CLIC Beam Dynamics Issues and Tolerances

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- Will not try to be exhaustive

  ⇒ focus on the most critical aspects
- Sorry, I cannot do justice to all the good work done

CLIC workshop, October 16, 2007

Goals of the Beam Dynamics Studies

- Establish that the luminosity performance goal can be met
  - not yet completed
- A problem of scaling
  - something that works at CTF3 does not necessarily work at CLIC
  - something that does not work at CTF3 does not need to fail at CLIC
  - similar situation for the main beam
- Need to rely on simulations

  ⇒ benchmarking is crucial

  ⇒ completeness of imperfections model is crucial
- Determine a design
  - specify tolerances/diagnostics needs
  - optimise including cost
- Developing a repository with relevant information
  - documentation for conceptual design report

Luminosity

$$\mathcal{L} = H_D \frac{N^2 f_{rep} n_b}{4\pi\sigma_x\sigma_y}$$

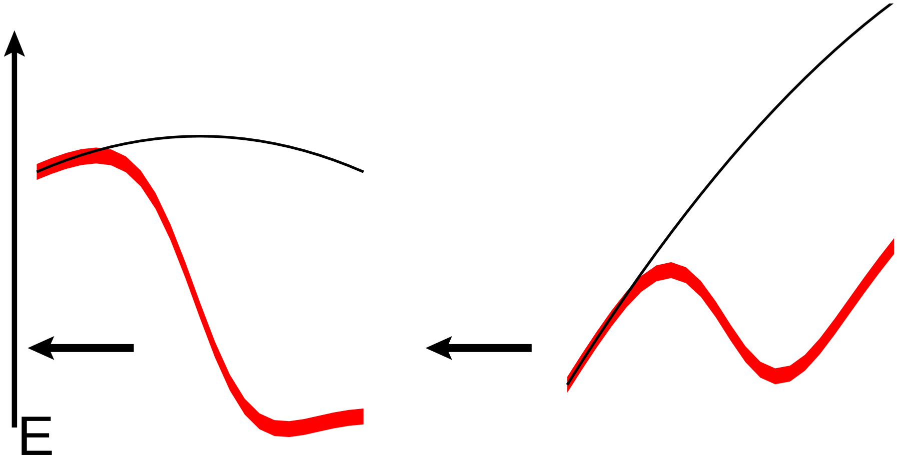
$$\mathcal{L} \propto H_D \frac{N}{\sqrt{\beta_x\epsilon_x}\sqrt{\beta_y\epsilon_y}} \eta P$$

- Efficiency η depends on beam current that can be transported

  $\Rightarrow$ decrease bunch distance $\Rightarrow$ long-range transverse wakefields in main linac

  $\Rightarrow$ increase bunch charge $\Rightarrow$ short-range transverse and longitudinal wakefields in main linac, other effects

- For scaling we keep the wakefield effect constant
- For each structure
  - determine $\sigma_z(N)$ that yields $\sigma_E/E = 0.35\%$
  - determine N that yields original transverse kick

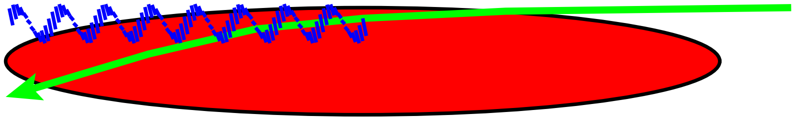


Beam Size Limit at IP

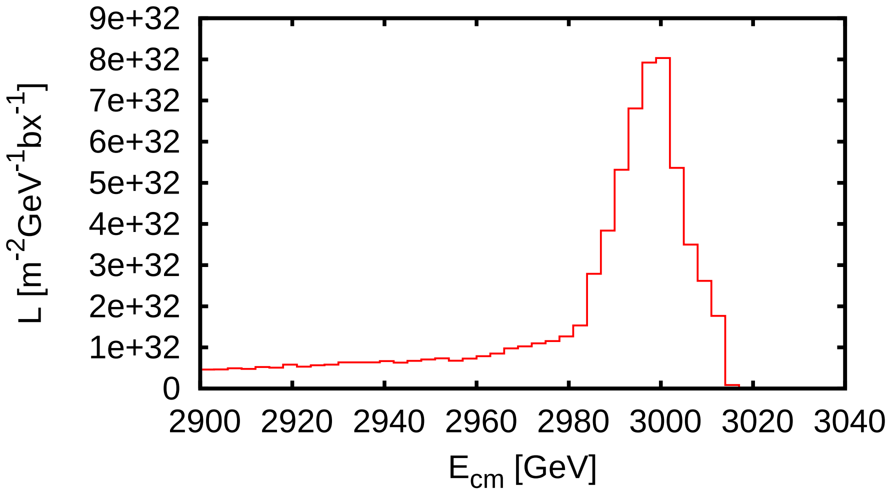
- Vertical beam size σ_y
  need to collide beams, beam delivery system, main linac, beam-beam effects, damping ring, bunch compressor

  $\Rightarrow$ vertical size $\sigma_y = 1\,\mathrm{nm}$ is reasonable

  $\Rightarrow$ $\epsilon_y = 20\,\mathrm{nm}$ is practical



- Horizontal beam size σ_x
  beam-beam effects, final focus system, damping ring, bunch compressors
- Fundamental limit on horizontal beam size arises from beamstrahlung (limits N/σ_x as function of σ_z)
- Other lower limit for σ_x is given by finite damping ring emittance and difficulty to yield very small β_x/σ_x in BDS



$\Rightarrow$ Use luminosity in peak as figure of merit

Main Beam Emittance Budgets and Luminosity

- For the vertical emittance a budget has been established
  - $\epsilon_y \leq 5\,\mathrm{nm}$ after damping ring extraction
  - $\Delta\epsilon_y \leq 5\,\mathrm{nm}$ during transport to main linac
  - $\Delta\epsilon_y \leq 10\,\mathrm{nm}$ in main linac
- For the horizontal emittance the old design gave
  - $\epsilon_x = 550\,\mathrm{nm}$ after damping ring extraction
  - $\epsilon_x = 660\,\mathrm{nm}$ before the beam delivery system with the growth mainly in the RTML
- The emittance budget
  - includes design, static and dynamic effects
  - requires 90% of the machines to perform better than the target
- The luminosity is calculated
  - using $\epsilon_x \leq 660\,\mathrm{nm}$, $\epsilon_y \leq 20\,\mathrm{nm}$ before the beam delivery system
  - tracking the beam through a perfect beam delivery system ($L^* = 4.3\,\mathrm{m}$, $L^* = 3.5\,\mathrm{m}$ needs optimisation)
  - simulating the beam-beam effects
  - dividing the found luminosity by 1.2

Main Linac

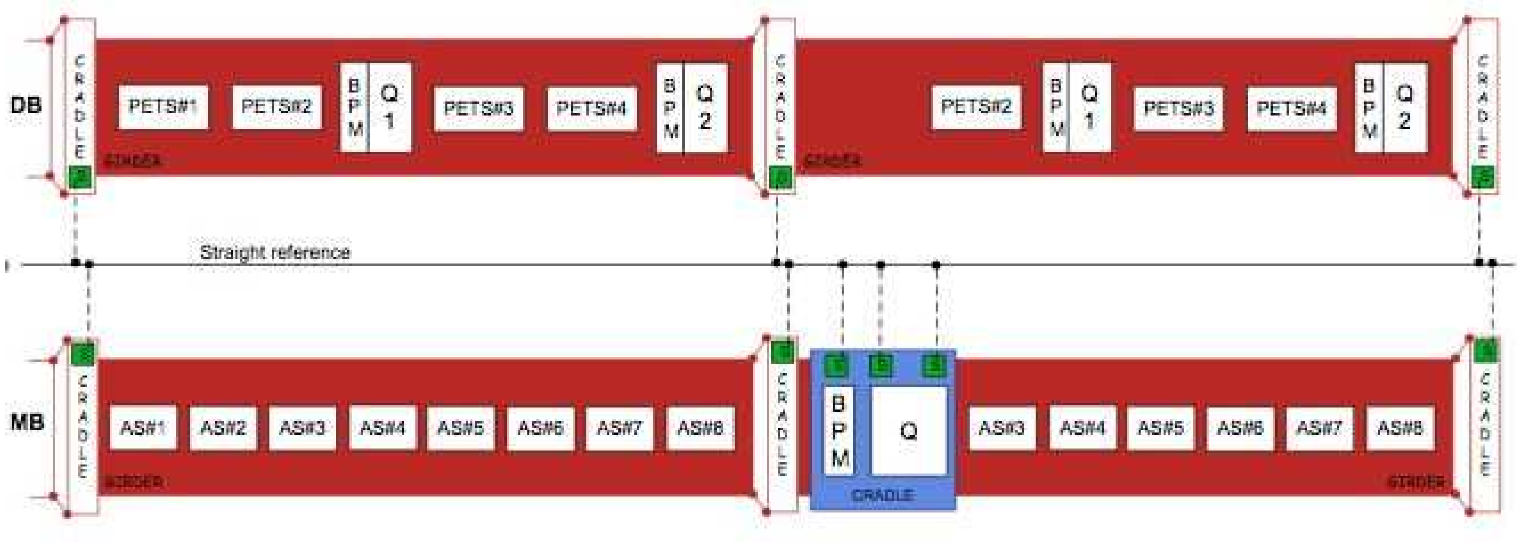
- Specific challenges are
  - single and multi-bunch wakefields, transverse kicks
  - dynamic and static imperfections of quadrupoles and BPMs
  - RF stability
- The main linac limits the charge per bunch and the bunch-to-bunch distance

  $\Rightarrow$ has been one of the optimisation drivers
- Goal is to keep static emittance growth below 5 nm for 90% of the machines
- Average dynamic growth should stay below 5 nm

Element	error	with respect to	tolerance CLIC	tolerance NLC
Structure	offset	beam	$5.8\,\mu\mathrm{m}$	$5.0\,\mu\mathrm{m}$
Structure	tilt	beam	$220\,\mu\mathrm{radian}$	$135\,\mu\mathrm{radian}$
Quadrupole	roll	axis	$240\,\mu\mathrm{radian}$	$280\,\mu\mathrm{radian}$
BPM	offset	straight line	$0.44\,\mu\mathrm{m}$	$1.3\,\mu\mathrm{m}$
BPM	resolution	BPM center	$0.44\,\mu\mathrm{m}$	$1.3\,\mu\mathrm{m}$

- Most relevant tolerances for 1nm growth after one-to-one steering
- Using DFS relaxes BPM position but constrains BPM resolution (example case 57 $\mu\mathrm{m}$ and 0.18 $\mu\mathrm{m}$), bumps help

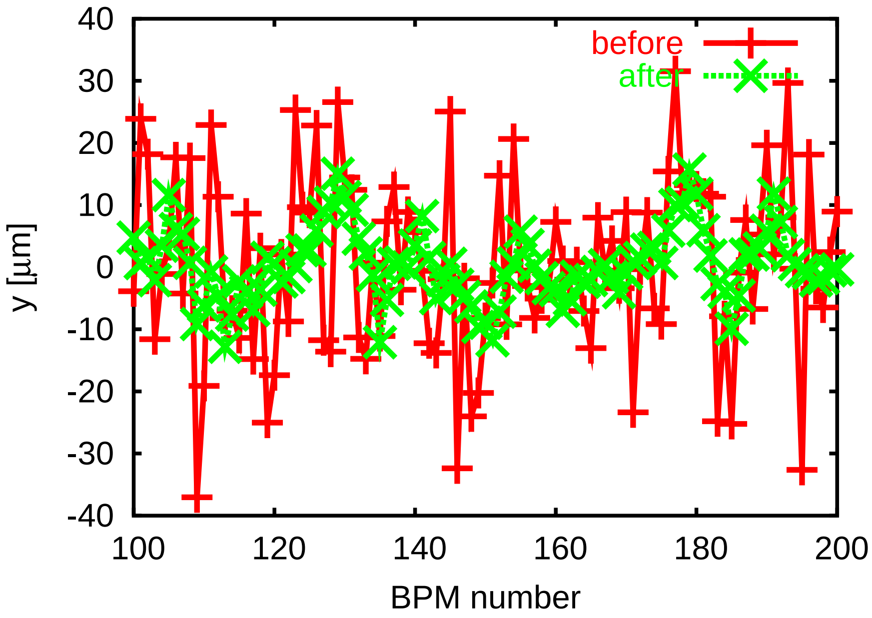
Beam-Based Alignment and Tuning Strategy



- Prealignment (typical $\mathcal{O}(10\,\mu\mathrm{m})$, H. Durand Mainaud et al.)
- One-to-one steering
- Dispersion free steering/ballistic alignment
- Structure alignment
- Tuning knobs

Dispersion Free Correction

- Basic idea: use different beam energies
- NLC: switch on/off different accelerating structures
- CLIC (ILC): accelerate beams with different gradient and initial energy



- Optimise trajectories for different energies together:

$$S=\sum_{i=1}^{n}\left(w_i(x_{i,1})^2+\sum_{j=2}^{m}w_{i,j}(x_{i,1}-x_{i,j})^2\right)+\sum_{k=1}^{l}w'_k(c_k)^2$$

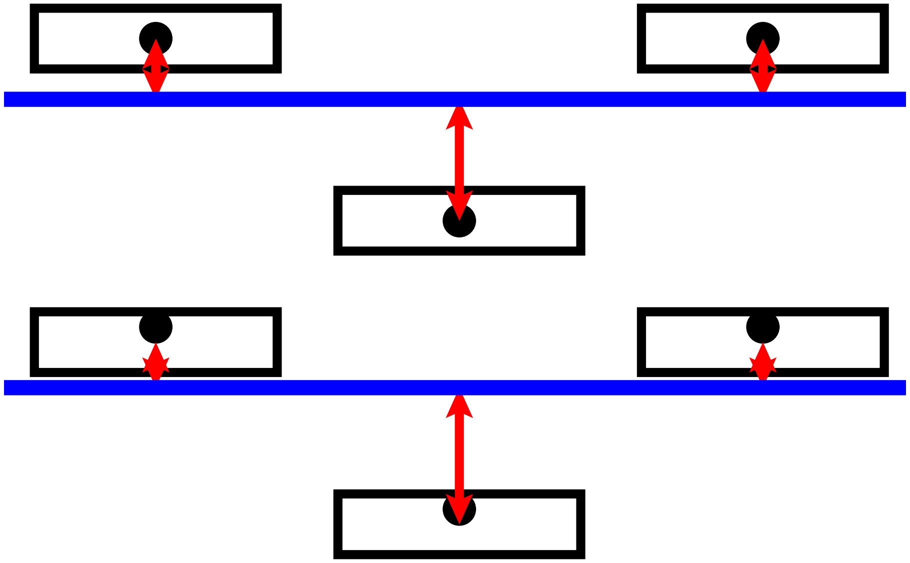
- Last term is omitted
- Idea is to mimic energy differences that exist in the bunch with different beams

Beam-Based Structure Alignment

- Each structure is equipped with a wake-field monitor (RMS position error $5\,\mu\mathrm{m}$)
- Up to eight structures are mounted on movable girders

⇒ Align structures to the beam

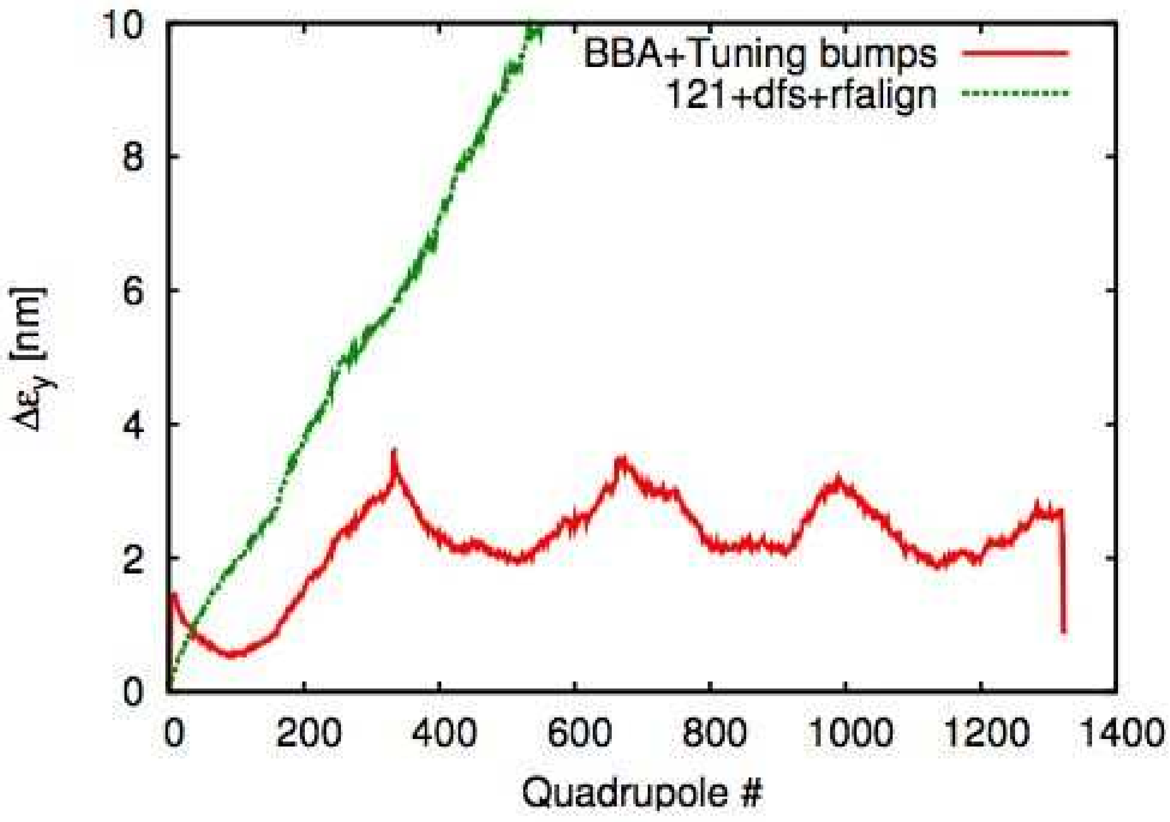
- For identical wakefields:
  - wakefield monitor errors are relevant
- For differeing wakefields
  - structure to beam offset is relevant
- Structure precision is relevant parameter for tilt
  - upper and lower half must be aligned to $\mu\mathrm{m}$ precision



- Tolerance and performance prediction are similar for CLIC and NLC
  - $5.8\,\mu\mathrm{m}/\sqrt{2}$ vs. $5\,\mu\mathrm{m}$
  - $5\,\mu\mathrm{m}$ vs. $5\,\mu\mathrm{m}$

Tuning Bumps

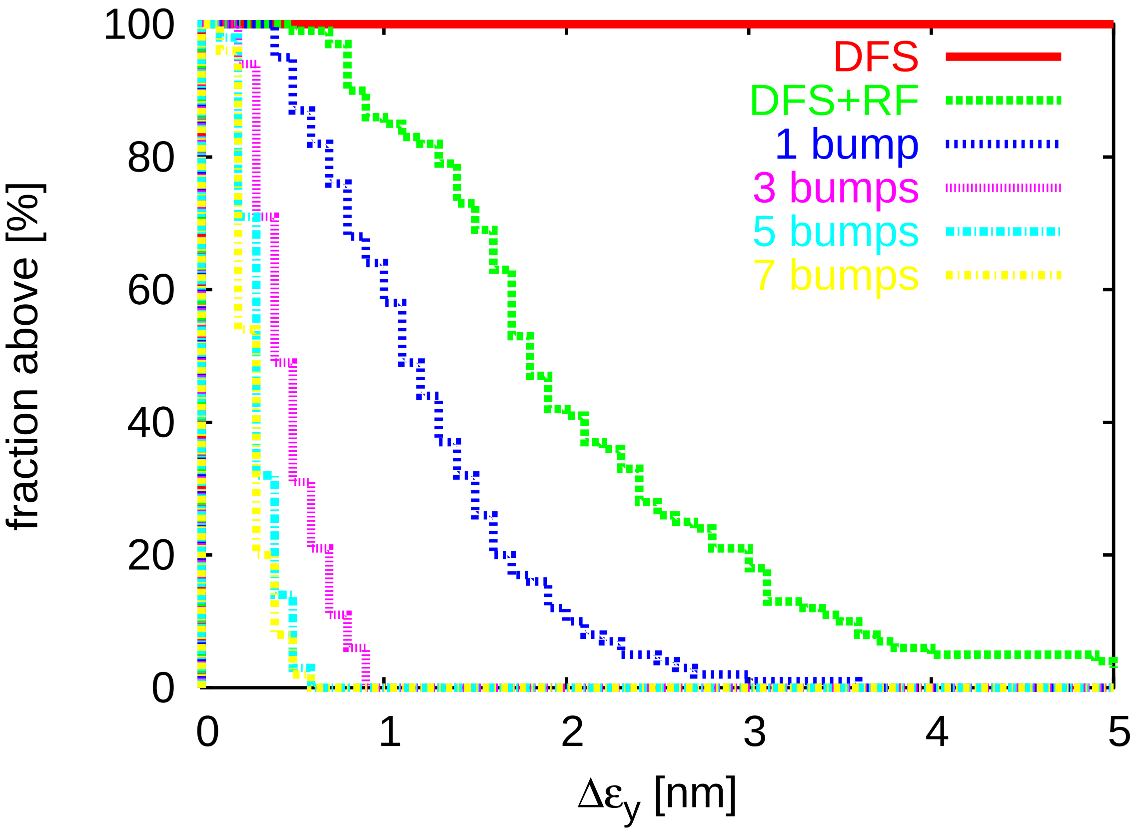
- Tuning bumps will be used to reduce the wakefield effects
  - the emittance is monitored at the end of the linac
  - structures are moved transversely until the emittance is minimal
- The additional local wakefield kick compensates integrated wakefield kick of all misaligned structures
- Figure shows results for old parameter set (P. Eliasson, D.S.)



- Similar procedure can be based on luminosity measurement
- Residual remains
  - energy spread in the beam
  - imperfect measurement/correction

Results for DFS and Bumps

- Target is 90% with $\Delta\epsilon_y \leq 5\,\mathrm{nm}$
- Simulation includes all misalignments but quadrupole roll
- Weigths for correction are optimised for best overall performance
- After RF alignment performance is marginally acceptable



- Already a single bump (two degrees of freedom) yields significant improvement

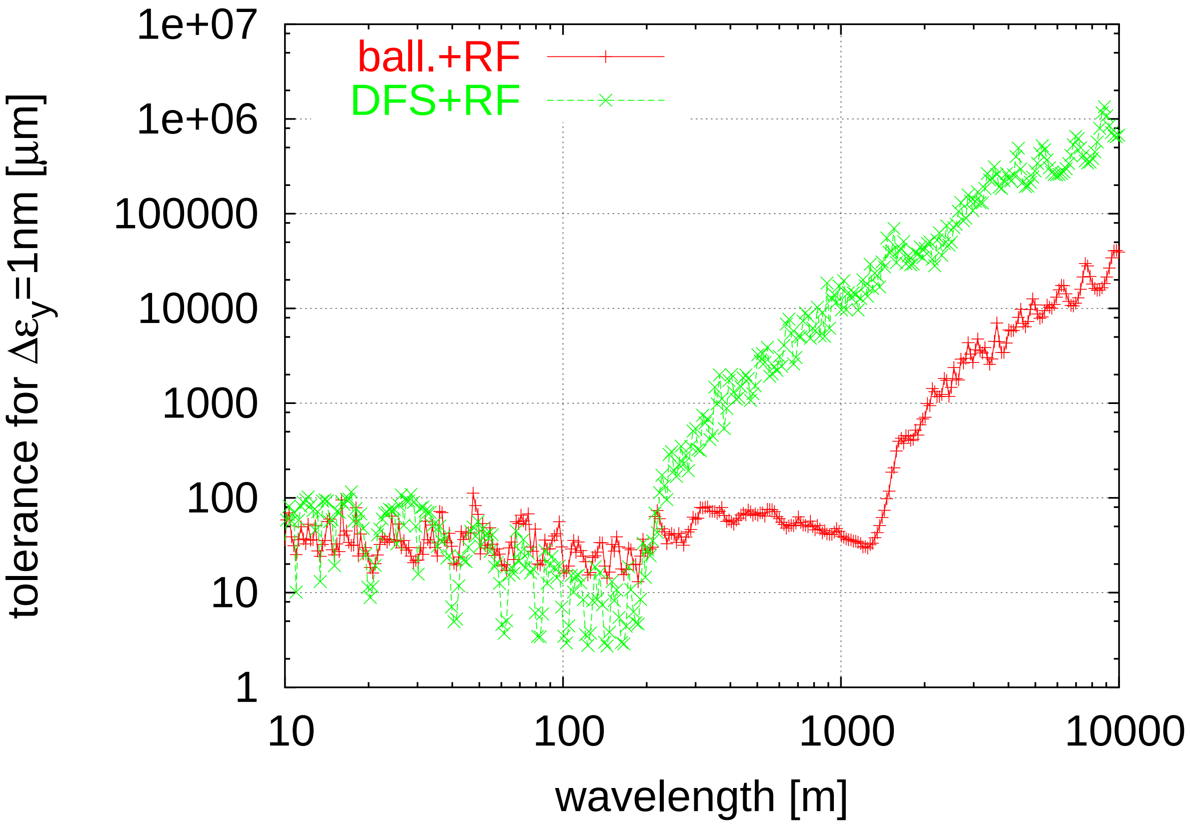
  - but we would use 3 or 5

$\Rightarrow$ Need to optimise taking into account time for convergence

- Final average emittance in nm (bumps): 2.0 (0), 1.1 (1), 0.4 (3), 0.2 (5), 0.15 (7)
- Ballistic alignment yields similar results

Long Distance Alignment

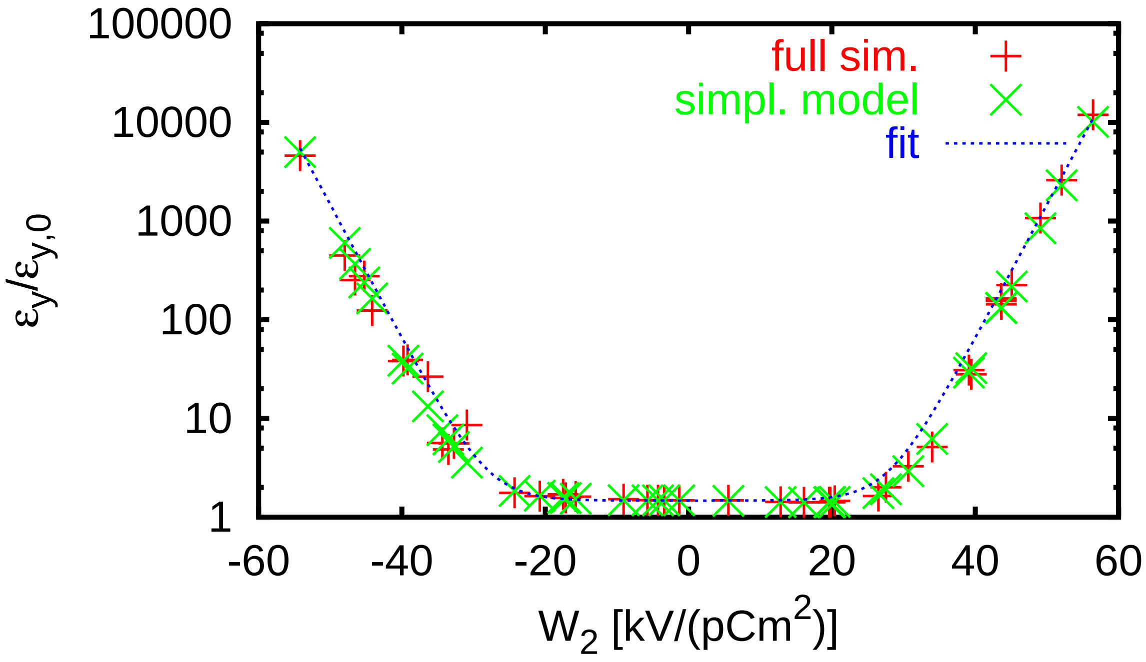
- Beam line elements are more difficult to align over long distances
  - we are investigating the alignment performance for this case
  - testing good material for long distance wires
- Simulation results to illustrate the point



⇒ The alignment tolerance depends on the correction method

Multi-Bunch Effects

- Efficiency also depends on bunch spacing
  - shorter bunch spacing improves efficiency
- Exponential additional emittance growth as function of long-range wakefield
- Small below $20\mathrm{kV}/(\mathrm{pCm}^2)$ for $N = 4 \times 10^9$



- Example for old parameters

$\Rightarrow$ require $W_\perp < 10\mathrm{kV}/(\mathrm{pCm}^2)\frac{4\times 10^9}{\mathrm{N}}\frac{\mathrm{G}}{150\,\mathrm{M\ V/m}}$

- First simulations of multi-bunch emittance growth show little effect

Hardware Requirements and Status

- Structure BPM error of $2\,\mu\mathrm{m}$ has been achieved at SLAC
  - but for different structure design
  - we still need to demonstrate this for our design
- BPM resolution 40 nm has been achieved
  - 100 nm with different technology will be demonstrated in EUROTeV

  ⇒ depends on outcome of that study, likely some follow up (long-term stability etc.)
- Quadrupole jitter of $0.8\,\mathrm{nm}$ has been achieved (S. Redaelli et al.)
  - but not in accelerator
  - and only using a costly suppport
  - in FFTB $2\,\mathrm{nm}$ with respect to ground have been achieved

  ⇒ more work is critical

  ⇒ tolerance for the final doublet is even tighter
- (BPM) alignment of 10 $\mu\mathrm{m}$ is expected to be achieved in LHC (H. Durand Mainaud)
  - needs verification and further improvements
  - alignment over longer distances are critical

Injectors

- Parameters exist (L. Rinolfi, S. Doebert)
- Beam stability had been investigated for old parameters (A. Latina, et al.)

  ⇒ less critical

  - will need to be redone at some point
- Alternative options are of interest and may require stability studies
  - Compton sources
  - undulator based source (rather not)

Predamping Rings

- Predamping Rings needs to be designed
- Most important stability issues need to be addressed

Damping Ring

- Design is better than current target of $\epsilon_x \leq 550\,\mathrm{nm}$, $\epsilon_y \leq 5\,\mathrm{nm}$, $\epsilon_z \leq 5\,\mathrm{keVm}$ (F. Zimmermann, M. Korostelev, Y. Papaphilippou)
- Design is very challenging
  - tiny emittances required (much lower than ATF)
  - intrabeam scattering
  - dynamic aperture
  - advanced wigglers needed (E. Levitchev et al.)
  - losses can present a problem
- Will be revisited to check full realism in some design aspects
  - e.g. place for vacuum pumps

Damping Ring (cont.)

- Other critical issues are
  - electron cloud (W. Bruns, G. Rumolo, F. Zimmermann, D.S.)

    ⇒ similar problems needs to be solved for the ILC, aim is to reduce secondary emission yield to less than 1
  - Fast beam-ion instability and impedances (Y. Papaphilippou et al.)

    ⇒ define the vacuum system and beam pipe
  - final emittance is dominated by intra-beam scattering

    ⇒ needs more theoretical work (M. Martini et al.)
  - beam-based tuning and feedback (Y. Papaphilippou et al.)

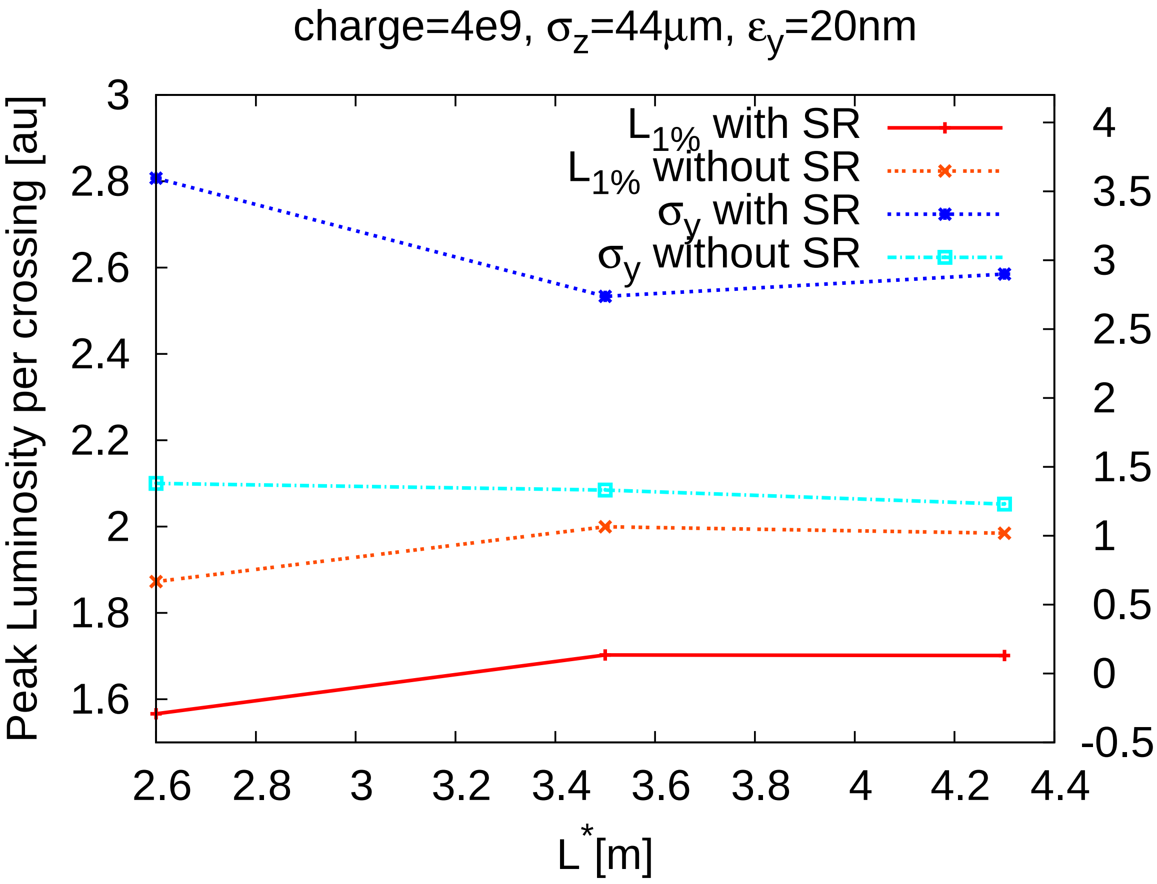
    ⇒ improved alignment algorithm to remove vertical dispersion
    - understand ATF and it's relevance
    - sofar mainly "conventional" tolerances
  - some hardware (diagnostics, wiggler, extraction)

Ring To Main Linac Transport

- Transports beam from damping ring to main linac
  - accelerates beam to $9\,\mathrm{GeV}$
  - compresses bunch in length to $45\,\mu\mathrm{m}$
  - emittance budget $\Delta\epsilon_x \leq 0.2\epsilon_{x,0}$ and $\Delta\epsilon_y \leq 5\,\mathrm{nm}$
- Full design of the system remains to be made
  - first preliminary lattices exist (A. Ferrari, A. Latina, F. Stulle)
  - learned from ILC that it can yield tight tolerances
- Specific challenges are
  - completion of the design
  - coherent synchrotron radiation in the bunch compressors
  - static and dynamic imperfections
  - RF stability
- Coherent synchrotron radiation is addressed by F. Stulle (PSI)
  - designed bunch compressor chicanes
  - impact of coherent synchrotron radiation is very small
  - is being updated

Beam Delivery System

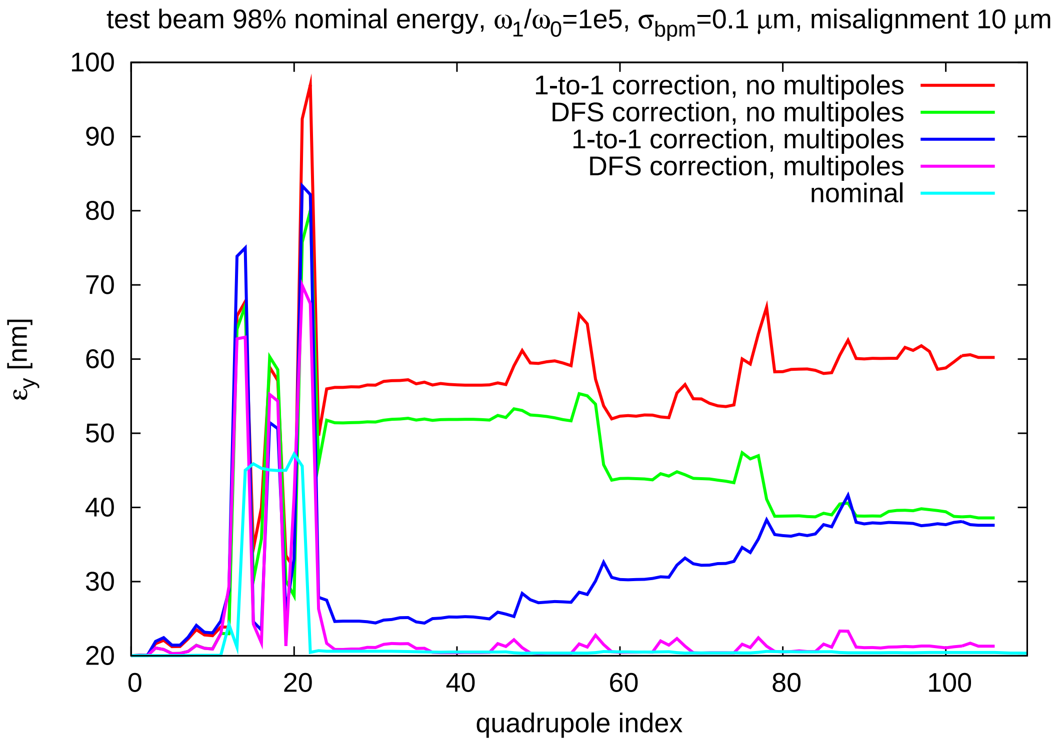
- Design of BDS is now quite mature (R. Tomas, also J. Resta Lopez, F. Zimmermann et al.)
  - being optimised for $L^* = 3.5\,\mathrm{m}$
  - laser wires, coupling measurement, energy measurement integrated
  - polarisation to be done
- Main issues
  - alignment and tuning
  - dynamic effects
  - wakefield effects (e.g. resistive wall wake)
  - Machine protection (collimators)



BDS Studies

- Since system design is tough, alignment is tough as well
- Have promising results for collimation system (A. Latina, R. Tomas)

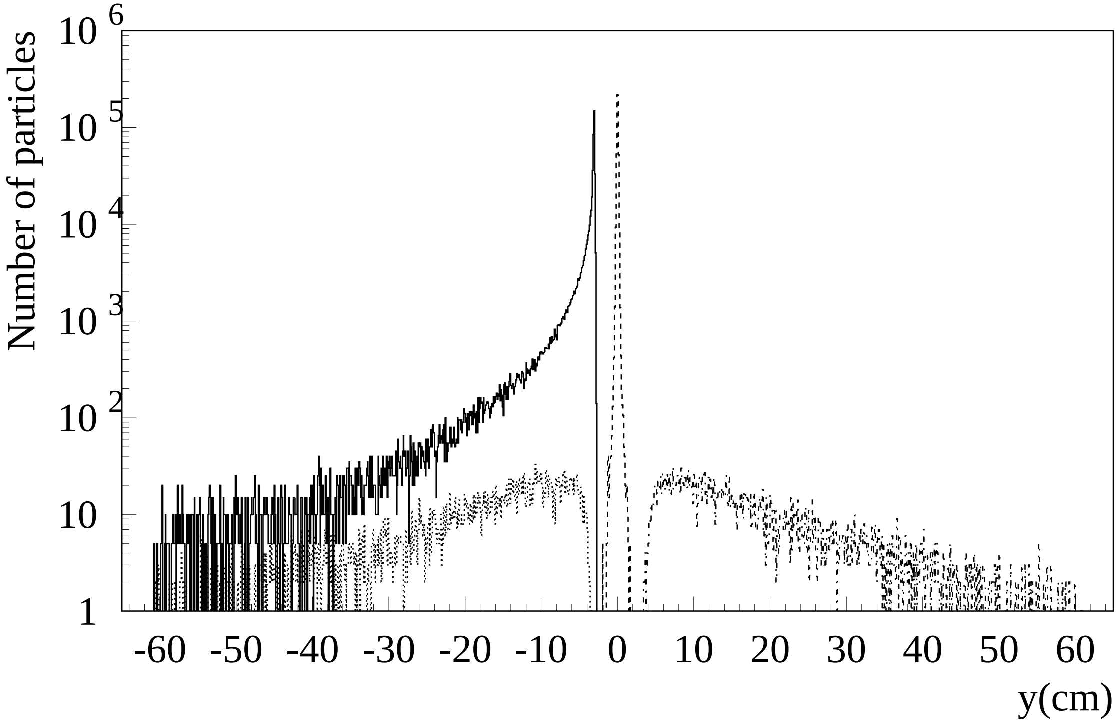
  - using DFS
- Do not yet have a solution for FFS
- Clearly an outstanding issue



- Feedback studies for the beam delivery system yielded first promising results but more work needed
- Tuning studies need to be advanced

Post Collision Line

- Extract the beam and measure beam propoerties relevant for luminosity optimisation
- Main challenges
  - mainly a design issue
  - avoid losses in spite of large energy spread, beamstrahlung and coherent pairs
  - identify places were the beam properties can be measured
- A design exists by A. Ferrari
  - more tests to be done
  - more instrumentation integration (K. Elsener, et al.)
  - operation studies



- Idea is to separate beam particles, beamstrahlung photons and coherent pairs

Drive Beam

- Design (sometimes with need to update) for some components exists (E. Adli, C. Biscari, R. Corsini, B. Jeanneret, L. Rinolfi, F. Stulle, T. Wilson, D.S.)
- Issues are
  - design/redesign of many components is needed
  - beam-based alignment and tuning
    - accelerator, conventional tolerances found, but needs update
    - combiner rings and beam transport need to be studied
      - RF deflector seemed OK (D. Alesini et al.)
    - decelerator, being updated and improved
  - drive beam phase stability
  - beam loading compensation for drive and main beam
  - collective effects
  - machine protection/losses

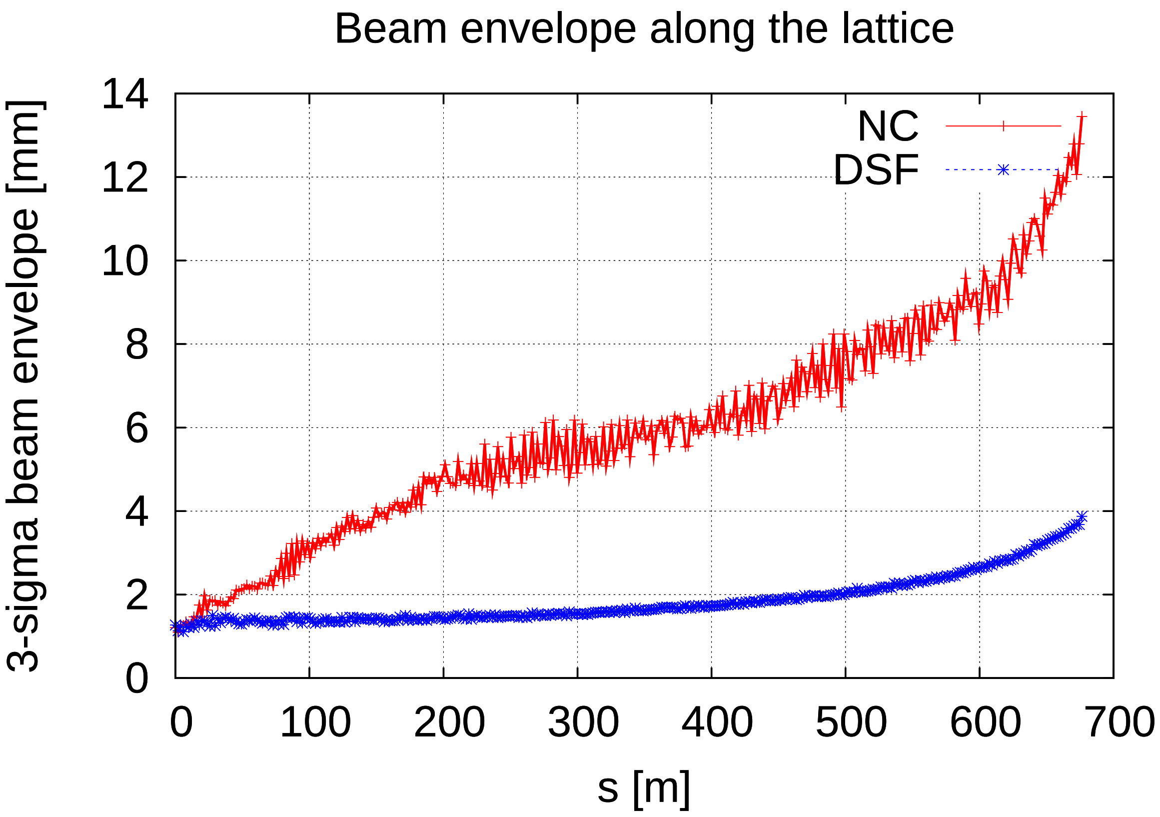
Drive Beam Decelerator

- Beam is decelerated to 10% of the initial energy

  $\Rightarrow$ envelope increase due to adiabatic undamping

  $\Rightarrow$ large energy spread develops, so avoid dispersion

- Wakefield effects can be severe
  - there have been structure designs that would have rendered a jittering beam unstable



- Studies by Erik Adli are advanced but need to be completed
- PETS tolerance of $\sigma_{x,y} \leq \mathcal{O}(100\,\mu\mathrm{m})$ and $\sigma_{x',y'} \leq \mathcal{O}(1\,\mathrm{mradian})$
- BPM tolerance of $\sigma_{BPM} = 20\,\mu\mathrm{m}$ is acceptable
- BPM resolution of $\sigma_{res} = 10\,\mu\mathrm{m}$ could be acceptable
- Initial quadrupole alignment of $\sigma_{quad} = 20\,\mu\mathrm{m}$ could lead some beam loss

Dynamic Imperfections

- A large number of dynamic imperfections exist

  e.g. ground motion, RF phase and amplitude jitter, element transverse jitter, magnet strength jitter, . . .

- These imperfections need to be adressed across the whole machine
  - the SLC problem: it was hard to tune any knob because the machine was always moving
  - but can start looking at individual components
- Effects have different timescales
  - fast ones can impact
- Imperfection can lead to direct luminosity reduction

  e.g. quadrupole transverse jitter in main linac

- They can lead to indirect luminosity loss
  - the required feedback impacts the beam
  - impact on static alignment and tuning procedures
- Fast losses lead to luminosity fluctuations and thus need to be limited
- budget for slow drifts can be more generous

Feedback Strategy

- Intra-pulse beam feedback
  - beam-beam feedback at the interaction point
  - feedforward at turn-arounds
- Pulse-to-pulse feedback
  - e.g. fast beam-beam feedback at interaction point
  - slower orbit feedback in BDS
  - slower main linac orbit feedback
  - . . .
- Retuning
  - e.g. beam waist at collision
  - . . .
- Complex beam-based alignment and tuning
  - not in normal running conditions
- Other feedback
  - not beam-based
  - element stabilisation
  - alignment system
  - tunnel temperature
  - . . .
- Independent feedbacks on the same property will have to share the overall feedback bandwidth

  ⇒ try to combine as much as possible

  - but need to know response

Some Sources

- Draft guess of a luminosity sources (for $\epsilon_y = 10\,\mathrm{nm}$)

  losses are per side

  numbers need to be reviewed, just to illustrate that many sources exist

  these five sources yield total loss of 10%

Source	budget	tolerance
Damping ring extraction jitter	1%	
Magnetic field variations	?%	
Bunch compressor jitter	1%	
Quadrupole jitter in main linac	1%	$\Delta\epsilon_y = 0.4\,\mathrm{nm}$ $\sigma_{jitter} \approx 1.5\,\mathrm{nm}$
Structure pos. jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 200\,\mathrm{nm}$
Structure angle jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04\,\mathrm{nm}$ $\sigma_{jitter} \approx 170\,\mathrm{nradian}$
RF jitter in main linac	1%	
Crab cavity phase jitter	1%	$\sigma_\phi \approx 0.01^\circ$
Final doublet quadrupole jitter	1%	$\sigma_{jitter} \approx 0.1\,\mathrm{nm}$
Other quadrupole jitter in BDS	1%	
...	?%	

Main Linac Single Bunch Dynamic Tolerances

- For jitters assumed no correction

  ⇒ multi-pulse emittance is important

- Value is given for 0.1 nm emittance growth

  - quadrupole position: $0.8\,\mathrm{nm}$

  - structure position: $0.7\,\mu\mathrm{m}$

  - structure angle: $0.55\,\mu\mathrm{radian}$

⇒ Tolerances are very tight

  - in particular for quadrupole

- ATL-model 1.2 nm for $10^5\,\mathrm{s}$ with $A = 0.5 \times 10^{-6}\,\mu\mathrm{m}^2\mathrm{s}^{-1}\mathrm{m}^{-1}$ using one-to-one steering

  ⇒ tuning bumps are needed

  - for three bumps $0.45\,\mathrm{nm}$, for seven $0.25\,\mathrm{nm}$

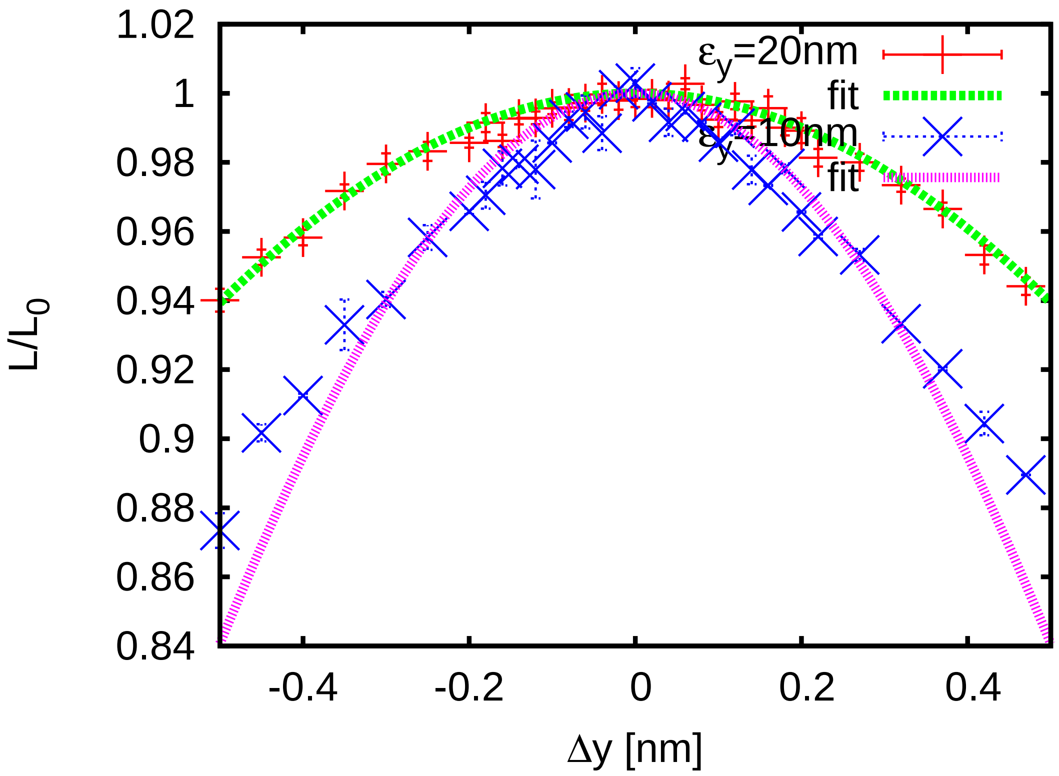
  ⇒ realignment every few days

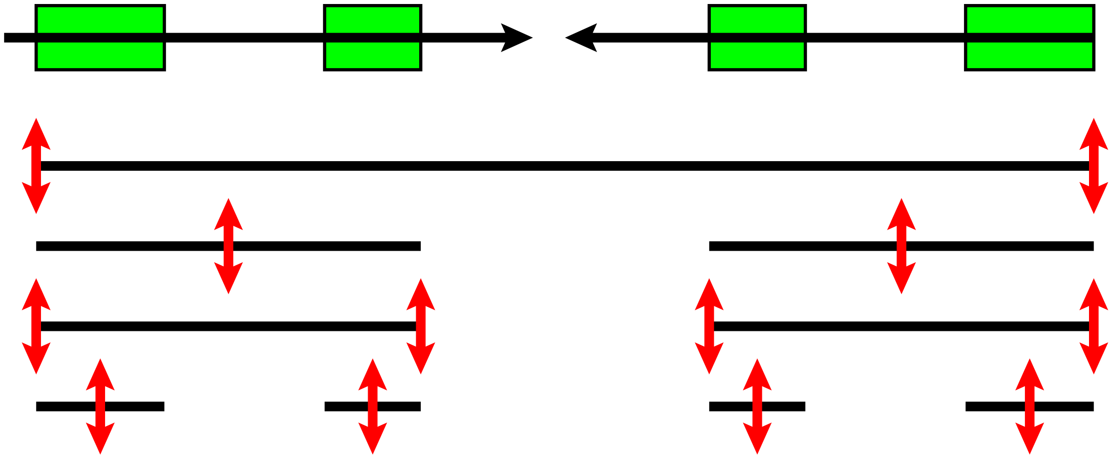
Beam-Beam Jitter Tolerance

- Beam-beam vertical jitter tolerance for 2% luminosity loss is $0.3\,\mathrm{nm}$ for rigid bunches
- Inclusion of beam-beam effects finds almost the same values
  - 0.28 nm yields 2.2%
- Tolerance on quadrupole stability depends on support layout
  - from 4 to $0.5\sigma_{beam-beam}$
  - single support seems excluded

$\Rightarrow$ tolerances 0.14–$0.18\,\mathrm{nm}$

- Will be addressed by A. Jeremie, C. Hauviller, D. Urner et al.



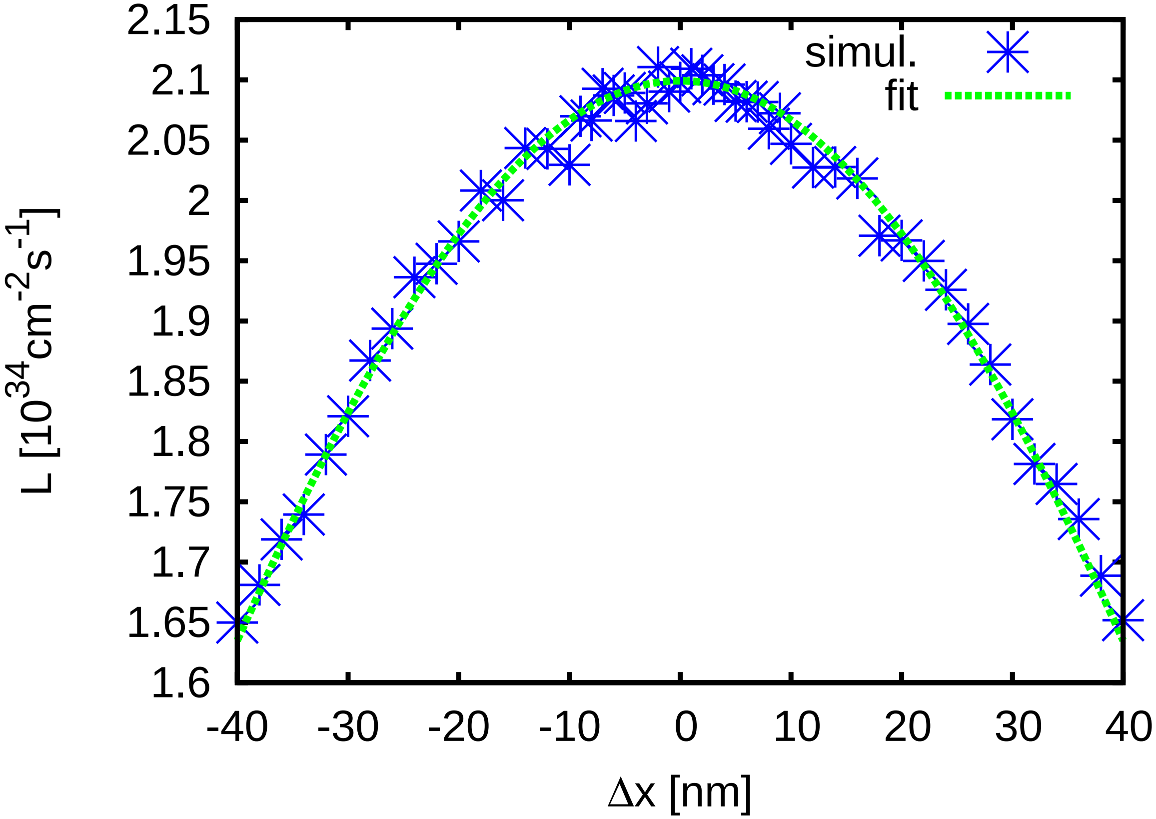


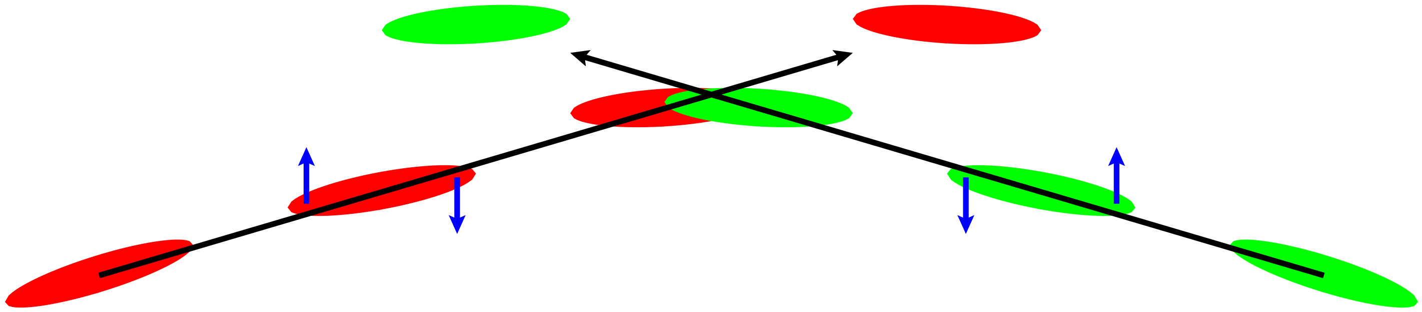
Crab Cavity Phase Stability

- Required phase stability can be easily calculated
- What matters is relative phase of electron and positron crab cavity
- Horizontal offset at IP is

$$\Delta x = \frac{\theta_c}{2}\Delta\Phi$$

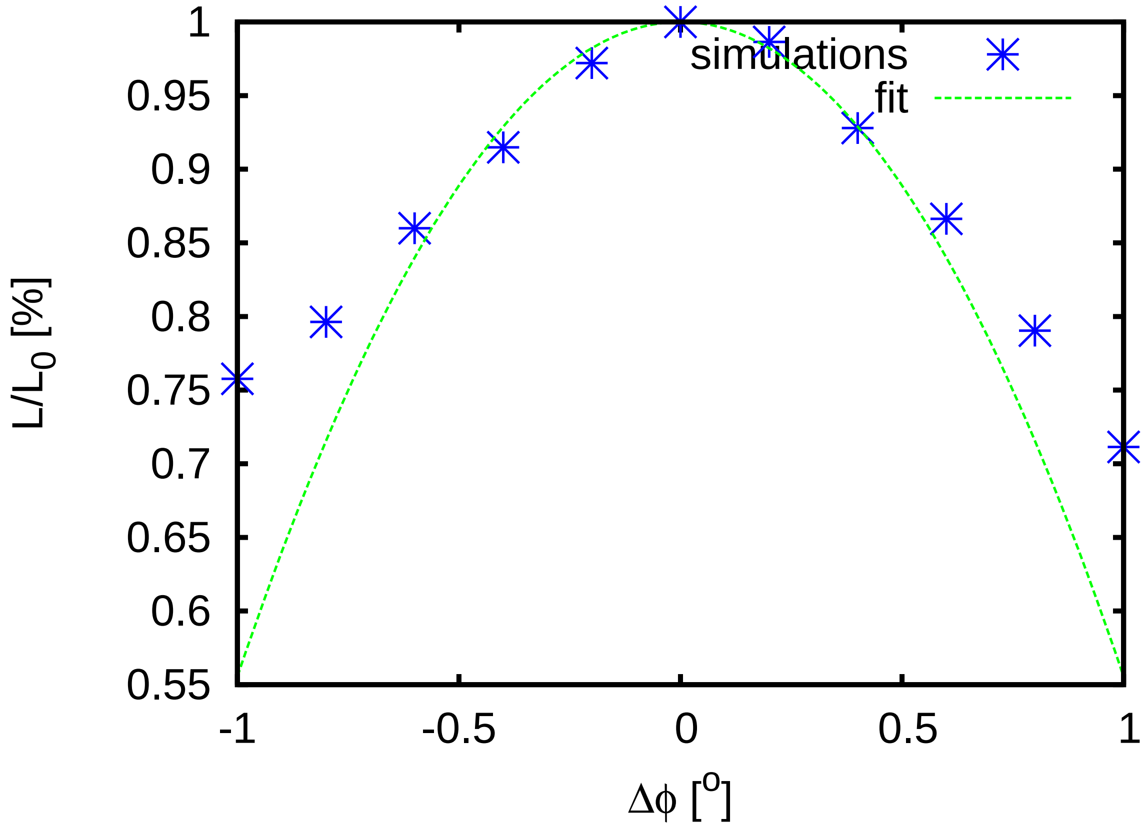
- For one 1% luminosity loss $\Delta\Phi \leq 0.011°$ (will be addressed by A. Dexter et al.)





RF Phase Errors

- RF phase errors are likely coherent along the main linac
- Limits from physics ($\sigma_s \leq 0.001s \Rightarrow \sigma_\phi \leq 0.2^\circ$) and luminosity loss (1% loss per side $\rightarrow \sigma_\phi \leq 0.15^\circ$)
  - $\Rightarrow$ phase tolerance of 0.01° for drive beam bunch compressor RF
  - $\Rightarrow$ transverse jitter tolerance for DB decelerator
  - $\Rightarrow$ other jitter sources to be investigated
- A small drive beam energy error leads to a phase error after compression

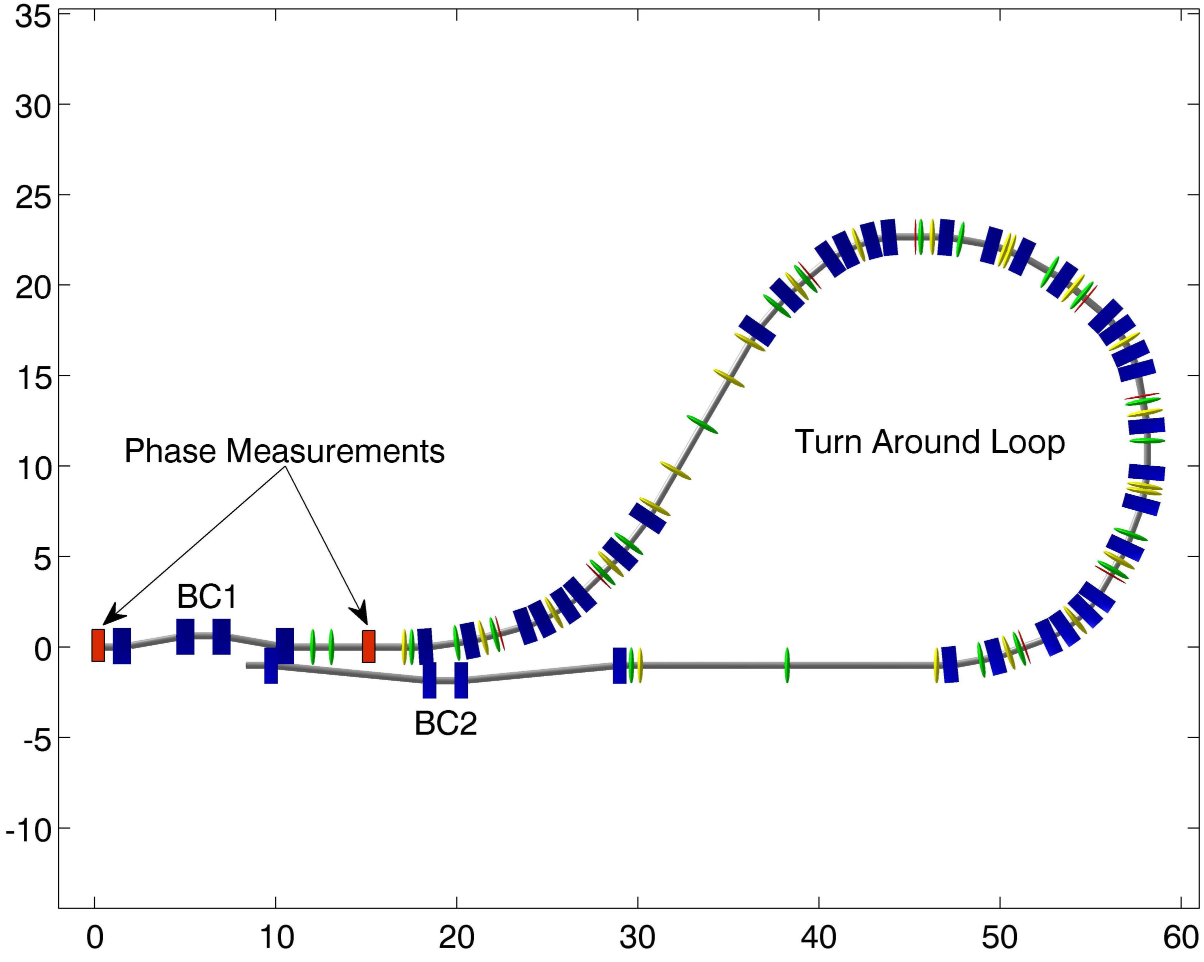


$\Rightarrow$ Need intra-pulse and pulse-to-pulse feedback

- many options exist, among them
- in the drive beam accelerator
- at the last turn-around

Mitigation Strategies

- Final feedforward shown
  - requires timing reference (J. Sladen, A. Andersson)
  - phase measurement/prediction (FP7)
  - tuning chicane (F. Stulle)
- Some options for DB bunch compressor system have been suggested
  - different dependence on imperfections
  - systematic study is needed



Fast Beam Ion Instability

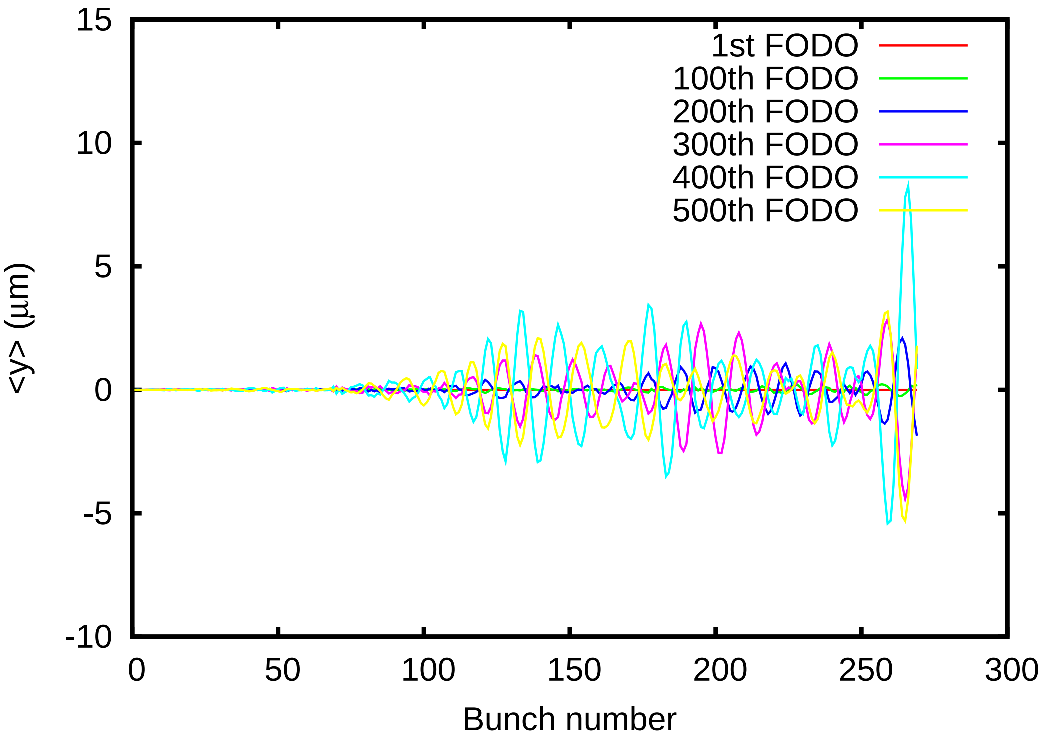
- Can be a problem in different sub-systems
- Growth rate does not depend much on optics, approximately

$$\frac{1}{\tau_e} = \frac{p\sigma_{ion}}{kT} \frac{Nnr_e c}{\sqrt{18}\sqrt{\epsilon_x \epsilon_y} a} \frac{1}{\sqrt{Q}}$$

- For main beam about 3 e-foldings per km and 10ntorr

⇒ Need $0.1\,\mathrm{ntorr}$ in transfer lines, DR, BDS

- For drive beam we find 0.6-efoldings per km and 10ntorr
  - ⇒ need very good vacuum



- New code developed by G. Rumolo
- Simulations for $1\,\mathrm{ntor}$ (CO and H_2O)

⇒ pressure is too high

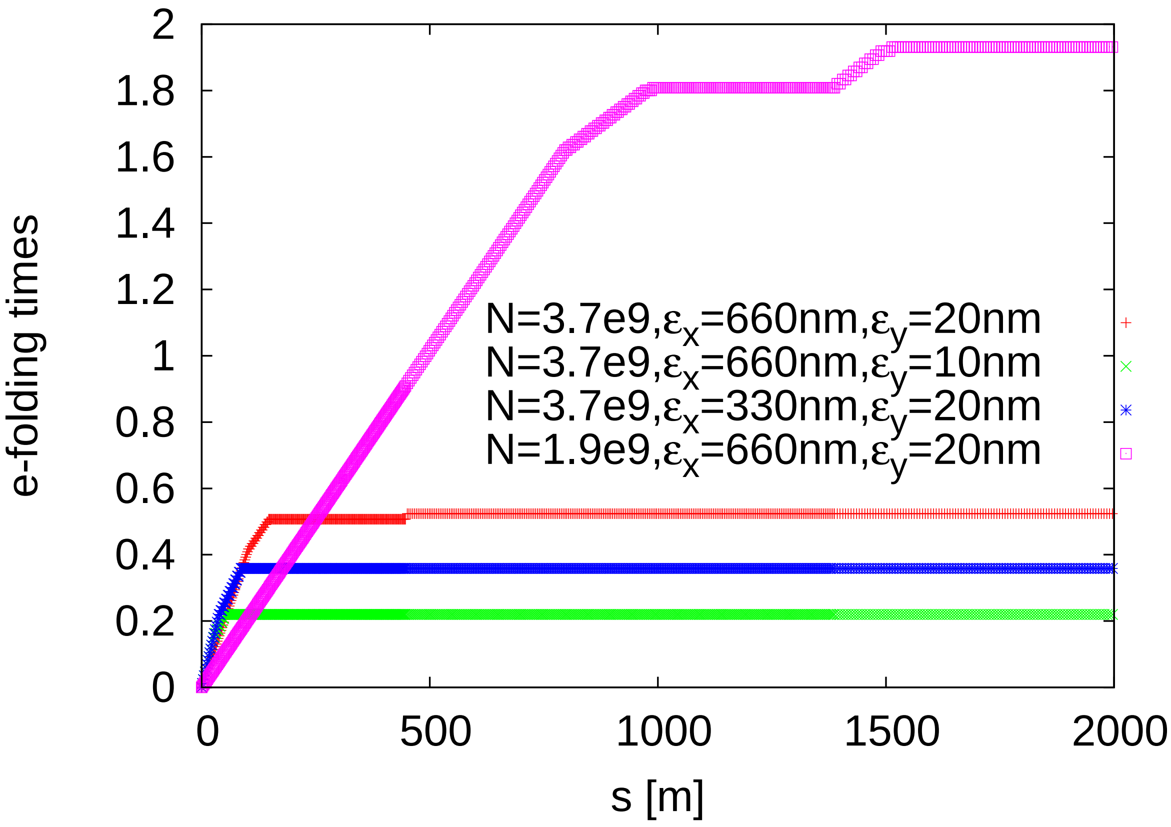
⇒ need more studies to cross check simple calculation

Fast Beam Ion Instability (cont.)

- In main linac better than 10 ntorr is a challenge
- But for small beam dimensions ions are not trapped

  ⇒ in plot stop growth when trapping condition is not fullfilled any more

⇒ Need simulation study



- Uncertainty is large
  - tunneling can increase ion production rate (one to two orders of magnitude in CLIC)
  - ions outside the beam can still affect it
  - beam parameters are important (e.g. small N)

Dynamic Effects During Main Beam Tuning

- For main linac each pulse during the DFS is being simulated
  - machine is static during other procedures
  - we want to understand impact on DFS

⇒ for quadrupole jitter direct emittance growth is equal to indirect

⇒ for beam jitter direct emittance growth is larger than indirect

- Dynamic effects during knob optimisation are also being studied (P. Eliasson)
  - emittance tuning at the end of the linac
  - luminosity tuning at interaction point

⇒ seem to be able to cope with luminosity fluctuations during knob optimisation

Conclusion

- Not all problems have been mentioned
  - machine protection
  - dark current
  - . . .
- Not all sub-systems for CLIC have been designed
- Tolerances for a number of them need to still be determined
- Some tolerances are very tough
- We need more integrated studies
- CLIC needs you
- Beam dynamics is split into two working groups
  - injector and damping rings
  - main and drive beam dynamics