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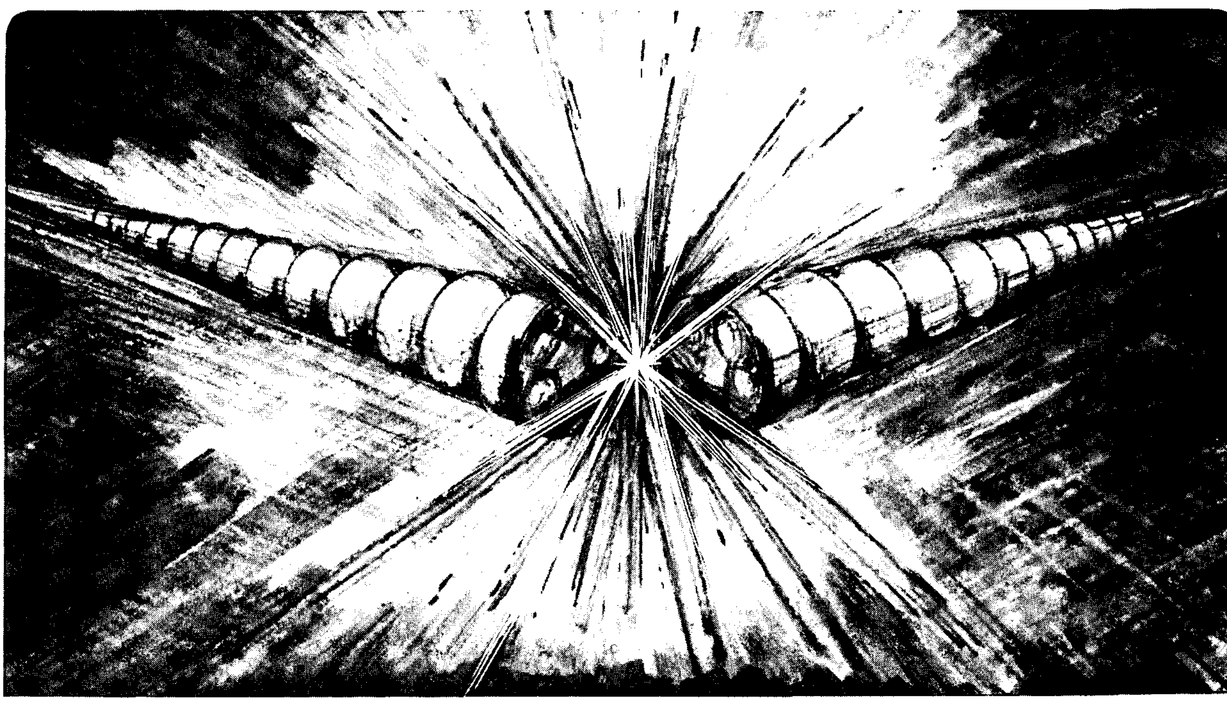

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HEAVY ION FUSION INJECTOR EXPERIMENTS*

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Summary

We report on three experiments performed in connection with the 2 MV electrostatic quadrupole (ESQ) injector under construction at Lawrence Berkeley Laboratory [1]. Scaled experiments have been conducted to study possible beam emittance growth due to beam aberrations in an ESQ injector. The experiment uses the SBTE (Single Beam Transport Experiment) accelerator system, quarter-scale ESQ setup and a potassium ion diode source. Measured emittance growth changes significantly with variations in current and diode energy, in good agreement with theoretical predictions. In addition, beam transport experiments were performed in a 1 MV axisymmetric electrostatic aperture column using a zeolite 1" diameter potassium ion source. Experimental measurements in good agreement with 2-1/2 D simulations showed that low emittance beams can be produced in axisymmetric structures. Finally, ESQ breakdown voltage tests without beam were performed at up to two times the quadrupole working voltage.

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1. Introduction

The 2 MV injector is being developed at LBL for the Heavy Ion Fusion Accelerator Research (HIFAR) program and the Induction Linac System Experiments (ILSE) experiment. The ILSE now under study at LBL will address the physics issues of particle beams in a heavy ion fusion driver scenario. The injector consists of a diode of up to 1 MV, followed by electrostatic quadrupoles (ESQ) to simultaneously focus and accelerate the ion beam to 2 MV. A 2 MV pulsed Marx generator is used to drive the injector ESQ-Diode system. We report on three experiments that are connected with the injector design and construction, the ESQ scaled experiment, beam transport in an electrostatic aperture lenses accelerating column experiment, and the quadrupole breakdown test experiment.

2. The ESQ Scaled Experiment

Recent studies of the ILSE injector are looking into a design option that combines a single gap diode (0.5 to 1 MV) with a (1 to 1.5 MV) ESQ accelerator. Beam dynamics simulations along the ESQ section are predicting a possible growth in the transverse emittance of the ion beam, known as the "energy effect." This effect is a result of phase space distortion due to the variation of particle energy with radial position in an electrostatic quadrupole. The distortion is most severe when the quadrupole voltage is a significant fraction of the beam energy. The objectives of the scaled ESQ experiment are to study the transverse beam dynamics in the ESQ and in particular the dependence of phase space distortion on the diode voltage and current.

The experiment is performed on the LBL Single Beam Transport Experiment (SBTE) accelerator. Figure 1 shows a schematic of the experimental setup. The quadrupole configuration is scaled to a quarter of the ILSE ESQ injector. The source is designed using EGUN calculations while preserving the ILSE injector diode perveance. An injector design with a 500 kV diode and a current of 790 mA is scaled into a 10 mA, 24.6 kV source diode at SBTE whereas an ILSE 1 MV diode design is scaled to 8.1 mA and 30 kV source. The SBTE accelerating column consists of a single 1.34" gap diode using an one inch alumino-silicate (Zeolite) potassium source. The source uses a 55° Pierce electrode and a 10 mm apertured fine extraction grid (100 lines per inch) to minimize emittance growth at the source exit. The quadrupoles are energized using the existing SBTE quadrupole d.c. power supplies connected to form an accelerating ESQ setup. The source is pulsed to +47 kV using the 120 kV SBTE Marx generator and a capacitor divider. The extraction grid is kept at +20 kV, thus maintaining a diode voltage of 27 kV (between extraction grid and source emitting surface). The ESQ exit quadrupole electrode voltage is -7 kV, whereas the input quadrupole voltage is 20 kV; thus the beam is accelerated from a diode energy of 27 keV to 54 keV at the ESQ exit.

The beam input parameters (source exit) were measured using a double slit emittance scanner. The measured input parameters which were found to be in agreement with previous EGUN calculations were used to simulate the beam envelope and transverse dynamics parameters for the experiment diode ESQ setups. The quadrupoles current (A.C. coupled and integrated) wave forms were monitored using a 2440 Tektronix scope. The beam current waveforms using a Faraday cup and the beam transverse phase space profile in the vertical and horizontal directions using double slit scanners, were monitored at the ESQ exit.

Figure 2 shows the space charge limited beam current measured vs. diode voltage to the 3/2 power, in agreement with EGUN calculations. The beam emittance and envelope were measured with the beam energy at the ESQ input set to the appropriate scaled versions of the 0.5 and 1 MV injector diodes. Figure 3 shows some of the beam envelope (radius 2Rrms, divergence 2Rrms) and transverse emittance measurements. They agree well with "WARP" 3D simulation results. Observed quadrupole current measurements were consistent with predicted beam induced image currents and in high current cases, with large beams hitting the quadrupoles. In addition, the measured quadrupole current was found to be consistent with Faraday cup total beam current measurements at the ESQ exit. One can see, as predicted, a significant emittance growth, up to 8 times, along the ESQ structure when using the 500 kV scaled diode. The observed emittance growth along the ESQ is associated with aberrations observed in the beam phase space profile. Figure 4 shows one of the measured beam phase space profiles in good agreement with simulation results using the "WARP" program. Furthermore, the emittance growth is reduced significantly when the source diode is set to scale the one MV injector diode. This experiment confirms the predicted advantage of 1 MV diode from the point of view of minimizing beam phase space distortions. On the other hand, raising the injector diode voltage may increase voltage breakdowns concerns in the diode. The scaled ESQ experimental setup can also be used to study quadrupole correction schemes proposed to eliminate the transverse emittance growth as observed along the ESQ when using the low voltage (500 kV) diode.

3. The ESQ breakdown experiment

The ESQ quadrupoles are designed to transport up to 1 MV 0.8 A 1 μs beams. The quadrupoles (Figure 5) are positioned between two support plates which also act as accelerating electrodes. Quadrupole voltages over 300 kV are needed in ILSE injector designs. The quadrupoles are contained in a graded insulating column. The insulators are covered with stainless steel shield rings to protect against X rays generated by stray electrons inside the ESQ. The quadrupoles are made of stainless steel. POISSON codes were used to design the electrodes and shields to minimize local electric fields. The object of the breakdown experiment is to test the ESQ design voltage holding capability. The injector Marx generator output pulse was used to condition and later to determine the quadrupole breakdown voltage. The Marx output waveform is a damped sine wave with a quarter period rise of 30 μs, a peak voltage of up to about 900 kV, a falling time of about 60 μs and a repetition rate of about one shot in 12 seconds. Two designs were tested: one with a quadrupole to support plate electrode gap of 5.5 cm and another with a quadrupole to support plate electrode gap of 7.6 cm. The Marx voltage was raised slowly and in small steps to allow a conditioning period of several hours to reach the quadrupole breakdown voltage. Later the voltage is reduced some to allow a no breakdown period of about two hours. We shall refer to that voltage as the breakdown voltage. The breakdown voltage of 700 kV was measured for the 7.6 cm and 550 kV for the 5.5 cm gap. These encouraging results enable us to look into designs of quadrupoles with working voltages of 350 kV, about half of the breakdown voltage.

4. Beam Transport Experiments in an Accelerating Column

Over the past few years, the HIFAR group at LBL had been studying a multiple aperture Pierce column injector. Prior to dismantling for construction of the new injector, a series of experiments were performed. These results were interesting in their own right. In addition, they provide an opportunity for code calibration and diagnostic checkout with direct relevance for the diode portion of the new injector. The accelerating column consists of a set of axisymmetric , electrostatic lenses, arranged in a conventional Pierce column geometry. The accelerating column concept had been considered as an option for the ILSE injector [2]. Beam transport experiments were performed along a "short" 1 MV column. The Marx generator described earlier was used to accelerate the beam up to 0.85 MV. Beam currents of up to 80 mA of potassium ions was delivered by an alumino silicate (Zeolite) one inch hot surface source [3] in a diode configuration. The beam current and duration can be determined by controlling the diode extraction electrode (grid) voltage. The diode gap is about 9 mm. The extraction pulse (up to 15 kV and 1 μs duration) is operated during the flat top period of the Marx output voltage. Electron trap electrodes were placed at the column exit. The trap prevents returning electrons from entering the column and damaging the extraction grid.

The beam current is measured at the column exit using a Faraday cup. The current can be monitored by a Rogowski current transformer positioned at the electron trap exit. The beam phase space profile including the beam envelope parameters and rms transverse emittance are measured using a double slit scanner. The first slit of the scanner is placed at a distance of about 11 inches from the electron trap at the column exit. The 5 cm long, 25 μm wide slits were aligned to be parallel to within 25 μm, giving a diagnostics system angular resolution of better than 0.2 mrad. The angular resolution is smaller than the beam phase space angular distribution caused by the source surface temperature.

Three source setups with various extraction grids were used. The first grid was made of nickel, 90% (optical) transparency and 70 wires per inch, and was found to be vulnerable and easily damaged. A stainless steel grid with a transparency of 50% and 200 wires per inch "survived" the experiments. Finally, we ran low current experiments without a grid.

Table 1 is a summary of experimental results measured when using the above source setups. The beam transverse dynamics in the above experiments is simulated using the EGUN and the GYMNOS 2-1/2D codes. Results of the simulations are shown in Table 1. They show very good agreement with the experimental results. Small "S" shape aberrations were observed in the measured beam phase space profiles. GYMNOS beam simulations suggest that the observed "S" shape can be associated with beam aberrations caused in the diode and in the vicinity of the extraction grid. The beam angular distribution at the beam center (not affected by the aberrations) is consistent with the angular distribution resulting from a source temperature of about 1000°C.

Table 1

Source extraction electrode	stainless steel grid		aperture (no grid)	
	simulated	measured	simulated	measured
Current (mA)	72	82	18	20
Radius (mm)	32.5	31.2	0.9	1.2
Angle (mr)	34.5	38.4	8	6
Emittance normalized (mm-mr)	0.26	0.25	0.05	0.04

Figure captions

Figure 1. Scaled ESQ experimental schematics.

Figure 2. Space charge limited diode (source) current vs. voltage to the 3/2.

Figure 3. Beam transverse dynamics, radius, angle and normalized emittance vs. diode voltage, in agreement with WARP simulations.

Figure 4. Measured, a, and simulated, b, beam phase space profile in X (radius) and X' (angle) at the ESQ exit.

Figure 5. ESQ voltage breakdown experiment setup.

References

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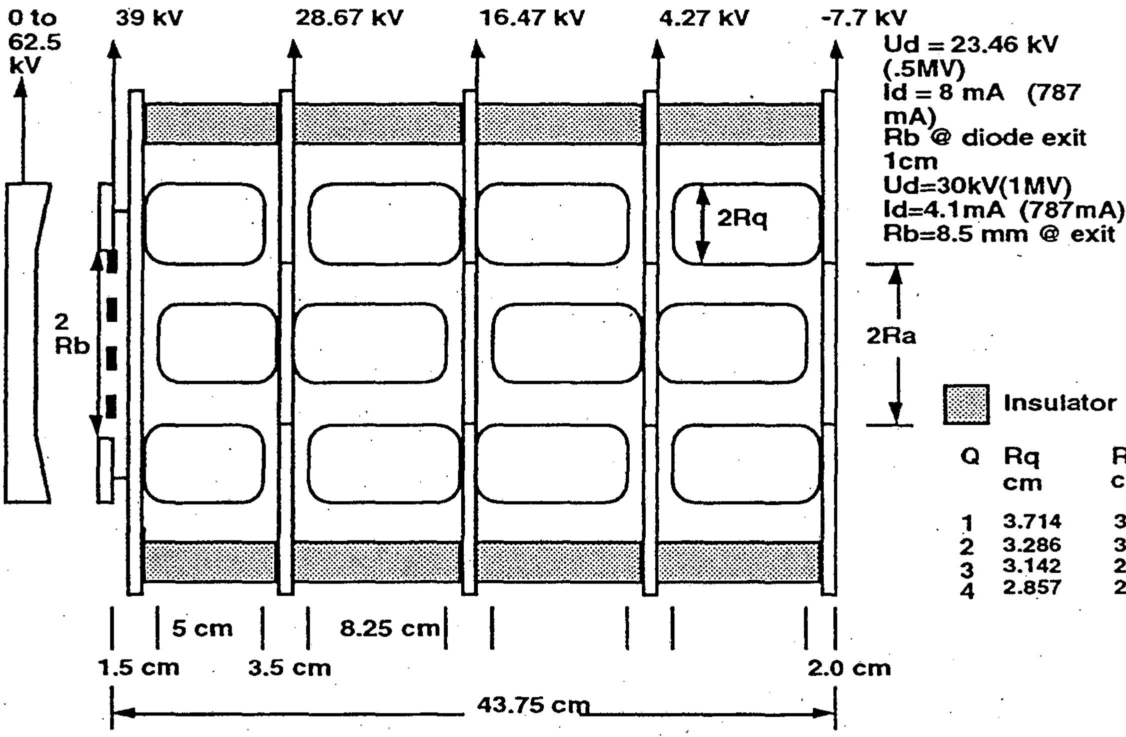
[2] ILSE Injector Workshop, Lawrence Berkeley Laboratory, Berkeley, CA, September 14-15, 1992.

[3] S. Eylon, E. Henestroza, W.W. Chupp, and S. Yu, International Symp. on Heavy Inertial Fusion, Frascati, Italy, May 1993.



Q	Rq cm	Ra cm
1	3.714	3.25
2	3.286	3
3	3.142	2.75
4	2.857	2.5

Figure 1

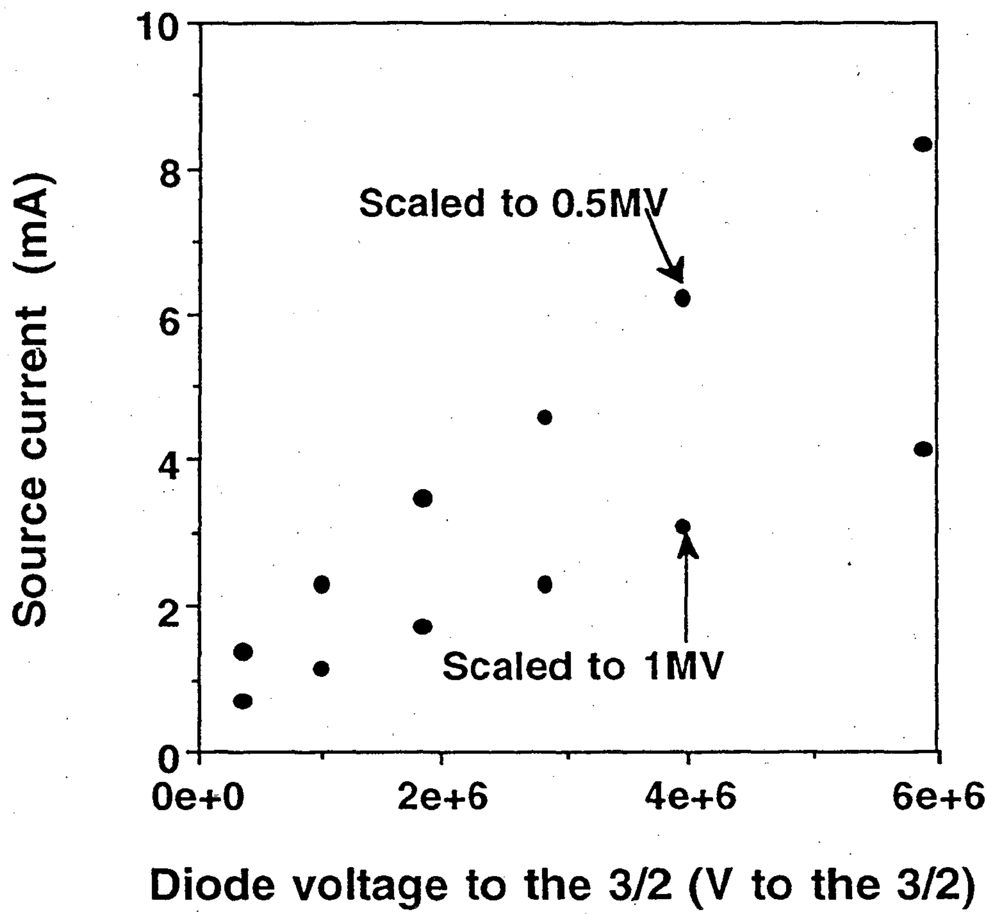
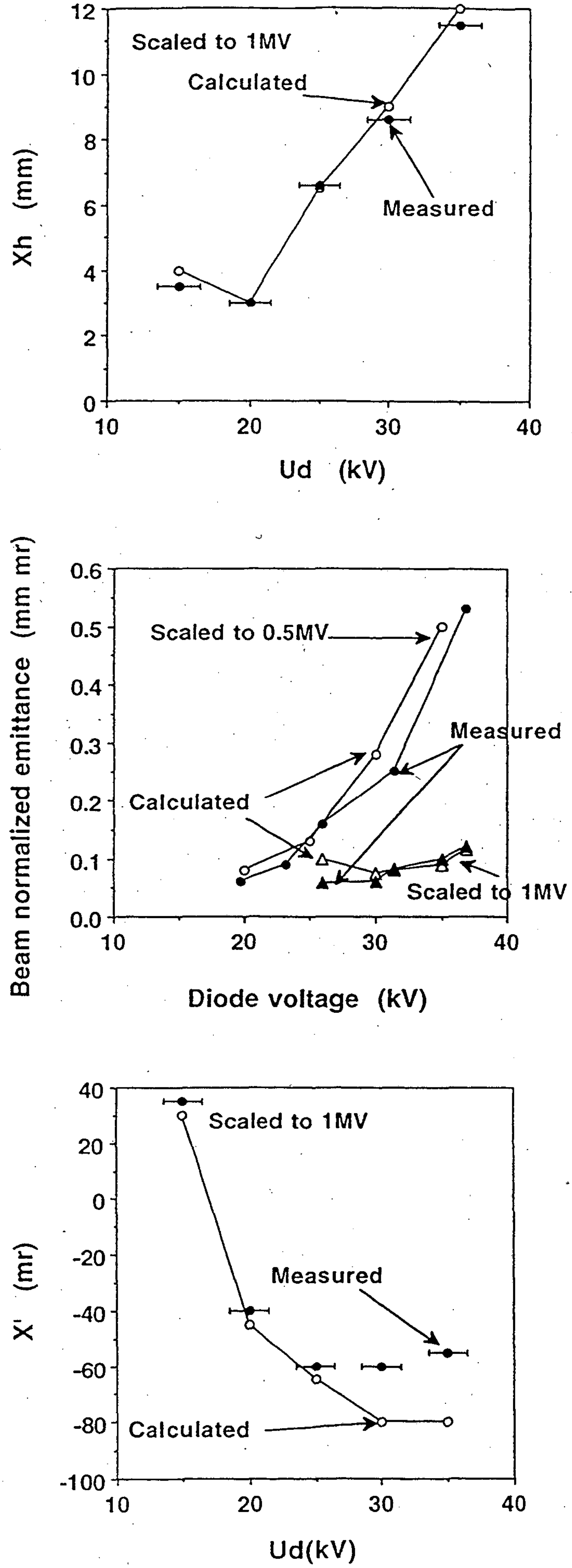

Source current (mA)
10
8
6
4
2
0
Scaled to 0.5MV
Scaled to 1MV
0e+0
2e+6
4e+6
6e+6
Diode voltage to the 3/2 (V to the 3/2)

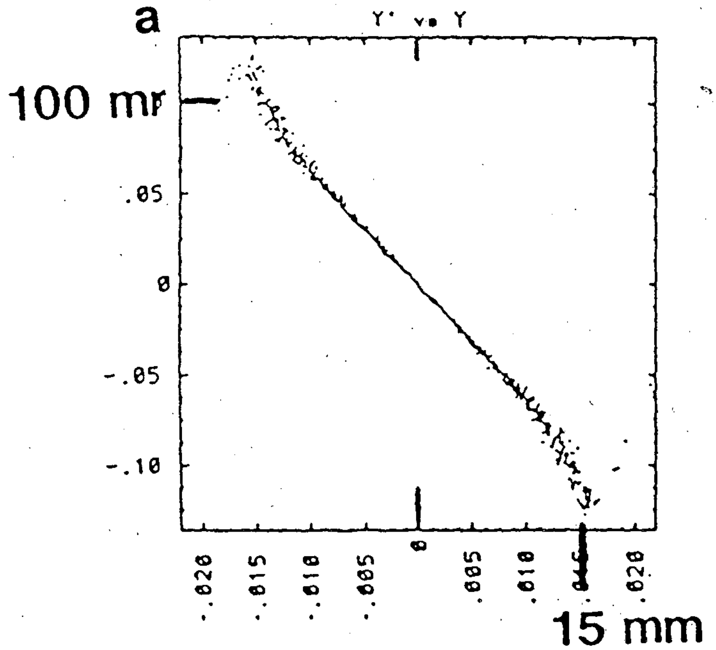
Figure 2



Scaled to 1MV
Calculated
Measured
Xh (mm)
Ud (kV)
Scaled to 0.5MV
Measured
Calculated
Scaled to 1MV
Beam normalized emittance (mm mr)
Diode voltage (kV)
Scaled to 1MV
Measured
Calculated
X' (mr)
Ud(kV)

Figure 3

a



b

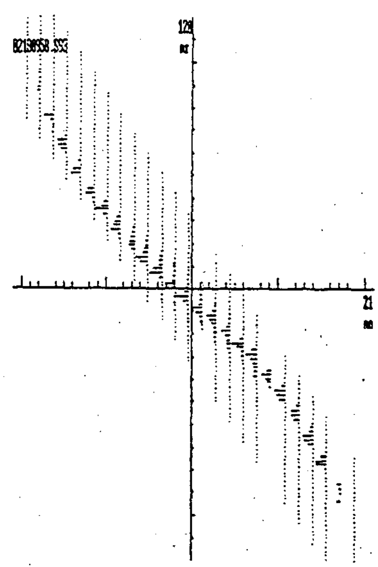


Figure 4

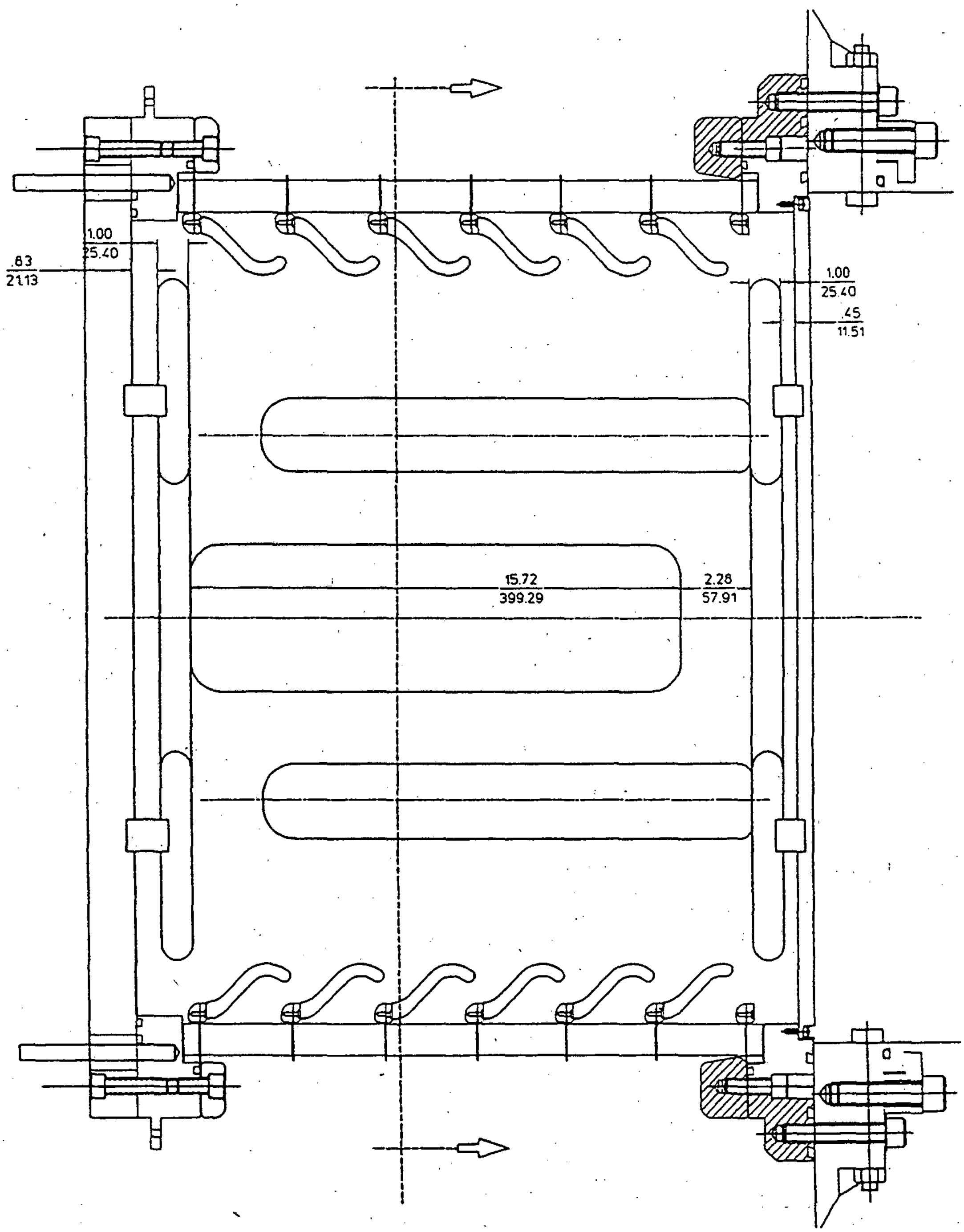


Figure 5