NORMAL CONDUCTING CW TRANSVERSE CRAB CAVITY FOR PRODUCING SHORT PULSES IN SPEAR3*

Zenghai Li†, Valery Dolgashev, Bruce M. Dunham, Kelly J. Gaffney, Bob Hettel, Xiaobiao Huang, Nadine R. Kurita, James A. Safranek, Jim Sebek, Kai Tian, SLAC National Accelerator Laboratory, Stanford, USA

Abstract

The ability to produce short pulse X-rays on the scale of 1-10 ps fwhm in the SPEAR3 storage ring light source would enable enhanced timing mode studies of dynamic processes in materials as they occur. The crab cavity approach appears to be optimal for SPEAR3 to produce short pulse X-rays. Furthermore, by using a two-frequency crabbing scheme, SPEAR3 would be able to produce short-pulse bunches while supplying the high average flux needed for regular users. While superconducting RF (SCRF) technology could be a natural choice for the CW crab cavity, the deflecting voltage for SPEAR3 crabbing appears to be within reach of more affordable normal conducting RF (NCRF). In this paper, we present a preliminary NCRF CW crab cavity design for SPEAR3.

INTRODUCTION

Short pulse X-ray beams have vital application in the study of fast dynamic processes in many scientific research disciplines such as chemistry, material science, environmental science, and biology. High repetition rate, high flux, ~1-10 ps fwhm short pulse X-ray beams generated in storage rings are complementary to the high peak brightness, ultrafast photon pulses of order 100 fs fwhm or less produced by X-ray FELs in terms of many performance measures such as pulse duration, repetition rate, stability, flux and availability. After studying several techniques for producing short X-ray pulses in SPEAR3, the crab cavity approach appears to be optimal [1, 2]. Crab cavities produce a transverse tilt in the electron bunches and a correlation between radiation emission angle and longitudinal position along the bunch so that photons from only a short slice of the bunch propagates through a slit in the X-ray beam line as schematically shown in Fig. 1.

The two-frequency crab cavity scheme, as shown in Fig. 2, is a newly proposed approach to generate intense short-pulse X-ray in storage rings while maintaining high average current in un-crabbed bunches [3,4]. For SPEAR3, two crab cavities with two different frequencies, the 6th and 6.5th harmonic of the main 476.3 MHz ring frequency, would be used to kick every other bunch in the ring. This approach enables operation with one or a few short-pulse bunches while simultaneously delivering many un-kicked bunches that supply the high average flux for non-timing mode users.

While SCRF appears to be a natural choice for CW crab cavity operation [5], implementing such a system for SPEAR3 would be costly since an entirely new 2 K cryogenic system would need to be installed. Since the kick voltage required for SPEAR3 is within reach of CW NCRF technology, this approach is more attractive.

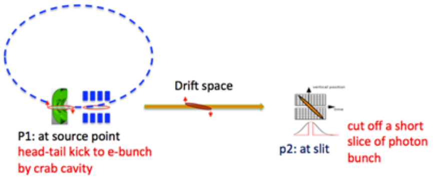

Figure 1: Schematic of using a crab cavity to generate a short photon pulse using a slicing slit in an X-ray beamline.

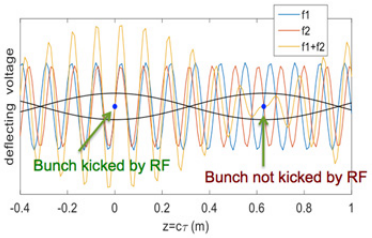

Figure 2: Two-frequency scheme generating simultaneous short and normal length photon pulses.

Table 1: Crab Cavity Specifications. Here x is Horizontal and y is Vertical Coordinate

Parameter	Value	Unit
Fundamental RF frequency f_0	476.314	MHz
Crab cavity frequency f_1	2858	MHz
Crab cavity frequency f_2	3096	MHz
Crab cavity voltage V_1	1.0	MV
Crab cavity voltage V_2	0.93	MV
Available space for crab cavities	4	m
Bunch kick factor k_d	<1500	V/pC/m
Sextupole field K_2L	< 0.2	1/m^2
Longitudinal impedance	< 8.3	kΩ at 3 GHz
Transverse impedance	1.9/4.7	MΩ/m in *y/x*
Beam aperture	12/36	mm in *y/x*
RF power and cooling	30	kW/m_length

DESIGN REQUIREMENTS

The working frequencies of the two crab cavities chosen for SPEAR3 are 2857.80 MHz (6th harmonic of main RF) and 3095.95 MHz (6.5th harmonic). The required combined peak deflecting voltage for the two frequency cavities is about 2 MV. Use of lower crabbing frequency would result in a higher deflecting voltage and may cause a high rate of injected beam loss. A frequency much higher than 3 GHz may produce a thermal load on the cavity walls which is difficult to cool. Our simulations show that to maintain the beam quality, the deflecting field needs to be very uniform transversely within the beam aperture. In addition, the two-frequency kicks need to be symmetric about the center of the crab cavity system to minimize

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† email address: lizh@slac.stanford.edu

vertical beam emittance; therefore 3 or 4 cavities are needed. The primary crab cavity specs are listed in Table 1.

STRUCTURE TYPE

The primary challenges of using NCRF for a CW cavity application are the CW power source and the cooling and temperature control of the cavity. The cavity has to be RF-efficient in order to reduce the RF power and cooling demand. Additional challenges include limiting short-range wakefields and suppressing long-range wakefields. The NCRF structure must operate with relatively low fields due to constraints set by its cooling circuit. Thus multi-cell structures are needed, leading to an increase in short-range wakefields and the number higher order modes (HOMs) to be dealt with. Therefore a larger beam aperture and effective HOM damping are essential. As the two crabbing frequencies are very close, the design studies presented here are primarily for the 2.858 GHz cavity.

Cavity Shape

We first attempted to minimize the RF power requirement for the CW NCRF cavity by looking for a design having high RF efficiency. Three different cavity shapes were studied (Fig. 3). Cavity shape a) is an elliptical cell design with a narrow racetrack beam pipe opening. Cavity shape b) is a novel RF dipole [6,7] operating with a TE11-like deflecting mode. Both cavity shapes are highly efficient, producing RF shunt impedance more than 2.5 times higher than a conventional elliptical cell design. However both a) and b) were found to have high short-range wakefields (SWF, due to a narrow gap) and significant deficiencies in transverse field uniformity, making them unsuitable for SPEAR3. We also found that improving shape b) to meet SPEAR3 requirements is not feasible for a 3 GHz operating frequency.

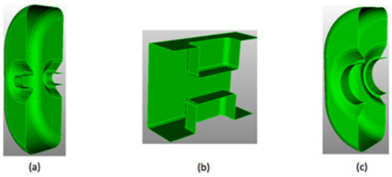
(a) (b) (c)

Figure 3: Three structure types studied.

Though lower in efficiency as compared to a) and b), an optimised conventional elliptical cavity, c) in Fig. 3, is a better choice for the SPEAR3 application. First, this shape has a very uniform deflecting field within the beam aperture. The sextupole component K_2L which characterizes the deflecting field distortion was found to be about 4 times smaller than the requirement. Second, a larger beam aperture reduces the SWF.

Cavity Parameters for SPEAR3

The dependencies of bunch kick factor (k_d) from SWF and RF power on beam aperture and total cavity length are shown in Fig. 4. The goal is to find a set of cavity parameters that will work for a NCRF design under the stringent SWF and RF power constraints. The dotted lines in Fig. 4 are the bunch kick factor k_d which increase linearly with the total cavity length, while, in contrast, the RF power drops as the length squared. With the kick factor k_d threshold of <1500 V/pC/m and a maximum 30 kW/m RF power limit, there is clearly a parameter region within which a NCRF cavity design would work. The thick green line segment in Fig. 4 illustrates a working parameter space for a cell iris radius of a=20 mm. This iris radius provides a wide range of cavity lengths that meets both the SWF and RF power requirements. We proceeded with a total cavity length of 2.65 m. This length would translate to a total of 52 pi-mode cells at 3 GHz, or 4 structures of 13 cells each. A list of cavity parameters based on this choice is shown in Table 2.

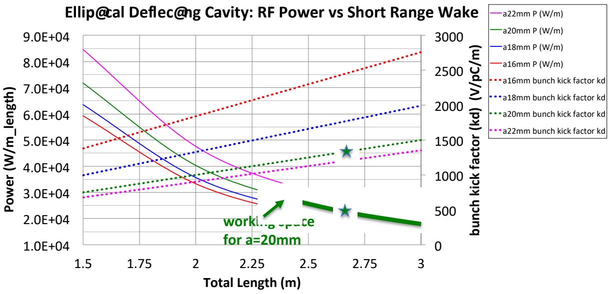

Figure 4: Bunch kick factor (k_d) and RF power dependence on beam aperture and cavity length. The four sets of curves are for beam aperture radii a=16 mm, 18 mm, 20 mm, and 22 mm respectively.

Table 2: NC Crab Cavity Parameters

Parameter	Value	Unit
Beam aperture	20	mm
Number of cell per structure	13	
Structure length	0.65	m
Number of structures	4	
Total length	2.65	m
Shunt impedance	21	MΩ/m
Sextupole field K_2L	0.05	1/m^2
Kick factor k_d (for σ_z= 5 mm)	1300	V/pC/m
RF power required	<40	kW/frequency

HOM AND FPC COUPLERS

LOM/HOM Damping Couplers

Waveguide couplers will be used for lower order mode (LOM) and HOM damping. Since the cavity needs significant space for water cooling, we have chosen to place both the horizontal and vertical HOM couplers on the horizontal plane such that the top and the bottom space are open for cooling channel implementation. The damping of both polarizations is achieved by the proper orientation of the couplers as shown in Fig. 5. The vertically orientated coupler damps the LOM and horizontal HOMs (H-HOM) and the horizontally orientated coupler damps the vertical HOMs.

Fundamental Power Couplers

The fundamental power coupler (FPC) is a conventional waveguide coupler with a racetrack coupling iris as shown Fig. 5. The z dimension of the coupler is made smaller than the cell length to allow more space for water

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cooling channels. A symmetrizing stub is used to maintain field symmetry and to minimize power leakage to the LOM/H-HOM coupler. Fig. 6 shows a 13-cell cavity with all the couplers.

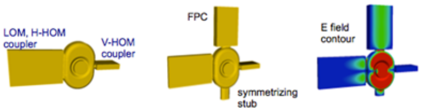

Figure 5: Left) Regular cell with two HOM couplers; Mid) FPC cell; Right) Electric field profile.

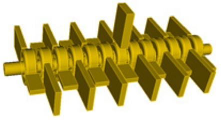

Figure 6: A 13-cell cavity with HOM and FPC couplers.

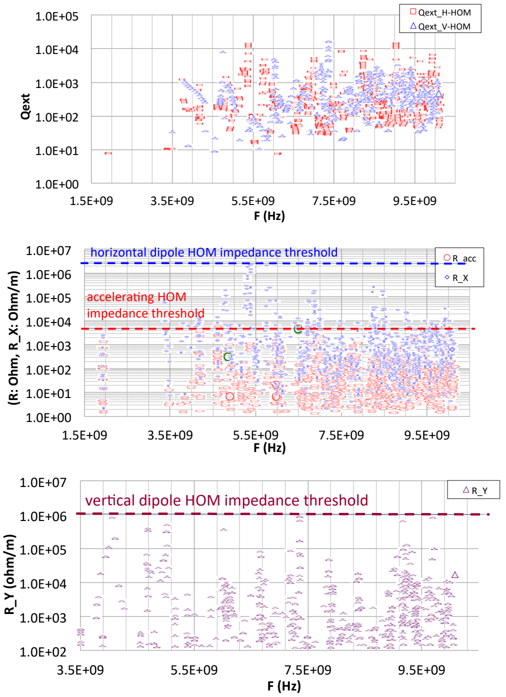

Figure 7: LOM and HOM damping results.

LOM/HOM Damping Results

The external Q (Qext) and LOM and HOM impedances up to 10 GHz are shown in Fig. 7. The dashed horizontal lines are the impedance thresholds. Symmetry-breaking by couplers causes mode-mixing of some of the horizontal HOMs. For each of the horizontal HOMs, both the accelerating and dipole components were calculated and plotted in Fig. 7. Effective damping is achieved using this coupling scheme. The impedance meets the SPEAR3 requirement.

Impedance of Same Order Modes

One potential issue with a multi-cell cavity is the existence of same-order pass-band modes (SOM) since no additional damping can be applied. It was found that due to longitudinal symmetry of the fields, there is a cancellation in the 13-cell cavity that reduces the impedances of the SOMs by orders of magnitude as shown in Fig. 8. This cancellation is achieved as long as the operating mode field is tuned flat, which is reasonably achievable for NCRF. With the natural wall loss damping Q_0 of 15000, the SOM impedances are well below threshold.

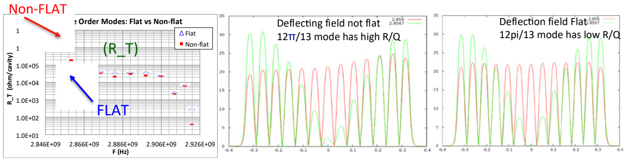

Figure 8: SOM impedances suppressed due to transient cancellation, as long as the operating mode field is flat.

THERMAL ANALYSIS

Unlike in an accelerating cavity, RF heating in the crab cavity is peaked at the tip of the cell opening, as shown in Fig. 9. Thus the cooling channels need to be as close to the beam opening as possible. Fig. 9 shows the preliminary design of straight cooling channels through the disk. The diameter of the channel is 10 mm so it can be machined using a drilling tool. The disk thickness is 14 mm in the design to accommodate the in-disk cooling.

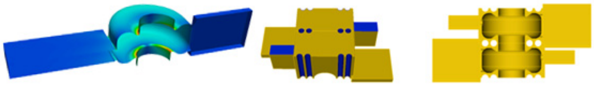

Figure 9: RF heating distribution and water cooling surfaces (blue).

The heating parameters for the thermal analysis are as the follows: deflecting gradient: 0.77 MV/m (2 MV in 2.65 m structure); RF heating per meter structure: 27 kW; heat transfer coefficient h: 15000 W/K/m^2. Shown in Fig. 10 are the temperature and thermal stress distributions. The temperature variation in the whole body is about 26^{o}C. The frequency shift due to the thermal expansion is 0.495 MHz, which could be compensated by a 10^{o}C water temperature change. The peak thermal stress is at the corner of the LOM/H-HOM coupling iris. It is about 35 MP and is below the copper yield strength [8, 9].

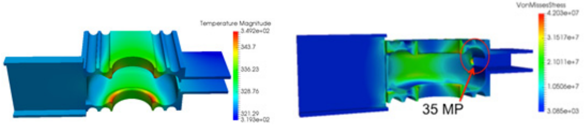

Figure 10: Temperature distribution (left) and thermal stress distribution (right).

CONCLUSION

The NCRF crab cavity is a viable option for SPEAR3 to produce short photon pulses. A 13-cell cavity design was studied. With a large circular beam aperture and effective damping, both the field quality and wakefields would meet the SPEAR3 requirement. The CW power source needed to power such a system is readily available. Structure cooling of respected power level is achievable. More detailed design optimizations are in progress.

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