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PLANNED USE OF PULSED CRAB CAVITIES FOR SHORT X-RAY PULSED GENERATION AT THE ADVANCED PHOTON SOURCE[*]

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Abstract

Recently, we have explored application to the Advanced Photon Source (APS) of Zholents'[1] crab cavity scheme for production of short x-ray pulses. We assumed use of superconducting (SC) cavities in order to have a continuous stream of crabbed bunches and flexibility of operating modes. The challenges of the SC approach are related to the size, cost, and development time of the cavities and associated systems. A good case can be made [2] for a pulsed system using room-temperature cavities. APS has elected to pursue such a system in the near term, with the SC-based system planned for a later date. This paper describes the motivation for the pulsed system and gives an overview of the planned implementation and issues. Among these are overall configuration options and constraints, cavity design options, frequency choice, cavity design challenges, tolerances, instabilities, and diagnostics plans.

INTRODUCTION

A significant segment of the storage ring light source user community is interested in time-resolved experiments. In many cases, the time resolution of interest is well below the typical 100-ps FWHM bunch durations available from storage rings at high current. However, providing high-intensity short pulses from a storage ring is problematical. Isochronous lattices [3] inherently suffer from low bunch current, which is unacceptable for many experiments and also often for the general user population (as it implies low total current). The laser slicing technique [4] also suffers from intensity issues and is difficult to implement for a high-energy ring such as the APS [5].

In contrast, Zholents' transverse chirping scheme [1] promises a reduction in pulse duration of two orders of magnitude with intensity that is 1% or more of normal. In this scheme, a deflecting cavity is used to impose a quasi-linear correlation between vertical momentum and arrival phase. If an undulator is placed at a downstream location with $n\pi$ difference in vertical phase advance ϕ_y, then the photons from the undulator will have an angle-time correlation. This correlation can be used to perform time-slicing or, using suitable x-ray optics, time-compression. A second downstream cavity with $\Delta\phi_y = m\pi$ is required in order to remove the chirp from the electron beam.

IMPLEMENTATION OPTIONS

The original concept, making use of ∼2.8-GHz, 6-MV superconducting cavities, was investigated in some detail for APS [6, 7, 8]. This scheme is challenging for APS because of the space required for the superconducting cavities, which would occupy at least half a 5-m-long straight section. In contrast, pulsed cavities should require less space. Further [9, 2], a pulsed system may be appropriate or even advantageous for certain pump-probe experiments.

Given the size of the pulsed cavities (about 0.5 m for a 9-cell cavity giving 6 MV deflection), it seemed feasible to install the cavities in a single APS straight section. In this case, one would use three cavities to form a closed bump. This has several advantages. For example, the absence of sextupoles between the cavities eliminates the major source of vertical emittance growth [6]. However, even these relatively short cavities are difficult to fit into a 5-m straight section with a normal APS undulator. Using a multi-objective method, we explored alternative configurations involving different numbers of cells in the three cavities, and concluded that a 3-9-9 configuration would provide the best performance with reasonable rf power consumption. However, the achievable x-ray pulse length was only about 3.5 ps FWHM. In addition, mechanical difficulties and ultimately multibunch stability issues (see below) made this scheme look untenable. As a result, we chose a configuration consisting of two pairs of 3-cell cavities installed in two consecutive straight sections. The voltage is limited to 4 MV per cavity pair, which is sufficient to reach our target of a 2-ps FWHM x-ray pulse duration.

SINGLE-PARTICLE BEAM DYNAMICS

Single-particle beam dynamics, tolerances, and performance were modeled in detail [10] using the parallel version of `elegant` [11, 12]. While only slight adjustments of the optics were needed to get the desired π phase advance, we need sextupole optimization [7] to minimize the single-pass emittance growth. Starting from a base vertical emittance of 13 pm (0.5% coupling), the single-pass growth for a 4-MV deflection is less than 3 pm. For a 1-kHz repetition rate, the equilibrium vertical emittance from tracking 10,000 turns is about 27 pm, just slightly more than the 25 pm value for normal APS operations.

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This grows to about 37 pm for a 5-MV deflection, impacting compression and giving results only marginally better than 4 MV. Hence, we designed the system with a limitation of 4 MV (i.e., two 3-cell cavities). For 4 MV, the system can provide 2-ps FWHM x-ray pulse duration with vertical slits closed to pass 1% of the pulse. In addition, horizontal slits are used to remove off-axis second-harmonic radiation, decreasing pulse duration by $\sim$30%.

Intercavity phase, voltage, and roll tolerances were investigated [10]. Some are quite challenging, e.g., on the order of $\pm 0.07^\circ$ for phase and $\pm 0.12\%$ for voltage.

Verification and monitoring of the proper phase and amplitude of the two sets of cavities is clearly required. In addition to diagnostics on the rf cavities themselves (see below), new photon diagnostics are under development [13] that will assess the $y' - t$ correlation using the radiation from a bending magnet between the cavity pairs. They utilize both optical and X-ray synchrotron radiation as detected by gated cameras and streak cameras, and will complement the out-of-zone coverage using the existing sector 35 synchrotron light diagnostics.

BEAM STABILITY

Beam stability is a worry whenever one contemplates putting a cavity in a storage ring. APS operates with 100-mA current, in various filling modes, including uniform 24- and 324-bunch fills as well as a “hybrid” mode consisting of a single 16-mA bunch on one side of the ring and 56 equally-populated bunches in a 0.5-μs-long train (with gaps) on the other side, leaving 1.59 μs on either side of the intense bunch. We intend to operate the crab cavity system only in hybrid mode since we need the large gaps to charge and discharge the cavity. Of course, the beam must be stable in all filling modes.

Single-Bunch Instabilities

Single-bunch instability investigations utilized the APS impedance database [14]. Without deflecting cavities the single-bunch current limit in the APS storage is determined by the vertical impedance [15], which is 20 mA with the chromaticity set at 10. With the deflecting cavities we found a significant increase in the horizontal impedance [16], which may reduce the threshold below 20 mA, depending on the configuration of system. For example, if the compression required three 9-cell deflecting cavities with aperture radius of $a = 20$ mm installed with $\beta_x = 20$ m, then the single-bunch limit would be 14 mA. In order to raise this limit back to 20 mA we have to maintain $[\beta_x Z_x] < 0.6\,[\beta_x Z_x]_{ref}$, where $[\beta_x Z_x]_{ref}$ corresponds to the configuration with a limit of 14 mA.

An earlier configuration had one 3-cell and two 9-cell cavities with $a = 23.5$ mm. The impedance is reduced by the smaller number of cells and the increased radius ($Z_x \sim 1/a^\alpha$, $\alpha \geq 1$, see [17]), so the requirement for 20 mA per single bunch is satisfied. Similarly, for the configuration discussed in this paper with four 3-cell cavities and $a = 21$ mm, the single-bunch limit should also be above 20 mA.

Recently [17], we speculated that the APS ring experiences a hitherto unaccounted-for resistive wall impedance in the horizontal plane. If this is the case, we may have to consider reducing the cavity impedance further or reducing β_x at the cavities.

Multibunch Instabilities

A Montecarlo technique [18, 19, 20] was used to determine maximum multibunch instability growth rates. The computation uses the frequencies, shunt impedances, and quality factors Q of lower- and higher-order modes. The mode frequencies, other than the working mode, are randomized to reflect likely cavity construction errors, then the growth rate is computed for each fill pattern. Comparison to the synchrotron radiation damping rate indicates whether the beam is stable. If not, one can determine the required mode damping to obtain stability. Computations are done at 200 mA to provide a safety margin.

For the original 9-cell cavities, the required damping was not achievable and stability could not be obtained in the vertical plane. Reducing the total number of cells from nine to three reduces the number of modes in the passband and, what is more important, moves the nearest mode away from the working mode. While this helped, at 200 mA the beam is still unstable in the vertical plane due to the nearest mode, although it is stable at 100 mA. Several solutions are available: 1. Decrease the shunt impedance of the working mode by a factor of two, which will require twice as much rf power. 2. Look at the impact of head-tail damping, which may provide sufficient additional damping to stabilize the beam. 3. Develop a feedback system, perhaps using the measured signal in the troublesome mode and an auxiliary cavity as the kicker. 4. Investigate further optimization of the cavity to minimize the impedance of the harmful mode.

CAVITY DESIGN

Details of the cavity rf design are presented elsewhere [21]. The cavity consists of three cells. Power couples to the structure symmetrically by two high-power WR284 waveguides connected to the middle cell. For damping of long-range wake fields each cell is loaded by waveguides. The waveguides are designed so the fields of the working mode do not propagate into the broadband loads, but lower- and higher-order modes are heavily loaded. The rf properties of the cell were calculated with the commercial 3D finite element code HFSS [22] and are shown in Table 1.

Fields in the cell for 2 MV maximum deflection were also computed. The maximum surface electric field in the cell is about 60 MV/m, while the maximum surface magnetic field is about 0.24 MA/m. These values are a good margin below operating values of existing S-band rf guns. A detailed thermomechanical design study was also carried out [23]. An optimal iris cooling scheme was developed that can handle the anticipated 1.5-kW average power level per cell.

Table 1: Main parameters of the deflecting structure.

Working mode frequency	2.815 GHz
Working mode Q	11900
Beam pipe aperture radius	21 mm
Iris radius	22 mm
Phase advance per cell	π
Structure length without beam pipes	111.7 mm
Iris thickness	18 mm
Kick / (Power)$^{1/2}$	1.19 MV/MW$^{1/2}$

RF SYSTEM

The rf system [24] will use one klystron at 2815 MHz to deliver a peak rf power of up to 25 MW at a pulse width of 1.3 μs and an eventual pulse repetition rate of 1 kHz. The rf power will be divided into four approximately equal parts by a waveguide variable power divider and two waveguide 3-dB hybrids. Each of the resulting four legs will feed approximately 3 MW into a 3-cell, normal conducting crab cavity via a magic tee that provides two inputs that are 180° out of phase with one another.

The precision measurement and regulation of the cavity-to-cavity and cavity-to-storage ring rf phase requires state-of-the-art performance from cavity phase measurement and rf phase reference distribution systems. Long-term phase stability requirements will be particularly challenging. The storage ring rf phase reference will be delivered to the crab cavity LLRF system via an active phase-stabilized link. Both mechanical phase shifters and ferrite I/Q modulators are being considered for making, respectively, fast and slow phase adjustments to each cavity.

Cavities 1 and 2 will be installed in the downstream end of sector 6, while cavities 3 and 4 will be installed in the downstream end of sector 7. In order to isolate the rf systems from sensitive beamline equipment, all rf components that are not inside the storage ring tunnel will be located in a new building constructed on the accelerator infield. This building will be in close proximity to the sector 6 and 7 shield wall penetrations in order to simultaneously minimize waveguide run length, rf losses, and thermally induced differential phase drift. For safety reasons, all four waveguide runs will have interlocked, redundant waveguide shutters to provide bidirectional isolation.

CONCLUSION

We have investigated in some detail the use of pulsed crab cavities for producing short pulses in the APS storage ring. A configuration employing pairs of 3-cell cavities in two locations was adopted in order to ease the damping of higher-order modes. Predicted performance with a 4-MV deflecting voltage is 2 ps FWHM with 1% transmission through the slits. Single-bunch thresholds should not be diminished from present values, although there are unresolved concerns about the resistive wall impedance in the horizontal plane. Multibunch instability in the vertical plane at 200 mA is still a concern and mitigating strategies are under consideration.

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