# Alignment studies

## Decelerator, TBL and CTF3 linac

CLIC Workshop 2008

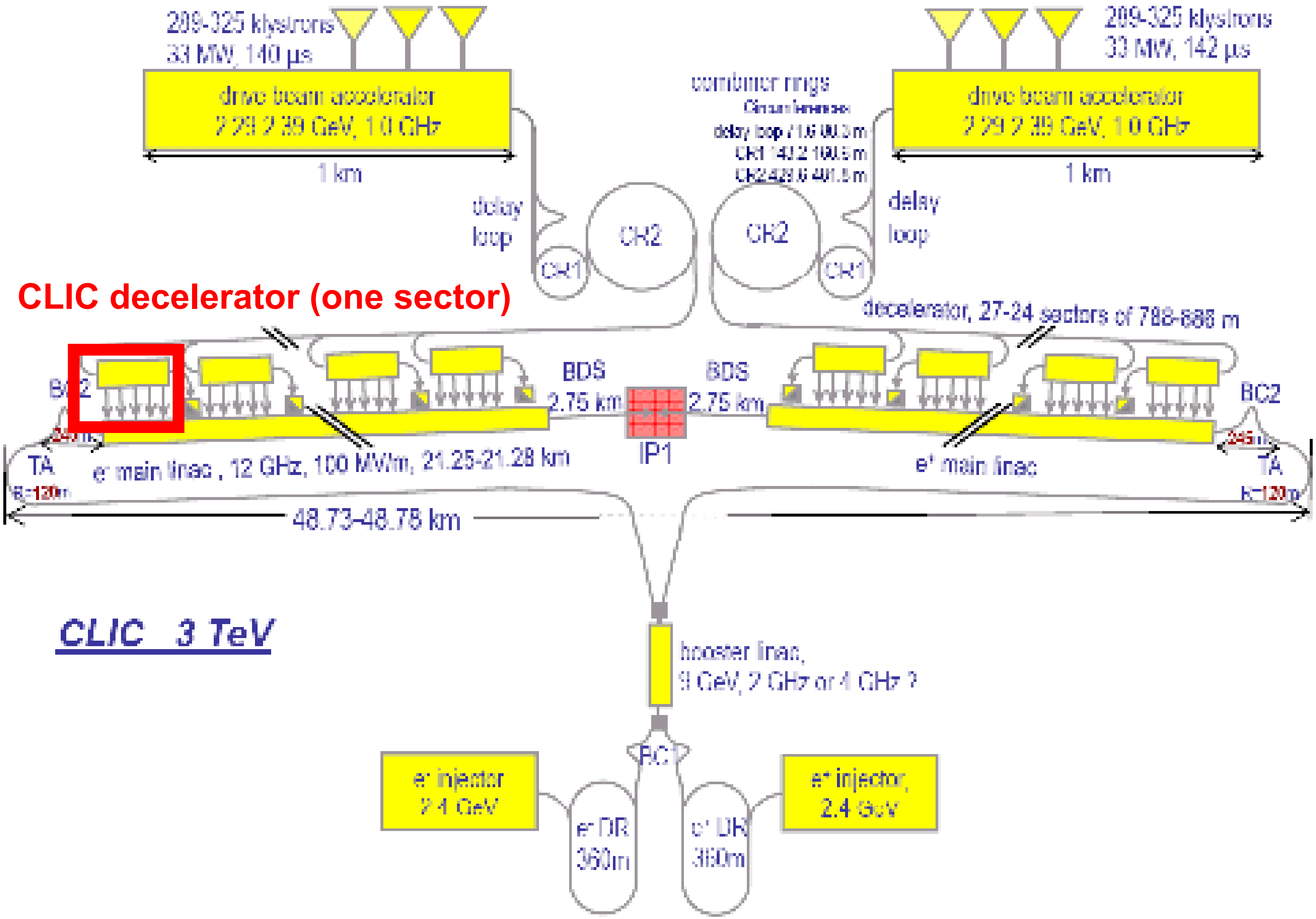
*Erik Adli, CERN/University of Oslo, October 16th 2008*

*Lots of useful input from the CTF3 team, especially P. Skowronski , F. Tecker and R. Corsini, as well as K. Fuchsberger,V. Ziemann and D. Schulte, is gratefully acknowledged*

# Outline

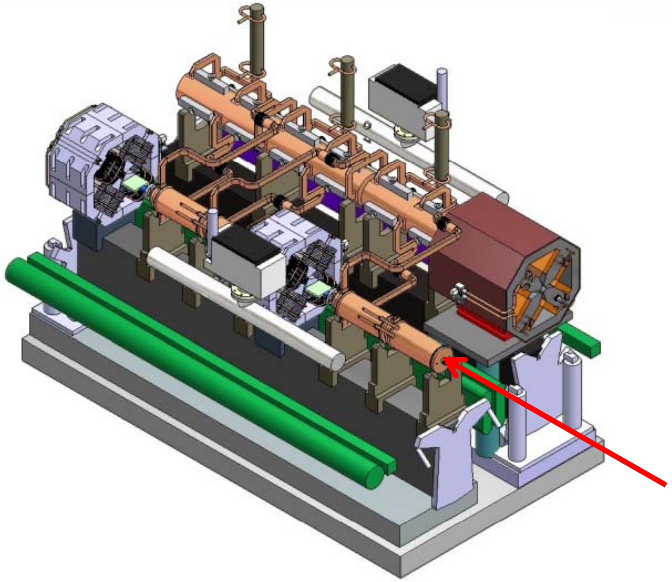
- The Decelerator and the need for Beam Bases Alignment
- TBL versus the Decelerator
- Test-case: steering for the CTF3 linac

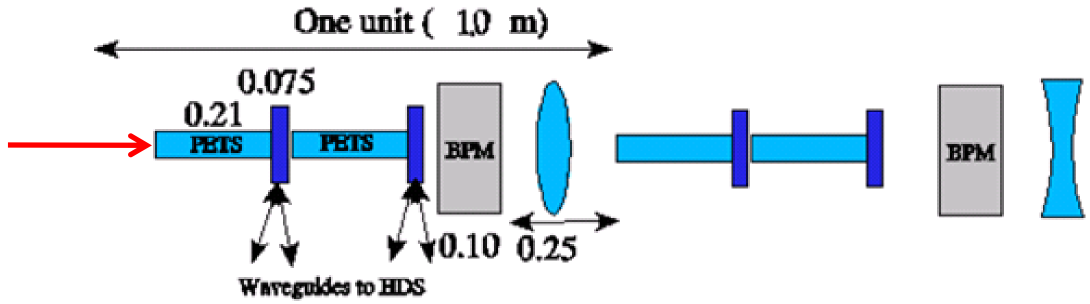
# The CLIC decelerator



# Lattice

- 24 decelerator sectors per main linac
  - Each sector recieves one drive beam pulse of 240 ns, per main beam pulse
  - Up to S=90% of the initial particle energy is extracted within each pulse leading to an energy extraction efficiency of about 84%
  - Varying sector length, because we require equal extraction efficiency per secor, while main linac module configuration changes






- **Baseline for decelerator studies**: we study the longest sector (1050 meter) with a PETS slot fill-factor of 71% ("worst case, for beam dynamics")
- Tight FODO focusing (large energy acceptance, low beta)
- Lowest energy particles ideally see constant FODO phase-advance $\mu \approx 90°$, higher energy particles see phase-advance varying from $\mu \approx 90°$ to $\mu \approx 10°$

# Deceleration and beam transport

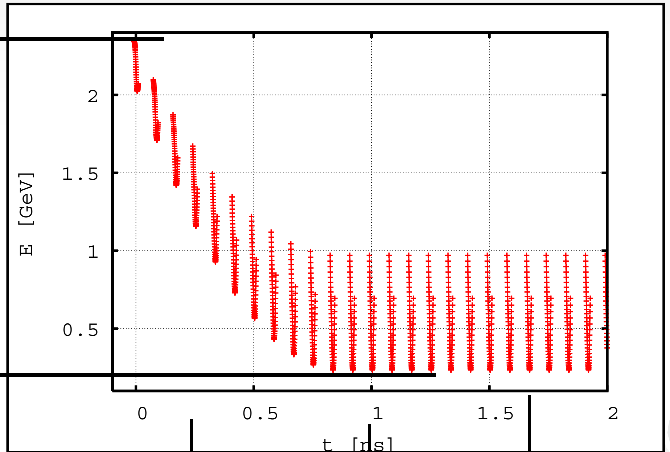
Goal: transport particles of **all** energies through the decelerator sector:
3-sigma beam envelope r < 0.5 x half-aperture

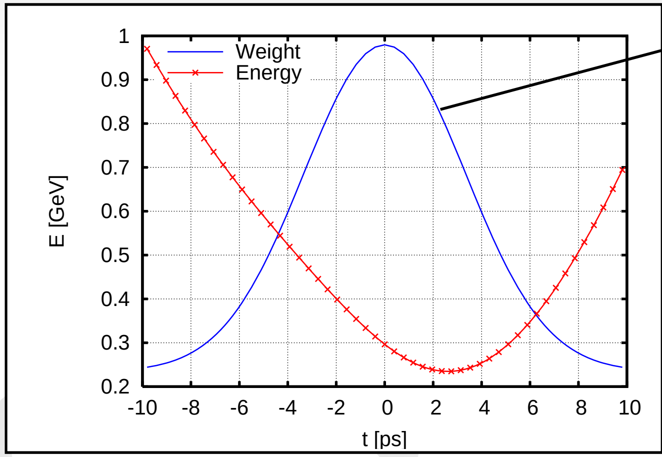
*Resulting energy profile (short* ***transient*** *+ long* ***steady-state****)*

**E**

**Ě**

**S=(E-Ě) / E = 90%**




**λ(z)**

**$\check{E} = E(1-S)$**
**$= E - N_{PETS}\Delta\hat{E}$ = 240 MeV**

**$t_b$ = 83ps**

**$t_{fill} = (L_{PETS}/v_g)(1-\beta_g)\ _g$ = 1ns**

**$\sigma_z$ = 1mm**

**$t_z$ = 3ps**

***Power extracted from beam (ss) :***

**$P \approx (1/4)\, I^2 L_{pets}^2 FF^2 (R'/Q)\, \omega_b / v_g$ = 136 MW**

***Power extraction efficiency (ss) :***

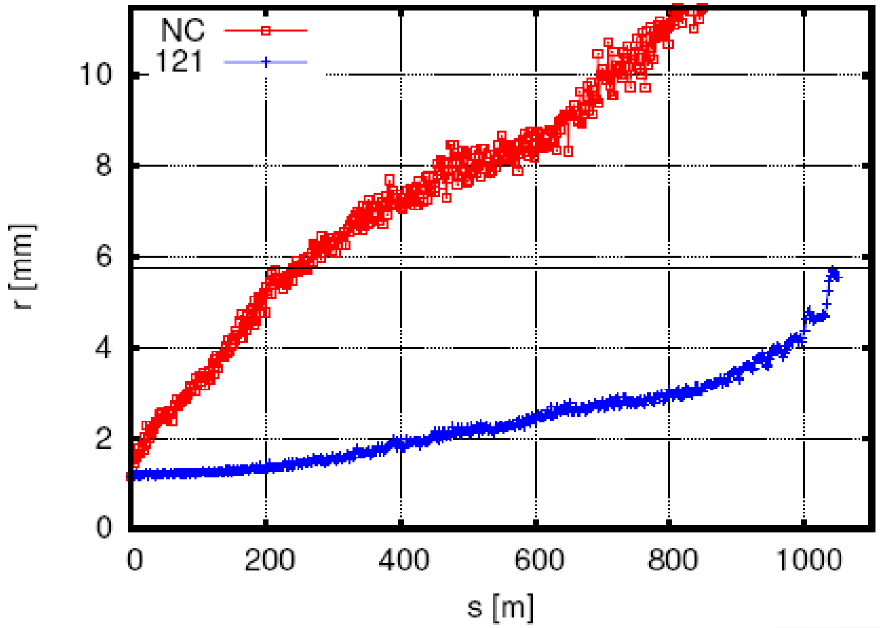
**$\eta = E_{in}/E_{ext} = S\, FF\, \eta_{dist}$ = 84%**

**Transport of the decelerator beam: compromise high S (better efficiency, larger envelope) and high E (poorer efficiency, smaller envelope). In this study S=90% used**

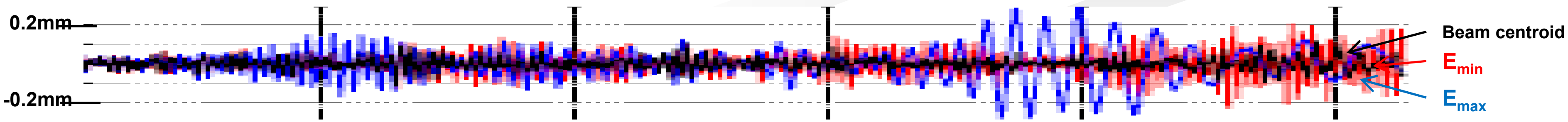
# Decelerator: Beam-based alignment

# 1-to-1 steering

- **Baseline** scenario for beam-based alignment:
  - *Quadrupoles on movers*
  - *All quads and all BPM  available for correction*
- Simple 1-to-1 steering forces the beam centroid through the center of each BPM
- After 1-to-1 steering the quadrupole offsets do not matter, and **the resulting envelope depends linearly on the BPM accuracy** (initial quad offsets irrelevant)
- As result the *centroid* also passes in the order of BPM accuracy from each quad centre
- However, the remaining quad kicks are enough to build up significantly *dispersive trajectories* so that the *envelope* is still large after 1-to-1 with BPM accuracy of 20 µm (misalign. + el. error)




| Tolerance | Value | Comment |
|---|---|---|
| PETS offset | 100 µm | $r_c$ < 1 mm fulfilled |
| PETS angles | ~ 1 mrad | $r_c$ < 1 mm fulfilled |
| Quad angles | ~ 1 mrad | $r_c$ < 1 mm fulfilled |
| Quad offset | 20 µm | As small as possible, within reasonable limits. 20 µm is within spec. of alignment system ($r_c$ < 1 mm ⇒ quad offset of 1 µm) |
| **BPM accuracy** | **20 µm** | **As small as possible, within reasonable limits.** |
| BPM precision | ? | |



# Dispersion-free steering

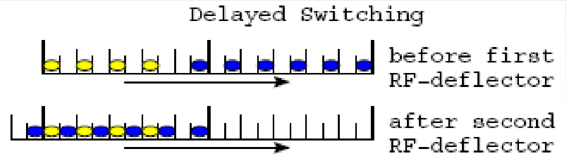
- 1-to-1 correction does not give an adequate steering due to the large variation of **dispersive trajectories**, we therefore seek to minimize the dispersive trajectories by applying **Dispersion-Free Steering** (DFS), [Raubenheimer and Ruth, 1991]
- Our implementation uses response matrices to minimize:

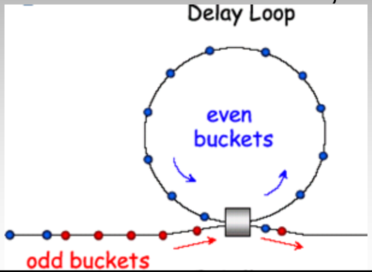
$$\chi^2 = w_0 \Sigma y_{0,i}^2 + w_1 \Sigma (y_{1,i} - y_{0,i})^2$$

- We need a test-beam that generates a difference trajectory with large energy leverage
  - however: higher energy beam not available and lower energy beam will not be stable (with the same focusing)
- Instead we take advantage of the PETS $\rightarrow$ reduced current, in form of **empty buckets**, can be used to generate **test beams with different energy**

# DFS: test-beam generation

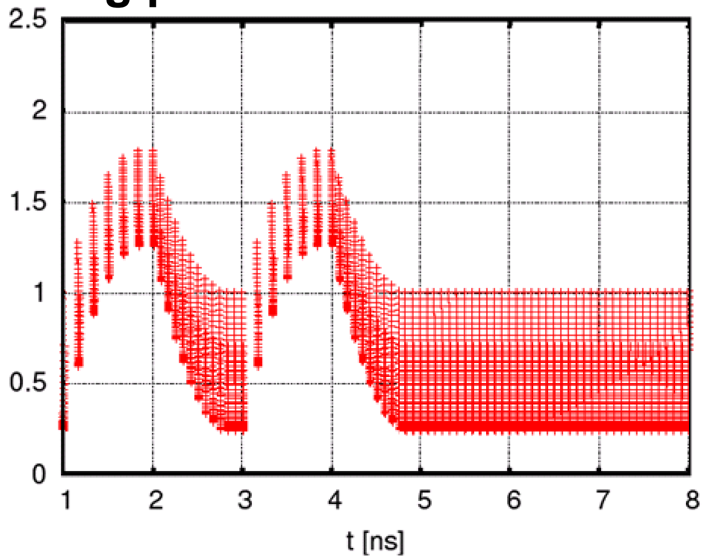
- By adjusting the switching of the drive beam linac buckets, one can generate the test-beam in the same pulse as the nominal beam



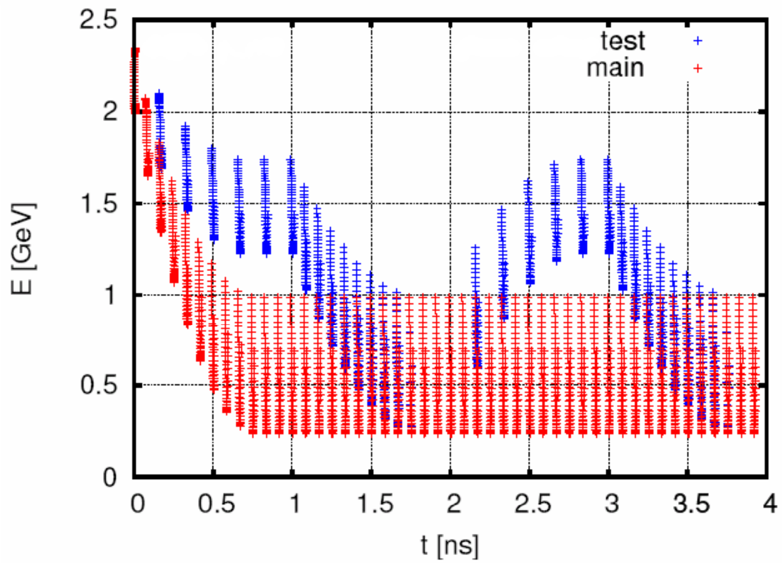




***Example of DFS beam generation scheme:***
**Of the 12 initial E+O pulses:**
- **First 3: nominal E+O recombination**
- **Next 3: Delay swithing to ~half of O buckets**
- **Next 3: nominal**
- **Last 3: Delay switching**

## Resulting pattern:




*Test-beam and nominal beam in the same pulse*



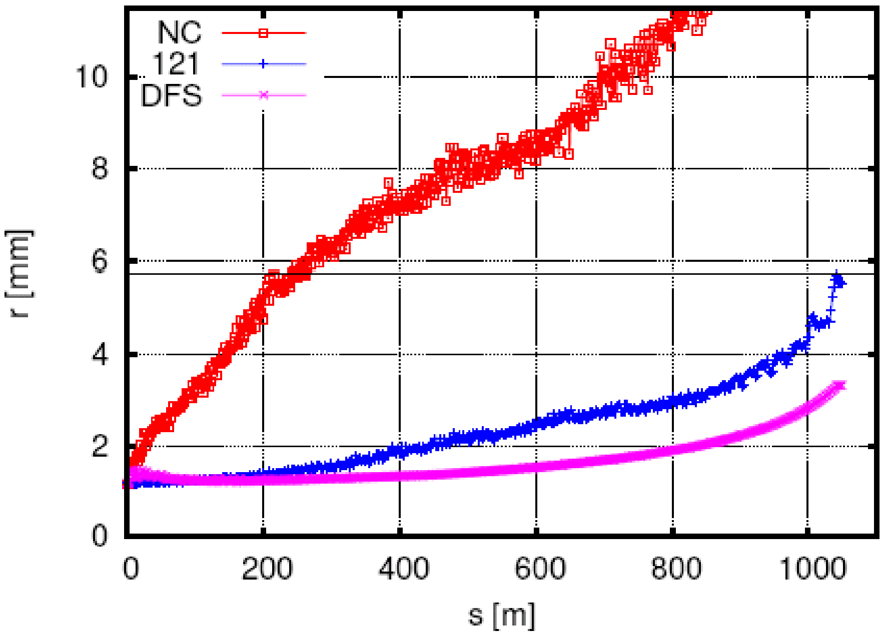

*Test-beam energy compared to nominal beam*

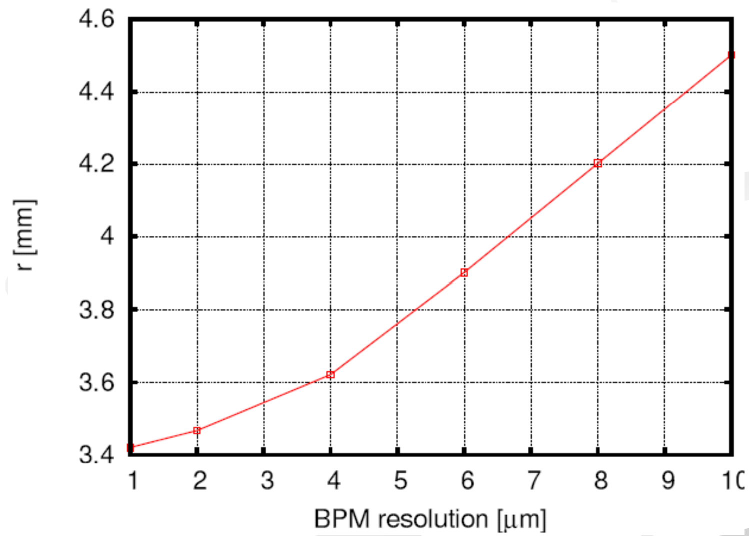
- **Advantages with this method :**
  - **quadrupole strengths are kept constant – machine unchanged**
  - **main-beam and test-beam can be combined in one pulse**
  - **Large energy-leverage**

*( The example scheme above might not be optimal wrt. BPM readings → to be investigated further )*

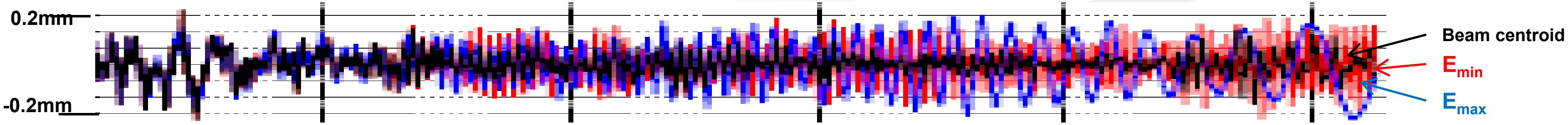
# Results: DFS

- After applying DFS we observe that the envelope is almost identical to the minimum envelope due to adiabatic undamping -> DFS has efficiently supressed the dispersive errors (this graph: resolution of 2 $\mu$m)
  - However, the envelope **depends linearly on the BPM resolution** when this contribution becomes significant
  - Start of lattice: DFS not effective, due to the small energy difference of the test-beam, but does not matter since the dispersive errors are also limited at the start




*Optimal weighting of absolute / difference trajectories found by simulation*

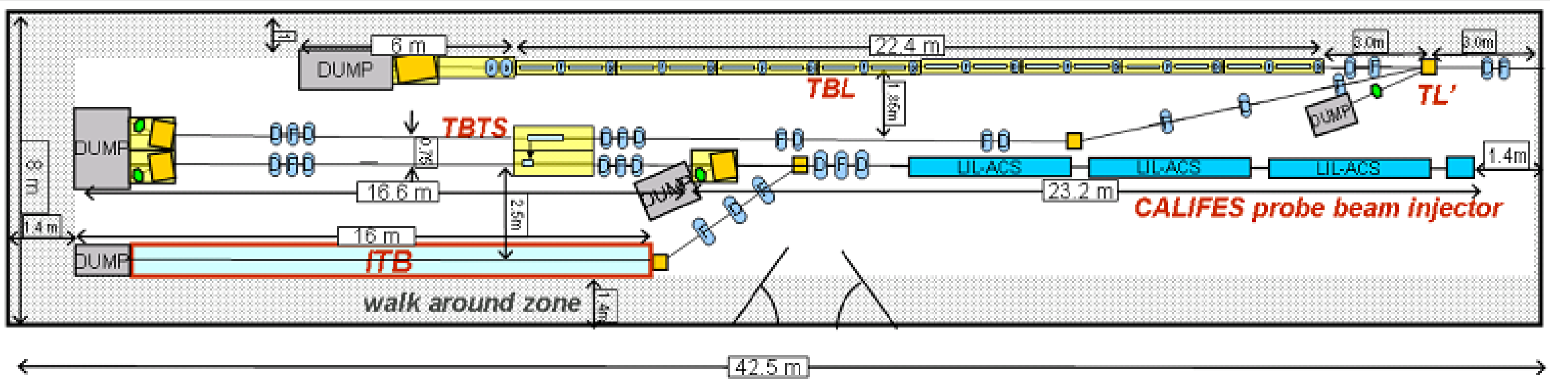


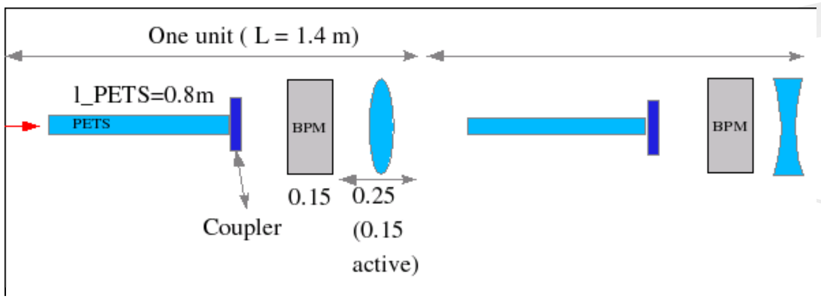
# TBL versus the decelerator

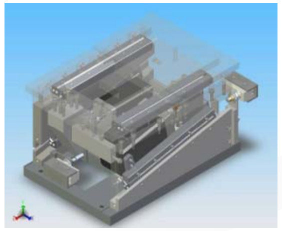
# TBL

***From Model to Reality: The Test Beam Line (TBL)***

*The Test Beam Line (TBL) is under construction as part of the CLIC Test Facility 3 (CTF3). TBL will be **a first prototype for the CLIC decelerator**. The targets are, among others, to investigate beam stability and minimum-loss transport during deceleration with high power extraction efficiency. In addition the TBL will serve as test-bed for Beam-Based Alignment of a decelerated beam, and as a general benchmarking of the simulation codes.*



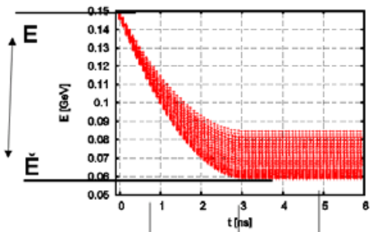
***TBL Quadrupole mover (Courtesy of CIEMAT , F. Toral)***

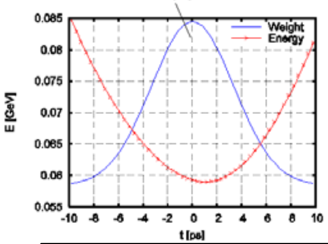
# TBL versus CLIC

| Parameters | Symbol | TBL value | CLIC value | Unit |
|---|---|---|---|---|
| Number of FODO cells | $N_{cell}$ | 8 | 500 | - |
| Bunch separation | $z_{bb}$ | 25 | 25 | mm |
| Bunch rms length | $\sigma_z$ | 1 | 1 | mm |
| Pulse length | $t_{pulse}$ | 140 | 240 | ns |
| Transient length | $t_{transient}$ | 3 | 1 | ns |
| Initial average current | $I_0$ | 30 | 100 | A |
| Power production | $P$ | 159 | 135 | MW |
| Initial energy | $E_0$ | 150 | 2400 | MeV |
| Final min. energy | $E_{min}$ | 59 | 240 | MeV |
| Final max. energy spread | $S$ | 61 | 90 | - |
| Initial norm. emit. | $\epsilon_{n\,x,y}$ | 150 | 150 | $\mu$m rad |

## TBL

λ(z)



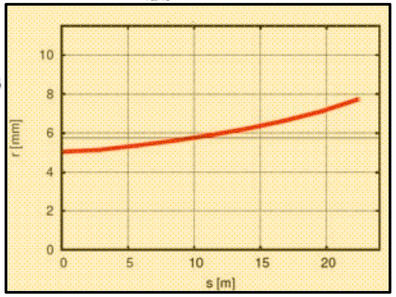




S=(E-Ě) / E
= 61%

Ě = E(1-S)
=E-$N_{PETS}\Delta\hat{E}$ = 59 MeV

$t_b$ = 83ps

$t_{fill}$ = ($L_{PETS}/v_g$)(1-$\beta_g$) $_g$ = 3ns




Power extracted from beam (ss) :

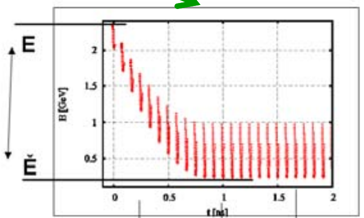
P ≈ (1/4) $I^2 L_{pets}^2 F(\sigma)^2$(R'/Q) $\omega_b / v_g$ = 159 MW

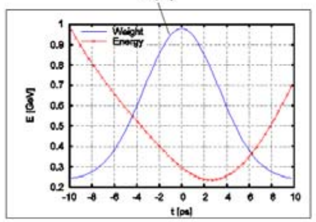
Power extraction efficiency (ss) :

$\eta = E_{in}/E_{ext}$ = 59%

## CLIC

λ(z)



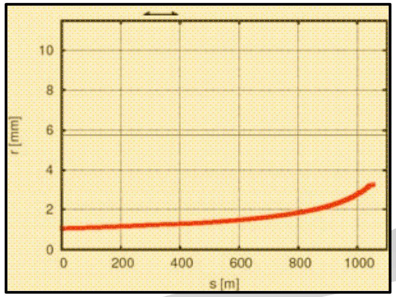




S=(E-Ě) / E
= 90%

Ě = E(1-S)
=E-$N_{PETS}\Delta\hat{E}$ = 240 MeV

$t_b$ = 83ps

$t_{fill}$ = ($L_{PETS}/v_g$)(1-$\beta_g$) $_g$ = 1ns




*Power extracted from beam (ss) :*

P ≈ (1/4) $I^2 L_{pets}^2$ FF²(R'/Q) $\omega_b / v_g$ = 136 MW

*Power extraction efficiency (ss) :*

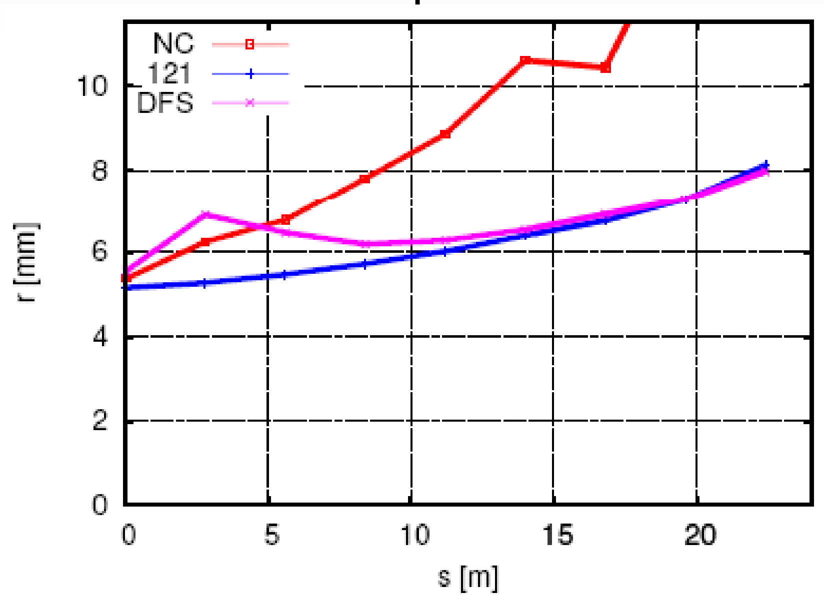
$\eta = E_{in}/E_{ext}$ = S FF $\eta_{dist}$ = 84%

# TBL versus CLIC – quad kicks

**Effect of $\sigma_{quads}$ = 20 μm**
- **CLIC: $r_c$ = 16 mm**
- **TBL: $r_c$ = 2.1 mm**

$\Rightarrow$ **Precise quadrupole alignment is also required for the TBL. $\sigma_{quads}$ = 20 μm leads to small increase in beam envelope while $\sigma_{quads}$ = 100 μm implies that BBA might be required**

**TBL with $\sigma_{quads}$ = 100 μm**

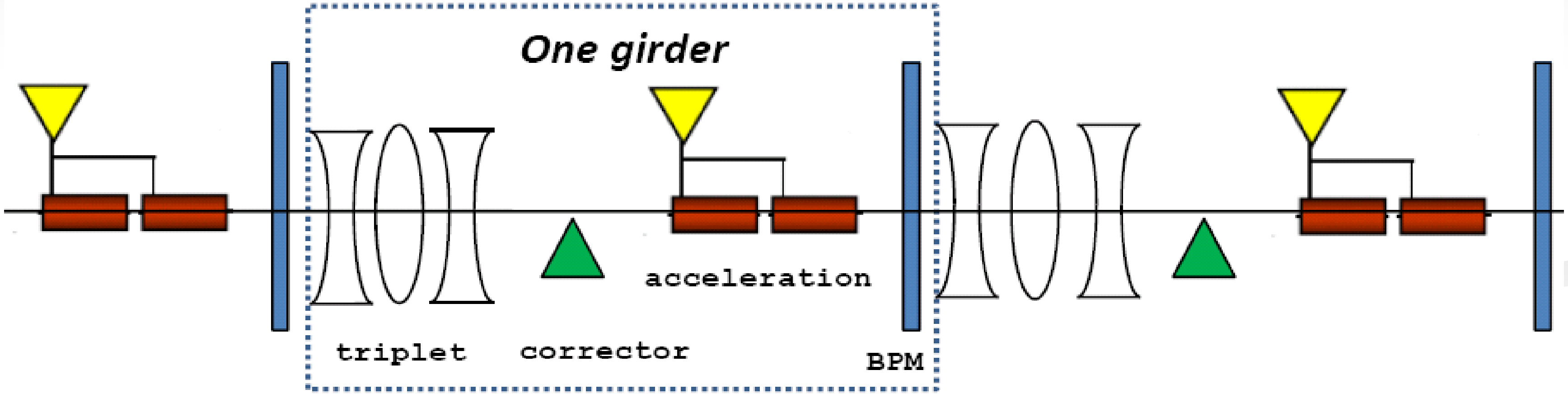



- 1-to-1 gives already good results; DFS is also effective, implying that TBL can provide a good test-bed for the decelerator BBA, but probably not before 2010

# CTF3 linac alignment work

# Test-case: CTF3 linac

*The CTF3 linac is fully loaded, implying that current jitter leads will lead to significant energy jitter – analogous to the Decelerator / TBL -> therefore selected as test-case for the Beam Based Alignment*




***Structure of the CTF3 linac (not to scale)***

*Purpose of this work thus two-fold:*

*1) Test of correction algorithms for CLIC on a relevant real machine*

*2) Aid operation of CTF3 by automating beam steering*

***For test of the Beam Based Alignment the exact same procedures are used for CTF3 linac as for the decelerator***

# Correction approaches studied

**Both schemes: global schemes, finds global solution for any lattice segment, using only the lattice response matrix(s).**

1) All-to-all (A2A): steers the beam to get BPM zero-readings, by simply inverting the response matrix of the nominal machine optics :

$$\Delta\theta = -\mathbf{R}_0^{\dagger}\mathbf{y}_0$$

2) Dispersion free steering (DFS) [4]: minimizes the difference of dispersive trajectories, using responses corresponding to optics with different dp/p; weighted against A2A :

$$\chi^2 = w_0 \Sigma y_{0,i}^2 + w_1 \Sigma (y_{1,i} - y_{0,i})^2$$

$$\frac{\partial \chi^2}{\partial \boldsymbol{\theta}} = 0 \Rightarrow \boldsymbol{\Delta\theta} = \begin{bmatrix} \sqrt{w_0}\mathbf{R}_0 \\ \sqrt{w_1}(\mathbf{R}_1 - \mathbf{R}_0) \end{bmatrix}^{\dagger} \begin{bmatrix} \sqrt{w_0}\mathbf{y}_0 \\ \sqrt{w_1}(\mathbf{y_1} - \mathbf{y}_0) \end{bmatrix}$$

**For BBA implementation details using placet-octave (A. Latina) : see talk E. Adli "Examples of PLACET Use for the DriveBeam"**
**Room: 40-S2-C01 16-Oct-2008 16:30**

SVD is used for Matrix inversion for both candidates: minimal LS solution, noise rejection/smoothing, easy compensation for defect BPMs and correctors → optimal global solution on any lattice segment.

**Difference decelerator / CTF3 linac:**
- **decelerator: test-beam with missing bunches**
- **CTF3 linac: changed optics by magnet scaling**

# Responses for steering

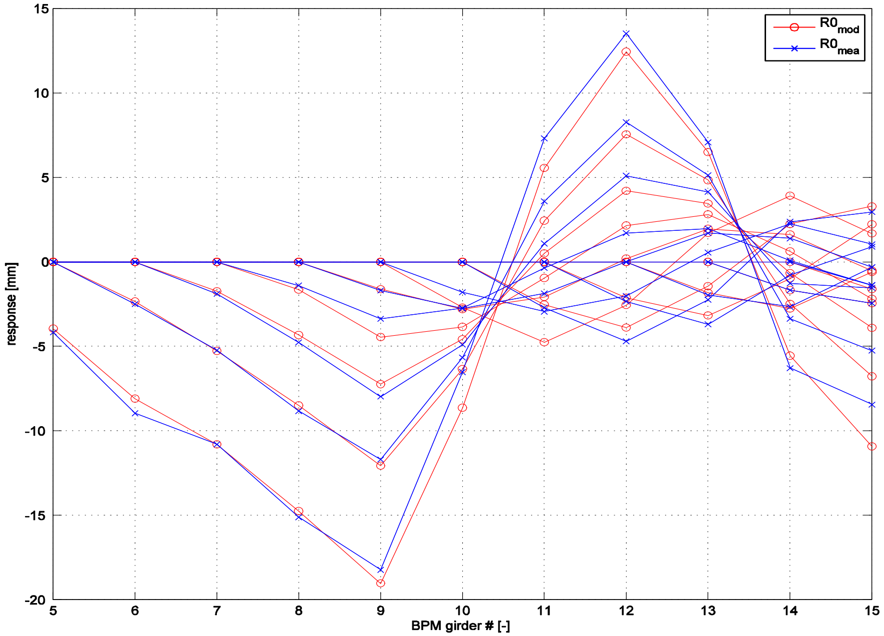
- Option 1) Using measured responses ("easy")
  - Taking measured responses and using these (correct) responses
  - Problem: might need to re-take responses when optics change, might be time consuming (especially for large machines)

- Option 2) Ideal: using model responses ("harder")
  - Requires a good model -> model identification might be necessary

# Model / machine

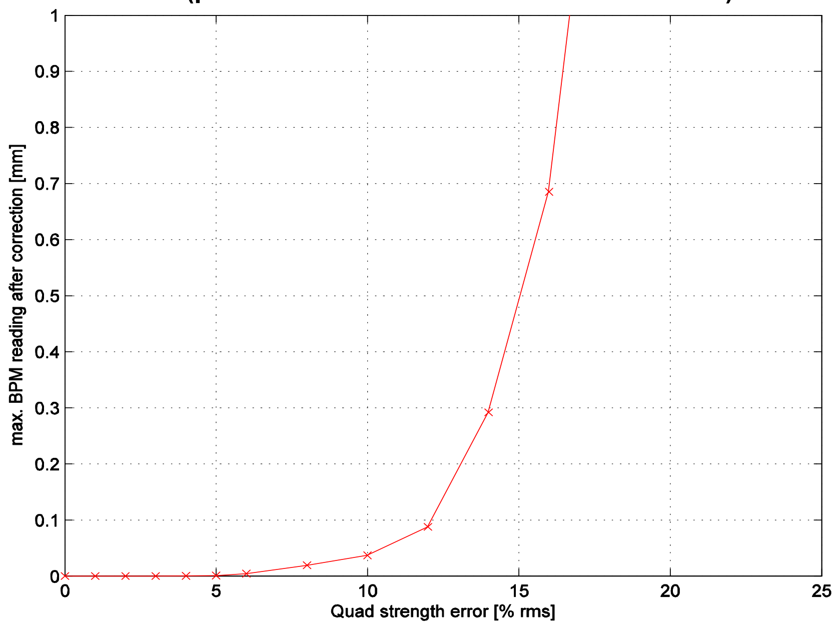
Model used (after global fit to compensate for BPM errors, and scaling between the two corrector families) .

We observe that there are still discrepancies model / machine, however, one do not need a perfect model in order to perform correction




**CTF3: model / machine discrepancy**

(perfect BPMs assumed for this simulation)

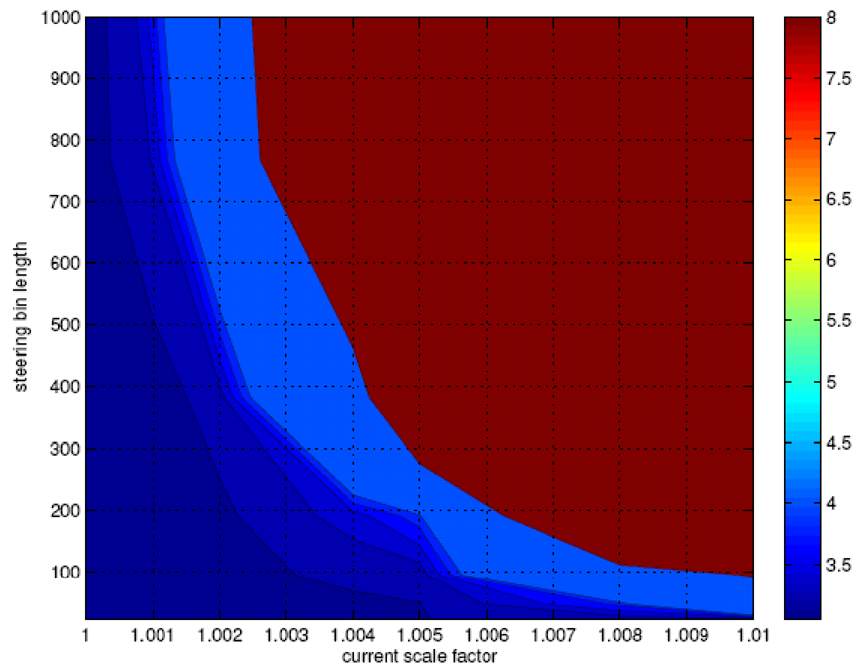



**CTF3: convergence of correction with a non-ideal model**

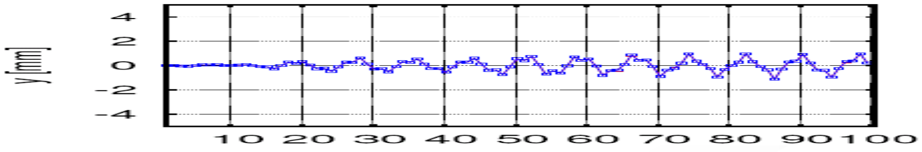
# Decelerator: model imperfections

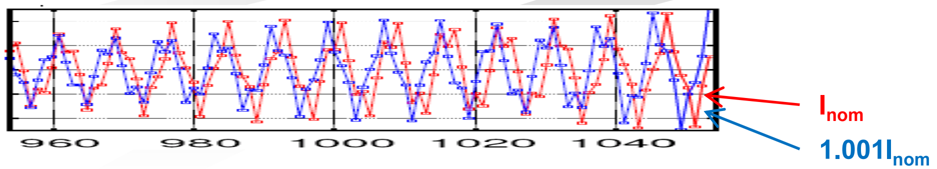
- One of the potential critical issues for the decelerator: response phase-change due small current errors

- **Current error versus steering model :**
  - Particles undergo up to 130 phase-space revolution in the decelerator lattice
  - Therefore, if the model-based steering would be performed in "one go“ 0.1% current difference model/machine would result in a poorly steered machine
  - The steering will be performed in bins (max. allowed size depending on the current difference) – by going to small enough bins the DFS **performs ok for up to 1% current jitter** (we need some margin)




***DFS performance with current error***

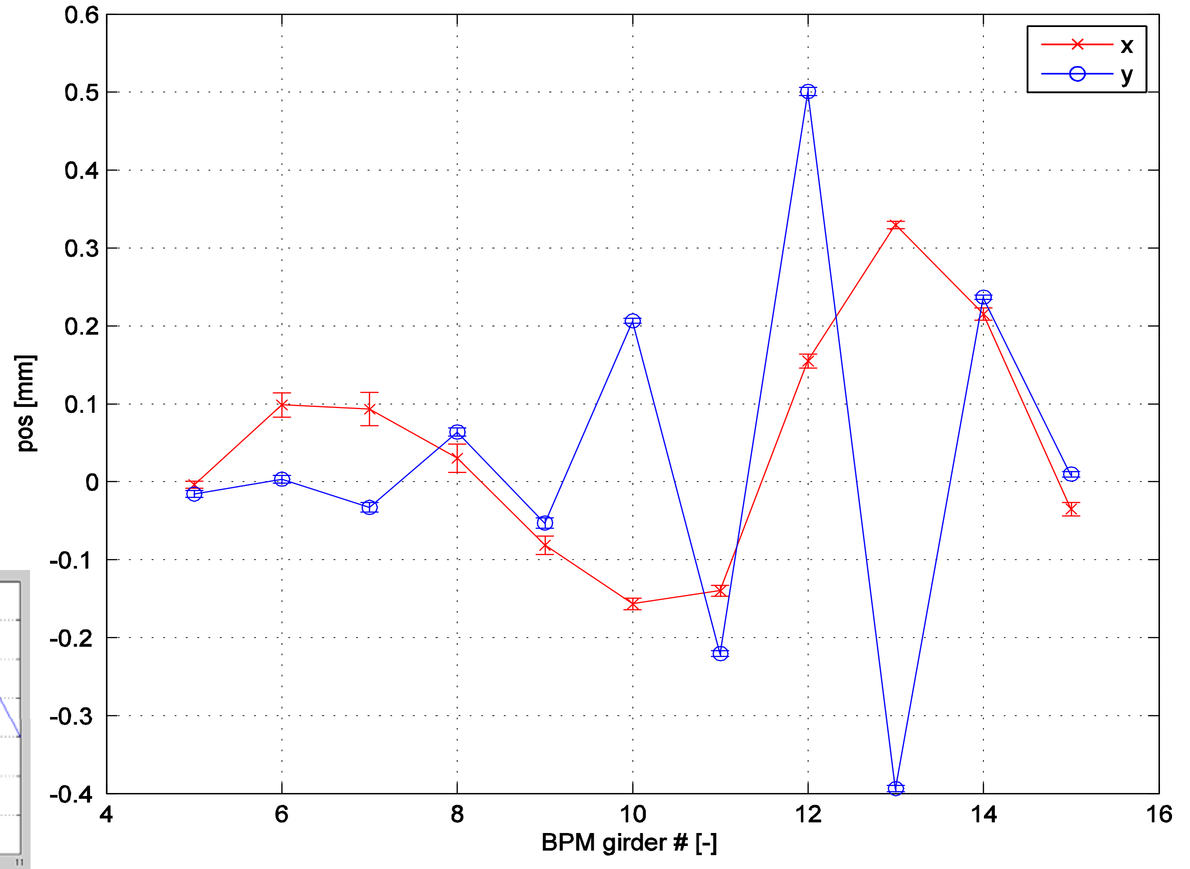


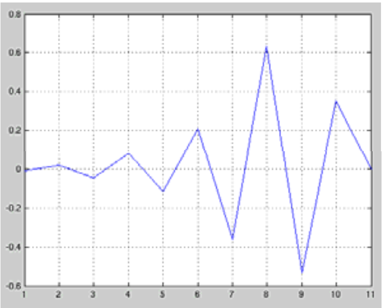



# Steering results

# CTF3: All-to-All

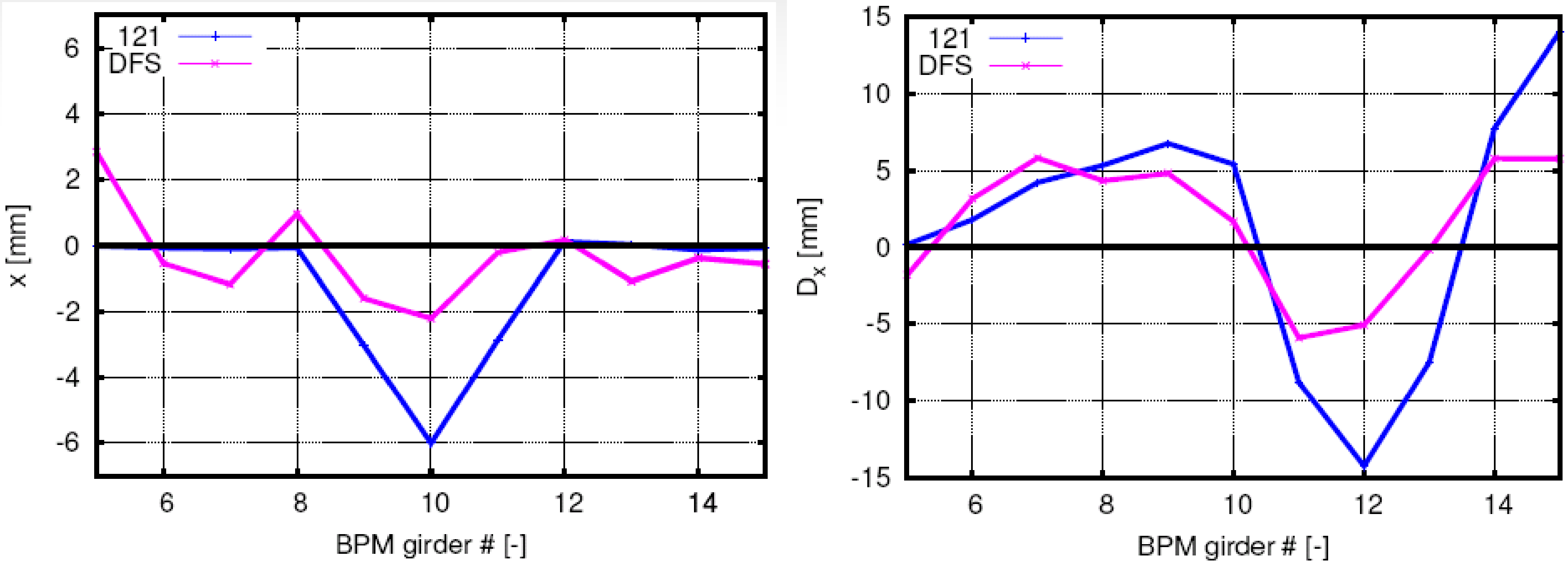
- **Model-based steering :**
- **Converges after ~4 iterations  (compared to 2 for machine respones)**
  - **10-20 s per iteration**
- **Defect corrector in the vertical (G14): shows the global LS solution found by SVD (for 10 correctors and 11 BPMs)**



# CTF3: Dispersion-free steering

- For the nominal CTF3 linac the all-to-all steering gave as good results as dispersion-free steering (residual dispersion ~ 5 mm)
- To verify the performance of DFS, a **test-case with simulated large BPM offsets** was defined
- The **position bump** leads to a factor three higher dispersion after the bump (15 mm)




- From the dispersion measurements we see that DFS has indeed managed **to reduce the disperison** by a factor ~3 (to ~5 mm, the minimum achieved without the bump as well)
- In addition: DFS is mostly oblivious to the BPM readings - in practice : DFS can also **give indications where problems are located**
- Details of DFS implementation: hard to find good parameters (BPM res of 10 um + beam jitter). Final parameters: $\Delta p/p$=0.2, $w_1/w_0$=10, SVD-cut: 0.7

# Conclusions / next step

- Simulations studies suggests that “advanced” Based-Alignment has proven necessary for the CLIC Decelerator (as well as other CLIC subsystems)

  (“advanced” in the sense “better performance than steering into BPM centers”)

- Algorithms foreseen for the Decelerator have been tested, with success, on the CTF3 linac

- Model-based All-to-All steering seems to work well (NB: only one working point tested), and the linac can therefore be automatically steered in around 1 min with this technique (4 iteration x 10-20 s)

- Next logical step: test of beam-based alignment in the Test Beam Line (TBL)

# Extra

# Global identifiaction

- LOCO: existing tool for this type of identifaction, used extensively in e.g. light-sources
- Discussion with AB/OP (J. Wenninger -> K. Fuchsberger): “LOCO can be used also for transport lines, but we have also written new applications for this type of identification”
- In fact: the parameter estimation code is quite quick to write, the interfacing is what takes time

**For this work a short code was written that does the global identification, and interfaces with the PLACET model (using placet-octave update by A. Latina, PLACET model construction mainly by H. Shaker) :**

***Global identification:***

**$E_{k=ij} = w_j(R\_mod_{ij} - R\_meas_{ij})$**

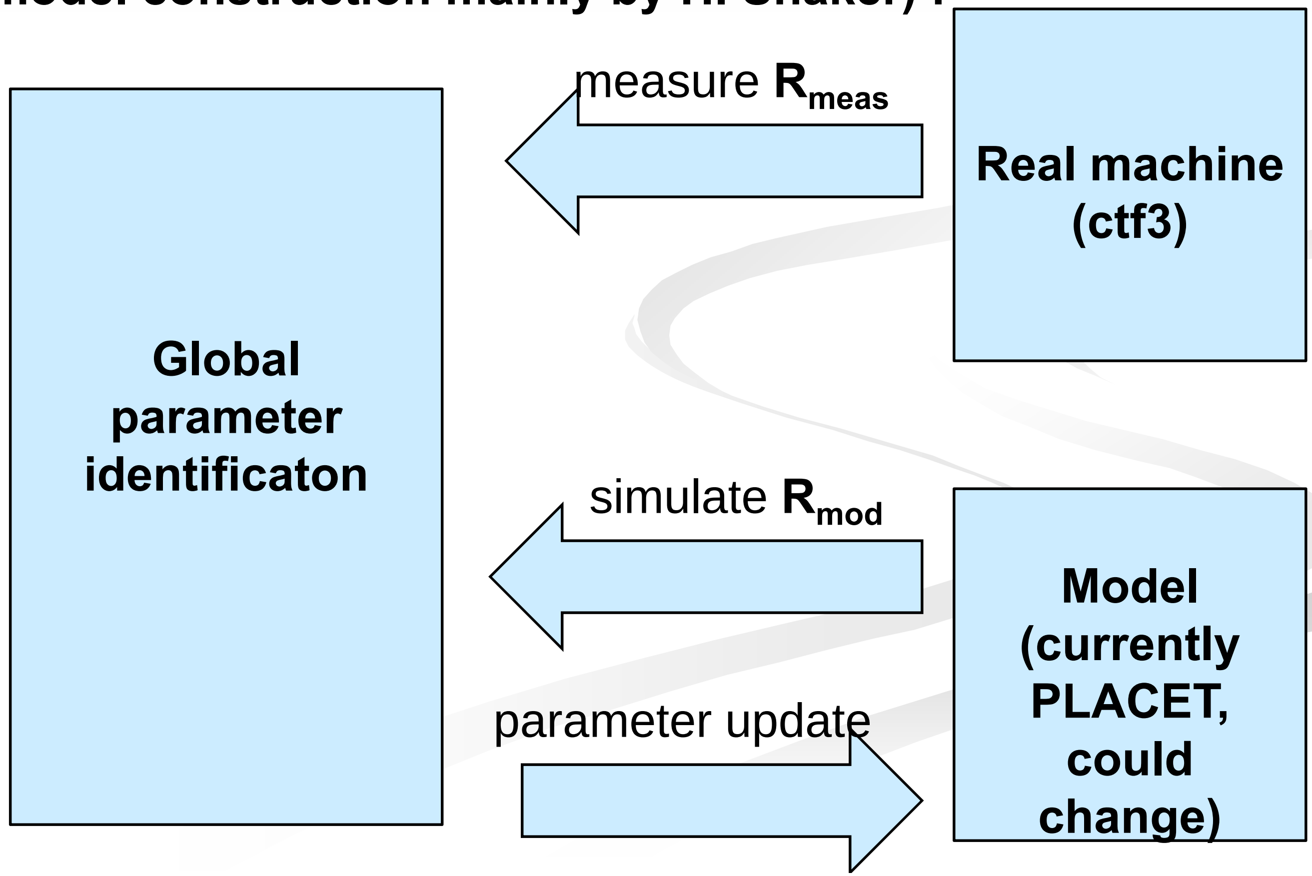
**•Target: minimize $\chi^2 = \Sigma E^2_{k=ij}$**

**•Procedure: Gauss-Newton**
**$\Delta K = - (\partial E / \partial K_l)^{+} E$**

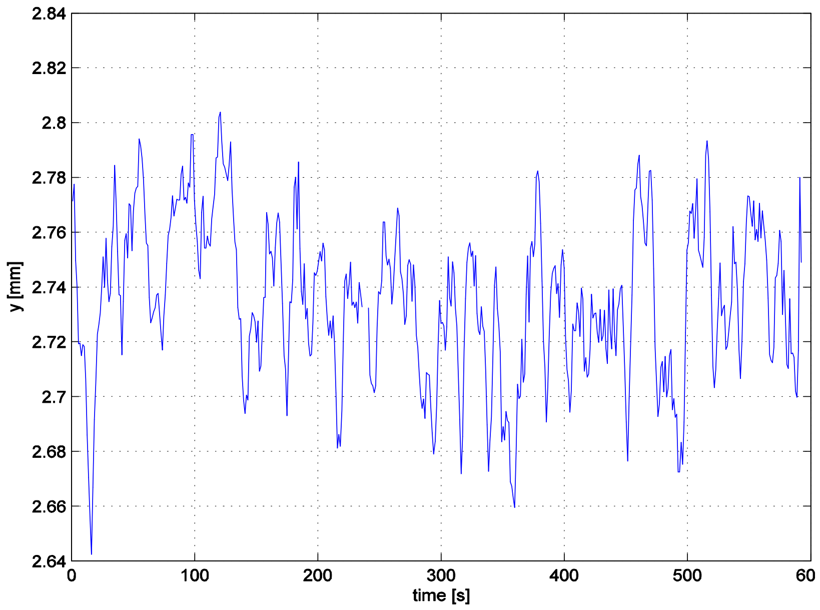
**Triplet cells: large fit uncertainties due to data imprecision. Analyzed using the covariance matrix:**

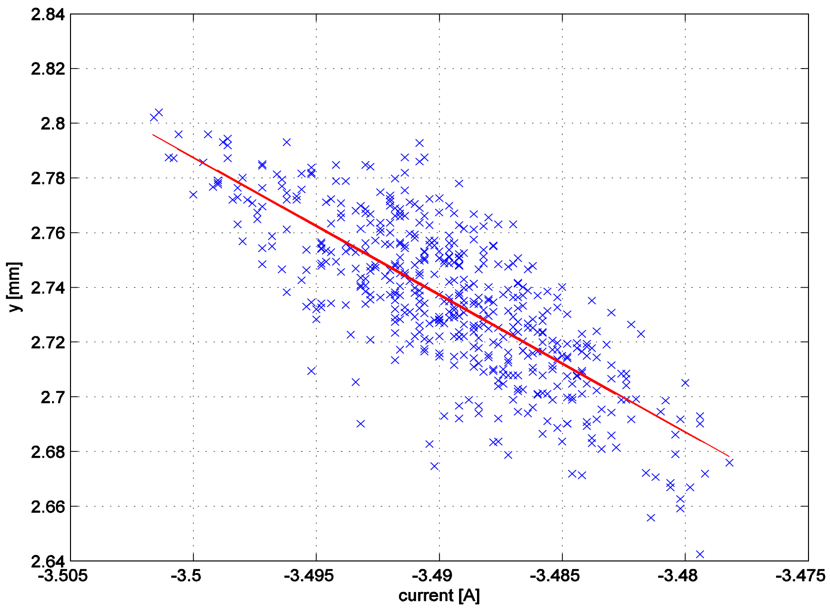
$$\left(\frac{\partial E}{\partial K}^T \frac{\partial E}{\partial K}\right)^{-1}$$

***Quadrupole parameters could not be improved***



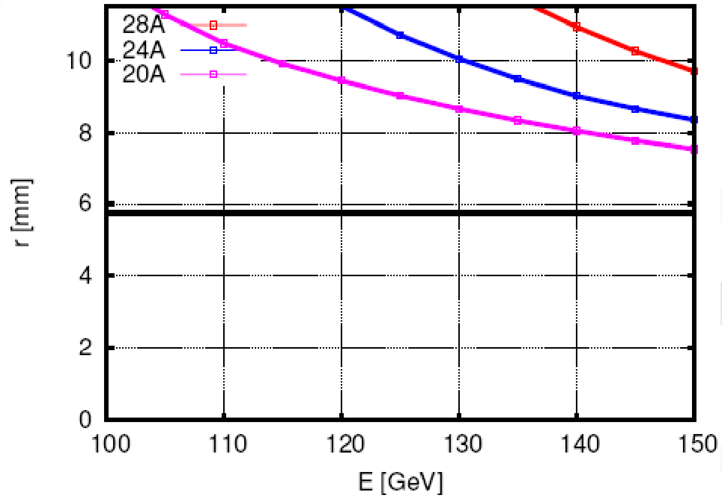
# Machine jitter



# Conclusions: TBL

- A first prototype for the decelerator
- With the effects taken into account it will be though to transport the 3-sigma core of the beam
  - Assuming 150 MeV initial energy, e.g. 120 MeV would make it much more difficult




***(beam jitter not included)***

- Hardware test-bed
  - PETS and tanks
  - BPMs, Loss monitors, ps time resolved measurement (charge, energy)
  - Quadrupole movers
  - etc

***A 3-sigma transport through TBL looks like a difficult task, but if we come close to it, it will be a great step towards proving feasibility of the CLIC decelerator***