PRODUCTION OF PROTONS AND NEGATIVE IONS WITH LOW ENERGY SPREAD

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Summary

The suitability of the duoplasmatron and RF ion source for the production of low energy spread beams required for klystron bunching on Van de Graaff accelerators has been investigated. An increase in the proton and negative ion beams obtained from the duoplasmatron source can be achieved by extracting from the edges of the arc. The energy spread depends on the source conditions and varies from 8 to 50 eV. In RF sources the energy spread is influenced by the oscillator design and coupling and is less than 50 eV for a push-pull system.

Introduction

The application of bunching by velocity modulation to ion beams injected into single ended or tandem Van de Graaff accelerators, in order to produce nanosecond pulse widths for time of flight experiments, requires an ion source with low energy spread. Energy spread in the ion beam causes debunching and an increase in the pulse width. The maximum permissible energy spread for a given pulse width is proportional to the bunching voltage but there is an upper limit to the bunching voltage which can be used due to the chromatic aberration of the injector system and the acceptance of the accelerator. In the case of a sine wave bunching potential, $E = E_m \sin \omega t$, it can be shown[1] that for a pulse width Δt, an energy spread δE will not appreciably affect the pulse width if $\frac{\delta E}{E_m} \ll \omega \Delta t$. ($\omega \Delta t$ normally 0.05 - 0.1). In our present applications an energy spread less than 100 eV is required. The ion source must also deliver a high percentage of atomic ions because even though negative ions could be formed from molecular ions by dissociation followed by charge exchange, the dissociation energy gives rise to an energy spread amounting to 1 keV for 30 keV ions[2]. The suitability of the RF type source and the duoplasmatron source both as positive and negative ion source has been investigated.

Measurement of Ion Beam Energy Spread

The energy spread has been measured by two methods, a retarding field probe[3] and a method which makes use of the energy dependance of the focal properties of an einzel lens. The latter method has the advantage that the measurement can be made on the full energy beam. Briefly this apparatus consists of an einzel lens with an off axis slit at the lens entrance sampling the beam and a second on axis slit in front of the electron multiplier detector. If an ion energy E requires a lens potential V to bring the beam into the detector then ion energy $E + \Delta E$ will be brought into the detector if the lens potential is increased to $V + \Delta V$ and $\Delta E = E/_V \, \Delta V$. A ramp voltage is applied to the lens and the energy distribution is displayed on an oscilloscope.

Duoplasmatron Ion Source

Proton Production

To obtain a high proton output from the duoplasmatron high gas pressure, magnet and arc currents are required and also a long arc. The large source powers required give rise to practical difficulties in some accelerator applications and in the course of experiments to increase the efficiency, the variation of proton output across the arc was measured. The design of the source was such that the arc could be moved across the emission aperture (.005 dia) in the source anode so that plasma could be sampled from points away from the arc centre. Positive ion beams extracted showed a variation in the ratio of proton to molecular ions with the position of the emission aperture with respect to arc centre. The proton percentage increased towards the arc perimeter (see fig 1) and 60 - 70% H_1^+ can be obtained with source conditions giving mainly molecular ions with on axis extraction, i.e. low pressure and arc current. The currents available with the arc displaced are smaller due to the fall off in plasma density but even when the current is reduced to 10% of the on axis current the increased proton yield is still useful for most Van de Graaff applications.

Energy Spread of Duoplasmatron Ion Beam

The energy spread of the ion beam increases slightly with arc current but the source magnetic field has the largest effect. With no magnetic field i.e. Unoplasmatron conditions the spread is about 8 eV at half height and increases to 50 eV with high arc current and magnetic field. The measurements are summarised in Table I.

Table I

Variation of Energy Spread with Arc Current and Source Magnet

P = Source pressure (Torr) I_A = Arc Current (A)
The energy spread is in eV and both the width at half intensity and full width are given.

P	I_A	MAGNET COIL CURRENT (A)											
		0		1		2		5		8		20	
0.2	1	9	23	9	29	9	32	14	27	9	23	14	27
"	3	9	23	9	27	11	23	16	36	14	32	16	47
"	5	9	20	9	27	9	32	14	41	32	63	36	86
"	10	11	23	14	29	20	45	18	54	29	65	54	99
0.8	1	8	13	7	24	8	16	18	38	27	59	35	86
"	3	8	14	9	29	16	45	20	54	32	76	32	72
"	5	9	27	9	34	16	45	23	52	23	76	32	68
"	10	7	23	14	41	20	50	23	63	32	68	32	81

Direct Extraction of Negative Ions from a Duoplasmatron Source

Negative ions can be formed in the dissociation of molecular hydrogen[4] by electrons $H2 + e \rightarrow H^- + H$. Suitable conditions should exist near the outside of an intense arc where the gas density is high. It was found that, as the duoplasmatron arc was moved off axis with respect to the emission aperture in the anode, the negative ion current increased and reached a peak value near the edges of the arc. The negative ion output also increased with arc pressure with a maximum at about 1 torr. There is also an optimum arc length of 0.13" and arc current of about 10 A for maximum ion current. The source magnetic field is also important since for every point of extraction off the arc axis there is a value of magnetic field which gives maximum negative ion output. Fig 2 curve 1 shows the variation of negative ion current with the amount of arc displacement, the magnet being optimised at each point for maximum H_1^- yield and the value of field required is given in curve 2. The increase in magnetic field required as the arc centre is approached is consistent with negative ions being formed on the outside of the arc, since increasing the magnetic field reduces the arc diameter so bringing the formation region over the emission aperture. It has been calculated that an incoming H2 molecule entering an arc with electron density 10^{15}/cc,[5] mean energy 8 eV[6] has a mean free path less than 1 mm for dissociation and ionisation.[7] In an arc 1 - 2 mm radius a large fraction of the incoming molecules will be removed by dissociation or ionisation in the outer arc region. Since negative ion formation by dissociative capture requires an H2 molecule it is more likely to occur in the outer region than at the arc centre where the gas density will be low. Previous workers[8,9,10] extracting from the arc centre have reported electron loads of about 1 mA/µA of H_1^- but in the present source the total source loading is only 2 - 3 mA for 80 µA H_1^-. In addition most of the electrons are stopped on the extractor due to the effect on the electron trajectories of the source magnetic field in the extractor gap which is distorted by the displacement of the intermediate electrode. The ratio of electron current accompanying the negative ion beam after the extractor is given in curve 3.

The energy spread of the negative ions varied between 4 - 8 eV at half height and 10 - 20 eV at full width and is independent of arc current, source magnetic field and arc position.

Positive Ion Energy Spread in R.F. Sources

Several workers[11,12] have investigated the energy spread of R.F. sources and reported spreads varying from 70 eV up to 1 keV. Two methods of coupling the R.F. power into the source are commonly used, inductive by means of a coil around the source at frequency of about 20 Mc/s and capacitively through two ring electrodes at frequencies of 80 - 120 Mc/s. The large energy spreads are usually associated with the inductively coupled source and were thought to arise from the longitudinal electric field due to the large R.F. voltage across the coil or modulation of the plasma potential, although the details of the mechanism involved have not been clearly stated. Energy spread measurements have been made on a source using three different oscillators in order to study the effects of frequency and type of coupling on the energy spread.

Source A

The R.F. power from a 20 Mc/s anode tuned oscillator (500 watts) was inductively coupled into the plasma with a 5 turn 2" diameter coil, the peak to peak R.F. voltage across the coil being variable from 1.5 to 2.5 kV. Total energy spreads greater than 1 keV were found at the high R.F. potentials, the spread being roughly proportional to the R.F. potential (fig 3).

Source B

An 80 Mc/s push pull oscillator delivered power into the source through two 1½" diameter coaxial copper rings spaced 2" apart and the peak to peak voltage applied to the electrodes was 150V. The power output was only 80 watts and a magnet coil at the base of the source could be used to contract the plasma and increase the extracted current. The energy spread at zero magnet current was 25 eV at half height and 80 eV full width. A similar oscillator of 120 Mc/s gave the same energy spread. The magnetic field was the parameter most affecting the energy spread which increased to 65 eV at half height with a field of 1000 gauss (fig 3).

Source C

This source was excited by a push-pull 20 Mc/s oscillator, 200 watts inductively coupled into the source with a coil of the same dimensions as used in Source A. It was still capable of oscillating in the normal mode when deliberately unbalanced by connecting the H.T. input away from the centre of the coil. With the oscillator balanced a total energy spread of 60 eV was obtained and was independent of the applied R.F. potential, (up to 1 kV). However, when the oscillator was unbalanced so the anode voltages swung in the ratio 2:1 the energy spread increased to about 150 eV.

Comparison of Sources

The low energy spread obtained with the balanced source C indicates that inductive coupling, frequency and the large R.F. potential across the coil are not the cause of the large energy spread observed in source A. It appears that the different oscillator circuit used is mainly responsible for the energy spread, probably for the following reasons. A capacity exists between the coil or ring electrodes and the plasma which is connected to earth both capacitively and through the source anode fig 4. A R.F. potential with respect to earth applied to the exciting electrodes gives rise to a leakage current through the plasma and its impedance to earth. If the R.F. potential applied to the electrodes is not symmetrical about AC earth then the plasma potential will tend to oscillate by an amount which depends on the relative impedances of the plasma with respect to earth and the electrodes. At high frequencies the plasma-anode impedance will be determined largely by the relative mobilities of the ions and electrons. Fluctuations in plasma potential will modulate the beam energy and will appear as an energy spread with D.C. measurements. In the push-pull case the R.F. potentials applied are symmetrical with respect to earth and there will be no net R.F. potential at the plasma and the energy spread will be that arising in the plasma.

Conclusions

The low energy spreads of ions from a R.F. source excited by a push-pull type oscillator make it suitable for klystron bunching systems, both as a positive and negative ion source (by inclusion of a charge exchange chamber). This has been confirmed by the production of 3.2 nS pulses in the AWRE tandem, as compared with 2.5 nS[15] from a duoplasmatron with charge exchange chamber and 1 nS[14] pulse width from tests of a positive ion bunching system for use in the terminal of a 6 MV machine. It will also be possible with the R.F. source to produce pulsed tritium beams. The direct extraction of negative ions from the duoplasmatron, in addition to giving the lowest energy spread, gives a beam with very low emittance and the source is probably capable of further development to give currents greater than the 80 µA already obtained.

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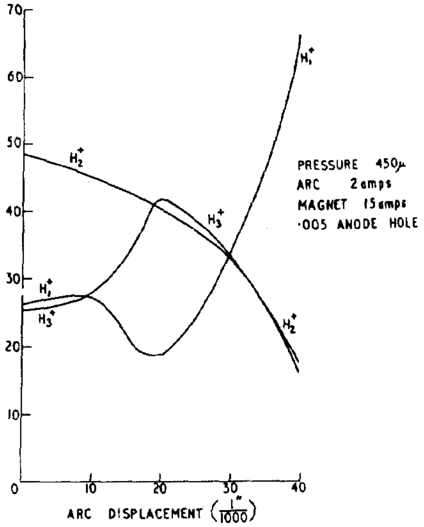

Fig. 1.

Percentage of protons and molecular ions extracted from a duoplasmatron source as a function of the distance of the point of extraction from the arc centre.

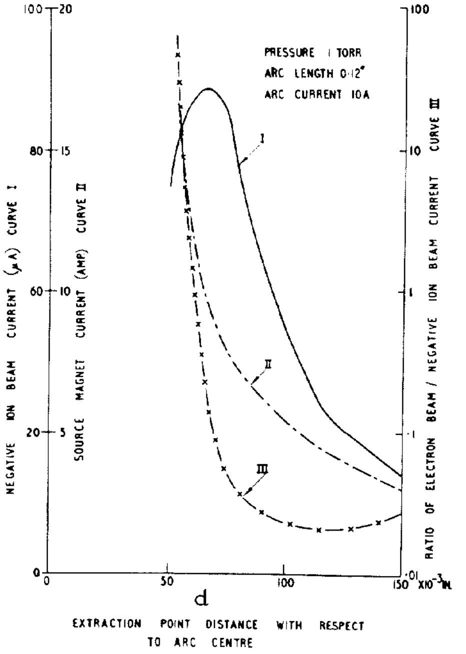

Fig. 2.
Direct extraction of Negative ions from a duoplasmatron source.

Curve I	Negative ion current (0.025" dia emission aperture in anode plate).
Curve II	Magnet current required for maximum H_1^- output. Field in arc gap 3A = 1 kG, 8A = 2 kG, 12A = 3 kG and 20A = 4 kG.
Curve III	Ratio of electron beam to negative ion beam.

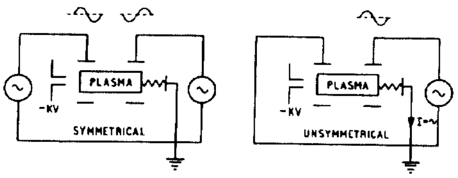

Fig. 4.
Ion Source equivalent circuit.

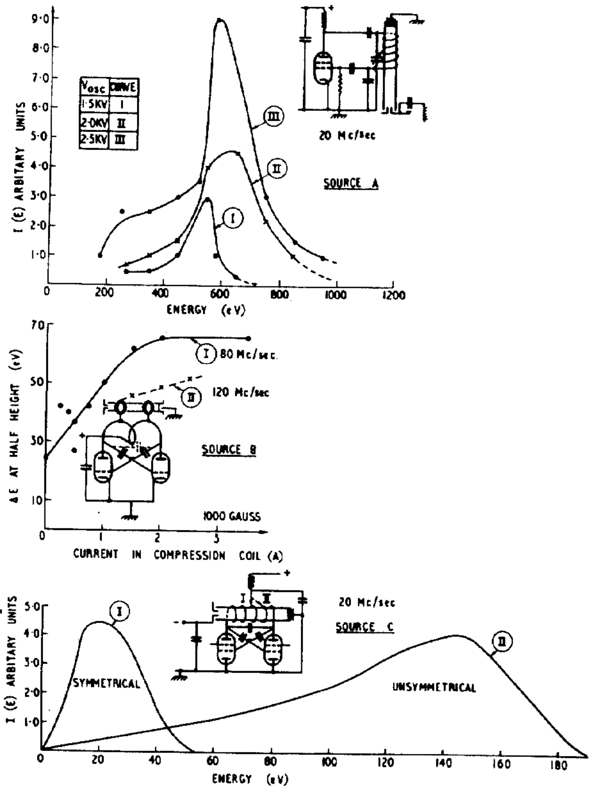

Fig. 3.
Energy spread of ions from a R.F. source excited by different oscillators and types of coupling.

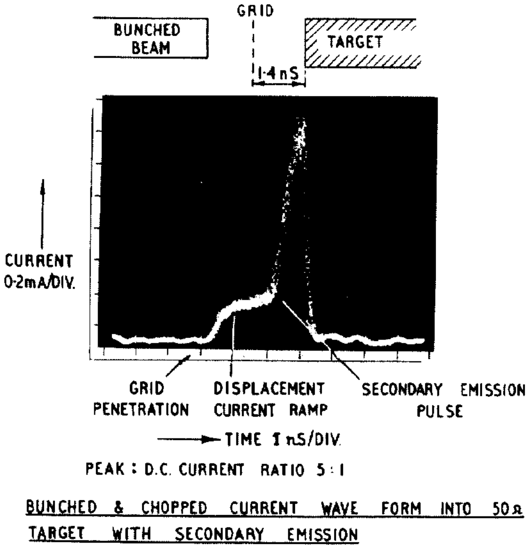

Fig. 5.
Bunched and chopped current wave form of beam from RF Source (B fig. 3).