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HIGH CURRENT EXPERIMENTS IN A WIDERÖE STRUCTURE

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Summary

High intensity Helium beams have been accelerated in the Unilac Wideröe structure. The experimental results, especially the space charge limit and the emittance growth, are reported and compared with computer simulations.

Introduction

Heavy ion drivers for inertial confinement fusion (ICF) depend on the ability to produce high intensity, high quality beams. Deterioration of the beam quality tends mainly to occur in the low energy stages of acceleration. Up to now there exists no self-consistent analytical theory for the three-dimensional high current dynamics in accelerators. Therefore experimental and computer simulation work is needed to clarify design issues and merits of various low beta structures.

The most promising scenarios for a driver incorporate the Wideröe structure. The main parameters of the GSI Wideröe structure are fairly identical with the requirements of an ICF-linac. Therefore, high current experiments were planned with Helium and Neon ions at the Unilac. In 1980 the studies have been started with He^+; Ne^+-beams will be foreseen after a reconstruction of the Unilac low energy transport line at the end of 1981.

Ion Source and Low Energy Beam Transport

During usual Unilac operation with highly charged heavy ions, the intensity of the beam is far below the values for space charge dominated transport and acceleration because of the limited yield from the ion source.

For the experiments to be reported here the reflex discharge source ELSIRE[1] was chosen which on a test stand yielded 12 mA of He^+ at 47 kV extraction voltage from an aperture of 4 mm diameter. The discharge was pulsed for 2 ms at 50 Hz, with pulse powers up to 20 kW. The extraction aperture was a straight hole with a 45° cone machined from its outer border.

In order not to interfere with the routine accelerator operation the source was placed in prolongation of one of the standard injection beam lines, about 14 m distant from the accelerator.

With this arrangement, however, only 1 mA He^+ could be transported to the Wideröe, while about 10 mA were requested. Even when a 7 x 3.1 mm multiaperture extraction was used and the source yielded 120 mA ion current only 1.1 mA were measured in front of the Wideröe. This value could finally be increased to 2.5 mA by installing a differential pumping system behind the source, thus reducing the pressure in the first part of the beam line from $3 \cdot 10^{-5}$ to $3 \cdot 10^{-6}$ mb. The remaining losses were attributed to emittance growth of the beam passing through several magnetic lenses. In fact, on the test stand the normalized emittance increased from 0.04 to 0.24 mm mrad when the beam was focused by a 80 mm aperture magnetic quadrupole triplet. Both, aberration and blow up due to loss of space charge compensation seem to cause this effect. With the 2.5 mA beam, the first Wideröe experiments were carried out. A considerable increase of the injection current was achieved in a following step by installing the source 3.5 m in front of the Wideröe during a two-week shut-down of the Unilac. Thereby, up to 13 mA could be injected.

Fig. 1 shows a view of the temporary experimental set-up, Fig. 2 is a schematic layout of this transport line and gives detailed information on beam diagnostic elements.

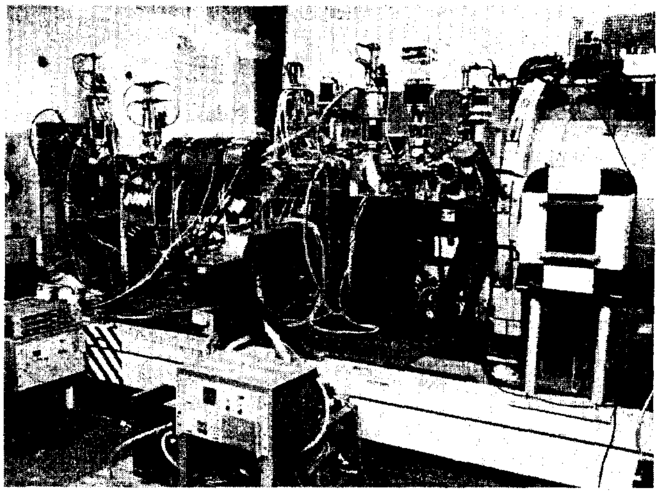

Fig. 1 View of the experimental set-up

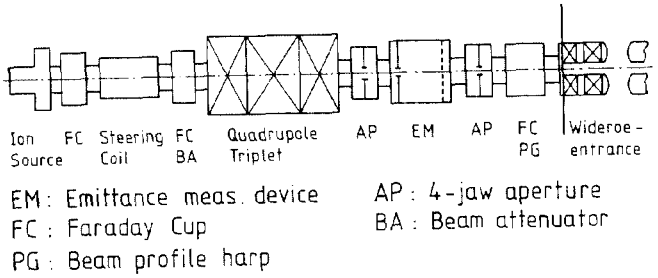

Fig. 2 Schematic drawing of the experimental set-up

The elaborate beam diagnostic system at the Unilac[2,3] allows for measuring of the following beam parameters: current by Faraday cups with magnetic and electric suppression of secondary particles, horizontal and vertical beam profiles with harps, transverse emittance in front and behind the Wideröe linac, energy and microstructure of the beam pulse by capacitive pick-ups. The double slit system is used for injection of beams with variable emittance. Thereby also a "pencil"-beam can be generated to measure the radial acceptance.

Computer Simulation

The six dimensional linear accelerator code PARMILA-GSI has been applied to calculate the beam dynamics with space charge dominated beams. This code is based on the 1978 Los Alamos version[4]. It has been extended to include the Wideröe structure operating in π-π or π-3π mode. Space charge forces can be included by a number of ways:
1. Forces due to particle - particle interaction, summing the forces point by point, no symmetries are assumed.
2. The charge distribution of a bunch is simulated by many rings. From this the radial and longitudinal electric fields are computed at the mesh points of a two-

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dimensional lattice in r-z space.

3. The forces in a homogeneous ellipsoid are calculated by an analytic expression of the electric field.

The code has usually been run for 500 particles, but the number can be increased up to 5000 particles.

GSI Wideröe Linac Parameters

Experimental and computer studies have shown that the most important effects on the beam are generated in the first part of the Wideröe linac. Therefore most of the experiments have been performed at Wideröe tank 1 energy. The parameters of tank 1 and some properties of very low intensity Unilac beams are listed in Table 1.

Table 1

Parameter and Performance of Wideröe Tank 1

Frequency	27.1 MHz
Entrance Energy	0.0117 MeV/u (β = 0.005)
Exit Energy	0.217 MeV/u (β = 0.0216)
Accelerating Mode	π - 3π
Focusing Lattice	F 0 D 0 (Magnetic Quadrupoles)
Number of Gaps	36
Gap Voltage Gradient	5.4 - 6.6 MV/m (U^{9+})
Range of Ions	Ar - U
Peak Current at	0.01 emA U^{9+}
UNILAC Operation	0.15 emA Ar^{13+}
Input Emittance (normalized)	ca. 0.25π·mm·mrad
Emmitance Growth	ca. 2.0
Brilliance (I/ε_N^2)	
Input	2.5 mA/(mm·mrad)^2
Output	0.5 mA/(mm·mrad)^2

Experimental Results

Current Limit

Fig. 3 shows the measured current limit of the Wideröe tank 1. Different sets of drift-tube quadrupole gradients were checked for maximum transmission. The radial matching was varied in a wide range by the triplet and two singulets (see Fig. 2). The resulting maximum output currents were in the range of 1.5 - 1.9 mA (equivalent current limits for 1.7 mA He^+: 9 mA Ne^+, 44 mA Bi^{2+}, 56 mA Xe^+, 100 mA U^+). The transmission decreases as the input current increases. At low intensity, the expected 25 % efficiency (synchronous phase 30°) was verified. Transmission starts to decrease above 4 mA of injected dc current. The injected 90 % emittance changed slightly for different current levels from 0.12 to 0.15 π mm·mrad. The brightness of the injected beam is quite high - 500-800 mA/(mm mrad)².

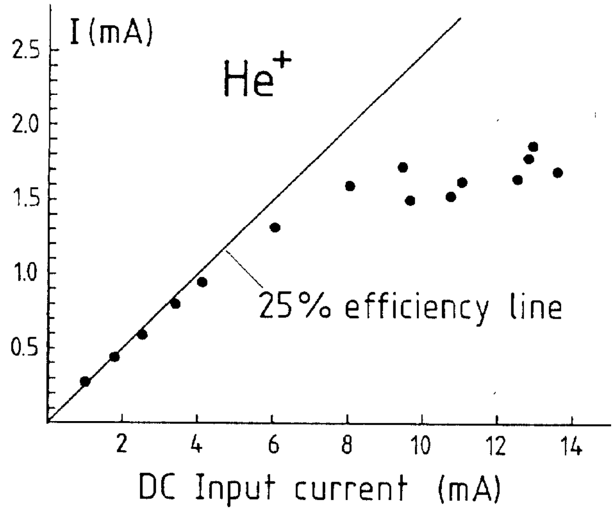

Fig. 3 Maximum current transmission

The numerical studies were performed with different space charge routines. In Fig. 4 the transmission is shown along the Wideröe linac, calculated with the ring model (s.above). The calculated current is about 25 % higher in comparison with the measured value. The recently implemented space charge routines deliver both higher and lower values. The explanation of the differences requires further work on the space charge model. In addition, the topic of optimum input beam parameters and quadrupole settings for maximum transmission requires a substantial effort.

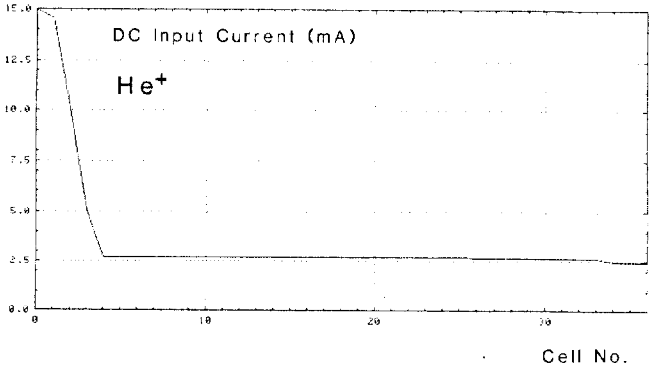

Fig. 4 Computed particle transmission in the Wideröe tank 1

The efficiency of the existing double drift bunching system decreases as the input current increases. At 2.5 mA no improvement of transmission could be measured with the bunchers switched on. This result fits to calculations with an unneutralized beam behind the bunchers.

The output energy could be measured very accurately with two capacitive pick-ups by the time of flight method. The design energy (see Table 1) was confirmed. The pulse width of about 3 nsec measured directly behind the Wideröe tank 1 did not differ from low current value. The pulse width at a 6.5 m distant pick-up increases at high current to 12 - 14 nsec, compared with 4 - 5 nsec at low current. The broadening of the pulse results from the energy spread after the accelerating process and the space charge forces acting on the drift between the both pick-ups. Both effects cannot be separated. Computer studies show that the energy spread after acceleration should not increase at higher intensity.

Emittance Growth

From the emittance scans at the entrance and exit of the Wideröe linac, the RMS and the total emittance was calculated. Within the accuracy of measurements the growth rates of the total and RMS emittance were in the same range.

Low intensity and low brightness beams have a growth rate of about 2 (Fig. 5). At current saturated mode of operation the emittance grows apparently more. In Fig. 6 a a typical measurement at maximum current is shown. The measured growth rates are well confirmed by computer studies (see Fig. 7). In Fig. 6 b the horizontal and vertical input emittances were reduced by a factor of 2 compared to Fig. 6 a without changing the brightness of the beam. The corresponding growth rate is than two times higher. At further reduction of the input emittance, Fig. 6 b demonstrates a growth rate of more than 20. It can also be seen from Fig. 6 c, that starting with input emittances of different sizes in both planes results in the same size of output emittances. This effect was observed down to an input brightness of about 40 mA/(mm mrad)². The measurements show in agreement with computer simulation that the emittance of a high brightness beam increases to a lower bound of the output emittance which is defined by the machine acceptance[5].

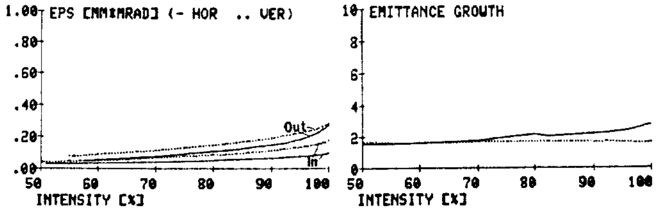

Fig. 5 Emittance growth at very low intensity

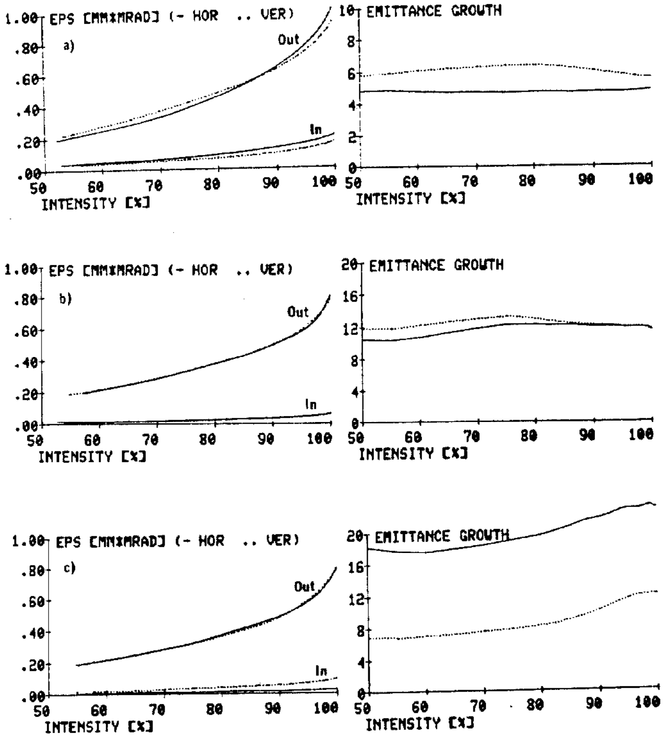

Fig. 6 Emittance growth at different input emittances

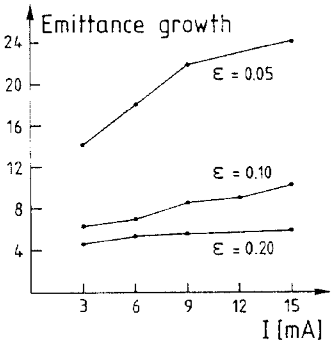

Fig. 7 Computed emittance growth

As the consequence of the measured emittance growth and the transported current an enormous dilution of the input brightness can be stated. The maximum brightness of the dc input beams was in the range of 400 to 1000 mA/(mm mrad)², whereas at the saturated current level the output brightness decreased to about 4 mA/(mm mrad)².

In the near future, experiments with medium intensity and brightness are planned in order to get more information on beam behavior in the transition region between low and saturated currents.

Conclusion

The GSI Wideröe linac was operated for the first time at the high current region where the structure is saturated. The measured output emittances indicated enormous growth rates for high brightness beams. The lower bound of the output emittance was experimentally found. The results are in a good agreement with the computer studies and encourage to proceed with design studies for high current rf linacs.

Acknowledgement

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