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H4-SMR 393/65

SPRING COLLEGE ON PLASMA PHYSICS

15 May - 9 June 1989

FIELD REVERSED CONFIGURATION EXPERIMENT IN THE TOROIDE COMPACTO-I

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ABSTRACT: The experiments on T.C.-I, Toroide Compacto-I, field reversed configuration device at UNICAMP have been carried out for the last three years. Using the basic available materials, a field distortion start crow-bar switch has been built and coupled to the machines. As the first step, the implosion phase of the FRC has been characterized by defining the optimum pressure operation at 10mTorr. The basic diagnostics operated at this phase are internal magnetic probes, flux excluded loops, IMACON, Spectroscopy, Faraday Cup and photodiode signals.

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INTRODUCTION

The T.C.-I device, operating at Plasma Laboratory UNICAMP [1], is a field reversed theta-pinch machine energized by using four capacitor banks with crow-bar switches, and built to study the FRC formation and instability suppression techniques. As the first step, the formation phase of the FRC configuration was studied by the analysis of helium plasma light emission and electromagnetic probe signals.

The capacitors banks parameters of T.C.-I are:

a) Main bank: C=28μF, V= 24kV (up to 50 kV), E=8 kJ (up to 35kJ), L=28nH B_z=6.5kG, t_{rise}=5μs, t_{decay}= 35μs, with crow-bar capability.

b) Pre-heating bank: C=1.6μF, V=25kV, E=0.5kJ, L=87nH, B=0.4 kG, t_{rise}=2μs, with crow-bar fired after 3 or 4 oscillations.

c) Bias bank: C=440μF, V= 2kV, E=0.9 kJ, L=1112nH, B=0.5kG, t_{rise}= 40μs, with no crow-bar.

d) Multipole or Magnetic divertor bank: C=7.4μF, V=25 kV, E=2.3kJ, L=75nH, B=2kG, t_{rise}= 3μs, with crow-bar, but is not operational yet.

The solenoid coil length (l) is 65cm with internal diameter of 16 cm and two 10cm mirror coils of 15 cm diameter, which results in a total inductance of 35nH. The vacuum vessel is a pirex tube of 14.5cm diameter which is pumped with a liquid nitrogen cooled diffusion pump to base pressure of 6 x 10^{-7}Torr. A fine control gas value is used to reach about 10mTorr stable helium gas injection which is pre-ionized by a R.F. generator of 100W at 30MHz.

The schematic view of the machine and the experimental set up is shown in figure I. In figure II, the discharge sequence is shown by external magnetic probes and Rogowski loop signals. The Rogowski loop wound around one of the solenoid coils has been calibrated using a Pearson Electronics wide band current transformer, model 411, which gives 24kA/V on the oscilloscope signal. The magnetic probes have been calibrated using one loop solenoid current and RLC oscillations calculations.

T.C.-I DISCHARGE SWITCH

The T.C.-I discharges are controlled by using high voltage, fast closing field distortion switch which is capable to operate in the voltages and currents up to 40kV and 300kA. Although the field distortion switch technology is well known for some years [2,3], we have developed an easy to build, reliable field distortion switch as part of development program on the field reversed configuration experiment. These switches have been built using locally available materials like nylon, brass and aluminium, and are operational at atmospheric pressure, although pressurized operation is also possible by minor modifications.

One of the electrodes, as can be seen on figure III, is held by external metal belt. So that loosening this belt, the gap distance of the switch can be changed very easily. Another convenient aspect of the switch is its trigger electrode positioning. During the operations of T.C.-I machine we observed that one critical adjustment was needed frequently without changing the relative angular position of trigger with respect to the two electrodes. This was accomplished by making the trigger electrode holder threaded and fitting up two screw-nuts at the end of long threaded trigger metal bar as can be seen in figure III.In this configuration the trigger electrode can be moved up or down just by screwing two nuts externally. Usually the trigger electrode is set at the midplane between two main electrodes. The threaded trigger electrode bar is insulated with high voltage insulation tape near the connection with trigger disk in order to force the discharges to happen always between the trigger disk and the electrodes. The trigger disk is usually made of hard conductive metal but we have used normal brass without problem. The trigger disk of 40mm diameter is made in such a way to fit into main electrode but with diameter bigger than inner diameter of two electrodes so that the electrodes can completely touch each other. The radius of curvature of the electrodes are 50mm and the edge of trigger electrode is rounded to about 1mm radius to avoid switch preferring due to sharp edge effect. The switch is mounted in aluminium plate spaced by thick nylon tube as can be seen in figure III and connected to capacitor plate.

ELECTRICAL SET UP AND OPERATION RESULTS

The schematic electrical set up to operate our switch is shown in figure IV. Basically, once the capacitor bank has been charged, the switch is fired when a sharp pulse is sent to the trigger electrode. The trigger pulse sequence is following, first a 300V sharp rise (10ns) pulse generated by 2D21 valve as the one that can be seen in figure 3, is sent to thyratron SC22 valve which generates a 15kV pulse. This 15kV pulse is sent to a ferrite isolation transformer of 1 to 4 which results in a trigger pulse of approximately 35 kV. This transformer pulse is then sent to switch trigger disk based at 50% of the gap voltage with the trigger electrode at mid gap position firing the switch.

In the case for which the trigger electrode is not well positioned, usually a current from hot electrode can go to trigger electrode voltage divider resulting frequently in arcing at the isolation transformer leads. Presence of this corona current can accuse the improper switch operation.

The pulse from isolation transformer is usually set negative to the capacitor bank charge voltage, so that during the trigger discharge pulse where trigger electrode initially charged to half voltage main capacitor charge, experiences a sudden negative voltage. This decrease in trigger voltage results in field emission between the trigger electrode and high voltage electrode, which in turn results in the breakdown between trigger electrode and hot electrode by charging the trigger electrode to same potential of the hot electrode which is immediately followed by breakdown to the second electrode.

In order to increase the sharpness of the trigger pulse and make the necessary isolation of trigger electrode, which it is charged to the half voltage of main charge, an isolation sharpner gap between the one to four transformer and trigger electrode is used. This isolation gap is simply made of two brass cylindre electrode with isolated pin trigger electrode spaced by glass tube with gap distance of few millimeters. A capacitor and resistor in parallel is also connected at the end of trigger electrode to avoid back discharge throughout hot electrode and trigger electrode.

In figure V is shown the typical discharge signal obtained by a Rogowski loop around one of T.C.-I solenoid conductor using these field distortion switch. This signal is the result of 5 superimposed discharges and indicate that very small jitter of less than 20 nanoseconds may be present. The switches described in this paper have worked for more than 1000 shots, and the electrodes seems to support very well these discharges. Any problems that have been detected so far are usually due to the mechanical or electrical failures external to the switch.

For voltage operation over 30kV or lower sound noise operation, the switch should be pressurized by replacing the wide open electrode aluminium plate holder with sealed plate with gas feed connections.

For the crow-bar switch operation, an identical start switch has been set side to side to work as crow-bar switch. Since the crowbarring time is usually chosen to be at maximum current (and minimum voltage), an extra capacitor bank is needed to give very strong trigger pulse to connect center switch plate to the ground plate. In figure VI-a is shown the case with and without crow-bar switch operation.

One of the biggest problems for us was the operation of main capacitor bank, where two start switches with crow-bar were set in parallel due to initial thinking that only one switch could not hold 30kV, 10kJ discharge. But exact synchronized discharge for two switches was very difficult when crow-bar switches were operated. In figure VI-b are shown the signals from each switch and from the main solenoid for the cases of good and bad operation. The causes of this assynchronism were probably due to excess jitter on one of switches or not exactly the same crow-bar switch fabrication. After some tries we decided to work with only one set of start, crow-bar switch, and so far, up to 25kV operation the switch has presented no major problem.

As a first step, we have characterized the implosion phase on T.C.-I using magnetic probes, Faraday Cup, Spectrometry and image converter camera.

In order to compare the values of the escaping particle from open ended regions of the device with other parameters in the implosion phase, current density measurements with a single cup, biased Faraday cup have been performed as shown in figure VII. In this figure a set of discharges were fired while the fill pressure was varied. The Faraday cup measurements indicated that the optimum pressure of operation is 10mTorr with density peak at the center of the tube and escaping plasma velocity of 8×10^6 cm/s was measured. This diagnostic also has been used to measure the escaping particles from the open ended region for the case with and without FRC formation. In the case of FRC formation, with bias field, the escaping plasma beam density is 2.6×10^{12} cm^{-3} whereas for the case of no bias field e.g., no FRC formation is 3.6×10^{12} cm^{-3}.

The base pressure of the system plays very important role on the FRC formation as can be seen from Faraday cup, spectrometer and photodiode measurements [4]. The spectroscopic measurements were done using a Jarrel Ash one meter Spectrometer, model 78-466, to measure the helium II (4686 Å) line intensity and broadening. The photodiode system is used to monitor the bremsstrahlung light emission from the center of the solenoid. The light is collected by a fiber optic cable and sent to the diagnostic room, where a HP-466A amplifier were used. In figure VIII-a and b is shown the case where the base pressure was poor ($\approx 6 \times 10^5$ Torr with no liquid Ni trap), in which case, the He II line is usually present only after the second compression and where the bremsstrahlung radiation is more intense (fig. VIII-b). For the case where the base pressure is 7×10^{-7} Torr, as can be seen in figure VIII-c and d, the situation is inverted, e.g., we can notice a higher He II line intensity on the first compression and more intense bremsstrahlung radiation at the same time. The best operation regime has been taken as one where He II emission is the strongest for different pressures with the base pressure of 7×10^{-7} Torr. The comparisons of three diagnostic methods, Faraday cup, spectrometry and photodiode measurements are shown in figure IX. All of them show the intensity peak value near the filling pressure value of 10mTorr.

Another important consideration is the effect of the time between the end of pre-heating phase to start of main phase (Δt_1). Since our device is equiped with crow-bar switch on pre-heating bank we can bring the main start time very close to the pre-heating phase without getting RLC oscillation effect from pre-heating capacitor discharge to main discharge. Figure VI shows the case where the time interval Δt_1 was kept at 18ls, and another at 8μs. In this figure the He II line is more intense, looking at the first implosion phase, in which the Δt_1 is shorter.

At the best operation regime an ion temperature of 70eV was obtained by measuring the Doppler broadening of He II (4686 Å) line which is shown in figure X. The smaller peak observed about 1.5 A before the center peak is not well understood yet, although it could be from macroscopic movement of the plasma body. The fast photographic pictures of the plasma implosion taken by an image converter camera, on streak mode, reveals that for the low gas filling pressure ($\approx$ 4.0mTorr) the implosion is very fast (0.8μs) and the plasma radius is small ($\approx$ 1.5cm) compared to the higher filling gas pressure case (20mTorr) for which case the implosion time is 4.8μs and plasma radius is 4.7cm. These results are shown in figure XI. By analysis of pictures with image converter camera for different filling pressure discharges with same base pressure (7 x 10^{-7}Torr), we have observed a good agreement with other diagnostics methods, giving as best operation filling pressure to be 10mTorr.

From all the observations described above, we can conclude that, base pressure need to be as low as possible, high escaping beam density from FRC configuration is obtained when high intensity bremsstrahlung and He II line emissions are observed in the center during the implosion phase. The best gas filling pressure of 10mTorr for our machine has been obtained by analysis of Faraday cup, photodiode, spectroscopy and image converter camera diagnostics.

The effect of time interval between the pre-heating and main discharge is important to obtain a good FRC formation, where shorter time interval is the best. More detailed analysis are needed on impurity and macroscopic movement effect on the temperature measurements of T.C.-I machine. Finally, more diagnostic systems, CO_2 laser interferometry, pressure probe, optical multichannel analyser are now being installed on the machine which can give further insight to the study of FRC plasma.

ACKNOWLEDGEMENTS

We would like to acknowledge the financial support to T.C.-I experiment from FAPESP, FINEP, CNPq and CNEN. We particularly would like to thank dr. Dick Siemon, from Los Alamos National Laboratory for providing us the basic materials to built T.C.-I device.

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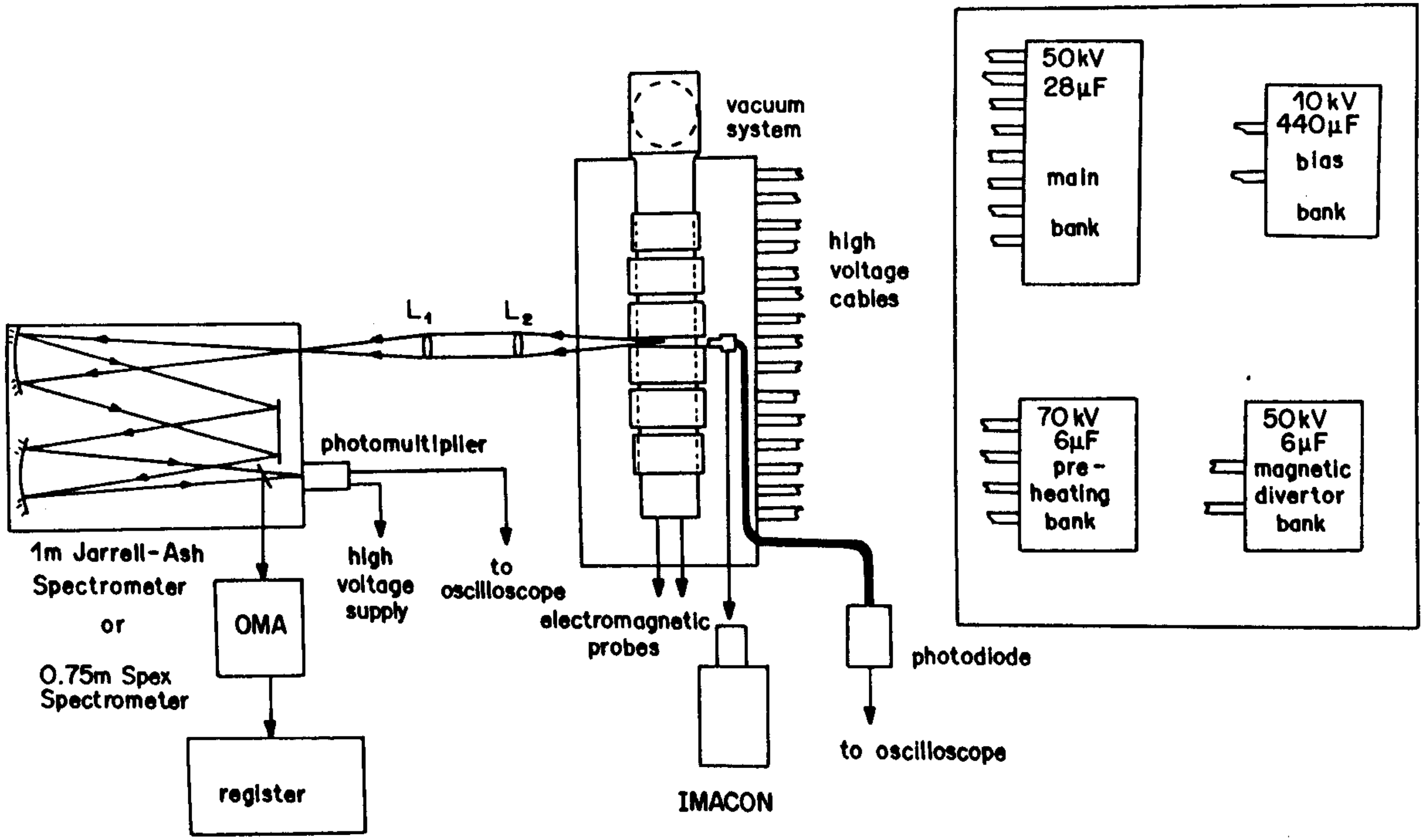
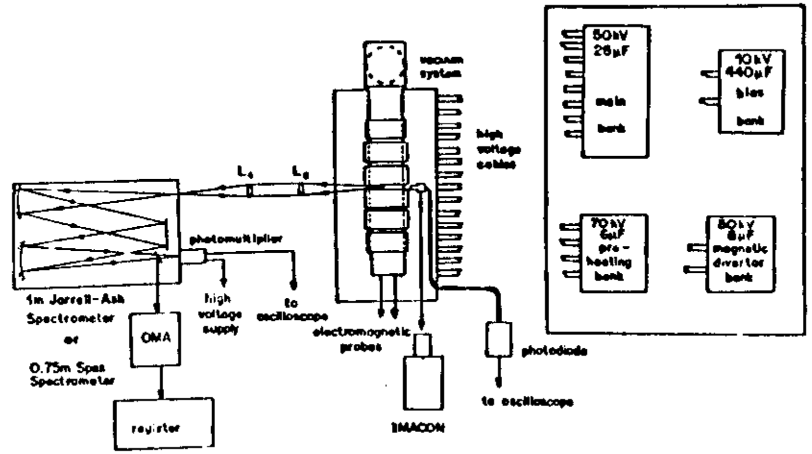


Figure I: Schematic view of the T.C.-I device.



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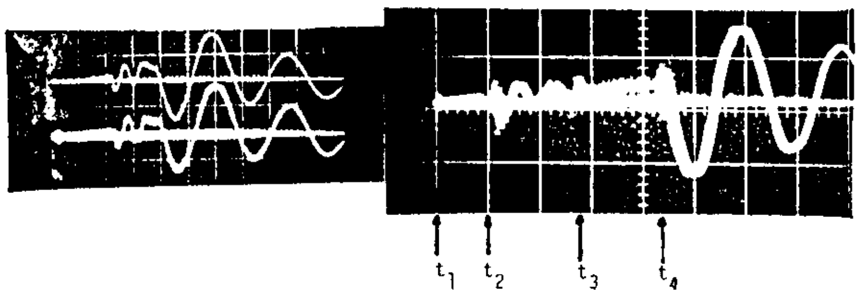


a) upper signal one loop

b) lower signal local probe

hor.: 10μs/div

vert.: 0.5v/div

c) Rogowski loop signal

hor.: 10μs/div; vert.: 0.5v/div

t_1 = start bias bank

t_2 = start pre-heating bank

t_3 = crow-bar pre-heating bank

t_4 = start main bank

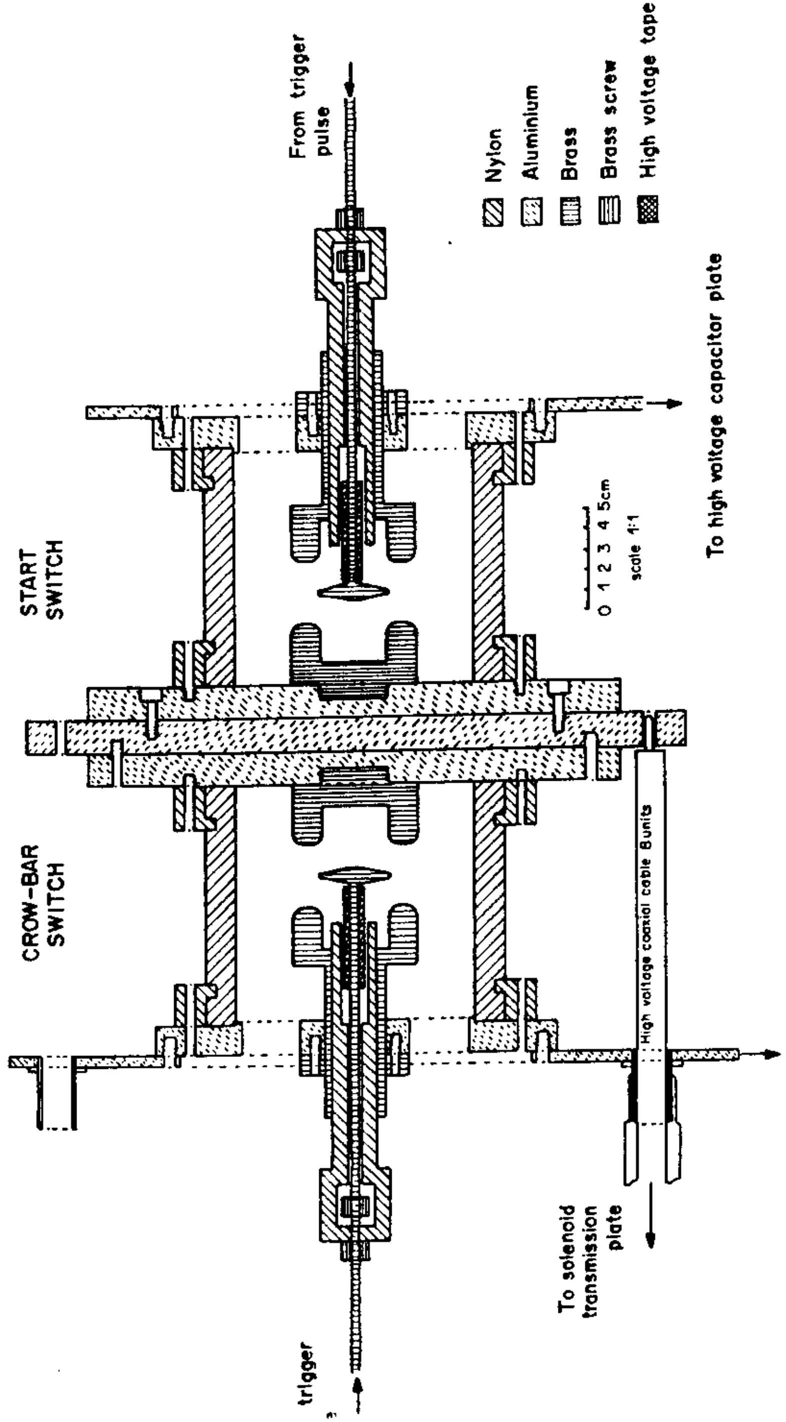


Figure III : Schematic view of the field distortion start and crow-bar switch.

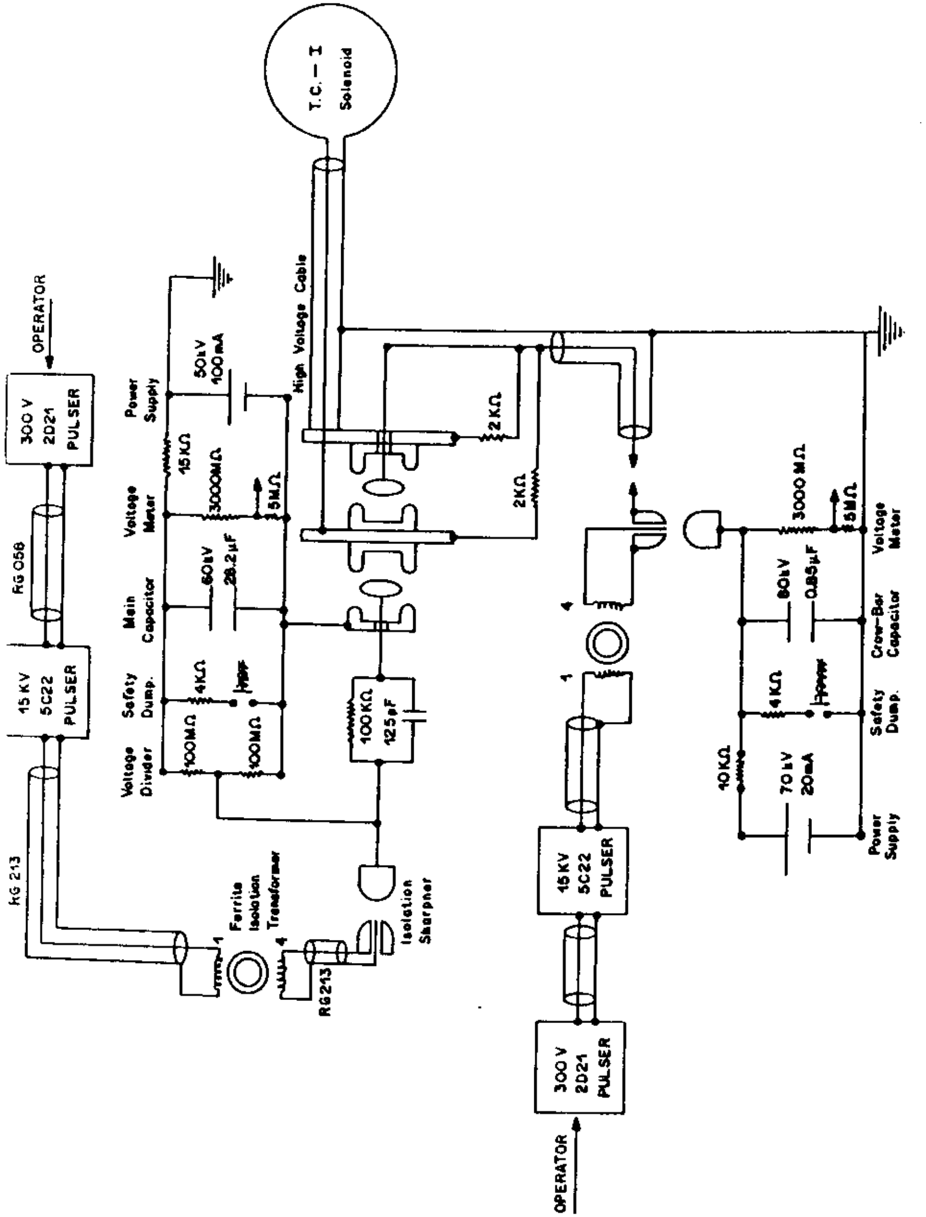


Figure IV: Electrical circuit of the T.C.-I device.

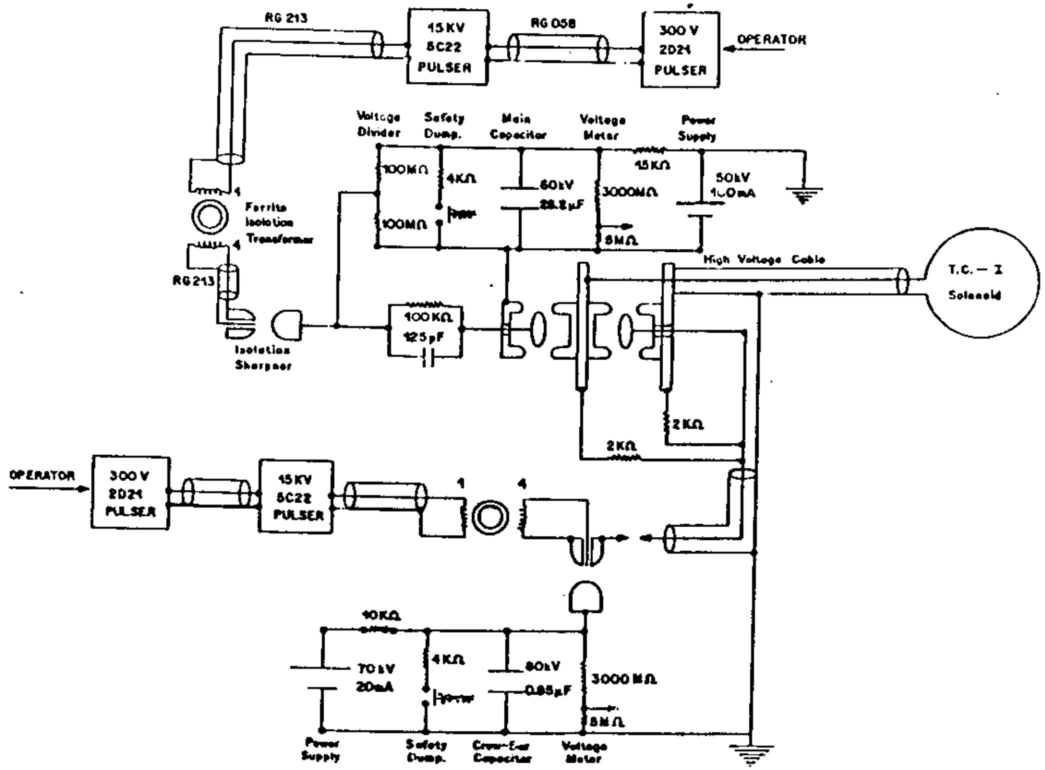
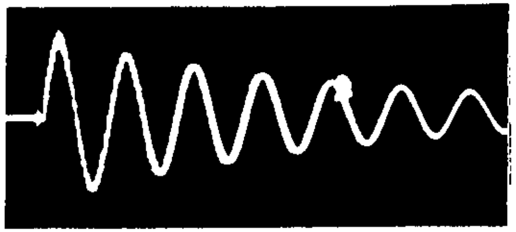
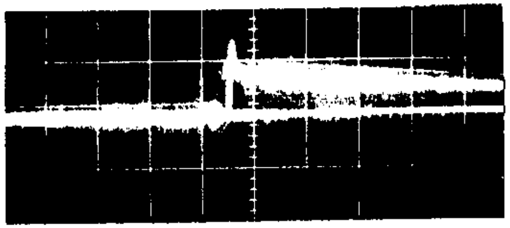


Figure IV: Electrical circuit of the T.C.-I device.

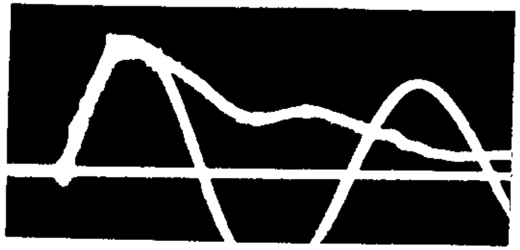


hor.: 5µs/div
vert.: 2v/div
5 discharges superimposed
P I - bank

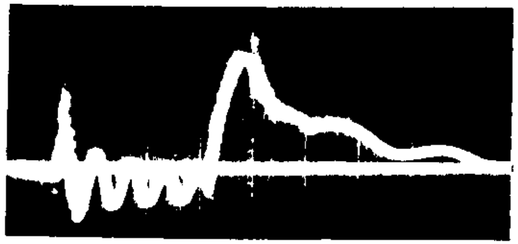


hor.: 5µs/div
vert.: 20v/div
10 discharges superimposed time delay generator.

Figure V - Sumperimposed discharge signals of the P.I. bank discharge and trigger pulse from time delay generator.

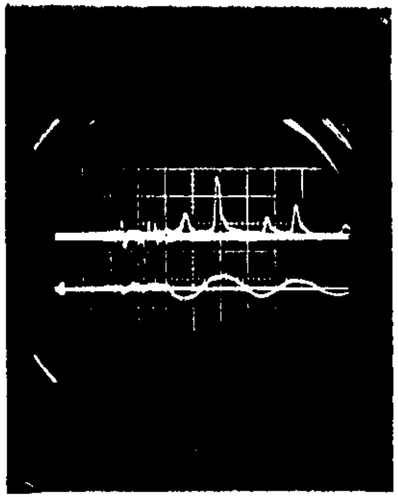


Two superimposed signals
hor.: 5µs/div
vert.: 5v/div



Complete discharge signal.
hor.: 10µs/div
vert.: 5v/div

Figure VI-a: Discharge signals taken by Rogowski loop around one of solenoids, for the cases with and without operation of crow-bar switch.



Typical Faraday Cup signal
Upper signal: Faraday Cup
hor.: 10µs/div
vert.: 2 v/div

Lower signal: external magnetic signal
hor.: 10µs/div
vert.: 10µs/div

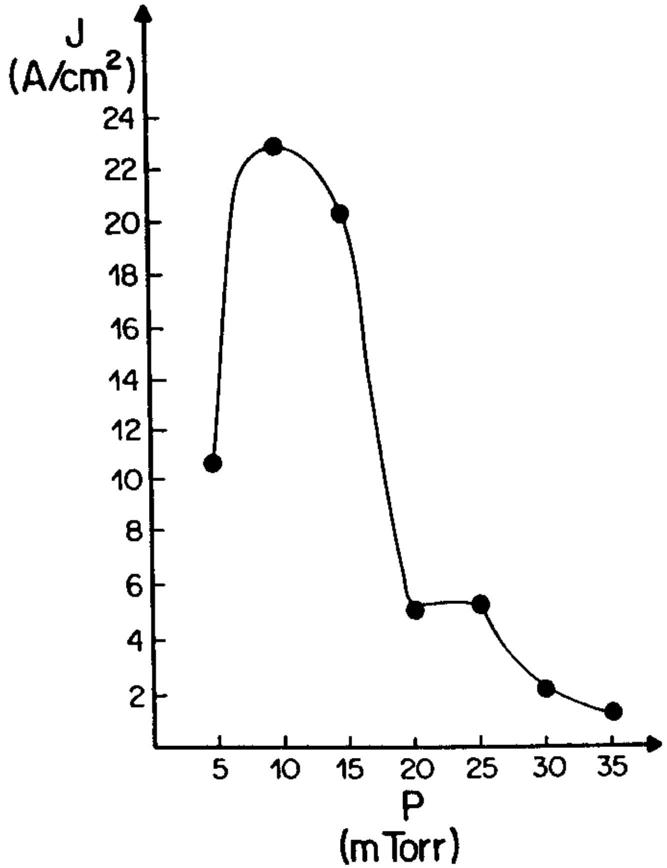
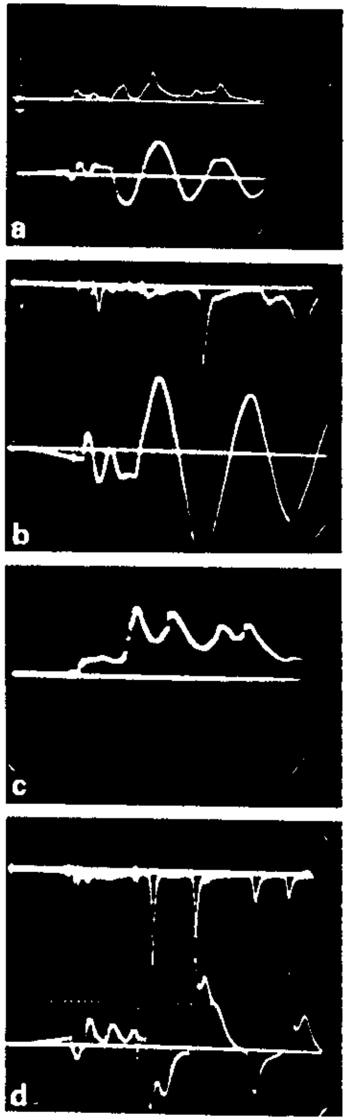


Figure VII: Current density obtained by Faraday cup at center



a) Upper signal:base pressure 6×10^{-5} Torr photodiode signal.
hor.: 10µs/div.

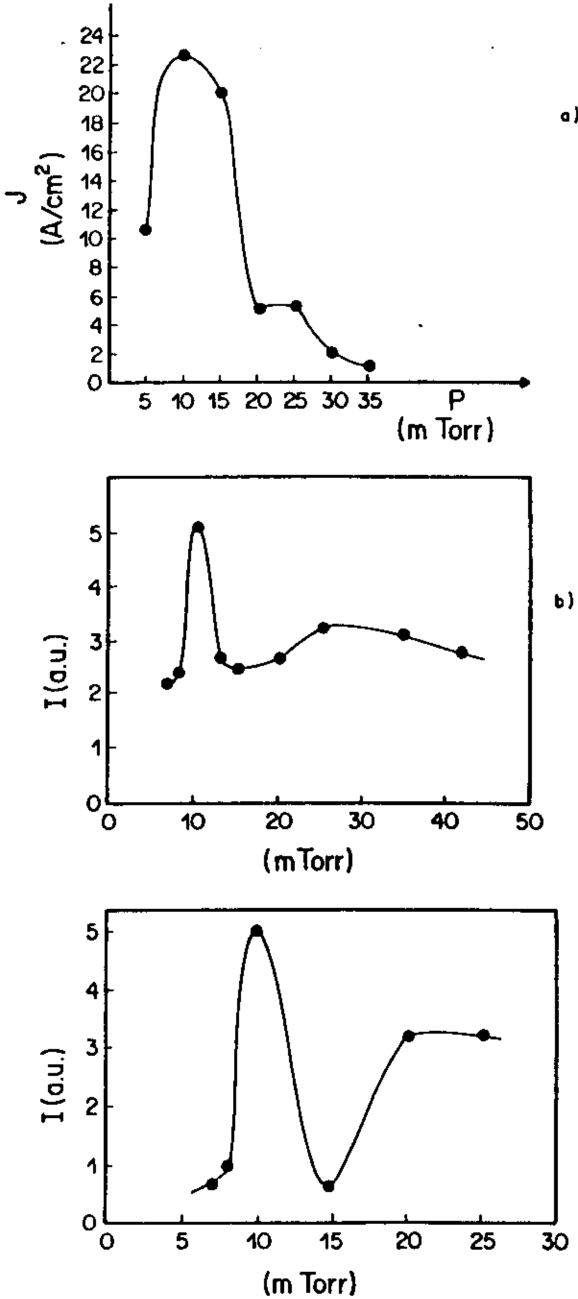
b) Upper signal: base pressure 6×10^{-5} Torr spectrometer sigjal for He II (4686 Å)
hor.: 10µs/div.

c) Same as a), but with base pressure of 7×10^{-7} Torr.

d) Same as b), but with base pressure of 7×10^{-7} Torr.

For All cases above, lower signals are magnetic probe signals.

Figure VIII : Influence of the base pressure on the emission of He II line and bremsstrahlung radiation obtained by spectrometer and photodiode set up.



a) Current density for different gas pressure.

b) Photodiode signal for different gas pressure.

c) Spectrometer signal for different gas pressure. He II line at 3µs.

Figure IX: Faraday cup, photodiode, spectrometric measurements for different gas filling pressure. All signals are taken at same discharge time (3µs after main bank discharge.

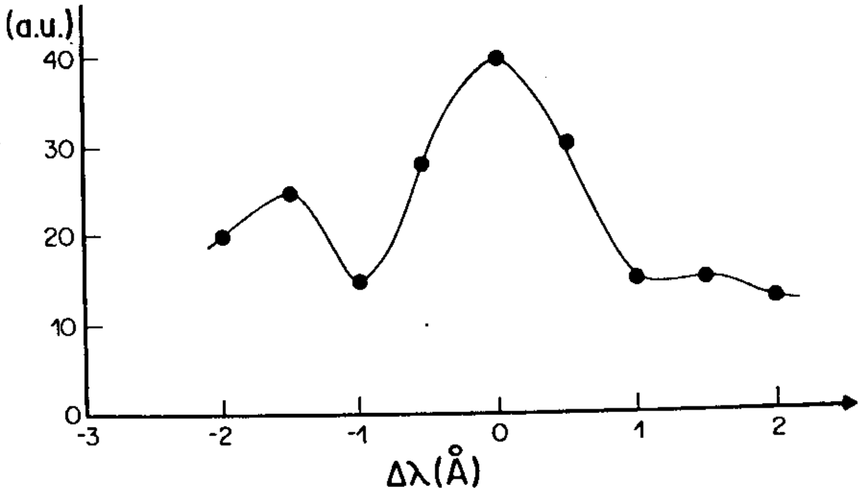
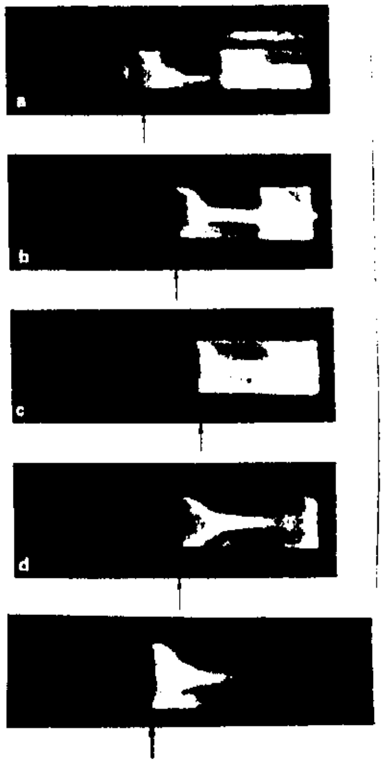


Figure X: Profile of the HeII line at t = 3 μs after the main discharge time. Ti = 70 eV.



a) Filling gas pressure: 4mTorr with no crow-bar.

b) Filling gas pressure: 10mTorr with no crow bar.

c) Filling gas pressure: 20mTorr with no crow-bar.

d) Filling gas pressure: 30mTorr with no crow-bar.

e) Filling gas pressure: 10mTorr with no crow-bar. 50μs/cm.

Figure XI: Streak photograph for different filling gas pressure and with no crow-bar operation. Arrows indicate the start of the main bank discharge.