Nuclear Inst. and Methods in Physics Research, A 910 (2018) 147–156

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

Novel optical interferometry of synchrotron radiation for absolute electron beam energy measurements

P. Klag [a,1], P. Achenbach [a,*], M. Biroth [a], T. Gogami [b,2], P. Herrmann [a], M. Kaneta [b], Y. Konishi [b], W. Lauth [a], S. Nagao [b], S.N. Nakamura [b], J. Pochodzalla [a], J. Roser [a], Y. Toyama [b,2]

[a] Institut für Kernphysik, Johannes Gutenberg-Universität, 55099 Mainz, Germany
[b] Department of Physics, Graduate School of Science, Tohoku University, Sendai, 980-8578, Japan

ARTICLE INFO

Keywords:
Electron accelerator
Beam energy measurement
Optical interferometry
Undulator
Synchrotron radiation

ABSTRACT

A novel interferometric method is presented for the measurement of the absolute energy of electron beams. In the year 2016, a pioneering experiment was performed using a 195 MeV beam of the Mainz Microtron (MAMI). The experimental setup consisted of two collinear magnetic undulators as sources of coherent optical synchrotron light and a high-resolving grating monochromator. Beam energy measurements required the variation of the relative undulator distance in the decimeter range and the analysis of the intensity oscillation length in the interference spectrum. A statistical precision of 1 keV was achieved in 1 h of data taking, while systematic uncertainties of 700 keV were present in the experiment. These developments aim for a relative precision of 10^{-5} in the absolute momentum calibrations of spectrometers and high-precision hypernuclear experiments. Other electron accelerators with beam energies in this regime such as the Mainz Energy Recovering Superconducting Accelerator (MESA) might benefit from this new method.

1. Introduction

During the last years, a new method of decay-pion spectroscopy was pioneered at the Mainz Microtron (MAMI), which has the potential to achieve mass measurements of several light hypernuclei with a precision better than 50 keV/c^2 [1,2]. Such a high precision is indeed required, *e.g.*, for the determination of the spin dependence of the charge symmetry breaking effect in light hypernuclei [3]. Furthermore, a planned precision measurement of the mass of lightest hypernucleus, composed of a proton, a neutron, and a Λ-particle, will address the so-called hypertriton puzzle [4]. Presently, the largest systematic error in these experiments originated from the uncertainty in the MAMI beam energy affecting the absolute momentum calibration of the spectrometers by $\delta p \approx \pm$ 100 keV/c, the sum of all other systematic errors contributed one order of magnitude less [2].

In this work, a novel interferometric method is presented for the measurement of the absolute energy of electron beams in the range of 100 to 200 MeV. The method is based on the analysis of the intensity oscillation length in the synchrotron spectrum from two collinear sources, thus reducing the energy determination to a relative distance measurement in the decimeter range and the spectroscopy of a narrow optical wavelength band.

The paper is organized as follows. After introducing different methods for the energy determinations at electron accelerators in Section 2, the MAMI accelerator is briefly reviewed in Section 3 with a focus on its energy stability and absolute energy determination. The operating principle of the novel method is presented in Section 4. In Section 5, the experimental setup used for the pioneering experiment at MAMI is described. Images of the synchrotron radiation from different measurements are shown in Section 6. Results from the evaluations of the spectra and the determination of the MAMI beam energy are shown in Section 7. A conclusion follows in Section 8.

2. Energy determinations at electron accelerators

In storage rings, the beam energy can be measured with a relative uncertainty of few 10^{-3} from the integrated dipole field along the ring [5]. At some facilities, *e.g.*, at the VEPP-4M collider at BINP and at the SPEAR3 electron storage ring, more precise determinations have been achieved with the resonant spin depolarization technique. Relative uncertainties for the energy measurement on the order of 10^{-5} were realized for VEPP-4M [6] and on the order of 3×10^{-6} for SPEAR3 [7].

* Corresponding author.
E-mail address: achenbach@uni-mainz.de (P. Achenbach).

[1] Part of doctoral thesis.
[2] Graduate Program on Physics for the Universe, Tohoku University (GP-PU).

https://doi.org/10.1016/j.nima.2018.09.072
Received 6 July 2018; Received in revised form 11 September 2018; Accepted 16 September 2018
Available online xxxx

The application of this method is limited to spin-polarized beams in high-energy storage rings and therefore cannot be used at MAMI, in which the beam is passing the accelerator only once.

The Compton backscattering method does not require a polarized beam and can be used in a wide range of beam energies from a few hundred MeV to a few GeV. The relative uncertainty of this method is usually on the order of 10^{-4} [5,8,9]. In these measurements, beam particles are collided head-on with photons from a laser. The maximum energy $E_\gamma^{\max}$ of the backscattered Compton γ-rays is measured with high-purity germanium detectors and converted into the central primary beam energy. The systematic uncertainty of the method is dominated by the absolute calibration of the energy scale of the detector for the γ-ray. The Compton backscattering of laser photons realized at BESSY I and BESSY II has reached accuracies of $\delta E/E = 5 \times 10^{-5}$ at 1718 MeV [9] and 2×10^{-4} at a lower energy of 800 MeV [8]. With the same method, a relative systematic uncertainty of $\delta E/E = 2 \times 10^{-5}$ was achieved for the 1840 MeV beam at BEPC-II [10].

The application of the method to lower beam energies is challenging because of the continuous decrease of the Compton edge with decreasing beam energy:

$$E_\gamma^{\max} = \frac{4\gamma^2 E_\lambda}{1 + 4\gamma^2 E_\lambda / E_{\text{beam}}} \approx 4\gamma^2 E_\lambda \,, \tag{1}$$

where E_λ is the energy of the laser photon and γ the Lorentz factor of the beam. When colliding laser photons of 800 nm with an electron beam of 500 MeV, the resulting energy spectrum extends to $E_\gamma^{\max} \sim 6$ MeV which can be determined with the best possible calorimeters with an uncertainty of a few keV, resulting in a theoretical resolution of a few 10^{-4}. For a beam energy of 195 MeV this theoretical best resolution increases to above few 10^{-3}. Furthermore, the γ-ray collimation as well as the finite electron beam emittance impacts on the γ-ray spectrum. Under certain beam conditions, the determination of the beam energy from the spectrum is significantly influenced [5].

To overcome these limitations, a new method is developed for the low energy electron beams at MAMI. Other electron accelerators with beam energies in this regime such as the Mainz Energy Recovering Superconducting Accelerator (MESA), currently under construction, might benefit from this work. MESA will consist of two cryo-modules with an acceleration capacity of 25 MeV each and three recirculation arcs for a maximum beam energy of 155 MeV. The MESA beam energy will be stabilized using the return arc with maximum longitudinal dispersion and two beam phase cavity monitors. Because of high demands from the experiments, among them the detection of order 10^{-8} parity-violating cross section asymmetries in electron scattering, the beam energy fluctuations need to be minimized to unprecedented low levels and the absolute beam energy needs to be determined with high precision.

3. The MAMI electron accelerator

MAMI is a multi-stage accelerator based on normal conducting radio-frequency (rf) cavities that can deliver a continuous-wave (cw) electron beam [11–13]. Electrons are drawn from the source with a static high voltage of 100 kV and are further accelerated by an injector linear accelerator (linac) to an energy of 3.5 MeV, reaching relativistic velocities of $\beta > 0.99$. The recirculating part consists of three cascaded racetrack microtrons (RTMs) and an additional harmonic double-sided microtron (HDSM) as a fourth stage. In each RTM, the beam is recirculated through two homogeneous 180° dipole magnets to a common linac section composed of a series of axially coupled accelerating cavities that are powered by several klystrons using a rf of 2.45 GHz. The first two RTMs accelerate the beam to 14.9 MeV and 180 MeV, respectively. The third RTM has 90 return paths to the linac section and the beam can be extracted from all even-numbered paths, so that this stage has a final energy from 180 to 855 MeV in 15 MeV steps. The beam intensity is limited by the available rf power to a maximum current of 100 μA. The HDSM consists of two normal conducting linacs through which the electrons are guided up to 43 times by a pair of 90°-bending magnets at each end. For stable beam dynamics, the linacs operate at the harmonic frequencies of 4.90 and 2.45 GHz. This stage can deliver a beam with energies of up to 1.6 GeV.

The energy spread of a typical beam from RTM3 is dominated by the stochastic emission of synchrotron radiation photons. This energy loss per turn grows with the third power of the beam energy. Fortunately, the strong longitudinal focusing in RTMs compensates synchrotron radiation losses in each turn by a proper phase migration. Residual rf phase and amplitude fluctuations have only little influence on the beam energy. The remaining width is $\sigma_{\text{beam}} < 13$ keV corresponding to a relative energy spread of $\Delta\gamma/\gamma = 1.5 \times 10^{-5}$ when expressing the beam energy by its Lorentz factor $\gamma = E_{\text{beam}}/m_e c^2$.

An excellent energy stability with a very small drift over time of less than 1 keV has been realized by a combination of two digital feedback loops [14]. A fast loop eliminates output energy deviations by acting on the rf phase using the time-of-flight dependence of bunches from the last return path to the extraction beam line. A slow loop stabilizes the measured tune of the RTM3 by small changes of the linac amplitude. [15]

The absolute beam energy can be measured using magnetic spectrometry inside the RTM3 stage of the accelerator by exact determination of the beam position on the linac axis and in a higher (73rd) return path. The main instrumentation is a 9.8 GHz XY beam position monitor (XYMO), whose transverse separation of its electrical center to the linac axis is known with a precision of approximately 0.4 mm. The resolution of the monitor is much higher than 0.1 mm in diagnostic pulse mode. For the energy measurements, the beam is first centered on the linac axis and then centered with the use of calibrated correction steerer magnets on the XYMO axis. From the correction currents, the bending radius of the beam in the 73rd turn can be calculated. The magnetic field B inside the RTM3 dipoles is known by NMR measurements and the field accuracy $\delta B/B$ is on the order of 10^{-4}. The total uncertainty of the beam energy δE_{73} at $E_{73} \approx 727$ MeV is 120 keV including contributions from geodetic measurement errors, calibration errors of the steerers, and dominant angle errors. By use of the well established and benchmarked particle tracking program PTRACE, the beam energy E_n of the extracted turn number n can be interpolated from the value E_{73}. The uncertainty for E_n is 130 keV when including a systematic error from the interpolation on the order of 55 keV. A conservative error estimation for the absolute energy of MAMI including rf phase and amplitude errors leads to a total accuracy of $\delta E_{\text{beam}} = 160$ keV [16].

4. Interferometry of synchrotron radiation

The method is based on interferometry with two spatial separated light sources driven by relativistic electrons [17–19]. The basic idea will be explained by means of the schematic drawing shown in Fig. 1. An electron beam with Lorentz factor γ passes a pair of undulators S_1 and S_2 separated by a distance d. Further details of the undulator pair can be found in Section 5.1. The succession of the wave trains T_1 and T_2 at the exit of the undulator pair is opposite to the order of the two sources because the electron velocity v is slower than the speed of light. These trains are separated along the axis by the distance

$$\Delta(\theta, d) = \left(\frac{2 + K^2}{4\gamma^2} + \frac{\theta^2}{2} \right) L_U + \left(\frac{1}{2\gamma^2} + \frac{\theta^2}{2} \right) d \,, \tag{2}$$

which is a linear function in d. Details on the superposition of the two wave trains are given in [17]. The slope is only dependent on the Lorentz factor γ and the observation angle θ with respect to the electron beam direction. The dimensionless undulator parameter is $K = (e/2\pi m_e c) \cdot B_0 \cdot \lambda_U$ and $L_U \simeq n\lambda_U$ is the length of the undulator with λ_U the undulator period and n is the number of periods. The undulators act as sources for the emission of coherent light with the amplitudes $A_{1,2}$ of the two wave trains having a phase difference of $\phi(\theta, d) = 2\pi\Delta(\theta, d)/\lambda_{\text{rad}}$