Consideration on the Conceptual Phase Stabilisation System

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CLIC meeting October 8, 2010

Main to Drive Beam Tolerance

- Integrated simulations have been performed with PLACET and GUINEA-PIG of main linac, BDS and beam-beam
  - system is assumed to be perfectly aligned (to determine BDS bandwidth effect)
  - assuming target emittance at BDS
- Resulting luminosity loss is about 2% for

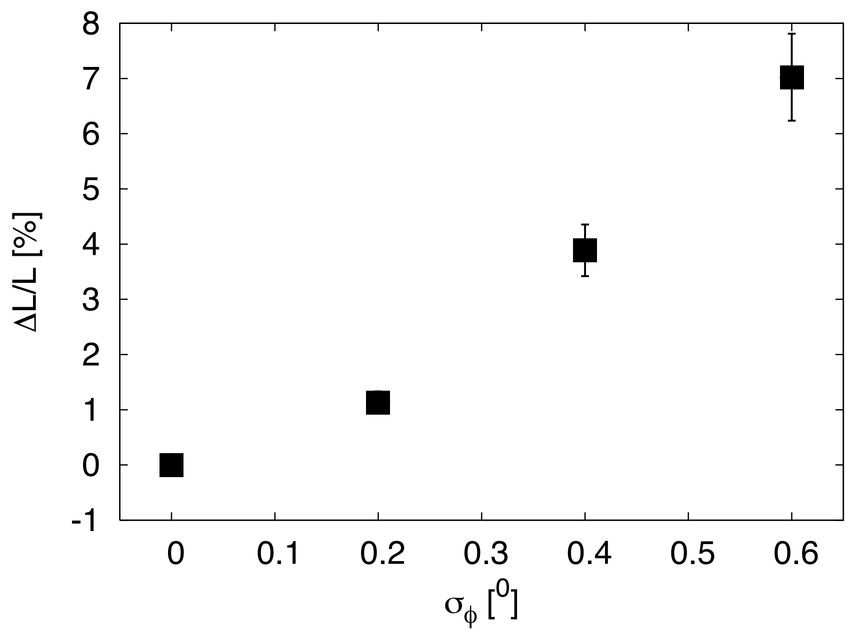
$$\frac{\sigma_G}{G} \approx 1 \times 10^{-3}$$

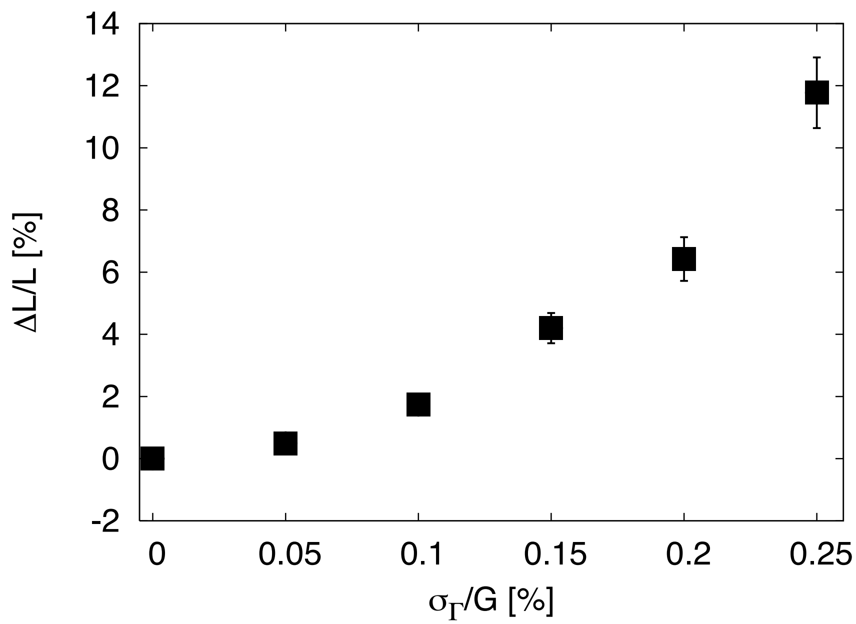
and

$$\sigma_\phi \approx 0.3^\circ$$

$$\frac{\Delta \mathcal{L}}{\mathcal{L}} \approx 0.01 \left[\left(\frac{\sigma_{\phi,coh}}{0.2^\circ} \right)^2 + \left(\frac{\sigma_{\phi,inc}}{0.8^\circ} \right)^2 + \left(\frac{\sigma_{G,coh}}{0.75 \cdot 10^{-3} G} \right)^2 + \left(\frac{\sigma_{G,inc}}{2.2 \cdot 10^{-3} G} \right)^2 \right]$$

- Main beam current needs to be stable to ≈ 0.1–0.2%





Emittance Growth

- To evaluate impact of RF error in misaligned machine assumed machine after ten days of ground motion and one-to-one alignment

  ⇒ emittance is close to nominal

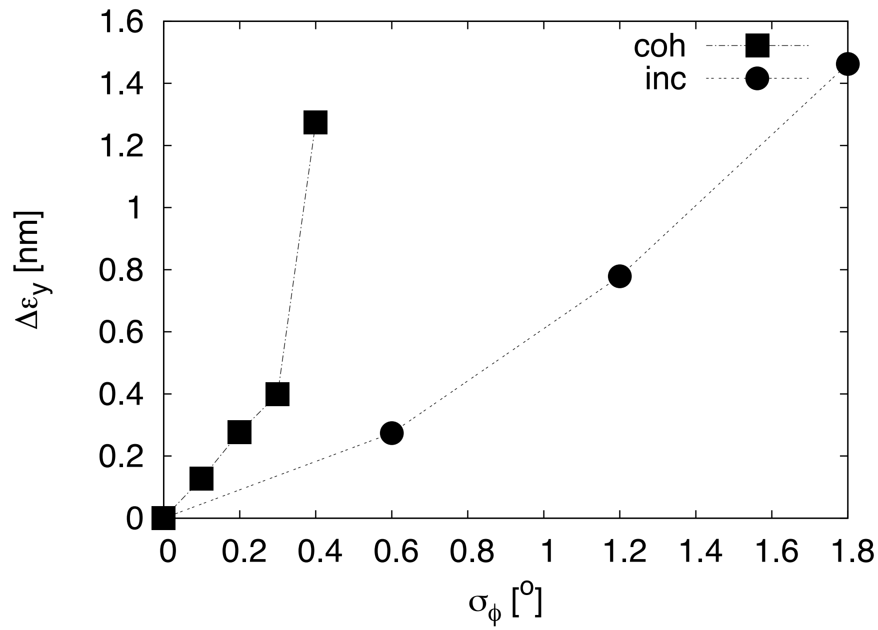
  ⇒ pessimistic, no dispersion optimisation

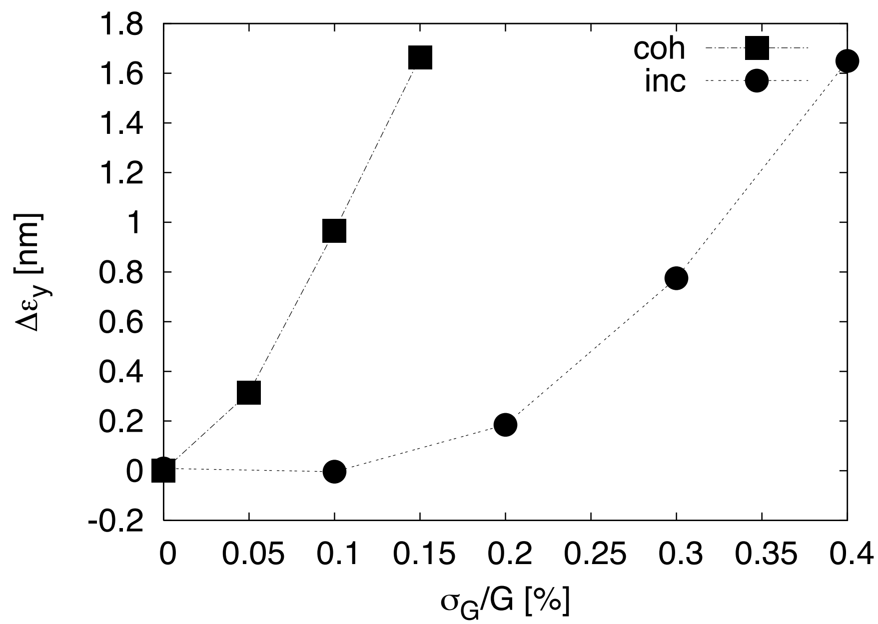
  - almost no emittance growth directly after dispersion free steering or ballistic alignment

  - only main linac emittance growth is considered

- $\Delta\epsilon_y = 0.8\,\mathrm{nm}$ corresponds to 2% luminosity loss

⇒ Resulting worst case luminosity loss from emittance growth is comparable to the one caused by limited BDS bandwidth





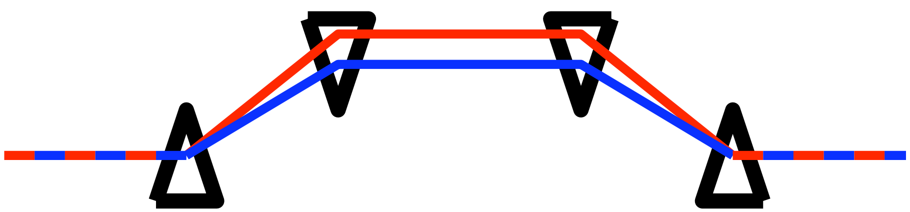
Drive Beam Tolerances

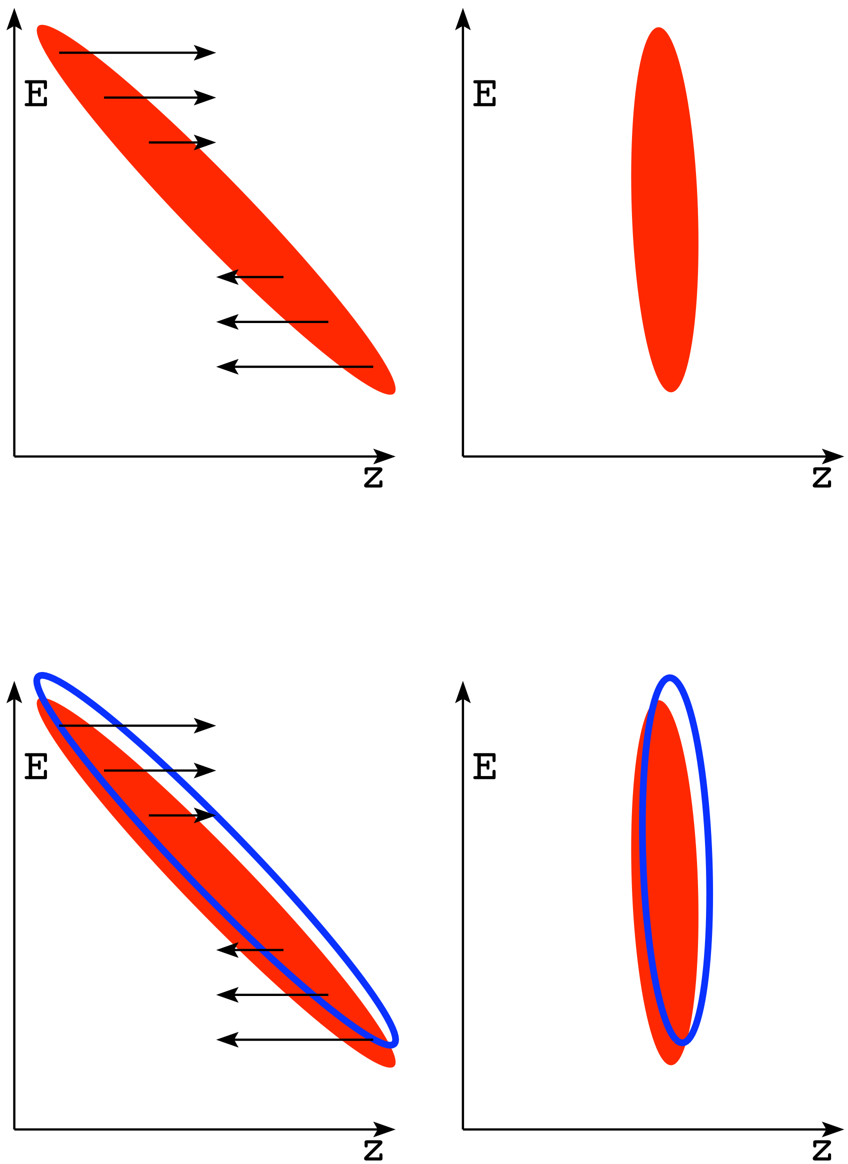
- We can re-write the tolerance for the RF amplitude and phase as tolerance for the drive beam phase, current and bunch length

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

- We want to stabilise the parameters separately
  - drive beam phase
  - drive beam current
  - drive beam bunch length
- We could to some extend correct current and length errors with the phase, but
  - only limited correction range
  - correction system becomes complex
- But errors of one parameter can drive other errors
  - particularly current errors can lead to phase errors

Impact of Bunch Compressor





- The drive beam needs to be compressed longitudinally

  ⇒ energy errors will translate into phase errors

$$\delta z = R_{56} \Delta E / E$$

- For fully loaded operation

$$\frac{\delta E}{E_0} = \frac{2\delta G}{G_0} - \frac{\delta N}{N_0}$$

⇒ Can attempt to avoid compression

Example Tolerances, Full Compression at Final Turn-Around

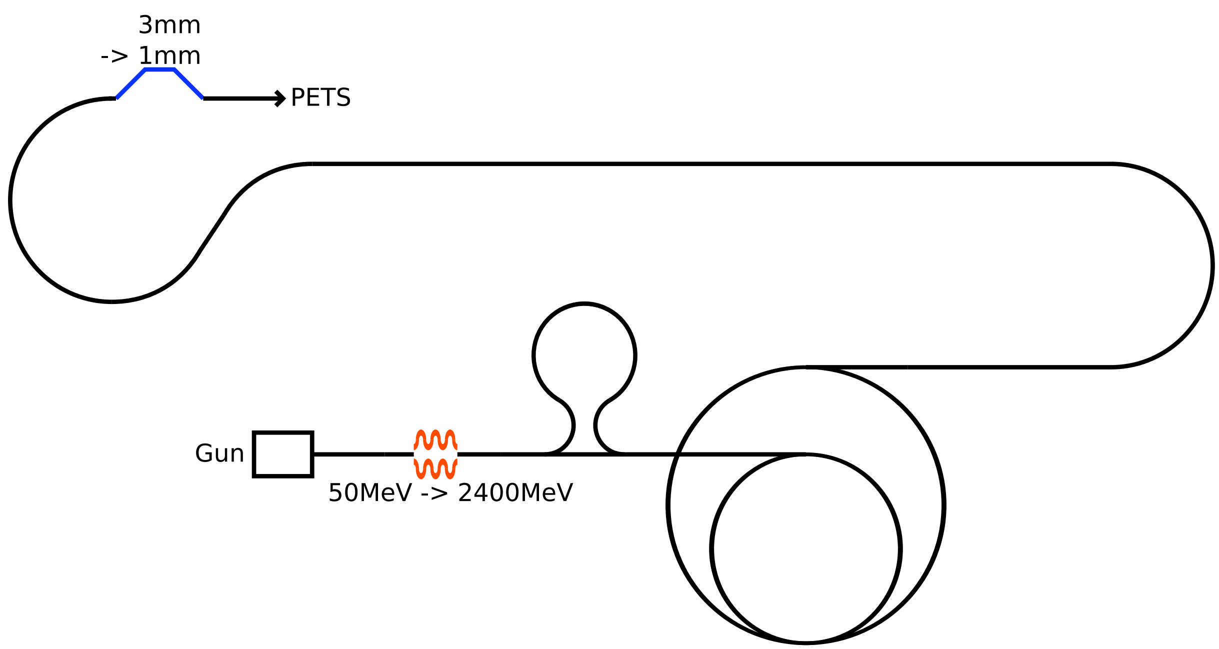
- White noise type pulse-to-pulse jitter assumed
- Total compression after drive beam accelerator
  - for a large energy chirp of 0.6% per $\sigma_z = 3\,\mathrm{mm}$ one requires $R_{56} \approx 0.5\,\mathrm{m}$

  $\Rightarrow$ relative energy error tolerance is 3×10^{-5}

  $\Rightarrow$ relative gradient tolerance is 1.5×10^{-5}

  $\Rightarrow$ relative charge tolerance is 3×10^{-5}

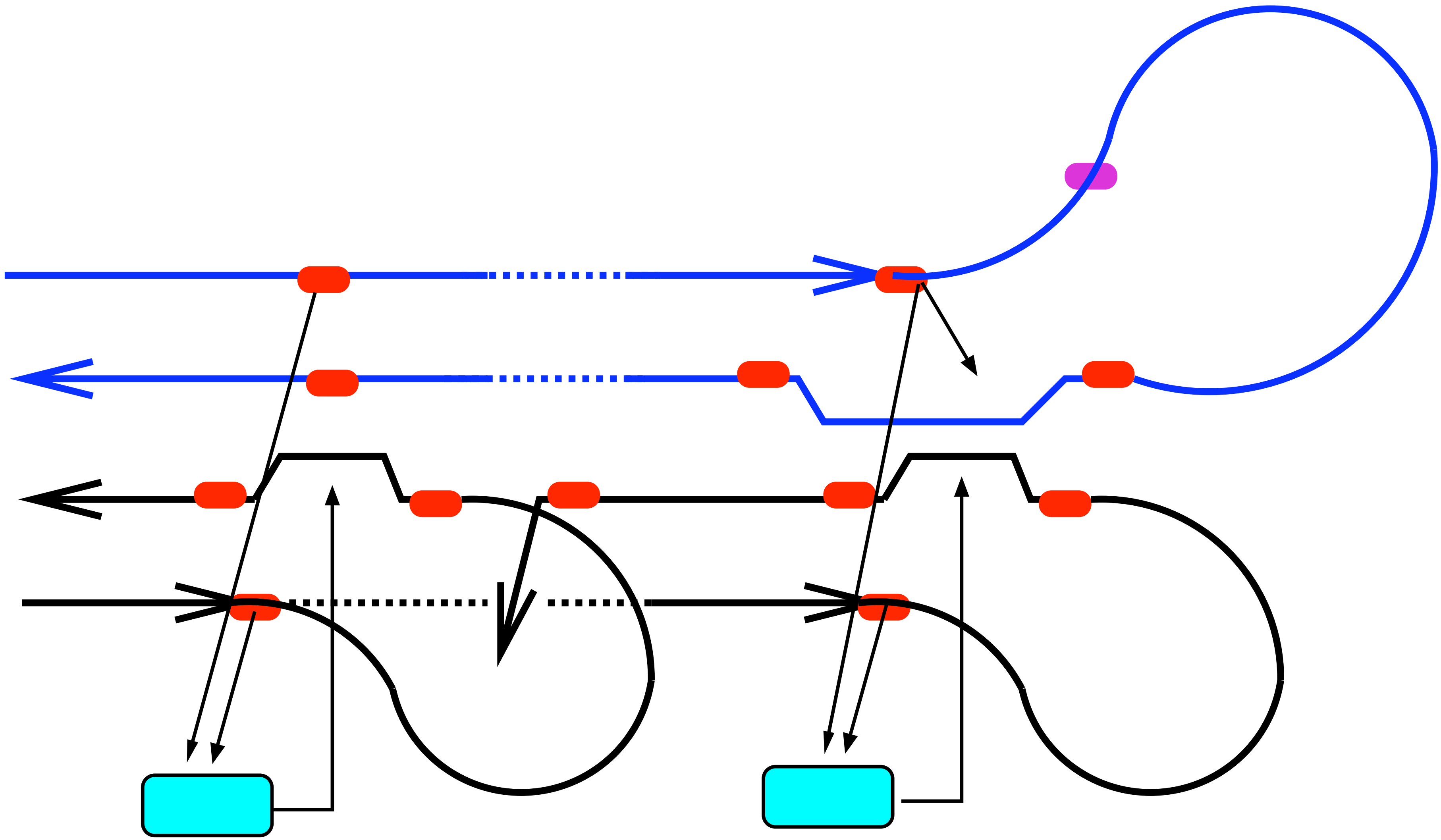
  $\Rightarrow$ phase tolerance is $0.02°$ at $1\,\mathrm{GHz}$



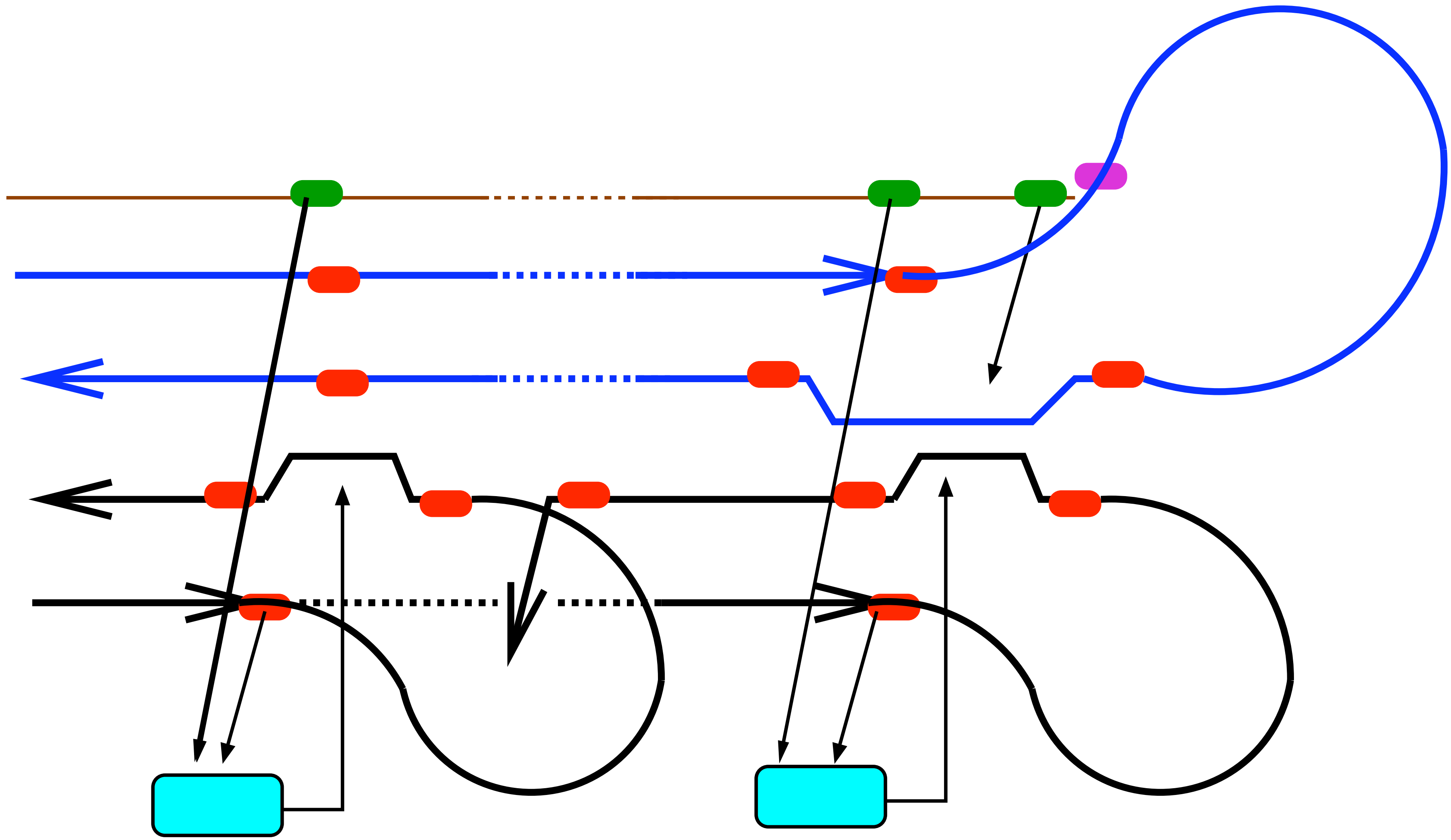
- Looks very tough

  $\Rightarrow$ try to find ways to relax the tolerances

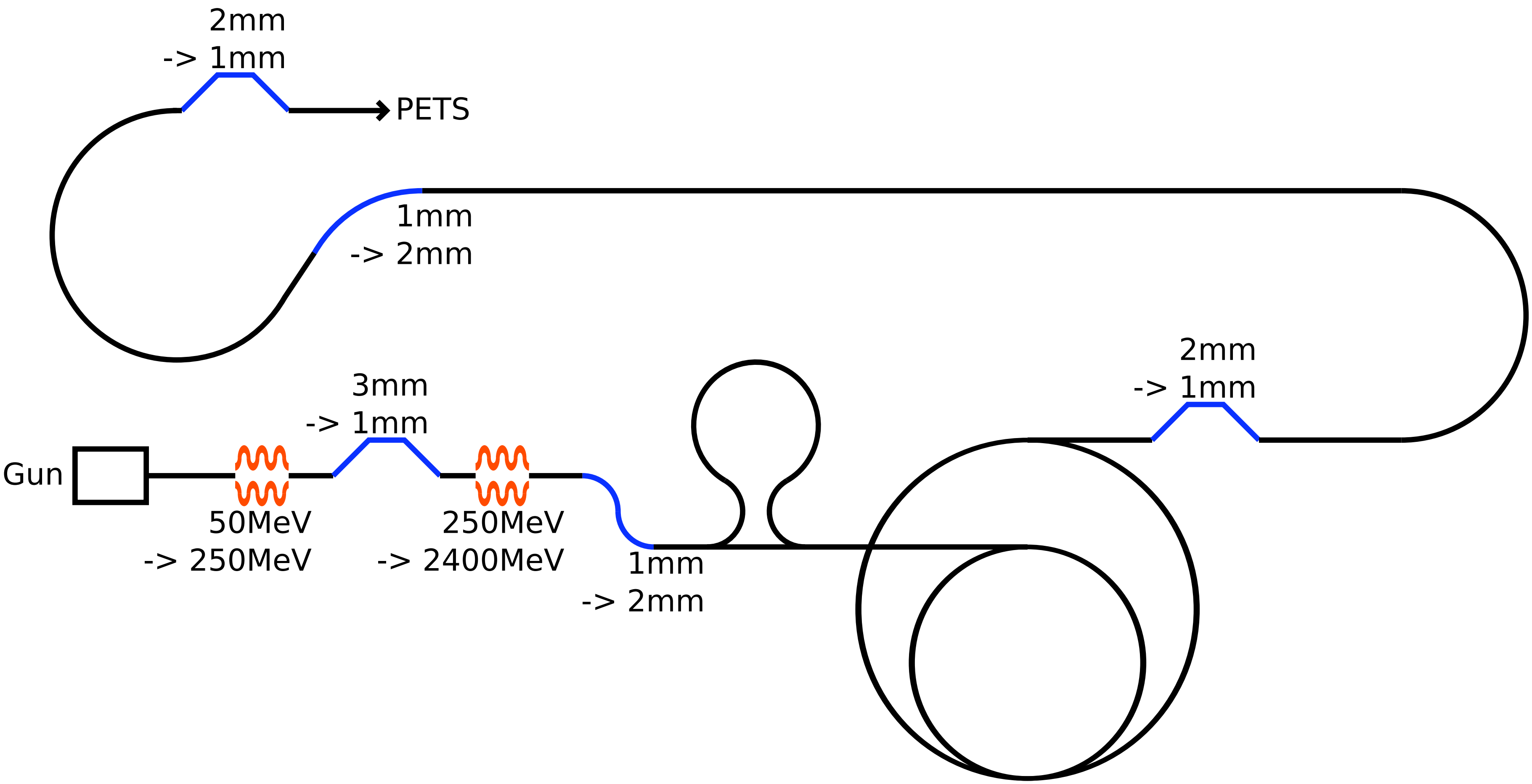
Main Beam as Phase Reference



External Phase Reference



Drive Beam Compression and Phase Stabilisation Concept

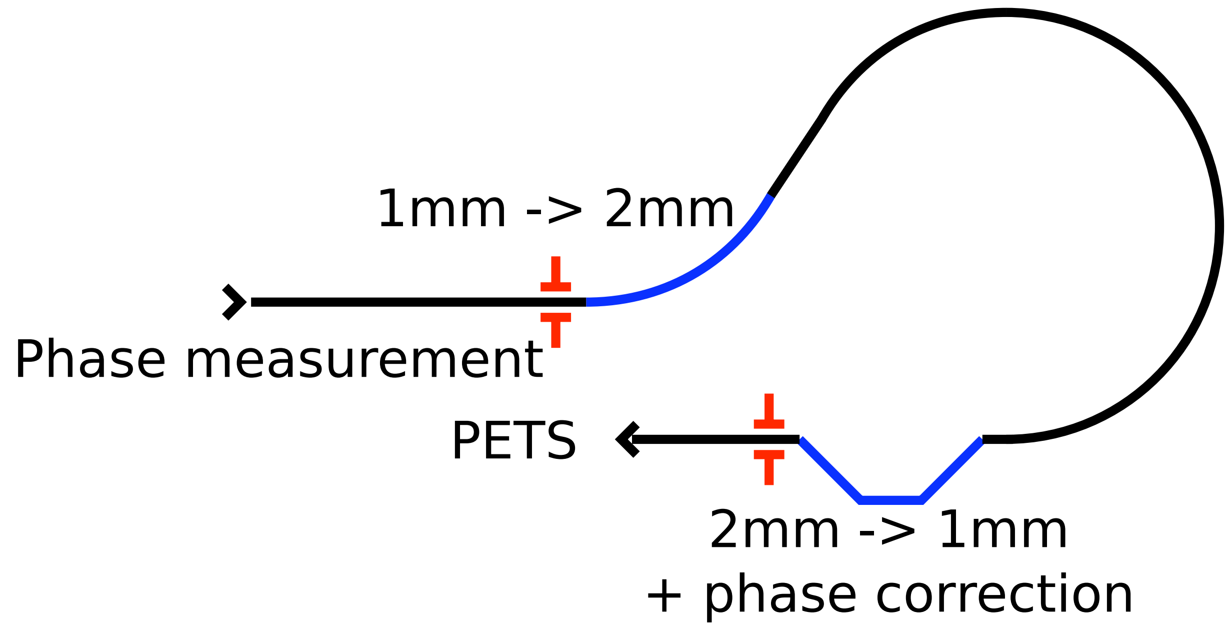


- Early compression allows large energy chirp ⇒ small R_{56} ⇒ larger energy tolerance

⇒ Energy error tolerance: 1.5×10^{-4}, gradient tolerance 1.5×10^{-5}, current tolerance 3×10^{-5}, phase tolerance 0.02° at $1\,\mathrm{GHz}$

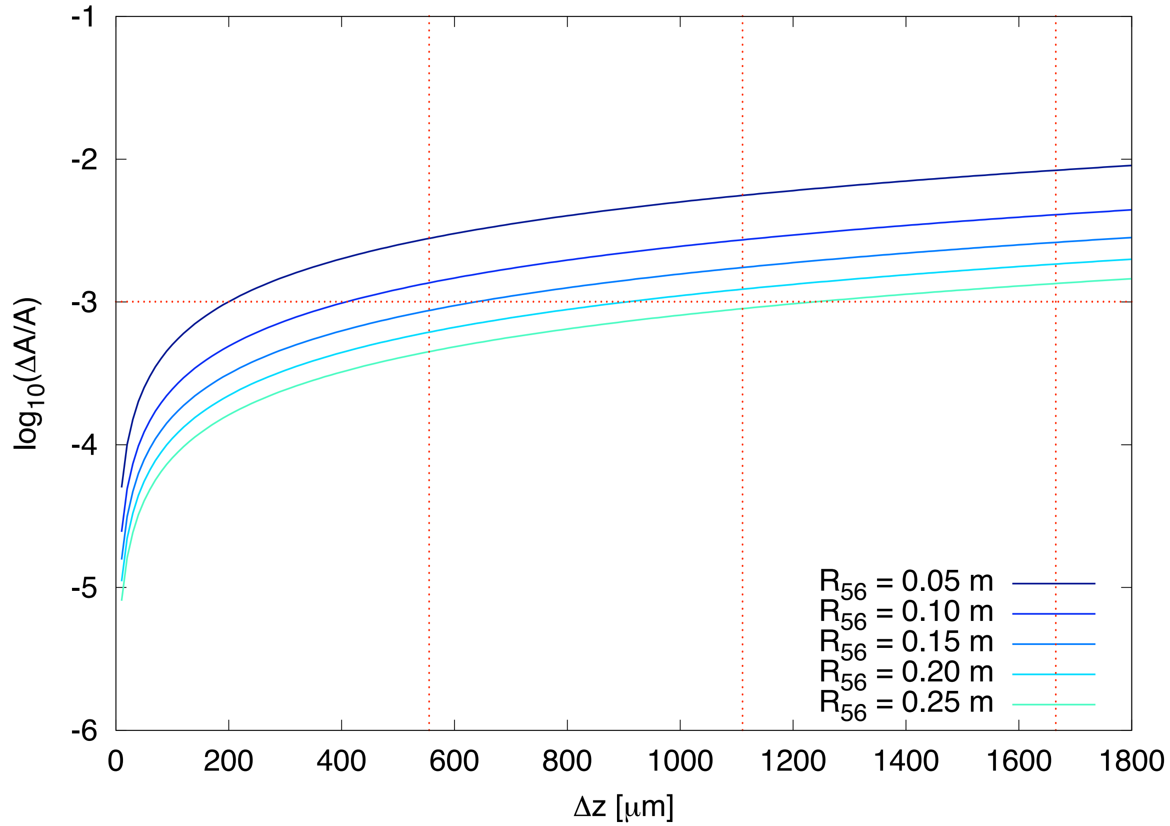
Feedforward at Final Turn-Around

- Final feedforward shown
  - ultima ratio
  - measure phase
  - adjust BC chicane with kicker to compensate error
- Requires
  - timing reference (FP6)
  - phase measurement/prediction (FP7)
  - tuning chicane (FP6, Frank S.)
- Missing will be kicker and amplifier
  - but collaboration with Oxford envisaged



Capture Range of Feedforward

- We have modified our previous design
- Longitudinal shifts change final bunch length
- We require that RF amplitude error caused by longitudinal shift is below 0.1%
- $R_{56} \approx 0.2\,\mathrm{m}$
- kicker strength is $350\,\mathrm{mradian}$ total kick
- Need to design kickers and amplifier
  - collaboration with Phil Burrows et al. and M. J. Barnes et al.



F. Stulle

Phase Tolerances before Feedforward

- Want to capture 4 times RMS tolerance before feedforward

  ⇒ in 0.4% of the pulses cannot capture one drive beam fully (Gaussian jitter)

  - assume gain factor of 10

- Assume feedforward capture range is 10° ($\Delta z = 0.7\,\mathrm{mm}$)

  - lattice is OK but kicker needs to be evaluated

  ⇒ can allow 2.5° RMS jitter before feedback (4σ capture)

  - assume gain factor of 10

    ⇒ 0.25° RMS jitter after feedforward

- Beam stability in current decelerator design requires less than 1% overcurrent

  ⇒ require 0.1% RMS fluctuation per 10/2 bunches (one PETS fill time), or reoptimise decelerator

  - current stability from preliminary CTF3 measurement is 0.1%

  - static variations still need to be cured

Baseline Bunch Compressor System

- Early compression in drive beam accelerator ($3\,\mathrm{mm} \rightarrow 1\,\mathrm{mm}$)

  $\Rightarrow$ can use relatively large energy spread $\Rightarrow$ small R_{56} $\Rightarrow$ large energy error tolerance

- Uncomression at end ($1\,\mathrm{mm} \rightarrow 2\,\mathrm{mm}$)

  - to limit coherent synchrotron radiation in delay loop and combiner rings

- Recompression after rings ($2\,\mathrm{mm} \rightarrow 1\,\mathrm{mm}$)
- Measure real phase at final phase feedforward
- Uncompress in turn-around
- Recompress before decelerator

  - used as correction chicane with small additional kicks

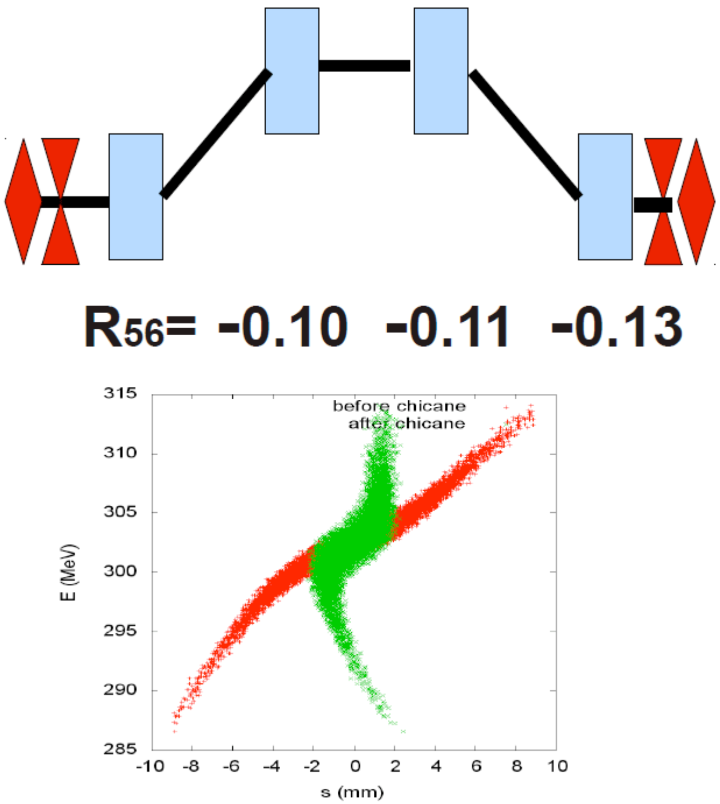
- To first order only RF errors at first compression are important
- assume (maybe optimistic) chirp of 2–3% per σ_z

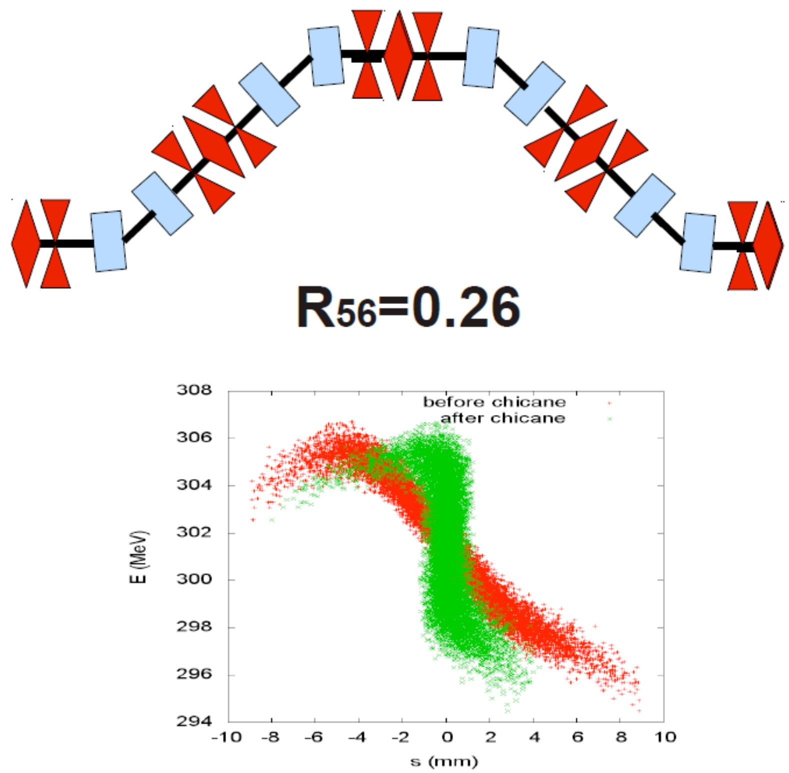
  $\Rightarrow$ $R_{56} = 67\text{–}120\,\mathrm{mm}$

  $\Rightarrow$ relative energy tolerance $1\text{–}2 \times 10^{-3}$ $\Rightarrow$ relative gradient tolerance is $0.5\text{–}1 \times 10^{-3}$ $\Rightarrow$ relative charge tolerance is $1\text{–}2 \times 10^{-3}$

  $\Rightarrow$ phase tolerance is $\approx 0.2^\circ$ at $1\,\mathrm{GHz}$

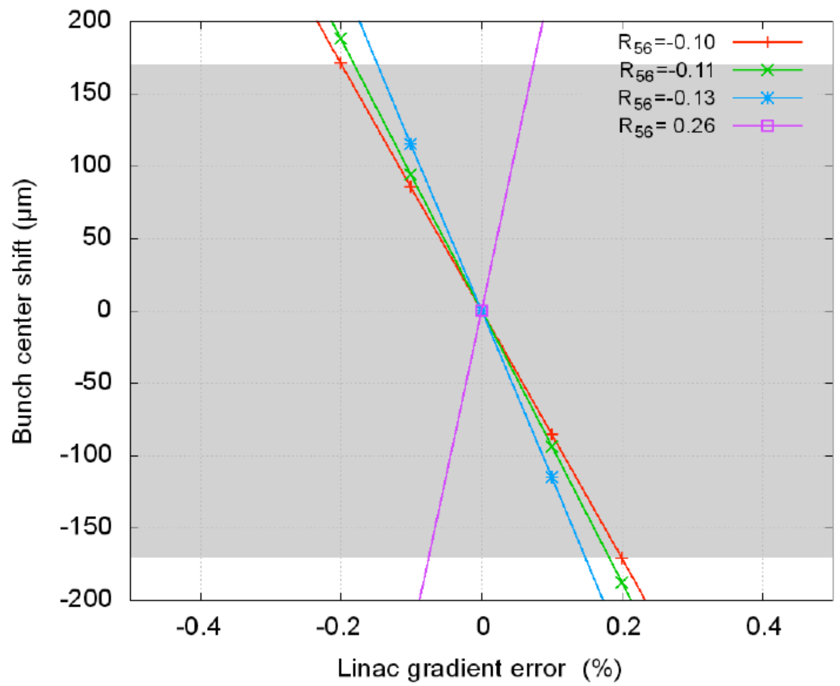
Bunch Compressor System Design

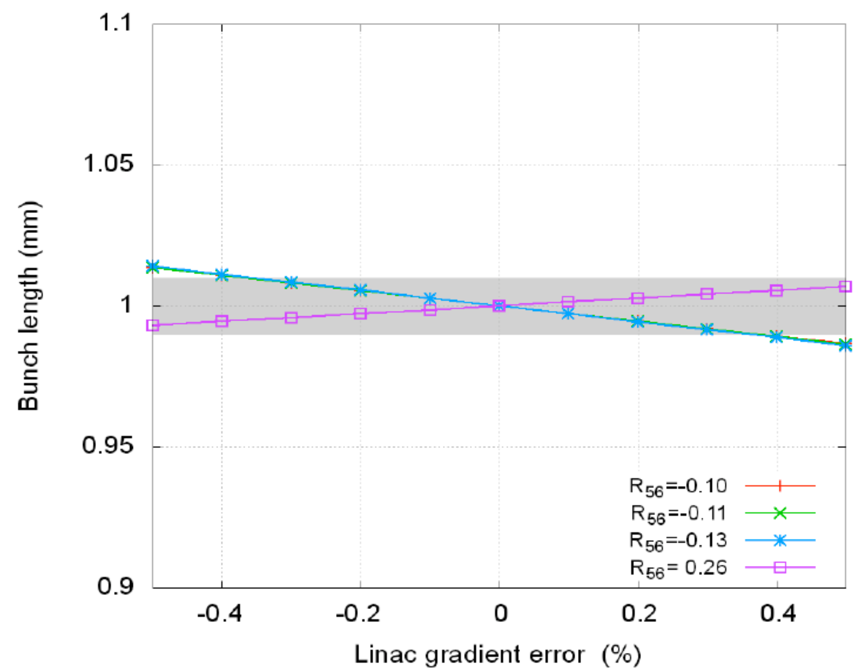




A. Aksoy

RF Gradient Tolerances





⇒ The RF amplitude tolerance is given by the phase error of the bunches, the length variations are small

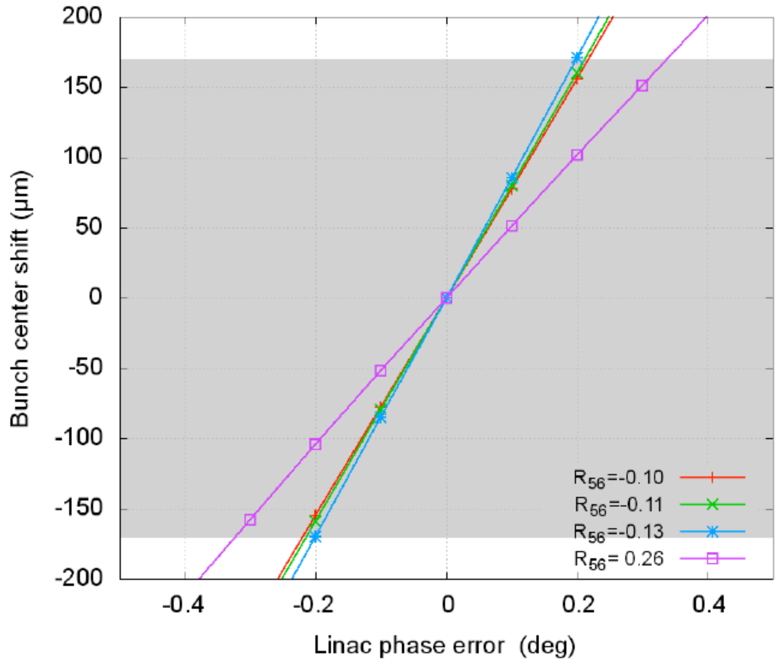
- The amplitude tolerance of the effective gradient is 2×10^{-3}

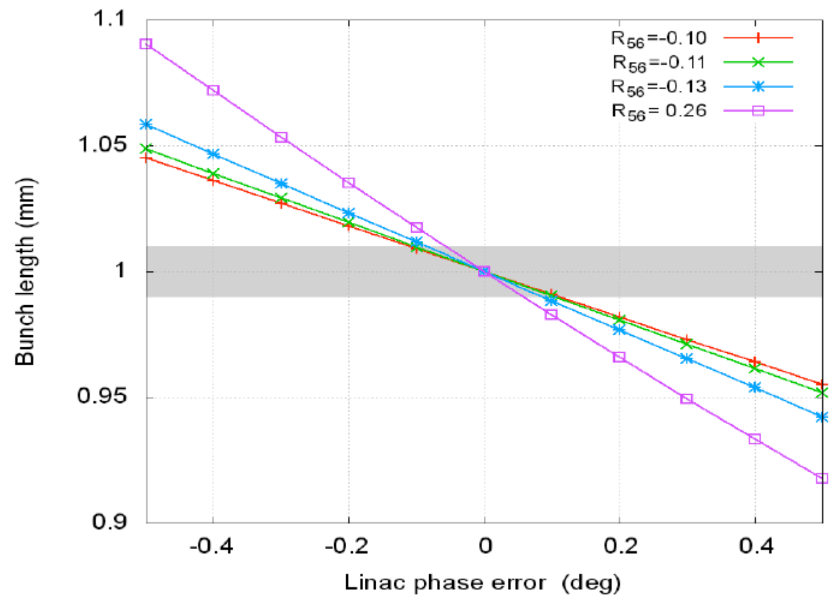
⇒ The tolerance is 0.1% for the accelerating power amplitude, i.e. 0.2% for the klystron power

⇒ it is 0.2% for beam current

A. Aksoy

RF Phase Tolerances





⇒ The phase tolerance is given by the bunch length variation

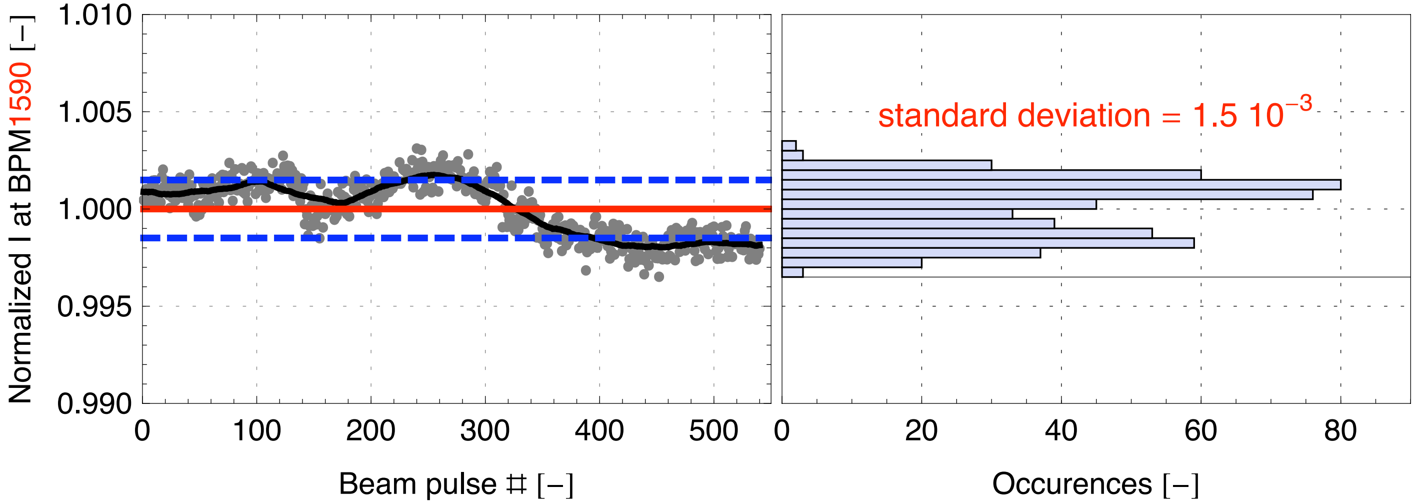
- The phase tolerance for the effective gradient is 0.1°

⇒ it is is 0.05° for klystron phase

⇒ it is is 0.1° for the beam phase

A. Aksoy

Current Measurement in CTF3

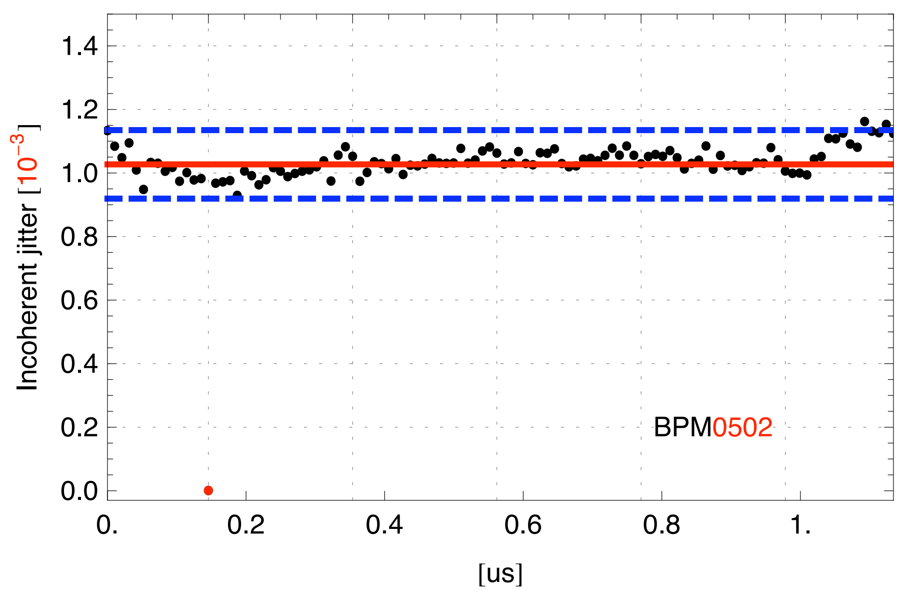


- No dedicated stabilisation effort in CTF3

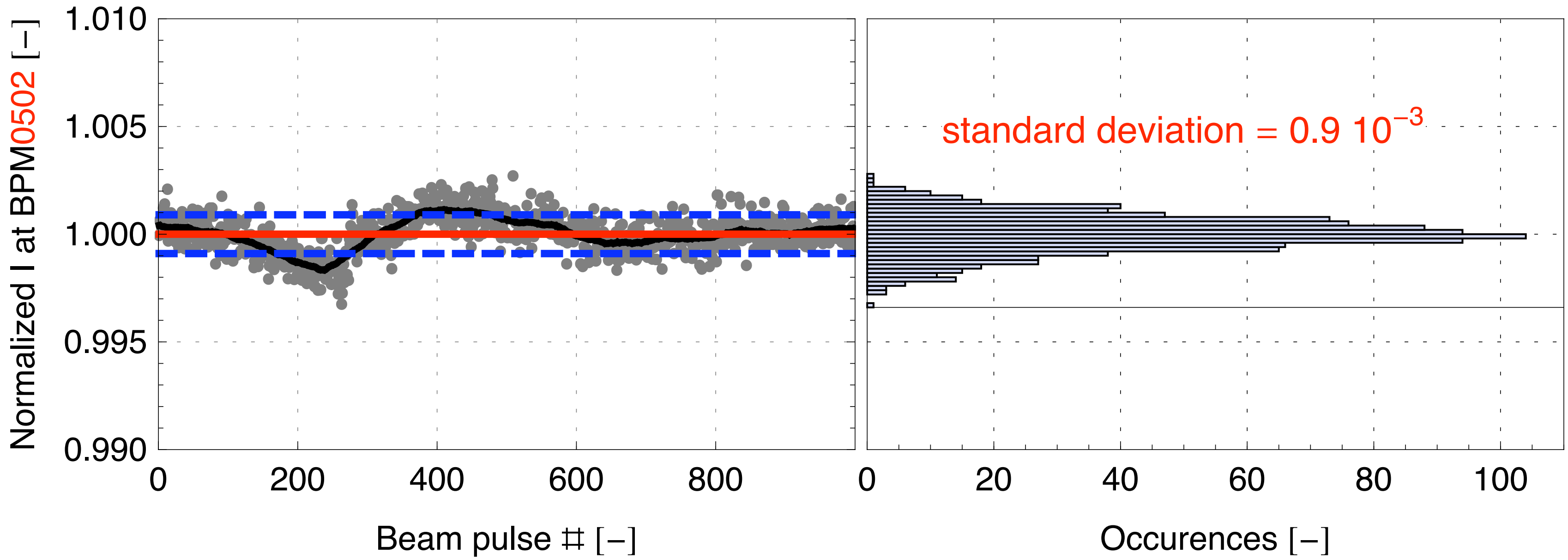
⇒ Current stability is close to needs for CLIC

- Dynamic charge variation from one pulse slcie to the next seems better than BPM resolution

G. Sterbini, S. Bettoni, et al.



Results of Better Power Supply

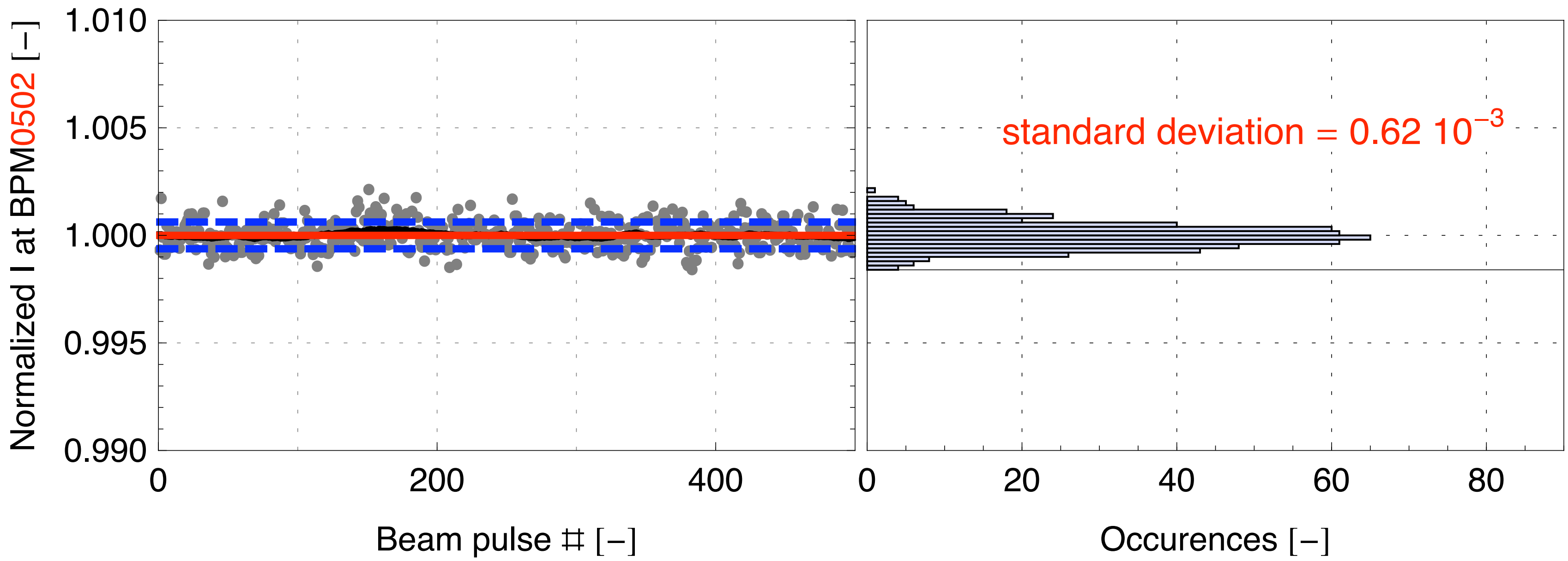


⇒ Significant improvement in current stability

⇒ Slow variations have been reduced strongly

G. Sterbini, A. Andersson, S. Bettoni et al.

Results of Pulse-to-Pulse Feedback



⇒ Current stability is further improved

⇒ Pulse-to-pulse current stability is already good enough, but certainly further improvement is welcome

G. Sterbini, S. Bettoni et al.

Phase and Power Measurement in CTF3

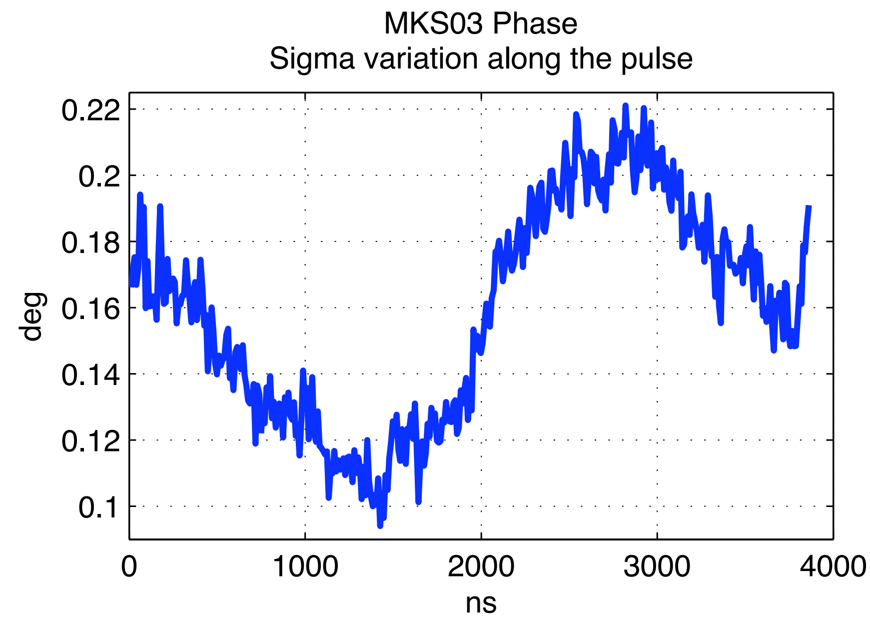
- Measurements of phase and power of CTF3 klystron indicate
  - pulse-to-pulse average phase stability with respect to local reference phase 0.035°
  - for each $10\,\mathrm{ns}$ times slice the pusle to pulse jitter is 0.07° (plot shows case with 0.2°)
  - pulse-to-pulse power stability of $< 0.2\%$

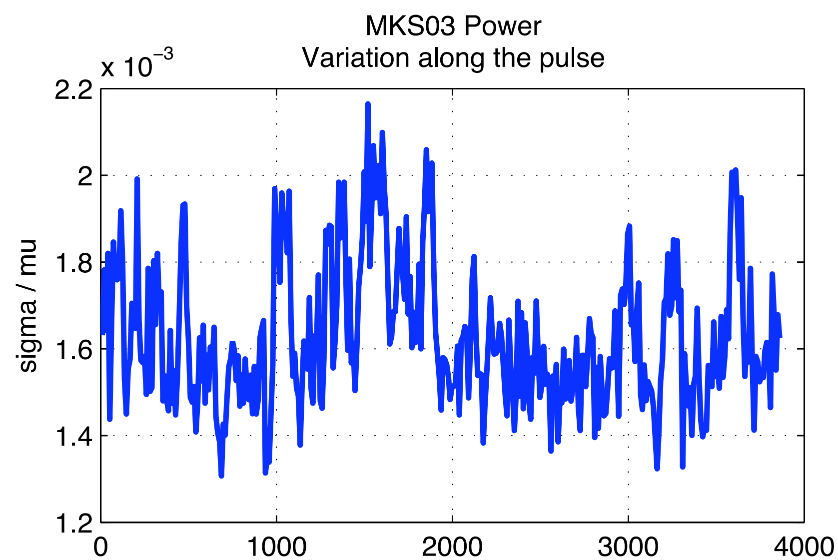
    $\Rightarrow$ gradient stability $\leq 0.1\%$

$\Rightarrow$ Corresponds to drive beam needs

$\Rightarrow$ Further improvements will reduce the importance of the hase feedback/feed-forward

A. Dubrovskiy





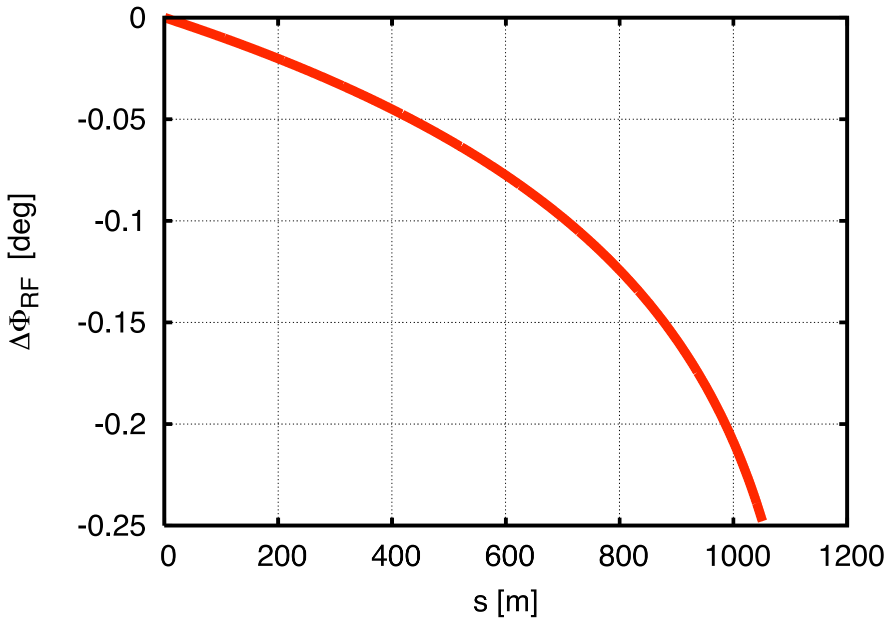
Drive Beam Turn-Around Jitter Tolerance

- Obviously magnet jitter tolerance should be relaxed if all magnets are on one power supply
  - isochronos arc
- Detailed study finds for 10^{-4} relative strength jitter
  - independent jitter of all magnet power supplies: RMS of $14\,\mu\mathrm{m}$
  - all magnets jitter coherently: RMS of $20\,\mathrm{nm}$
  - quadrupoles and dipoles each jitter coherently: RMS of $13\,\mathrm{nm}$

$\Rightarrow$ For reasonable cabling the tolerances are relaxed

F. Stulle

Transverse Drive Beam Jitter



Caluclation by E. Adli

- Longitidinal motion due to transverse angles
- Assumed that systematic effect is tuned out

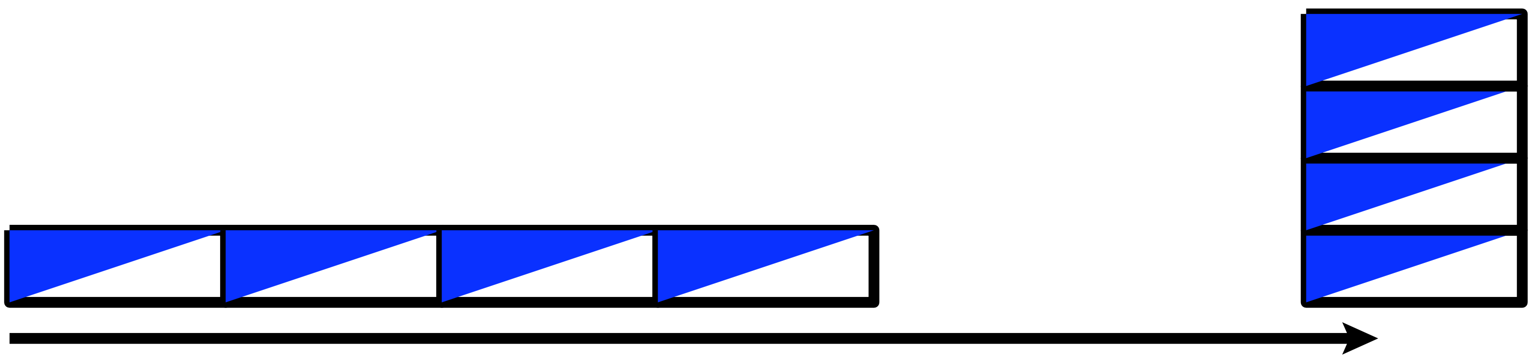
$\Rightarrow$ Only jitter component left

- Decelerator is most important (largest phase advance)
- Need to average over local phase error to obtain effective phase error

$$\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta x'}{\sigma_{x'}}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2 + \left(\frac{\Delta y'}{\sigma_{y'}}\right)^2 \leq 1^2$$

Filtering and Intra-Pulse Feedback

- Long drive beam pulse at generation $\approx 140\,\mu\mathrm{s}$
- End of pulse catches up with beginning due to combiner rings



- Also design of sequence of acceleration and bunch compression for drive beam can help to achieve required performance
  - but still need to beam able to measure final jitter

Impact of Combiner Ring and Delay Loop

- Simulation of transfer through delay loop and combiner rings
- Simple estimate for white noise

$$\sigma_{ML} = \sqrt{\frac{1}{N_{fill}}} \sigma_{DB-bunch}$$

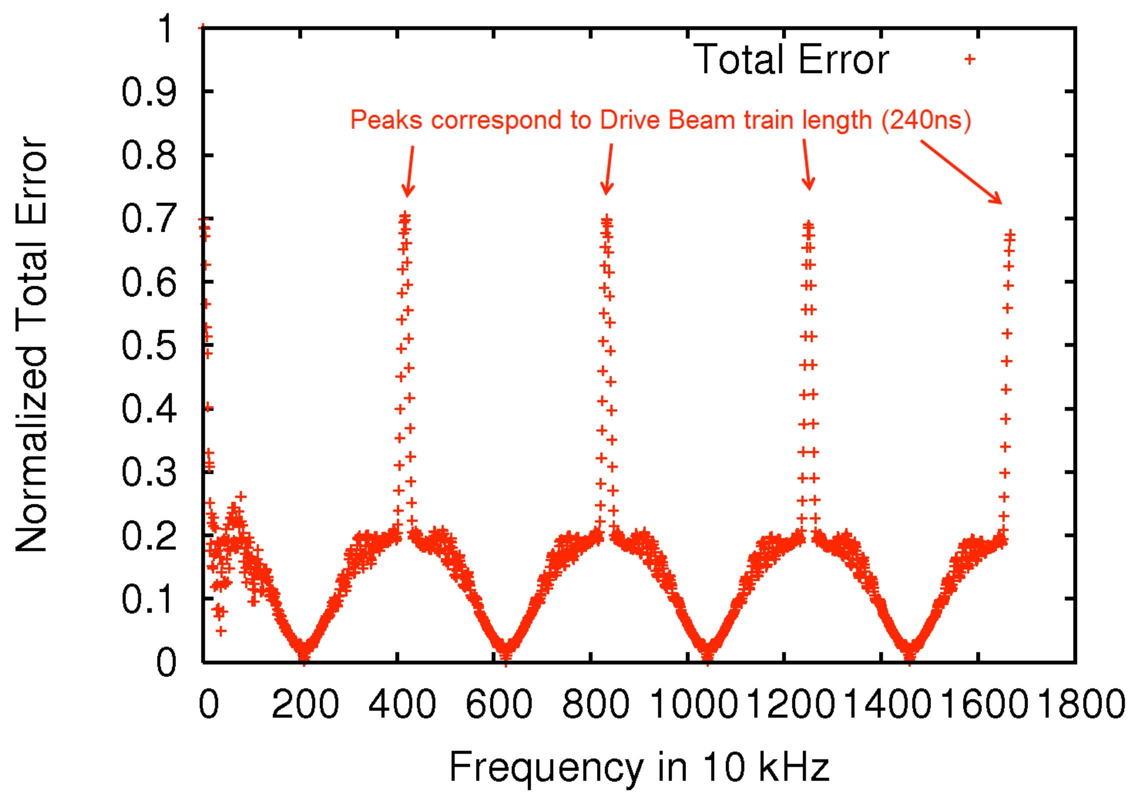
- 2×10^{-3} per $10\,\mathrm{ns}$ initial drive beam pulse will become $\approx 4 \times 10^{-4}$ per $10\,\mathrm{ns}$ final drive beam pulse

⇒ Most frequencies are filtered

⇒ Mainly harmonics of $4\,\mathrm{MHz}$ are still important

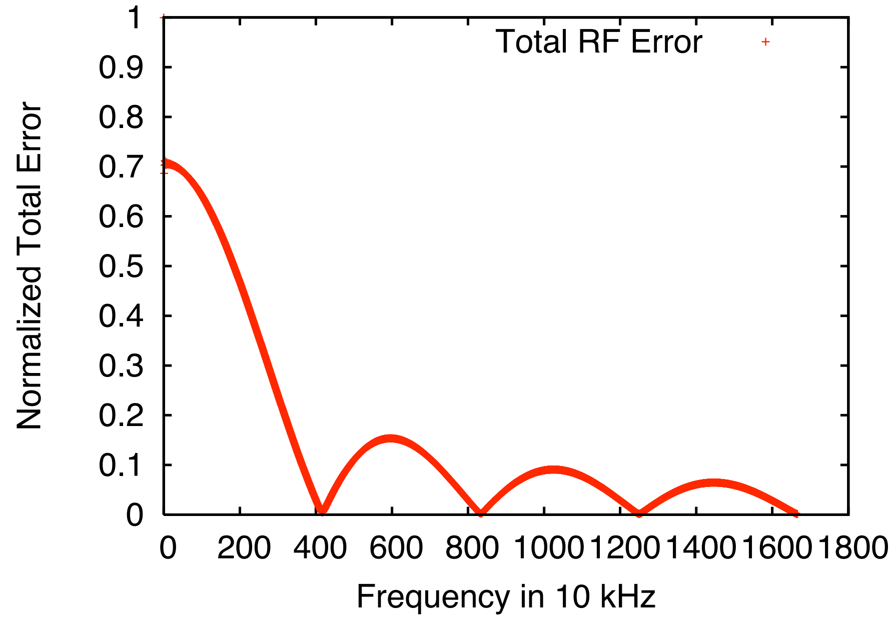
  - corresponds to train length

- Note reduction to 0.7 in harmonic peaks because we use RMS of all timeslices

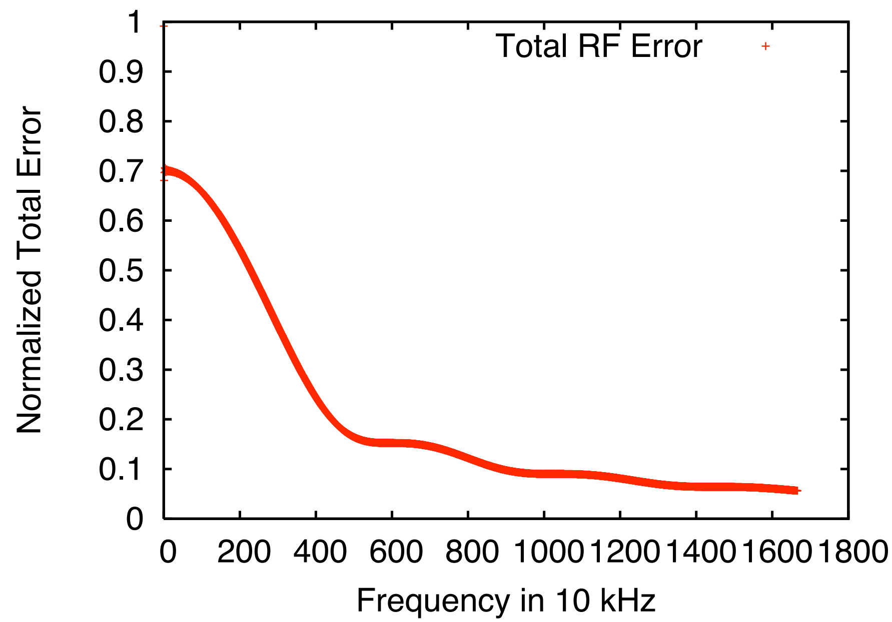


A. Gerbershagen

Impact of Drive Beam Accelerating Structure Fill Time



- We purposefully have chosen the drive beam accelerator structure fill time to be one train length
  - external RF effect will average out over one structure length
  - simplfied rectangular response used for now
  - waiting for input
- Reduction of an imperfection as a function of the frequency
  - upper plot RF error (phase or amplitude)
  - lower plot bunch charge (into energy error)



A. Gerbershagen

Combined Effect

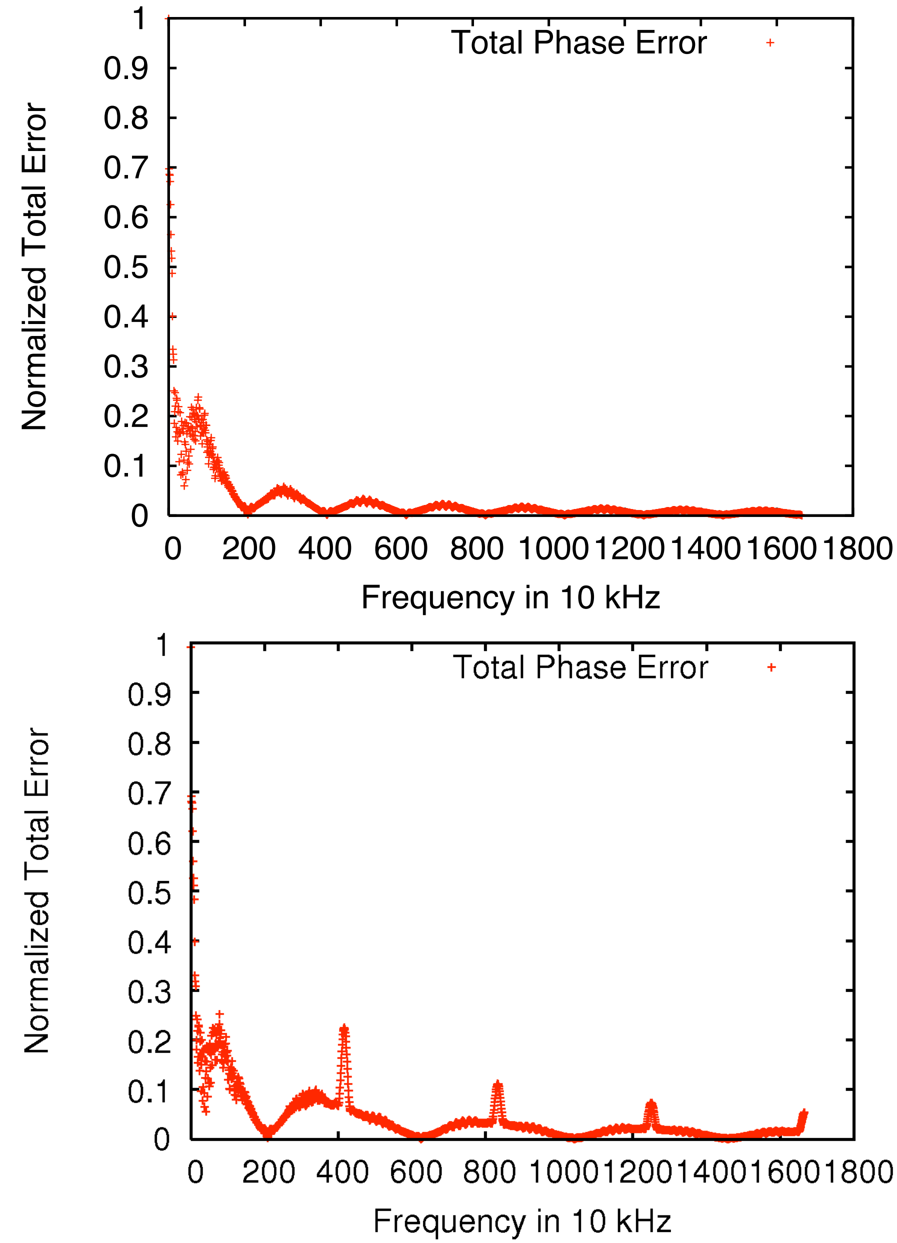
- The impact of the chosen fill time plus combiner rings
- Reduction of an imperfection as a function of the frequency
  - upper plot RF error (phase or amplitude)
  - lower plot bunch charge (into energy error)

⇒ The choice of fill time significantly reduce RF error impact

⇒ Beam current error impact is not reduced as much

⇒ Main concern remain the low frequency components

- Will use feedback for them



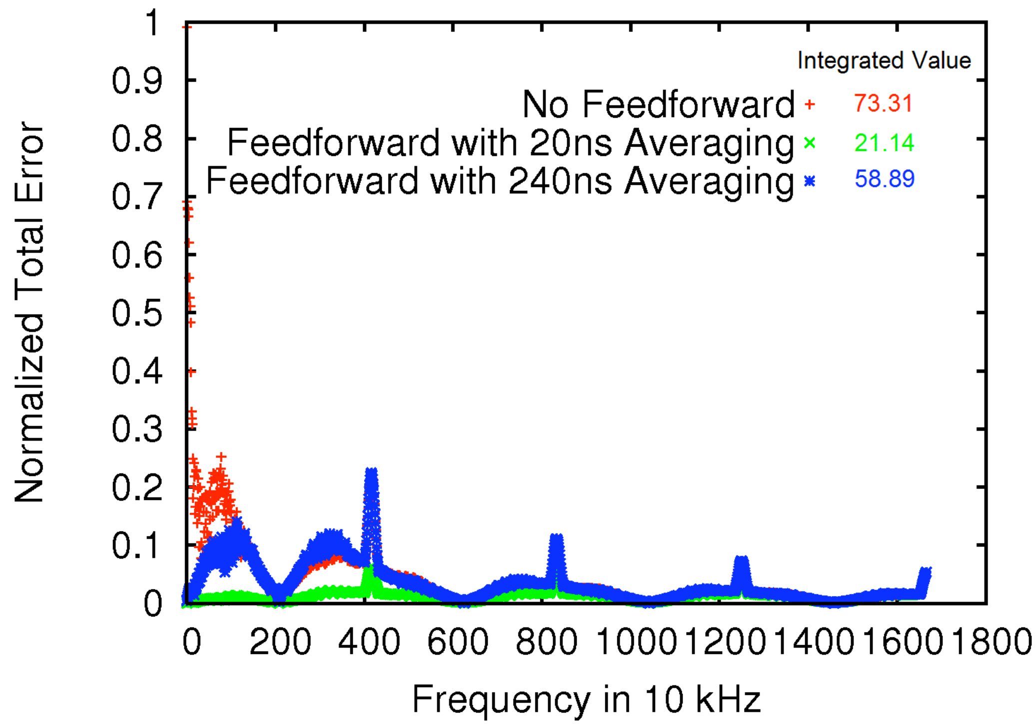
A. Gerbershagen

Final Turn-Around Feed-Forward

- Feed-forward at final turnaround integrated with RF errors
  - correcting the mean offset of the train
  - correcting the mean of each $20\,\mathrm{ns}$ time bin

$\Rightarrow$ If we can only correct average value, we can only cure low frequency noise

$\Rightarrow$ Need a large bandwidth at final turn-around



A. Gerbershagen

Main Beam to Main Beam Phase Tolerance

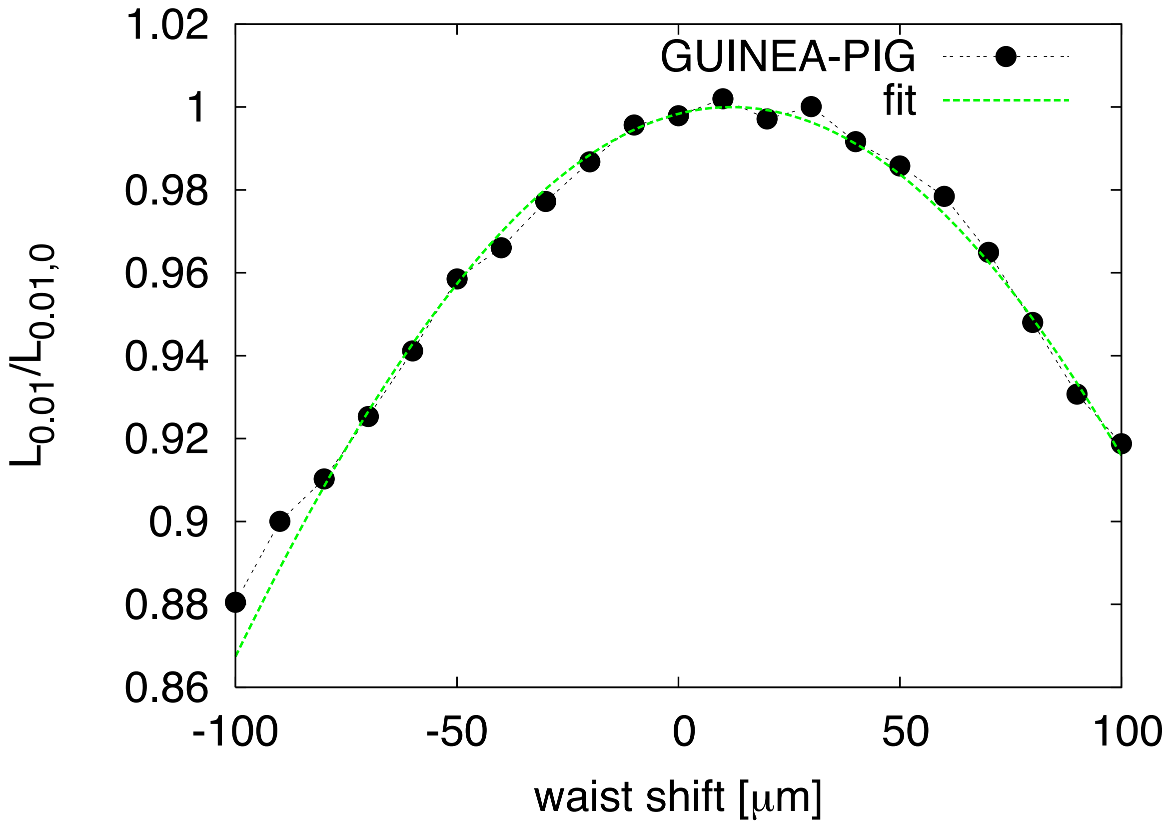
- RMS collision timing shift

  1% loss for shift of $21\,\mu\mathrm{m}$

$$\frac{\Delta\mathcal{L}_{0.01}}{\mathcal{L}_{0.01,0}} \approx 0.01\left(\frac{\sigma_{IP,z}}{21\,\mu\mathrm{m}}\right)^2$$

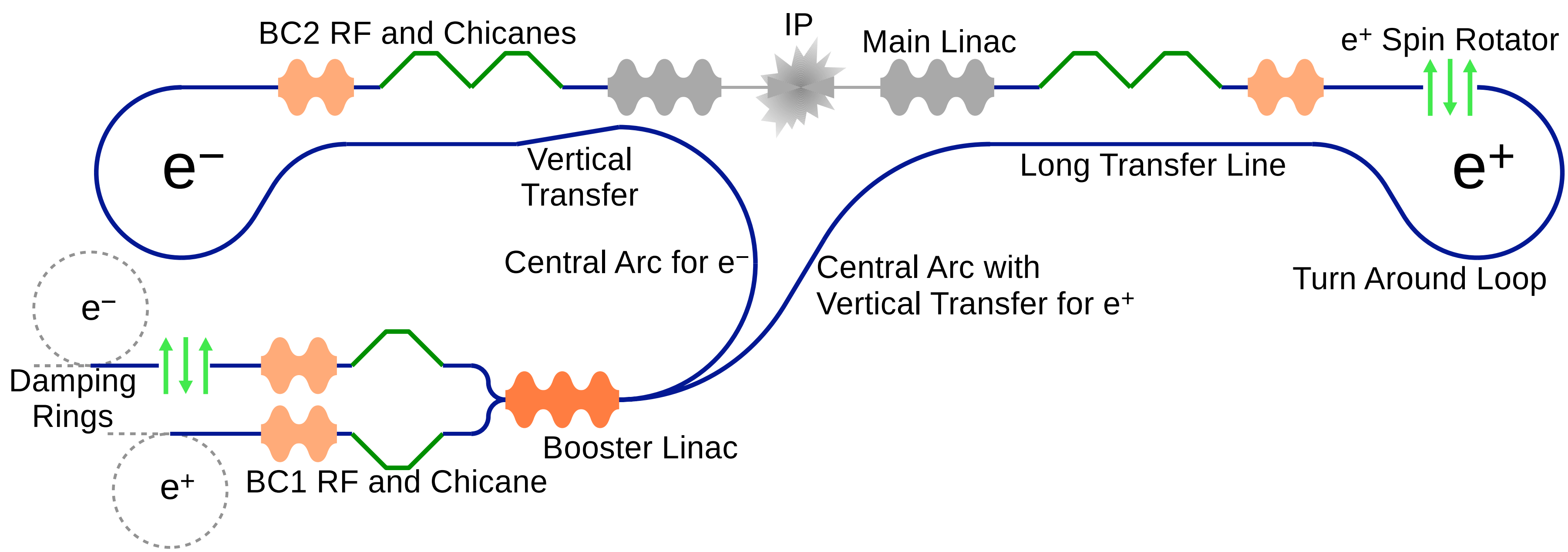
$$\Delta_{IP} = \frac{\Delta z_1 - \Delta z_2}{2}$$

⇒ Independent timing jitter of beams can be $30\,\mu\mathrm{m}$ for 1% luminosity loss



- Shift of collision point with respect to waist

Main Beam Phasing



- In central complex external timing reference assumed
- Along the main linac
  - distributed timing system
  - use of main beam as timing reference

Resulting Longitudinal IP Jitter

- If the main beam serves as a timing reference we find
  - Beam-beam phase jitter at the interaction point

$$\sigma_{IP} \approx \sqrt{\frac{1}{2}}\left(\frac{6}{7}\sigma_{MB\rightarrow RF} \oplus \sigma_{MB}\right)$$

σ_{MB}: Timing error of outgoing main beam

$\sigma_{MB\rightarrow RF}$: Error of picking up phase of outgoing main beam and turning this into BC2 RF phase

Note: the factor $6/7$ is due to the second bunch compressor

⇒ Relative rhase error of the two outgoing main beams needs to be $\leq 42\,\mu\mathrm{m}$

- If we use the X-FEL system as timing reference we find

$$\sigma_{IP} \approx \sqrt{\frac{1}{2}}\left(\frac{1}{7}\sigma_{MB} \oplus \frac{6}{7}\left[\sigma_{ref} \oplus \sigma_{ref\rightarrow RF}\right]\right)$$

σ_{ref}: Timing error of reference timing at final turn-around with respect to central clock

$\sigma_{ref\rightarrow RF}$: Error of picking up phase of external reference and turning this into BC2 RF phase

⇒ Relative rhase error of the references at final turn-around needs to be $\leq 42\,\mu\mathrm{m}$

- Energy error also leads to main beam phase jitter

Main to Drive Beam Phase Errors

- If the main beam serves as a timing reference we find
  - Main beam vs. drive beam phase jitter in main linac

$$\sigma_{MD} \approx (\sigma_{MB\to RF} \oplus 0 \times \sigma_{MB}) \oplus (\sigma_{MB\to ref} \oplus \sigma_{DB\to corr} \oplus a\sigma_{DB})$$

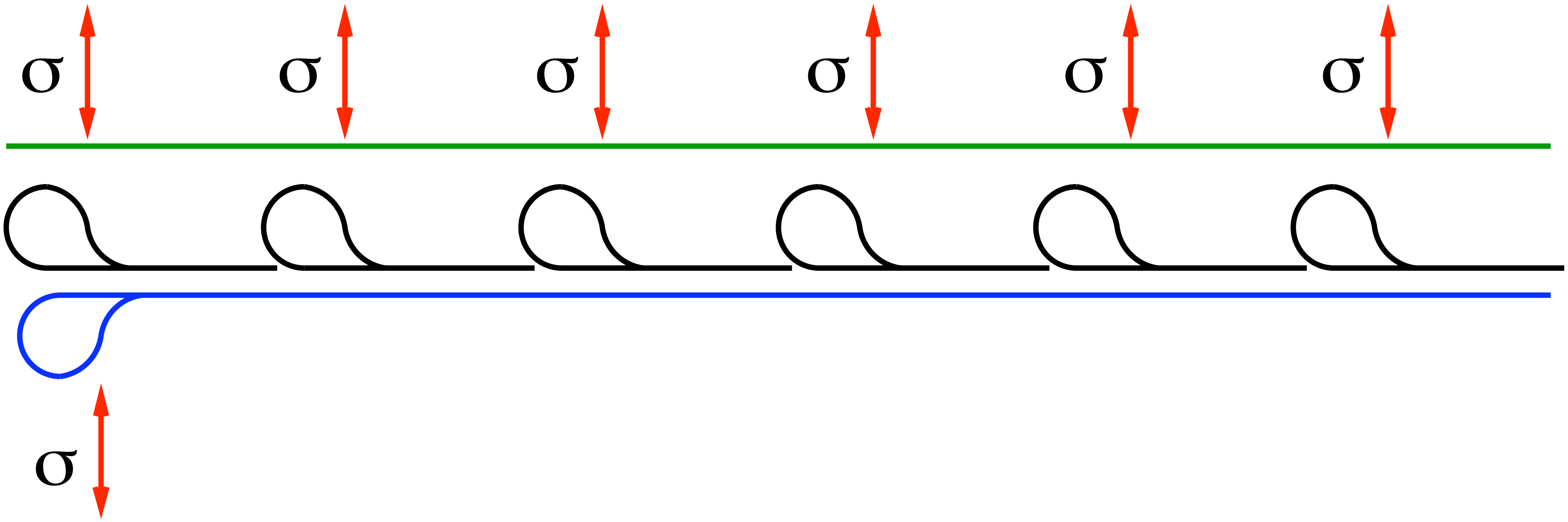
- If we use the X-FEL system as timing reference we find
  - Main beam vs. drive beam phase jitter in main linac

$$\sigma_{MD} \approx \left(\frac{1}{7}\sigma_{MB} \oplus \frac{6}{7}\left[\sigma_{ref} \oplus \sigma_{ref\to RF}\right]\right) \oplus (\sigma_{ref} \oplus \sigma_{DB\to corr} \oplus a\sigma_{DB})$$

  or roughly

$$\sigma_{MD} \approx \sigma_{ref\to RF} \oplus \sqrt{2}\sigma_{ref} \oplus \sigma_{DB\to corr} \oplus a\sigma_{DB} \oplus \frac{1}{7}\sigma_{MB}$$

Local Error Model



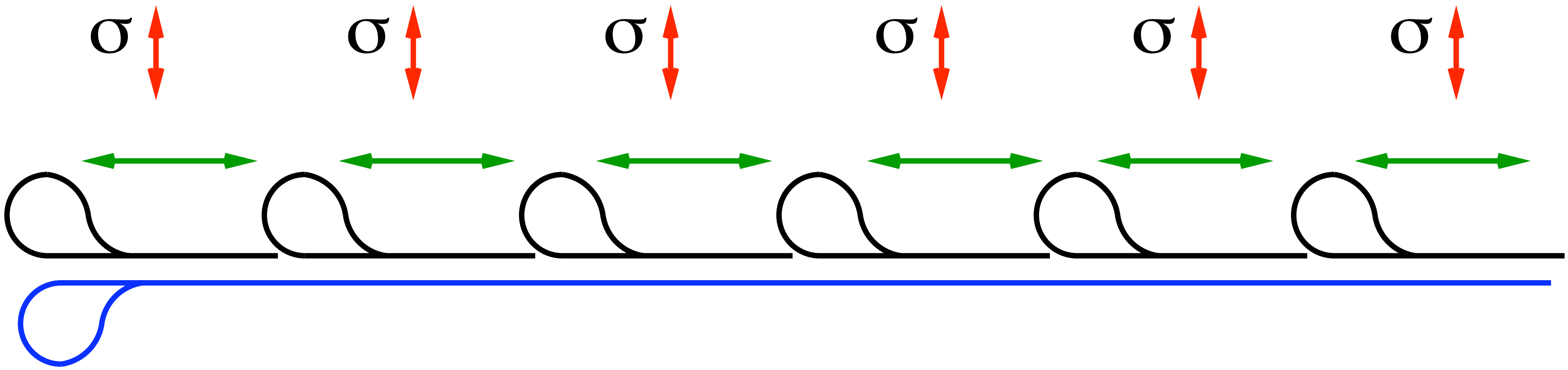
- Phase error at each point is independent of each other point

Simple Calculation for Local Control Error

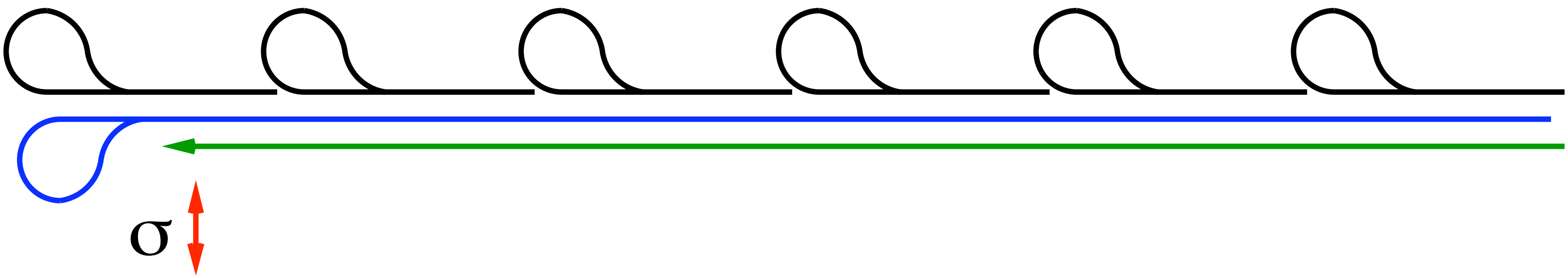
- Let us assume that all errors are local
  - main beams have no phase jitter when going into transfer line
  - external timing system has the right signal in the fibers everywhere
- Local timing errors will occur due to
  - picking up the signal from the main beam
  - or picking up the signal from the fibers
  - error in controling the main beam bunch compressor RF
  - or error in controling the drive beam feed-forward

⇒ In this case tightest tolerance comes from main beam error
  - $14\,\mu\mathrm{m} = 0.2^\circ$ lead to 1% luminosity loss due to incorrect main beam energy
  - tolerance on main to incoherent drive beam phase is more relaxed (0.8°)

Global Error Models



- Timing error exists between each pair of points



- Timing of main beam is wrong with respect to reference time
- Timing of drive beam feedforward is correct for main beam

Simple Calculation for Global Control Error

- The only error considered is
  - a phase jitter of the outgoing beam
  - or a random walk-like error of the external timing

⇒ The jitter of the outgoing main beam can be $0.4^\circ = 30\,\mu\mathrm{m}$, limited by IP jitter

- The total difference between the two ends of the BC timing references is $\sigma \approx \sqrt{50}\sigma_\phi$, σ_ϕ the RMS drift from one sector to the next

⇒ $\sigma_\phi \approx 4\,\mu\mathrm{m} \approx 0.05^\circ$ from IP jitter tolerance

- On top will have phase errors between main and drive beam sectors, roughly doubling the luminosity loss

⇒ $\sigma_\phi \approx 3\,\mu\mathrm{m} \approx 0.03^\circ$

- at DESY $\sigma_\phi \approx 3\,\mu\mathrm{m}$ has been achieved over $300\,\mathrm{m}$, not far

RTML Sensitivity

- No active compensation assumed, each value results in $\Delta\mathcal{L}/\mathcal{L} = 0.01$ or an energy jitter of $0.2\,\%$ at linac enetrance (external timing)
- Note: the tolerances will be tighter
- Energy jitter from damping ring:
  - 2×10^{-4} for main beam as timing reference
  - 4×10^{-4} for external timing reference
- Phase jitter from damping ring:
  - $0.2°$ at $1\,\mathrm{GHz}$ for main beam as timing reference
  - $0.35°$ for external timing reference
- Phase error of first bunch compressor (BC1) at $4\,\mathrm{GHz}$:
  - $0.08°$ for main beam as timing reference
  - $0.14°$ for X-FEL scheme
- Gradient error in booster linac (without energy feedforward):
  - 1×10^{-3}
  - energy feedforward would measure energy at turn-around and change BC2 RF phase
- BC2 phase jitter tolerance:
  - $0.2°$ at $12\,\mathrm{GHz}$

RTML Sensitivity Improvements

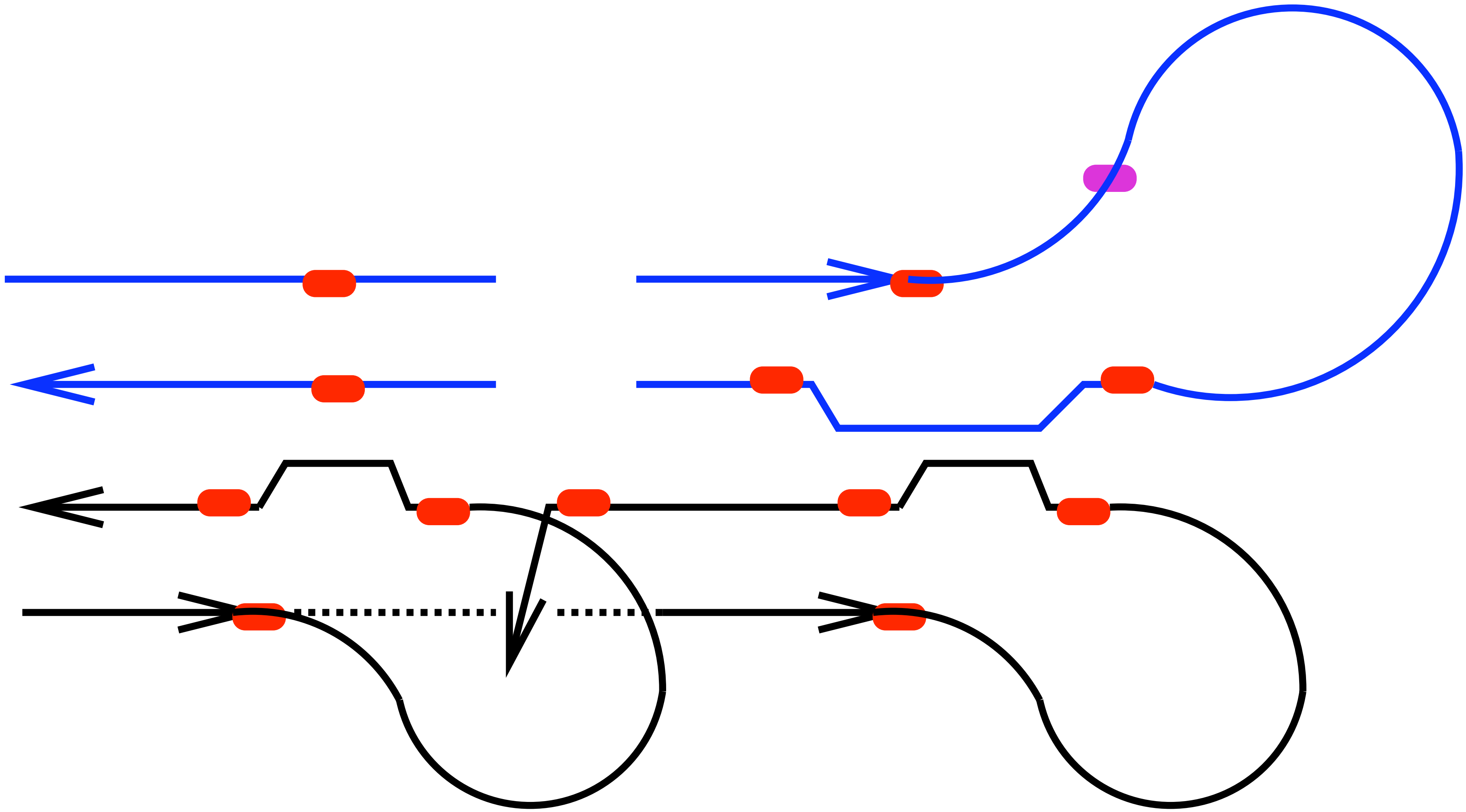
- Coupling of RF for both main beams would help
  - but currently different time slices are used
- Phase errors from the damping rings could be cured in BC1 with Feed-fowrad
- For the beam-based timing system a waist feed-forward could further relax the tolerances
  - we could measure the relative phase errors of the outgoing main beams
  - we could move the waist longitudinally with a feed-forward system
    - either fast quadrupoles
    - or kick the beams in sextupoles
    - or accelerate/decelerate beam just before the final doublet, where the chromaticity is uncorrected
    - details need to be worked out

Feedback and Tuning Strategy

- Feedback to deal with slow variations
- Tuning to deal with static or slow imperfections
- Need a path length tuning system for each turn-around
  - in drive beam and main beam
- Need an adjustment of path length from one drive beam turn-around to the next
- Similarly for the combiner rings, the delay loop and the drive beam accelerator complex

⇒ Slow drifts of relative phasing of the beams do not appear to be an feasibility issue

Feedforward and Feedback Layout



Some Other Issues

- Performance of hardware, in particular distributed timing
- Drive beam source design

  - and stability
- Damping ring phase, energy and charge stability

  - phase could be cured in BC1

  - tight requirements for sources, waiting for feedback from working group
- Relative phasing of the drive beam to the RF is an issue

  - stabilised by stabilising temperature etc.

  - e.g. RF network requires $0.2\,\mathrm{K}$ stability (Walter, Module WG)

  - other options exist, e.g. measuring the phases

Further Work

- Integration of injectors and damping rings
  - for the injectors already bunch-to-bunch charge variation of 1% is required (0.1% for main linac accelerating structure fill time
- Study of BDS improvements, in particular the waist shift options
- Exploration of other potential phase stability issues
- Tracking of bunches through relevant systems to verify performance
- Simplified model of error propagation to achieve specifications
  - correlations between errors
- Slow feedback estimates

Conclusion

- We have two options to provided a distributed phase reference system in the main linac
  - use the outgoing main beam
  - X-FEL-like system
  - or a combination
- Decision needs to be based on further input from hardware performance
  - both seem to not be too far
- We seem to have a concept for drive beam generation and transport complex that leads to acceptable tolerances
  - demonstration of hardware

  ⇒ close to becoming a performance and cost issue
  - ready for improvements (cost, performance)
  - e.g. one central feedforward
- The effective loop and transfer line lengths are measured and can be corrected with feedback
- We need to look further into effects within the drive beam accelerator pulse
- More work to be done

Experiments in CTF3