Impedance of pumping holes

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Methods of impedance computation

- S.S. Kurennoy, IHEP 92-84 technical report (1992)
- S.S. Kurennoy, Part. Acc. **39**, pp. 1–13 (1992)

- Pumping holes are rather difficult to compute directly using FEM/FIT due to their small relative size (although it is possible)[1]
- Instead, holes can be treated as perturbations, represented by elementary dipoles
- For frequencies below hole cutoff and additional assumptions, the problem can be further reduced to an *electrostatic* problem according to works of S.S. Kurennoy.
  Effects of corrugations / interconnects (see D. Amorim's talk) and finite conductivity / layering of the material (see P. Krkotic's talk) are not considered in this approach.

[1] M. Takao et al., "Estimation of the Longitudinal Impedance of the ATF Damping Ring", Proc. PAC1991 (1991)

Methods of impedance computation

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Longitudinal hole impedance (one hole, below cutoff)

$$Z(\omega, 0) = -iZ_0 \frac{\omega}{c} (\alpha^{el} + \alpha^{mag}) e_r^2(0)$$

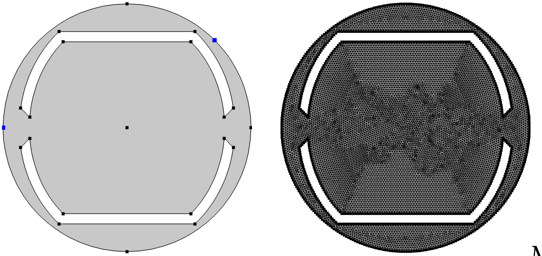
$\alpha^{el,mag}$ polarization constants defined by hole geometry

$e_r(0)$ $= \epsilon_0 E_r / \lambda$
normalized electric field at the hole position,
produced by a line charge λ ar $\vec{r} = 0$.

- Use the fact that hole geometry and chamber fields have been separated analytically.
- Compare $e_r(0)$ for different designs by electrostatic 2D simulations to check their relative efficiency in reducing impedance issues.

Input for $e_r(0)$ simulations

✠ using COMSOL Multiphysics 5.2, COMSOL Inc., `http://www.comsol.com/`

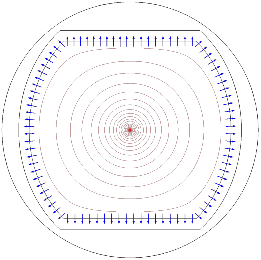


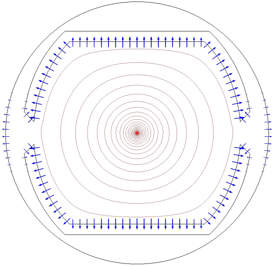
Design Mesh

- In this first attempt, very coarse estimates of beam pipe parameters were used.
- For comparison, the impedance of a circular pipe with $R = 19\,\mathrm{mm}$ was also computed numerically (although this is a simple analytical expression).

First results

✠ using COMSOL Multiphysics 5.2, COMSOL Inc., `http://www.comsol.com/`



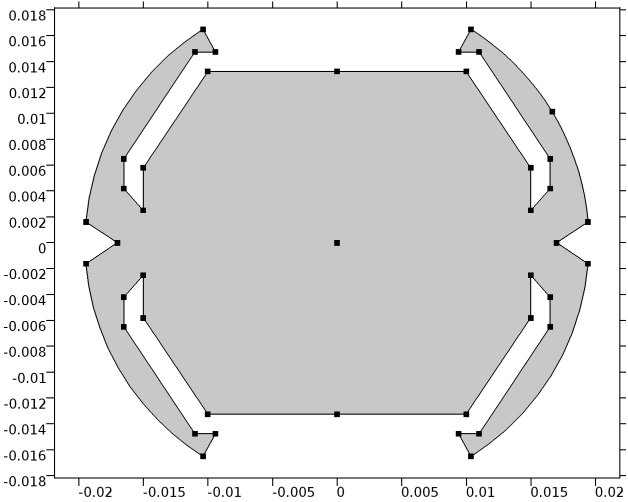


liner FCC

Setup	$e_r(0)/\mathrm{m}^{-1}$	$Z/Z^{\mathrm{ref}} \propto e_r^2(0)$
19mm circular (ana.)	8.3766	1
19mm circular	8.3764	$1 - 5 \times 10^{-5}$
13mm circular (ana.)	12.243	2.136
liner sketch	12.922	2.380
FCC sketch 1 (0 deg)	0.770 72	8.5×10^{-3}
FCC sketch 1 (45 deg)	8.39×10^{-9}	$< 10^{-10}$

Updated chamber simulation

- ✠ based on drawings by C. Ganton (via S. Arsenyev / impedance database)
- ✠ using COMSOL Multiphysics 5.2, COMSOL Inc., `http://www.comsol.com/`



This is just a rough approximation of the mechanical drawing…

Updated chamber simulation

- based on drawings by C. Ganton (via S. Arsenyev / impedance database)
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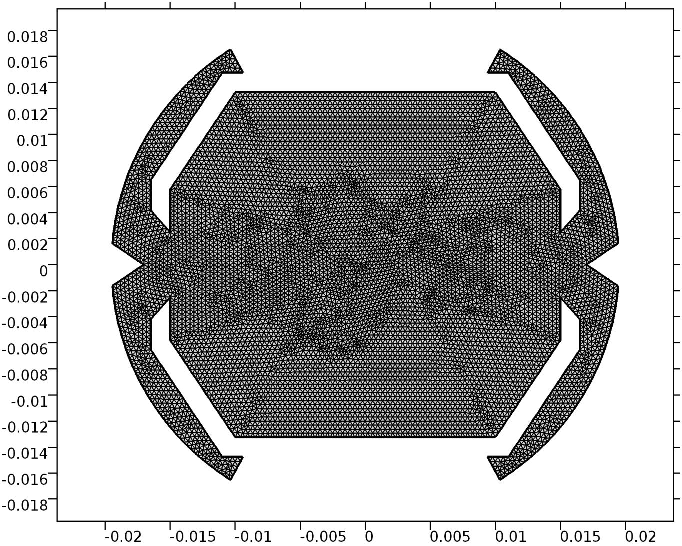
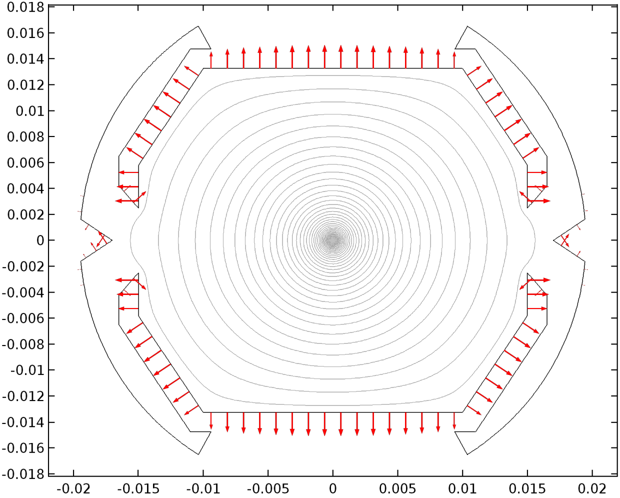


Electrostatic result

✠ using COMSOL Multiphysics 5.2, COMSOL Inc., `http://www.comsol.com/`



gray isolines	electric potential
arrows	Boundary electric field (log scale)

Electrostatic result

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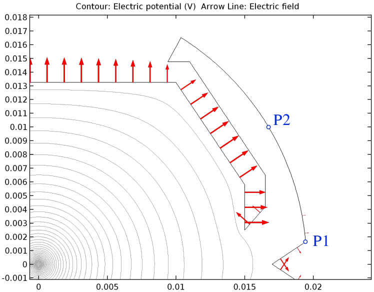
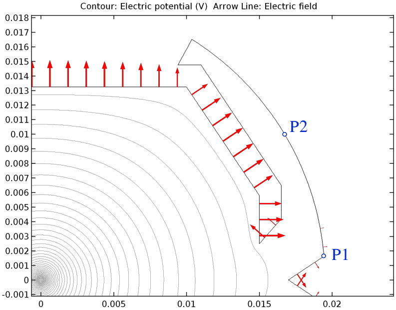


Setup	e_r^0/m^{-1}	$Z/Z^{\mathrm{ref}} \propto e_r^2(0)$
19mm circular (ana.)	8.3766	1
13mm circular (ana.)	12.243	2.136
liner sketch	12.922	2.380
FCC sketch 1 (0 deg)	0.770 72	8.5×10^{-3}
FCC sketch 1 (45 deg)	8.39×10^{-9}	$< 10^{-10}$
FCC sketch 2 (P1)	0.1045	1.56×10^{-4}
FCC sketch 2 (P2)	4.448×10^{-5}	$< 10^{-10}$

One hole behind beamscreen



- Insert circular hole with $d = 5\,\mathrm{mm}$ diameter at P2.[2]
  $\alpha^{\mathrm{el}} = -2d^3/3, \quad \alpha^{\mathrm{mag}} = 4d^3/3$

[2] S.S. Kurennoy, Part. Acc. **39**, pp. 1–13 (1992)

Multiple holes (simplistic approach)

- For holes in the same longitudinal coordinate, the impedances should add up

$$Z(\omega, 0) = -\mathrm{i}Z_0 \frac{\omega}{c} \sum_n (\alpha_n^{\mathrm{el}} + \alpha_n^{\mathrm{mag}}) e_{r,n}^2(0) \tag{1}$$

- For holes in different longitudinal coordinates, interference patterns emerge.

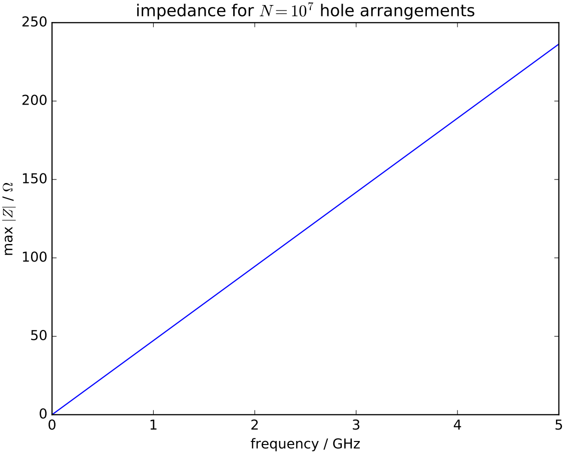
$$W(t) = \sum_m^M W_m(t - \tau_m) \tag{2}$$

For regular longitudinal intervals, this leads to sharp resonances in the impedances, bounded by $MZ(\omega, 0)$.

Boring linear impedance plot

- Four holes in symmetric P2 positions: same $e_r(0)$ value.

$$Z(\omega, 0) = -\mathrm{i}\frac{8}{3}\frac{Z_0}{c}d^3 e_r^2(0)\ \omega$$



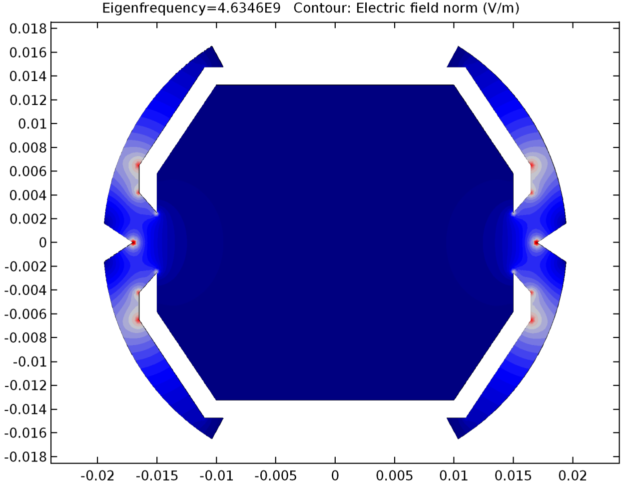
dZ/df Slope comparison

- impedance $Z \propto d^3$, while hole area $A \propto d^2$
- if no other boundary conditions apply, replace larger hole with N smaller holes to get better impedance properties.

$$Z(f,0) = -\mathrm{i}\frac{16}{3}\frac{Z_0}{\sqrt{\pi}c}\left(\frac{A}{N}\right)^{3/2} e_r^2(0)\, f$$

Above cutoff: studying eigenmode patterns (1)

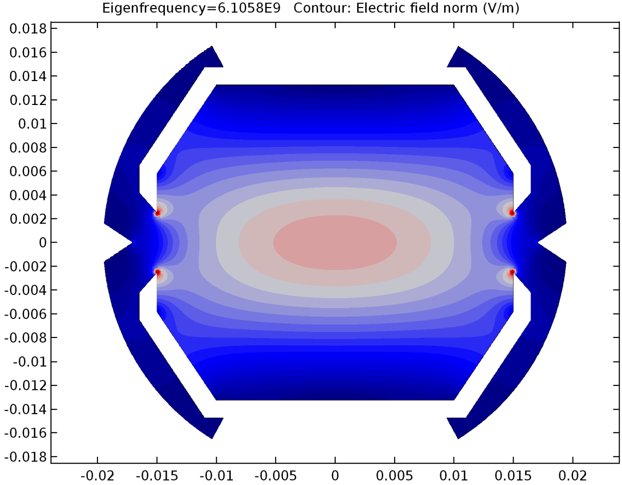
✠ using COMSOL Multiphysics 5.2, COMSOL Inc., `http://www.comsol.com/`



- Pattern is concentrated outside of screen.
  → low coupling between holes and beam.

Above cutoff: studying eigenmode patterns (2)

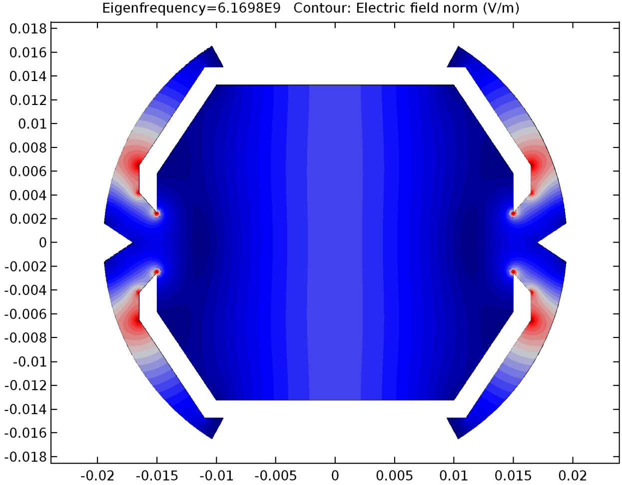
✠ using COMSOL Multiphysics 5.2, COMSOL Inc., `http://www.comsol.com/`



- Pattern is concentrated inside of screen.
  → low coupling between holes and beam.

Above cutoff: studying eigenmode patterns (3)

✠ using COMSOL Multiphysics 5.2, COMSOL Inc., `http://www.comsol.com/`



- Pattern is distributed.
  → non-negligible coupling.

Summary

- Preliminary results are promising,
  indicating that hiding the pumping holes behind the screen decreases the low-frequency impedance at least by two orders of magnitude.
- More but smaller holes may reduce impedance if other approximations hold and mechanical contraints allow for it.
  They also aid computation as the hole cutoff frequency increases.
  Two small in-cross section holes in close vicinity (instead of one larger one) were also used for LHC, see e.g.[3] [4]

[3] A. Mostacci, "Beam-Wall interaction in the LHC liner", Ph.D. thesis (University of Rome, 2001)

[4] A. Mostacci and F. Ruggiero, "Pumping slots and thickness of the LHC beam screen", LHC Project Note 195 (1999)

Next steps

- Understand more theory (read paper recommendations from U. Niedermayer and B. Salvant).
- make estimates more precise, e.g. by trying to include longitudinal changes (stiffeners, corrugations). Integrate with existing approaches.
- If possible, compare hole results with full FEM methods.

Acknowledgments

Thanks to all colleagues from CERN, TU Darmstadt, GSI, the FCC and EuroCirCol collaborations, and everyone else for their contribution!

By the way: read my PhD thesis about beam diagnostics :-D

`http://dx.doi.org/10.17877/DE290R-17221`