The CLIC Decelerator

Beam Dynamics Requirement for RF and Instrumentation

CLIC Workshop 2008

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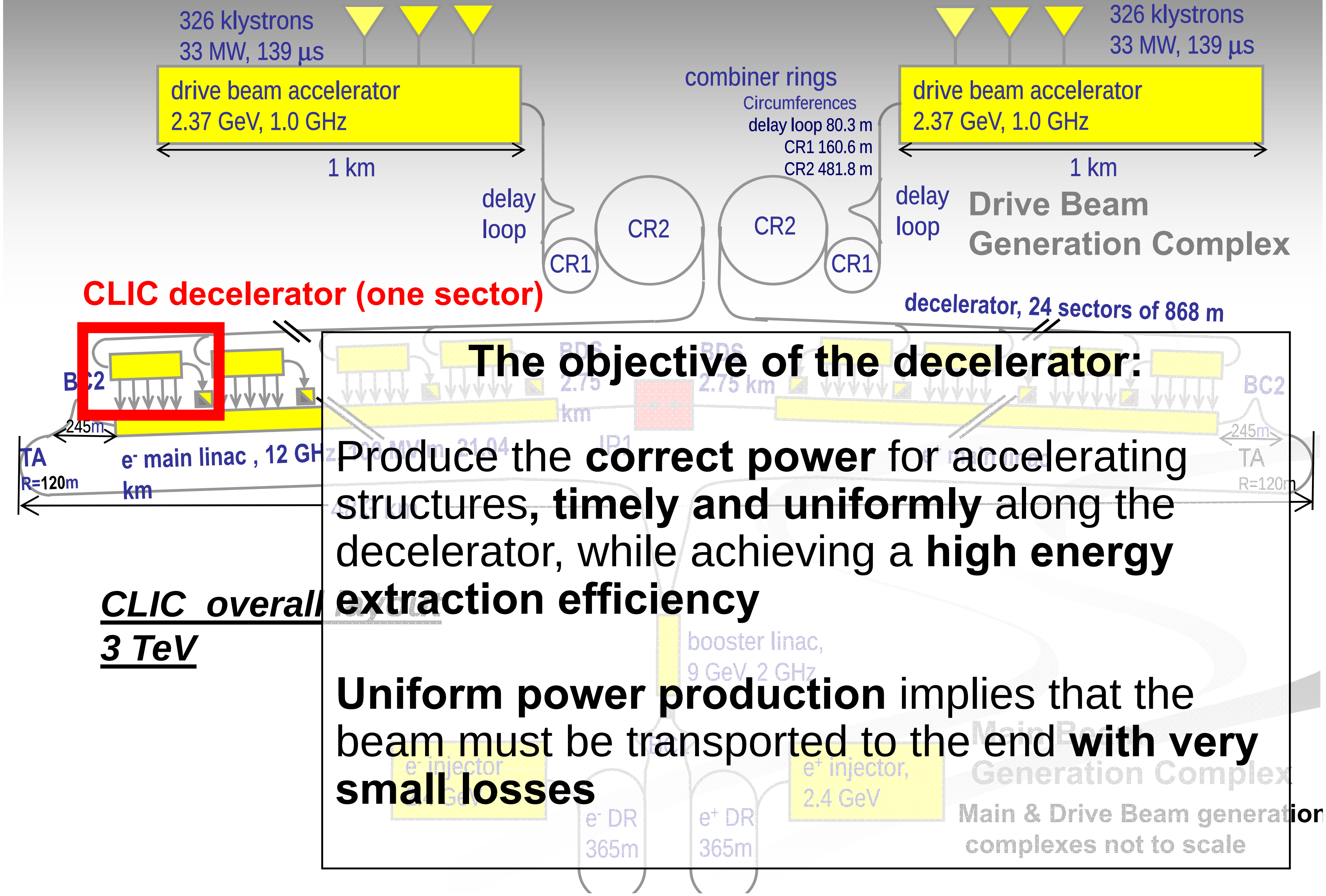
Lots of input by D. Schulte + the rest of the CLIC team is gratefully acknowledged

Outline

- Introduction to the Decelerator
- Longitudinal dynamics
- Transverse dynamics
- Alignment and tolerances
- Instrumentation needs: outlooks

The CLIC decelerator



CLIC decelerator (one sector)

CLIC overall layout
3 TeV

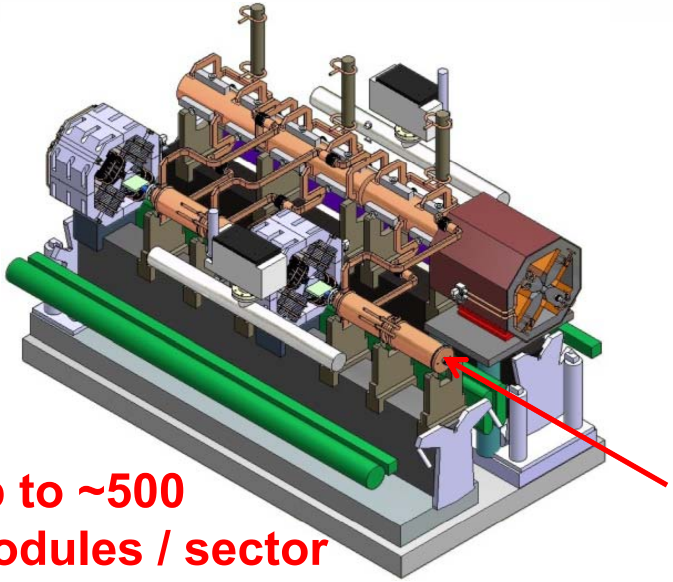
The objective of the decelerator:

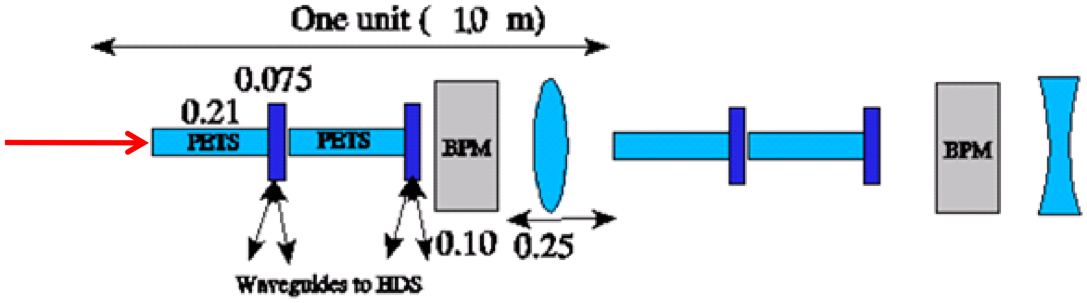
Produce the **correct power** for accelerating structures**, timely and uniformly** along the decelerator, while achieving a **high energy extraction efficiency**

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

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





up to ~500 modules / sector

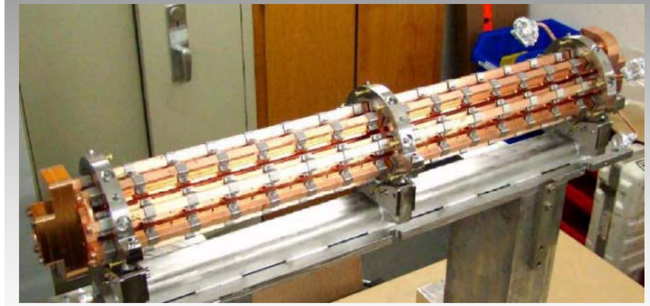
100 A, 2.4GeV

- **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 $\mu \approx 10°$

Longitudinal dynamics

Energy extraction and power production

PETS



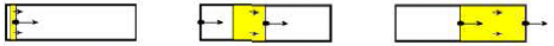
(1 m PETS for TBTS)

PETS 12 GHz fundamental mode:

f=12.0 GHz, R’/Q=2295 Linac-Ohm/m, beta=0.453, Q~7000, L_{PETS} = 21.3 cm

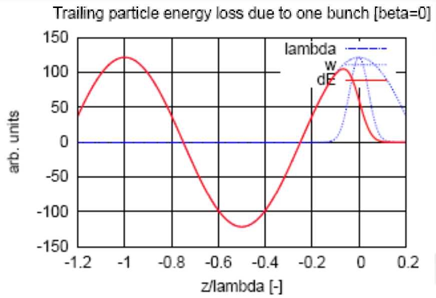
Input to PLACET from PETS design (I. Syratchev): delta wake for fundamental mode for structure with high group velocity.

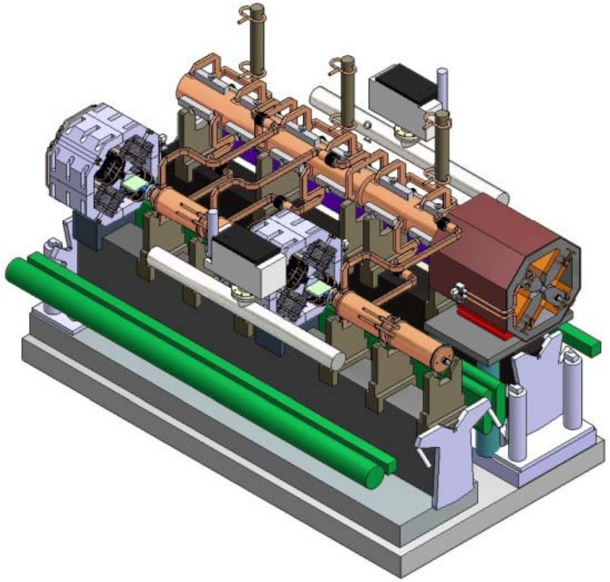
$$w_L(z) = \omega_L \frac{R'}{Q}\frac{1}{1-\beta_L}\cos(\omega_L \frac{z}{c})(L - z\frac{\beta_L}{1-\beta_L})$$

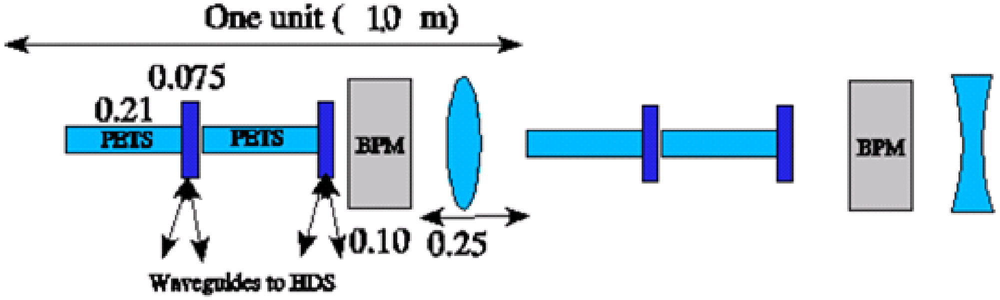


Energy loss: resonantly built up multi bunch wake + noticeable single bunch wake

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







The effect of deceleration

Baseline parameters [2008]:

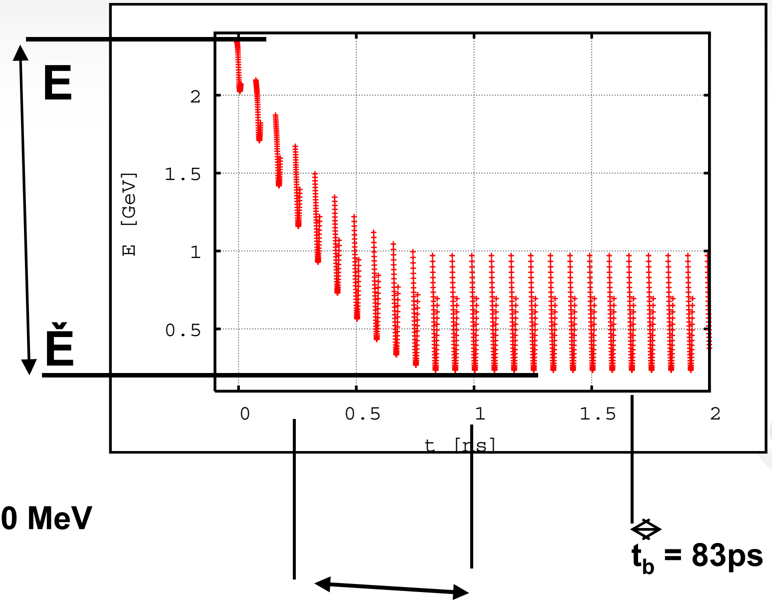
E_0 = 2.4 GeV, I = 101 A, t ≈ 240 ns (2900 bunches)
Gaussian bunch, σ_z = 1 mm,
$\varepsilon_{Nx,y} \approx 150\ \mu m \rightarrow \sigma_{x,y} \approx 0.3$ mm at β_{max} = 3.4 m

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

t_{pulse} = 240 ns

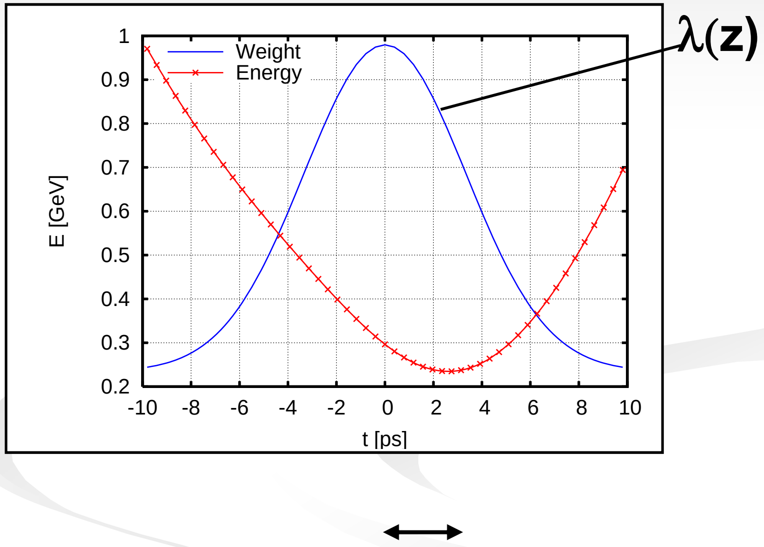
S=(E-Ě) / E
= 90%

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



σ_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***

Transverse dynamics

Sources and mitigation of beam envelope growth

Metrics and criteria

- Because of the minimum-loss requirement we use as **metric the 3-sigma envelope** for the worst particle, defined as :

$$r \equiv \max \sqrt{(|x_i| + 3\sigma_{x,i})^2 + (|y_i| + 3\sigma_{y,i})^2}$$

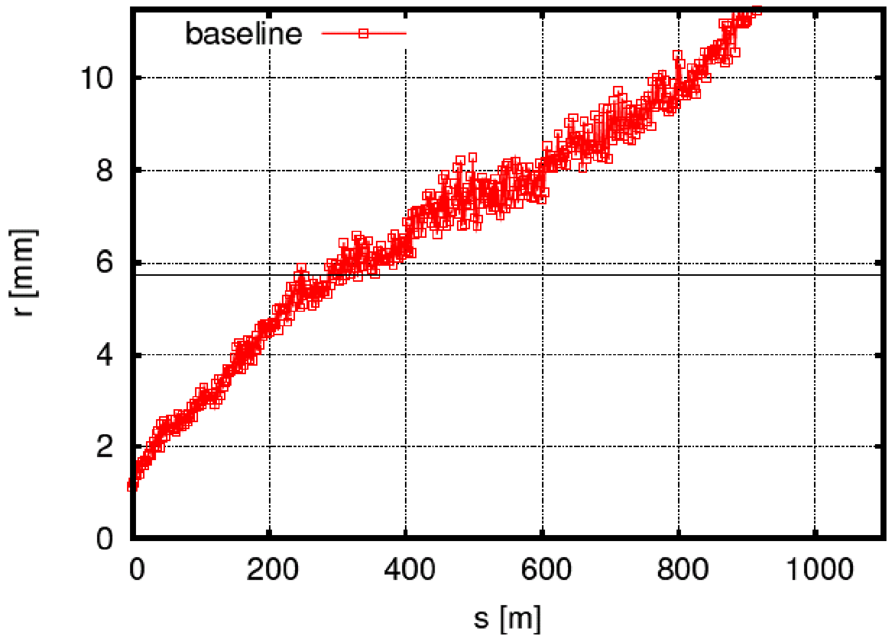
Given for maximum of simulated machines (usually 100)

- **Simulation criterion** for minimum-loss transport: $\boldsymbol{r < \frac{1}{2} a_0}$ =5.75 mm
  - Factor ½ : margin for unmodelled effects (particularly higher-order wake fields!)
  - We require p_{clic}>99%. 50 accelerator sectors ⇒ p_{sector}>99.98% of simulated machines should satisfy this criterion (!)

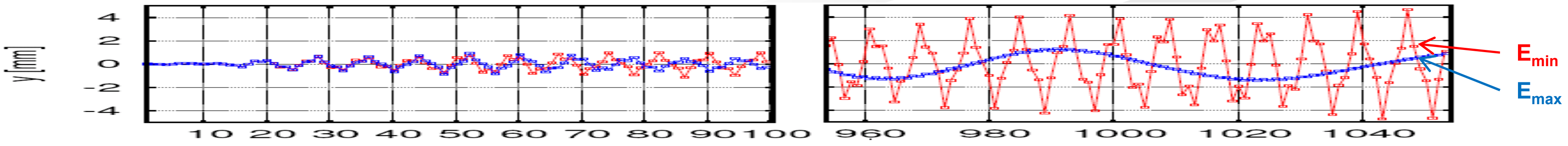
Ideally we want the decelerator to be as robust as a (good) klystron – "push the button, and it should deliver the power!" – thus we approach the study with "worst-case" scenarios

Results: baseline

- Beam envelope, r, along the decelerator sector lattice for baseline parameters, incl. component misalignment as expected after static alignment (baseline: σ_{quad}=20 μm)



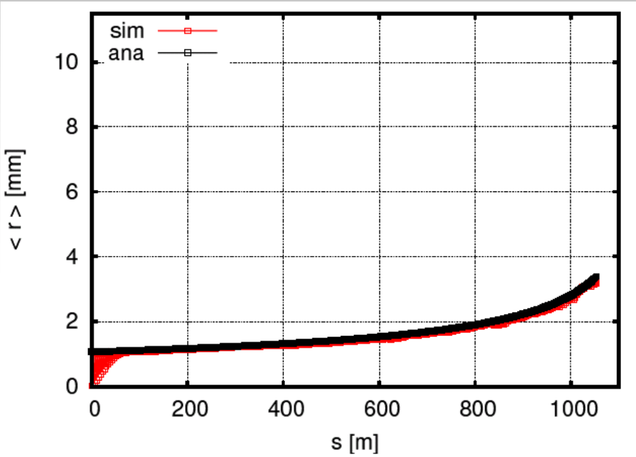
- Driver of envelope: mix of higher and lower energy particles



Minimum final envelope

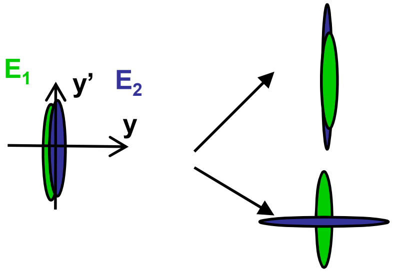
Adiabatic undamping in a **perfect machine** : $\propto \sqrt{(\gamma_i/\gamma_i)}$

3-sigma particle in a perfect beam, perfect machine



r_{min} = 3.3 mm
(factor ~3 increase)

- Relative phase-space orientation of transverse distribution:
  - **irrelevant** for **r**
  - emittance growth not necessarily good indication of envelope growth



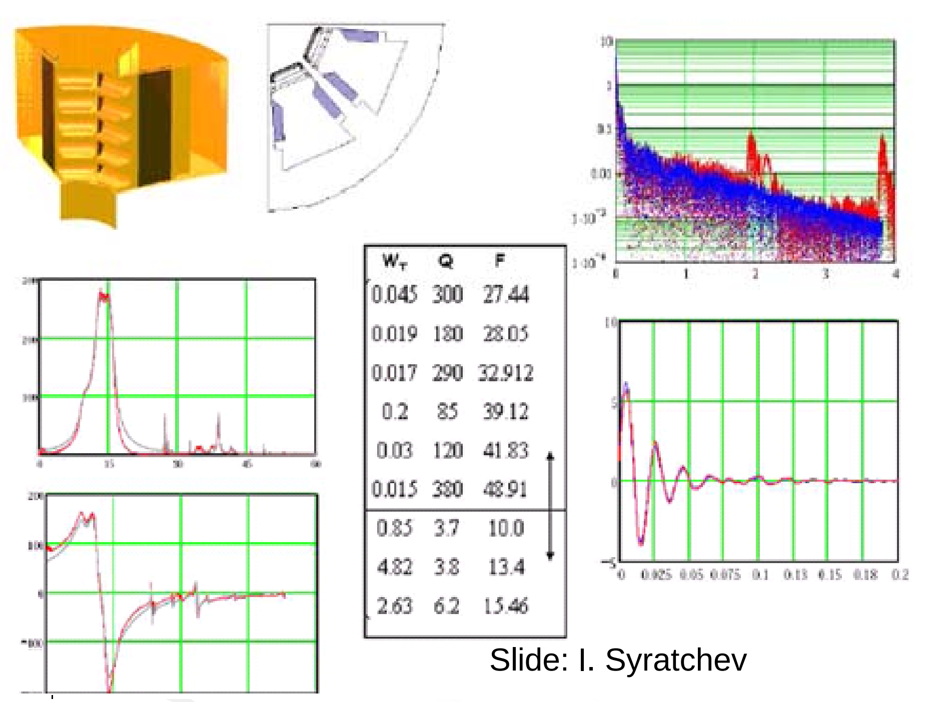
the two cases results in ~ the same r

- To study the various contributions to the envelope growth it is often useful to work with a "pencil beam" of **slice centroids** only, and we denote the *centroid envelope* as $\mathbf{r_c}$

Transverse wakes: dipole modes

- PETS transverse impedance is simulated and a set of discrete dipole modes are extracted to represent the impedance (I. Syratchev)

- Each mode implemented in PLACET (f_T, w_T, Q_T, β_T) and included in the PETS element (D. Schulte)



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

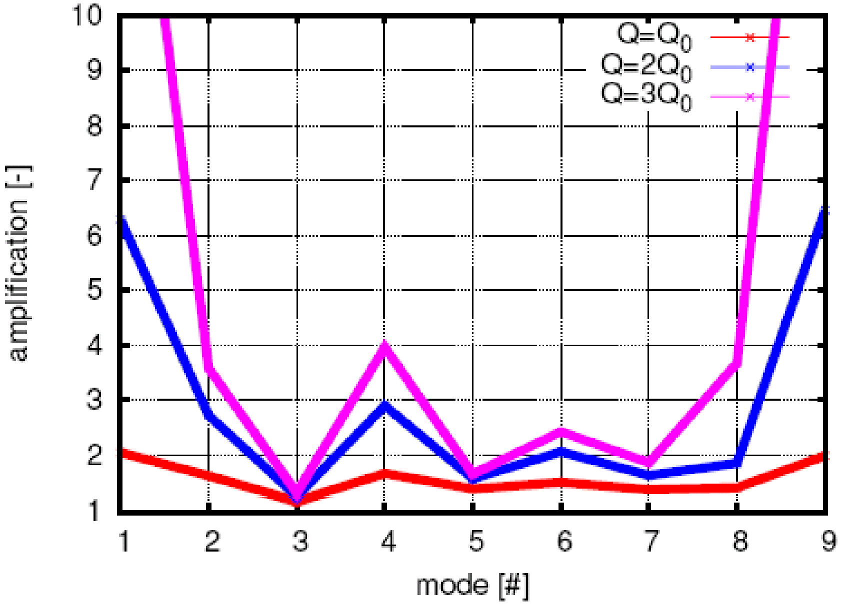
Slide: I. Syratchev

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

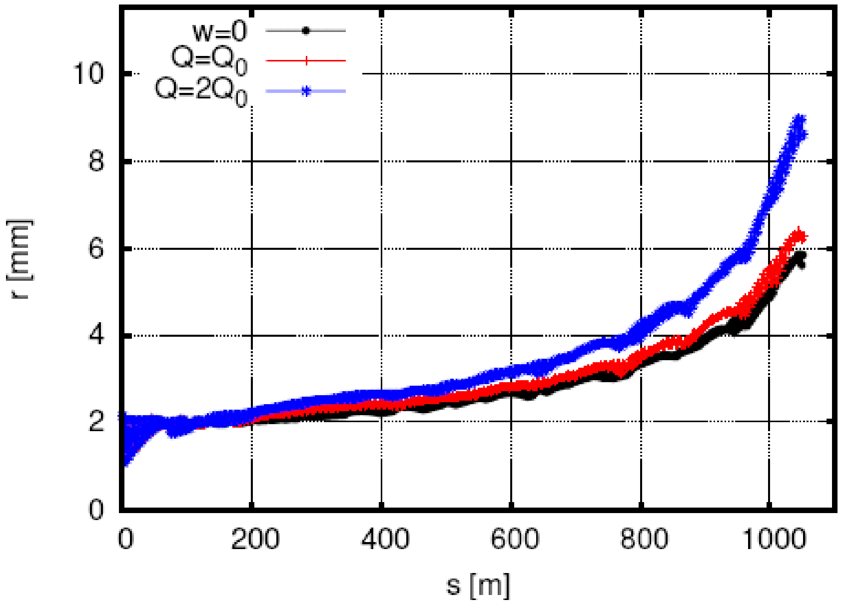
$$\Delta y'_w = \sum_{modes} \frac{\Delta p_{y,w}}{m_w c} = \sum_{modes} y_s \frac{q_s q_w}{E_w} W_{\delta T}(z) [rad]$$

Input to PETS design

- During the 12 GHz PETS design, beam dynamics simulations were done in an iterative process with the PETS design to ensure small amplification due to transverse wakes. **Summary:**



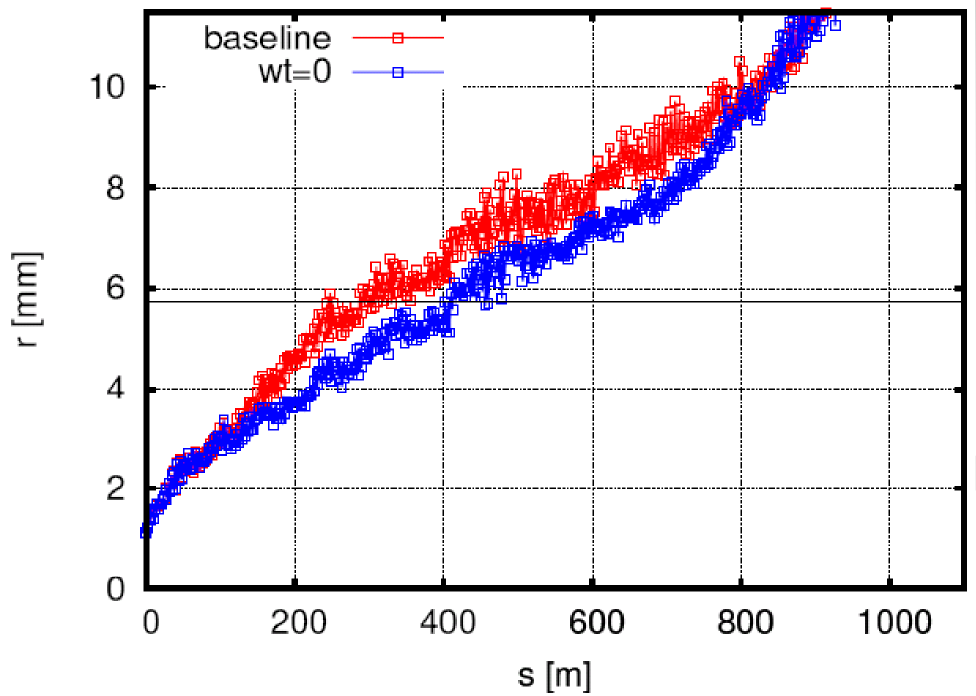
Amplification of centroid motion, r_c, for each dipole mode (beam jittered at mode frequency)



Amplification of total beam envelope, r, jitter on all mode frequencies (1σ jitter in total)

Results: baseline

- Baseline + case w/o transverse wakes



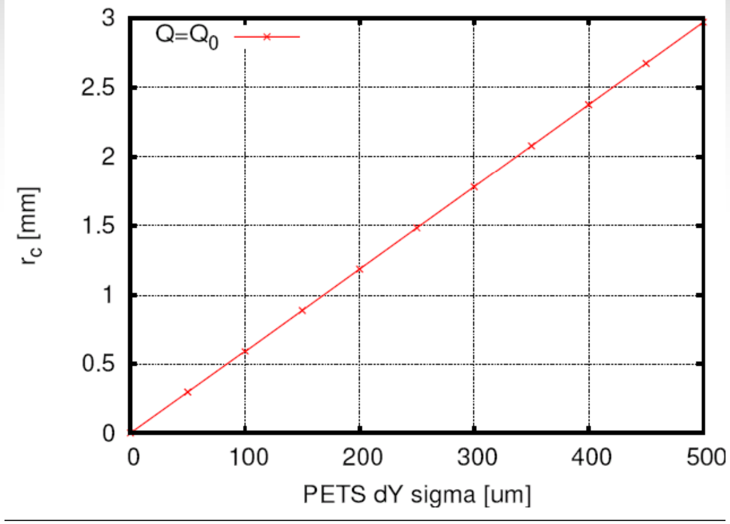
"Guide" to graphs: red will usually mean baseline parameters

- Effect PETS **transverse wakes mitigated efficiently for nominal PETS parameters**. Envelope is now mainly driven by quadrupole kicks. However, Q=2Q_0 leads to unacceptable wake amplification.
- However, **quadrupole kicks alone + undamping** already leads to unacceptable beam envelope

Alignment

Alignment tolerance requirement

We require that no single misalignment should drive our centroid (pencil beam) envelope more than 1 mm, r_c < 1 mm (here max. out of 10000 mach)**:**



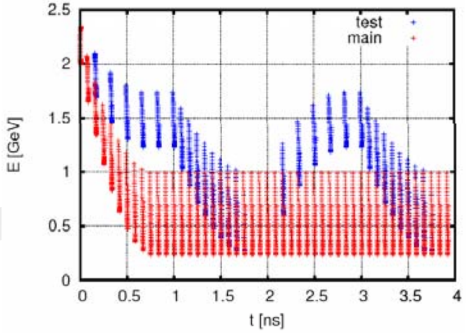
Tolerance	**Value**	**Comment**
PETS offset	100 μm	r_c < 1 mm fulfilled
PETS angles	~ 1 mrad	r_c < 1 mm fulfilled
Quad angles	~ 1 mrad	r_c < 1 mm fulfilled
Quad offset	20 μm	As small as possible, within reasonable limits. 20 μm is within spec. of alignment system (r_c < 1 mm ⇒ quad offset of 1 μm)
BPM accuracy (incl. static misalignment and elec. error)	?	
BPM precision (diff. measurement)	?	

Seems feasible for all misalignment types, except quad offset

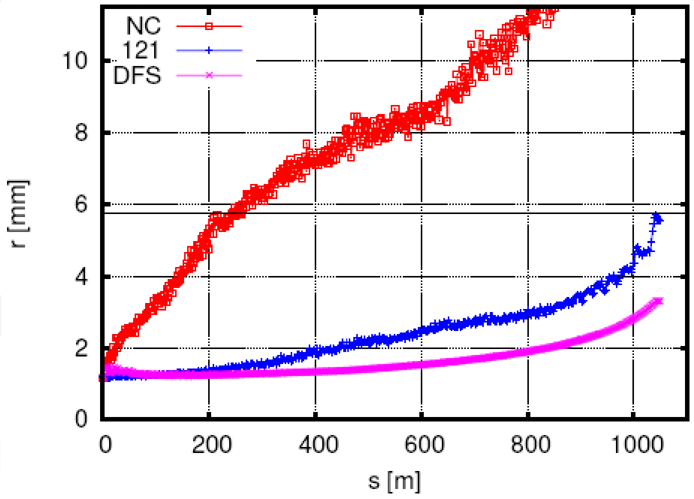
⇒ **Beam-Based Alignment of quads necessary**

Need for Beam-Based Alignment

- Beam envelope several factors far too large for an uncorrected machine
- 1-to-1 steering steers the beam centroid into BPM centres. 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)
- Thus of interest to **minimize dispersive trajectories**: e.g. Dispersive Free Steering: using empty bunches by delayed switching we can in principle perform **Dispersive-Free Steering within one pulse, without changing any machine or beam parameters**, except the SHB switching.



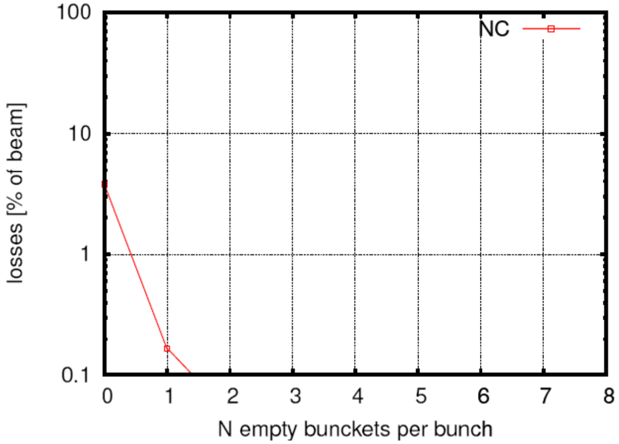
Tolerance	Value	Comment
PETS offset	100 µm	$r_c < 1$ mm fulfilled
PETS angles	~ 1 mrad	$r_c < 1$ mm fulfilled
Quad angles	~ 1 mrad	$r_c < 1$ mm fulfilled
Quad offset	20 µm	Must be as small as possible. 20 µm is within spec. of alignment system ($r_c < 1$ mm $\Rightarrow$ quad offset of 1 µm)
BPM accuracy	20 µm	Must be as small as possible.
BPM precision	~ 2 µm	Suppresses significant tails in distribution of envelopes



For more on BBA: see talk E. Adli "Alignment studies: Decelerator and CTF3" Room: 60-6-002: 16-Oct, 14:20)

BBA and tune-up aspects

- Significant losses (several %) is expected if the nominal beam is transported in a machine before beam-based alignment is applied
  - Losses also means difficulties for response-based steering machines like DFS (sensitivity to current jitter, BPM might become less predictable with losses)
- The BBA should be initialized with a low current beam (**short pulse as well as empty buckets**) – the resulting higher energy and smaller avg. current leads to much smaller envelope and losses
  - Implies that BPMs must be sensitive down to a fraction of nominal current



- The average current will gradually be increased (less empty buckets). For each increase in current a BBA procedure, first 1-to-1 then DFS will be applied to the initial beam. When nominal avg. current is reached one can increase pulse length towards the nominal

Instrumentation

Work in progress

Main tasks of Drive Beam instrumentation:

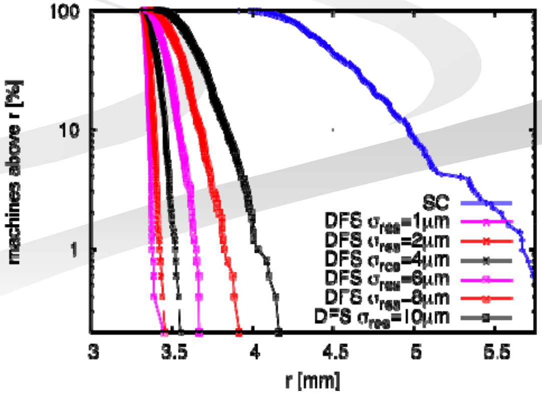
- “Do we transport the beam well?”
  - If not: “why not? What and where is the problem?”
- “Do we produce the correct power (amplitude and phase)?”
- Ensure performance of beam-based alignment
- Commissioning: special needs

Along lattice: BPMs

The need for beam-based alignment implies:

- One BPM per quadrupole (baseline)
- Total number of BPMs: ~ 24 * 2 * 900 = ~ 40000
- Production beam: 100 A (50 A for BBA/DFS)
  - **BPM accuracy: ~ 20 um** (incl. static misalignment)
  - **BPM diff. meas: 2 um**   (<-> precision of ~ 1 um ?)
- Commission beam: ~ 100/N A, (N ~ 10)
  - BPM (abs. pos.) accuracy: ~ 20 um
  - BPM diff. meas : up to 10 um probably ok (with gradually better resolution up to 2 um for 100 A)
- Expected centroid displacement:
  - < 3 mm (uncorrected machine)
- Expected rms size
  - < 4 mm (uncorrected machine)
- Available length for BPMs: ≈ 9 cm
- **Time resolution: ~ 20 ns** (fraction of t_p)
- Machine protection: yes (TBC)

(exact values will need further study)



At sector start : I and FF

- Power production depends mainly on PETS parameters, bunch frequency + **current** and **Form Factor** :

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

- We suggest to be able to estimate power production from drive beam entering the decelerator to within ~0.1%

- *Precision* measurement of these parameters at the start of the lattice:
  - **Current measurement, precision: <= 0.1%**
  - Form factor, precision: <= 0.1 %
  - $F(\sigma) \propto \exp(-(1/2)\sigma^2/\lambda^2)$ → **bunch-length meas. precison: ~1%** (**one-shot** measurement is probably ok)

- In addition: **continuous current monitoring** along lattice, but with **relaxed precision (~1%)** - ideally: BPMs used as current monitors?

Along lattice: loss monitors

- Important for tune up, failure monitoring and localization of fault

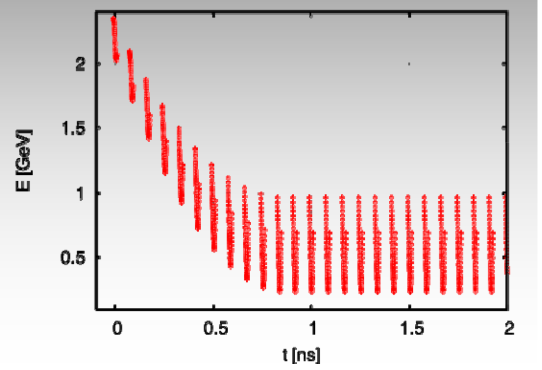
- High sensitivity (could risk small but steady losses along the lattice). Suggested sensitivity: ~1% of one bunch: 80 pC on one detector (depending on interval)

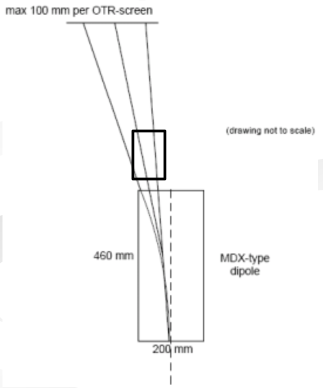
- Spatial intervals of detectors: TBD, but order of some 10’s of meter is suggested

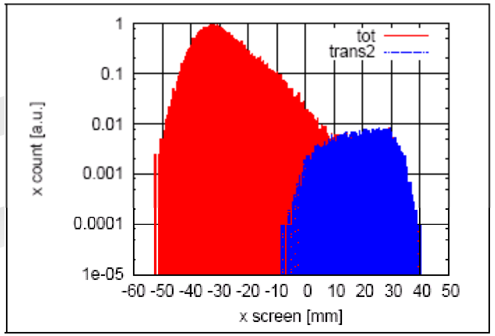
- Challenge: separate drive beam losses and main beam losses (main difference: E)

Sector dump: energy measurement

- Spectrometer dump
  - Measure energy extracted from beam
- Desirable: one **fast BPM** (12 GHz) to verify time-resolved centroid energy of each bunch
  - ~ 10um seems sufficient, depending on geometry
- Desirable: **segmented dump**, total beam energy measurement (cross-check with power production)
  - ~ 100 um screen resolution
  - ~ 3 OM dynamic range
  - ~ 20 ns time resoltion (segmented dump)



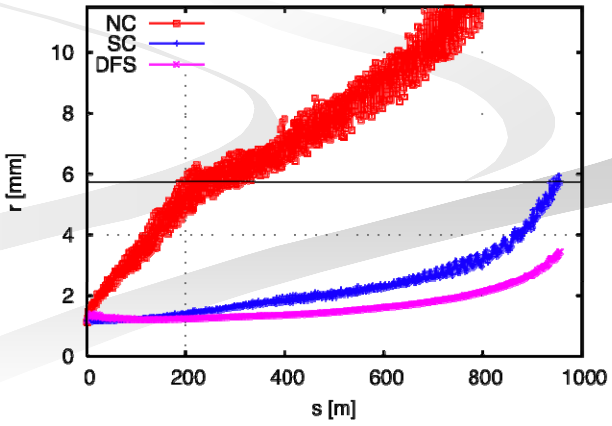




150um - dE/E=1

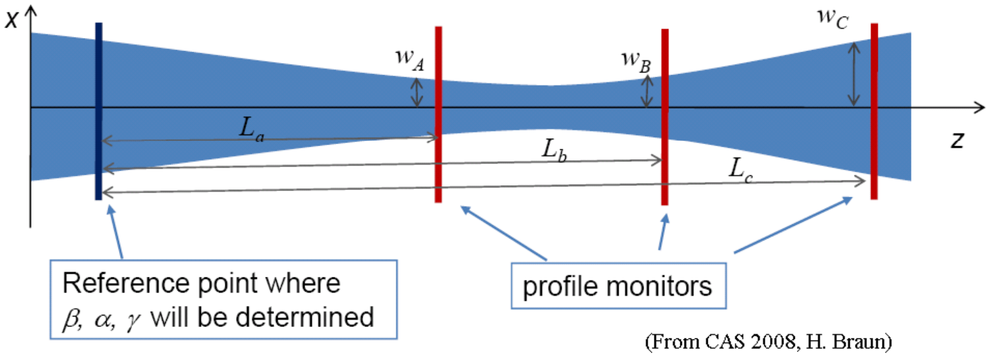
Along lattice: transverse profile monitors

- At selected positions along the lattice
  - ~10 per decelerator would give good picture of envelope growth
  - Important for tune up and failure monitoring
  - 1 sigma transverse size:
    - uncorrected machine : 0.3 mm at start up to 3 mm at end
    - Corrected machine: 0.3 mm at start up to 1 mm at end
  - Range: desired to observe 3 sigma size
  - Precision: 50 um adequate



Dump: transverse phase-space

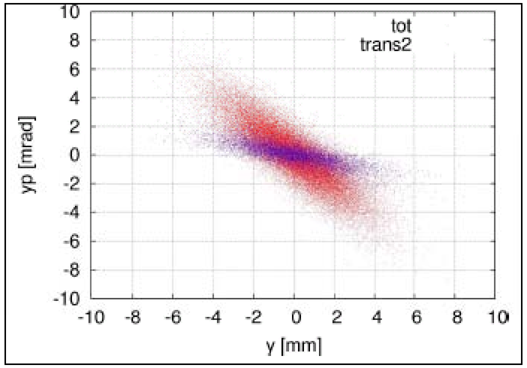
- Transverse phase-space
  - Useful for tune-up
  - Useful for verification of beam dynamics
  - Set of profile monitors better than quad-scan, due to energy spread :
  - See the transverse screens slide (need to have at least 3 profiles towards the end of the decelerator)



Reference point where β, α, γ will be determined

profile monitors

(From CAS 2008, H. Braun)

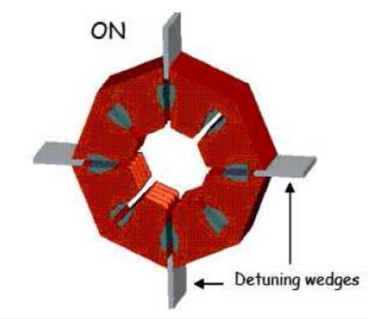


Conclusion: decelerator

- Simulations gives **reasonable confidence for minimum-loss transport of the decelerator beam**
- **Beam-Based Alignment is needed**, and **Dispersion-Free Steering** seems to be an excellent alternative
- Dispersion-Free Steering comes almost "**for free**" with the use of delayed switching
- **Tune-up procedures** must be applied
- Simulations need to be benchmarked and technology needs to be proven: **TBTS and TBL**

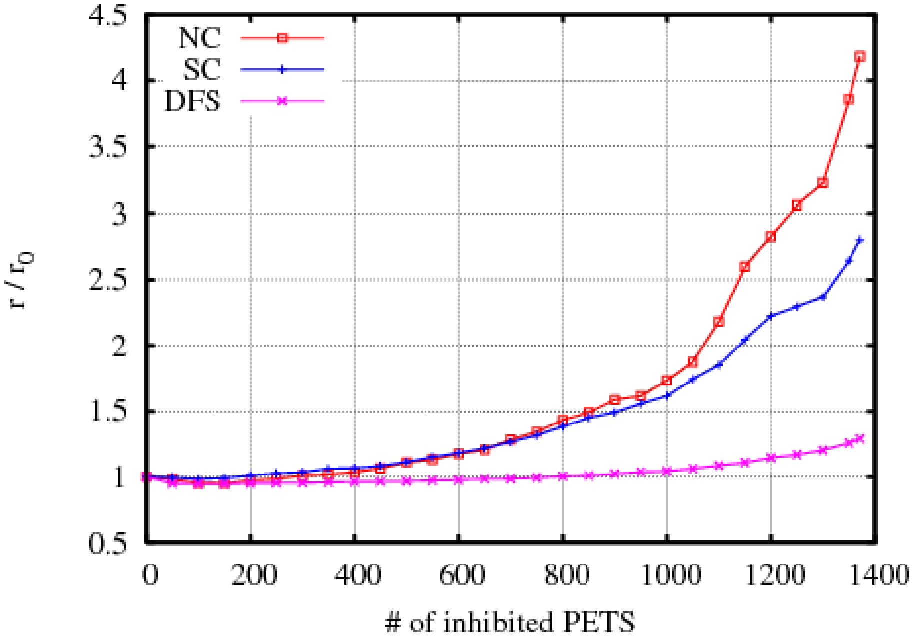
Extra (more)

PETS: effect of inhibition



- "Petsonov": on/off mechanism
  - Simulated as R/Q=0, $Q_T=2Q_{T0}$ (worst-case)
- Effect of inhibition on the beam dynamics:
  - the lack of deceleration leads to higher minimum beam energy and thus less adiabatic undamping and less energy spread
  - dipole wake kicks increase; for a steered trajectory the change of kicks will in addition spoil the steering
  - the coherence of the beam energy will increase, and thus also the coherent build up of transverse wakes

A number of random PETS inhibited (averaged over 100 seeds)

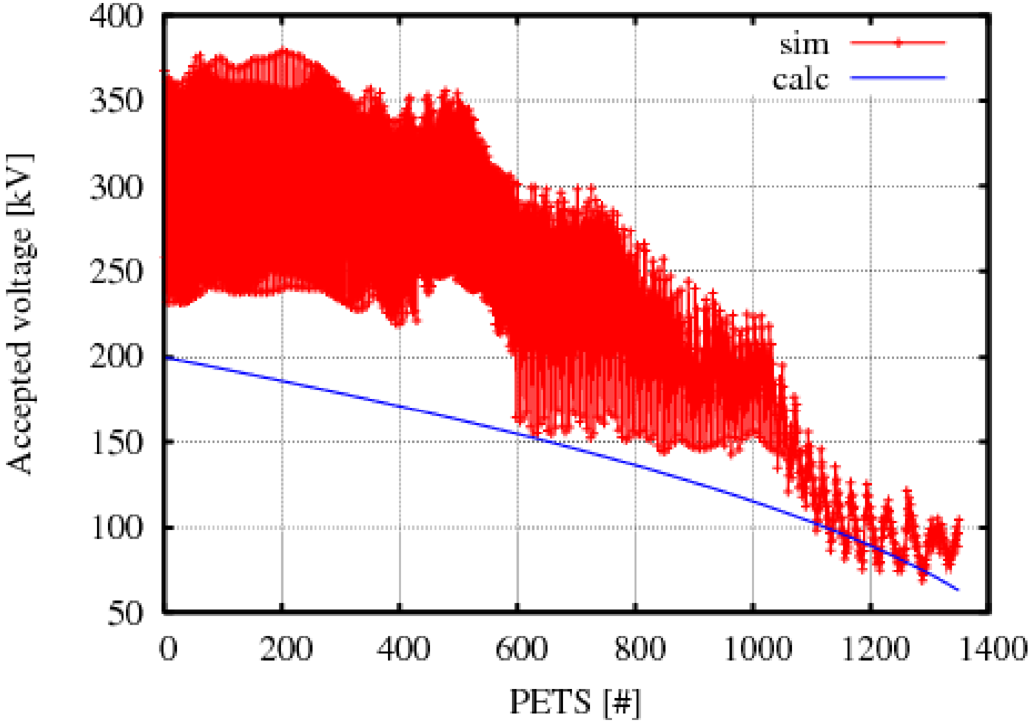


Negligible effect on beam envelope for up to 1/3 of all PETS inhibited, and even more for a DFS steered machine

PETS: estimation of accepted break down voltage

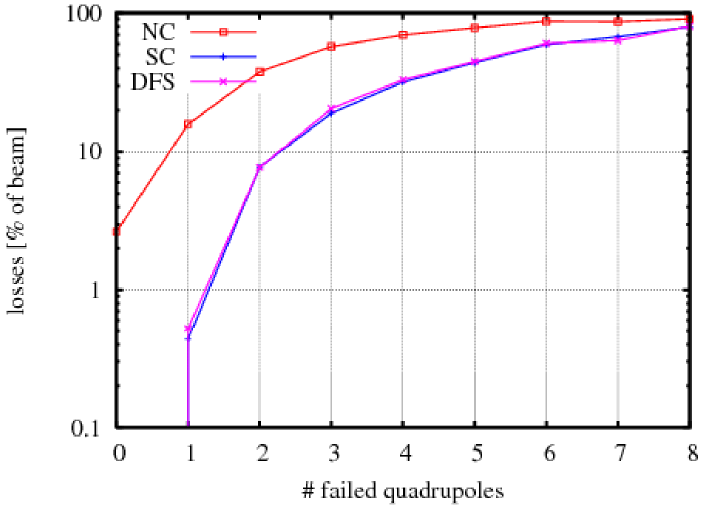
- Maximum accepted transverse voltage accepted if we require r_c < 1 mm due to this kick

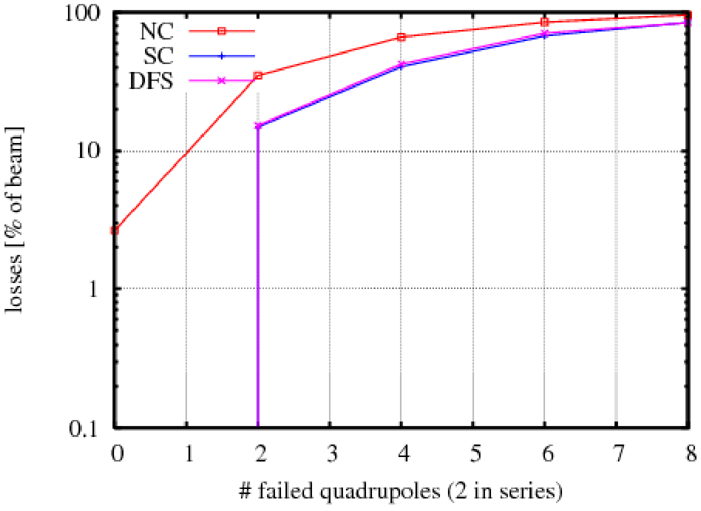
$$U = \Delta y' \times E = \frac{r}{A\hat{\beta}} / \sqrt{\frac{E_i}{E_f}} \times E_i = \frac{r}{A\hat{\beta}} \sqrt{E_i E_f}$$



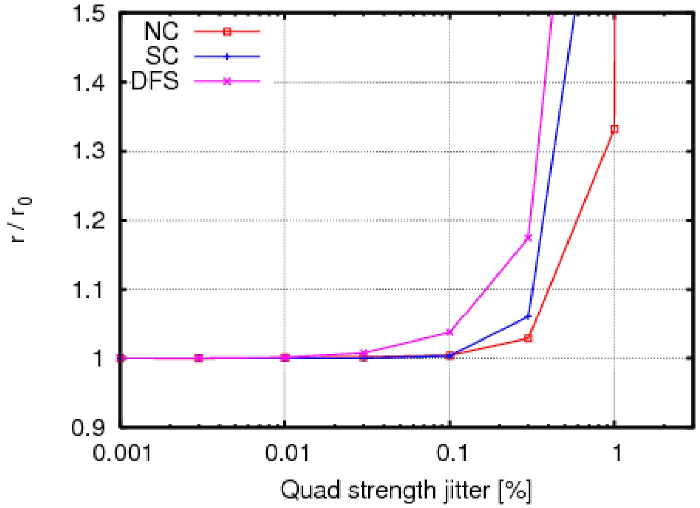
Quadrupole jitter and failure

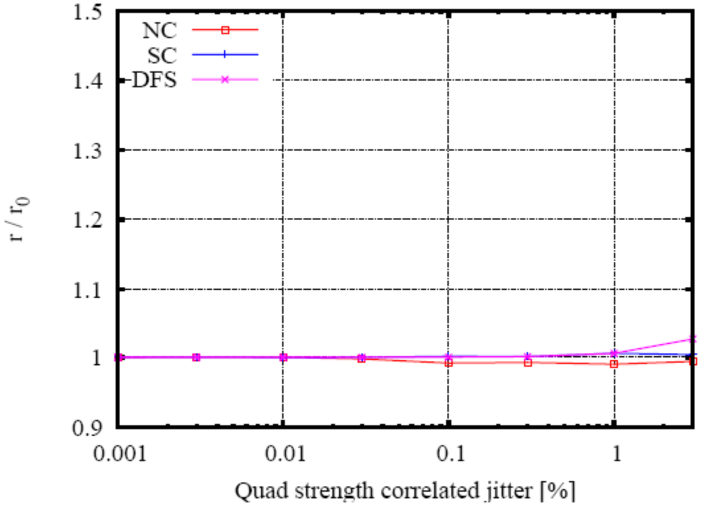
Losses as function of random quad failure





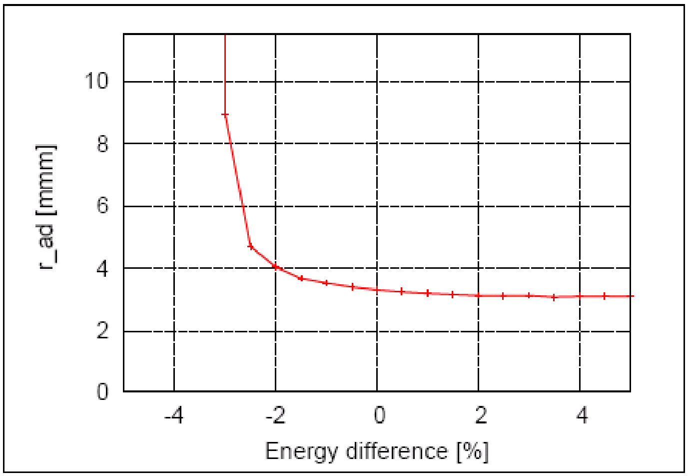
Envelope increase as function of quad jitter





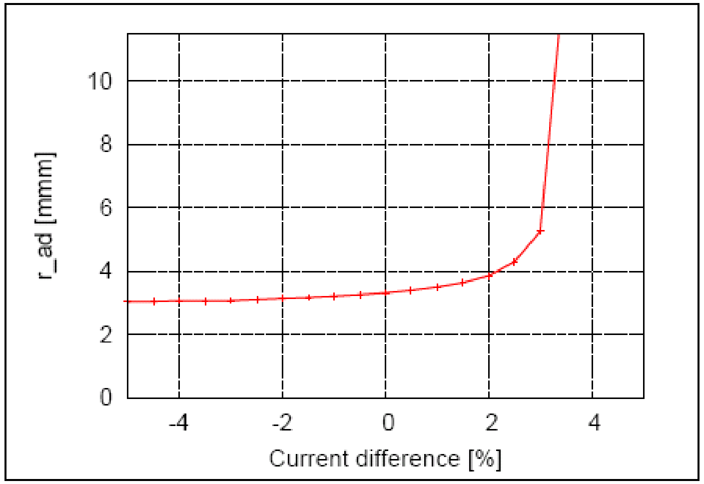
Lattice focusing

For a given optics 3% change, or more, in initial current or energy will induce losses



Beam blow-up due to wrong energy

$$E_{unstable}/E_0 \quad < (1-S)\left(\frac{\sin(\mu/2)}{\sin(180^0/2)}\right)+S \approx 0.97$$



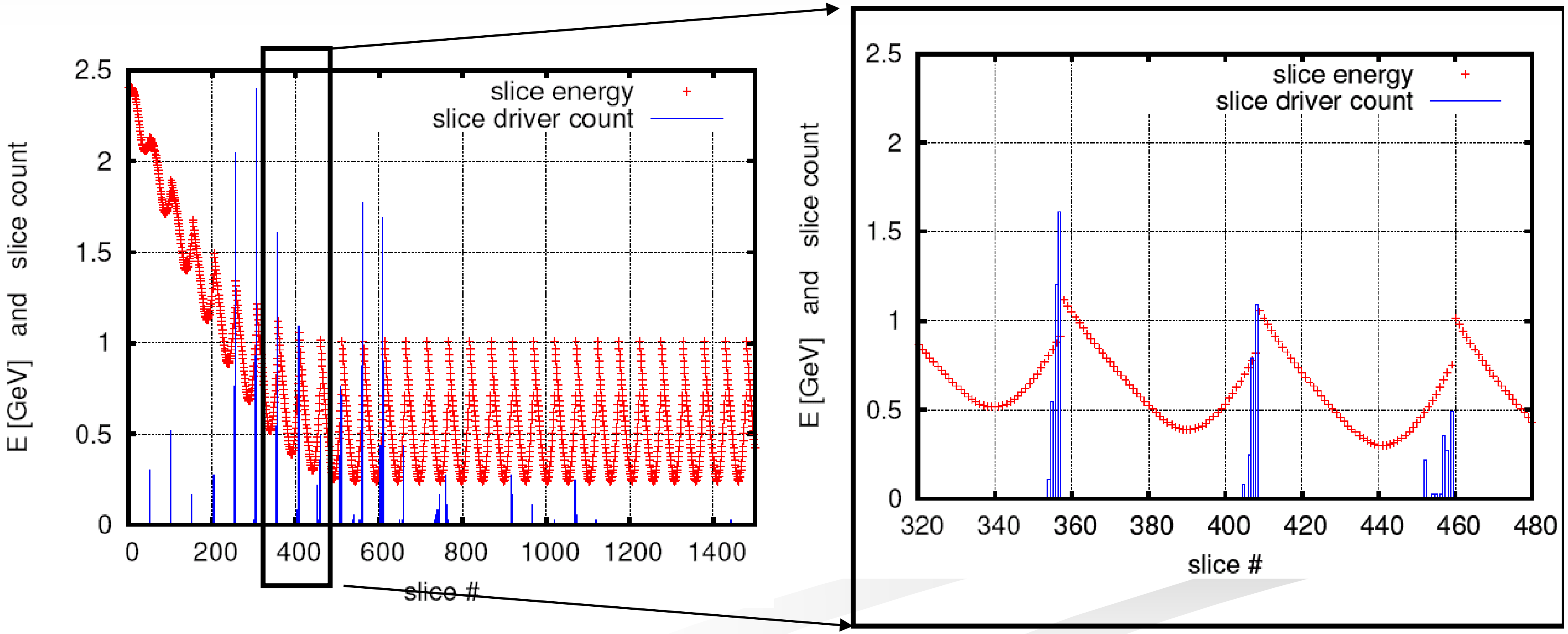
Beam blow-up due to wrong current

$$I_{unstable}/I_0 > \frac{1}{S}-\left(\frac{1}{S}-1\right)\frac{\sin(\phi_0/2)}{\sin(180^0/2)} \approx 1.03$$

Origin of wake amplification

- Further investigation shows the amplification of the envelope typically [depending on scenario] is driven by particles towards the end of the bunch

  → single bunch dipole wake significant



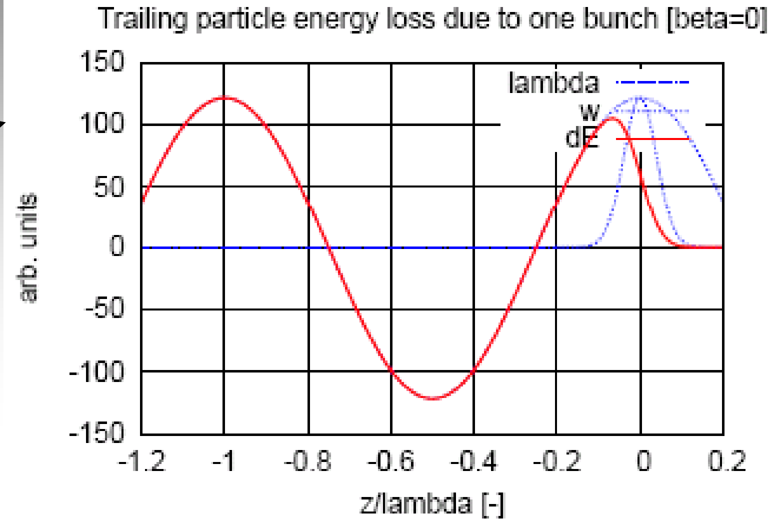
Corollary: since single bunch wake is sine-like, shorter bunch-length might reduce PETS wake amplification

PETS energy extraction

Single particle energy loss:

$$\Delta E(z) = N e^2 \int_z^{\infty} dz' \lambda(z') w_L(z'-z)$$

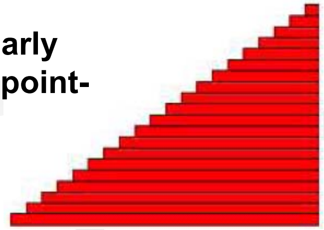
example for Gaussian bunch



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)



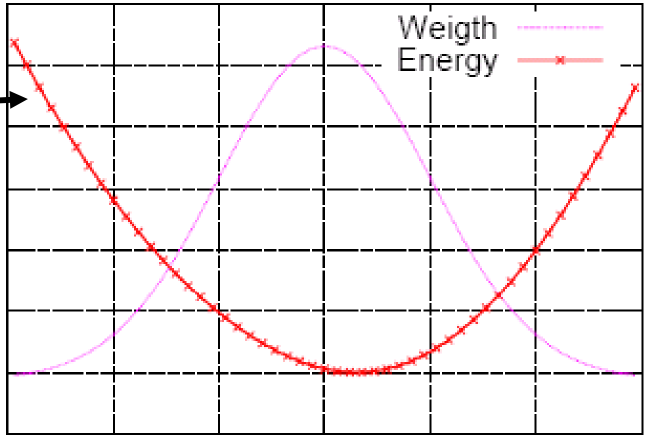
Energy loss from leading bunches + single bunch component:

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

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

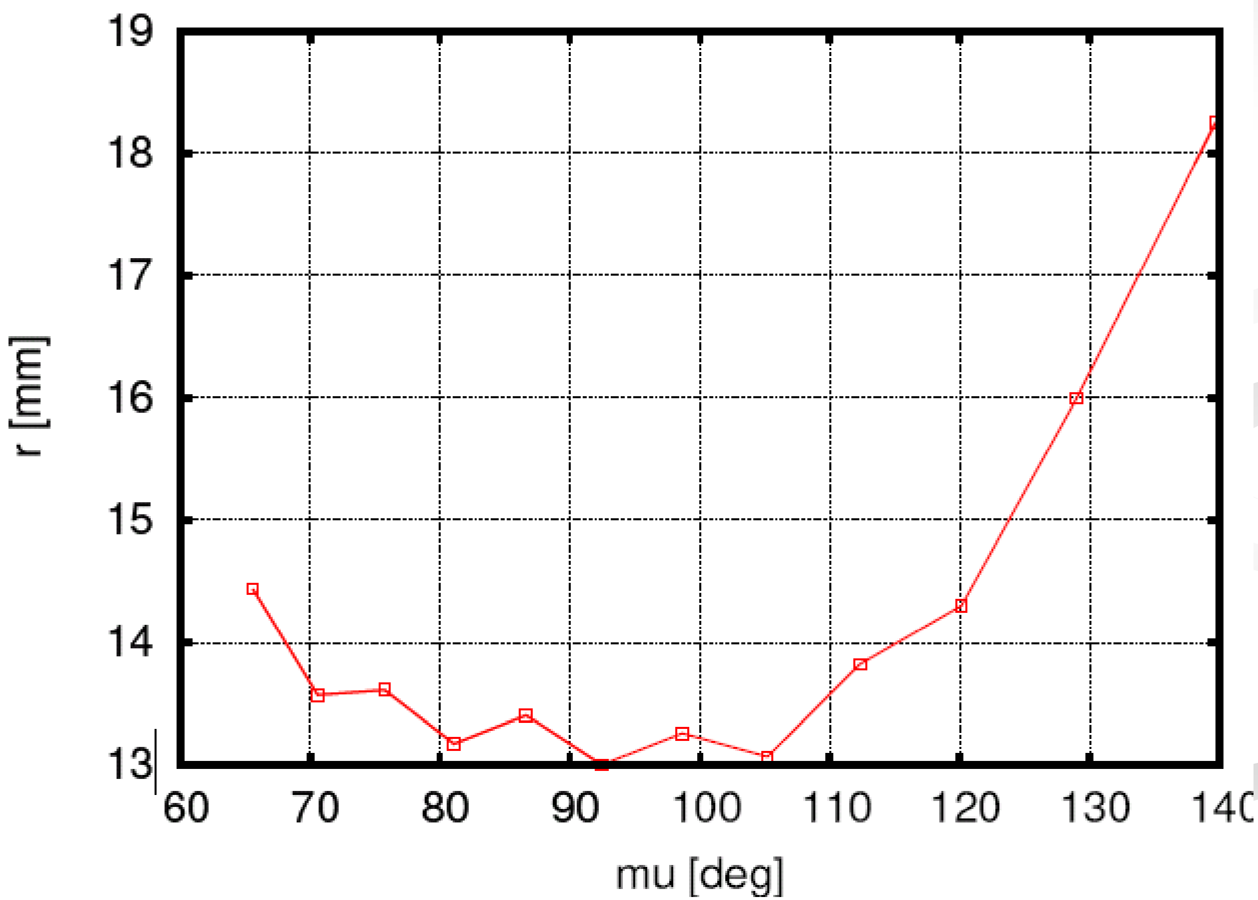


Integrating ΔE over bunch gives second form factor, and times f_b gives extr. power:

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

(x 1/2 for linac-Ohms)

Dependence on FODO phase-advance



Simulation overview

The following effects are included in the simulation studies :

- PETS transverse effects (baseline)
  - Transverse wakes (long and short range)
  - RF-kicks
  - Adiabatic undamping
- Lattice component misalignment (baseline)
  - PETS misalignment (offset, angle)
  - Quadrupole misalignment (offset, angle)
  - BPM misalignment (offset, angle), BPM finite precision
- Beam perturbations (studied separately)
  - Beam offset
  - Beam jitter

Not included in the simulations for the work presented here :

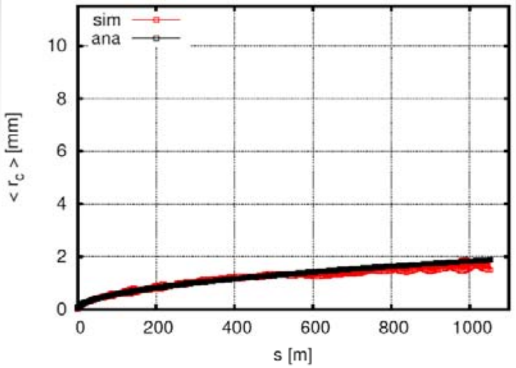
- Higher-order wakes
  - Effect should be limited within $r < \frac{1}{2}a_0$ (but probably worth looking further into)
- Resistive-wall wake
  - Estimates following the strategy in [B. Jeanneret et al.] show that the effect is small
- Longitudinal effects and phase jitter
  - Some result established in earlier work [D. Schulte]
  - On-going work
- Background and halo simulations
  - On-going work by I. Ahmed
- Energy spread: Spread is small comparable to PETS induced spread, but to fulfill S=90% E_0 should be increased by ~ $E_0 (1+3\sigma_E)$ which is “assumed” here

Effect of quadrupole kicks

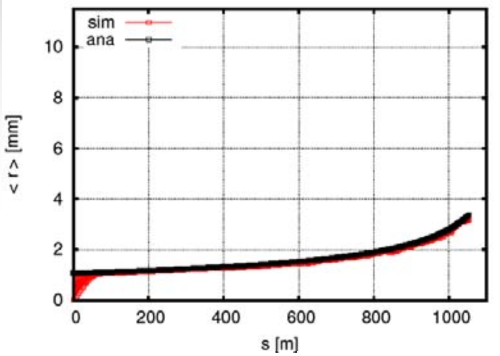
- Random kicks from offset quads increase the centroid envelope as $\sqrt{(N_{quad})}$
- For a FODO lattice without PETS the contribution would be have been $r_c \approx 2$ mm for quad offsets of 20 μm

quad kicks alone (lowest E drives r)

$$\frac{\sigma_{quad}}{\cos(\mu_{cell}/2)} 2\sqrt{2N_{cell}}$$



"×"

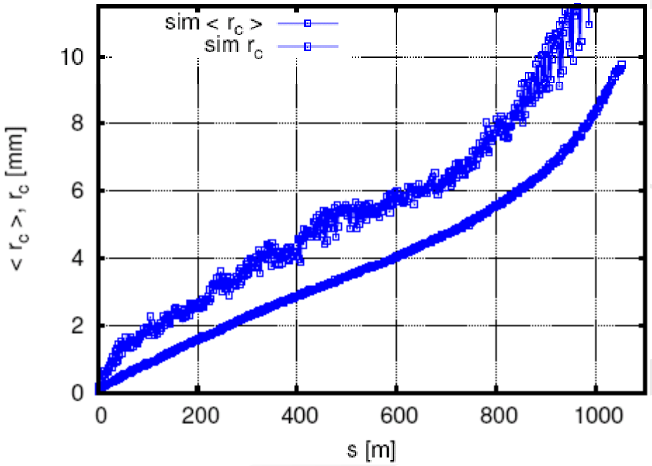


adiabatic undamping (lowest E drives r)

$$\approx 3\sqrt{2L_{cell}\varepsilon_N/\gamma_f}$$

- However, the combined effect of quadrupole kicks and the adiabatic undamping leads to a quickly increasing beam envelope:

=



quad kicks + adiabatic undamping

Thus: quadrupole kicks + ad. undamping alone drives the beam envelope above our limit (perhaps a bit surprisingly)

Decelerator: conclusions

- Simulations gives **reasonable confidence for minimum-loss transport of the decelerator beam**
- **Beam-Based Alignment is needed**, and **Dispersion-Free Steering** seems to be an excellent alternative
- Dispersion-Free Steering comes almost "**for free**" with the use of delayed switching
- **Tune-up procedures** must be applied
- Simulations need to be benchmarked and technology needs to be proven: **TBTS and TBL**

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	Must be as small as possible to be able to transport alignment beam
BPM accuracy (incl. static misalignment and elec. error)	20 μm	Must be as small as possible to be able to do initial correction
BPM precision (diff. measurement)	~ 2 μm	Allows efficient suppression envelope growth due to dispersive trajectories

Static tolerances

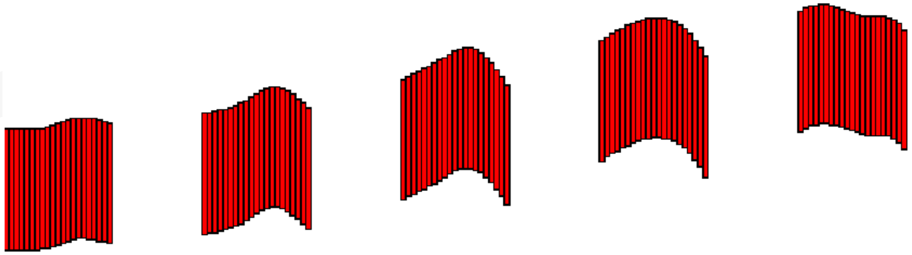
Tolerance	**Value**	**Comment**
Quadrupole position jitter	1 μm	$r/r_0 < 5$ %
Quadrupole field ripple	$1 \cdot 10^{-3}$	$r/r_0 < 5$ %
Current jitter	< 1%	Stability req. only – RF power constraints might be tighter.
Beta mismatch, dβ/β	10 %	$r/r_0 < 5$ %

Dynamic tolerances

Baseline parameters for this study

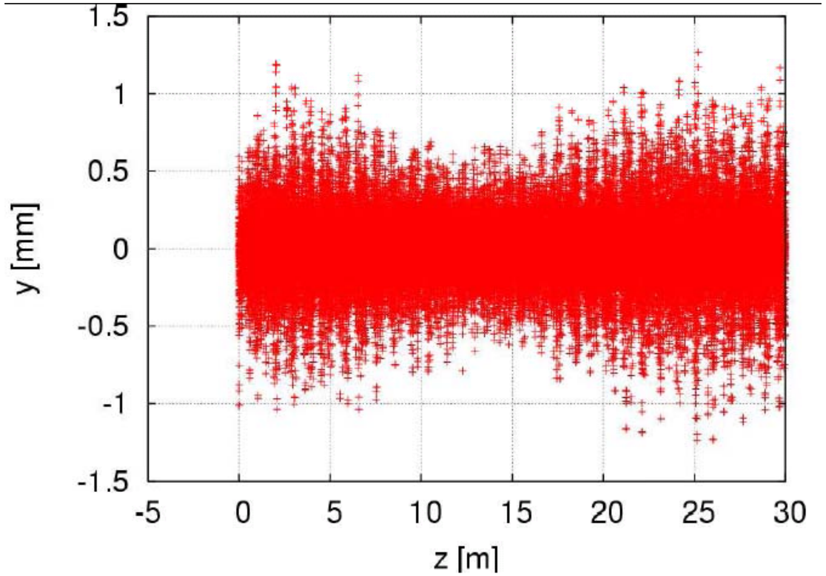
- **Baseline parameters** [CLIC parameters 2008]
  - **E_0 = 2.4 GeV**
    - σ_E=0 in most simulations (see later slide for more on σ_E)
  - **I = 101 A**
  - f_b = 12 GHz (bunch spacing d = 25 mm)
  - t ≈ 240 ns (2900 bunches)
  - Gaussian bunch, σ_z = 1 mm
  - $\varepsilon_{Nx,y} \approx 150\ \mu m \rightarrow \boldsymbol{\sigma_{x,y} \approx}$ **0.3 mm** at β_{max} = 3.4 m
  - **Half-aperture: a_0=11.5 mm** (driven by PETS)

- **Simulation tool: PLACET** (D. Schulte)
  - Sliced beam model:
    - bunch divided into slices with individual (z, E)
    - each slice: transverse distribution
    - BPM, Quad and PETS elements

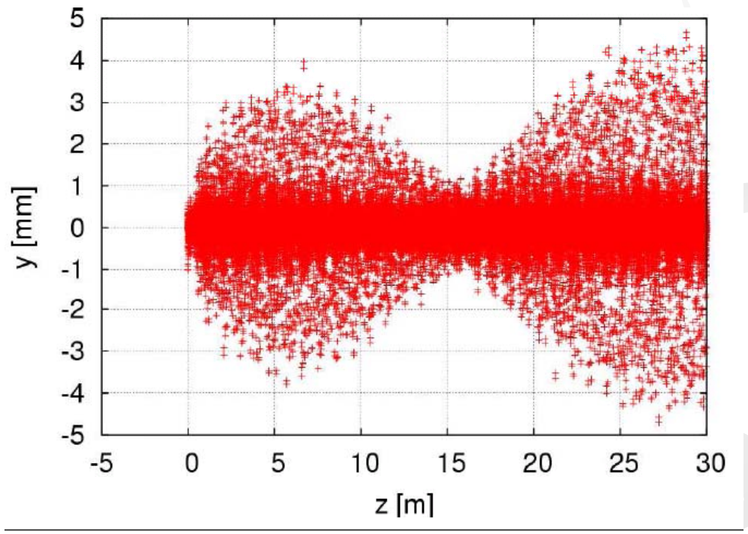


Instabilities along the beam

- NB: Q-factor larger than the nominal increase multi-bunch wake and might lead to instability growing along the beam
- Here illustrated for $Q=Q_0$ and $Q=2Q_0$
- Deemed unacceptable (even if centroid r_c envelope is constrained)



$Q=Q_0$



$Q=2Q_0$

Dispersion-free steering

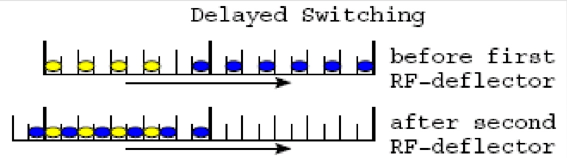
- 1-to-1 correction does not give an adequate steering due to the large variation of dispersive trajectories, we therefore seek to minimize the dispersive trajectories by applying Dispersion-Free Steering (DFS), [Raubenheimer and Ruth, 1991]
- Our implementation uses response matrices to minimize:

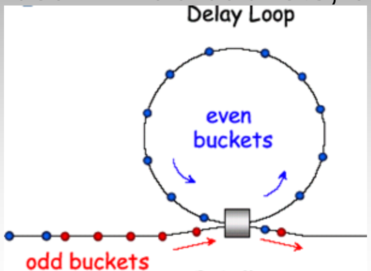
$$\chi^2 = w_0 \Sigma y_{0,i}^2 + w_1 \Sigma (y_{1,i} - y_{0,i})^2$$

- 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 generate a 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



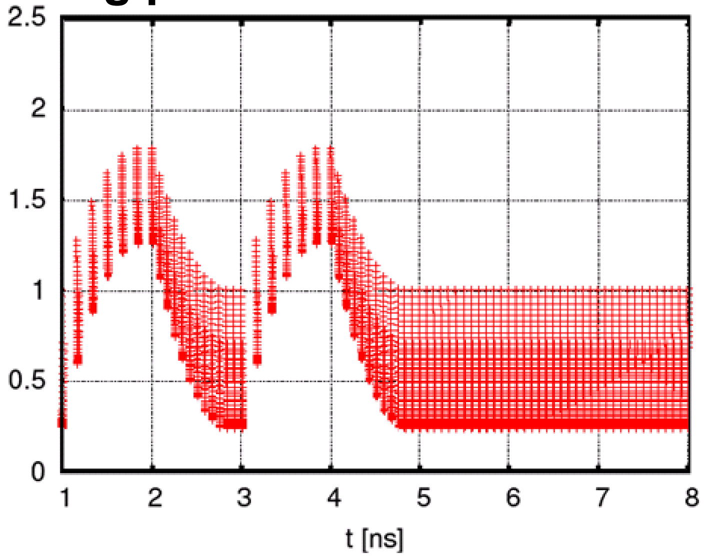


Example of DFS beam generation scheme:

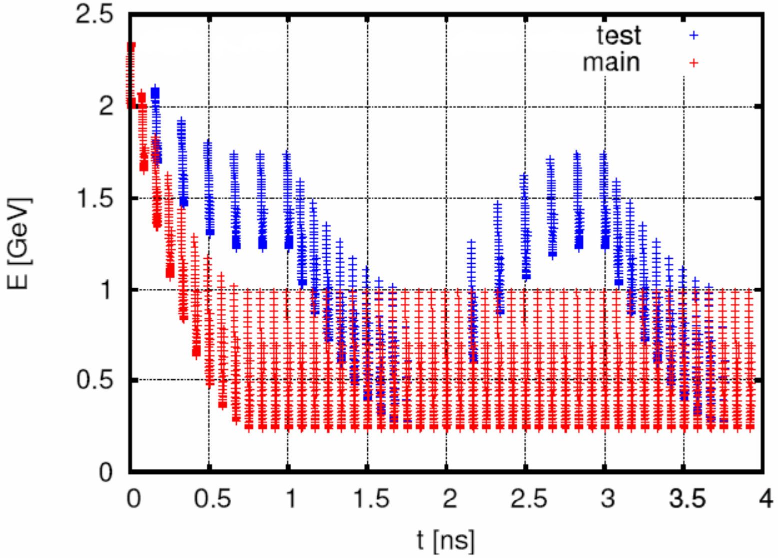
Of the 12 initial E+O pulses:

- **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)