Damping Rings

Impedance budget and effect of chamber coating on CLIC DR beam stability

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Acknowledgements
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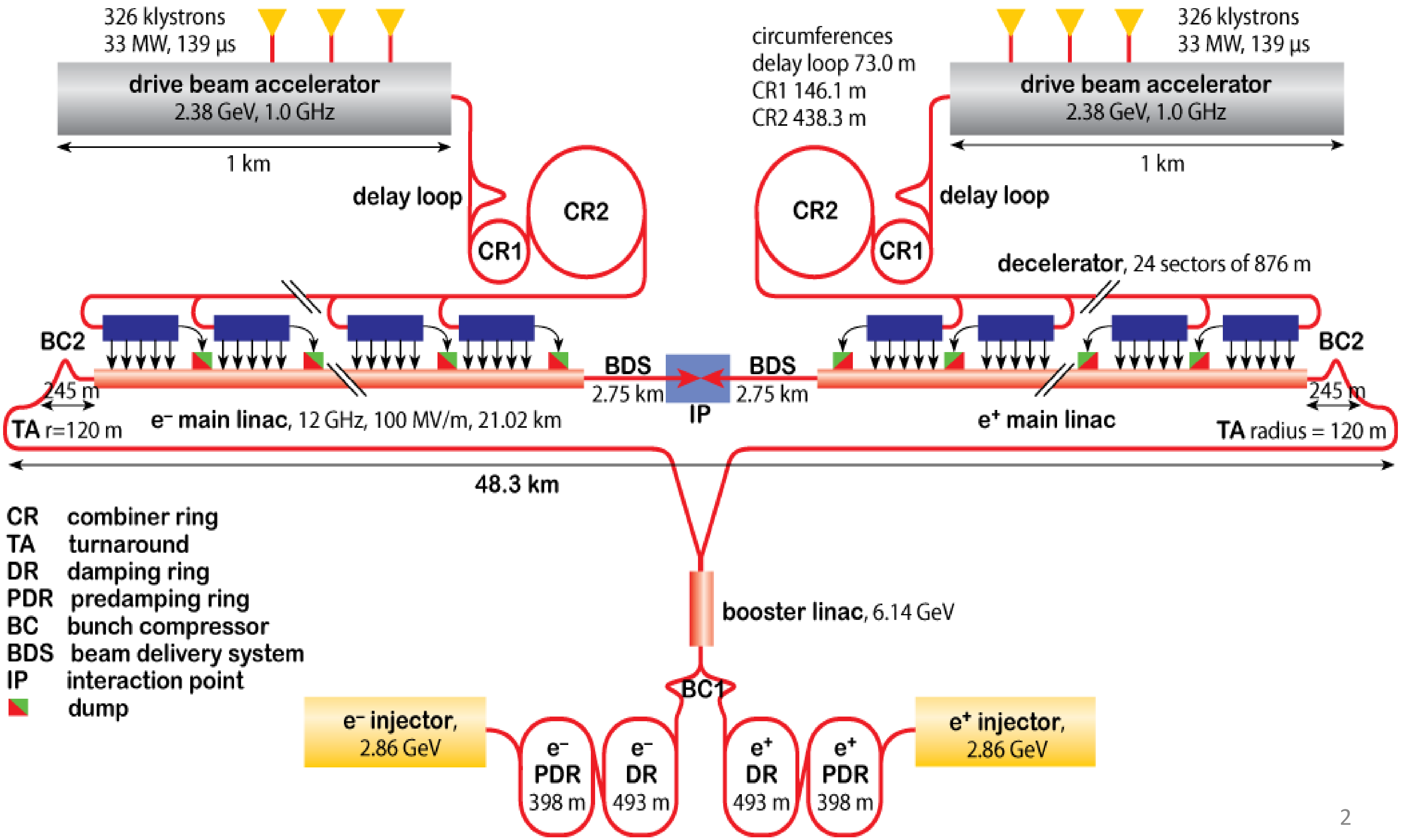
Overall layout 3 TeV



Damping Rings

COLLECTIVE EFFECTS STUDIED/UNDER STUDY:

Effects caused by the presence of a large number of particles in the beam leading to the creation of fields acting back on the beam

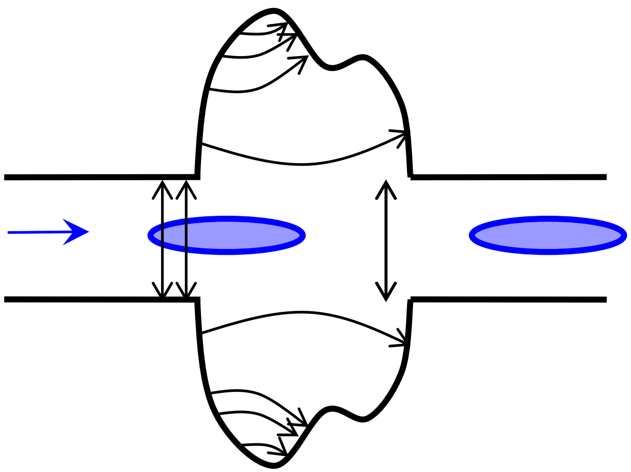
- SPACE CHARGE AND IBS
- ELECTRON CLOUD
  - BUILD UP AND BEAM STABILITY
  - BROAD BAND IMPEDANCE BUDGET
- SINGLE BUNCH INSTABILITIES → WAKE FIELDS/IMPEDANCE
  - HIGH FREQUENCY RESISTIVE WALL
  - BROAD BAND IMPEDANCE BUDGET
- COUPLED BUNCH INSTABILITIES
  - LOW FREQUENCY RESISTIVE WALL
  - FAST IONS INSTABILITIES

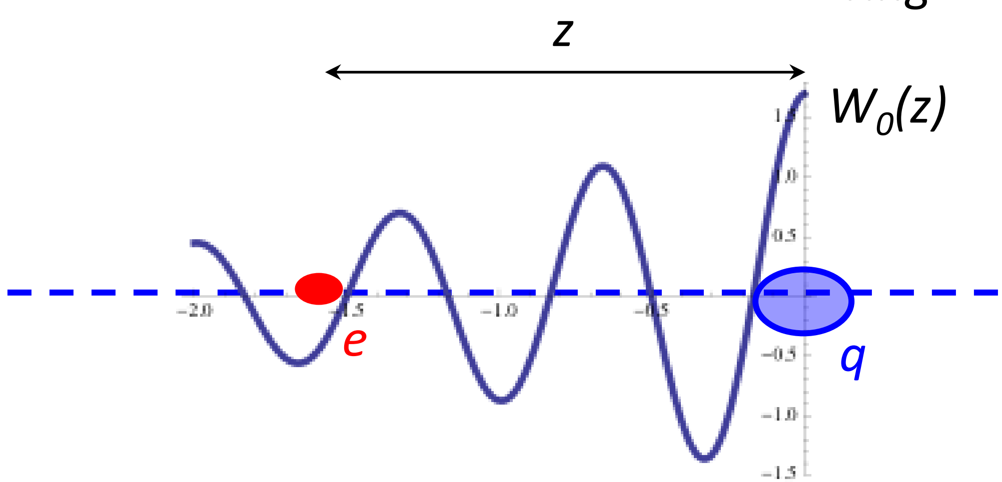
✓Estimate the instabilities thresholds

✓Limit the achievable beam current and the performance of the DR

Damping Rings

WAKE FIELDS/IMPEDANCE





Origin of wake fields

✓Geometric discontinuities

✓Pipe with finite conductivity

•Act back on the beam leading to instabilities, energy loss

•The interaction of a bunch of charged particles with the surroundings and therefore the energy loss is expressed in terms of impedance

•Estimate the impedance of each element in the ring

$$\int_0^L F_{||}(s,z)ds = -eqW_{||}(z)$$

$$Z_{||\,(\perp)}(\omega) \equiv \frac{1}{c}\int_{-\infty}^{\infty} dz\, e^{-i\omega z/c} W_{||\,(\perp)}$$

Outlook

- Simulation
- Analysis results
- Summary- conclusion
- Next steps

Simulation

1. Broadband Model (DR):

   - First approximation

   - Used to model the whole ring

   - Scan over **impedance to define an instability threshold** → Estimate the impedance budget

2. Thick wall in wigglers (Resistive wall model)

   - Expected to be a strong impedance source (6.5 mm radius)

   - Copper

   - Stainless steel

   - Effect of coating

   → Check how much is the contribution to the total impedance budget

Simulation

- Single bunch collective phenomena associated with impedances (or electron cloud) can be simulated with the HEADTAIL code

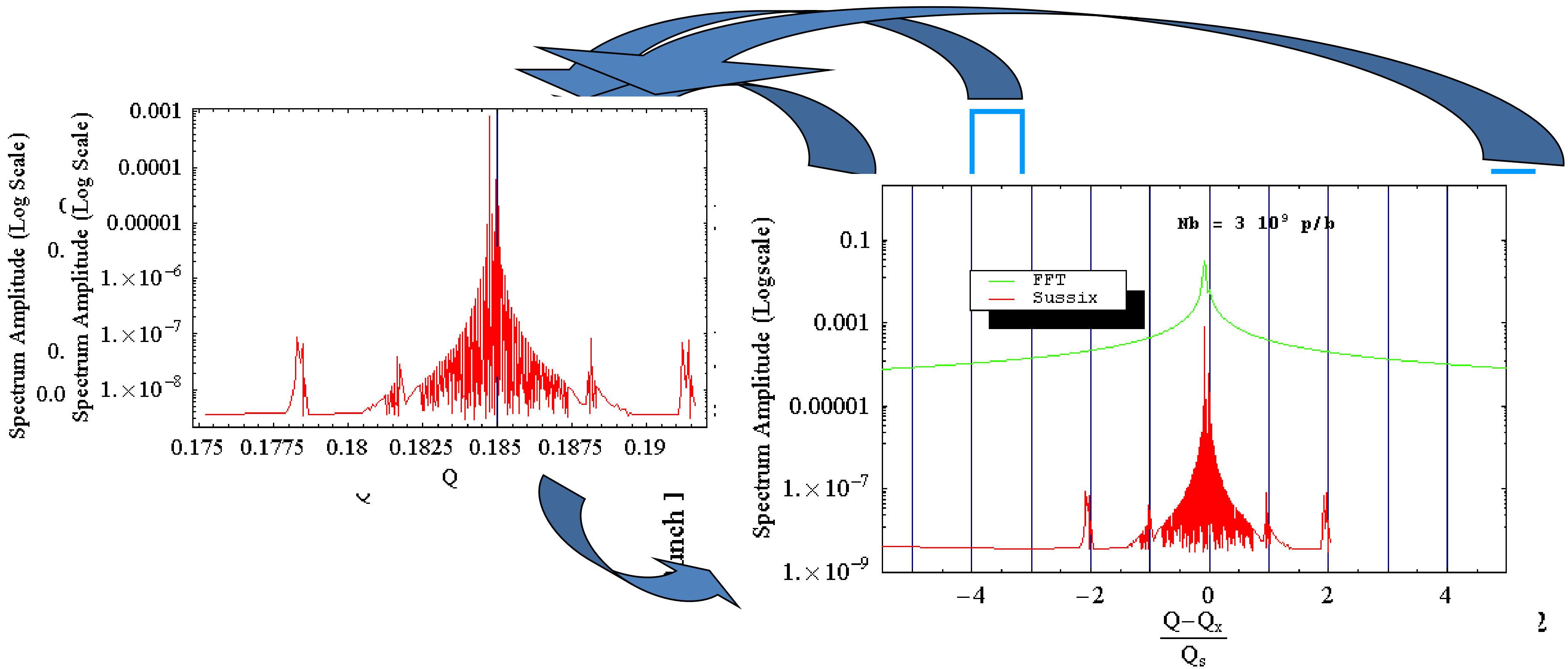
- Beam and machine parameters required in the input file

- Effect of the impedance is simulated as a single kick to the bunch at a certain point of the ring

- HEADTAIL computes the evolution of the bunch centroid as function of number of turns simulated

Methods : *What to do with HEADTAIL outputs ?*

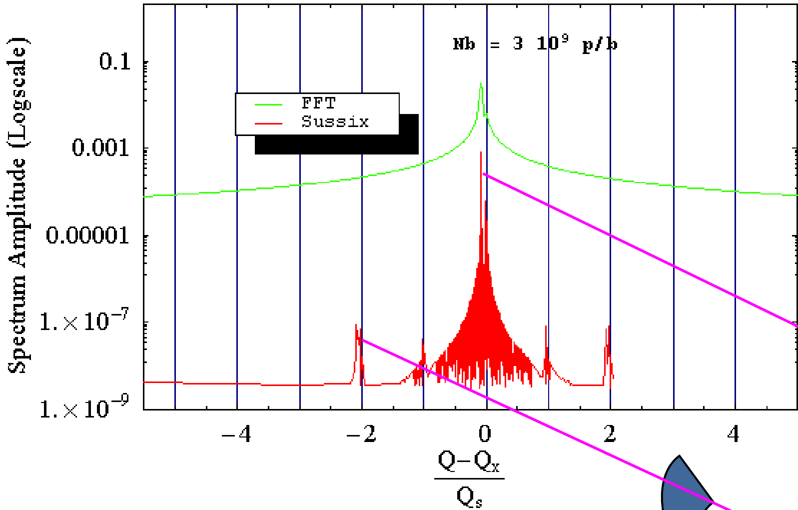
1. Extract the position of the centroid of the bunch (vertical or horizontal) turn after turn → simulated BPM signal
2. Apply a classical FFT to this simulated BPM signal (*x*)
3. Apply SUSSIX* to this same simulated BPM signal (actually $x - j\,\beta_x x'$)
4. Translate the tune spectrum by Q_{x0}=0 and normalize it to Q_s



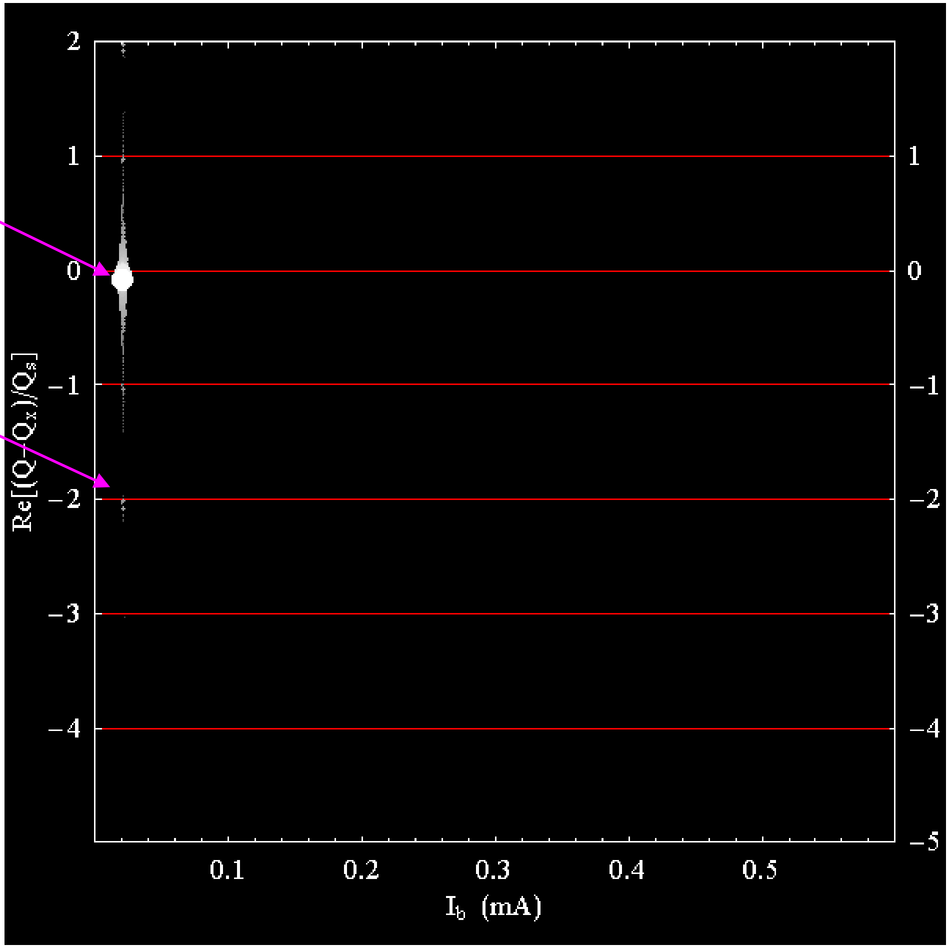
B.Salvant

Another visualization of the tune spectrum

for Nb = 3 10^9 p/b (I_b = 0.02 mA)



Displaying the Sussix spectrum on one line per bunch intensity



The dots are brighter and bigger if the amplitude is larger

B.Salvant

New update of the lattice design at 3 TeV

Parameters	1GHz	2GHz
Energy [GeV]	2.86	2.86
Circumference [m]	427.5	427.5
Energy loss/turn [MeV]	3.98	3.98
RF voltage [MV]	5.1	4.5
Stationary phase [^{o}]	51	62
Natural chromaticity x/y	-115/-85	-115/-85
Momentum compaction factor	1.3e-4	1.3e-4
Damping time x/s [ms]	2/1	2/1
Number of dipoles/wigglers	100/52	100/52
Cell/dipole length [m]	2.51/0.58	2.51/0.58
Dipole/wiggler field [T]	1.0/2.5	1.0/2.5
Bend gradient [$1/m^2$]	-1.1	-1/1
TME phase advance x/z	0.408/0.05	0.408/0.05
Bunch population [10^9]	4.1	4.1
IBS growth factor x/z/s	1.5/1.4/1.2	1.5/1.4/1.2
Hor.Ver. norm. emittance [nm.rad]	456/4.8	472/4.8
Bunch length [mm]	1.8	1.6
Longitudinal emittance [keVm]	6.0	5.3
Space charge tune shift	-0.10	-0.11

Simulation Parameters

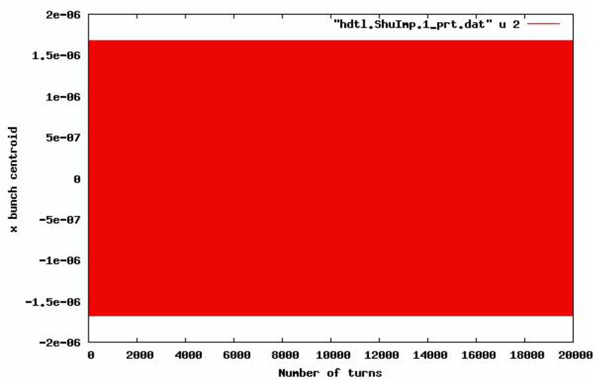
- $<\beta_x> = 3.475$ m (DR)
- $<\beta_y> = 9.233$ m (DR)
- $<\beta_x> = 4.200$ m (wigglers)
- $<\beta_y> = 9.839$ m (wigglers)
- Bunch length 1σ = 1.8 mm
- $Q_x = 48.35$, $Q_y = 10.40$, $Q_s = 0.0057$

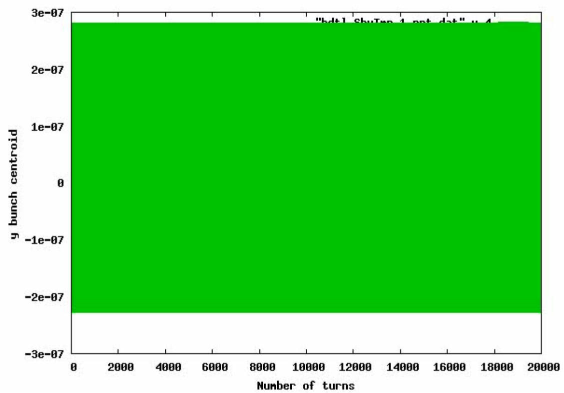
from Y. Papaphilippou, F.Antoniou

Broadband model

- Model all the DR
- Round (the impedance source is assumed to be identical in the horizontal and vertical plane)
- Average beta functions used: $< \beta_x > = 3.475$ m, $< \beta_y > = 9.233$ m
- Scan over impedance, from 0 to 20 MΩ/m, in order to **define the instability threshold** → estimate the impedance budget

Horizontal and vertical motion

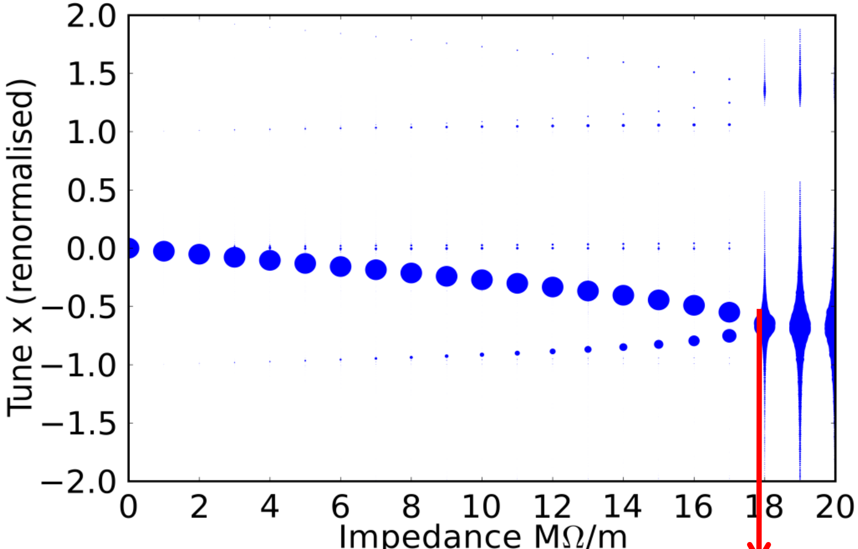




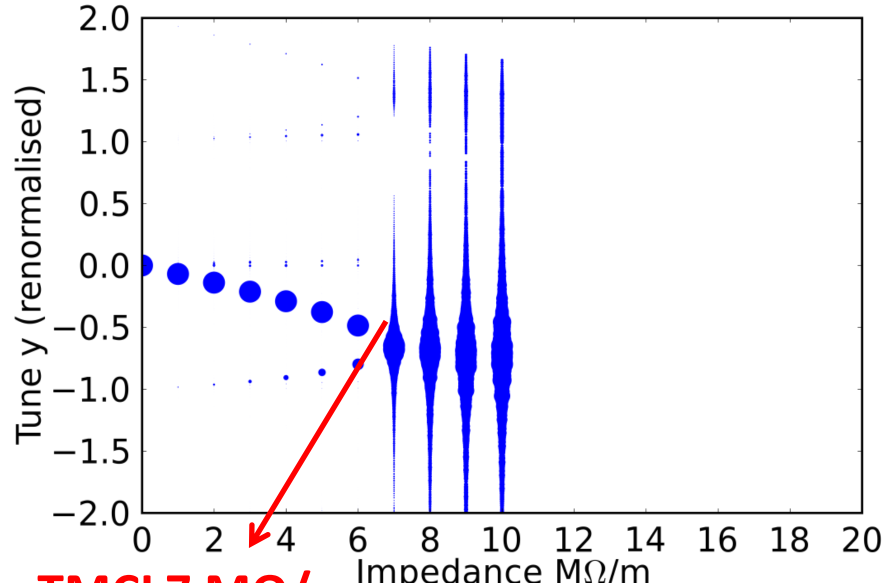
- Centroid evolution in x and y over the number of turns, for different values of impedance
- **Zero chromaticity**

➢ As the impedance increases, an instability occurs

Mode spectrum of the horizontal and vertical coherent motion as a function of impedance

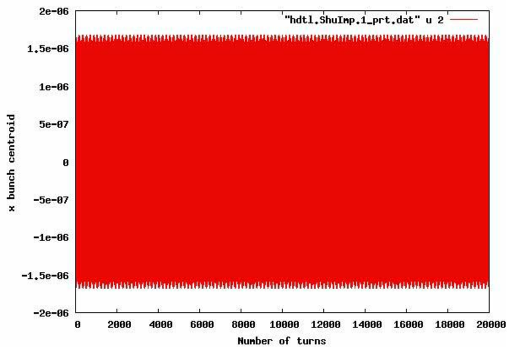


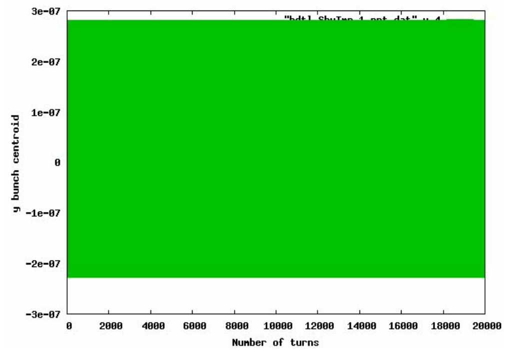
TMCI 18 MΩ/m



TMCI 7 MΩ/m

Horizontal and vertical motion



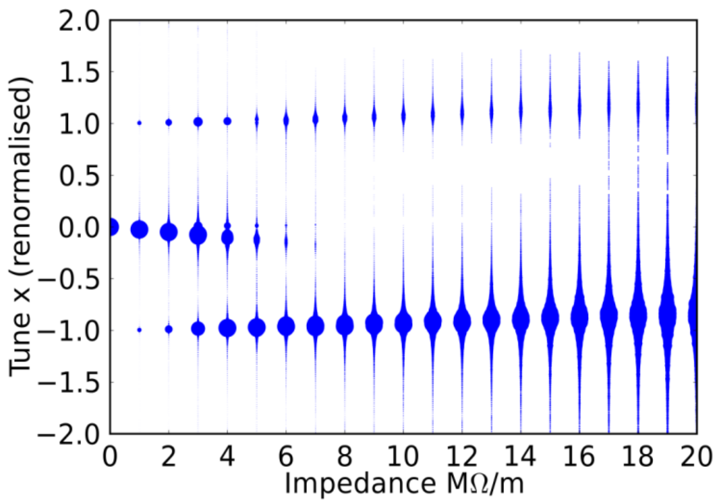


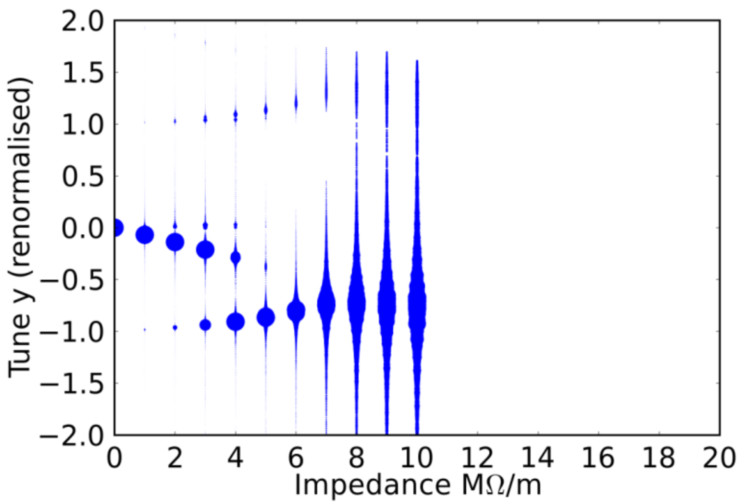
- Operate with positive chromaticity

Horiz.chrom. ξ_x	0.018
Vert. chrom. ξ_y	0.019

➢ Instability growth in both planes

Mode spectrum of the horizontal and vertical coherent motion as a function of impedance





- No mode coupling observed
- Higher TMCI thresholds
- Mode 0 is damped
- Higher order modes get excited (m = -1)

➢ Presence of chromaticity makes the modes move less, no coupling

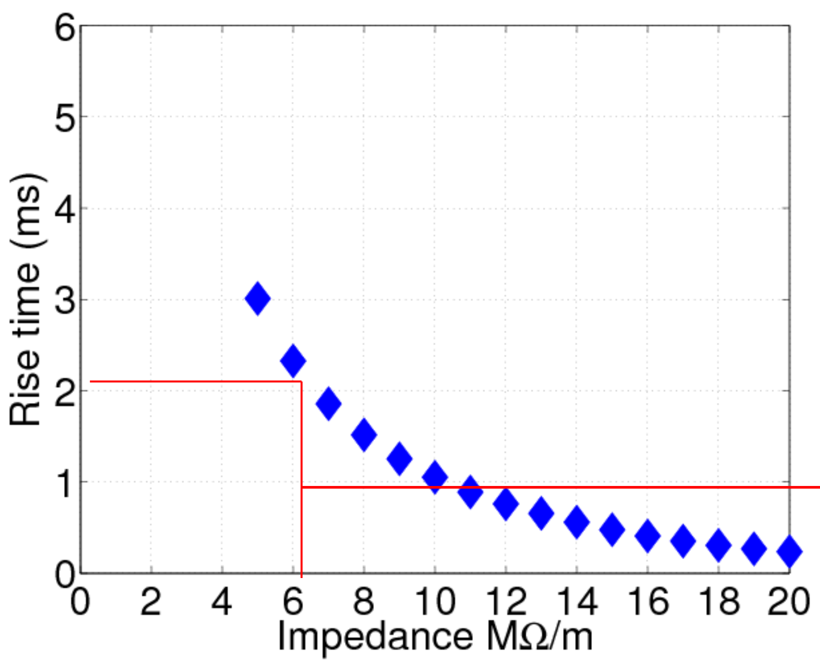
➢ Another type of instability occurs, called the head-tail instability

▪ Instability threshold?

Broadband model

→ No TMCI instability (fast), therefore no direct observation from the mode spectrum of the impedance threshold
→ **Need to calculate the rise time** (=1/growth rate) of the instabilities (damping is not implemented in HEADTAIL)
→ The instability growth rate is calculated from the exponential growth of the amplitude of the bunch centroid oscillations

Rise time– x plane



- If the rise time < damping time, the instability is faster than the damping mechanism
- Damping time τ_x=2 ms

Threshold ~6.5 MΩ/m

Broadband model

Chromaticity ξ_x / ξ_y	Impedance threshold MΩ/m	
	x	y
0/ 0	18	7
0.018/ 0.019	6.5	6
0.055/ 0.057	4	4
0.093/ 0.096	5	3
-0.018/ -0.019	4	5
-0.055/ -0.057	2	2
-0.093/ -0.096	2	2

- Chromaticity make the modes move less, therefore it helps to avoid coupling (move to a higher threshold)
- Still some modes can get unstable due to impedance
- As the chromaticity is increased, higher order modes are excited (less effect on the bunch)

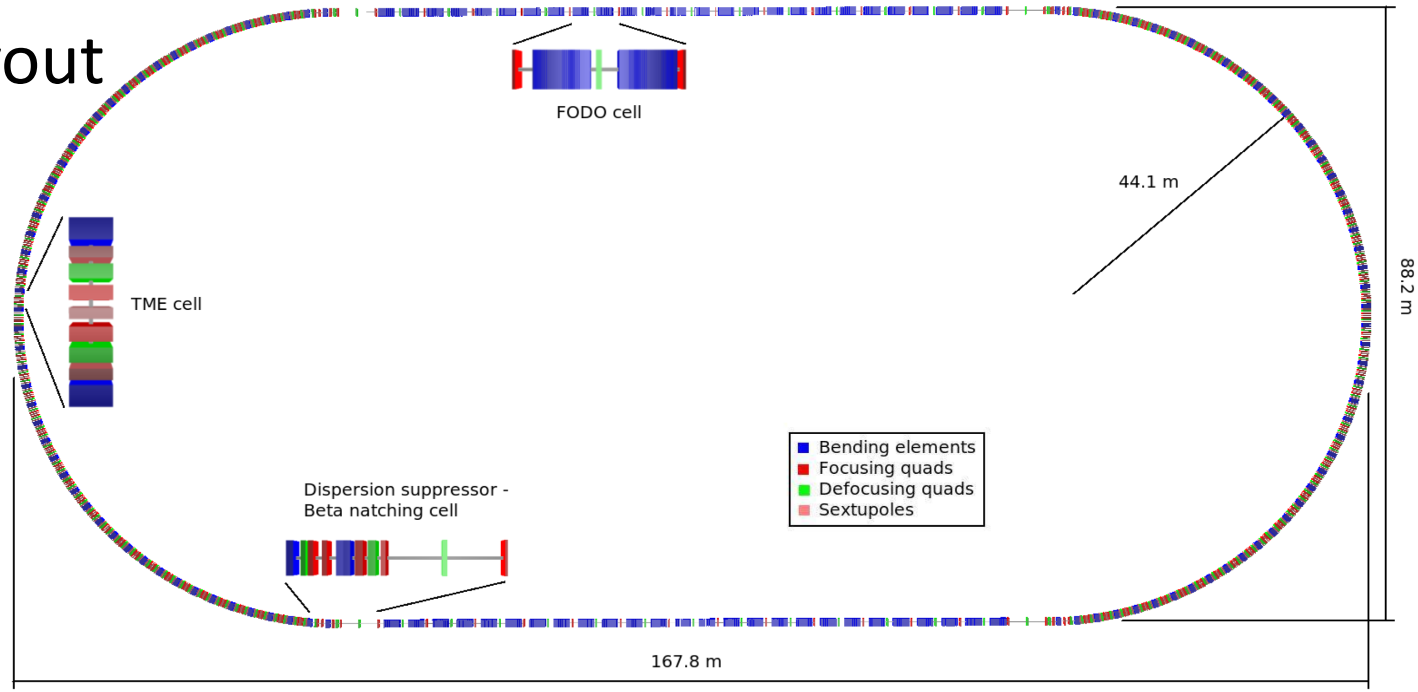
➢ The goal is to operate at 0 chromaticity which allows for a larger impedance budget (7 MΩ/m)

➢ But since chromaticity will be slightly positive, a lower impedance budget has to be considered, 4 MΩ/m

➢ SPS, 7 km, 20 MΩ/m

Thick wall in wigglers

DR layout



C = 427.5 m, $L_{wigglers}$ = 104 m **Wigglers occupy ~ ¼ of the total ring…**

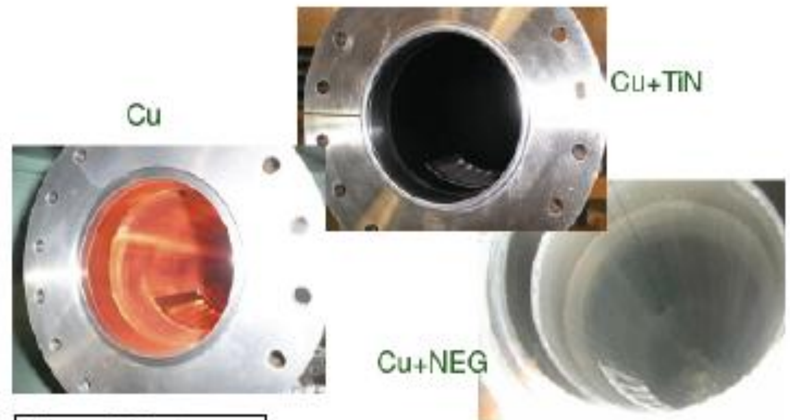
- Because of the small aperture of 6.5 mm compared to 9 mm of the rest of the ring, the contribution of the wigglers is expected to take a significant fraction of the available impedance budget of 4 MΩ/m.
- Moreover, layers of coating materials can significantly increase the resistive wall impedance.

Y.Papaphilippou, F.Antoniou

Beware…

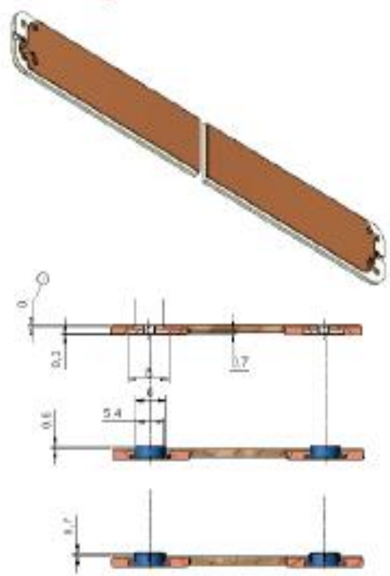
From LER 2010 Workshop

- Some techniques to fight electron cloud (or have good vacuum) do not come for free and can be serious high frequency impedance sources:
  - Surface coating with low SEY materials (Cu, NEG, TiN, a-C)
  - Non-smooth surfaces (natural roughness, grooves)
  - Clearing electrodes
  - NEG coating for pumping

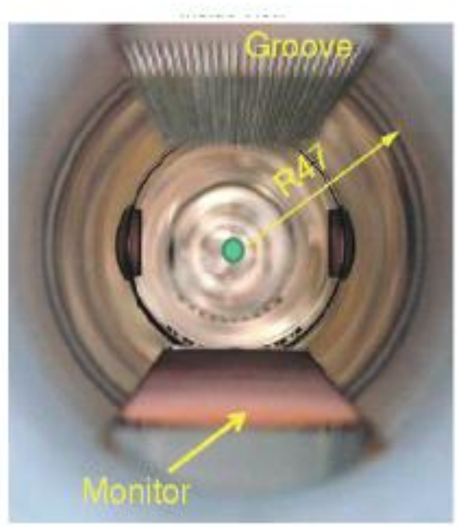


From S. Suetsugu

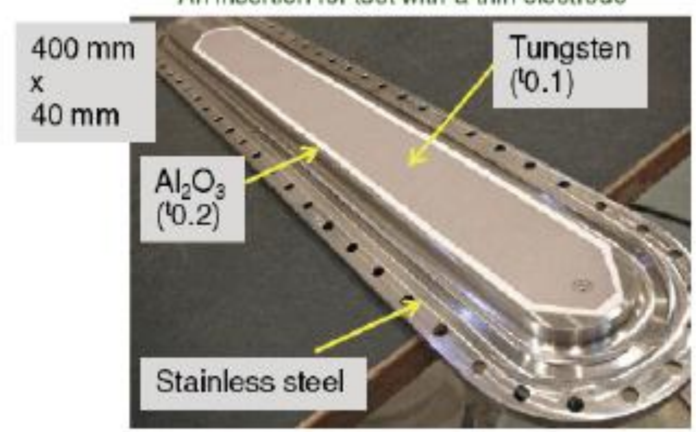
Clearing electrodes for DAFNE



From T. Demma

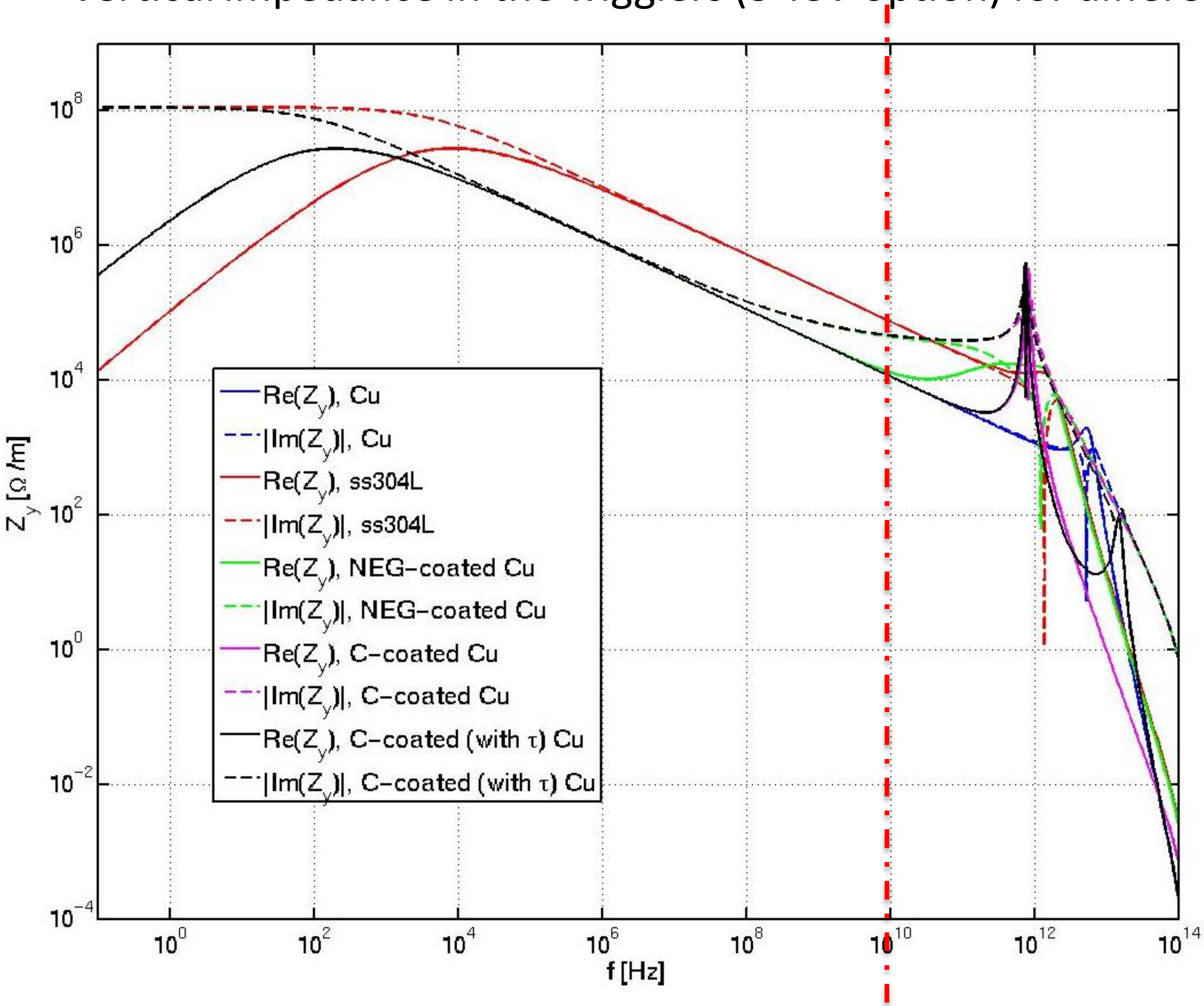


An insertion for test with a thin electrode



Resistive Wall Impedance: Various options for the pipe

- Vertical impedance in the wigglers (3 TeV option) for different materials



$\Rightarrow$ Coating is "transparent" up to ~*10* GHz

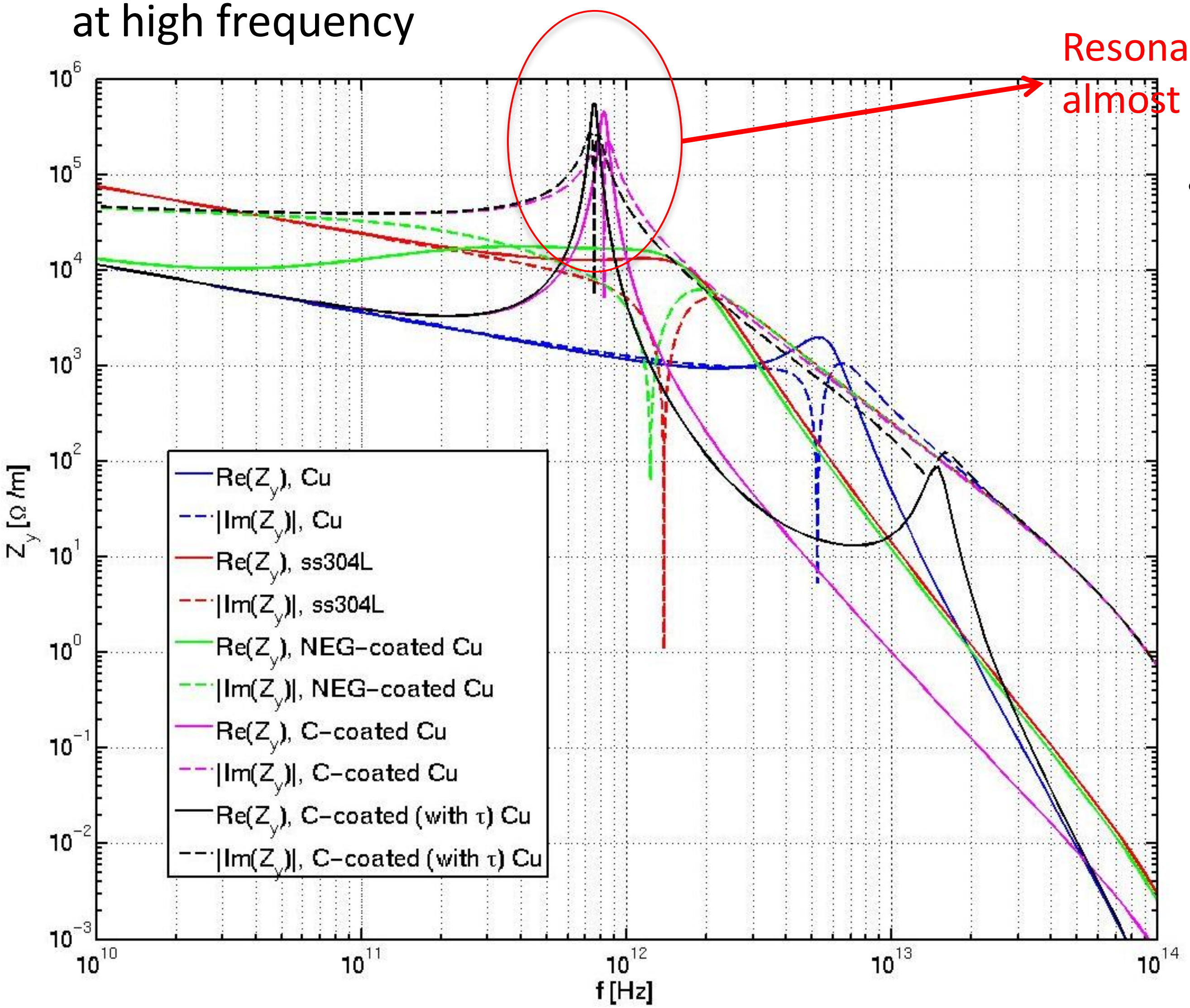
$\Rightarrow$ But at higher frequencies some narrow peaks appear!!

$\Rightarrow$ So we zoom for frequencies above 10 GHz →

N. Mounet, LER Workshop, January 2010

Resistive Wall Impedance: Various options for the pipe

- Vertical impedance in the wigglers (3 TeV option) for different materials: zoom at high frequency

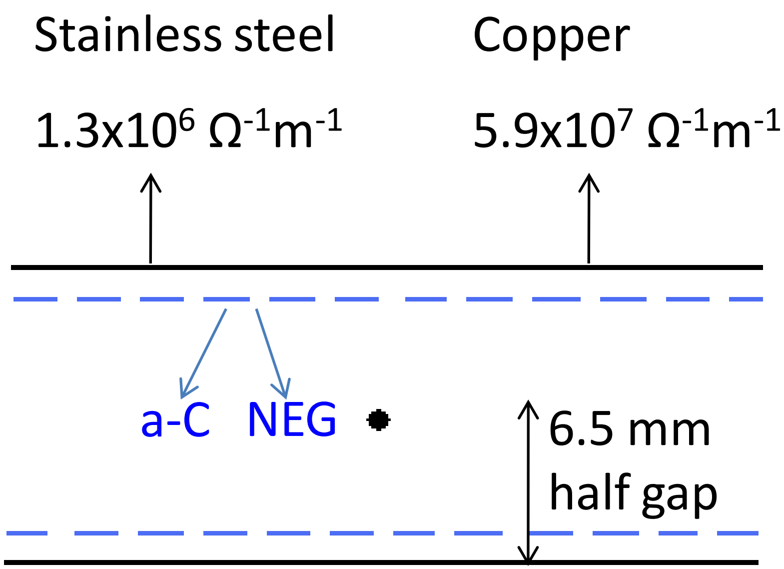


- Layers of coating materials can significantly increase the resistive wall impedance at high frequency
  - Coating especially needed in the low gap wigglers
  - Low conductivity, thin layer coatings (NEG, a-C)
  - Rough surfaces (not taken into account so far)

⇒ Above *10* GHz the impact of coating is quite significant.

N. Mounet, LER Workshop, January 2010

Thick wall in wigglers



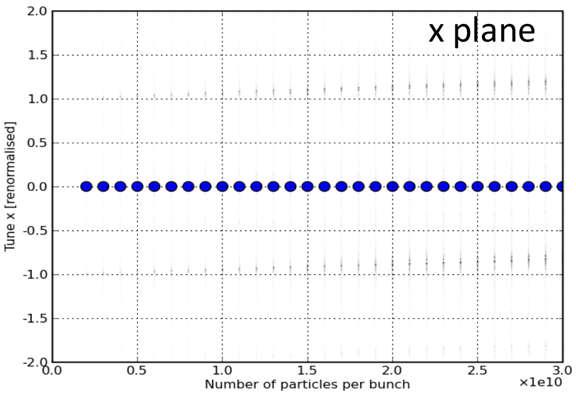
- Amorphous carbon (aC) on stainless steel (ss) (0.0005 mm/ 0.001 mm)
- Non-evaporated getter (NEG) on stainless steel (0.001 mm/ 0.002 mm)
- Amorphous carbon on copper (0.0005 mm/ 0.001 mm)
- NEG on copper (0.001 mm/ 0.002 mm)

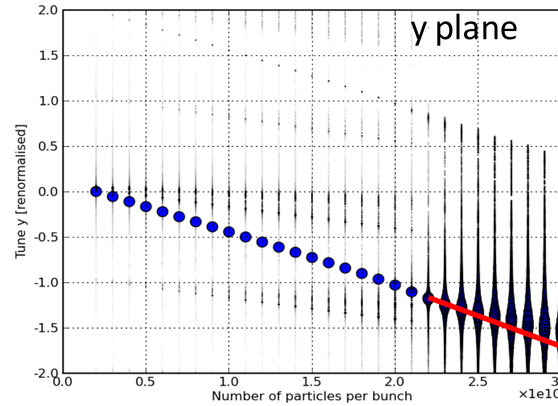
NEG (Non Evaporated Getter)
- Important for good vacuum
- EDR
- Same conductivity as ss

Amorphous carbon (a-C)
- Important for the electron cloud
- PDR

- Scan over intensity, from **1.0 10^9 to 29.0 10^9**
- Average beta for the wigglers: $<\beta_x>$ = 4.200 m, $<\beta_y>$ = 9.839 m
- Neglect the effect of the broadband impedance (single kick due to resistive wall from the wigglers)

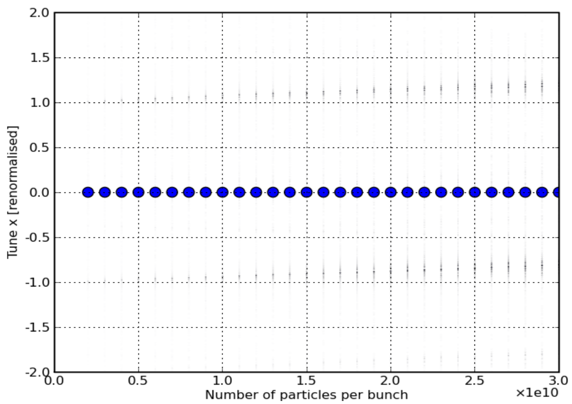
Example: Stainless steel (coated with NEG or a-C)

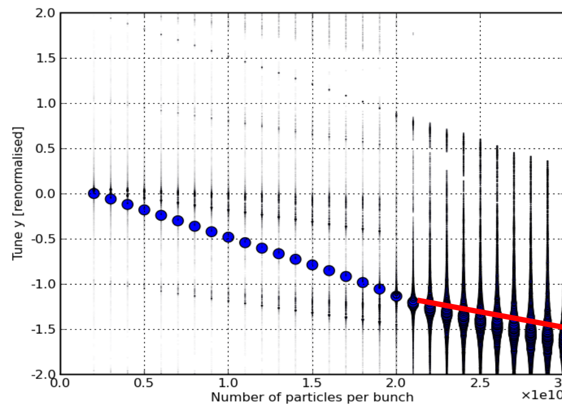




- Horizontal: Stable, mode -1 is moving up
- Vertical: Coupling of mode 0 and mode -1 at 21x10^9 (~5 times the nominal intensity)

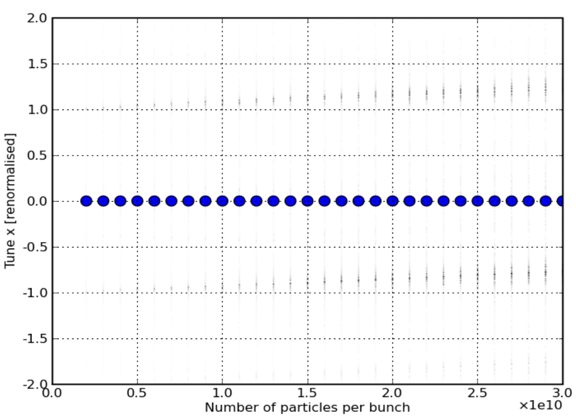
TMCI at 21x10^9

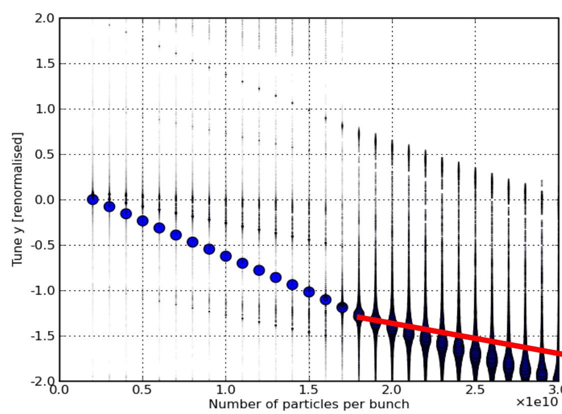




Coating with 0.001 mm NEG

TMCI at 20x10^9





Coating with 0.001 mm a-C (less conductive than NEG)

TMCI at 17x10^9

Results

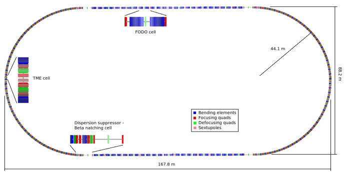
Materials	TMCI thresholds
Stainless steel (ss)	21 x 10^9
aC on ss (0.0005 mm)	19 x 10^9
aC on ss (0.001 mm)	17 x 10^9
NEG on ss (0.001 mm)	20 x 10^9
NEG on ss (0.002 mm)	19 x 10^9
Copper	> 29 x 10^9
aC on copper (0.0005 mm)	> 29 x 10^9
aC on copper (0.001 mm)	> 29 x 10^9
NEG on copper (0.001 mm)	> 29 x 10^9
NEG on copper (0.002 mm)	26 x 10^9

- Copper is better than ss but also more expensive!
- Adding a layer of coating → reduces the thresholds (the thicker, the more they are reduced)
- Coating doesn't have a big impact for the wigglers (still in the range of tolerance: 4.1 10^9 the nominal intensity)
- Further study…

Next steps

- Give 3 or more kicks (more realistic)
  - Coated wigglers
  - Coated rest of the machine
  - Broadband resonator
- Effect of
  - different thickness of the coating
  - different radius of the pipe
- High frequency effects of resistive wall → calculate $\varepsilon(\omega)$, $\mu(\omega)$, $\sigma(\omega)$ for hf of the coating material→ experimental methods
- Use the multi-bunch version of HEADTAIL (impact of the resistive wall on the multi-bunch)
- Space charge study
- Do some real tune shift measurements in one of the existing rings (SLS, CesrTA)

Summary- conclusion



1 kick, <β> → **BB** (1st approximation)

BB → Impedance budget → 4 MΩ/m, for nominal intensity 4.1 10^9

- **RW**
  - RW wigglers
  - RW rest of the ring
- **BB**
  - Cavities
  - Kickers
  - Pick ups
  - etc

>3 kicks, <β> → RW

RW wigglers → Unstable at 17 10^9 (aC on ss) → ~1 MΩ/m (25% of the total impedance budget)

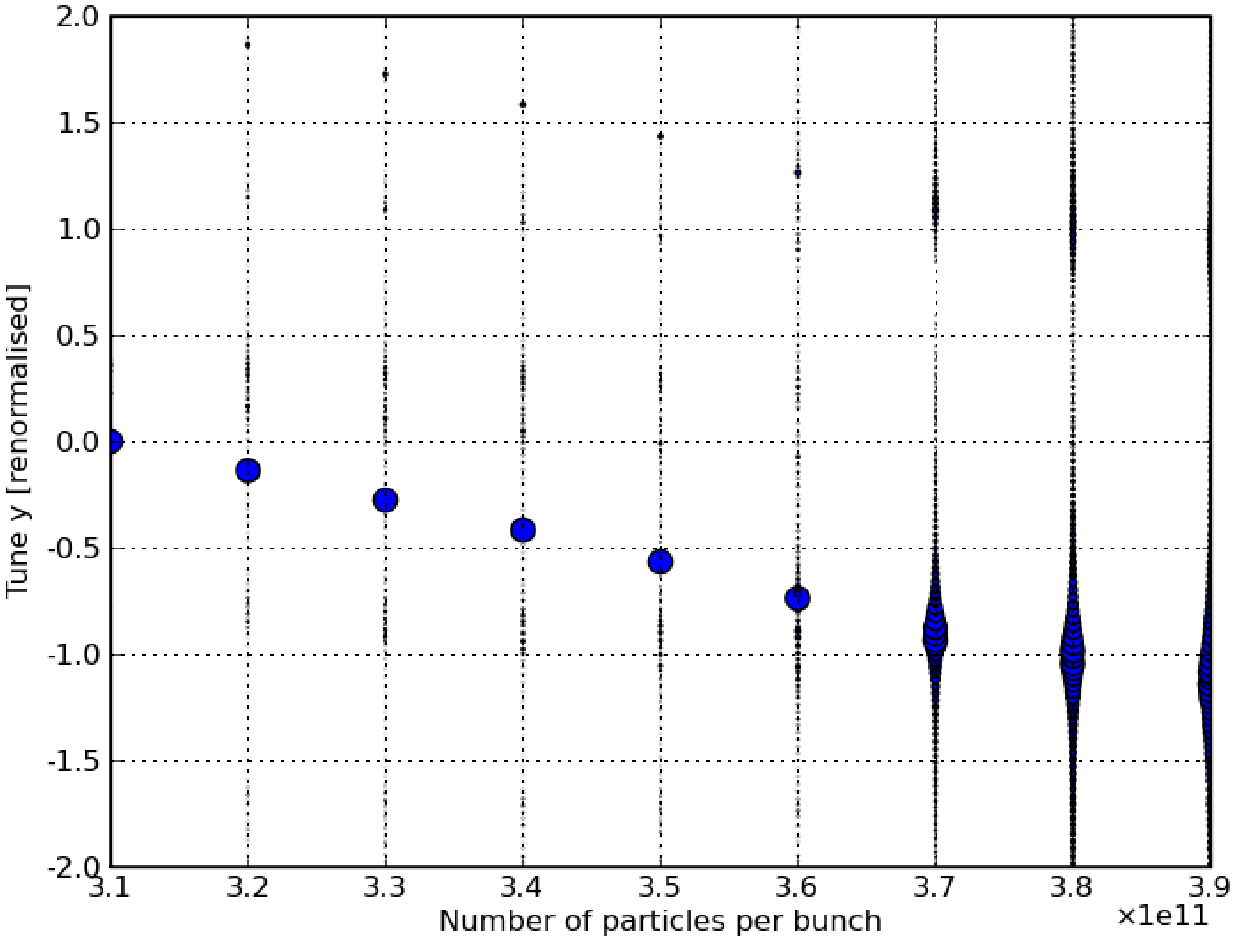
→ Add up all the different contributions

→ Reduce the impedance budget

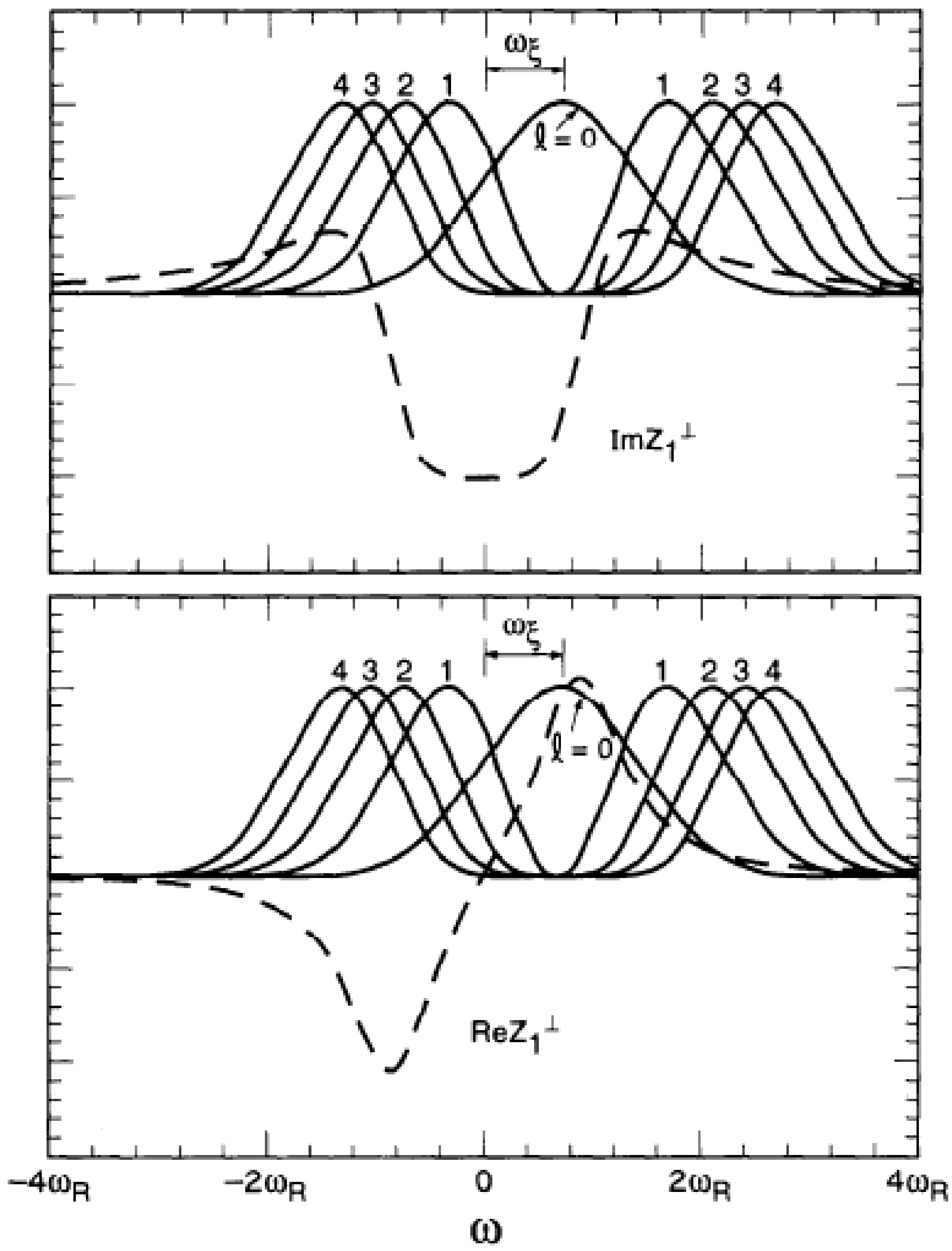
→ Impedance database with all the components

Appendix

- **This case (copper) is stable only for this intensity range**
- **Extend the intensity [30.0-110.0]10^9**



Azimuthal modes and impedance



Tune shift

For a Gaussian beam, we have $h_l(\omega)$ given by Eq. (6.143) and

$$\Omega^{(l)} - \omega_\beta - l\omega_s \approx -\frac{1}{4\pi}\frac{\Gamma\left(l+\frac{1}{2}\right)}{2^l l!}\frac{N r_0 c^2}{\gamma T_0 \omega_\beta \sigma} i\left(Z_1^\perp\right)_{\text{eff}}.$$

19.2.2 Resistive Wall Impedance

The particle beam induces an image current in the vacuum chamber wall in a thin layer with a depth equal to the skin depth. For less than perfect conductivity of the wall material, we observe resistive losses which exert a pull or decelerating field on the particles. This pull is proportional to the beam current and integrating the fields around a full circumference of the accelerator, we get for the associated longitudinal resistive wall impedance in a uniform tube of radius r_w at frequency ω_n

$$\left.\frac{Z_\parallel(\omega_n)}{n}\right|_\mathrm{res} = \frac{1-\mathrm{i}}{n}\frac{\bar{R}}{c r_\mathrm{w}}\sqrt{\frac{\mu_\mathrm{r}\omega_n}{2\epsilon_0\,\sigma}} = \frac{1-\mathrm{i}}{n}\frac{\bar{R}}{r_\mathrm{w}\sigma\,\delta_\mathrm{skin}}\ , \tag{19.40}$$

where the skin depth is defined by [145]

$$\delta_\mathrm{skin}(\omega_n) = \sqrt{\frac{2}{\mu_0\mu_\mathrm{r}\,\omega_n\,\sigma}}\,. \tag{19.41}$$

The longitudinal resistive wall impedance decays with increasing frequency and therefore plays an important role only for low frequencies. The transverse resistive wall impedance for a round beam pipe is

$$Z_\perp(\omega_n)_\mathrm{res} = \frac{2\bar{R}}{r_\mathrm{w}^2}\left.\frac{Z_\parallel(\omega_n)}{n}\right|_\mathrm{res}\ . \tag{19.42}$$

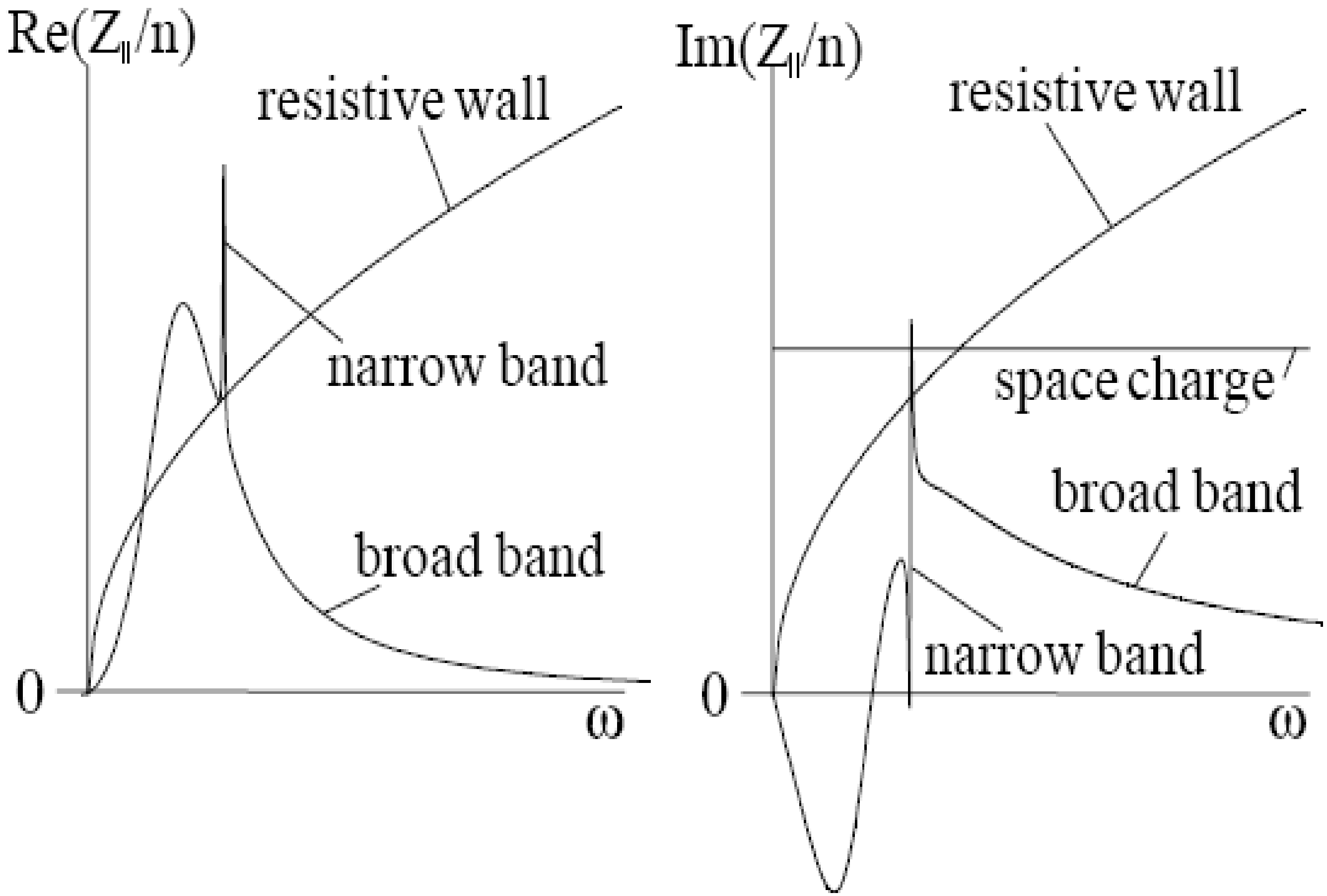


Fig. 19.7. Qualitative spectra of resistive and reactive coupling impedances in a circular accelerator

Fig. 19.7 we show qualitatively these resistive as well as reactive impedance components as a function of frequency.

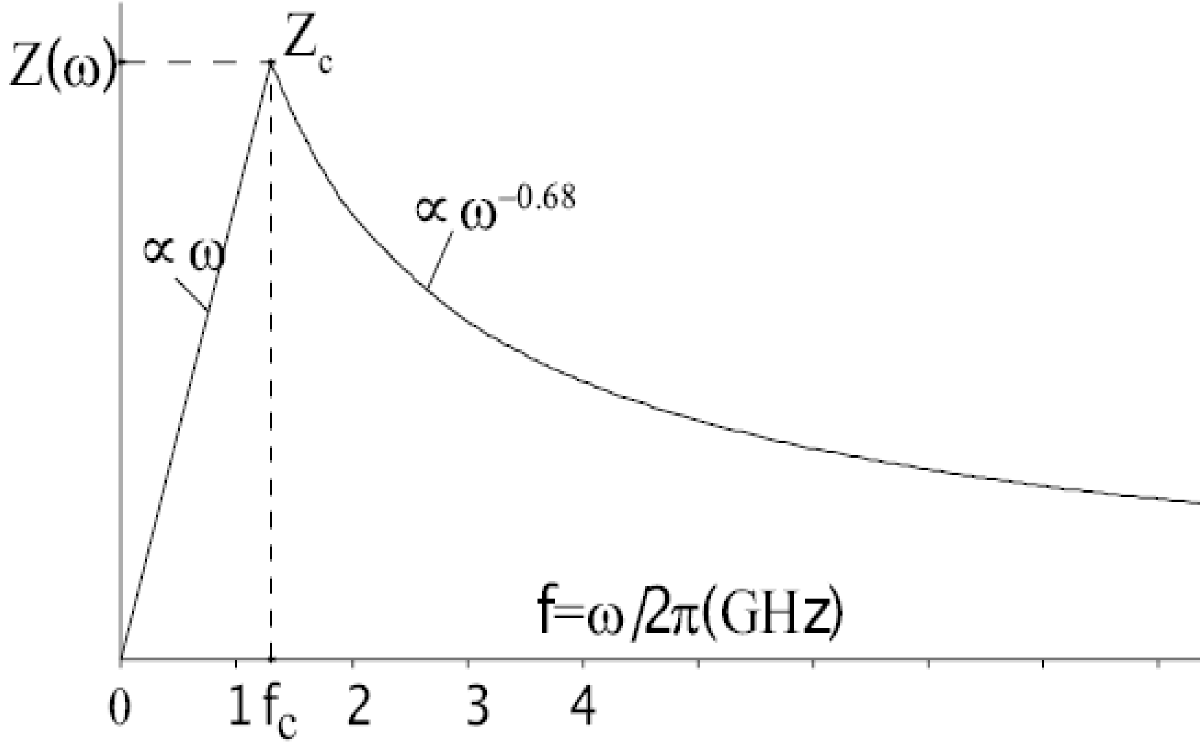


Fig. 19.8. Impedance spectrum of the storage ring SPEAR

Resistive wall model

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E_s}{\partial r}\right) + \lambda^2\tilde{E}_s = 0,$$

$$\tilde{E}_r = \frac{ik}{\lambda^2}\frac{\partial\tilde{E}_s}{\partial r}, \qquad (2.5)$$

$$\tilde{B}_\theta = \left(1 + \frac{\lambda^2}{k^2}\right)\tilde{E}_r,$$

where we have defined a parameter

$$\lambda = \sqrt{\frac{2\pi\sigma|k|}{c}}\,[i + \mathrm{sgn}(k)] \qquad (2.6)$$

with $\lambda^2 = 4\pi i\sigma k/c$. The sign of λ is chosen so that its imaginary part $\mathrm{Im}\,\lambda > 0$. The parameter λ^{-1} has the dimensionality of length; it is related to the *skin depth* as a function of frequency $\omega = kc$ inside the metal wall:

$$\delta_{\text{skin}} = \frac{1}{\mathrm{Im}\,\lambda} = \frac{c}{\sqrt{2\pi\sigma|\omega|}}. \qquad (2.7)$$

Resistive wall model 2

In what follows, we will assume $|\lambda|$ is much larger than $1/b$, i.e., the skin depth is much shorter than the pipe radius b. This assumption is good if wave number $|k|$ is much greater than $c/4\pi\sigma b^2$, or equivalently, if we are interested in the region

$$|z| \ll \frac{b}{\chi}, \tag{2.9}$$

where χ is a small dimensionless parameter defined by

$$\chi \equiv \frac{c}{4\pi\sigma b}. \tag{2.10}$$

For example, if $b = 5$ cm and the wall is made of aluminum, we have $\chi = 1.5 \times 10^{-9}$ and our approximation breaks down at a distance $\gtrsim 3 \times 10^7$ m behind the beam.

In case the vacuum chamber wall has a finite thickness t, our approximation also requires $|\lambda| \gg 1/t$. If $t = 3$ mm, the approximation breaks down at distance $\gtrsim 1 \times 10^5$ m. The corresponding low-frequency field components leak through the pipe wall, leading to the Laslett analysis of tune shifts (1.30–1.31).