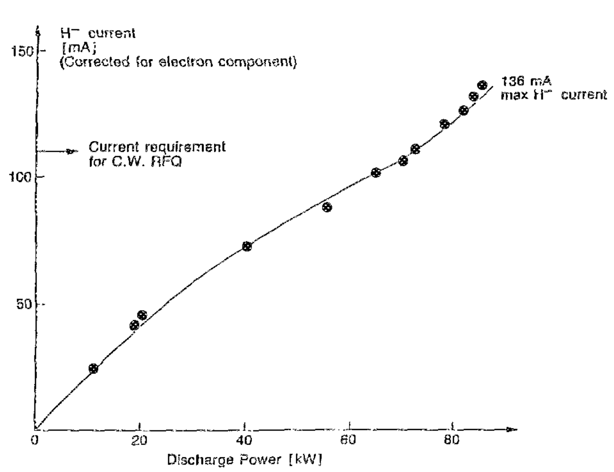

FIG. 4. Current of H^- extracted from a single aperture in a volume plasma source.

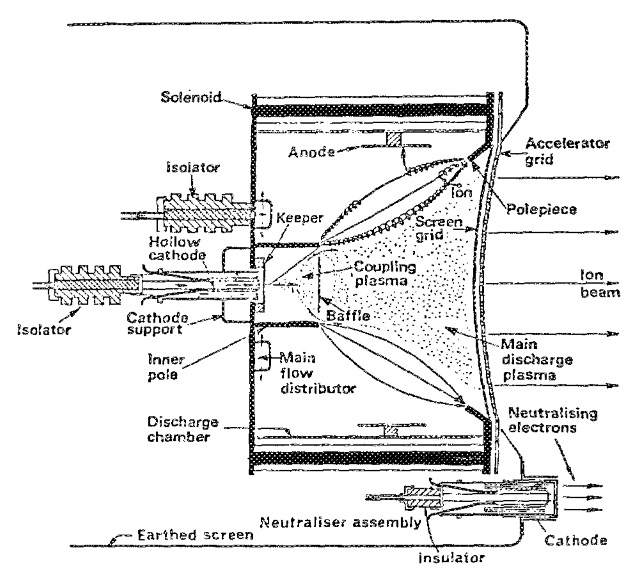

FIG. 5. Thruster ion source.

TABLE I. Space applications activities at Culham Laboratory.

Electric propulsion systems for ancillary propulsion of satellites
Electric propulsion systems for primary propulsion of spacecraft
Advanced propulsion systems other than ion thrusters, such as arcjets, rf, and microwave thrusters
Fusion propulsion system studies
Space environment simulation for plasma wake and charging investigation
Solar array interactions with the space environment
Plasma chemistry and materials studies, and in particular, oxygen erosion of spacecraft materials
Space particle impact simulation
Space diagnostics development and test
MHD aspects of hypersonic flight
Future space infrastructure studies

University Graz. This is concerned with spacecraft plasma interactions and electromagnetic effects in low earth and polar orbits. The work involves the simulation of plasma conditions in the ionosphere to study wake formation by a large body, and the writing of computer codes to predict such wakes. Experimental and computational study of the possible charging of spacecraft in the auroral zones is also an important aspect of the work. Table I lists current areas of activity in space applications, growing from the one base in beams and plasmas.

III. LOW-ENERGY BEAMS

The ion sources developed as thrusters have a very high perveance, or more correctly, perveance density. When normalized to hydrogen, the value averaged over the thruster area is $\sim 3\text{–}4\times 10^{-6}$ A cm^{-2} V$^{-3/2}$, compared with the JET injector value of $\sim 8\times 10^{-9}$ A cm^{-2} V$^{-3/2}$, due to the close grid spacing and the use of accel–decel grids.

As pointed out by several workers (e.g., Kaufman *et al.*[14]), such sources provide large-area low-energy, reasonable current beams for surface treatment. Culham has developed, partially with its own funding; partially with Department of Trade and Industry; and partially with industry, systems for low-energy applications as listed in Table II.

IV. ION IMPLANTATION AT HIGH ENERGIES

The potential of Simox produced by high-energy implantation was pointed out by Hemmett *et al.*[15] in developing material for research purposes. The possible exploitation of the process in the UK led to a development program funded by Government and industry, with the ambitious objective of producing a commercially viable implanter at a rating of 100 mA O^+ at 200 kV. Some aspects of the plasma source are described in the next section. Here, we highlight design issues of the accelerator.

A. Design of high-voltage insulator/accelerator support

There are two major requirements in an insulated accelerator support structure. Voltage isolation (both internally and externally) is a must. Good vacuum pumping to minimize losses of the ion beam and creation of so-called devious particles and electrons is very desirable. We have solved these problems using a large insulator first built for the JET injectors. The main insulator is an 80-cm-diam, 80-cm-long porcelain tube of low cost (Fig. 6). It is important to note that attention has to be paid in detail in the design in order to limit long path breakdown.

Even in this structure, gas flow from the ion source can be at a level that secondary ion and electron production in the accelerator gap can be significant. In particular, the electrons are accelerated back into the source and deposit substantial energy which is a limitation to lifetime for industrial equipment which must be operational for many hours without failure. Equally, the x rays generated by these electrons are a problem in the industrial environment. At Culham we are investigating these issues as a part of our underlying research program.

B. Optimization of beam optics

We have designed high-energy accelerators for implantation on the basis of single-gap acceleration as seen in Fig. 6,

TABLE II. Low-energy ion beams developed for industry and research.

Ion species	Energy	Total current	Current density	Application
A^+	200 eV	1 A	2 mA/cm^2	Ion beam milling and research
O^+	100–300 eV	100–300 mA	0.5–1 mA/cm^2	Reactive ion etching and surface processing
O^+	20–60 eV	50 mA	0.01–0.05 mA/cm^2	Simulation of surface errosion

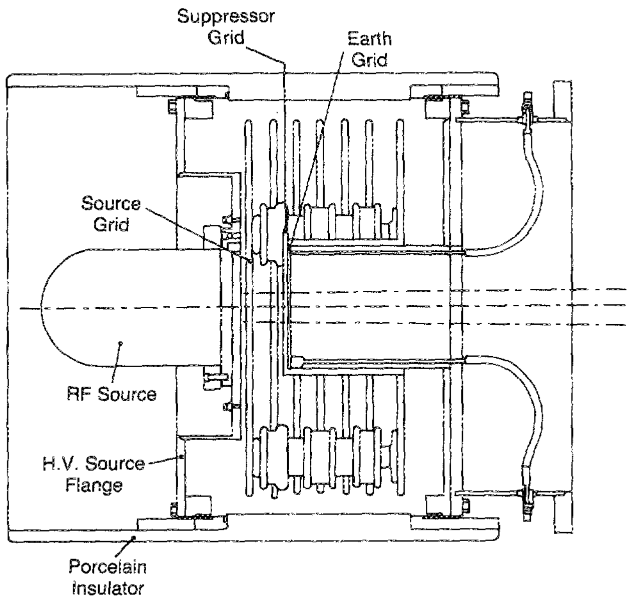

FIG. 6. 200-kV accelerator and insulator (80 cm ϕ) showing open structure for high pumping speed.

rather than multiple gap (so-called tetrode) used for the JET injector in order to minimize the pumping problem referred to above. The perveance density in such accelerators is significantly lower, and the aspect ratio, defined as the ratio of aperture radius or width to accelerator gap, is correspondingly lower. We are presently extending our beam optics data base to these lower values.

V. DIAGNOSTIC BEAMLINES

One of the most direct spinoffs from Culham's Fusion Program into the Culham commercial business area has been the design and manufacture of custom-built diagnostic beamlines for other fusion laboratories.

Two such have already been built and are now operational: one at the Texas University Tokamak (TEXT)[16]; the other, at PBX-M at Princeton.[17] The latter is described elsewhere at this Conference. Both of these systems represent the transition, already started when working for JET, from the laboratory development beamline system to an industrial product with industrial standards of guarantee and specification. An extension of this is a recent proposal to build a complete beamline for research purposes as a turnkey installation. A number of such proposals are now being evaluated in the fusion and research fields, and in the area of industrial application.

VI. ION SOURCE DEVELOPMENT

As stated above, ion sources based on the magnetic multipole confinement geometry with ionization due to electrons from hot filaments have been the work horse of the fusion program. They have also considerable scope for applications in the industrial field (e.g., nitrogen source for implantations[18]). There is still scope for further optimization for heavy ions, indeed, for some novel concepts to be incorporated.

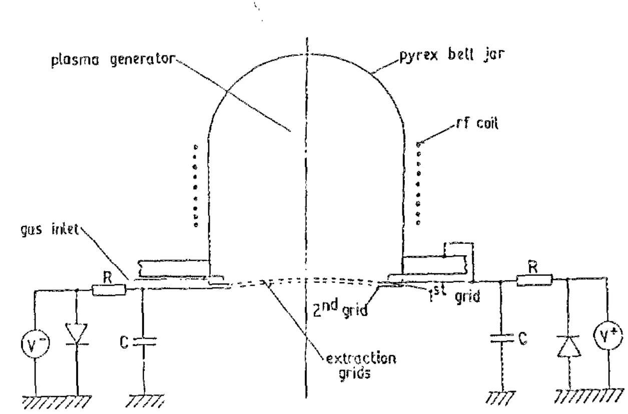

FIG. 7. rf discharge ion source.

However, a major challenge lies in the use of noninert gases and metal vapors as highlighted by several authors at this Conference. In particular, Culham has been concerned with gases such as oxygen, which lead to degradation of hot filaments at a rate incompatible with industrial applications. Culham has chosen to overcome this problem using rf discharges, as shown schematically in Fig. 7. Attention to detail in design has yielded a high efficiency in producing a uniform plasma over a large area. Such sources can be coupled as hybrids: a development presently taking place in collaboration with an industrial partner.

VII. CONCLUSIONS

The author has described a range of applications of ion beams and plasma technology now being exploited at Culham Laboratory in its commercial business area. As stated above, this ranges up to complete turnkey systems, although it includes feasibility studies, component development, and contract research and development. In a generic sense, Culham is concerned with any application of particle interactions, in either beams or plasmas. We are seeing a continuous growth in this business area.

ACKNOWLEDGMENTS

It is a pleasure to use this opportunity to thank the members of the Particle Beam Division at Culham, associated engineers, and the Commercial Division, for not only their contributions to this paper, but also their efforts in creating this very dynamic area of business. Also, the author would like to acknowledge those from other laboratories and organizations, whose ideas have influenced Culham over the years. They may feel that this paper does not refer adequately to their work, but the objective was to review the Culham developments; not the total international effort.

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