COLLECTIVE EFFECTS IN THE CLIC-BDS

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- COLLECTIVE EFFECTS IN THE CLIC BEAM DELIVERY SYSTEM
- RESISTIVE WALL
  - COUPLED BUNCH EFFECTS
  - SINGLE BUNCH EFFECTS
  - CALCULATION OF THE WAKE FIELDS
- FAST ION INSTABILITY
- OUTLOOK:
  - MULTI-BUNCH SIMULATIONS
  - SINGLE BUNCH STUDY
  - IONS

Collective effects in the BDS

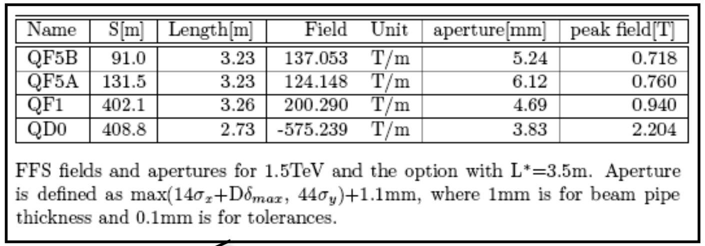
The main contributors to collective mechanisms in the BDS are:

- Resistive wall wakes of the **beam chamber**, in general due to the small pipe radius and which can give a large contribution especially in the regions of the final quadrupoles (where the β functions are very large).
- Geometric and resistive wall wake fields of the tapered and flat parts of the **collimators** (pipe radius changes and small apertures).
- Ions in the electron line and electrons in the positron line
- HOMs and LOMs in **crab cavities**

These collective phenomena result into:

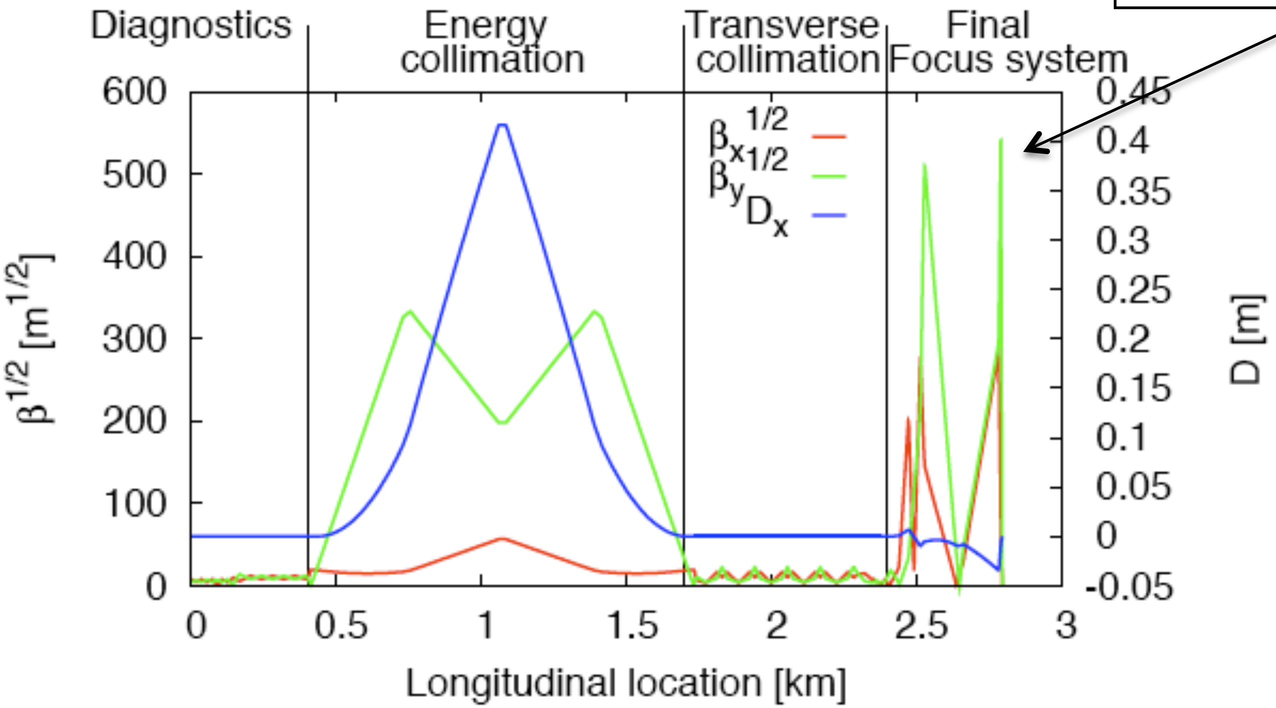
- *Single bunch effects* (both instability and emittance growth). These can be excited by the geometric wakes (short range) as well as the high frequency part of the resistive wall impedance
- *Coupled bunch effects* (unstable coherent motion of the bunch train). Long range resistive wall or narrow band resonator wake fields as well as ions and electrons are the source of bunch to bunch coupling

LAYOUT of the Beam Delivery System (3TeV)



Name	S[m]	Length[m]	Field	Unit	aperture[mm]	peak field[T]
QF5B	91.0	3.23	137.053	T/m	5.24	0.718
QF5A	131.5	3.23	124.148	T/m	6.12	0.760
QF1	402.1	3.26	200.290	T/m	4.69	0.940
QD0	408.8	2.73	-575.239	T/m	3.83	2.204

FFS fields and apertures for 1.5TeV and the option with L^*=3.5m. Aperture is defined as $\max(14\sigma_x + D\delta_{max},\ 44\sigma_y)$+1.1mm, where 1mm is for beam pipe thickness and 0.1mm is for tolerances.



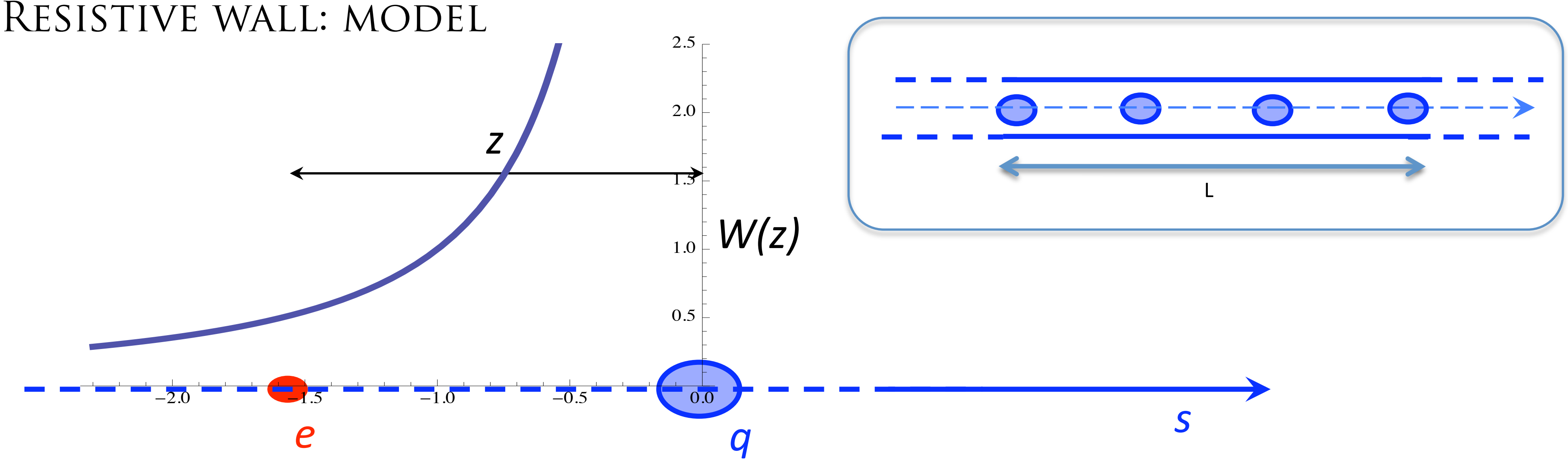
From R. Tomás *et al.* CLIC'08

Resistive wall effects can be strong and cause luminosity reduction

→ Energy collimation section and FF system with very high beta's and small apertures

→ Collimators with low apertures and low conductivity

RESISTIVE WALL: MODEL



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

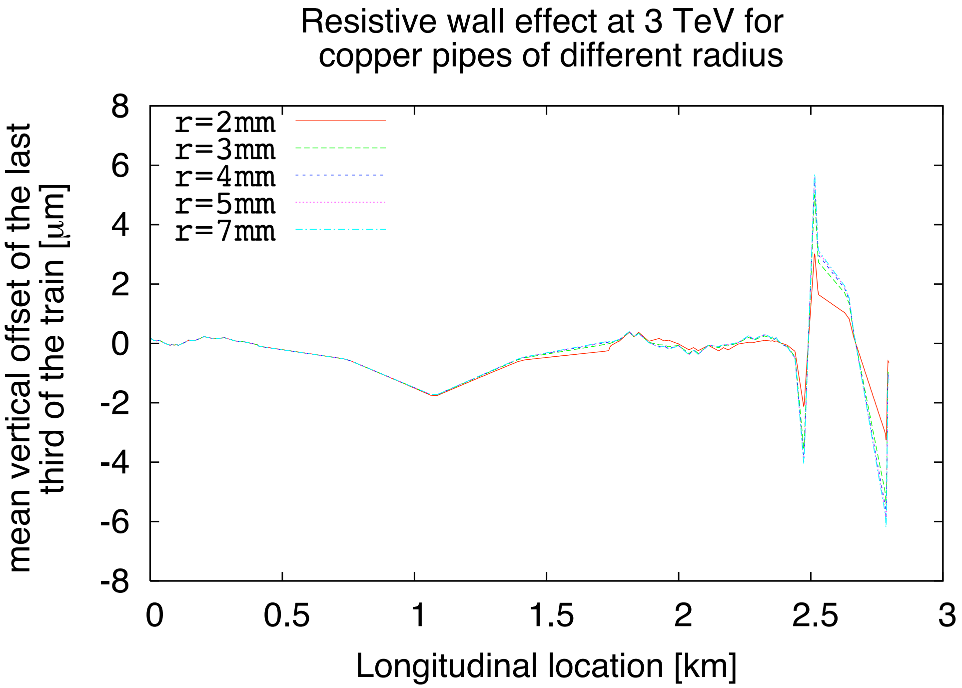
- Using a Twiss file of the BDS, an initially offset bunch train is tracked through about 2000 points of the BDS line
- All particles in bunches subsequent to the first one feel a transverse kick in each point resulting from the sum of the resistive wall contributions (integrated over the distance L between points) of all the preceding bunches.

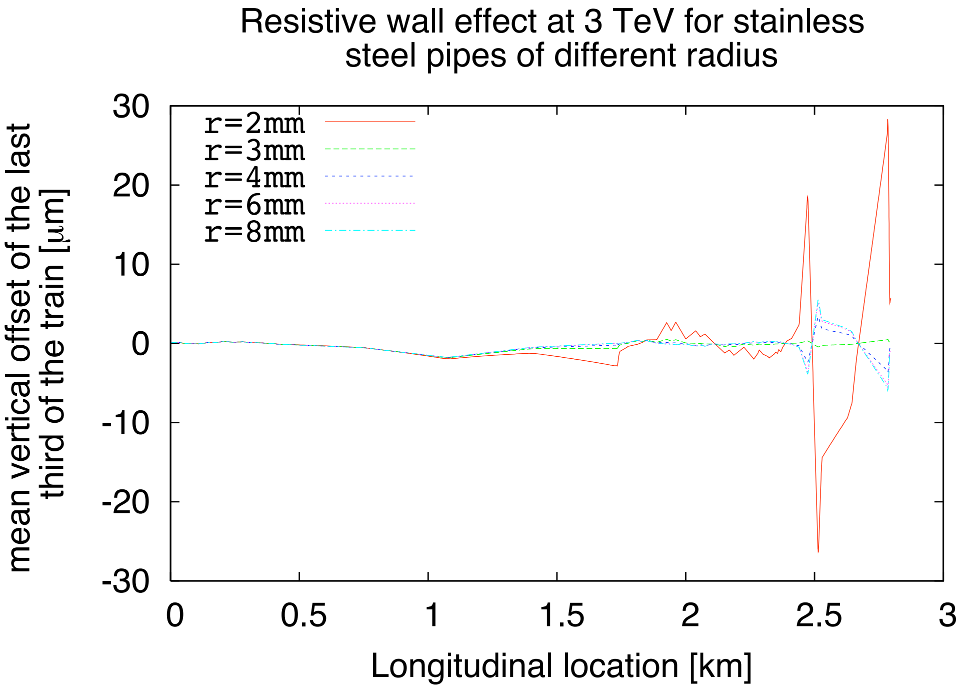
$$\int_0^L F_\perp(s,z)ds = -eqxW_\perp(z)$$

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

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

Long range resistive wall effect @3TeV


Resistive wall effect at 3 TeV for copper pipes of different radius


Resistive wall effect at 3 TeV for stainless steel pipes of different radius

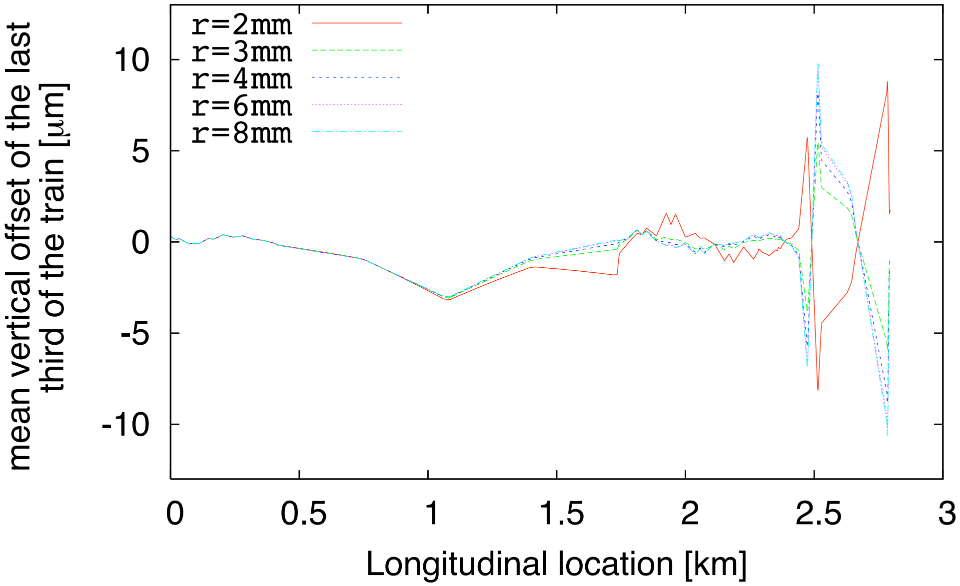
Coupled bunch resistive wall effects

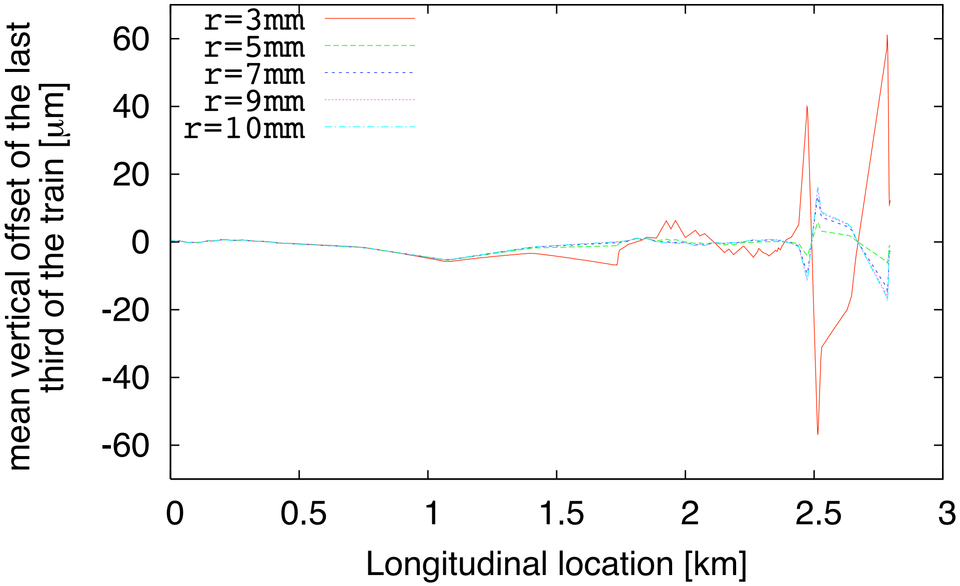
→ We assume a constant radius all along the BDS

→ Chamber radius has been scanned from 2 to 8 mm

→ For a Cu chamber, the resistive wall effect is completely suppressed for r>4mm, whereas for a StSt chamber at least r=6mm is required (safe choice r=8mm)

Long range resistive wall effect @1TeV


Resistive wall effect at 1 TeV for copper pipes of different radius


Resistive wall effect at 1 TeV for stainless steel pipes of different radius

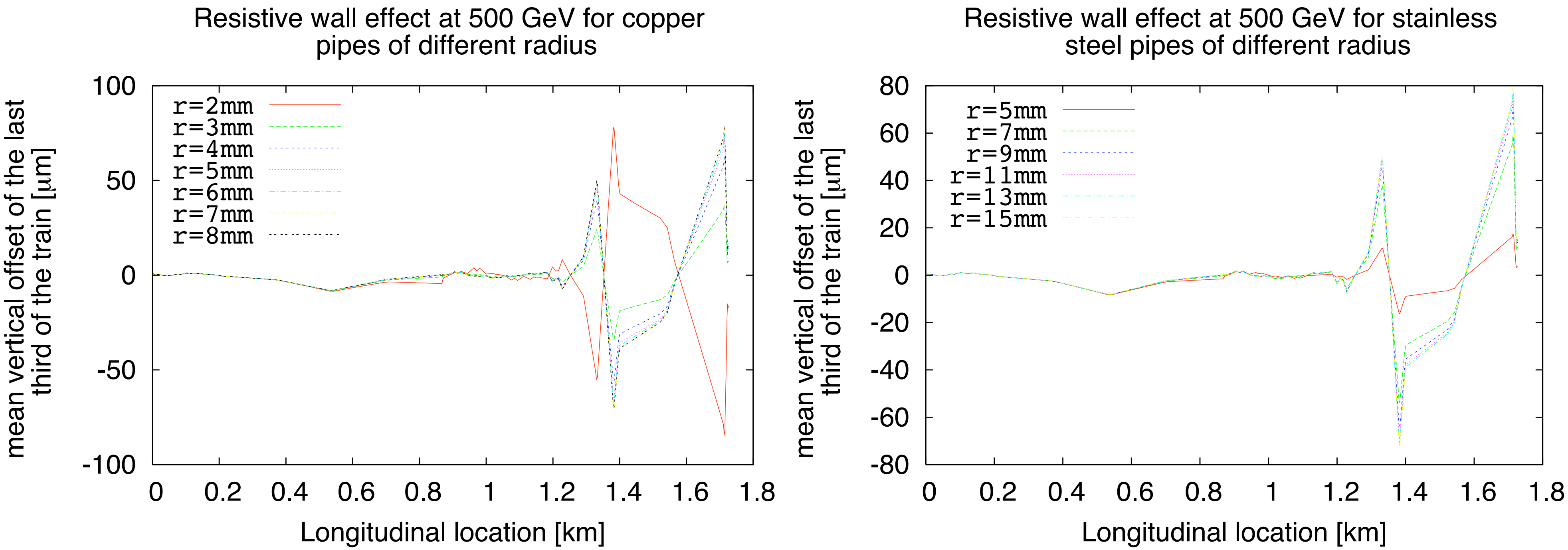
Coupled bunch resistive wall effects

→ We assume the same lattice at 1TeV as at 3TeV

→ Chamber radius has been scanned from 2 to 10 mm

→ Because of the lower energy (factor 3) the effect becomes more visible even for larger radii. For a Cu chamber, the resistive wall effect is completely suppressed for r>6mm, whereas for a StSt chamber at least r=9mm is required.

Long range resistive wall effect @500GeV



Coupled bunch resistive wall effects

→ Simulations have been run with the 500GeV lattice

→ Chamber radius has been scanned up to 15 mm

→ Here there is the combined effect of the lower energy (factor 6), the different beta functions and the shorter system. For a Cu chamber, the resistive wall effect is completely suppressed for r>7mm, whereas for a StSt chamber at least r=11mm is required.

Short range effects @3TeV

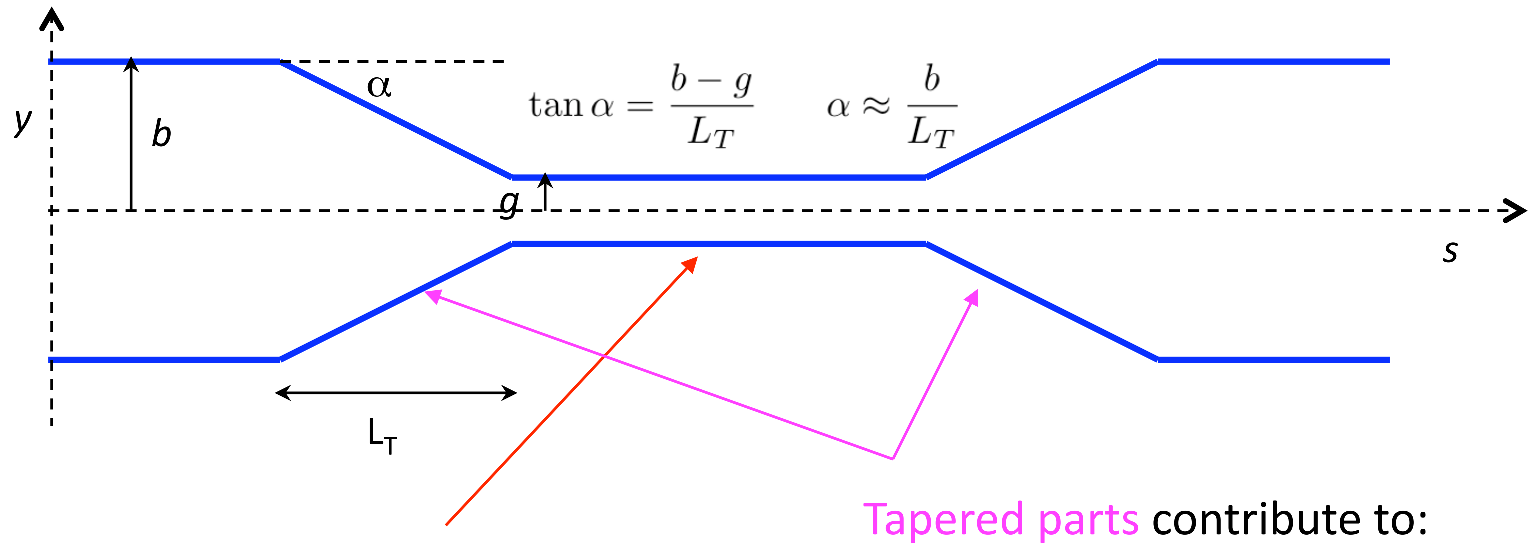
Single bunch effects

→ Short range wake fields are both geometric (due to the cross section size variation, when the pipe does not a uniform radius along the line) and due to resistive wall

→ However, the resistive wall regime is different from the one used for coupled bunch studies and classical formulae are not applicable (see following slides)

→The geometric contribution can be minimized with smooth tapering instead of abrupt cross section changes

→ Extensive studies were done in 2006-2007 in relation with collimators (see the relative EPAC, PAC papers)



Flat part contribute to:

1. Resistive wall wakes

Tapered parts contribute to:

1. Geometric wakes
2. Resistive wall wakes

Geometric wake

For smooth tapering, the kick is given by *(Stupakov, 1997)*

$$\boxed{\alpha \ll \frac{g\sigma_z}{h^2}}$$

$$\Delta y' = \frac{N r_e}{\gamma\sqrt{2\pi}\sigma_z}\left[(2\pi h I_2 - 2I_1)\Delta y + 2I_1 y\right]\exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

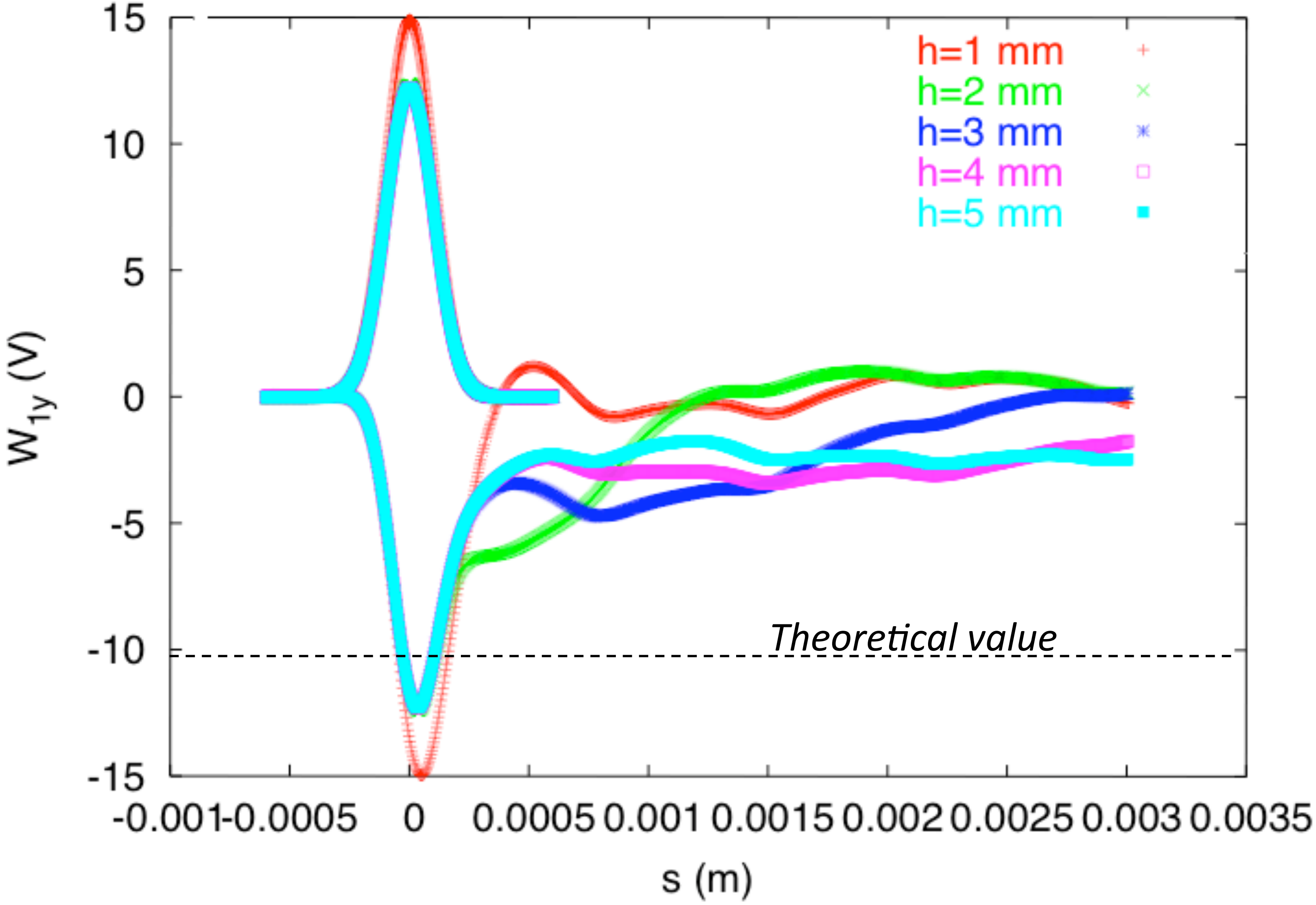
$$I_1 = \int_0^{L_T}\left(\frac{b'^2}{b^2}\right)ds \qquad I_2 = \int_0^{L_T}\left(\frac{b'^2}{b^3}\right)ds$$

In diffraction regime $\alpha \gg \dfrac{g\sigma_z}{h^2}$

$$\Delta y' = \frac{N r_e\sqrt{2}}{\gamma g^2}\exp\left(-\frac{z^2}{2\sigma_z^2}\right)(0.85\Delta y + 0.43 y)$$

whereas in the intermediate regime, the following formula holds:

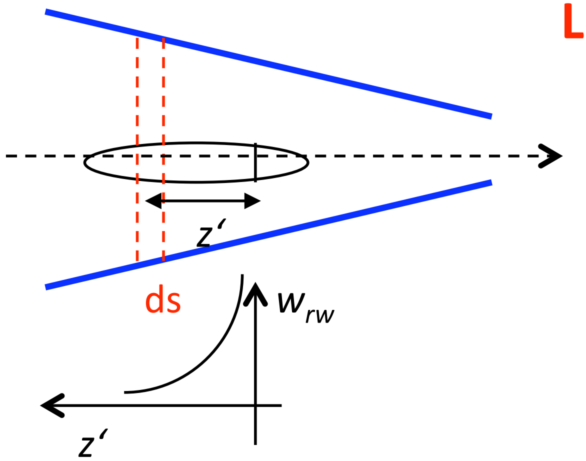
$$\Delta y' = \frac{2.7 N r_e\sqrt{2\alpha}}{\gamma\sqrt{\sigma_z g}}\exp\left(-\frac{z^2}{2\sigma_z^2}\right)(0.85\Delta y + 0.43 y)$$



Comparing the theoretical value from formula in intermediate regime with W. Bruns‘ Gdfidl simulations.

The upper curve represents the probe bunch (normalized to the highest value of the wake for plotting purposes) and the lower curves are the wakes referring to the labelled cases.

Resistive wall wake in the various ranges



Long range (traditional, can be found in all text books)

$$\Delta y'(s) = \frac{4Nr_e\sqrt{\lambda}ds}{\sqrt{2}\pi\gamma\sigma_z b^3(s)}\left[Y_{Dy}(s)\Delta y + Y_{Qy}(s)y\right] \times$$

$$\times \int_0^\infty \frac{1}{\sqrt{z'}} \exp\left[-\frac{(z+z')^2}{2\sigma_z^2}\right] dz'$$

Intermediate and short range w or w/o a.c. conductivity *(calculated starting from the paper of K. Bane & M. Sands,'95)*

$$\begin{aligned} W_1^\perp(z,s) = \frac{cZ_0}{\pi b^3(s)} \Bigg[& \overbrace{\frac{s_0 \exp\left(-\alpha_t \frac{z}{s_0}\right)}{3(\alpha_t^2+k_t^2)} \left(\alpha_t \cos(k_t \frac{z}{s_0}) + k_t \sin(k_t \frac{z}{s_0}) - \alpha_t\right)}^{\text{Short range part, } \alpha_t \text{ and } k_t \text{ depend on relaxation time (a.c. conductivity)}} - \\ & - \frac{\sqrt{2}}{\pi} \int_0^z \int_0^\infty \frac{x^2 \exp\left(-x^2 \frac{z'}{s_0}\right) dx}{x^6+8} dz' \Bigg] \end{aligned}$$

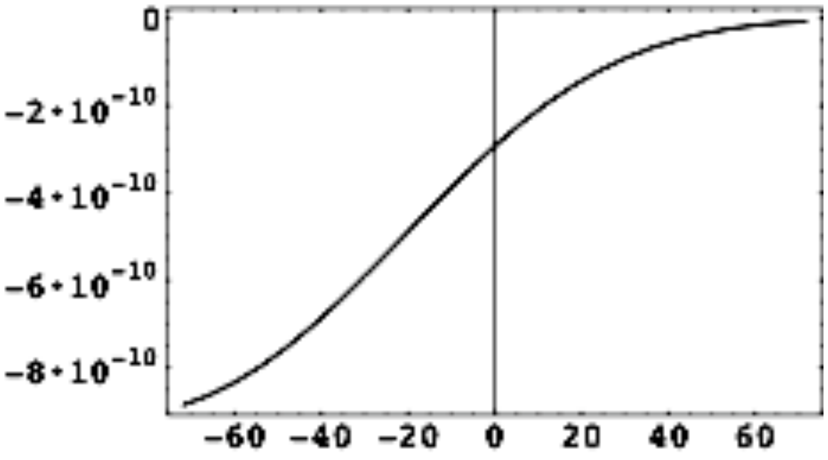
A **PLACET module** applying kicks from geometric and resistive wall wakes to the bunch particles was built and implemented into the code

Comparison of calculation of using the intermediate range wake function...

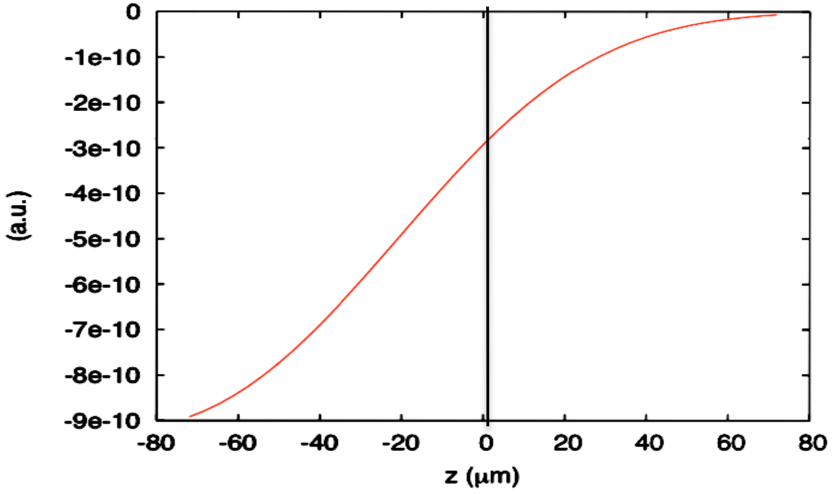
$$\Delta y'(s) = \frac{N r_e ds}{\gamma\sqrt{2\pi}\sigma_z}\int_0^\infty W_1^\perp(z',s)\exp\left[\frac{(z'+z)^2}{2\sigma_z^2}\right]dz'$$

$$\Delta y' = \int_{L_c}\Delta y'(s)ds$$

... by its integral over the bunch with some typical CLIC numbers...

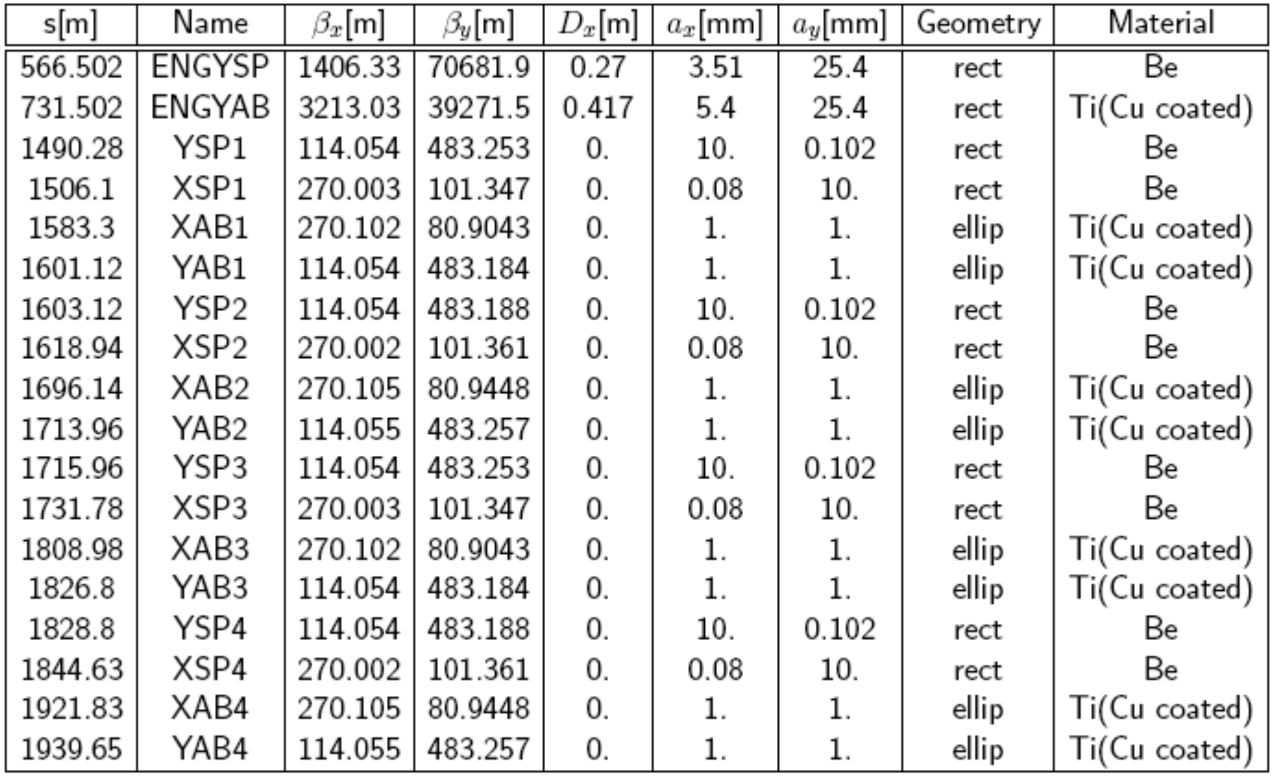


... with MATHEMATICA or...



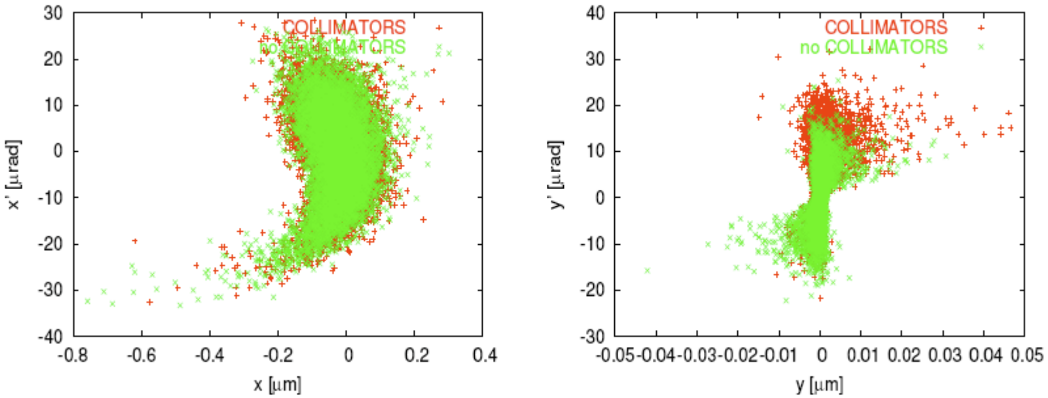
... with PLACET module

BDS Collimator Parameters



s[m]	Name	β_x[m]	β_y[m]	D_x[m]	a_x[mm]	a_y[mm]	Geometry	Material
566.502	ENGYSP	1406.33	70681.9	0.27	3.51	25.4	rect	Be
731.502	ENGYAB	3213.03	39271.5	0.417	5.4	25.4	rect	Ti(Cu coated)
1490.28	YSP1	114.054	483.253	0.	10.	0.102	rect	Be
1506.1	XSP1	270.003	101.347	0.	0.08	10.	rect	Be
1583.3	XAB1	270.102	80.9043	0.	1.	1.	ellip	Ti(Cu coated)
1601.12	YAB1	114.054	483.184	0.	1.	1.	ellip	Ti(Cu coated)
1603.12	YSP2	114.054	483.188	0.	10.	0.102	rect	Be
1618.94	XSP2	270.002	101.361	0.	0.08	10.	rect	Be
1696.14	XAB2	270.105	80.9448	0.	1.	1.	ellip	Ti(Cu coated)
1713.96	YAB2	114.055	483.257	0.	1.	1.	ellip	Ti(Cu coated)
1715.96	YSP3	114.054	483.253	0.	10.	0.102	rect	Be
1731.78	XSP3	270.003	101.347	0.	0.08	10.	rect	Be
1808.98	XAB3	270.102	80.9043	0.	1.	1.	ellip	Ti(Cu coated)
1826.8	YAB3	114.054	483.184	0.	1.	1.	ellip	Ti(Cu coated)
1828.8	YSP4	114.054	483.188	0.	10.	0.102	rect	Be
1844.63	XSP4	270.002	101.361	0.	0.08	10.	rect	Be
1921.83	XAB4	270.105	80.9448	0.	1.	1.	ellip	Ti(Cu coated)
1939.65	YAB4	114.055	483.257	0.	1.	1.	ellip	Ti(Cu coated)

(see "*Beam Collimation System Performance for CLIC at 1500 GeV*", Javier Resta Lopéz)

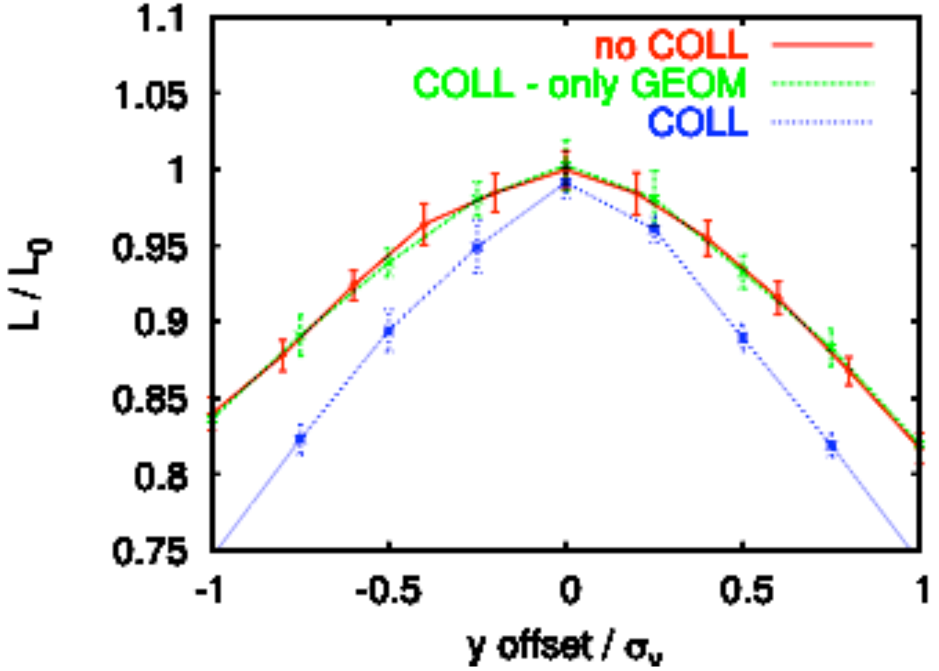


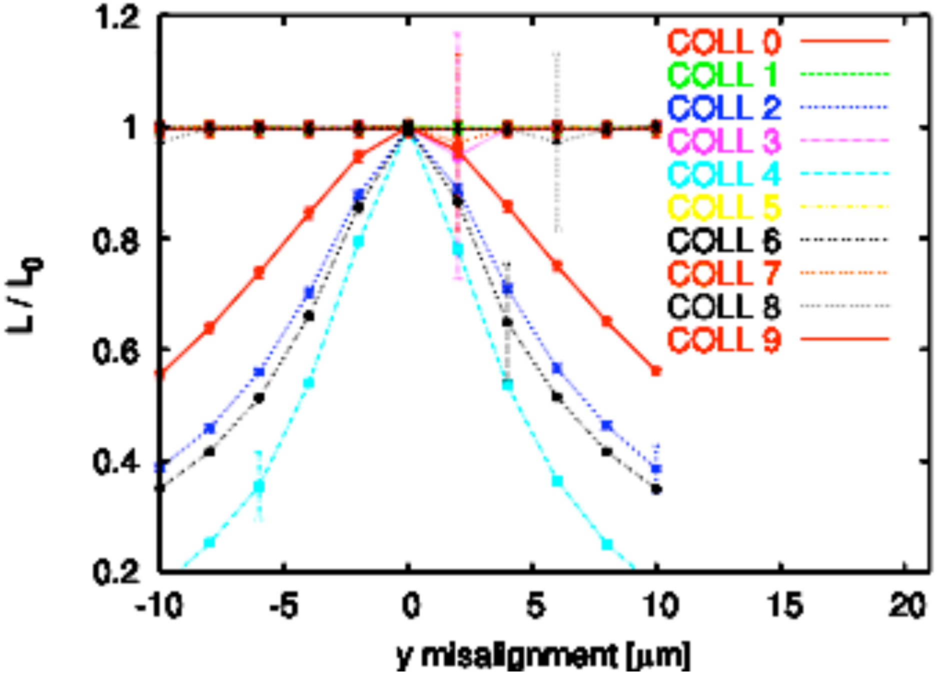
A. Latina, GR, D. Schulte, EPAC 2006

(jitter $= 1\,\sigma_y \sim 0.25\mu$m)

Using PLACET with the wake fields of the collimators, the luminosity reduction curves were calculated for:

1. Vertical jitter
2. Collimator misalignment: collimators are vertically offset one by one, obviously only the effect of the vertical collimators is visible.
3. More recent evaluations presented by J. Resta-Lopez today

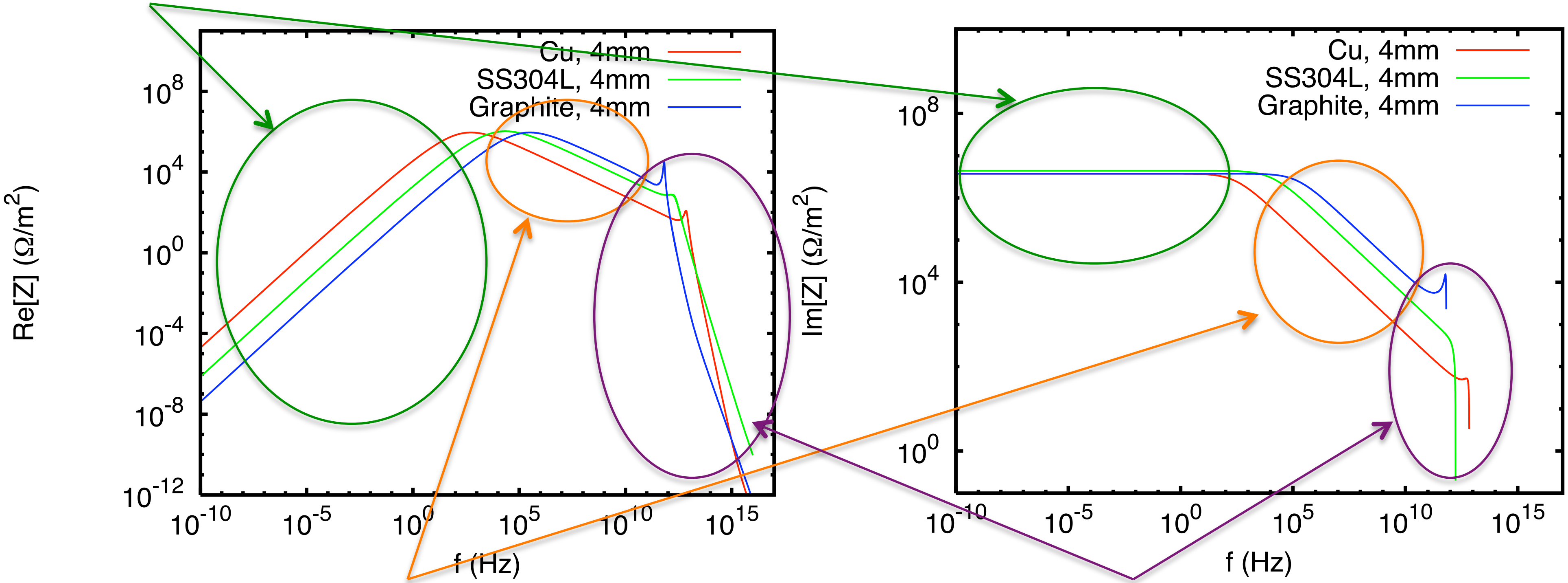




Resistive wall impedances and wake fields

There are new formulae for the transverse resistive wall impedance of a chamber wall with an arbitrary number of conductive layers extending over a finite length (E. Métral, N. Mounet)

The formulae are valid for arbitrary beam energy, in all frequency regimes and include the effects of ac conductivity at high frequency



Low frequency regime, imaginary part does not depend on σ, real part has opposite dependence than traditional

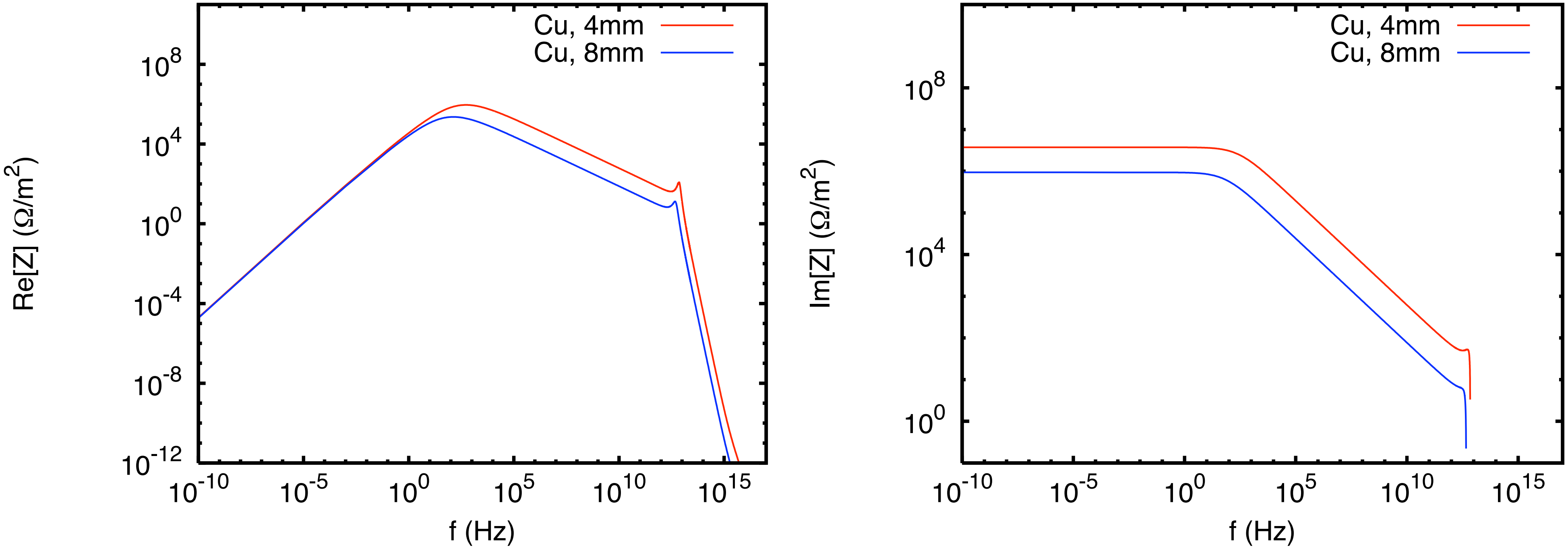
Traditional regime, goes like $\sigma^{-1/2}$

Peak in high frequency regime, curve also depends on the relaxation time of the metal

Resistive wall impedances and wake fields

If we assume the same material (same conductivity and same relaxation time) and different radii, we can see the dependence on the chamber size in the different frequency regimes.

Expected: scaling like b^{-3} in the „traditional“ regime, like b^{-2} in low frequency for the imaginary part (image charges).

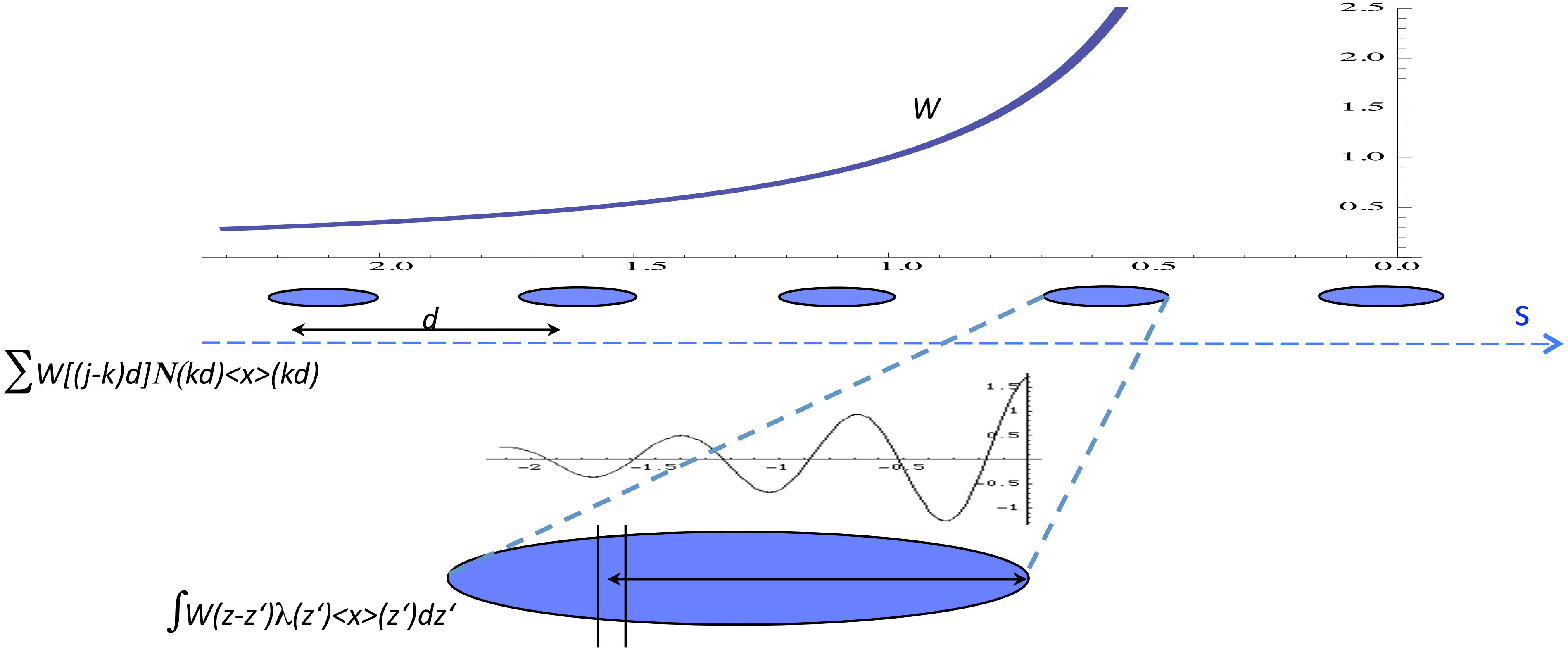


Resistive wall impedances and wake fields

From frequency domain to time domain to find the wakes

- **Short range**: over a bunch length
- **Long bunch regime**: over a train length, sampled with the bunch spacing

N. Mounet developed an algorithm to carry out the inverse Fourier transform of the impedance functions (which extend over a huge frequency range) based on separated polynomial interpolations of the exact impedance function over a suitable number of frequency subsets (Impedance Meeting, CERN, 27.08.2009)



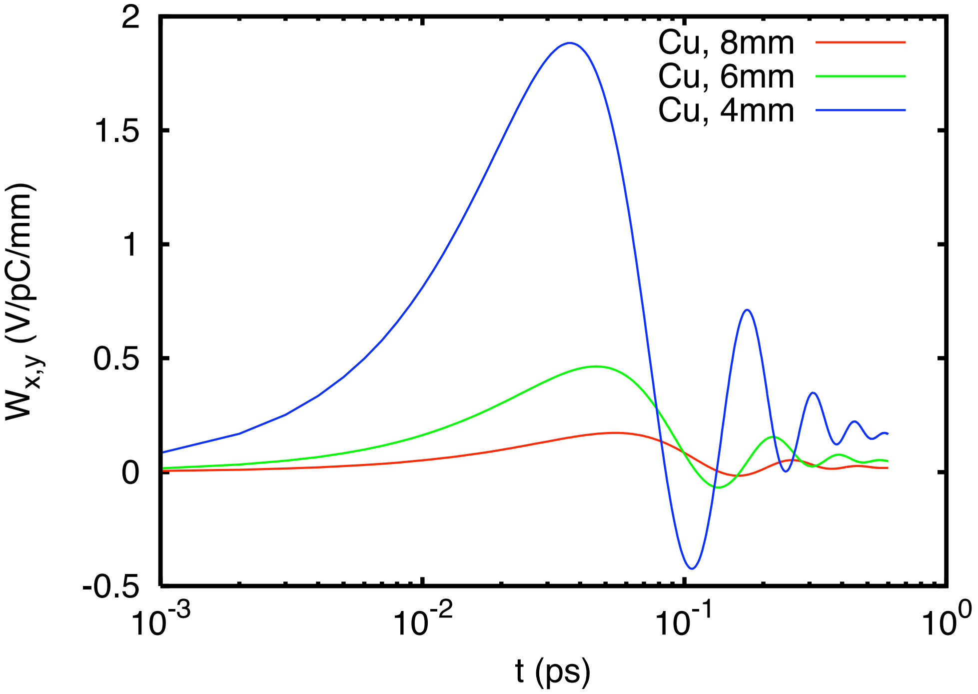
$$\sum W[(j-k)d]N(kd)\langle x\rangle(kd)$$

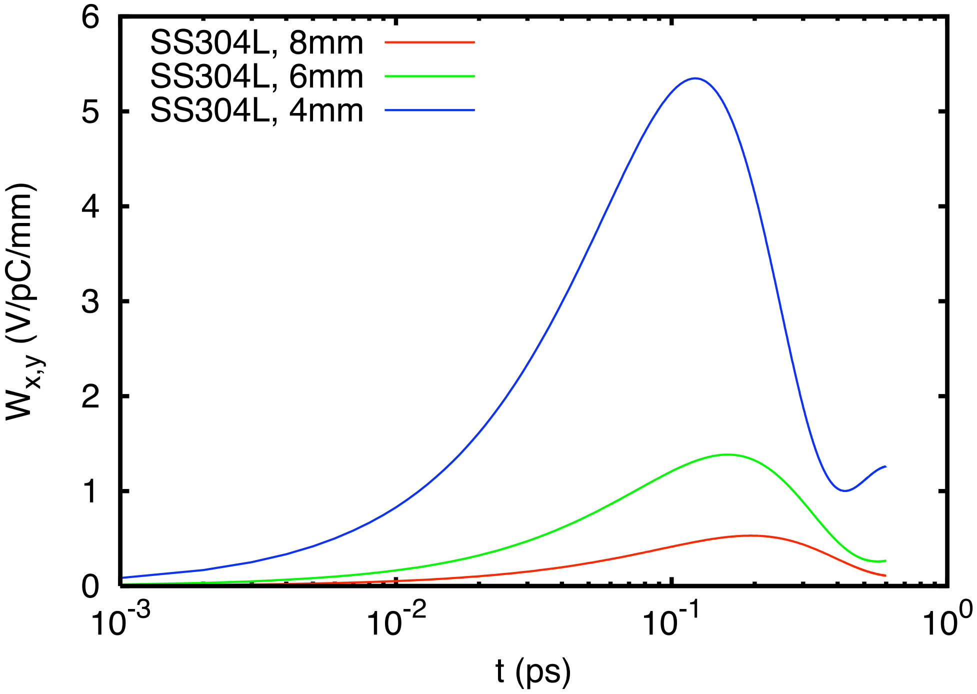
$$\int W(z-z')\lambda(z')\langle x\rangle(z')dz'$$

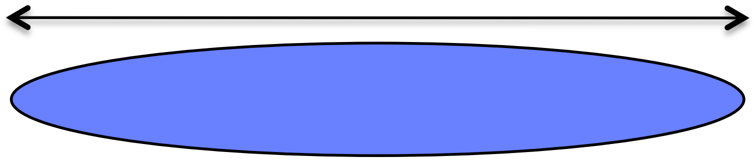
Resistive wall impedances and wake fields

Short range wake fields for *copper* and *stainless steel* (CLIC-BDS bunch ≈0.6ps)

- The shape depends both on the conductivity and on the relaxation time
- For higher conductivity (Cu) the expected high frequency oscillatory behavior appears over the bunch length we are considering

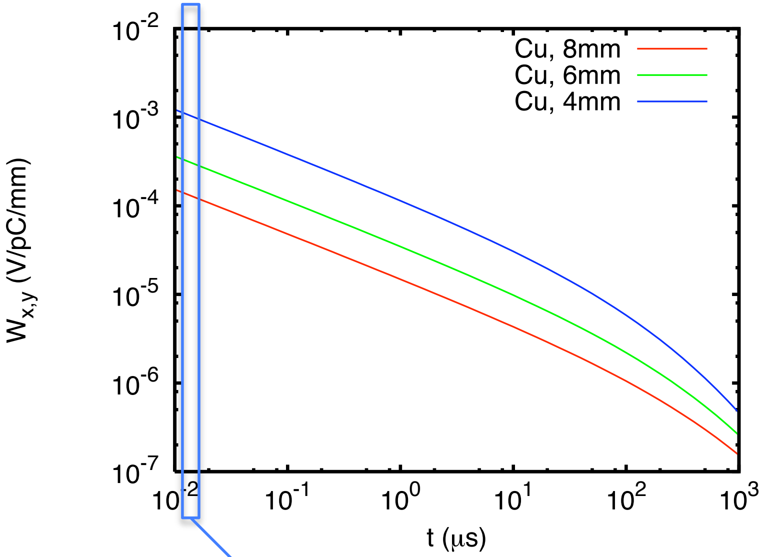


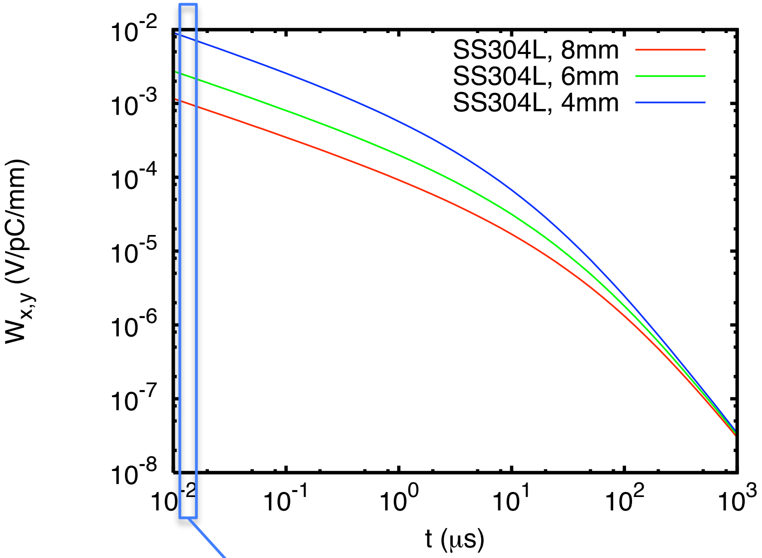




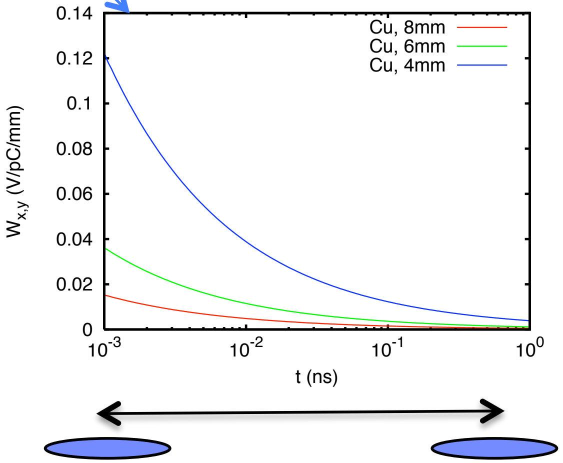
Resistive wall impedances and wake fields

Long range wake fields for *copper* and *stainless steel* (CLIC-BDS bunch train ≈150μs)

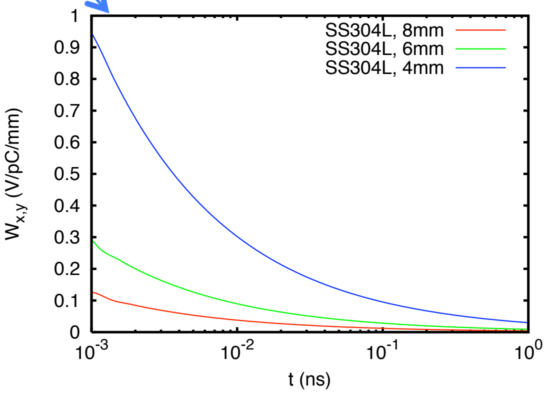




How it decays between subsequent bunches

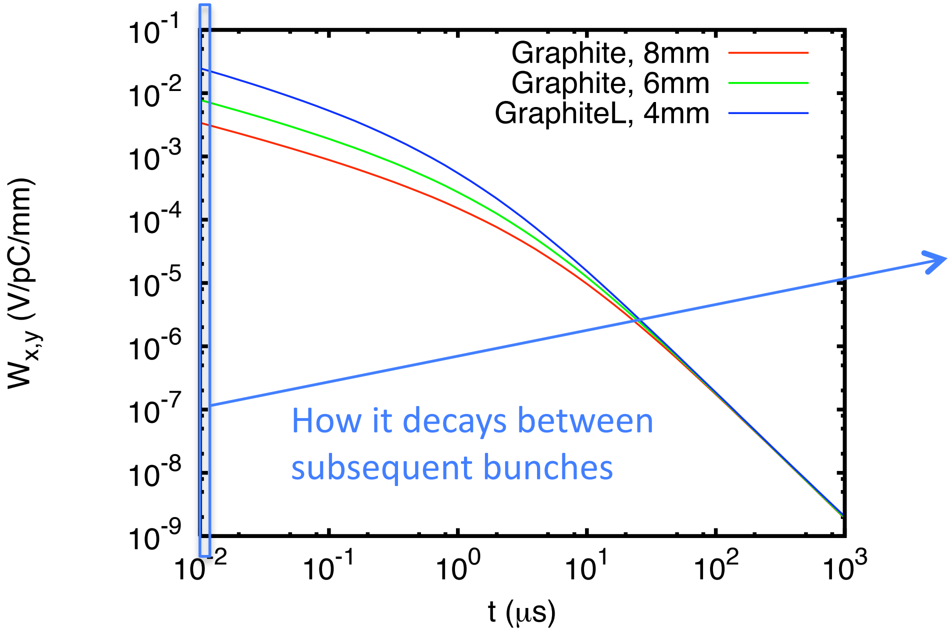


How it decays between subsequent bunches

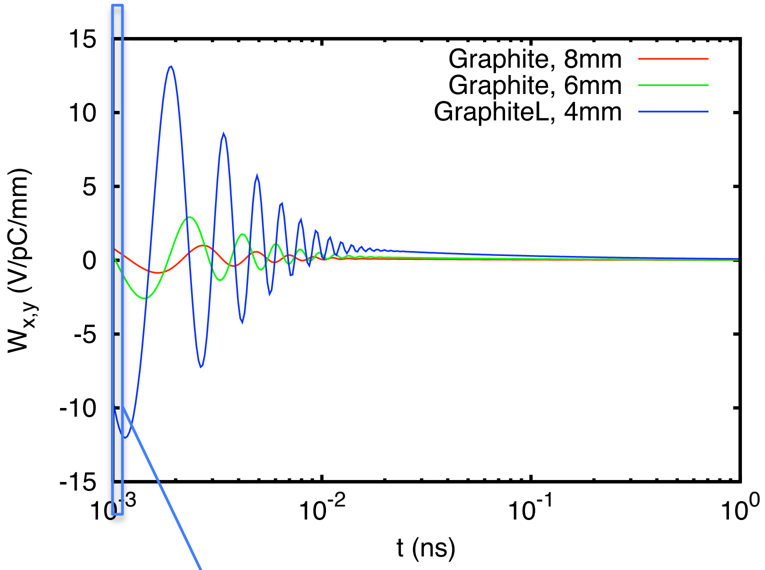


Resistive wall impedances and wake fields

Short and long range wake fields for graphite (lower conductivity)



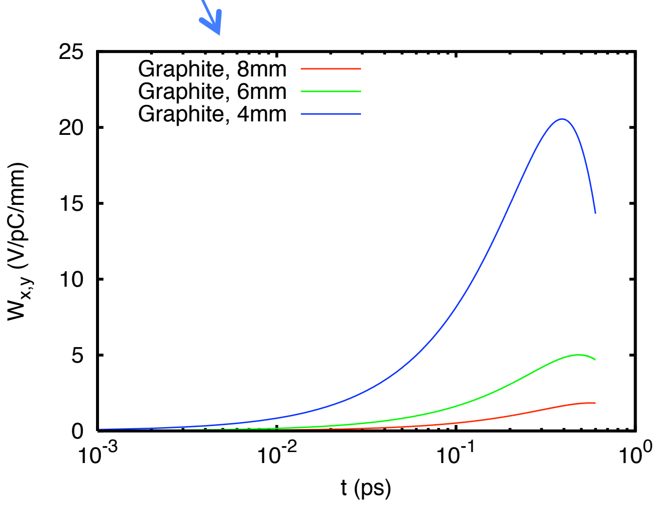
How it decays between subsequent bunches



How it decays within one single bunch

Lower conductivity is important for collimators:

1. For the multibunch:
    - I. Over the train length the behavior differs quite a lot from the traditional RW
    - II. The short range regime may become significant even in the bunch to bunch
2. For the single bunch, it is important to know the relaxation time.



Comments on the fast ion instability

Considerations on the fast ion instability for the BDS (electrons)

1. 2km of untrapped ions are unlikely to make the beam unstable for reasonably low pressure values
2. Assuming vacuum pressures up to 100nTorr (CO and H_2O), the beam was not found to be unstable in FASTION simulations
3. However, the FASTION simulation was done without field ionization (see talk on ‚Vacuum specifications for the CLIC linacs‘).....
   A. The new model of field ionization, which calculates the critical area from the region in which the electric field exceeds the threshold value to ionize 1/10 of the molecules, can give ionization rates two or three orders of magnitude higher.
   B. To be checked: what fraction of the BDS can give rise to significant field ionization

FUTURE PLANS

- Refine **coupled bunch instability simulations** with resistive wall
  - Implement a realistic aperture model for the BDS in the code
  - Use the correct resistive wall wake fields (expected not to make a large difference for the pipe resistive wall in multi-bunch regime, but potentially affecting both the collimator wake fields in multi-bunch and the single bunch in general)
  - Implement the effect of collimators (which also requires the use of Yokoya factors due to the flat design of collimators, as opposed to the round beam chamber)
- Improve **single bunch simulations**, done with PLACET
  - Geometric wake fields: use EM simulation codes in time domain, e.g. CST Particle Studio, to calculate them (not trivial due to the short bunches) and import them as tables into PLACET
  - Resistive wall wake fields: use the correct calculation, i.e. implement the module for the wake field calculation (N. Mounet, J. Snuverink) into PLACET
- Possibly integrate single-bunch and multi-bunch simulations
- Check for possible **ion issues**
  - Check how much of the BDS can be affected by field ionization and calculate the critical areas
  - Run BDS simulations with field ionization