2016

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HyeKyoung Park
Old Dominion University

A. Castilla
Old Dominion University

J. R. Delayen
Old Dominion University

S. U. De Silva
Old Dominion University

V. Morozov

Repository Citation

Park, HyeKyoung; Castilla, A.; Delayen, J. R.; De Silva, S. U.; and Morozov, V., "Analyses of 476 Mhz and 952 MHz Crab Cavities for JLAB Electron Ion Collider" (2016). *Physics Faculty Publications*. 313.
https://digitalcommons.odu.edu/physics_fac_pubs/313

Original Publication Citation

Park, H., De Silva, S., Castilla, A., Morozov, V., & Delayen, J. (2016). *Analyses of 476 MHz and 952 MHz Crab Cavities for JLAB Electron Ion Collider*. Paper presented at the 7th International Particle Accelerator Conference, May 8-13, 2016, Busan, Korea.
http://accelconf.web.cern.ch/AccelConf/ipac2016/papers/wepmr034.pdf

ANALYSES OF 476 MHZ AND 952 MHZ CRAB CAVITIES FOR JLAB ELECTRON ION COLLIDER*

HyeKyoung Park[2,1#], A. Castilla[1], J. R. Delayen[1,2], S. U. De Silva[1,2], V. Morozov[2]
[1]Center for Accelerator Science, Old Dominion University, Norfolk, VA 23529, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

The Center for Accelerator Science at Old Dominion University has designed, fabricated and successfully tested a crab cavity for Electron Ion Collider at Jefferson Lab (JLEIC) [1]. This proof-of-principle cavity was based on the earlier MEIC design which used 748.5 MHz RF system. The updated JLEIC (called MEIC earlier) design [2] utilizes the components from PEP-II. It results in the change on the bunch repetition rate of stored beam to 476.3 MHz. The ion ring collider will eventually require 952.6 MHz crab cavities. This paper will present the analyses of crab cavities of both 476 MHz and 952 MHz options. It compares advantages and disadvantages of the options which provide the JLEIC design team important technical information for a system down selection.

BACKGROUND

The RF Dipole (RFD) proof-of-principle cavities for various applications have proven the robustness of the electromagnetic design. Multipacting was easily processed. Its compact design and absence of lower-order-modes allows effective cryomodule engineering design.

The first RFD proof-of-principle cavity was a 400 MHz crabbing cavity [3,4] built for LHC Hi-Lumi project. The cavity was tested multiple times at 4K and 2K. It reached the quality factor of 1.2×10^{10} and the transverse kicking voltage of 7 MV at 2K [5], which exceeded the requirement of 3.4 MV. A 499 MHz RFD deflecting cavity was also built as a superconducting cavity option for JLab 12GeV energy upgrade [6], and a 750 MHz crab cavity was developed for the JLab electron-ion collider [1]. These 3 cavities are shown in Fig.1.

Figure 1: Built and tested RFD proof-of-principle cavities. From left, 400MHz LHC Hi-Lumi crab cavity, 499 MHz JLab deflecting cavity, 750 MHz JLab MEIC crab cavity.

The cavity performance optimization parameters have been extensively studied for the RFD cavity [3], which provided a good start of the JLEIC crab cavity.

JLEIC Machine

The collider schematic is shown in Fig. 2. Electron and ion rings are vertically stacked and the figure-8 shape preserves the ion polarization.

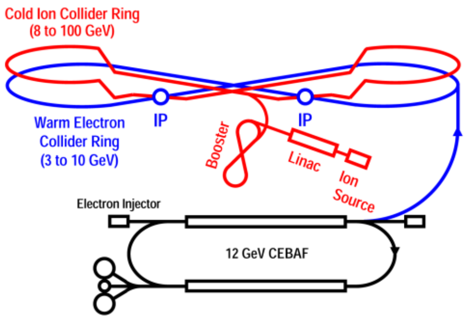

Figure 2: Machine layout of JLEIC [2].

Figure 3 shows the close up near IP where local crabbing cavity is located. IPs employ the crossing angle of 50 mrad. The luminosity requirement is 7.5×10^{33} cm^{-2}s^{-1}. Because of the requirement for high luminosity, the JLEIC collider design has adopted continuous wave SRF crabbing as part of its fundamental design [2].

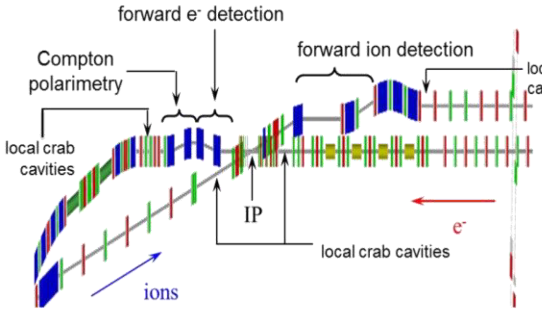

Figure 3: IP region detail of JLEIC [2].

Scope of Analyses

JLEIC is in design stage where beam parameters are not yet fully fixed. However, the effect of these parameters on the crab cavity can be studied. The most crucial parameters for a cavity is operating frequency and beam aperture. In general, the larger beam aperture degrades the cavity performance. We studied the cavity

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*Work supported by U.S DOE Award No. DE-SC0004094. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
#hkpark@jlab.org

performance parameters based on the two candidate frequencies and a range of beam aperture. The RFD cavity has many available parameters that can be used to optimize the performance but only a few major parameters were used. The results provide how many cavities should be built to produce the required kicking voltage based on the crabbing design parameters shown in Table 1.

Table 1: JLEIC Crab Crossing Design Parameters [2]

Parameter	Unit	Electron	Proton
Energy	GeV	10	100
Bunch frequency	MHz	952.6	
Crab crossing angle	mrad	50	
Betatron function at IP	cm	10	
Betatron function at crab cavity	m	200	750
Integrated kicking voltage	MV	2.8	18.4

ANALYSES RESULTS

Crab Cavity Options

The operating frequency of crab cavity determines the radius of the cavity cross section. This frequency affects cavity performance significantly when the beam aperture is fixed regardless of the frequency. Besides comparing two different frequencies we also compared with a squashed elliptical crab cavity for a reference. Relative cavity sizes are shown in Fig. 4.

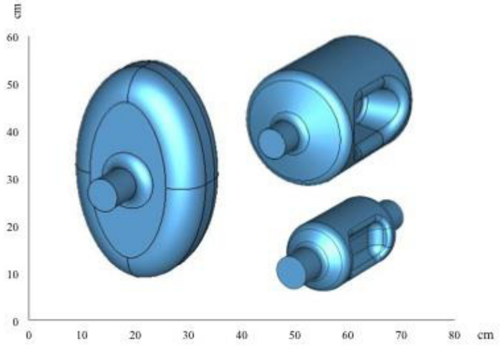

Figure 4: Relative cavity size shown with 70mm beam aperture. From left, 952 MHz elliptical crab cavity, top right 476 MHz RFD cavity, and bottom right 952 MHz RFD cavity.

The elliptical crab cavity utilizes TM mode and its distinct disadvantage is the existence of lower-order-modes and relatively larger size.

Comparison between 476 MHz and 952 MHz

The cavity was slightly modified to reduce the number of parameters as shown in Fig. 5.

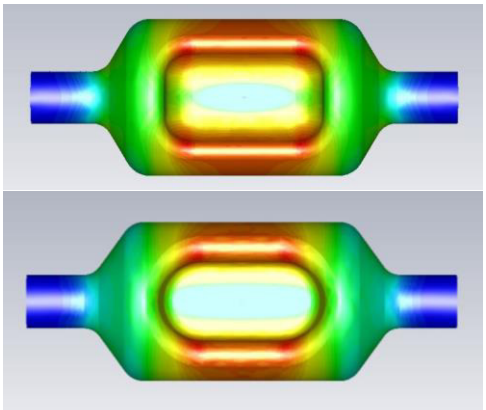

Figure 5: Initial design on top and modified design on bottom, both showing surface magnetic field distribution.

The cavity parameters of particular interest are E_p/E_t and B_p/E_t. Ratios of peak fields and transverse field are used to estimate the kicking voltage when a peak electric or magnetic field is assumed.

Figs. 6 and 7 show the trend of E_p/E_t and B_p/E_t for both frequencies respectively.

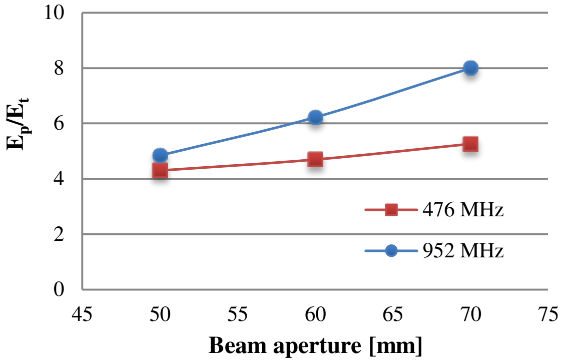

Figure 6: E_p/E_t vs. beam aperture.

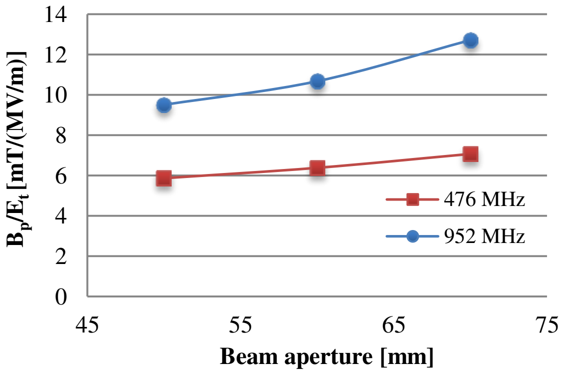

Figure 7: B_p/E_t vs. beam aperture.

The E_p/E_t is more sensitive for higher frequency. The peak electric field can be reduced by increasing the bar height [3] where the electric field is concentrated. This type of optimization parameter based on the geometry will have less room for an optimization for a smaller cavity size.

For B_p/E_t, the sensitivity against the beam aperture is similar in both frequencies. But as the beam aperture increases the smaller cavity is affected more. It is also a dimensional limit like E_p/E_t case.

Another cavity characteristic is R_tR_s. It is a product of the transverse shunt impedance and the surface resistance which indicates the efficiency of a cavity. Fig. 8 is R_tR_s at different beam apertures.

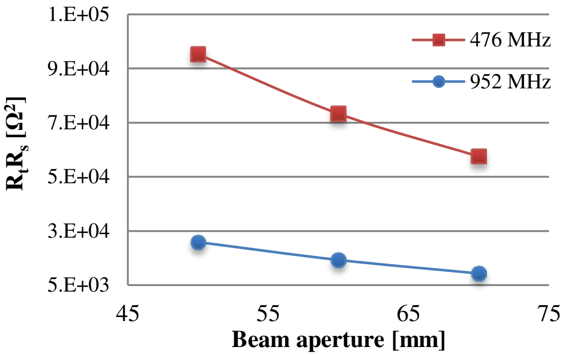

Figure 8: R_tR_s vs. beam aperture.

The kicking voltage can be estimated by practically reachable fields either limited by a field emission (peak electric field) or by a critical field causing breakdown of superconductivity (peak magnetic field). In our estimate, we assumed the peak electric field 35 MV/m and 56 mT which are easily achievable by the current SRF technology. Available kicking voltage by each beam aperture is plotted in Fig. 9. The decrease of voltage is almost linear for the beam aperture for both frequencies.

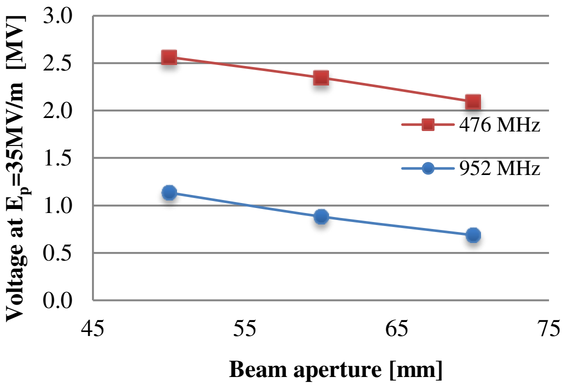

Figure 9: Kicking voltage vs. beam aperture.

Elliptical Crab Cavity

An optimized squashed elliptical cavity was briefly studied for a reference. The cavity parameters of 952 MHz with 70 mm are shown Table 2. Due to much smaller E_p/E_t, it would produce a higher voltage than RFD cavity of same frequency when the same peak surface electric field is assumed. However it should be noted that B_p/E_p of elliptical cavity is much higher than that of RFD cavity of same frequency and aperture which is 1.6 mT/(MV/m). The peak electric field of 35 MV/m corresponds to 87.5 mT of peak magnetic field for the elliptical crab cavity and 56 mT for the RFD cavity. So far, RFD cavities have achieved peak magnetic field above 100 mT. Therefore, the RFD cavity has a room to increase the voltage.

Table 2: Performance parameters of 952 MHz elliptical crab cavity.

Parameter	Unit	Value
E_p/E_t	-	2.2
B_p/E_t	mT/(MV/m)	7.7
B_p/E_p	mT/(MV/m)	3.5
R_tR_s	Ω^2	1.7×10^4
Voltage	MV	2.4

CONCLUSIONS

The design and optimization of RFD crab cavities for JLEIC is a work in progress which requires a close collaboration with the teams of machine design and beam physics. Recently the crab cavity frequency has been determined to 952.6 MHz [2]. This higher frequency with possible larger beam aperture presents an optimization challenge on an RFD crab cavity. The preliminary results show that the machine will require a smaller number of cavities if an elliptical crab cavity is used. However all the other aspects must be weighed to find the best solution for JLEIC. There are still much work should be done, for example a complete optimization for both options when the beam parameters are fixed and the comparison of engineering cost between the options. Also, a multi-cell RFD crab cavity [7] opens up new possibilities.

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