Nuclear Inst. and Methods in Physics Research, A 872 (2017) 169–173

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

A test set-up for electron collector efficiency measurements

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ARTICLE INFO

Keywords:
Electron cooling
Secondary electrons

ABSTRACT

A low-energy test set-up for the measurement and optimisation of secondary electron currents from the collector in electron coolers is presented. A variable-field Wien filter and current-measuring aperture plates grant insight into the trajectory and energy distribution of the secondary particles. While secondary electrons flowing back from the collector can be bent away and dumped, these electrons in turn create new secondaries ("tertiaries"), and the resulting cascade is what ultimately limits the performance of the whole collector assembly, i.e. collector, optics, and Wien filter as a complete unit. Our set-up aims at understanding the behaviour of secondary and tertiary electrons inside this assembly. Using the included diagnostic devices, the efficiency of the collector itself can be measured as a function of the beam parameters and optics; some measurements of a COSY-style collector are given as an example.

1. Introduction

Hadron storage rings often include an electron cooler to maintain a low-emittance hadron beam in the face of heating effects, e.g. internal targets such as that planned for PANDA [1]. In these coolers, an electron beam is transported on the same trajectory and at the same speed as the hadron beam, allowing heat to be transferred from the hadrons to the electrons, which remain cold as they are renewed continuously. A continuous longitudinal magnetic field from the source to the collector makes the electron beam angular momentum dominated, compensating for space charge forces and keeping the effective transverse temperature low [2,3]. The cooling force benefits from a high current density; however, since the individual particles are hardly affected by the cooling interaction, most of the power stored in the beam can be recovered by decelerating it after the interaction region, enabling operation up to the single-digit MeV energy range with amperes of current without supplying and consequently dissipating the corresponding amount of power [4], the latest example being the 2 MeV COSY cooler [5].

Secondary electrons entering the deceleration section from the collector side are re-accelerated, after which they enter the beam pipe with ill-defined properties and partially collide with limiting apertures. As the resulting loading of the high voltage source, emission of X-rays, and deterioration of vacuum conditions interfere with the operational stability of the device, it is desirable to suppress the secondary electrons [4].

Prior research done by BINP has shown that a Wien filter as part of the collector optics is a suitable means to suppress electron backflow, increasing the total recuperation efficiency by a factor of 100 [6]. It does so by subjecting all particles to a force that depends on their velocity and direction of travel, allowing to tune the system such that the primary beam moves through the filter unaffected, whereas the beam travelling in the opposite direction is bent and stopped by a conductive plate. However, stopping these particles in turn creates new secondaries with a different energy and angle distribution. This gives rise to a cascade that depends heavily on the geometry of the electrodes and the vacuum chamber, making it inaccessible for analytical calculation. Apart from their broad initial distributions of energy, angle, and location, the trajectories of the particles are further complicated by cyclotron motion resulting from the longitudinal magnetic field. Although numerically calculating all possible trajectories in a statistically significant fashion is demanding in terms of time and memory, computer simulations can predict the behaviour of such a system qualitatively, which is sufficient to understand the necessary design principles and limitations.

2. Physical background

2.1. Secondary electron emission

The spectrum of secondary electrons emitted from a metal surface during collection of an electron beam shows two main features, namely a low-energy peak between 0 and 50 eV and another peak at the primary energy. The former stems from a transfer of kinetic energy to other

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http://dx.doi.org/10.1016/j.nima.2017.08.025
Received 21 April 2017; Received in revised form 12 August 2017; Accepted 14 August 2017
Available online 23 August 2017
0168-9002/

electrons inside the material, thereby releasing them, while the latter results from some primary electrons being scattered and reflected. There is a low-intensity background in the intermediate region as a combination of both effects [7,8].

2.2. Suppression of secondary electrons with a Wien filter

Since the beam of secondary electrons exits the collector optics near the symmetry axis, removing it without affecting the primary beam requires a force that depends on the direction of movement. This force is provided by a Wien filter, i.e. a field configuration in which an electric field $\vec{E} = E_x\vec{e}_x$ and a magnetic field $\vec{B} = B_y\vec{e}_y$ are perpendicular to each other and to the beam velocity $\vec{v} = v_z\vec{e}_z$. Choosing the field strengths such that

$$E_x = v_z B_y, \tag{1}$$

the resulting force is zero for the primary beam and

$$F_{\text{sec}} = e(E_x + v_z B_y) = 2eE_x \tag{2}$$

for a beam travelling in the opposite direction with the same velocity. The total force is chosen such that the secondary beam is deflected onto a collector plate.[1] Due to the non-zero beam diameter, off-centre particles do not travel through the filter on an equipotential line, which distorts the beam profile unless the field plates are specially optimised; also, the filter properties are not independent of the beam current because the potential distribution of the beam is added to that of the filter. These problems lead to an increase in effective beam diameter, thereby potentially deteriorating the performance of the collector itself; however, since these matters have been discussed in previous work [6], we will concentrate on the secondary electrons.

3. Experimental set-up

In order to gain a quantitative understanding of the secondary currents in the collector system of an electron cooler without the need to build and operate the high voltage acceleration and deceleration sections of such a device, a test set-up has been put into operation at Helmholtz-Institut Mainz, employing only the components necessary to produce, collect, and diagnose a realistic beam with energy recovery. As all relevant effects take place at a potential between that of the source cathode and that of the source anode, the intermediate high voltage sections present in a real cooler are unnecessary for this set-up and are consequently omitted, resulting in a comparatively compact device with easily extendible instrumentation. The electron source delivers a current of up to 0.5 A with a beam energy of 17 keV. Currently, a copy of the collector used in the COSY cooler is installed. A schematic sketch of the set-up is shown in Fig. 1.

The device contains several optical and diagnostic elements arranged such that their interaction with the primary beam is at a minimum. These are, ordered from source to collector:

- A Wien filter configured not to deflect the primary beam from its reference orbit at its average energy,
- A fluorescent screen and a beam position monitor (not shown in the sketch),
- A four-segment current-measuring scraper with a central aperture diameter of 25 mm,
- A field-shaping electrode called “deceleration anode” making up the positively biased half of the deceleration section, with the same central aperture as the scraper, and
- The suppressor electrode as the negatively biased half.

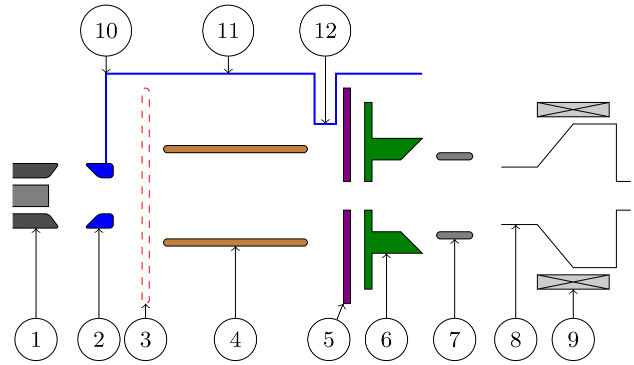

Fig. 1. Schematic view of the set-up (not to scale). (1) Source cathode, (2) Source anode, (3) WF collector plate, (4) WF electric field plates, (5) Segmented scraper, (6) Deceleration anode, (7) Suppressor, (8) Collector, (9) Deflecting coils, (10) Anode flange, (11) Beam pipe profile, (12) Reduced beam pipe diameter. The cooling region accompanied by acceleration and deceleration sections would be located between (2) and (3) in an electron cooler.

Fig. 2 shows a CST [9] simulation of the electric potential along the symmetry axis. Inside the collector, the beam is bent by a transverse magnetic field $B_{\perp,\text{col}}$ to prevent it from being reflected at the end flange.[2] Since this field changes the trajectories of the secondary electrons as well, a part of them can be suppressed in this way, as will be seen in Section 4. The suppressor electrode mounted in front of the collector entrance creates a local potential minimum that cuts off the low-energy part of the secondary electron spectrum by reflecting those having insufficient energy to overcome the barrier. While the permissible depth of this minimum depends on the beam current [4], it can never be as low as the cathode potential so as not to reflect the primary beam. Therefore, the elastic peak cannot be suppressed in this way. However, as the remaining secondaries have a relatively narrow energy distribution and are spatially collimated by the subsequent apertures in the deceleration anode and the scraper, they are deflected by the Wien filter in a well-defined manner and collected on the respective plate.

The currents flowing through all aperture plates are measured with a resolution of 1 nA. Note that some measurements related to secondary electrons have to be carried out with a relatively low beam current to limit the thermal power dissipated by the respective collector plates. Even though the magnitude of the beam current influences the behaviour of the device only slightly, most measurements presented here were carried out with small beam currents to ensure mutual comparability.

Details of the set-up can be found in [10].

4. Results

By varying the deflecting force of the Wien filter while keeping E/B constant, the deflection of the secondary beam can be observed. For minimum deflection of the primary beam, the plate voltages are $\pm 12\,\beta\,\text{kV}\,\text{mT}^{-1}$; with a plate distance of 60 mm and an energy of 17 keV, this gives a field strength of $100\,\text{V}\,\text{mT}^{-1}\,\text{mm}^{-1}$. The result of this measurement is presented in Fig. 3; for the corresponding simulation results and visualisation of the geometry, see Figs. 4 and 5. With the WF turned off, the secondary beam reaches the source anode aperture and is reflected back to the collector. The fraction of this beam that is not lost cannot be distinguished from the primary collector current. At low values of the WF field strength (region “1”), the secondary beam is deflected onto the anode flange, contributing to the beam pipe

[1] Note that as $B_\parallel \gg B_y$, the total angle of deflection is perpendicular to F_{sec} [6], i.e. the beam is bent into the paper plane in Fig. 1.

[2] In this set-up, the collector end flange holds an ion pump whose HV supply is referenced to the cathode potential. While other configurations are conceivable, any axially symmetric collector will reflect particles travelling on the central axis to some degree.