The CLIC Decelerator

Beam Dynamics studies

E. Adli, CERN AB/ABP / UiO

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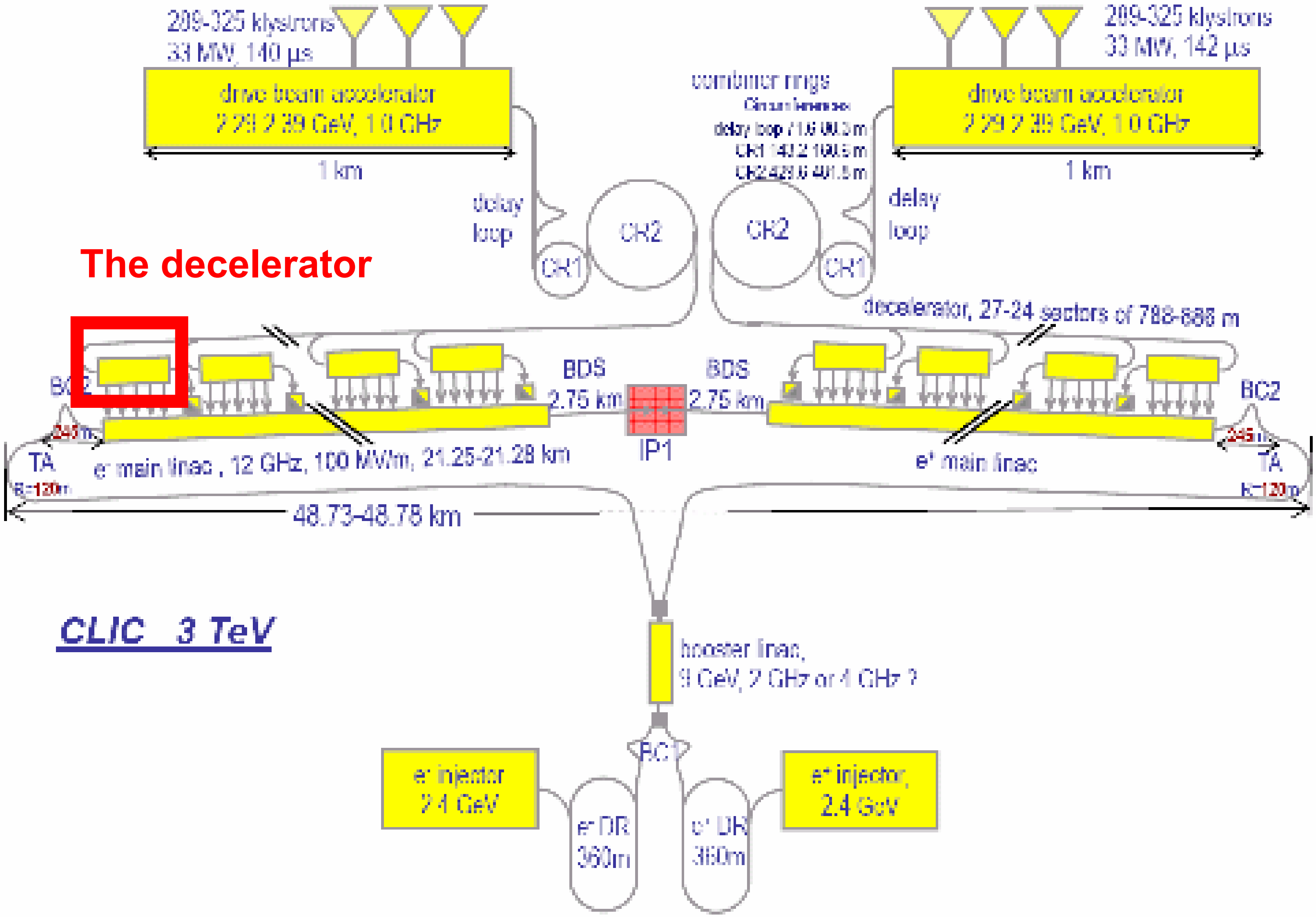
What are we talking about?



The goal of the CLIC decelerator

- Producing the **correct power for accelerating structures**, **timely and uniformly** along the decelerator, while achieving a **high extraction efficiency**

- Uniform power production implies that the beam must be transported to the end with **very small losses**

- Beam dynamics depends on the same parameters as power output and efficiency
  $\rightarrow$ Beam stability deeply interweaved with power extraction

Outline

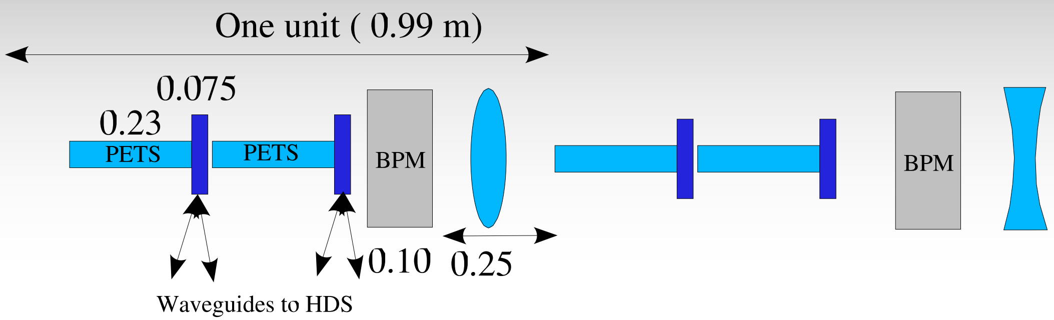
1. Longitudinal wakes and power extraction
2. Transverse single particle dynamics

   ...and linking 1. and 2.

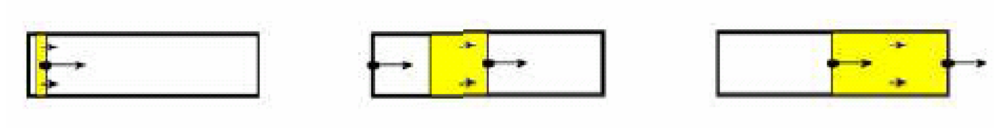
3. PETS – transverse wakes and break down
4. Machine misalignments and tolerances
5. Conclusions and outlooks

Model and setup

- The decelerator lattice:
  - FODO cells with PETS (some empty "slots")



  - Reference: decelerator station #26
  - PETS wake fields are modeled as "sausage fields" traveling out of the PETS with a group velocity



  - Longitudinal monopole wake (decelerates the beam)
  - Transverse dipole wake (vertical kicks)
  - All lattice elements can be offset or tilted

- Beam: a sliced beam model is use; $n_{bunches}$ > bunches needed to reach steady-state in energy
  - We assume a well-matched beam, with ε_N=150 μm
  - Initial beam can be offset or jittered

Longitudinal wakes and power extraction

The effect of deceleration – in one slide

E

$S=(E-\check{E}) / E$

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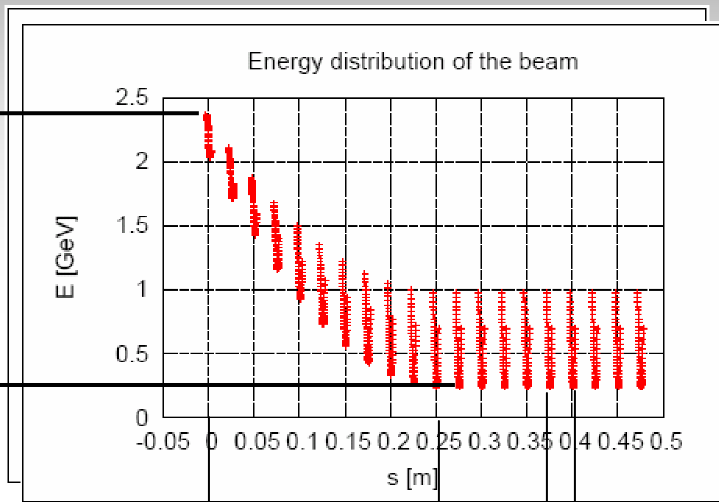
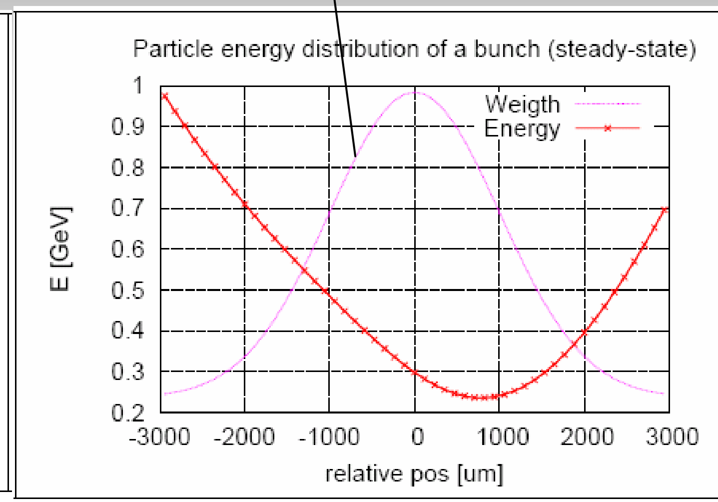


$\lambda(z)$



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

d

n_{ss}

σ_z

$$n_{ss} = (L_{PETS}/d)(1-\beta_g)/\beta_g$$

Power extracted from beam (ss)

$$P \approx (1/4)\, I^2 L_{pets}^2 F(\sigma)^2 (R'/Q)\, \omega_b / v_g$$

Power extraction efficiency (ss)

$$\eta = E_{in}/E_{ext} = PN_{PETS} / IE/e$$

Symbol definitions + some parameters

(for reference)

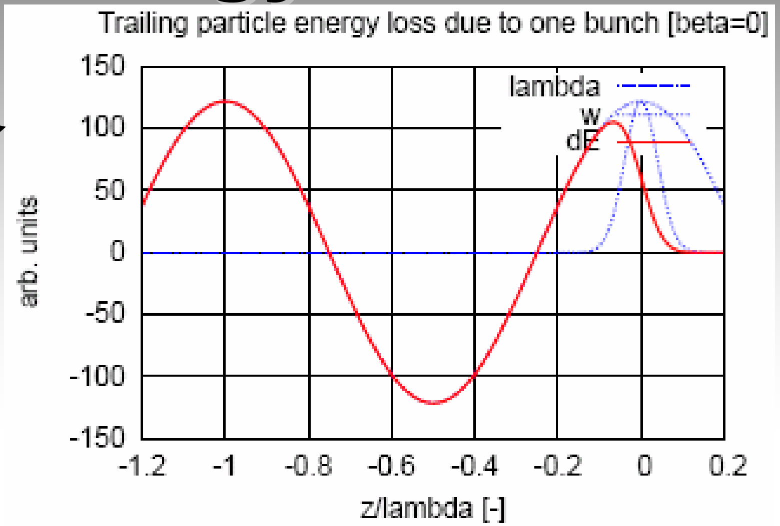
Symbol	Example value	Description
$\lambda_L = \frac{c}{f_L}$	$25.00\ mm$	Longitudinal mode wavelength ($11.99GHz$)
β_L	0.459	Normalized longitudinal group velocity
R'/Q	$2222.0\ Linac - \Omega/m$	Impedance [linac-convention] (the value in circuit-ohms is half)
a	$11.5mm$	PETS half-aperature
$\{\omega_{Ti}, \lambda_{Ti}, \theta_{Ti}, \beta_{Ti}\}$		Transverse mode parameters
$d = \frac{c}{f_b}$	$25.00\ mm$	Bunch distance
P	135.0 MW	PETS power production, ss
N_{PETS}	1372	Number of PETS per drive beam sector
q	$7.9nC$	Bunch charge
I	95.3 A	Current
E	2.4 GeV	Initial beam energy
$\check{E}$	0.24 GeV	Final miminum energy
$S = \frac{E-\check{E}}{E}$	0.90	Maximum final energy spread, ss
$\Delta\hat{E} = e\hat{U}$	1.54 MV	Maximum deceleration voltage ($\check{E} = E - N\Delta\hat{E}$)
$< U >= \frac{P}{I}$		Average deceleration voltage ($P =< U > I$)
$\eta = \frac{PN_{PETS}}{EI} = \frac{<U>}{\hat{U}}S$	84.8 %	Power Extraction Efficiency coefficient, ss
σ_z	$1mm$	Bunch rms length
$F(\sigma_z)$	96.9 %	Bunch form factor
L_{PETS}	0.2314 m	PETS active length ($37 \times 6.253mm$)
L_{UNIT}	$0.938\ m$	One unit length (FODO half-length)
ε_N	$150\mu m$	Normalized emittance
r		3-σ beam envelope (90% envelope if 100 machines)
r_c		centroid beam envelope (90% envelope if 100 machines)
r_{ad}	$3.3mm$	3-σ envelope, resuling from adiabatic undamping alone (perfect beam and machine)

PETS energy extraction

Single particle energy loss:

$$\Delta E(z) = Ne^2 \int_z^\infty dz' \lambda(z') w_L(z'-z)$$

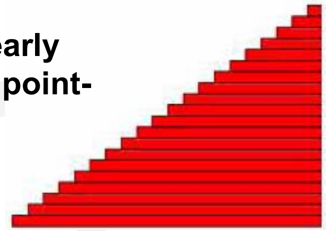
example for Gaussian bunch



PETS longitudinal d-wake, including group velocity:

$$w_L(z) = \omega_L \frac{R'}{Q} \frac{1}{1-\beta_L} \cos(\omega_L \frac{z}{c})(L - z\frac{\beta_L}{1-\beta_L})$$

field builds up linearly (and stepwise, for point-like bunches)

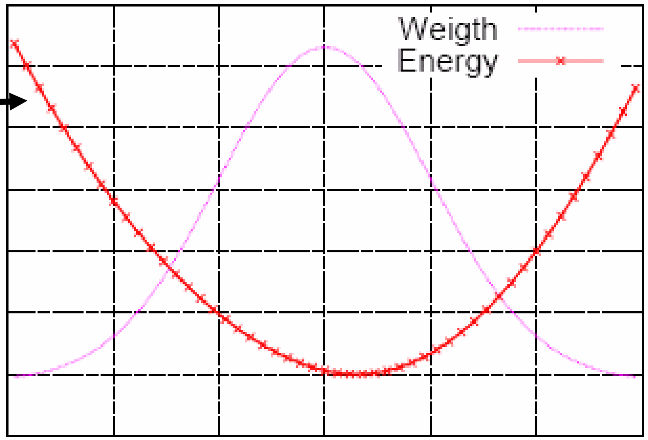


Energy loss from leading bunches + single bunch component:

$$\Delta E(z) = \Delta E_{sb}(z) + \Delta E_{mb}(z)$$

Approx: sb component equal to mb, and linear field increase:

$$\Delta E(z) \approx \frac{n_{ss}}{2} L_{PETS} A N e^2 F(\lambda) \cos kz$$



if mb assumption is good, wake function is recognized for particle energy loss of z

Integrating ΔE over bunch gives second form factor, and times f_b gives extr. power:

$$P \approx \frac{1}{2} I^2 L_{PETS}^2 F^2(\lambda) \frac{R'}{Q} \omega_L \frac{1}{\beta_L c}$$

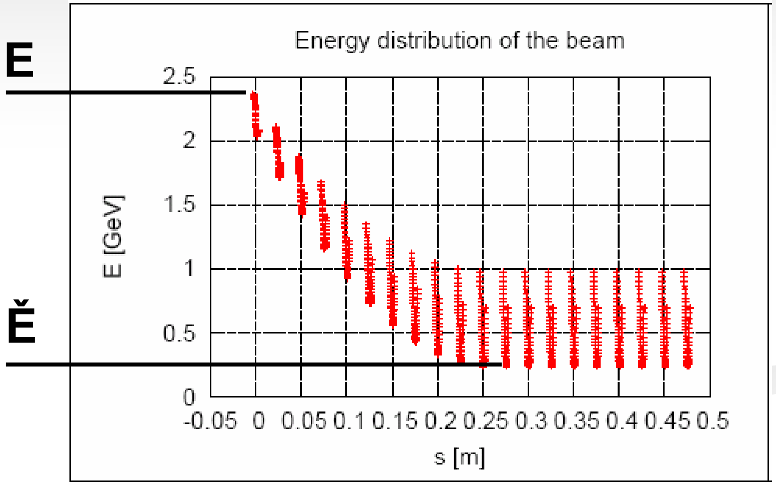
(x 1/2 for linac-Ohms)

Extraction efficiency: η

$\eta = E_{in}/E_{ext}$: **steady state** power extraction efficiency

$$P = < U > I$$

$$\eta = \frac{PN}{IE/e} = \frac{PS}{I\Delta\hat{E}/e} = \frac{< U >}{\hat{U}} S$$



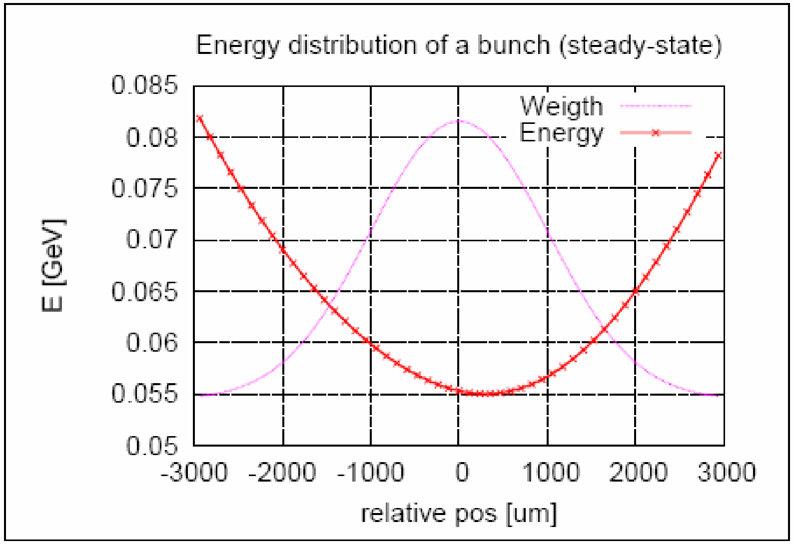
what we want: the maximum voltage Û as close to the average voltage <U> as possible (for a point-like bunches: <U> = Û and η = S)

Extraction efficiency: TBL case and CLIC case

- What is the extraction efficiency, η?

For TBL:

$n_{ss} = (L_{PETS}/d)(1-\beta_g)/\beta_g = 39 \rightarrow$ **multi-bunch ok**



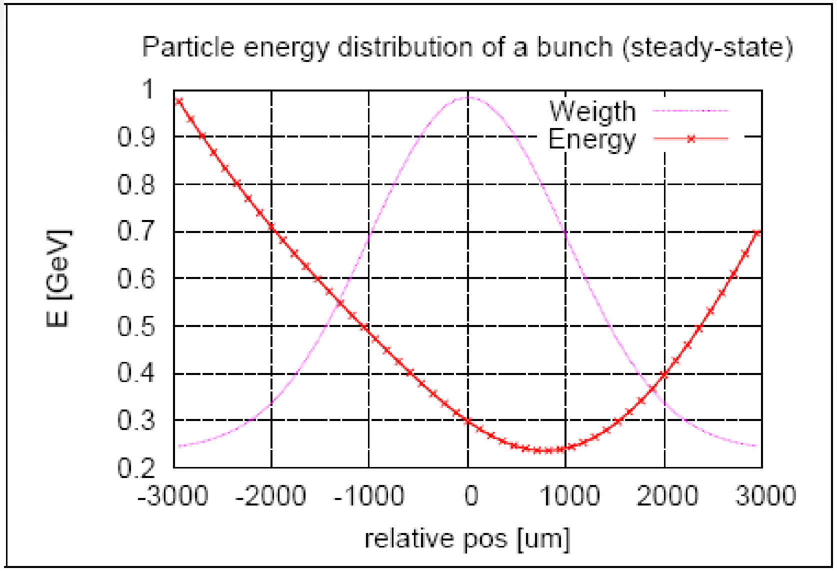
Steady state bunch energy profile

<U>/ Û = F(λ)

$$\eta = \frac{PN}{IE/e} = \frac{PS}{I\Delta\hat{E}/e} = \frac{\{\Delta E_{mb}(0)NF(\lambda)f_b\}S}{I\Delta\hat{E}/e} = SF(\lambda)$$

For CLIC:

$n_{ss} = (L_{PETS}/d)(1-\beta_g)/\beta_g = 11 \rightarrow$ **sb significant**



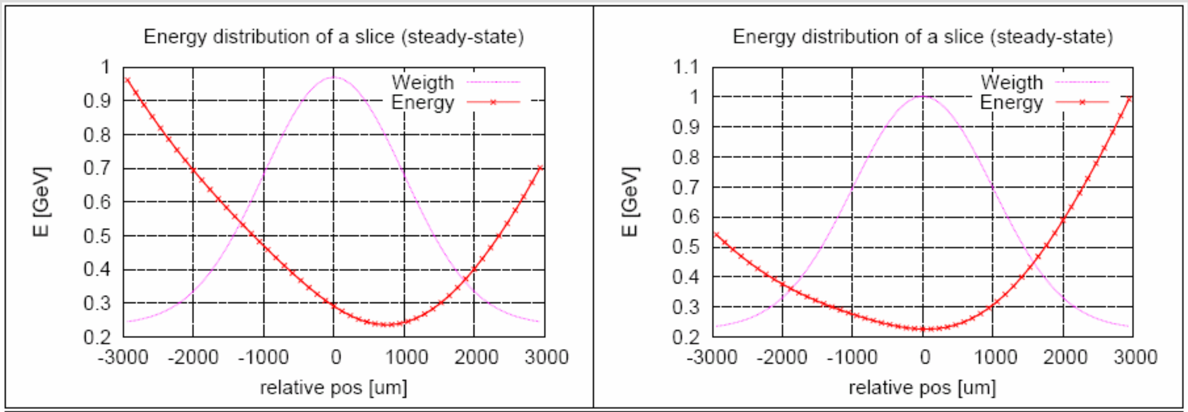
SB has shifted point of most dec. particle. Û relatively larger and therefore also E (for a given S)

Practical implications if sb is significant :

- $\eta = SF(\lambda)\eta_{dist} < SF(\lambda)$
- For a given S, $E = \Delta\hat{E}N/S$, where $\Delta\hat{E}$ must be found PLACET routines

Detuning

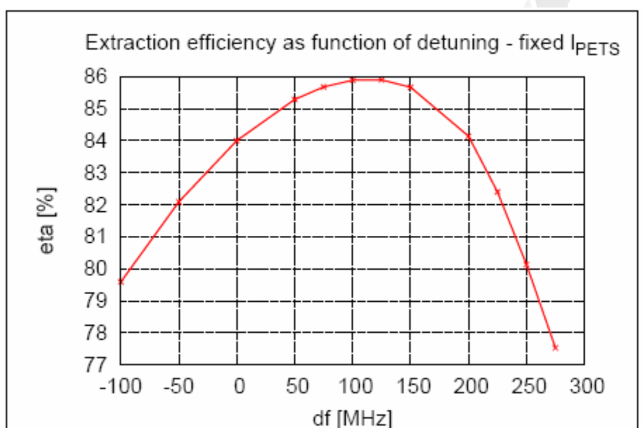
- The effect of single-bunch wake can be compensated by detuning the longitudinal mode frequency



$\Delta f = 0$ (no detuning) | $\Delta f = 125 MHz$ (optimum)

(not most recent parameters)

- Efficiency "corrected" with detuning, and increases towards η = SF(λ)

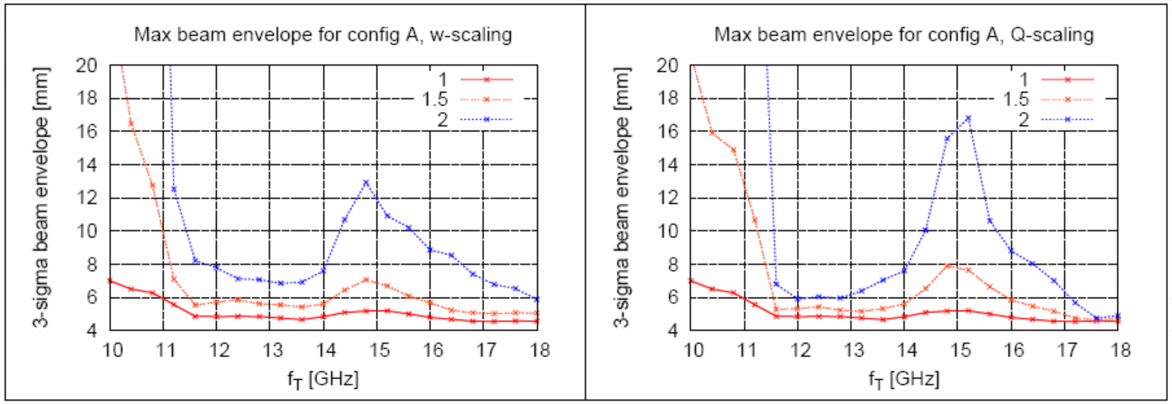


η as function of Δf - FIXED l_{PETS}

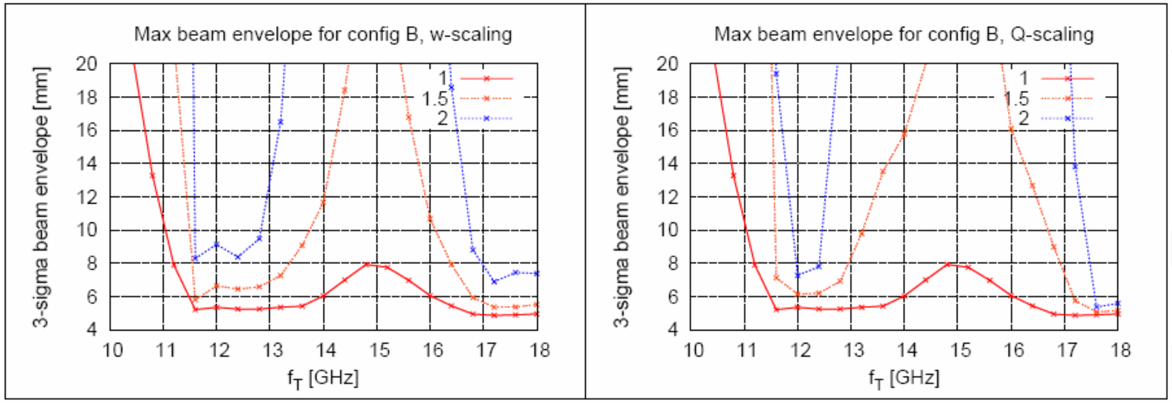
(not most recent parameters)

Detuning

- However, beam stability shown to be significantly worse due to more coherent wake build-up



No detuning, $d = 25mm$ — No detuning, $d = 25mm$



Optimal detuning, $d = 25mm$ — Optimal detuning, $d = 25mm$

(not most recent parameters)

Summary: power parameters

- Dependences:

Parameters of interest for power production

(list not exhaustive, e.g. σ_z, F ...)

P	135 MW	PETS steady state power output
E	2.4 GeV	Initial beam energy
S	90.0 %	Max. final energy spread
I	95 A	Current
L_{PETS}	0.23 m	PETS length
η	85 %	Power Extraction Efficiency coefficient
λ_L	25.0 mm	Longitudinal mode wavelength (detuning)

7 parameters. Various dependencies leaves only 4 free parameters.

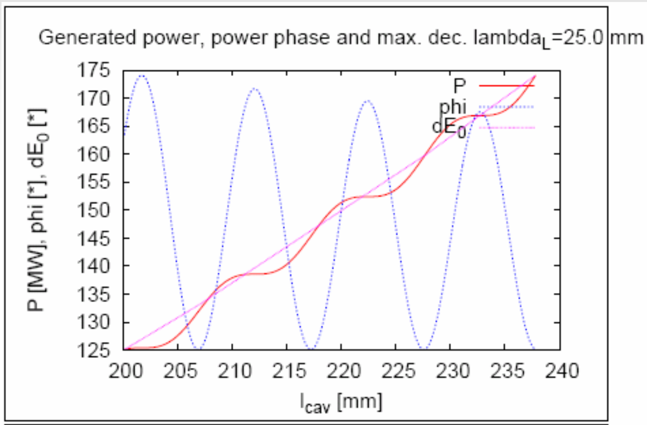
E.g. if we choose P, S, L_{PETS},λ_L then I, E and η is **given.**

Or, if we choose P,S,E,$\eta = \eta_{max}$ then I, L_{PETS} and λ_L is **given.**

- This can now be used to study the effect of changes parameter variation to the beam
- But first: some single particle dynamics to link power extraction to transverse dynamics

Power: the effect of discrete charge

- Model dependent "problem"?
- Calculated extracted Power doesn't follow $P \propto L^2_{PETS}$ but has an overlying oscillation
- Comes from the hard-edge PETS model where bunches are chopped out



$(\phi_{min} = 0^o, \phi_{max} \approx 1^o)$

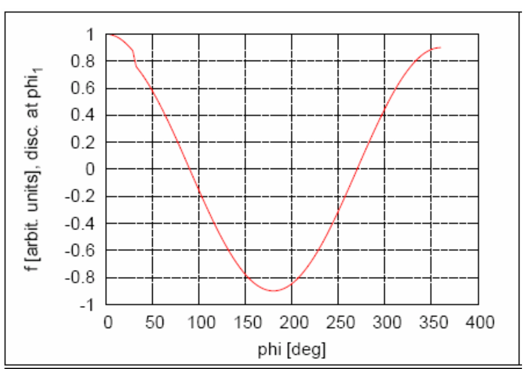
$(n/2)\lambda(1-\beta_g)/\beta_g$

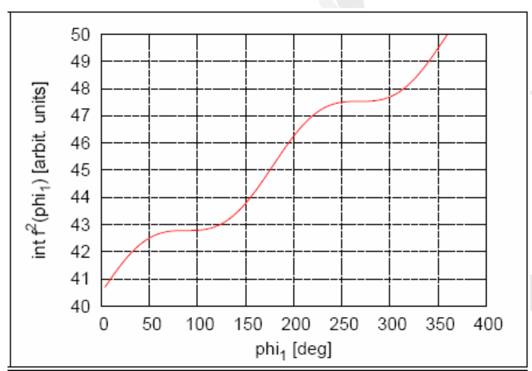
$l_{PETS}[cm]$	$E_0[GeV]$	$I[A]$	$\eta[\%]$
23.3	2.35	93.4	84.9
23.3+0.1	2.35	92.6	**85.6**
23.3-0.1	2.35	94.2	**84.2**

Ultimate effect:

+/-1 σ_z in L_{PETS} has a huge impact on power extraction efficiency (~ impact as detuning)

- This effect can be reproduced by 10 short lines of code





- Questions: is this a REAL effect to take into account, or not? Effect will be "smeared out", but maybe still there?

Single particle dynamics

(beam dynamics ignoring transverse wakes)

Single particle dynamics - I

FODO focusing

- Constant FODO phase-advance for the most decelerated particles

- **Least decelerated particles** will have a larger phase-advance, and beta (but still be focused)

$$\sin\phi/2 = L/2f \Rightarrow \sin\phi/2 \propto 1/p$$

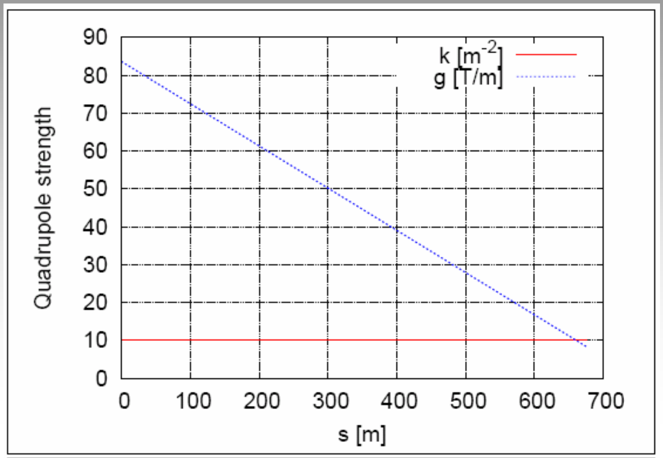
$$\Rightarrow \frac{\sin 90/2}{\sin\check{\phi}/2} = \frac{2.4}{0.24} \Rightarrow \sin\phi/2 = \frac{1}{10}(\frac{1}{2}\sqrt{2}) \Rightarrow \check{\phi} = 8^o$$

Adiabatic undamping

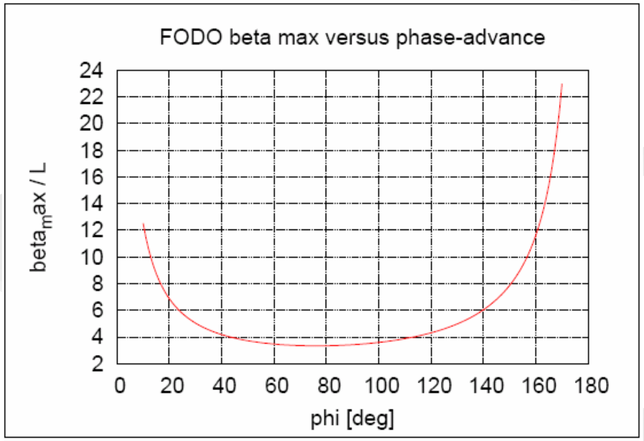
- **Most decelerated particles** will be have emittance growth due to adiabatic undamping

$$y' = y_0'(\frac{1}{1+\delta}), \delta = -\frac{\Delta\hat{E}}{E}$$

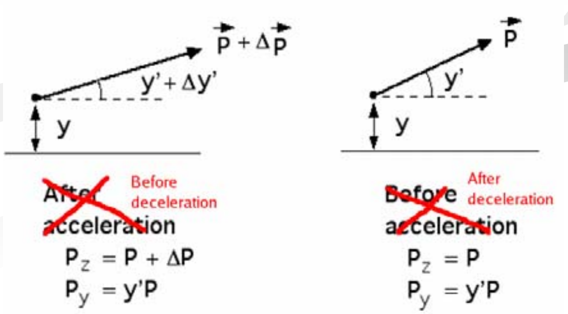
$$\varepsilon_1 = \frac{E_0}{E_1}\varepsilon_0$$



Quadrupole strength along the lattice

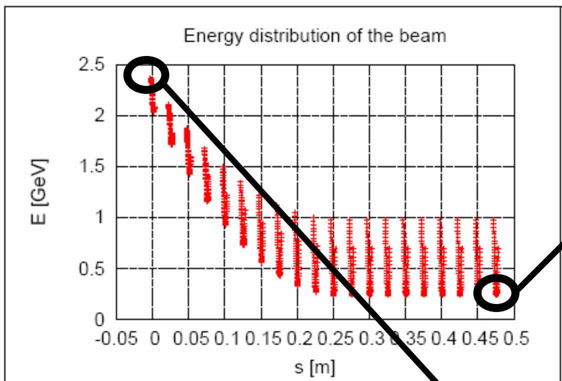


β

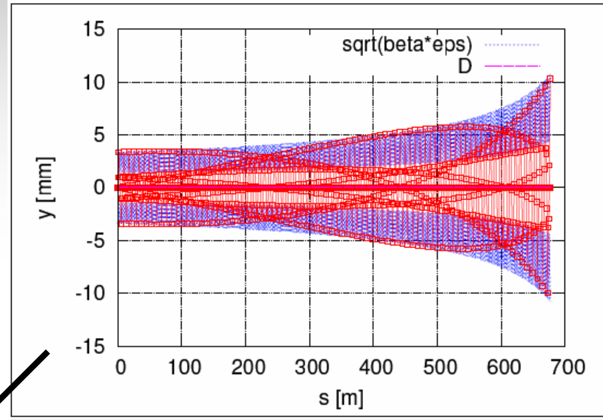


Single particle dynamics - II

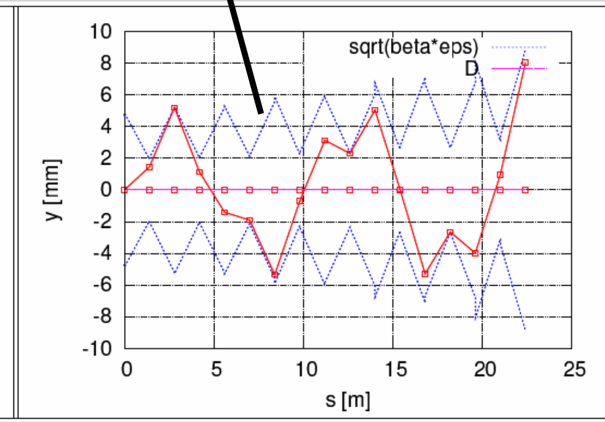
Behavior of least and most decelerated particle in CLIC and TBL (w_T=0)



$\sqrt{(\beta\varepsilon(s))}$

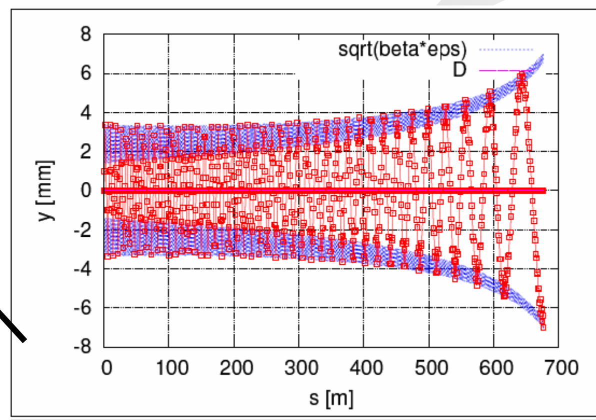


Most decelerated particle, CLIC, $\sigma = \sqrt{\beta\varepsilon(s)}$ $(w_T = 0)$

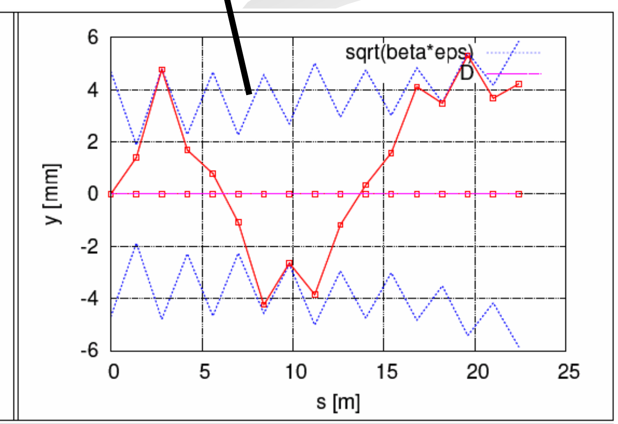


Most decelerated particle, TBL, $\sigma = \sqrt{\beta\varepsilon(s)}$ $(w_T = 0)$

$\sqrt{(\beta(s)\varepsilon)}$



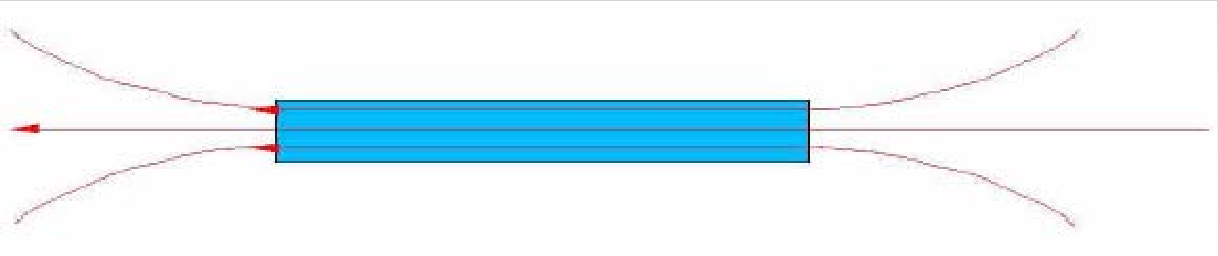
Least decelerated particle, CLIC, $\sigma = \sqrt{\beta(s)\varepsilon}$ $(w_T = 0)$



Least decelerated particle, TBL, $\sigma = \sqrt{\beta(s)\varepsilon}$ $(w_T = 0)$

RF kicks

- RF focusing edge-kick are implemented in the model



- Gauss' laws gives the kick at entrance and exit :

$$\Rightarrow \Delta y' = \frac{e}{E}\int E_y ds = \frac{e}{E}\frac{g}{2}\frac{y}{l}l = \frac{g[V/m]}{2E[V]}y$$

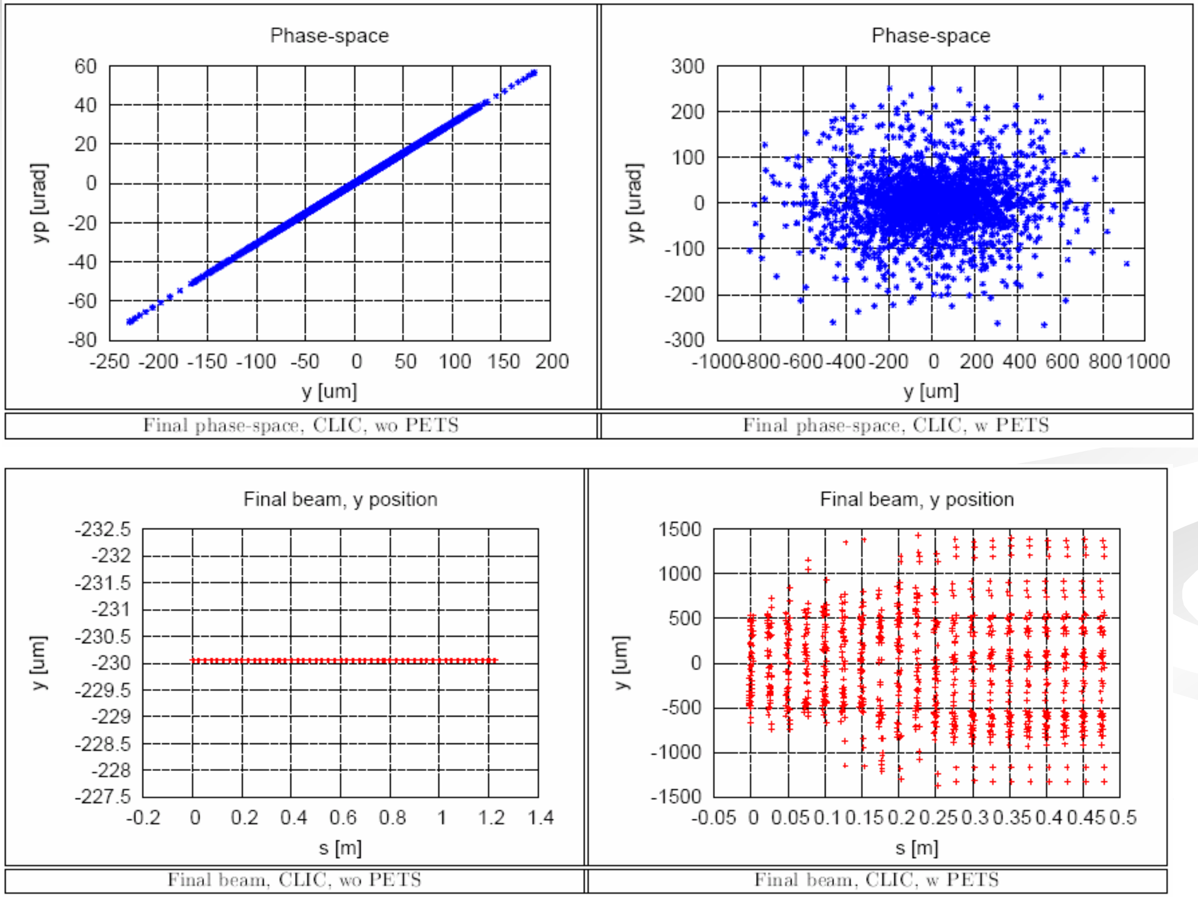
- Opposite sign, so cancels to first order :

$$\begin{bmatrix} y \\ y' \end{bmatrix} = \begin{bmatrix} (1+AL) & L \\ -A^2L & (1-AL) \end{bmatrix} \begin{bmatrix} y \\ y' \end{bmatrix}_0, A = \frac{g[V/m]}{2E[V]}$$

$\rightarrow$ Effect very small for our parameters

Chromatic effects

- The chromatic effects due to the huge energy spread (spread in phase-advance) leads to complete dilution of the phase space



Final phase-space, CLIC, wo PETS | Final phase-space, CLIC, w PETS

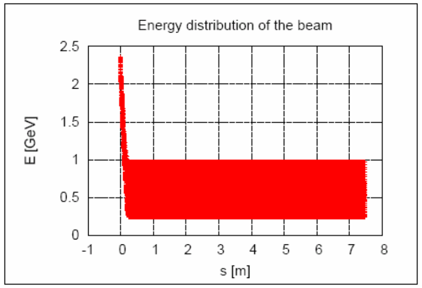
Final beam, CLIC, wo PETS | Final beam, CLIC, w PETS

- Together with huge spread → challenges for instrumentation?

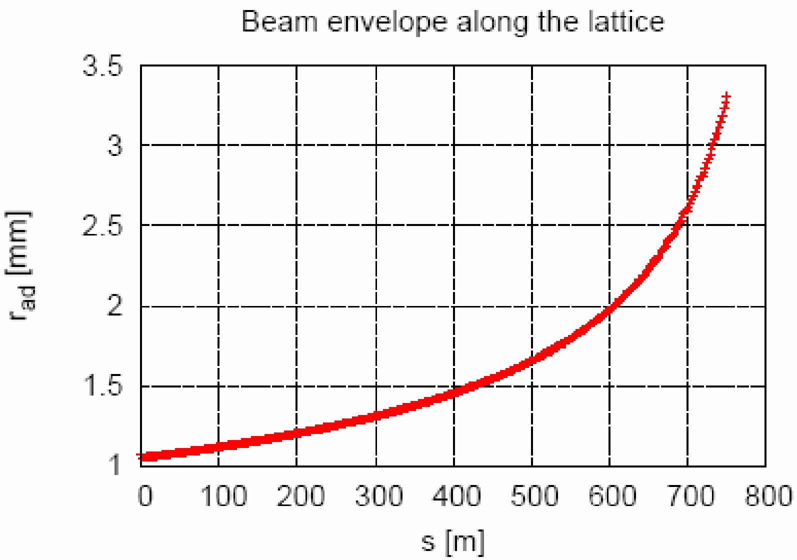
Metric: 3-sigma beam envelope

- Requirement: transport along the whole lattice with **very small losses**
- **Metric**: 3-sigma beam envelope, **r**
- **r** : Worst macro particle drives envelope, along lattice, for 90 out of 100 worst machines (if applicable)
- A significant part of the beam envelope increase along the lattice comes from the ad. undamping alone. It is therefore useful to define the 3-sigma envelope for a perfect machine and perfect beam, $\mathbf{r_{ad}}$

$$r_{ad} = \sqrt{3^2 \sigma_x{}^2 + 3^2 \sigma_y{}^2} \approx 3 \cdot 2 \sqrt{L_{FODO/2} \frac{\varepsilon_N}{(1-S)E}}$$



Metric: the transient head is only ~0.3% of beam, but new head grows if cut → must be taken into account



Variation in current and energy

What happens if the incoming current/energy varies by some percent (everything else kept the same)?

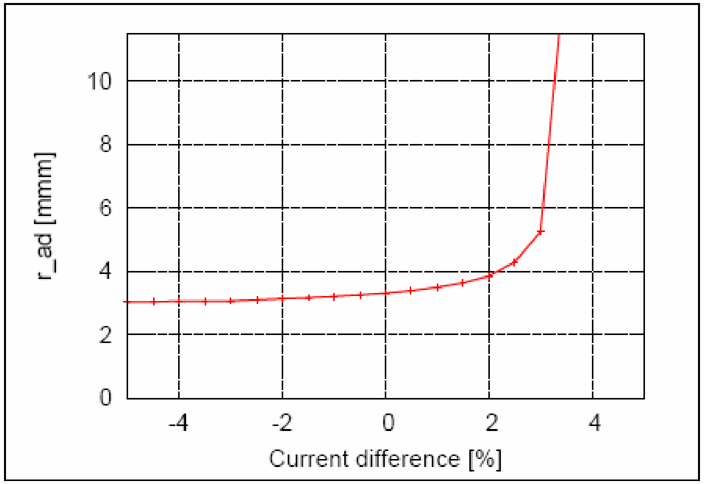
What happens to beam if the current is off by some %?

$$\sin(\phi/2) \approx L/2f \propto 1/E$$

$$(E - \check{E}) = N\Delta\hat{E} \propto I$$

$$\frac{\sin(\phi_0/2)}{\sin(\phi/2)} = \frac{\check{E}}{\check{E}_0}$$

Stability limit: $\Rightarrow \frac{I}{I_0} = \left(\frac{\frac{E}{E_0} - \frac{\sin(\phi_0{}^0/2)}{\sin(180^0/2)}}{\frac{E}{E_0} - 1}\right) = \frac{10 - \frac{1}{2}\sqrt{2}}{10 - 1} = 1.0325$

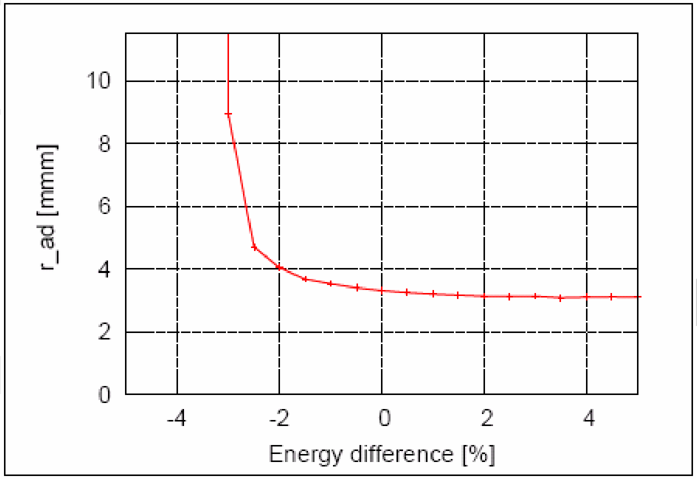


Beam blow-up due to wrong current

What happens to beam if the energy is off by some %?

$$\frac{\sin(\phi_0/2)}{\sin(\phi/2)} = \frac{\check{E}}{\check{E}_0} = \frac{E_0(\frac{E}{E_0} - S_0)}{E_0(1 - S_0)}$$

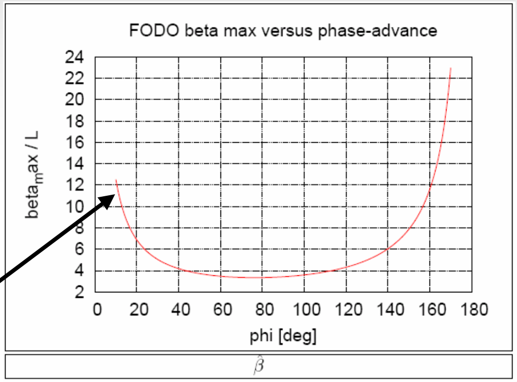
Stability limit: $\Rightarrow \frac{E}{E_0} = (1 - S_0)\left(\frac{\sin(\phi_0/2)}{\sin(180^0/2)}\right) + S_0 = (0.9 + 0.1\frac{1}{2}\sqrt{2}) = 0.97$



Beam blow-up due to wrong energy

Initial energy spread

- What is the main effects of initial uncorrelated energy spread?
- No direct impact on power production
- Energy spread due to deceleration will in any case be much larger
- However, there is some impact on beam stability
  - Can scale down lattice → least decelerated particles even higher beta → reaches single particle envelope of most decelerated particles at ~few percent energy increase
  - After that, energy can be increased to avoid envelope increase, at the cost of extraction efficiency



Rule of thumb: in order to keep beam envlope we must increase energy by a factor:

$$E = E_0 + 3\sigma_E$$

The extraction efficiency goes as 1 / E, so

$$\eta \propto 1/E = 1/(E_0 + 3\sigma_E)$$

giving

$$\frac{\eta}{\eta_0} = \frac{E_0}{E_0 + 3\sigma_E} = \frac{1}{1 + 3\sigma_E/E_0} \approx 1 - 3\frac{\sigma_E}{E_0}$$

→ initial uncorrelated energy spread of more than ~1% σ is bad!

Putting it together

Power extraction and beam envelope

Example 1: Drive Beam energy

*What happens in the Decelerator if we change the Drive Beam energy by a factor **$E=cE_0$**?*

We want to keep **$P=P_0$** (WDS power stays the same), and $\eta=\eta_0$ (don't want to compromise extraction efficiency)

We have the relations: $P \propto I^2 L_{PETS}^2 (\frac{R'}{Q}\frac{1}{\beta_g})$ $\eta = \frac{PN}{IE/e} \propto \frac{I L_{PETS}^2 (\frac{R'}{Q}\frac{1}{\beta_g})}{E}$

Implying for ***$E=cE_0$*, $P=P_0$** and **$\eta=\eta_0$** : $I = \frac{I_0}{c}$ $L_{PETS}^2 (\frac{R'}{Q}\frac{1}{\beta_g}) = c^2 L_{PETS,0}^2 (\frac{R'}{Q}\frac{1}{\beta_g})_0$

The effect on r_{ad} : $\frac{r_{ad}}{r_{ad,0}} = \sqrt{\frac{E_0}{E}} = \frac{1}{\sqrt{c}}$

Increasing E gives also additional positive effects due to both:

- Higher beam rigidity
- Smaller wake

To quantify this, we run simulations with realistic errors and transverse wakes included

Results:

$E=1.2E_0$	$\Rightarrow r_{ad} = \frac{1}{\sqrt{1.2}} r_{ad,0}$	$r \approx \frac{1}{\sqrt{1.3}} r_0$
$E=(1/1.2)E_0$	$\Rightarrow r_{ad} = \sqrt{1.2}\, r_{ad,0}$	$r \approx \sqrt{1.3} r$

Conclusion: increasing/reducing E by 20% decreases/increases the envelope by a factor ~15% (10% without transverse wake amplification)

Example 2: TBL beam envelope

In TBL (PETS and lattice fixed), if we can't get the beam through (r too high), and if we have freedom in both I and E, how do we decrease r while keeping η as large as possible?

We have the relations: $r \propto \sqrt{1/(E-aI)}$ $\Rightarrow \frac{E-aI}{E_0-aI_0} = (\frac{r_0}{r})^2$ **and** $\eta = \frac{PN}{EI} \propto \frac{I}{E}$

$\Rightarrow \frac{E}{E_0} = (1-S_0)(\frac{r_0}{r})^2 + S_0$ $\Rightarrow \frac{I}{I_0} = (1-1/S_0)(\frac{r_0}{r})^2 + 1/S_0$ $\Rightarrow \frac{\eta_{E=E_0}}{\eta_{I=I_0}} = (2-S_0-1/S_0)\times\{(\frac{r_0}{r})^4 - (\frac{r_0}{r})^2\} + 1$

Putting in some numbers: $E = 120MeV,\ I = 30A,\ P = 159MW,\ r = 15.7mm$

$$\frac{r}{r_0} = \frac{11.5}{15.7} = 0.73$$

$$\Rightarrow \frac{\eta_{E=E_0}}{\eta_{I=I_0}} = (2-S-1/S)\times\{(\frac{r_0}{r})^4 - (\frac{r_0}{r})^2\} + 1 = 0.87$$

I=I$_0$: $\Rightarrow \frac{E}{E_0} = (1-S)(\frac{r_0}{r})^2 + S = 1.21$

$$\frac{\eta}{\eta_0} = \frac{E_0}{E} = 0.82$$

sim with wakes: $r = 10.3$

E=E$_0$: $\Rightarrow \frac{I}{I_0} = (1-1/S)(\frac{r_0}{r})^2 + 1/S = 0.72$

$$\frac{\eta}{\eta_0} = \frac{I}{I_0} = 0.72$$

sim with wakes: $r = 10.2$

Conclusion: for the same beam envelope increasing E is signif. better (in addition P is kept)

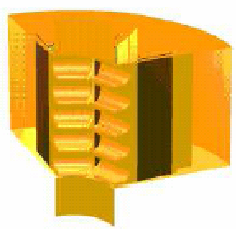
PETS transverse wakes

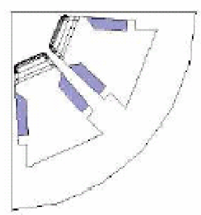
envelope growth due to transverse wakes

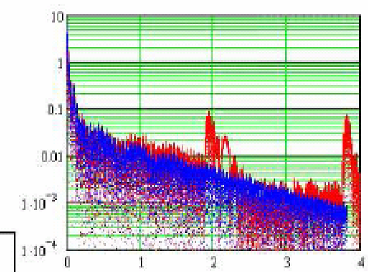
PLACET input: dipole wake function

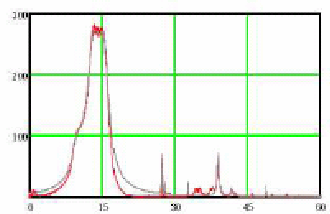
- PETS are modelled with GdfidL (I. Syratchev)

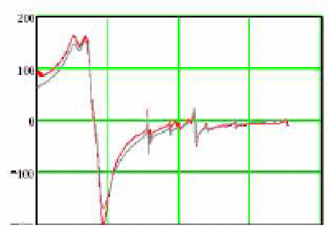
- For a given PETS structure, the transverse δ-wake / impedance is calculated



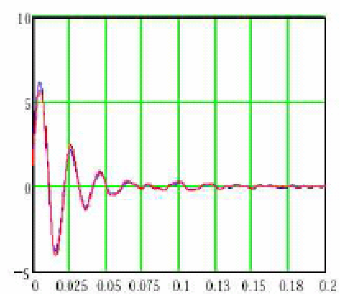








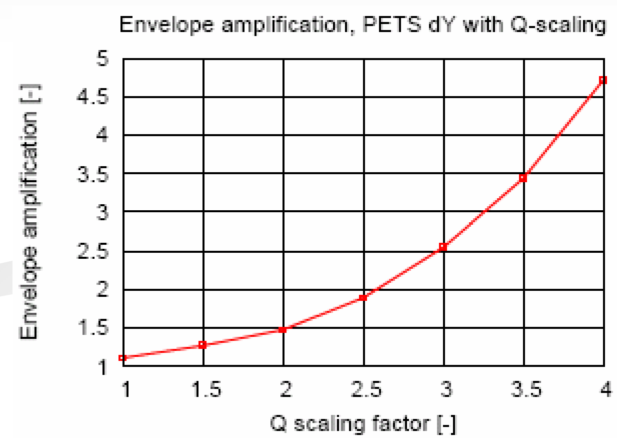
W_T	Q	F
0.045	300	27.44
0.019	180	28.05
0.017	290	32.912
0.2	85	39.12
0.03	120	41.83
0.015	380	48.91
0.85	3.7	10.0
4.82	3.8	13.4
2.63	6.2	15.46

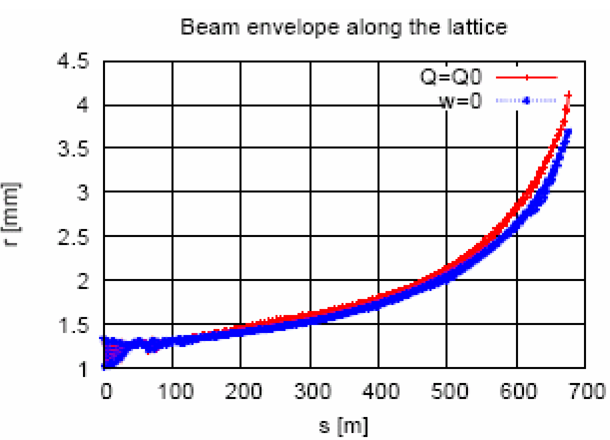


Slide: I. Syratchev

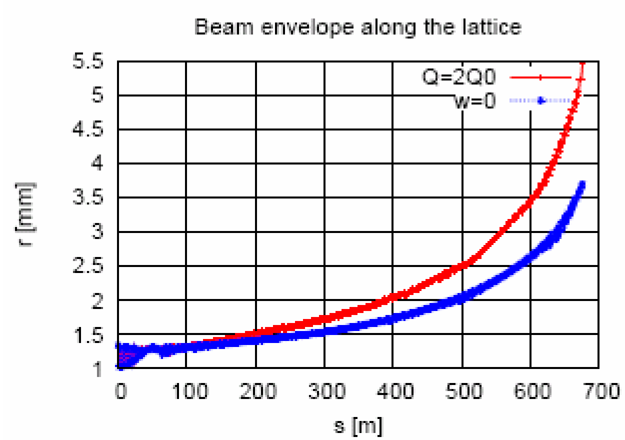
Goal: transverse wakes should not amplify beam jitter

- 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)
- For the PETS design a number of simulations has been run (work with I. Syratchev)
- Current PETS design: basically no problem for *nominal* PETS parameters (both CLIC and TBL lattice checked)
- Amplification is the average of the 9 modes

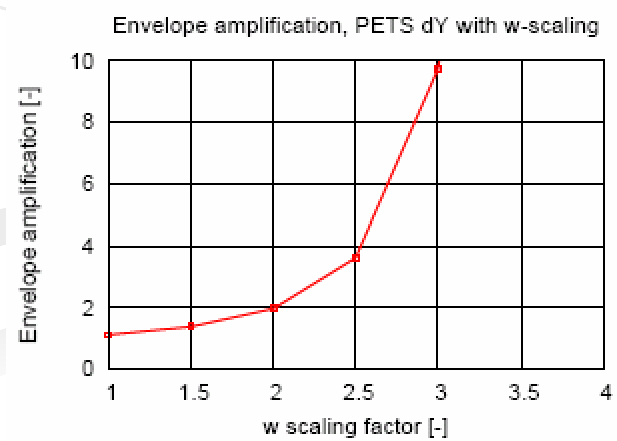




$Q=Q_0$

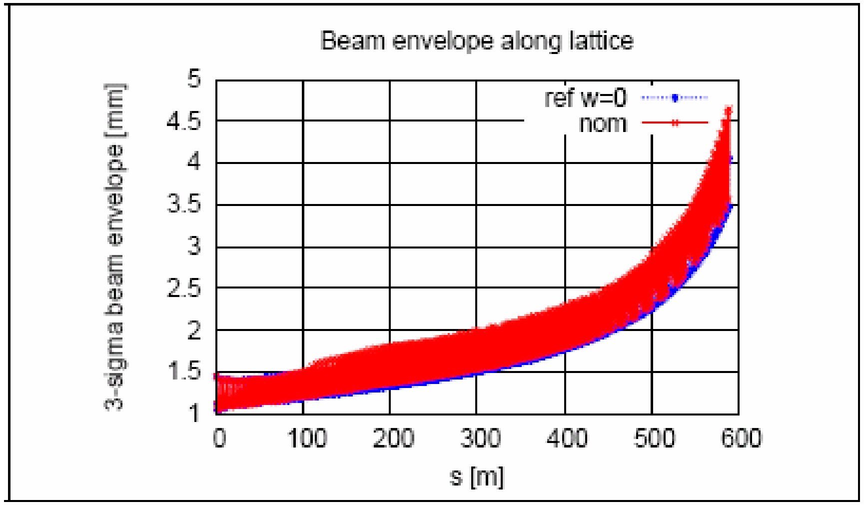


$Q=2Q_0$

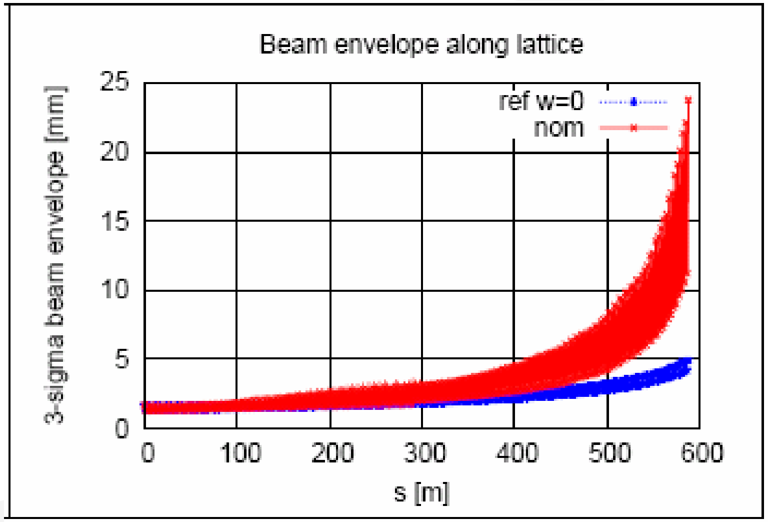


Why so tight focusing?

- We have FODO half-cell length of 1 m
- Are all these expensive quads really needed?
- Example: CLIC β_0 versus $1.5\beta_0$ lattice
  - Beam blow-up due to larger wake amplification



4A, Q=1.5Q₀ (1m, no detuning): $r = 4.6mm$



7A, Q=1.5Q₀ (1.5m, no detuning): $r = 23.8mm$

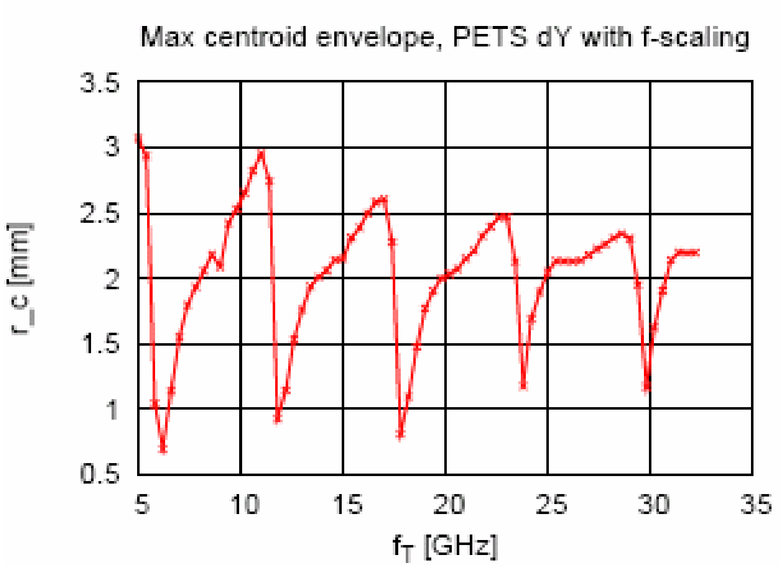
(not most recent parameters)

Dependence on mode frequencies

Beam blow-up depends on z/λ_{T_i}: $\sin(\frac{2\pi}{\lambda_{T_i}} z) = 0 \Rightarrow z = \frac{n}{2}\lambda_T \Rightarrow f_T = \frac{n}{2} 12 GHz$ (zeros)

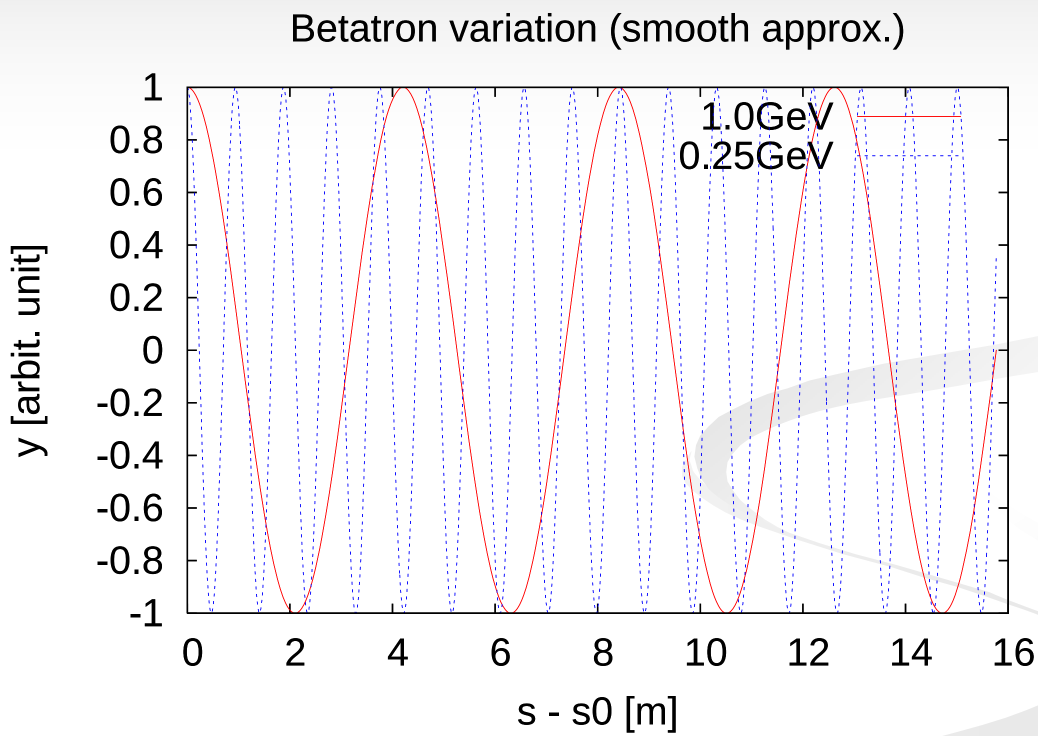
SUM mode, Σw, $\overline{Q}$

$w = 8.3$, $Q = 4.6$



Wake build-up and decoherence

- **Amplification of jitter is actually reduced due to the large energy spread:**



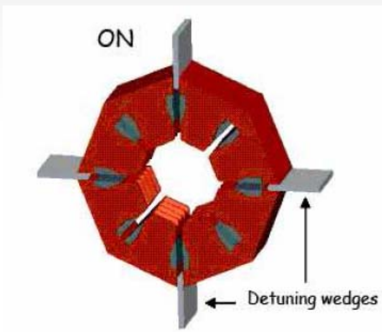
• **Decoherent wake build-up: leads to several times smaller beam-envelope than would be the case otherwise**

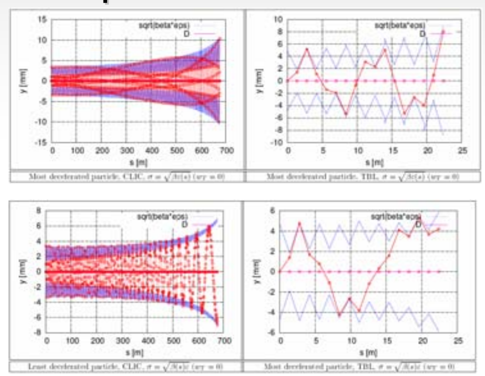
PETS failure scenarios

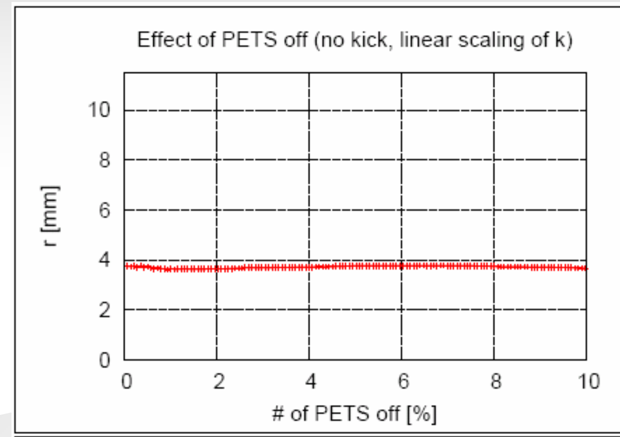
first looks

PETS off

- What happens if a number of PETS are “off” (no field) and lattice is not scaled accordingly? (Quads might not be individually powered)
- Slightly less deceleration → slightly larger betas, but also slightly less ad. undamping
- Simulations: **not a problem** for up to 10% PETS off

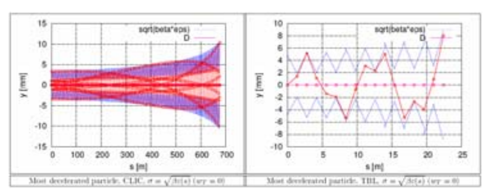


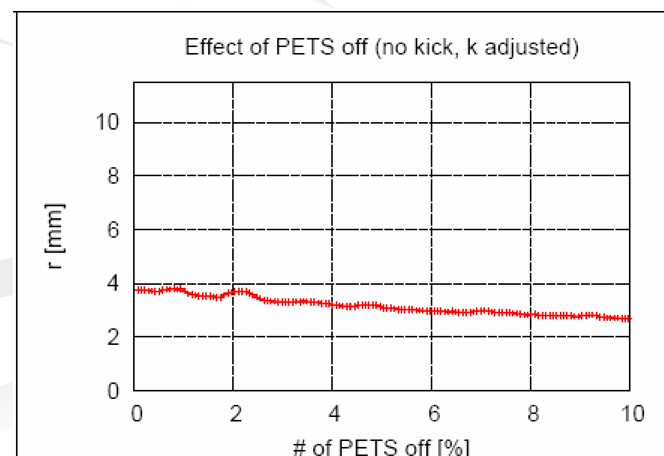




Effect of turning PETS off, quad scaling kept linear

- What if we adjust the focusing to still focus the most decelerated?
  - Constant beta, but slightly less ad. undamping





Effect of turning PETS off, quad scaling adjusted to PETS' off

(Study to be extended, with misalignments etc.)

PETS break down

- PETS break down might lead to significant transverse field components that might kick the beam
- Studies with I. Syratchev; simple model used :

* We assume oscillating transverse field in the PETS

* But, we assume oscillating at 12 GHz, and thus all the bunches are hit at crest (worst case a.)

* finite bunch length: but we assume constant field (worst case a.) -> how many percent wrong? $\cos(\frac{\omega}{c}\sigma_z) = 0.97$

$\Rightarrow$ we model break down field as dipole field, constant along the whole train

* The kick angle is related to the "transverse voltage" as follows

$$\Delta y' = \frac{1}{E}\int F_y ds = \frac{1}{E}\int eE_y ds \equiv \frac{e}{E}U_\perp$$

$$U_\perp[V] = \Delta y' \times E[eV]$$

Criterion

* We now ask the question: **what is the maximum transverse voltage we can accept, at a given location in the lattice, in order to have a maximum resulting centroid envelope increase of $r = 1mm$?**

We assume worst case assumption for the break down kick:

- kick happens close to $\beta = \beta_{max}$
- initial perfect beam (corresp. to kick at worst place on phase-space ellipse)

Voltage tolerances without wake amplification

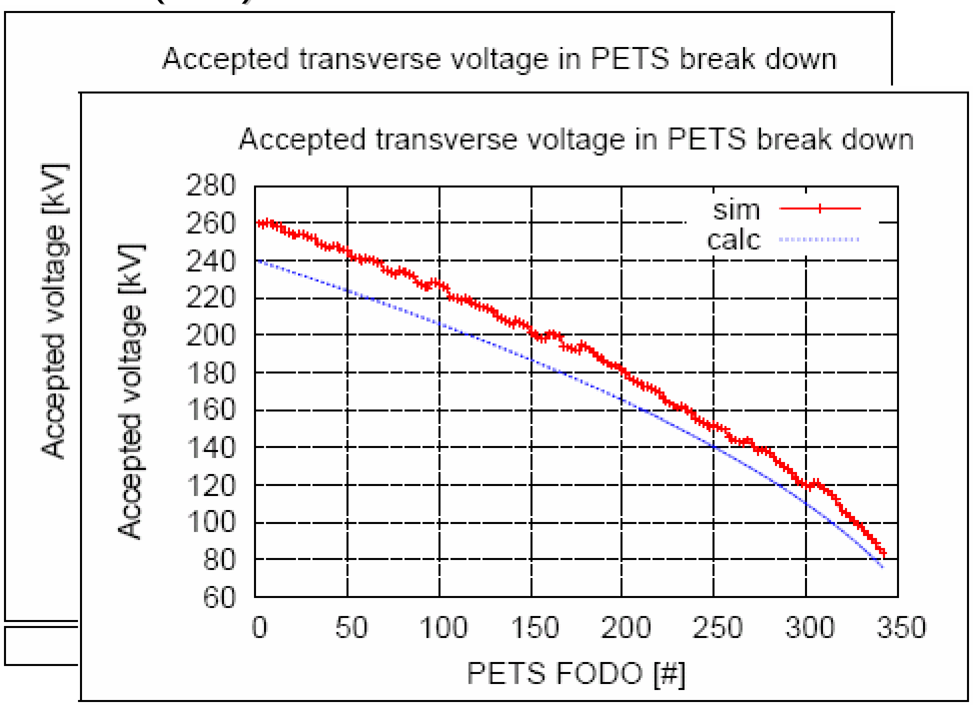
- General estimate

$$U_\perp = \Delta y' \times E = \frac{r}{A\widehat{\beta}} / \sqrt{\frac{E_i}{E_f}} \times E_i = \frac{r}{A\widehat{\beta}} \sqrt{E_i E_f}$$

E_i: energy of most dec. particle at point of kick

- Analytical formula (A=1) versus simulation without transverse wakes:

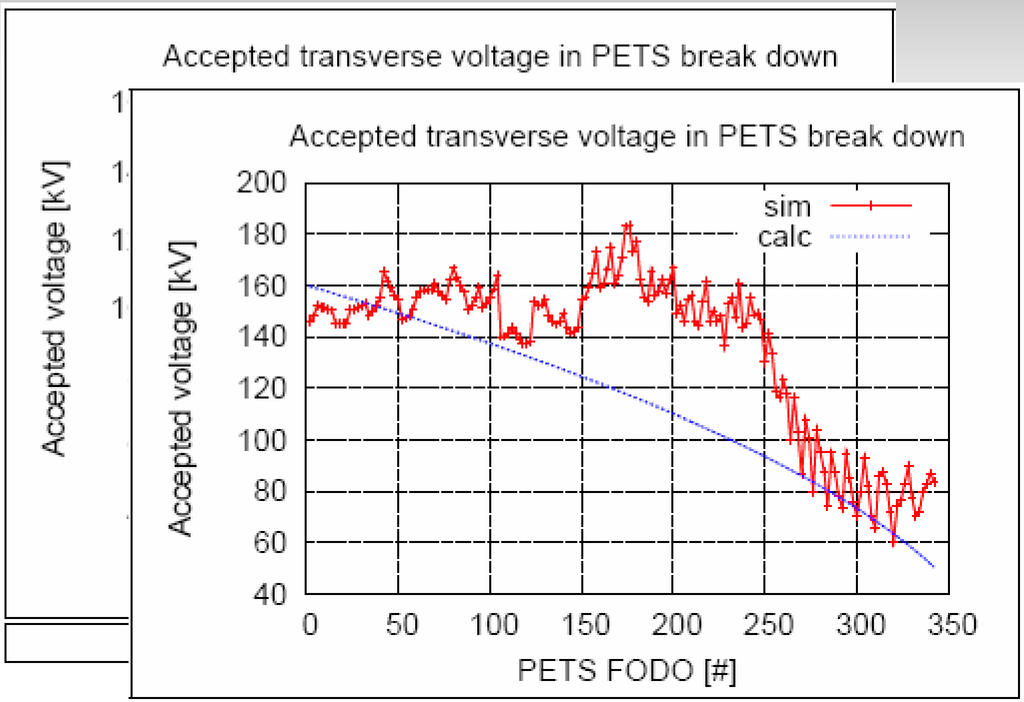
A=1



Voltage limit, simulations ($w_T = 0$)

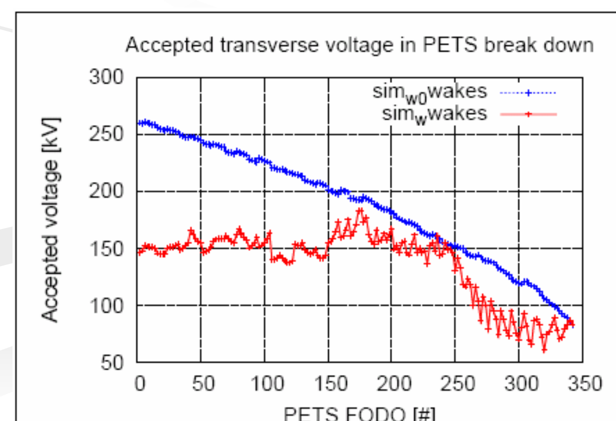
Voltage tolerances including wake amplification

- Analytical formula, we estimate A=1.5, (based on other simulations)



Voltage limit, simulations

(Plot comparing simulations w/ and w/o wakes)

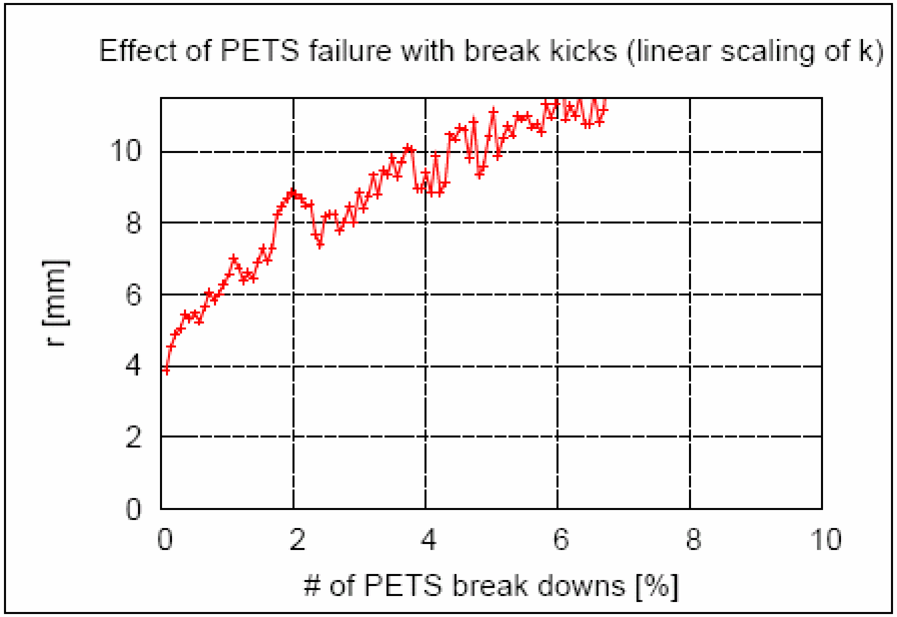


Voltage limit, simulations

Prelim. conclusions: values of ~150kV seems to acceptable at the start of the lattice, and ~50kV towards the end of the lattice.

Effect of multiple break downs

- With this model, assuming a break down field of 100kV, in an arbitrary direction, we can observe the expected √-increase of stochastic kicks



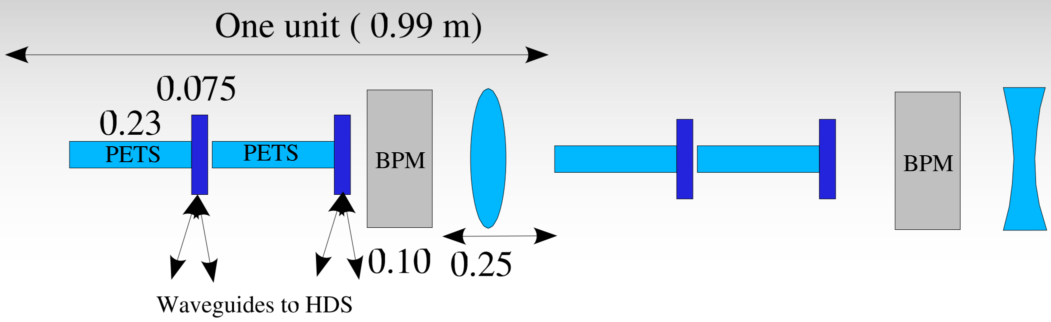
Effect of PETS break kick (quad scaling linear)

(Study to be extended)

Misalignment and tolerances

Machine misalignments

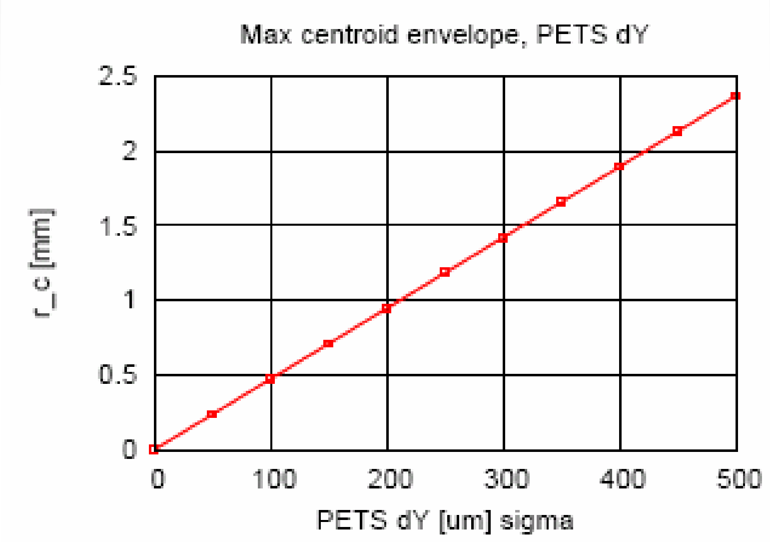
- Study of **the effect of misalignment** of machine components → tolerances

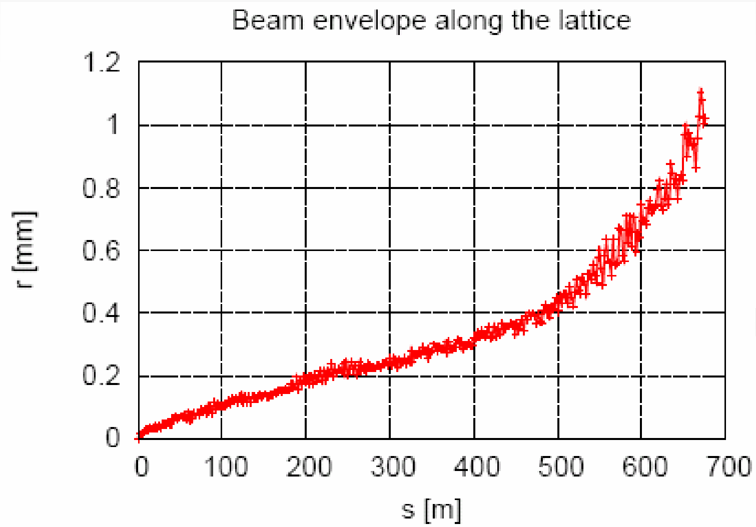


- Each misalignment type (PETS, Quads) studied separately
- The initial beam will be assumed on the reference trajectory
- **Misalignment metric**: misalignment will affect the macro particle centroid motion. As metric here the envelope of the centroids (outmost particle), r_c , will be used (total 3-sigma beam envelope will be: $r = r_{ad}$ "+" r_c (the "+" is only in worst case a real +)
  - 100 random machines simulated for each case, and r_c is then defined as max. envelope along lattice of 90 out of 100 worst machines.
- **Tolerance criterion**: a misalignment should not add more than 1 mm beam offset → $r_c < 1$ mm

1) Position offset of PETS

- A PETS off axis will induce transverse kicks (dipole wake $\propto y_{source}$ wrt. PETS)
- We scatter the PETS in y: σ_{PETS} = {50 ... 500}µm





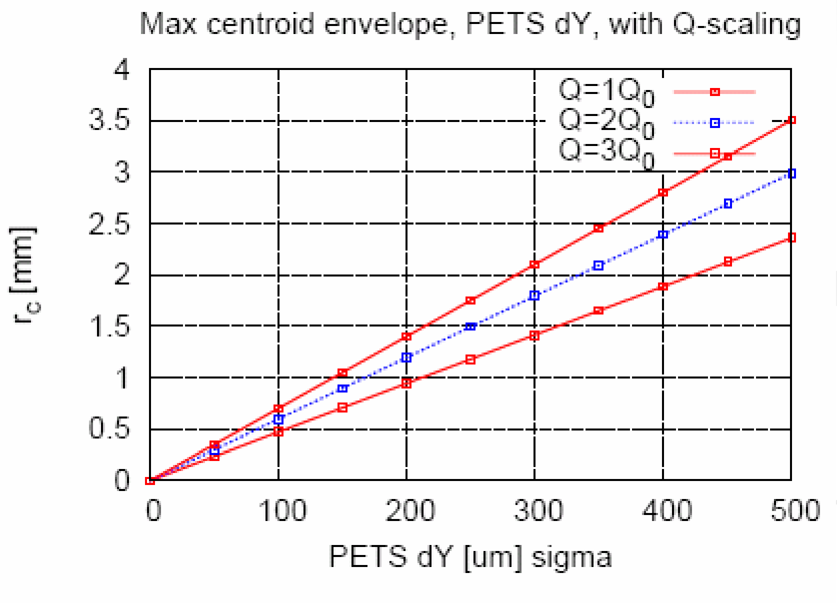
(r for σ_{PETS} < 200 mm, 100/100 machines)

- Prelim. criterion: centroid envelope < 1 mm

  $\Rightarrow \sigma_{PETS} < 200\ \mu m$

Position offset of PETS with Q-scaling

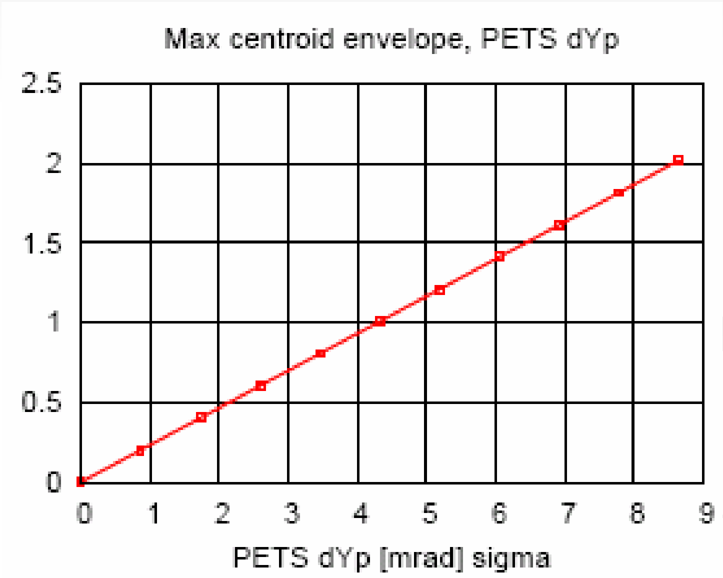
- Also interesting to see effect of larger Q in this scenario (previous PETS simulations imply that the effect should not be drastic)



→ with margin on Q: ⇒ **σ_{PETS} < 100 mm**

2) Angle offset of PETS

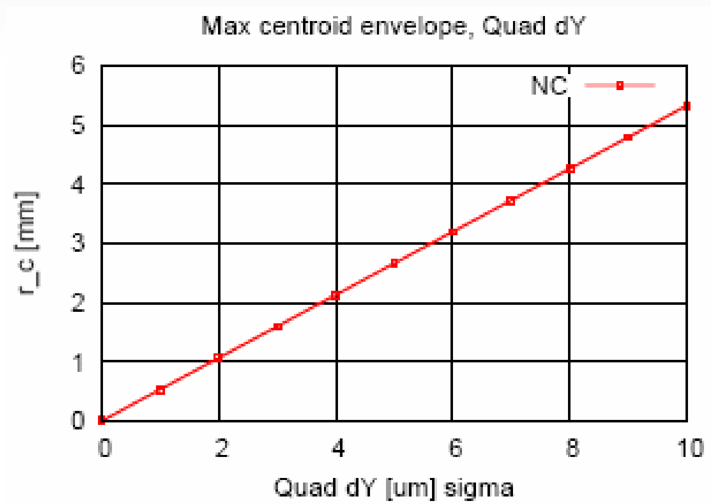
- An angle offset (around x,y) of the PETS centre should basically have the same effect as the corresponding position offset, $\sigma_{PETS,\theta} = (\sigma_{PETS} / 0.5 l_{PETS})*2$. Just to confirm:



- Prelim. criterion: centroid envelope < 1 mm
  $\Rightarrow \sigma_{PETS,\theta} < 4$ mrad
- (An angle offset around s: negligible effect)

3) Position offset of quadrupoles

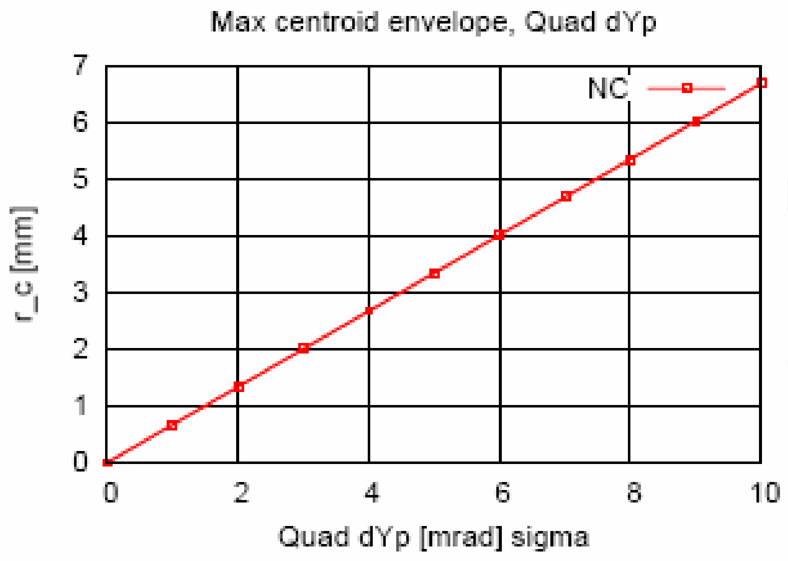
- Offset of quads will induce a dipole kick
- We scatter the quads in y: σ_{quad} = {1 ... 10}μm



- We see that without correction we should require a final pre-alignment σ_{PETS} < 2 μm (not feasible)
- Solution: beam-based alignment (BBA)

4) Angle offset of quadrupole

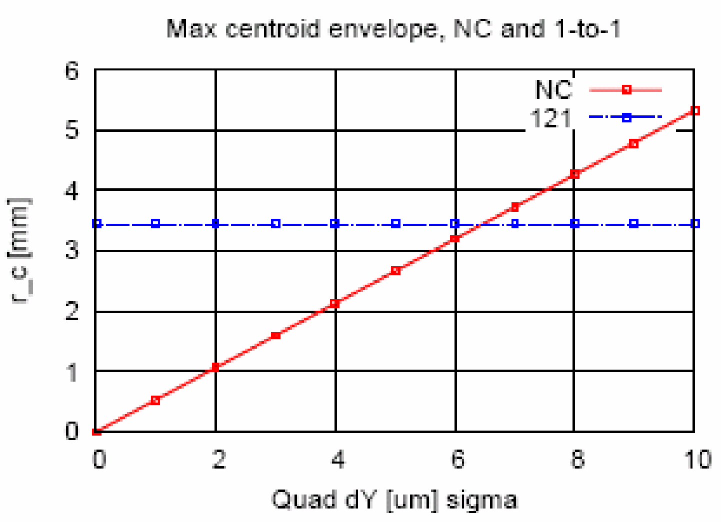
- A small rotation around s (skew quadrupole) will have negligible effects for the 8 FODO cell lattice in question
- A small rotation around x, y (pitched quad) expected to have very small effect (integrated force ≈0)
  - Pitch angle around y: $\sigma_{quad,\theta}$ = {0 ... 10}mrad .



$\Rightarrow \sigma_{PETS,\theta} < 1$ mrad

BBA for quads: 1-to-1 correction

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



σ_{BPM} = 20μm

- Effectively: **quad position error σ_{quad}, is transferred to BPM position error σ_{BPM}**
- However, still quite large envelope (much larger than ~σ_{BPM} due to the diluted phase-space)
- 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 trajectory") 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 $E_1=0.8\times E_0$
- Effectively: **quad position error $\sigma_{quad,}$ is transferred to BPM resolution error σ_{res}**

BBA for quads: dispersion free steering

- Due to finite BPM resolution, the difference in test-beams must be weighted against the absolute reading of the BPMs

- Thus, we want to minimize a weighted metric:

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

This is an overconstrained system. The least squares solution wrt. the correctors, can be found by solving the matrix equations

$$\frac{d\chi^2}{d\theta} = \frac{d}{d\theta} w_0 (\mathbf{y}_0 - \mathbf{R}_0 \Delta\theta)^T (\mathbf{y}_0 - \mathbf{R}_0 \Delta\theta) + w_1 ((\mathbf{y}_1 - \mathbf{y}_0) - (\mathbf{R}_0 - \mathbf{R}_1)\Delta\theta)^T ((\mathbf{y}_1 - \mathbf{y}_0) - (\mathbf{R}_0 - \mathbf{R}_1)\Delta\theta) = 0$$

$$\Rightarrow \begin{bmatrix} \sqrt{w_0}\mathbf{y}_0 \\ \sqrt{w_1}(\mathbf{y}_1 - \mathbf{y}_0) \end{bmatrix} = \begin{bmatrix} \sqrt{w_0}\mathbf{R}_0 \\ \sqrt{w_1}(\mathbf{R}_1 - \mathbf{R}_0) \end{bmatrix} \Delta\theta$$

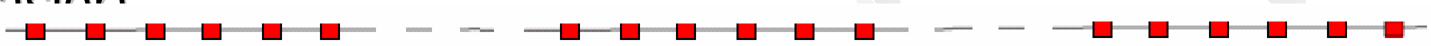
$$\Rightarrow \Delta\theta = \begin{bmatrix} \sqrt{w_0}\mathbf{R}_0 \\ \sqrt{w_1}(\mathbf{R}_1 - \mathbf{R}_0) \end{bmatrix}^\dagger \begin{bmatrix} \sqrt{w_0}\mathbf{y}_0 \\ \sqrt{w_1}(\mathbf{y}_1 - \mathbf{y}_0) \end{bmatrix}$$

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

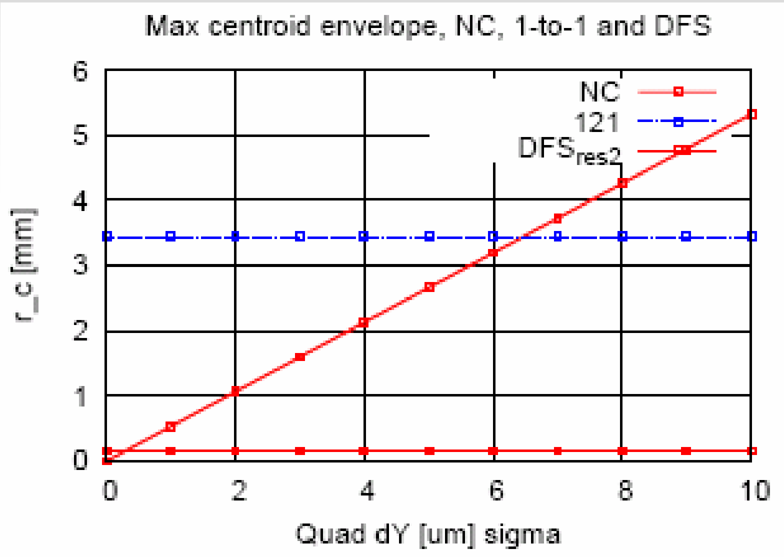
- Trick: we can use a beam with lower current instead! Wakefields will be lower and beam will quickly have higher energy – "**PETS based DFS**"

- Can either reduce bunch charge, or take out a number of bunches (easier)

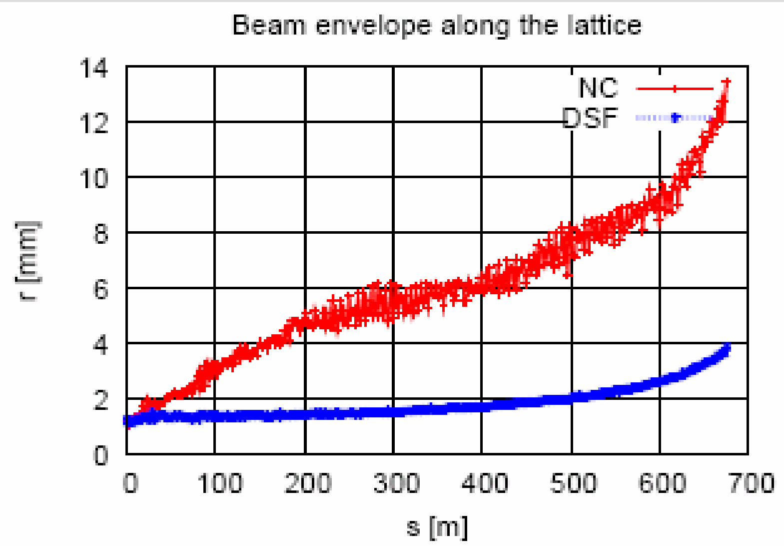


- Results seems to be at least as good as for energy test beam

Dispersion free steering: results

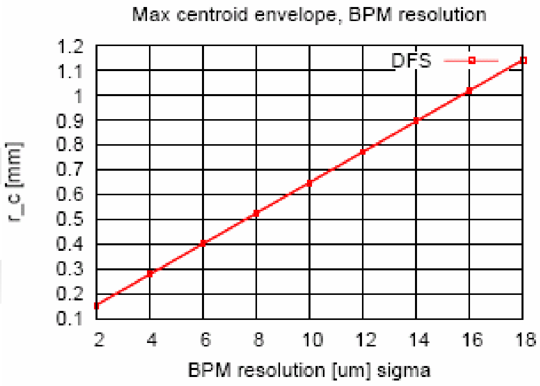


σ_{BPM} = 20μm
σ_{res} = 2μm



Conclusions DFS:

- DFS correction gives very good results for this simulation setup.
- DFS seems to give even better results than 1-to-1 for $\sigma_{BPM} = \sigma_{res}$
  - Not yet completely understood why, but identified to be due to the deceleration



Some conclusions: tolerances

- The previous results, combined with the tolerance criterion (one type of misalignment r_c < 1 mm), implies alignment tolerances for the CLIC lattice elements:

- PETS positioning misalignment : $\sigma_{PETS} \leq 100\mu m$ (allows for some margin in the Q-factor)
- PETS angle error: $\sigma_{PETS-\theta} \leq 1mrad$
- Quadrupole initial positioning misalignment: $\sigma_{quad} \leq 20\mu m$
- BPM positioning misalignment: $\sigma_{BPM} \leq 20\mu m$
- BPM resolution: $\sigma_{res} \leq 10\mu m$
- Quadrupole angle error tolerance is quite high
- Dispersion free steering with reduced current test-beams (eventually other effective beam based alignment schemes) must be applied to the lattice, with initial 1-to-1 corrections

Conclusions and outlooks

Some conclusions

- Starting to have a good understanding of the beam dynamics of the decelerator
  - Missing still: better analytic predictions for the wake amplification (not critical, since simulations can quickly provide the results)
- Using the present model no major problems have been identified so far
  - In any case: in the design one can always “trade” extraction efficiency against beam size
  - Other effects might have to be studied: e.g.non-linearities in lattice, non-linearites in wakes res. wall wake,
  - Alignment tolerance are tight, but less tight than for the main beam
- Beam-based alignment seems to be necessary and possible, but again with looser requirements than for the main beam

Thanks for input from and collaboration with Daniel, Igor, Andrea, JBJ, HB, P. Lacet, +++

~~*"Deceleration? Simple! It's just like acceleration, only the opposite" N.N.*~~

Plans and outlooks for next year

- Connect models and simulations to reality
  - Participation in first TBL PETS tests

- Preparation for full TBL
  - The big question: what can we learn, and what not, from the TBL
  - This requires an in-depth look at beam instrumentation for TBL and CLIC (e.g. influence on measurement from the large energy spread)

- On-going work on analytical models for wake amplification and beam stability

- Plus lots of potential other issues:
  - more PETS break down scenarios / operation scenarios, timing issues, possible improvements of PLACET models, work of PLACET integration with CTF3 etc. etc.