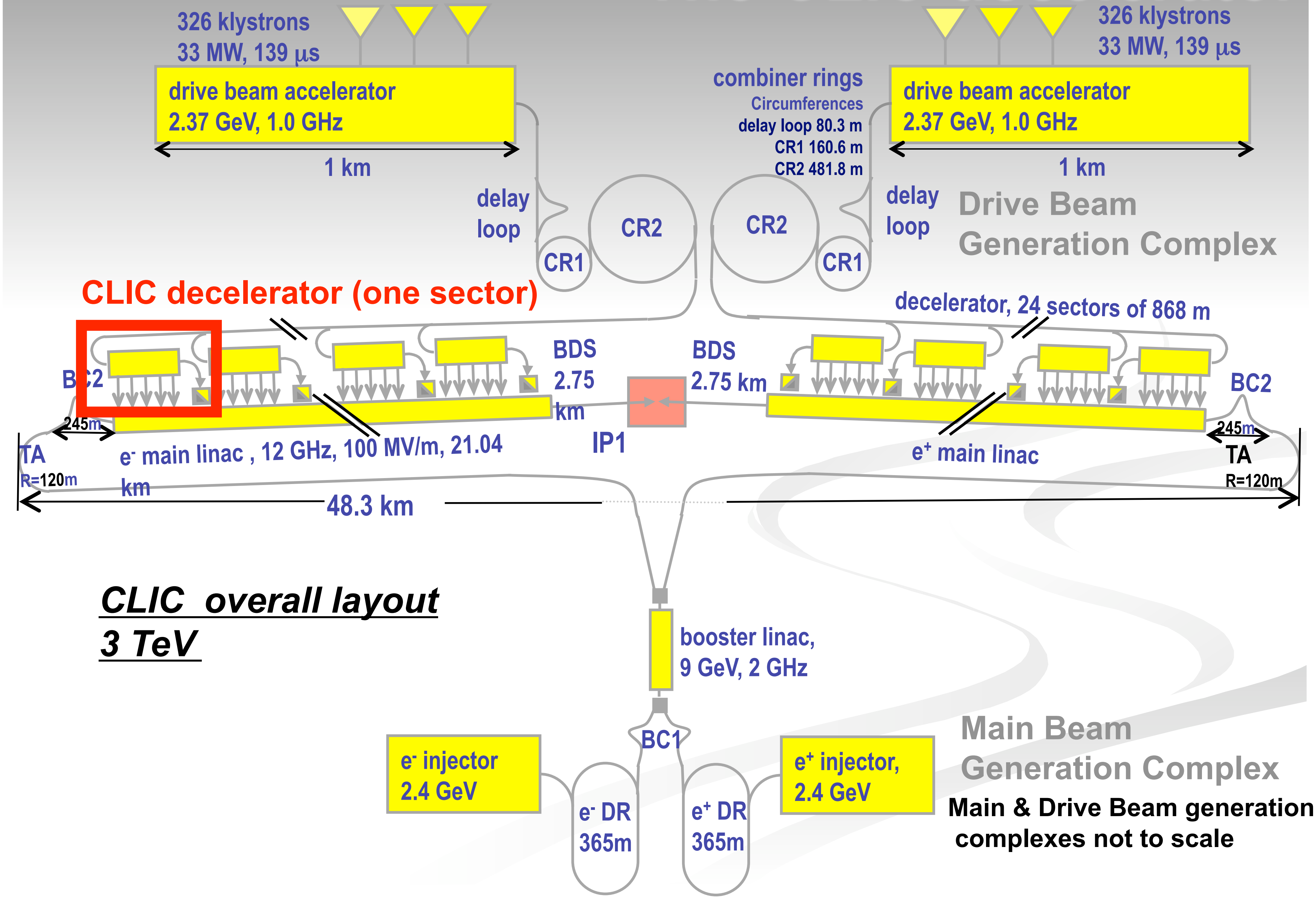
CLIC Drive Beam Decelerator

Beam transport: wake fields and alignment

ILC-CLIC LET Beam Dynamics Workshop

Erik Adli, University of Oslo and CERN, June 23th 2009

The CLIC decelerator



326 klystrons
33 MW, 139 μs

drive beam accelerator
2.37 GeV, 1.0 GHz

1 km

delay loop

CR1

CR2

combiner rings
Circumferences
delay loop 80.3 m
CR1 160.6 m
CR2 481.8 m

CR2

CR1

delay loop

326 klystrons
33 MW, 139 μs

drive beam accelerator
2.37 GeV, 1.0 GHz

1 km

Drive Beam Generation Complex

CLIC decelerator (one sector)

decelerator, 24 sectors of 868 m

BC2

245m

TA
R=120m

BDS
2.75 km

BDS
2.75 km

IP1

e^- main linac , 12 GHz, 100 MV/m, 21.04 km

e^+ main linac

BC2

245m

TA
R=120m

48.3 km

CLIC overall layout
3 TeV

booster linac,
9 GeV, 2 GHz

BC1

e^- injector
2.4 GeV

e^- DR
365m

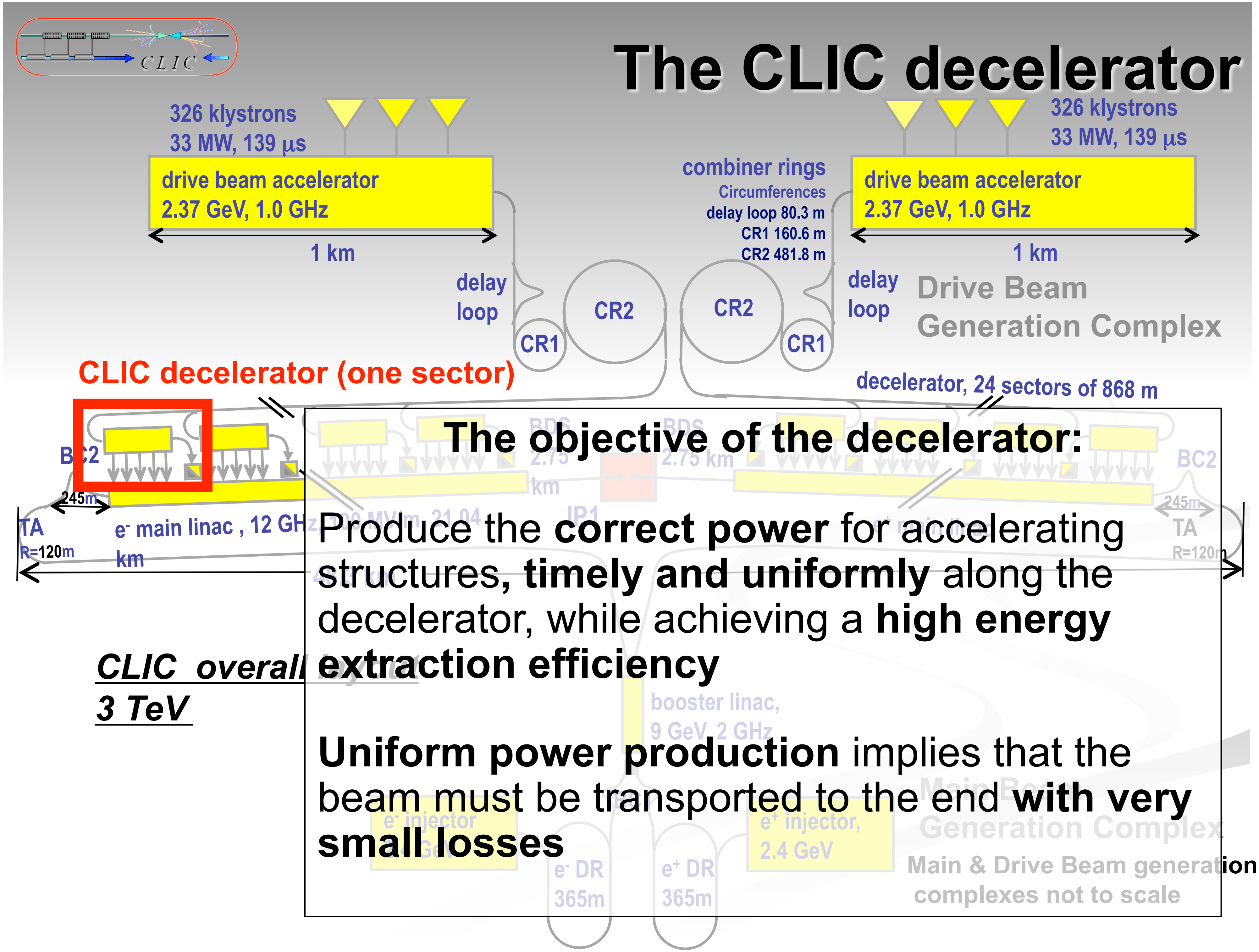
e^+ DR
365m

e^+ injector,
2.4 GeV

Main Beam Generation Complex

Main & Drive Beam generation complexes not to scale

The CLIC decelerator

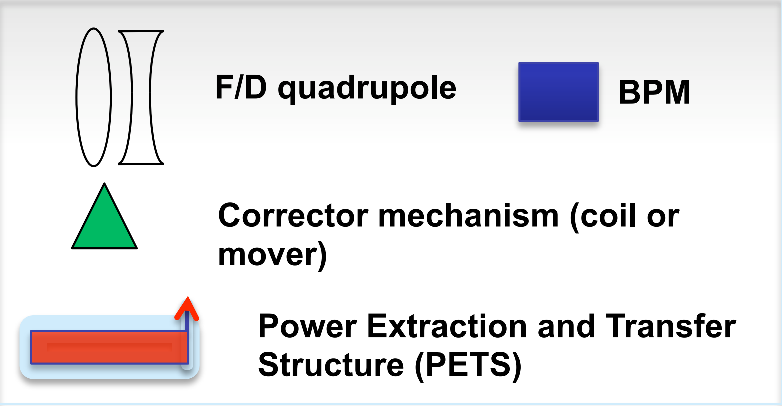


The objective of the decelerator:

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 and beam

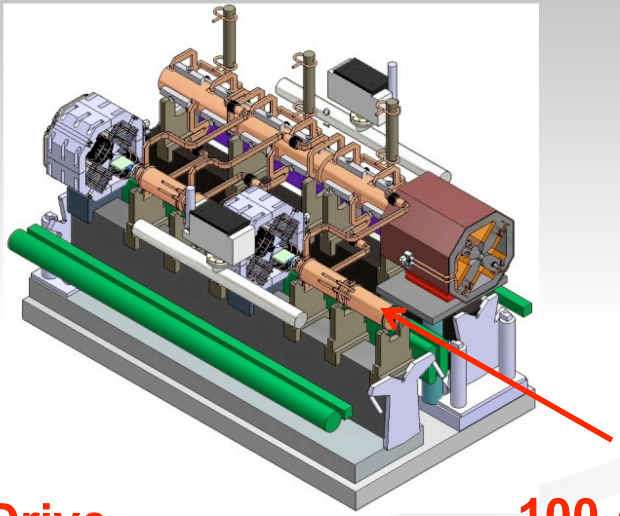


F/D quadrupole

BPM

Corrector mechanism (coil or mover)

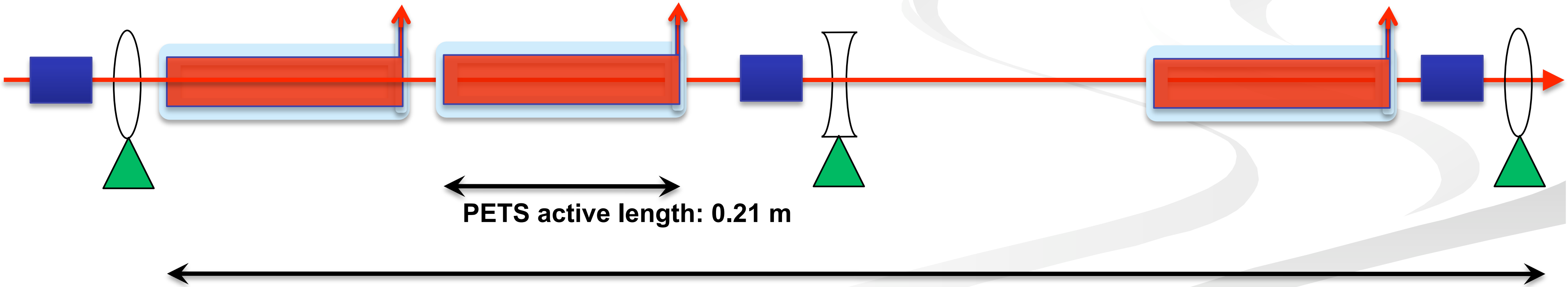
Power Extraction and Transfer Structure (PETS)



Drive Beam

100 A, 2.4GeV

f_b = 12 GHz, σ_z = 1 mm rms

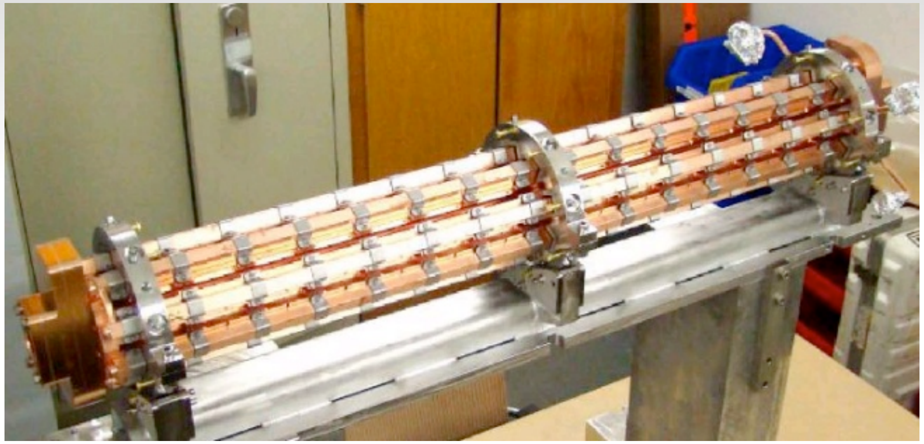


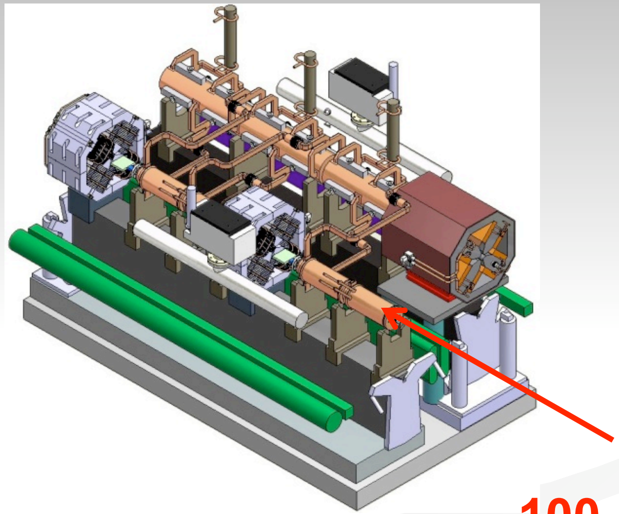
PETS active length: 0.21 m

One FODO cell: 2.01 m - up to 524 FODO cells per deceleration sector

Each decelerator sector up to 1 km long (one 1 km sector simulated)

Power extraction





12 GHz PETS
(for Two-beam Test Stand experiments)

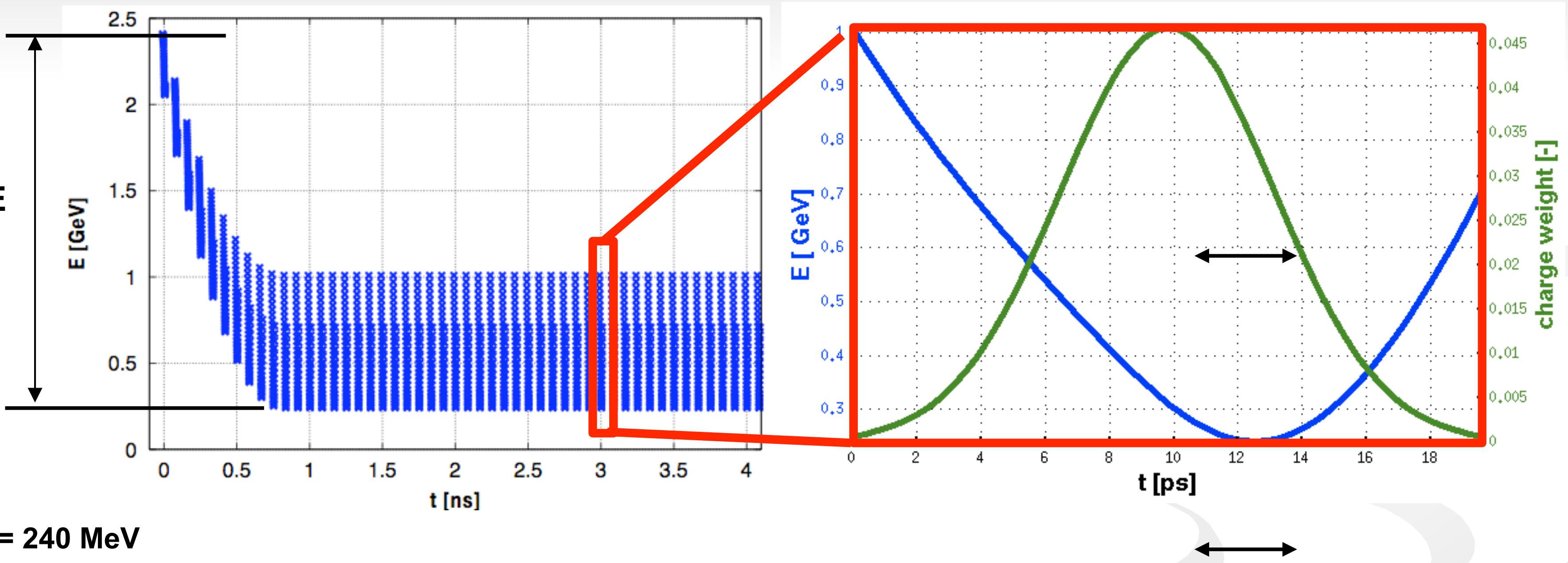
CLIC Module
(with up to 4 PETS)

The effect of deceleration

Energy profile of the Drive Beam at the end of a Decelerator Sector

*(short **transient** + long **steady-state**)*

t_{pulse} = 240 ns



E

Ě

S=(E-Ě) / E
= 90%

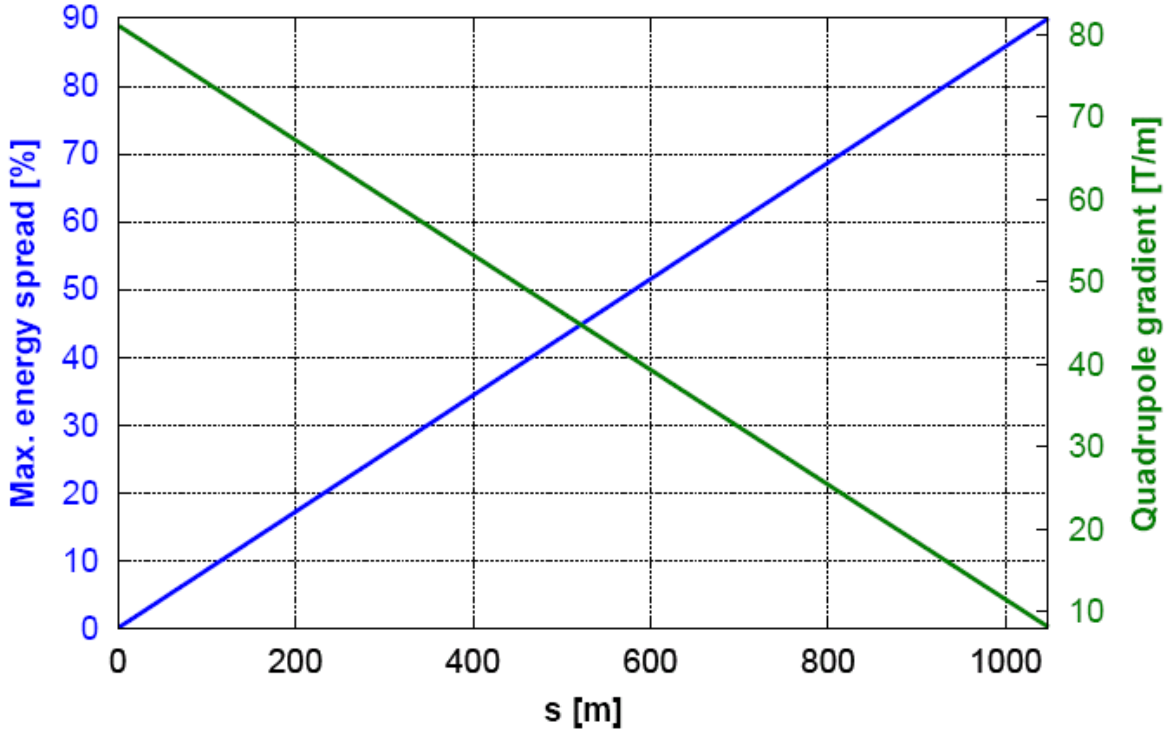
Ě = E(1-S)
=E-$N_{PETS}\Delta\hat{E}$ = 240 MeV

σ_z = 1mm, t_z = 3ps

Special requirement: we have to transport particles over the whole energy range

Focusing strategy

- Tight **FODO focusing** (large energy acceptance, low beta)
- **Lowest energy particles ideally see constant phase-advance μ≈90°**
- Higher energy particles see phase-advance varying from μ≈90° to μ≈10° (towards the end of the lattice)
  - Perfect machine and beam : high energy envelope contain in low energy envelope
  - Energy acceptance (e.g. of generated halo particles) only -3% of E_0 at the entrance; but increasing along the lattice
  - Implies that each of the (~ 40'000) quadrupoles should ideally have a different gradient

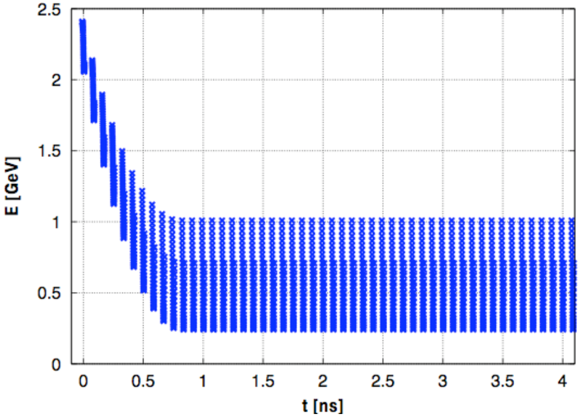


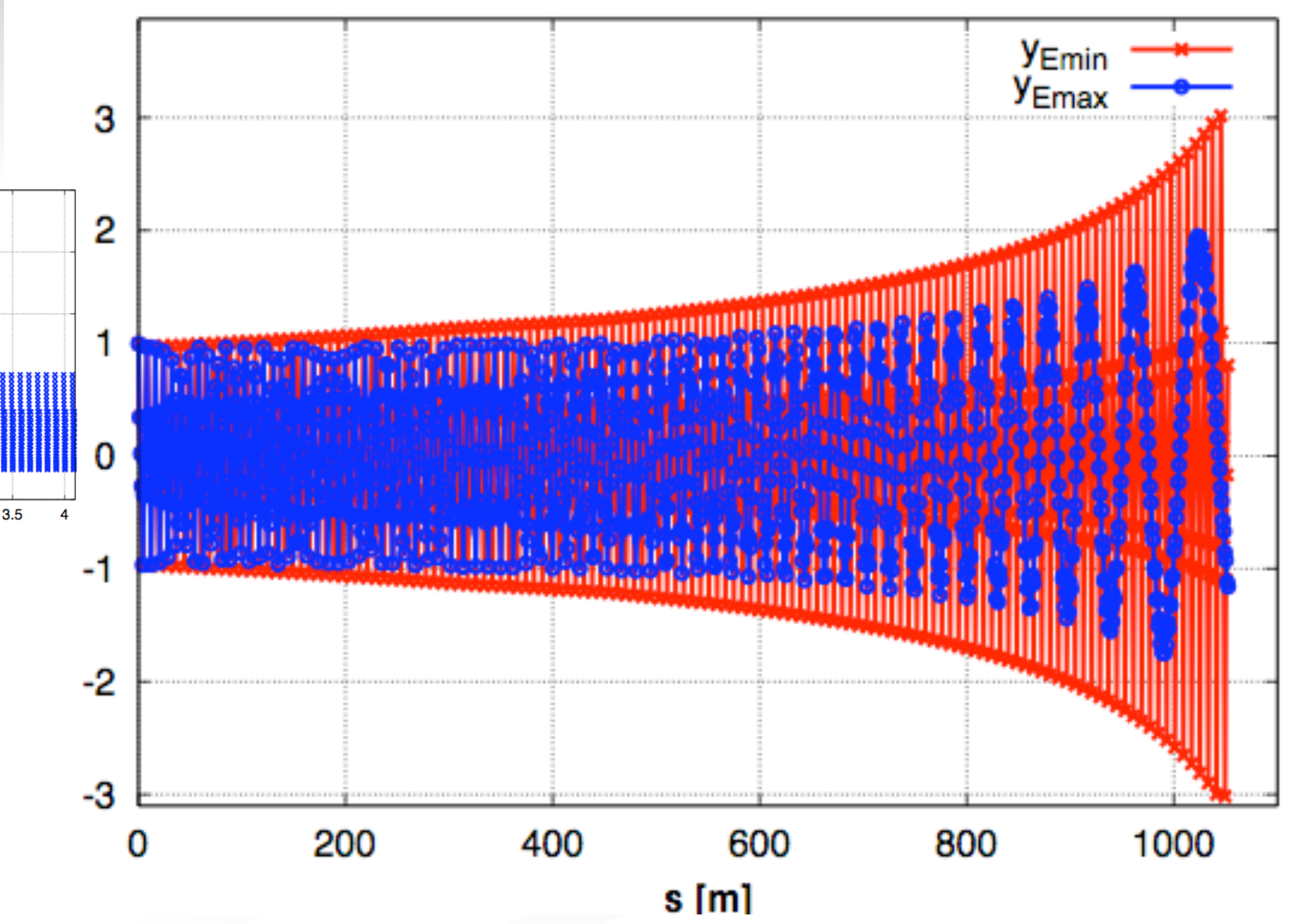
Envelope growth in an ideal machine

metrics: $y_c=\sqrt{(\varepsilon\beta)}$, $r_c=\max_{beam}\sqrt{(\varepsilon\beta)}$

$E_{Least\ dec}$: $y_c=\sqrt{(\varepsilon\beta(s))} \sim beta_{final} / beta_0$

$E_{most\ dec}$: $y_c=\sqrt{(\varepsilon(s)\beta)} \sim \sqrt{\gamma_i/\gamma_f}$

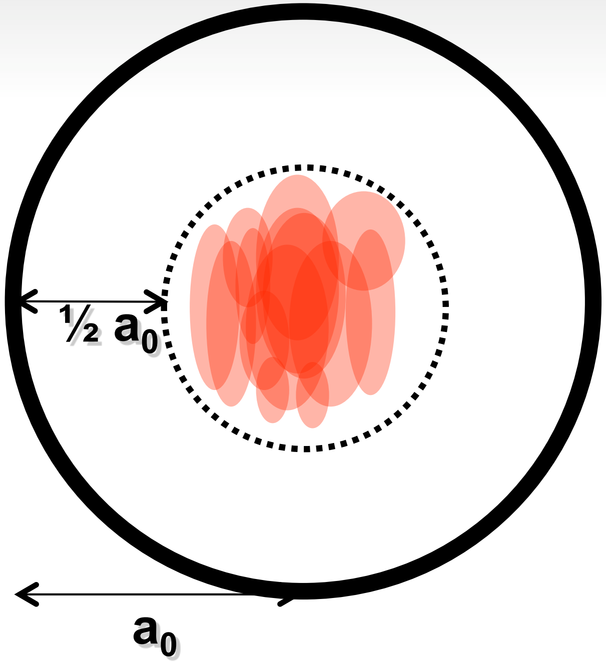


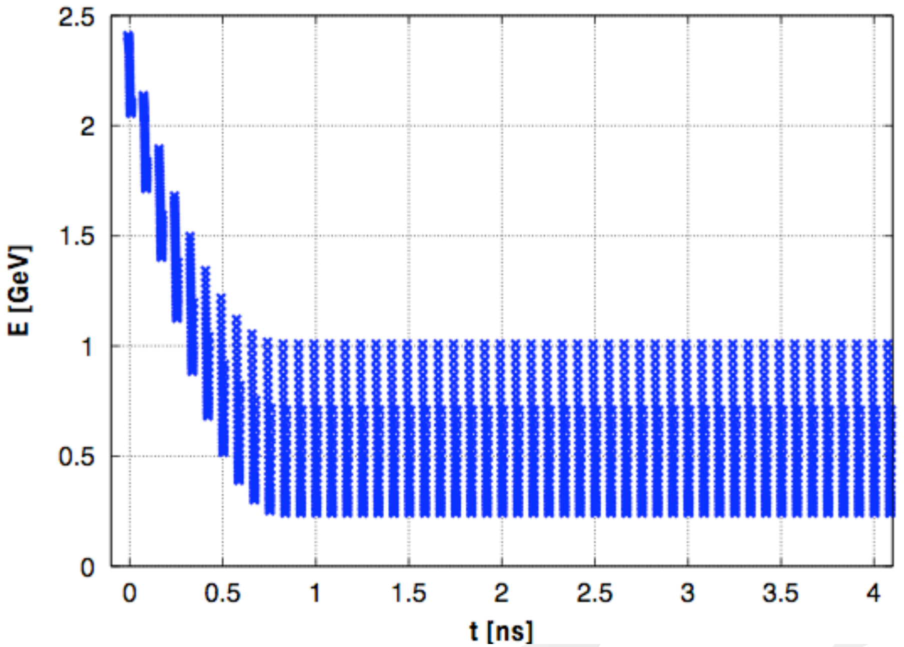


Transport challenges

Requirement: robust transport of particles of *all* energies
Criterion: 3σ of any slice of the beam must be within ½ a_0

Challenges :
I) Machine misalignment
II) PETS wake fields

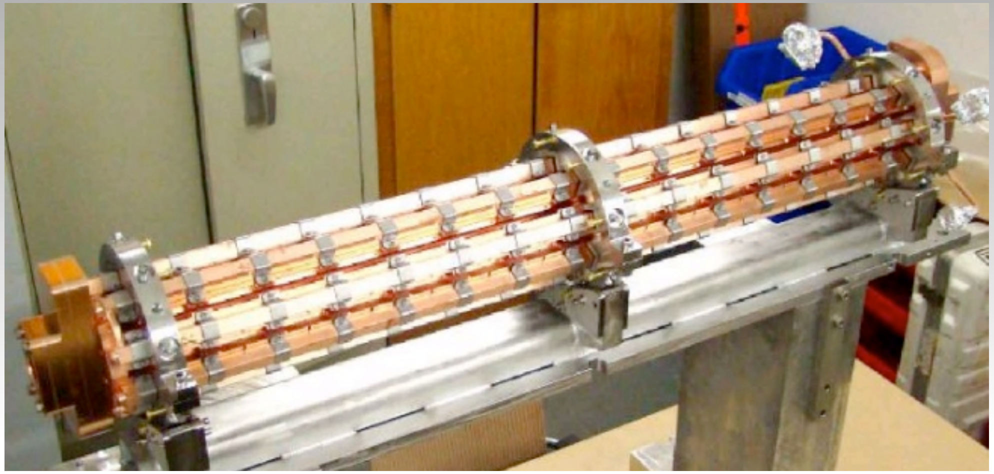




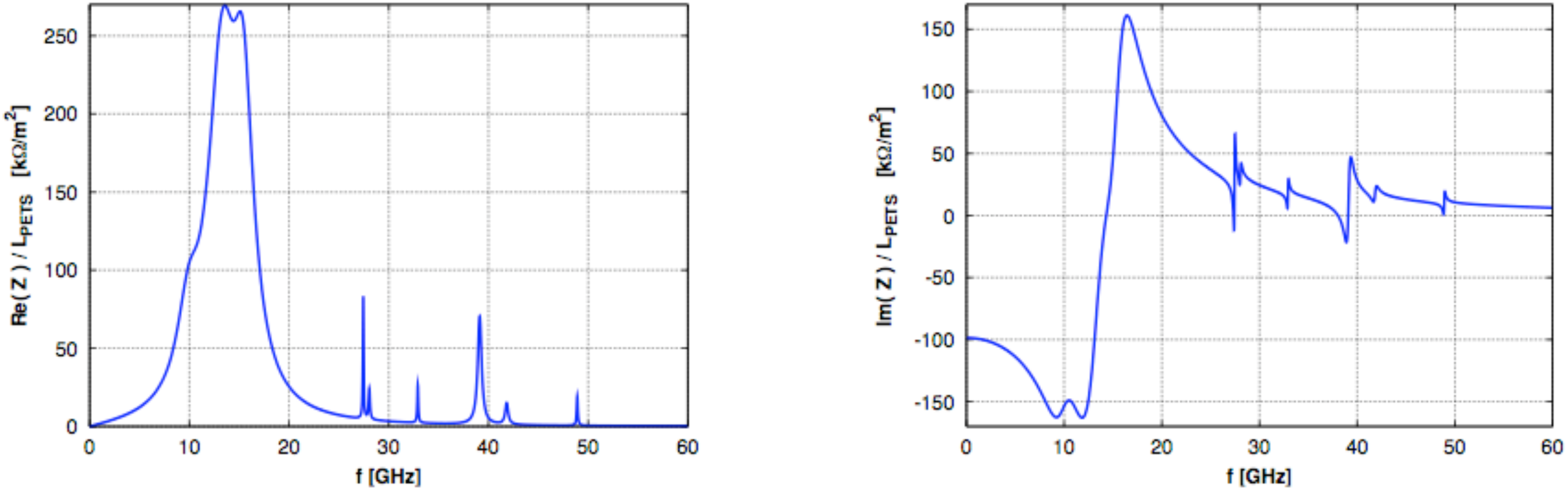
The PETS induced energy spread:
a curse for I) and a blessing for II)

Wake field amplification

PETS impedance



(Time-domain simulations with GdfidL: I. Syratchev)

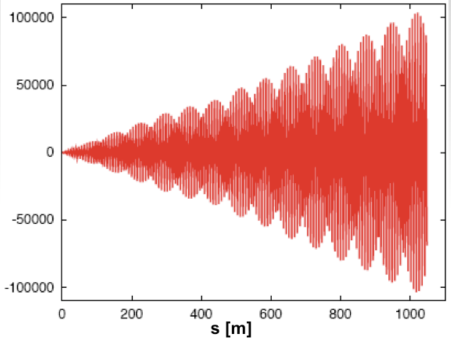


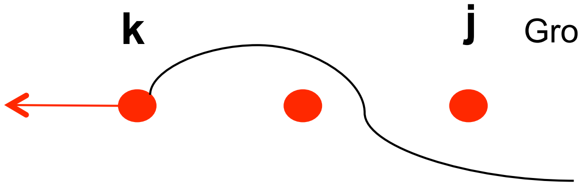
Large amplitude broad modes as well as high Q cavity modes - spectrum shown is exactly what is simulated with PLACET

Some estimations of dipole wake amplification

The amplification along a constant energy offset beam can be calculated analytically, assuming point-like bunches (PLB)
[D. Schulte, Multi-bunch calculations for the CLIC min linac], adapted for the decelerator

basic physics: trailing particle is driven on resonance, resulting in linear amplitude growth





Growth due to direct effects:

$$a_{jk} = i\Sigma_{n=1}^{N_{\rm PETS}} \frac{L_{\rm PETS}\Sigma_{l=1}^{9} W'_{T,l}(z_k - z_j)\beta^*(s_n)q_k e}{2E_j(s_n)}$$

Indirect effects: [D. Schulte]

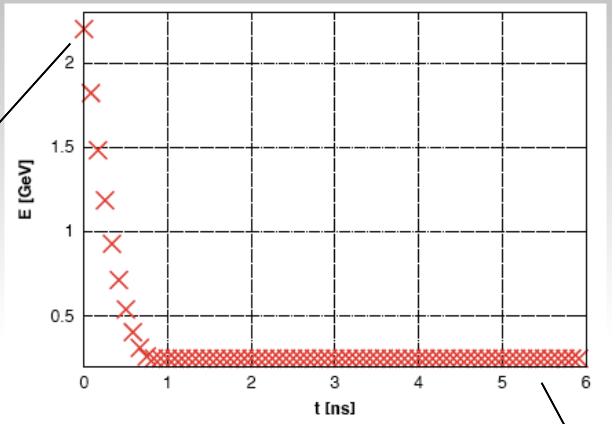
$$\lim_{m\to\infty}\left(1+\frac{\mathbf{a}}{m}\right)^m = e^{\mathbf{a}} = \Sigma_{k=0}^{\infty}\frac{\mathbf{a}^k}{k!} = \Sigma_{k=0}^{N-1}\frac{\mathbf{a}^k}{k!} \equiv \mathbf{A}$$

Final bunch offset wrt. initial bunch offset for a long line can then easily be calculated

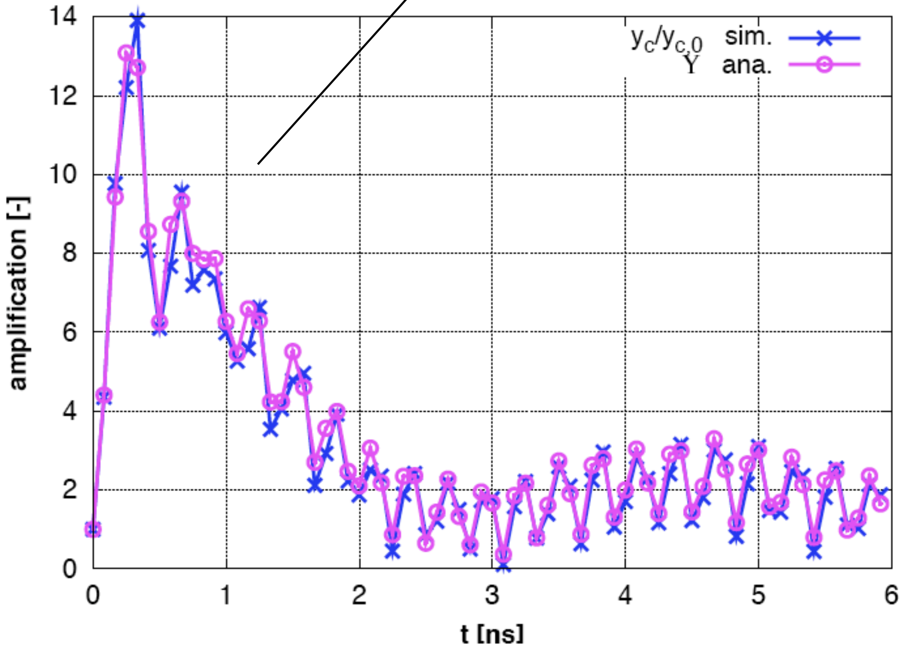
$$\mathbf{y}_f = \mathbf{A}\mathbf{y}_i$$

Analytical estimations of wake amplification

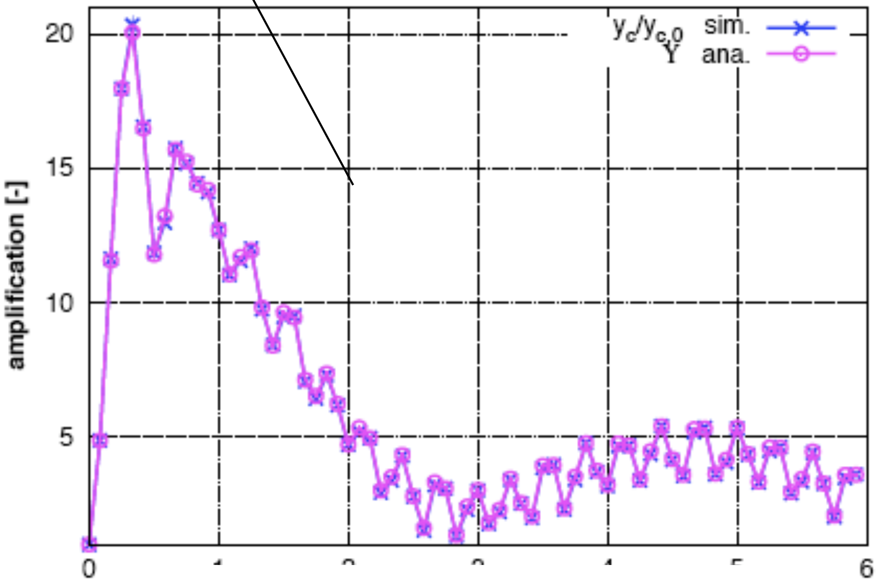
Instructive as starting point : calculation (and simulation) for point-like bunch trains experiencing most and least deceleration
(but here same E for all bunches):



Characteristic
transients ~ $a^k / k!$ + high Q effects



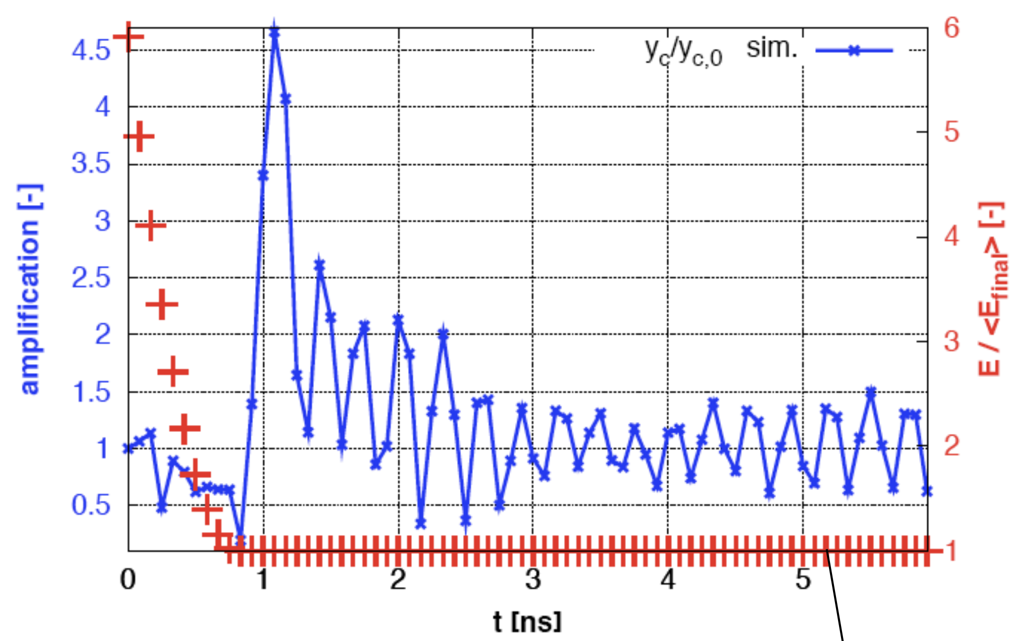
$$\Sigma \frac{1}{\beta(s_n)}$$



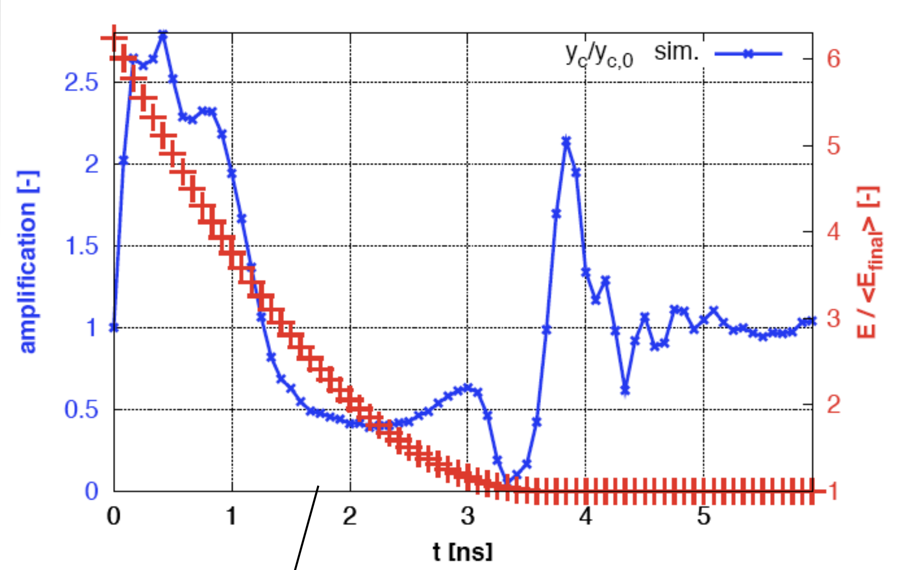
$$\int_0^L ds \frac{1}{\gamma} = \frac{L}{\gamma_{\rm final} - \gamma_0} \ln \frac{\gamma_{\rm final}}{\gamma_0}$$

Decoherence "for free" in transient

Bunch-to-bunch energy difference results in strong de-coherence. Thus, a BNS-like effect saves us, by "pushing the transient into the steady-state part, where the PETS induced energy spread is large

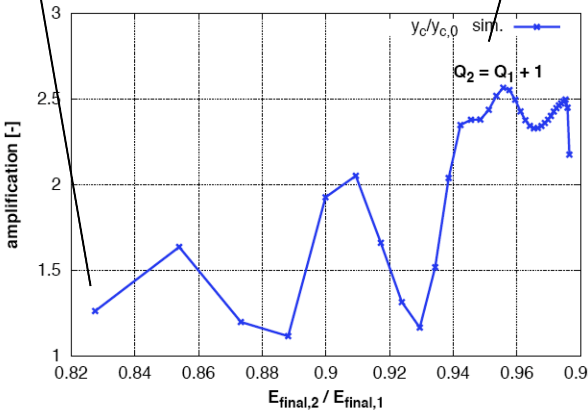


Baseline PETS (v_g ~ 0.5)



"slow PETS" design (v_g ~ 0.15)

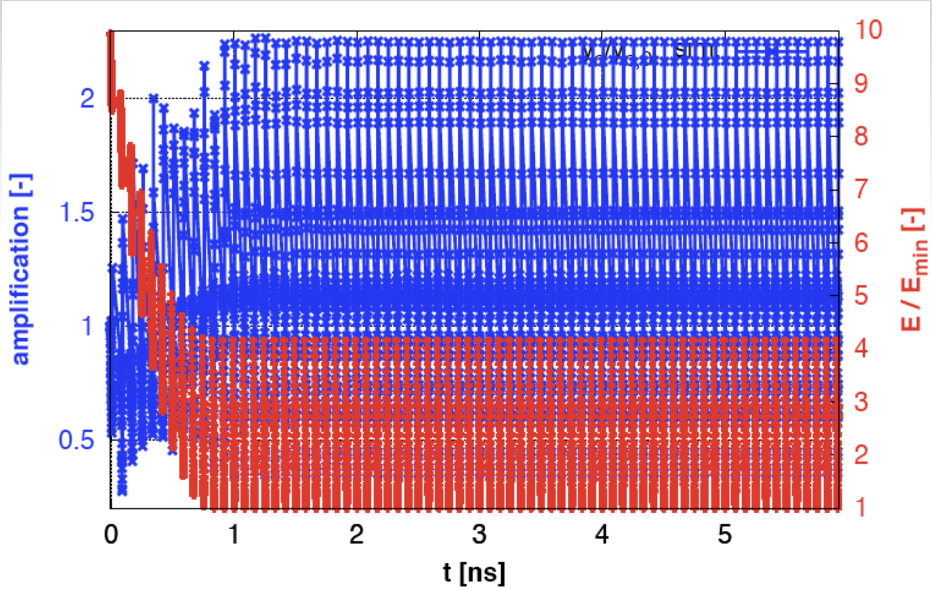
(Power ~ R'/Q / v_g)



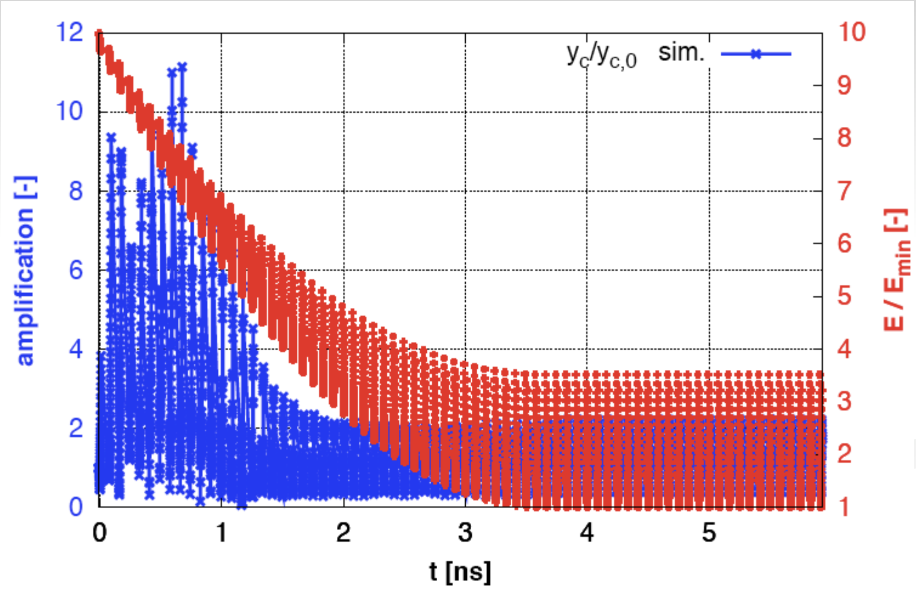
$$Q = \frac{1}{2\pi} \int_0^L \frac{ds}{\beta(E,s)}$$

Full simulation (long bunches)

Single-bunch effects aggravates the situation in the transient for the "slow PETS", and also leads to amplification of factor ~2 in the steady-state



Basline PETS



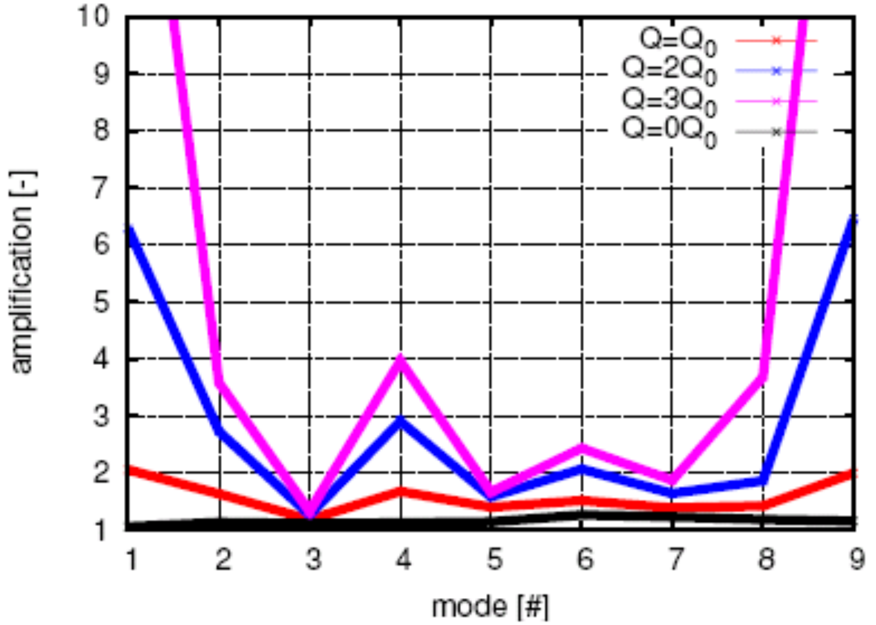
Slow PETS

Conclusion: sufficient de-coherence at train head is needed for a robust PETS design

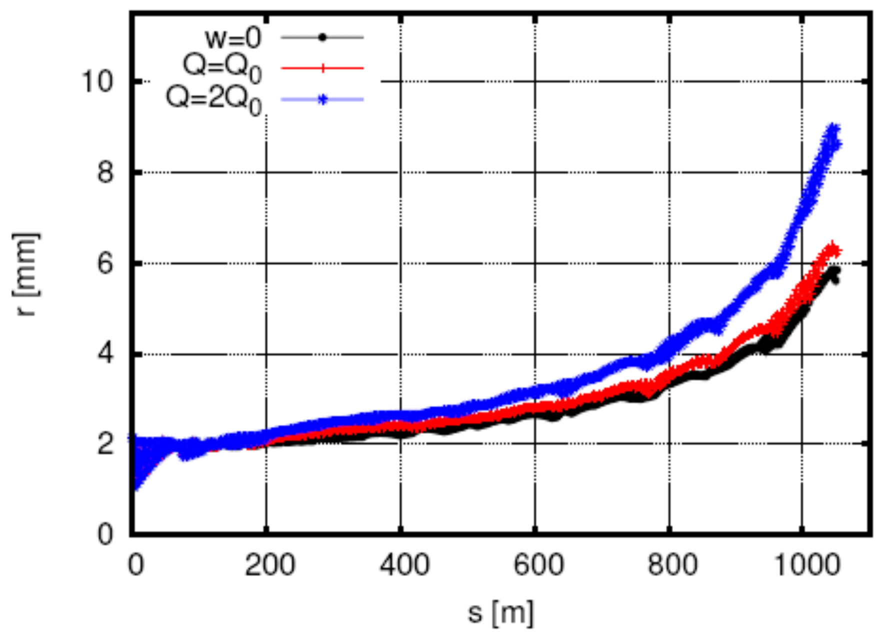
Q_2 - Q_1 >~ 2.5 seems to be a good rule of thump

Intrinsic energy spread (not included here) mitigates the situation, however changes in transverse modes might aggravate the situation

Summary of PETS wake analysis



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



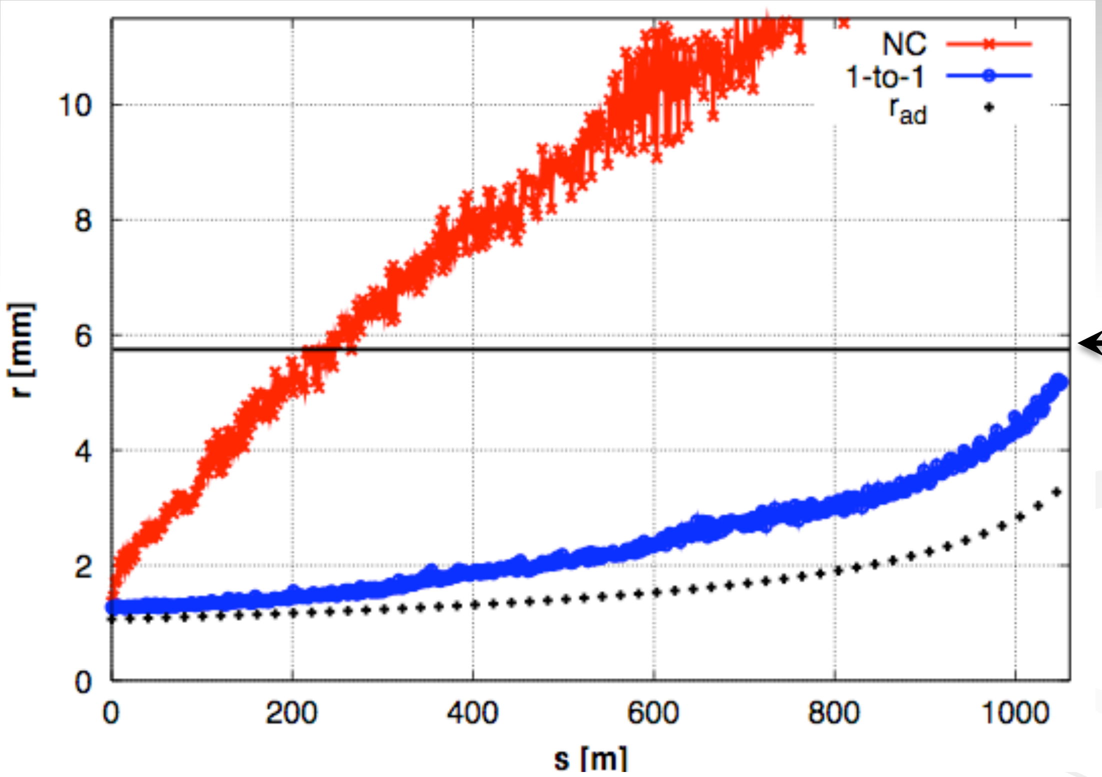
Amplification of total beam envelope, r, jitter on all mode frequencies (1σ jitter in total)

For the CLIC decelerator PETS baseline parameters provide adequate mitigation of the dipole wake, but the margin is small

Machine misalignment

Orbit correction

(unsteered envelope growth: combined effect wakes and quad kicks + ad. undamping)



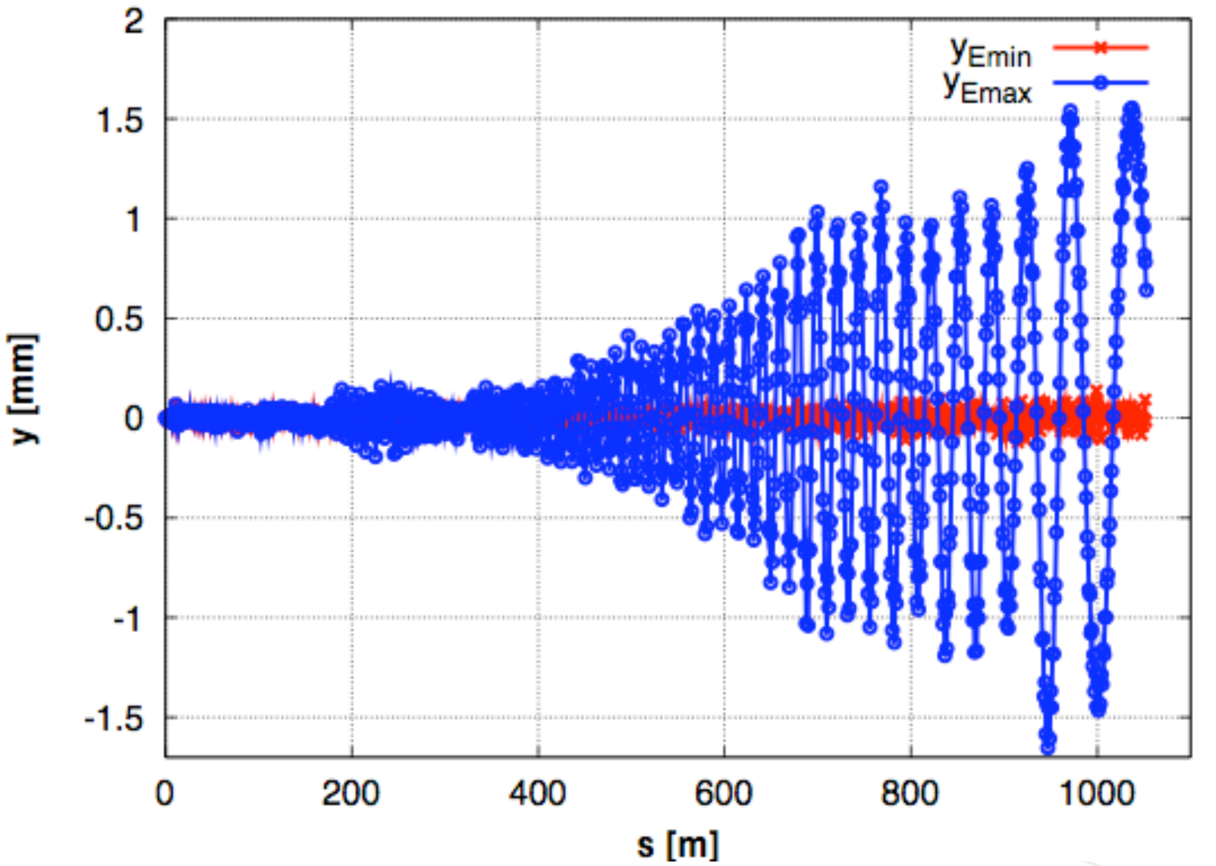
aperture

wake field limit

Simple steering into the centre of the BPM (1-to1) gives relatively large residual beam envelope (even with BPM accuracy of 20 μm and one BPM per quad)

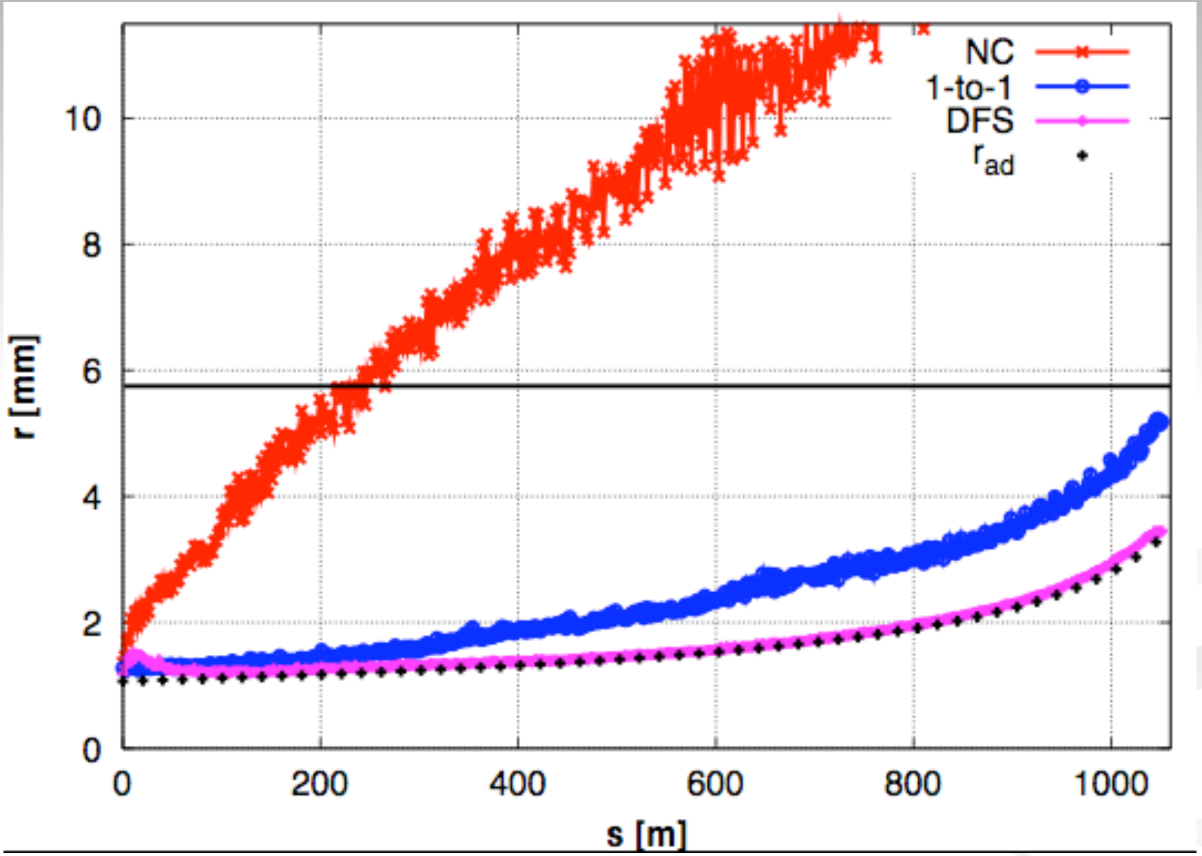
Standard simulations: 100 machines, while we want 99.98% of machines to work (48 decelerators to work together, 99.98%)

Result of 1-to-1 correction



- Low **energy centroid is confined** to some 10 μm
- Residual kicks in quadrupoles drive dispersion
- Different energy particles: large dispersive trajectoris

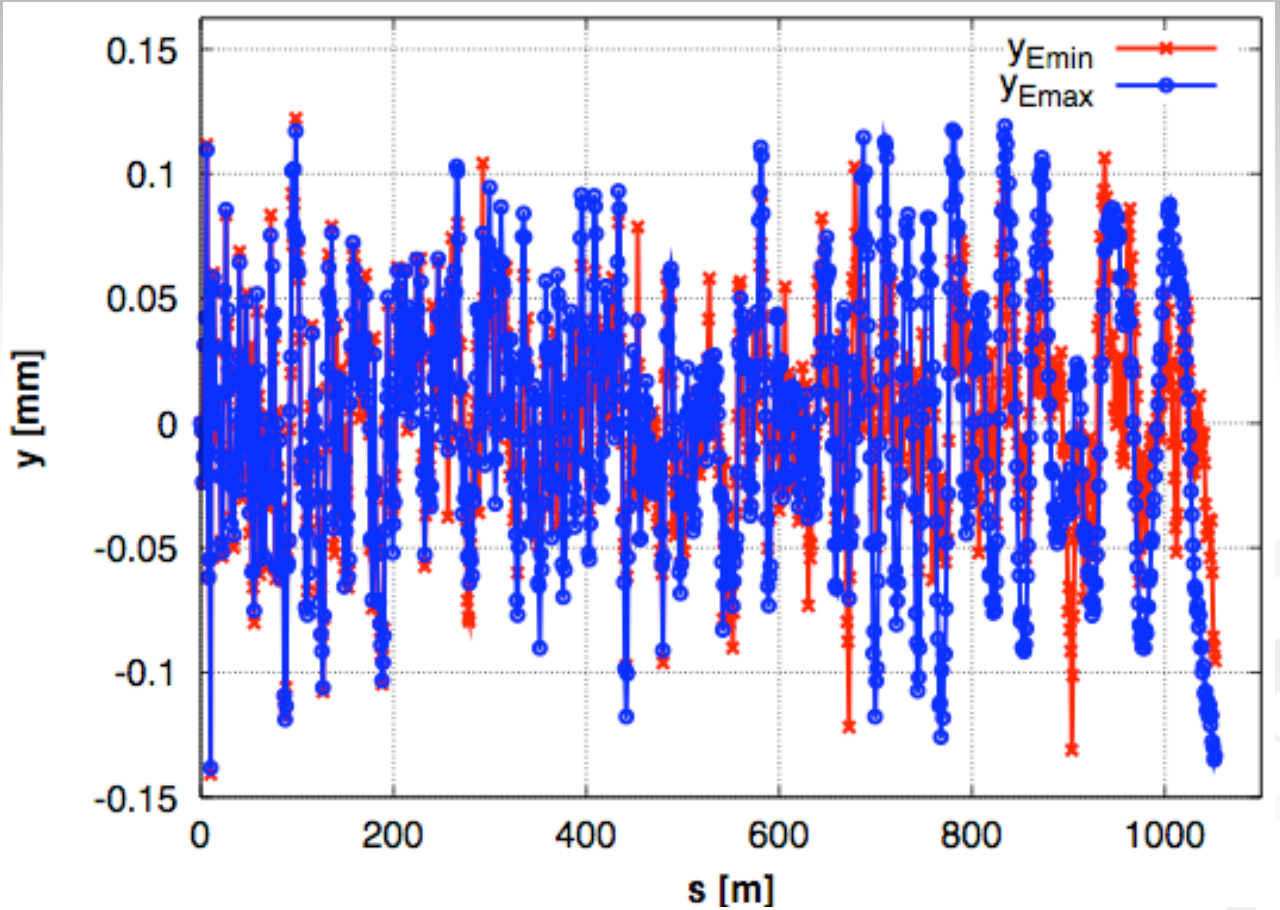
Dispersion-free correction



Dispersion-free correction takes out dispersion and drives the whole beam very close to the BPM centres

NB: correction strategy is to first perform 1-to1 then DFS

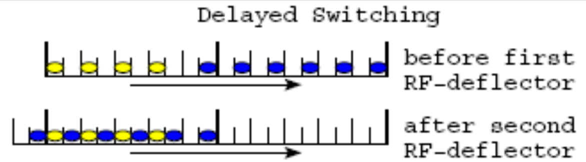
Result of dispersion-free steering

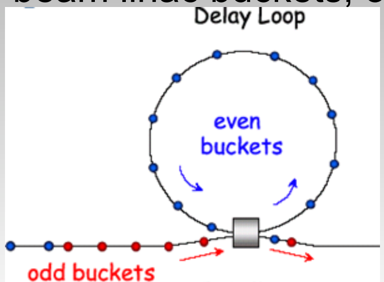


- Dispersive errors reduced to almost zero

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

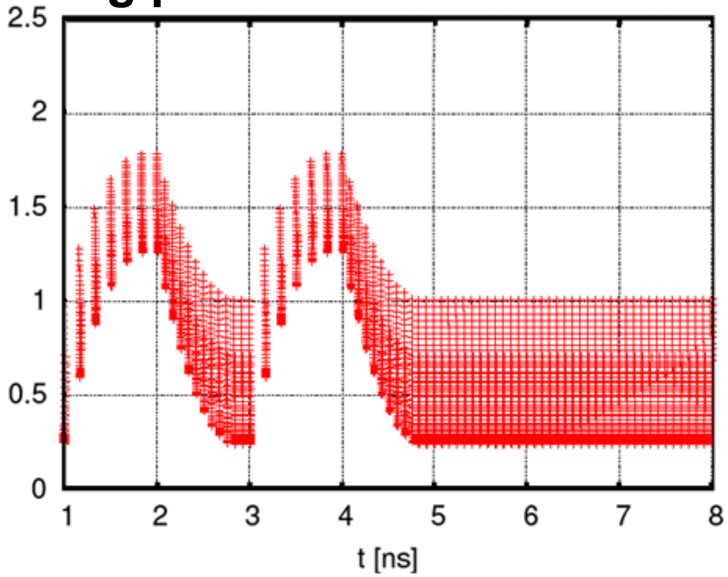




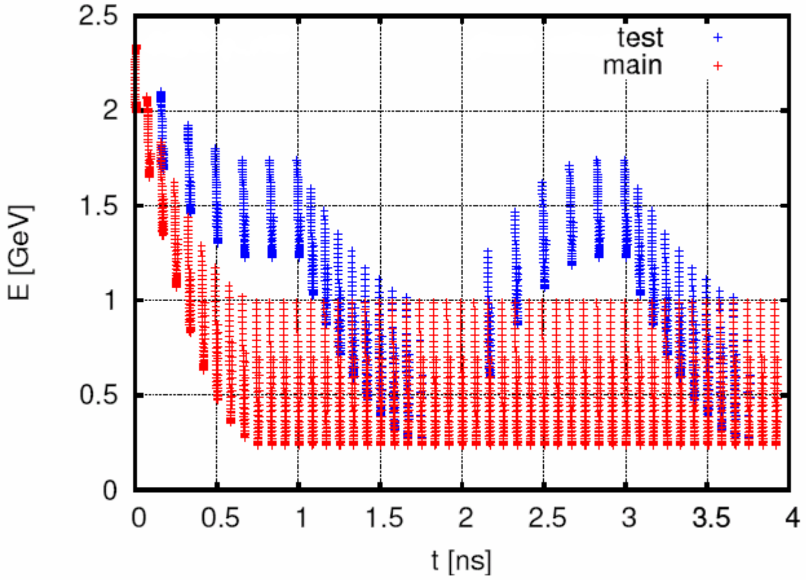
Example of DFS beam generation scheme:
Of the 12 initial E+O pulses:

- **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

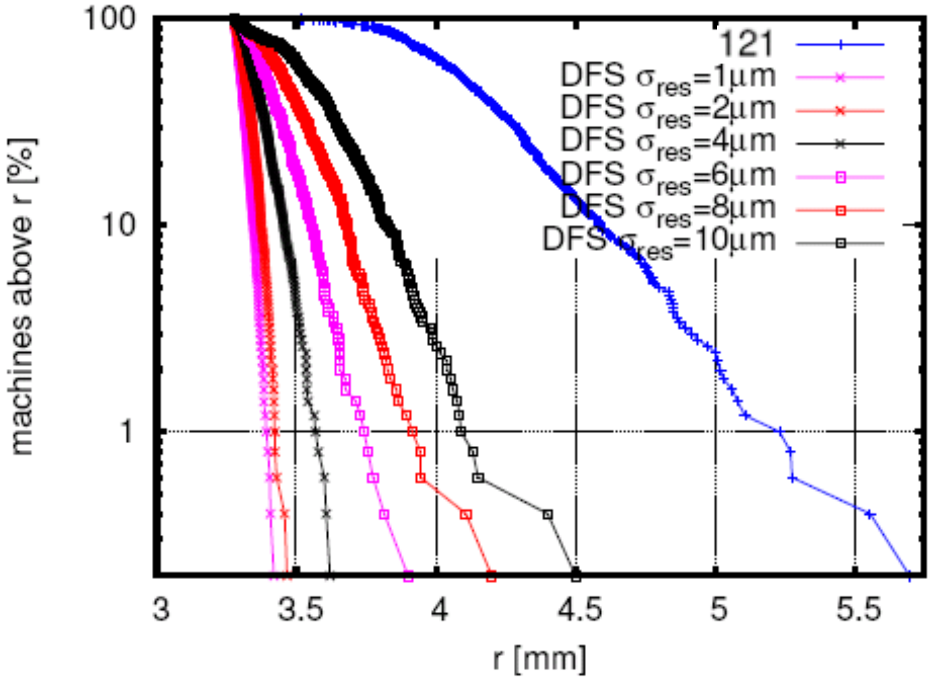
- **Advantages with this method :**
  - **quadrupole strengths are kept constant – machine unchanged**
  - **main-beam and test-beam can be combined in one pulse**
  - **Large energy-leverage , almost insensitive to DFS weigth over 4 O.M.**

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

Specifications resulting from wake field and correction works

Tolerance limits for each machine misalignment for each misalignment specified by requiring envelope growth of max. $r_c < 1$mm originating this misalignment alone

- We remind of the confidence required p_{sector}>99.98%
- Cannot simulate enough machines to test this statistically, so we investigate the tail of the the accumulated distribution of the machine envelopes, r
- By adopting BPM precision ~ 2 μm we ensure minimal envelope growth with respect to the minimum possible, taking into account effects of transverse wake fields machine misalignment



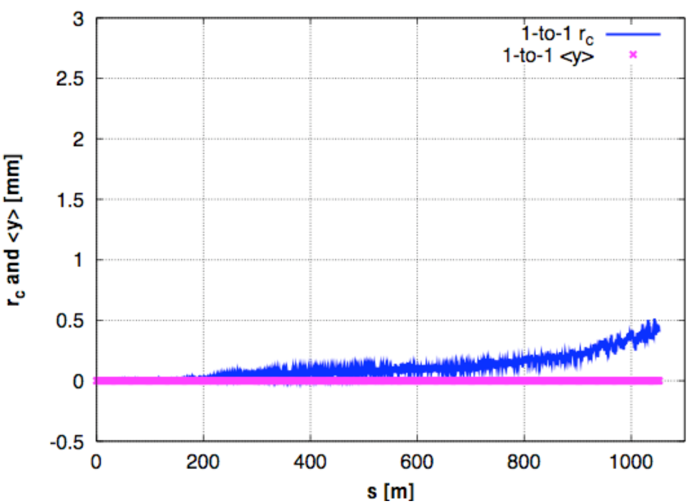
Tolerance	Value	Comment
PETS offset	100 μm	$r_c < 1$ mm fulfilled
PETS angles	~ 1 mrad	$r_c < 1$ mm fulfilled
Quad angles	~ 1 mrad	$r_c < 1$ mm fulfilled
Quad offset	20 μm	Must be as small as possible. 20 μm is within spec. of alignment system ($r_c < 1$ mm ⇒ quad offset of 1 μm)
BPM accuracy	20 μm	Must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

Conclusions

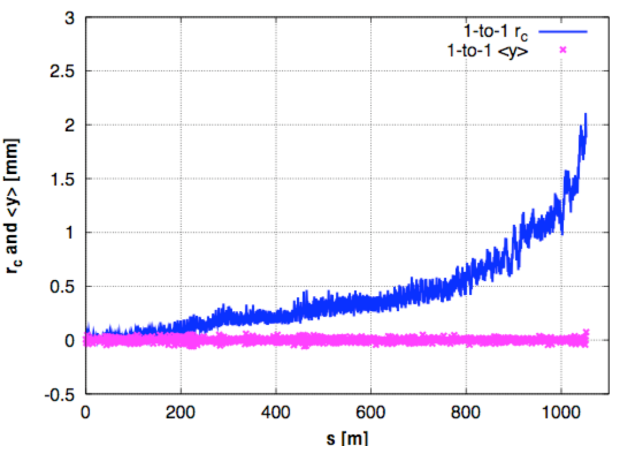
- The Beam Dynamics studies have found solutions to the main challenges of the CLIC Drive Beam Decelerator **the wake fields and alignment**
- Study has been tight integration Bead Dynamics and RF people
- First experimental results (DFS in CTF3, beam in TBTS PETS) gives good confidence in simulation studies
- Not studies in detail (yet):
  - **Space Charge**, γ_{but}~500, but I~40 kA -> direct SC few % effect on transverse focus spread (small wrt. to PETS induced spread) Further study would profit from inclusion of space charge in PLACET
  - Vacuum tolerances (**Ion effects**), for the moment being implemented in PLACET (G. Rumolo, B. Dalena), se also next talk by M. Fitterer
  - Halo generation and tracking: se next talk by M. Fitterer

The end (extra)

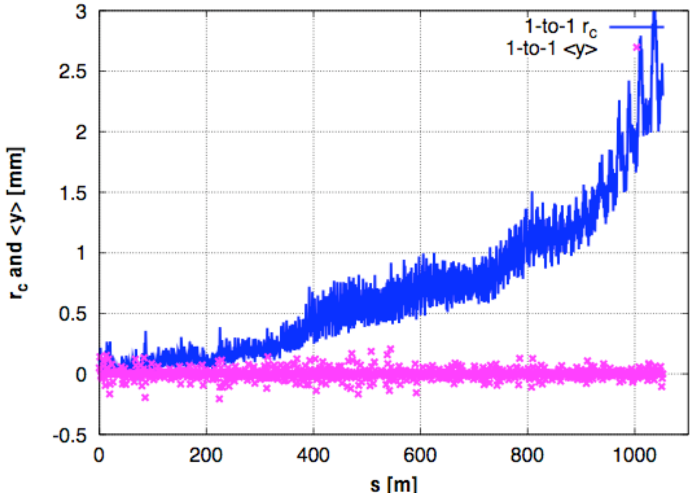
Effect on reducing number of BPMs



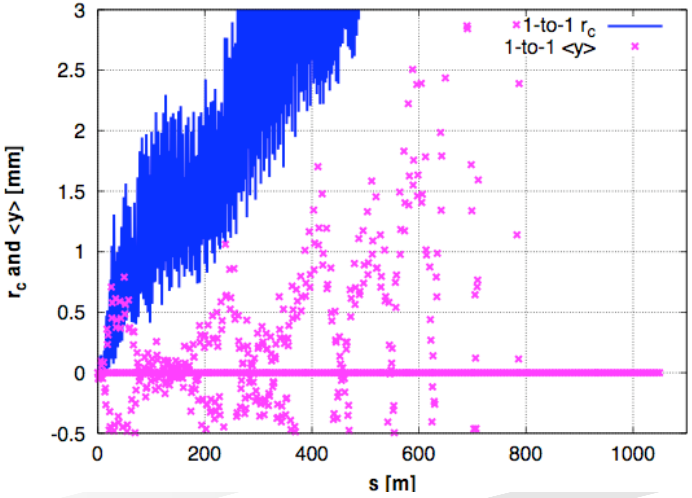
N=1



N=2



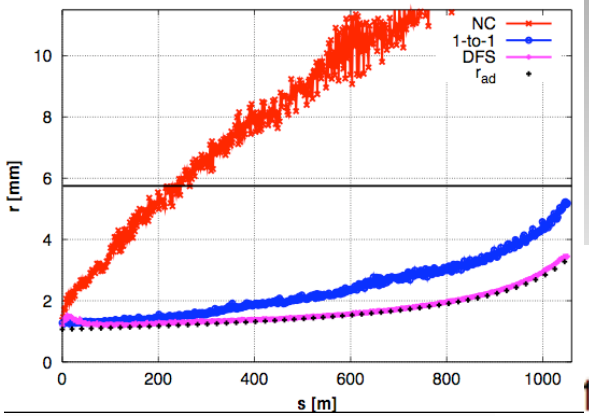
N=3

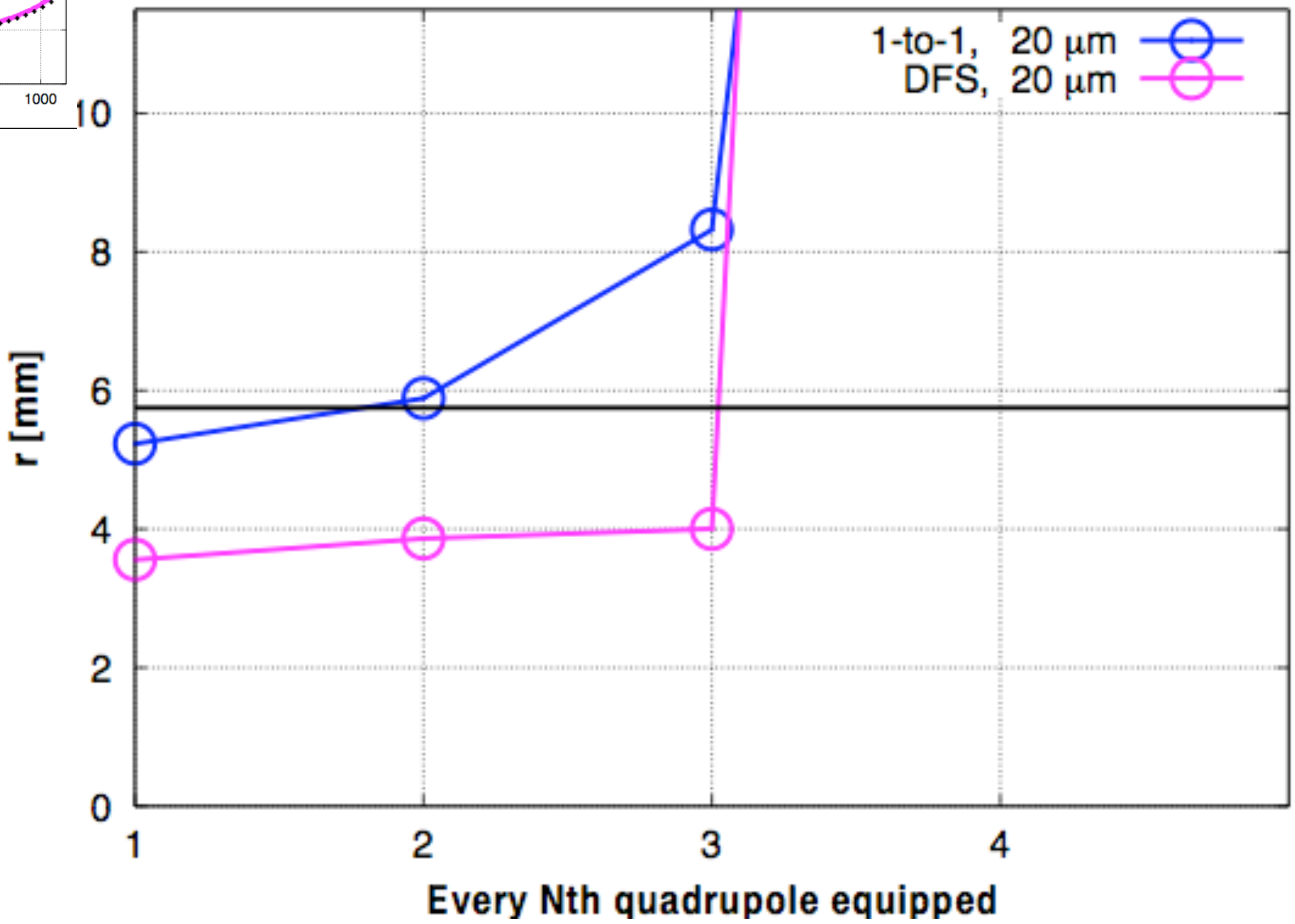


N=4

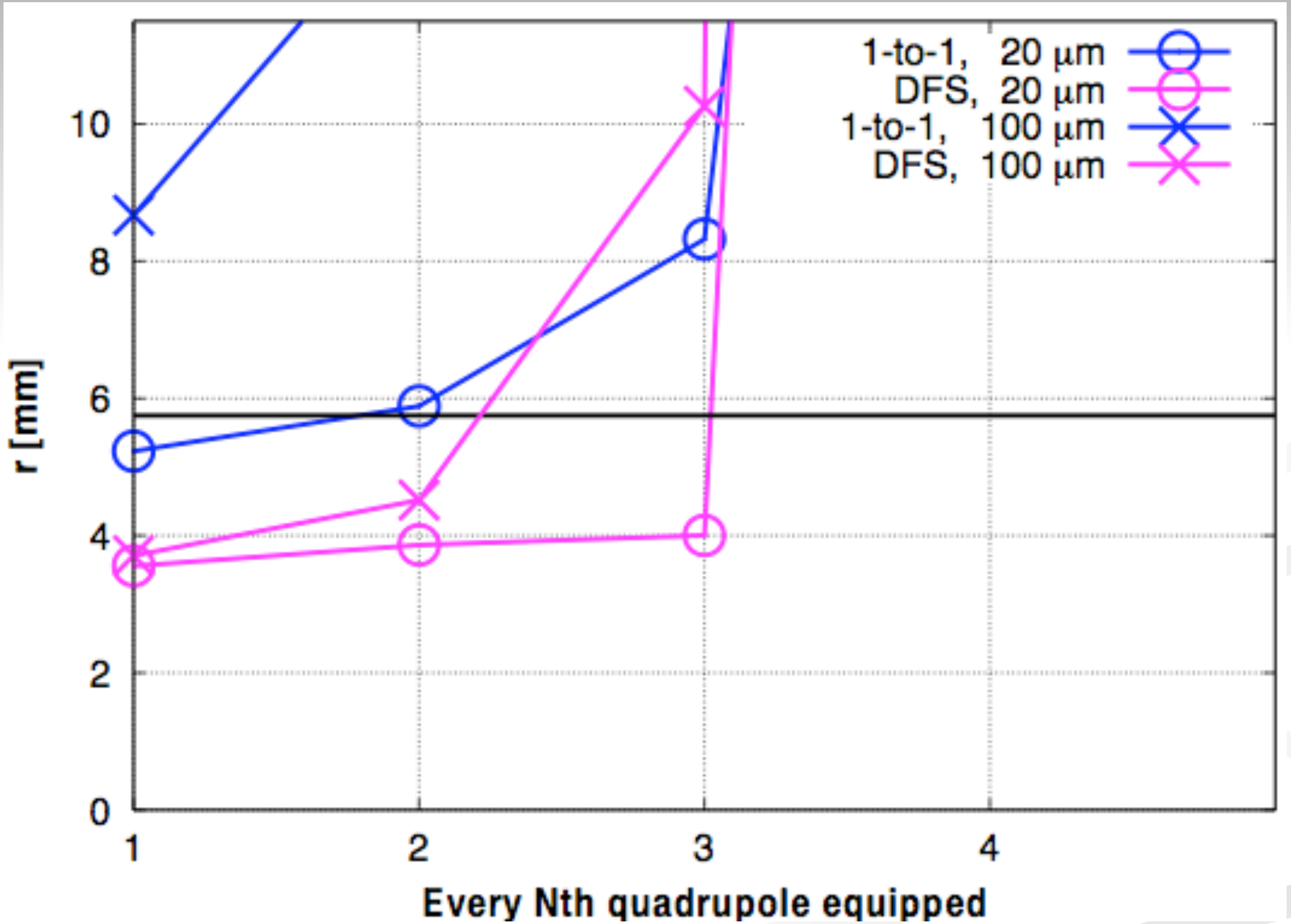
(perfect BPMs and single machine simulated, for illustration purposes)

Total effect – quad rms 20 μm





Total effect – quad rms 100 μm



Equipping only every 2nd BPM puts harder limits on alignment