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HEAVILY DAMPED CRAB CAVITIES FOR HIGH LUMINOSITY COLLISIONS*

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Abstract

Next generation colliders require crab cavities to mitigate parasitic collisions caused by finite crossing angle for luminosity leveling and detector data pile up reduction. The Electron Ion Collider (EIC) crab cavity designs will be introduced as an example to fulfill the geometrical constraints, crabbing voltages, multipole components, Higher Order Mode (HOM) power and impedance budgets. Operational challenges such as tuning, high gain low delay control loop, amplitude and phase noises control will be discussed.

INTRODUCTION

Crab cavities are used in modern colliders to compensate the loss of luminosity due to a finite crossing angle at the interaction point (IP). The High-Luminosity Large Hadron Collider (HL-LHC) needs horizontal crabbing for CMS and vertical crabbing for ATLAS [1], the EIC needs horizontal crabbing for IP6, and potentially for IP8 [2]. These two circular machines adopt local crabbing scheme, both bunches need to be crabbed before the IP and uncrabbed after the IP. The International Linear Collider (ILC) needs horizontal crabbing for the IP [3]. Table 1 shows the parameter comparison of these projects. While comparing with the other two projects, EIC has larger crossing angle, lower cavity frequency, higher crabbing voltage and tighter impedance budget. The need of 197 MHz crab cavity for Hadron Storage Ring (HSR) makes it difficult to design (as a pressure vessel), fabricate (fabrication error control, electron beam welding) and surface treatment. HL-LHC uses different types of cavities thus longitudinal and transverse impedance do not overlap. Considering the number of cavities needed to provide the crabbing voltage needed, as well as the need to be upgradable for the second IP, for EIC, the longitudinal impedance budget is two orders of magnitude lower comparing with HL-LHC for 197 MHz and three orders of magnitude lower for 394 MHz, while the transverse impedance budget is one order of magnitude lower for both 197 MHz and 394 MHz. Due to the high current and short bunch length, especially for electron bunch, the HOM power of both 197 MHz and 394 MHz systems are high while comparing with HL-LHC. ILC is a pulsed machine with CW crab cavity operation, thus the average HOM power is low. The longitudinal space allocation of 15 m is tight for EIC since four 197 MHz crab cavities and two 394 MHz crab cavities need to be fitted in. In HL-LHC and ILC, the adjacent beampipe is included into the crab cryomodule design. While in EIC it is not possible since the crab system can be adjacent to a beampipe, or a superconducting magnet, or beam position monitor, or sometimes, tunnel wall. To follow the Au energy ramp, the 197 MHz system needs ~1 MHz tuning range, and the requirement for 394 MHz gets doubled. The preliminary specifications on multipole components require careful design of the cavity, especially on the shape of the capacitive poles. Beyond the cryomodule, the Low Level RF (LLRF) system of EIC crab is also challenging. It needs a high gain low delay control loop, with tight tolerances on phase and amplitude noise.

These requirements are mitigated during the cavity and cryomodule designs. They strongly influence the decisions made during the designs. These will be discussed in detail.

197 MHz HSR CRAB CAVITY

Similar to HL-LHC, two designs were proposed at the beginning, Double Quarter Wave (DQW, Figure 1a) [4] and RF-dipole (RFD, Figure 1b) [5]. Both designs were advanced on RF designs like crabbing voltages and damping, with the RF properties summarized in Table 2. Both designs use two waveguides (one horizontal and one vertical) for HOM damping, with DQW one waveguide absorber and one coaxial absorber (Figure 1a) [4], and RFD two waveguide absorbers (Figure 1b) [5]. Both designs were expected to meet the RF performance requirements, as well as the space allocations. The DQW design is elongated to enhance the crabbing voltage while comparing with HL-LHC design thus is not favored for stress, while RFD remains to be cylindrical thus is favorable as a vacuum vessel and is also easier to be integrated with a helium vessel. RFD with two waveguide absorbers is downs elected as the baseline due to its maturity in engineering design.

The RFD 197 MHz was further studied with coaxial absorbers (Figure 1c) instead of waveguide absorbers [4], with its impedance spectrum shown in Figure 2. The advantages of the coaxial absorbers design include lower cost, lighter weighted, using off-the-shelf absorbers instead of further R&D, simpler waveguide structure, simpler engineering and easier transportation, while without degradation on RF performance (peak fields, HOM spectrum, multipacting etc.) [6]. Coaxial absorbers have less power handling capacity compared with waveguide absorbers, but enough for RFD 197 MHz in HSR. There were concerns about the possible impedance enhancement on the coaxial design, detailed error analyses cleared these concerns. RFD 197 MHz with coaxial absorbers is chosen as the current

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Table 1: Parameter Comparison of Three Projects that Use Crab Cavities

	EIC	HL-LHC	ILC
Crossing angle [mrad]	25*	0.590, two IPs, one vertical one horizontal	14
Frequency [MHz]	197 & 394 for HSR 394 for ESR	400, DQW (vertical) & RFD (horizontal)	1300/2600/3900
Voltage [MV]	33.83 from 197, -4.75 from 394 for HSR, 2.9 from 394 for ESR, per side.*	6.8 per IP per side as the baseline, upgradable to 12~13	1.845@1.3 GHz, 250 GeV 7.4@1.3 GHz, 1 TeV Inversely proportional to frequency
Space allocation – longitudinal	15 m for HSR, 4.5 m for ESR, per side.*	~3.5 m	3.8 m
Space allocation – transverse	1.0 m for HSR, 0.7 m for ESR, to adjacent wall	0.194 m, to adjacent beampipe center	0.1967±0.0266 m, to adjacent beampipe center
Longitudinal	316 kΩ for HSR 26 kΩ-GHz for ESR	2.4 MΩ	Depends on cavity short range wake field
Horizontal	2.64 MΩ/m for HSR 0.96 MΩ/m for ESR	1.5 MΩ/m	48.8 MV/m for 250 GeV 195.2 MV/m for 1 TeV
Vertical	13.2 MΩ/m for HSR 0.96 MΩ/m for ESR	1.5 MΩ/m	61.7 MV/m for 250 GeV 246.8 MV/m for 1 TeV

* These numbers are for IP6 only, which is the current baseline. It is under consideration to have the second IP at IP8 with 37.5 mrad crossing angle, 50% more than IP6 thus the voltage and longitudinal space allocation also need to be 50% more.

Table 2: Comparison Between DQW and RFD

Property	DQW	RFD	Specs
f_0 [MHz]	197.0	197.0	197.0
1^{st} HOM [MHz]	304.2	350.5	
G [Ω]	68.2	99.8	
R/Q [Ω]	1159.7	1106.0	
V_t [MV]	11.5	11.5	11.5
E_p [MV/m]	44.8	44.9	45
B_p [mT]	69.5	79.6	80
Cavity Length [mm]	821.8	949.5	1500
Cavity height [mm]	452.5	589	
Cavity width [mm]	584.4	589	
Max longi Imped [k Ω]	1.62	3.64	
Max trans Imped [k Ω]	0.22	0.60	
Max HOM power [kW]	3.2	10	

baseline. It is planned to put 2 cavities in 1 cryomodule, with their HHOM dogbone waveguides overlapping longitudinally to save space, so that for four 197 MHz and two 394 MHz can be fitted into 15 m longitudinal space. It is decided to use 100 mm to 75 mm taper, majorly due to longitudinal space limitation.

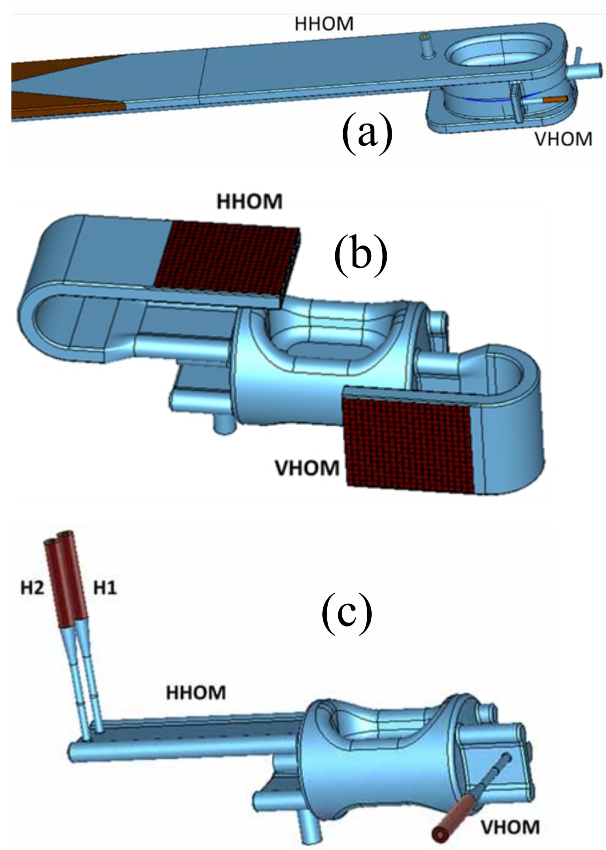

Figure 1: Change of the 197 MHz crab cavity baseline de- sign: (a) DQW design, (b) RFD with waveguide absorbers and (c) RFD with coaxial absorbers.

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Preliminary studies on the specifications for the multipole components of the fundamental mode suggested that the sextupole b3 is about one order of magnitude higher than the specs thus needs to be lowered [7]. Simulations showed that by carefully curve the capacitive poles, the tight requirement on b3 can be met without degradation of the other components [8]. Decision is made to freeze the prototype of 197 MHz design with flat poles due to continuous studies needed to finalize the multipole components specs [9]. The design of the 197 MHz cavity for first article cryomodule is aimed on changing the poles shape only, which will be machined from ingot Nb, with the other components to be identical with the prototype and will use 4 mm Nb sheet. Machining the poles from ingot Nb ensures the accuracy of the pole shape so that the multipole components of this cavity will not be compromised.

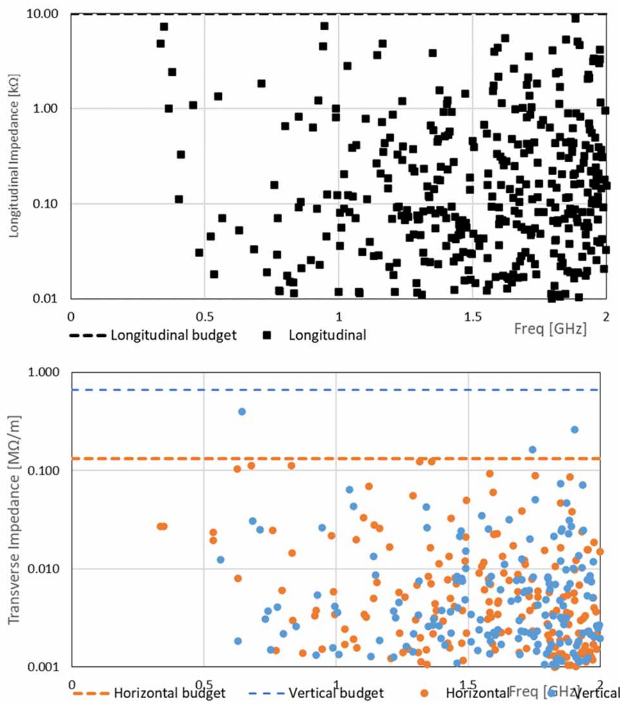

Figure 2: Impedance spectrum of 197 MHz RFD with coaxial absorbers. Impedance budget lines (10 kΩ longitudinal, 0.132 MΩ/m horizontal and 0.66 MΩ/m vertical) are also shown in plots.

It is decided to use the same FPC window that is designed for ESR 591 MHz cavity with 400 kW power. For 197 MHz crab cavity, the power is lower, at 60 kW. The FPC port is also the same as the 591 MHz design, at 100 mm. The inner conductor differs from the 591 MHz design, it is a straight E probe without potato chip shape tip. The E probe is designed to be 75 Ω to suppress the multipacting so that bias voltage on the E probe is not needed [8]. There is no multipacting on the ceramic window, majorly due to the relative low power while comparing with ESR 591 MHz application. During the design the bias voltage option is kept for redundancy though. The ESR 591 MHz uses coaxial to waveguide transition on the FPC, for 197 MHz crab cavity, this cannot be used, since 197 MHz waveguide is big and the design cannot be fitted into the tunnel due to transverse space allocation. A quarter wave stub is designed so that the E probe can be water cooled and bias voltage can be applied.

The 197 MHz cavity frequency acceptance range is ±25 kHz. Tuner is designed to hide the cavity frequency between revolution lines (around 78 kHz) during energy ramp, with the extreme case of Au ion with 196.158 MHz minimum and 197.050 MHz maximum resonance frequency, and a maximum 14 kHz/second tuning speed, due to the energy ramping speed that is limited by the superconducting magnets. The tuner should have a range of ±472 kHz, with center frequency (with zero tuner force) at 196.643 MHz, while cavity operational frequency at 197.050 MHz. With such a big tuning range, both push and pull are needed. Mechanical simulation showed that this large tuning range can be met, with tuning sensitivity of 126.4 kHz/mm and tuning force of 2740 lb/mm, and a tuning range of ±682 kHz, limited by the allowable stress [9]. Further mechanical studies are needed to ensure the 120,000 tuning cycles can be achieved, which is estimated using 600 per run for Au ion for 20 years with 10 times safety factor. More tuning cycles will be needed for smaller tuning range, for example, 120,000 tuning cycles for proton runs with ±110 kHz and more tuning cycles during store.

394 MHz CRAB CAVITY

197 MHz crab cavity design is more advanced while comparing with 394 MHz crab cavity due to its higher priority. For 394 MHz crab cavity, both Wide-Open-Waveguide (WOW, Figure 3a) design with SiC beamline absorbers and RFD design with on-cell damping (single-ridged waveguide to rectangular waveguide and then to waveguide absorbers, with 2 HHOM waveguides and 2 VHOM waveguides, Figure 3b) [6]. The later is chosen as the baseline because of two reasons: 1, it is similar to the 197 MHz design thus no prototype is needed and 2, for the ESR application, the HOM power produced in the former design is higher than that in the former design (in 50 kW range). The WOW type bare cavity (without SiC absorber and transitions) produces 69 kW HOM power. With transitions and SiC absorbers, it will produce 179 kW HOM power, further optimization could reduce the HOM power, but not to the 50 kW level. The impedance spectrum of the baseline design is shown in Figure 4, up to 8 cavities can be placed in ESR without going beyond its impedance budget, and the design also meets the HSR impedance budget. Further optimization is on-going to 1, push the design to higher crabbing voltage with 45 MV/m and 80 mT field limits; 2, to minimize the HOM power on the waveguide absorbers, and 3, to suppress the multipole components. The tuner design is challenging since the tuning range needs to be doubled while comparing with 197 MHz design.

RF CONTROL

The crab cavity noise control is estimated using the HSR emittance growth (assumed to be comparable with Inter-Beam Scattering IBS). For 275 GeV proton, the amplitude

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noise needs to be within 7.1e-6 and the phase noise needs to be within 1.8e-6rad [10]. For comparison, HL-LHC with <1%/hr emittance growth gives 13.3e-6 amplitude noise and 8.2e-6 rad phase noise. A feedback system is needed to relax the tight tolerance.

The fundamental of the crab cavity has a large transverse impedance so that high crabbing voltage can be achieved. The beta function at the crab cavity location is also large. To fight against it, a high gain low delay feedback LLRF control loop is needed. With FPC external Q at 1.75e6, a ~6,000 gain is needed, with a ~380 nS delay [11]. Further studies are on-going trying to relax these requirements. It is planned to place the amplifiers on top of the crab cavities and outside the tunnel so that the delay can be minimized.

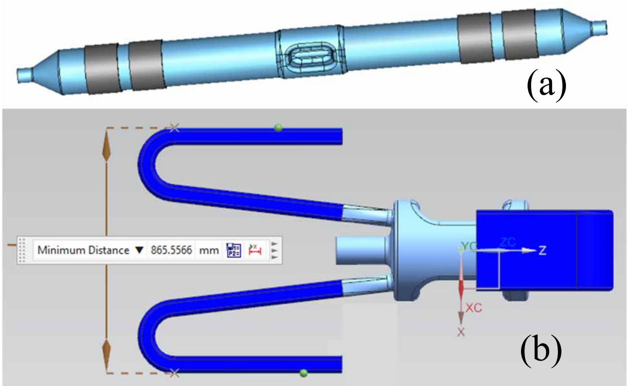

Figure 3: 394 MHz crab cavity designs: (a) WOW type with SiC absorbers and (b) RFD with 4 waveguide absorbers.

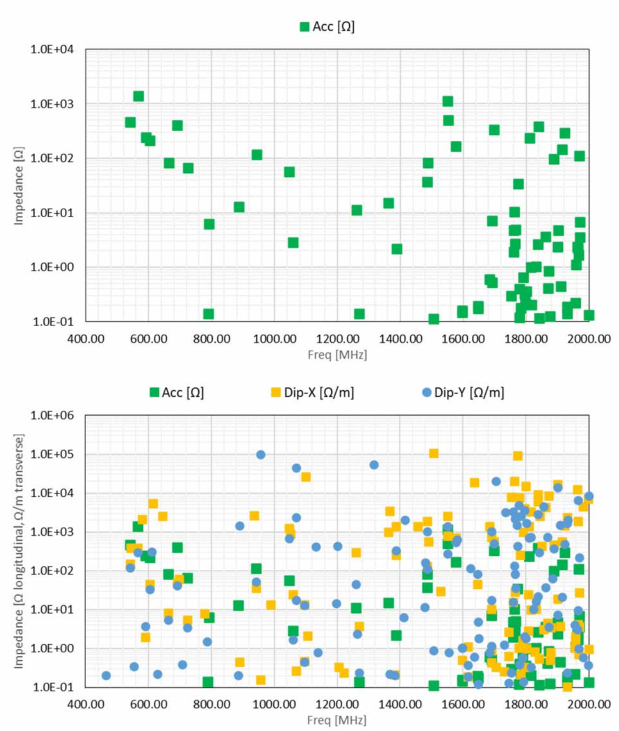

Figure 4: Impedance spectrum of the 394 MHz RFD with 4 waveguide absorbers. Up to 8 cavities can be placed in ESR without going beyond its impedance budget.

SUMMARY

In this paper, parameters related to the crab cavity system of three projects, EIC, HL-LHC and ILC, are compared. Crab cavities for EIC project is discussed in detail. For 197 MHz crab cavity, RFD design is chosen over DQW design, coaxial absorber design is chosen over waveguide design, straight poles are used in prototype, while they will be curved in first article cryomodule, and for FPC, 75Ω E-probe, FPC window that is designed for ESR 591 MHz SRF cavity and quarter wave stub are used. Tuner plates that can provide a large tuning range is also integrated in the prototype. For 394 MHz crab cavity, RFD with 4 waveguide absorbers is chosen over WOW type with SiC absorbers majorly due to HOM power generated in ESR, and further optimizations will be done. The RF control for EIC crab cavity system is challenging.

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