STATUS AND NEW DEVELOPMENTS OF THE HIGH INTENSITY ECR SOURCE SILHI, CW AND PULSED MODE

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Abstract. SILHI is the ECR Source of Light Ions for High Intensity beams constructed and tested at CEA-Saclay. The first aim is to produce up to 100 mA cw proton beams at 95 keV for IPHI, the Injector of Protons for High Intensity beams (5 MeV RFQ and 10 MeV DTL). This prototype is developed by a CEA – CNRS-IN2P3 collaboration for applications such as Accelerator Driven Systems for nuclear waste transmutation, production of radioactive ion beams or secondary particles. SILHI is also used to study the production of deuteron and H^- beams for the IFMIF and ESS projects respectively. The present status of SILHI and the experiments planned for the near future in both cw and pulsed modes are presented in this paper. 80 mA cw proton beams are now currently produced at 95 keV with a high availability (~1 spark per day). The proton fraction is around 90 % and the typical r-r' rms normalized emittance after transport through a single solenoid LEBT without beam losses is 0.3 π mm.mrad. The best beam characteristics are obtained when an ECR zone is created at the frontier between the plasma chamber and the RF ridged transition. Extensive emittance measurements performed with different gas injection in the LEBT have shown a factor 3 emittance reduction. Space charge compensation measurements in cw mode will be undertaken with a four-grid analyzer to understand this behavior. Time resolved space charge compensation measurements in pulsed mode are also discussed. The highest total beam current of 120 mA (240 mA/cm^2) can be extracted with two ECR zones located at the plasma chamber extremities. Nevertheless a new electrode design must be done for this configuration to avoid excessive beam losses in the extraction system.

I. INTRODUCTION

CEA and CNRS have undertaken an important R&D program on very high beam power (MW class) light-ion accelerators for several years. The two French research agencies are especially interested by applications such as Accelerator Driven Transmutation of Waste (ADTW), new generation of exotic ion facilities or neutrino and muon production for high-energy particle physics. The CEA is also implied in projects such as ESS (European Spallation Source) and IFMIF (International Fusion Material Irradiation Facility) [1-2]. The R&D program is essential since the performances requested by these projects are one to two order of magnitude higher than those achieved by the most powerful existing accelerators. Severe beam loss limitations to allow hands-on maintenance and the necessity to achieve a very high availability with a reduced number of beam trips add new constraints which make the R&D effort even more indispensable to have a realistic view of the new generation of high-power accelerators.

The strategy carried by the CEA–CNRS collaboration has been to restrict the R&D program to a limited number of essential subjects with a maximum overlap on the different projects. The R&D effort is then concentrated on three topics : -1- IPHI ("Injector of Protons for High-Intensity beams"), a prototype of linac front end up to 10 MeV with beam currents up to 100 mA CW, -2- Construction and test of β<1 superconducting cavities, -3- Improvement of the codes for accurate beam dynamics calculations. This R&D program is now in progress [1] with strong international collaborations and partnerships with industry. The collaborations are especially fruitful with several Laboratories in Europe (INFN in Italy, Frankfort University in Germany…), USA (Los Alamos), Japan (JAERI) and Russia (MRTI).

The construction of SILHI, a "Source of Light Ions with High Intensities", has been decided in July 1994. The main objective was to produce 100 mA proton or 140 mA deuteron CW beam currents at 95 keV with rms normalized emittances lower than 0.2 π mm.mrad. An ECR source has been chosen to reach these performances with a high reliability - availability (no filament or antenna in the plasma) [3,4]. Thanks to a fruitful collaborations with the CEA-Grenoble PSI team and the Los Alamos LEDA-APT team, the first SILHI proton beam was produced in July 1996. SILHI is mainly developed to be the source of the IPHI prototype. The 95 keV proton beam will be accelerated up to 5 MeV by a 8 m long RFQ and up to 10 MeV by an Alvarez type DTL [5]. Tests with up to 100 mA CW proton beams are foreseen (1 MW beam power at 10 MeV). Experiments with SILHI are also devoted to the production of deuterons for IFMIF and H- for ESS.

The experimental set up and the source performances are presented in section II. Emittance reductions achieved by injection of heavy gases in the LEBT are briefly described. The analysis of reliability – availability based on two continuous runs of 100 hours are also discussed. Section II ends with some remarks on the commissioning and lifetime of the source. Section III describes the developments foreseen in the near future. The design of the new extraction system and LEBT are presented. The new LEBT equipped with two solenoids and new diagnostics is in its final configuration which allows to inject the beam in the IPHI RFQ. Preliminary studies of a new H- ECR source are also briefly exposed.

II. DESIGN AND PERFORMANCES

II-1. Ion source, LEBT and beam diagnostics.

The ion source operates at 2.45 GHz with an ECR axial magnetic field of 875 Gauss. The source and its ancillaries are installed on a 100 kV high voltage platform to produce 95 keV beams. The 90 mm inner diameter plasma chamber is 100 mm long. Both ends are lined with 2 mm thick boron nitride (BN) discs. The molybdenum plasma electrode is designed with a single 8 mm diameter aperture. The quartz RF window is located behind a water cooled bend in order to be protected from back-streaming electrons. The RF power is produced by a 1.2 kW magnetron source and is fed to the source via standard rectangular wave-guides with a four stub automatic tuning system. A three section ridged wave-guide transition is located between the plasma chamber and the bend to enhance the RF field. The magnetic field is now produced by only two coils tuned and positioned independently. Coils and plasma chamber are located inside an iron magnetic shield (Fig.1).

The five-electrode extraction system has been designed with the multi-particle code Axcel [6] (Fig.2). An intermediate electrode located in the accelerating gap can be tuned to minimize the distortions in the phase-space distribution [7] and to modify the beam focusing. An electrode at ~ - 2 kV is inserted between two water-cooled grounded electrodes to avoid the acceleration of electrons produced by ionization of the residual gas in the LEBT. To avoid damages in case of beam losses the electrodes are made using an original assembly of copper and tantalum [8].

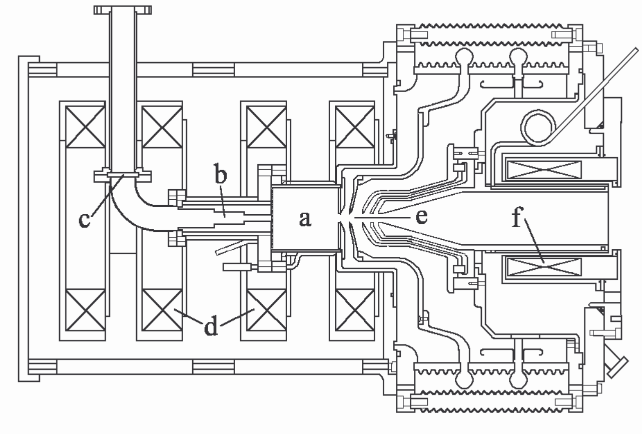


Fig.1 : Source and 95 kV extraction column
a) plasma chamber, b) RF ridged transition, c) quartz window, d) coils, e) 5 electrode extraction system, f) DCCT.

The single solenoid LEBT (Fig.3) has been designed to characterize the extracted beam. The 0.22 T iron shielded solenoid (560 mm long, 250 mm inner diameter) set 1.05 m after the plasma electrode focuses the beam in a diagnostic box. The ion source gas load is pumped by two 1000 l/s turbomolecular pumps, the first one at the exit of the accelerating column and the second one on the Emittance Measurement Unit (EMU) box.

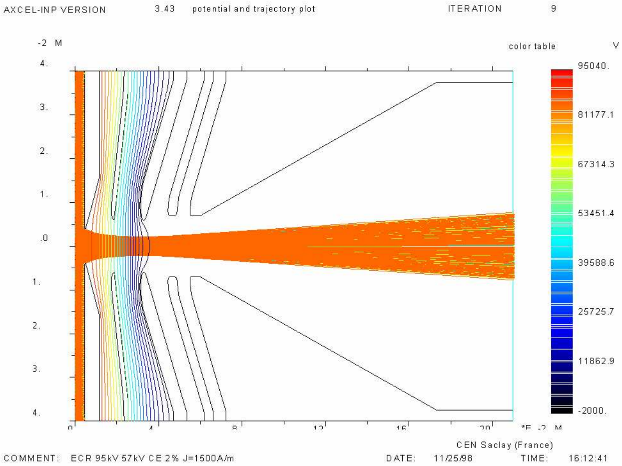


Fig 2. 95 keV-76 mA extraction simulation with 98 % space charge compensation from the repeller

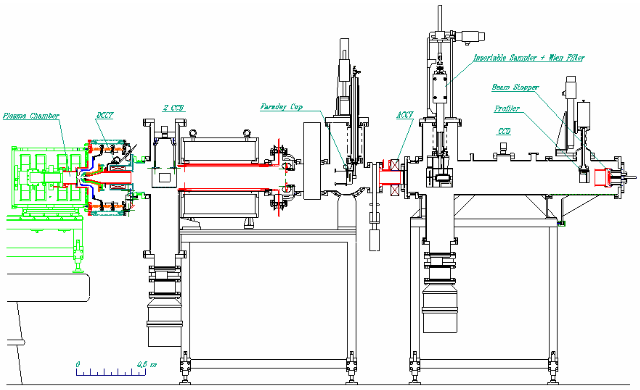


Fig 3. Source and LEBT
(Single solenoid configuration and EMU)

To allow an accurate matching to the RFQ a precise knowledge of the beam characteristics is required at the cavity entrance. Presently the beam position and size are obtained from CCD cameras. Faraday cup, beam stopper and toroids (DCCT and ACCT) are used to measure the beam current and its high-frequency fluctuations. Insulated screens give information on beam losses and beam axis. The EMU uses the classical "hole-profiler" techniques. A 0.2 T-1 MV/m Wien filter is placed behind the 0.2 mm diameter sampler to analyze the species ($H^+/H_2^+/H_3^+$) and to measure the proton beam emittance. The sampler designed for beam power densities up to 1 kW/cm^2 cannot be used to measure the emittance in the RFQ entrance conditions.

II-2. Beam characteristics

The extracted beam parameters have been analyzed for many configurations of RF power and hydrogen mass flow [9], and recently versus the tuning of the source magnetic field. By moving a single ECR zone from the RF input towards the plasma electrode (the second one being in the extraction zone), the extracted current decreases rapidly by a factor two and the proton fraction goes down from 88 % to 72 %.

The best performances are clearly obtained when the two ECR zones are located at the ends of the plasma chamber, on the BN disk at the RF input and close to the plasma electrode (Fig. 4). Figure 5 compares the extracted beam intensity measured with the Bergoz DCCT as a function of RF power when the source is working in single and double ECR zone running mode. The source efficiency increases to 0.145 mA/W indouble ECR mode instead of 0.105 mA/W in the single ECR mode. Several coil positions have been investigated with the two ECR zones at the same location but a lower magnetic field in the center of the plasma chamber compared to the one plotted in figure 5. No improvement or lower performances were observed, in particular with a magnetic field almost constant and equal to B_{ECR} along the plasma chamber. Further investigations will be done with other magnetic field profiles after some mechanical adaptations.

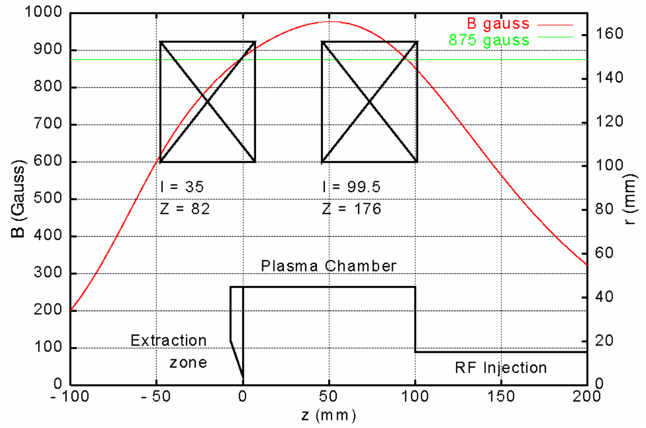


Fig. 4: Source axial magnetic field configuration in the double ECR zone mode.

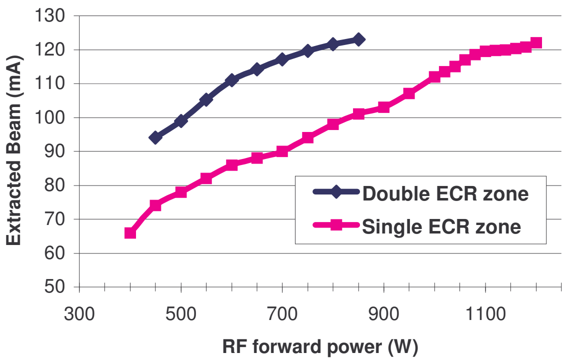


Fig.5: Extracted Beam current vs RF forward power, Comparison between single and double ECR zone running mode

Table I gives the requirements and the present performance of the source. More than 100 mA CW can be routinely accelerated at the nominal energy. For a 80 mA CW proton beam produced in the single ECR zone mode the losses are very low in the extraction system and in the LEBT (20 µA on the intermediate electrode and ~ 1 mA on the grounded electrodes with a limited temperature increase of 5 °C). The nominal r,r' rms normalized emittance is lower than 0.3 π mm mrad and the proton fraction better than 85 %. The other species are contained within 12 % for H_2^+ and 3 % for H_3^+ (Fig. 6). Recent measurements have shown strong improvements of the emittance when a buffer gas (H_2, N_2, Ar or Kr) is injected in the LEBT. Emittance reductions as important as a factor of 3 have been observed while the proton fraction is unchanged and the beam losses induced by recombination are below 5 % for the heaviest gases [10]. The space-charge compensation factor has been measured at several points along the LEBT to understand the emittance reduction phenomena. The measurements done using a Four-Grid Analyzer (FGA) are discussed in a companion paper [11]. Experiments on the time evolution of the space-charge compensation are also presented at this conference [12]. In the framework of the CEA-INFN collaboration, complementary measurements have been done at lower energy to verify the TRIPS source design [13].

TABLE I : SILHI requirements and present status.

Parameters	Requested	Status
Energy [keV]	95	95
Intermediate electrode voltage [kV]	65	48
Proton extracted beam [mA]	100	111
Total extracted beam [mA]	110	126
Proton fraction [%]0	> 90	88
Extraction aperture [mm]	10	8
Extracted beam density [mA/cm²]	140	243
Forward RF power [W]	1200	850
Duty cycle [%]	100	100
Hydrogen mass flow [sccm]	< 10	~2.0
Beam noise [%]	± 1	± 2
r-r' rms norm. emittance (LEBT) [π.mm.mrad]	0.2	0.11 (75 mA)

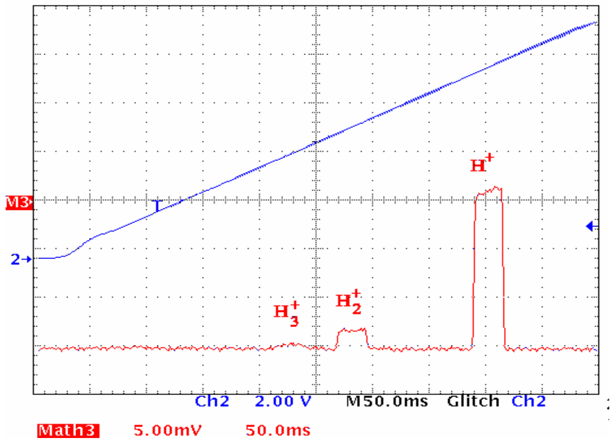


Fig. 6: Species fraction analysis with a ramping 1MV/m Wien filter electric field.

I-3. Tune up, RAM and Lifetime.

The plasma is easily obtained when the RF power is larger than 350 W with the standard magnetic field and operating gas pressure (10^{-3} Torr in the plasma chamber). The source is generally operated 5 days a week for 8 hours daily runs. Less than 10 min. are needed each morning to restart the source with a 100 mA CW beam at 95 keV. The tune up time is reduced to 2 min. after a shut down using an automatic procedure. This computer aid is really helpful to save time for experiments. Less than 6 hours are usually needed to obtain the nominal beam parameters after an operation in the source or in the LEBT. This recovery time for pumping, HV column conditioning and tune up is mainly induced by the BN disc outgassing under plasma warming. Few days are needed after a modification of the extraction system. The source and LEBT have been moved in a new building last year, the results obtained before a full dismantling / reassembling were recovered 3 weeks after the beginning of the pumping.

Two long runs have been performed to analyze the reliability – availability of the source. In December 1997 the source has been continuously operated during 5 days (103 hours) with a 100 mA CW beam at 80 keV. The global reliability reached 94.5 % with 53 shutdowns mainly induced by HV sparks. Most of the sparks occurred during the first 24 hours (conditioning period). The mean time between failures (MTBF) for the last 4 days turned out to be 5.5 hours and the mean time to repair (MTTR) was lower than 6 min. (not taking in account 2 stops due to failures in the compressed air ancillaries). The second test has been performed in May 1999 with a 75 mA CW beam at 95 keV, the availability reached 98 % for a continuous operation of 106 hours. The beam has been interrupted 13 times by HV sparkdowns and 11 times by a problem of high voltage transformer "outgassing" which has been solved since then. The MTBF turned out to be 4 hours and the MTTR 5.22 minutes, a 27.5 hours uninterrupted operation has been completed. The beam reliability obtained during these two test runs is plotted in Fig 7 as a function of the elapsed run time. A new 270 hours test run is planned for October.

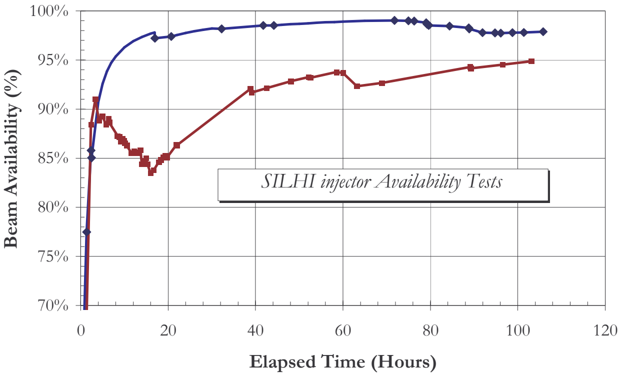


Fig. 7: Beam reliability vs elapsed run time (hours) for the 2 long test runs 100 mA-80 keV (blue), 75 mA-95 keV (brown).

The source has been designed to reach a long lifetime. The RF window in quartz has been installed behind a water-cooled bend (Fig. 1) to escape the beam of electrons produced and accelerated in the HV extraction system. The RF window works well since the production of the first beam in July 1996. Nevertheless the BN disc located at the RF entrance is affected by the backstreaming electrons and must be systematically replaced. Its lifetime is estimated to be higher than 1000 hours for ~ 100 mA CW beams, then more than 40 days of continuous operation for such beams.

II-4. Pulsed Mode of Operation

The tuning of a high intensity CW linac must be done with a pulsed beam, starting with a very low duty cycle and increasing the beam power progressively. Rather short plasma rise and fall times have been achieved during some preliminary experiments done using a modulation of the 2.45 GHz magnetron power supply [9,14]. Plasma pulses with 10 µs rise time and 40 µs fall time have been observed (without beam extraction) measuring the current collected on the intermediate electrode polarized at – 300 V. Nevertheless the measurement of a 60 mA – 75 keV extracted pulsed beam on the Faraday cup showed much slower transitions, 2 ms and 100 µs respectively for the rise and fall time. The slow rise-time could be induced by variation of the pressure in the plasma chamber at the beginning of each pulse. New tests will be done to optimize the pulsed mode of the source.

III. NEW DEVELOPMENTS

The main aim for the short-term work on SILHI is to improve the reliability – availability and to develop non-interceptive diagnostics. New emittance and space-charge compensation studies will be also done to have a better understanding of the beam dynamics in the LEBT. A new extraction system will be designed and tested and the LEBT will be installed in its final configuration to inject in the IPHI RFQ. A new experimental setup will be built to investigate the ECR source performances for the production of H^-.

III-1. Reliability - Availability

The accelerating column is composed of three 67 mm long Al_2O_3 insulators and stainless steel flanges (Fig 1). The vacuum seal is made by O-ring compression between metal and ceramic. As most of the sparks could be due to an accumulation of charges on the ceramics, new tests will be done after a metallization of the insulators to avoid this phenomenon. Both internal and external surfaces will be metallized using a PVD process to reach 300 MΩ ± 10 MΩ for each insulator leading to a negligible drain current.

A constant effort to improve the electromagnetic compatibility (EMC) of the hardware installed on the HV platform has already allowed to avoid most of the beam interruptions induced by HV sparkdowns. Nevertheless the control computer or the PLC still require a reset after some sparks, efforts on the EMC will be going on.

A new control - command system based on FieldPoint modules linked to LabView is under test. The installation of this National Instrument system is the first step toward the use of EPICS (Experimental Physics and Industrial Control System) selected for the IPHI project. This powerful system must allow a better and faster control of the equipments.

III-2. Matching to the IPHI RFQ

Two identical solenoids are now installed in the LEBT to match the beam to the RFQ acceptance with a good separation of the parasitic species (Fig. 8). Figure 9 shows the LEBT as it is presently including an iris diaphragm with an adjustable aperture (Fig 10) and the first of two magnetic steerers installed under-vacuum. In the final injection beam line two torroids (DCCT and ACCT) and a collimator will be added after the second solenoid.

A precise knowledge of the beam characteristics at the RFQ entrance is now one of the first IPHI project priorities. The aim is to avoid beam losses that could induce RF sparks in the RFQ or even seriously damage of the cavity. A new diagnostic box is installed at the RFQ front-end position 3.7 m away from the plasma electrode. Beam power densities up to 50 kW/cm^2 preclude the use of classical interceptive diagnostics, several types of diagnostics based on optical analysis will be tested. Preliminary studies have been done on a new x-x' or y-y' EMU based on the measurement of beam profiles using a CCD camera [15]. New developments are needed to improve the accuracy of this technique which has the advantages to be simple to install and to give fast measurements. A new way to measure the beam profile using the absorption of a laser beam is also investigated. As demonstrated at LANL [16] measurements of the light intensity of the Doppler-shifted Balmer alpha transition could be used to deduce the proton fraction. This device coupled with DCCTs would be a very efficient diagnostic for on-line source tuning. The first measurements will be done between the extraction column and the first solenoid.

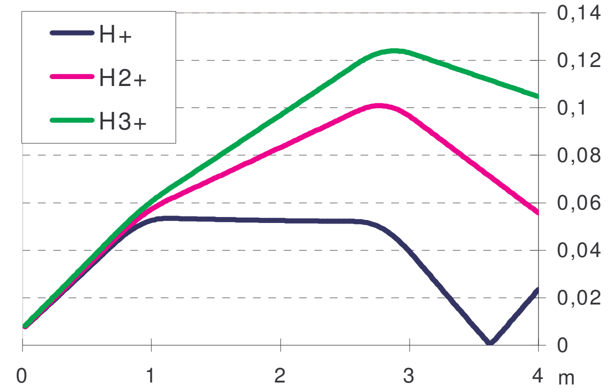
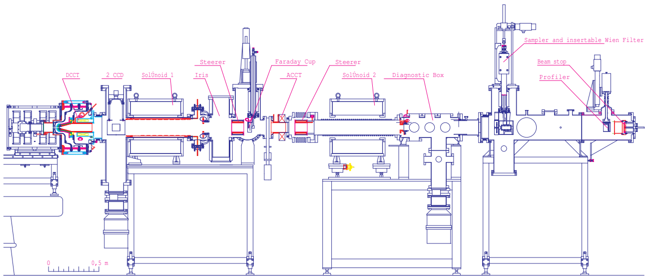


Fig. 8: Specie envelopes in the two solenoid LEBT



Fig; 9: New LEBT configuration

An accurate control of the beam intensity is also required for most of the applications, especially for ADTW systems. This must obviously be done at the level of the ion source or in the LEBT. Tests will be done to adjust the extracted current using a feedback loop on the RF power of the source. A tunable aperture iris has also been designed and built at CEA-Bruyères le Chatel. The total aperture of this water-cooled iris made in copper can be continuously adjusted from 0 to 100 mm. This slow tuning add flexibility to the fast control of the RF power in order to keep a good stability of the extracted current.

III-3. Enhancement of the extraction system

Following the beam dynamics calculations in the extraction system done with the Axcel code the beam envelopes in the LEBT (fig. 8) are studied using the homemade code MultiPart [17]. Some discrepancies with the measured profiles are observed but it is clear that the beam diameter in the first solenoid occupies almost half of its inner diameter. The initial divergence must then be reduced to avoid aberrations and beam losses in the LEBT for beam intensities around or above 100 mA. The length of the accelerator gap (D_{ag}) has been decreased from 33.3 mm to 24.8 mm to reduce the beam divergence.. The transport in the LEBT is easier since this modification but aberrations are still observed. Despite the electric field increase, the spark rate does not augment. A new optimization of the extraction system is undertaken to decrease D_{ag} once more. As a first attempt the minimum divergence is found for D_{ag}= 20 mm. A carefully optimization of the electrode shapes have to be done simultaneously to minimize extraction distortions and to lower the maximum electric field. Crosscheck of different codes is underway to confirm this result.

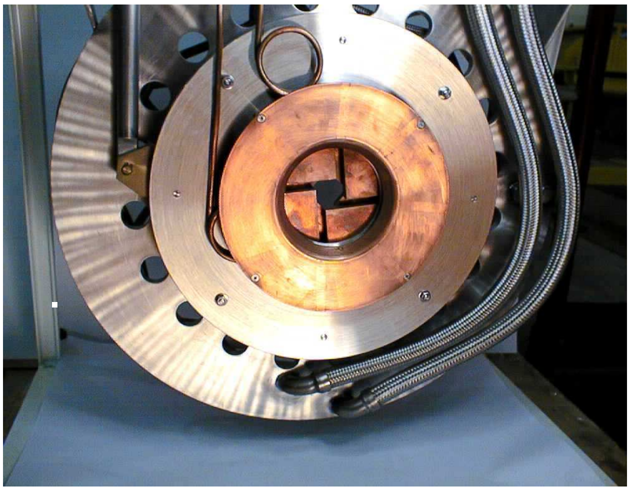


Fig. 10: Water cooled Iris picture

III-4. ECR source for H^-

Preliminary studies toward the construction of an ECR H^- ion source are in progress. SILHI spare parts will be used in a new test bench based on the running mode with a single ECR zone (see section II.2). The high-energy electrons created in this ECR zone will be trapped by a dipole magnetic filter. A 200 mm long plasma chamber and an intermediate iron shield will be used to minimize the magnetic field in the extraction region. In a first step a tantalum plasma electrode will be used in order to increase the negative ion production [18]. A second magnetic filter will separate electrons and H^- ions in a 10 kV extraction system. The design will take into account future evolution such as Cs injection with heating of the plasma electrode, higher energy extraction and installation of plasma diagnostics. This project is funded, the test bench construction will start before the end of the year.

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