HIGH FREQUENCY SRF CAVITY STUDY FOR BUNCH SHORTENING IN PEPX*

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Abstract

The proposed PEPX is a diffraction limited storage ring light source, or "ultimate storage ring (USR)", which can be built in the PEP tunnel at SLAC. The 4.5 GeV PEPX design based on the USR with a natural emittance about 10 pm-rad can be used to drive a high-gain soft X-ray FEL with a desired high peak current over 300 A. In PEPX-FEL application, the bunch length is reduced to 1 ps from 10 ps through a set of multi-cell SRF cavities at 1.428 GHz in CW mode, providing about 300 MV RF voltage. In this paper, the 1.5 GHz JLAB C100 cavity for the CEBAF upgrade and the 1.3 GHz Cornell ERL cavity are investigated for PEPX. The simulation results show that the beam induced higher order modes (HOM) in the Cornell ERL cavity will not limit PEPX operating at its desired beam current, but the HOMs in the C100 cavity will. Therefore, a 7-cell cavity design with larger irises and beam pipe radius similar to the Cornell ERL cavity but operating at 1.428 GHz is proposed. Preliminary results on the rf parameters of the cavity will be presented and a possible HOM damping scheme will be discussed.

INTRODUCTION

There is a growing scientific interest in X-ray FEL sources that can provide a continuous train of evenly spaced, low peak power, and coherent photon pulses at a high repetition rate up to 1 MHz for time-resolved photon experiments. SLAC has explored a concept for implementing a high repetition rate, low peak brightness soft X-ray FEL based on a diffraction limited ultimate storage ring (USR) built in the PEP tunnel. The proposed PEPX light source, as illustrated in Fig. 1, would have the practical advantage of serving a large number of users on many "normal" (spontaneous radiation) beam lines as well as an FEL user community, and thus make it an extremely powerful resource for synchrotron radiation science [1].

PEPX can provide a natural emittance about 10 pm-rad with a special lattice designed to minimize the nonlinear effects of the high-order resonances. Furthermore, the electron beam in USR can be used to drive a high-gain soft X-ray FEL by shortening the bunch length and increasing the bunch charge to achieve the desired peak current of 300 A or more through high frequency SRF cavities installed in a bypass section [2]. The main parameters of PEPX-USR and PEPX-FEL are summarized in Table 1.

* Work supported by the Department of Energy under Contract Number: DE-AC02-76SF00515.

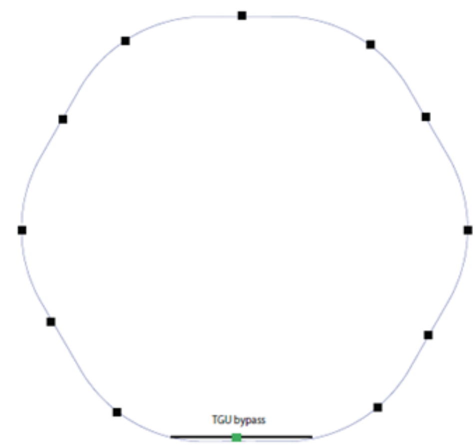

Figure 1: A layout of PEPX to drive a soft X-ray FEL in a 120-meter bypass. Most electron bunches (black squares) are stored in the ring while select bunches (in green) are sent through a bypass where they pass through a transverse gradient undulator (TGU) and lase. The lasing bunch is injected back into the ring and in three damping times is ready to lase again.

Table 1: Main parameters of PEPX as a conventional ring-based synchrotron light source or a driver of a free electron laser in a bypass.

Parameter	PEPX-USR	PEPX-FEL
Beam Energy [GeV]	4.5	4.5
Circumference [m]	2200	2200
Peak Current [mA]	200	10
Bunch Charge [nC]	0.5	0.75
Emittance, x/y [pm-rad]	12/12	160/1.6
Energy Spread [10^{-3}]	1.25	1.55
Bunch Length [mm]	3.0	0.3
RF Voltage [MV]	8.3	282
RF Frequency [MHz]	476	1428
Damping Time [ms]	18	18

To shorten the electron bunch from 10 ps to 1 ps, a set of SRF cavities operating at 1.428 GHz in CW providing approximately 300 MV are needed. The beam induced higher order modes (HOMs) in the SRF cavities are a concern: they can drive multi-bunch instability, limit the number of bunches in the storage ring, and generate heating on the walls. In the next section the HOM strengths in both the JLAB C100 and the Cornell ERL cavities are calculated to evaluate their effect on the beam in PEPX. Finally, an improved SRF cavity design for bunch shortening in PEPX is proposed.

JLAB C100 AND CORNELL ERL CAVITIES FOR PEPX

JLAB C100 Cavity

The proposed SRF cavity for PEPX will operate at 1.428 GHz, tripling the RF frequency of 476 MHz used in PEP-II. The use of the 1.5 GHz JLAB C100 SRF 7-cell cavities developed for the CEBAF upgrade [3] can achieve a 100 MV effective voltage in each cryomodule of 8 cavities. The required voltage of 282 MV for PEPX can be provided by three cryomodules similar to those used in the CEBAF upgrade.

Each 7-cell C100 cavity is equipped with two TESLA type HOM couplers on one side of the beam pipe and one waveguide fundamental coupler on the other as shown in Fig. 2. There are two HOM dipole bands below the beam pipe cutoff frequency that would be damped by the two HOM couplers. Their damping results simulated by ACE3P, parallel 3D Advanced Computational Electromagnetic simulation suite developed at SLAC, are shown in Fig. 3 [4]. The results agree well with measured data taken in the eight cavities of JLAB C100 module 4 [5], although the measured frequencies exhibit some scatter as shown in Fig. 4.

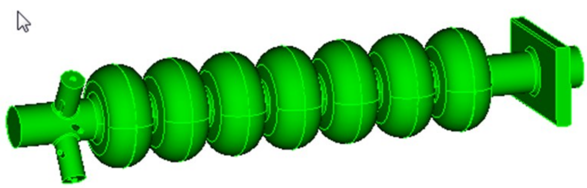

Figure 2: Model of the JLAB C100 SRF cavity used in the simulation.

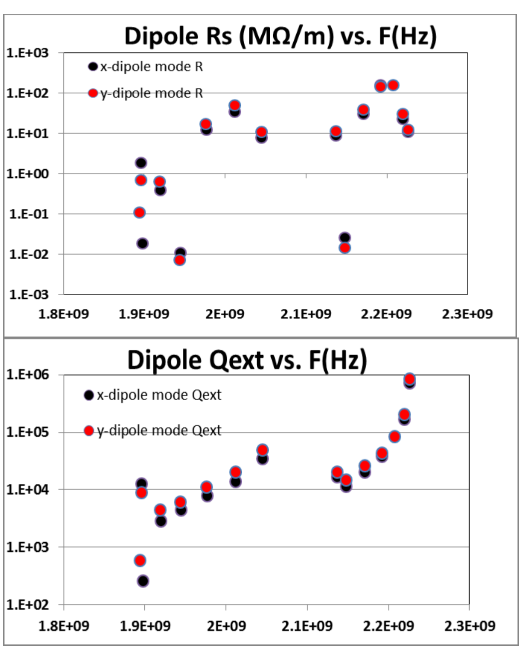

Figure 3: For the first two dipole bands in the JLAB C100 SRF cavity: simulated Rs (top) and Qext (bottom).

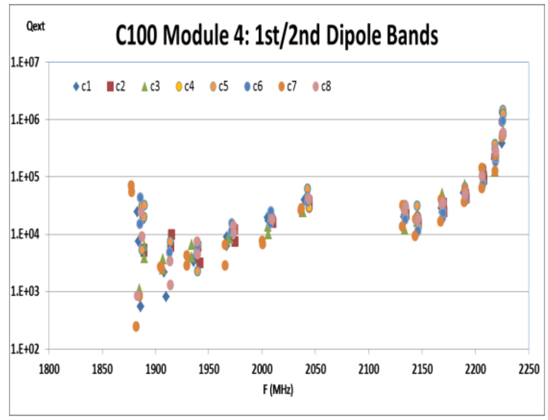

Figure 4: Measured Qext for the first two dipole band modes in the JLAB C100 module 4.

The coupled bunch instability due to the HOMs in the JLAB C100 cavities was evaluated for PEPX. The HOMs in a cryomodule will have a spread in frequencies and Qext values due to manufacture and tuning procedure. To estimate the growth rate of instability, we first generate distributions for each of these modes following either a uniform or Gaussian distribution. The mean frequencies were taken from the simulations, and the RMS scatter was obtained from the measurements of the JLAB C100 module 4. In the simulations, three cryomodules were used assuming accelerating gradients of 20 MV/m; 4000 seeds were simulated. The statistical results for a beam current of 200 mA are listed in Table 2.

Table 2: Statistical results of the growth rate of the coupled bunch unstable modes in the JLAB C100 cavity for PEPX.

		Uniform	Gaussian
Horizontal Mode	Fastest growth time	20 μs	20 μs
	Mean growth time	43 μs	40 μs
	Rms growth time	42 μs	39 μs
Vertical Mode	Fastest growth time	12 μs	12 μs
	Mean growth time	29 μs	27 μs
	Rms growth time	28 μs	26 μs

The HOM damping in the JLAB C100 is moderate, but satisfies the requirement for the CEBAF upgrade to 0.1 mA. However, the beam current for PEPX is 200 mA. If the target fastest growth time of 0.07 ms is assumed for the feedback system, the strength of the two pairs of dangerous HOM modes around 2.2 GHz in the JLAB C100 cavity need to be reduced by two orders of magnitude.

Cornell ERL Cavity

Cornell has proposed a 5 GeV superconducting energy recovery linac (ERL) light source design, which can

ISBN 978-3-95450-143-4

provide a high average current of 100 mA with low emittance of 30 pm-rad at 77 pC bunch charge [6]. In order to suppress the beam induced HOMs, the 1.3 GHz 7-cell SRF cavity cell shapes are optimized for the Cornell ERL [7]. In addition, large beam pipes are adopted to allow all the HOMs to propagate out of the cavities into the beam pipes where they can be damped by absorbers (see Fig. 5). Simulation results, as shown in Fig. 6, show that the Cornell ERL cavity can support a beam current up to 200 mA, similar to the current used in PEPX. Therefore, the possibility of using the Cornell ERL cavity for PEPX is investigated.

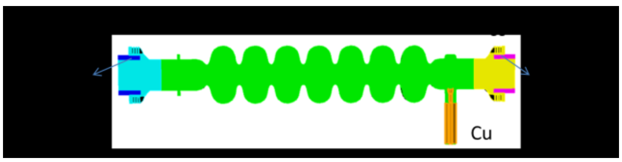

Figure 5: Model of Cornell ERL cavity used in the simulation (different colors represent different materials.)

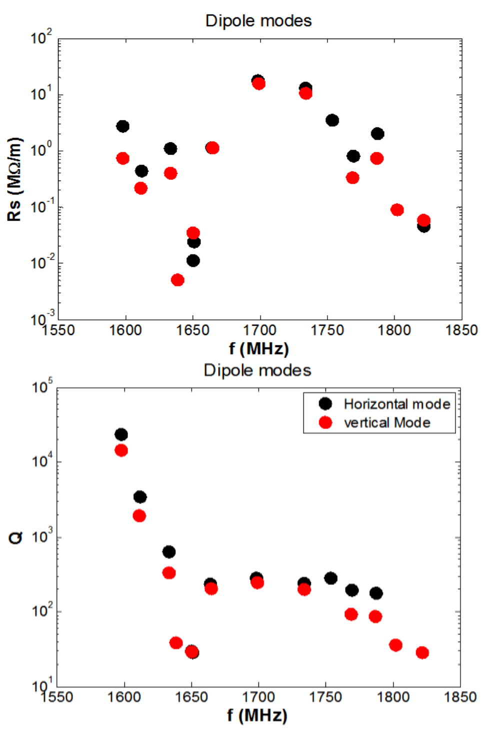

Figure 6: The first two dipole band HOMs in the Cornell ERL cavity: simulated Rs (top) and Qext (bottom). The dielectric constant of the absorber is ε=30-i10.

In the simulations all the HOM frequencies were scaled by the factor 1.5/1.3. Assuming three cryomodules with accelerating gradients of 20 MV/m, simulations using the calculated HOM parameters show that the fastest growth times are 1.45 ms and 1.63 ms for the horizontal and vertical modes, respectively (see Fig. 7), if a beam current of 200 mA is assumed. With these growth rates, the feedback system should be able to completely control the instability. The calculated HOM damping results, however, need to be confirmed by experiments.

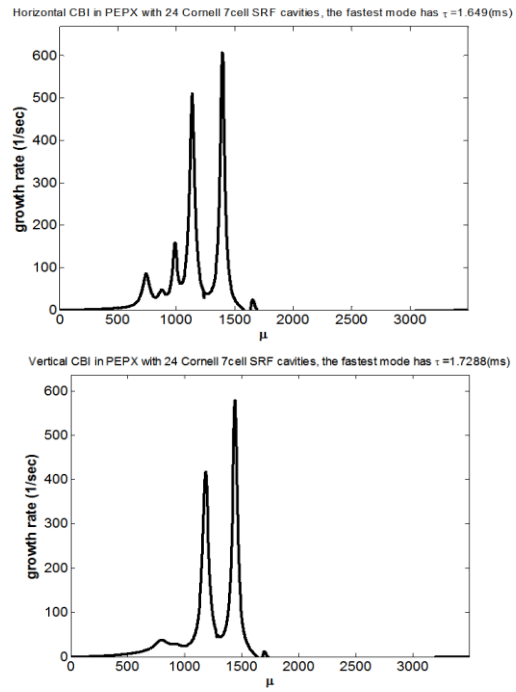

Figure 7: For Cornell ERL cavity: the growth rate of the coupled bunch unstable modes for horizontal mode (top) and vertical mode (bottom).

SRF CAVITY OPTIMIZATION FOR PEPX

Using the Cornell ERL cavity design for PEPX seems promising. We plan to adopt the Cornell ERL cavity design by scaling its frequency from 1.3 to 1.428 GHz as the baseline design for PEPX.

An SRF cell shape can be specified by the parameters shown in Fig. 8. The PEPX rf system will operate at 1.428 GHz, and thus the cell length is fixed, being equal to a half of the wavelength. A larger iris radius can be used to reduce the wakefield and increase the cell coupling but it decreases the operating mode shunt impedance. The iris radius is set to 35 mm, which is the same as the TESLA and Cornell ERL cavities. The two elliptical shapes at the equator and iris of the cell will affect the maximum peak surface electric and magnetic fields as well as the shunt impedance. They are the main parameters to be optimized. The cell height is used to tune the cell to the correct frequency.

The Cornell ERL cavity's mid-cell shape is scaled with the scaling factor of 1.428/1.3. Additional cell shape optimization is performed to aim for higher R/Q, lower peak surface electric and magnetic fields. Higher R/Q can increase accelerator efficiency, while lower Epk/Eacc and Hpk/Eacc can suppress field emission as well as reduce cryogenic loss. The optimal cell's RF parameters are close to those of the Cornell ERL cavity as presented in Table 3.

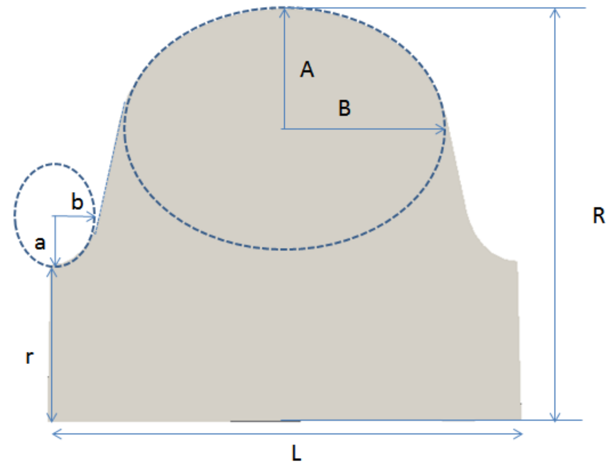

Figure 8: Parameterization of PEPX SRF cavity.

Table 3: Calculated RF Parameters for the Middle Cell of the Cornell ERL and PEPX Cavities

	F (GHz)	R_iris (mm)	R/Q (Ω/cell)	Kcc (%)	Ep/Eacc	Hp/Eacc (mT/MV/m)
Cornell ERL	1.3	35.98	111	2.1	2.18	3.32
PEPX	1.428	35.00	106	2.5	2.16	3.41

We also carried out multipacting simulations for the mid-cell using ACE3P below 30 MV/m. Resonant trajectories were found on the equator with impact energies between 25 to 50 eV at Eacc=20 to 30 MV/m. The maximum accelerating gradient of the proposed SRF cavity for PEPX would be 20 MV/m. Below 20 MV/m, the mid-cell design for PEPX is considered multipacting free. To be safe, the cell shape will be further optimized to push the multipacting barriers to higher field levels.

Two end cells are also designed to have similar Epk/Eacc and Hpk/Eacc as the mid-cell. The 7-cell SRF cavity without the fundamental and HOM couplers for the PEPX rf system is shown in Fig. 9. The large beam pipe radius of 52 mm allows all the HOMs to propagate into the beam pipes. The operating mode field is flat within 98% across the cells of the cavity.

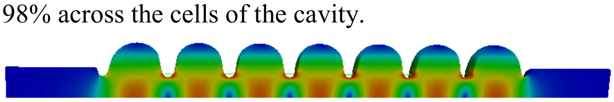

Figure 9: The operating mode electric field in the proposed 7-cell cavity for PEPX.

FUTURE PLANS

Recently, Stanford Synchrotron Radiation Light Source (SSRL) at SLAC has also proposed using a high frequency RF system in the SPEAR3 ring to shorten the bunch, and deliver a total stored current of 500 mA. The SRF middle and end cell shapes proposed for PEPX can be used for the SPEAR3. In the amount of space available, the RF system at 1.428 GHz should provide a total voltage of 50 MV in the SPEAR3 ring. In order to achieve the required voltage, strong damping, and a compact design, we plan to use 7*3-cell cavities operating at 1.428 GHz, installed with JLAB type waveguide HOM couplers developed for high current FEL application [8]. In addition to the dipole mode effects on the beam, the monopole modes, especially those in the same pass band (SPM), which are strongly trapped both in the JLAB C100 and the Cornell ERL cavities, can cause a heating problem. The 3-cell cavity design can reduce the number of SPM modes from 6 to 2 and their frequencies with a big mode separation could be controlled to be far away from the beam harmonics.

ACKNOWLEDGEMENTS

We thank J. Guo for providing us with the HOM measurement data at JLAB. The work used the resources of NERSC at LBNL which is supported by the Office of Science of the U.S. DOE under Contract No. DE-AC03-76SF00098.

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ISBN 978-3-95450-143-4