The CLIC Decelerator

Overview and beam physics

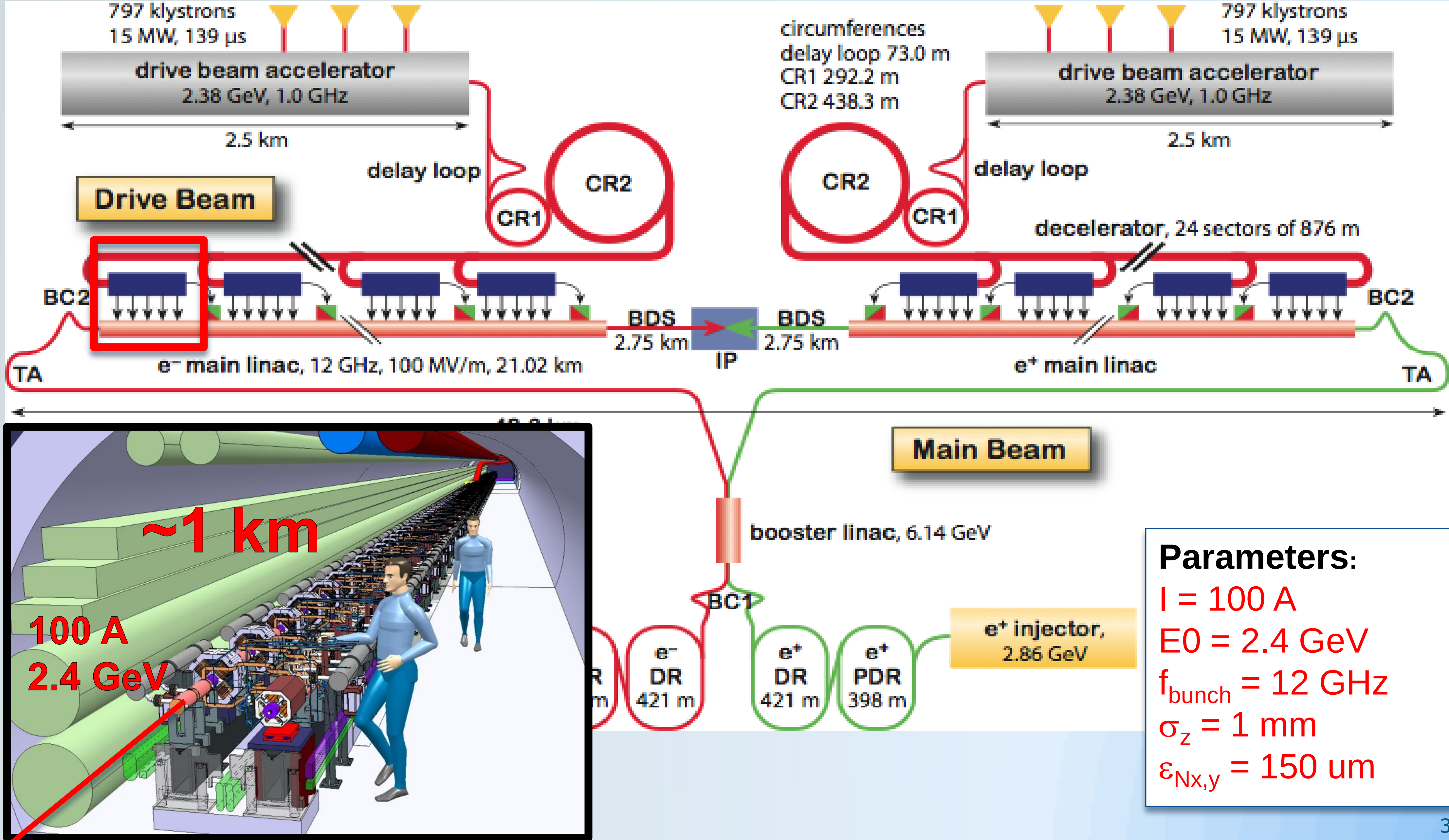
International Workshop on Linear Colliders 2010

October 20, 2010

Erik Adli, Department of Physics, University of Oslo and CERN

- Requirements
- Beam physics
- Component specifications
- Test facilities
- Conclusions

The CLIC Drive Beam decelerators



Parameters:

I = 100 A

E0 = 2.4 GeV

f_{bunch} = 12 GHz

σ_z = 1 mm

$\varepsilon_{Nx,y}$ = 150 um

Requirements: power production

Decelerator: power source for main linacs. Power production:

$$P = \frac{1}{4}(R'/Q)\frac{\omega_{\mathrm{rf}}}{v_g}L^2_{\mathrm{PETS}}\eta^2_{\Omega,\mathrm{PETS}}I^2F^2(\lambda)F^2(\phi)$$

Requirements for 1% luminosity loss: $\Delta E/E < 7 \times 10^{-4}$.
Converted to drive beam decelerator requirements :

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \approx 0.01\left[\left(\frac{\sigma_{\phi,coh}}{0.2^\circ}\right)^2 + \left(\frac{\sigma_{\phi,inc}}{0.8^\circ}\right)^2 + \left(\frac{\sigma_{I,coh}}{0.75\times10^{-3}I}\right)^2 + \left(\frac{\sigma_{I,inc}}{2.2\times10^{-3}I}\right)^2 + \left(\frac{\sigma_{\sigma_z,coh}}{1.1\times10^{-2}\sigma_z}\right)^2 + \left(\frac{\sigma_{\sigma_z,inc}}{3.3\times10^{-2}\sigma_z}\right)^2\right]$$

D. Schulte, WG2,6,7,8, Wednesday 14:00

The drive beam generation is discussed separately : WG6, Session5, Thursday 08:30

Here we focus on the consequences for the decelerator.

Decelerator requirements

The decelerator beam transport : robust performance of each of the 2 x 24 decelerator sectors - 42 km beam line. Will require a very large number of components.

A number of studies have been performed to with the aim to optimize specifications, in order to contain cost and power consumption (this talk).

- Requirements
- **Beam physics**
- Component specifications
- Test facilities
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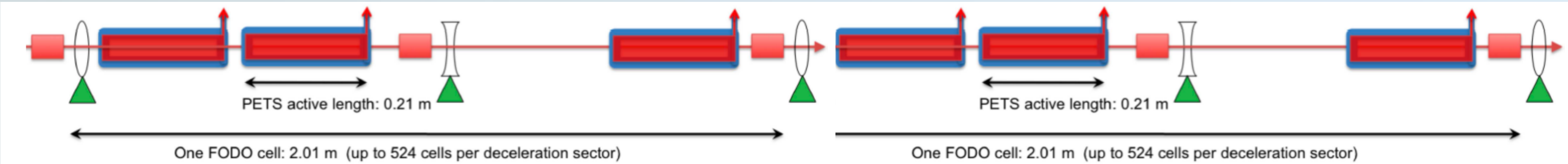
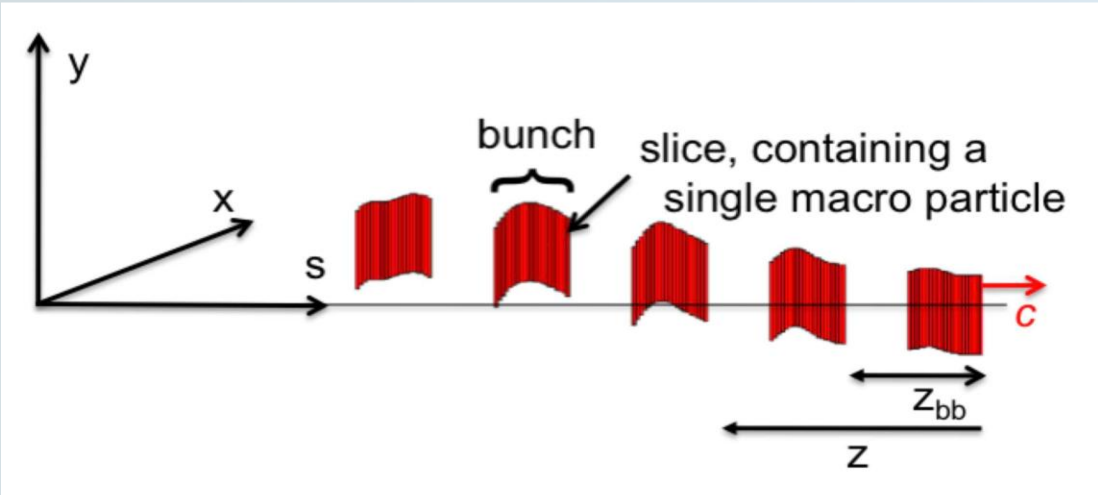
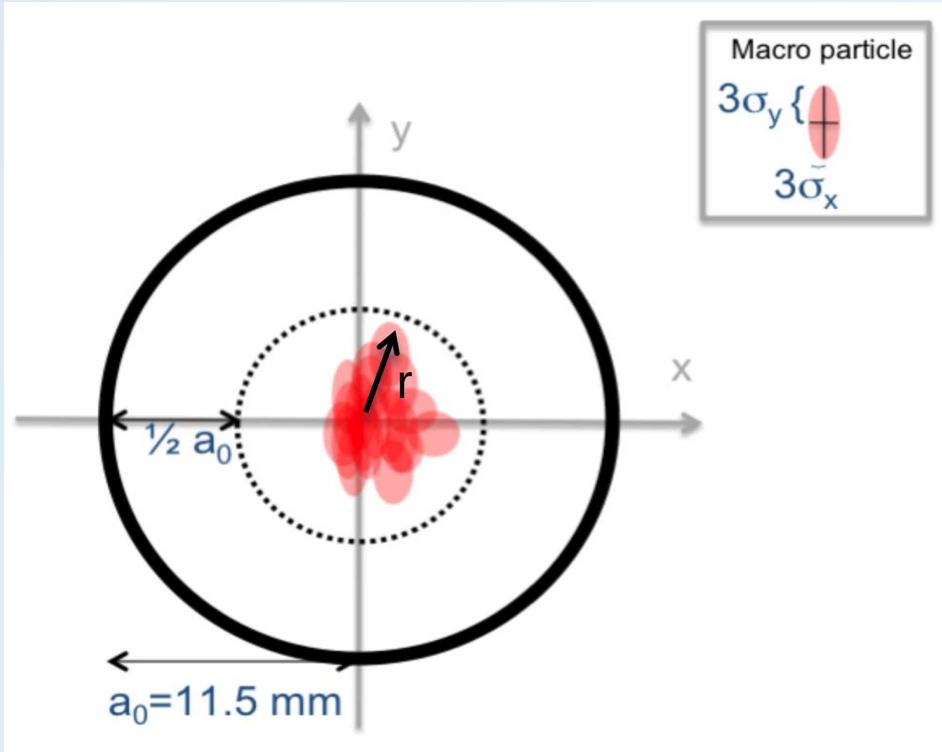
Decelerator studies

Main tool: simulation studies (tracking code PLACET), with an element representing the Power Extraction and Transfer Structures, including fundamental and dipole modes wake field calculations, and both single and multi-bunch effects.



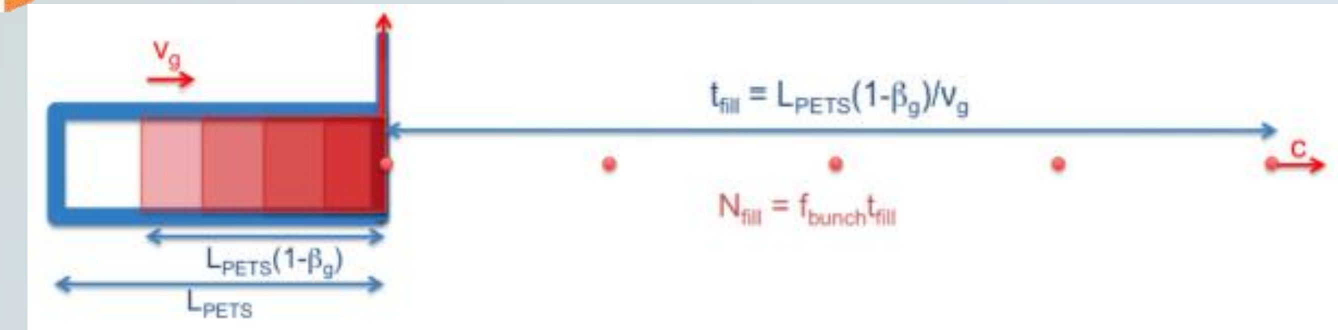


Macro-particle beam model, sliced beam with tracking of 2nd order moments



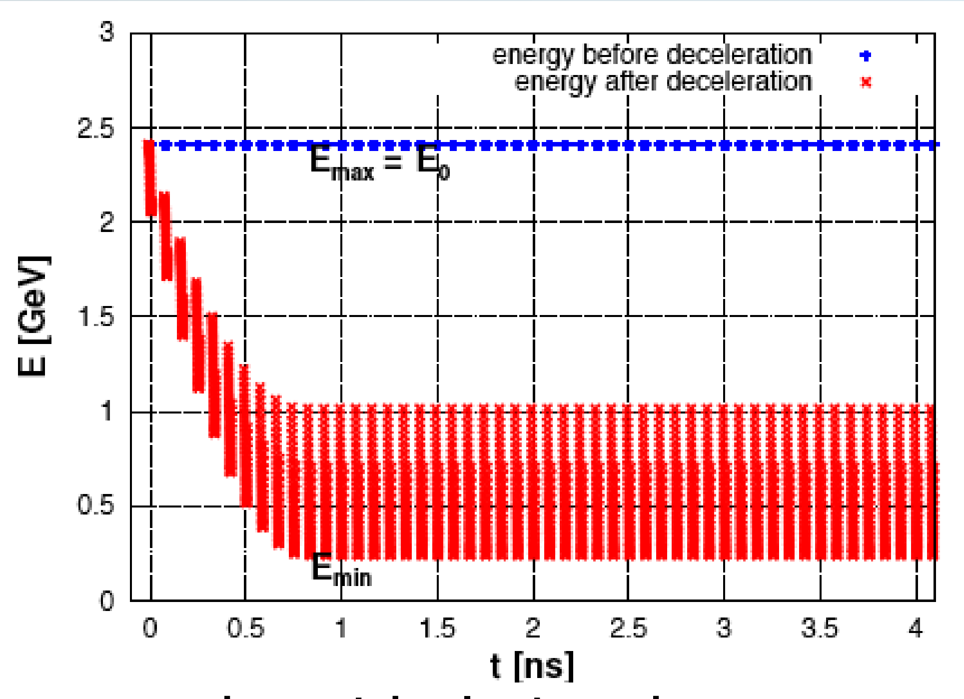
Simulation metric: r = 3σ of *worst* beam slice

PETS induced energy spread

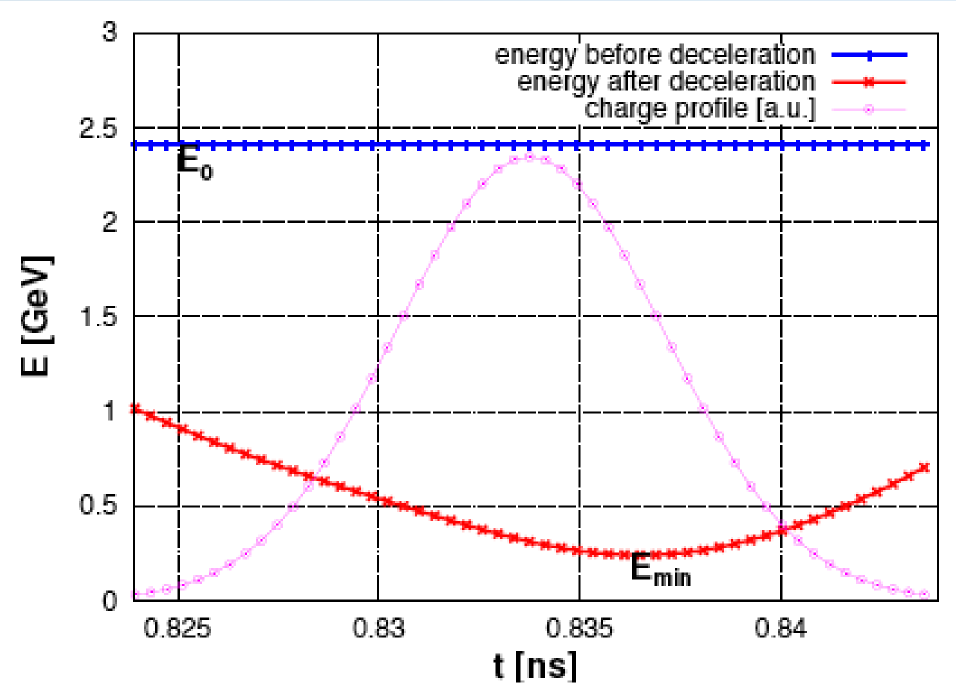


$\eta_{extr} = 0.90$

$$E_{\mathrm{most}}(n) = E_0(1 - \eta_{\mathrm{extr}}\frac{n}{N_{\mathrm{PETS}}})$$



beam at decelerator end
(pilot beam, w/o beam loading compensation)



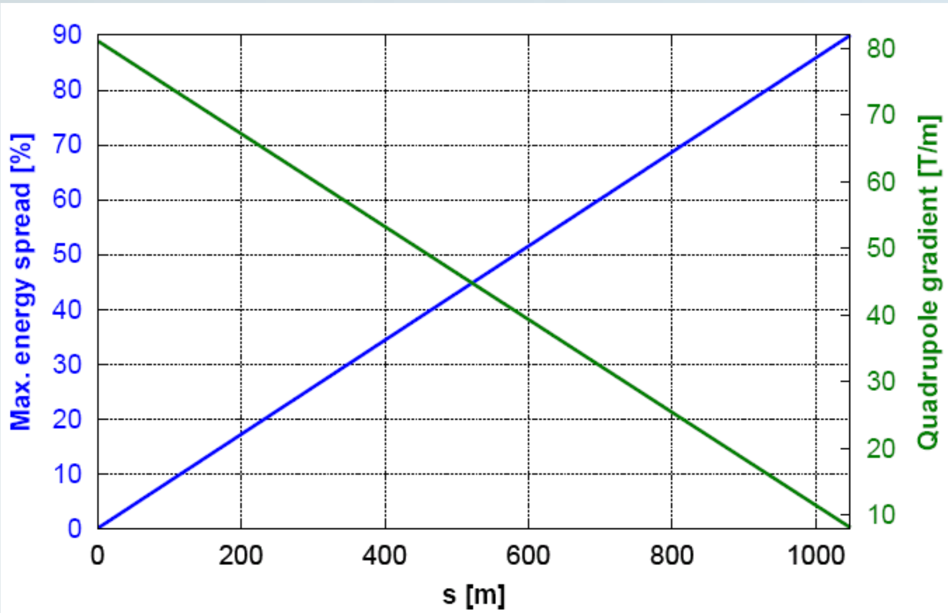
steady-state bunch at decelerator end
(pilot beam, w/o beam loading compensation)

Decelerator beam: the high group velocity PETS will induce up to **90% energy spread** at the decelerator end, as well as significant intra-bunch energy spread. To ensure reliable rf power production it is of importance that electrons of all energies are robustly transported along the lattice**.**

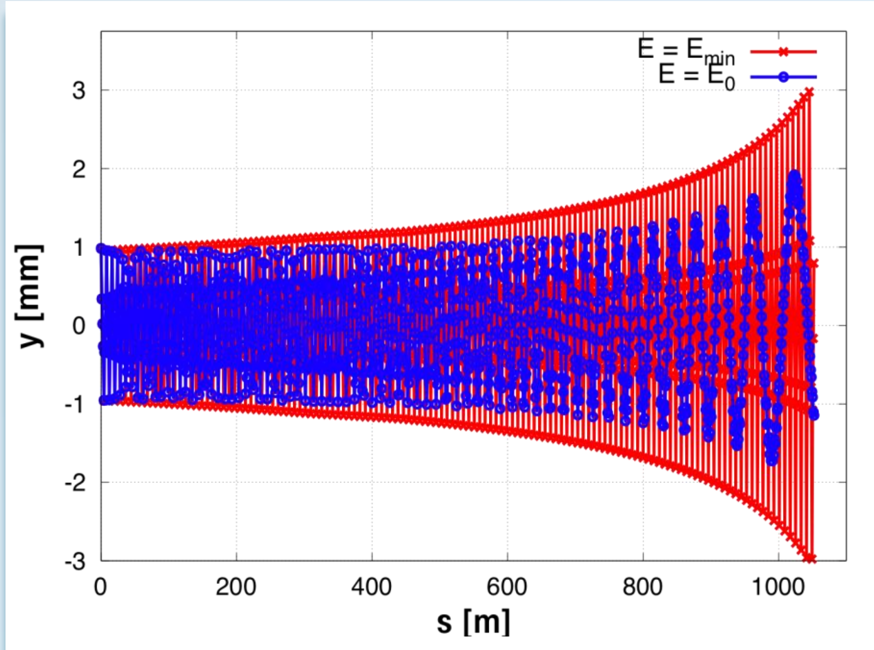
Overall criterion for beam transport r < ½ radius (5.8 mm)

Focusing strategy

- Focusing strategy: lowest energy particles ideally see constant phase-advance $\mu \approx 90°$
- Higher energy particles see phase-advance decreasing from $\mu \approx 90°$ to $\mu \approx 10°$
  - Perfect machine and beam : high energy envelope contain in low energy envelope
  - Energy acceptance : -3% of E_0 at the entrance; but increasing along the lattice
  - Each of quadrupoles should ideally have a different gradient



$$k_{E_0}(n) = k_0(1 - \eta_{\rm extr} \frac{n}{N_{PETS}})$$



3-sigma particles in a perfectly aligned machine

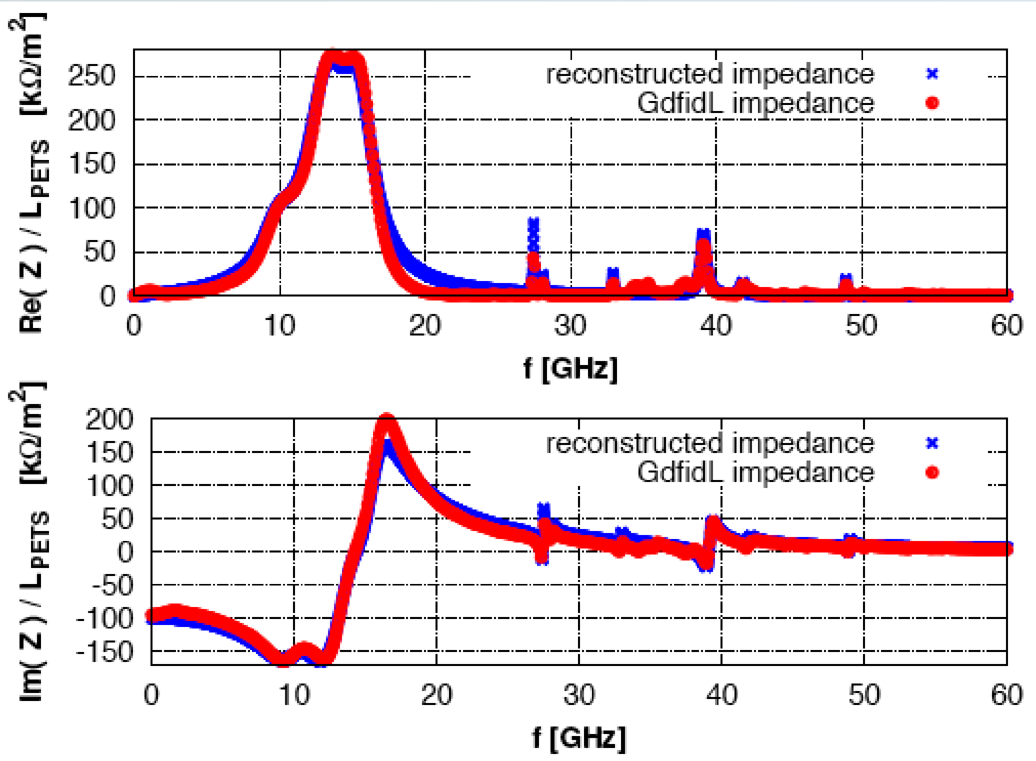
Least decelerated particle has a tune of $\mu \approx 70$, and an increase of β of $\beta_{Fmax}(E_0)/\beta_{F0} = 4$.
Most decelerated particle has a tune of $\mu \approx 135$, and an increase of action of $J_{max}(E_{min}) / J_0 = \gamma_0/\gamma_f = 10$

$$\sigma(s) = \sqrt{2J(s)\beta(s)}$$

3-σ envelope for perfect machine: r_{ad} = 3 mm

Transport challenge: dipole wake

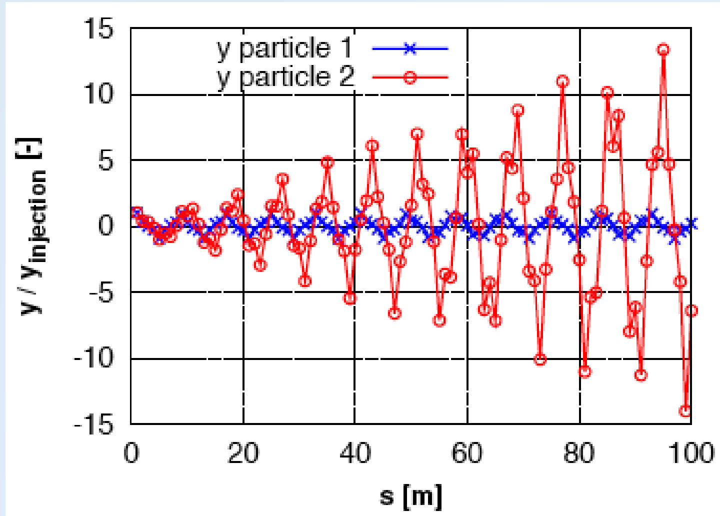
Sufficient mitigation of transverse electro-magnetic forces, due to the **PETS high group velocity dipole wake**, has been a major challenge for the two-beam accelerator concept.



$$W_T'(z) = 2k_T' \sin(\frac{\omega_T}{c} z) \exp(-\frac{1}{2} \frac{1}{Q(1-\beta_T)} \frac{\omega_T}{c} z)$$

Tracking simulations approximate simulated PETS impedance by a number of discrete modes, each characterized by $\{f, k_T, Q, \beta\}_i$

PETS 12 GHz prototype (TBTS 1 m)



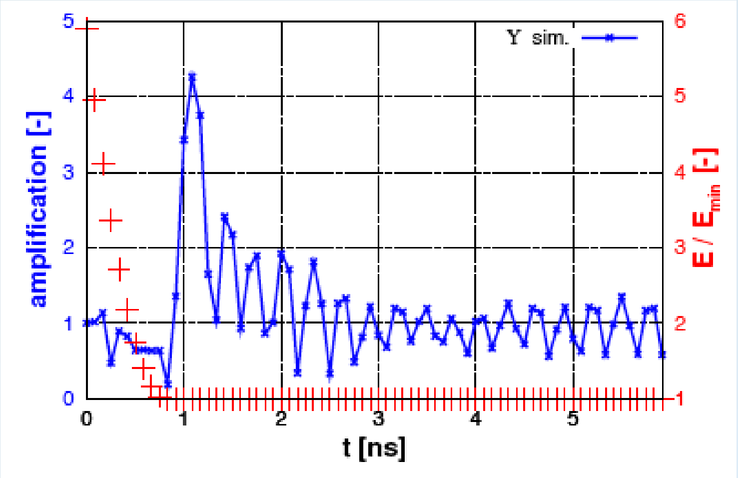
Principal effect of dipole wake: resonant linear increase of betatron amplitude of driven particle.

A. Cappelletti, WG6, Wednesday 10:30

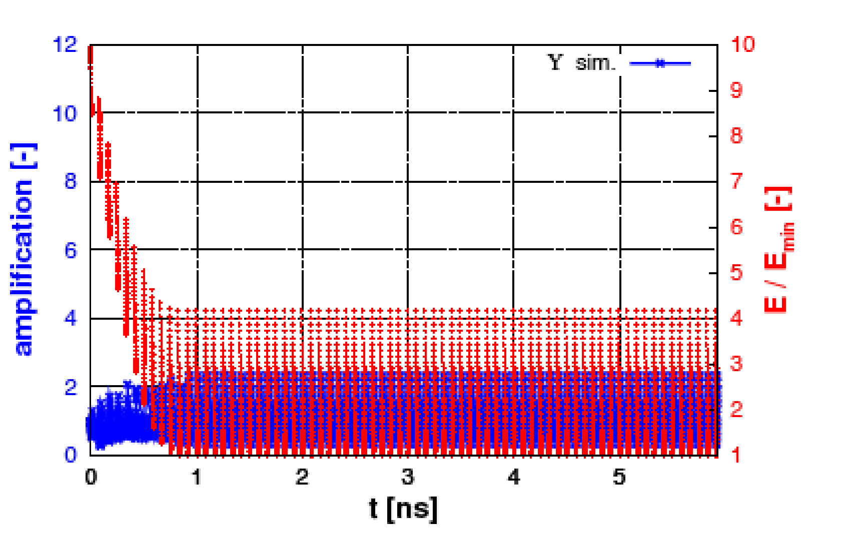
Transport challenge: dipole wake

The multi-bunch amplification due to the dipole wake is large. The PETS induced energy spread mitigates the amplification, however, to a level depended on the PETS design. Here illustrated by calculating the amplification of action due to dipole wakes, at the decelerator end.

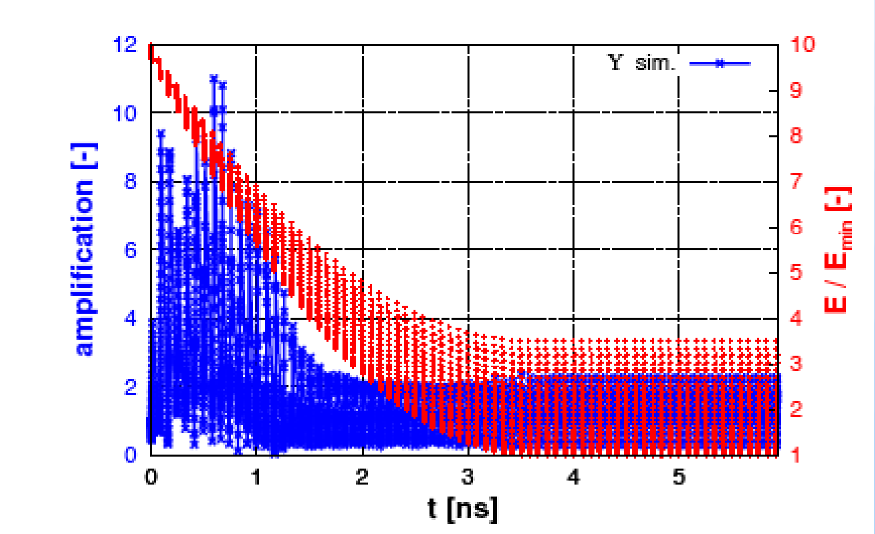
Rf power production is proportional with (R'/Q) / v_g = const. However, PETS with too low group velocity do not develop energy spread fast enough to decohere the wake build-up.



Point-like bunches.

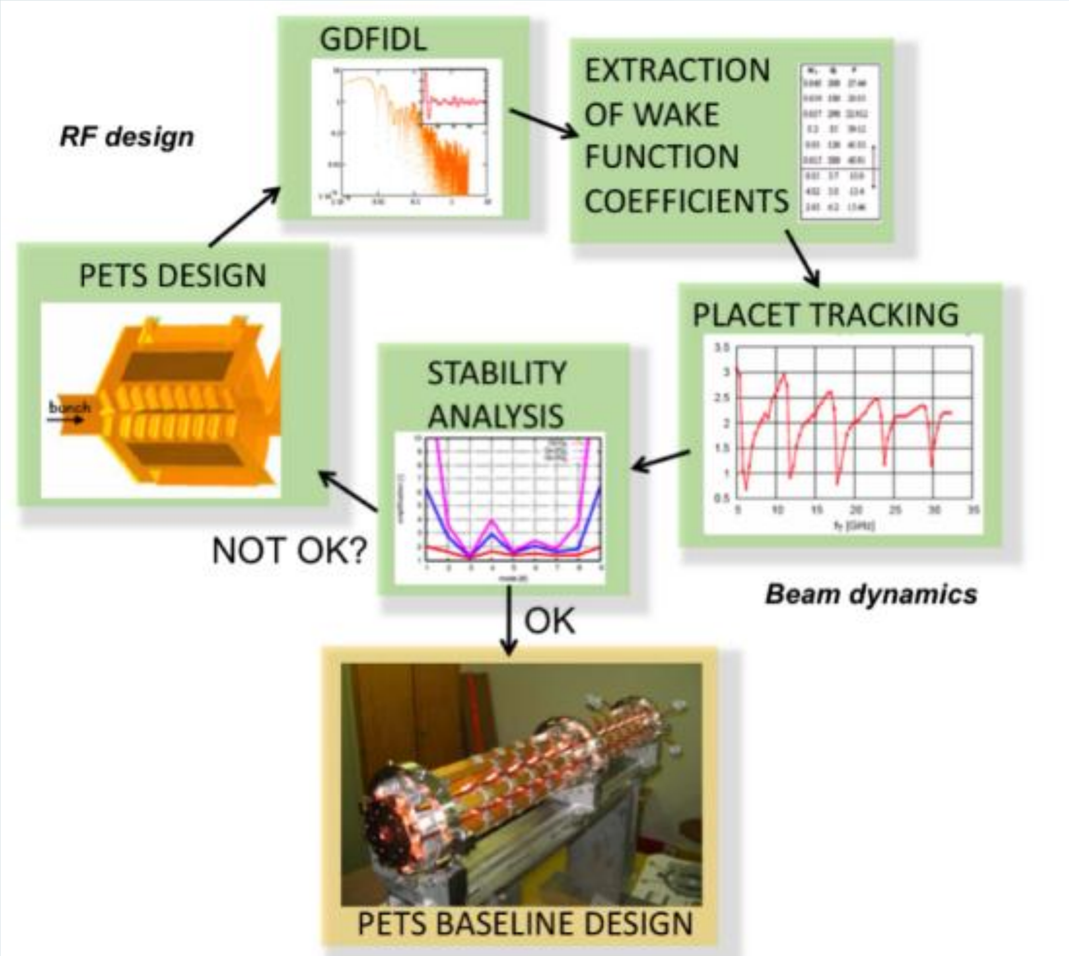


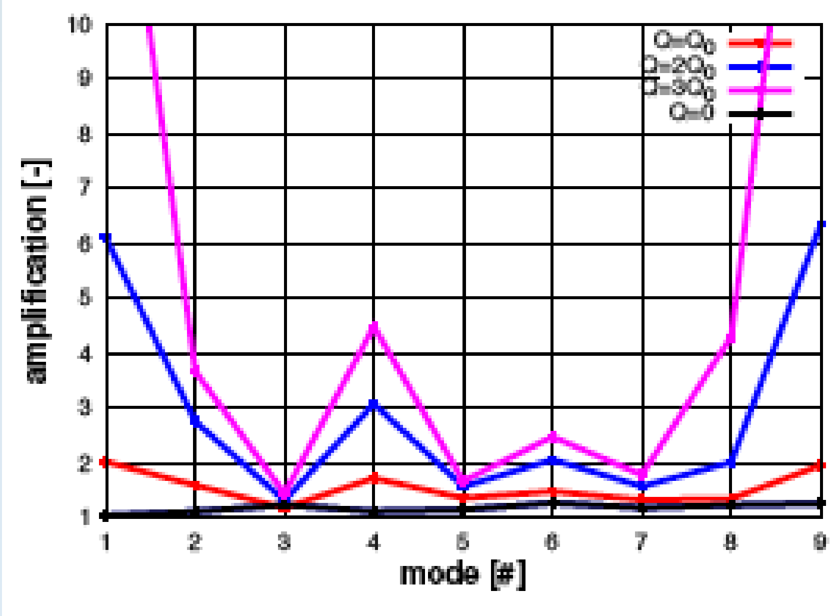
1 mm bunches, baseline PETS



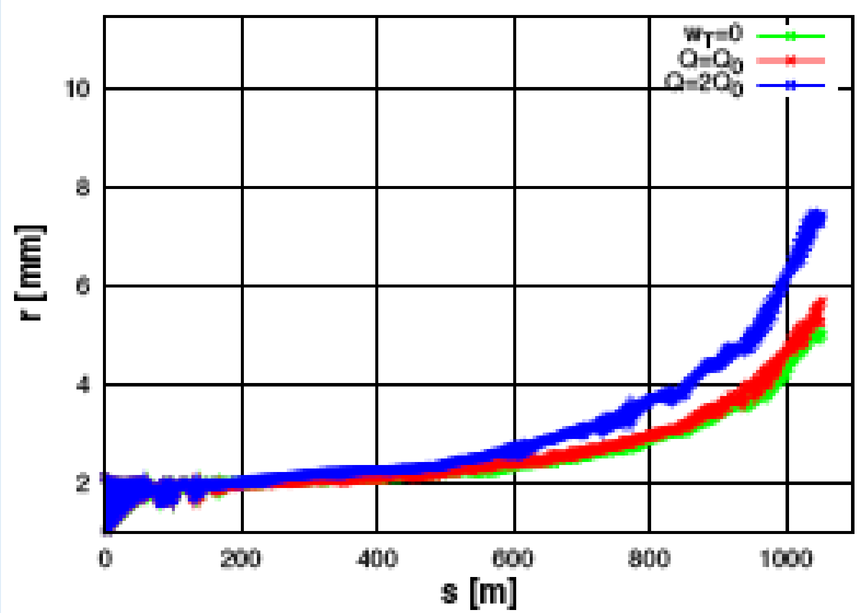
1 mm bunches, "slow" PETS design

Dipole wake status: PETS baseline design





(a) Dipole mode amplification



(b) Envelope growth along the lattice

Large series of potential PETS design variants have been examined for robust mitigation of the transverse wake, for all beam modes, and all errors sources. After several iterations rf and beam dynamics expertise, a PETS baseline indicating adequate wake mitigation, has been secured.

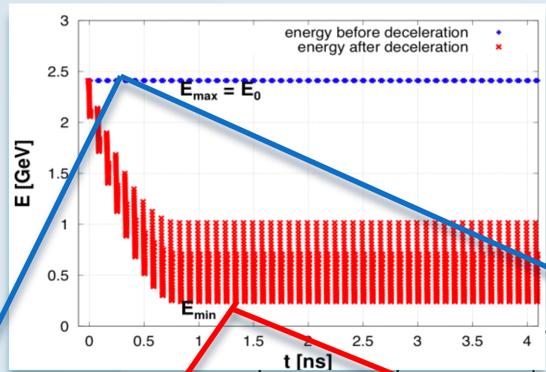
Transport challenge: orbit correction

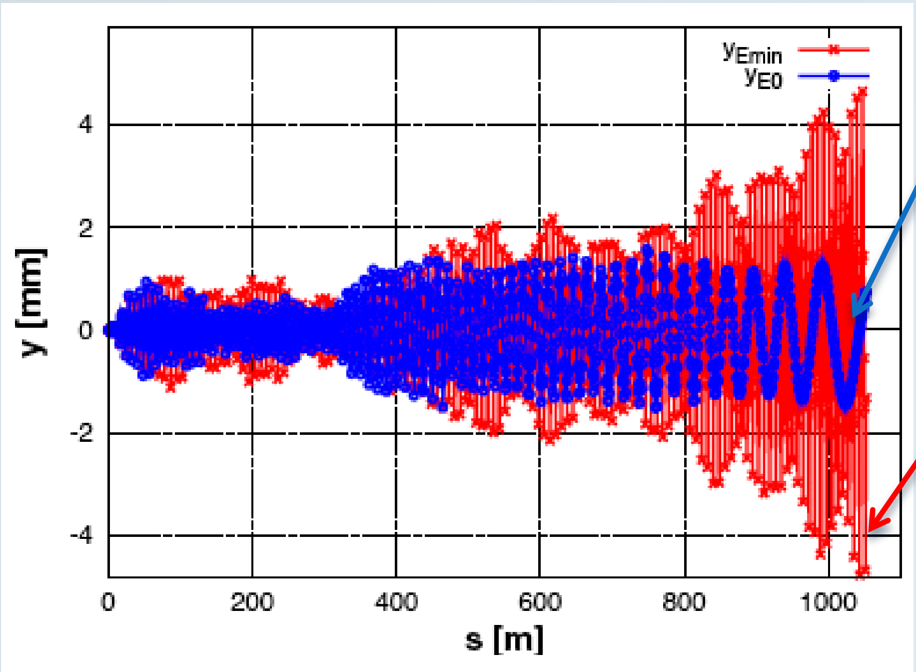
Kicks from misaligned quadrupoles might drive beam envelope out of vacuum chamber, even for pre-alignment of 20 μm. Estimate for uncorrected machine sets scale :

$$\langle r_c \rangle_{\mathrm{Emin}} = \Sigma_{j=1}^{N} R_{Fi}(\xi_j/f)\sqrt{\frac{\gamma_j}{\gamma_f}} \approx 2\sqrt{N}\frac{\sigma_{\mathrm{quad}}}{\cos(\phi_{\mathrm{FODO}}/2)}\sqrt{\frac{(1-\frac{1}{2}\eta_{\mathrm{extr}})}{(1-\eta_{\mathrm{extr}})}}$$

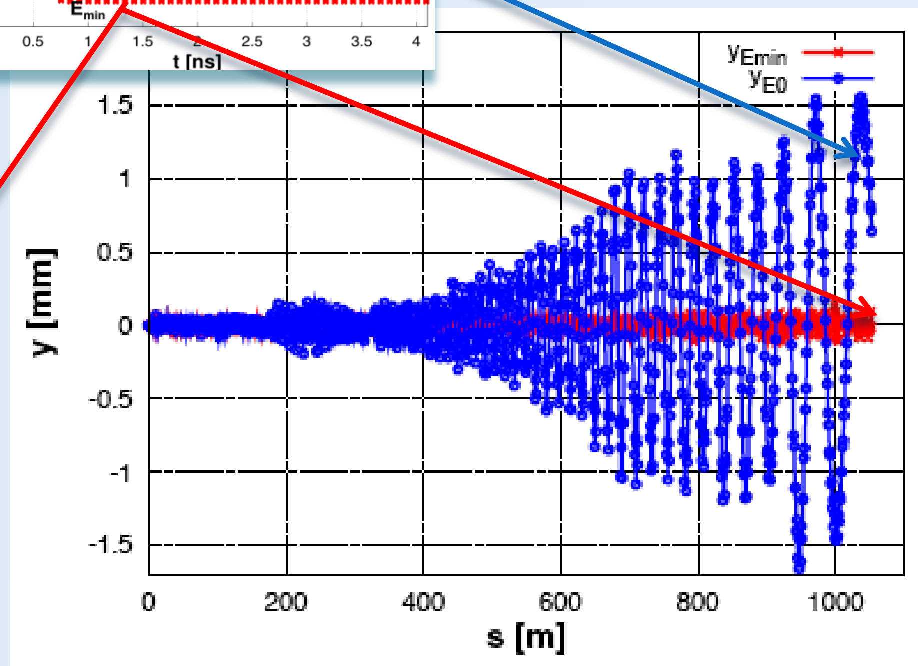
With 1000 quadrupoles and 20 μm rms offset, the expected centroid envelope is ca. 4 mm.

90% energy spread of decelerator beam poses a challenge for beam transport : Dispersive trajectories of higher / lower energy particles : 1-to-1 correction does properly correct only the beam centroid.





Beam transport for ideal injection into a misaligned machine



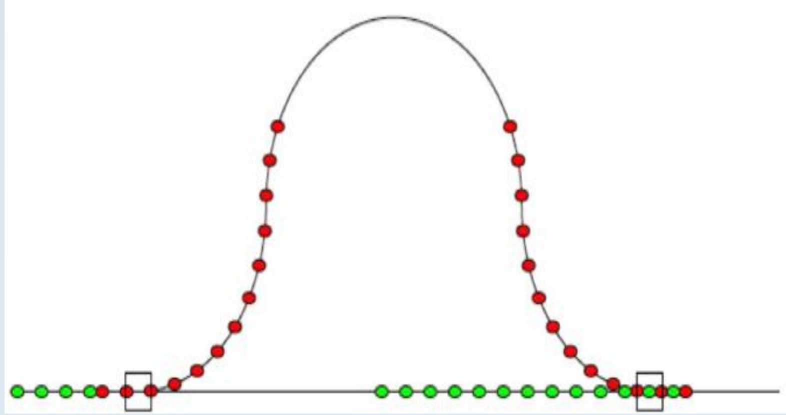
Beam transport for ideal inj. into a 1-to-1 corrected machine

Transport challenge: orbit correction

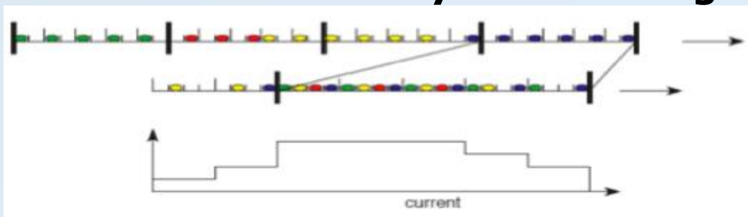
We seek to improve the situation by imposing that particles of different energies shall follow same trajectory, i.e. minimizing the energy dependence of the trajectories; a dispersion-free correction.

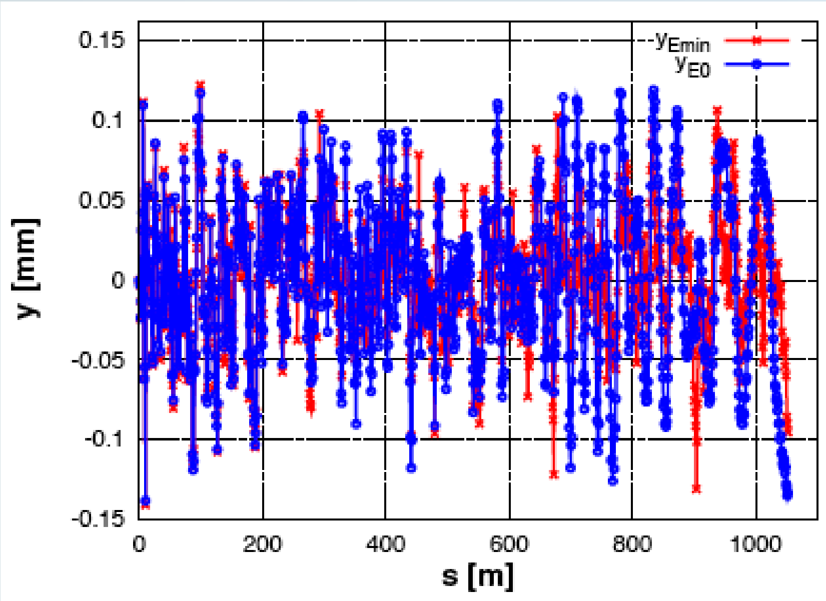
We propose a scheme based on drive beam bunch-manipulation and exploiting PETS beam loading, to generate a test-beam.

Use of "delayed switching" in the drive beam generation. The test beam can have almost any energy leverage. One-pulse correction.

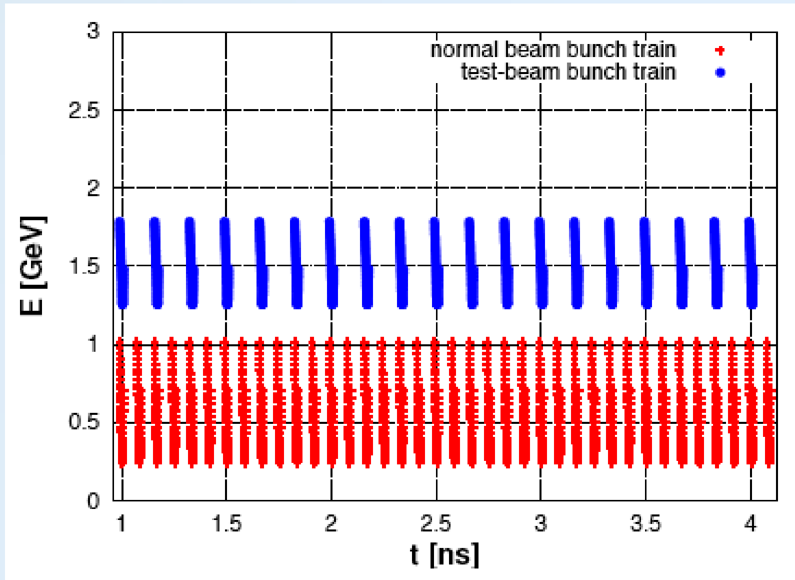


The effect of delayed switching





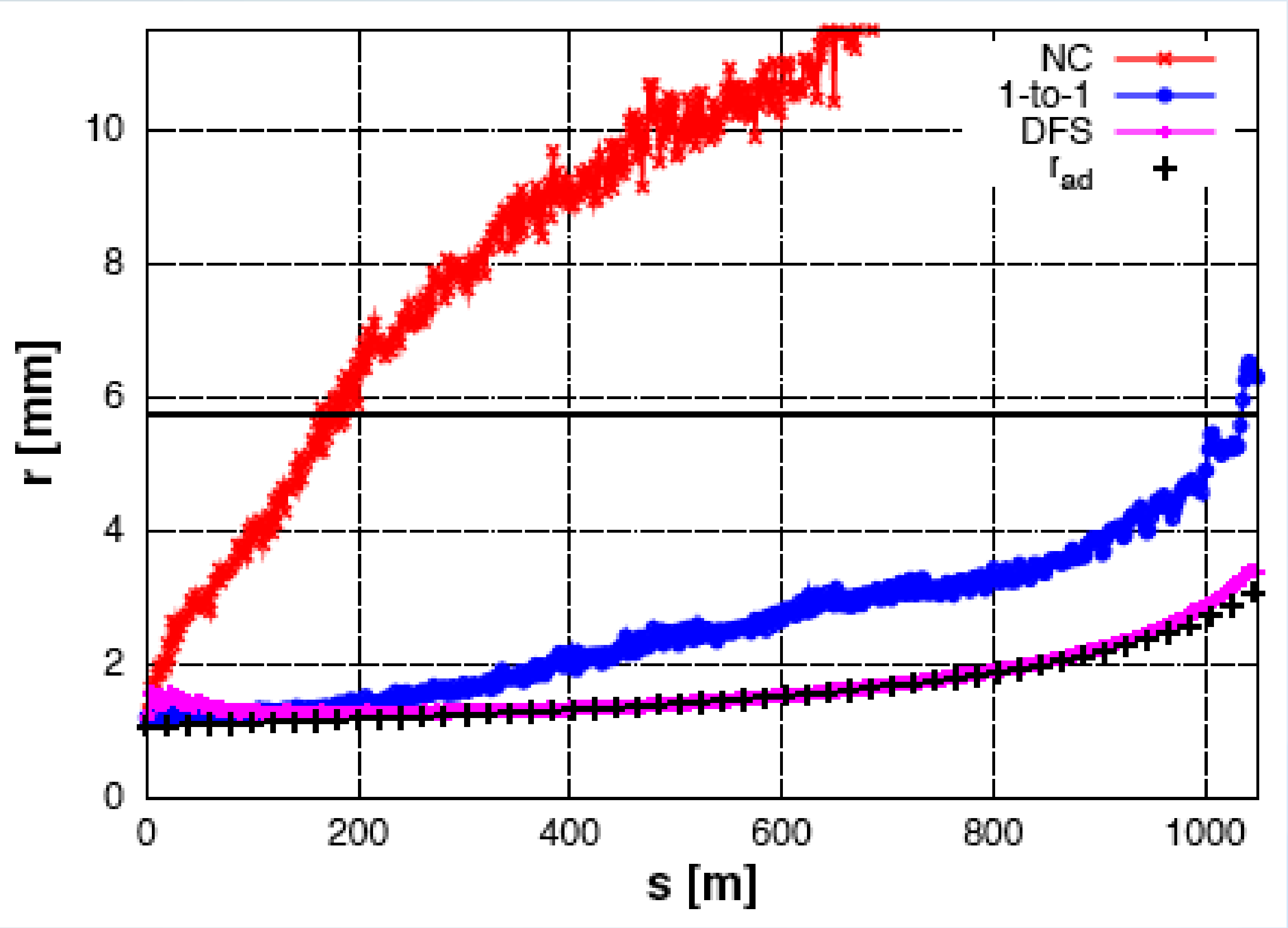
Beam transport for ideal inj. into a dispersion-free steered machine



Energy profile of main beam and example test-beam

Beam transport with dispersion-free correction

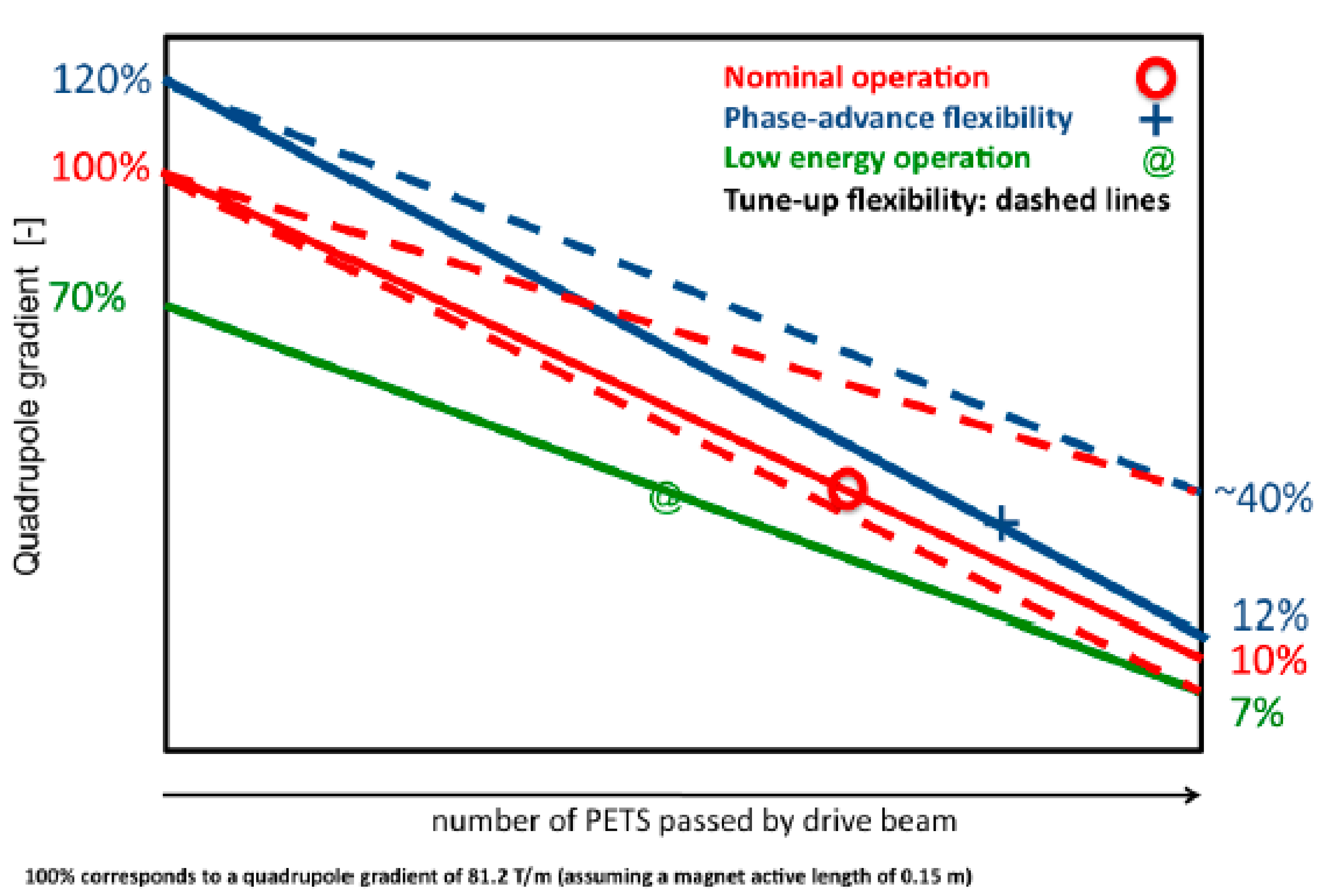
- Results of simulation including the combined effects of wake fields and misalignment, for the CLIC base line parameters :



3-σ envelope of 500 simulated machines (worst case r)

- Requirements
- Beam physics
- **Component specifications**
- Test facilities
- Conclusions

Decelerator operational scenarios



Tune-up beams: low current, negligible beam-loading. Not needed (nor optimal) to go to full phase-advance

Quad specifications: baseline parameters

- Specification: one quadrupole per meter gives beta function (for most decelerated particles) of
  $<\beta> = 1.25$ m
  - Deemed necessary for robust mitigation of dipole wake
  - Gives r = 3.3 mm (out of a_0 = 11.5 mm) for ideal beam
- Results in ~42'000 decelerator quads
- Powered magnets is the baseline
  - failure tolerant serial powering scheme a necessity
- Tuneable permanent magnets option investigated
  - must cover all operational scenarios

A. Vorozhtsov, WG6, Wednesday 09:30

D. Siemaszko, S. Pittet, WG6, Wednesday 09:50

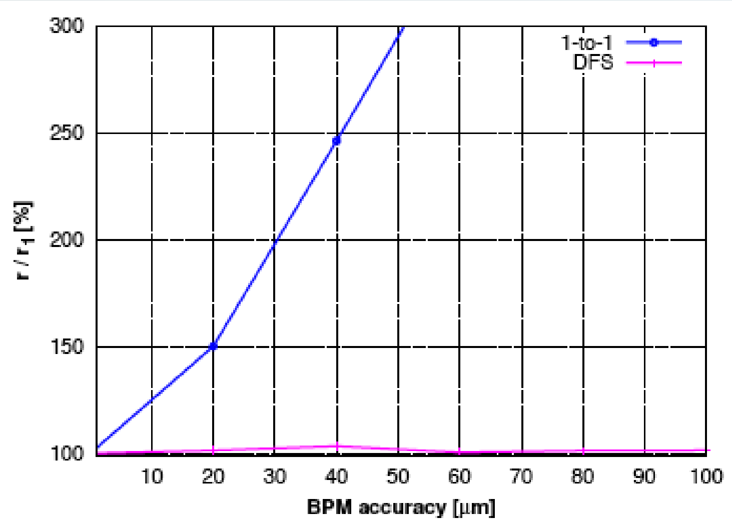
J. Clarke, WG6, Wednesday 11:40

Quadrupole specifications			
Total nb. of quads	N_{tot}	~42000	-
Inner radius of vacuum chamber	a_0	11.5	mm
Max. integrated gradient	$\hat{G}$	12.2	T
Tunabiliy		See operational scenarios	
Magnet design accuracy rms	$\sigma(Gl)/(Gl)$	1×10^{-3}	-
Resulting magnet design tolerance	$\Delta(Gl)/(Gl)$	$\sqrt{3} \times 10^{-3}$	-
Max. dodecapole component at 11 mm	Int B6 / Int B2	3×10^{-4}	-
Power supply accuracy rms	$\sigma(I)/I$	5×10^{-4}	-

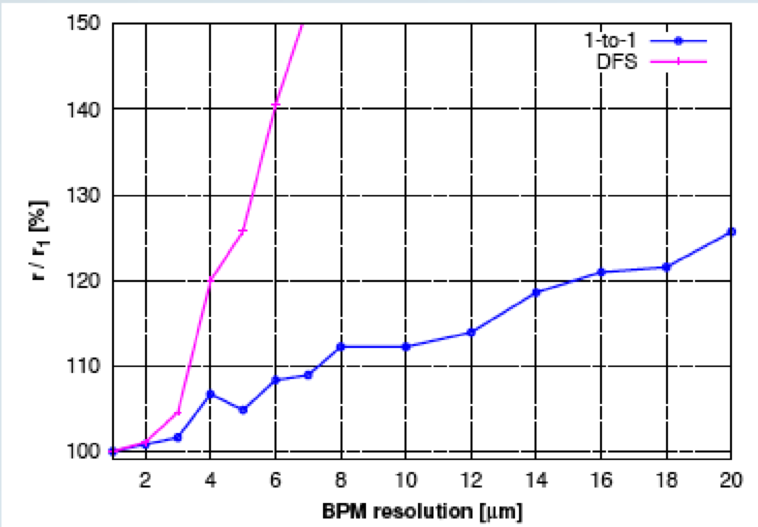
BPM specifications: baseline parameters

Beam-based correction performance drive the BPM specifications.
Target: negligible envelope growth due to quadrupole kicks.

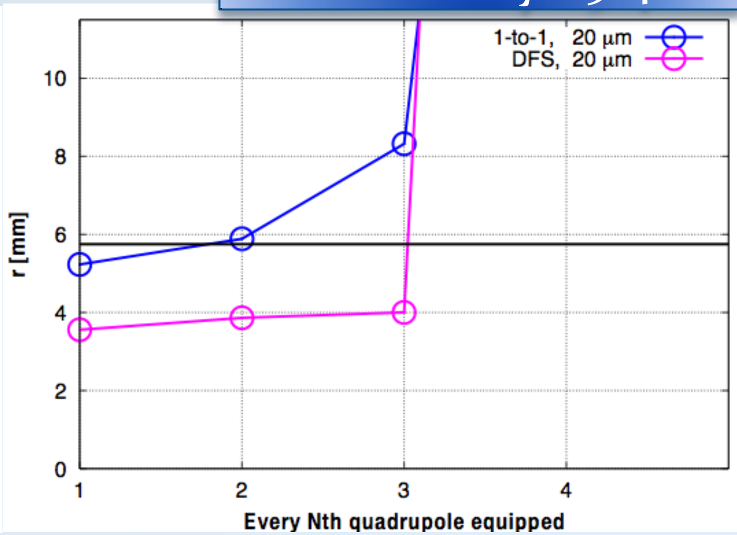
S. Smith, WG8,
Wednesday 09:40



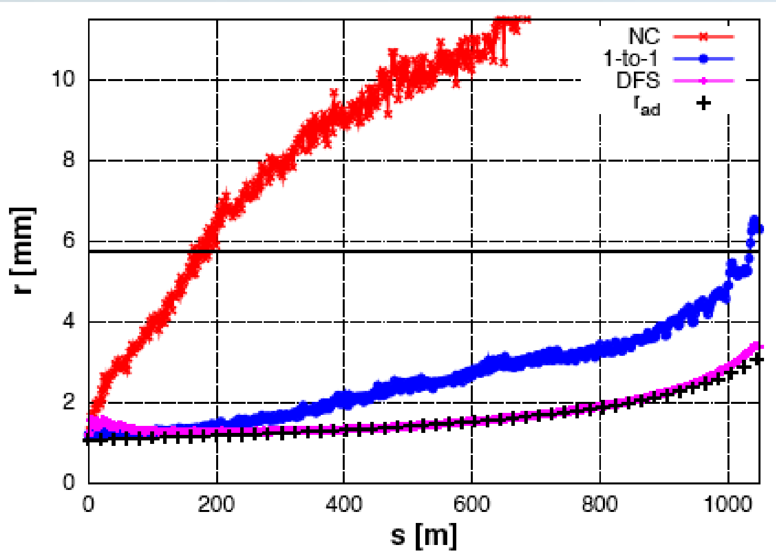
Effect of BPM accuracy



Effect of BPM resolution



Effect of # of BPMs



Results with baseline parameters

Quantity	Symbol	Value	Unit
# of quadrupoles per BPMs	N	~2/3	-
Total number of BPMS	N_{tot}	~28000	-
Production beam			
BPM accuracy	σ_{acc}	20	μm
BPM resolution	σ_{res}	2	μm
Time resolution	t_{res}	60	ns
Pilot beam			
BPM accuracy	σ_{acc}	20	μm
BPM resolution	σ_{res}	4	μm
Time resolution	t_{res}	60	ns

Vacuum system specifications

Collective effects studies for the 100 A drive beam :

1) Fast-ion instability

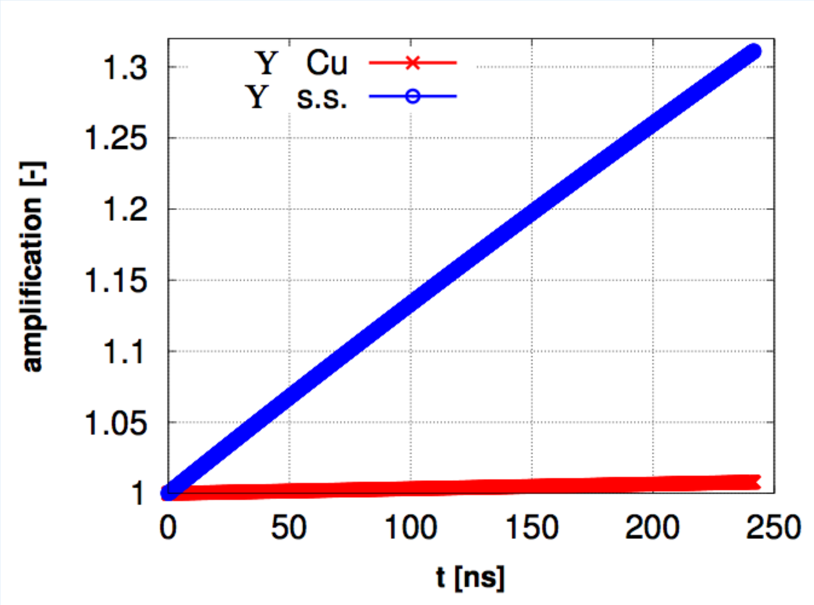
Analytic approximations, neglecting the large energy spread), yields one fast-ion instability rise-time with p = 40 nTorr.

Decelerator: **p < 40 nTorr**

2) Resisitive wall instability

Analytic calculations yield a significant (unacceptable) amplification of beam offsets for $\sigma_{res} = \sigma_{s.s}$ while negligible for $\sigma_{res} = \sigma_{Cu}$.

Decelerator: $\boldsymbol{\sigma_{res} \sim \sigma_{Cu}}$



Amplification of a coherent beam offset due to the resistive wall wake

Comparison with requirements for the rest of the drive beam long transfer lines :

B. Jeanneret, WG4,6, Thursday 08:30

Other specifications

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

Tolerance	Value	Comment
Quadrupole position jitter	1 μm	$r/r_0 < 5$ %
Quadrupole field ripple	$5 \cdot 10^{-4}$	$r/r_0 < 5$ %
Current jitter	< 1%	Stability req. only – RF power constraints might be tighter.
Beta mismatch, $d\beta/\beta$ Injection offset, y/σ_y	~10 % < 0.2	$r/r_0 < 5$ % $r/r_0 < 5$ %

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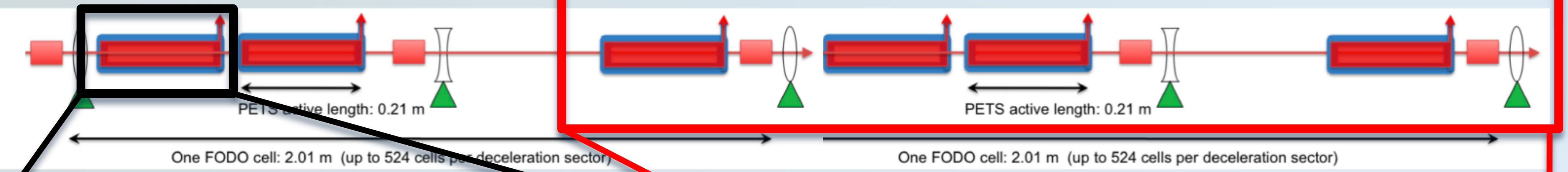
Decelerator test-facilities

Decelerator sector: ~1 km, ~90% of 2.4 GeV beam energy extracted

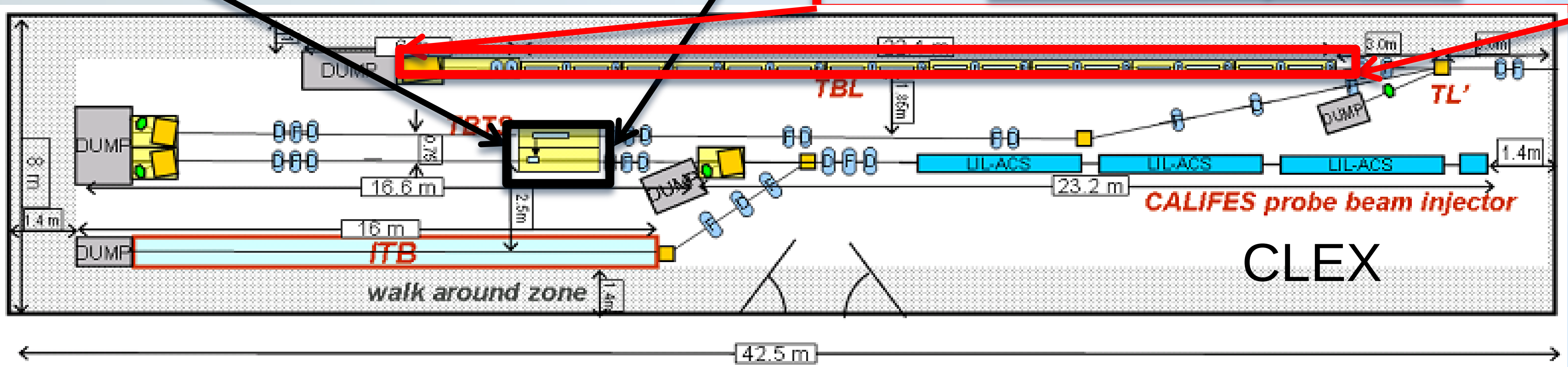


Two-beam Test Stand: test the characteristics of a **single** PETS

A. Palaia, WG6, Thursday 09:30

Decelerator Test Beam Line: test of **beam transport** with > 50% of a 150 MeV beam energy extracted under betatron motion (16 PETS)

R. Lillestøl, WG6, Wednesday 11:00



- Requirements
- Beam physics
- Component specifications
- Test facilities
- **Status and conclusions**

CLIC decelerator status

- Simulation framework in place allowing for detailed specification
- A CLIC baseline has been reached where simulations show satisfying beam transport for the baseline parameters
- Component specifications are sometimes tight, but within the feasibility limits

- Items outstanding :
  - **Experimental tests of heavily decelerated beam**
  - More detailed studies of collective effects for the decelerating beam
  - More detailed machine protection and beam loss studies
  - Benchmarking with other simulation codes would be comforting
  - Further cost optimization (clever component design, further optimization); might be seen in context of a larger iteration of drive beam parameters (TDR?)

- Requirements
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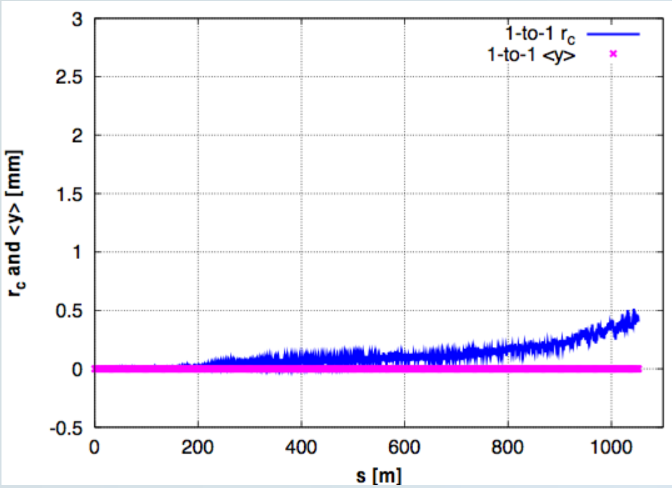
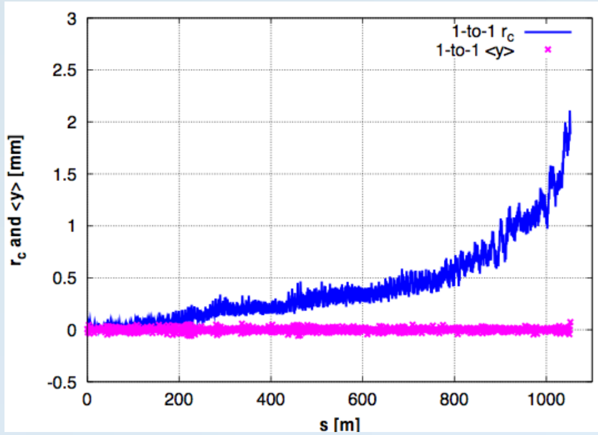
- Extra

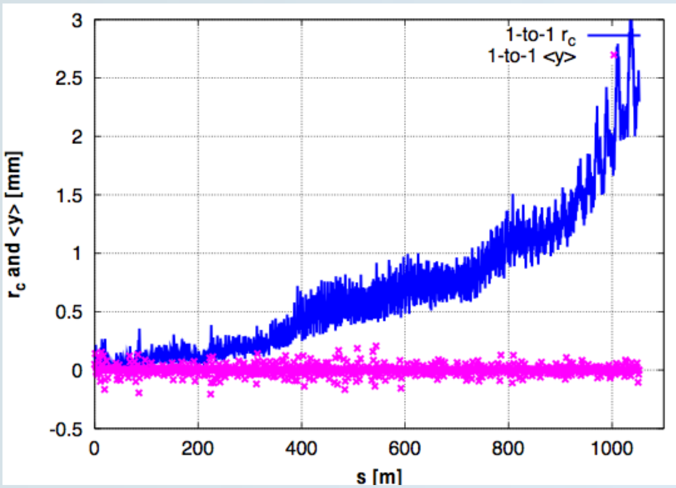
Effect on reducing number of BPMs



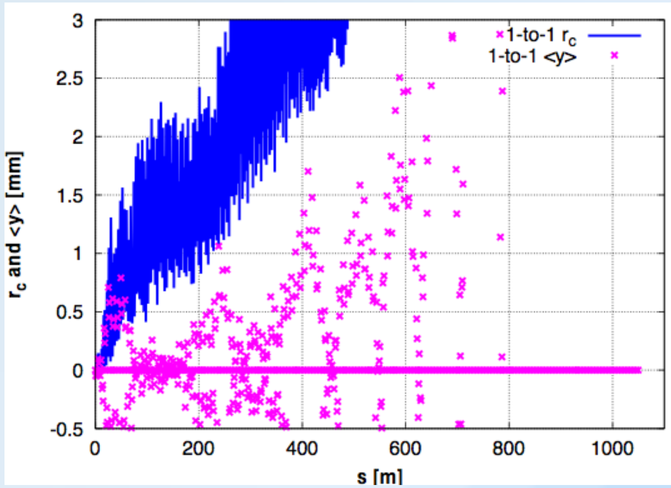
N=1



N=2



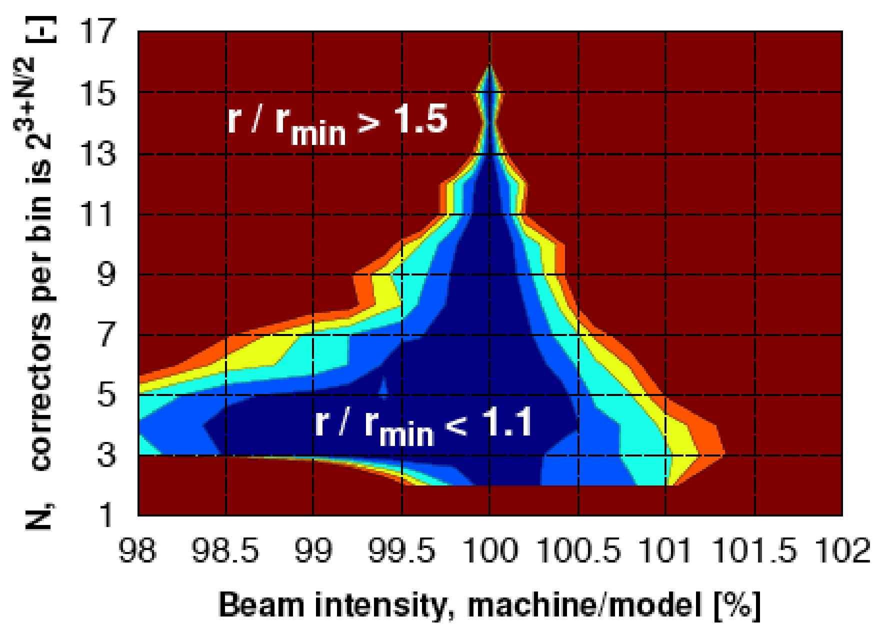
N=3

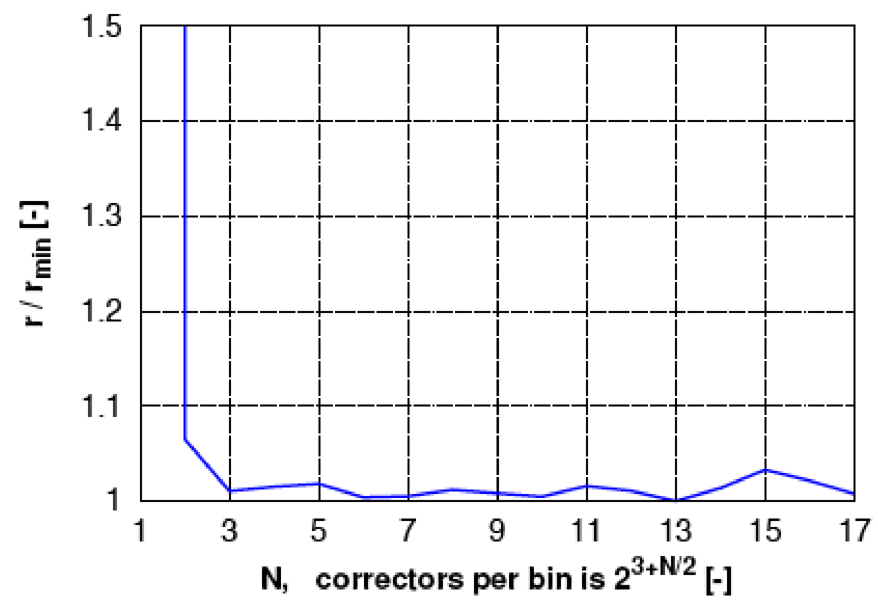


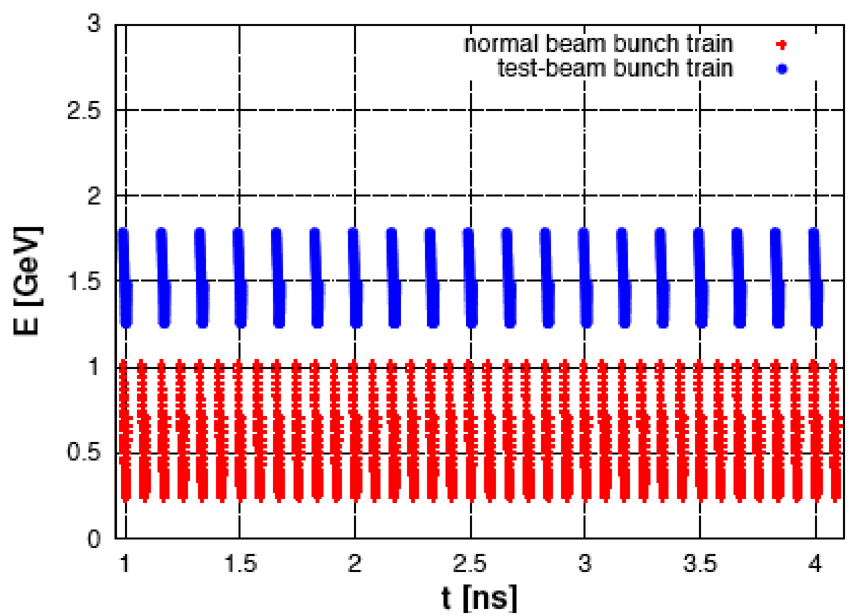
N=4

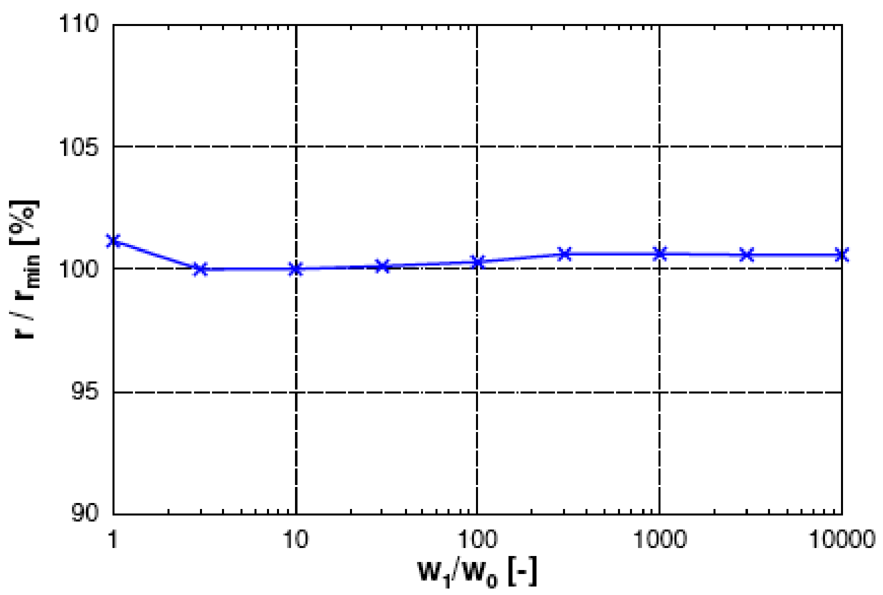
(perfect BPMs and single machine simulated, for illustration purposes)

Dispersion-free steering details

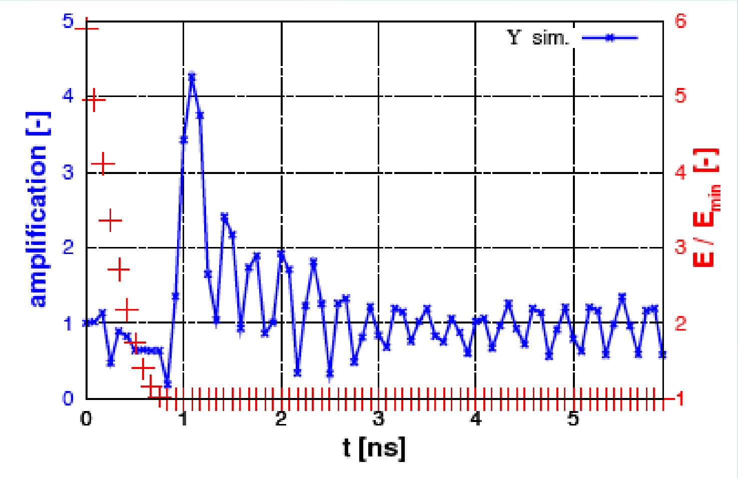


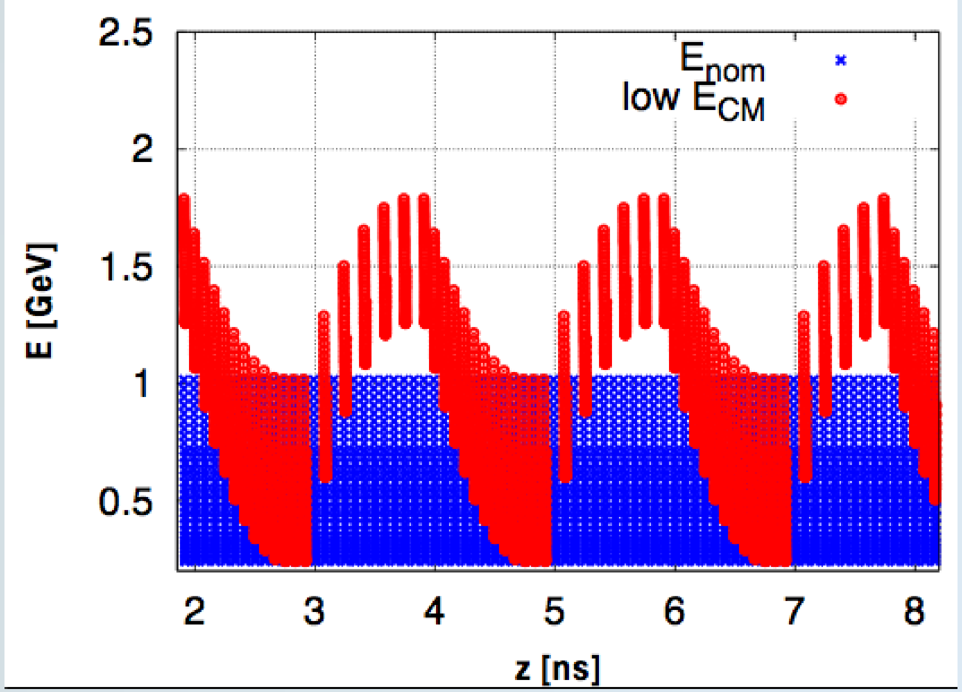


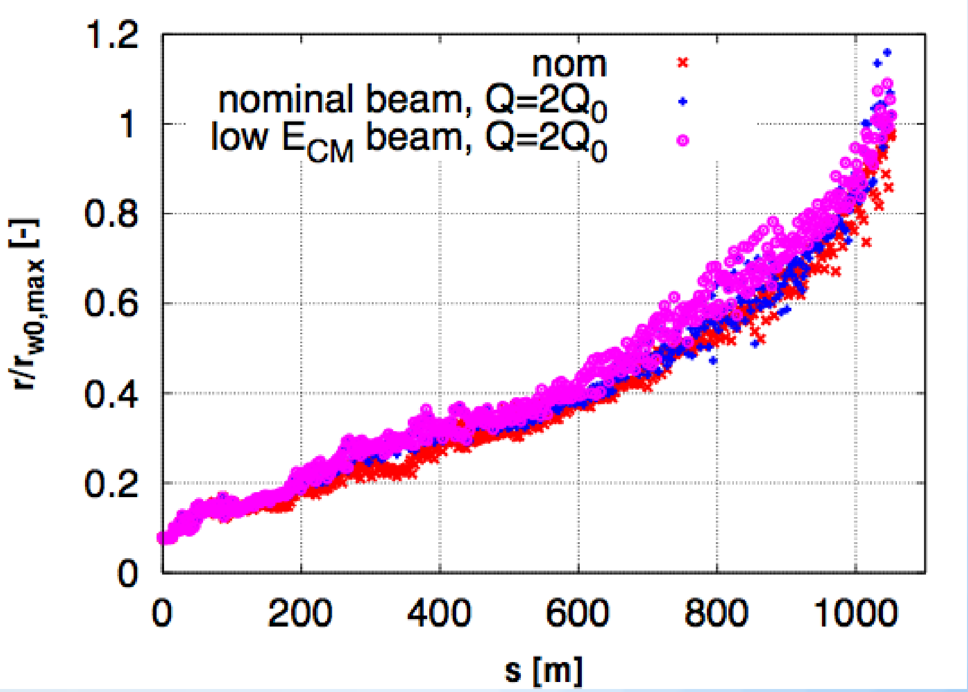




Delayed switching: low energy running



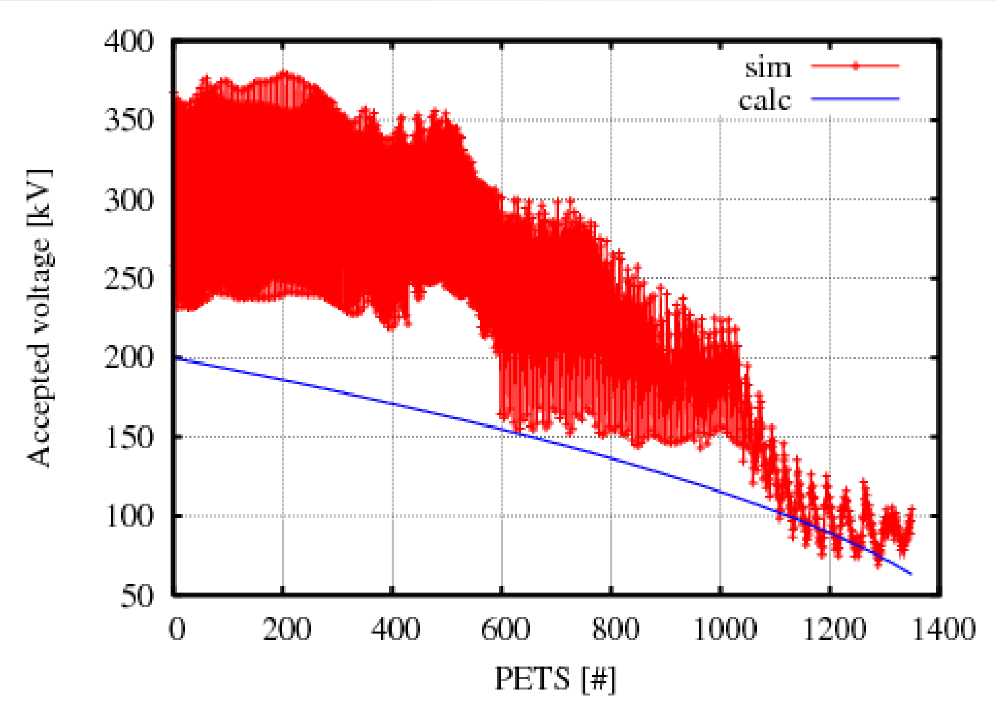


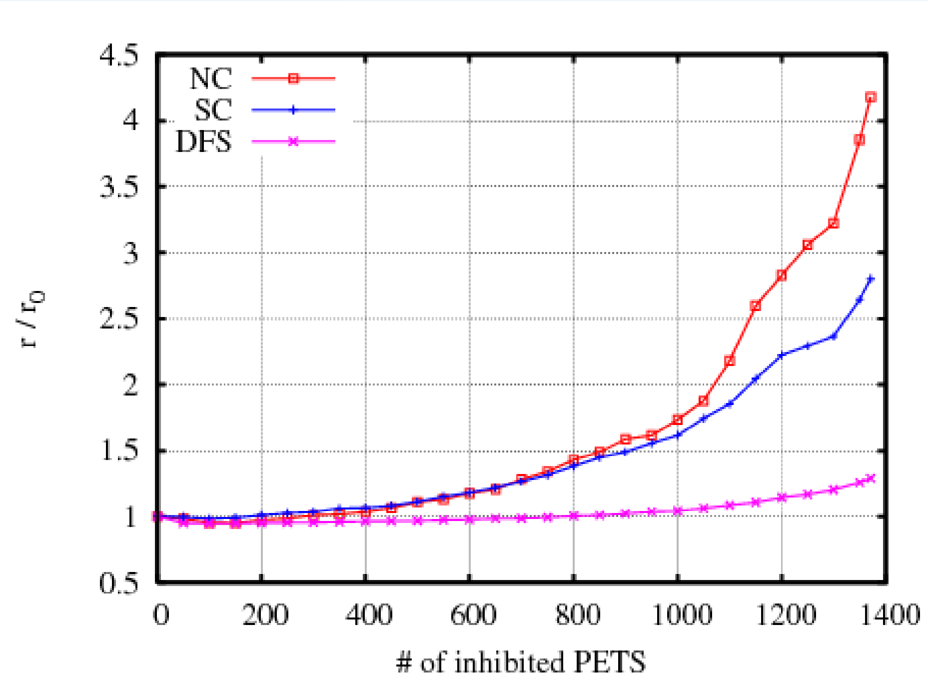


Power phase-lag in the decelerator

PETS on/off and kicks

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





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