DIAGNOSTICS FOR ELECTRON COOLED BEAMS

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Abstract

Nearly all modern storage rings use an electron cooling device to increase the phase space density of the circulating beam before its transfer to another accelerator or the experiments. For fast and efficient cooling, the properties of the electron and hadron beams need to be monitored before, during and after the cooling process.

In this paper we review the various techniques, both destructive and non-destructive, used to measure and optimise the different parameters that determine the quality of the cooling.

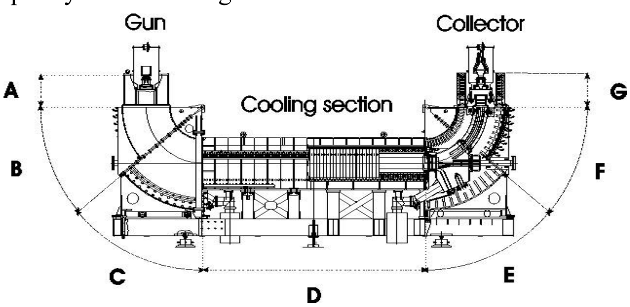

Figure 1: Electron cooler layout.

DIAGNOSTICS FOR THE ELECTRON BEAM

A typical electron cooling device (fig. 1) consists of three parts: i) the electron gun, where an intense and mono-energetic electron beam is generated, ii) the interaction region, where the cooling of the circulating beam takes place through Coulomb interaction between the electrons and the ions, and iii) the collector, where the electron beam is decelerated and the beam power recuperated. The whole system is immersed in a strong longitudinal magnetic field, which is needed to counteract the space-charge force of the electron beam [1].

The cooling time τ can be approximated by the following formula:

$$\tau = \frac{0.6\pi r^2 A \beta^4 \gamma^5 \theta^3}{\eta I_e Z^2},$$

where η is the fraction of the ring occupied by the cooler, I_e the electron current, θ is the relative difference in angle between the electrons and ions ($\theta = \theta_i - \theta_e$, where θ_i is the ion beam angle, θ_e the electron beam transverse temperature $v_t/v_{//}$), A the atomic mass, Z the charge state of the ions and βγ the relativistic factors. From the above formula the following parameters of the electron beam should be known: i) the electron current, ii) the beam position, iii) the velocity (both in magnitude and direction), iv) the longitudinal energy spread and v) the transverse energy. It is worthwhile to note that these parameters vary with radial position and also in the axial direction.

Beam destructive methods

Probes inserted into the electron beam will in most cases immediately melt or evaporate. The power-density load is such that the absolute limit in the energy of the electron beam is 20 keV when one considers such methods. In fact 10 keV seems more realistic unless the electron beam is pulsed.

Such devices also change the space-charge fields and self-fields of the electron beam resulting in measurements that may not necessarily reflect the real beam distribution. The current intersected by the probe is also an additional load on the high voltage power supply and hence can only be used at low electron beam currents.

Faraday cups, scintillation screens and pinhole collimators

The beam position and current density can be measured as a function of radial position and axial distance by the use of a water-cooled Faraday cup [2]. If a phosphor screen coupled to a camera is used, then one obtains a direct image of the current density distribution of the electron beam (fig. 2).

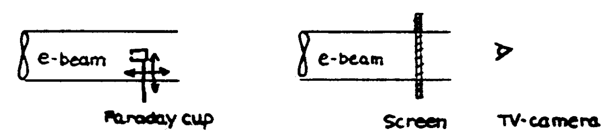

Figure 2: Electron beam measurement with a Faraday cup or scintillation screen.

By inserting a moveable pinhole collimator in the measurement system, a “pencil beam” is generated and one obtains information on the divergence of the electron beam. This parameter is of the utmost importance for electron cooling as it gives a measure of the straightness of the guiding magnetic field.

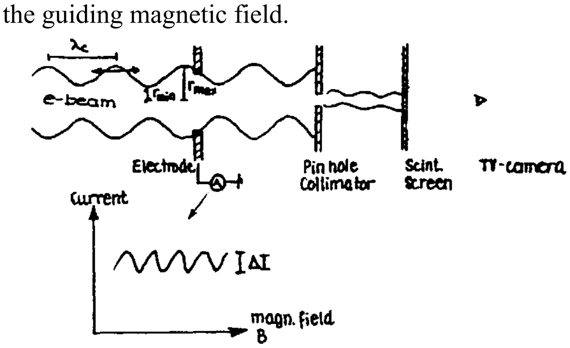

Figure 3: Measurement of the electron beam ripple.

Measurement of the beam ripple

The cyclotron motion of the electron is superimposed on a slow drift rotational motion caused by the crossed space-charge electric field and the longitudinal magnetic field. These two motions cause the electron beam radius to oscillate in the axial direction with the Larmor wavelength. When changing the magnetic field, the change in beam radius can be measured as a current falling onto an iris shaped electrode (fig. 3). Since the variation in current is related to the Larmor radius, $r_L = ½(r_{max}-r_{min}) = 2\Delta I/I$, it is possible to extract the transverse energy of the electron beam $E_t = ½m(r_L\omega_c)^2$..

Cross wires

For low power density electron beams, cross wires [2] can be used to determine the beam position, size and density distribution. A thin tungsten wire that is made to intersect with the electron beam becomes incandescent and a camera can view the light given off. To measure the density distribution, the current on the wire can be recorded as a function of the radial position of the wire. This technique was used to validate the principle of a variable density electron gun for the IMP-Lanzhou electron cooling device (fig. 4).

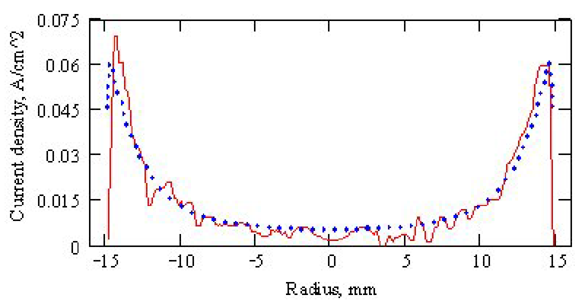

Figure 4: Electron beam density distribution measurement with a cross wire. The dots represent the calculated values and the solid line the measured distribution.

Non-destructive methods

A number of non-destructive methods for measuring the electron beam parameters exist and amongst the different methods the following have been tried on many cooler synchrotrons: i) electrostatic pick-up electrodes, ii) microwave radiation, and iii) laser beam diagnostics.

Pick-up electrodes

Cylindrical electrodes [2] situated inside the electron cooler vacuum chamber can be used to accurately determine the mean position of the electron beam. Electron beams used for cooling are DC, and thus have to be intensity modulated by applying a sinusoidal variation on the accelerating voltage for a signal to be measured on the pick-up. Gain switching of the head amplifiers enables the pick-up stations to also measure the position of the ion beam in the interaction region. In this way alignment of the two beams can be obtained relatively quickly and accurately. In addition to their function as beam position monitors, the electrodes can be used as clearing electrodes in space-charge neutralisation experiments [3].

Microwave radiation

Electrons spiralling around the magnetic field lines emit radiation with a total power proportional to the transverse energy of the electrons [4]. This radiation can be detected with an antenna situated outside the beam anywhere along the trajectory. The power spectrum is centred at the cyclotron frequency, ω_c, but is Doppler-broadened with a width of $2\omega_c\beta$ (fig. 5). The power signal is very small, thus no absolute measure of the transverse energy is possible, but the main optical parameters such as the longitudinal magnetic field can be optimised with this method. Detection of microwave radiation is also only possible with intense electron beams.

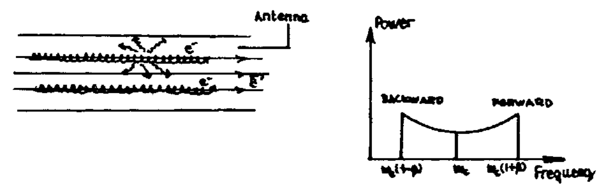

Figure 5: Electron beam microwave radiation.

Laser beam diagnostics

The principle [5] here is to measure the spectral density of Doppler-shifted backscattered light that is sent anti-parallel to the electron beam (fig. 6). The scattered laser light is blue-shifted with a reduction in wavelength by a factor 2-5. The analysis of this light is normally performed with a photomultiplier or a high-resolution Fabry-Perot spectrometer.

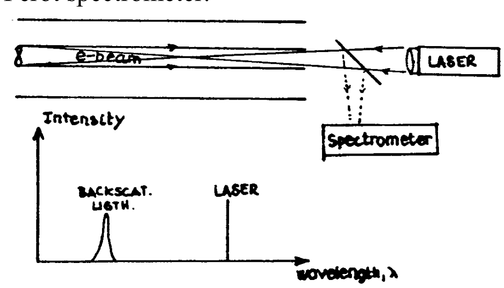

Figure 6: Principle of the laser beam diagnostics.

Laser beam diagnostics is a very powerful way of determining a number of very important characteristics of the electron beam. The velocity of the beam can be found from the Doppler shift in wavelength and the width of the backscattered spectrum gives the longitudinal energy spread. The electron beam current can even be estimated from the amplitude of the scattered light.

Scanning a thin laser beam across the electron beam makes it possible to measure current densities, velocity profiles and spreads as a function of radial position.

ION BEAM & COOLING DIAGNOSTICS

To measure the performance of the cooling process it is imperative to monitor a number of parameters of the circulating ion beam. The parameters of interest are i) the number of stored particles, ii) the particle momentum and momentum spread, iii) the ion beam position, and iv) the ion beam size. Furthermore the devices should be able to measure changes in these parameters with time constants smaller than the cooling times.

Schottky scans

A wealth of information on the beam can be obtained from the Schottky signals of the beam [6]. In the longitudinal plane the absolute momentum of the beam can be measured and the electron beam energy can be adjusted. The momentum spread of the beam at equilibrium as well as the intensity of the beam can also be obtained by analysing the frequency distribution. In the transverse plane the beam emittance and information concerning the ring optics (tune, chromaticity) can be extracted from the Schottky sidebands.

Schottky signals are observed on spectrum analysers and when used to observe the variation of the spectral density around a given frequency as a function of time (receiver mode), the longitudinal and transverse cooling times can be estimated. To follow the complete cooling process it is necessary to down mix the signals with the use of a single sideband mixer having a bandwidth of around 100 kHz followed by fast digitising and a Fourier transform. In this way a time resolution of a few milliseconds is obtainable with only a slight degradation in the signal to noise ratio. This technique was used quite extensively for the Pb ions cooling tests performed in 1997 on LEAR [7].

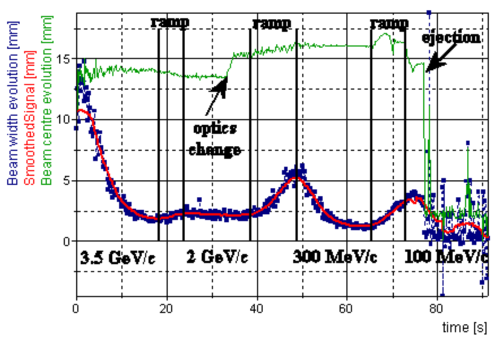

Figure 7: Antiproton vertical size & position during the AD deceleration measured by the IPM.

Ionisation profile monitors (IPM)

The principle is to measure the profiles of electrons (or ions) created in ionising collisions between the circulating ion beam and the rest gas molecules. By applying a transverse electric field the electrons are accelerated on to a detector, typically a multi channel plate (MCP) followed by a phosphor screen. Cooler rings typically operate in vacuums of the order of 10^{-11} torr and the ionisation rate is limited to some 10^4 s^{-1}. The MCP helps to amplify this number but in certain cases where the circulating beam intensity is low, additional systems, such as a gas injector, have to be envisaged. This is the case on the AD machine at CERN where the 10^7 antiprotons in the ring do not give a sufficient signal and a N_2 gas injector is needed to create a local pressure bump around the IPM [8].

IPMs are used to monitor the evolution of the beam size, the beam position in the IPM, and also the beam intensity at any given energy. An example of an IPM measurement is shown in fig. 7.

Neutral channel and recombination detectors

During the cooling process the centre of mass energy difference becomes very small and ions can capture an electron by radiative or di-electronic recombination. In the next bending magnet their trajectory becomes very different from that of the circulating ions. For proton beams, neutral hydrogen atoms are formed and travel straight towards a detector. For partially stripped ions, the down charged ions can be lost in the bending magnet. If the ring acceptance is large, then multiple charge states of the same ion can circulate in the machine.

The choice of detector depends on the required information. A scintillator coupled to a photomultiplier is used to measure the recombination rate from which the transverse energy of the electron beam can be evaluated. It is also a good means to correct any angular deviations between the electron and ion beams as the maximum signal is obtained when the beams are correctly aligned. Using a camera behind the scintillator, one can derive the profile and position of the ion beam from the profile and position of the recombined beam.

CONCLUSIONS

Many possibilities exist to measure both the electron and ion beam parameters in a cooler ring. For electron beams the least complicated systems are beam destructive and thus are only suitable for use on a test bench before installation in the ring. Non-destructive instrumentation used to determine the ion beam characteristics are also well suited for measuring the efficiency of the cooling process. Pick-ups can be used to accurately align the two beams whereas Schottky scans and ionisation profile monitors can record the complete cooling process in all three planes.

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