OPTICAL ELECTRON BEAM DIAGNOSTICS FOR RELATIVISTIC ELECTRON COOLING DEVICES

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Abstract

New magnetized high energy coolers like the one proposed for the High Energy Storage Ring (HESR) at the Facility for Antiproton and Ion Research (FAIR) have specific demands on the diagnostic of the electron beam. Due to high voltage breakdowns they only allow a very small beam loss so non-invasive beam diagnostic methods are necessary. For beam profile measurement a system based on beam induced fluorescence (BIF) was designed and is under installation at the 100 keV polarized test setup at the Mainzer Mikrotron (MAMI) at the moment. For the diagnostic of other observables of the cooling beam, like the electron beam energy or the electron temperature, a Thomson scattering experiment is planned at the same setup. The planned experiments for the beam profile measurement are presented and the challenges of the Thomson scattering method are discussed.

INTRODUCTION

A crucial demand in every cooling device is a perfect overlap of the cooling beam with the cooled beam to achieve high cooling rates. The optimization of the cooling rate e.g. for a proton beam is often done by optimizing the H^0-signal. This signal is maximized if both beams are overlapping and propagate with the same velocity. In this case the recombination rate of the protons with the cooling electrons is high. Since the Hydrogen Atoms are neutral they are not deflected by magnetic fields and can be detected after the next bending magnet. For the cooling of beams with higher energies one needs a longer cooling section i.e. smaller angular deviations can cause overlap problems. Furthermore for cooling antiprotons as it is planned in the (HESR) [1] there is no H^0-signal which could indicate a good cooling rate. This requires special beam diagnostics of the cooling beam. The diagnostic has to be be non destructive because of the high beam power and it should not affect the magnetic field flatness of the cooling section. There are already several non destructive beam diagnostic methods which are used in different accelerators like a scintillation profile monitor [2], [3] or the Laser wire scanner at the synchrotron source PETRA III [4]. These methods can be adapted for the use in electron cooling devices.

BEAM INDUCED FLUORESCENCE

For protons and ions beam profile measurement based on beam induced fluorescence is a common technique. The idea is to image the fluorescing residual gas on a photo detector with a spatial resolution as shown in Fig. 1.

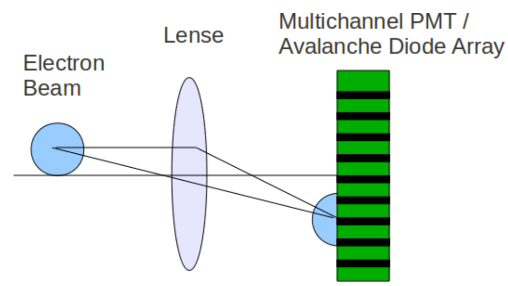

Figure 1: Principle of scintillation profile monitor

The production of the scintillation light depends on the residual gas pressure, the beam current and the composition of the residual gas. Different gases show different excitation spectra and consequential have different fluorescence spectra.

At the same velocity the ionization energy loss of electrons and protons are similar, they amount to $4.4\,MeVcm^2/g$ and $4.3\,MeVcm^2/g$ respectively for $\beta = 0.55$ in N_2. This should lead to a corresponding light output. From the energy loss and the photo production coefficient from [5] we can therefore estimate the fluorescence rates for electrons in nitrogen gas. For our detection device with a solid angle $\Omega = 4.7 \cdot 10^{-2}\,sr$ we expect a count rate of $450\,Hz/cm$ of longitudinal beam extension at a pressure of 10^{-6} mbar and a $10\,\mu A$ beam. A special vacuum chamber has been designed to test this assumption (Fig. 2).

This chamber allows to image the transverse beam profiles through silica windows which are transparent down

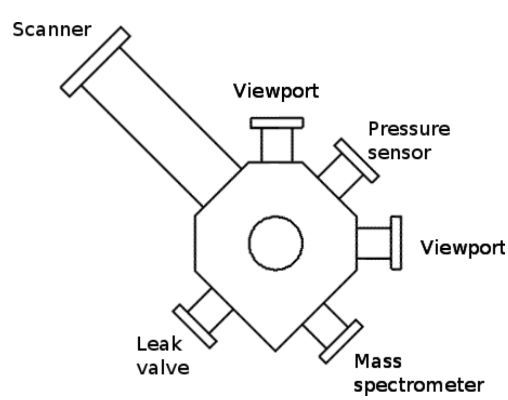

Figure 2: Vacuum chamber for beam induced fluorescence studies. The electron beam goes into the plane of the paper

to 200 nm. With the leak valve which is controlled by the pressure sensor the residual gas pressure can be changed from 10^{-5} mbar to 10^{-8} mbar automatically. A mass spectrometer detects the partial gas pressure and enables the analysis of the photon yield of different scintillation gases. The chamber is currently under installation at the polarized test source (PKAT) [6] at the Mainzer Mikrotron (MAMI).

THOMSON SCATTERING

Theory

Thomson scattering describes elastic scattering of a photon on a free electron. It is the low energy limit of the compton scattering process. Figure 3 shows a schematic view of Thomson scattering.

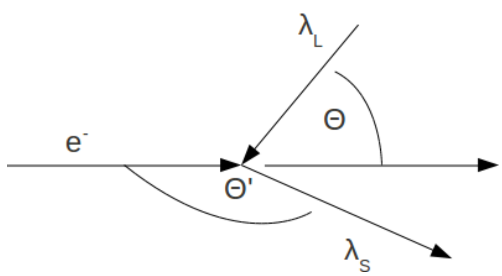

Figure 3: Thomson scattering scheme

A photon λ_L hits the electron beam under an angle Θ and is scattered under the scattering angle Θ'. The scattered photon λ_S gains energy due to the Doppler shift. The wavelength of the scattered photon as a function of the angle between incident photon and electron and the angle between scattered photon and electron can be evaluated with

$$\lambda_S = \lambda_L \frac{(1+\beta\cos\Theta')}{(1+\beta\cos\Theta)} \qquad (1)$$

where β is the electron velocity in units of the speed of light. The scattering process is determined by the Thomson cross section

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(1+\cos^2\Theta'\right) \qquad (2)$$

with r_e = classical electron radius. The event rates i.e. how many photons are scattered can be calculated wit the following equation

$$R = \frac{1}{2} r_e^2 (1+cos^2(\Theta')\, N_L n_e \epsilon \Delta\Omega l \frac{(1+\beta cos(\Theta))}{(1+\beta cos(\Theta'))\gamma} \qquad (3)$$

with N_L = Number of incident photons per Joule, n_e = Electron density, ϵ = Detector system efficiency, $\Delta\Omega$ = Detector solid angle, l = Interaction length, $\frac{(1+\beta\cos(\Theta))}{(1+\beta\cos(\Theta'))\gamma}$ = factor results from Lorentz transformation.

Beam Diagnostics

In 1987/1988 a pioneer experiment demonstrated the feasibility of Thomson scattering for our purpose [7], [8]. At that time however, the signal to noise ratio suffered from the low power and repetition rate of the Laser system. We revisit this approach in the light of the enormous developments in Laser technology since that time. The presented setup uses the following angles $\Theta = 90°$ and $\Theta' = 180°$ like a Laser wire scanner. In this case the rate of the scattered photons only depends on the electron density in the electron beam. By moving the Laser beam through the electron beam a beam profile measurement can be done. Due to the low cross section, mostly dominated by the classical electron radius squared the necessary Laser power is very high and it is only reasonable for high electron densities. In Tab. 1 the event rates for different setups are shown. For the calculation a 100 W Laser system and an electron beam current of 1 A and a diameter of 3 cm was chosen.

Table 1: Scattering Rate for Different Cooling Devices

Electron Energy	λ_L	λ_S	Event Rate
100 keV (PKAT)	1.06 µm	475 nm	100 s^{-1}
2 MeV (COSY)	10.6 µm	220 nm	$6.5 \cdot 10^3\ s^{-1}$
4.5 MeV (HESR)	10.6 µm	50 nm	$1.3 \cdot 10^4\ s^{-1}$
8 MeV (ENC)	10.6 µm	20 nm	$2 \cdot 10^4\ s^{-1}$

Like the BIF measurements the Thomson scattering experiment will also be done at the PKAT. As seen in Tab. 2 the gun is capable of delivering peak currents of 60 mA with a diameter of 2 mm so the electron density is the same as in a cooling device with 2 A and 3 cm. To perform this experiment we use the setup shown in Fig. 4. This enables a detection of the scattered photons in forward direction while the electrons are bend by 270° which suppresses the background generated from fluorescent light in the beam dump.

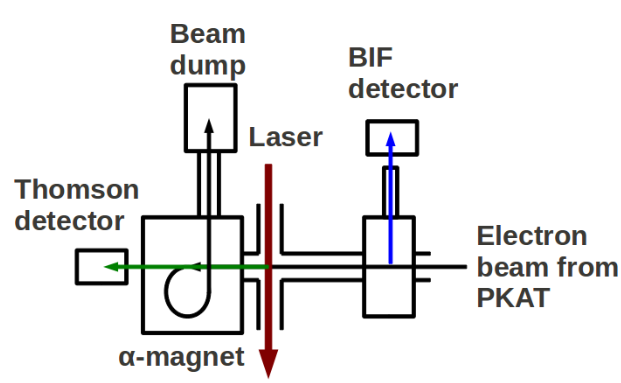

Figure 4: Schematic view of the future diagnostic setup at the PKAT

An other advantage of the Thomson scattering method is the possibility to measure the electron energy. This can be done in with the same setup which is used for the beam profile measurement. In this case a frequency analysis of

Table 2: PKAT Parameter Setup

Electron Energy	100 kev
DC current	200 μA
Beam diameter	2 mm
Peak current (pulsed)	60 mA
Pulse duration	10 ns
Rep. rate	50 Hz

the scattered photons is needed instead of a the scattering rate. This can e.g. be done with a Fabry-Perot interferometer at an virtual arbitrary accuracy. Since Eq. 1 establishes a well defined relation between the angle and the velocity (i.e. the energy) the error in energy determination is mainly limited by the accuracy of the angle measurement.

This can be very interesting for the cooling of antiprotons. Because of the missing H^0-signal an energy matching of both beams which is needed for an efficient cooling process is more difficult. With a good energy measurement the adjustment of the electron beam can be done faster and more efficient.

Challenges

As mentioned above one of the challenges with Thomson scattering is the very low cross section. Because of that very high laser photon fluxes and laser powers are needed. These high power Laser beams have to be transported and focused to the interaction point without significant losses to get high signal rates and avoid a damaging of parts of the beam line. For the beam profile measurements with Thomson scattering the acquisition of a Laser system with the following specifications is planed.

Table 3: Laser System Specifications

Wavelength	1064 nm
Beam diameter	100 μm
Pulse power	2 J
Pulse duration	20 ns
Rep. rate	50 Hz

Since the PKAT is not able to deliver a DC beam with 60 mA the timing between electron and Laser beam is essential for this experiment. One possibility to solve the timing problem is shown in Fig. 5. A fraction of the Laser pulse will be frequency doubled send to the photo cathode of the PKAT while the main part of the pulse is delayed. The Laser pulse has to be delayed for the time it takes the electron bunch to travel from the cathode to the interaction point. There both beams collide under an angle of 90°. The Thomson scattered photons are detected behind the α-magnet which bends the electrons by 270°. Mirrors in the Laser beam line allow a transverse shift of the Laser beam and a transverse scanning of the electron beam. The number of scattered photons is proportional to the electron density of the electron beam. If one assumes a Gaussian profile of the electron beam a Gaussian fit to the intensity of the scattered photons as a function of the displacement of the Laser provides the transversal beam profile.

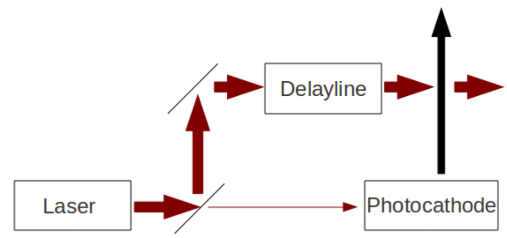

Figure 5: Laser system setup

Because of the low scattering rates all kind of background has to be avoided. This includes beam induced fluorescence as well as electron beam loss at the wall of the vacuum chamber or radiation emitted by the beam dump. To decrease the background the photo detector can be synchronized to the Laser pulses.

OUTLOOK

The vacuum chamber for the BIF measurement is currently under installation so first results should be achievable within the next months. For the Thomson scattering further modifications at the PKAT beam line are in preparation and the acquisition of an adequate Laser system is planned for 2011.

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