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TERAHERTZ DIAGNOSTIC FOR THE ADVANCED PHOTON SOURCE PARTICLE ACCUMULATOR RING*

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Abstract

Electron beam microbunching instabilities can present operational limits on the practical operation of storage ring accelerators. In the present work, we outline components of a synchrotron radiation diagnostic beamline for the Advanced Photon Source Particle Accumulator Ring operating at frequencies up to approximately 1 THz.

INTRODUCTION

The Particle Accumulator Ring (PAR) is an electron storage ring at the Advanced Photon Source (APS). The principal function of the ring is an accumulator ring, damping multiple (<30) injections from the linac into a single bunch [1]. For the Advanced Photon Source Upgrade (APS-U), we require accumulation of charge in a single bunch up to 20 nC [2]. At such high charges, measurement and control of electron beam instabilities may be important [3].

The intensity of coherent synchrotron radiation (CSR) is dependent on the longitudinal bunch profile. Observation of CSR can provide a sensitive diagnostic tool to detect instabilities. We propose an extension of the optical synchrotron radiation diagnostics port to support the detection of long wavelengths of incoherent synchrotron radiation (ISR) and CSR in the terahertz range, without installing a new beam port and without disturbing existing optical synchrotron radiation diagnostics.

In the present work, we outline the design of the PAR terahertz diagnostic beamline. Performance requirements of the beamline are outlined. The operating principles of the proposed instruments are summarised. Implementation of the beamline subsystems is outlined.

THEORY

We have chosen a spatial separation of the terahertz and optical frequencies because of the different opening angles of synchrotron radiation. For bending magnet radiation, an approximation to the vertical opening angle Θ_{vert} is [4]:

$$\Theta_{\text{vert}} = 1.66188 \times \left(\frac{c}{fR}\right)^{(1/3)} [\text{rad}], \quad (1)$$

where c is the speed of light in vacuum, f is the frequency of synchrotron radiation (much less than the frequency corresponding to the critical photon energy), and R is the bending radius.

The waveguide cutoff frequency of a rectangular chamber describes the frequency limit for waves that can propagate in the beam pipe: whether or not they are directly emitted by the bunch. The low-frequency cutoff is limited by the cutoff frequency of the synchrotron light monitor port acting as a waveguide. For a waveguide with rectangular profile, the cutoff frequency f_c is defined as:

$$f_c = \frac{c}{2a}, \quad (2)$$

where a is the larger dimension of the waveguide. The bending magnet vacuum chamber defines the input aperture to the beamline, and is rectangular in profile. For a waveguide of dimension 100 × 40 mm [5], the low-frequency cutoff frequency is 3 GHz.

Rather than synchrotron radiation, waves propagating at frequencies above cutoff could be wakefields from the beam pipe, cavities, or other components. This can distort the measurement at lower frequencies. Hence, we must also consider the formation length of the (bending magnet) synchrotron radiation which is at significantly higher frequency. A cutoff frequency f_{cutoff} incorporating the formation length of synchrotron radiation is given by [6–9]:

$$f_{\text{cutoff}} = \sqrt{\frac{\pi}{6}}\, c \sqrt{\frac{R}{h_c^3}}, \quad (3)$$

where h_c is the chamber gap height. For a bending radius of $R = 1$ m, and chamber gap height of $h_c = 0.04$ m, $f_{\text{cutoff}} = 27$ GHz. The detector should therefore be sensitive at frequency ranges higher than 27 GHz. The high frequency limit is bound by the length scale of longitudinal bunch substructure that may produce CSR (extending up to a few hundred GHz).

The longitudinal impedance due to synchrotron radiation for the PAR at an electron beam energy of 470 MeV is illustrated in Fig. 1 [5]. Additionally, the minimum focus point size is reduced at higher frequencies. A good compromise seems to be 100 GHz to approximately centre on this frequency range, and where the focus point size matches the detector acceptance.

A problem is that the timescale of electron bunch instability substructures in the PAR is undetermined. Simulations have been performed of the longitudinal impedance due to the PAR vacuum components [10], and there are also measurements of the loss factor [11]. We suspect that the bunch may be far above the microbunching instability threshold, with potentially <10 ps substructures.

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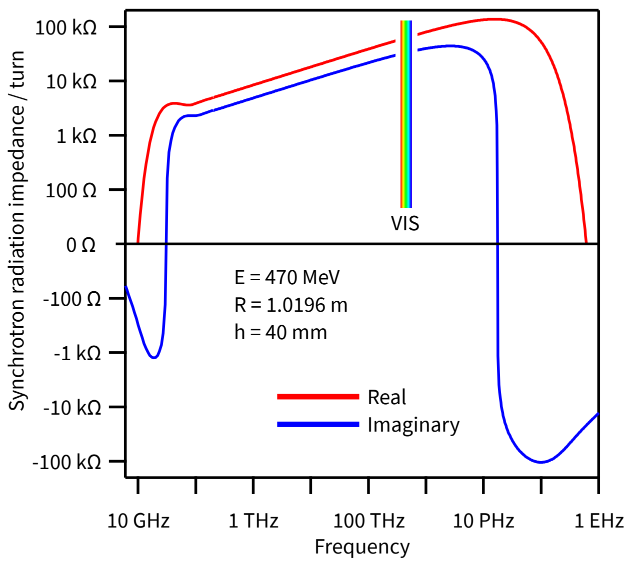

Figure 1: Simulated longitudinal impedance due to synchrotron radiation for an electron between two infinite, conducting, parallel plates in a PAR dipole [5]. The real component corresponds to the emitted radiation and thus describes the synchrotron radiation spectrum emitted in the PAR.

APPARATUS

The terahertz diagnostic provides for an in-vacuum mirror assembly and transmission viewport to direct terahertz radiation to a suitable terahertz detector system. The apparatus is illustrated schematically in Fig. 2.

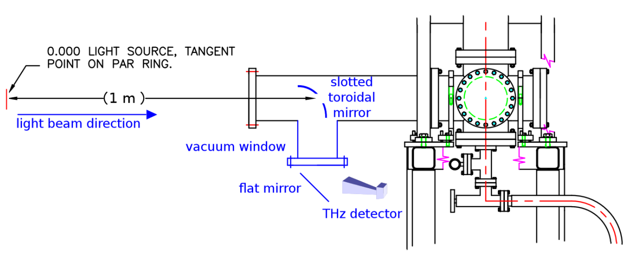

Figure 2: Schematic of terahertz diagnostic apparatus in the APS PAR [5]. Implementation is limited to the replacement of a single spool piece that is part of the existing PAR photon monitor vacuum transport line [12].

The design is required to retain the original visible synchrotron radiation transport function for the photon monitor which is located outside of the accelerator enclosure [12, 13]. The proposed terahertz diagnostic mechanical assembly is illustrated in Fig. 3 [14].

In order to accommodate alignment adjustments to the mirror without breaking vacuum, the mirror is supported by a translatable mechanical assembly. The principal components of the mirror assembly are illustrated in Fig. 4 [14].

As illustrated in Fig. 5, the toroidal mirror focusses and reflects the terahertz beam 90° out of the vacuum chamber while the visible synchrotron radiation passes through the

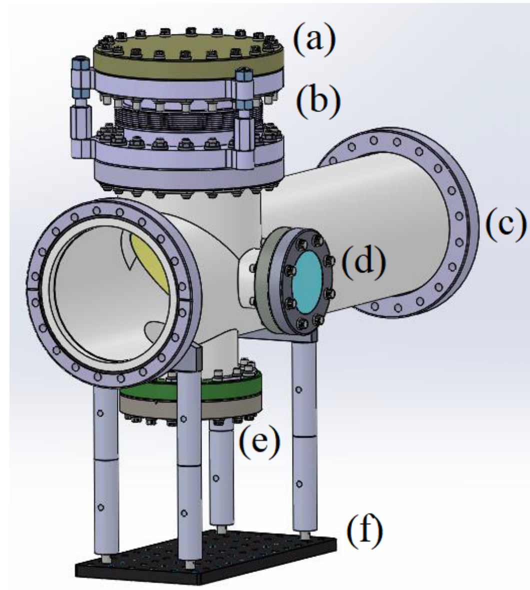

Figure 3: Overview of terahertz diagnostic principal components [14]. The chamber replaces a spool piece on the optical photon monitor of the PAR. (a) Mirror assembly. A toroidal mirror is used to reflect terahertz radiation out of the quartz crystal mirror, where a detector is positioned. The fixed toroidal mirror has a clear aperture centered on the axis of the optical path to allow simultaneous transmission of the visible SR light through the chamber to the existing PAR photon monitor. (b) Bellows. (c) Stainless steel chamber weldment. (d) Optical viewport. (e) Quartz crystal window. (f) Aluminium breadboard and optical posts.

slot. No water cooling is required for the mirror because the total energy deposition is negligible.

FEATURES

We denote two frequency ranges of interest. The existing optical synchrotron light monitor beamlines are served by synchrotron radiation at optical wavelengths ('optical'), and the radiation collected by the terahertz diagnostic, extending to sub-terahertz frequencies ('terahertz').

Focussing of Terahertz Radiation at Detector

For the present application, we have chosen not to make use of the transverse profile of the terahertz photon beam, and there is not sufficient space for a telescope setup or similar. Focussing of the terahertz beam inside the vacuum chamber serves two purposes: first, the beam size should be reduced to fit through the vacuum window (63 mm aperture) and, second, it should maximize the flux at the detector. To meet these requirements, a single focussing element is sufficient.

A magnification of 0.3 leads to a focus point 0.3 m after the mirror. This is achieved by a focal length of 231 mm. The focal length requires a horizontal radius R_h = 653 mm and vertical radius of R_v = 326 mm. Different radii for the

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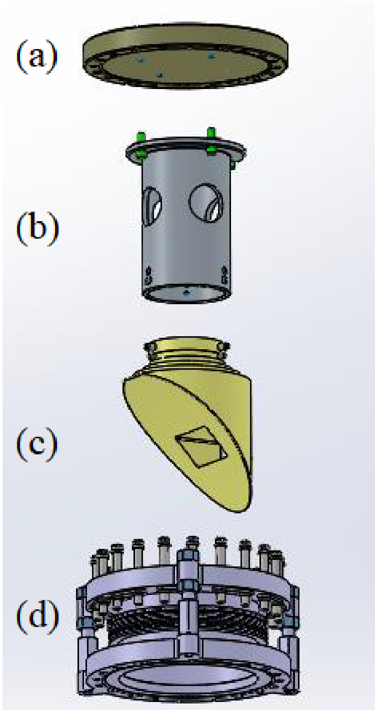

Figure 4: Exploded view of mirror assembly principal components [14]. (a) Mirror holder flange. (b) Mirror holder. (c) Toroidal mirror with rectangular clear aperture. (d) Vacuum bellows.

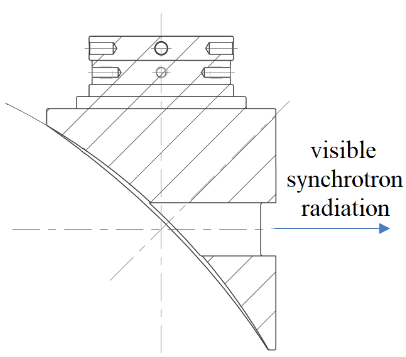

Figure 5: Cross section view of the toroidal mirror.

horizontal and vertical plane are needed because the radiation is reflected at a 90° angle, leading to a toroidal shaped mirror [15]. A toroidal shape is easier to manufacture than an off-axis paraboloid mirror and introduces less spherical aberrations.

The diameter of the waist in terahertz radiation at the focus is dependent on the radiation wavelength and is ~6 mm for frequencies >300 GHz, and extending up to 11 mm at 100 GHz. A Schottky diode detector with a horn antenna is proposed [5], with an aperture of 13.6 mm transverse extent [16].

Optical Light Beamline Optical Stay Clear

The existing photon beamline has a finite acceptance angle of 49 mrad in the horizontal plane [17], which corresponds to requiring a clear aperture of full width 49 mm at the mirror position. In both the horizontal and vertical planes, this is limited by the transverse diameter of the lens 145 mm, and the longitudinal position of the lens from the source (2.985 m) [17].

However the opening angle of the fan of optical synchrotron radiation in the vertical plane is significantly narrower than this. Simulations in Synchrotron Radiation Workshop (SRW) [18] indicate that allowing a clear full aperture of 23 mrad in the vertical plane will obscure less than 10^{-6} of the optical light [5]. This corresponds to requiring a full aperture larger than 23 mm height at the position of the toroidal mirror. To achieve this, optical wavelength synchrotron radiation and terahertz radiation are separated in angle using a slotted mirror. The spatial distribution of synchrotron radiation is illustrated in Fig. 6.

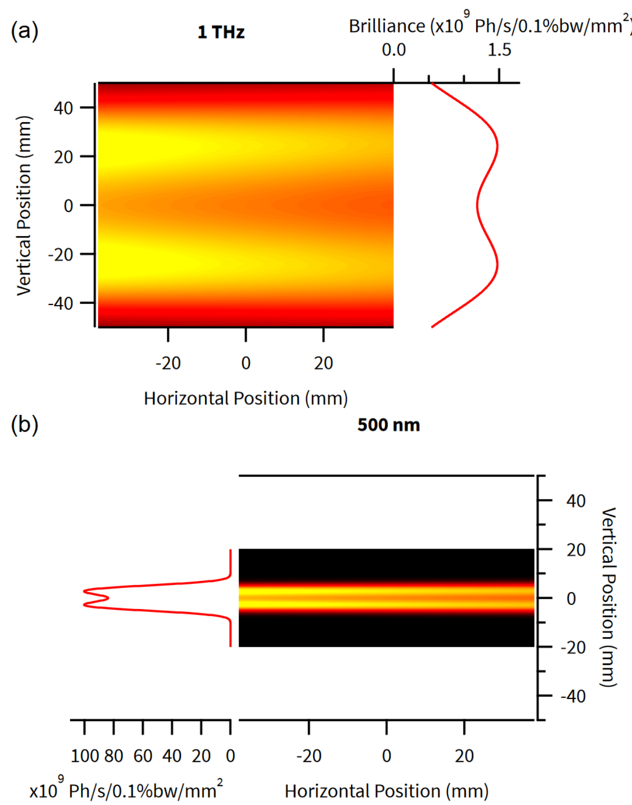

Figure 6: Simulations in SRW [18] of the beam profile from a single electron (point-like source) [5]. (a) Spatial distribution of synchrotron radiation at 1 THz frequency. (b) Spatial distribution of optical synchrotron radiation at 500 nm wavelength.

Hence for the terahertz diagnostic, we require a clear aperture for optical synchrotron radiation of no less than 49 mrad in the horizontal and 23 mrad in the vertical.

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Transparency of Terahertz Window

At the frequency range of interest (50–2000 GHz), the window needs to be transparent to terahertz radiation. At these frequencies, the window material should be single crystal SiO_2 (quartz). Future terahertz detectors might be polarization dependent. To maintain the polarization of the beam in the presence of a birefringent quartz window, a z-cut orientation is used so that the optical axis of the crystal is perpendicular to the flat surfaces.

Detector

The terahertz detection bandwidth should match the experimental needs. At this initial proof-of-principle stage, the bandwidth of the detector system should be at the frequency where the highest flux is expected. While the emitted power at the lower frequencies is expected to be higher, terahertz beam transport is more efficient for higher frequencies. We consider a detector system broadly similar to previous systems at other laboratories [19–21]. The detector architecture is summarised schematically in Fig. 7 below.

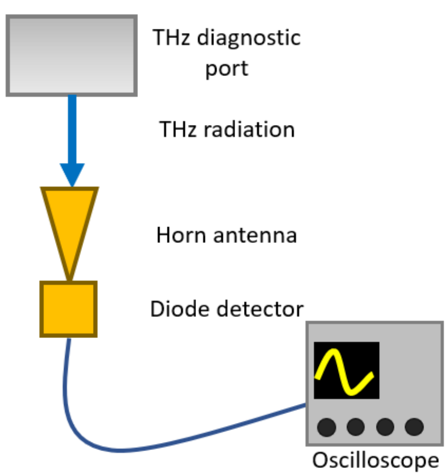

Figure 7: Schematic of detector arrangement for the PAR terahertz diagnostic during the initial phase.

The system outlined in Fig. 7 is composed of several key components: a horn antenna, a diode detector, and an oscilloscope.

By way of example, we consider a Schottky diode and horn antenna as a potential RF detector [22]. These diodes have a fast response time (<100 ps), and so are capable of resolving single bunches. We would propose operating at the 100 GHz frequency range for the PAR, able to observe microbunching distributions on the timescale of 10 ps.

Fast data acquisition systems have been developed for bunch instability measurements [23]. For an initial phase of measurements, we plan to read out the diode signal using an oscilloscope.

In order to observe the electron beam in the PAR at turn-by-turn or bunch-by-bunch, we require bandwidth at minimum equal to the revolution frequency of the PAR (9.77 MHz). To observe individual bunchlets injected from the linac (which operates at 2.856 GHz), the analog bandwidth of the detector should exceed 3 GHz. To avoid a pile-up of the detector signal by consecutive bunchlets, an even higher frequency is needed to ensure the detector signal is completely decayed before the next bunchlet signal arrives.

Detector Signal Amplification

The detector amplifier should not degrade the analog performance of the detector and should be sufficiently fast to observe the bunchlets from the linac. That requires at minimum a frequency of 3 GHz. However, if the amplifier is much faster than the following readout electronics, additional noise is introduced. A low-noise amplifier is needed to ensure a sufficient signal-to-noise ratio. Since this equipment is to be installed outside of the tunnel, adjustments can be made without beam intervention.

SUMMARY

A sub-terahertz beamline has been designed, and is in the process of fabrication and installation in the PAR ring at the APS. This beamline could be used as a diagnostic for beam instabilities in the PAR ring.

Beyond the use of CSR for the detection of microbunching instabilities, CSR is also a useful source of infrared radiation. Other laboratories have proposed compact storage rings as sources of CSR [24, 25], and at APS, the PAR could potentially serve as a useful source of CSR.

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