Collective effects in the CLIC-Damping Rings

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in CLIC Workshop 09, 14 October 2009

- New parameter table and 500GeV option
- Comments on the electron cloud
  - Known results
  - Mitigation techniques
- Other collective effects
  - Single bunch effects
    - Space charge
    - Instabilities due to broad band impedance
  - Multi bunch effects
    - Resistive wall
    - Fast ion instability
- Summary

Updated list of parameters with the new lattice design at 3 TeV

Parameter	Symbol	Value
Energy	p_0 (GeV)	2.424
Norm. transv. emitt.	$\epsilon_{xn,yn}$ (nm)	381, 4.1
Bunch length	σ_z (mm)	1.53
Momentum spread	σ_δ	1.43 $\times 10^{-3}$
Bunch spacing	ΔT_b (ns)	0.5
Bunch population	N_b	4.1×10^9
Circumference	C (m)	365.2
Coupling	(%)	0.13
Mom. compact.	α	8×10^{-5}
Number of bunches	n_b	312
Tunes	$Q_{x,y,s}$ (m)	69.82, 33.80
Store time/train	T_{st} (ms)	20
Energy loss	ΔE (MeV/turn)	3.857
Damping times	$\tau_{x,y,z}$ (ms)	1.5, 1.5, 0.74
RF frequency	f_{rf} (GHz)	2
RF voltage	V_{rf} (MV)	4.115
Bend length	L_{bend} (m)	0.545
Bend chamber rad.	R_{bend} (cm)	2
Number of bends	N_{bend} (m)	96
Wiggler length	L_w (m)	2
Wiggler field	B_w (T)	2.5
Number of wigglers	N_w (m)	76
Wiggler radius	r_w (mm)	9

With combined function magnets

Parameter	Symbol	Value
Energy	p_0 (GeV)	2.86
Norm. transv. emitt.	$\epsilon_{xn,yn}$ (nm)	480, 4.7
Bunch length	σ_z (mm)	1.4
Momentum spread	σ_δ	1 $\times 10^{-3}$
Bunch spacing	ΔT_b (ns)	0.5
Bunch population	N_b	4.1×10^9
Circumference	C (m)	493.05
Coupling	(%)	0.1
Mom. compact.	α	6×10^{-5}
Number of bunches	n_b	312
Tunes	$Q_{x,y,s}$ (m)	58.2, 18.8
Store time/train	T_{st} (ms)	20
Energy loss	ΔE (MeV/turn)	5.9
Damping times	$\tau_{x,y,z}$ (ms)	1.6, 1.6, 0.8
RF frequency	f_{rf} (GHz)	2
RF voltage	V_{rf} (MV)	7.2
Bend length	L_{bend} (m)	0.4
Bend chamber rad.	R_{bend} (cm)	1
Number of bends	N_{bend} (m)	96
Wiggler length	L_w (m)	2
Wiggler field	B_w (T)	2.5
Number of wigglers	N_w (m)	76
Wiggler radius	r_w (mm)	9

$\Rightarrow$ Advantages: DA increased, magnet strength reduced to reasonable, reduced IBS

$\Rightarrow$ Relative to collective effects (main changes):

- Higher energy, larger horizontal emittance (good)
- Longer circumference (bad)

From Y. Papaphilippou

Updated list of parameters for the 500 GeV option

Parameter	Symbol	Value
Energy	p_0 (GeV)	2.424
Norm. transv. emitt.	$\epsilon_{xn,yn}$ (nm)	381, 4.1
Bunch length	σ_z (mm)	1.53
Momentum spread	σ_δ	1.43×10^{-3}
Bunch spacing	ΔT_b (ns)	0.5
Bunch population	N_b	4.1×10^9
Circumference	C (m)	365.2
Coupling	(%)	0.13
Mom. compact.	α	8×10^{-5}
Number of bunches	n_b	312
Tunes	$Q_{x,y,s}$ (m)	69.82, 33.80
Store time/train	T_{st} (ms)	20
Energy loss	ΔE (MeV/turn)	3.857
Damping times	$\tau_{x,y,z}$ (ms)	1.5, 1.5, 0.74
RF frequency	f_{rf} (GHz)	2
RF voltage	V_{rf} (MV)	4.115
Bend length	L_{bend} (m)	0.545
Bend chamber rad.	R_{bend} (cm)	2
Number of bends	N_{bend} (m)	96
Wiggler length	L_w (m)	2
Wiggler field	B_w (T)	2.5
Number of wigglers	N_w (m)	76
Wiggler radius	r_w (mm)	9

Parameter	Symbol	Value
Energy	p_0 (GeV)	2.86
Norm. transv. emitt.	$\epsilon_{xn,yn}$ (nm)	1545, 4.9
Bunch length	σ_z (mm)	1.49
Momentum spread	σ_δ	1.2×10^{-3}
Bunch spacing	ΔT_b (ns)	0.5
Bunch population	N_b	7.5×10^9
Circumference	C (m)	493.05
Coupling	(%)	0.03
Mom. compact.	α	6.4×10^{-5}
Number of bunches	n_b	354
Number of trains	n_t	2
Tunes	$Q_{x,y,s}$ (m)	58.2, 18.8
Store time/train	T_{st} (ms)	40
Energy loss	ΔE (MeV/turn)	1.06
Damping times	$\tau_{x,y,z}$ (ms)	8.8, 8.9, 4.5
RF frequency	f_{rf} (GHz)	2
RF voltage	V_{rf} (MV)	3.7
Bend length	L_{bend} (m)	0.4
Bend chamber rad.	R_{bend} (cm)	1
Number of bends	N_{bend} (m)	96
Wiggler length	L_w (m)	2
Wiggler field	B_w (T)	2.5
Number of wigglers	N_w (m)	2
Wiggler radius	r_w (mm)	9

$\Rightarrow$ Relative to collective effects (main changes):

- Higher energy, larger horizontal emittance (good)
- Longer circumference (bad)
- Shorter total wiggler length (good for aperture and for e-cloud)

From Y. Papaphilippou

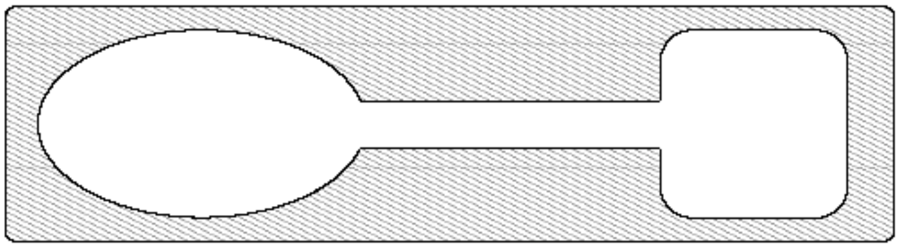
Vacuum chamber sizes and photoemission yields

Vacuum chamber dimensions

	CLIC DR Arc	CLIC DR Wiggler
horizontal semi axis /mm	22	16
vertical semi axis /mm	18	9
antechamber-slot half height		3
chamber area /cm^2	12.4	5.8

D. Schulte, R. Wanzenberg, F. Zimmermann, in Proceed. ECLOUD'04

Design of the vacuum chamber with antechamber in the arcs (it has double sided ante-chamber in the wigglers)



The antechamber absorbs most of the synchrotron radiation and can be replaced by a an alternative scheme with dedcicated absorber sections. The net effect scales down the photoemission yield

Photoemission yields

	CLIC DR Arc	CLIC DR Wiggler
N_0 /10^{10}	0.5	0.5
ρ/m	8.67	4.58
dN_γ/dz [/e^+/m]	5.764	10.903
$Y_{\rm eff}$	0.01	0.01
dN_{e^-}/dz [/e^+/m]	0.0576	0.109
$dN_{e^-}/dz^{\rm ion}$ [/e^+/m]	4×10^{-8}	4×10^{-8}

Electron cloud (positron ring): how it affects the beam

Tune shift

The tune increases along a train of positively charged particle bunches because the bunches at the tail of the train feel the strong focusing effect of the electron cloud formed by the previous bunches.

Electron cloud instability in rings

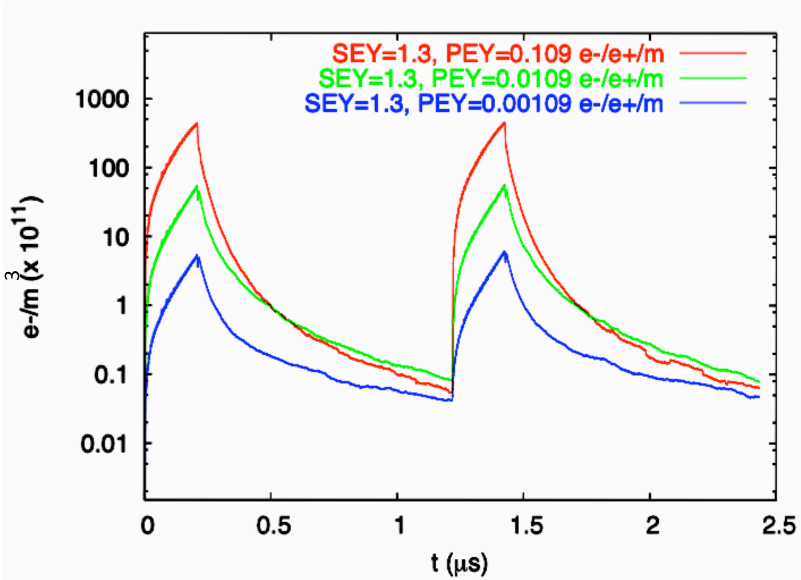
⇒ Coupled bunch phenomenon: the motion of subsequent bunches is coupled through the electron cloud and the amplitude of the centroid motion can grow.

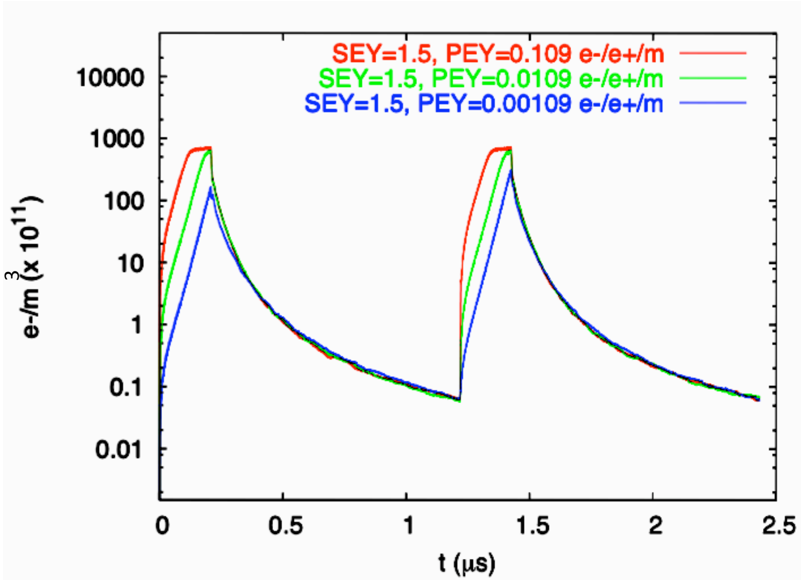
⇒ Single bunch phenomenon: the motion of head and tail of a single bunch can be coupled through an electron cloud and give rise to an instability

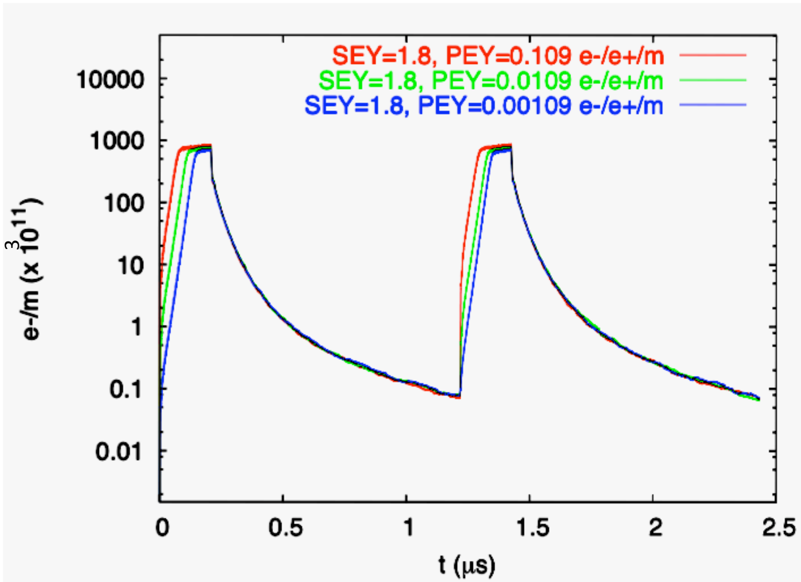
The electron cloud build up crucially depends on bunch length, spacing, current and on the dimensions of the beam chamber. It is marginally influenced by the beam transverse sizes. Therefore, no substantial change is expected in the previous electron cloud build up

Electron cloud build up in the wigglers (simulations with Faktor2)

Central densities for different PEYs and SEYs







→ The electron cloud in the wigglers can have high density values if

- ✓ The PEY is high enough (i.e., more than 0.01% of the produced radiation is not absorbed by an antechamber or by special absorbers), even if the SEY is low
- ✓ The SEY is above 1.3, independently of the PEY

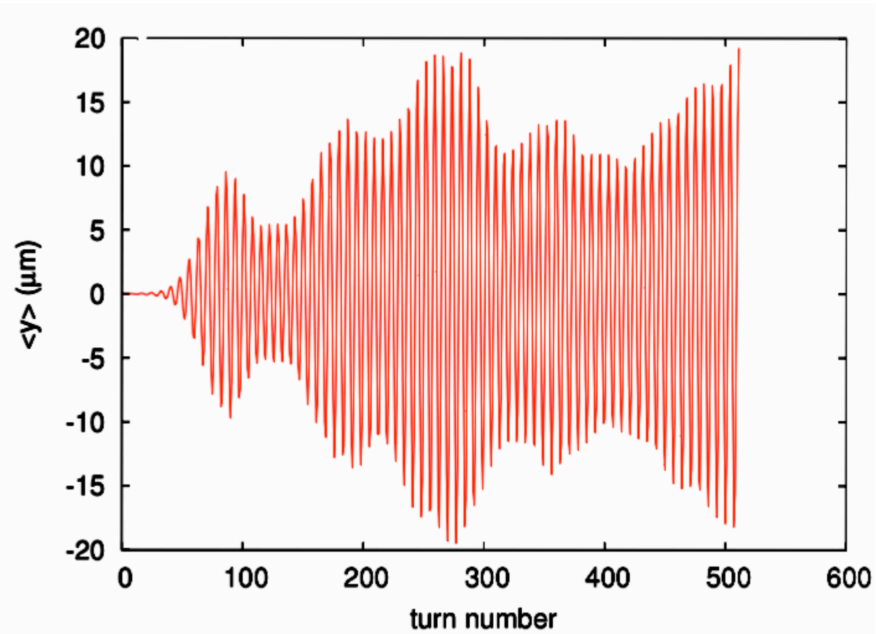
Instability simulations to check beam stability (simulations done with HEADTAIL)

→ In case of electron cloud build up, we assume these density values in arcs and wigglers:

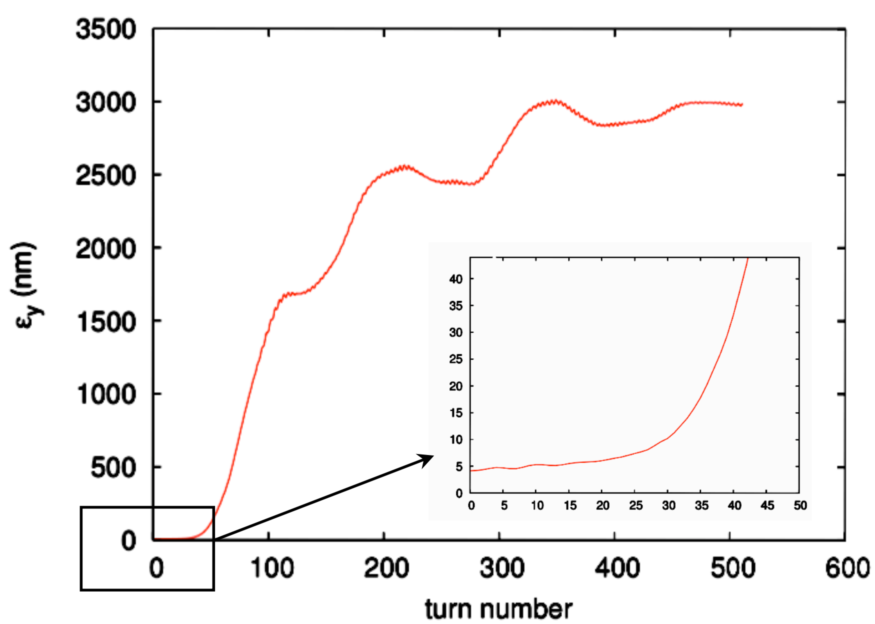
$$\rho_{wig} = 1.8 \times 10^{13}\ m^{-3} \qquad \rho_{dip} = 3 \times 10^{11}\ m^{-3}$$

→ The beam is affected by a strong and fast instability

→ However, with the new parameters we may gain a small factor from the higher energy and the larger transverse emittance (assuming the same total wiggler and dipole length). Besides, at 500GeV there are fewer wigglers and the integrated effect will be much lower



*** Vertical centroid motion**



*** Vertical emittance evolution**

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:

- ✓ Low impedance clearing electrodes
- ✓ Solenoids (KEKB, RHIC) -however only usable in field free regions!
- ✓ Low SEY surfaces -> see M. Taborelli's talk on the AEC'09 Workshop
  - ▪ Grooved surfaces (SLAC)
  - ▪ NEG and TiN coating
  - ▪ New coatings presently under investigation (SPS and Cesr-TA)

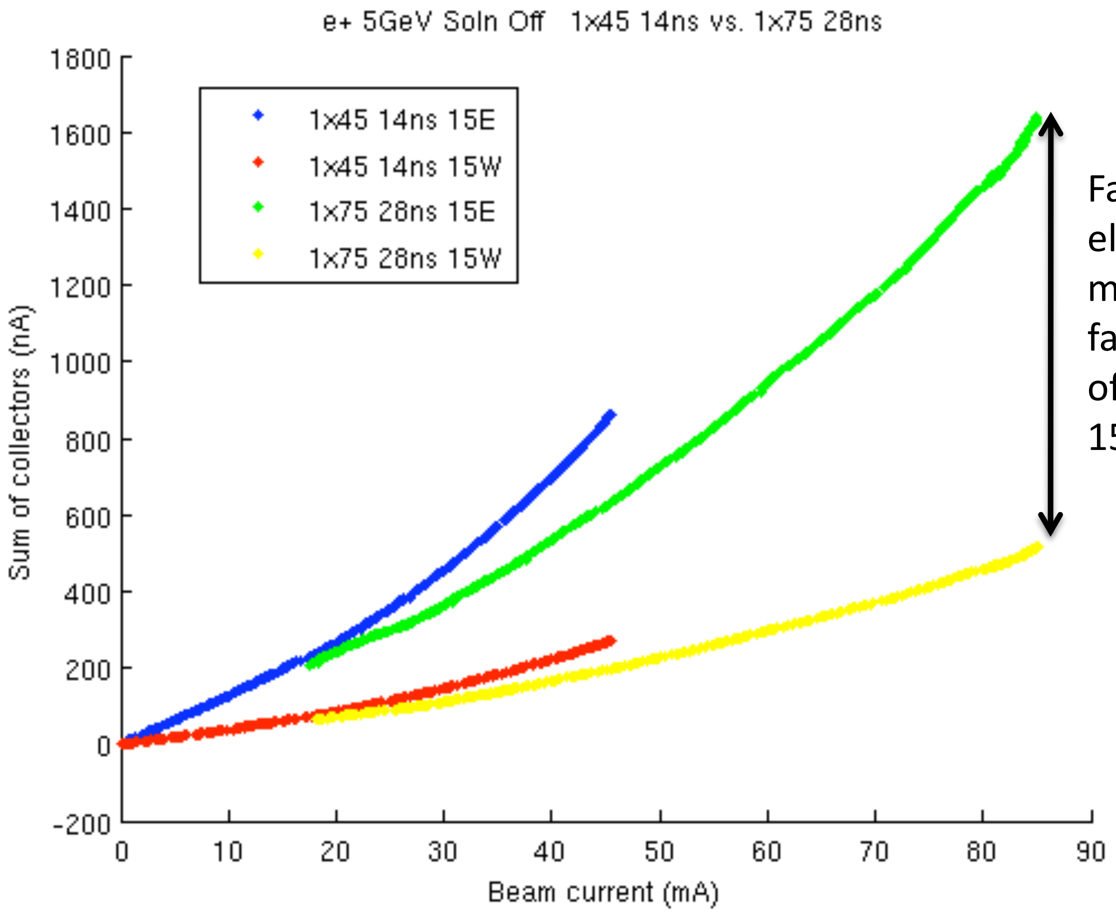
Carbon coatings, intensively studied by the SPS Upgrade Working Team, seem very promising and a possible solution.....

PEY of 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.

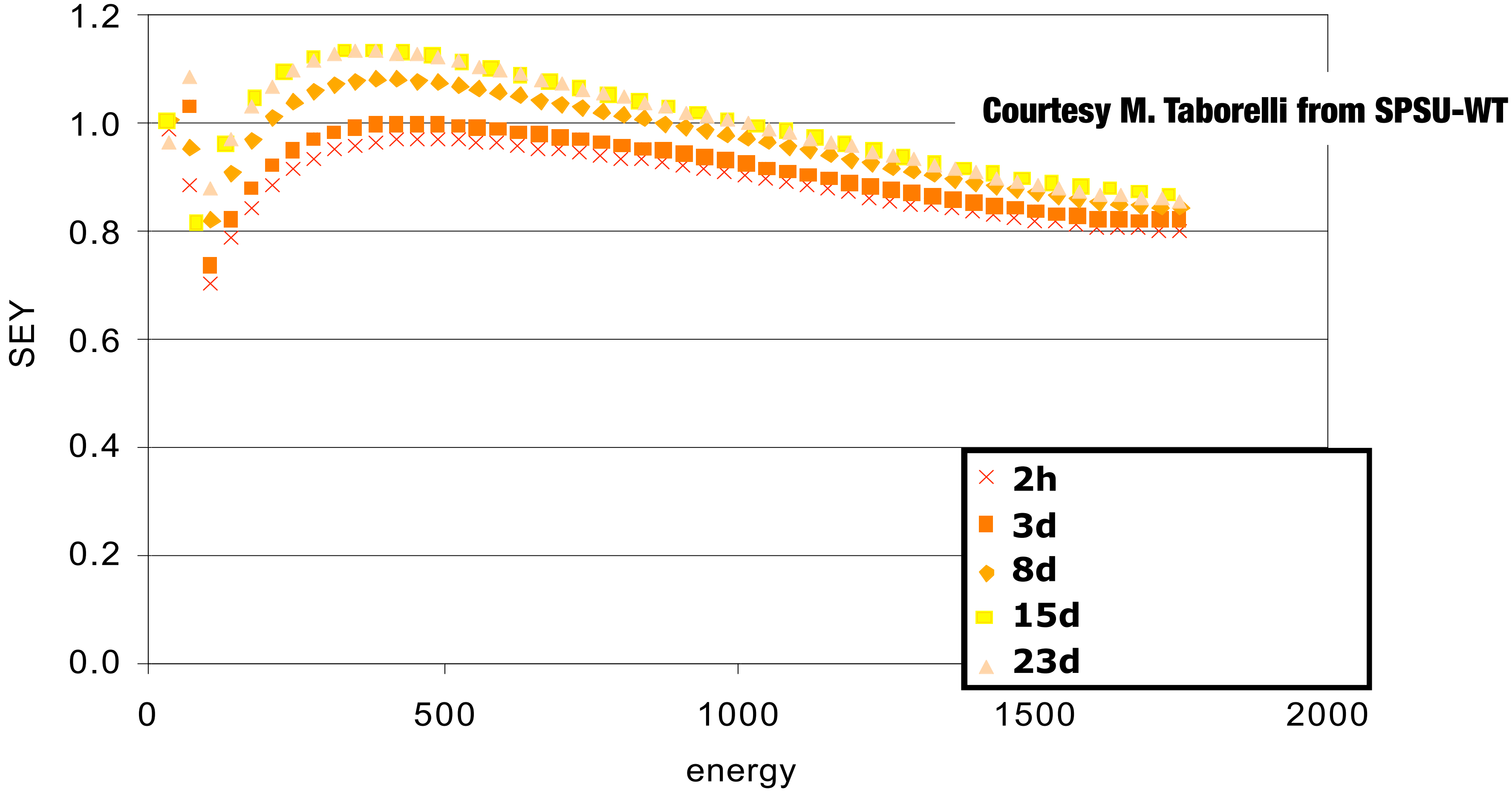
15W is a C-coated chamber

15E is an Al chamber



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

SEY of 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.

SINGLE BUNCH: SPACE CHARGE

- **Tune spread** induced by space charge can be estimated analytically integrating the space charge induced gradient all around the lattice to take into account of the beam size change due to the betatron modulation
- The horizontal tune spread is in the order of 0.01 (new 3TeV) and 0.006 (500GeV)
- The effect is much stronger in the vertical plane because the beam is smaller in this plane

New 3TeV

$$\Delta Q_y = \frac{N_b r_e C}{(2\pi)^{3/2}\gamma^3\sigma_z}\sqrt{\frac{1}{\epsilon_y}}\cdot\left\langle\frac{\sqrt{\beta_y}}{\sqrt{\beta_x\epsilon_x + D_x^2\sigma_\delta^2} + \sqrt{\beta_y\epsilon_y}}\right\rangle \simeq -0.185$$

500GeV

$$\Delta Q_y = \frac{N_b r_e C}{(2\pi)^{3/2}\gamma^3\sigma_z}\sqrt{\frac{1}{\epsilon_y}}\cdot\left\langle\frac{\sqrt{\beta_y}}{\sqrt{\beta_x\epsilon_x + D_x^2\sigma_\delta^2} + \sqrt{\beta_y\epsilon_y}}\right\rangle \simeq -0.21$$

SINGLE BUNCH: INSTABILITIES

- **Longitudinal**

  ✓ The Boussard criterion (including in the formula the suppression factor $(b/\sigma_z)^2$) would give a maximum impedance **value of ~5Ω**

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

- **Transverse**

  ✓ The TMCI threshold is given by the formula below

  ✓ The CLIC-DRs are in short bunch regime, and the formula translates into a tolerable **impedance value of ~15 MΩ/m** if $\omega_r = 2\pi$ x 6 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

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

COUPLED BUNCH INSTABILITY FROM RESISTIVE WALL (I)

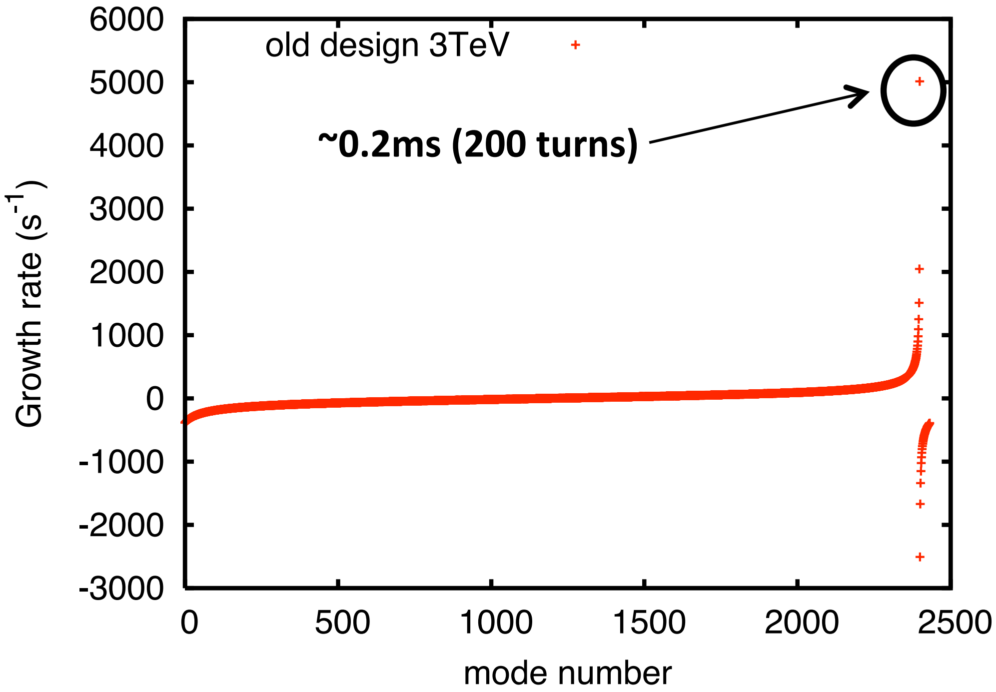
- **Transverse**

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

$$\cdot\frac{\sum_{p=-\infty}^{\infty} Z_1^{x,y}(\omega_p) h_m(\omega_p - \omega_{\xi x,y})}{\sum_{p=-\infty}^{\infty} h_m(\omega_p - \omega_{\xi x,y})},$$

with

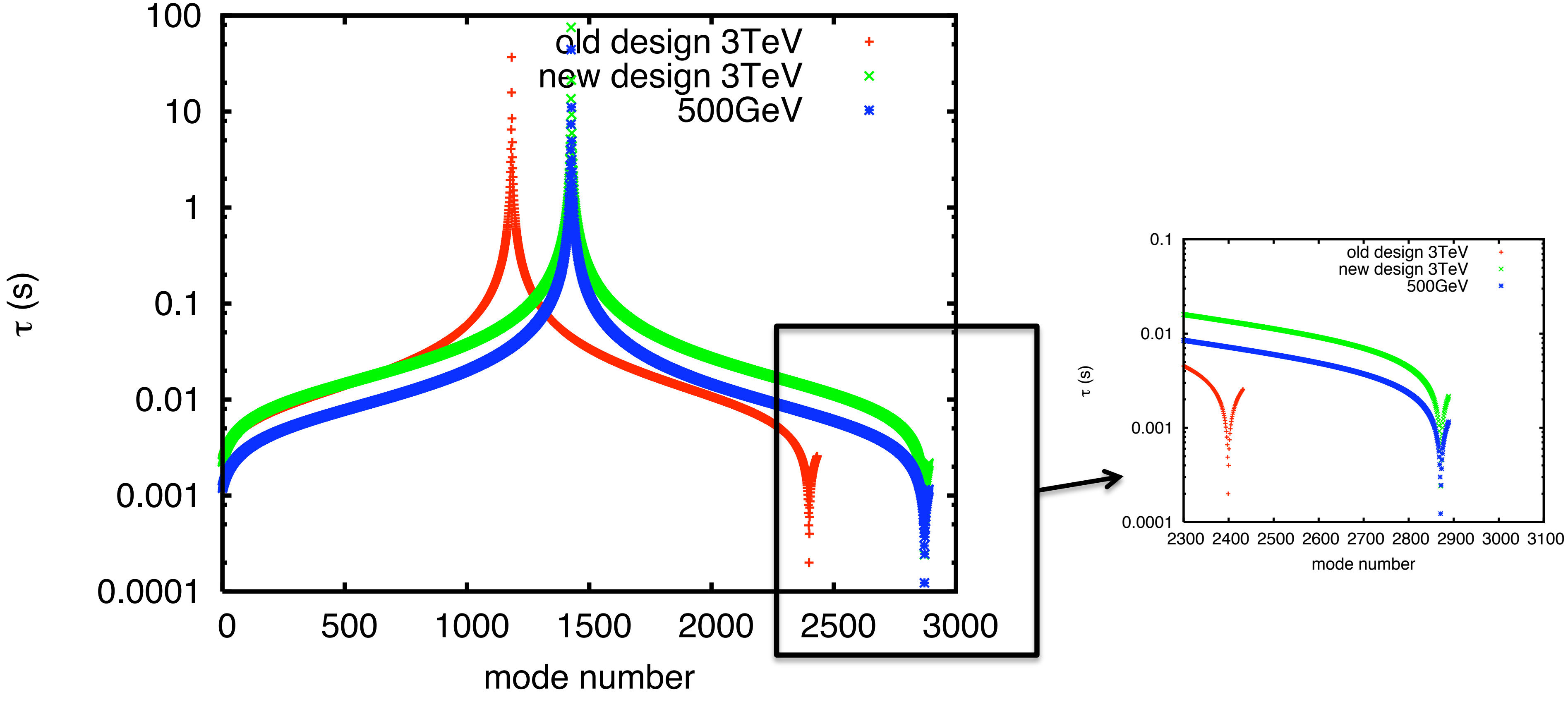
$$h_m(\omega) = \left(\frac{\omega\sigma_z}{c}\right)^{2m} \exp\left(-\frac{\omega^2\sigma_z^2}{c^2}\right)$$
$$\omega_p = (pM + \mu + Q_{x,y} + m\nu_s)\omega_0 \qquad .$$
$$\mu = 0, 1, ..., M-1$$
$$m = 0, \pm1, \pm2, ...$$



Pessimistic estimate because:
- wigglers only cover half of the ring, which gives possibly a factor 2
- instability rate has to be scaled by n_b/M, because the formulae assume a uniformly filled ring.

COUPLED BUNCH INSTABILITY FROM RESISTIVE WALL (II)

- **Transverse**

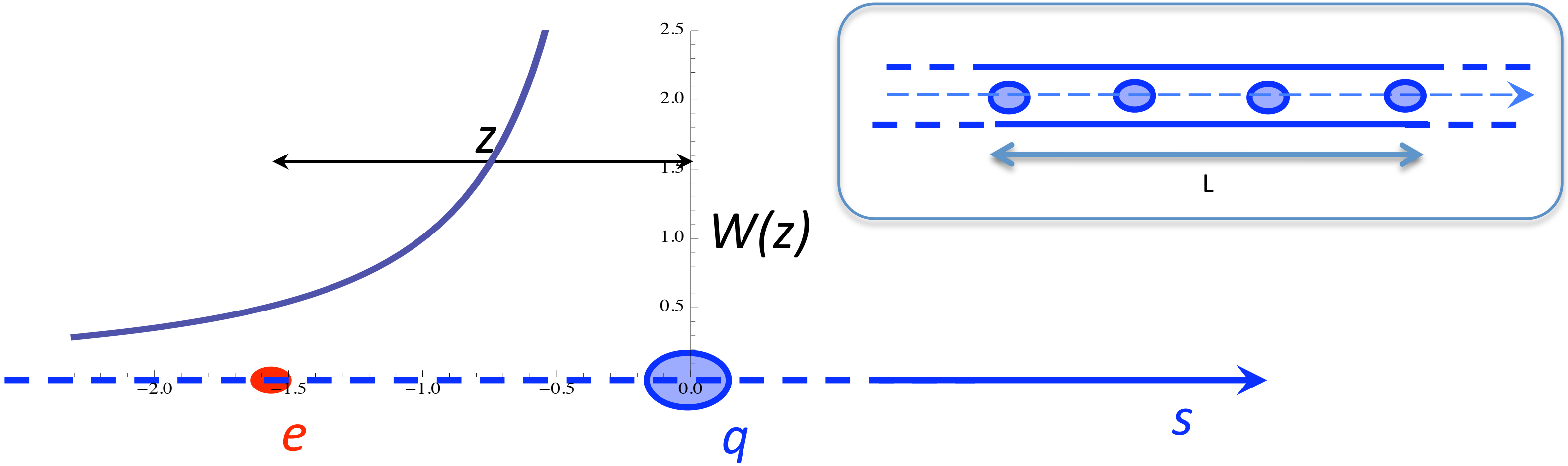


The lowest rise time does not change much with the new design

- it is slightly higher for the new 3TeV design (~0.3ms or 200 turns)) and slightly lower for the 500GeV design (~0.1ms or 70 turns)

COUPLED BUNCH INSTABILITY FROM RESISTIVE WALL (III)

- **HEADTAIL simulations**



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 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.

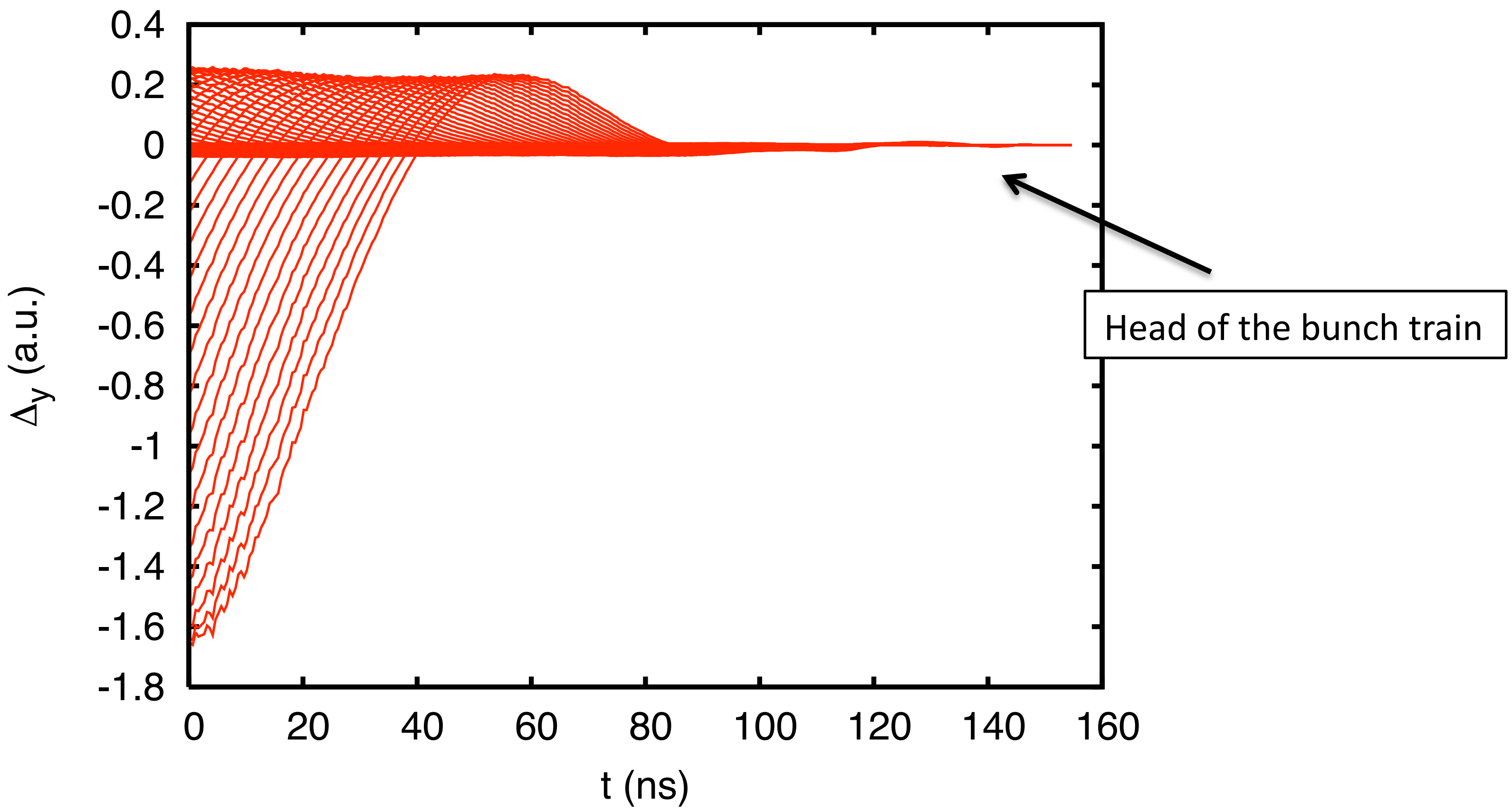
$$\int_0^L F_\perp(s,z)ds = -eqxW_\perp(z)$$

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

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

COUPLED BUNCH INSTABILITY FROM RESISTIVE WALL (IV)

- **HEADTAIL simulations with the parameters of the new 3TeV design**



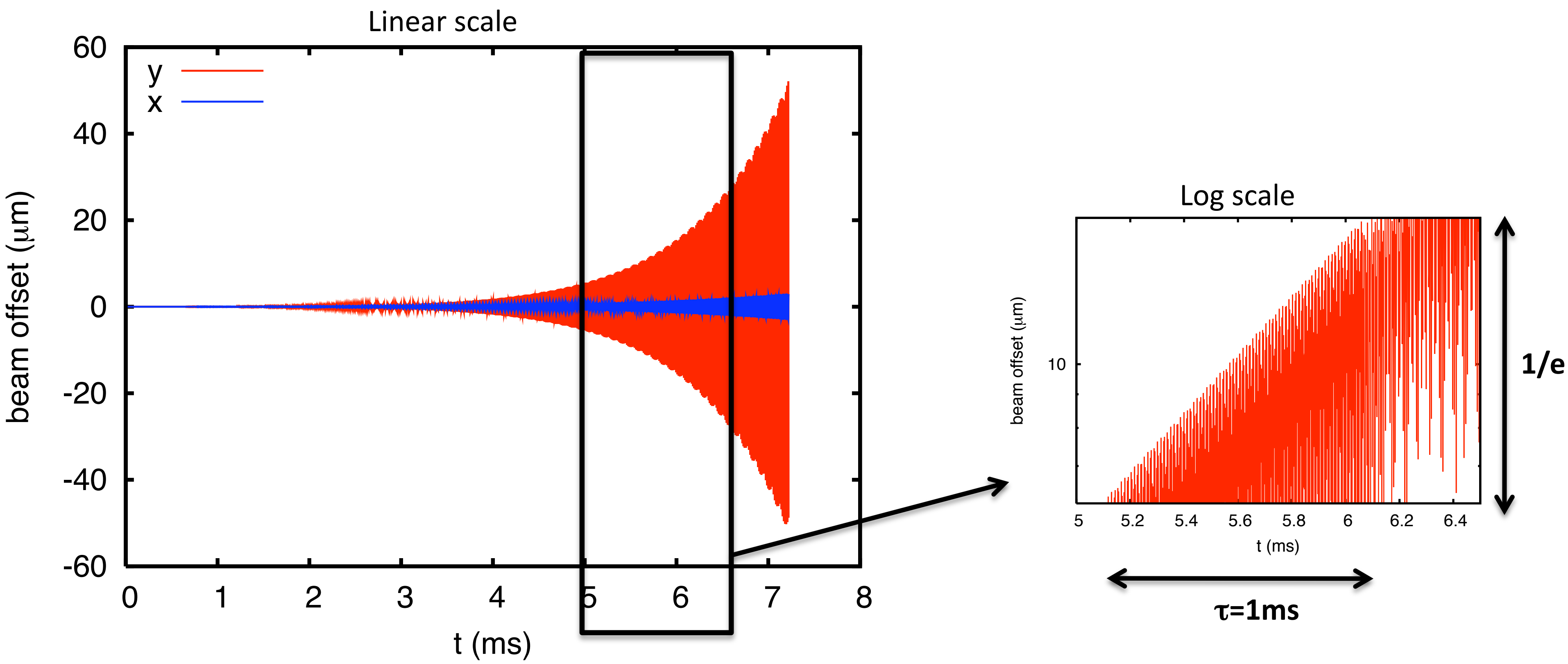
In the plot

→ 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 FROM RESISTIVE WALL (V)

- **HEADTAIL simulations**



In the plot

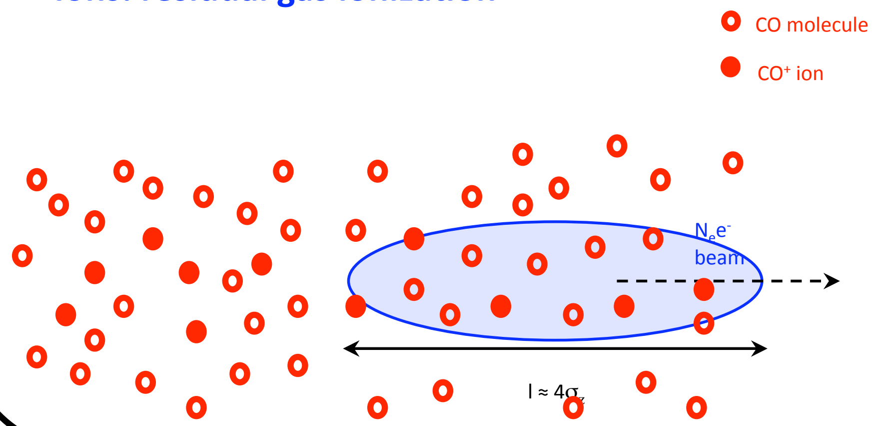
→ The evolution of the vertical centroid of the train exihbits an exponential growth in both the horizontal (slow) and vertical (fast) plane

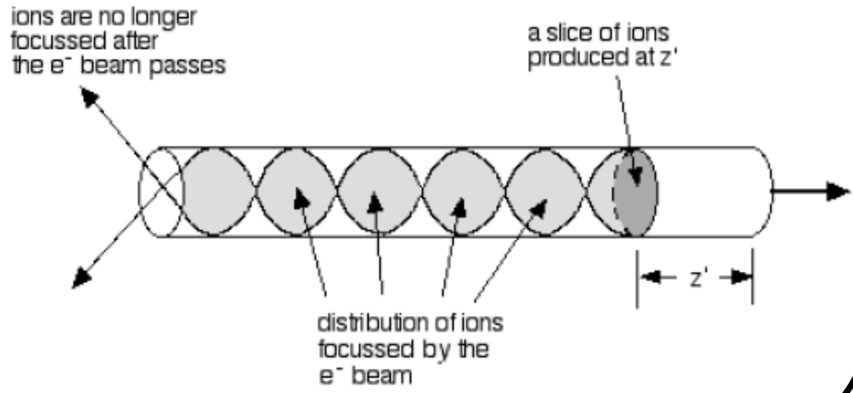
→ The rise time is larger than the calculated one because the simulation takes into account the real wiggler length and the train length

FAST ION (I)

The ions produced by gas ionization can be focused by the electric field of the following bunches and they accumulate in the vicinity of the beam (trapping condition)

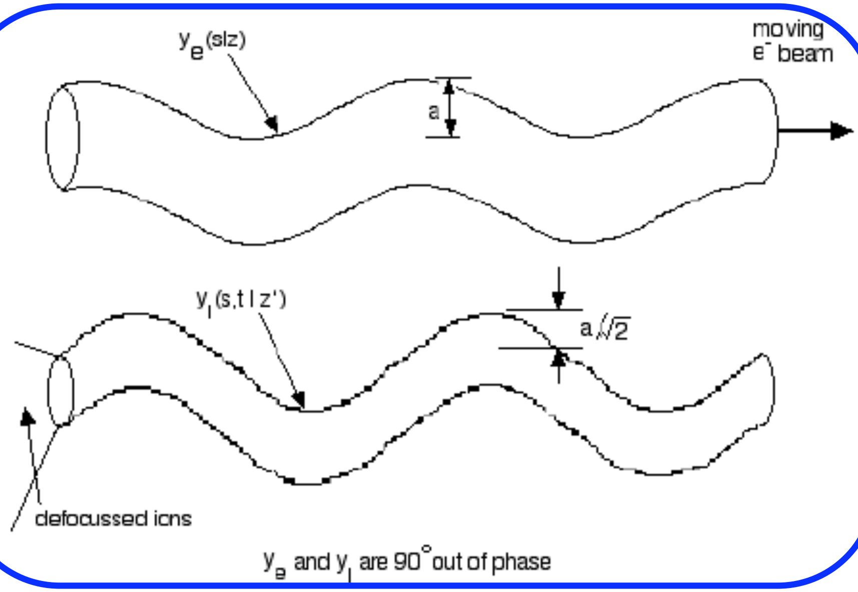
Ions: residual gas ionization





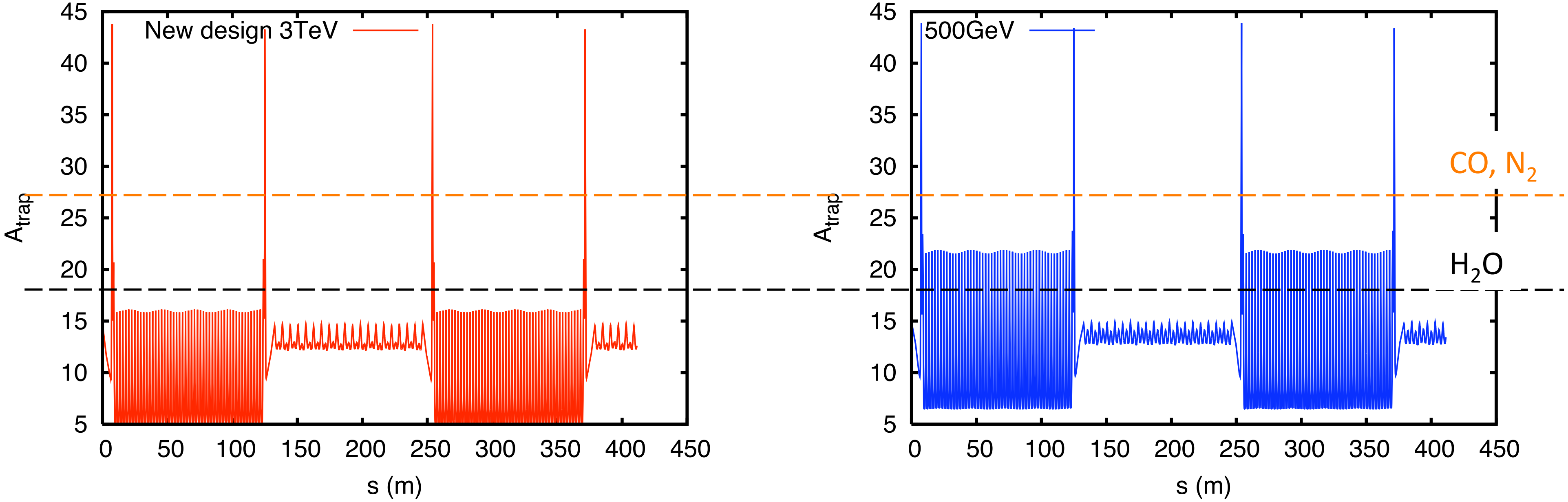
The ion cloud can affect the motion of the bunches and an unstable ion-electron coupled motion can be excited

Two-stream instability



FAST ION (II)

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 beta functions, and therefore different beam sizes)



This means that molecules like N_2, CO are trapped around the beam almost along the full ring. H_2O is below the threshold for trapping over a shorter length for the 500 GeV design

FAST ION (III)

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

Trapped ions cause tune spread (p=1 nTorr)

$$\Delta Q_{ion} \simeq \frac{N_b n_b r_e C}{\pi\gamma\sqrt{\epsilon_x\epsilon_y}}\left(\frac{\sigma_{ion} p}{k_B T}\right) \simeq \begin{cases} 0.04 & \text{for new design@3TeV} \\ 0.06 & \text{for 500GeV option} \end{cases}$$

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

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

Conclusions

- Some collective effects have been estimated with the new parameters for the CLIC-DRs (also for the 500GeV option)
- The electron cloud build up is not expected to change much in the positron ring and poses constraints on PEY and SEY of the beam pipe.
  - Wigglers should be designed such as to be able to absorb 99.9% of the produced synchrotron radiation
  - The maximum SEY should be kept below 1.3
  - Special **chamber coatings** (under study) could be a viable option
- Space charge causes a very large tune spread in the vertical plane (up to -0.2). Tolerable?
- Instabilities (impedances)
  - Single bunch: they can be avoided with a smooth impedance design
  - Resistive wall coupled bunch: rise times of 100s of turns, therefore they can be controlled with feedback
- Fast ion instability:
  - Dangerous molecules are likely to be trapped all along the electron ring
  - In absence of a wide band feedback system, it poses a serious constraint on the acceptable vacuum pressure (0.1 nTorr)