Nuclear Inst. and Methods in Physics Research, A 880 (2018) 15–21

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

Effect of electron beam cooling on transversal and longitudinal emittance of an external proton beam

K. Kilian[a], H. Machner[b,*], A. Magiera[c], D. Prasuhn[a], P. von Rossen[a], R. Siudak[d], H.J. Stein[a], H. Stockhorst[a]

[a] Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
[b] Fakultät für Physik, Universität Duisburg–Essen, Lotharstr. 1, 47048 Duisburg, Germany
[c] Institute of Physics, Jagellonian University, 30059 Krakow, Poland
[d] Institute of Nuclear Physics, Krakow, Poland

ARTICLE INFO

Keywords:
Charged particle beam
Electron cooling
Emittance

ABSTRACT

Benefits of electron cooling to the quality of extracted ion beams from storage rings are discussed. The transversal emittances of an external proton beam with and without electron cooling at injection energy are measured with the GEM detector assembly. While the horizontal emittance remains the vertical emittance shrinks by the cooling process. The longitudinal momentum variance is also reduced by cooling.

1. Introduction

The emittance and related topics are discussed in detail in a series of monographs like [1,2] and [3] or notes [4] just to name a few. However, we like to make some short remarks to make the paper better understandable. In addition there are different definitions in the literature. It seems therefore useful to give here the definitions which we will apply.

The quality of a particle beam is expressed in terms of the emittance. It is a measure of the deviation of the beam particles from its design path. Deviations from the design path are measured as the momentum deviation and the space deviation. Since both quantities have three dimensions the emittance is a volume in the sixth dimensional phase space. The dimension parallel to the motion of the particle is called the longitudinal emittance. The other two dimensions are referred to as the transverse emittances. In a circular accelerator no dissipative forces act on the particles, i.e. forces which depend on the velocity v, the emittance is conserved (Liouville's theorem). It can be simply reduced by scraping particles from the beam, i.e. by loss of intensity. It is known that particle beams with small emittance will allow higher precision experiments than those with larger emittance. Therefore methods have been derived which allow to reduce the emittance of a beam without losing intensity. For higher energies it is the stochastic cooling invented by van der Meer and collaborators [5,6]. At lower energies it is electron cooling invented already in 1966 by Budker [7,8].

The paper is organised as follows. First we describe the 100 kV electron cooler followed by the emittance measurement of the extracted beam: In a first step that of an uncooled but accelerated proton beam, then in a second step that of a cooled and accelerated beam. Finally we summarise the measured values.

2. e-Cooler

In analogy to the kinetic theory of gases one defines transversal and longitudinal temperatures which are the mean quadratic deviations of the transversal or longitudinal velocities of the particles in the rest system where the average particle velocity is zero. From this one has

$$\frac{kT_{x,y}}{2} = \frac{1}{2} m_0 \overline{v^2_{x,y}} = \frac{p_0^2}{m_0} \frac{\epsilon_{x,y}}{\beta_{x,y}} \tag{1}$$

$$\frac{kT_z}{2} = \frac{1}{2} m_0 \overline{v^2_z} = \frac{p_0^2}{2 m_0 \gamma^2} \left(\frac{\Delta p_z}{p_0} \right)^2 . \tag{2}$$

The factor $1/\gamma^2$ in Eq. (2) comes from the Lorentz boost in beam direction, m_0 is the rest mass of the hadron. Cooling is thus another word for reducing the emittance or the momentum spread. The machine to reduce the emittance is therefore named cooler. As mentioned in the introduction electron or e-cooling was invented by Budker [7,8]. Here we shortly discuss the electron cooler or e-cooler at COSY Jülich. It is the so called 100kV cooler not to be mistaken with the more recently installed 2MV cooler. Fig. 1 gives the cross section of the apparatus.

---

[*] Corresponding author.
E-mail address: hartmut.machner@uni-due.de (H. Machner).

https://doi.org/10.1016/j.nima.2017.10.055
Received 22 July 2017; Received in revised form 3 October 2017; Accepted 19 October 2017

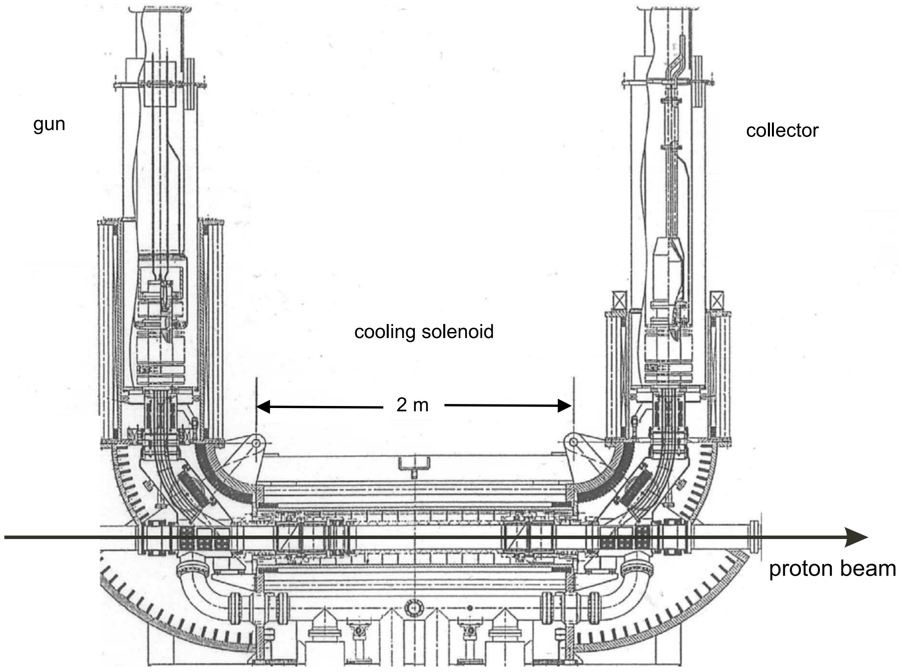

Fig. 1. The 100 kV e-cooler at COSY Jülich. The support is not shown. For details see text.

Table 1
Parameters of the 100 kV e-cooler at COSY. In cases where no entry is in the column applied, the parameters are not variables.

Parameter	Design	Applied
Effective cooling length (m)	1.40	
Beam tube diameter (m)	0.15	
Beam axis above ground (m)	1.8	
E-beam diameter (mm)	25.4	
Magnetic field range (mT)	$3 * 10^9$	$8 * 10^8$
Maximal e-beam voltage (V)	$1.5 * 10^9$	$2.7 * 10^8$
E-beam current at 25 kV (A)	1.8	0.1–0-6
Collector loss factor (%)	<0.05	0.01–0.04
Vacuum pressure in cooling region (hP)	5–10$* 10^{-9}$	1–10$*$ 1ß$^{-9}$
Electron gun perveance (μA/V$^{3/3}$)	0.8	

The principle of operation is that the hot hadron beam is surrounded by a cold electron beam. Both beams move with the same velocity and let us assume the same velocity distribution. Then the ratio of their temperatures is given by the ratios of their masses and therefore the electron gas is cold. The hadron beam is indicated in the figure by the arrow. The electrons are produced in a cathode and accelerated. This arrangement is called gun. The electron beam is then deflected by a dipole magnet by 90° into a solenoidal magnet, where it overlaps the hadron beam. Interaction is provided by the Coulomb force. The electrons are then deflected once more and dumped on a collector. After some time the temperature of the hadrons becomes the one of the electrons. The parameters of the e-cooler are given in Table 1.

During the cooling process electron capture is possible:

$$e^- + p \rightarrow \mathrm{H}^0 + h\nu \,. \tag{3}$$

This reaction was used to study the progress of cooling [9]. The neutral hydrogen atoms are unaffected in the next dipole of the COSY accelerator and move straight. At a position behind a window outside of the accelerator vacuum the dimension of this beam is measured by two wire chambers with wires in x- and y-direction. Then from a given β function from the magnetic lattice at the point of the capture reaction, i.e. in the cooler, the emittance can be calculated. In Ref. [10] for such a measurement at injection momentum of 294 MeV/c, emittances $\epsilon_{x,y} = 2.5$ mm mrad were obtained. It should be stressed that this refers to internal beams while our study is concerned with the emittances of external beams. The loss of particles due to recombination is marginal [11,12].

3. Measurements

To measure the emittances the following procedure was applied. To protect the delicate solid state detectors the beam current was reduced to a permissible intensity. This was done by de-bunching the beam behind the ion source before entering the injector cyclotron (μ-pulsing). The full beam intensities with bunching were those given in Table 2. The injection energy of 45 MeV corresponds to a momentum of 294 MeV/c. The cooler was put to 24.5 kV. The uncooled beam was then accelerated to 800 MeV/c for a following experiment. For the cooled beam this was 1440 MeV/c. The emittances were measured in two steps: first positions in x- and y-direction were measured simultaneously, then in a second step momentum components $p_{x,y,z}$ were measured, again simultaneously.

3.1. Extraction

When external experiments require high beam currents, although for a short time interval, fast kicker extraction is applied [13]. In contrast to the fast kicker extraction method, stochastic extraction is capable to slowly extract the beam over a long period of time. This is the method applied here. The beam particles are driven by swept noise into the 11/3 order resonance in the horizontal plane created by sextupole magnets. In this extraction process the horizontal beam emittance is determined by the extraction mechanism, whereas the vertical emittance is solely determined by the optics of the COSY ring.

3.2. Emittance measurements

Here we are interested in the application of a proton accelerator. The common technique in the literature is to measure in one step the spatial intensity distribution. This is done for instance by viewing on a phosphor or alumina screen via a 45° mirror with a CCD camera and analysing the digitised pixel distribution. Another straightforward way to measure the proton beam size is to drive a scraper into the beam or move the beam