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SMITH-PURCELL RADIATION FOR BUNCH LENGTH MEASUREMENTS AT THE INJECTION OF MESA*

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Abstract

MELBA is a test apparatus for the injector of the energy recovering, superconducting accelerator *MESA* in Mainz. A chopper-buncher system containing two circularly deflecting cavities and a first and second harmonic buncher cavity have been built. They serve to produce short bunches with a longitudinal extension < 600 µm (1degree of RF-phase) in the longitudinal focus for beam currents of up to 10 mA. We intend to use Smith-Purcell Radiation (SPR) to test this arrangement. SPR is generated if a charged particle passes close to a periodic metallic structure, e.g. a grating. The signal has a coherent part which increases its intensity quadratically with the bunch charge if the bunch length is smaller than or comparable to the grating period. Different gratings can be placed below the electron beam to determine the length of the electron bunches. This measurement is non-destructive. The generated THz radiation will be observed with a bolometer cooled down to 4.2 K which offers sufficient sensitivity in our regime of operation.

MOTIVATION

With the approval of the Cluster of Excellence *PRISMA*[2] and thus the means to build the energy-recovering and superconducting accelerator *MESA*[3] at the University of Mainz, unique conditions for research in the field of particle and hadron physics are created. An important part of the new accelerator *MESA* is the low energy beam transport system connecting the 100 keV electron source with the injector accelerator. Here the spin manipulation and the bunch preparation for the injector take place. Due to the low energy, space charge will be a challenging issue at this part. At the moment, a test setup is being built up to check the functionality of devices and compare the beam parameters with the simulation. An interesting issue is the bunch preparation system. At this part we expect high impact of the space charge by reason of the necessary bunch compression. A non-destructive possibility to characterize the longitudinal beam profile can be achieved using Smith-Purcell Radiation (SPR). To do so one needs to observe the coherent part of the SPR. Dominance of the coherent spectral fraction was for instance demonstrated in [1] where it was stated to be more than 5 orders of magnitude larger than the incoherent part at a bunch charge of 66 pC. In this experiment the duty factor was 5×10^{-6}. In our experiment the interesting range of bunch charges is between 0.1 and 10 pC. Since the coherent fraction scales with the square of the bunch charge, we infer from the mentioned results that the a coherent/incoherent fraction will be of the order of one for the lowest bunch charge and of course much more favorable at the higher charges. Due to cw operation the average power levels will be sufficiently large, we estimate > 1 nW for the lowest charge. To obtain information on the bunch shape a spectrally resolved measurement is needed. To keep the apparatus simple the SPR-observation angle will be fixed and gratings with varying periods will be introduced to obtain spectral information on the coherent part. In the following we describe the principle of operation and the components of our set up.

BUNCH PREPARATION SYSTEM

The continuous beam out of the electron source has to be converted into ultra-short bunches < 1° in order to fit into the accelerator acceptance. First, two circularly deflecting chopper cavities provide bunches with a length of ≈ 160°. Then a pair of buncher cavities with harmonic and second harmonic resonant frequency produce a linear velocity modulation which leads to ultra-short bunches after a drift of 1.5 m (Fig. 1). The functionality of this Chopper-buncher system at lower bunch charges is theoretically and experimentally understood and proven [2]. For the operating range of *MESA*, the influence of space charge on longitudinal bunch compression at high beam currents has to be controlled by a re-adjustment of the buncher parameters. We aim to support this procedure by using bunch shape information obtained by a diagnostic device located at the position of the longitu-

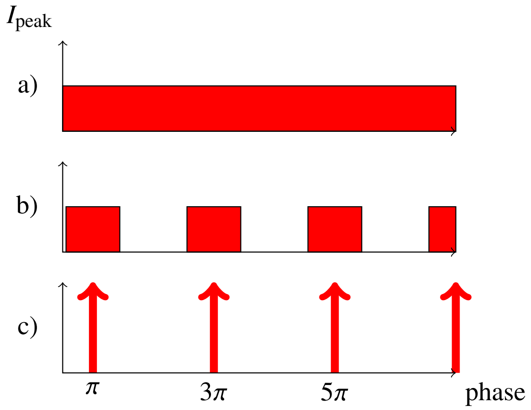

Figure 1: Matching of longitudinal emittance using a chopper, buncher system. Electron beam a) out of the source, b) after the chopper and c) after the buncher.

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[2] Precision Physics, Fundamental Interactions and Structure of Matter

[3] Mainz Energy Recovering Superconducting Accelerator

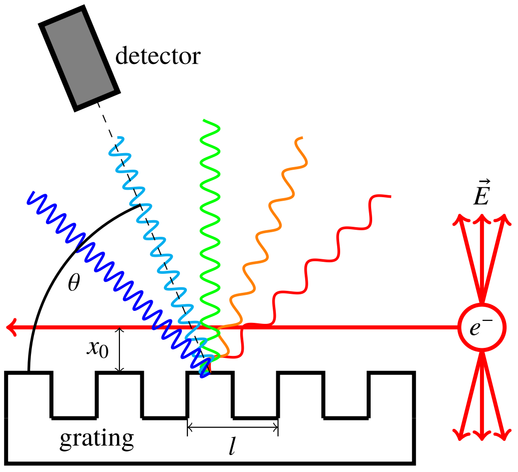

Figure 2: Smith-Purcell radiation of an electron passing a periodic grating. The wavelength depends on the angle of observation, the velocity of the e^- and the period l of the grating.

dinal focus. Smith-Purcell radiation is such a non-invasive method to measure bunch lengths at high currents.

SMITH-PURCELL RADIATION

When an electron passes close to the surface of a metallic grating, radiation is emitted because of the interaction of the particle with the periodic structure. The wavelength λ of the emitted radiation can be described as follows. [3]

$$\lambda = \frac{l}{n}\left(\frac{1}{\beta} - \cos\Theta\right) \tag{1}$$

where l is the period of the grating, β is the velocity of the particle, n is the order of radiation and Θ is the angle of observation (Fig. 2). It is thus possible to select a wavelength by changing the position of the detector. In order to calculate the emitted power and its angular distribution, a model of the emission process is required. The details of this calculation are omitted here and can be found in [4] and [5]. The following formulas are taken again from [1]. The radiated intensity for one electron can be described as follows.

$$\left(\frac{\mathrm{d}I}{\mathrm{d}\Omega}\right)_1 = \frac{e^2\omega^3 Zl}{4\pi^2 c^3 n} R^2 \exp\left[-\frac{2x_0}{\lambda_e}\right] \tag{2}$$

R is a constant which depends on the shape of the grating. λ_e is given by:

$$\lambda_e = \lambda \frac{\beta\gamma}{2\pi\sqrt{1+\beta^2\gamma^2\sin^2\Theta\sin^2\Phi}} \tag{3}$$

Where γ is the relativistic Lorentz factor, Θ is the observation angle perpendicular to the movement of the electron (Fig. 2), *Phi* is the angle perpendicular to Θ and $Z = N \cdot l$ is the total length of the grating. In the case of a real beam, the whole ensemble of many electrons N_e has to be considered.

$$\left(\frac{\mathrm{d}I}{\mathrm{d}\Omega}\right)_{N_e} = \left(\frac{\mathrm{d}I}{\mathrm{d}\Omega}\right)_1 \left(N_e S_{\mathrm{inc}} + N_e^2 S_{\mathrm{coh}}\right) \tag{4}$$

The signal consists of a coherent and an incoherent part. The following integrations take into account the beam size of an assumed Gaussian beam.

$$S_{\mathrm{inc}} = \frac{1}{\sqrt{2\pi}\sigma_x}\int_0^\infty \exp\left[\frac{-2x}{\lambda_e} - \frac{(x-x_0)^2}{2\sigma_x^2}\right]\mathrm{d}x \tag{5}$$

$$S_{\mathrm{coh}} = \left|\frac{1}{\sqrt{2\pi}\sigma_x}\int_0^\infty \exp\left[\frac{-x}{\lambda_e} - \frac{(x-x_0)^2}{2\sigma_x^2}\right]\mathrm{d}x\right|^2 \tag{6}$$

$$\cdot\left|\frac{1}{\sqrt{2\pi}\sigma_y}\int_{-\infty}^\infty \exp\left[-ik_y y - \frac{(y-y_0)^2}{2\sigma_y^2}\right]\mathrm{d}y\right|^2 \tag{7}$$

$$\cdot\left|\int_{-\infty}^\infty \exp\left[-i\omega t\right] f(t)\mathrm{d}t\right|^2 \tag{8}$$

The transverse distributions of the particles in the beam can be measured using wire scanners. σ_x and σ_y are the RMS-width, the coordinates of of the beam center are denoted by x_0 and y_0. The quantity $f(t)$ that appears in the above expression is the, as yet unspecified, distribution of the particles in the time domain. If the bunch length $L_{\mathrm{bunch}} = \beta \cdot c \cdot t_{\mathrm{bunch}}$ is longer than the lattice period l the Fourier integral in the coherent part will vanish and only the incoherent part in Eq. 4 will remain. For bunched beams whose bunch length is comparable to or shorter than the wavelength of the radiation, S_{coh} can dominate and there is coherent enhancement of the emitted radiation over the incoherent part by a factor approaching N_e. This is critically dependent on the longitudinal (time) profile of the bunch.

SPR APPARATUS

The SPR apparus is installed downstream of the MEsa Low-energy Beam Apparatus (*MELBA*) [6]. The emitted SPR is observed at an fixed angle in order to keep the system simple. Here several different gratings can be placed next to the beam and the detector is at a fixed position (Fig. 3) which

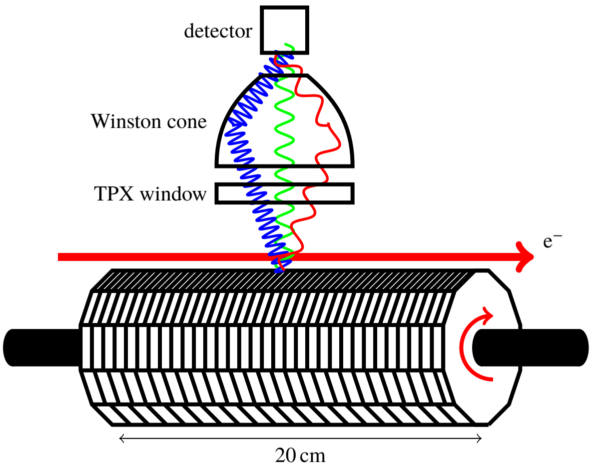

Figure 3: Experimental arrangement to detect Smith-Purcell Radiation. Up to 20 gratings with different periods l can be placed next to the beam.

allows to get frequency domain information of the bunch without the need to install potentially lossy and mechanically complicated angle scanning Tera hertz optics. The SPR radiation leaves the vacuum System through a polymer (TPX) window. For the different gratings the power of the signal is measured. If the grating period l is in the order of the bunch length, coherent enhancement of the SPR will increase the signal by a factor approaching N_e. By knowing the period l, the bunch length can be determined.

DETECTOR

A big issue is the detection of THz radiation at a low power of some pW. In this case, a thermal detector, a so called *bolometer* [7], is used. An absorber is coupled to a thermal reservoir cooled down to 4 K (Fig. 4). This is necessary in order to reduce the noise. The temperature of the thermal mass is measured and is proportional to the power of the absorbed SPR. The preamplifier must be powered by batteries to avoid interferences from the mains supply. An isolation vacuum and a shield of liquid nitrogen provides an operation time of the detector of $T_{\text{operation}} \approx 250\,\text{h}$. After this time, the helium reservoir has to be refilled. Fig. 5 shows the bolometer during the filling process of liquid nitrogen.

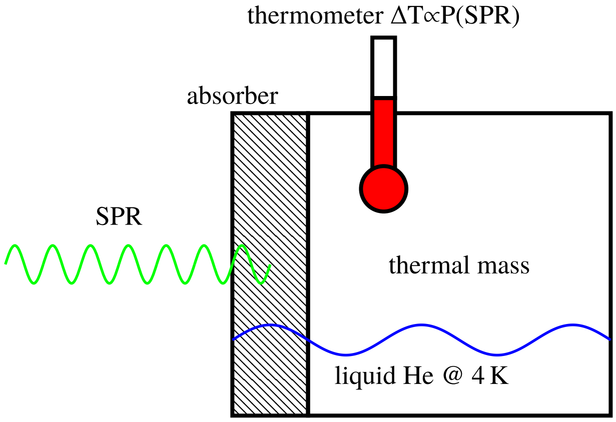

Figure 4: Detection of SPR radiation at a frequency of some THz at a power of ≈ pW. The thermal detector is cooled down with liquid helium at 4 K to reduce noise.

CONCLUSION

At the moment, *MELBA* is running and first measurements of the transverse beam profile have been done. The next step is the mounting of the chopper-buncher system. The manufacturing of the SPR apparatus will be completed at the end of May. The detector will be calibrated using an external THz source. We intend to use unbunched beams to investigate the stability of the system, in particular the transverse focusing and the distance towards the grating. Tests with bunched beams with the goal to observe the coherent signal will be possible by the end of the year.

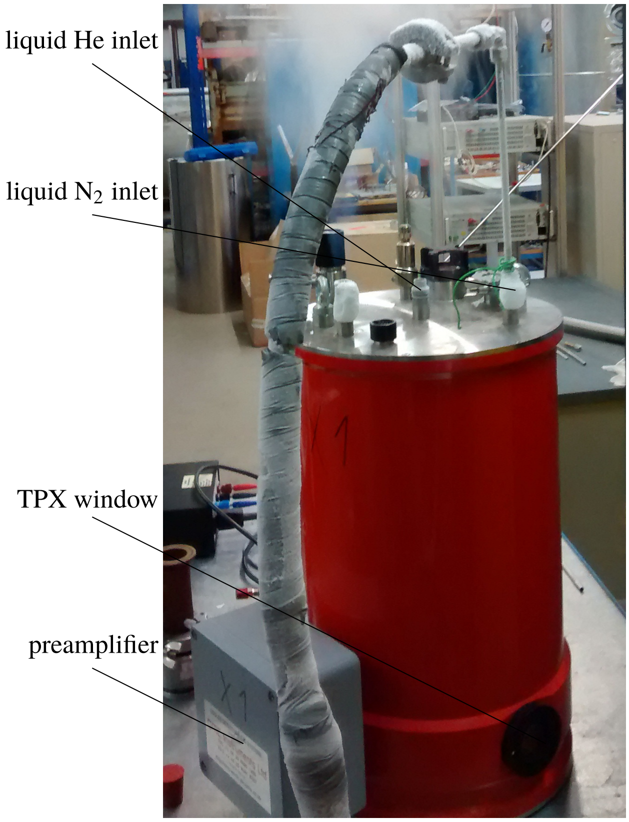

Figure 5: Detector for THz radiation down to 2 pW [8]. The picture shows the refilling process of liquid nitrogen due to isolation issues of the 4 K reservoir.

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