Test Beam Line (TBL)

Beam Dynamics studies

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The purpose of the TBL

- Validate the drive beam decelerator concept
  - Demonstrate the efficiency of RF power production
  - Demonstrate the stability of the drive beam
  - Demonstrate algorithms and technology for CLIC

Purpose and content of presentation

Purpose of presentation:

"try to outline alignment precision requirements, starting from the energy extraction requirement"

Contents:

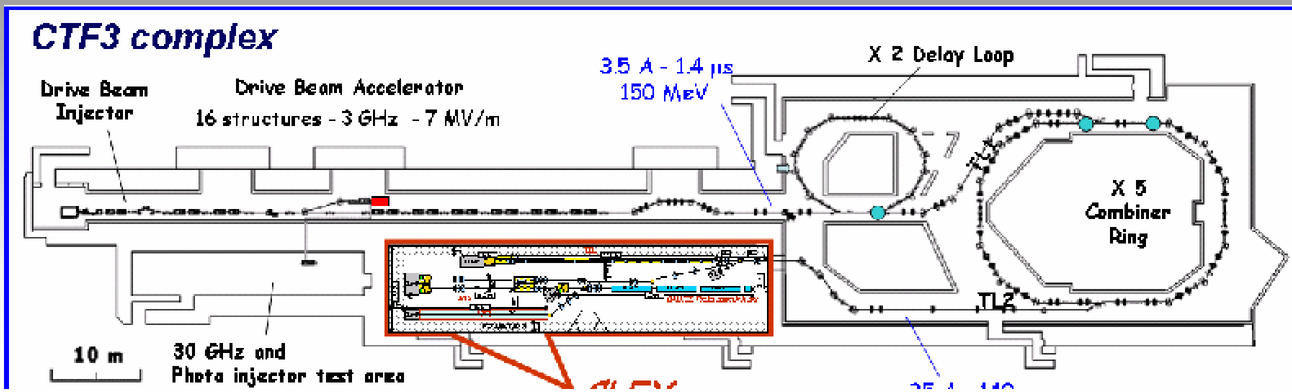
1. Energy extraction and beam envelope
2. Beam stability with transverse wakes (summary)
3. Effect of component misalignments

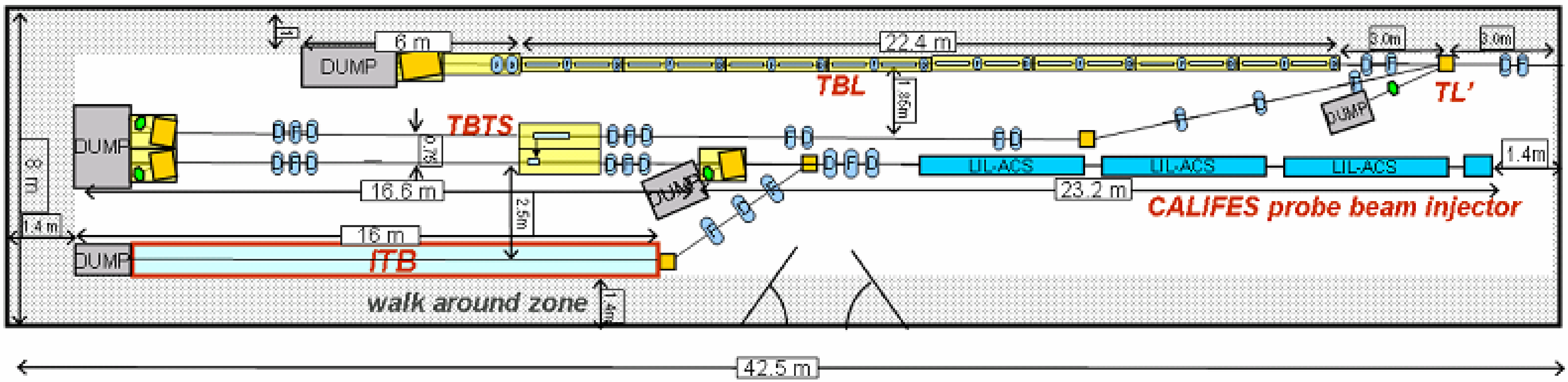
"CLIC" versus "TBL": the graphs and numbers here are for TBL, unless other stated, but the principles are the same for CLIC (one deceleration station)

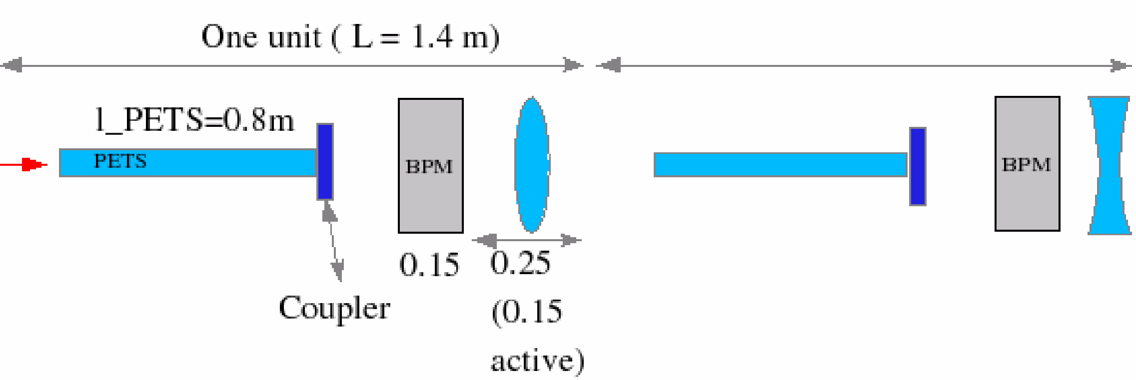
Part I

Energy extraction and beam envelope

Simulation set-up: LATTICE







Simulation lattice:

16 units of one of each:

- **PETS (coupler as drift)**
- **Quad**
- **BPM**

The CTF3 drive beam

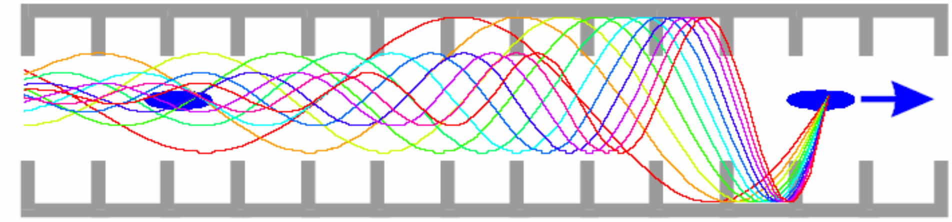
- High-current, low-energy beam for strong wake field generation
- Initial beam parameters used for these simulations:
  - E_0 = 150 MeV (no energy spread)
  - I = 30 A
  - d = 25 mm (bunch spacing, f_b = 12 GHz)
  - Gaussian bunch, σ_z = 1 mm
  - N = 200 (enough for steady-state situation to be reached).
  - $\varepsilon_N = 150\ \mu$m

Deceleration

- Particles will feel parasitic loss and induce a wake field in the PETS
- The wake field will interact with and further decelerate :

    1) rear part of bunch (**single-bunch** effect)

    2) following bunches (**multi-bunch** effect)



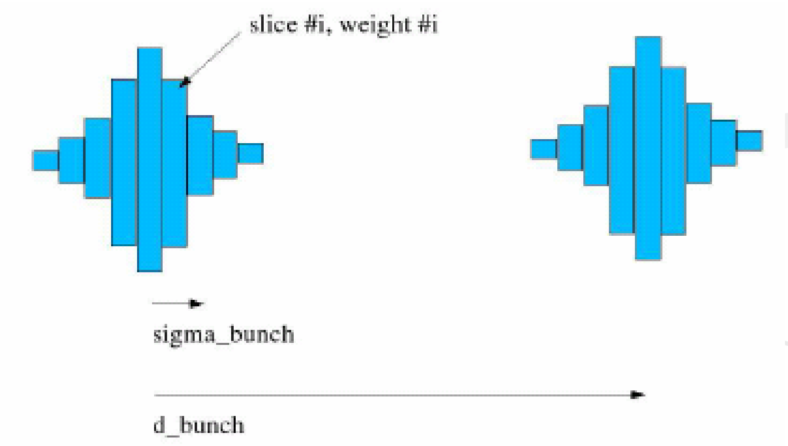
- The integrated effect in a PETS on a witness particle due to a source particle is given by (h.o.m. ignored)

$$\int_0^{l_{cav}} F_L(z)ds \approx -q_s q_w w_L(z)$$

where w_L is the std. longitudinal monopole wake function

Simulation software: PLACET

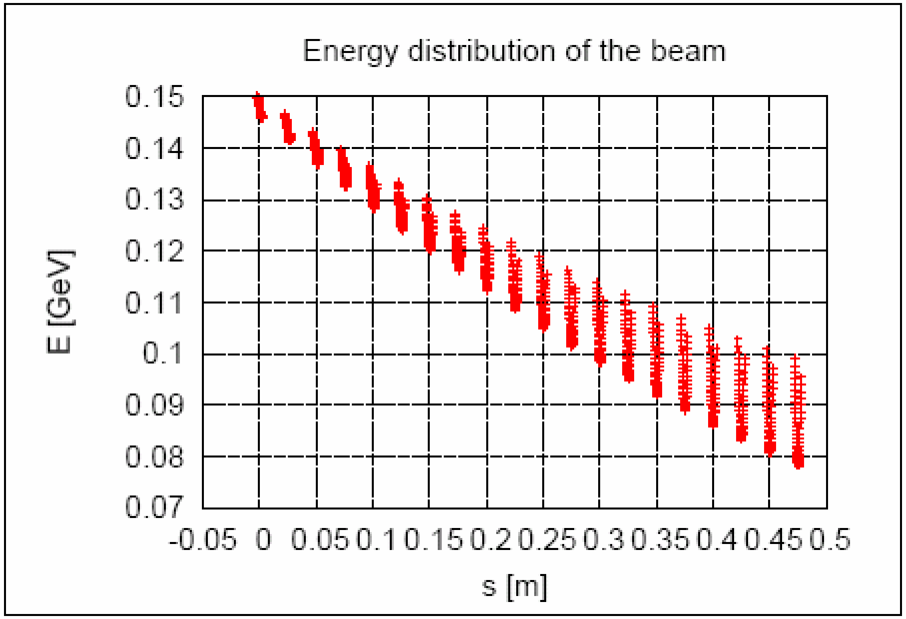
- The simulation package used here is PLACET (D. Schulte)
- Allows to study the effect of single-bunch + multi-bunch wakes precisely
- Beam model used here: sliced beam with a Gaussian longitudinal profile



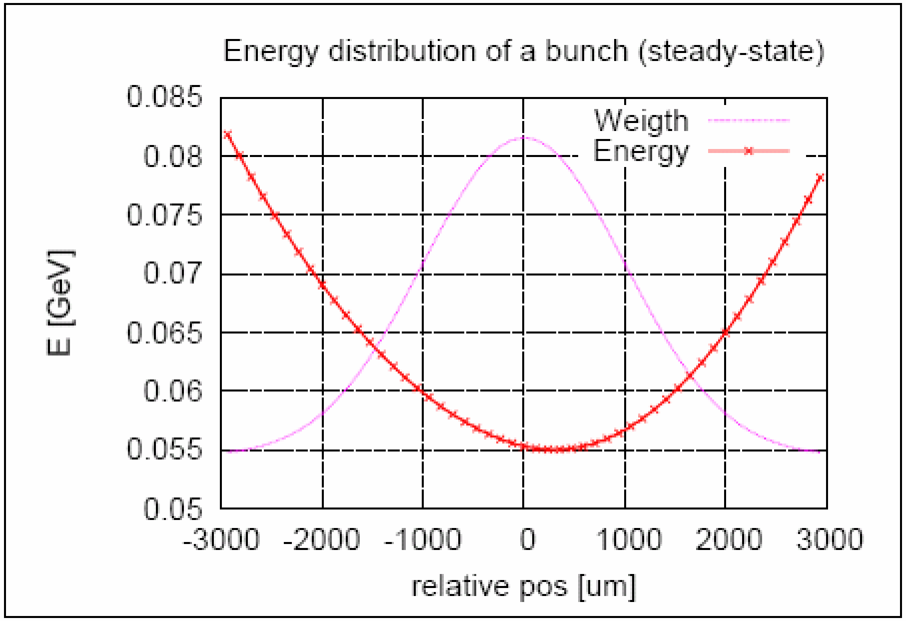
- wake acting on a given slice is simply the sum contribution from all leading slices (multi- and single-bunch effects treated on equal footing)

Simulation results: energy extraction

- PETS longitudinal wake parameters:
  - R'/Q = 2294.7 Ω/m (linac-convention)
  - f_L=11.99 GHz
  - β_g = 0.4529
- Beam energy profile after lattice: (initial: flat E_0=150Mev)



Beam energy after lattice

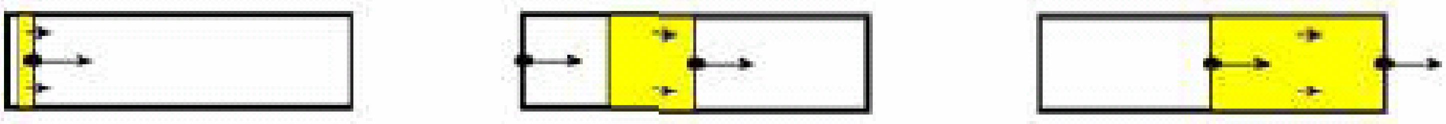


Steady state bunch energy profile

- **NB: start of beam / bunch is to the left! (PLACET output def.)**

Wake calculations and group velocity

- The wake is calculated using GdfidL (I. Syratchev), modeled as a single monopole mode traveling out of the PETS with a high group velocity (β_g) [and extracted to HDS]



- In the longitudinal wake function this leads to
  - factor $1/(1-\beta_g)$ (concentration of the field)
  - catch-up distance for the trailing bunch, $s = z\beta_g/(1-\beta_g)$

- The wake parameters R'/Q, β_g and f are taken as input to PLACET the simulation δ-wake:

$$W_{\delta L}(z) = \omega_L \frac{R'}{Q} \frac{1}{1-\beta_L} \cos(\omega_L \frac{z}{c})(L - z\frac{\beta_L}{1-\beta_L})[V/C]$$

Steady-state

- Catch-up with field from *n* bunches ahead at a distance s = ndβ_g/(1-β_g)

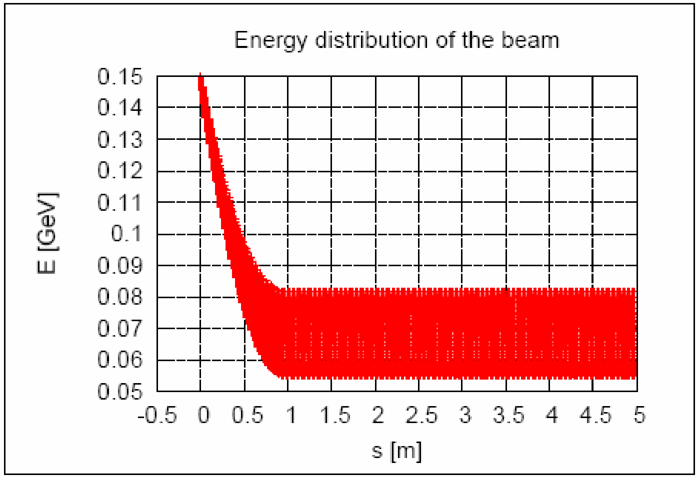
- Steady-state energy profile is thus reached after

  n = (l_{PETS}/d)(1-β_g)/β_g = 39 bunches

- Steady-state power can be calculated as $P = \frac{\omega}{4v_g}(R'/Q)l^2{}_{PETS}I^2F^2(\sigma)$

  (P = 172MW, or P ≈ 166MW if wall losses are included)

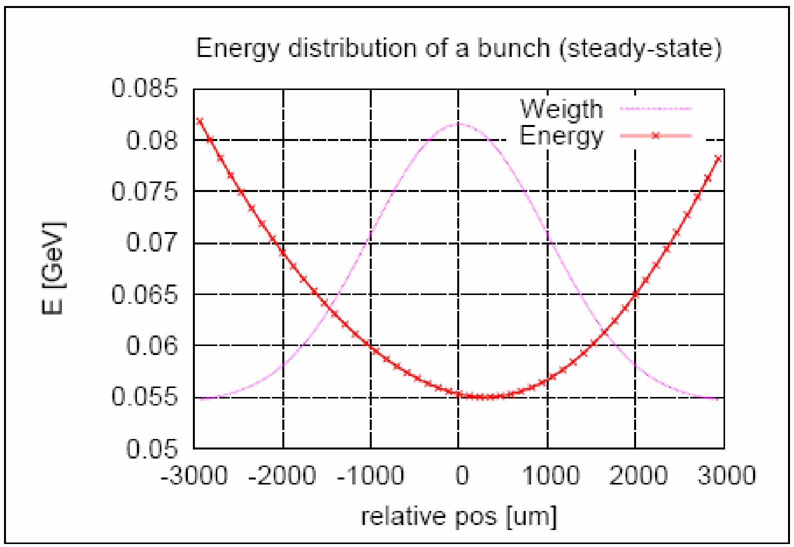
When the bunch profile and energy extraction efficiency is discussed we always talk about the **steady-state situation**.



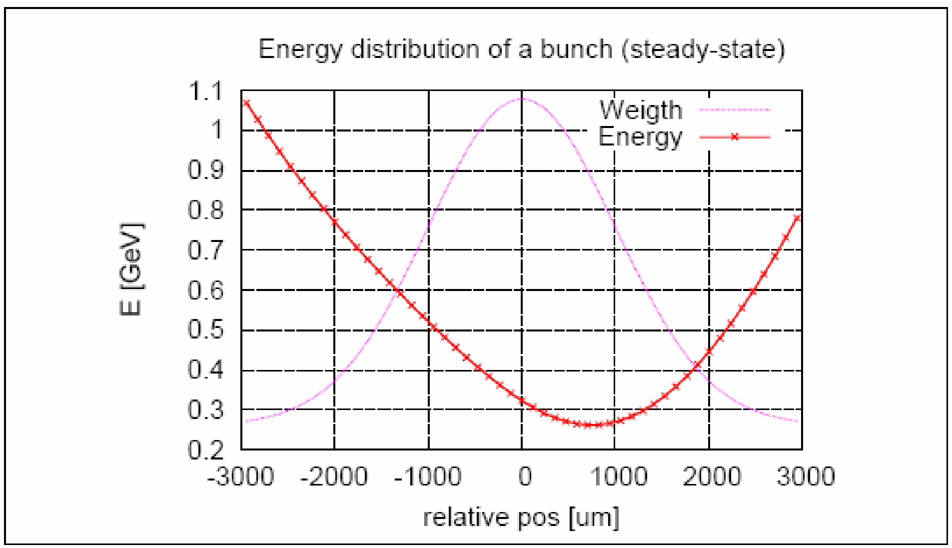
Beam energy after lattice

Steady state bunch profile

- The steady-state bunch profile depends on the multi-bunch effects as well as the single-bunch effects
- Multi-bunch wake alone would form a symmetrical energy profile (cosine-like wake function, combined with Gaussian distribution)
- Single-bunch wake: last part of the bunch will be more decelerated than the first -> point of minimum energy shifted towards the end
- However, for our case, **$n = (l_{PETS}/d)(1-\beta_g)/\beta_g = 39$** multi-bunch is **dominant**



Steady state bunch energy profile



CLIC 12 GHz, $\eta_{dist} = 97.3\%$ ($l_{PETS,CLIC} = 0.3 l_{PETS,TBL}$)

- Compare with e.g. profile for CLIC 12 GHz (**l_{PETS}= 0.23 m)**

Energy extraction efficiency: η

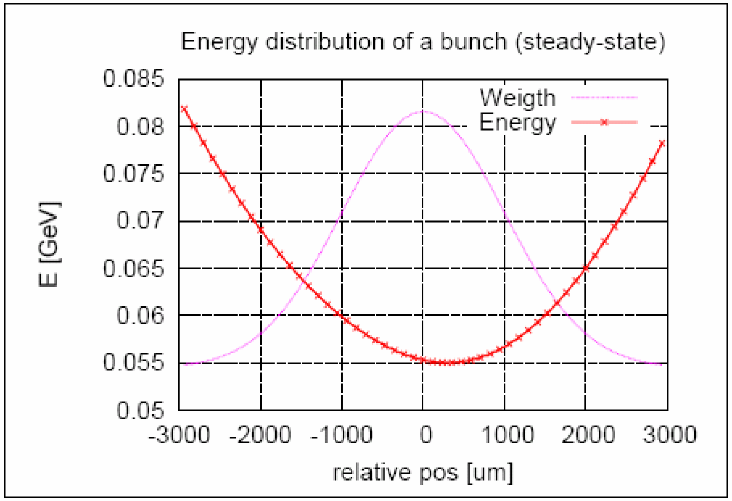
- $\eta = P_{in}/P_{out}$: **steady state** power extraction eff: $\eta = P[W] \times N \,/\, E0[eV] \times I[A]$

- Suggestion: it could be useful to express the extraction efficiency as:

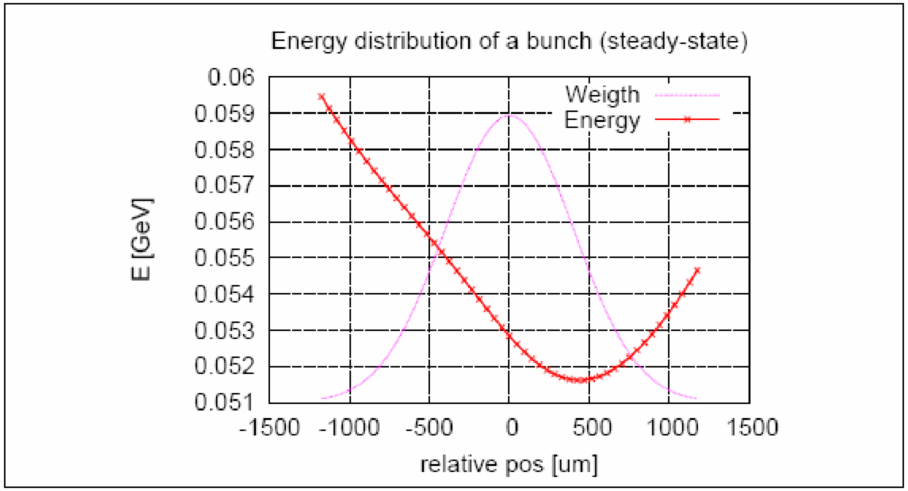
$$\eta = S \times F(\sigma) \times \eta_{dist}$$

where for TBL nominal parameters we get:

- S = 63.3 % (max energy spread)
- $\eta = S \times F(\sigma) \times \eta_{dist} = 63.3\,\% \times 96.9\,\% \times 99.9\,\% = 61.3\,\%$



Steady state bunch energy profile



$\sigma_z = 400\mu m$ $(\eta = S \times F(\sigma) \times \eta_{dist} = 65.6\% \times 99.5\% \times 99.0\%\ )$

- (can be changed with detuning: not discussed further here)

The CTF3 drive beam

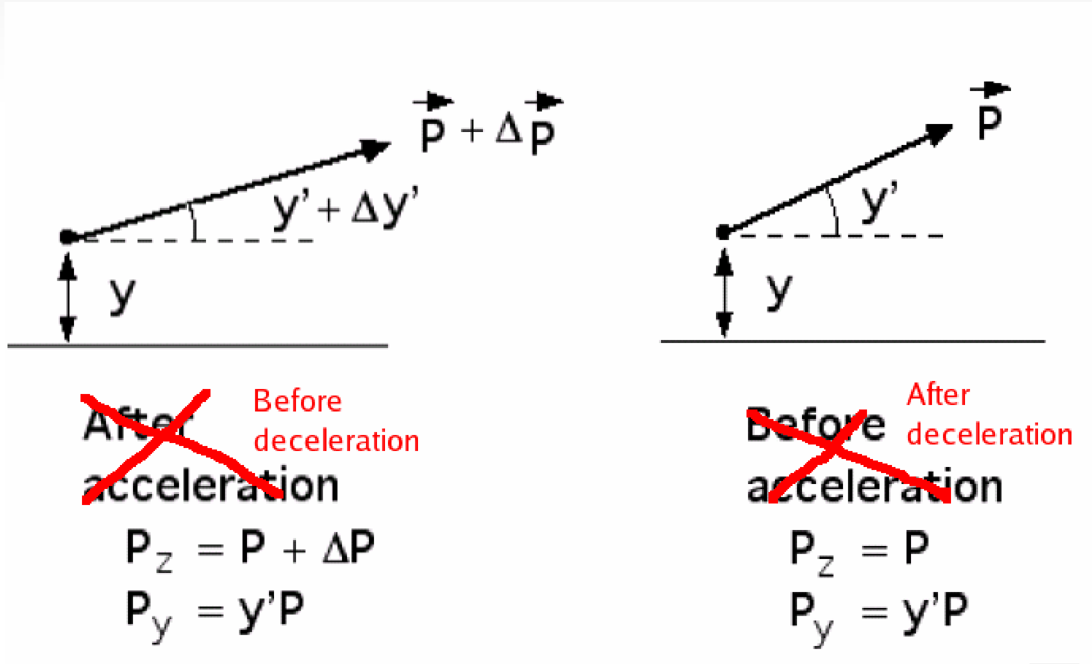
- High-current, low energy beam for strong wake field generation

- Initial beam parameters used for these simulations:
  - E_0 = 150 MeV (no energy spread)
  - I = 30 A
  - d = 25 mm (f_b = 12 GHz)
  - Gaussian bunch: σ_z = 1 mm
  - N = 200 (enough for steady-state situation to be reached).
  - $\varepsilon_N = 150\ \mu$m

- **Resulting parameters:**
  - **P = 166 MW (steady-state power production)**
  - **S = 63.3 % (max .energy spread)**
  - **η = 61.3 % (steady-state extraction efficiency)**

Energy spread and beam envelope

- Why is the max. energy spread, S, important?
- In the TBL we will have the effect of *adiabatic undamping*



(fig: A. Chao)

- The divergence, y'=dy/ds, and thus also the beam envelope will increase with decreasing energy

Calculation of the max. beam envelope

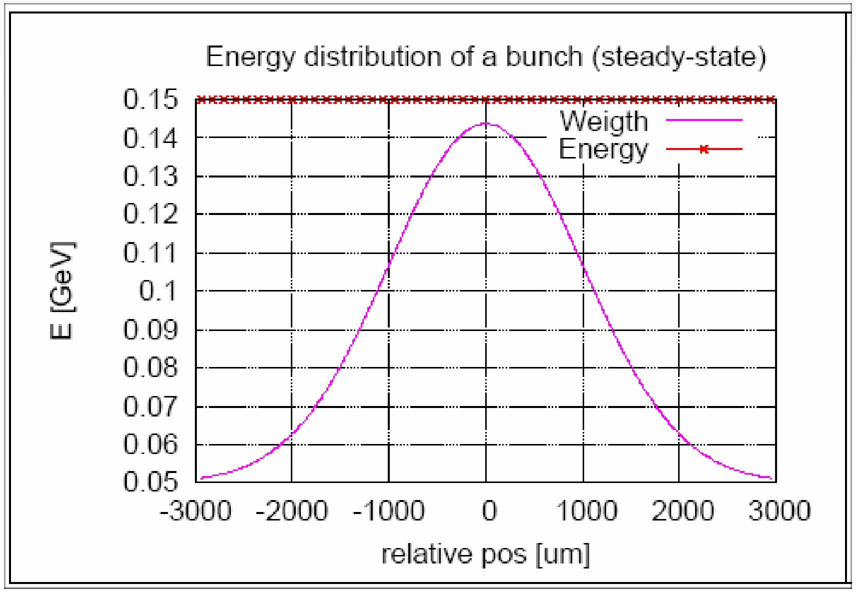
- This implies that as the beam is decelerated its transverse size will grow, even without considering transverse wake kicks or machine imperfections
- The rms beam size is
$$\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y}} = \sqrt{\beta_{x,y}\varepsilon_{N,x,y}/\gamma}$$
- We define the adiabatic “3-sigma beam envelope” as
$$r_{ad} = \sqrt{3^2\sigma_x{}^2 + 3^2\sigma_y{}^2}$$

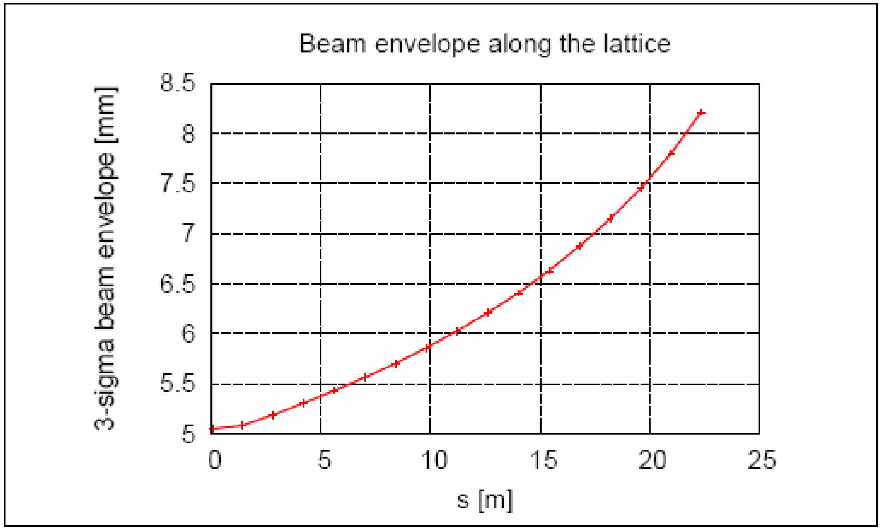
where γ ***is for the lowest energy particle*** in the bunch

- Setting in for *S*, with γ_0 the initial gamma we get the value in the middle of a quad:
$$r_{ad} = \sqrt{3^2(\breve{\beta}+\hat{\beta})\varepsilon_N/(1-S)\gamma_0} \approx 3\cdot 2\sqrt{L_{unit}\varepsilon_N/(1-S)\gamma_0}$$
- For our initial parameters we get
$$r_{ad,after} = 8.3mm, r_{ad,initial} = 5.0mm$$
- Meaning: with the nominal paramters cited above we will have a resulting 3σ beam size of 8.3mm due to the adiabatic undamping alone (while half-aperture is a_0=11.5mm) !

Beam envelope along the lattice

- Thus, beam envelope along the lattice $r_{ad} \propto 1/\sqrt{\gamma}$,
  γ for lowest particle





3-σ beam envelope along lattice (adiabatic effects alone)

The CTF3 drive beam

- High-current, low energy beam for strong wake field generation

- Initial beam parameters used for these simulations:
  - E_0 = 150 MeV (no energy spread)
  - I = 30 A
  - d = 25 mm (f_b = 12 GHz)
  - Gaussian bunch: σ_z = 1 mm
  - N = 200 (enough for steady-state situation to be reached).
  - $\varepsilon_N = 150\ \mu$m Initial beam parameters used for these simulations:

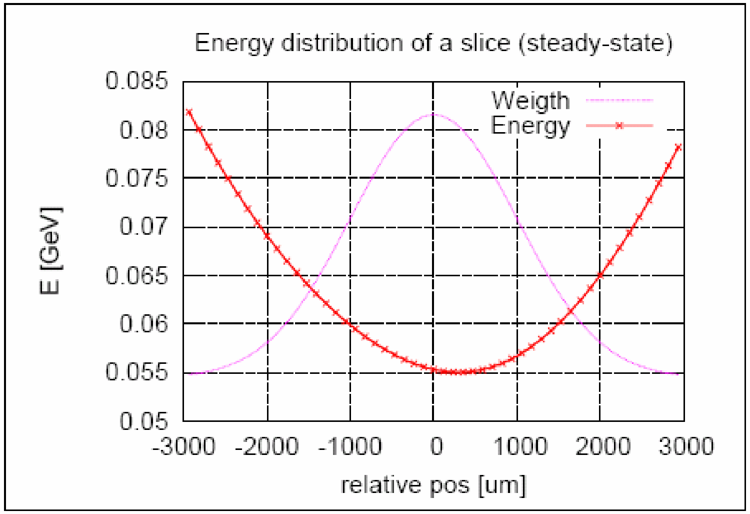
- Resulting parameters:
  - P = 166 MW (steady-state power production)
  - S = 63.3 % (max .energy spread)
  - η = 61.3 % (steady-state extraction efficiency)
  - **r_{ad} = 8.3 mm (3-sigma envelope due to adiabatic effects alone)**

Smaller beam envelope?: reduce the current

- The adiabatic envelope, r_{ad}, can be made as small (large) as we want by decreasing (increasing) the current, I.
- For the TBL, *I* can be calculated on the fly as function of *r*, E_0, *N* and PETS parameters (only because: $\eta \approx S \times F(\sigma)$, $\eta_{dist} \approx 1$)
- (Calcs omitted)
- However, decreasing the current will mean less power extracted, P, and less extraction efficiency η achieved (while we want to show as high P and η as possible)
- E.g. for if we want a $r_{ad} = (2/3)a_0 = 7.7$mm we must reduce current to I=27A (with a corresponding lower P=135 W, $\eta = 55\%$)

Challenge: beam dynamics calculations

- We have up to 90% energy spread *S* (CLIC)
- Spread acts stabilizing (different betatron wavelength lead to decoherence of transverse kicks) – but difficult to calculate the effect
- Also the finite group velocities and damping makes calculations difficult
- No analytical formulas or framework available (ongoing work, try to get somewhere, but no results so far)
- → **need for simulations**



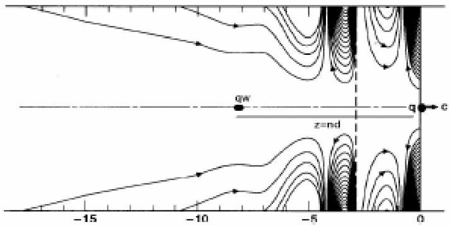
Steady state bunch energy profile

Part 2

Effect of transverse wakes (summary)

Transverse wakes

- A source particle q_s induces wake fields in PETS cavity



- A witness particle q_w, following at a distance z, is kicked by the fields from leading particles

- The total transverse force on q_w is given by (1D)

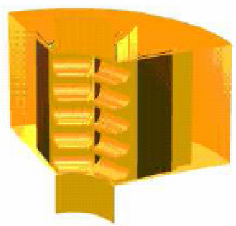
$$\int_0^{l_{cav}} F_y(z)ds \approx -\Delta y q_s q_w w_T(z)$$

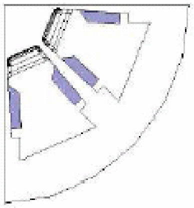
where $w_T(z)$ is the transverse dipole wake function - the "δ-wake" (h.o.ms ignored here)

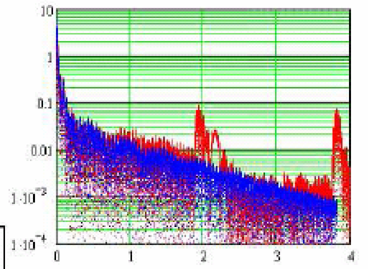
PLACET input: dipole wake function

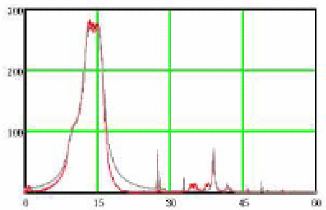
- PETS are modelled with GdfidL (I. Syratchev)

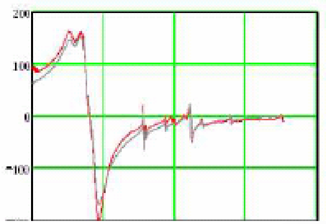
- For a given PETS structure, the transverse δ-wake / impedance is calculated



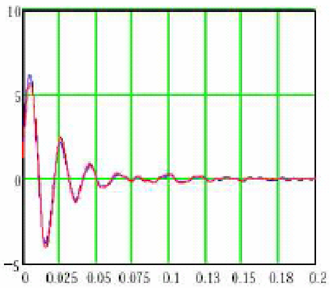








W_T	Q	F
0.045	300	27.44
0.019	180	28.05
0.017	290	32.912
0.2	85	39.12
0.03	120	41.83
0.015	380	48.91
0.85	3.7	10.0
4.82	3.8	13.4
2.63	6.2	15.46



Slide: I. Syratchev

PLACET simulations

- Multiple modes identified from GdfidL calc

- For each mode, w_{T_i},Q_i,f_{T_i}, β_{T_i} are identified

- The total wake function for each mode thus:

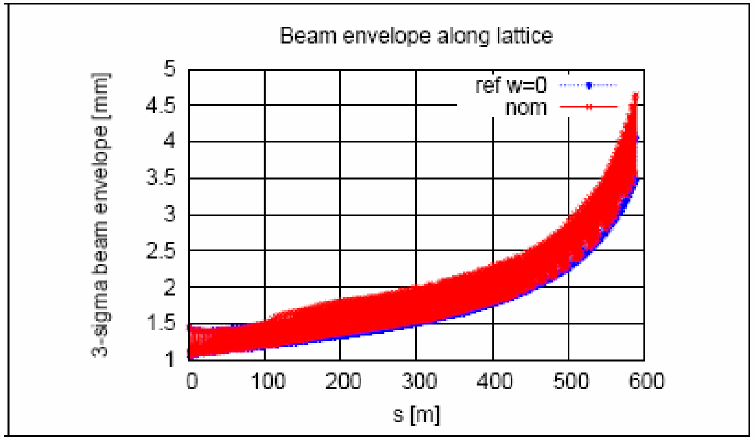
$$W_{T_i}(z) = w_{T_i} \sin(\omega \frac{z}{c})(L - z_{ij} \frac{\beta_T}{1-\beta_T})e^{-z\omega/2cQ(1-\beta_T)}[V/Cm]$$

- Transverse kick of q_w :

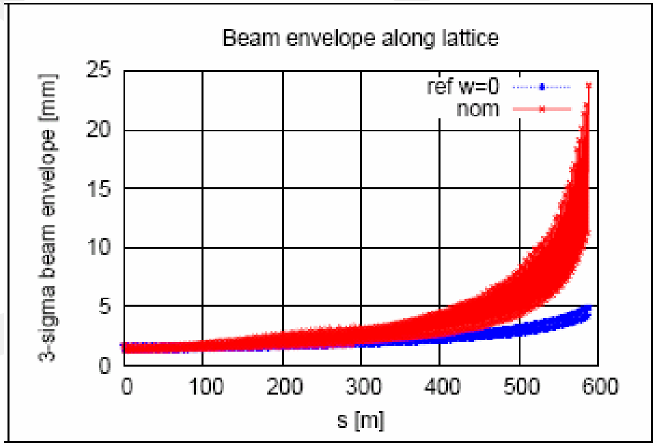
$$\Delta y'_w = \sum_{modes} \frac{\Delta p_{y,w}}{m_w c} = \sum_{modes} y_s \frac{q_s q_w}{E_w} W_{\delta T}(z)[rad]$$

Goal: transverse wakes should not amplify beam jitter

- A design target for the PETS is to ensure that beam jitter are not amplified significantly due to transverse wakes (and leading to beam blow-up)
- A number of simulations has been run (initiated by I. Syratchev)
- Results: basically no problem for *nomina*l PETS parameters (both CLIC and TBL lattice checked)
- (Example: CLIC low β/high β FODO lattice)



4A, $Q=1.5Q_0$ (1m, no detuning): $r = 4.6mm$



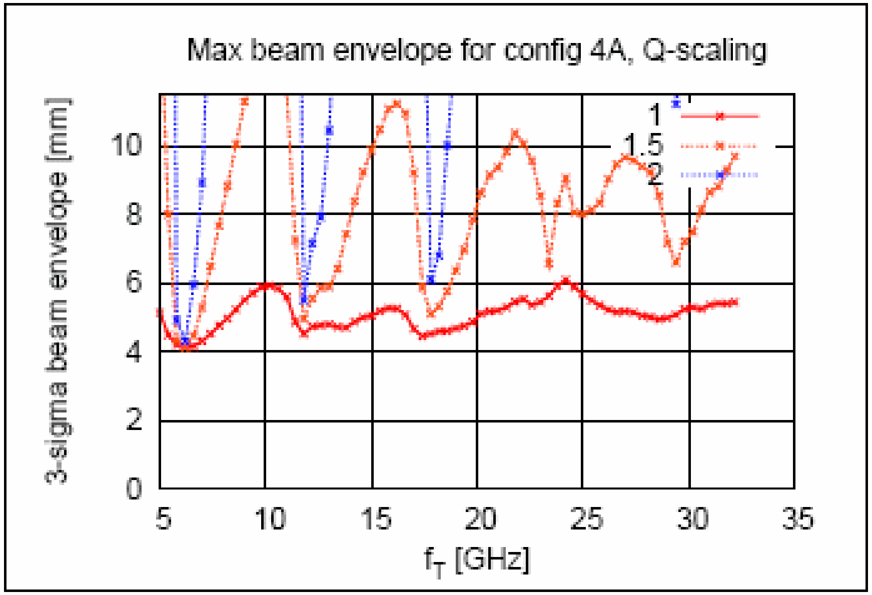
7A, $Q=1.5Q_0$ (1.5m, no detuning): $r = 23.8mm$

More examples of PETS test simulations

- Metric used: $3 - sigma$ beam envelope at end of lattice
- Initial conditions: beam with initial static offset + jitter at the transverse resonance frequency
- Beam blow-up depends on z/λ_{T_i}: $\sin(\frac{2\pi}{\lambda_{T_i}}z) = 0 \Rightarrow z = \frac{n}{2}\lambda_T \Rightarrow f_T = \frac{n}{2}12GHz$ (zeros)

SUM mode, Σw, $\overline{Q}$

$w = 8.3$, $Q = 4.6$



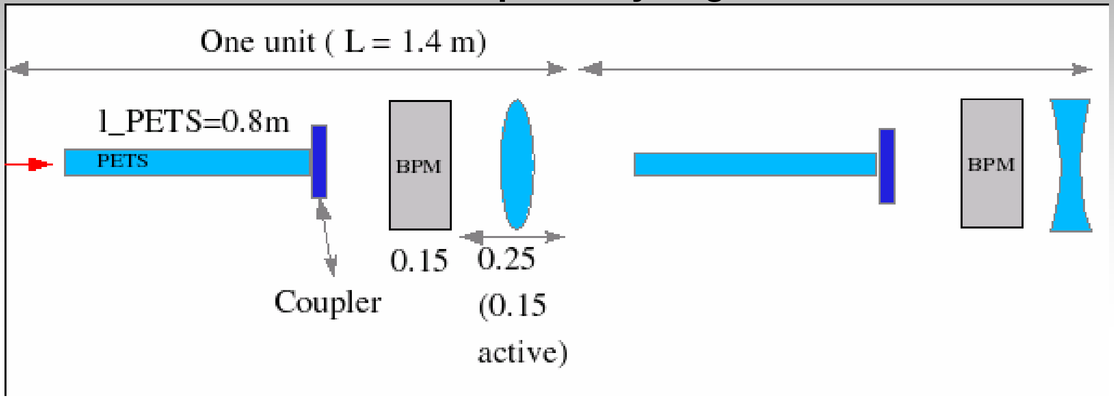
Config 4A: $\omega/Q = const$

Part 3

Effect of component misalignment

5 types of misalignment studied

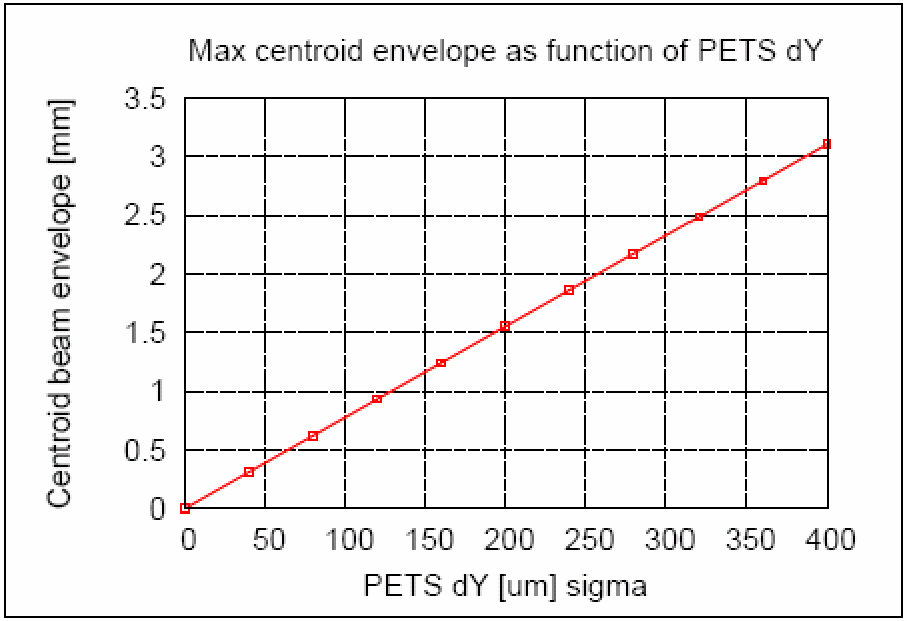
- In part 1 and 2: all simulations was with a **perfectly aligned machine**



- Now: will study **the effect of misalignment** of machine components
- Each misalignment (PETS, Quads) studied separately
- 100 random machines simulated for each case. Metric: max. **centroid** offset, r_c, along lattice (of all machines)
- The initial beam will be assumed to be on the reference orbit
- Adiabatic effect is NOT included in order to study each effect separately (no macroparticles distribution)
- Total 3-sigma beam envelope will therefore be
  - 3-sigma adiabatic envelope “+” centroid envelope : r_{ad} “+” r_c (where the “+” is only in worst case a real +)
- Still: with the adiabatic envelope r=8.3mm (versus half-aperture of a_0=11.5mm) **we do not have a large “envelope budget” for component misalignment**

1) Position offset of PETS

- A PETS off axis will induce transverse kicks (dipole wake $\propto y_{source}$)
- We scatter the PETS in y: σ_{PETS} = {40 ... 400}μm



$\sigma_{PETS} = \{40...400\}\mu m,$

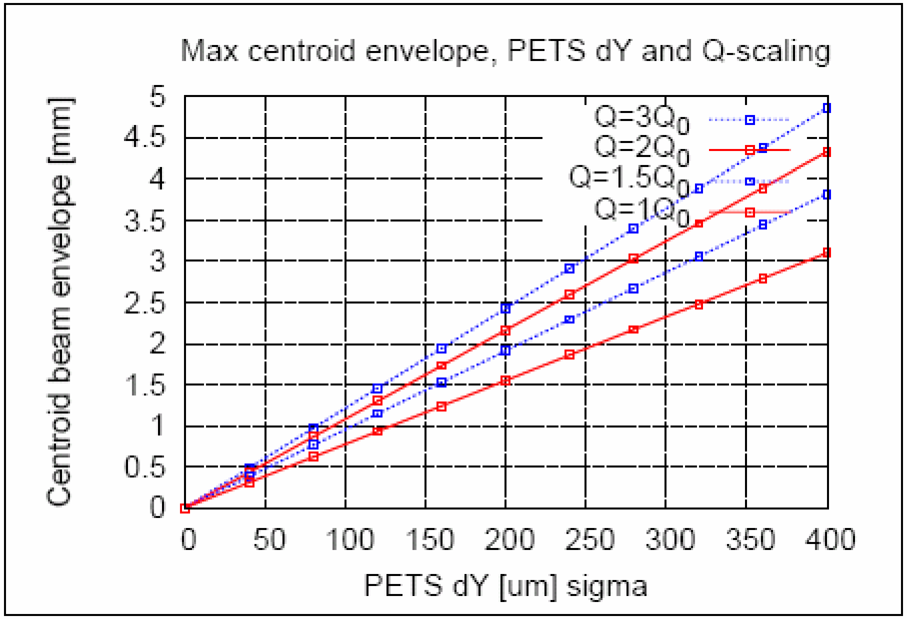
(linear graph due to the linear lattice model and same seeds in all simulations - all info in one point)

- Prelim. criterion: centroid envelope < 1 mm

  $\Rightarrow \sigma_{PETS} < 120\ \mu m$

Position offset of PETS with Q-scaling

- Also interesting to see effect of large Q in this scenario (previous PETS simulations imply that the effect should not be drastic)

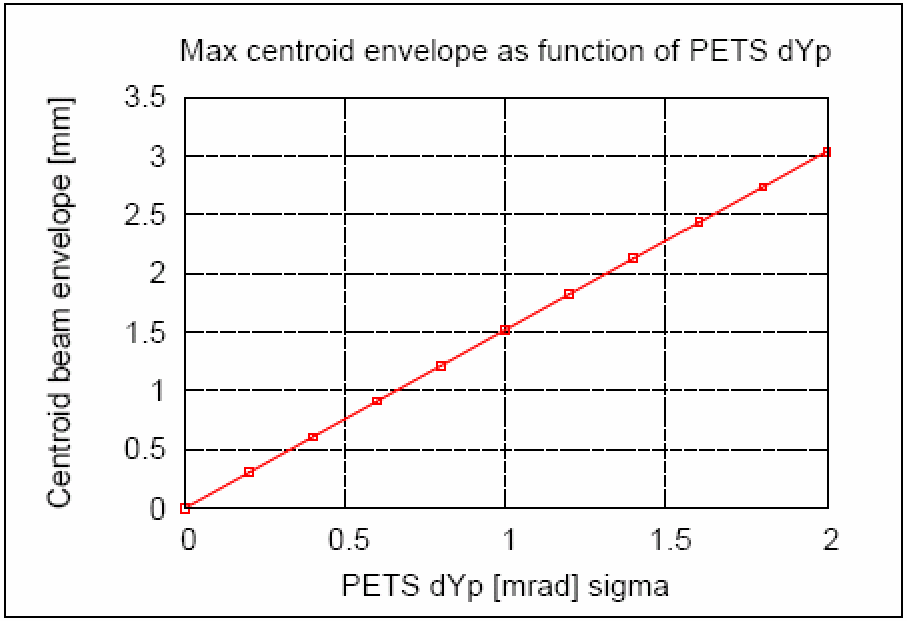


$$\sigma_{PETS} = \{40...400\}\mu m,\ Q = \{1..3\}$$

- We see that as long as σ_{PETS} < 100 μm we are still OK, even for a factor $Q=3Q_0$
- (But this is not “worst case scenario” for PETS: jitter on resonance)

2) Angle offset of PETS

- An angle offset (around x,y) of the PETS centre should basically have the same effect as the corresponding position offset, $\sigma_{\theta-PETS} = (\sigma_{PETS} / 0.5 l_{PETS})*2$. Just to confirm:

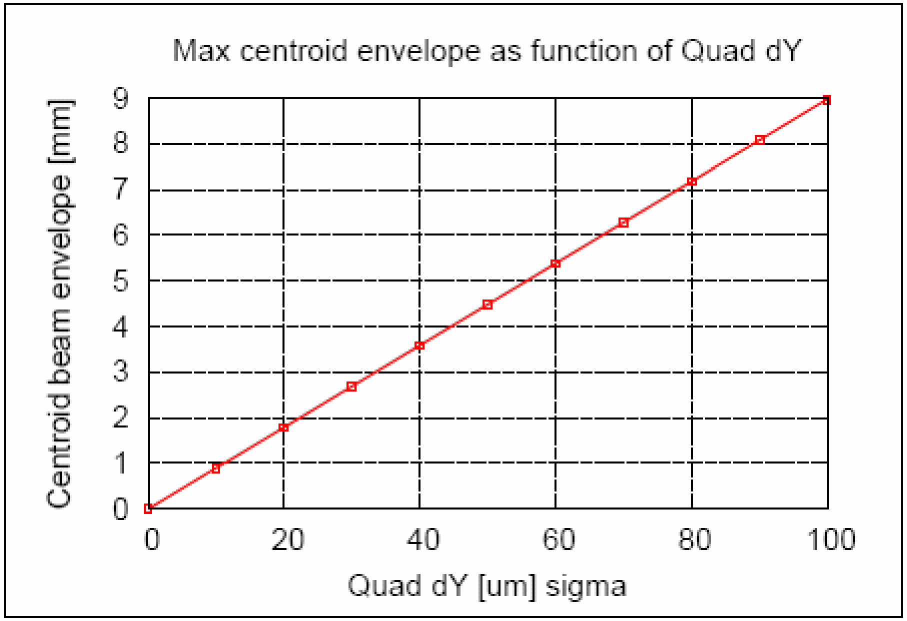


$\sigma_{\theta-PETS} = \{0...2\} mrad$

- Prelim. criterion: centroid envelope < 1 mm
  $\Rightarrow \sigma_{\Theta-PETS} < 0.6$ mrad
- (An angle offset around s: negligible effect)

3) Position offset of quadrupoles

- An offset in a quad will induce a dipole kick
- We scatter the quads in y: $\sigma_q = \{10 \ldots 100\}\mu m$

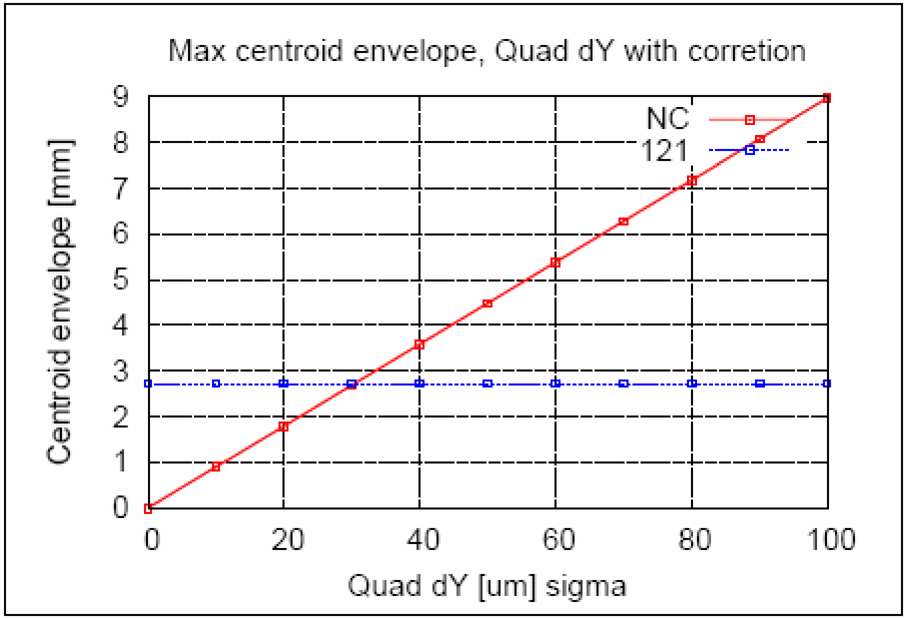


$$\sigma_q = \{0 \ldots 100\}\mu m$$

- We see that without any correction of the quad positions we should require a final alignment $\sigma_{PETS} < 10\ \mu m$ (probably not feasible with prealignment ?)
- Solution: beam-based alignment (BBA)

BBA for quads: 1-to-1 correction

- Quads in TBL (as in CLIC) will be on movers
- The simplest BBA: steer each quad so that the beam goes through centre of the following BPM



$\sigma_q = \{0...100\}\mu m$, w/ correction

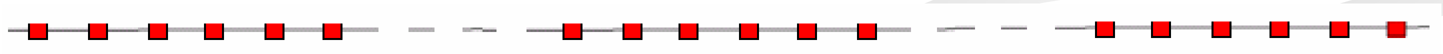
- Implementation: correction can in principle be performed in one go. **b:** BPMs after one pulse. **R:** the response matrix: $\Delta y_c = \mathbf{R}^{+}\mathbf{b}$
- Effectively: **quad position error σ_q, is transferred to BPM position error σ_{BPM}**
- 1-to-1 correction can be needed as a first correction – but we can do better

BBA for quads: dispersion free steering

- The dipole kicks resulting from quad offset will induce dispersion (in the sense "energy-dependent trajectories") in the lattice
- Idea: move quads so that beams of different initial energies follows the same trajectory
- E.g. send the nominal beam with E_0 and a test-beam with $E_1=0.8\times E_0$
- This can, in principle, be implemented by generating the response matrix of both the nominal beam, $\mathbf{R}_1$, and for a beam of e.g. lower energy, $\mathbf{R}_2$, measure and do the correction $\Delta \mathbf{y}_c=(\mathbf{R}_1 - \mathbf{R}_2)^{+}(\mathbf{b}_1-\mathbf{b}_2)$ (weighted against 1-to-1 correction)
- Effectively: **quad position error σ_q, is transferred to BPM resolution error σ_{res}**

Special variant of DFS needed for TBL

- TBL and CLIC deceleration station:
  - cannot use lower energy beam due to beam stability
  - higher initial energy beam not available
- Trick: we can use a beam with lower current instead Wakefields will be lower and beam will quickly have higher energy
- Can either reduce bunch charge, or take out a number of bunches (probably easier?)

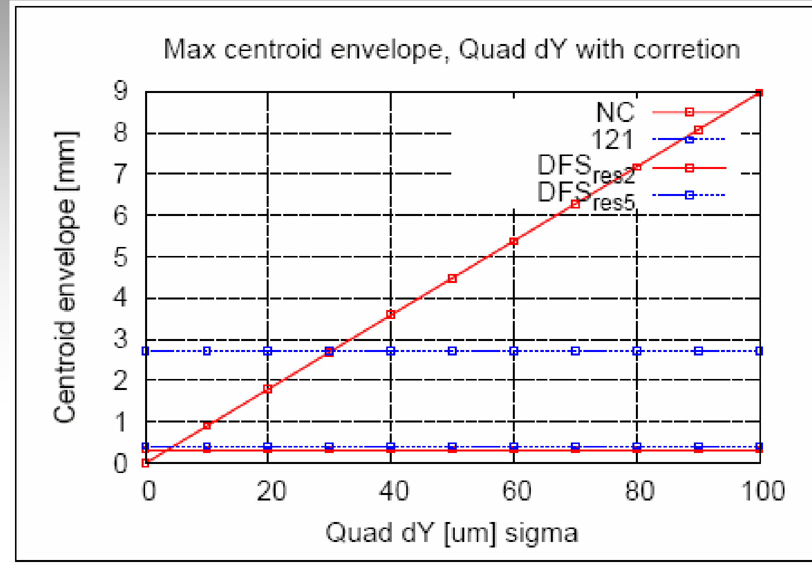


- Results seems to be as good as for energy test beam
- All results from now are run with optimal DFS weighting

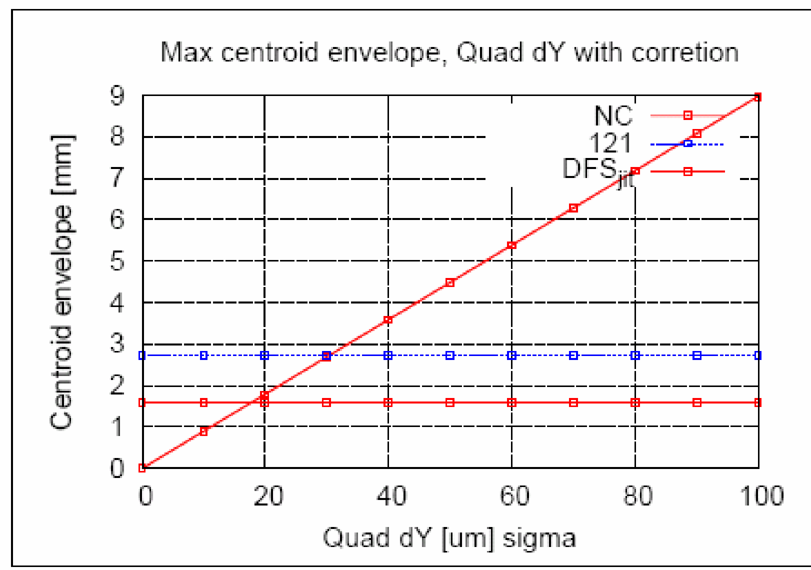
NB: now very easy to test new BBA algorithms in PLACET with then new Octave interface (A. Latina)

Correction with current test beam DFS

- Seemingly very good result (with our linear lattice and ideal elements), and shows the principle
- Remains to be studied: the DFS algoritm is, among other things, sensitive to jitter in the main/test beams. E.g. inducing uncorrelated random jitter σ_{beam}=100μm on both beams gives a substantially worse result. However, this can be partially remedied (D. Schulte), but not studied further here.
- In the worst case: 1-to-1 correction would give as good result as DFS



$\sigma_q = \{0...100\}\mu m$, w/ correction



$\sigma_q = \{0...100\}\mu m$, w/ correction

TBL as a test-bed for the CLIC station

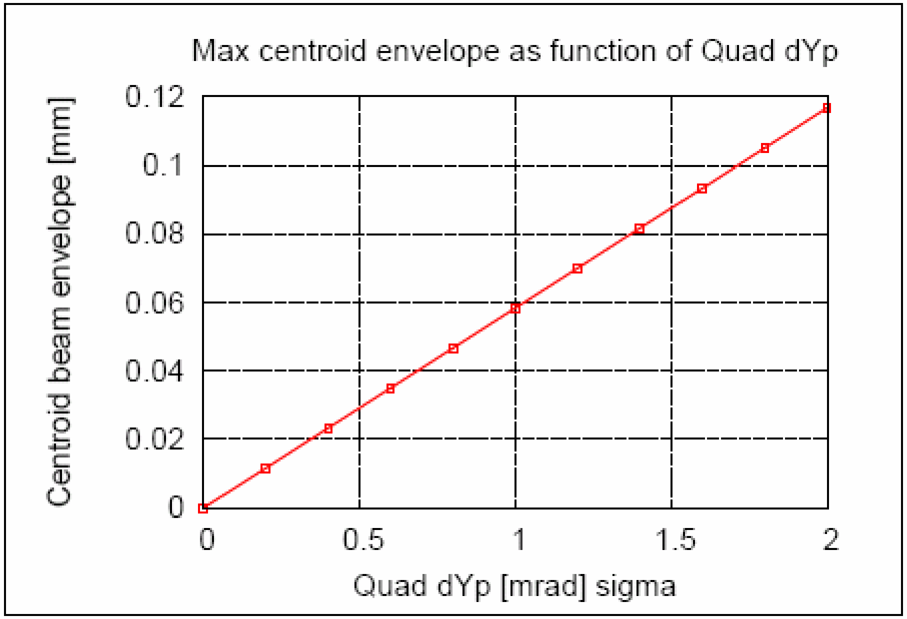
- In any case: it would be very interesting to use the TBL to test the concept of dispersion free steering and other beam-based alignment

- One would like to have similar conditions to the CLIC station (ideally: similar alignment precision and BPM resolution)

- TBL: also test-bed for automation of BBA ?

4) Angle offset of quadrupole

- A small rotation around s (skew quadrupole) will have negligible effects for the 8 FODO cell lattice in question
- A small rotation around x, y will have negligible effect (integrated force ≈0, due to negligible motion in a quad)
- Quad angle offset in y: $\sigma_{\theta q}$ = {0 ... 2}mrad . Just to confirm:

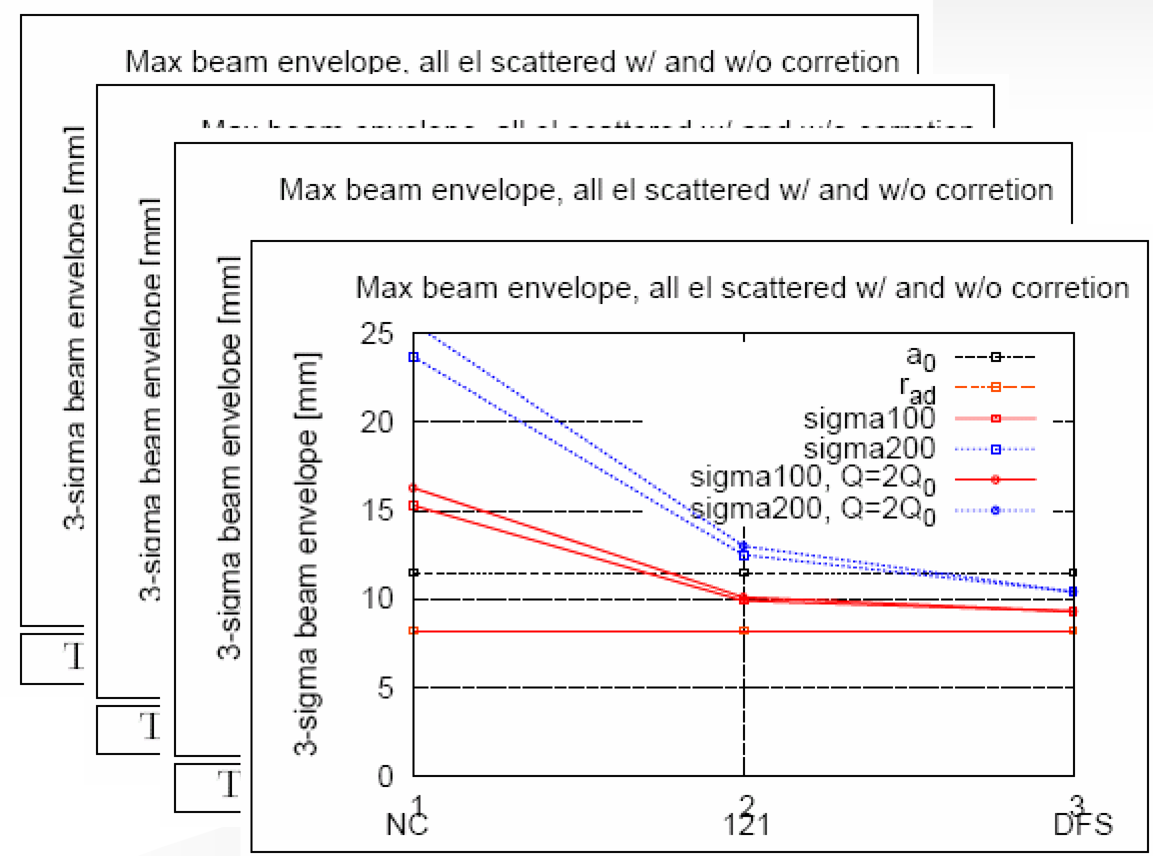


$$\sigma_{\theta-q} = \{0.2...2\} mrad$$

- Negligible for even relatively large rotation

Wrap-up: full simulation

- We now put errors on all elements simultaneously, in both x and y
  - $\{\sigma_{PETS}, \sigma_{\theta-PETS}, \sigma_q, \sigma_{BPM}\}_{,x,y}$ {100,200} um (or corresponding angle)
- This time we observe the *total* 3-sigma beam envelope, r_{ad} "+" r_c (w and w/o correction)



Total 3-sigma enevelope, all elements scattered

- Now, we put alignment error a factor two
- Now: with $Q=2Q_0$

Discussion

- Trustworthiness of the simulation results

“Are we now sure to get the TBL beam through???”

- In “favour”
  - Our metrics are conservative

- In “disfavour”
  - several important idealizations:
    - lattice: except scattering and BPM res: ideal lattice elements
    - lattice: linear lattice
    - beam: Initial 0 bunch energy spread
    - beam: gaussian bunch shape
    - wakes: Only monopole and dipole wake
    - wakes: PETS Q factor difficult to predict
    - ...and more

- First conclusion: a TBL is still needed...

Conclusions

- The nominal PETS parameters given seem satisfactory
- We see that the difference between a position accuracy of σ = 100 μm and σ = 200 μm is significant
- Under the conditions in these simulation, with σ = 200 μm we cannot get the beam fully through even when doing 1-to-1 correction (only with perfect DFS steering) (without reducing I, P and η)
- The margin for σ = 100 μm is much more comforting. Ideally :

  $\Rightarrow$ σ_{PETS} <= 100 μm (minimize transverse wake kick)
  $\Rightarrow$ $\sigma_{\theta-PETS}$ <= 0.5 mrad (same reason)
  $\Rightarrow$ σ_{quads} < =100 μm (get beam through in order to prepare for further corrections)
  $\Rightarrow$ σ_{BPM} <= 100 μm and σ_{res} <= 5 μm
  $\Rightarrow$ Mover positioning resolution in x and y: same O.M. as σ_{res}