HIGH EFFICIENCY ELECTRON COLLECTOR FOR THE HIGH VOLTAGE ELECTRON COOLING SYSTEM OF COSY

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Abstract

A high efficiency electron collector for the COSY high voltage electron cooling system was developed. The main feature of the collector is usage of special insertion (Wien filter) before the main collector, which deflects secondary electron flux to special secondary collector, preventing them fly to the electrostatic tube. In first tests of the collector in COSY cooler efficiency of recuperation better then 10^{-5} was reached. Before assembling of the cooler in Juelich upgrades of the collector and electron gun were made. After the upgrade efficiency better then 10^{-6} was reached. Design and testing results of the collector are described.

INTRUDUCTION

In electron cooling method the process of heat exchange between ions and electrons occurs in the beam reference system. As a result the process almost doesn't change electron beam energy. It means that after interaction with ion beam electrons with sufficiently high energy must be utilized. Utilization of the beam on full energy is serious technical task, because stored power in the beam is very large. Moreover, such approach means that high voltage power supply (PS) must be constructed for big load current (about 1 A). To avoid this problem the method of recuperation of electron beam energy is used in electron cooling devices. An idea of the method is to decrease electron beam energy in electrostatic tube that is connected to the same high voltage PS which is used for acceleration of electrons. After that electron beam is directed to a special collector where they are absorbed by its surface. Usual energy of electrons absorbed in a collector is 1÷5 keV and it is defined by a special collector PS.

Using recuperation method one can decrease maximum load current of the high voltage power supply to the value of about several mA, or even less, because its consumption is determined only by high voltage divider, which distributes voltage along acceleration column, and by leakage current from the high voltage terminal to the ground. Load current for collector PS is equal to beam current but its operation voltage is several kV. Moreover, stability of collector PS voltage can be much worse.

Power consumption in divider is determined during system design and doesn't change during operation. The most important cause of appearance of the leakage current from high voltage terminal is losses of full energy electrons (I_{leak}). The most part of such electrons are secondary particles reflected from a collector. The ratio I_{leak}/I_{beam} (where I_{beam} – main beam current) is called efficiency of recuperation. Besides increasing of load to high voltage PS bad efficiency of recuperation in electron cooling systems can cause other problems. Full energy electrons which hit wall of vacuum chamber are source of radiation. Besides worsen of radiation safety it can cause problems in reaching good vacuum conditions and decrease electric strength of the cooler.

In coolers EC-35, EC-40 and EC-300 produced in BINP for IMP (China) and CERN the efficiency was improved with the help of special electrostatic bending plates installed in toroid parts of the coolers [1]. These method allows to increase efficiency of cooler recuperation from 10^{-3} to 10^{-6}. But in 2 MeV cooler for COSY shape of magnetic system and high energy of electrons make using of such method very complicated. In this case one should improve collector efficiency.

Efficiency limit of the axially symmetric collector with electrostatic and magnetic closing of secondary electrons, which are usually used in electron cooling devices, was estimated in [2] and its value is about 10^{-4}. For COSY high voltage electron cooler [3] such efficiency is not enough because needed value is about 10^{-5} [4]. In order to satisfy the requirement a new collector with suppression of secondary electrons by Wien filter was designed.

WORK PRINCIPLE

The main idea of the collector with Wien filter is to install a special insertion with crossed transverse electric and magnetic fields before ordinary collector (Fig. 1).

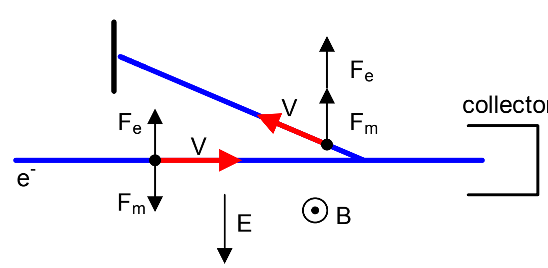

Figure 1: Principle of the collector with Wien filter work.

For main beam action of fields compensate each other but for secondary beam, which moves back, magnetic field acts in opposite direction and secondary beam is deflected to a special electrode (secondary collector). In the 2 MeV cooler the collector with Wien filter is placed in longitudinal magnetic field that is related with features of the cooler [3]. Because of the field, secondary electrons move not to electrostatic plates in but in direction parallel to them that protects the plates and their PS.

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During entrance to the filter, electron is accelerated or decelerated by edge fields of the plates, that depends on coordinate of an electron. It means that in the filter, electrons, flying closer to positive plate, have higher velocity than in the center of the beam. Since Lorenz force depends on the particle velocity, resulting force for primary beam is not equal to zero for accelerated and decelerated electrons. This results in change of shape of the primary beam and can decrease perveance and efficiency of electron collector. In order to avoid this problem transverse magnetic field should have gradient *n*:

$$B_x = B_\perp \frac{n}{R} y, \quad B_y = B_\perp \left(1 + \frac{n}{R} x\right),$$

where $R = \frac{pc}{eB_\perp}$, $n = \frac{1}{2\gamma^2}$, x and y – coordinates in transverse direction [5]. For low energy beam $n \approx 0.5$.

CONSTRUCTION

The collector consists of two parts: main collector and Wien filter (Fig. 2). The bottom flange of the combined collector is attached to the deceleration tube of the cooler.

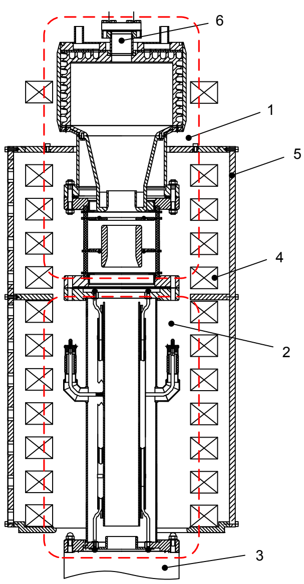

Figure 2: Sketch of the collector: 1 – main collector with the suppressor and pre-collector electrodes, 2 – vacuum chamber of the Wien filter, 3 – electrostatic tube, 4 – coil for longitudinal magnetic field, 5 – magnetic shield, 6 – flange for additional vacuum pumping

Main Collector

Main collector (Fig. 3) is intended to collect almost all electrons of main beam and need to be cooled, since power of main electron beam is up to 15 kW. Its construction is based on collectors, which were used is previous electron cooling devices produced by BINP for CSR (China) and LEIR (CERN). Efficiency of the main collector is about 10^{-3}.

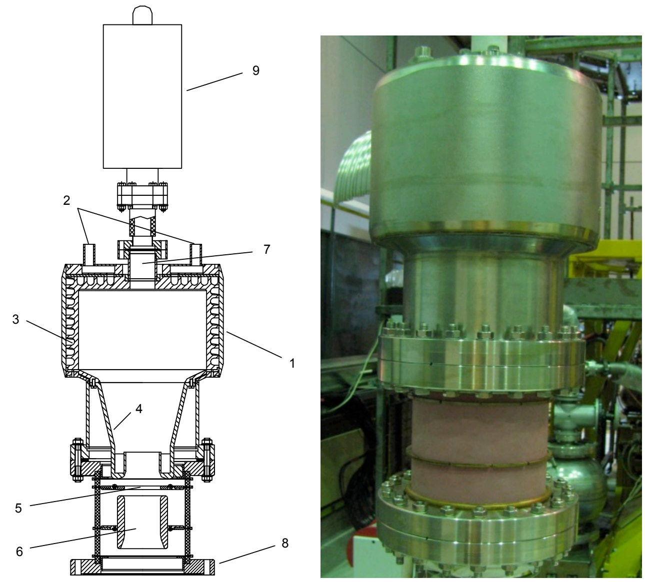

Figure 3: Left – sketch of the main collector: 1 – cooled main electrode, 2 – tubes for input and output of oil for cooling, 3 – channels for collector cooling, 4 – input part of the main electrode, 5 – suppressor electrode, 6 – pre-collector electrode, 7 – tube for additional vacuum pumping, 8 – vacuum flange, 9 – additional vacuum pump. Right – photo of the main collector.

Wien Filter

To produce magnetic field in the collector it is placed in solenoid which consists of 12 coils: 11 coils in magnetic shield and one last coil with opposite current (Fig. 2). The coil provides more uniform distribution of electron flux on the collector surface to avoid its local overheat and to increase efficiency of magnetic closing of secondary electrons. The solenoid is covered by magnetic screen. In Fig. 4 a top view of the Wien filter and part of the magnetic screen with permanent magnets are shown.

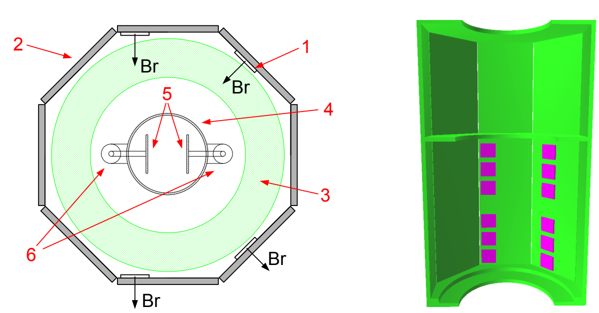

Figure 4: Left – tor view of the wien filter, right – 3D view of magnetic system of Wien filter from Mermaid program.

Permanent magnets were chosen to produce transverse magnetic field in the filter. Such solution decreases size of the system and exclude additional PS. Total number of magnets is 24 with Br=1.3 kG. Integral of transverse magnetic field along axis is 1400 G·cm. Length of electrostatic plates is 38 cm.

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Permanent magnets (1) are placed on plates of magnetic screen (2) around coils of longitudinal magnetic field (3). Vacuum chamber (4) contains electrostatic plates (5) for production of transverse electric field. The plates are connected to high voltage power supplies via special connectors (6).

Vacuum chamber of the filter (see Fig. 2) includes electrostatic plates and secondary collector which absorbs electrons reflected from the collector and deflected in Wien filter. Inner diameter of the secondary collector is 5 cm. Main beam diameter in this region is about 3 cm.

UPGRADE OF THE WIEN FILTER

As it was said, electric field in the Wien filter is produced by two plates. Width of the plates is equal to distance between them. It lead to big inhomogeneity of the field. This inhomogeneity results to change of the main beam shape and to increase its characteristic size, which can worsen collector efficiency.

After tests of the collector in special test bench and in high voltage electron cooler it was decided to upgrade its construction in order to improve homogeneity of the field. For this a special shim was added in edges of electrostatic plates (Fig. 5).

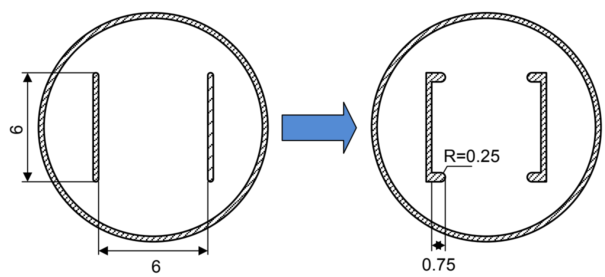

Figure 5: Shim added to plates of the Wien filter during the upgrade. Left – before upgrade, right – after upgrade.

The electric field was calculated for such construction with the Mermaid program [6]. In Fig. 6 one can see that the field was improved significantly in the region ±2 cm where main beam with radius 1.5 cm.

In Fig. 7 changes of the main beam shape for constructions before the upgrade and after it are shown. One can see that before the upgrade beam has almost triangular shape, but after the upgrade it is round i.e. effective beam size remains unchanged.

EXPERIMENTAL RESULTS

Test Bench

First experiments on recuperation with the new collector were made on a special test bench [5]. The test bench is a straight system with a gun in the bottom and collector in the top. The system was used to test the high voltage terminal of the 2 MeV cooler with all electronics.

In Fig. 8 results of collector efficiency measurements on the main beam current are shown

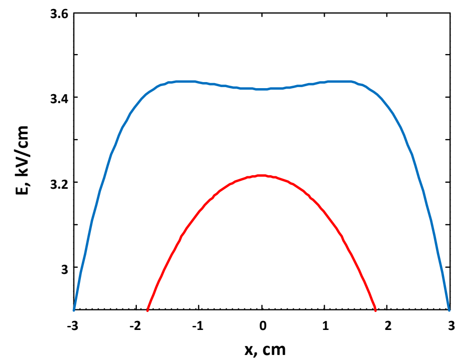

Figure 6: Transverse elecric field in Wien filter: red – before upgrade, blue – after upgrade

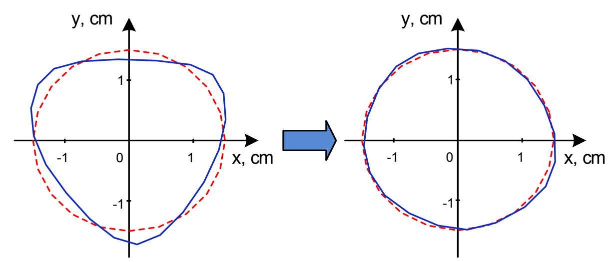

Figure 7: Main beam profule before (red) and after passing the Wien filter (blue): left – before upgrade, right – after upgrade.

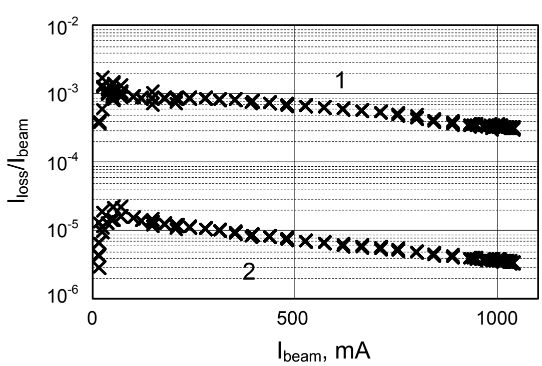

Figure 8: Dependence of efficiency of the main collector (1) and combined collector (2) on main beam current in test bench.

One can see that efficiency of the collector is about $3{\cdot}10^{-6}$ for current higher than 1 A. But the problem of measurement in such straight system is that electrons, reflected from the collector go to the gun, where they can be reflected by electrostatic potential and fly again in the collector. It means that efficiency measured in such system can be much better then real efficiency of the collector.

Commissioning in BINP

After tests in the test bench the collector was installed in the high voltage cooler during its assembling in the

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Budker INP. Many tests were carried out for the different electron energy in the coiling section. Results show that efficiency of recuperation strongly depends on quality of beam transportation, because uncompensated transverse kicks can significantly increase beam size.

In Fig. 9 the best results of collector efficiency measurements on beam current are shown. The measurements were made for energy 30 keV where motion of the electrons though electron cooling system is adiabatic and beam transportation from gun to collector is much easier.

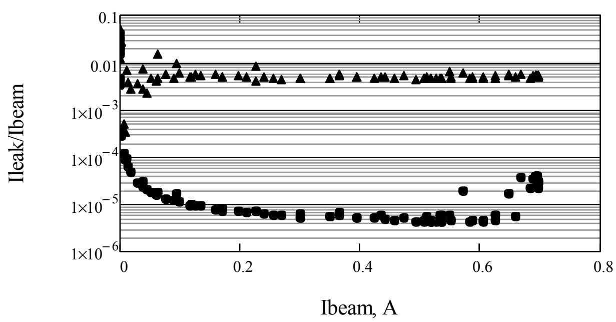

Figure 9: Dependence of efficiency of the main collector (triangulars) and combined collector (rounds) on main beam current. Experiment on HV cooler in BINP.

Generally the efficiency is slightly worse then for measurements in the test bench. It is difficult to define the reason of the difference: does it related with worse transportation of the beam or with not ideal measurements in the straight system (i.e. test bench).

Commissioning in COSY

As it was said, after the disassembling of the cooler in BINP the collector was upgraded. First tests of the upgraded collector were carried out only after assembling of the cooler in the COSY ring.

In Fig. 10 results of efficiency measurements on beam current are shown. Electron energy in the cooling section is 908 keV. One can see that efficiency of the collector is better then 10^{-6} for current 0.9 A that is much better then in tests before the upgrade.

Worse efficiency for lower current is related with features of the cooler. In the cooler beam position depends on beam current. Because of this for different currents we need to adjust transport channel optics to obtain optimal recuperation efficiency. For the measurements shown in Fig. 10 the transport channel was optimized for 0.9 A, which results in worse efficiency for lower currents.

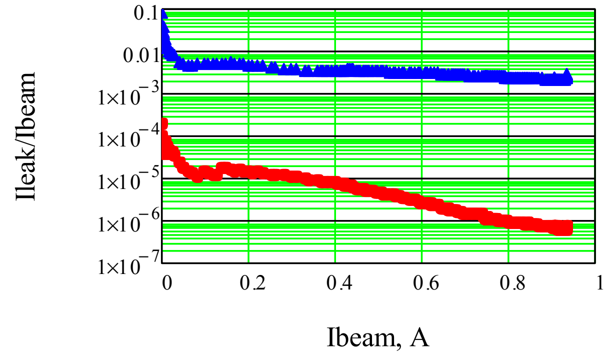

Figure 10: Figure 8: dependence of efficiency of the main collector (blue) and combined collector (red) on main beam current. Experiment on HV cooler in COSY.

CONCLUSION

Using a Wien filter together with axially symmetric electron collector allows to improve recuperation efficiency in high voltage electron cooling devices to the values 10^{-6} or better. Efficiency of such collector strongly depends on quality of electron beam transportation from gun to collector.

Inhomogeneity of transverse electric field in the Wien filter worsens collector efficiency by changing main beam shape.

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