First Calculations on Beam Loading in the CLIC RF deflectors

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OUTLINE

1) General considerations on Beam loading in RFD: CTF3 studies

2) Scaling laws CTF3→CLIC

3) Beam loading effects in CLIC: TW RFD in CR1 and CR2

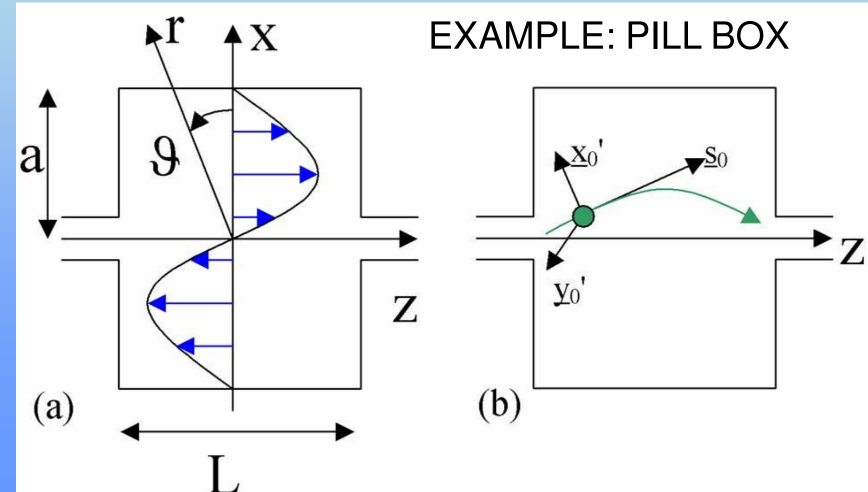
4) Conclusions

General considerations on Beam loading in RFD:
Deflecting field excited by the beam in RF deflectors

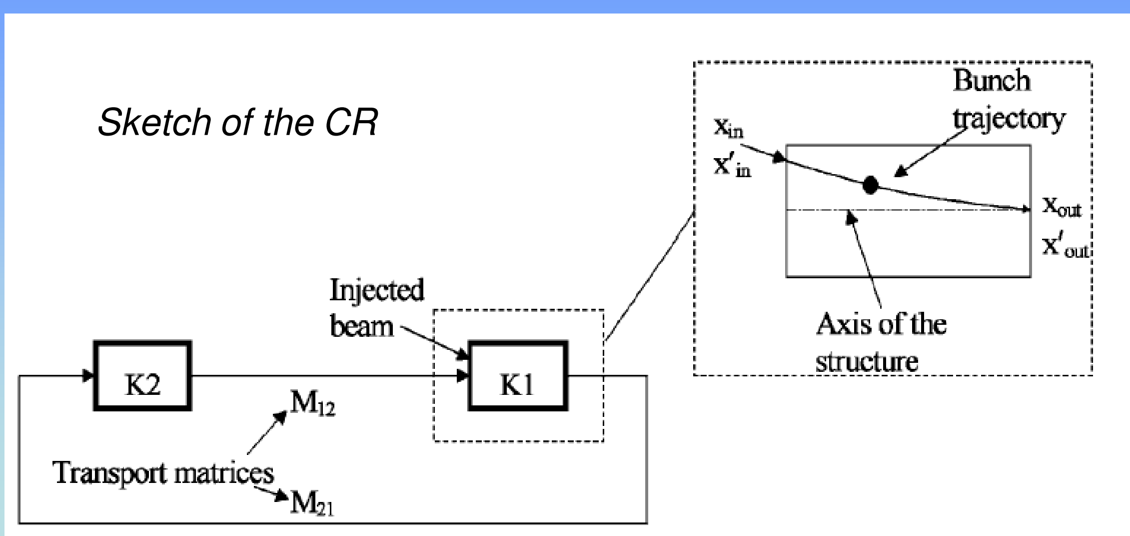
The **deflecting field has a longitudinal electric field** off-axis.

Unwanted deflecting field can be **excited by the beam if it passes off-axis** into the deflectors both in the horizontal than in the vertical plane.

The transverse deflecting voltage and the longitudinal one are **90 deg out-of-phase** as states by the Panofsky-Wenzel theorem.



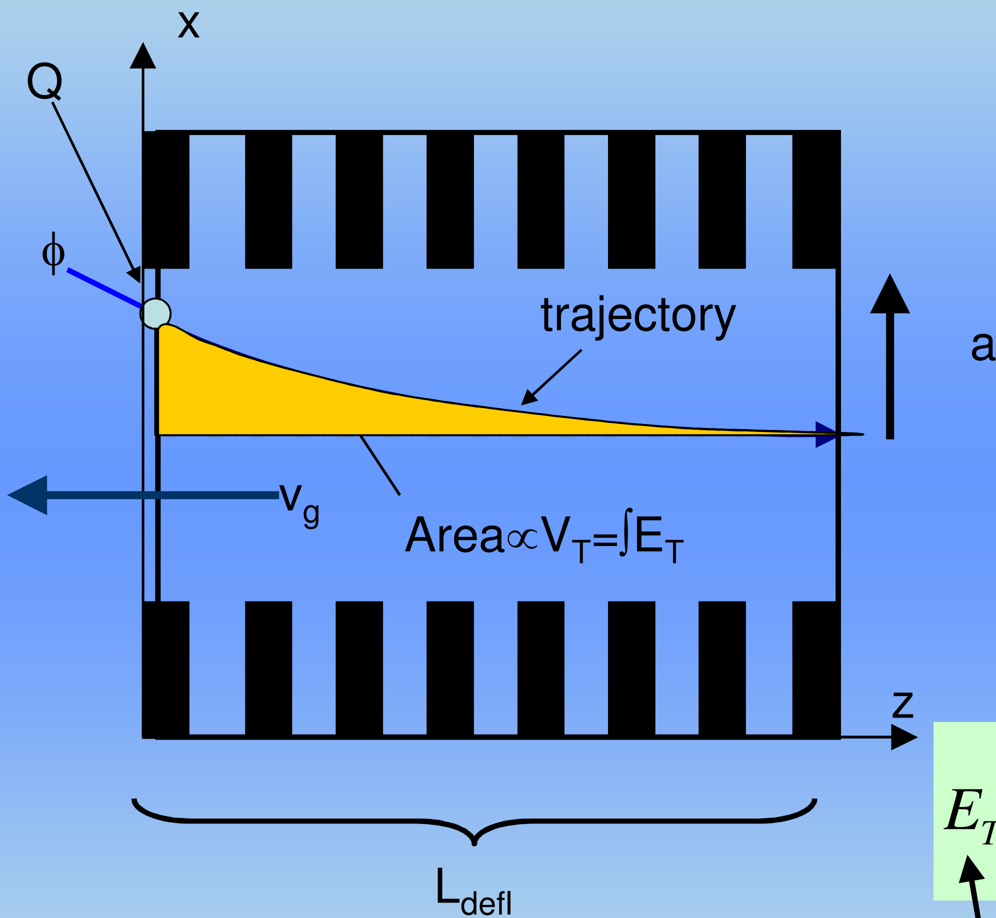
$$\tilde{V}_{x\_RFD} = j\frac{c}{\omega_{RF}}\nabla_x \tilde{V}_{z\_RFD}$$



In the CR we can have **beam loading effects** in the horizontal (deflecting) plane, **even in the case of perfect injection** since the bunch passes off axes into the deflectors.

General considerations on Beam loading in RFD:

HOW the Beam loading works (TW case)



Trajectory of the leading bunch translated according to the group velocity

Leading bunch charge

$$E_T = \frac{1}{2} q \frac{\omega_{RF}^2}{c} \frac{R}{Q} x \left(z - \frac{T_{RF}}{4} v_g \right)$$

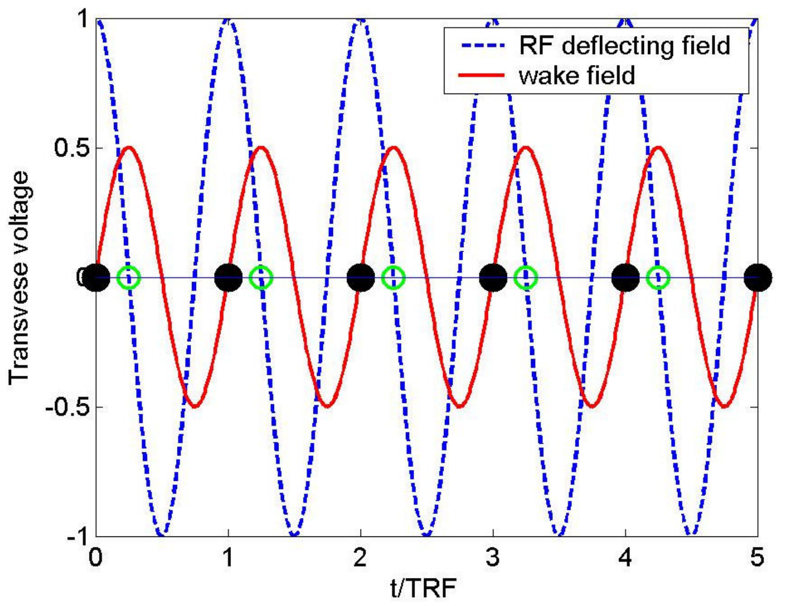
Transverse field seen by a trailing bunch

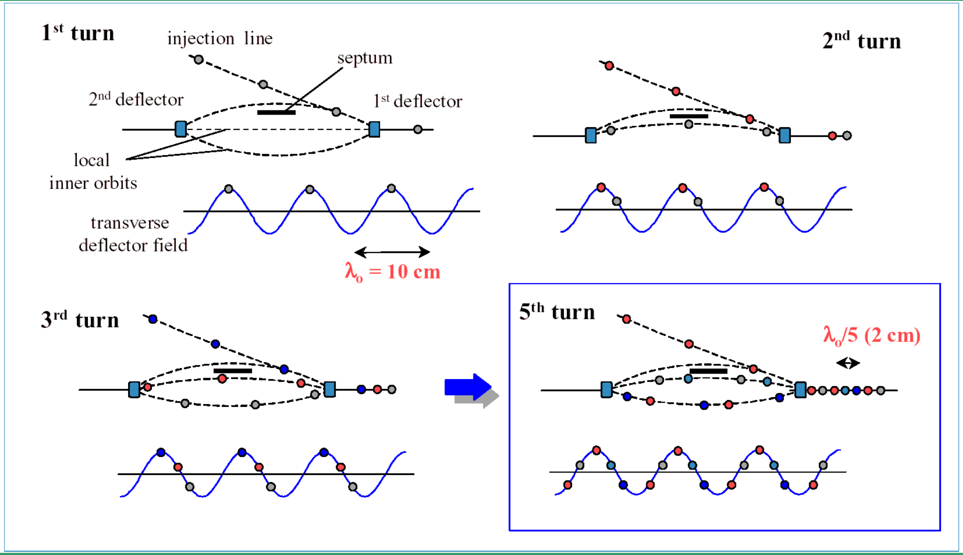
RFD parameters

General considerations on Beam loading in RFD:

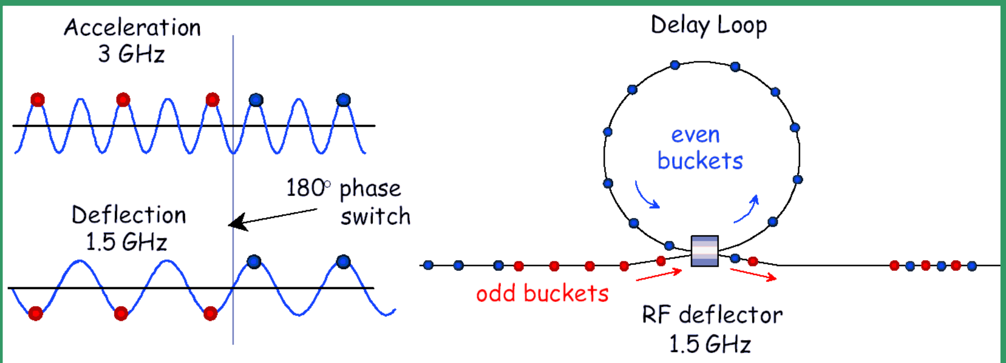
Combiner Ring and Delay Loop

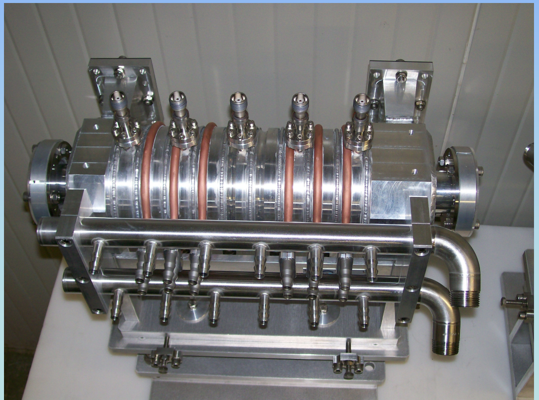
Since the excited field is 90 degree out of phase with respect to the deflecting one the **beam loading is more crucial in the CRs than in the DL** because the bunches, during recombination, passes on the zero crossing of the main deflecting voltage.





For this reason the **RFDs of the CR have been designed with fast filling time**, in order to empty the structure as soon as possible. The most simple structure that satisfy this requirement is a TW short structure.

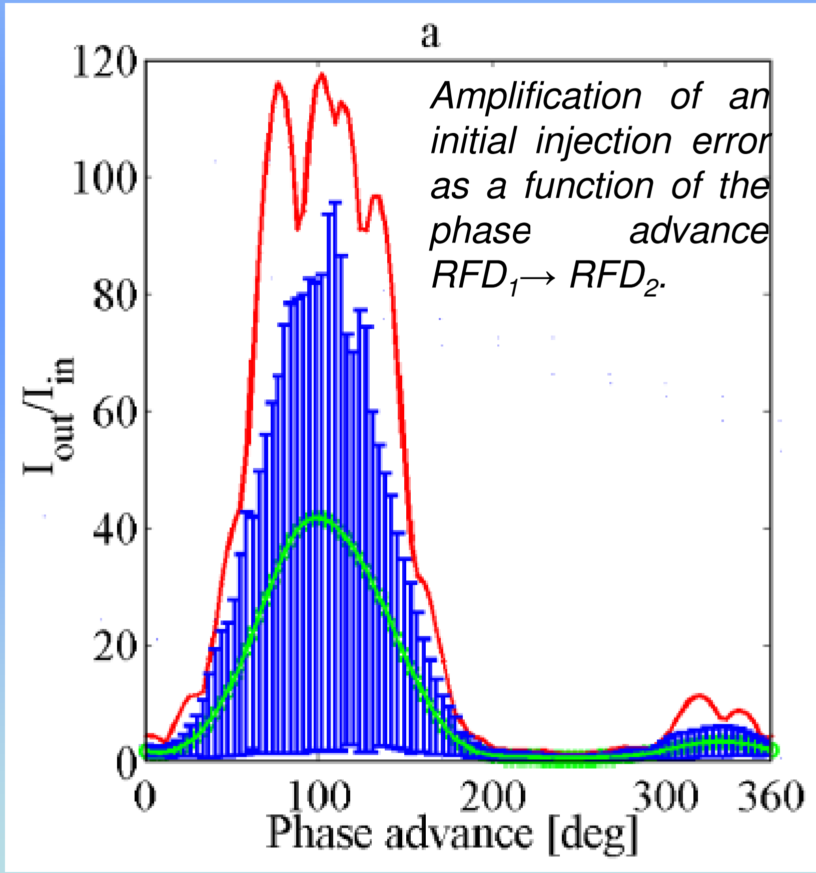


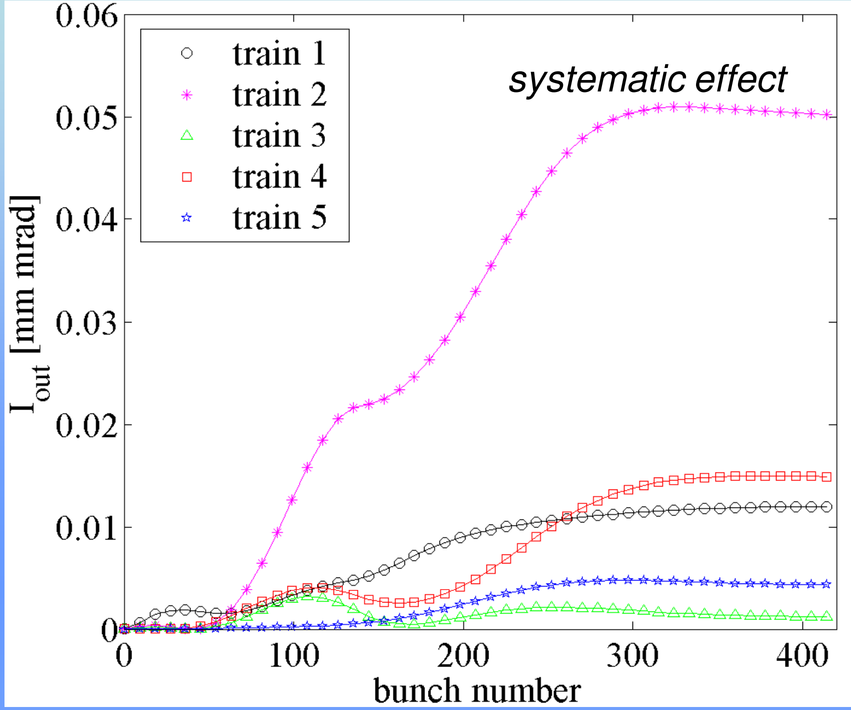


Beam loading studies in CTF3

The beam loading in the CR (and also DL) of **CTF3 effect have been extensively studied** by means of a dedicated **tracking code**.

The studies have been done:
-**without injection errors**: "systematic effect";
-with injection errors.





The most synthetic information is given by the **Courant-Snyder invariant of each bunch** after the merging process that can be compared with the nominal projected emittance in case of "systematic" effect, or with the initial invariant in case of injection error.

From the calculation we found that:
-the **systematic effect perfectly controllable.**
-with a proper choice of the machine parameters even in case of injection errors the **amplification factor can be taken under control**.

D. Alesini and A. Gallo, ***Effect of beam loading in the RF deflectors of the CLIC test facility CTF3 combiner ring,*** PRST AB 7, 2004
D. Alesini and F. Marcellini, ***CTF3 Delay loop RF deflectors design and beam loading effect analysis,*** submitted to PRST

Scaling laws

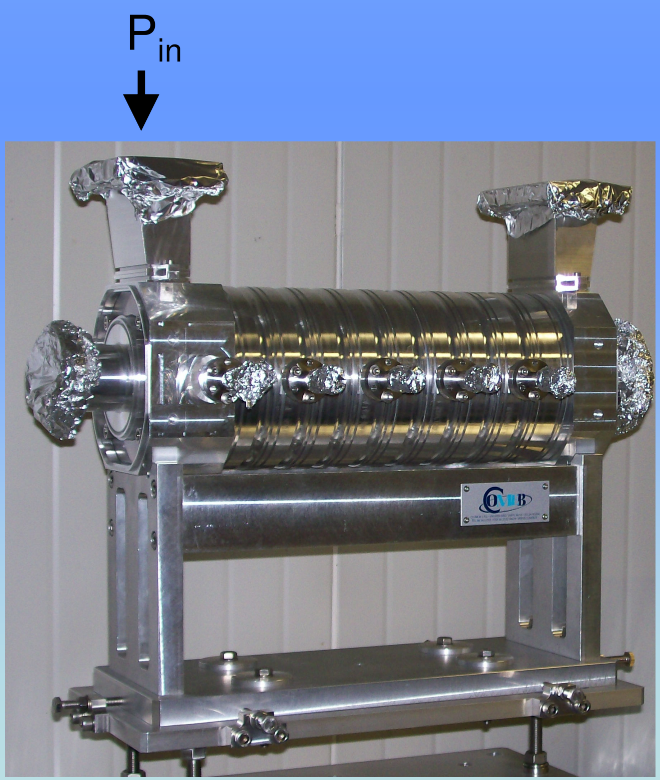
It is possible to find **first order scaling laws** for the beam loading effects in the CR.

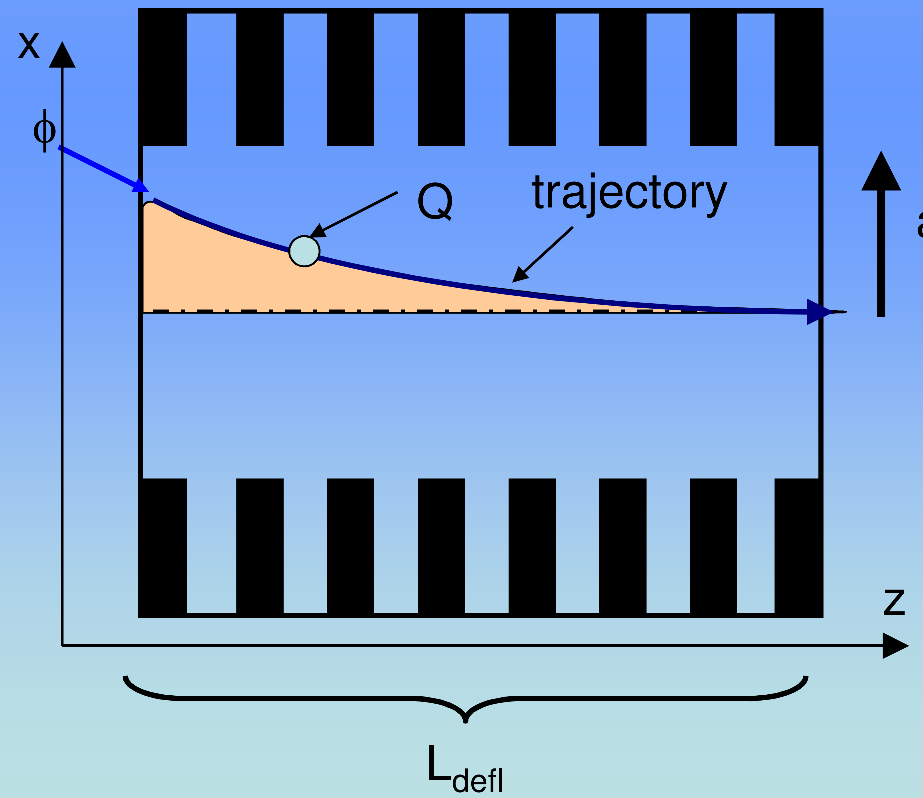
These scaling laws depends on:

-the **beam parameters**: charge **q**, energy $\mathbf{E_0}$, nominal deflection ϕ;

-the **RFD parameters**: RFD length $\mathbf{L_{defl}}$, working frequency $\mathbf{f_{RF}}$, iris aperture **a**, maximum available/allowable input power $\mathbf{P_{IN}}$.

In the next considerations when we consider one parameter we suppose to fix the others.



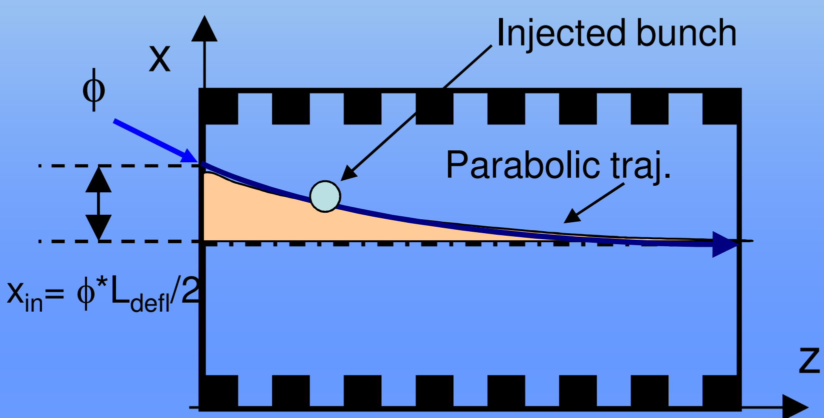


Scaling laws: L_{defl}

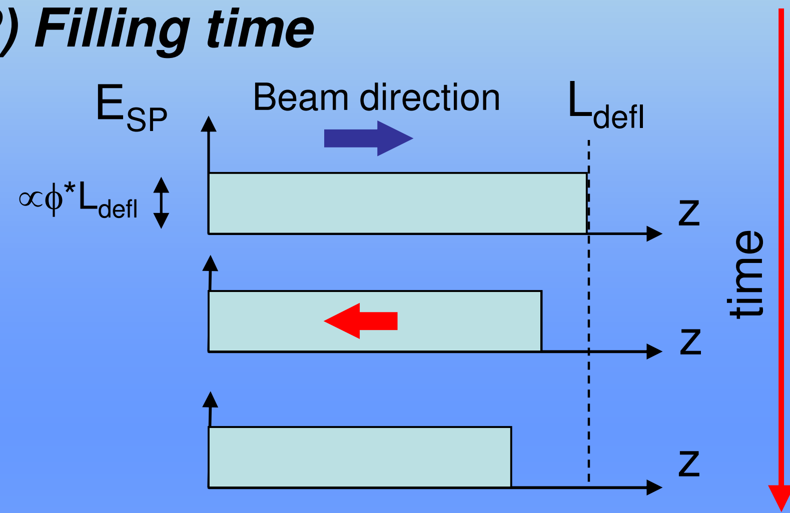
The structure length is, obviously, related to the nominal deflection, beam energy and available input power. Let us fix all these parameters.

Changing L_{defl}, corresponds to change both the bunch trajectory inside the deflector and the filling time

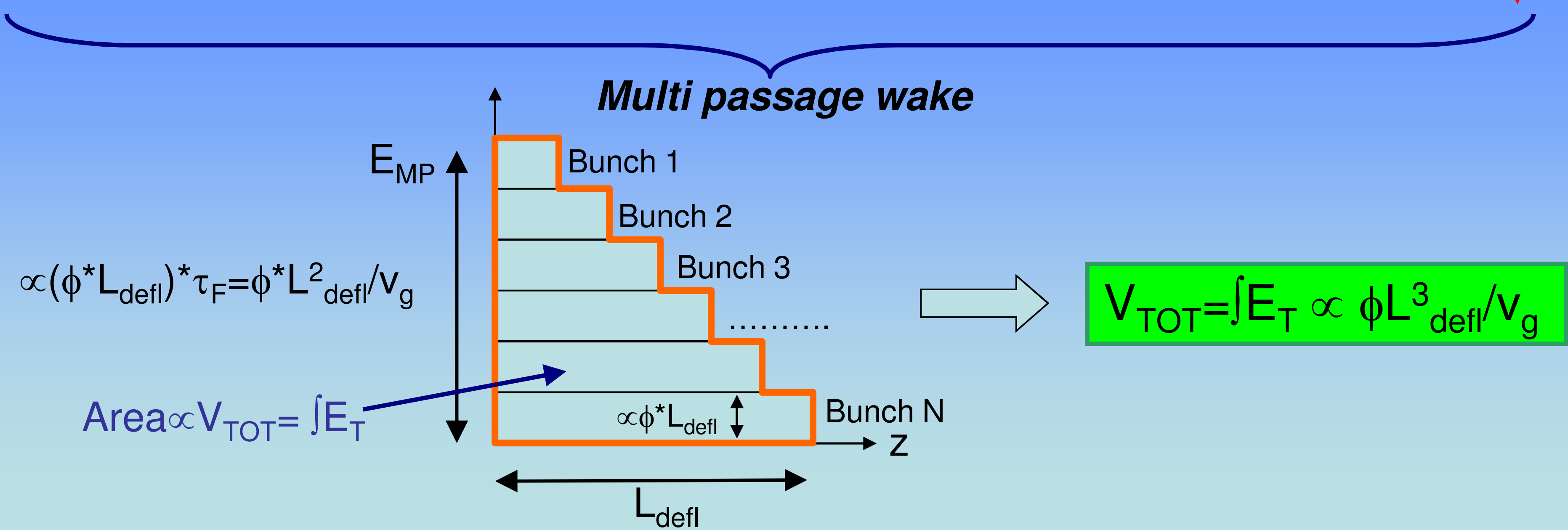
1) Bunch Trajectory



2) Filling time



Multi passage wake



Scaling laws: CLIC/CTF3

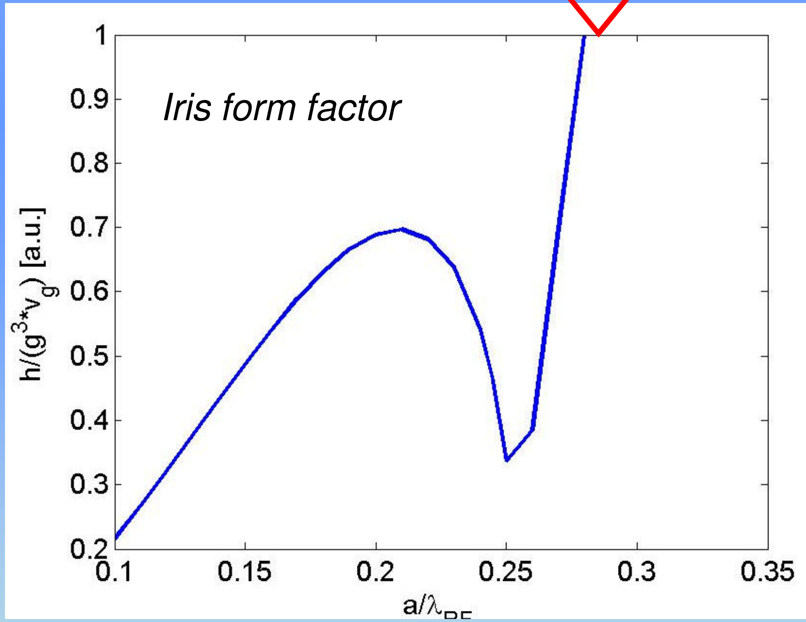
From previous consideration it is possible to find a ***general scaling law*** for the beam loading effects.

$$\langle x_{osc}\rangle \propto \phi \frac{q}{E_0} f_{RF}^2 \frac{R}{Q} \frac{L_{defl}^3}{v_g} \quad \Rightarrow \quad \langle x_{osc}\rangle \propto q\phi^4 E_0^2 P_{IN}^{-3/2} f_{RF}^0 \frac{h(a/\lambda_{RF})}{g^3(a/\lambda_{RF})\, v_g(a/\lambda_{RF})}$$

$$L_{defl} = \phi E_0 \frac{1}{\sqrt{P_{in} Z_T}} \underbrace{=}_{\sqrt{Z_T} = f_{RF}\, g(a/\lambda_{RF})} \phi E_0 \frac{1}{f_{RF}\, g(a/\lambda_{RF})\sqrt{P_{in}}}$$

$$\frac{R}{Q} \propto f_{RF}\, h(a/\lambda_{RF})$$

$$\frac{\langle x_{osc}\rangle\big|_{CLIC}}{\langle x_{osc}\rangle\big|_{CTF3}} = \underbrace{\frac{\phi_{CLIC}}{\phi_{CTF3}} \frac{q_{CLIC}}{q_{CTF3}} \left(\frac{E_{0\_CLIC}}{E_{0\_CTF3}}\right)^2}_{\approx 900} \left(\frac{P_{IN\_CLIC}}{P_{IN\_CTF3}}\right)^{-3/2}$$



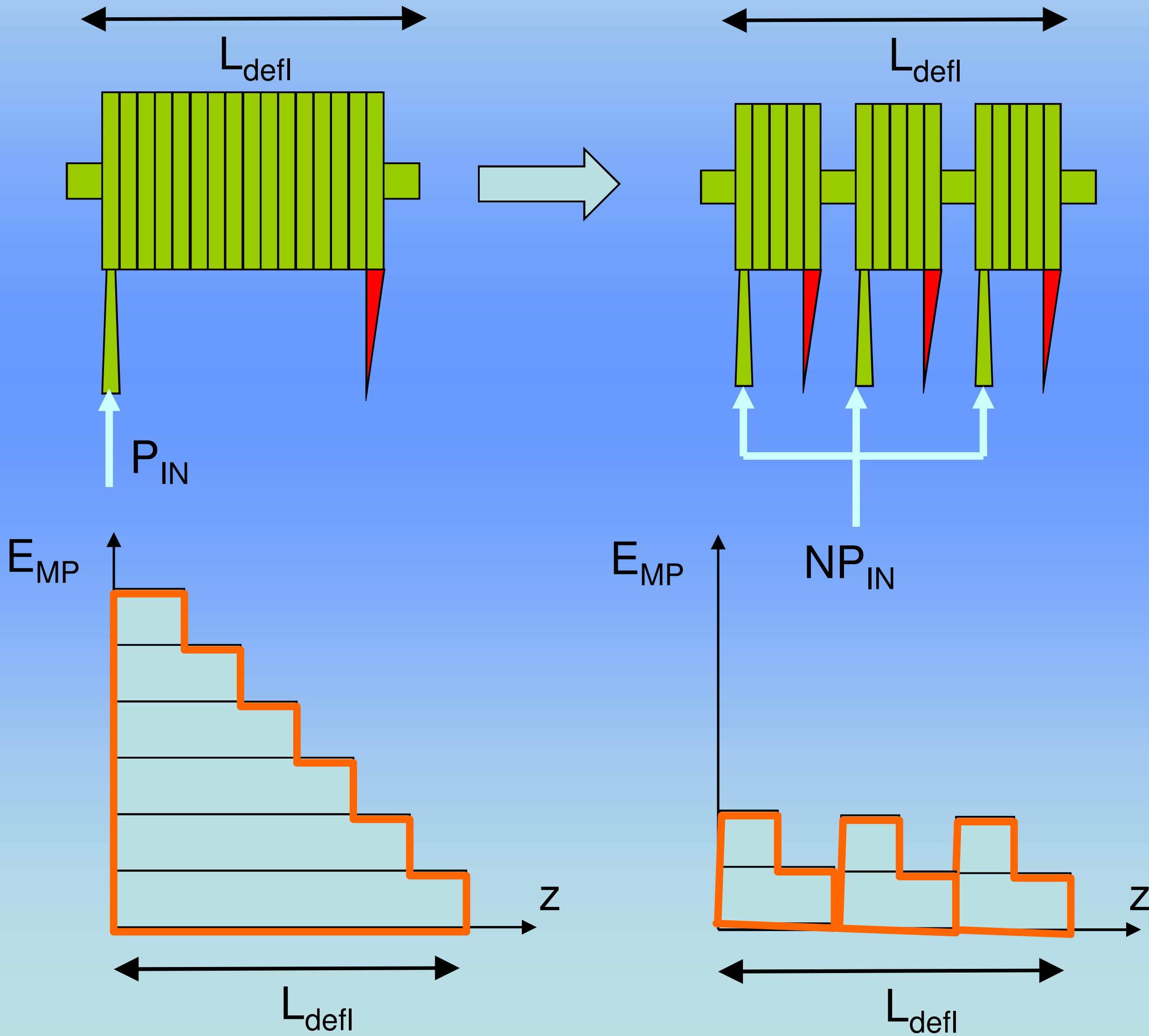
backward forward

Not possible for klystron available input power and average dissipated power in each structure.

~~$P_{IN\_CLIC} \approx 100 P_{IN\_CTF3}$~~

Multiple deflectors

The only practical solution is to use more RFDs. This is equivalent to have a **strongly damped structure**.
In this case **the effect of the wake is reduced by a factor N^2.**
The main disadvantage is that one has to feed each structure with the nominal input power and therefore one has to have **N times the available input power**.



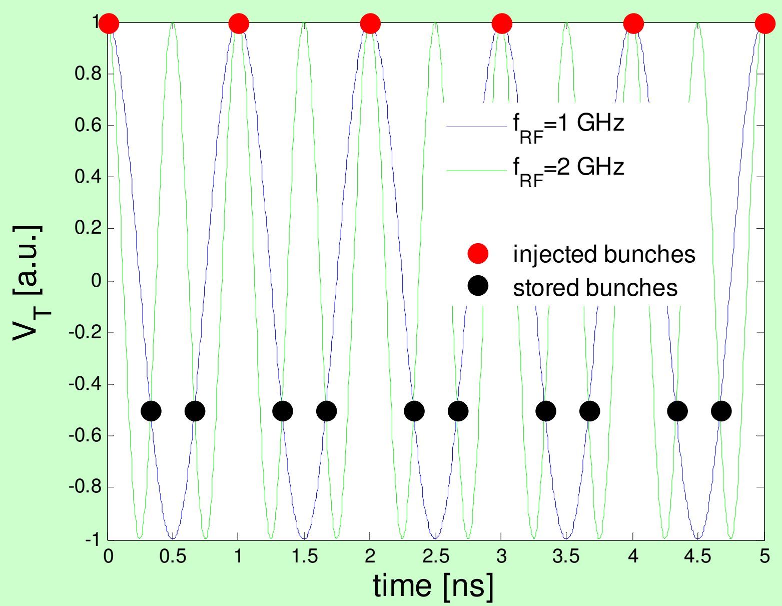
$$\langle x_{osc} \rangle \propto \phi \frac{q}{E_0} f_{RF}^2 \frac{R}{Q} \frac{L_{defl}^3}{N^2 v_g}$$

$$P_{IN\_CLIC} \approx \frac{100}{N^2} P_{IN\_CTF3}$$

N=4

$$P_{IN\_CLIC} \approx 6 P_{IN\_CTF3}$$

RFD Parameters for the CR1



Optics Parameters	
β_x @ RFD	4 m
Phase advance $RFD_1 \rightarrow RFD_2$	90 deg

Beam Parameters	
Bunch charge (q)	8.4 nC
Beam Energy (E_0)	2.37 GeV
Number of bunches (Nb)	244*3
Norm. emittance (ε_N)	150 mm*mrad

In the case of CR1 **the recombination factor 3 (instead of 4) mitigate the beam loading effects** with respect to CR2.

In this case, in fact, the beam loading is **not perfectly 90-deg out of phase**.

For this reason the **number of multiple deflector can be limited to 2**.

RFD Parameters	
Working frequency (f_{RF})	2 GHz
Deflector length (L_{defl})	1.1 m
Number of multiple deflector (N)	2
R/Q	1450
Total input power P_{IN}	35 MW
Average diss. Power per unit length (dP_{diss}/dz)	47 kW
Iris aperture (a)	2 cm
Group velocity/c (v_g/c)	0.0155

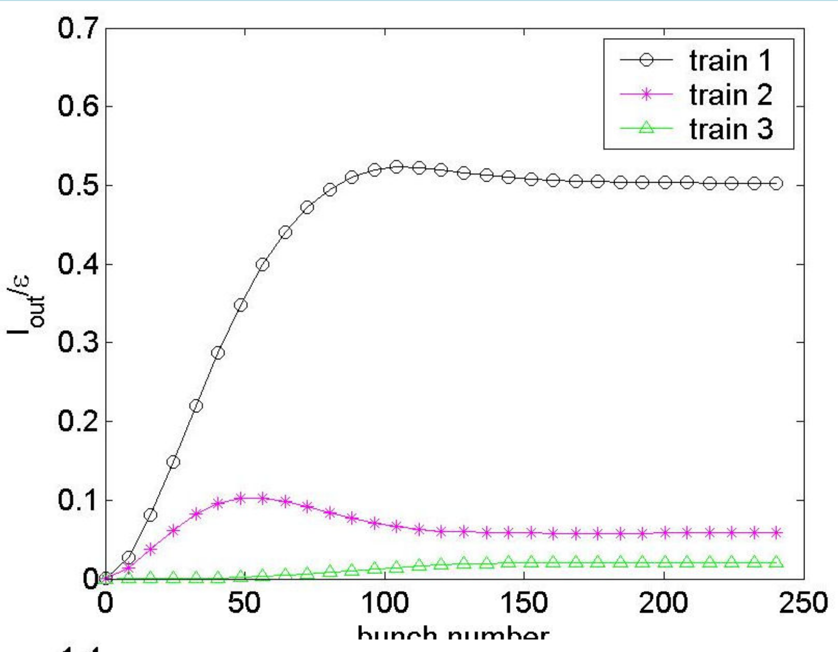
Beam Loading in CR1: systematic effects

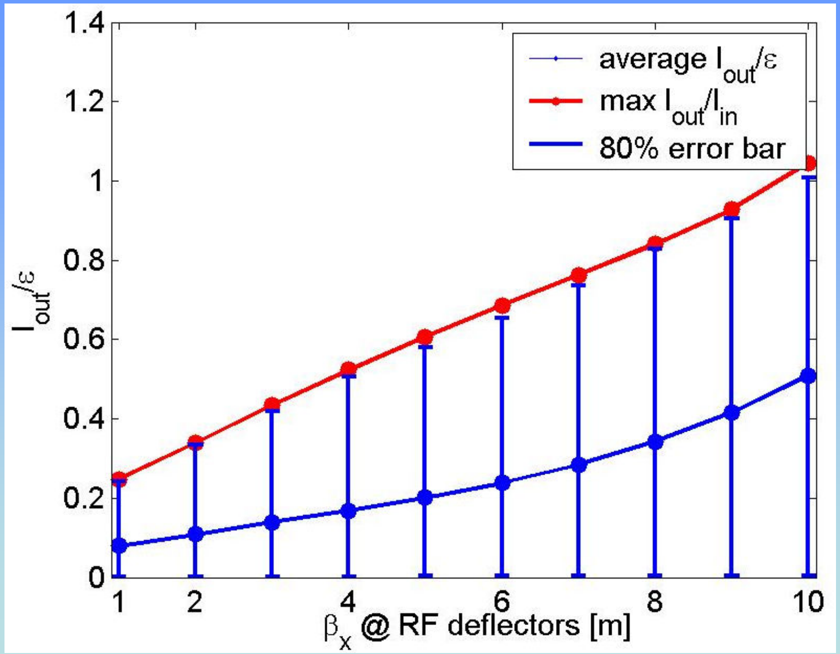
With the tracking code we have calculated the "**systematic**" effect.

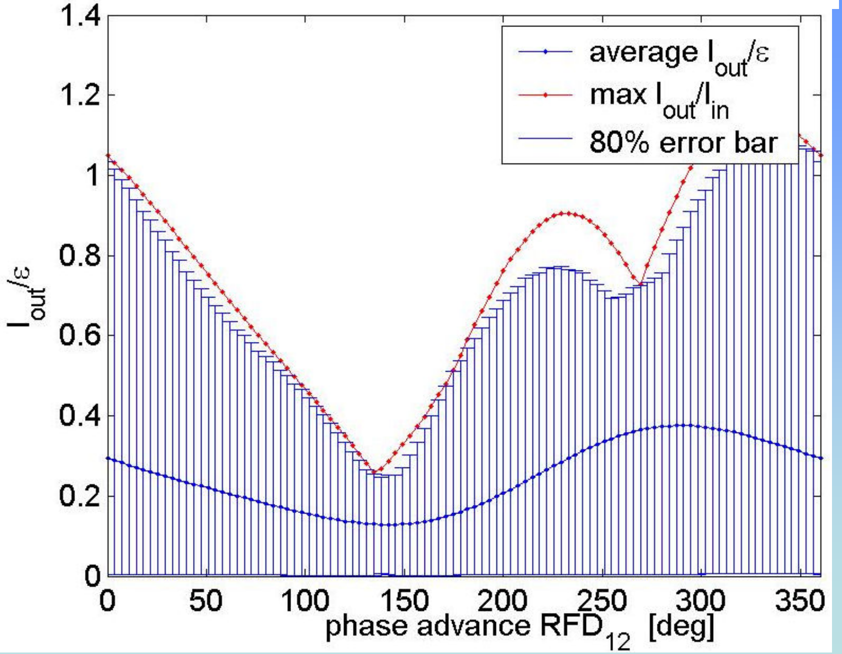
The **ratio between the output CS invariant of each bunch and the nominal projected emittance** has been calculated for different **phase advances** between the two deflectors and for different **horizontal β-function** at the deflectors.

The results shows that the **beam loading is controllable** even if **more critical** with respect to the CTF3 case.

An **increase of the number of deflectors** can further reduce the BL effects.





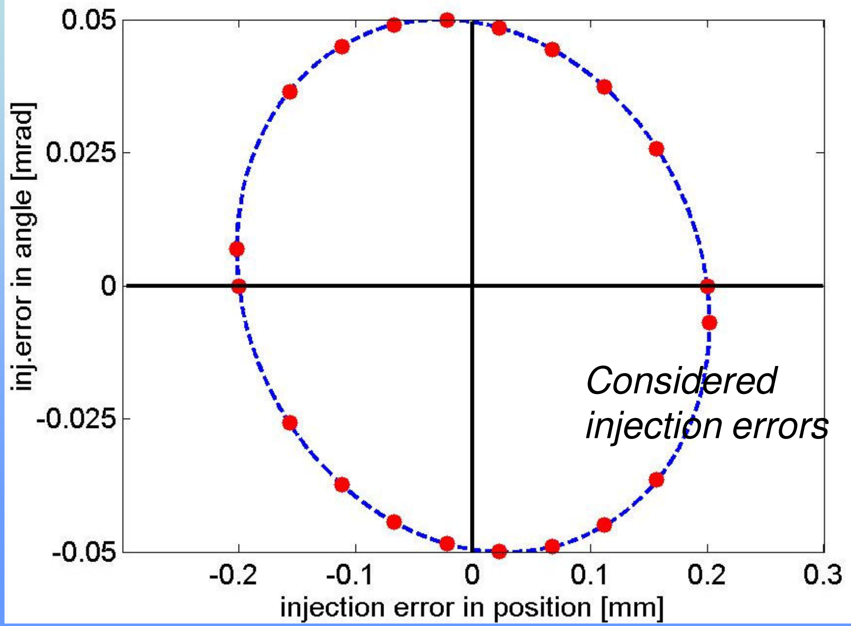


Beam Loading in CR1: Injection errors

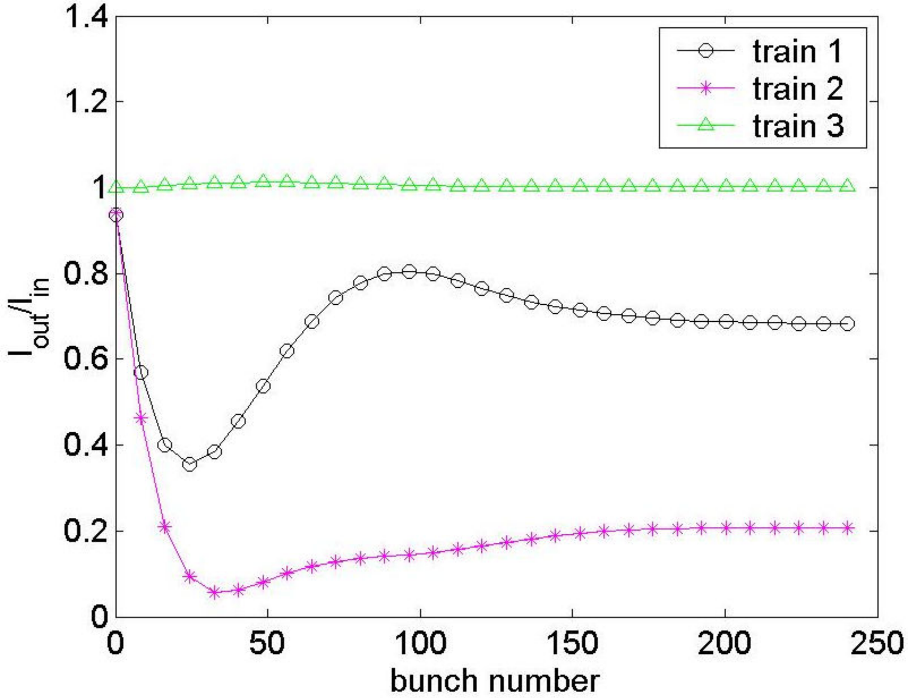
The case of **injection errors** has also been explored.

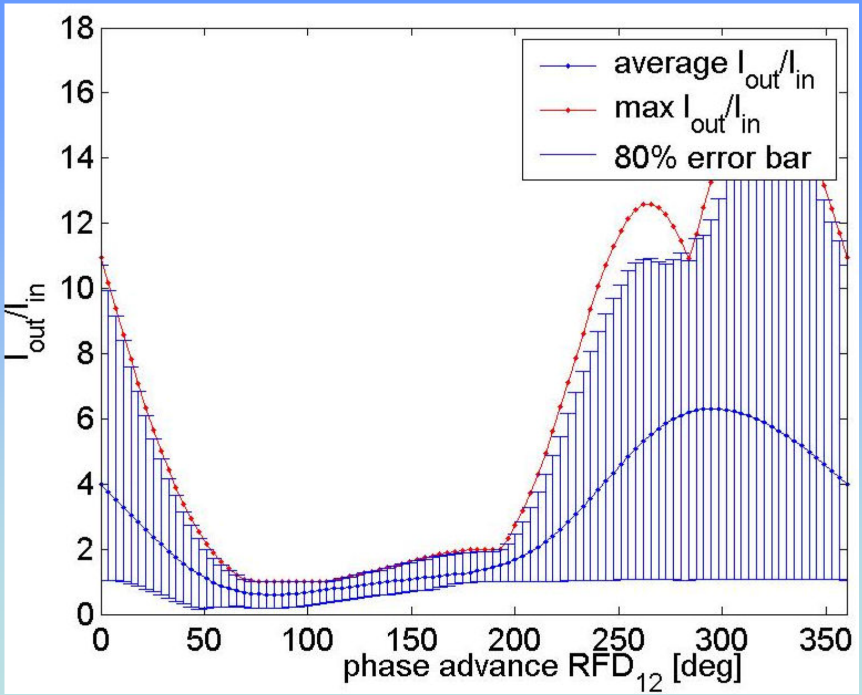
The **ratio between the output CS invariant of each bunch and the initial invariant** has been calculated for different **phase advances** between the two deflectors and for different injection errors.

The results shows that the amplification factor can be taken under control in a wide range of CR1 tunes.

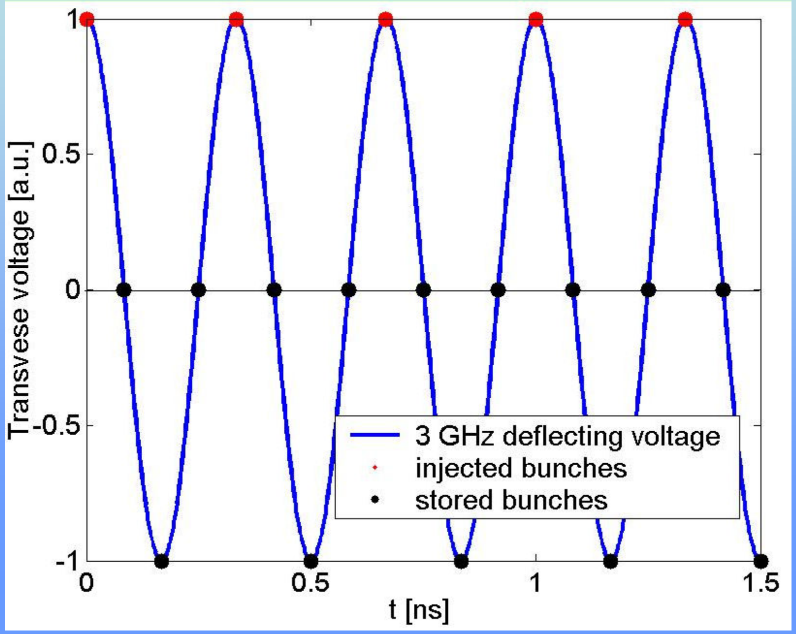


Plots referred to the case of an injection error in position





RFD Parameters for the CR2



Optics Parameters	
β_x @ RFD	2 m
Phase advance $RFD_1 \rightarrow RFD_2$	200 deg

Beam Parameters	
Bunch charge (q)	8.4 nC
Beam Energy (E_0)	2.37 GeV
Number of bunches (Nb)	244*3*4
Norm. emittance (ε_N)	150 mm*mrad

In the case of CR2 we have a **"pure" 90 deg out of phase beam loading** and the situation is much more critical.

To mitigate the BL effect the **number of multiple deflector has to be increased to 4 or 6** and the **horizontal β-function at the deflectors has to be reduced** with respect to the case of CR1.

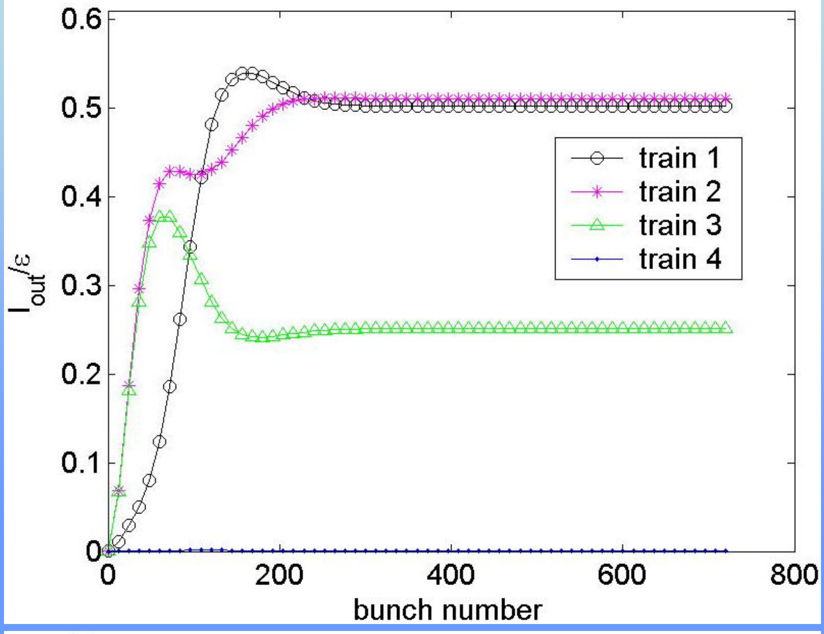
RFD Parameters	
Working frequency (f_{RF})	3 GHz
Deflector length (L_{defl})	1.1 m
Number of multiple deflector (N)	4
R/Q	1350
Total input power P_{IN}	35 MW
Average diss. Power per unit length (dP_{diss}/dz)	62 kW
Iris aperture (a)	2 cm
Group velocity/c (v_g/c)	0.0217

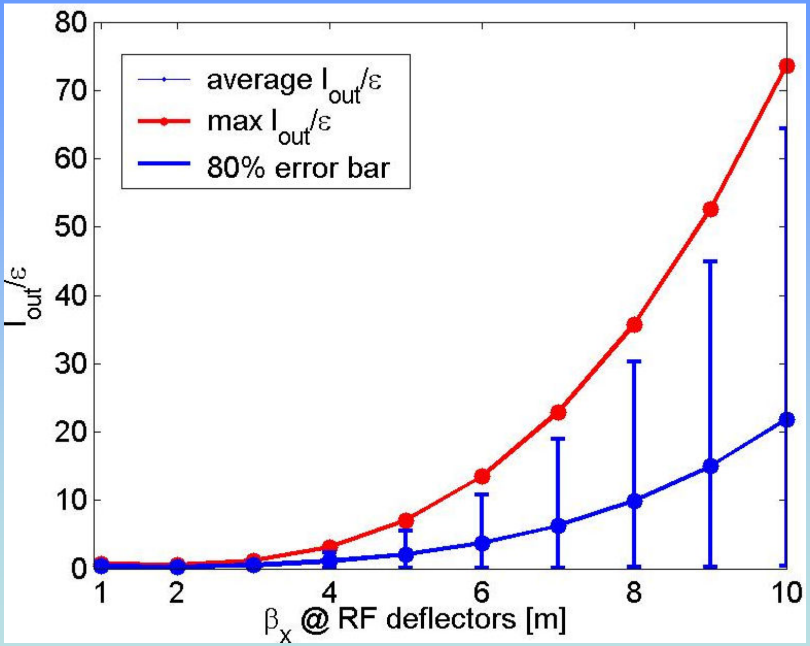
Beam Loading in CR2: systematic effects

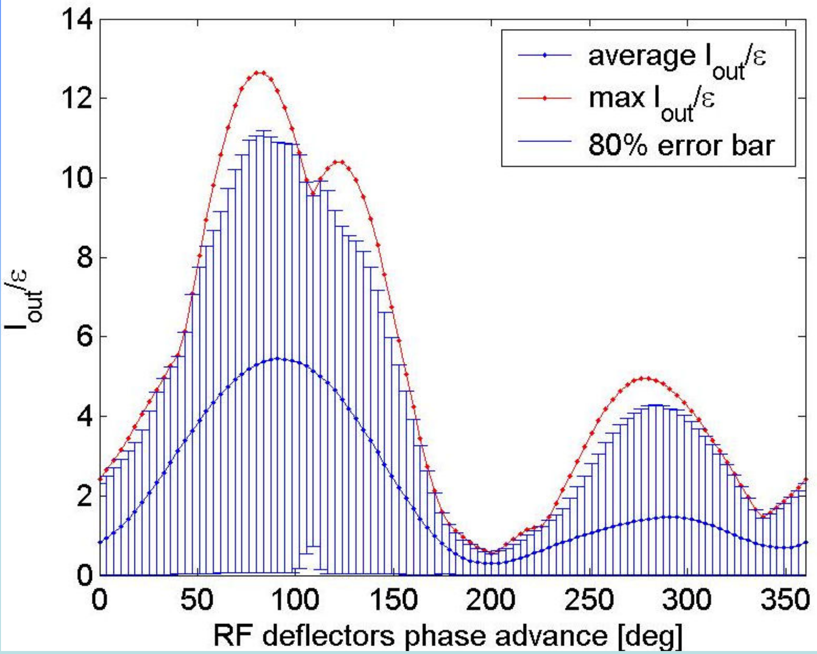
The results shows that with 4 multiple RFDs the systematic effect **is controllable.**

Nevertheless to have a ratio **I_{out}/ε below 2 the "permitted"** tunes are limited to few tens of degrees around a phase advance equal to 200 deg.

Also **the horizontal β-function at the deflectors is critical** and shoud be **below 2 m.**



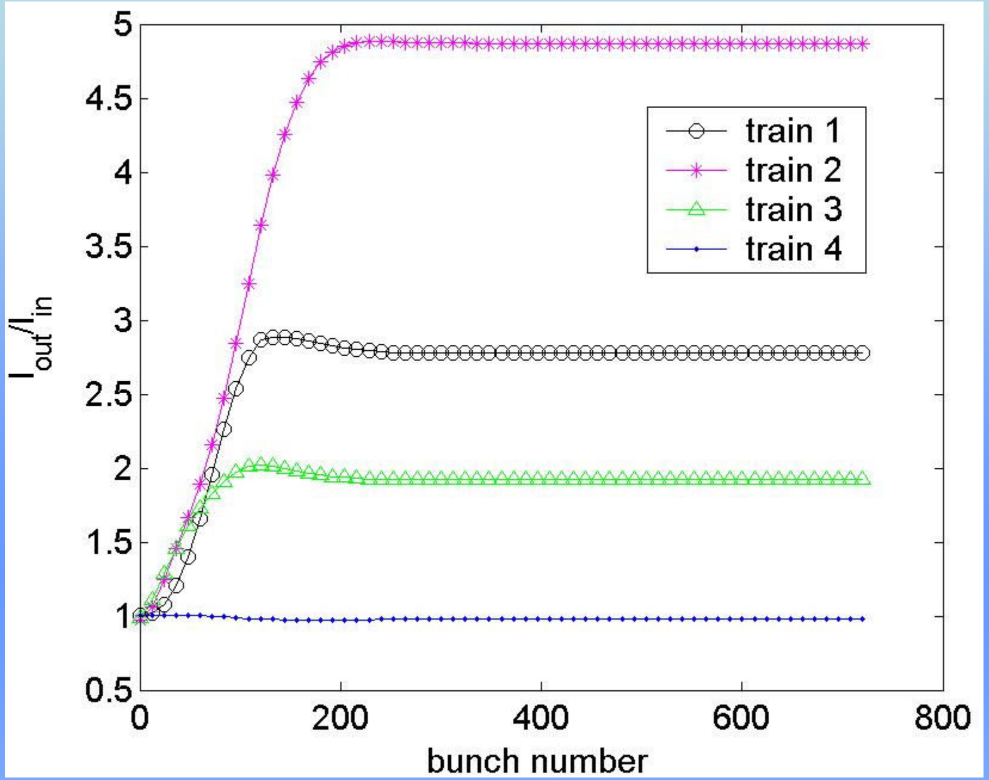


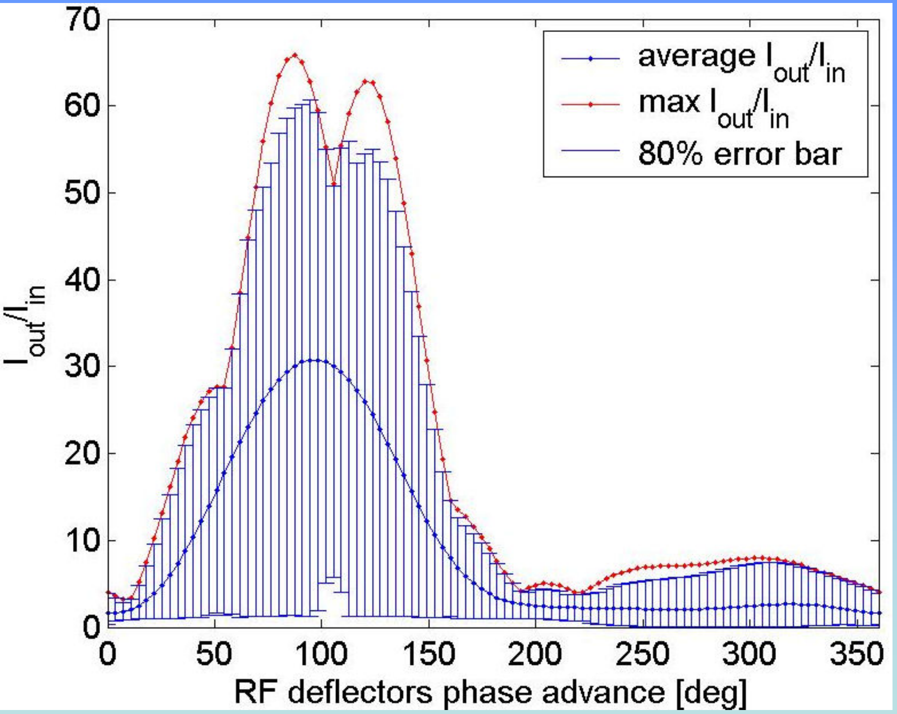


Beam Loading in CR2: Injection errors

The case of injection errors has also been explored.

The amplification factor can be taken below a factor 10 in a wide range of tunes and below a factor 5 in a restricted range.



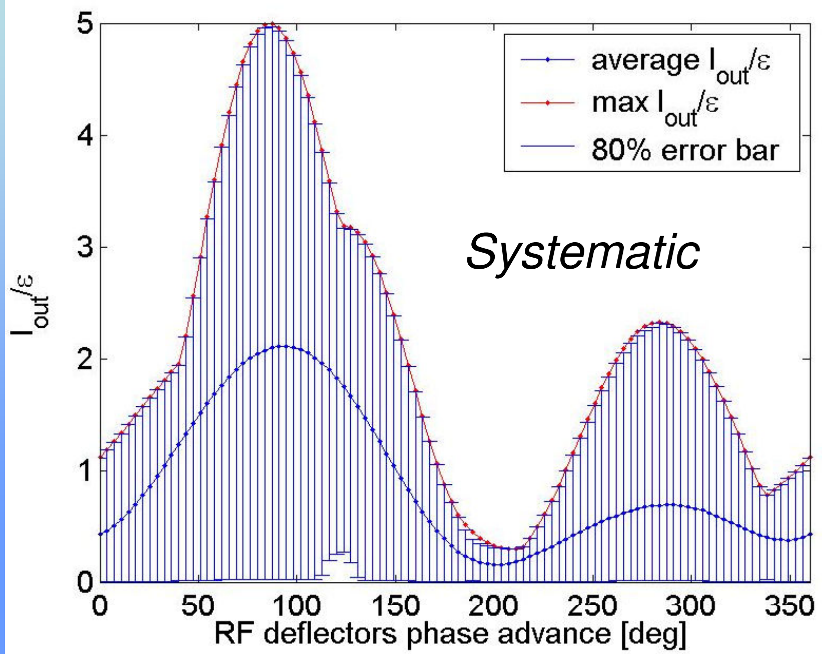


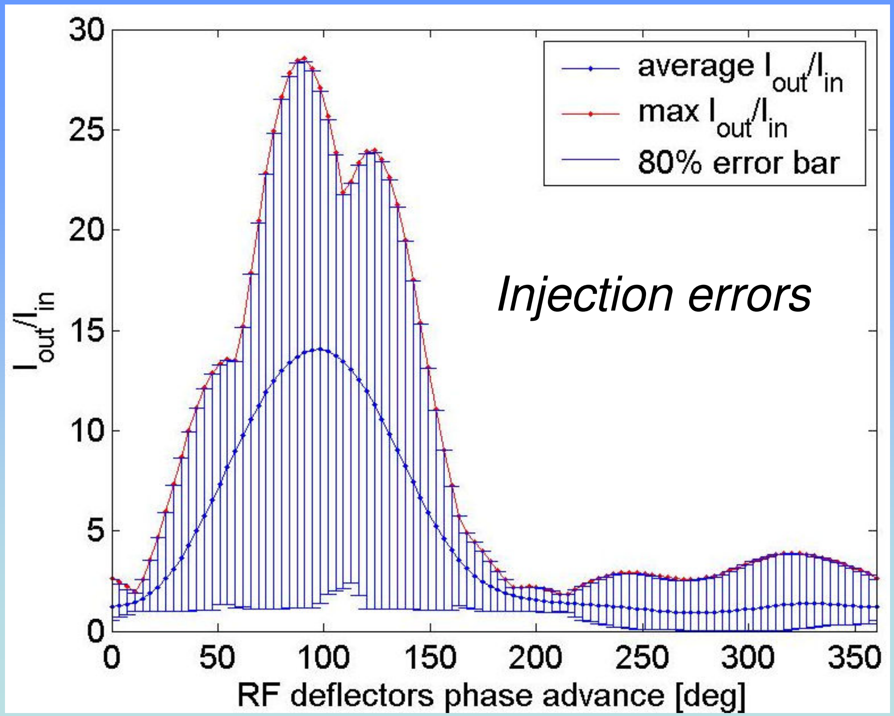
Beam Loading in CR2: N=4→N=6

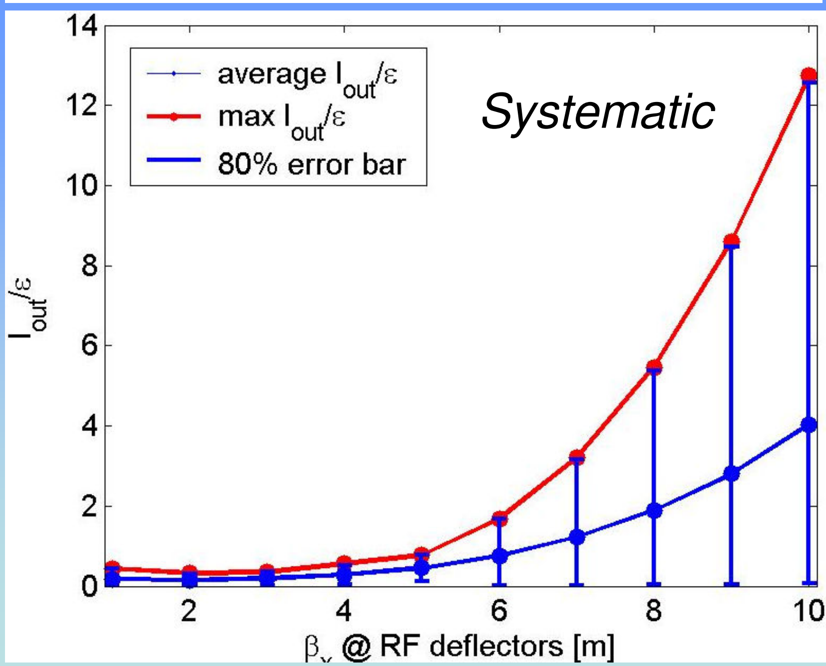
To further reduce the beam loading effects the **number of multiple RFDs has to be increased from 4 to 6**.

This corresponds to an **average length of each sub-deflector below 20 cm**.

In this case the situation is less critical and the permitted range of tunes increases.







Conclusions

First order scaling laws for the beam loading effects in the RFDs have been found.

They shows the **much more criticality in the CLIC CR compared to the CTF3 case**

Simulations with the tracking code have confirmed these predictions.

To **mitigate the BL effects multiple deflectors have to be used**. This is equivalent to use a strongly damped system.

The use of **multiple deflectors complicate the design from the power distribution and RF points of view** since each sub-deflector has to be fed with the nominal input power.

Results of the **tracking code simulations have been finally illustrated**. They shown that with a proper choice of the number of multiple deflectors and machine parameters the BL effects can be taken under control.

The BL in the RFD has to be carefully taken into account in the CLIC design.

To be done…

Effects of the **bunch length**

DL calculations

Analysis of the **vertical mode polarity** to define the damping requirements

Thanks to…

C. Biscari and A. Ghigo for helpful discussions, suggestions,…