Computational Needs for the ILC

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- This talk is not a detailed status review

  or a precise to-do list

- It is mainly advertisement

  - where can you join?

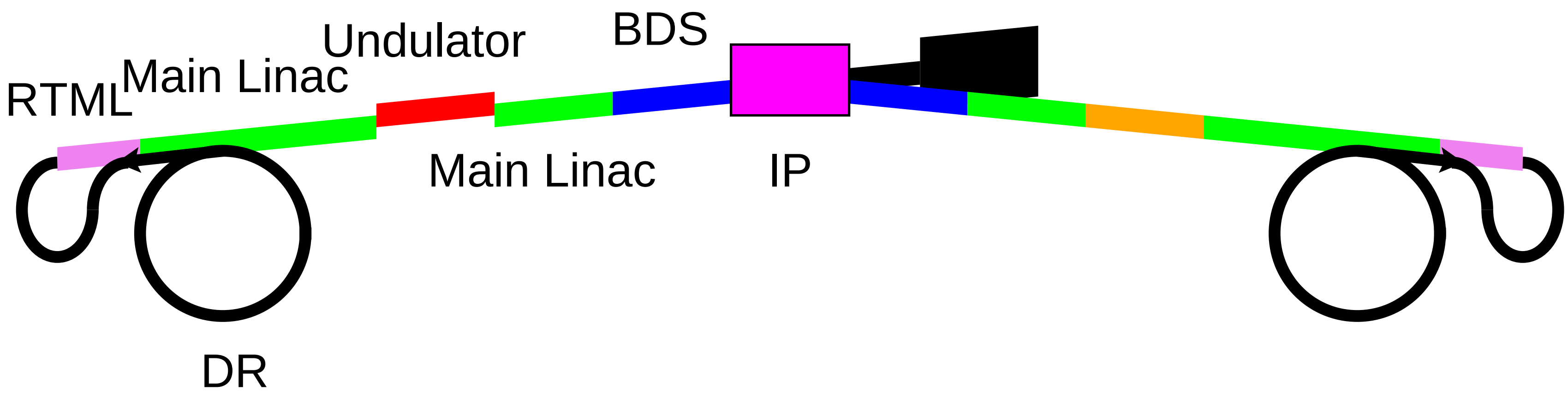
- It gives my personal view

- It focuses on beam simulations in damping ring and LET

- Do to the large number of studies and people I cannot give credit to all of them

Introduction

- The ILC is a proposed linear electron-positron collider based on superconducting RF technology
  - focus is on $E_{cm} = 500\,\mathrm{GeV}$



- Second IP and electron source not drawn
- It is a world-wide effort supported by the Global Design Effort (GDE)

The GDE

- International organisation led by Barry Barish
  - supported by large and small institutes
  - complex organisation
  - work is organised in working groups
- Aim is to have
  - Reference Design Report (RDR) end of 2006

    based on current baseline configuration

    includes cost
  - technical design report to be ready for a decision as soon as LHC physics results are available
- Sample sites have been chosen in the different regions

  Japan, near Fermilab, DESY, CERN

ILC Parameters

- For ILC different parameter sets have been defined

  $\Rightarrow$ also investigate flexibility

		Nominal	Low Q	Large Y	Low P	High L
E_0	$[GeV]$	250	250	250	250	250
$\mathcal{L}$	$[10^{34} cm^{-2} s^{-1}]$	2.12	2.00	1.78	2.01	5.16
N	$[10^{10}]$	2	1	2	2	2
n_b		2820	5640	2820	1330	2820
f_{rep}	$[Hz]$	5	5	5	5	5
Δz	$[ns]$	308	154	308	462	308
ϵ_x / ϵ_y	$[\mu m]$	10 / 0.04	10 / 0.03	12 / 0.08	10 / 0.035	10 / 0.03
β_x / β_y	$[mm]$	21 / 0.4	12 / 0.2	10 / 0.4	10 / 0.2	10 / 0.2
σ_x / σ_y	$[nm]$	655.2 / 5.7	495.3 / 3.5	495.3 / 8.1	452.1 / 3.8	452.1 / 3.5
σ_z	$[\mu m]$	300	150	500	200	150

$\Rightarrow$ Duty cycle is limited ($\approx 0.5\%$)

$\Rightarrow$ Emittances are small

Simulation Goals

Concentrate on beam performance studies

- We are building a consensus

- Feasibility of ILC has been stablished

  ⇒ there could a surprise

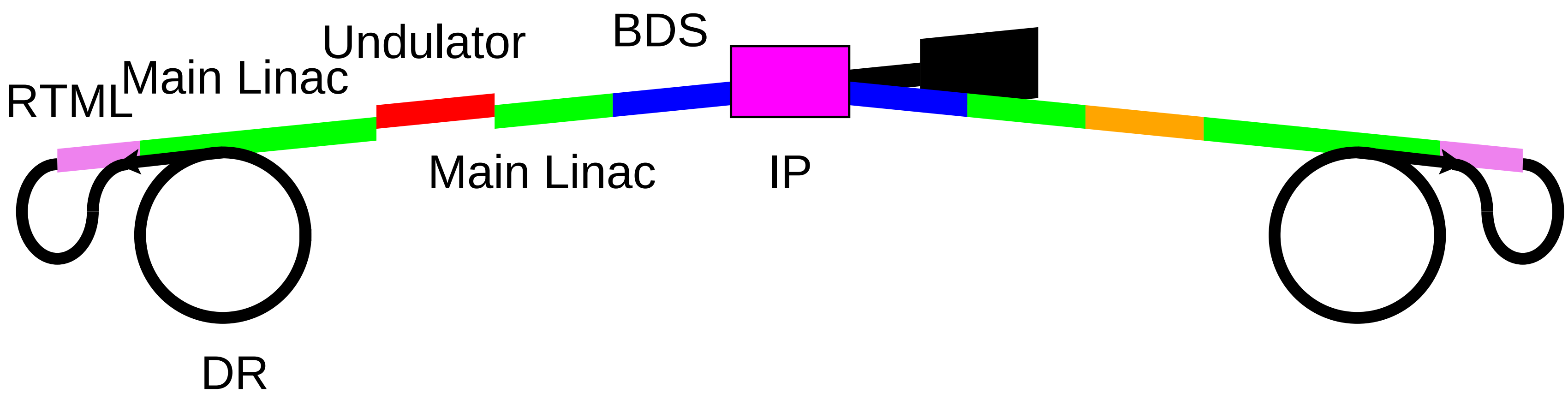
- It has not been fully established that the performance goal can be met

  ⇒ are working on it

- Cost is of prime importance, currently seems high

  ⇒ are working on this, requires to exactly know the limits

  ⇒ trade-offs are needed



ILC vs. Ring-Based Collider

- In most systems, beam passes once

  ⇒ injection all the time

  ⇒ feedback is difficult

  ⇒ dynamic effects are important

- ILC can be separated into three main areas

  - the injectors → single pass

  - the damping rings → multi-pass

  - the beam transport from damping ring to the interaction point and beam dump (LET) → single pass

- Experience with high energy linear colliders are limited, only one existed sofar

  - emittances are very small and beams are tiny at collision

  - huge effort goes into benchmarking of different codes with each other

  - try to find benchmarks with real machines, e.g. ATF2

  - vital to make sure that the models are correct

  - beam-beam effects are critical

Damping Ring

- Damping ring circumference (6km) is smaller than train length

  ⇒ need to interleave bunches

  ⇒ bunch distance reduced to 6 ns (even 3 ns for alternative parameters)

- Goal is to achieve $\epsilon_x = 8\,\mu\mathrm{m}$, $\epsilon_y = 20\,\mathrm{nm}$, $\sigma_E/E = 1.4 \times 10^{-4}$, $\sigma_z = 6\,\mathrm{mm}$

- Important effects that still need simulation are

  - dynamic aperture
  - electron cloud
  - fast beam-ion instability
  - alignment and tuning
  - impedances
  - ...

- Effort for simulations can be roughly compared to LHC (well no beam-beam)

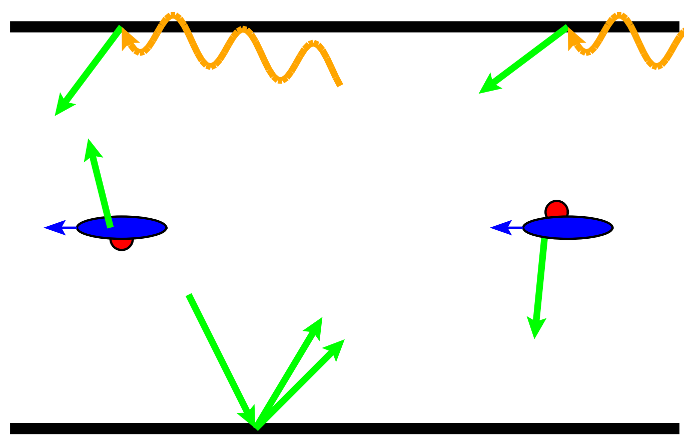
- A large number of people are working on this, report of CERN meeting

Electron Cloud

- Multi-pacting in positron damping ring

  ⇒ build-up of electron cloud to charge compensation limit

  ⇒ threshold density for beam stability



- Single positron damping ring does not work even for $\delta_{max} = 1.2$)

  ⇒ stacked rings

  ⇒ clearing electrodes

  ⇒ grooved surfaces

- Electrodes and grooves seem to work (H. Fukuma, R. Kirby, S. Kurokawa, F. Le Pimpec, M. Pivi, T. Raubenheimer, G. Stupakov, L. Wang, G. Xia)

  ⇒ but still more simulations useful

  ⇒ experiments carried out, further planned

Dynamic Aperture

- Very important for positrons due to large incoming emittance
- Could also become more relevant for electrons, since cost engineers may ask for smallest possible beam pipe
- Dynamic aperture depends critically on magnet imperfections

  - currently limit is tight (few sigma)

  $\Rightarrow$ careful and repeated study may be required, need clever approach

Fast Beam-Ion Instability

- Can be avoided using very good vacuum pressure

  - NEG coating required in many parts,

  $\Rightarrow$ detailed study is necessary

Impedances

- Book keeping of all sources is vital

  ⇒ strong interaction with the hardware design/cost

  ⇒ large amounts of RF simulations needed

  ⇒ important studies, e.g. multi-bunch instabilities, need clever approaches

- Beam loading has transient during extraction (due to positron source)

  ⇒ needs study to understand the impact of the beam loading variation

Alignment and Tuning

- Alignment and tuning procedure tested at ATF

  - did not yield expected performance

  - after extraction the emittance is much larger (increasing with bunch charge)

  ⇒ need better understanding of the errors and systematic effects, similar to LET

  - excellent test bed for further studies

Low Emittance Transport

- From damping ring to IP and beam dump
- System design is quite advanced
- Important to study mitigation of static and dynamic imperfections
  - Combination of them could be severe
- Use codes to evaluate LET performance
- Are the performance predictions correct?
  - correct and complete imperfections model

    wakefields, e.g. cavities, collimators...

    diagnostics performance

    model for static imperfections, e.g. prealignment model from LICAS...

    dynamic model, e.g. ground motion, RF stability...

    can give tolerances based on the models
  - integrated studies
  - code benchmarking
- Can use experience/synergy with other previous and current studies (NLC, JLC, CLIC)

Integrated Simulations

- Integration of different systems is necessary
  - include correlations in the beam
  - feedback in different areas need to work together
  - tuning and alignment applied in one system are affected by noise generated in another
  - we sometimes need one system to tune and align the other

    e.g. main linac dispersion correction with bumps in bunch compressor and BDS

    luminosity tuning
- Integration of different timescales is necessary
  - have intra-pulse and pulse-to-pulse feedback
  - tuning takes time and can interfere with feedback
  - alignment can be be sensitive to dynamic effects
  - dynamci effects can be sensitive to tuning and alignment
- Different codes are being developed and are quite mature

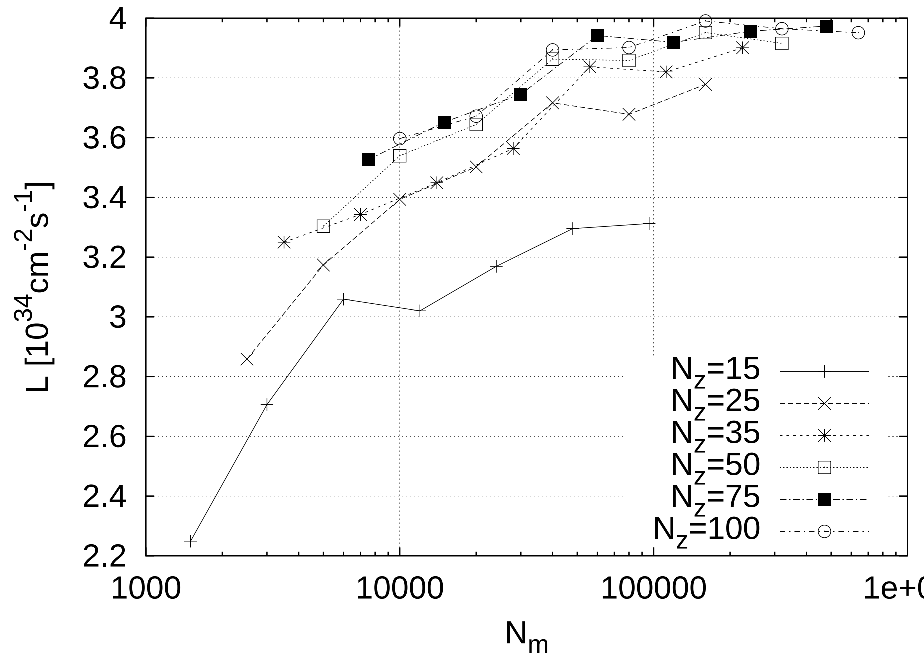
  BMAD/ILCv, CHEF, MATLIAR, LUCRETIA, MERLIN, PLACET, SLEPT...

Computing Time Needed

- Beam-beam requires $\mathcal{O}(10^5)$ particles
- Typical full simulation of one bunch takes $\approx 2 \times 5\,\mathrm{minutes}$

  $\Rightarrow$ tracking one train of 2820 bunches takes 20 days

  $\Rightarrow$ to track 1000 pulses one would need more than fifty years
- CPUs seem not to become that much faster any more
- But they contain more than one core



TESLA example

$\Rightarrow$ take short cuts, e.g single bunch simulations

$\Rightarrow$ would likely profit from parallel codes in the long term (but normally will run 100 seeds)

- some care needs to be taken for wakefields and the beam-beam interaction
  - wakefields need to be calculated at least in each cavity, i.e. ≈ 8000 times

Beam-Beam Interaction

- Each beam focuses oncoming one

  Focal strengths described by disruption parameters

  $$D_{x,y} = \frac{\sigma_z}{f_{x,y}} = \frac{2Nr_e\sigma_z}{\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}$$

- $D_x \approx 0.15$, $D_y \approx 18$

  $\Rightarrow$ luminosity increase (H_D)

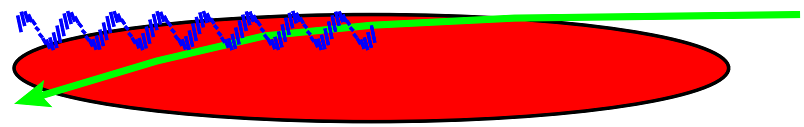
- Beamstrahlung

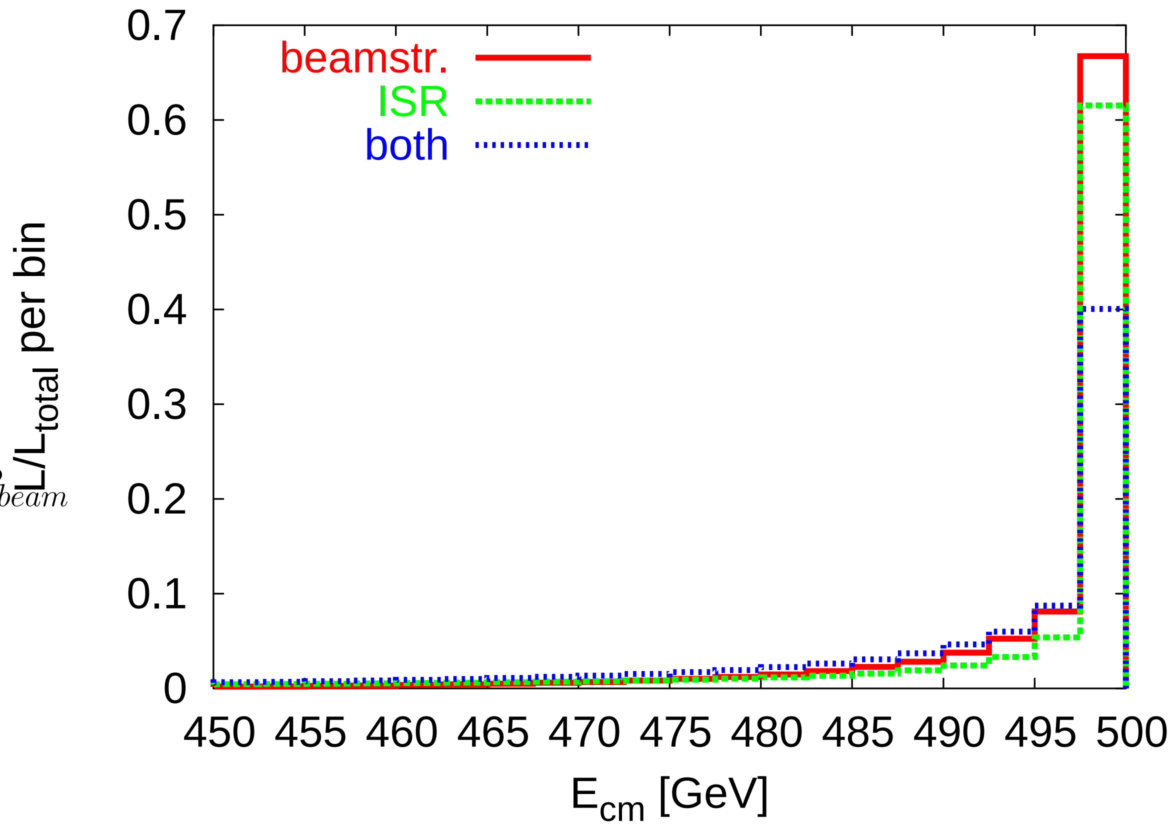
  $$\Delta E \propto \left(\frac{N}{(\sigma_x+\sigma_y)}\right)^2, \quad \mathcal{L} \propto \frac{N}{\sigma_x\sigma_y}P_{beam}$$

  $\Rightarrow$ affects physics

  $\Rightarrow$ flat beams

- Beamstrahlung effect comparable to initial state radiation



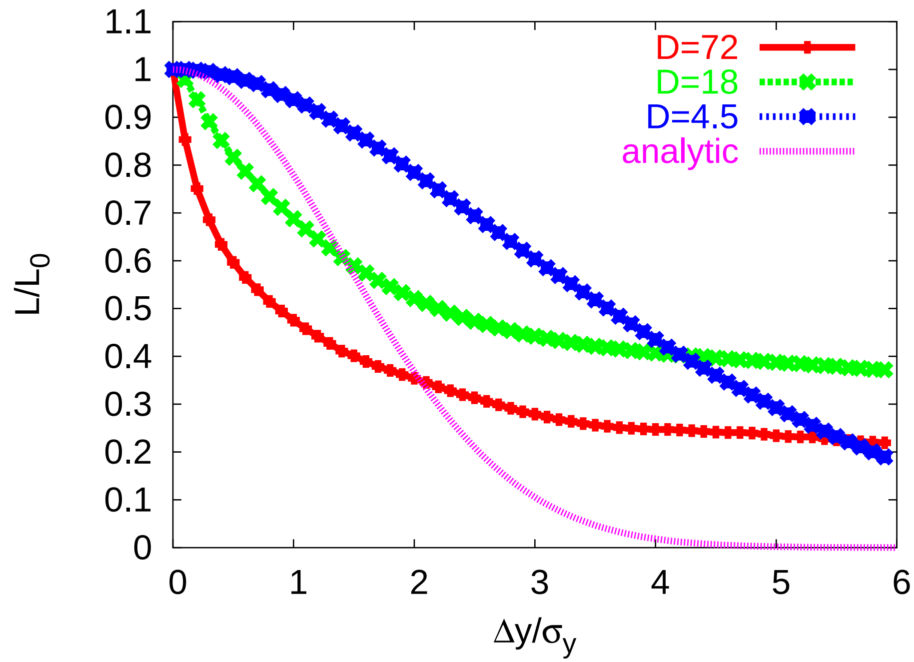


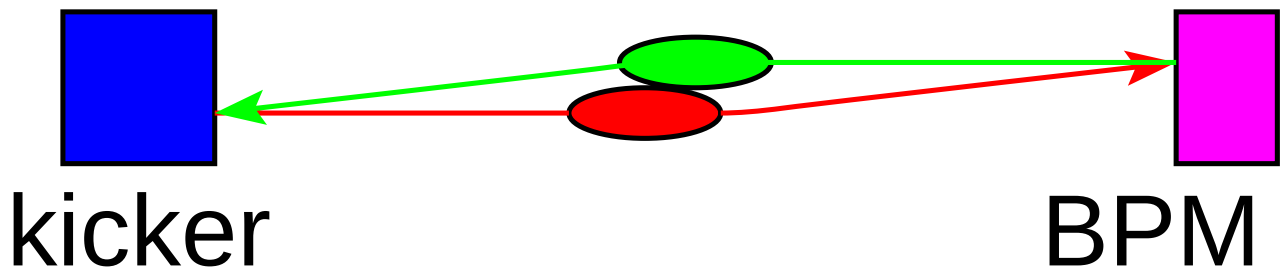
Beam Offset and Luminosity

- Beam vertical size is tiny (5.7 nm)
- Repetition rate is low (5Hz)
- Final quadrupoles may move significantly and directly translate this to beam offset

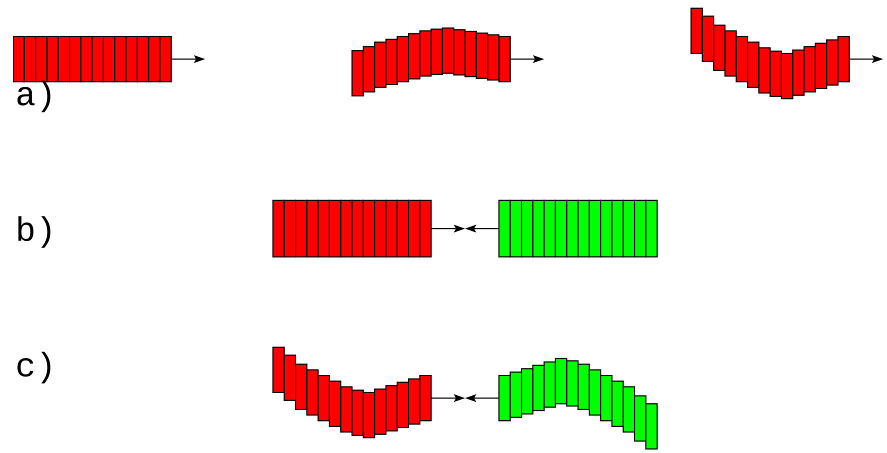
⇒ Need to stabilise beam

⇒ intra-pulse interaction point feedback





The Banana Effect



At large disruption, correlated offsets in the beam can lead to instability

The emittance growth in the beam leads to correlation of the mean y position to z

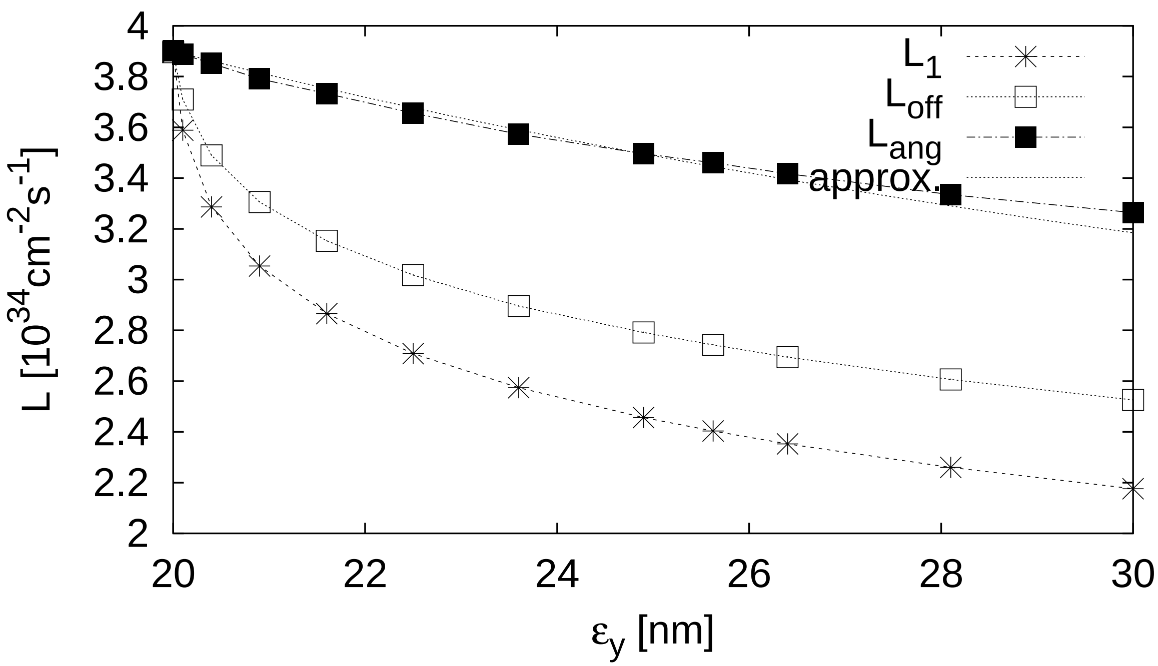
a) shows development of beam in the main linac

b) simplified beam-beam calculation using projected emittances

c) beam-beam calculation with full correlation

⇒ Luminosity loss increased

⇒ Cure exists

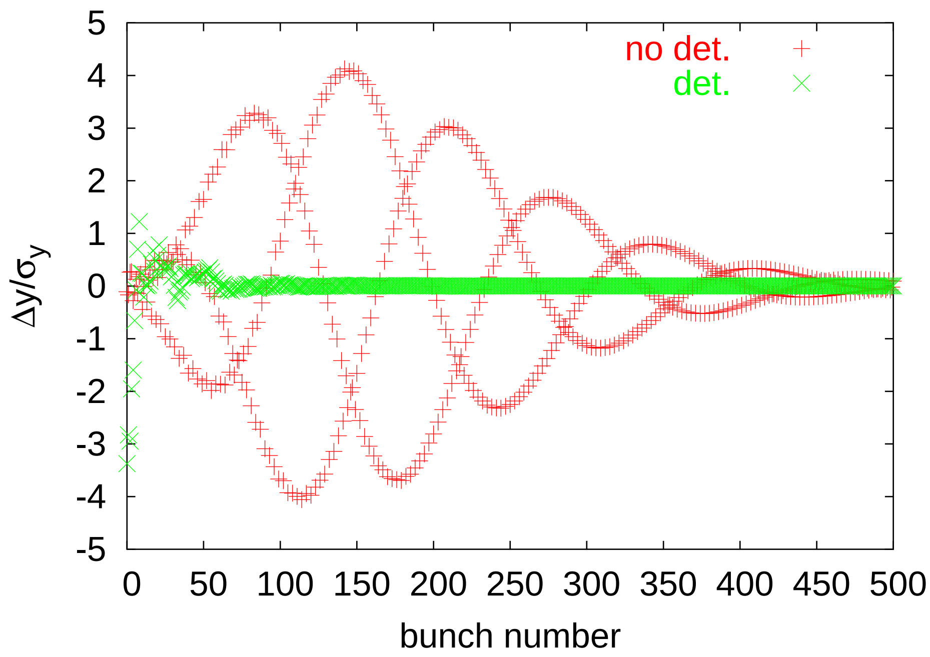


Beam-Based Alignment and Tuning

- In different sub-systems comparable procedure
  - survey
    $\Rightarrow$ external alignment
  - align with beam
    $\Rightarrow$ use BPMs
  - use tuning knobs
    $\Rightarrow$ optimise signal, e.g. luminosity, beam size, background
- Different beam-based alignment methods are studied
  - dispersion free steering
  - ballistic alignment
  - kick minimisation
  - quadrupole shunting

Main Linac Multi-Bunch Effects

- Long-range wakefields are important
  - ⇒ in main linac cavity detuning is essential
  - ⇒ need to ensure that this detuning is present
- For similar bunches wakefield effects yield steady state
  - ⇒ single-bunch simulations can give useful information
  - ⇒ but one has to aware of potential problems
    - e.g. bunch-to-bunch variations



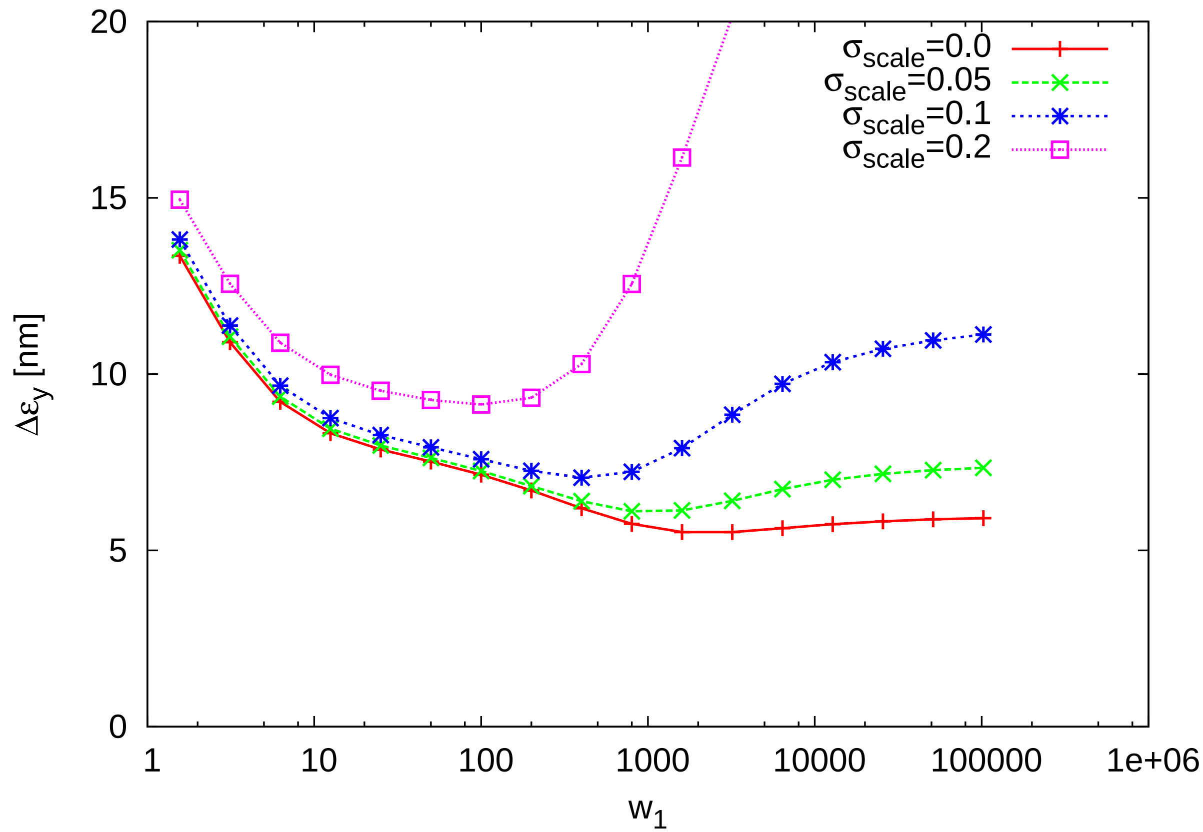
All main linac cavities are scattered by 500 $\mu\mathrm{m}$

Longrange wakefields are represented by a number of RF modes

$$W_{\perp}(z) = \sum_{i=0}^{n} a_i \sin\left(\frac{2\pi z}{\lambda_i}\right) \exp\left(-\frac{\pi z}{\lambda_i Q_i}\right)$$

Single Bunch Dispersion Steering Simulations

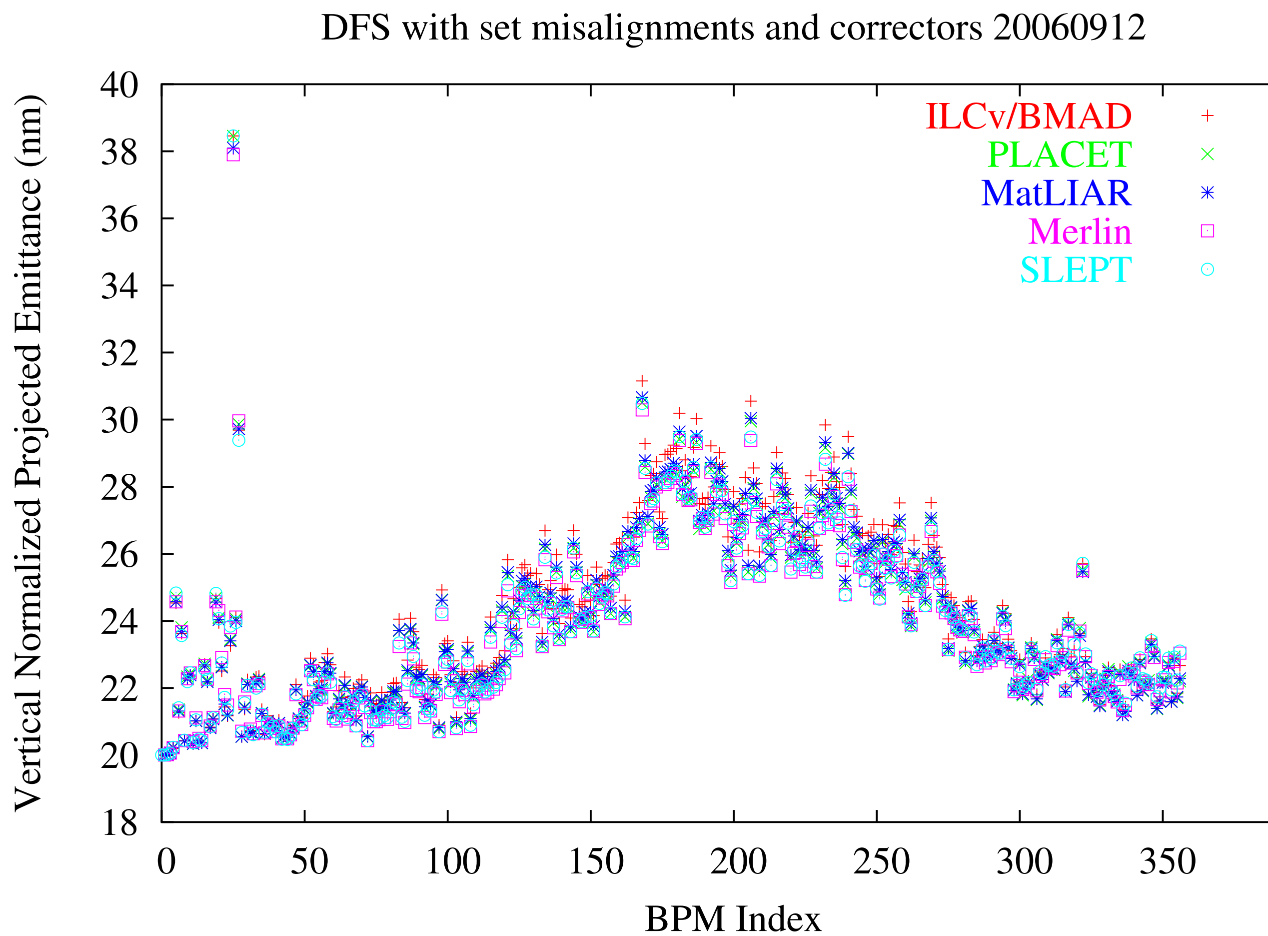
- Aim is 90% of machines at $\Delta\epsilon_y \leq 10\,\mathrm{nm}$
- P. Eliasson, K. Kubo, A. Latina, P. Lebrun, F. Poirier, K. Ranjan, D. Schulte, J. Smith, N. Soljak, N. Walker...
- Not all results are benchmarked against others
  - small differences in the assumptions etc.
- Concensus is:
  - beam-based alignment is close to the target but not quite sufficient
  - some further improvement needed with other means



Benchmarking

- Comparison of tracking for a single machine, after applying the beam-based correction in one machine
  - quadrupole position errors are corrected using dipole correctors
  - effectively tests subtraction of two large numbers

  ⇒ programs seem to agree quite well
- Comparison of beam-based alignment seems also to agree for test cases



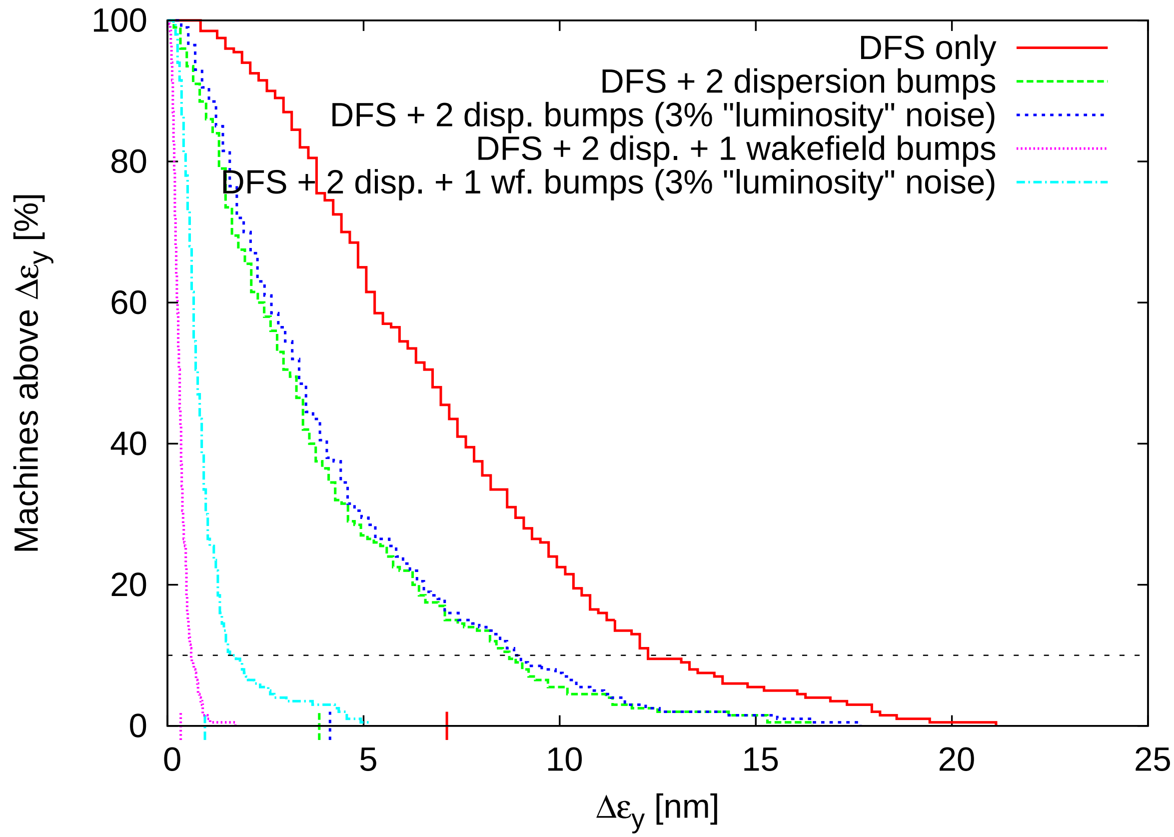
Thanks to Jeff Smith and all who sent him the data

Tuning Bumps

- The emittance growth after dispersion steering is still too large

  ⇒ further improvement needed

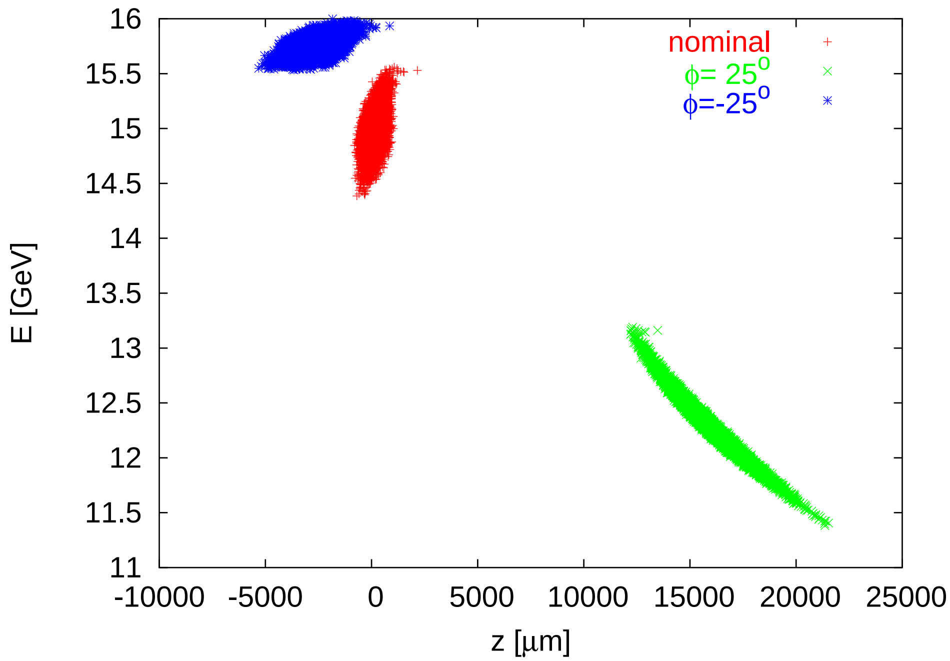
- Possible solution are emittance tuning bumps
  - measure the beam size after the main linac, i.e. with a laser wire
  - modify the beam dispersion at the beginning and end of the main linac to minimise beam size

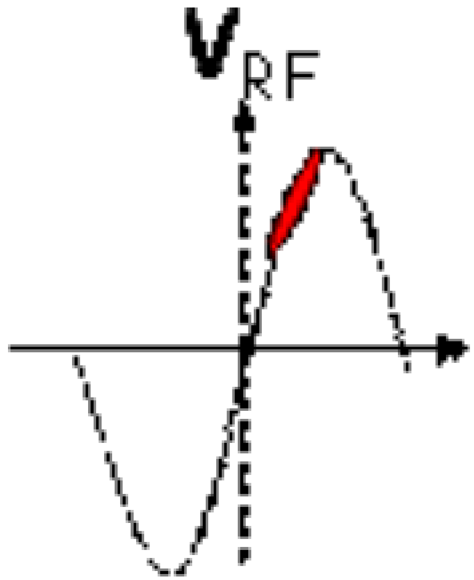


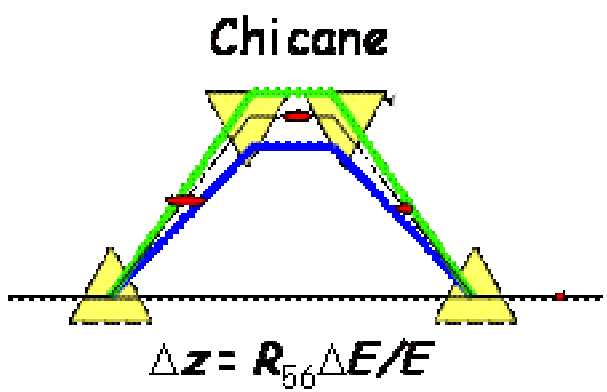
P. Eliasson et al.

Alignment of Beginning of Main Linac

- Dispersion free steering requires different energy beams at the main linac entrance
- Need to use bunch compressor to generate energy difference



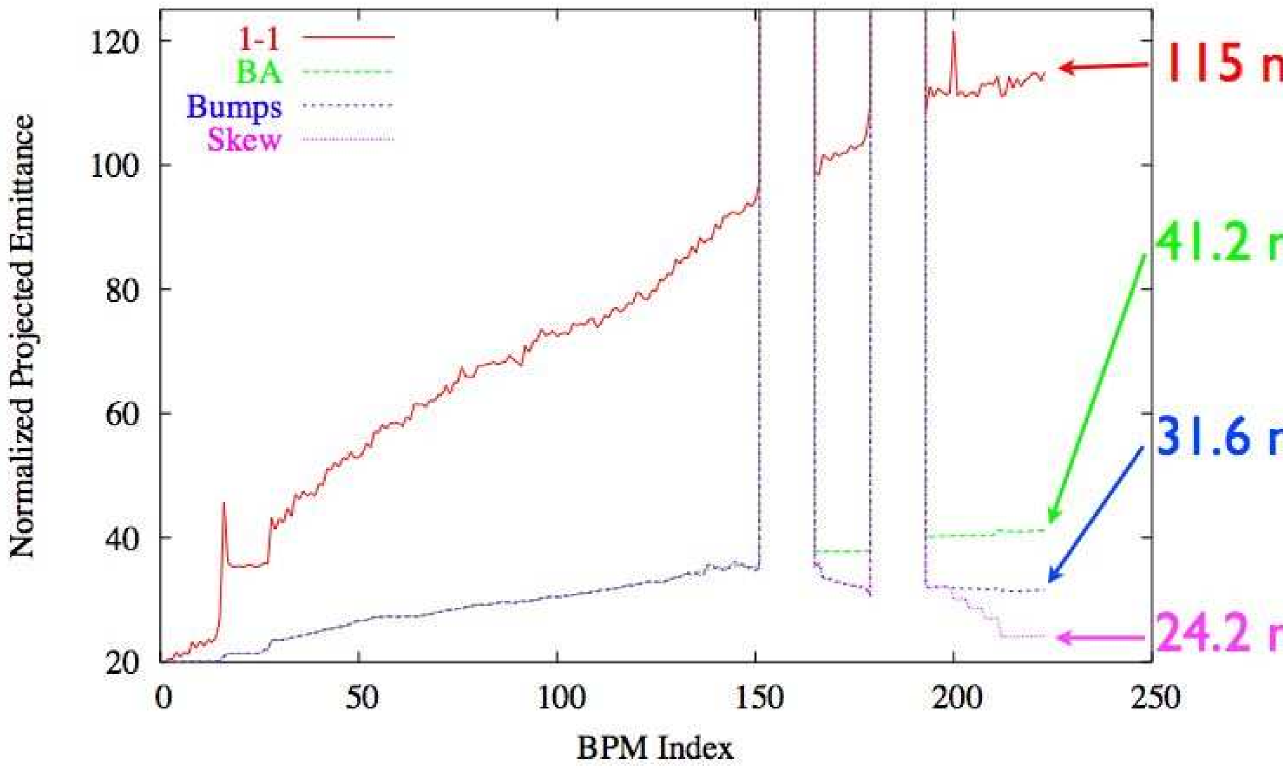




⇒ Results seem even better than simple energy difference (A. Latina et al.)

Ring To Main Linac Transport

- Alignment and tuning is difficult
  - large horizontal dispersion can couple into vertical plane
  - cannot easily use incoming energy difference
- Excellent progress due to Jeff Smith
  - use ballistic alignment for the magnets
  - use emittance tuning bumps
  - correct skew



- Wish some improvement
- Need to investigate ballistic alignment sensitivity to stray fields
- Need to confirm results

Beam Delivery System

- Very complex optics to squeeze beam to nanometer size
- Strategy
  - switch off sextupoles/octupoles
  - align BPMs to quadrupoles by quad shunting
  - align quadrupoles
  - align sextupoles/octupoles (switch them on first)
  - using correction knobs
- Achieved performance is not yet quite sufficent (G. White)

  ⇒ Improvement of method

  ⇒ Inclusion of dynamic errors

  ⇒ confirmation

- A previous test facility (FFTB) achieved 70nm (E=46.6GeV)
  - 40nm had been expected
  - the difference has been attributed to beam jitter
- A new test facility is planned (ATF2)
  - 37nm target beam size (E=1.3GeV)
  - demonstration of nm beam position control
- Alignment and tuning for ATF2 and FFS are quite similar

  ⇒ excellent benchmark of procedures

Dynamic Studies

- Codes are prepared for these studies
  - availability of full lattice, feedback design
  - results should come soon
- Some studies have already been performed

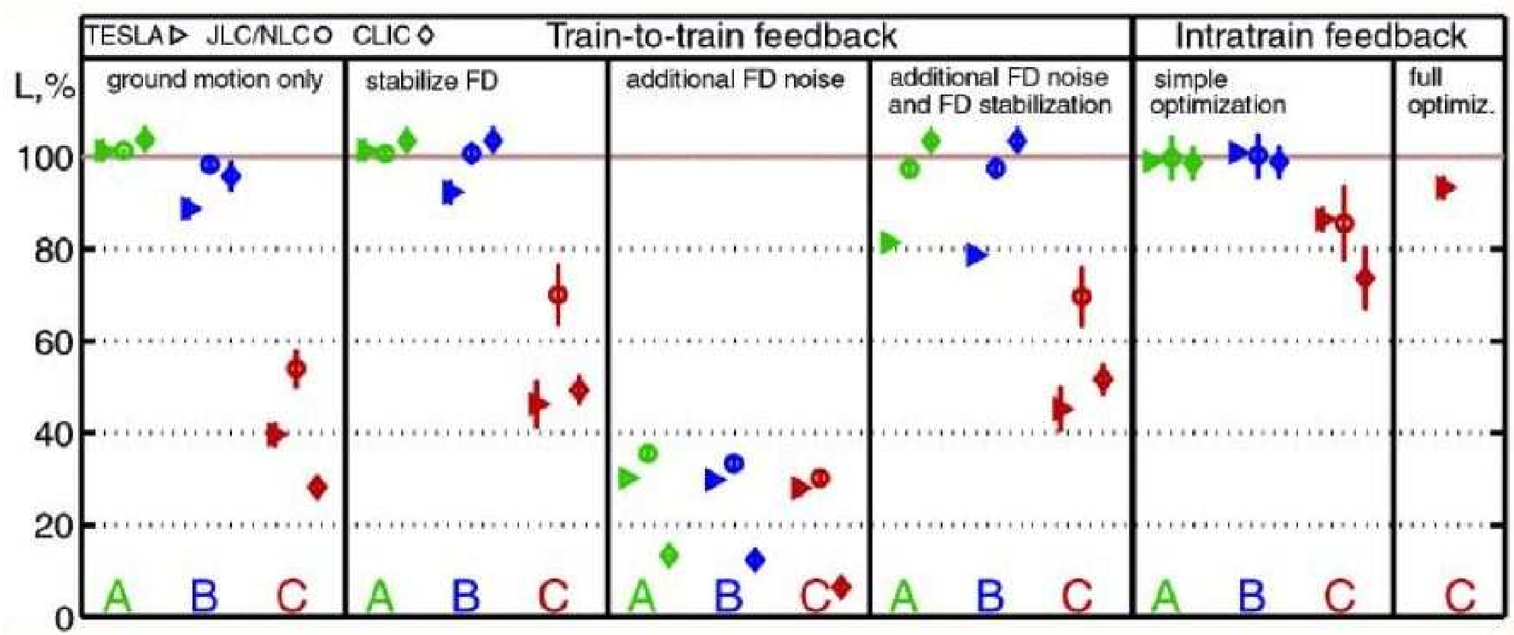
  ⇒ intra-pulse feedback (G. White et al.)

  ⇒ pulse-to-pulse feedback (L. Hendrikson et al.)

  ⇒ for Technical Review Committee TRC (A. Seryi et al., D. Schulte)
- Intra-pulse orbit feedback systems at different locations
  - feed-forward after DR, before helical undulator, at end of main linac, at IP
- Pulse-to-pulse orbit feedback along whole machine
  - local feedback (cascaded)?, overall correction?
- Tuning knobs
  - e.g. waist at IP, coupling, ...
- Studies of impact of dynamics on alignment started (K. Ranjan, D. Schulte)

  ⇒ so far no severe problem

Effect of Ground Motion



- Simulations performed for second Technical Review Committee
  - largely based on two independent codes
- Three different sites, A=quiet, B=medium, C=noisy

⇒ Intra-pulse feedback is essential

⇒ Intra-pulse luminosity optimisation advantageous

Instrumentation

- Complex instrumentation is needed
  - laser wires
  - luminosity and pseudo luminosity measurement
  - energy, polarisation...
- They are used to optimise tuning knobs, so need to study
  - systematic errors of the measurement
  - orthogonality of knobs in realistic machine
- This needs very carefull study including realistic initial conditions and dynamic effects

Losses and Background

- Losses affect machine design, e.g. post collision line
- Background sources in ILC are
  - machine related, e.g. beam halo, synchrotron radiation, ...
  - physics related
  - arising from beam-beam interaction
- Much can be done using beam dynamics tacking codes
  - but simulations with secondary generation is also required

  ⇒ they tend to be time consuming, but in most cases should be embarrassingly parallel

  - examples are MARS, BDSIM
- Development of background tuning is important
  - many machines had higher background than expected

Other Studies

- Rotating modes in cavities due to non-perfect zylindrical symmetry

  $\Rightarrow$ transfer of horizontal beam jitter into vertical emittance growth ($\epsilon_x \ll \epsilon_y$, R. Jones, R. Miller)

  $\Rightarrow$ needs further investigation
- Crab crossing cavities
- Full beam dynamics with polarisation

  - tools being developed (helical collaboration)
- Sources alignment and tuning (in particular positron source)
- Integration of damping ring and LET (simple models?)
- Beam-based alignment procedure robustness

  - studies show (K. Ranjan, F. Ostiguy, N. Solyak, J. Smith)

    in DFS a few percent of failures are acceptable provided equipment is identified

    otherwise emittance growth can be significant

  - Important further studies

    how can we identify faulty equipment?

    are there better ways of mitigating the effects?

Conclusion

- Currently no unsurmountable problem has been indentified for the ILC beam dynamics
- Significant simulation work is still required
  - for detailed understanding of collective effects, alignment and dynamic aperture in damping ring
  - to find solutions for the beam-based alignment of all LET components
  - to study dynamic effects in more detail
  - full integration of different systems and timescales for full performance predictions
  - to help to optimise cost
- Vital input is required from
  - wakefield simulations
  - instrumentation modelling
  - imperfections predictions
- Development of parallel codes seem useful
  - full blown parrallel system for wakefields
  - simple parallel clusters with commodity hardware for beam dynamics, for best CPU performance per money, use build-in networks

Thanks

- I would like to thank K. Kubo, N. Walker and A. Wolski for very useful discussion
- Jeff Smith, Glen White, Peder Eliasson and Andrea Latina for providing input and plots
- All the people who performed simulations and made suggestions
- The author is supported in by the Commission of the European Communities under the 6th Framework Programme, contract number RIDS-011899

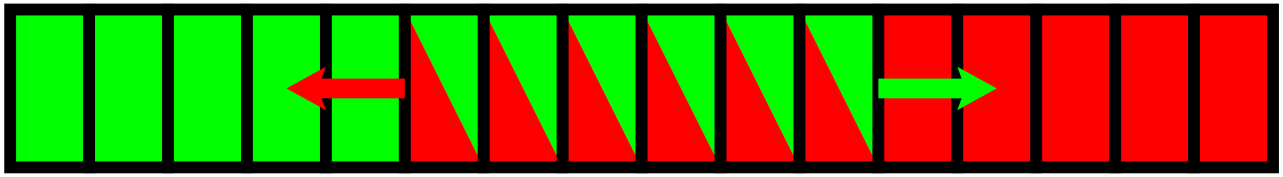
Parallelisation of Tracking

- Simple solution for multi-bunch tracking in single beam pulse
  - run each bunch on different computer node
    $\Rightarrow$ send $\approx 3.2\,\mathrm{MB}$ of wakefield data per bunch
  - run short section of linac on different nodes
    $\Rightarrow$ send $\approx 5\,\mathrm{MB}$ of beam date per bunch

  $\Rightarrow$ both can give speed-up of $\mathcal{O}(100)$
- Can speed up single-bunch tracking
  - 8000 `ReduceAll` of wakefield data need 10s on a slow cluster
    $\Rightarrow$ gain factor $\mathcal{O}(10)$
  - tracking can be quite parallel in RTML and BDS
    wakefields in bunch compressor linacs and collimators
  - in main linac beam can be represented by fewer particles
    $\Rightarrow$ additional speed-up possible
  - but might want to include more wakefields

$\Rightarrow$ CPU limit will come from available number distributed over the seeds

Beam-Beam Simulations



- Time per collision varies from few seconds to many minutes (60s for example case)

  $\Rightarrow$ this is a bottleneck as soon as the tracking has been parallelised
- Time is used
  - particle tracking $\rightarrow$ distribute particles over CPUs
  - field solver $\rightarrow$ very fast (FFTW, hard to speed up on distributed memory machines)
  - secondary generation $\rightarrow$ distribute collisions over CPUs
- Can gain by many cores in single node
- Simple approach, store each slice on a separate node

  $\Rightarrow$ for 50 slices, ≈ 15 times faster than single computer (can do two collisions at a time)