SLAC-PUB-13649
May 2009

TRAPPED MODE STUDY FOR A ROTATABLE COLLIMATOR DESIGN FOR THE LHC UPGRADE*

Liling Xiao[1], Cho-Kuen Ng, Jeffery Claiborne Smith, SLAC, Menlo Park, CA, US
Fritz Caspers, CERN, Geneva, Switzerland

Abstract

A rotatable collimator is proposed for the LHC phase II collimation upgrade. When the beam crosses the collimator, it will excite trapped modes that can contribute to the beam energy loss and power dissipation on the vacuum chamber wall. Transverse trapped modes can also generate transverse kicks on the beam and may thus affect the beam quality. In this paper, the parallel eigensolver code Omega3P is used to search for all the trapped modes below 2 GHz in two collimator designs, one with rectangular and the other with circular vacuum chamber. It is found that the longitudinal trapped modes in the circular vacuum chamber design may cause excessive heating. Adding ferrite tiles on the circular vacuum chamber wall can strongly damp these trapped modes. We will present and discuss the simulation results.

INTRODUCTION

SLAC proposed a rotatable jaw collimator design for the LHC phase II collimation upgrade through the US LHC accelerator research program (LARP) [1]. Figure 1 illustrates two collimator vacuum chamber designs. The rectangular vacuum chamber design was first proposed. The circular vacuum chamber design is currently considered for its easier fabrication and better vacuum pumping.

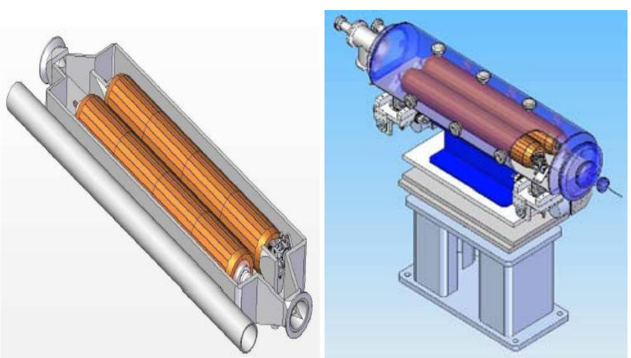

Figure 1: 3D solid models of the SLAC rotatable collimators (Courtesy of Steven Lundgren). Left: Rectangular vacuum chamber design; Right: Circular vacuum chamber design.

There are 20 facet faces on each cylindrical jaw surface and two jaws are rotatable and will move in and out with a 2mm to 42 mm gap during operation. When a beam happens to hit a jaw, the jaw can be rotated to introduce a clean surface for continued operation. The rotatable collimator is designed for 20 year life-time. Four thin flexible EM foils are used to connect the moving jaw ends to the rigid vacuum chamber.

A beam can excite trapped modes in the vacuum chamber of the collimator. These trapped modes can cause beam energy loss and heating on the vacuum chamber wall as well as coupled bunch instabilities. In this paper, the parallel finite-element frequency domain code Omega3P is used to calculate the trapped modes below 2 GHz [2]. For modes above 2 GHz, their wakefield effects are negligible for the LHC long bunch length (σ = 7.55 cm). Furthermore 42mm beampipe radius gives a cutoff frequency of 2.1GHz for the TE_{11} mode, and 2.7GHz for the TM_{01} mode. Therefore, the trapped modes below 2 GHz cannot propagate out of the two end beampipes.

SIMULATION MODEL

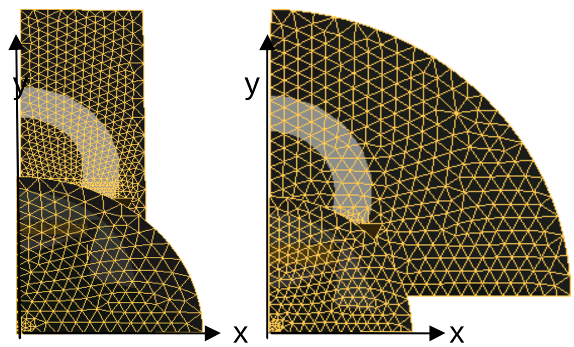

Figure 2: Cross sectional views of the finite element meshes of the rotatable collimators. Left: the rectangular vacuum chamber design; Right: the circular vacuum chamber design.

The finite element (FE) meshes used for modeling the rotatable collimators are shown in Figure 2. The actual circular vacuum chamber design is not purely cylindrical. The bottom portion of each end of the cylinder is cut-off and a flat plate is attached for supporting the heavier jaws. The mechanism for positioning the jaw and the universal joint is omitted in our simulation models. With these omissions, we expect that it will shift the mode frequency a bit without changing the mode pattern. Due to symmetry, only a quarter of each collimator design is required for the calculations of trapped modes. The tetrahedral elements in the mesh use quadratic curved surfaces so that they conform to the geometry with high fidelity. Near the axis, a denser mesh and finite elements with third order basis functions are employed for Omega3P calculations in order to achieve high accuracy for determining the RF parameters of trapped modes.

*Work supported by the US.DOE under contract DE-AC02-76SF00515
[1] liling@slac.stanford.edu

Contributed to the 2009 Particle Accelerator Conference, 05/04/2009 -- 05/08/2009, Vancouver, Canada

SIMULATION RESULTS

With magnetic boundary conditions on the x and y symmetry planes of the quarter model, longitudinal modes with Ez components along the beam in the z direction can be found using Omega3P. The longitudinal modes will generate beam energy loss and power dissipation on the vacuum chamber wall. With magnetic/electric boundaries on the y/x symmetry planes, transverse modes with Ey components between two jaws can be determined. The transverse modes will be excited when a beam crosses the collimator at a y-offset from the axis, generating transverse kicks in the y-direction as well as beam energy loss.

Longitudinal Trapped modes

The collimator jaws are designed to move in and out, so the properties of the trapped modes depend on the operating state of the collimator. When the jaws are fully retracted with a 42 mm gap, the loss factors of the longitudinal modes are found to be the largest. The loss factors and Qs of the trapped modes for the two collimator designs with rectangular and circular vacuum chambers and 42 mm jaw gap are shown in Figure 3. Even with this gap size, the modes have insignificant field intensities along the beam path (see Figure 4), and hence the loss factors are very small for both collimator designs.

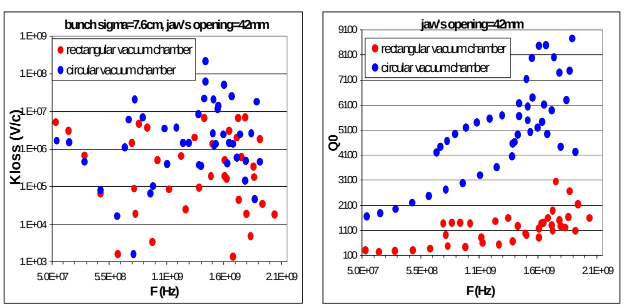

Figure 3: Loss factors (Left) and Qs (Right) of longitudinal trapped modes. Stainless steel vacuum chamber wall and copper jaws are used for Q calculation.

Using the LHC beam parameters, the total transient power can be calculated by the following formulas:

$$E = Nq^2 \sum k_i, \qquad P = E/(N*T_b)$$
$$N = 2808, q = 18.4nC, T_b = 25ns \qquad (1)$$
$$P(cir.) = 7W, \qquad P(rec.) = 0.7W$$

Here, *E* and *P* are the total energy and power generated by the trapped modes with loss factors k_i, *N* is the number of bunches, *q* the bunch charge, and T_b the bunch spacing interval, respectively. It can be seen that the transient power for both designs is small and this will not cause heating concerns for the collimators with good thermal conduction.

More severe heating effects result from resonant heating when a mode frequency is in phase with all the bunches. In the worst scenario that all these trapped modes are in resonance, the power generated is

$$P = I^2 \sum (\frac{R}{Q})_i e^{-\omega_i^2 \sigma^2 / 2c^2} * Q_i,$$
$$I = q/T_b = 0.582A \qquad (2)$$
$$P(cir.) = 515W, P(rec.) = 15W$$

where *R* is the shunt impedance, ω_i the mode angular frequency, and σ the bunch length, respectively. The power dissipation for the circular design is much higher than that for the rectangular design, and may cause heating problems for the collimator. This is because the trapped modes have higher Qs in the circular design (see Figure 3). It is desirable that the trapped mode frequencies should be shifted away from multiples of the beam harmonic at 40MHz to reduce resonant heating.

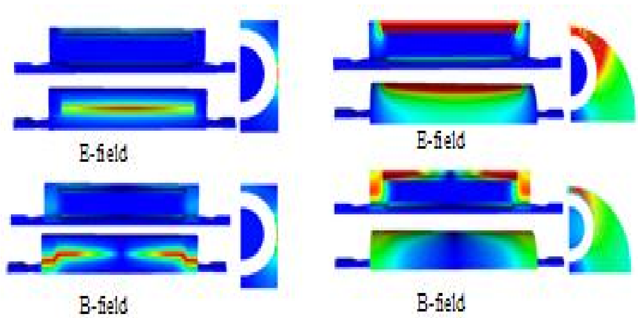

Figure 4: The lowest longitudinal trapped mode. Left: rectangular vacuum chamber design; Right: circular vacuum chamber design.

Figure 4 shows the field distributions of the lowest trapped modes. In the rectangular design, the mode is TEM-like and its fields concentrate between the jaw and the chamber wall. In the circular design, the mode is a cavity mode and its fields spread around the jaws and have high intensities on the chamber wall, which results in a higher Q.

Transverse trapped modes

The beam passage with a y-offset can excite transverse trapped modes that are potential sources of the coupled bunch instability. Thus it is important to determine the kick factors of the trapped modes. Due to the small gap between the jaws, the Ey component of a trapped mode is very strong over the full length of the collimator. When the two jaws are fully inserted with a 2 mm gap, the kick factors are found to be the highest. Figure 5 shows the kick factors and Qs of the transverse modes for fully inserted jaws. While the kick factors are comparable for the two designs, the Qs are much higher for the circular design, as explained in a previous section.

Work is in progress to evaluate the effects of the trapped modes on the bunch instability.

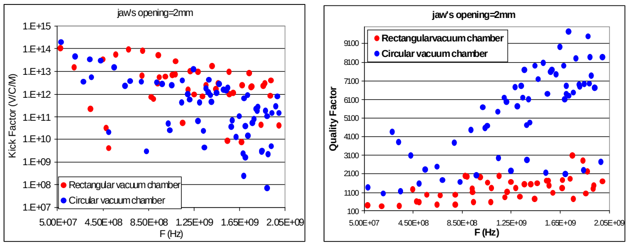

Figure 5: Kick factors (Left) and Qs (Right) of transverse trapped modes.

For large beam offsets, the beam heating due to transverse trapped modes need to be taken into account. The dependence of the loss factor on the beam offset is shown in Figure 6. The maximum beam offset is about a few ten microns and the resultant heating power due to the transverse trapped modes can be neglected. Table 1 lists the maximum trapped mode heating on the vacuum wall including all the longitudinal and transverse modes for both collimator designs.

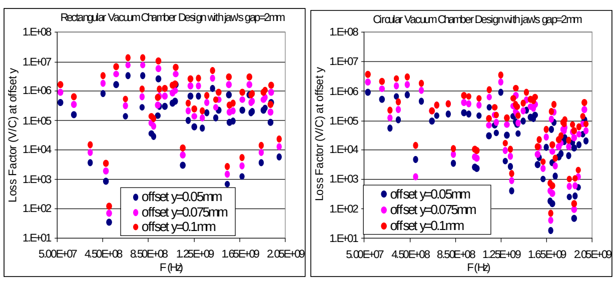

Figure 6: The loss factors for the transverse trapped modes for the rectangular design (Left) and circular design (Right). Form factors are not included.

Table 1: Maximum trapped mode heating

Max. Power dissipated on wall	Beam offset at y-direction	0.100mm	0.075mm	0.050mm
Rectangular Vacuum Chamber	Transverse Modes	11w	6W	3W
	Longitudinal Modes	15W		
Circular Vacuum Chamber	Transverse Modes	27W	15W	7W
	Longitudinal Modes	515W		

FERRITE-LOADED COLLIMATOR

The trapped modes in the circular design may cause excessive heating or beam instability. Since the trapped mode frequencies will vary a bit with slight changes in the chamber and any mode could easily overlay with a 40MHz resonance, we should simply ensure all trapped modes have low Qs [3]. For this purpose, we have investigated the use of lossy ferrite material mounted on the vacuum chamber wall as shown in Figure 7. The ferrite material TT2-111R had been used as HOM absorbers for the Cornell ERL prototype. The complex permeability and permittivity of the ferrite had been measured in the frequency range from 1GHz to 15 GHz at room and low temperatures [4-5]. We used the average values of the data measured at room temperature and between 1GHz to 2 GHz in our simulations and found that the modes in this range can be strongly damped with Qs less than 100. The permittivity of the ferrite will become really large towards low frequency [6] and lead to detuning with little damping. Further study for damping lower frequency modes below 1GHz is in progress. This realistic tile layout will also be investigated for this conceptual design.

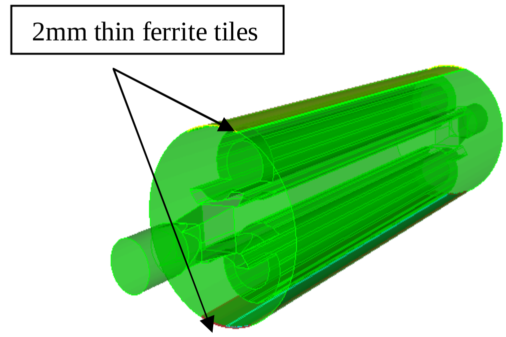

Figure 7: Model of the collimator with circular vacuum chamber mounted with lossy ferrite materials at top and bottom of the chamber wall.

FUTURE PLANS

We will continue to investigate other lossy materials in damping the trapped modes in the circular vacuum chamber collimator, including thermal and mechanical analysis. The beam instability due to the transverse trapped modes will be evaluated. The possibility of using BPMs in the jaw assembly to determine the position of the beam during a machine setup time is underway.

REFERENCES

[1] Smith, J. C. et al., “Design of a Rotatable Copper Collimator for the LHC Phase II Collimation Upgrade,” EPAC08.

[2] Ng, C. et al., “State of the Art in EM Field Computations,” EPAC06.

[3] Tuckmantel, J., “HOM Dampers or not in SUPERCONDUCTING RF Proton Linacs,” BE-Note-2009-009 RF

[4] Shemelin, V. et al., “Measurements of ε and μ of Lossy Materials for the Low Temperature HOM Load,” ERL 04-9

[5] Liepe, M. et al., “First Studies for a Low Temperature Higher-Order-Mode Absorber for the Cornell ERL Prototype,” PAC03

[6] http://www.trans-techinc.com/