Collective effects in the CLIC Damping Rings

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with the valuable inputs and contribution of F. Antoniou, M. Barnes, S. Calatroni, J. Calvey, J. Crittenden, A. Grudiev, E. Koukovini-Platia, N. Mounet, M. Palmer, Y. Papaphilippou, D. Schoerling, M. Taborelli, A Vivoli, F. Zimmermann
for the 6th CLIC-ACE, 2 February 2011

- Most recent parameter table with two options
- Collective effects studied/under study
  - Space charge and IBS
  - Electron cloud
    - Build up and beam stability
    - Heat load in superconducting wigglers
  - Single bunch instabilities
    - High frequency resistive wall from coating
    - Broad band impedance budget
  - Coupled bunch instabilities
    - Low frequency resistive wall
    - Fast ion instabilities
- A list of future studies

Damping Ring parameter table

Parameters	1GHz	2GHz
Energy [GeV]	2.86	
Circumference [m]	427.5	
Energy loss/turn [MeV]	4.0	
RF voltage [MV]	5.1	4.5
Stationary phase [°]	51	62
Natural chromaticity x / y	-115/-85	
Momentum compaction factor	1.3e-4	
Damping time x / s [ms]	2.0/1.0	
Number of dipoles/wigglers	100/52	
Cell /dipole length [m]	2.51 / 0.58	
Dipole/Wiggler field [T]	1.0/2.5	
Bend gradient [1/m2]	-1.1	
Tunes x / y	49.64/11.34	
Bunch population, [e9]	4.1	
IBS growth factor x/z/s	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

Y. Papaphilippou

→ Reduced circumference
- Lower space-charge tune-shift

→ Increased momentum compaction factor
- Longer bunch for reducing space-charge tune-shift and increasing CSR instability threshold

→ RF frequency of 1GHz (two trains)
- Halving peak power and current, thereby reducing transient beam loading
- Increase harmonic number i.e. longer bunch (see above)
- Less e-cloud production (bunch spacing doubled)
- Less pronounced Fast Beam Ion Instability (doubling critical mass above which particles get trapped, clearing gap between the two trains)

Space charge

- Space charge causes a **negative tune-shift** that can be estimated by integrating all over the ring circumference the contribution from a section *ds* of the ring. For a Gaussian beam, the formula reads

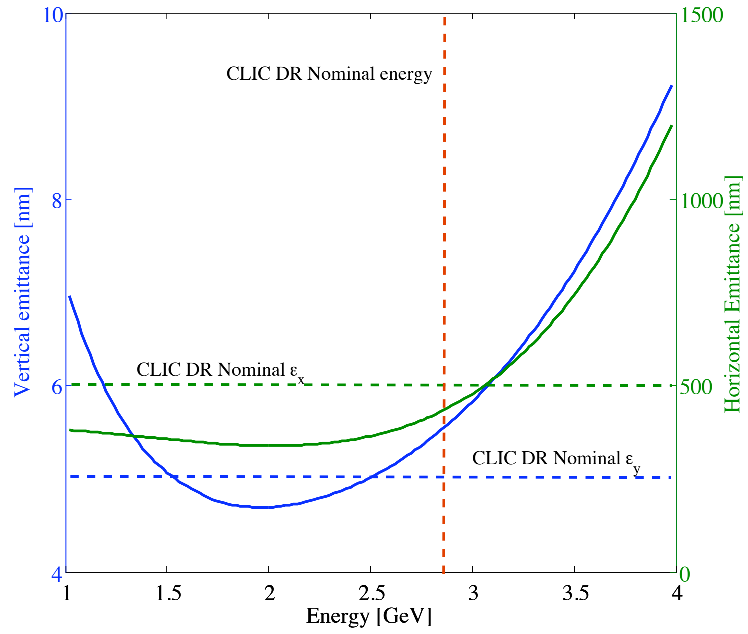
$$\Delta Q_{x,y} = -\frac{N_b r_e C}{(2\pi)^{3/2}\gamma^3\sigma_z}\oint\frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x+\sigma_y)}ds$$

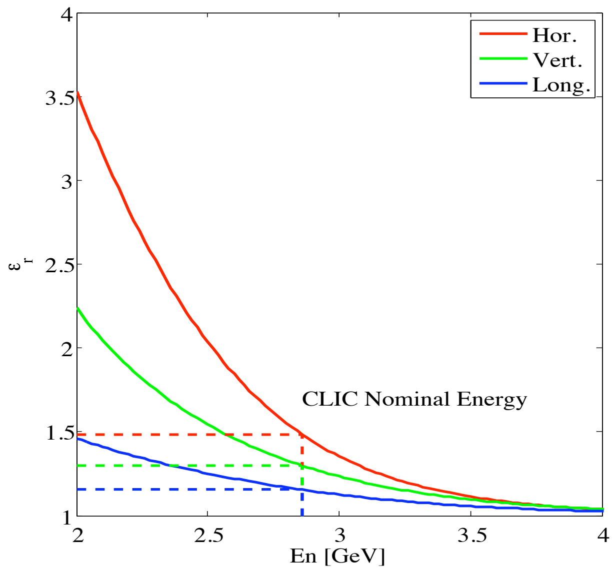
- For the present CLIC damping ring parameters, the vertical tune-shift after damping was reduced to -0.1 (versus -0.2 for the previous parameter) by
  - Reducing the circumference
  - Lengthening the bunch with larger momentum compaction
- For a previous ring version (slightly shorter ring, with lower energy and vertical SC tune-shift of -0.2), HEADTAIL simulations without the effect of radiation damping showed that the emittance growth is ~10% (i.e. 5% of the beam size). More ORBIT-PTC simulations envisaged.
- Note that high-intensity proton rings (e.g. PS) operate with SC tune-spread > 0.2 in both planes, without significant emittance growth over more than 1s and for for much larger emittances

IBS blow up versus ring emittance

F. Antoniou, Y. Papaphilippou, A. Vivoli

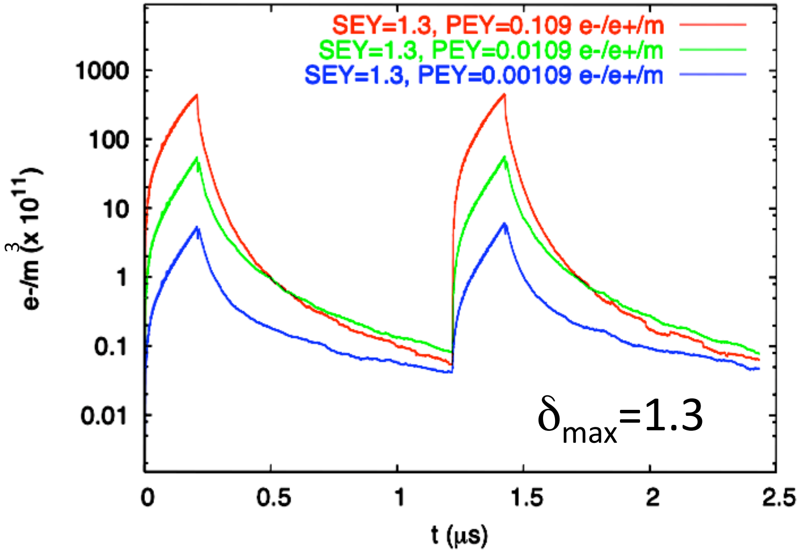
- Scaling of emittance growth due to IBS with energy obtained with Piwinski formalism for the same optics and constant output longitudinal emittance
- Broad minimum for transverse emittance ~2-3GeV
- Higher energy reduces ratio between zero current and IBS dominated emittance
- Choice of 2.86GeV in order to relax collective effects while achieving target emittances with contained IBS blow up
- Model predictions successfully compared with IBS tracking code
- CESR-TA measurements foreseen to benchmark predictions

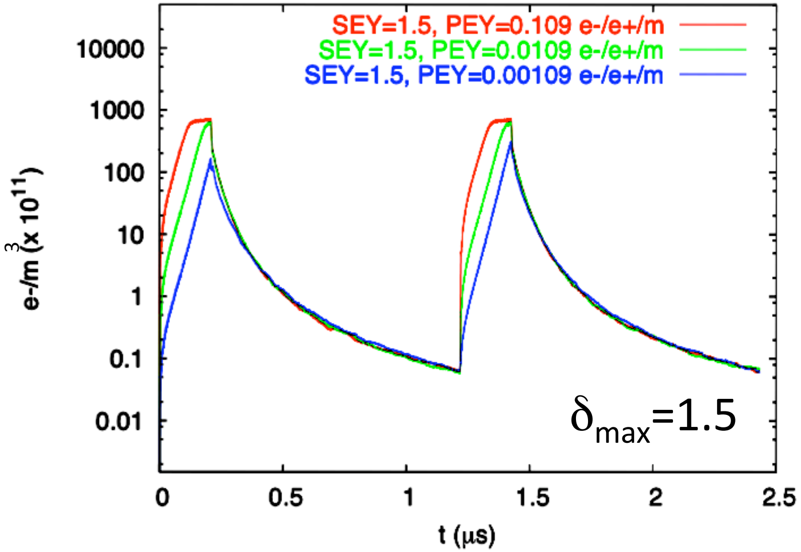


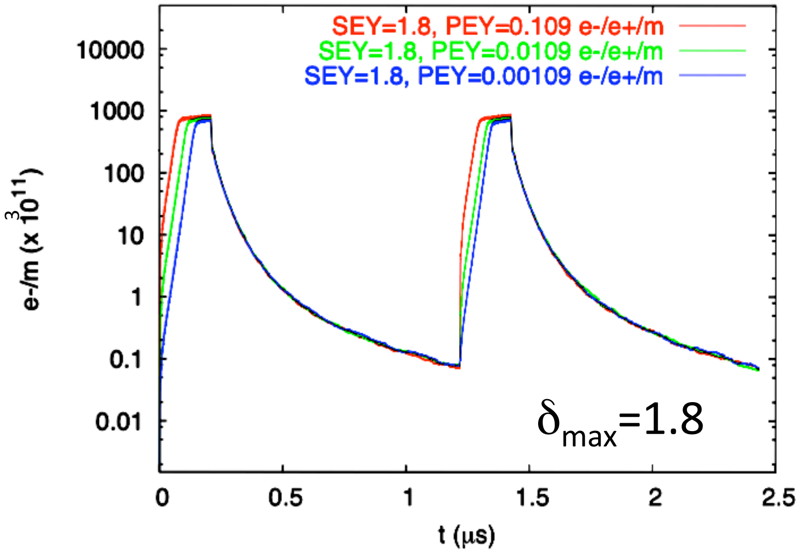


E-cloud @ 2 GHz: build up in wigglers

Central densities for different PEYs and SEYs







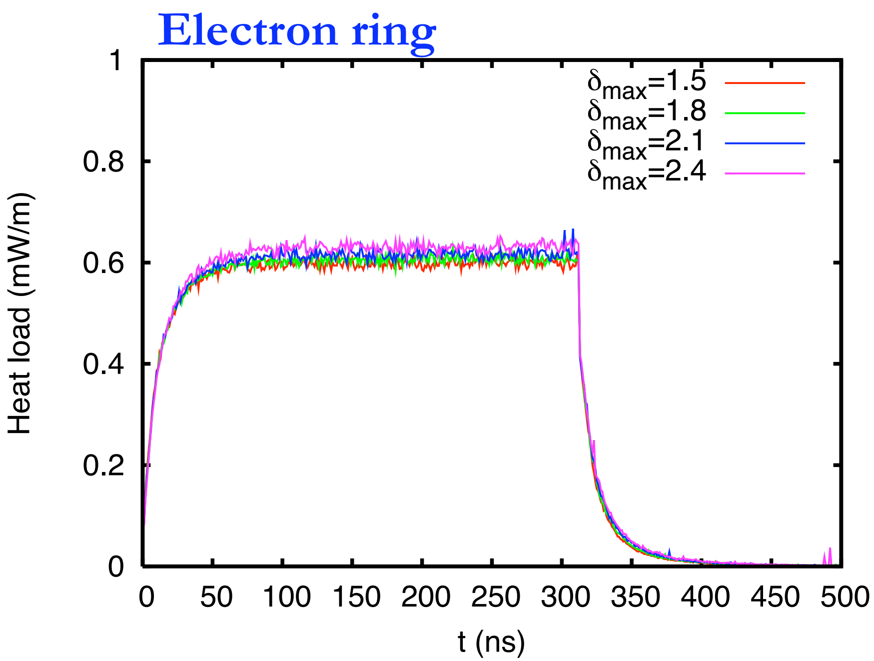
→ To **prevent the electron cloud in the wigglers** from reaching saturation density values causing beam instability (HEADTAIL simulations):

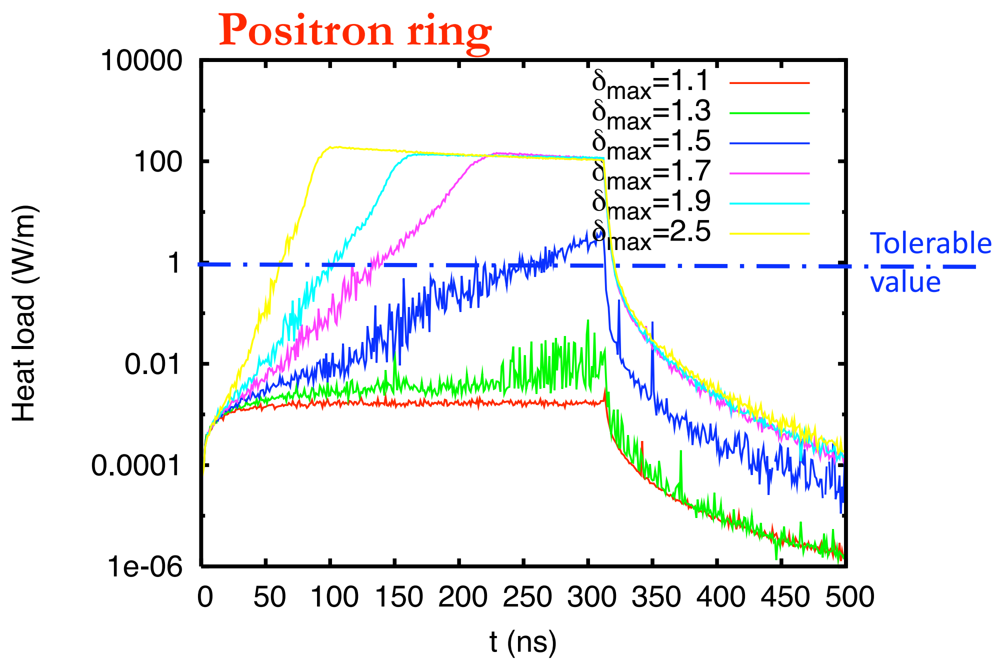
- ✓ Low PEY (i.e., 0.01% of the produced radiation not absorbed by an antechamber or by special absorbers or η_{PE} lowered to relax this constraint), though SEY is low
- ✓ SEY below 1.3, independently of the PEY

E-cloud @ 1 GHz: heat load in wigglers

- 2010-11: we have a baseline design for the superconducting wigglers (as shown in Yannis' talk)
- Based on the present design, we have assumed 99.9% of the synchrotron radiation to go into the absorbers, so that only 0.1% of the total incident radiation ends up uniformly scattered around the wiggler walls and produces photoelectrons (D. Schoerling)
- Calculations of heat load were done with the ECLOUD code
- The maximum Secondary Emission Yield (δ_{max}) has been scanned from 1.1 to values above 2
- Knowing from ANKA about significant heat load measured in a superconducting wiggler, simulations were done both for the positron and the electron ring.

E-cloud @ 1 GHz: heat load in wigglers





- No significant multipacting (heat load) for the **electron ring** (<1 mW/m)
  - Vacuum specification determined by the fast ion instability
- Multipacting appears in the **positron ring** for δ_{max} above 1.3 (but causes strong e-cloud over 1 train passage for values above 1.4-1.5)
  - For values of δ_{max} above 1.4 the heat load grows to values above 1 W/m!
  - Anyway, electron clouds with these values make the beam unstable…
  - With 1GHz, δ_{max} below 1.3 and 0.1% of residual radiation seem acceptable!
  - Low SEY coating (a-C, NEG) is needed

Against the electron cloud….

→ If there is electron cloud in the CLIC-DR, the beam becomes unstable!

- o Conventional feedback systems cannot damp this instability (wider band needed)
- o It is necessary to find techniques against the formation of the electron cloud

→ Several mitigation techniques are presently under study (LER2010):

- ✓ Low impedance clearing electrodes
- ✓ Solenoids (KEKB, RHIC) -however only usable in field free regions!
- ✓ Low SEY surfaces
  - ▪ Grooved surfaces (SLAC)
  - ▪ NEG and TiN coating
  - ▪ New coatings presently under investigation (SPS and Cesr-TA)

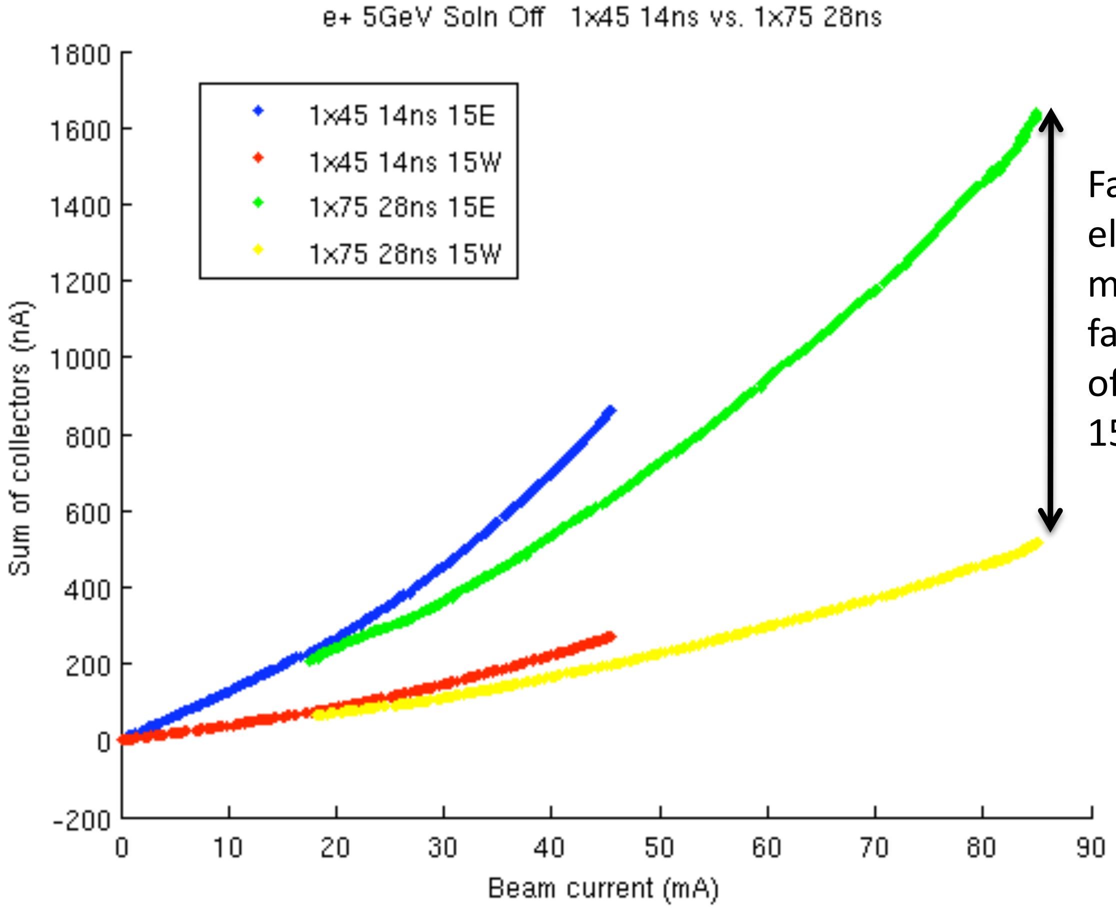
Carbon coatings, intensively studied by the SPS Upgrade Working Team, seem very promising and a possible solution.....

PEY of an a-C coated surface

- Run with positrons at 5 GeV, example of intensity scan at Cesr-TA
- Comparing data with two bunch spacings and train lengths (45 x 14ns, 75 x 28ns). The total electron current is displayed as a function of the beam current.

15W is a C-coated chamber

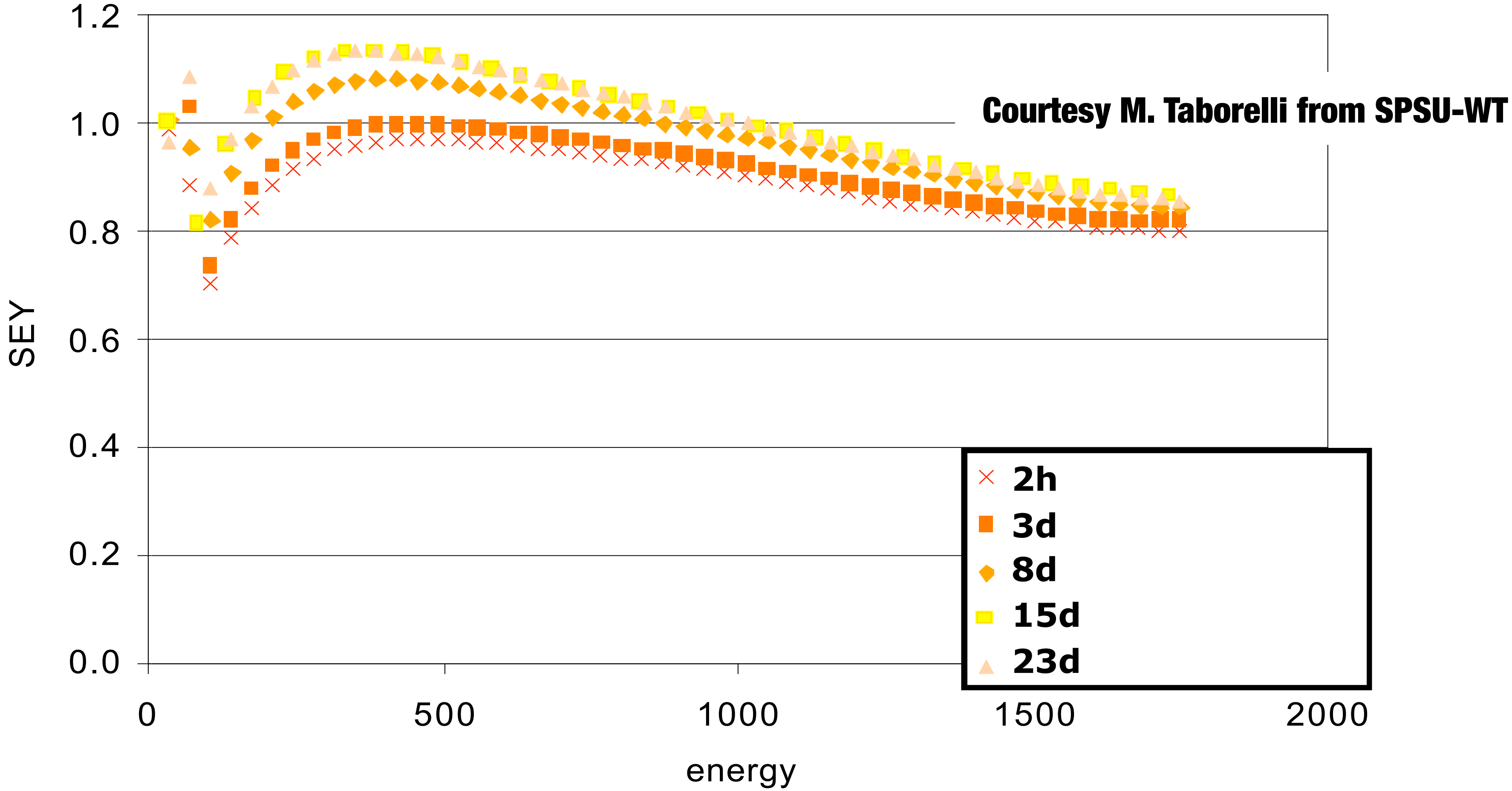
15E is an Al chamber



Factor 4 less electron flux, to be multiplied by a factor 2 difference of photoelectron in 15W wrt 15E

J. Calvey, M. Palmer, S. Calatroni, GR

SEY of an a-C coated surface



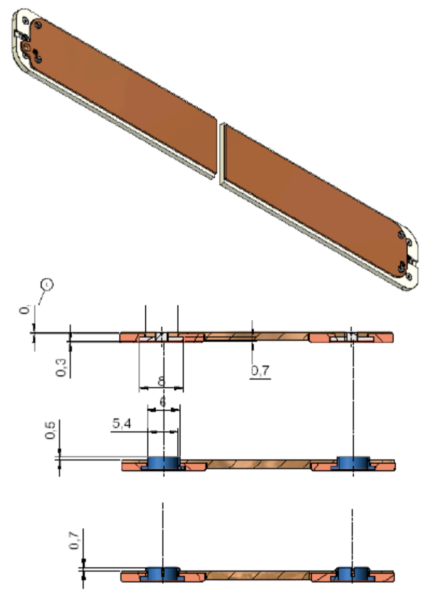
The maximum SEY starts from below 1 and gradually grows to slightly more than 1.1 after 23 days of air exposure.
The peak of the SEY moves to lower energy.

Beware…

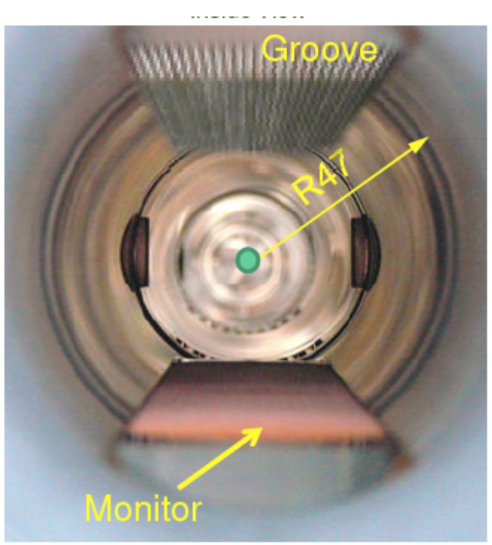
From LER 2010 Workshop

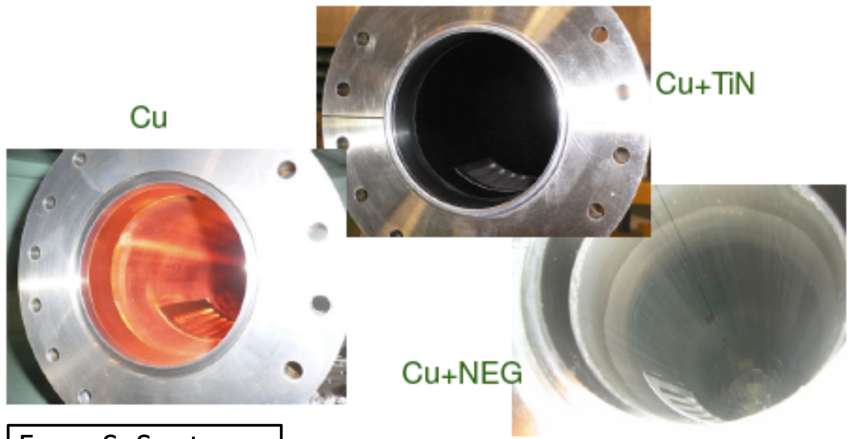
- Some techniques to fight electron cloud (or have good vacuum) do not come for free and can be serious high frequency impedance sources:
  - Surface coating with low SEY materials (Cu, NEG, TiN, a-C)
  - Non-smooth surfaces (natural roughness, grooves)
  - Clearing electrodes
  - NEG coating for pumping

Clearing electrodes for DAFNE



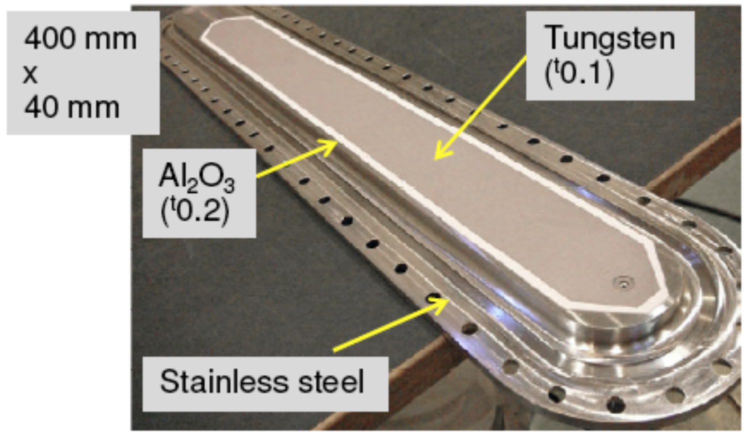
From T. Demma





From S. Suetsugu

An insertion for test with a thin electrode

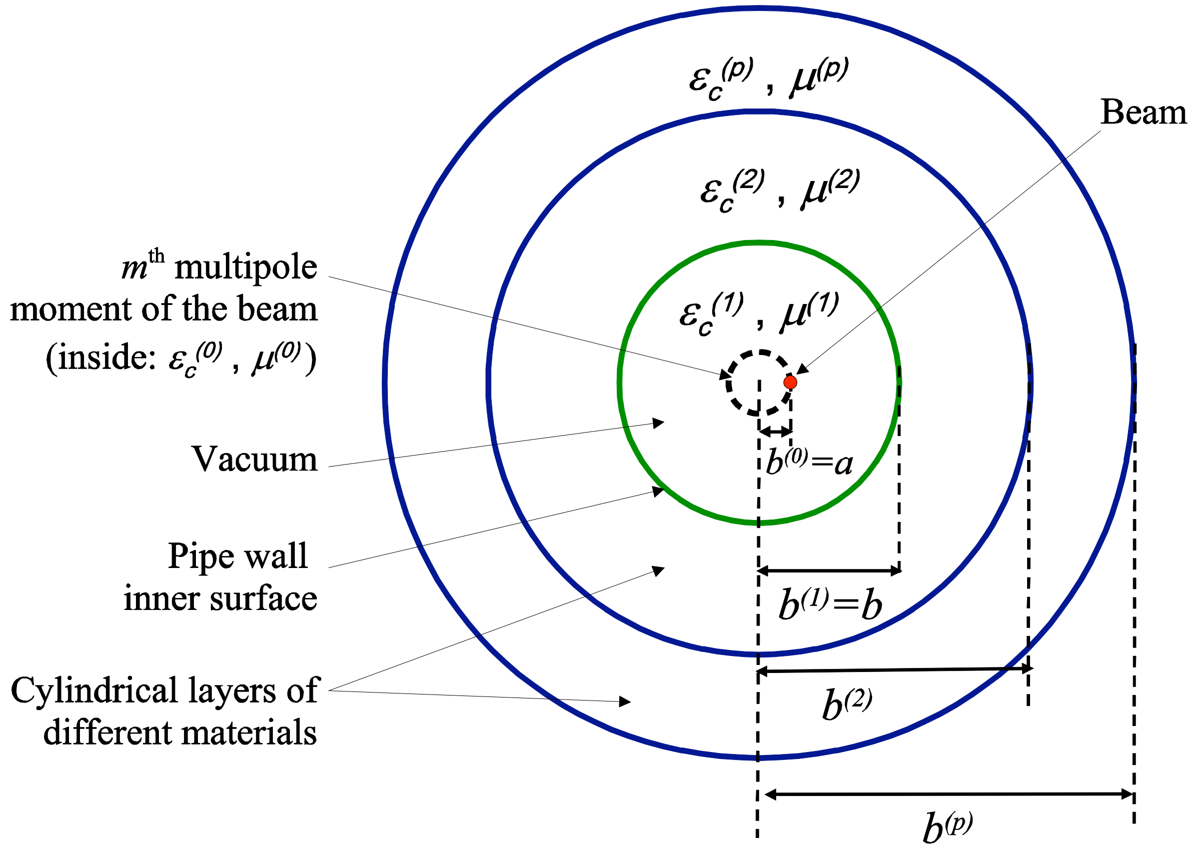


Resistive wall in the CLIC-DR regime

- Layers of coating materials can significantly increase the resistive wall impedance at **high frequency**
  - Coating especially needed in the low gap wigglers (not yet decided for the electron ring, as NEG is not proved to pump at low temperatures)
  - Low conductivity, thin layer coatings (NEG, a-C)
  - Rough surfaces (not taken into account so far)

N. Mounet

Pipe cross- section:



CLIC-DR Resistive wall impedance w/o coating

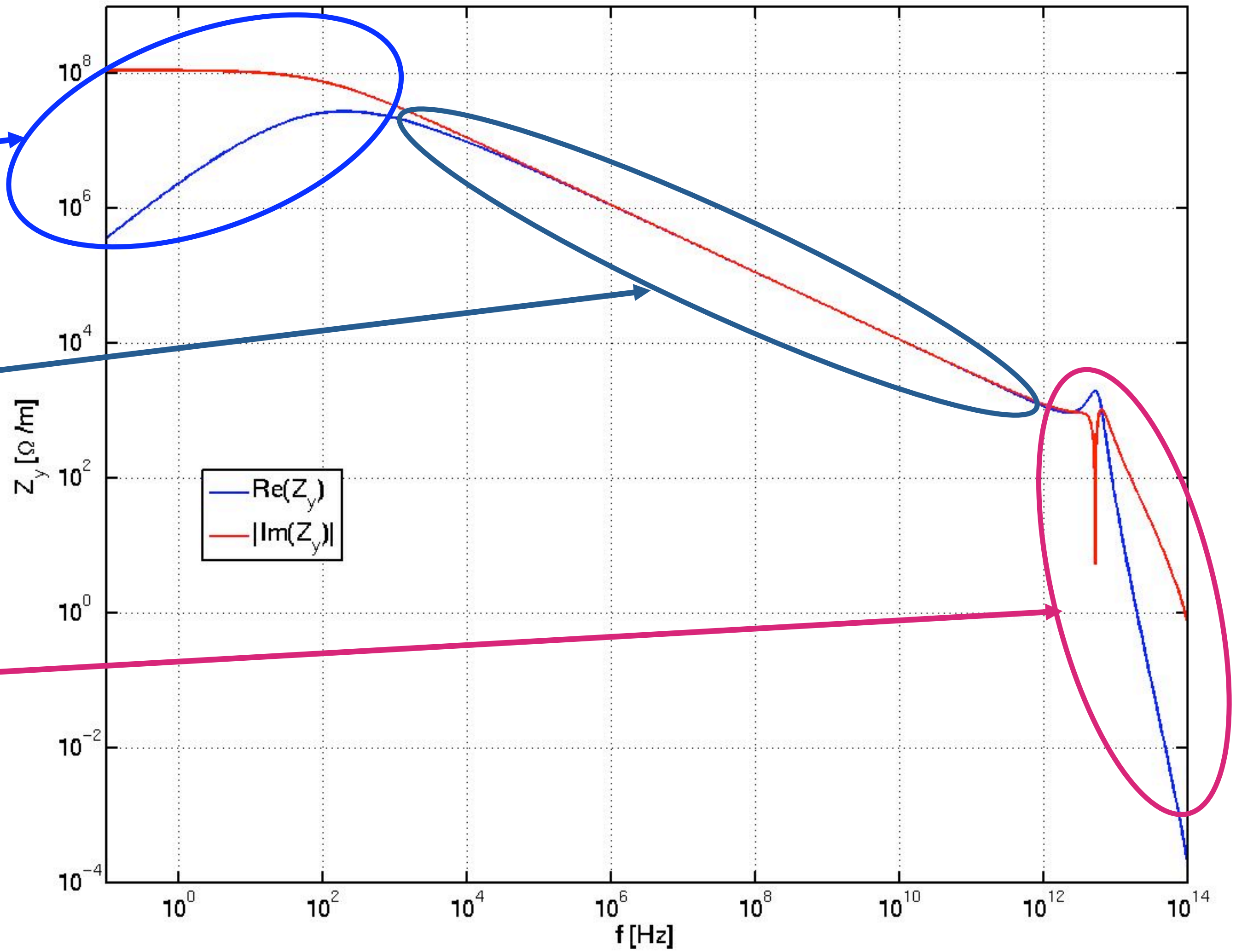
- Vertical impedance in the wigglers (pipe made of copper without coating)

Low frequency or "inductive-bypass" regime: finite thickness, full penetration of the em fields

"Classic thick-wall" regime

High frequency regime:

ac conductivity and relaxation time



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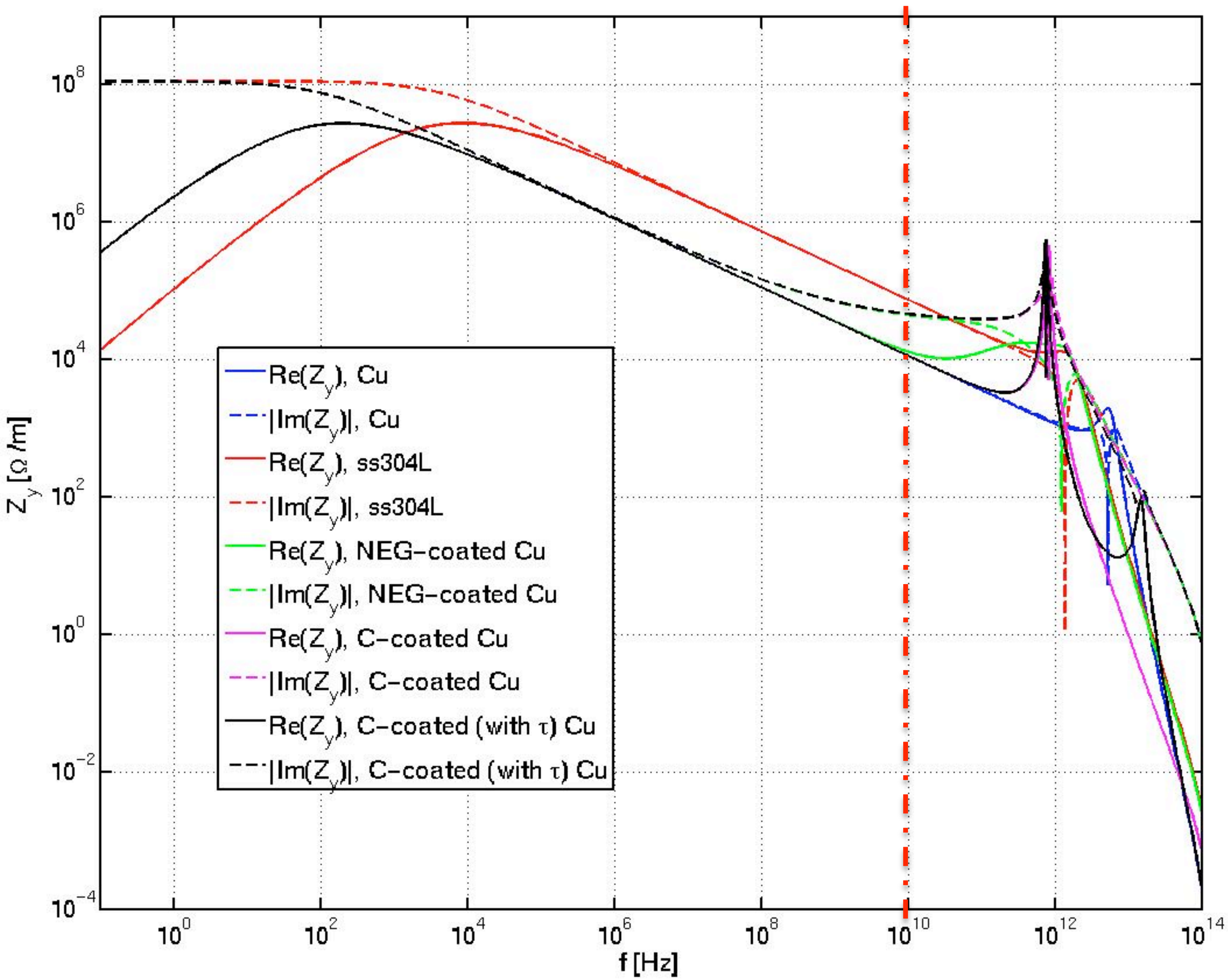
CLIC-DR resistive wall for different coatings

- Vertical impedance in the wigglers for different materials: global view



⇒ Coating is "transparent" up to ~*10* GHz

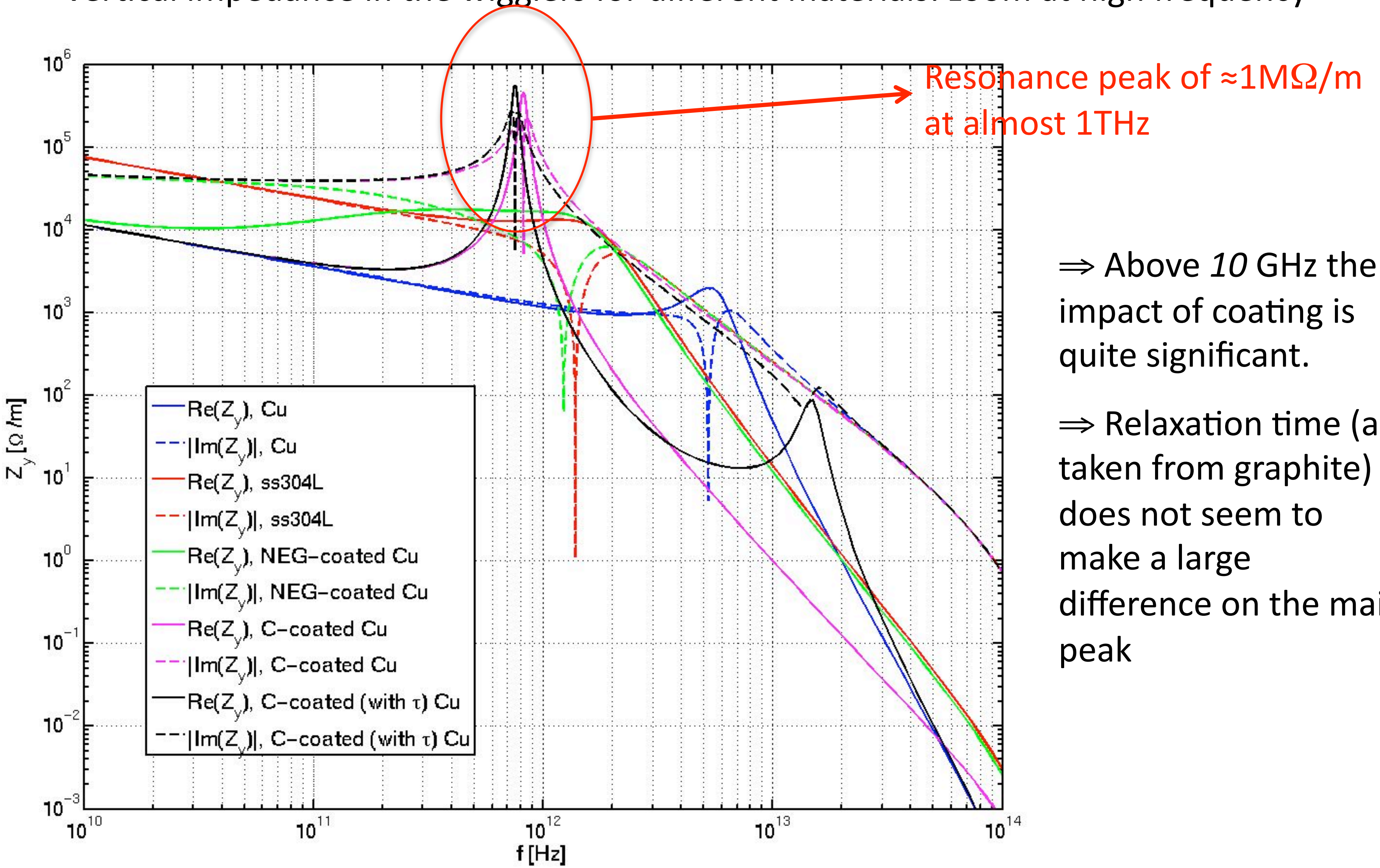
⇒ But at higher frequencies some narrow peaks appear!!

⇒ So we zoom for frequencies above 10 GHz →

N. Mounet

CLIC-DR resistive wall for different coatings

- Vertical impedance in the wigglers for different materials: zoom at high frequency

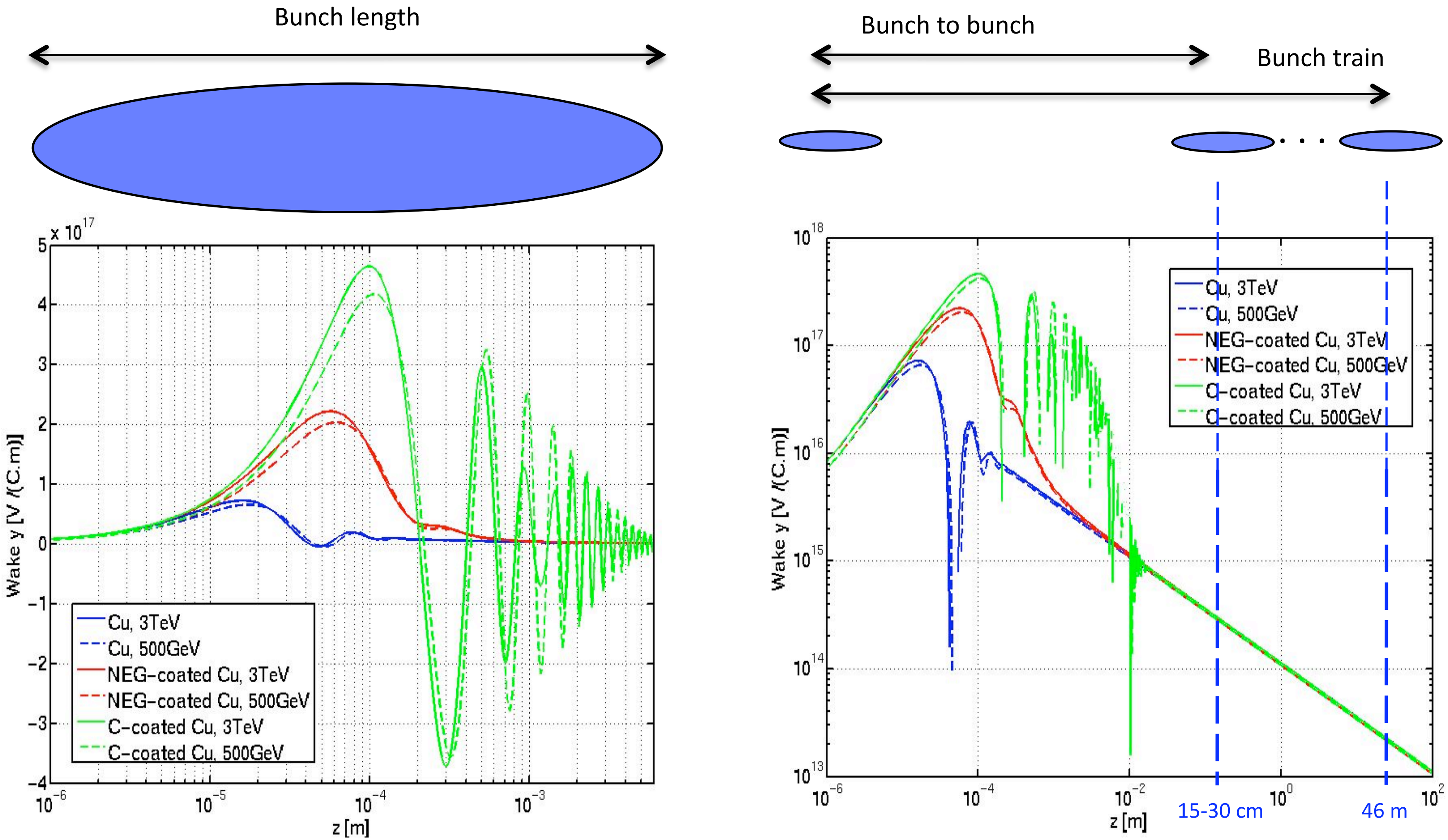


⇒ Above *10* GHz the impact of coating is quite significant.

⇒ Relaxation time (as taken from graphite) does not seem to make a large difference on the main peak

N. Mounet

Time domain: Wake fields, input for simulations



- The presence of coatings strongly enhances the wake field on the scale of a bunch
- The single bunch instability threshold should be evaluated through simulations, no expected impact on the coupled bunch instability
- This will lower the **transverse impedance budget for the DRs**

N. Mounet

Broad-band impedance budget: single bunch

- **Longitudinal**

✓ The Boussard criterion (including in the formula the suppression factor $(b/\sigma_z)^2$) would give a maximum normalized impedance **value of up to 3Ω**

$$\left|\frac{Z_0^{||}}{n}\right| < 1.7\ln(2) Z_0 \frac{|\eta|\gamma}{N_b r_0}\sigma_\delta^2\sigma_z$$

- **Transverse**

✓ The TMCI threshold is given by the formula below for resonator impedance

✓ The CLIC-DRs are in short bunch regime, and the formula translates into a tolerable **impedance value of about 12 MΩ/m** if $\omega_r = 2\pi$ x 5 GHz

$$\xi < \frac{Q_s}{\omega_r\sigma_t} \quad \text{if} \quad \omega_r\sigma_t \leq 1$$

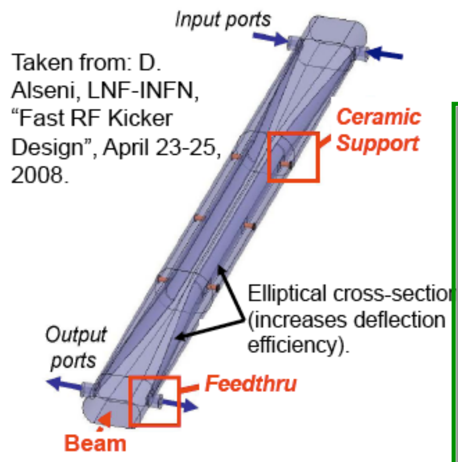
$$\xi < \sqrt{2} Q Q_s (\omega_r\sigma_t)^2 \quad \text{if} \quad \omega_r\sigma_t \gg 1$$

where

$$\xi = \frac{\omega_r/2\pi < \beta_y > R_T N_b \mathrm{e}}{3.75\, QE/\mathrm{e}}$$

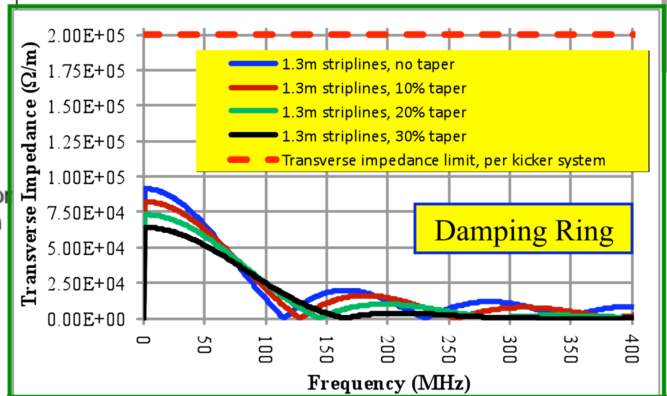
Impedance database: program launched

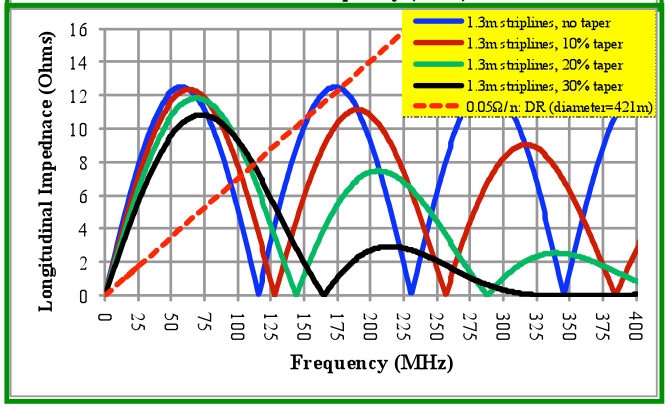
- Contributions of **coatings** to resistive wall
- **Kickers**: Choice to go for tapered stripline kickers to reduce the transverse and longitudinal impedance. Striplines to be designed and prototyped under the Spanish program Industry for Science (M. Barnes)
- **Cavities**: values scaled from the NLC DR RF cavity design, impact of the HOMs on the beam stability/energy loss to be evaluated also depending on the absorbers (A. Grudiev)
- All the wake fields will be used for detailed **HEADTAIL simulations**, as is presently done for the SPS/LHC to predict the instability thresholds

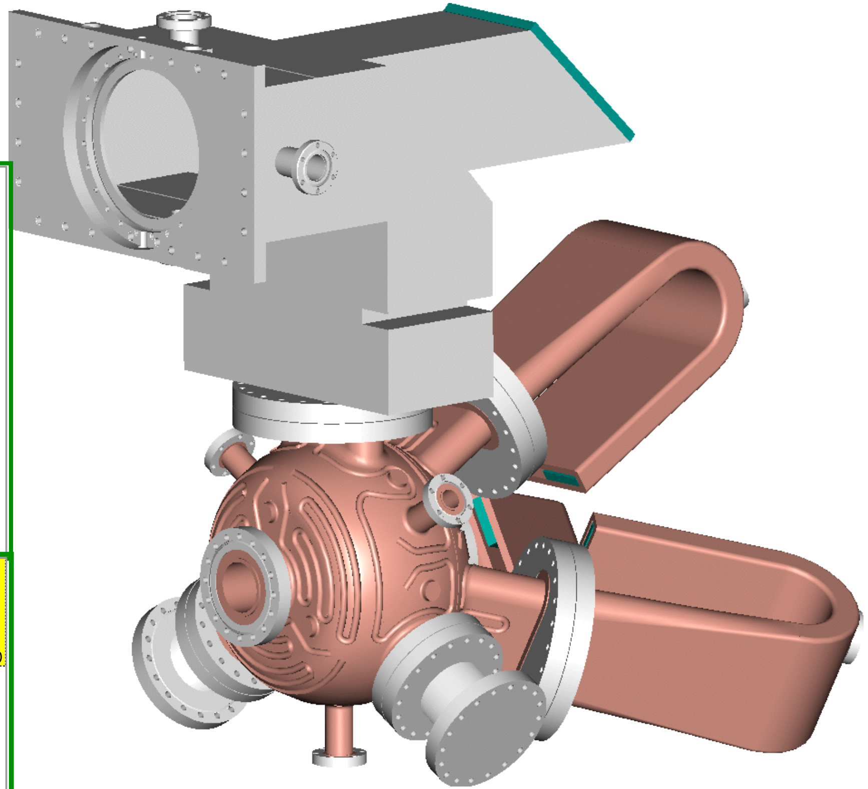


DAΦNE Striplines (~0.94m)

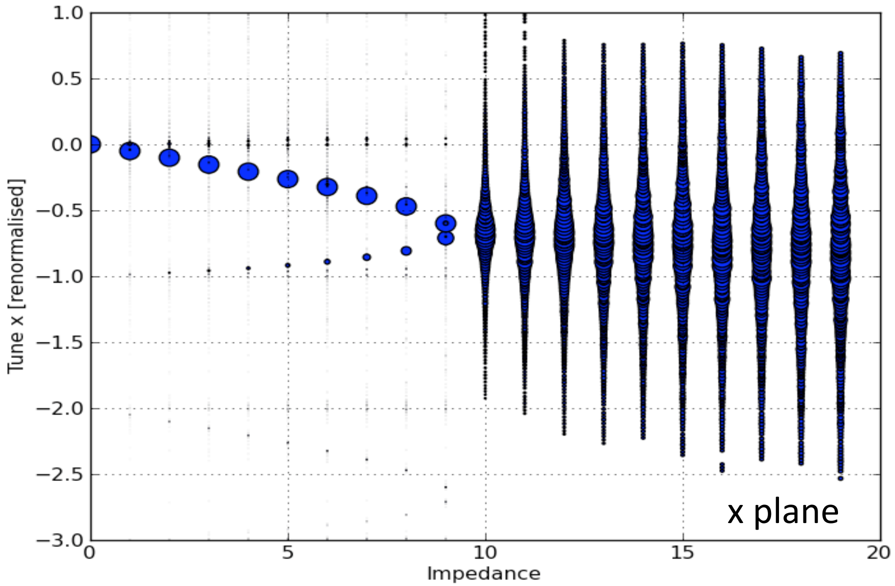
Note: taper ≈ 30% of overall length.

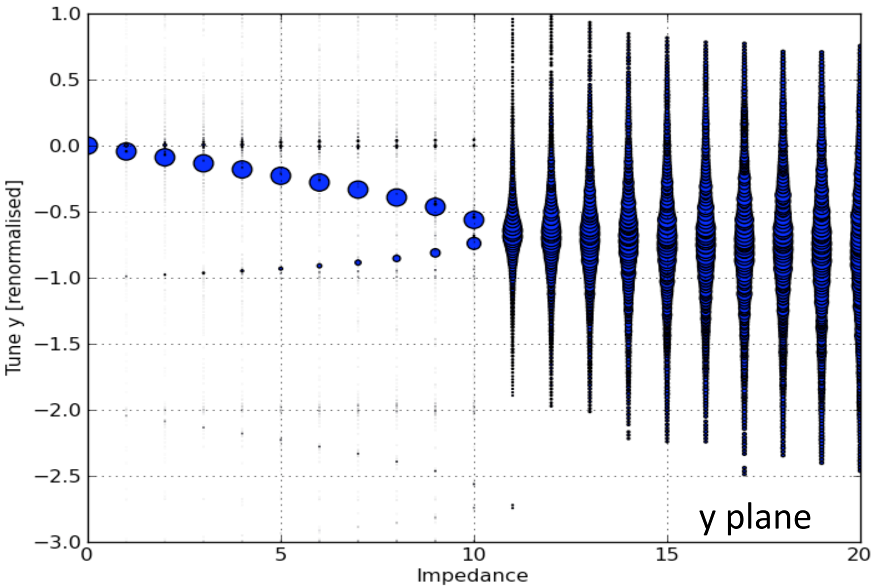






Impedance budget: TMCI threshold





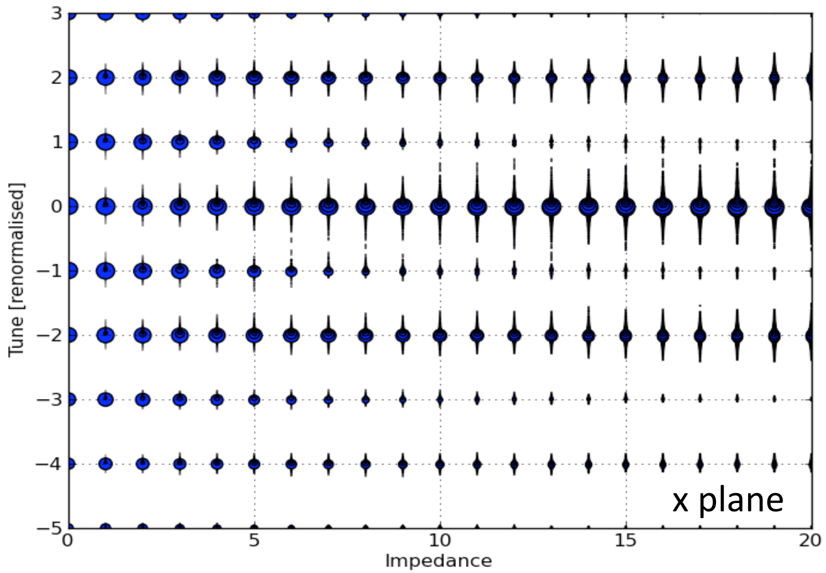
<u>Mode spectrum of the horizontal and vertical coherent motion as a function of BB impedance</u>

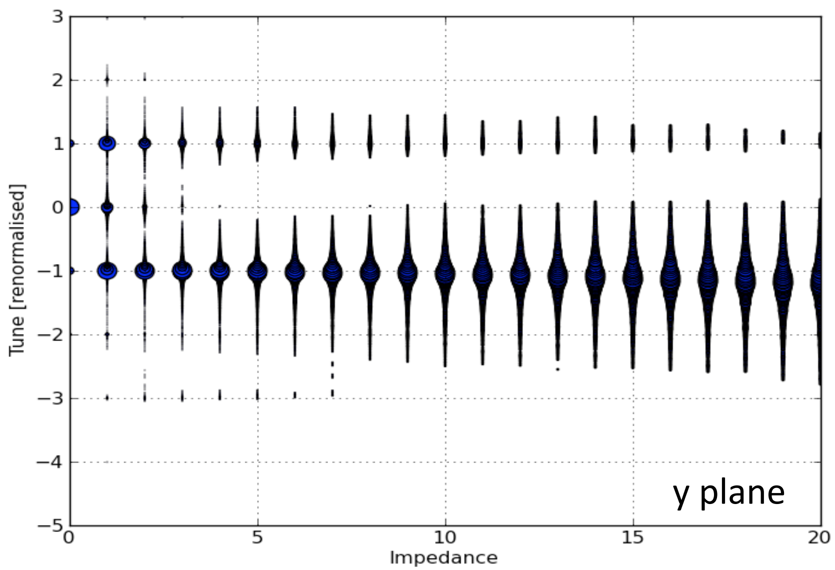
- Plot all the tunes (Q-Qx)/Qs and (Q-Qy)/Qs with impedance
- Mode spectrum represents the natural coherent oscillation modes of the bunch
- The shift of the modes due to impedance causes them to merge and leads to an instability

❑ The mode 0 is observed to couple with mode -1 in both planes, causing a TMCI instability, for a symmetric impedance source of about 11MΩ/m

E. Koukovini

Impedance budget: TMCI threshold





<u>Can positive chromaticity help increase the threshold?</u>

Horiz.chrom. ξ_x	0.2
Vert. chrom. ξ_y	0.2
Geometry	Round

- ➢ Chromaticity makes the modes shift less, no visible coupling
- ➢ Another type of instability (head-tail) is observed on mode -1 (higher for larger $\xi_{x,y}$)
- ➢ Dangerous as long as rise time is shorter than damping time (lowers impedance budget to only few MΩ/m for low chromaticity values)

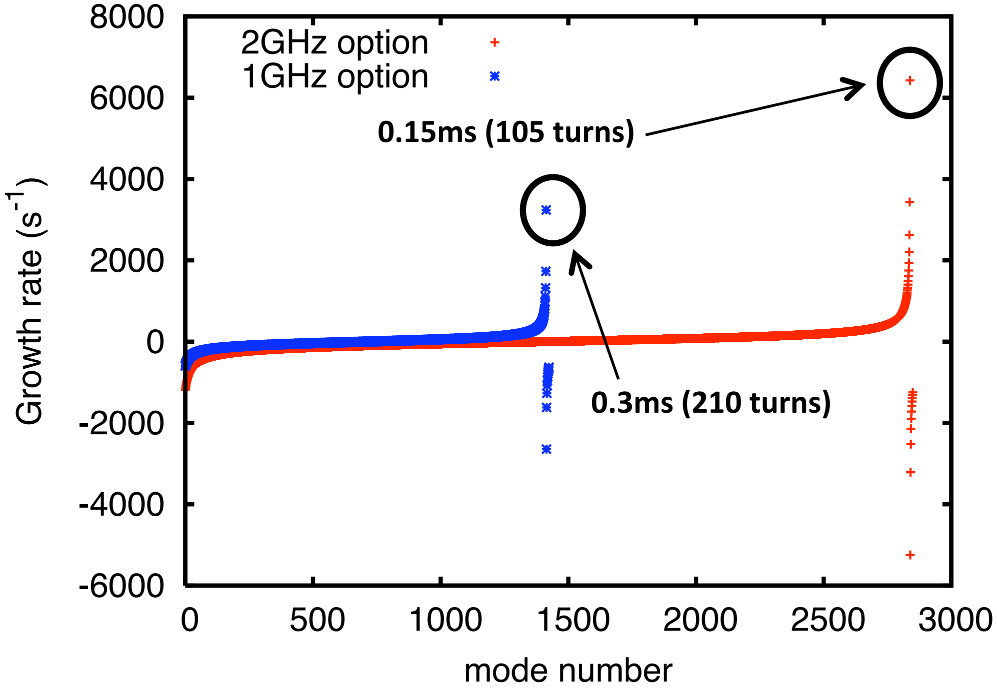
E. Koukovini

Coupled bunch instability from resistive wall

$$\Delta\omega_{\mu,m}^{x,y} = -\frac{\mathrm{i}}{2}\frac{\Gamma(m+1/2)}{2^m m!}\frac{N_b r_0 c^2 <\beta_{x,y}>}{\gamma C \sigma_z} \cdot \frac{\sum_{p=-\infty}^{\infty} Z_1^{x,y}(\omega_p) h_m(\omega_p - \omega_{\xi x,y})}{\sum_{p=-\infty}^{\infty} h_m(\omega_p - \omega_{\xi x,y})},$$

with

$$h_m(\omega) = \left(\frac{\omega\sigma_z}{c}\right)^{2m} \exp\left(-\frac{\omega^2\sigma_z^2}{c^2}\right)$$
$$\omega_p = (pM + \mu + Q_{x,y} + m\nu_s)\omega_0 \quad .$$
$$\mu = 0, 1, ..., M-1$$
$$m = 0, \pm 1, \pm 2, ...$$



Pessimistic estimate because:

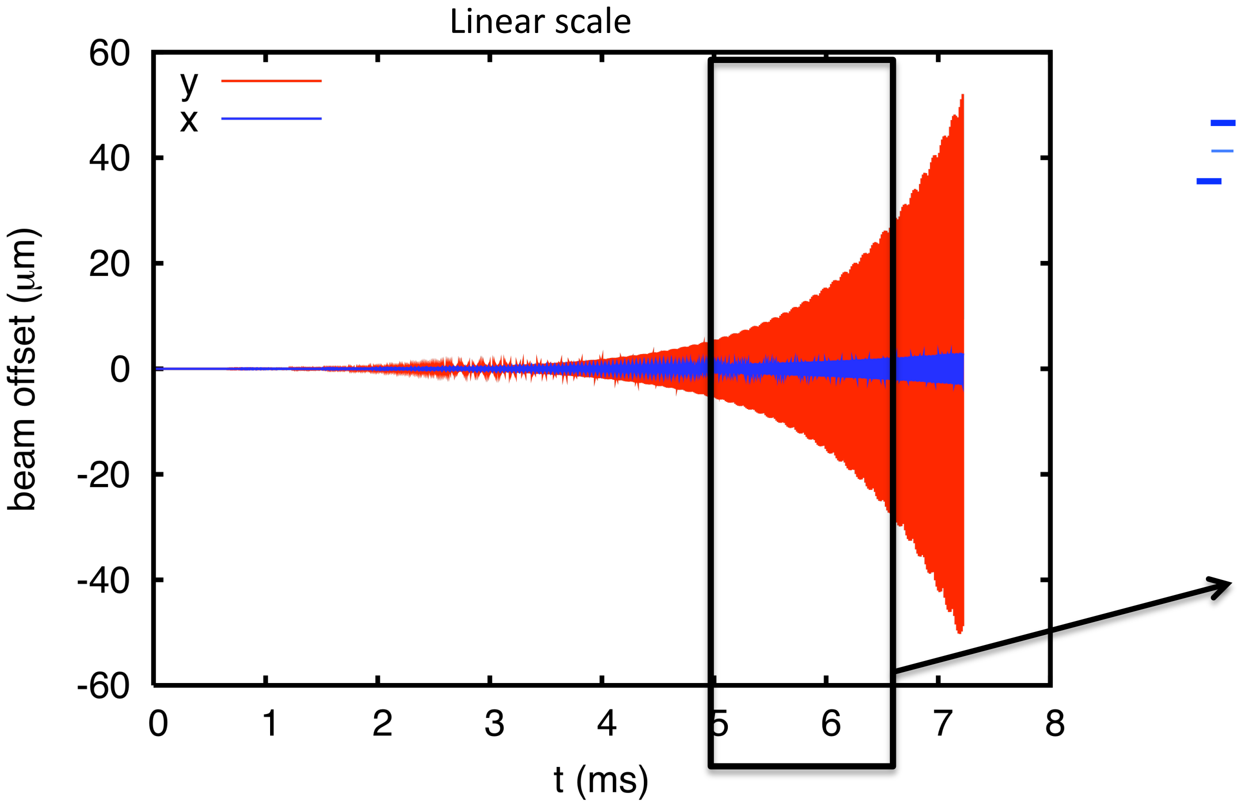
1. Wigglers only cover half of the ring, which gives possibly a factor 2
2. Instability rate has to be scaled by n_b/M, because the formulae assume a uniformly filled ring.

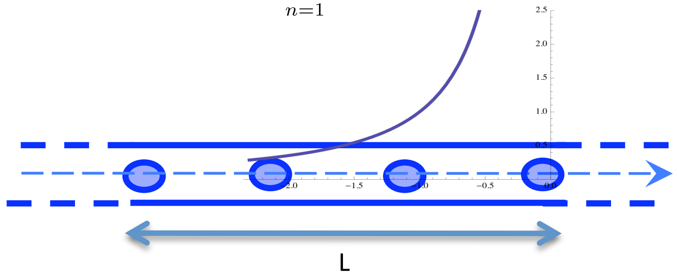
However we assumed a Cu pipe!

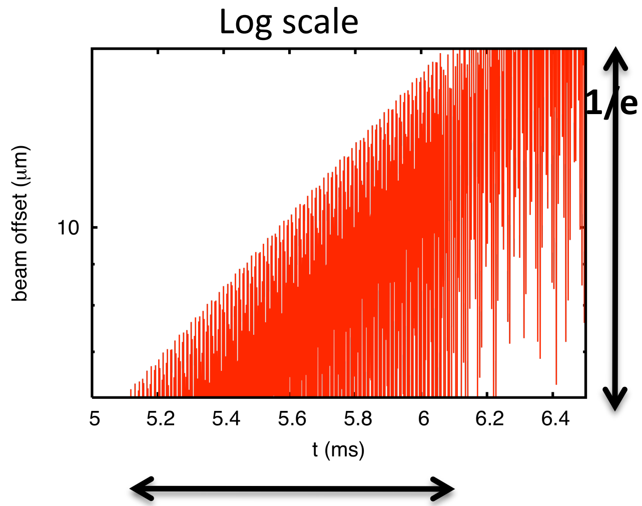
Coupled bunch instability: macroparticle simulation

HEADTAIL simulations with the parameters of the 2 GHz option

$$\Delta x'_{i,j} \propto N_e \sum_{n=1}^{N-i-1} [W_{\perp d}(ncT_b)\langle x\rangle_n + W_{\perp q}(ncT_b)x_j]$$







τ=1ms

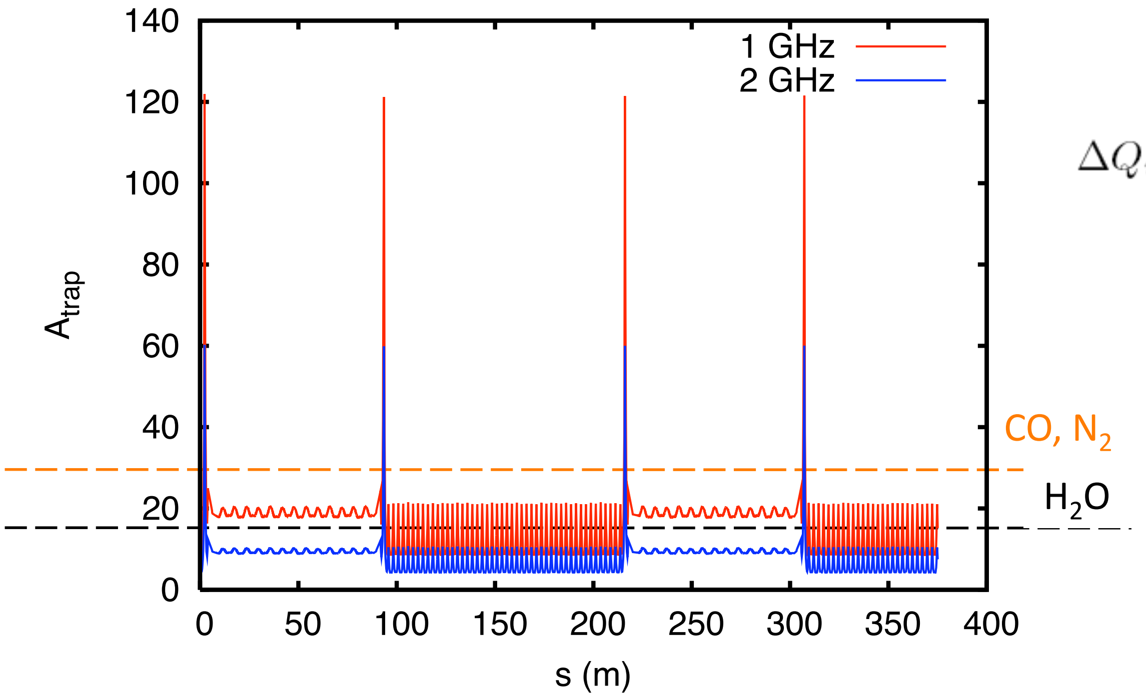
In the plot

→ The evolution of the vertical centroid of the train exhibits an exponential growth in both the horizontal (slow) and vertical (fast) plane

→ The **rise time** is larger than the calculated one by about a factor 5-10, because the simulation takes into account the real wiggler length and the train length

Coupled bunch instability: fast ion effects

The ions trapped around the beam are those having a mass number above a critical value, which depends on the location in the ring (due to the different beam sizes)



$$\Delta Q_{ion} \simeq \frac{N_b n_b r_e C}{\pi\gamma\sqrt{\epsilon_x\epsilon_y}}\left(\frac{\sigma_{ion} p}{k_B T}\right) \simeq \begin{cases} 0.008 & 1\text{GHz} \\ 0.02 & 2\text{GHz} \end{cases}$$

$$\tau_{inst} \simeq \frac{0.1\cdot\gamma\sigma_x\sigma_y}{N_b n_b c r_e \beta_y \sigma_i}\left(\frac{k_B T}{p}\right)\sqrt{\frac{8}{\pi}}$$

✓ Molecules like N_2, CO trapped almost along the full ring (1 and 2GHz).

✓ For the 1 GHz option the critical masses for trapping are twice as large, reducing the fraction of the ring over which ions like H_2O can be trapped.

✓ With a pressure of 1nTorr moderate tune shift, but intolerable instability growth time (few turns for both options)!

From summary talk of LER 2010: instabilities and beam quality degradation

- Many types of instabilities observed in the existing machines, often limiting their performance, and enhanced by low emittance design
  - Coupled bunch instabilities (e.g., e-cloud in DAΦNE, FBII in SOLEIL)
  - Transverse Mode Coupling Instability (ELETTRA)
  - Head-tail instabilities on mode 0, or higher (ELETTRA, SOLEIL)
  - Bunch lengthening, hitting the microwave instability threshold (DAΦNE, ELETTRA)
  - Emittance blow up (DAΦNE, SOLEIL)
  - CSR causing microwave-like instability (ANKA)
- Instability suppression:
  - High positive chromaticity, but this excites higher order head-tail modes and could deteriorate the beam lifetime
  - Landau cavities for bunch lengthening
  - Impedance reduction (→ low impedance design, HOM absorption)
  - Active feedback system (multi-bunch or single-bunch)
  - Quality of the vacuum, low SEY surfaces
  - Still unidentified self-stabilizing mechanism for FBII? Seldom observed in existing light sources, formulae are pessimistic

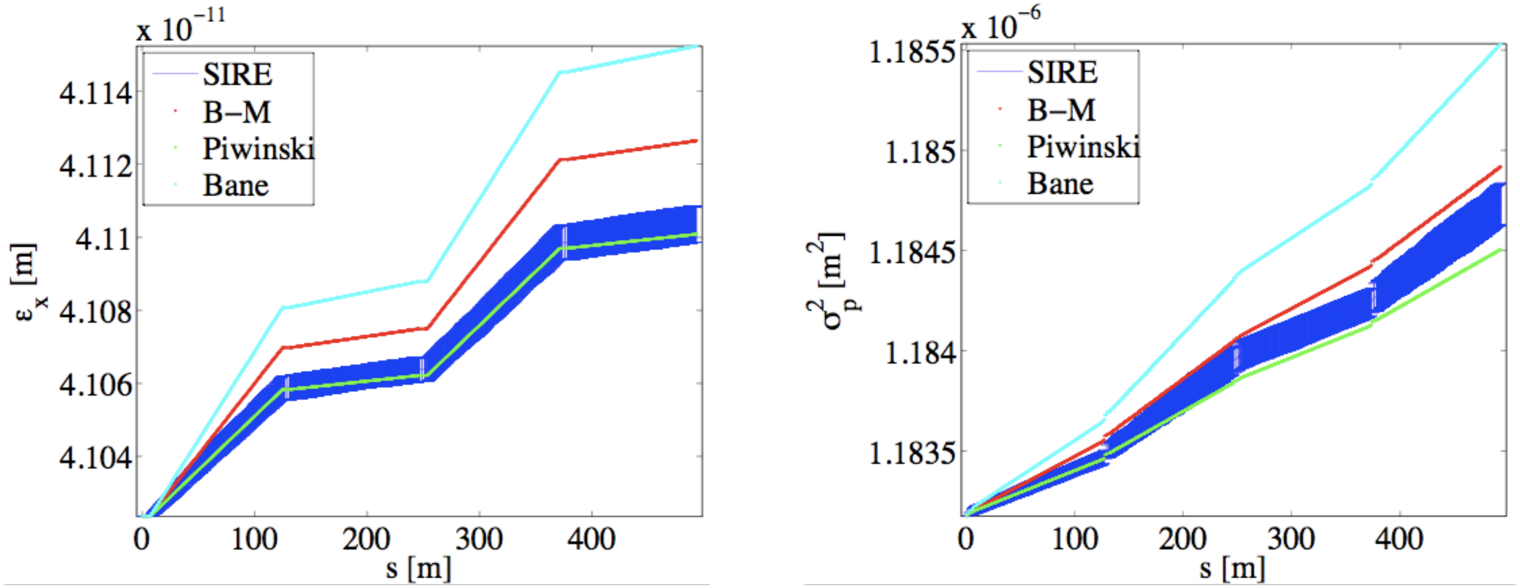
A list of future studies

- High frequency effects of resistive wall (general and from coated chambers):
  - ✓ Properties of the coating material
    - → Measure or calculate $\varepsilon(\omega)$, $\mu(\omega)$ and $\sigma(\omega)$
    - → Ac conductivity (relaxation time)
    - → Anomalous skin effect (breaking of Ohm's law at high frequency)
  - ✓ Yokoya's factors, applicable in the classical resistive wall regime, maybe not valid at high frequency (and the wiggler chambers are flat) → underway!
  - ✓ Influence of surface roughness, of temperature (wigglers are cold, better for Cu but worse for a-C?), of curvature …
  - ✓ Tests to be possibly foreseen in Cesr-TA?
- Impedance database:
  - ✓ Stripline kickers: em simulations, build prototype, bench measurements, tests in ATF (M. Barnes, C. Belver)
  - ✓ Include more available contributions:
    - → Instrumentation (BPMs, emittance measurements devices)
    - → Clearing electrodes (maybe option to be kept in consideration)
- Feasibility and specifications of a feedback system
- Macroparticle simulations:
  - ✓ Space charge
  - ✓ Single and multi-bunch instability thresholds with impedances from database
- Coherent synchrotron radiation

⇒ Issue → Limited manpower!

IBS tracking code

F. Antoniou, A. Vivoli, et al.



- Developed Monte-Carlo tracking code for IBS including synchrotron radiation damping and quantum excitation (SIRE, based on MOCAC)
- Agreement between analytical emittance growth (especially Piwinski approach) and the mean values obtained by 20 SIRE runs
- Final emittances obtained by SIRE are within the CLIC DR budget
- Benchmarking with measurements foreseen at CESRTA

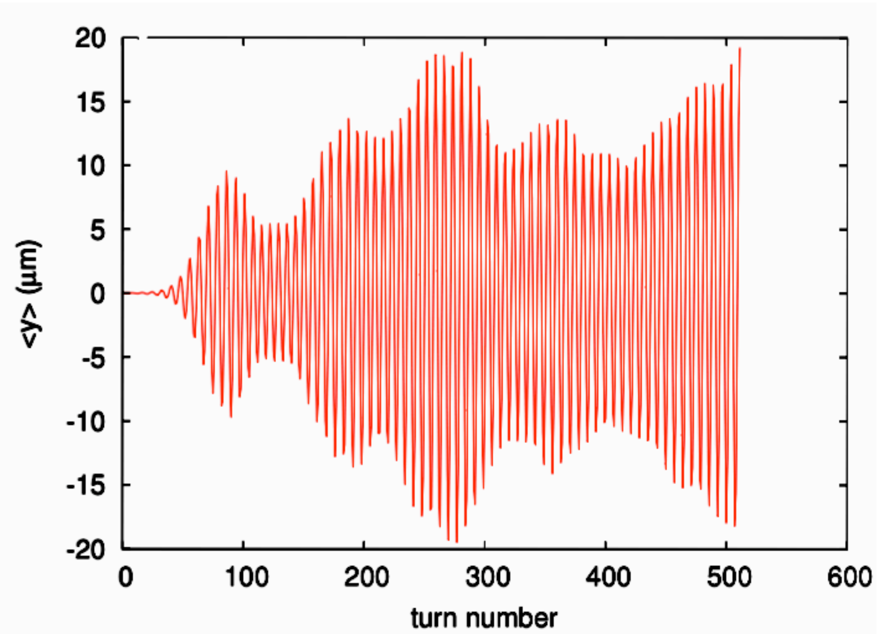
Beam stability with e-cloud (HEADTAIL)

→ In case of electron cloud build up, we assume these density values in arcs and wigglers (saturation values weighted by the fraction of coverage):

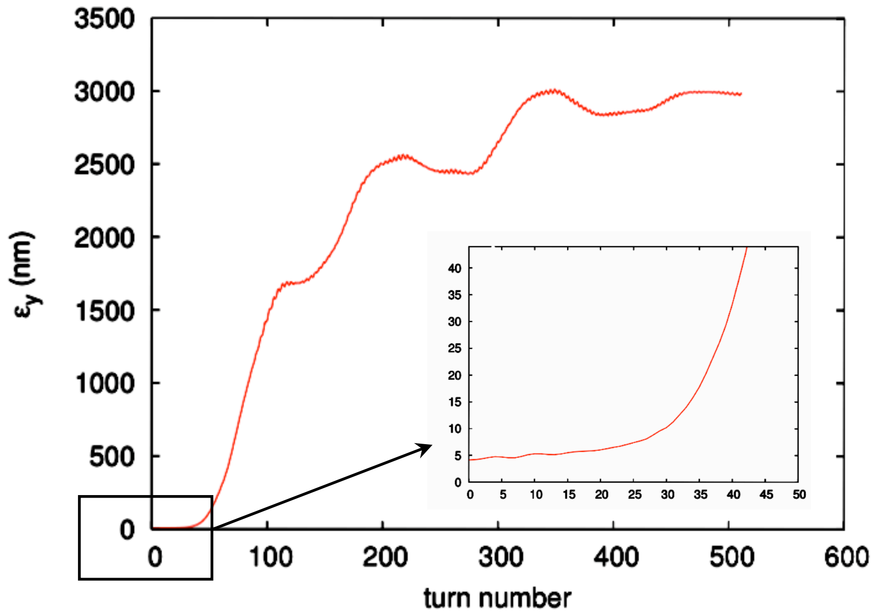
$\rho_{wig} = 2 \times 10^{13}\ m^{-3}$ $\rho_{dip} = 3 \times 10^{11}\ m^{-3}$

→ The beam is affected by **a strong and fast instability in the vertical plane**

→ The presence of an electron cloud in the wigglers is not compatible with stable operation of the positron damping ring. **Electron cloud suppression is necessary!**

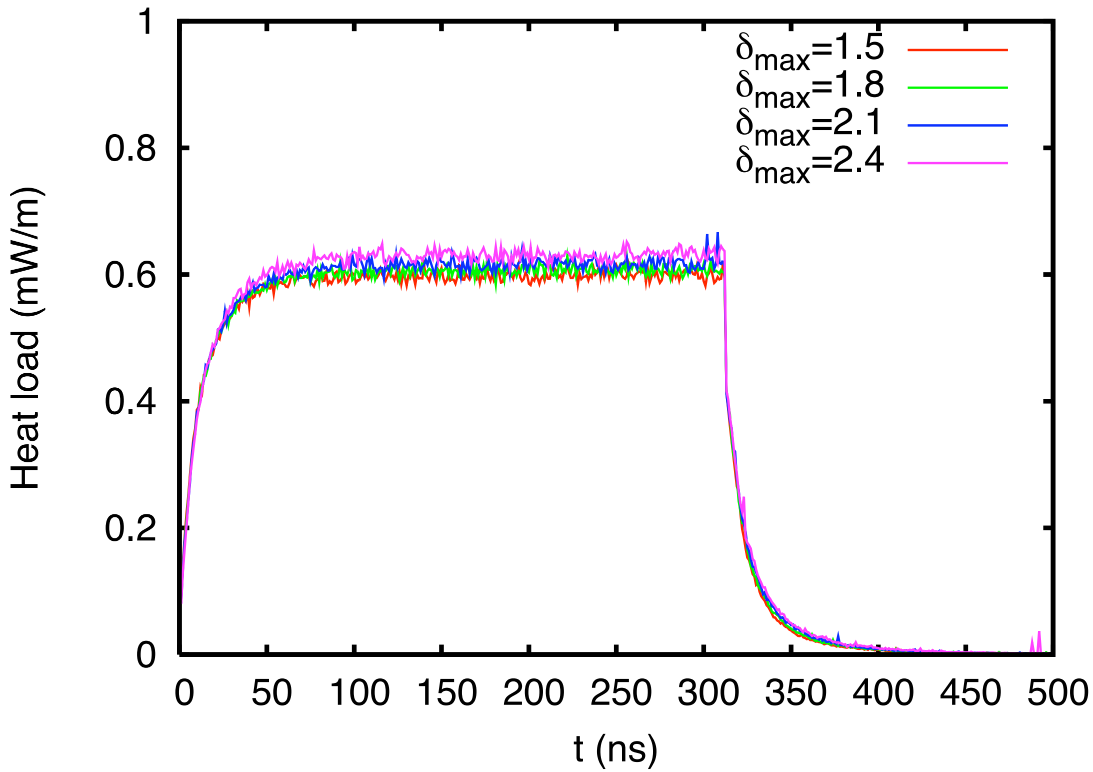


*** Vertical centroid motion**



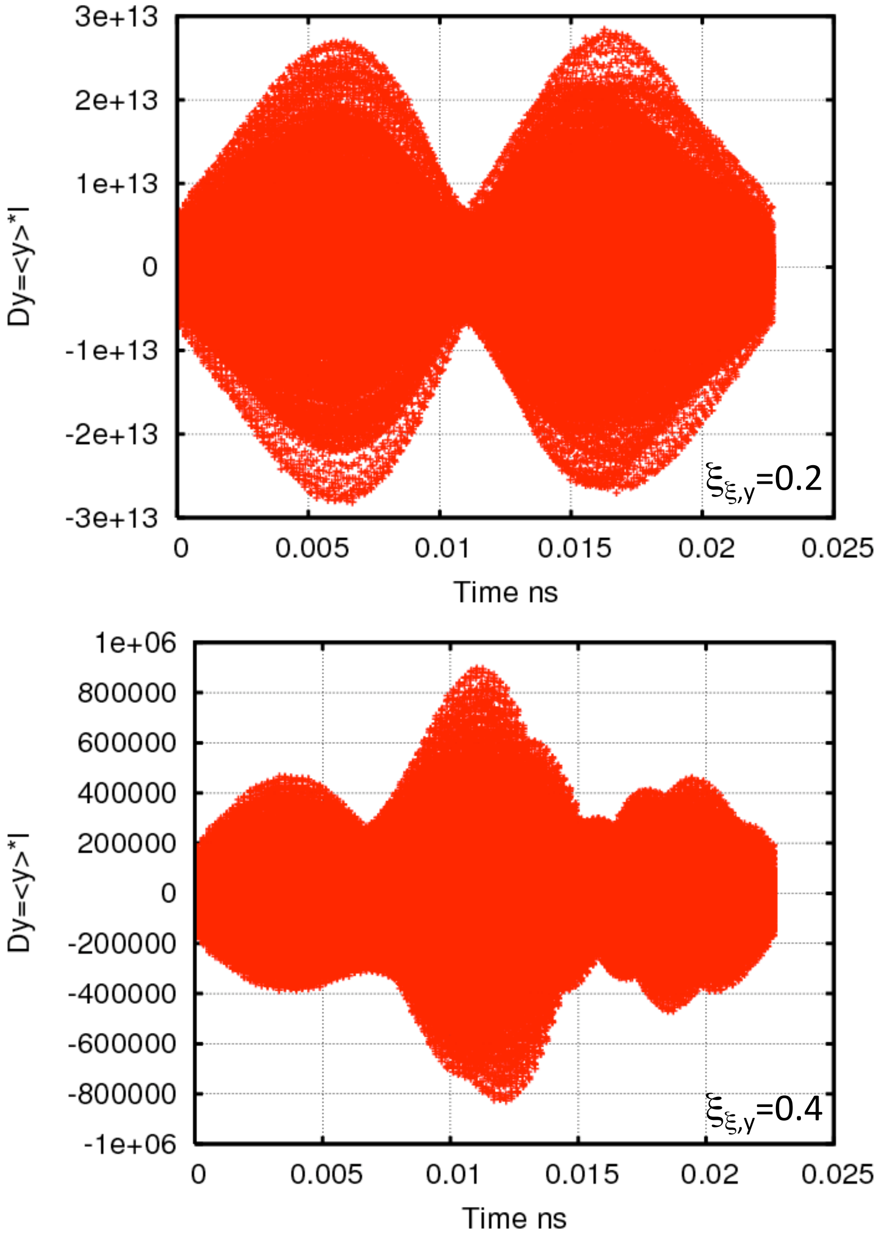
*** Vertical emittance evolution**

E-cloud @ 1 GHz: the electron ring



- Multipacting does not affect the electron beam in the wigglers
- For values of δ_{max} up to 2.4 the heat load remains well below 1 mW/m
- Actually, no serious e-cloud build up or induced heat load limitations seem to be present in the electron ring

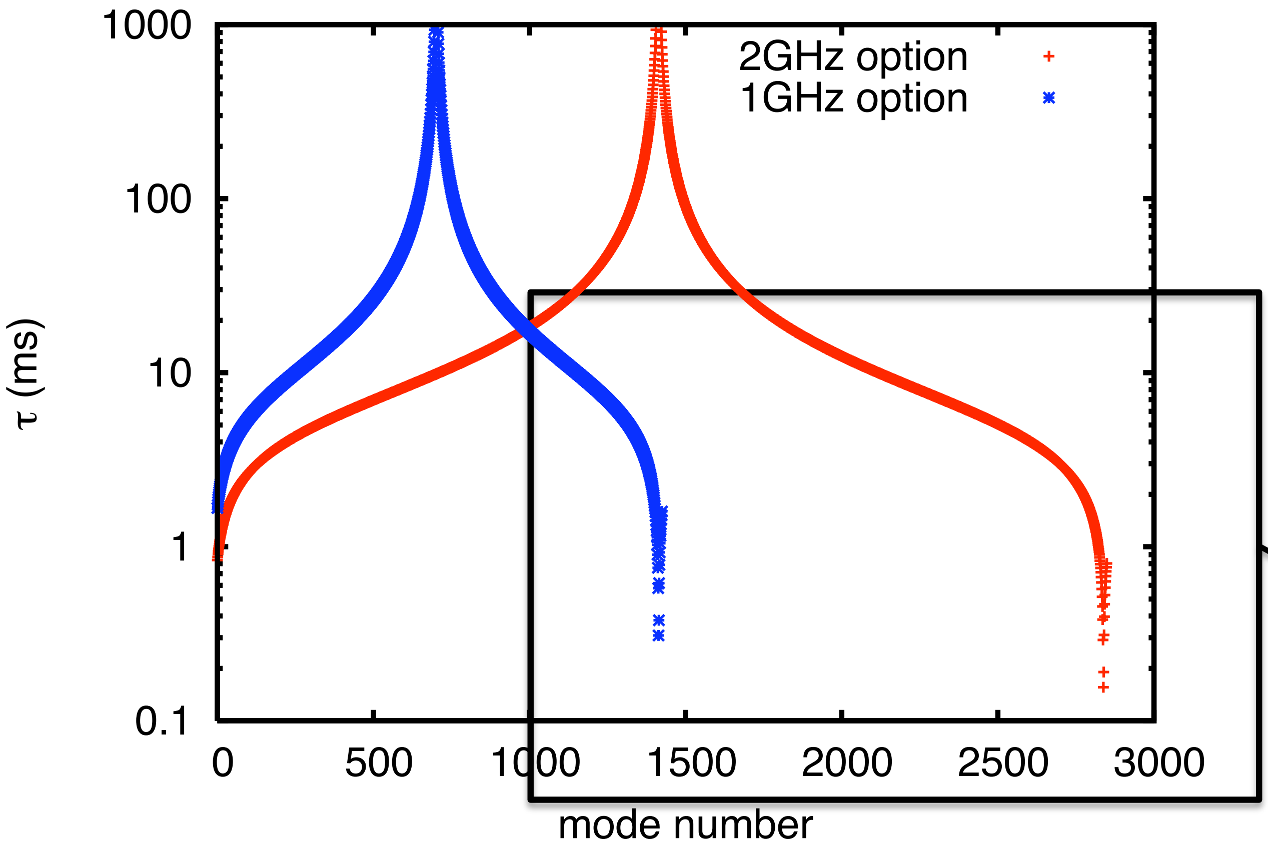
Impedance budget: TMCI threshold

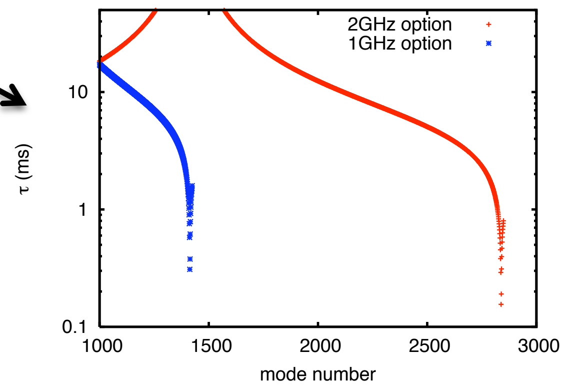


- Head-tail instability is observed for positive values of chromaticity
- The pattern on the bunch length shows only 1 node, confirming that the mode |l|=1 has become unstable when $\xi_{x,y}$=0.2
- For higher chromaticity values, higher order modes become visibly unstable (even combination of modes with different numbers)
- The rise time of these modes should be compared with the damping times to assess how dangerous they really are
- Maybe better run with negative chromaticity and suppress the unstable mode 0 with an active damper?

E. Koukovini

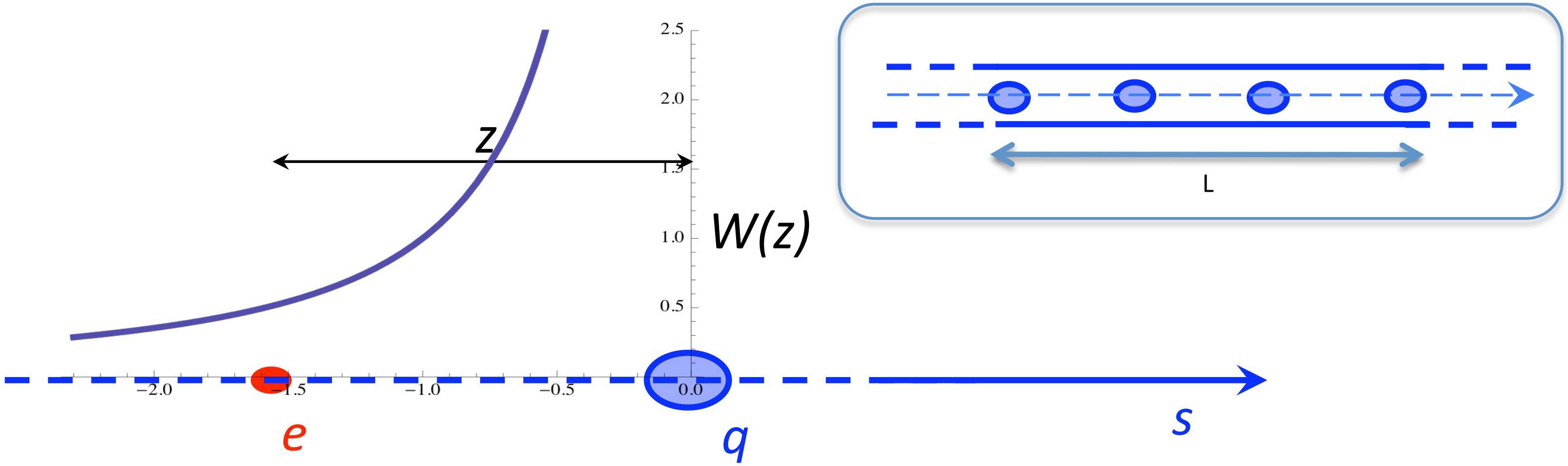
Coupled bunch instability from resistive wall





The expected lowest rise time is slightly higher for the 1 GHz option (~0.3ms or 210 turns) and is about twice lower for the 2 GHz option (~0.15ms or 105 turns)

Coupled bunch instability: macroparticle simulation



Present simulation model for HEADTAIL **multi-bunch**:

- A bunch train (made of disk-like macroparticle sets) is tracked through one or more interaction points chosen around the ring
- All particles in bunches subsequent to the first feel a transverse kick in each point resulting from the sum of the resistive wall contributions (integrated over the distance L between points) of all the preceding bunches.

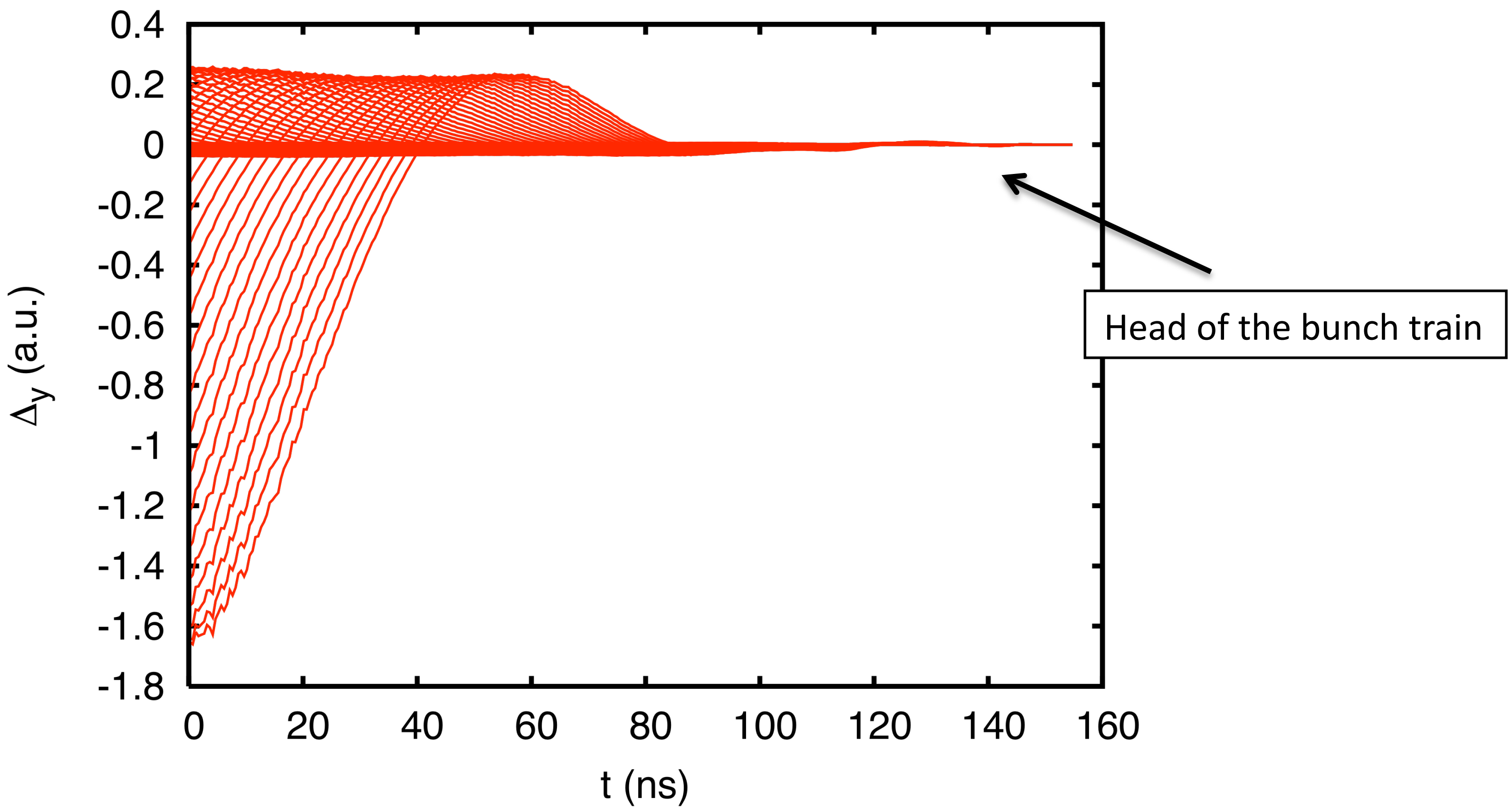
$$\int_0^L F_\perp(s,z)ds = -eqxW_\perp(z)$$

$$\Delta x'_i \propto N_e \sum_{n=1}^{N-i-1} W_{\perp d}(ncT_b)\langle x\rangle_n$$

$$\Delta x'_{i,j} \propto N_e \sum_{n=1}^{N-i-1} [W_{\perp d}(ncT_b)\langle x\rangle_n + W_{\perp q}(ncT_b)x_j]$$

Coupled bunch instability: macroparticle simulation

HEADTAIL simulations with the parameters of the 2 GHz option



In the plot

→ Superposition of snapshots of the bunch by bunch vertical BPM signal taken every 50 turns during the first 5000 turns of evolution

→ The unstable wave develops at the tail of the train and propagates to the front

Coupled bunch instability: fast ion effects

The trapped molecules (like N_2, CO, H_2O) can cause tune shift and instability

Trapped ions cause tune spread (p=1 nTorr)

$$\Delta Q_{ion} \simeq \frac{N_b n_b r_e C}{\pi\gamma\sqrt{\epsilon_x \epsilon_y}} \left(\frac{\sigma_{ion} p}{k_B T}\right) \simeq$$

and a fast instability having a **rise time of few turns for both designs**, calculated with the following formula.

$$\tau_{inst} \simeq \frac{0.1 \cdot \gamma \sigma_x \sigma_y}{N_b n_b c r_e \beta_y \sigma_i} \left(\frac{k_B T}{p}\right) \sqrt{\frac{8}{\pi}}$$