NEW DEVELOPMENTS IN HIGH ENERGY ELECTRON COOLING

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Abstract

Electron cooling of hadron beams is a powerful technique by which accelerator facilities achieve the necessary beam brightness for their physics research. An overview on the latest developments in high energy electron cooling (electron beam energy higher than 500 keV) is given. Technical feasibility for electron beam energy up to 8 MeV is discussed.

INTRODUCTION

The use of electron coolers in the range of electron beam energy lower 400 keV is well established and state of the art. For higher electron energies there exists up to now only one machine – the Recycler Electron Cooler (REC) of Fermilab with a terminal voltage of 4.4. MV [1]. The cooler was successful installed into the Recycler during the summer of 2005 and was operating until end of 2011 when the Tevatron was shut off. The cooling opened the possibility for several times higher, record luminosities. The REC overcame not only the great challenge of operating 4.4 MV pelletron accelerator in the recirculation mode with up to 1A beams, but also resolved the hard issue of high quality magnetised beam transport through non-continuous magnetic focusing beamline [2]. The next unique high energy electron cooler -the 2 MV COSY electron cooler- is now under commissioning in the Budker Institut in Novosibirsk and will be installed in the Cooler Synchrotron COSY in spring of next year [3]. Development of high energy electron coolers is a technical challenge due to the engineering problems like high voltage generation, power transmission to the gun and collector in the accelerator "head" and the power transmission to the magnetic coils at the accel/decel tubes for magnetised electron beam transport. Today there is a need for further development. In the high energy storage ring HESR for antiprotons in the FAIR facility in Darmstadt a 4.5 MV electron cooler is planed [4]. The proposed concept of a polarized Electron-Nucleon Collider (ENC) integrates the 15 GeV/c HESR of the FAIR project for protons/deuterons and an additional 3.3 GeV electron ring [5]. A new 8.2 MV electron cooler is an essential part in this concept. In the NICA collider project of the JINR Dubna a 2.5 MV electron cooler is foreseen with one electron beam per each ring of the collider [6]. There are some special features of high energy cooling. The cooling rate decreases with γ^{-2}. To obtain a maximum friction force the "waveiness" of the magnetic force line should be as small as possible to get a smaller contribution to the effective electron velocity [7]. To get a high cooling rate magnetised electron cooling is necessary. All low-energy (3-400 keV) electron coolers are based on magnetised cooling. The electron beam transport and alignment of electron and ion beam is done with continuous magnetic field. Strong magnetic field completely suppresses transverse temperature of electron beam, so that effectiveness of cooling is determined by a very low longitudinal temperature of electrons. Non-magnetised cooling relies on the fact that rms velocity spread of electrons is comparable or smaller than the one of ions which need to be cooled. For the REC (non-magnetised case) cooling times of about one hour was sufficient. The new coolers for COSY and the new future projects should provide a few orders of magnitude more powerful longitudinal and transverse cooling. This requires new technical solutions. The basic idea of the new COSY cooler and for the future HESR and NICA collider coolers is to use a high magnetic field along the orbit of the electron beam from the electron gun to the collector. Faster cooling times are essential for the future projects. The technical problems for electrostatic accelerator at 8-10 MV and needed electron beam currents up to 3 A look too hard. An alternative can be a low frequency linac with bunched electron beam. Today this system achieved electron peak currents of about 10 A [8].

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ENGINEERING PROBLEMS OF HIGH ENERGY ELECTRON COOLERS

The engineering problems are listed in the following:

- High voltage generators (< 10 MV).
- High voltage performance.
- Limiting performance of accelerator tubes.
- Power transmission to the accelerator "head" (gun, collector).
- Power transmission to the magnetic coils (at accel/decel tubes).
- Electron current and high voltage stability (1-3 A, 10^{-5}).
- Electron beam formation, transportation and recovering.
- Magnetic field measurement system in the cooling section.
- Magnetic field straightness in the cooling section ($< 10^{-5}$).
- Electron beam diagnostics.

Power transmission in commercial available pelletrons is realised by isolated rotating shafts combined with generators located on high voltage level. In case of magnetised coolers, where additional power is needed for the magnetic coils around the accel/decel tubes this method seems to be too complicated. Another solution is cascaded resonant transformers and proposed turbines on high voltage level or combinations of both. The technical solution is strongly influenced by the location of the magnetic coils at the accelerator/ decelerator tubes. Due to the difficulties the magnetic coils (superconducting) in

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the NICA collider electron cooler project are arranged out side of the high voltage vessel.

HIGH VOLTAGE SYSTEMS

Overview

There exist different high voltage generators, which are possible candidates for the high voltage system of a high energy electron cooler. The REC of Fermilab is based on a 4.4 MV electrostatic accelerator (pelletron [9]) which works in the energy recovery mode (i.e. electrons are decelerated and captured in the collector after they interact with the antiprotons in the cooling section). The pelletron is a well-tested electrostatic accelerator, which has been built for voltages as high as 25 MV. The pelletron is commercial available. In the Upsalla design for the 4.5 MV electron cooler for the HESR a commercial pelletron is foreseen [10]. The accelerator can be adapted to the inclusion of a longitudinal magnetic field, but the problem of the thermal cooling of the solenoids needs a solution. The pelletron is constructed in a modular way. A future increase of the high voltage to at least 8 MV seems possible. The Cockcroft–Walton (CW) generator (or Greinacher multiplier) is an electric circuit which generates a high DC voltage from a low voltage AC or pulsing DC input. This is proposed for the 2.5 MV electron cooler in the NICA project in Dubna. A compact cyclotron to accelerate negative hydrogen ions up to 8 MeV is proposed as optimal solution to the problem of charging the high voltage terminal of the 8 MV electron cooling system for the High Energy Storage Ring at FAIR [11]. A Dynamitron uses capacitive coupling to the individual stages of the accelerating/decelerating columns for the generation of the high voltage. This technique is difficult to adapt to the requirement of a longitudinal magnetic field in the accelerating/decelerating columns and is not modular. However, Dynamitron accelerators for Accelerator Mass Spectroscopy have demonstrated a high voltage stability of $\leq 10^{-5}$, which meets the requirements for the HESR electron cooler. The industrial electron accelerators of ELV type are constructed on the base of the cascade generator with a parallel feed of cascades. These accelerators are manufactured in the Budker Institute of Nuclear Physics (BINP) in Novosibirsk[12]. The electron beam power for ELV-type accelerators is up to 400 kW. Beam energy range is 0.3 MeV to 2.5 MeV. The distinguishing feature of cascaded rectifier circuits is the method of coupling ac power to all of the rectifier stages. These methods may be classified as inductive or capacitive with series or parallel coupling. With series-coupled systems, the rectifier stages nearer to the input ac power supply must transmit ac power to the farther stages. This increases the internal impedance of the system and the voltage droop under load. With parallel-coupled systems, all of the rectifier stages receive the same input ac power, which reduces the internal impedance and reduces the voltage droop under load. For the COSY high energy electron cooler the high voltage (up to 2 MV) and power for the magnetic coils (of about 300 W per coil pair) at the accel/decel tubes are generated by a cascaded resonant transformer.

A novel idea from Budker institute is to use small turbines. They are used for high voltage generation, power for the magnetic coils in side the high voltage tank and for power of gun and collector in the terminal.

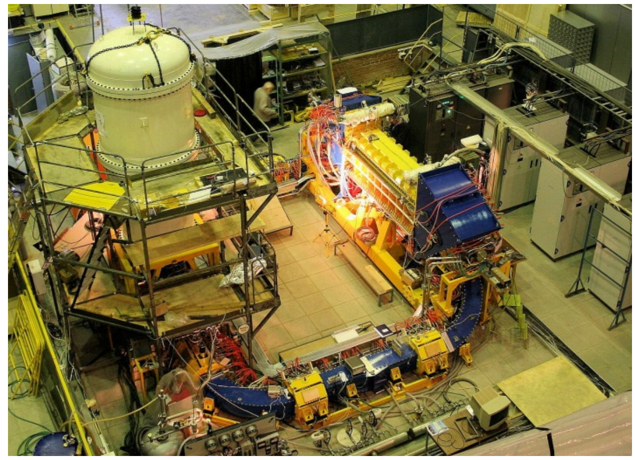

Figure 1: Commissioning of the 2 MV electron cooler at BINP, Novosibirsk [3].

High Voltage System of the 2 MV COSY Electron Cooler

The high voltage terminal is supported by a column consisting of 33 identical high voltage sections (HV sections) [3]. The whole assembly is placed inside a vessel filled with SF_6 under pressure up to 10 bar. Each HV section contains two coils providing guiding magnetic field for acceleration and deceleration tubes and the high voltage power supply generating up to 60 kV. Total power consumption of one section is about 300 W. The key problem of the accelerating/decelerating column is the transfer of the energy to 33 sections and to gun and collector, which are located at high voltage potential. The concept of the power supply is based on idea of a high frequency cascaded resonant transformer (20 kHz, 40 kW). The system consists of 33 transformers with cascaded connection. The electrical energy is transmitted from section to section from the ground to high-voltage terminal. Along this way the energy is consumed by the regular high-voltage section. The main problem of such decision is leakage inductance of the transformers. They are connected in series and the voltage from power supply is divided between inductance leakage and a useful load. In order to solve this problem the special compensative capacitance is used. The impedance of leakage inductance is decreased significantly on the resonance frequency.

Gas Turbines

In the last years the COSY Juelich-BINP Novosibirsk collaboration was studying prototype elements for a magnetised cooler [13]. The turbine electro generator driven by compressed gas was tested. This gas is used to produce power for individual high voltage sections and, at the same time, to cool the 500 Gauss coils (Fig. 2). For

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experiments with HV sections in pressurized SF_6 gas the vessel of a 1-1.5 MV industrial accelerator of ELV type was used (Fig. 3). The height of a single HV section equals 4 cm while the gap between them is 2 cm. The voltage between sections at SF_6 pressure of 1.6 bar is shown in Fig. 4. The HV stability was measured using an ADC installed in the HV terminal. The relative HV stability is about 10^{-5}. The concept of turbines looks very promising. But now there needs further development to increase efficiency and reliability of the turbines. One idea is to use more powerful turbines (5kW, commercial available) and combine it with small cascaded resonant transformers [14].

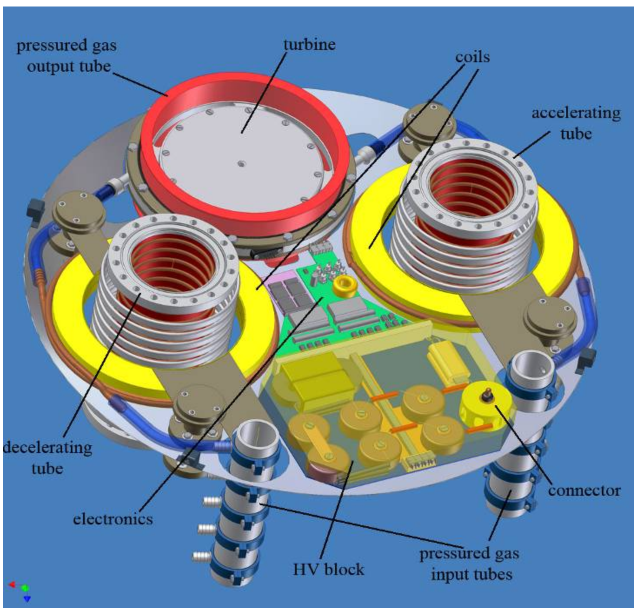

Figure 2: High voltage section with turbine and magnet coils around the acceleration and deceleration tubes [13].

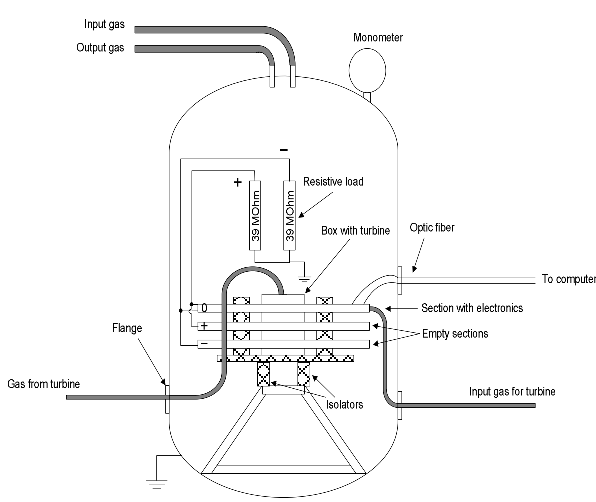

Figure 3: HV sections scheme of experiments.

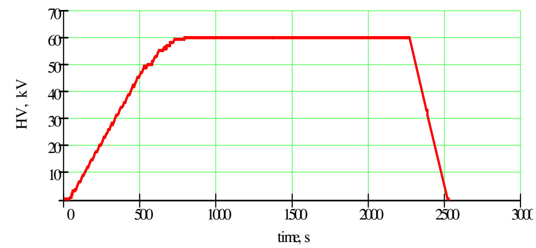

Figure 4: Voltage between sections (SF_6 1.6 bar).

The prototype of a turbine operates at BINP at the accelerator mass spectrometer (AMS) few years at the high voltage terminal (1 MV) to produce power for magnet and stripper target [15].

BEAM DIAGNOSTICS

The new proposed relativistic electron cooling devices have special needs and demands on the beam diagnostics. The cooling beam and the cooled beam have to overlap and propagate with the same velocity to ensure a small cooling time. This matching is done e.g. for cooling of a proton beam by optimising the H^0 signal. In this case the protons of the cooled beam are recombining with the electrons of the cooling beam. The resulting Hydrogen atoms are neutral. They are not deflected by magnetic fields and can be detected after the next bending magnet. For the cooling of antiprotons in the HESR there is no H^0 signal which could indicate a good cooling rate. Due to this fact special beam diagnostics in the cooling section is necessary. One challenge for the electron cooler design is beam alignment between electrons and antiprotons along the long interaction cooling section (e.g. of about 24 m length for HESR cooler). The deviation of the electron beam relative to the antiproton beam should be smaller than 10^{-5} radians rms to fulfil the beam quality and lifetime demands of the antiprotons [10]. To minimise deviations of the electrons relative to the antiprotons, beam-based alignment would be preferable. Then the offset of the electron beam relative to the antiproton beam is measured and corrected using additional corrector windings. This requires beam position monitors in the cooling section with a resolution of 1×10^{-5} m. The diagnostic has to be non destructive because of the high beam power. It should also not affect the magnetic field flatness of the solenoids inside the cooling section. There are already several non destructive beam diagnostic methods established. They are used in different accelerators like a scintillation profile monitor [16], [17] or the Laser wire scanner at the synchrotron source PETRA III [18]. These methods can be adapted for the use in relativistic electron cooling devices.

Beam Profile Monitors

Beam profile measurements are vital for the machine operation, in particular for setting up beam cooling. Profiles have to be measured without affecting the circulating beam. A joint effort by the beam instrumentation groups at GSI Darmstadt and COSY,

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Juelich resulted in an ionization profile monitor (IPM) being operational at ESR [19] and COSY [20]. The IPM was designed to become a standard profile monitor for the future FAIR [21] machines. The IPMs real time performance together with high sensitivity and resolution make it a very valuable instrument. However, high cost and presence of components prone to aging in vacuum triggered the search for alternative methods. A profile monitor utilizing scintillation of residual gas offers a viable alternative to an IPM for certain beam conditions [22, 23]. The gas atoms and molecules are excited by the beam particles and emit visible light shortly after the excitation [24]. After passing a vacuum window the light is focused by an optical system and is detected by a multi-channel photomultiplier or an image intensified camera. Measuring the photon distribution allows reconstructing the initial beam profile. The method is also applicable for the electron beam. To increase scintillation light intensity for the scintillation profile monitor (SPM) a local pressure bump is introduced for the duration of profile measurement. Nitrogen injection is done by means of a commercially available piezo-electric valve. At 4×10^{-8} mbar and beam intensities of the order of 5×10^{9} protons in the ring reasonable S/N ratio is achieved. The temporary pressure bumps did not have any impact on machine operation. Fig. 5 shows the measured beam profiles (top plot) as the proton beam was being cooled. The lower plot shows the beam current. The injection occurred at t = 5s and was followed by 10s of electron cooling (accompanied by beam losses). The beam was then accelerated and slowly extracted from the ring to an external experiment. Profile data was recorded during electron cooling at injection energy only (5.9s – 15.3s). Beam shrinking due to cooling is clearly seen. SPM performance was verified by comparing measured profiles with the IPM results. This measurement shows good agreement between SPM and IPM data.

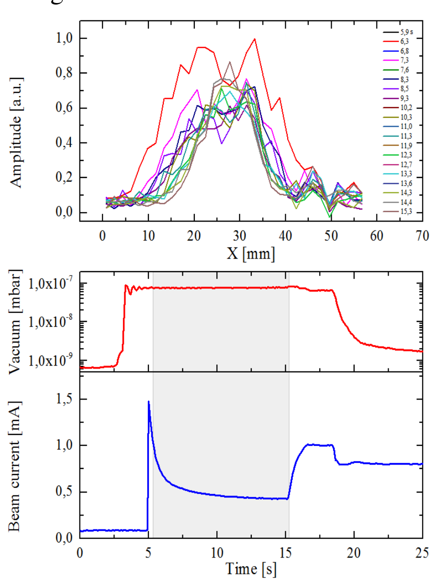

Figure 5: Horizontal beam profiles measured with the SPM (top plot), vacuum reading (centre plot) and beam current (lower plot) [25].

Electron Gun with Variable Beam Profile

The electron gun design is based on the slightly changed gun previously used for electron coolers in Lanzhou CSRe, CSRm and LEIR [26]. The only difference is the four-sector control electrode with separate feeding of all sectors via additional feed throughs (Fig. 6). This small change opens a new possibility for non-axially modulation of the electron beam profile, which could be used in some applications. Combined with beam position monitors this feature of the gun provides beam shape monitoring when it passes the transport channels.

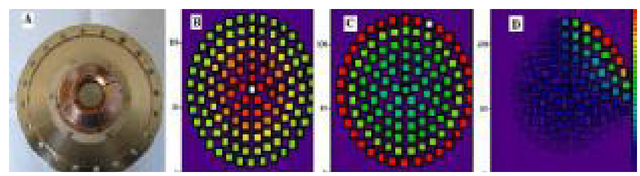

Figure 6: A -photo cathode with grid electrodes, B - parabolic shaped beam with maximum at centre, C - “hollow” beam with minimum at centre, D - AC component of beam with RF voltage on single sector [27].

Thomson Scattering

Thomson scattering describes elastic scattering of a photon on a free electron. It is the low energy limit of the Compton scattering process. In 1987/1988 a pioneer experiment demonstrated the feasibility of Thomson scattering for electron beam diagnostics [28], [29]. At that time, however, the signal to noise ratio suffered from the low power and repetition rate of the Laser system. A revision of this approach make sense due to the enormous developments in Laser technology since that time. The proposed setup (Fig. 7) uses 90 and 180 degrees angles between laser and electron beam like a Laser wire scanner [30]. 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 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. Another advantage of the Thomson scattering method is the possibility to measure the electron energy. This can be realised with the same setup which is used for the beam profile measurement. In this case a frequency analysis of the scattered photons is needed instead of the scattering rate (e.g. realised with a Fabry-Perot interferometer). This can be very interesting for the cooling of antiprotons. With a good energy measurement the adjustment of the electron beam can be done faster and in a more efficient way.

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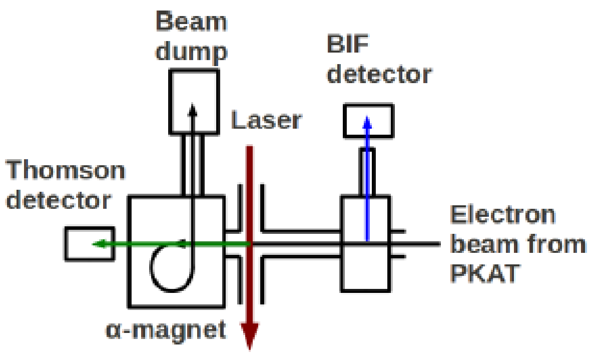

Figure 7: Schematic view of the setup at Mainz [30].

CONCLUSION

The gained experience of the 4.4 MV REC at Fermilab and the 2 MV COSY electron cooler at FZ Juelich will push the development of future relativistic electron coolers for HESR at FAIR Darmstadt and NICA at Dubna. The idea of using turbines for the high voltage system of electron coolers looks very promising and should be developed further. A combination of turbines and small cascade transformers could be a technical solution for the next high voltage magnetised electron coolers. An improved beam diagnostics for the hadron and electron beam will help to optimise the cooling process.

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