PRE-ACCELERATION OF HIGH-CURRENT ION BEAMS

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Summary

The injection of high-current ion beams into linear accelerators is more complicated than that of low-current beams as two electrostatic systems: beam extraction and pre-acceleration are linked by the space charge action. This interaction between the parameters of extracted beams and of electrostatic pre-acceleration columns is examined both, experimentally and by computer simulations. The aim of the study is to find out the best overall conditions for the generation of high-current beams of certain energy, intensity, brightness, and ion species, within the restrictions imposed by existing systems.

As a main result, it can be shown that the ratio of the extraction and pre-acceleration voltages is the dominating parameter to influence the quality of the transported beam.

Introduction

Heavy-ion induced inertial-confinement fusion experiments[1] require high power density on the final target. This means, however, that already the injection system must provide high-brightness high-current ion beams, independently of the chosen accelerator type. Similar beam quality requirements will be needed to feed the heavy ion synchrotron now under discussion at GSI[2].

This was the reason to start experiments on the UNILAC injector with the aim to demonstrate its capability of pre-accelerating high-quality beams, delivered by the existing high-current ion sources.

Beam Generation

The high-current ion source CORDIS[3], developed at GSI, was chosen to provide the beam and operated with H, N, Ne, and Ar. During the whole operating time of 80 h CORDIS worked very reliably, with reproducible ion current parameters from day to day, and no service at all was necessary. The discharge is of the multicusp/reflex type and provides a homogeneous, quiet plasma of large cross section for a large range of densities. A variety of extraction systems can be used, according to the individual needs of ion current parameters.

The following extraction configurations have been used during the experiments: Single-aperture triode (EX2), triode with 13 apertures (EX3), and single-aperture pentode (two-gap system with screening electrode enclosed between two grounded electrodes)[4] (EX4). A screening electrode is always necessary with high-current extraction systems in order to impede that the space-charge compensating electrons were accelerated back into the source, causing very high thermal load and leaving the beam uncompensated.

The ion trajectories produced by the system EX2 were simulated using the code AXCEL-GSI[5]; in these calculations, the ion current density was varied until the code predicted full transmission of the extracted beam for the given acceptance angle of 30 mrad. The corresponding emittance diagrams are shown in fig. 1. a, b. The simulated figures fit very well the actual emittance figure, measured in 1 m distance from the source.

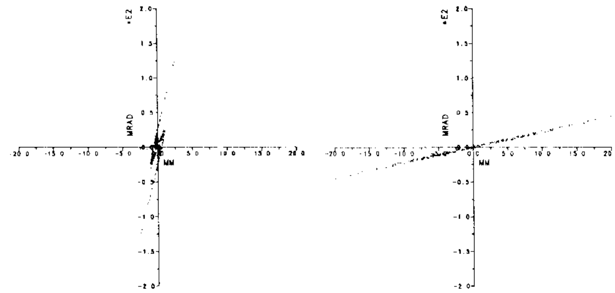

Fig. 1. Emittance diagrams of the simulated beam, 18.6 mA at 40 kV argon. a): immediately behind the extraction system; b): after a drift space of 0.5 m, assuming full space-charge compensation.

Between extraction system and acceleration column a drift space of 0.5 m length is inserted, imposed by mechanical restrictions. Dipoles and quadrupoles are avoided, to preserve the rotational symmetry of the beam, since asymmetries in the charge-density distribution would lead to strong aberrations of the accelerated beam, see below. The drifting beam is space-charge compensated to a high degree (> 90 %) due to ionization of the residual gas in the beam line; this is confirmed by the mentioned emittance measurement.

Acceleration

For the acceleration of high ion currents a single-gap structure[6] is better suited than multi-gap devices. Basing on previous experiences with the GSI 300 kV accelerator[7] computer simulations were conducted, again using the code AXCEL-GSI, to find an optimized gap configuration to start with. The charge-density distribution at the gap entrance resulted to be the most important parameter influencing the quality of the accelerated beam. As a general rule, the equipotentials of the accelerating lens - including the beam space-charge - should assume shapes closely similar to spheres.

The effect induced by an inhomogeneous distribution is demonstrated by simulations, see figs. 2 - 4.

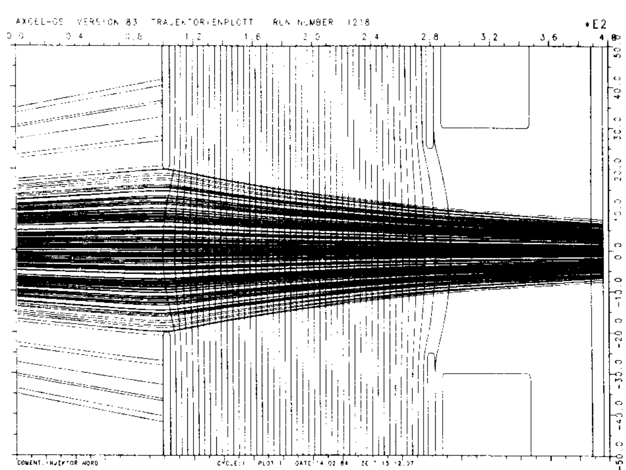

Fig. 2. Simulated argon beam passing the single-gap accelerating column; 190 kV voltage, zero current assumed.

While an injected Ar^+ beam of 15 mA with bell-shaped charge distribution (see emittance diagram fig. 1 b) is transformed into a hollow beam even a 150 mA beam keeps its solid profile as long as its density distribution at the gap entrance is uniform. Of course, a part of this 150 mA beam is lost in the gap because of its insufficient focusing strength.

Transport on Ground Potential

Immediately after the ground electrode a screening electrode on negative potential is inserted to maintain the space-charge compensation of the ion beam downstream. The necessary voltage depends on the geometry and on the charge density within the beam. − 5 kV applied to a 60 mm long and 60 mm wide tube proved sufficient in all cases.

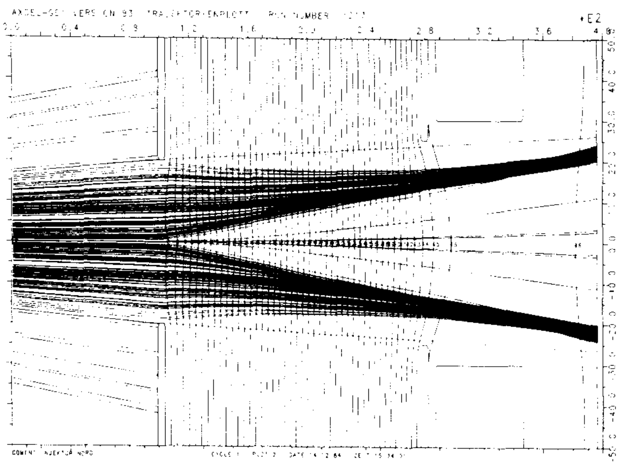

Fig. 3. As fig. 2, but beam current 15 mA with bell-shaped density distribution according to the emittance diagram in fig. 1 b.

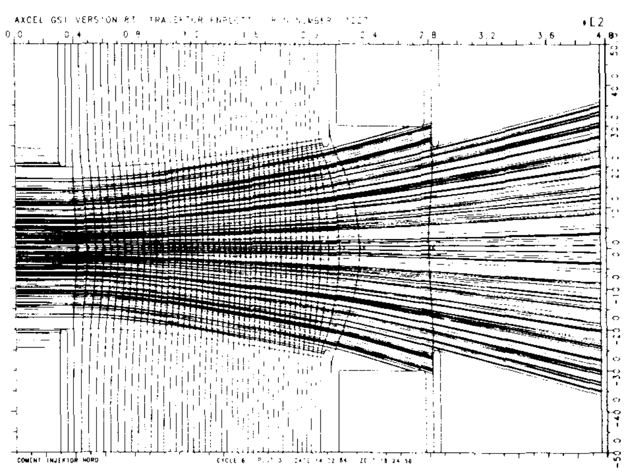

Fig. 4. As figs. 2 and 3, but beam current 150 mA with uniform density distribution.

At residual gas pressures in the order of 10^{-5} mbar, the build-up times for space-charge compensation[8] in the following part of the beam line, see fig. 5, are short as compared to the applied pulse lengths of about 1 ms. The typical triangular pulse shape, found in cases were the compensation time was comparable to the pulse length[9], did not occur during the experiments reported here.

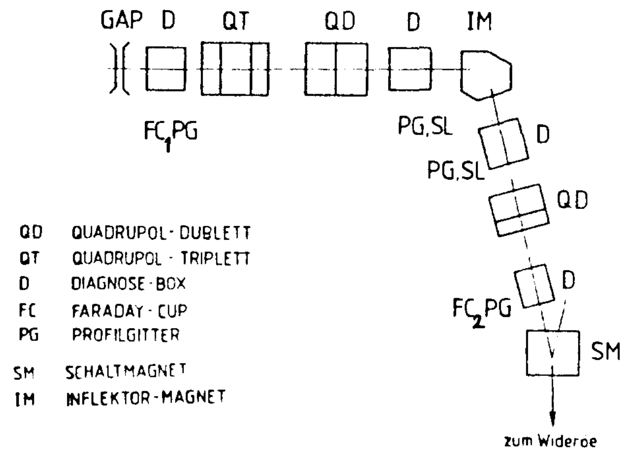

Fig. 5. Beam line on ground potential.

Operating

For a given acceleration structure, there always exists one optimum parameter set of extraction voltage, ion current, and acceleration voltage, to yield the highest ion current within the acceptance of the following beam line. These parameters, however, are coupled together. For example, the extracted ion current depends on the extraction voltage, while the total energy (sum of extraction and acceleration voltage) is determined by the needs of the RF accelerator, in our case 11.7 keV/amu. For the definite optimization there is only the ratio of extraction over acceleration voltage left, together with geometrical parameters of the system which cannot be changed during one run.

Fine-tuning can still be accomplished by slightly varying the ion source operation parameters gas pressure, discharge power, and cathode emission which in a complicated way once more influence the extracted ion current. Changing these parameters also leads to a variation of the charge-state composition in the source plasma, with high discharge voltage and low pressure, for example, higher charge states are favoured.

Measurements

For experiments with the elements H, N, Ne, and Ar, the following extraction and acceleration configurations were applied:

Symbol	Type	Aperture(s)	Extr. gap widths / mm
EX1	Triode	1•ø6/5/5	4.5, 1
EX2	Triode	1•ø7/5/5	4.5, 1
EX3	Triode	13•ø2.5/2.5/2.5	4.5, 1
EX4	Pentode	1•ø13/13/8/8/8	1, 4.5, 1, 1
BE1	acc.gap	ø40/50	100
BE2	acc.gap	ø40/50	180

In the two Faraday cups with 30 mm aperture, see fig. 5, the following currents could be measured:

Extr.	Gap	Voltages/kV	Ion	I_{FC1}/mA	I_{FC2}/mA
EX1	BE1	26+134	N^+	12.0	5.0
EX2	BE1	32+117	Ne^+		8.0
EX3	BE2	25+200	Ne^+		10.0
EX3	BE2	37+210	Ne^+	22.0	20.0
EX3	BE2	30+210	Ne^{++}		1.2
EX4	BE2	43+190	Ne^+	30.0	12.0
EX4	BE2	45+160	H^+		5.5
EX3	BE2	25+190	Ar^+		16.0
EX3	BE2	25+190	Ar^{++}		3.0

The fact that the emittance values measured immediately behind the source are much smaller than the values quoted above obviously marks a considerable emittance growth due to the acceleration process. A possible explanation can be seen in a re-distribution of the ions caused by non-linear space charge forces. This effect can be active only in the uncompensated part of the beam, that is, within the gap.

During these experiments it was felt that the physical limits of the existing structure were almost reached. For higher currents to be transported, a new "compound system", see figs. 6, 7, was designed which incorporates an electrostatic einzel lens as an active component. Such a system should facilitate loss free pre-acceleration for a large range of currents, ion species, and acceptance conditions[10]. Special care has been taken to suppress aberrations by appropriate electrode shaping.

Conclusion

The transmission values for different structures typically range between 0.7 and 0.9. The highest losses were seen with the pentode extraction system, indicating a severe mismatching between the produced high-brightness beam and the acceleration gap; the best transmission was obtained by the multi-aperture triode.

The beam waist after acceleration, situated halfway between gap and first triplet, had widths of 30 with the pentode and about 5 mm with triodes, even with multi-aperture systems. The divergences amounted to about 20 mrad; this leads to absolute emittance values between 100 and 500 mm mrad, the latter one exceeding the following beam line acceptance.

References

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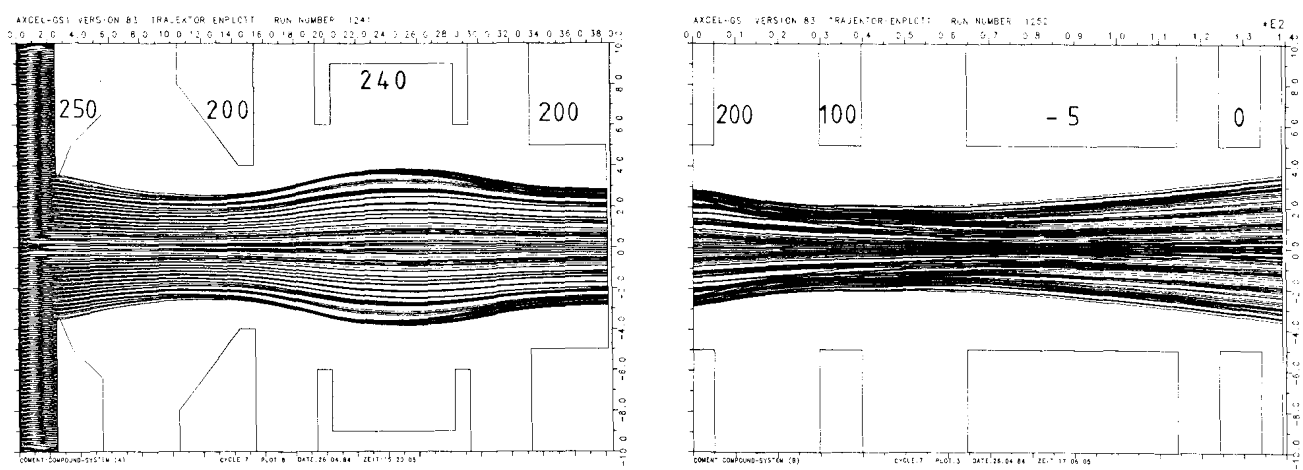

Fig. 6. Simulated ion trajectories in the compound system. Electrode potentials in kV; 26 mA of argon. Left: extraction part. Right: acceleration part, with compressed horizontal scale.

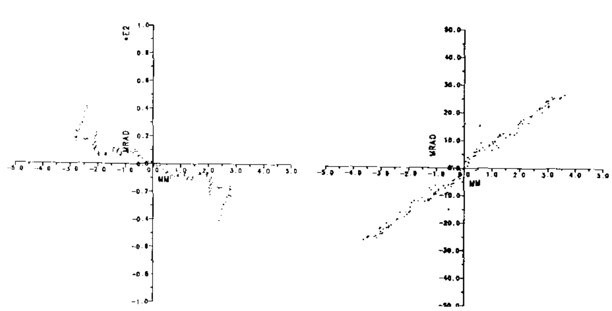

Fig. 7. Calculated emittance diagrams after first (left) and second part (right) of the compound system.