Review of holes and slots impedance studies for LHC, HL-LHC and FCC: history and current status

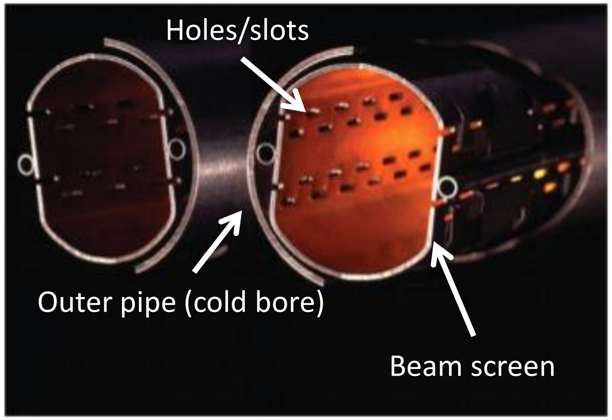
N.Biancacci and S.Arsenyev

HSC meeting 05-02-2018

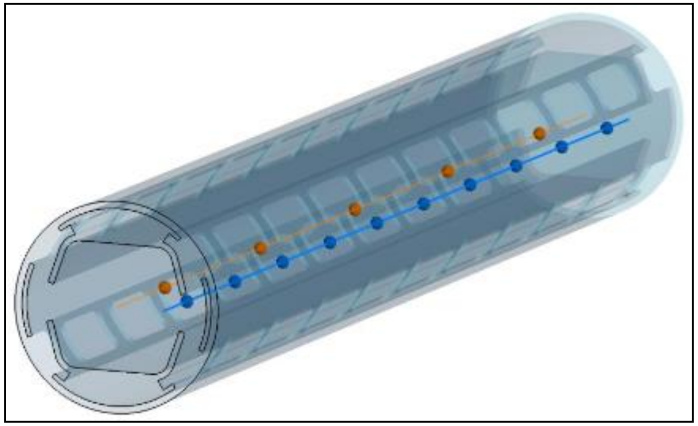
Acknowledgements: D.Amorim, S.Antipov, F.Caspers, A.Grudiev, E.Métral, A.Mostacci, B.Salvant.

Introduction

- Accelerated beams in storage rings travel inside beam screens embedded in (super-) conducting magnets.
- Smooth uniform beam pipe -> image currents dissipates on the conductive walls -> main source of machine impedance and beam induced heating.
- In reality we have also (and not only) pumping holes and slots necessary to:
  - maintain vacuum requirements
  - shield cold bore (LHC) from beam induced heating.



LHC beam screen



FCC-hh beam screen design

We review the theory, models and measurements of the impedance of holes and slots on a beam screen.

Outline

- Theoretical models
- Measurements
- Simulations
  - FCC-hh
  - LHC
  - HL-LHC
- Summary and future work

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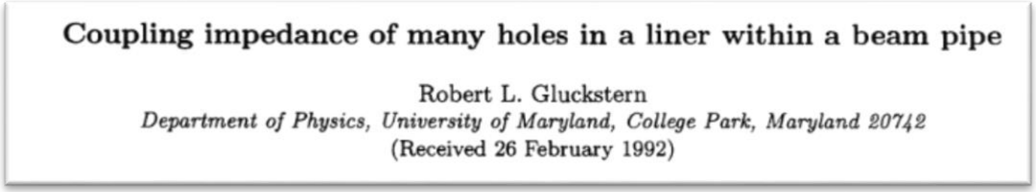
R.L.Gluckstern



Coupling impedance of many holes in a liner within a beam pipe

Robert L. Gluckstern
Department of Physics, University of Maryland, College Park, Maryland 20742
(Received 26 February 1992)

- Longitudinal and transverse reactance
- Contribution of hole and forward waves in the coax region.
- Transverse impedance valid only for $M \geq 3$. See next slide.
- Address the coherent modes when holes are uniformly displaced.

Susceptibility

Number of holes

Machine radius

$$\frac{Z_{\parallel}(k)}{Z_0} = \frac{jk}{8\pi^2 b^2}(\psi_{\rm in} - \chi_{\rm in})P, \qquad Z_{\perp} = \frac{Z_{\parallel}}{n}\frac{2R}{b^2},$$

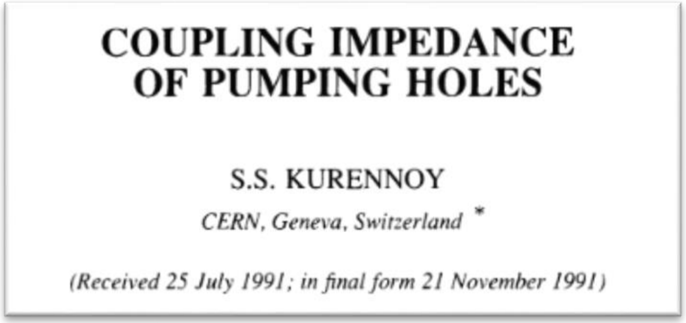
Pipe radius

Polarizability

Strictly applicable only for
azimuthal symmetric structures:
i.e. not with one hole only!

https://cds.cern.ch/record/234213/files/PhysRevA.46.1110.pdf

S.Kurennoy

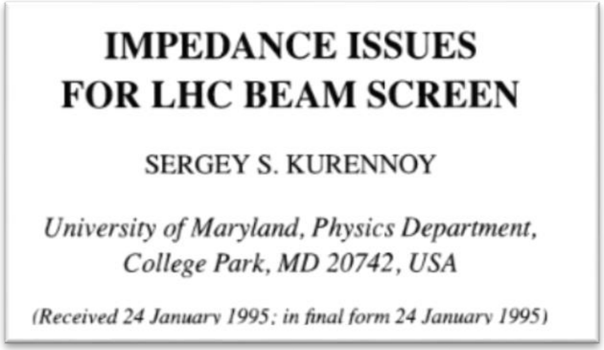


COUPLING IMPEDANCE OF PUMPING HOLES

S.S. KURENNOY

CERN, Geneva, Switzerland *

(Received 25 July 1991; in final form 21 November 1991)



IMPEDANCE ISSUES FOR LHC BEAM SCREEN

SERGEY S. KURENNOY

University of Maryland, Physics Department,
College Park, MD 20742, USA

(Received 24 January 1995; in final form 24 January 1995)

- Longitudinal and transverse reactance
- Accounts for many holes per cross sections.
- Elliptic, round, rectangular shapes
- Dependence of hole impedance on position
- Dependence on aspect ratio
- Trapped modes shunt impedance
- High frequency impedance and randomization effect.

$$Z(\omega) = -iZ_0 \frac{\omega}{c} \frac{(\alpha_m + \alpha_e)}{4\pi^2 b^2} \, ,$$

$\uparrow$

Same as Gluckstern for 1 hole: $\alpha_m \propto \frac{\psi_s}{2}$, $\alpha_e \propto \frac{\chi_s}{2}$

$\uparrow$ $\uparrow$

Magnetic and electric moments

Azimuthal hole (h) and beam (b) angles

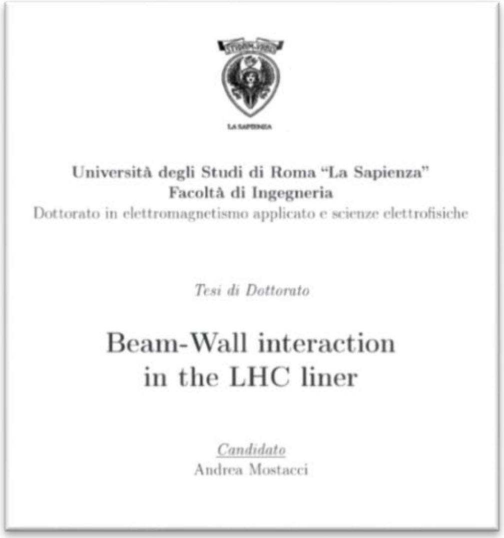
$$\vec{Z}_\perp(\omega) = -iZ_0 \frac{\alpha_m + \alpha_e}{\pi^2 b^4} \vec{a}_h \cos\left(\varphi_h - \varphi_b\right)$$

$\uparrow$

Factor 2 larger than Gluckstern. Same if $\mathrm{M_{cs}} \geq 3$ due to restoration of axi-symmetry, with M_{cs} number of holes per cross-section.

https://cds.cern.ch/record/222184/files/p1.pdf
https://cds.cern.ch/record/1120216/files/p167.pdf

A.Mostacci



Università degli Studi di Roma "La Sapienza"
Facoltà di Ingegneria
Dottorato in elettromagnetismo applicato e scienze elettrofisiche

Tesi di Dottorato

Beam-Wall interaction in the LHC liner

Candidato
Andrea Mostacci

- Hole impedance consider:
  - Hole itself
  - Forward TEM wave (FW)
  - Backward TEM wave (BW)
- Accounts for losses due to finite inner and outer pipes resistivity
- Computes shares of losses between pipes
- Resonant effect of many holes equally spaced
- Simplified formula for large number of holes and attenuation length larger than hole spacing:

Number of holes (longitudinally)

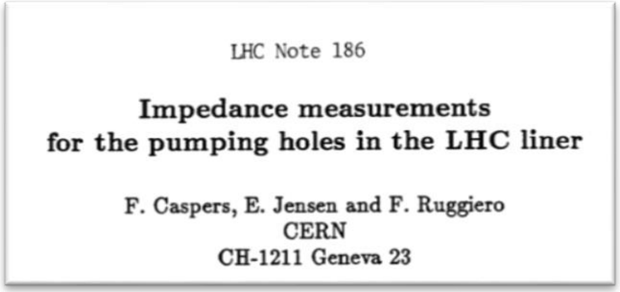
Attenuation length α

$$Z_{RE}(\omega) \simeq Z_0 \frac{\omega^2 (\alpha_m + \alpha_e)^2}{16\pi^3 b^4 \ln(d/b) c^2} \left[\underbrace{\frac{N}{2}}_{\text{Hole itself}} + \underbrace{\frac{N}{\alpha D}}_{\text{FW}} + \underbrace{\frac{e^{-\alpha D N} - 1}{(\alpha D)^2}}_{\text{BW}} \right]$$

Outer (coaxial) radius

Hole spacing D

Other theoretical works



LHC Note 186

Impedance measurements
for the pumping holes in the LHC liner

F. Caspers, E. Jensen and F. Ruggiero
CERN
CH-1211 Geneva 23

https://cds.cern.ch/record/236170/files/CM-P00062668.pdf

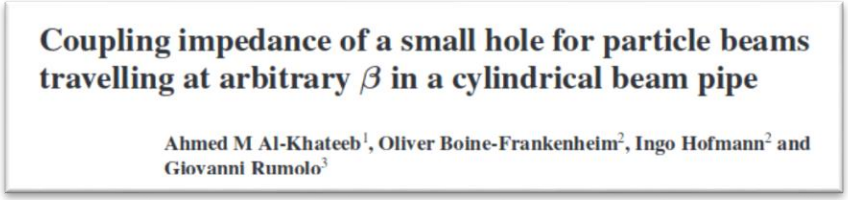
- Detailed power loss computation (accounting for the forward wave only)
- Agrees with A.Mostacci (real part)

Coupling impedance of a hole in a coaxial beam pipe

S. De Santis,[1,2] M. Migliorati,[2] L. Palumbo,[1,2,*] and M. Zobov[2]
[1]*Dipartimento di Energetica–University of Rome "La Sapienza," Rome, Italy*
[2]*INFN–Laboratori Nazionali di Frascati, Cassella Postale 13 00044 Frascati, Italy*
(Received 18 January 1996)

https://journals.aps.org/pre/pdf/10.1103/PhysRevE.54.800

- Any β (fields)
- Impedance accounting real and imaginary parts.
- Longitudinal and transverse
- Benchmarked with simulations.
- Agrees with S.Kurennoy (Imag part only).



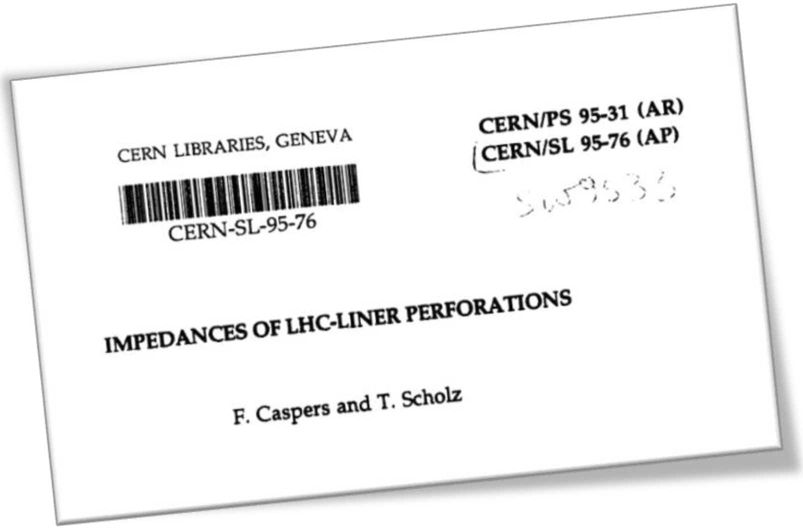
Coupling impedance of a small hole for particle beams travelling at arbitrary β in a cylindrical beam pipe

Ahmed M Al-Khateeb[1], Oliver Boine-Frankenheim[2], Ingo Hofmann[2] and Giovanni Rumolo[3]

- Impedance at any β

https://web-docs.gsi.de/~boine/pubs/ahmed2.pdf

A comprehensive review



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IMPEDANCES OF LHC-LINER PERFORATIONS

F. Caspers and T. Scholz

- Comprehensive revision work of available models
- Effect of different geometries (Kurennoy)
- Effect of hole position w.r.t. the beam (Kurennoy)
- Effect of hole thickness (Gluckstern)
- Real part of impedance (Kurennoy, Sands)
- Comparison with Mode Matching (Filtz)
- Leakage measurements (Caspers)
- Impedance above cutoff (Chou)

Effect of hole shape

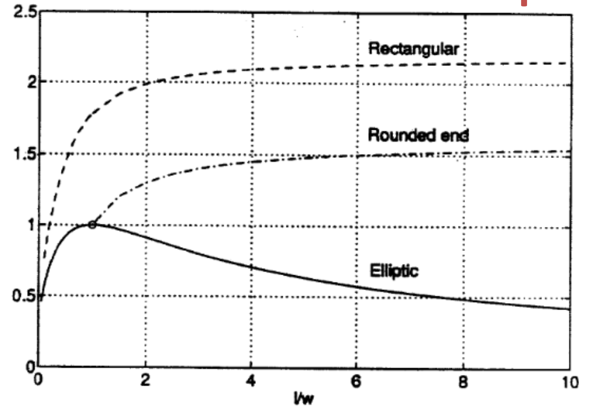
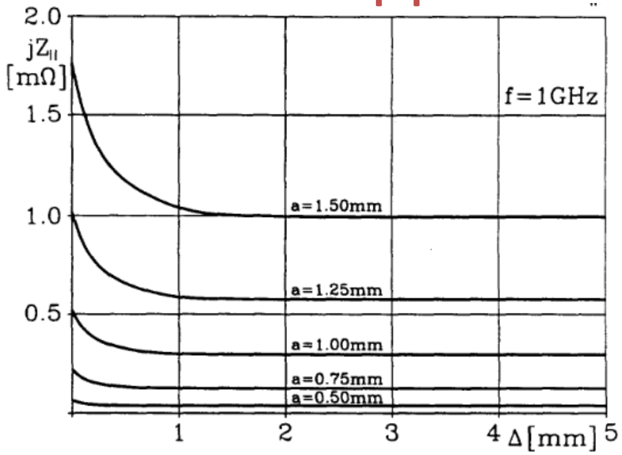


Fig.2: Impedance for several types of perforations as a function of length.

Effect of pipe thickness



https://cds.cern.ch/record/286107/files/sl-95-076.pdf

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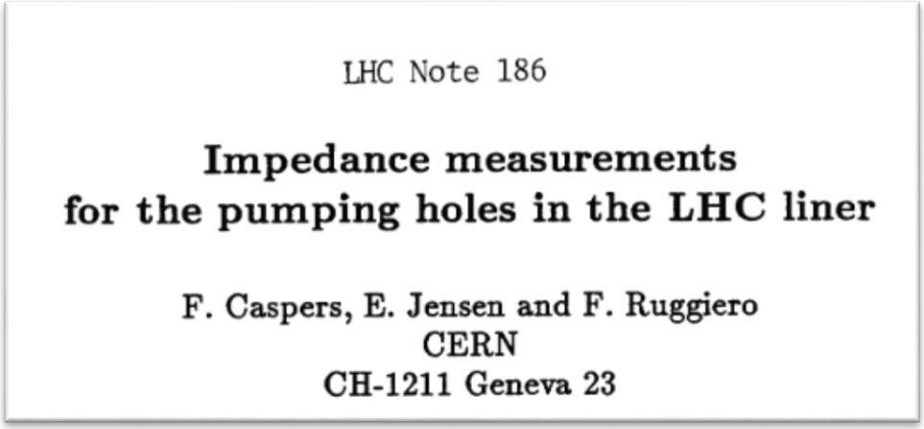
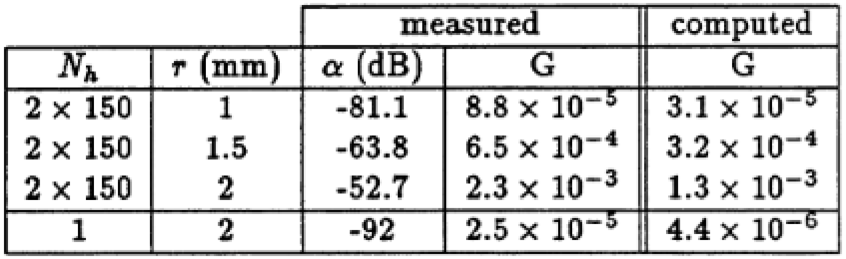
Triaxial wire measurements



LHC Note 186

Impedance measurements for the pumping holes in the LHC liner

F. Caspers, E. Jensen and F. Ruggiero
CERN
CH-1211 Geneva 23

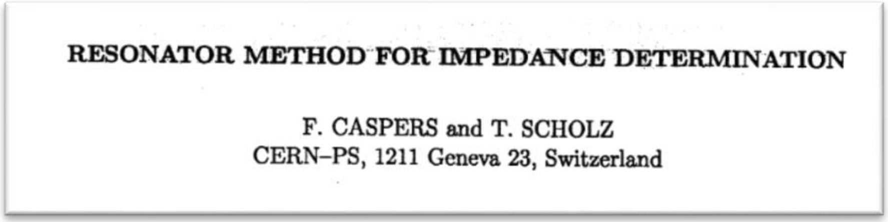


		measured		computed
N_h	r (mm)	α (dB)	G	G
2×150	1	-81.1	8.8×10^{-5}	3.1×10^{-5}
2×150	1.5	-63.8	6.5×10^{-4}	3.2×10^{-4}
2×150	2	-52.7	2.3×10^{-3}	1.3×10^{-3}
1	2	-92	2.5×10^{-5}	4.4×10^{-6}

- Performed transmission measurement on a LHC liner
- Triaxial wire method: forward transmission from a wire in the pipe to the outer coaxial
- Derives also an analytical formula for power loss in due to holes and TEM wave.
- Agreement with analytical formula within a factor 2 (150 holes).

https://cds.cern.ch/record/236170/files/CM-P00062668.pdf

Triaxial resonator measurements



RESONATOR METHOD FOR IMPEDANCE DETERMINATION

F. CASPERS and T. SCHOLZ
CERN–PS, 1211 Geneva 23, Switzerland

- TEM resonant wire method setup
- Higher accuracy measuring resonance frequency shift
- Good agreement with Kurennoy predictions accounting for:
    - Correction for hole thickness
    - Correction for field pattern

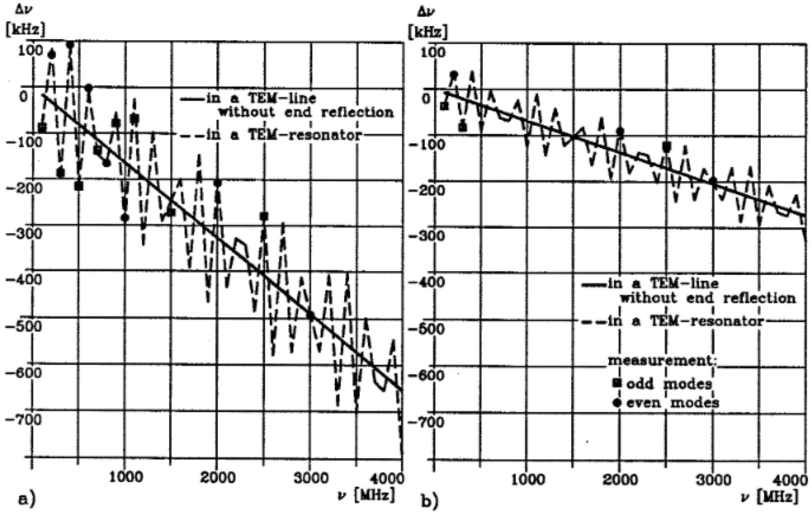


Figure 3: Frequency shift versus resonance frequency for 200 holes with (a) 4 mm diameter and (b) 3 mm diameter, calculation (dotted line) and measurement (points)

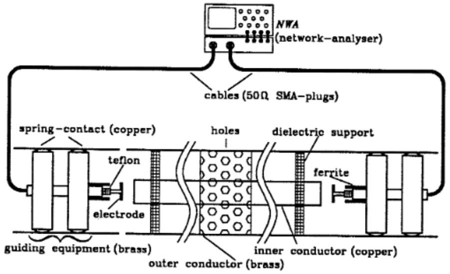


Figure 1: Experimental set-up for the resonator impedance measurement method

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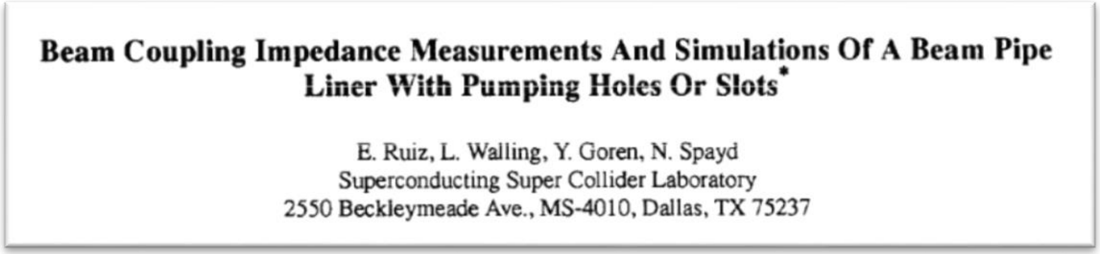
Wire measurements



Beam Coupling Impedance Measurements And Simulations Of A Beam Pipe Liner With Pumping Holes Or Slots*

E. Ruiz, L. Walling, Y. Goren, N. Spayd
Superconducting Super Collider Laboratory
2550 Beckleymeade Ave., MS-4010, Dallas, TX 75237

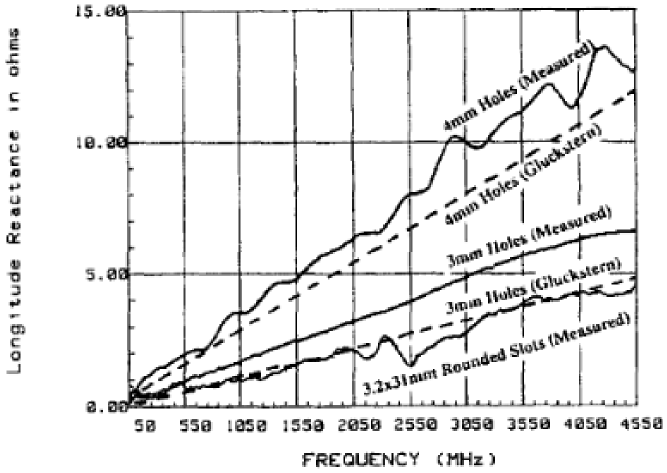


Figure 1. Measured Longitudinal Reactance of 1010 3 mm and 4 mm diameter holes and 160 rounded slots.

- Measured with classical stretched wire method
- Setup requires lot of skills as low impedance
- Good agreement between Gluckstern/Kurennoy and measurements, both longitudinal and transverse.
- Good agreement also with HFSS

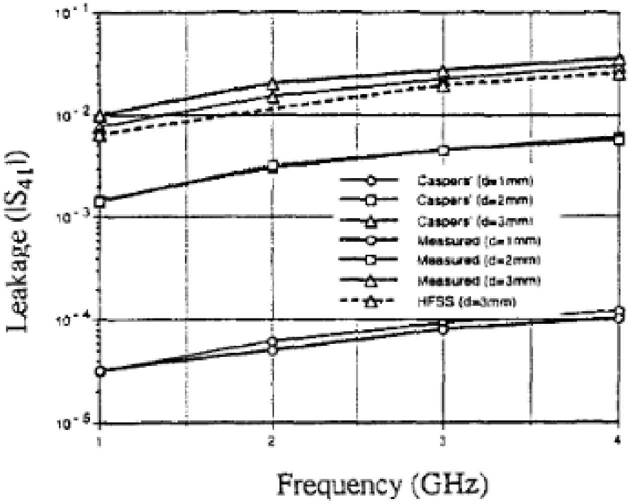


Figure 3. Leakage through a 1 mm thick liner with 1010 holes of various diameters.

https://accelconf.web.cern.ch/accelconf/p93/PDF/PAC1993_3405.PDF

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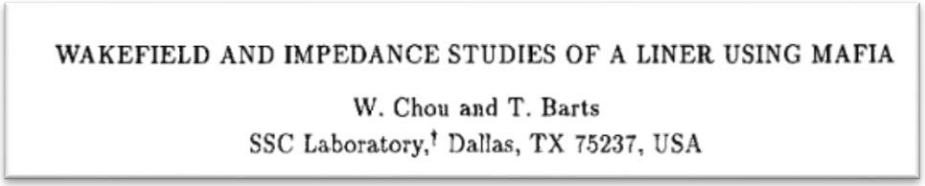
Simulations



WAKEFIELD AND IMPEDANCE STUDIES OF A LINER USING MAFIA

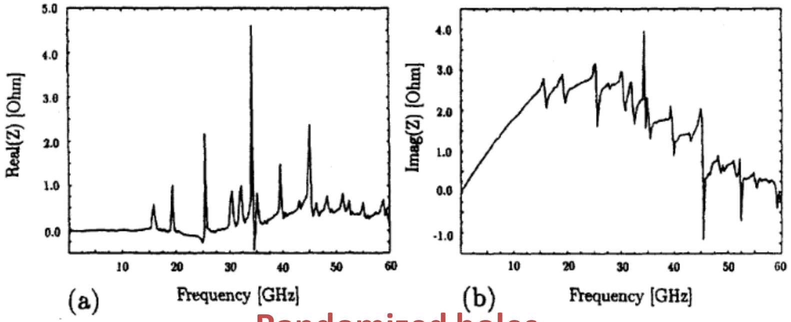
W. Chou and T. Barts

SSC Laboratory,† Dallas, TX 75237, USA

- MAFIA simulations (now CST).
- Good agreement with Kurennoy for small holes.
- Divergence for large hole dimension or short bunch length.
- Beneficial effect of randomization.

http://aip.scitation.org/doi/pdf/10.1063/1.45358

Series of holes



Randomized holes

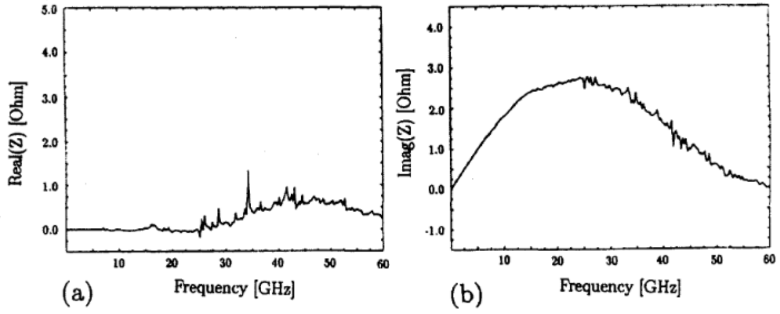


Fig. 23: Real part (23a) and imaginary part (23b) of the longitudinal impedance calculated with MAFIA for a randomised hole pattern.

MAFIA & Kurennoy

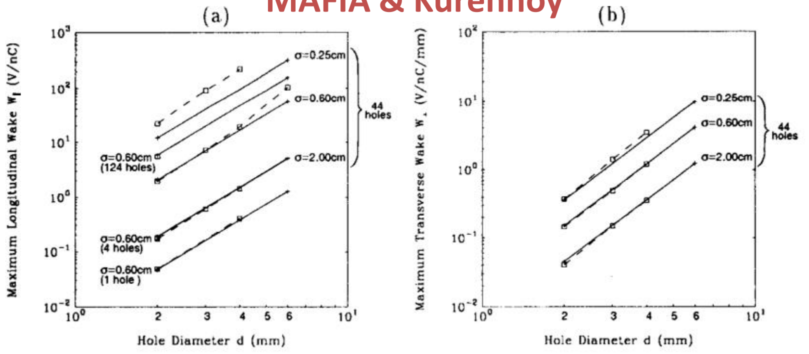


Figure 2: The peak values of the wake potentials of a liner. The solid lines are computed using Eqs. (13)-(14). The squares and dashed lines are the MAFIA results. (a) $w_\parallel^{max}$, (b) $w_\perp^{max}$.

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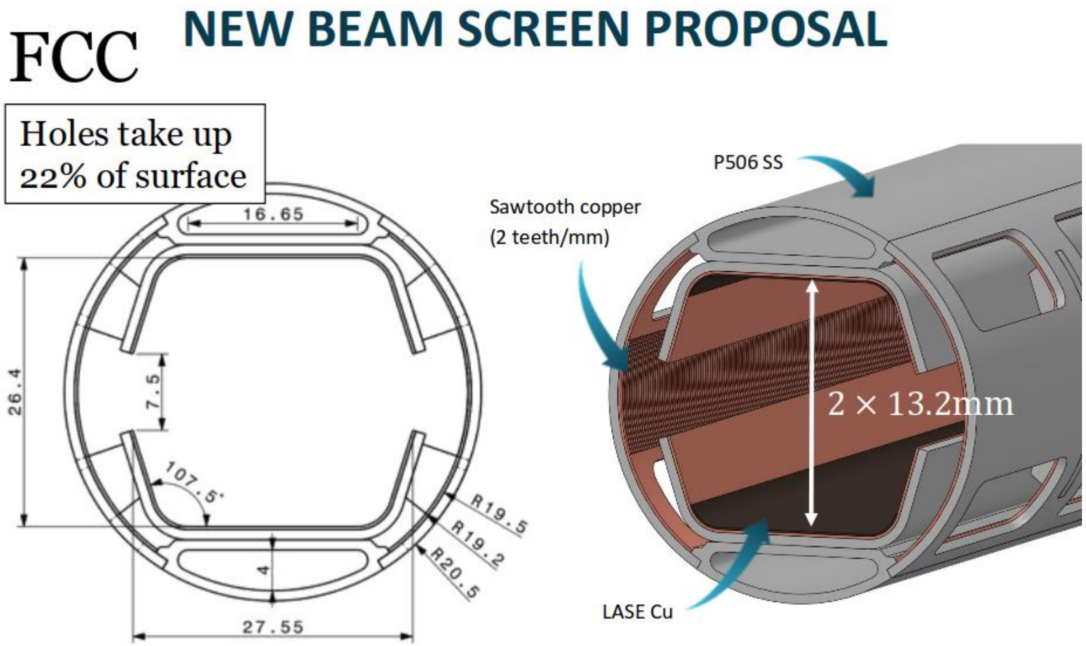
Simulations: FCC-hh case



FCC

NEW BEAM SCREEN PROPOSAL

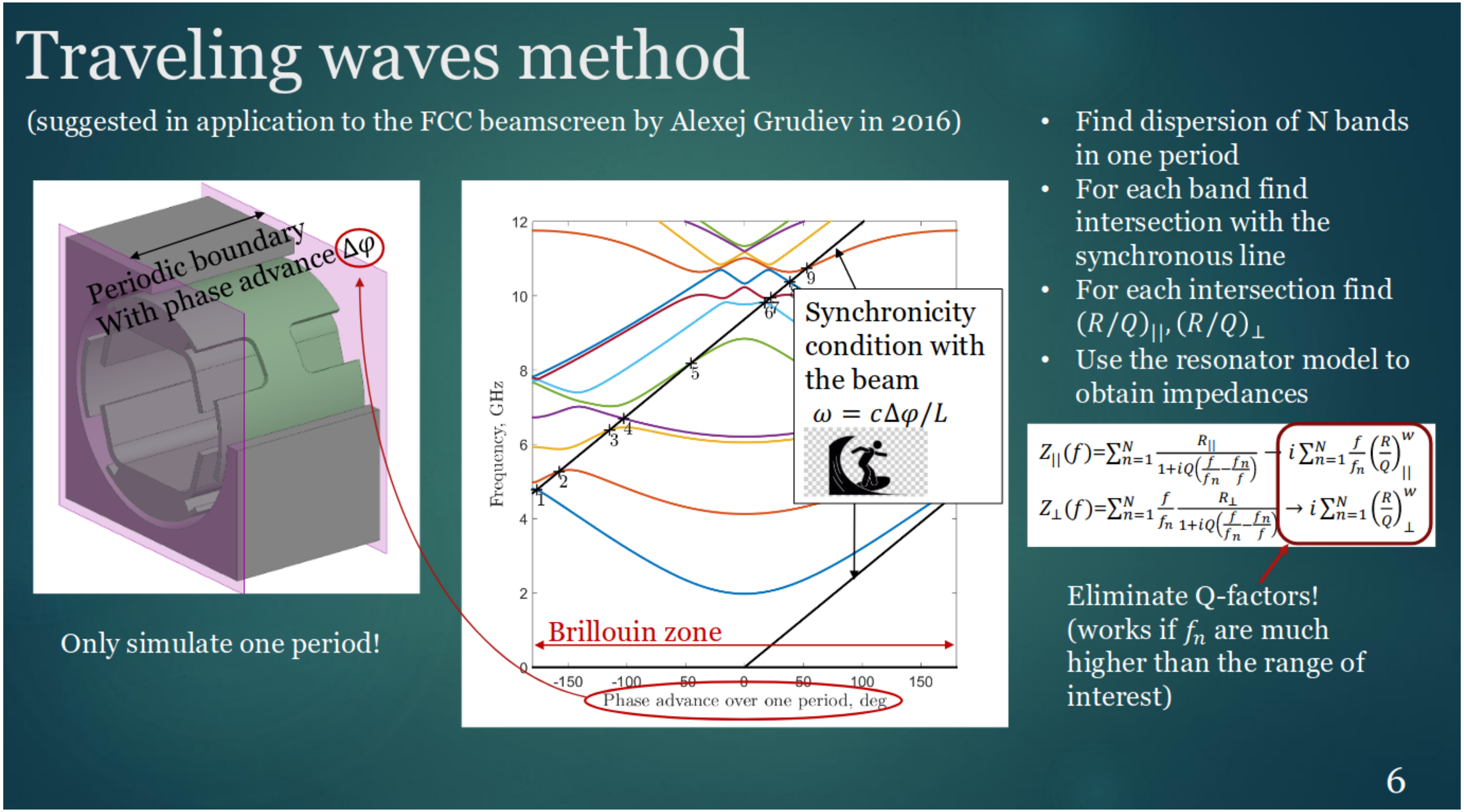
Holes take up 22% of surface

- FCC beam screen design (it is similar for HE-LHC)
- Impedance of holes needs to be quantified
- Not small (2.4 cm long) with respect to bunch length (7-8 cm rms)
- Studied by Sergey Arsenyev with Travelling Wave (TW) and Wakefield methods

https://indico.cern.ch/event/681147/contributions/2791137/attachments/1560105/2455602/FCC_pumping_holes_Design_Meeting.pdf

https://indico.cern.ch/event/677471/contributions/2773553/attachments/1552428/2439528/FCC_pumping_holes.pdf

Simulations: FCC-hh case



Traveling waves method

(suggested in application to the FCC beamscreen by Alexej Grudiev in 2016)

Only simulate one period!

Synchronicity condition with the beam

$\omega = c\Delta\varphi/L$

- Find dispersion of N bands in one period
- For each band find intersection with the synchronous line
- For each intersection find $(R/Q)_{||}, (R/Q)_{\perp}$
- Use the resonator model to obtain impedances

$$Z_{||}(f)=\sum_{n=1}^{N}\frac{R_{||}}{1+iQ\left(\frac{f}{f_n}-\frac{f_n}{f}\right)}\to \boxed{i\sum_{n=1}^{N}\frac{f}{f_n}\left(\frac{R}{Q}\right)_{||}^{w}}$$

$$Z_{\perp}(f)=\sum_{n=1}^{N}\frac{f}{f_n}\frac{R_{\perp}}{1+iQ\left(\frac{f}{f_n}-\frac{f_n}{f}\right)}\to \boxed{i\sum_{n=1}^{N}\left(\frac{R}{Q}\right)_{\perp}^{w}}$$

Eliminate Q-factors!
(works if f_n are much higher than the range of interest)

6

https://indico.cern.ch/event/681147/contributions/2791137/attachments/1560105/2455602/FCC_pumping_holes_Design_Meeting.pdf

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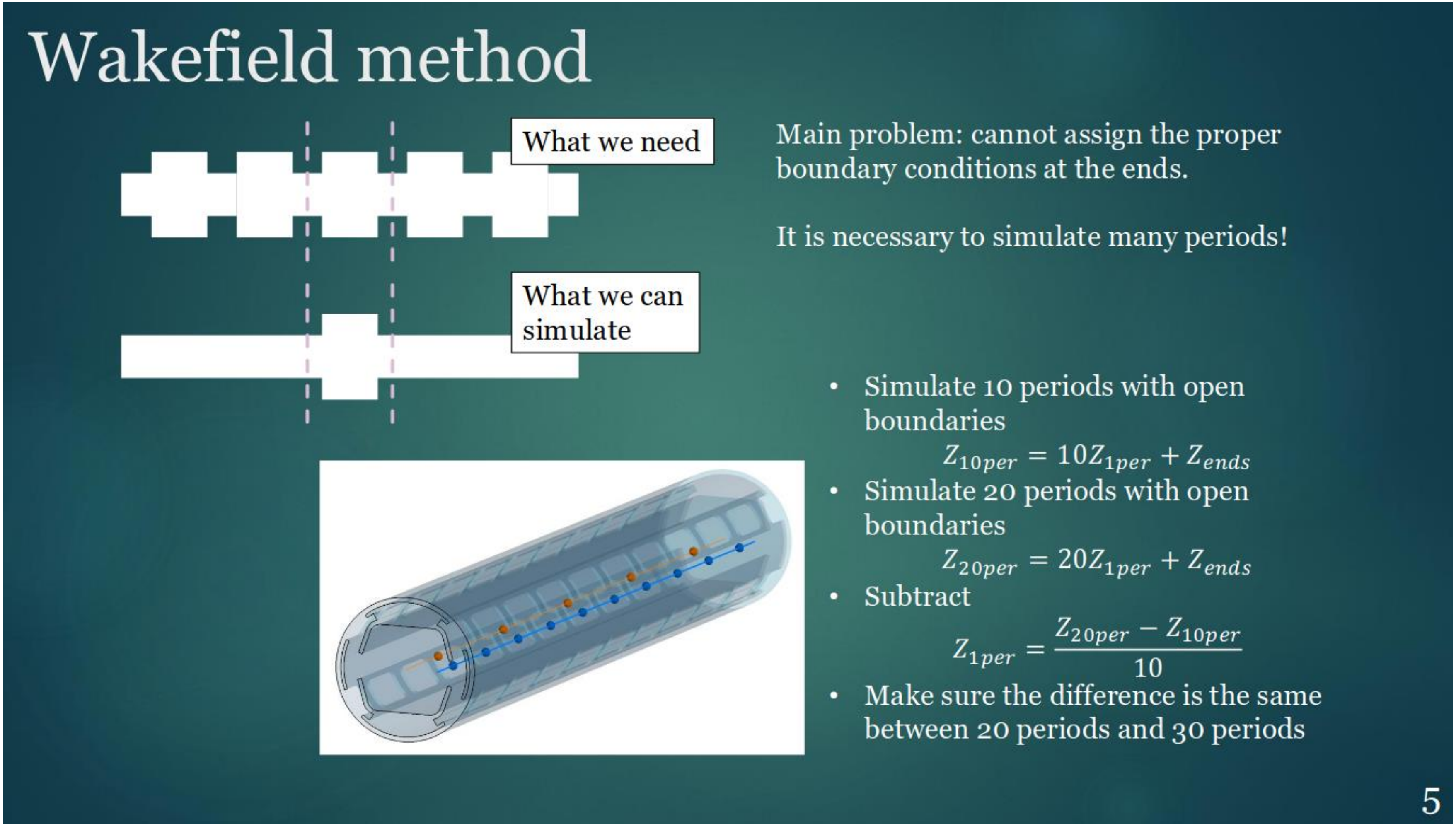
Simulations: FCC-hh case



Wakefield method

What we need

What we can simulate

Main problem: cannot assign the proper boundary conditions at the ends.

It is necessary to simulate many periods!

- Simulate 10 periods with open boundaries

$$Z_{10per} = 10Z_{1per} + Z_{ends}$$

- Simulate 20 periods with open boundaries

$$Z_{20per} = 20Z_{1per} + Z_{ends}$$

- Subtract

$$Z_{1per} = \frac{Z_{20per} - Z_{10per}}{10}$$

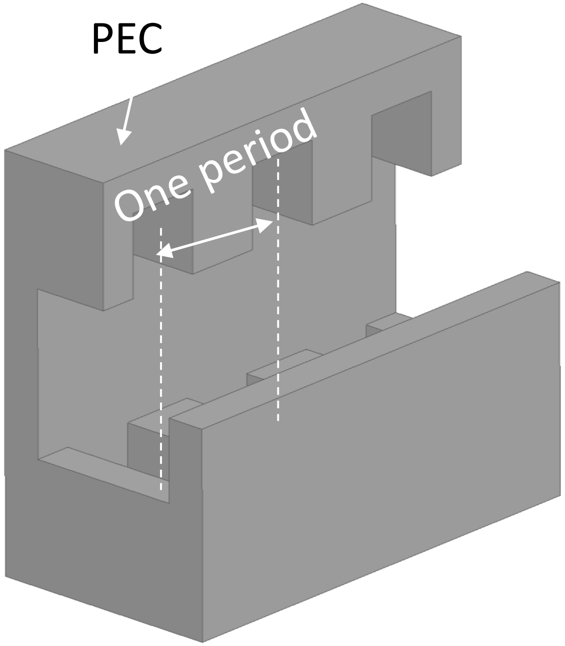
- Make sure the difference is the same between 20 periods and 30 periods

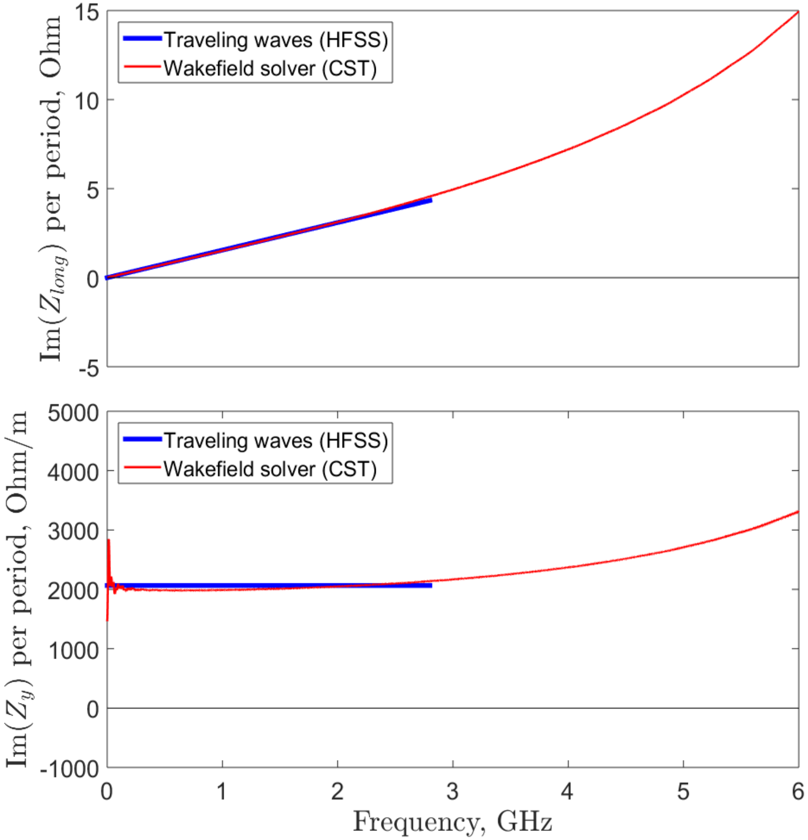
5

https://indico.cern.ch/event/681147/contributions/2791137/attachments/1560105/2455602/FCC_pumping_holes_Design_Meeting.pdf

https://indico.cern.ch/event/677471/contributions/2773553/attachments/1552428/2439528/FCC_pumping_holes.pdf

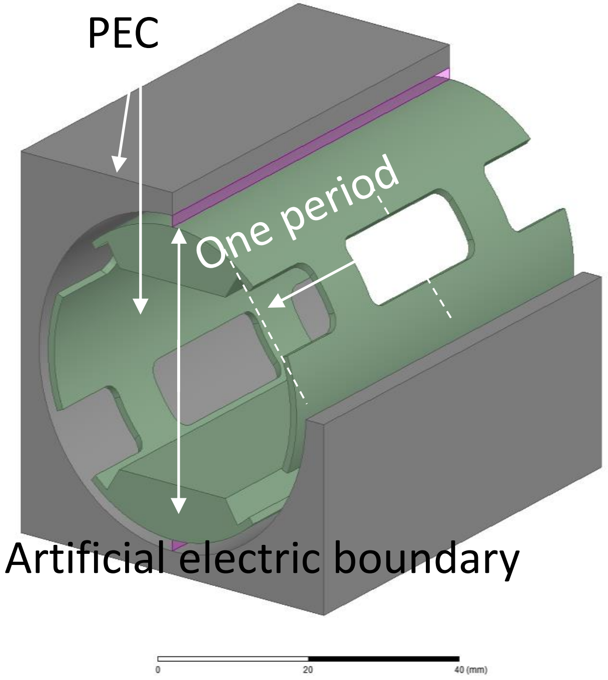
Benchmarking: Rectangular bellows (no TEM mode)

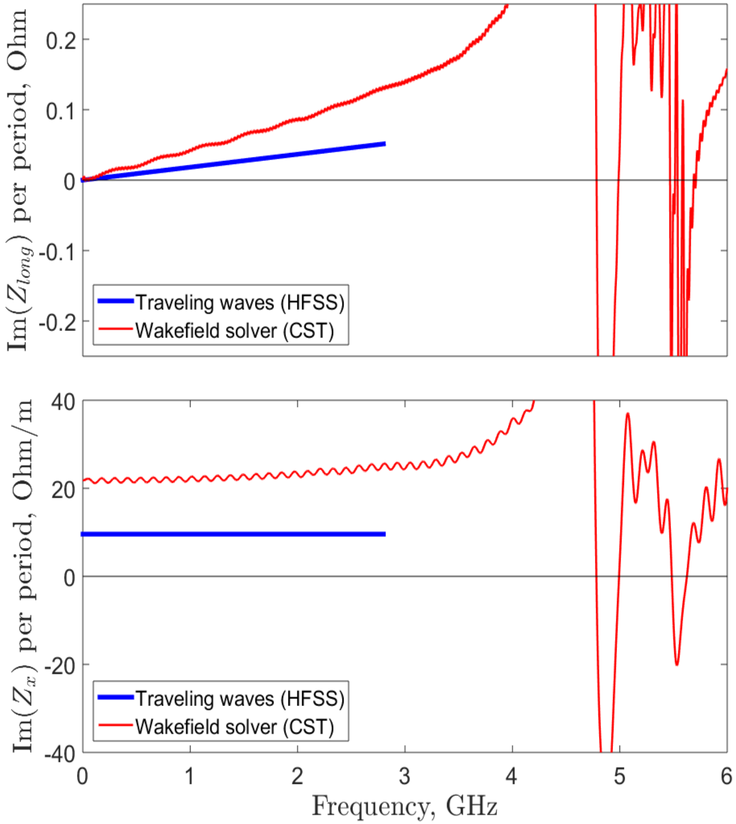




- Simple bellow structure
- Good agreement between wakefield and travelling wave methods
- No TEM propagation

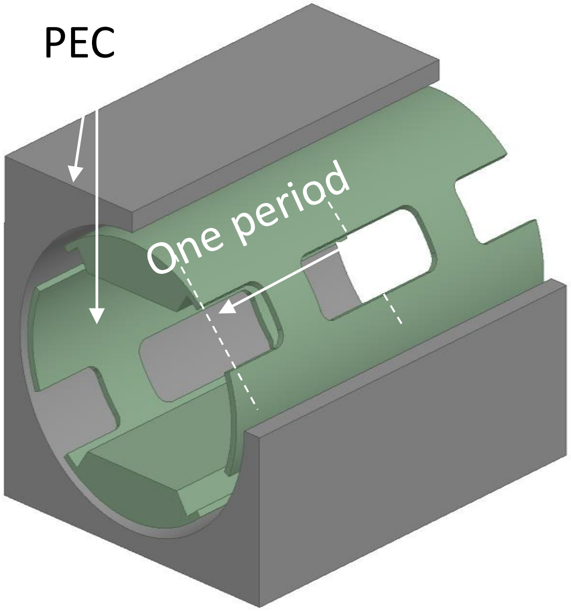
Benchmarking: FCC beam screen with no shielding (no TEM mode)

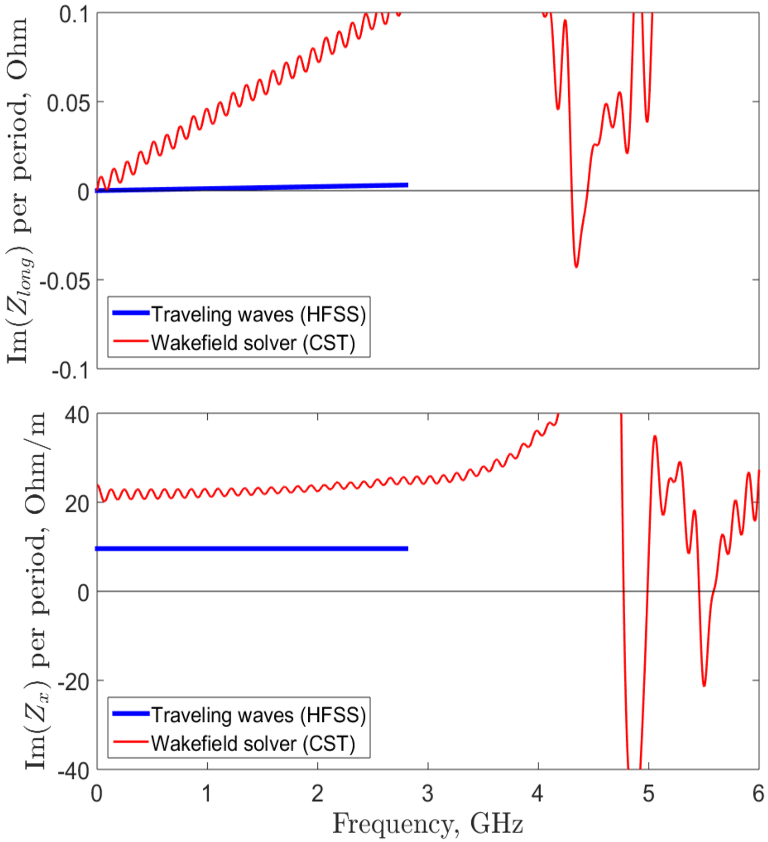




- FCC-hh beam screen
- Artificial electric boundary avoids TEM waves to propagate
- Factor 2 disagreement between wakefield and travelling wave methods

Benchmarking: FCC beam screen with no shielding (with TEM mode)

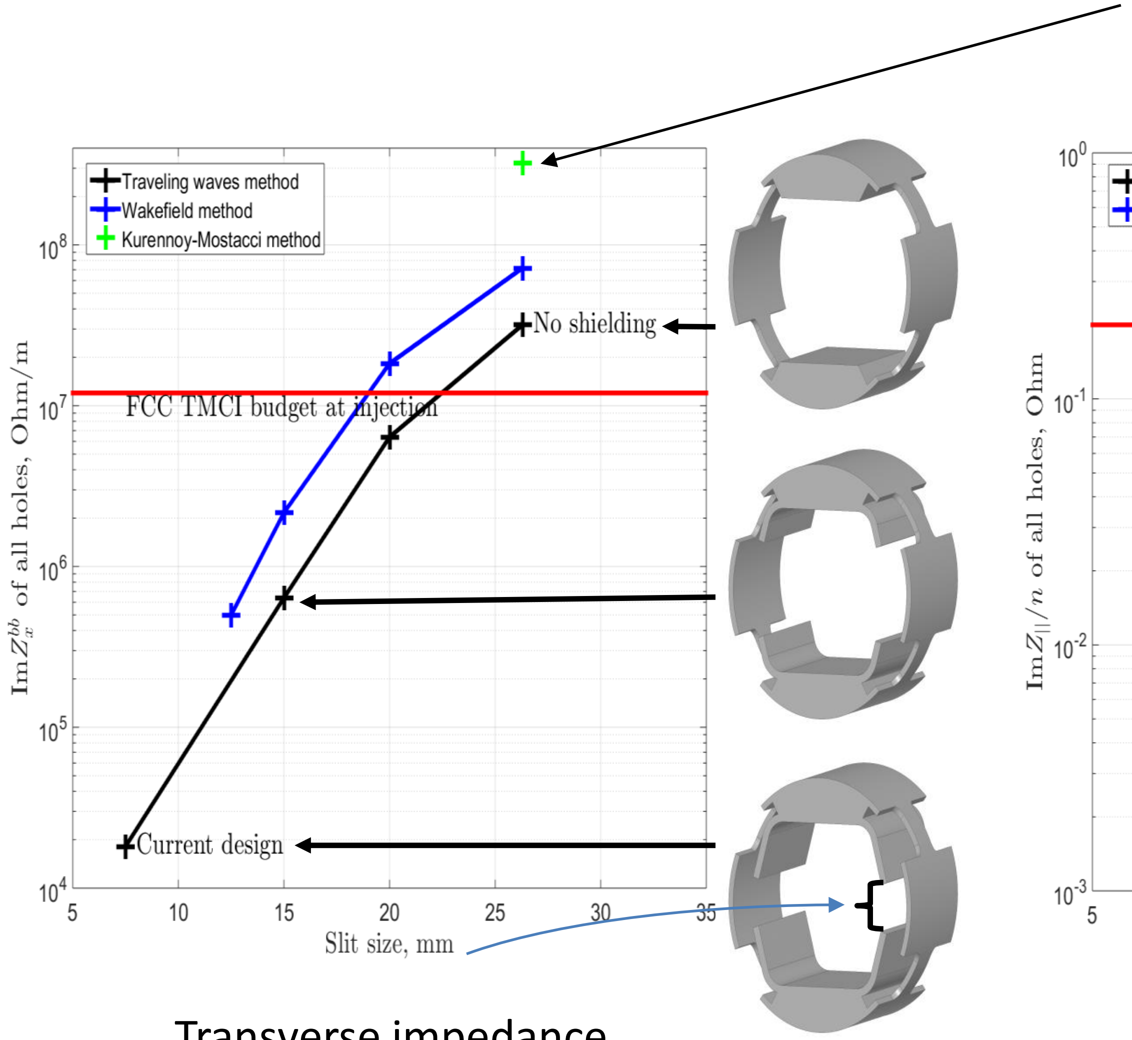




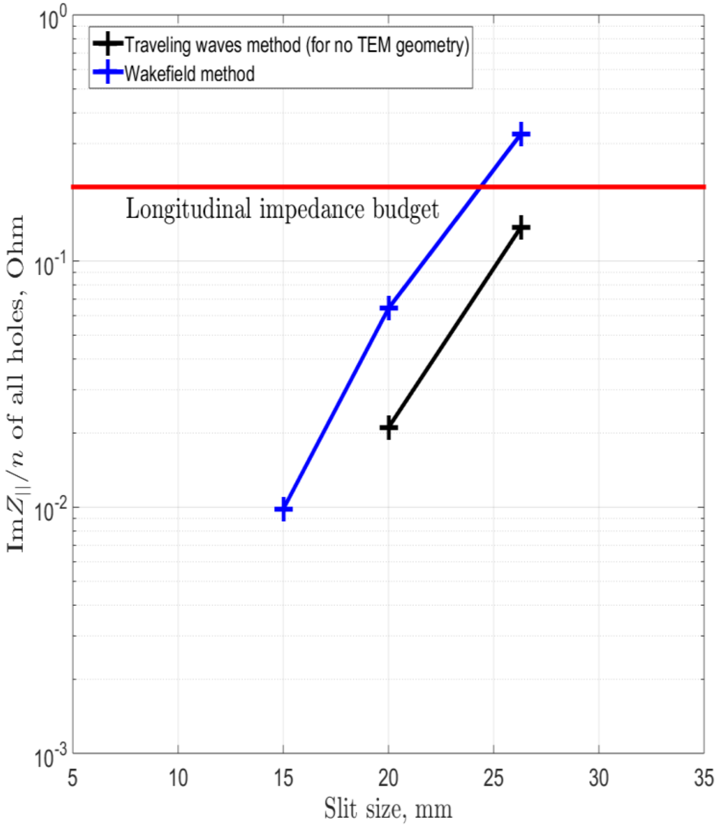
- FCC-hh beam screen
- TEM can propagate
- Large disagreement between wakefield and travelling wave methods
- To be checked the travelling wave method with better resonator model from G. Dome, tech. report SPS,ARF/77-11 as we are above cut off.

Estimates for FCC (so far)

Analytical estimate (Kurennoy-Mostacci) can only be applied to unshielded holes and is wrong (holes are not small)



Transverse impedance



Longitudinal impedance

- Screening is very effective at reducing impedance
- The present design looks safe, but disagreements remain

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The LHC impedance model

- Design report:
  - Computed with Gluckstern formula 0.5 $M\Omega/m$

$$\frac{Z_{\|}(k)}{Z_0} = \frac{jk}{8\pi^2 b^2}(\psi_{\text{in}} - \chi_{\text{in}})P,$$

$$Z_{\perp} = \frac{Z_{\|}}{n}\frac{2R}{b^2},$$

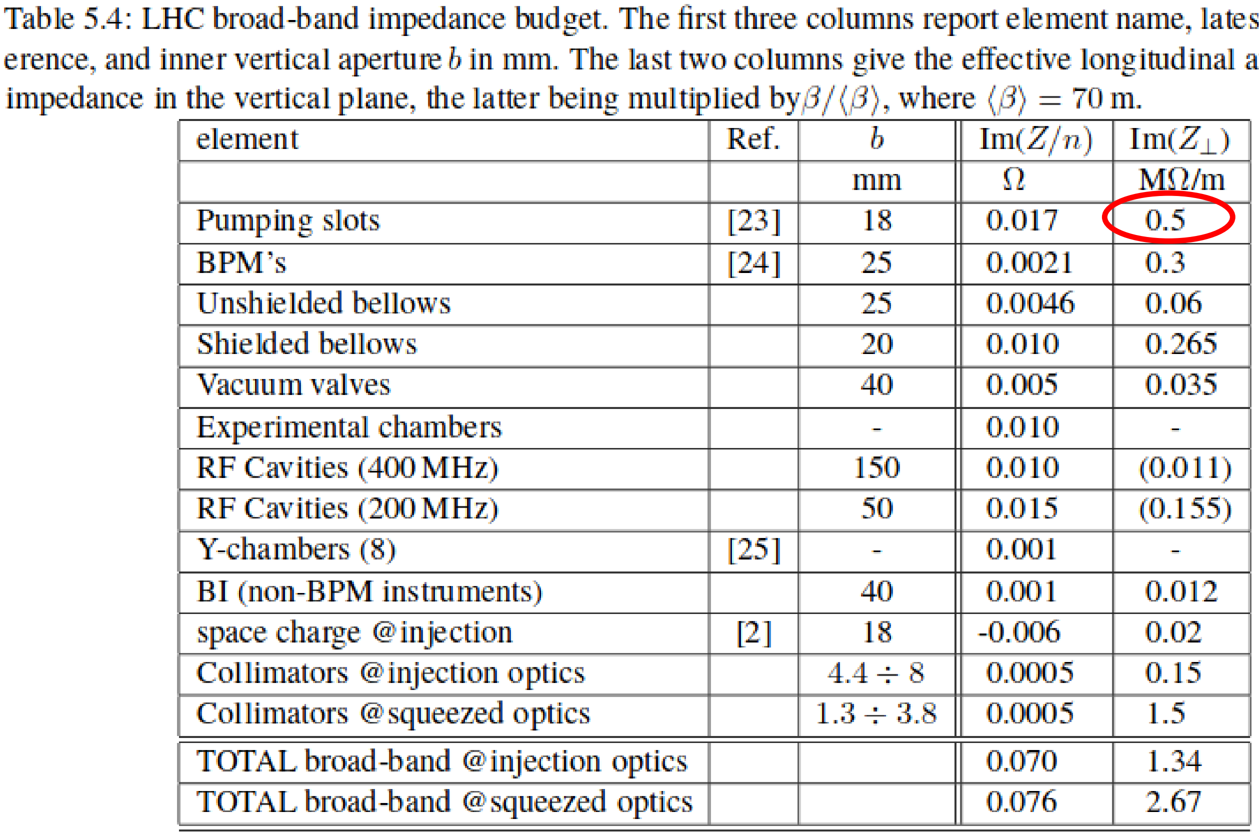


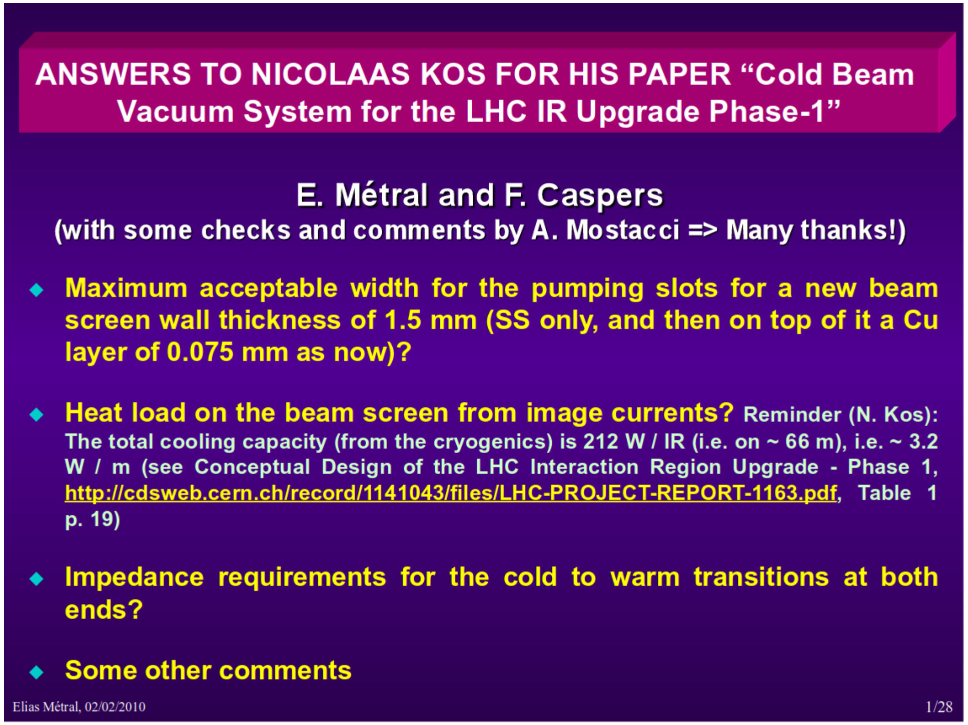
Table 5.4: LHC broad-band impedance budget. The first three columns report element name, latest relevant reference, and inner vertical aperture b in mm. The last two columns give the effective longitudinal and transverse impedance in the vertical plane, the latter being multiplied by $\beta/\langle\beta\rangle$, where $\langle\beta\rangle = 70$ m.

element	Ref.	b	$\mathrm{Im}(Z/n)$	$\mathrm{Im}(Z_{\perp})$
		mm	Ω	MΩ/m
Pumping slots	[23]	18	0.017	0.5
BPM's	[24]	25	0.0021	0.3
Unshielded bellows		25	0.0046	0.06
Shielded bellows		20	0.010	0.265
Vacuum valves		40	0.005	0.035
Experimental chambers		-	0.010	-
RF Cavities (400 MHz)		150	0.010	(0.011)
RF Cavities (200 MHz)		50	0.015	(0.155)
Y-chambers (8)	[25]	-	0.001	-
BI (non-BPM instruments)		40	0.001	0.012
space charge @injection	[2]	18	-0.006	0.02
Collimators @injection optics		$4.4 \div 8$	0.0005	0.15
Collimators @squeezed optics		$1.3 \div 3.8$	0.0005	1.5
TOTAL broad-band @injection optics			0.070	1.34
TOTAL broad-band @squeezed optics			0.076	2.67

http://inspirehep.net/record/656250

The LHC impedance model

- Design report:
  - Computed with **Gluckstern formula: 0.5 $M\Omega/m$**
- Update from N.Kos (E.Métral and F.Caspers) with new beam screen specifications.



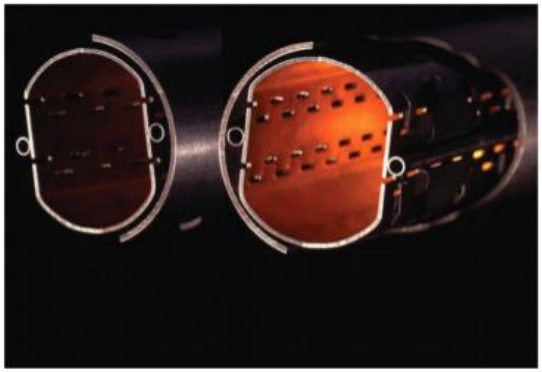
ANSWERS TO NICOLAAS KOS FOR HIS PAPER “Cold Beam Vacuum System for the LHC IR Upgrade Phase-1”

E. Métral and F. Caspers

(with some checks and comments by A. Mostacci => Many thanks!)

- Maximum acceptable width for the pumping slots for a new beam screen wall thickness of 1.5 mm (SS only, and then on top of it a Cu layer of 0.075 mm as now)?
- Heat load on the beam screen from image currents? Reminder (N. Kos): The total cooling capacity (from the cryogenics) is 212 W / IR (i.e. on ~ 66 m), i.e. ~ 3.2 W / m (see Conceptual Design of the LHC Interaction Region Upgrade - Phase 1, http://cdsweb.cern.ch/record/1141043/files/LHC-PROJECT-REPORT-1163.pdf, Table 1 p. 19)
- Impedance requirements for the cold to warm transitions at both ends?
- Some other comments

Elias Métral, 02/02/2010 1/28



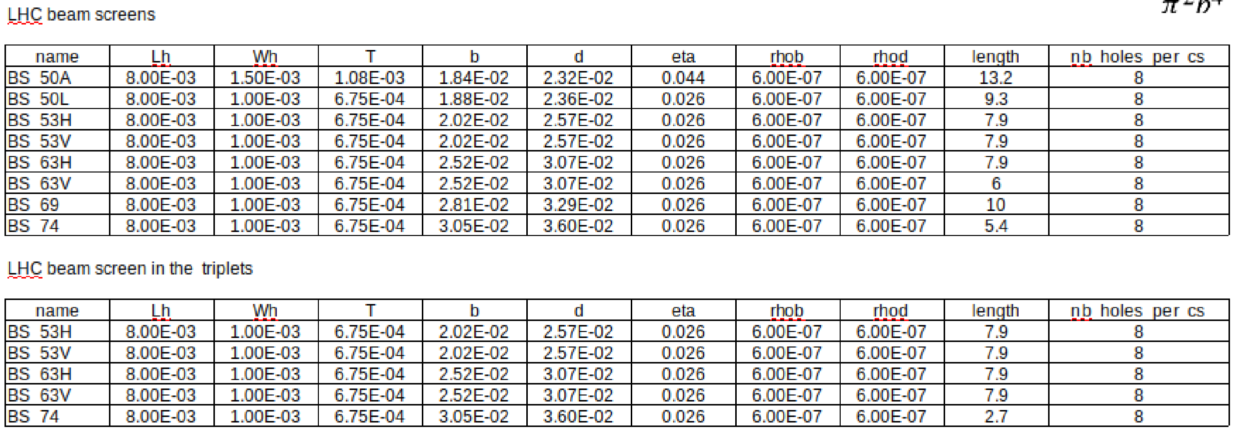
Updated with respect to power loss considerations.

http://impedance.web.cern.ch/impedance/LHC/PumpingSlots_AnswersToNicolaasKos_Final.pdf

The LHC impedance model

- Design report:
  - Computed with Gluckstern formula 0.5 $M\Omega/m$
- Update from N.Kos (E.Métral and F.Caspers) with new beam screen specifications.
- Now in the LHC impedance model (N.Mounet, B.Salvant): **1.8 $M\Omega/m$** computed with **Kurennoy's formula** (not accounting for axi-symmetry factor 2 reduction, maybe a bit pessimistic)

$$\vec{Z}_{\perp}(\omega) = -i Z_0 \frac{\alpha_m + \alpha_e}{\pi^2 b^4} \vec{a}_h \cos(\varphi_h - \varphi_b)$$



LHC beam screens

name	Lh	Wh	T	b	d	eta	rhob	rhod	length	nb holes per cs
BS 50A	8.00E-03	1.50E-03	1.08E-03	1.84E-02	2.32E-02	0.044	6.00E-07	6.00E-07	13.2	8
BS 50L	8.00E-03	1.00E-03	6.75E-04	1.88E-02	2.36E-02	0.026	6.00E-07	6.00E-07	9.3	8
BS 53H	8.00E-03	1.00E-03	6.75E-04	2.02E-02	2.57E-02	0.026	6.00E-07	6.00E-07	7.9	8
BS 53V	8.00E-03	1.00E-03	6.75E-04	2.02E-02	2.57E-02	0.026	6.00E-07	6.00E-07	7.9	8
BS 63H	8.00E-03	1.00E-03	6.75E-04	2.52E-02	3.07E-02	0.026	6.00E-07	6.00E-07	7.9	8
BS 63V	8.00E-03	1.00E-03	6.75E-04	2.52E-02	3.07E-02	0.026	6.00E-07	6.00E-07	6	8
BS 69	8.00E-03	1.00E-03	6.75E-04	2.81E-02	3.29E-02	0.026	6.00E-07	6.00E-07	10	8
BS 74	8.00E-03	1.00E-03	6.75E-04	3.05E-02	3.60E-02	0.026	6.00E-07	6.00E-07	5.4	8

LHC beam screen in the triplets

name	Lh	Wh	T	b	d	eta	rhob	rhod	length	nb holes per cs
BS 53H	8.00E-03	1.00E-03	6.75E-04	2.02E-02	2.57E-02	0.026	6.00E-07	6.00E-07	7.9	8
BS 53V	8.00E-03	1.00E-03	6.75E-04	2.02E-02	2.57E-02	0.026	6.00E-07	6.00E-07	7.9	8
BS 63H	8.00E-03	1.00E-03	6.75E-04	2.52E-02	3.07E-02	0.026	6.00E-07	6.00E-07	7.9	8
BS 63V	8.00E-03	1.00E-03	6.75E-04	2.52E-02	3.07E-02	0.026	6.00E-07	6.00E-07	7.9	8
BS 74	8.00E-03	1.00E-03	6.75E-04	3.05E-02	3.60E-02	0.026	6.00E-07	6.00E-07	2.7	8

Beam screen

Length hole

Width hole

Thickness

Pipe radius

Cold bore radius

Hole surface %

Pipe resistivity

Cold bore resistivity

Length of segment

Number of holes per cross section

https://gitlab.cern.ch/IRIS/LHC_IW_model

The LHC impedance model

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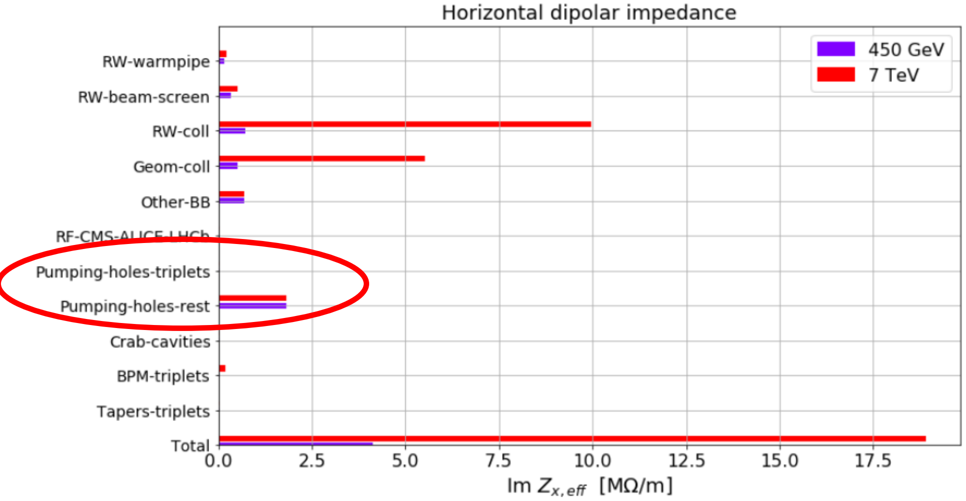

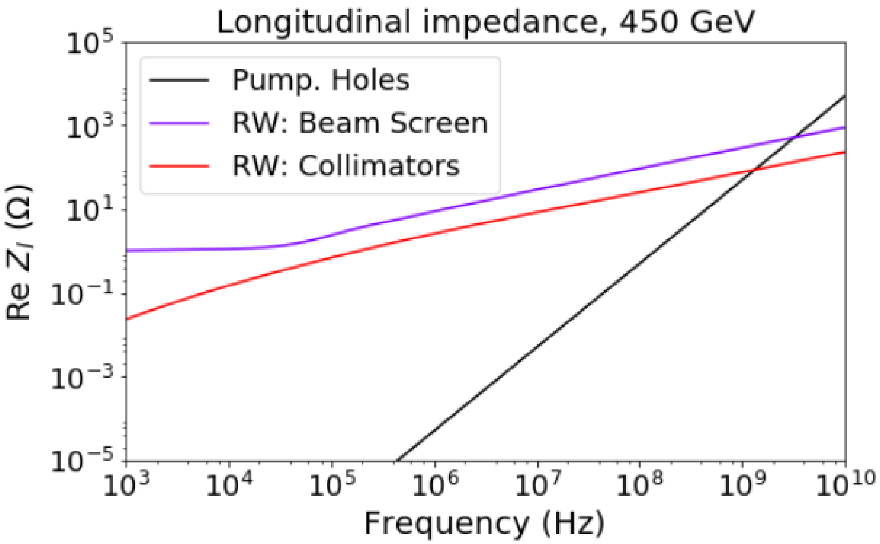

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- Now in the LHC impedance model (N.Mounet, B.Salvant): 1.8 $M\Omega/m$
- Implementation:
  - Longitudinal impedance:
    - Compute Re(Zlong) with A.Mostacci simplified formula
    - Add Kurennoy resonator impedance: seems a pessimistic approach as adds another real part to the longitudinal impedance.
  - Longitudinal wake:
    - Computed with Kurennoy: resonator model.
  - Transverse impedance
    - Compute the impedance with Kurennoy's formula: resonator model.
  - Transverse wake:
    - Compute the impedance with Kurennoy's formula: resonator model.

https://gitlab.cern.ch/IRIS/LHC_IW_model

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  - Longitudinal wake:
    - Computed with Kurennoy: resonator model.
  - Transverse impedance
    - Compute the impedance with Kurennoy's formula: resonator model.
  - Transverse wake:
    - Compute the impedance with Kurennoy's formula: resonator model.
- Same computation method applied to the HL-LHC

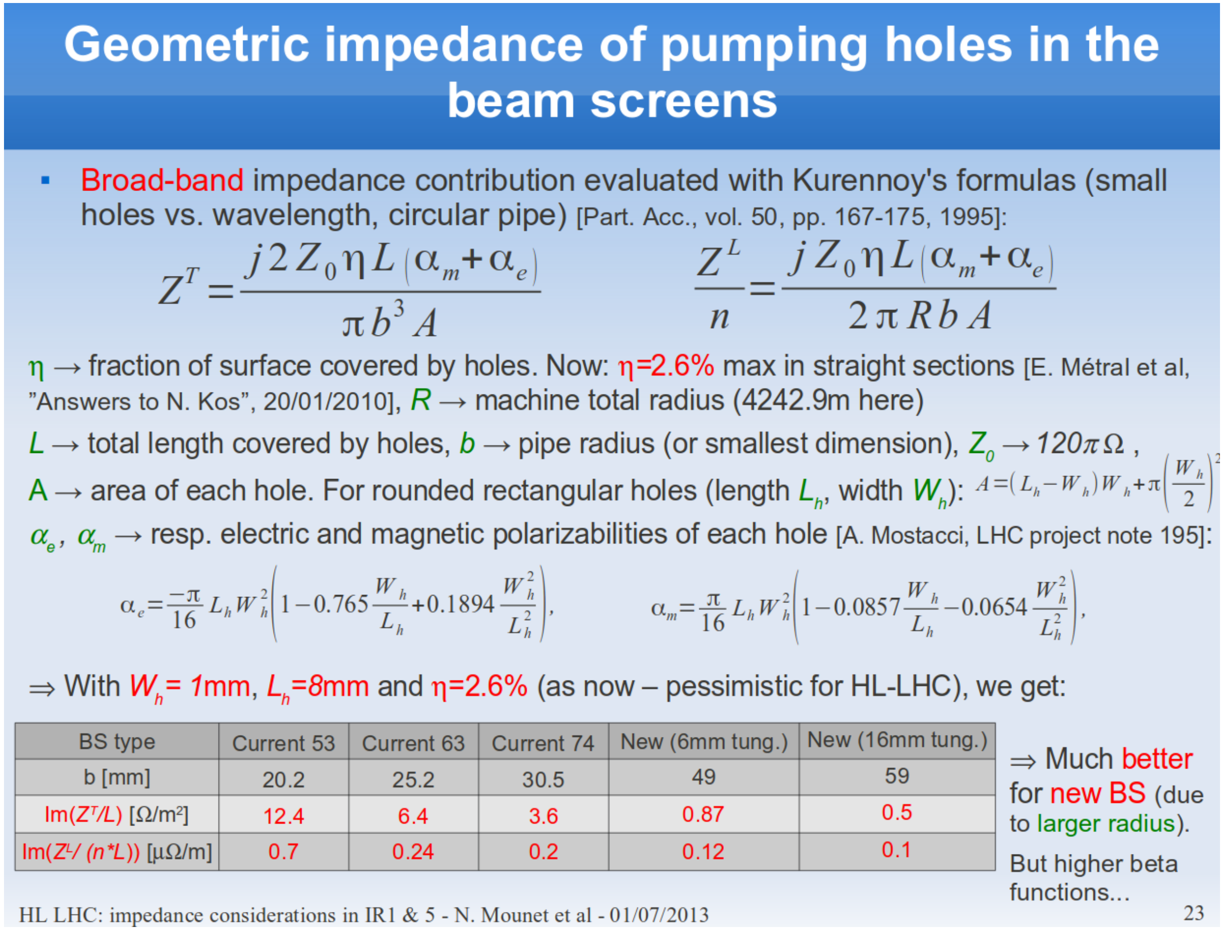
https://gitlab.cern.ch/IRIS/LHC_IW_model

Outline

- Theoretical models
- Measurements
- Simulations
  - FCC-hh
  - LHC
  - HL-LHC
- Summary and future work

HL-LHC holes in the triplets

- Updated by N. Mounet (and others)
- Accounts for larger beam screen radius.
- Simulations with CST performed on octogonal shape (F.Riminucci)



Geometric impedance of pumping holes in the beam screens

- Broad-band impedance contribution evaluated with Kurennoy's formulas (small holes vs. wavelength, circular pipe) [Part. Acc., vol. 50, pp. 167-175, 1995]:

$$Z^T = \frac{j 2 Z_0 \eta L (\alpha_m + \alpha_e)}{\pi b^3 A} \qquad \frac{Z^L}{n} = \frac{j Z_0 \eta L (\alpha_m + \alpha_e)}{2 \pi R b A}$$

η → fraction of surface covered by holes. Now: η=2.6% max in straight sections [E. Métral et al, "Answers to N. Kos", 20/01/2010], R → machine total radius (4242.9m here)

L → total length covered by holes, b → pipe radius (or smallest dimension), $Z_0 \rightarrow 120\pi\Omega$,

A → area of each hole. For rounded rectangular holes (length L_h, width W_h): $A=(L_h-W_h)W_h+\pi\left(\frac{W_h}{2}\right)^2$

α_e, α_m → resp. electric and magnetic polarizabilities of each hole [A. Mostacci, LHC project note 195]:

$$\alpha_e = \frac{-\pi}{16} L_h W_h^2 \left(1 - 0.765 \frac{W_h}{L_h} + 0.1894 \frac{W_h^2}{L_h^2}\right), \qquad \alpha_m = \frac{\pi}{16} L_h W_h^2 \left(1 - 0.0857 \frac{W_h}{L_h} - 0.0654 \frac{W_h^2}{L_h^2}\right),$$

⇒ With W_h= 1mm, L_h=8mm and η=2.6% (as now – pessimistic for HL-LHC), we get:

BS type	Current 53	Current 63	Current 74	New (6mm tung.)	New (16mm tung.)
b [mm]	20.2	25.2	30.5	49	59
Im(Z^T/L) [Ω/m²]	12.4	6.4	3.6	0.87	0.5
Im($Z^L/(n*L)$) [μΩ/m]	0.7	0.24	0.2	0.12	0.1

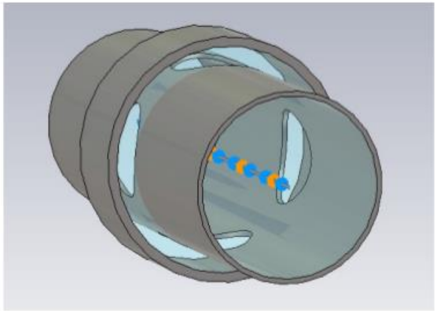
⇒ Much better for new BS (due to larger radius).

But higher beta functions...

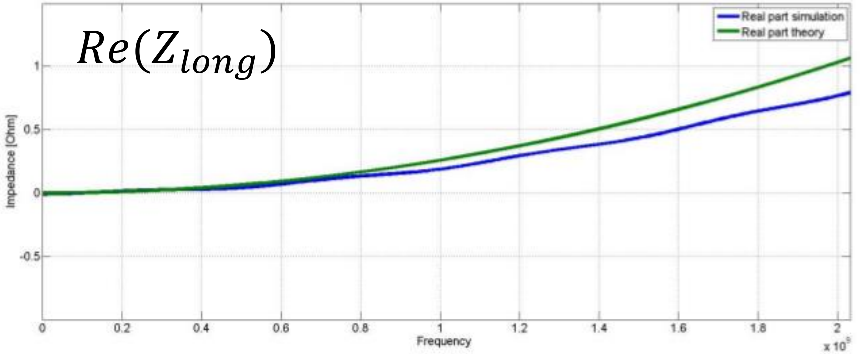
HL LHC: impedance considerations in IR1 & 5 - N. Mounet et al - 01/07/2013 23

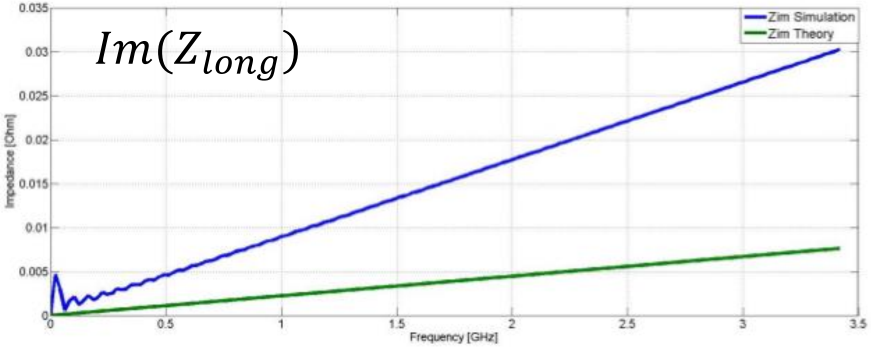
https://impedance.web.cern.ch/impedance/documents/BeamScreens_IR1_IR5_HLLHC-expanded.pdf

Holes simulations in CST (F.Riminucci)



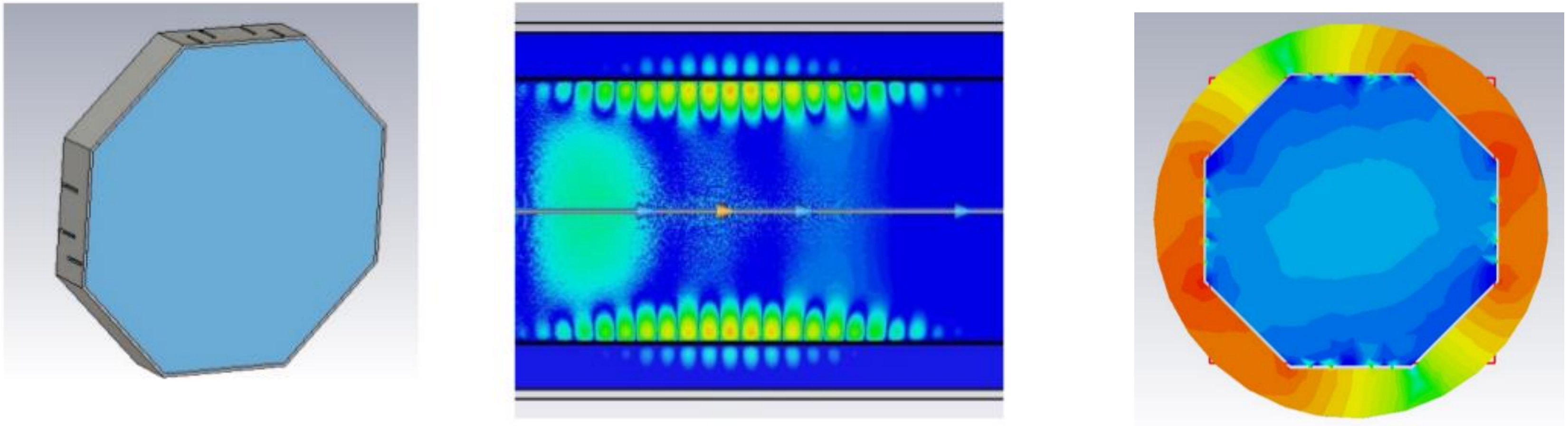
- Master thesis on impact of holes on HL-LHC impedance
- Studied the updated triplet region beam screen geometry
- Basic checks performed:
    - Good agreement with A.Mostacci formula for real part.
    - Factor 4 disagreement in imaginary part
- Reason not clear (large holes?): to be investigated further.





Holes simulations in CST (F.Riminucci)

- Master thesis on impact of holes on HL-LHC impedance
- Studied the updated triplet region beam screen geometry
- Basic checks performed:
  - Good agreement with A.Mostacci formula for real part.
  - Factor 4 disagreement in imaginary part
- Reason not clear (large holes?): to be investigated further.
- Simulations of octogonal beam screen performed
- Impact of high order modes studies and quantified.



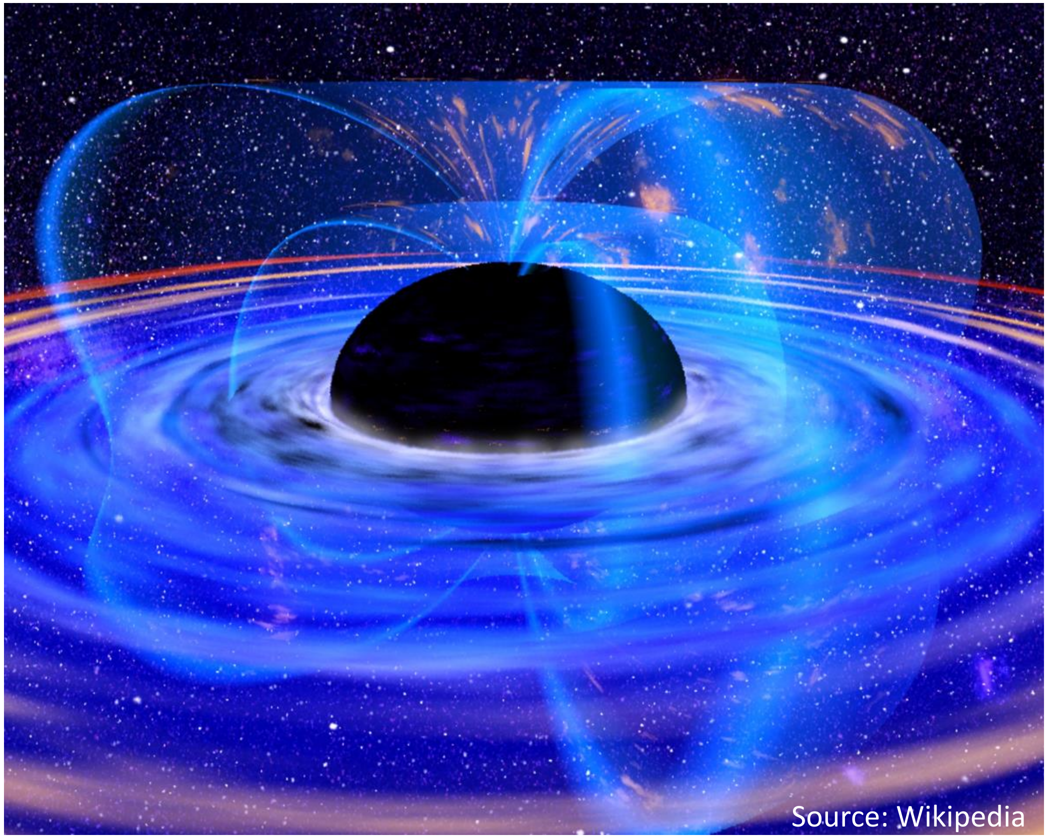
Outline

- Theoretical models
- Measurements
- Simulations
  - FCC-hh
  - LHC
  - HL-LHC
- Summary and future work

Summary and next steps

- Lot of work done during the last decades
- Both **simulations** and **measurements** performed are in **agreement** (or within factor 2) **with expectations**.
- **Impact of small holes** with respect to wavelength **is well covered by theoretical models** (OK for LHC, HL-LHC beam screens).
- Addressed also (but not covered here**): trapped modes, higher order propagating modes** in the coaxial regions -> might be **important second order effects**, not to be forgotten!
- **Large holes impedance** mainly **assessed with 3D codes**.
- **Lack of theoretical models for large holes** (to our knowledge at least…): powerful techniques exist (mode matching) that could explore these regimes.
- FCC-hh:
  - Simulations performed with **wakefield/travelling wave methods**.
  - **Work on going to clear out discrepancies** and bridge to known theories for small holes.
  - Need to **assess the heating to the cold bore as well**.
- LHC:
  - **Mixed approach for longitudinal impedance** (**A.Mostacci + Kurennoy**) -> too pessimistic?
  - **Kurennoy's formula used in transverse plane** for $M_{cs} < 3$ -> too pessimistic?
  - **LHC liner measurements in good agreement** (within factor 2) with expectation (attenuation -> Z_l).
  - No details on trapped modes or higher order modes.
  - **Large dependence of power loss on hole manufacturing** (see A.Mostacci's thesis) -> **can be responsible of larger heating among sectors?** Should not change with time, and normally in shadow of resistive wall…
- HL-LHC:
  - **Same modeling as for LHC**
  - **Simulations performed for octagonal triplet** beam screen
  - Benchmark cases show **discrepancy of factor 4 w.r.t. theory** -> **to be further investigated.**

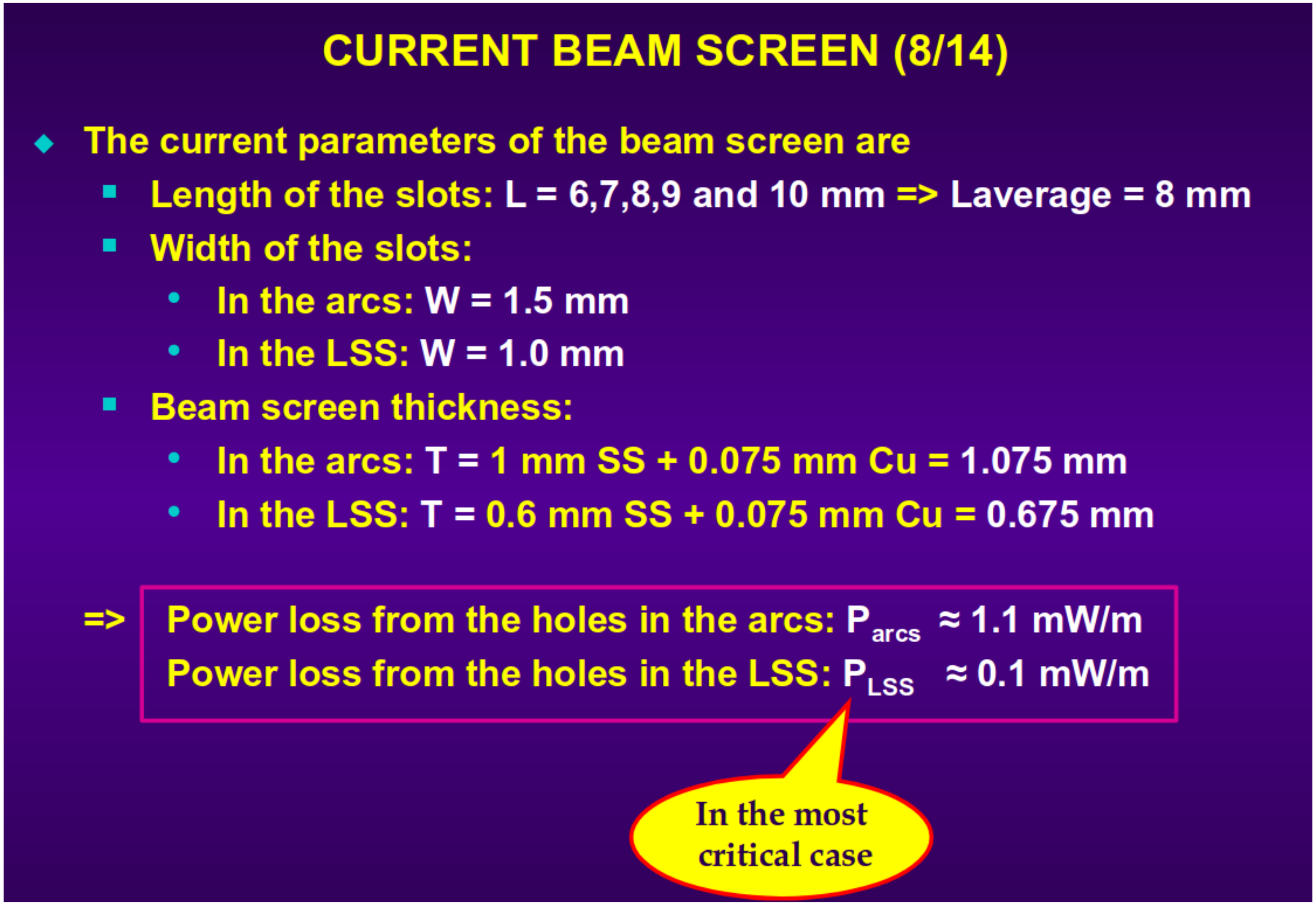
Thanks for your attention!



Source: Wikipedia

Backup

Update of power loss after beam screen update



CURRENT BEAM SCREEN (8/14)

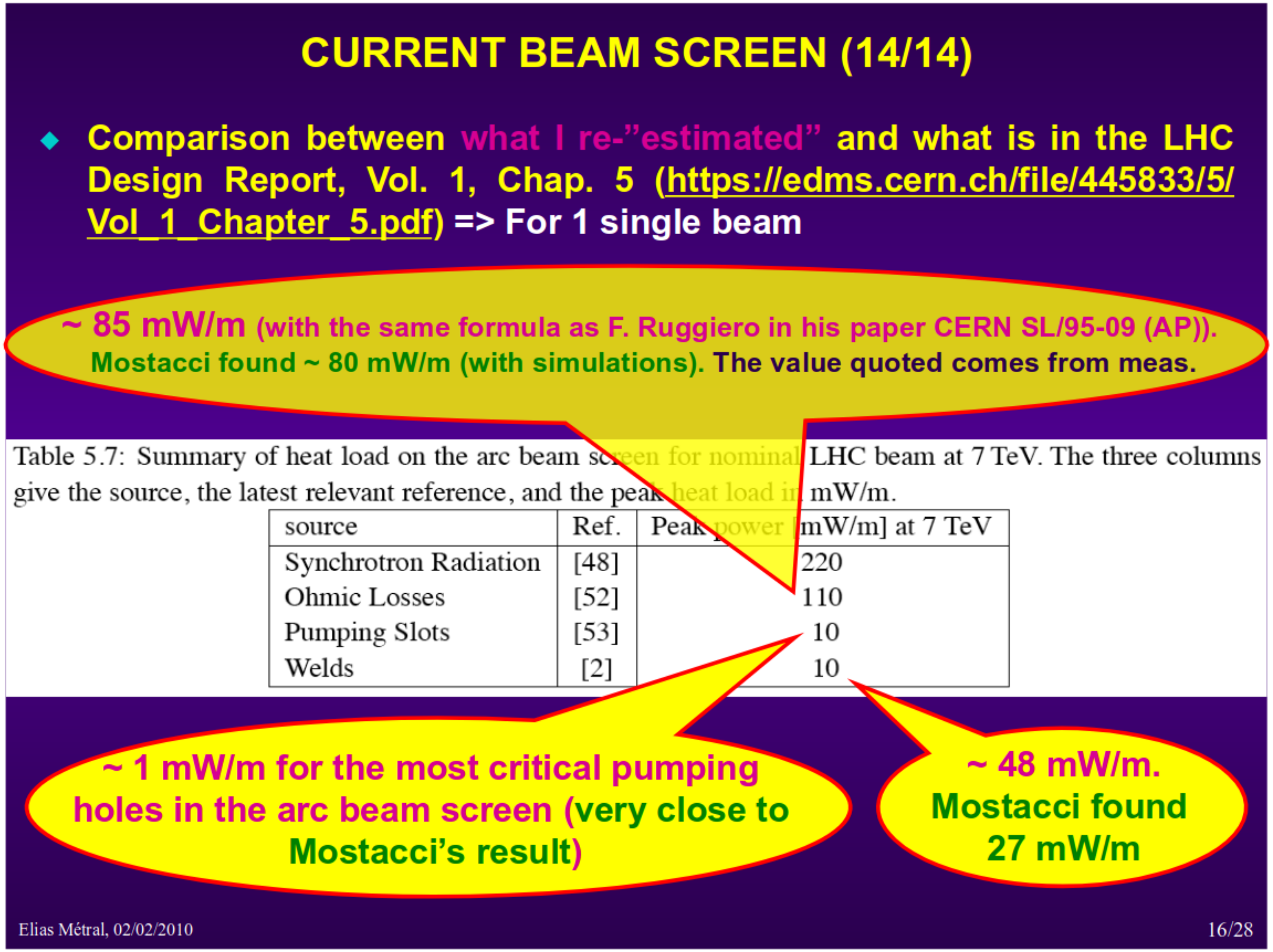
- The current parameters of the beam screen are
  - Length of the slots: L = 6,7,8,9 and 10 mm => Laverage = 8 mm
  - Width of the slots:
    - In the arcs: W = 1.5 mm
    - In the LSS: W = 1.0 mm
  - Beam screen thickness:
    - In the arcs: T = 1 mm SS + 0.075 mm Cu = 1.075 mm
    - In the LSS: T = 0.6 mm SS + 0.075 mm Cu = 0.675 mm

=> Power loss from the holes in the arcs: $P_{arcs} \approx 1.1$ mW/m

Power loss from the holes in the LSS: $P_{LSS} \approx 0.1$ mW/m

In the most critical case

Update of power loss after beam screen update



CURRENT BEAM SCREEN (14/14)

- Comparison between what I re-"estimated" and what is in the LHC Design Report, Vol. 1, Chap. 5 (https://edms.cern.ch/file/445833/5/Vol_1_Chapter_5.pdf) => For 1 single beam

~ 85 mW/m (with the same formula as F. Ruggiero in his paper CERN SL/95-09 (AP)). Mostacci found ~ 80 mW/m (with simulations). The value quoted comes from meas.

Table 5.7: Summary of heat load on the arc beam screen for nominal LHC beam at 7 TeV. The three columns give the source, the latest relevant reference, and the peak heat load in mW/m.

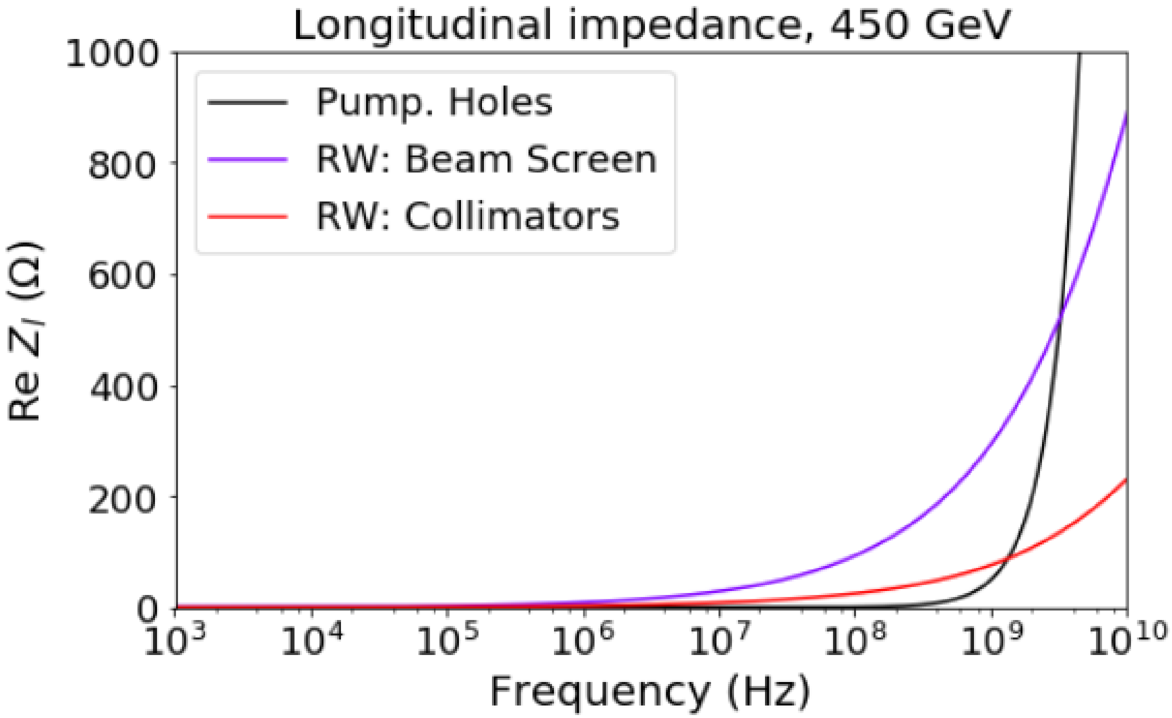
source	Ref.	Peak power [mW/m] at 7 TeV
Synchrotron Radiation	[48]	220
Ohmic Losses	[52]	110
Pumping Slots	[53]	10
Welds	[2]	10

~ 1 mW/m for the most critical pumping holes in the arc beam screen (very close to Mostacci's result)

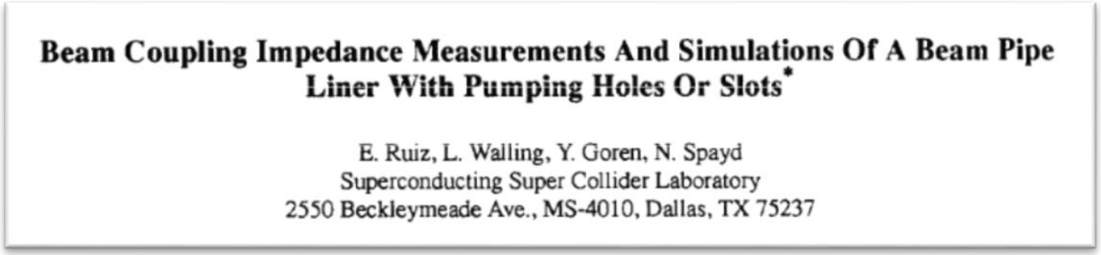
~ 48 mW/m. Mostacci found 27 mW/m

Elias Métral, 02/02/2010

16/28


Longitudinal impedance, 450 GeV
Pump. Holes
RW: Beam Screen
RW: Collimators
Re Z_l (Ω)
1000
800
600
400
200
0
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Frequency (Hz)

Wire measurements



Beam Coupling Impedance Measurements And Simulations Of A Beam Pipe Liner With Pumping Holes Or Slots*

E. Ruiz, L. Walling, Y. Goren, N. Spayd
Superconducting Super Collider Laboratory
2550 Beckleymeade Ave., MS-4010, Dallas, TX 75237

Transverse impedance for various hole and slot geometries was also simulated and compared to calculations by Kurennoy for a zero-thickness liner. Kurennoy predicts a factor of 2 reduction in transverse impedance when there are 3 or more holes in one radial cross-section. We find results half of Kurennoy's predictions, which is consistent when the reduction due to wall thickness is taken into account. Simulation results are shown in Table 2 while measurement results are shown in Figure 2.

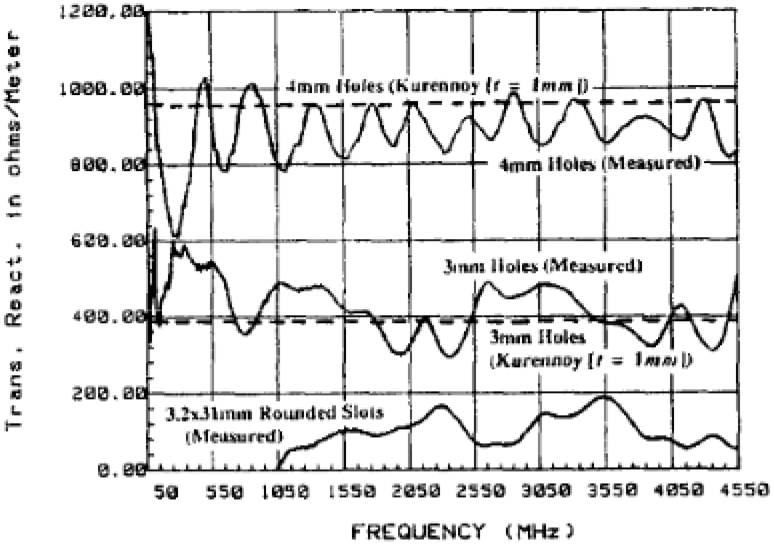


Figure 2. Measured Transverse Reactance of 1010 3 mm and 4 mm diameter holes and 160 rounded slots.