AIP | Review of Scientific Instruments

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Citation: Rev. Sci. Instrum. **61**, 665 (1990); doi: 10.1063/1.1141900
View online: http://dx.doi.org/10.1063/1.1141900
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v61/i1
Published by the American Institute of Physics.

Reflections (invited)

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(Presented on 14 July 1989)

The interplay between three issues—ion sources, electrostatic beam formation and acceleration, and beam transport—is considered from a historical perspective, with reference to several important innovations.

INTRODUCTION

I was asked to give a talk on reflections on 20 y in ion sources; but immediately realized that my battles go back longer. In 1951, I started my Ph.D. studies on *d,n* and *d,p* reactions on the 9-MeV cyclotron, under Roy Middleton, who is well known to many of you. The ion source at the center of the machine was a PIG in both senses of the word. The gas was fed into it by leaking through a palladium tube; the tubes often broke and we poor students were blamed. Now I know it was due to energy release in cold fusion and we were not so clumsy.

Later, in 1965, I started a project on laser-produced multiply charged ions to investigate issues relevant to solar corona or solar wind constituents. This did not get far for many reasons; but it started me thinking about many issues to do with ion sources and beams and my interests expanded rapidly in the 1970's. I want to address some of these issues today under three headings: (i) ion sources, (ii) electrostatic-beam formation and acceleration, and (iii) beam transport.

I. ION SOURCES

In my view, progress in ion sources is due to three things: innovation, physics evaluation, and technological advances. It would be invidious to single out individuals, although the composition of this summary board does represent some of the most innovative ion source people in the world. What I want to do is to take two examples close to my interests.

A. ECR sources

Richard Geller for several years developed ECR plasmas as a contribution to the European Fusion program. As the program turned away from such studies, he had the insight to realize the potential as a source of multiply charged ions. To misquote an old saying "If you can't join them, beat them." This was the innovative first step.

It is interesting to see that the second step is still being taken. The physics of these sources is not yet clear, except in one issue I believe; i.e., the cutoff density relates to the rf frequency and thus magnetic field.

Those of us who argue in the fusion field for particle heating rather than rf, point out this weakness in rf systems. However, we are overwhelmed by all the rf physicists who want to study the physics as much as to achieve the end result. You in the ion source field have gone for results first.

The third step is coming, based on the advancing technology of high frequency generators, and high field superconducting magnets. This quantum jump will, as emphasized at this meeting and in these reviews, bring about a major improvement in sources.

B. Bucket and filter sources

Buckets have provided useful containment systems for plasma generation; not uniquely so, but dominantly so. In my view, the addition of a magnetic filter as pioneered at Berkeley is a major innovation whose total capabilities have not yet been exploited.

The modification of electron energy distribution or temperature has undoubtedly been a major element in H^+ and H^- sources. The possibility that it could lead to lower ion temperatures seems not yet to have been exploited. So the first step was taken but not completed.

The second step has been partially taken. Some work on the physics of filters has been done. But I feel we need to delve more deeply and ask and answer more questions.

The third step is also in progress. Alternative ways of coupling energy into discharges are being exploited. Ways of introducing metal vapors, exotic gases, etc., are all being pushed.

Where does this take us, and where do we want to go? Looking forward is always more difficult than looking backwards. Should we take Peter Rose's statement of 10 mA of $q = 4^+$? This gets us to higher energies. Or do we take Professor Takagi's statement of low energies and hence low q/NA for clusters? or both?

Since I come from a background of plasma sources I am not qualified to address Professor Takagi's issues—anyway he has done so already.

Rather I will emphasize the need to reoptimise sources for heavy ions. We have, in many cases, built on our experience of hydrogen and deuterium sources without addressing the effect of increased mass in the sources. This I believe will accelerate the new examination of containment in ion sources which will couple to the alternative methods of plasma creation for a new. generation of hybrid sources. Technological improvements will continue to make further progress possible.

I want to make a final comment on sources concerning the physics. We are all recognizing more and more how little we know of the collisional processes in the source and at the walls. Hydrogen, the simplest atom, and a relatively simple

 0034-6748/90/010665-02$02.00

molecule, cannot be evaluated properly. I see computer calculations—but each application involves new assumptions. H^+ codes are not the same as H^- codes; and what about the walls?

II. ELECTROSTATIC ACCELERATION

This is an area in which there is relatively little innovation and a major degree of consensus. That is, for positive ions, about which I will talk first; negative ion accelerators are more controversial.

Recent innovations are really limited to variable energy at constant current. Wulf Kunkel rightly pointed out that positive ions extract themselves, and all we need to do is design accelerators. This is why analytical modeling, of which I am still a strong proponent, has been successful. The Langmuir-Blodgett relations work well when coupled to lens theory.

Computer modeling helps in detail of evaluating aberrations and so minimizing emittance growth. John Whealton's papers show some of this. But even some of this work can be done analytically.

As I have already said, we at Culham are still pursuing beam optics studies. We are concerned with low perveance systems arising from high voltage beams and restricted current. For heavier ions, charge-exchange losses can be large and need to be evaluated. High x-ray yields are observed and need to be explained.

Negative ion beams from volume sources are more difficult to describe. They do not self-extract and the application of an accelerating voltage plays a role inside the plasma. Present computational models are, to the best of my knowledge, all H^- positron models and do not correctly describe the extraction/acceleration process. Our approach to this is purely empirical and we have as a community some proof of quasiconstant perveance beams formed in the first stage of acceleration.

III. BEAM TRANSPORT

This is an area which is a theoretician's delight. After the critical early work on space-charge neutralization, little has been done of an innovative nature. Even at that period of time, theoreticians went mad. Now the subject is quieter, but still is dominated by theories of stability and equilibrium. Unfortunately, in my view, it is difficult to discuss stability without having understood equilibrium.

There are no two theories that coincide in any one aspect of this problem. Curiously every theory has been tested against experiment and found to be consistent. One thing however, does seem to be established, i.e., that most positive ion beams in fusion applications are space-charge dominated and not emittance limited.

In this respect the results reported by Dudnikov at this meeting on the focusing of intense beams of low transverse energy are very interesting.

I would recall that many years ago, the work in the USSR highlighted the problem of beam transport in magnetic fields from nonquiescent sources. This led them to the conclusion that high power could not be produced for fusion experiments.

The development of a quiescent 10-A source at Berkeley changed this. But even so, we all based our systems on close-coupled gas neutralizers. We have all been careful about decoupling sources and neutralizers and incorporating focusing elements. This result at Novosibirsk has radically changed our views, and our perceptions.

IV. CONCLUSION

Finally let me thank all of you for the stimulation and excitement of working with and talking to you. May I wish all of you success in continuing to develop this subject and to applying it for the benefit of humanity.