TERAHERTZ COHERENT SYNCHROTRON RADIATION IN THE MIT-BATES SOUTH HALL RING*

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Abstract

We investigate the terahertz coherent synchrotron radiation (CSR) potential of the South Hall Ring (SHR) at MIT-Bates Linear Accelerator Center. The SHR is equipped with a unique single cavity, 2.856 GHz RF system. The high RF frequency is advantageous for producing short bunch length and for having higher bunch current threshold to generate stable CSR. Combining with other techniques such as external pulse stacking cavity, femtosecond laser slicing, the potential for generating ultra-stable, high power, broadband terahertz CSR is very attractive. Beam dynamics issues related to short bunch length operation, such as multi-bunch instability (perhaps associated with the high frequency RF system), are considered. The SHR is ideal for experimental exploration of such issues, which could affect bunch length, bunch intensity and beam stability. Results of initial tests of low momentum compaction lattices and bunch length measurements are presented and compared to expectations.

INTRODUCTION

The recent development of electron accelerator-based sources has demonstrated the generation of high power broadband THz light via CSR [1] [2]. Results of initial scientific experiments for High-Tc superconductors and living biological tissues in the BESSY II storage ring as a steady-state THz CSR source were published in 2004 and 2005 [3][4].

The potential scientific significance of electron ring-based THz sources has led to proposals to explore CSR in existing storage rings as well proposals for new facilities. Experiments on stable and bursting CSR, as well as femtosecond laser slicing have been conducted in several rings. Theories have been developed to explain these results. A detailed list of references can be found in [5].

The LBNL CIRCE ring proposal provides an optimized design for a dedicated ring to produce CSR in the Far Infrared (THz) spectral region [6] [7]. It features ultra-stable, femtosecond laser slicing and broadband bursting operation modes. It would permit very high average power for THz spectroscopy and imaging, and also address the needs for high-field and ultrafast time-domain experiments. So far, the theoretical predications of CSR generation have been in good agreement with the results of BESSY II experiments [8]. However, to ensure that the specifications for new dedicated rings can be met, significant technical hurdles must be explored in more depth [9]. For example, beam dynamic issues associated with high bunch intensity, high circulating beam current under low α lattice for stable CSR operation. The possibility of using external pulse stacking in the THz frequency range for high field (MV/cm), nonlinear THz spectroscopy needs to be demonstrated as well.

The convenience of producing ultra-stable CSR and the ability to serve a multitude of beamlines simultaneously are the distinguishing merits of a storage ring-based CSR THz source.

The unique 2.856 GHz RF system, flexibility in ring configurations, and availability in the coming years, make the SHR an ideal facility for exploring storage ring CSR and its scientific opportunities.

SHR CSR POTENTIALS

The MIT-Bates SHR was originally built for nuclear physics with both pulse stretcher and storage operation modes. The 2.856 GHz RF system was implemented to enhance smooth extraction operation. The ring now runs primarily in storage mode for internal target experiments. Typical stored current exceeds 200 mA, and is limited mainly by target background. The SHR parameters are listed in Table 1. Possible RF cavity and CSR source magnet upgrades are also listed.

Table 1: SHR Parameters

	Present	**Upgrade**
Energy (GeV)	0.4-1.0	0.4-1.0
Circumferenc e (m)	190.02	190.02
RF freq.(GHz)/Vol.(kV)	2.856 /140	2.856 /1500
Harmonic Number	1812	1812
Bending radius	9.144 m	1.33, 4, 9.144m*
Magnet gap	7.2 cm	
Total stored Current (mA)	200-300	10-120 for CSR

* For optimal CSR production and flexibility of operation energy, several of the 3.6m long dipoles for CSR ports will be replaced, each by three short magnets.

There are two advantages of using higher RF frequency for CSR production. First, it is possible to make short bunch length with relative large momentum compaction. This is obvious from the expression of natural rms bunch length in a storage ring:

$$\sigma_s \propto (\alpha E / f_{rf} V_{rf})^{1/2} \sigma_E$$

where α is the momentum compaction, E is the beam energy, f_{rf} and v_{rf} are the RF frequency and cavity gap voltage respectively, and σ_E is the rms beam energy spread.

0-7803-8859-3/05/$20.00

In the case of SHR, due to the high RF frequency, 1-2 ps rms bunch length can be obtained with α in the 10^{-4} range. Large α is favorable for stable beam orbits and stable operation.

Secondly, the CSR emission power is proportional to the square of the electron bunch intensity. For stable CSR in a storage ring, the electron bunch intensity has a threshold, above which quasi-chaotic bursts will occur. These bursts are unsuitable for most experiments. An estimation of this microbunching instability threshold [8] [10], consistent with experimental observations, can be written as:

$$N \le A \frac{f_{rf} V_{rf} \sigma^{7/3}}{\rho^{1/3}} F$$

where A=1.67 [MKS] units, σ is the natural bunch length, F is the numerical integral of bunch equilibrium distribution from the dimensionless Haïssinaki equation [11]. The maximum F value used in calculations is about 5-7, depending on the assumption of perturbation wavelength λ (for $\lambda \sim 2\sigma$, $F_{max} \sim 4.7$).

High RF frequency and voltage are critical to reach higher bunch intensity limit, and hence, the higher power limit for stable CSR. The use of higher RF frequency and voltage is not a new idea. It was first suggested to install a superconducting 2.856 GHz RF system into the phase 1 SXLS storage ring for CSR generation in 1994 [12]. In light of the successful operation of the SHR RF system for several years, it is feasible to further explore high CSR production by increasing RF voltage.

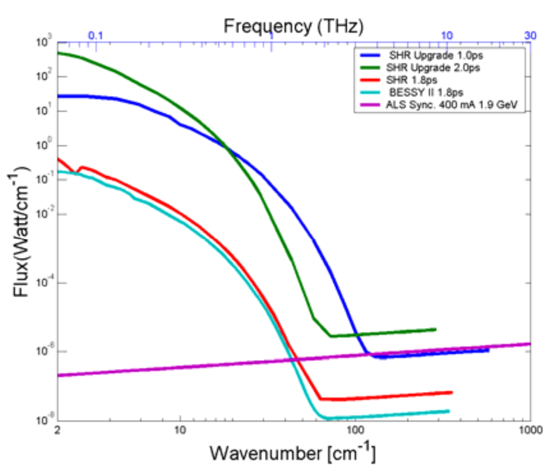

Figure 1: SHR CSR power spectrum horizontal acceptance/port: 300 mrad for upgrades, 60 mrad for all others.

Figure 1 compares the calculated CSR spectrum of the SHR to those of BESSY II and the ALS. Calculations are carried out both for present conditions (red) antipations after upgrades (blue, green curves). The calculations use free space SR wakefield and two plates shielding cutoff approximation [13]. A more sophisticated calculation [14] including wakes of SR shielded wakes [15] and resistive wall shows difference only for long bunch length due to shielding. Details are described in [16].

As a research facility, the SHR has several strengths. These include large circumference (190m at its operation energies range) with two, long straight (~30m) sections which provides flexible machine configurations, large bending magnet gap (7.2 cm) and ample floor space for IR beam lines (Figure 2).

A preliminary superconducting RF cavity design indicates that three cavities are needed to provide 1.5 MV total gap voltage. The existing 50 kW CW RF power system will be sufficient to support the operation of these superconducting cavities. Minor lattice modification is needed to extend the present RF straight length by slightly pushing quadrupoles in this dispersion free short straight section outwards.

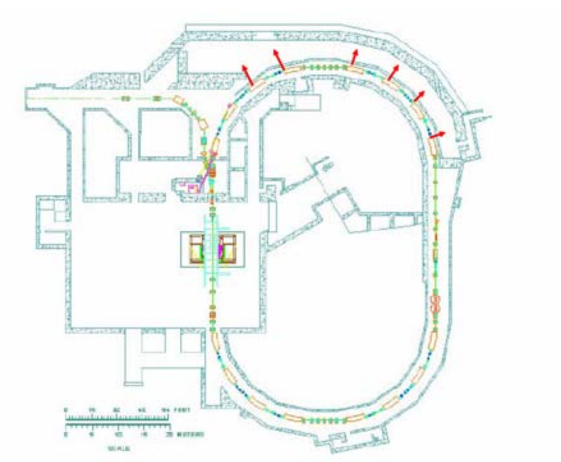

Figure 2: SHR ring plan view. Red arrows: IR beam line locations.

LOW ALPHA LATTICE OPERATION

An initial test run of low α lattice was conducted in December 2004. Bunch lengths were measured using a streak camera. The rms bunch length was reduced from 18 ps (lattice for the nuclear experiments) to 3.6 ps (with a new low α lattice). For a better comparison of measured bunch length to calculations, we express the rms bunch length as:

$$\sigma_z = \left(\frac{EL}{f_{rf}} \right) \frac{f_s}{V_{rf}} \sigma_E$$

where f_s is the synchrotron oscillation frequency, L is the ring circumference. All the terms in the above expression are well defined or measured except rms energy spread "σ_E". The natural energy spread is well defined by synchrotron radiation damping, but the real energy spread (use $\Delta E/E$ to denote late on) can be different if coherent synchrotron oscillations are presented. The measured rms bunch lengths vs. f_s/V_{rf} are plotted for lattices with different α in Figure 3. Compared to the calculated (straight) lines, the fitted rms energy spread is larger than the natural one.

The cause of coherent synchrotron oscillation has to be further investigated. However we noticed that RF frequency deviation introduced electron path length discrepancy, which can trigger coherent synchrotron oscillations. Also, during the test, the ring RF frequency was manually adjusted in a separated location at considerable inconvenience. As the RF frequency for the lattice LMC3 was casually set, coherent synchrotron oscillations were more visible. This may explain why the fit $\Delta E/E$ value for LMC4 lattice which has a smaller α is more closer to σ_E than that for LMC3 with a larger α. For very long bunches, the fitted $\Delta E/E$ is very close to σ_E.

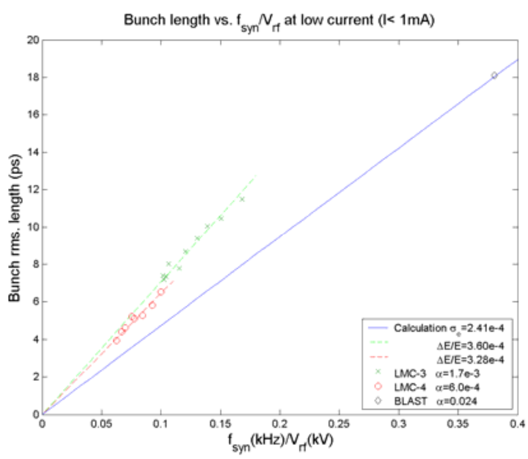

Figure 3: Bunch length vs. f_{syn}/V_{rf}.

Details of low α lattices and bunch length measurement are presented in reference [17].

RESEARCH PLAN

A second test run is scheduled for the first week of June, 2005 which will include more lattice studies. The CSR will be extracted from the Compton polarimeter B16 line which features an angular aperture of about 9 mrad (H) x 18 mrad (V). For test purposes, the THz radiation will be directly extracted through a quartz window. Based on the test at NSLS [18], the transmission of the 6 mm thick fused quartz view port is about 60% at 10 cm^{-1}. The nominal measurement set up is shown in Figure 4.

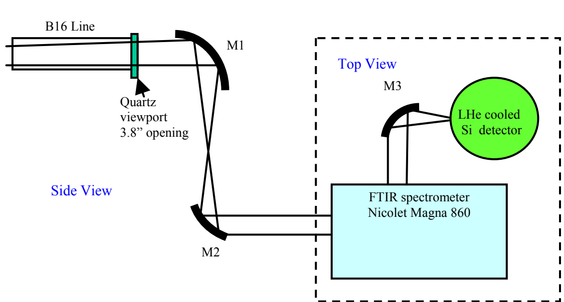

Figure 4: CSR power and spectrum measurement.

The long term research plan is likely to be:

- Build a test THz beam line which will serve SHR CSR studies and provide a stable, high power, broadband THz source for interested users.
- Beam dynamics study for stable CSR operation with the 2.856 GHz RF system.
- Bunch–bunch filling, to support single or selected multi-bunch operation modes.
- External pulse stacking [19] study for very high pulse energy.
- 2.856 GHz Superconducting RF cavity developments to explore very high power stable CSR operation.
- Femtosecond laser slicing with high bunch intensity to extend CSR spectrum to higher frequency.

ACKNOWLEDGEMENT

The low α lattice test was conducted during a short break in the schedule for the BLAST experiment. The run was made possible by the enthusiastic support of Bates staff. BNL/NLSL provided key instrumentation and expertise for bunch length and CSR measurements.

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