Consideration on the Conceptual Phase Stabilisation System

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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

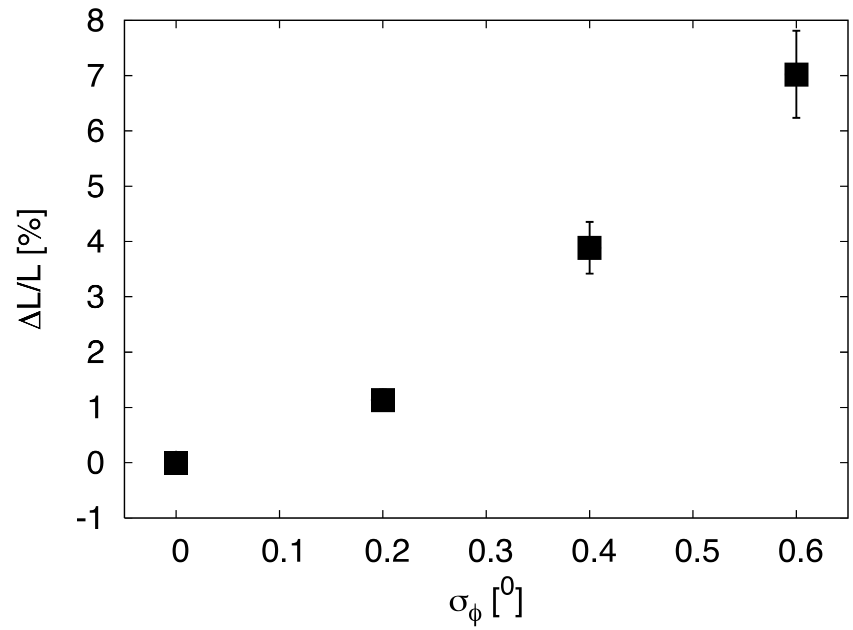
$$\frac{\sigma_G}{G} \approx 1 \times 10^{-3}$$

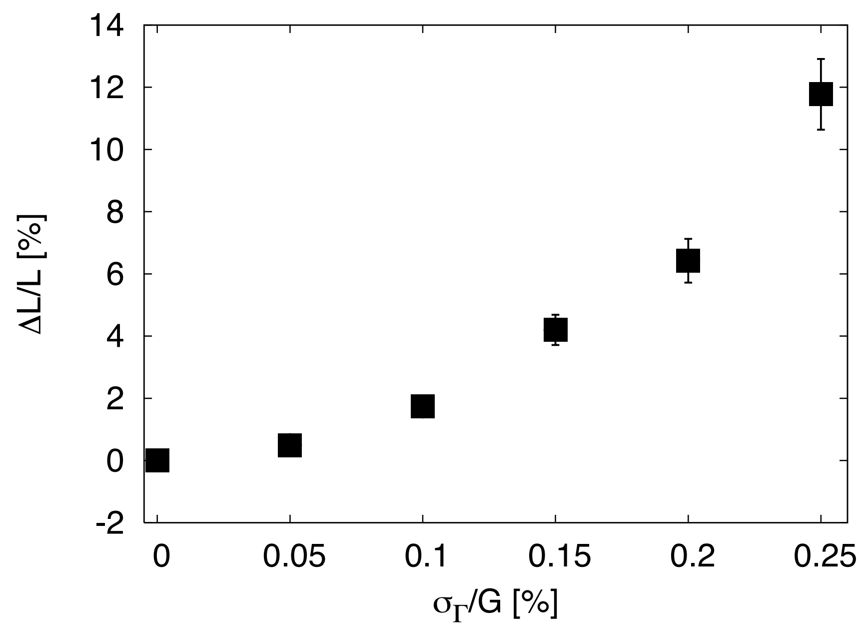
and

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

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

- 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

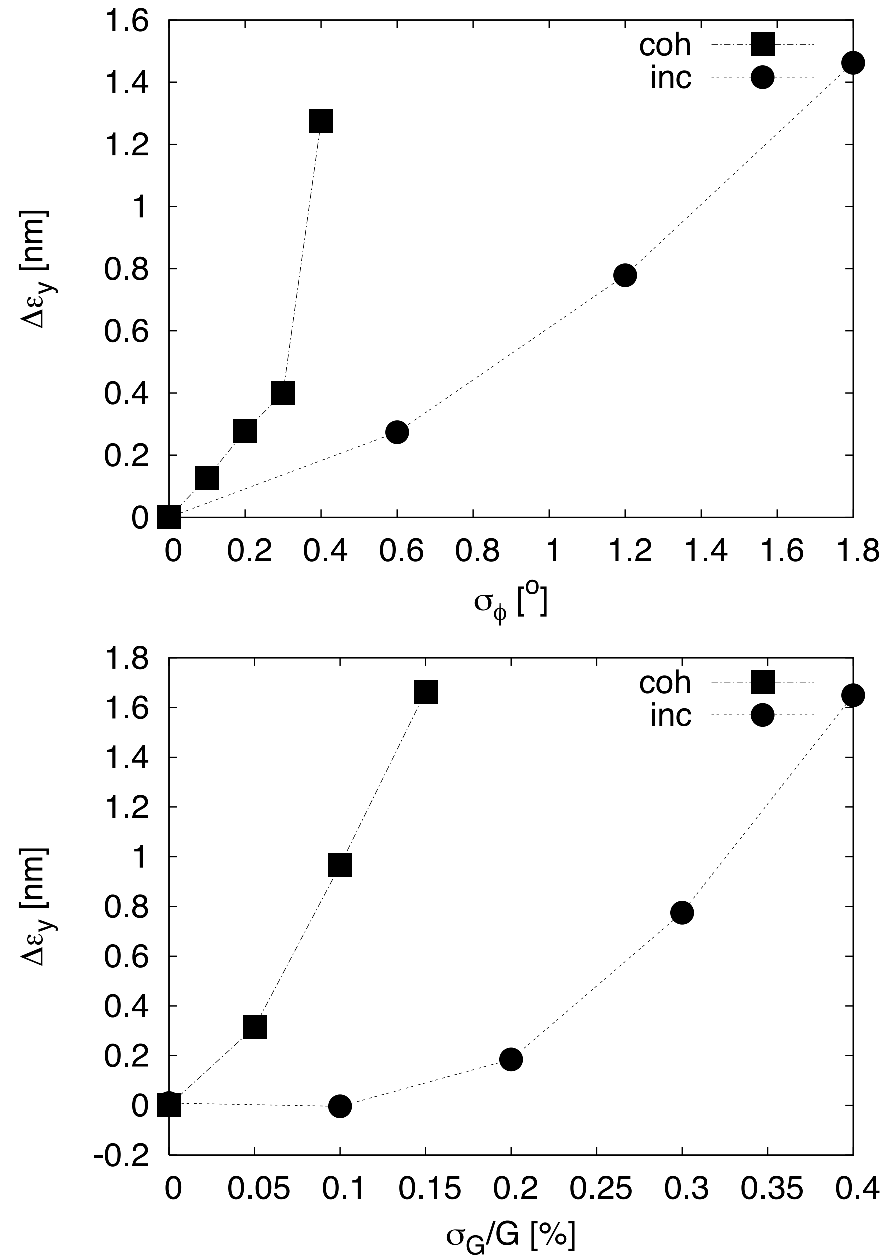
  ⇒ emittance is close to nominal

  ⇒ pessimistic, no disperison optimisation

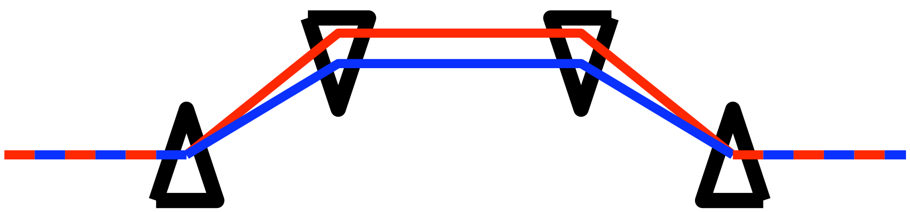
  - only main linac emittance growth is considered

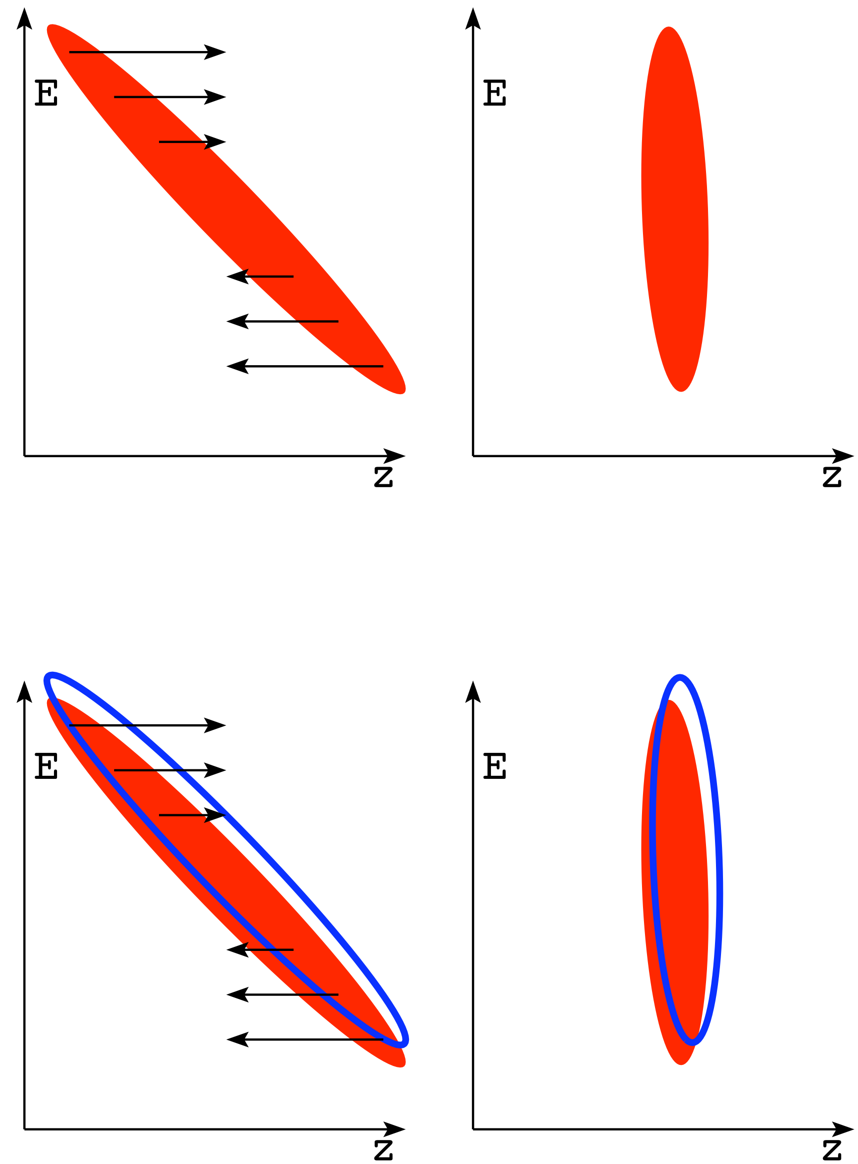
- $\Delta\epsilon_y = 0.8\,\mathrm{nm}$ corresponds to 2% luminosity loss

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



Impact of Bunch Compressor





- The drive beam needs to be compressed longitudinally

  $\Rightarrow$ energy errors will translate into phase errors

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

- For fully loaded operation

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

$\Rightarrow$ 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
  - energy chirp of 0.6% per $\sigma_z = 3\,\mathrm{mm}$ requires $R_{56} \approx 0.5\,\mathrm{m}$

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

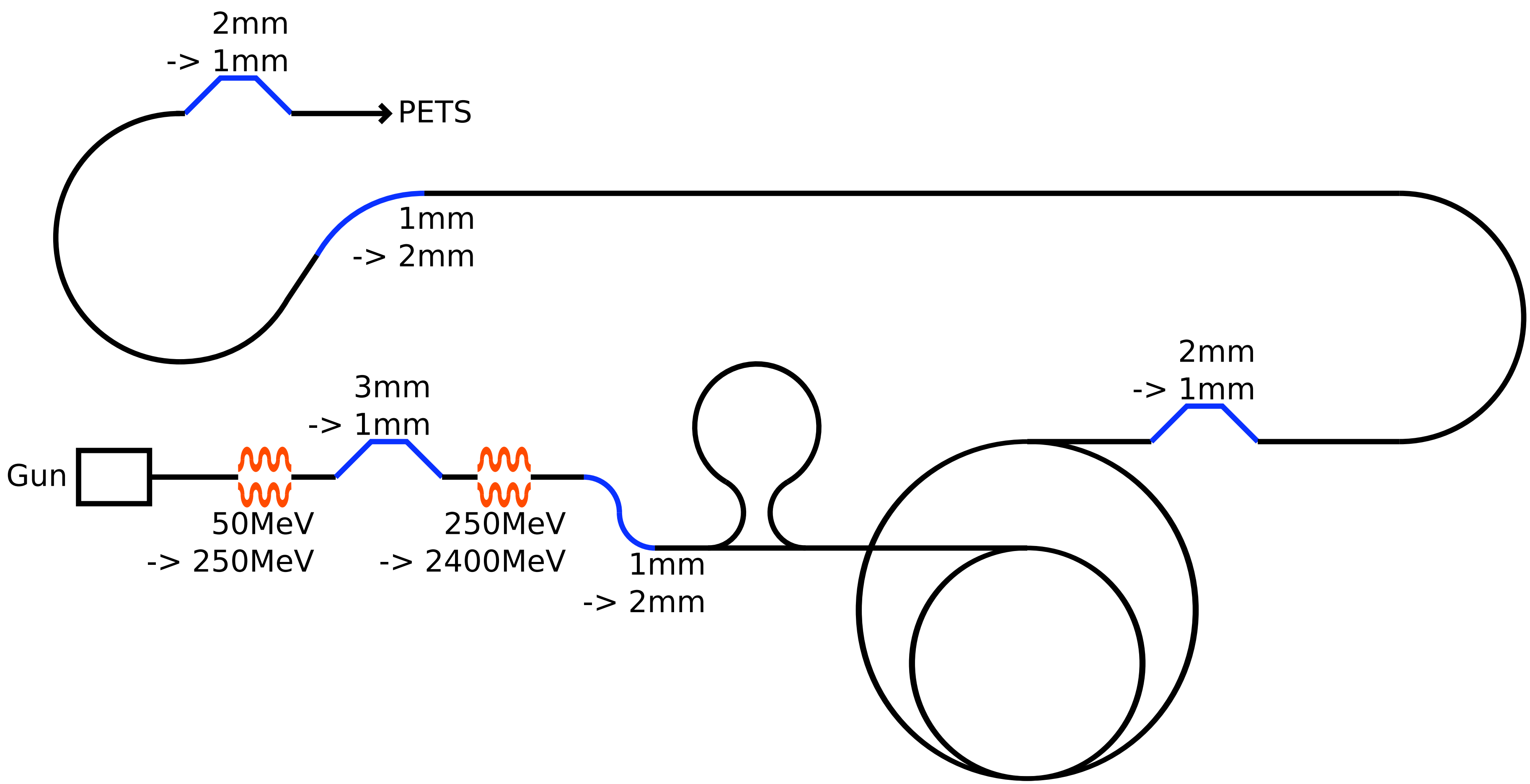
  $\Rightarrow$ relative gradient tolerance is 1.5×10^{-5}

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

  $\Rightarrow$ phase tolerance is 0.02° at $1\,\mathrm{GHz}$
- Looks very tough

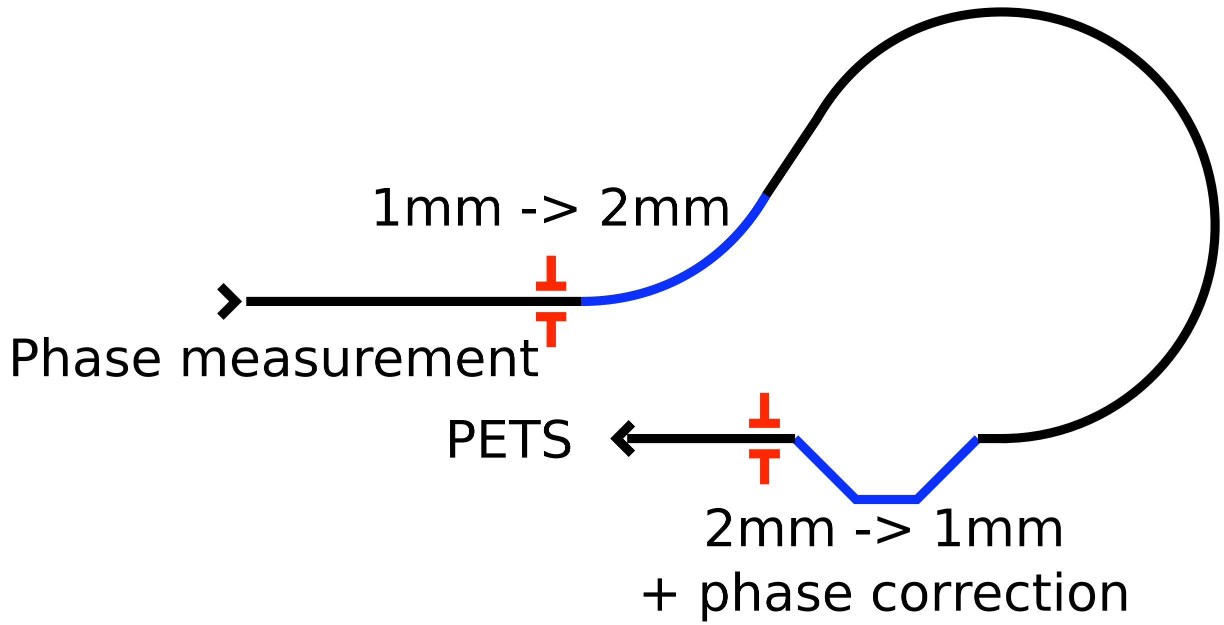
  $\Rightarrow$ try to find ways to relax the tolerances

Drive Beam Compression and Phase Stabilisation Concept



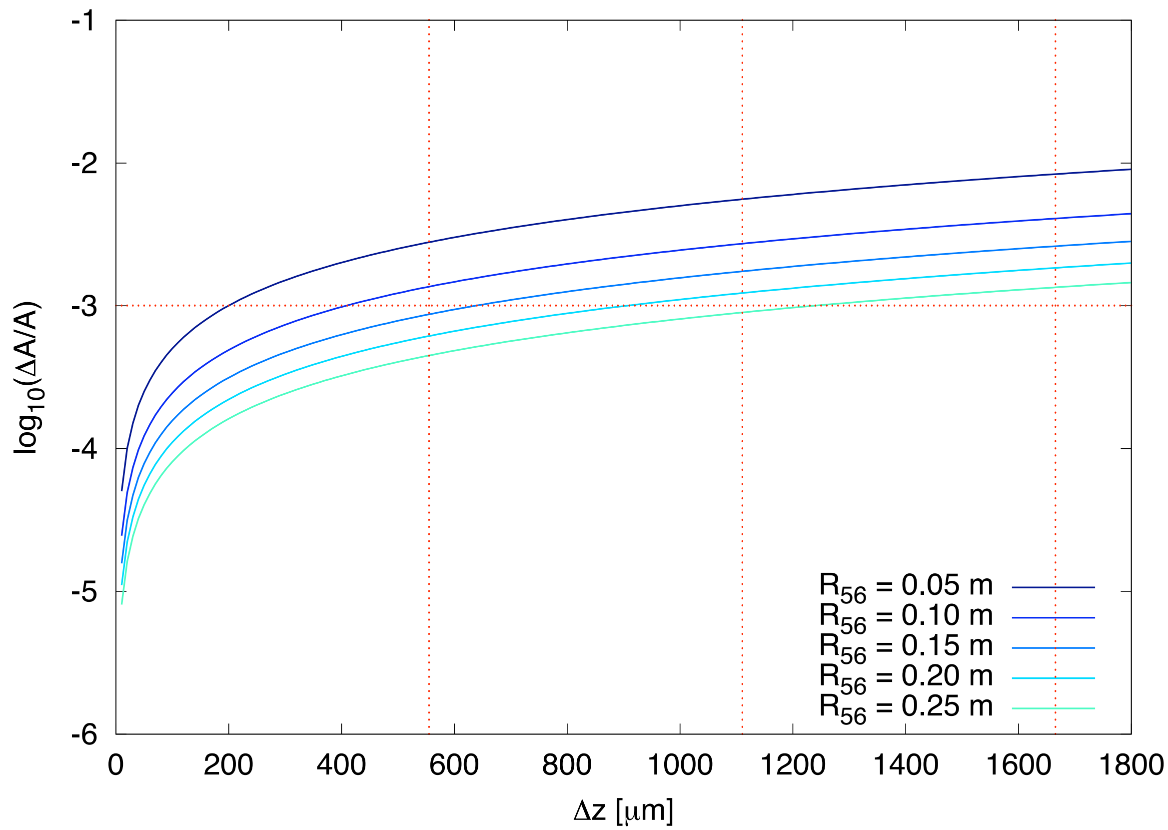
Feedforward at Final Turn-Around

- 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%
- $R_{56} \approx 0.2\,\mathrm{m}$
- System with 16 $1\,\mathrm{m}$ long kickers would need up to $\approx 1\,\mathrm{MW}$ power during kick
  - less than $1\,\mathrm{m}^3$ for power supplies (FONT-type)



Tolerances before Feedforward

- Can cure phase error
  - could also cure intensity error if we rely on off-crest running
- Want to capture 3–4 times RMS tolerance before feedforward
  - 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

$\Rightarrow$ can allow 2.5° RMS jitter before feedback (4σ capture)

  - assume gain factor of 10

  $\Rightarrow$ 0.25° RMS jitter after feedforward

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

$\Rightarrow$ 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 ($3\,\mathrm{mm} \rightarrow 1\,\mathrm{mm}$)

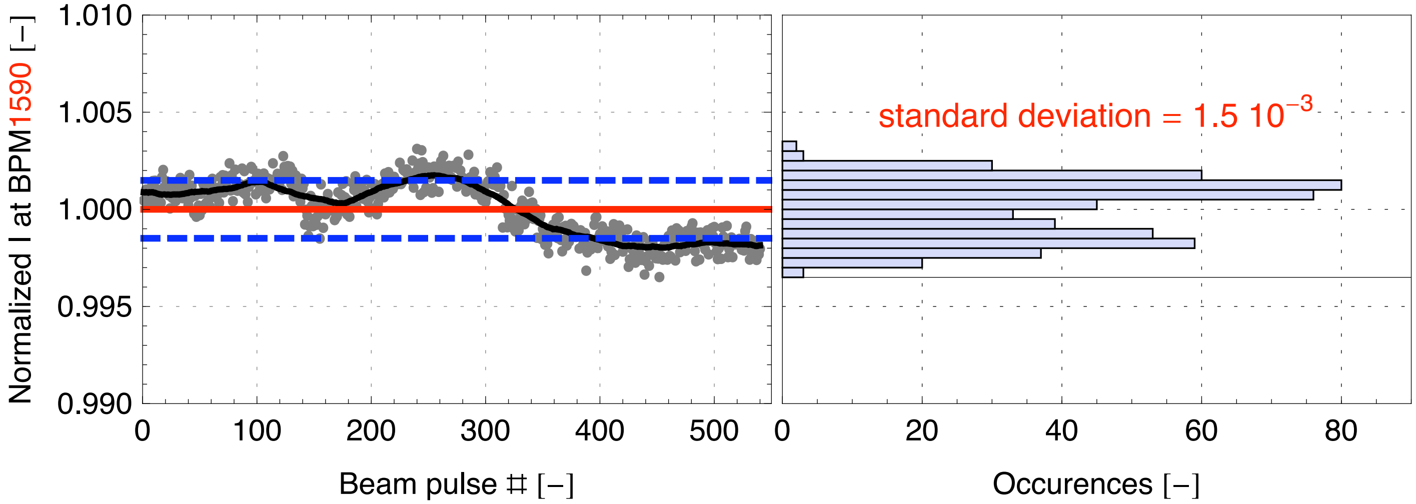
  $\Rightarrow$ can use relatively large energy spread $\Rightarrow$ small R_{56} $\Rightarrow$ large energy error tolerance
- Uncomression at end ($1\,\mathrm{mm} \rightarrow 2\,\mathrm{mm}$)
  - to limit coherent snychrotron radiation in delay loop and combiner rings
- Recompression after rings ($2\,\mathrm{mm} \rightarrow 1\,\mathrm{mm}$)
- 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 $1\,\mathrm{GHz}$

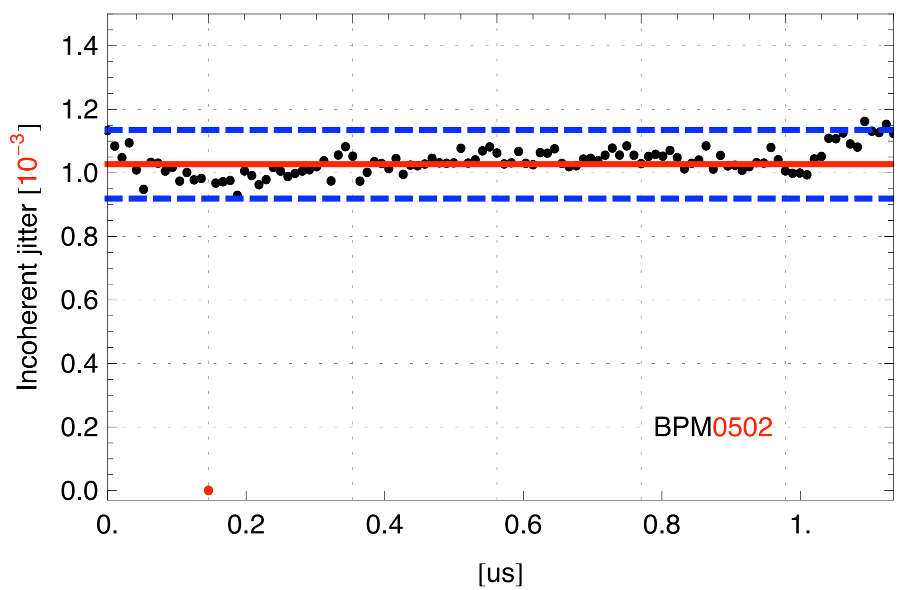
Current Measurement in CTF3



- No dedicated stabilisation effort in CTF3

⇒ Current stability is close to needs for CLIC

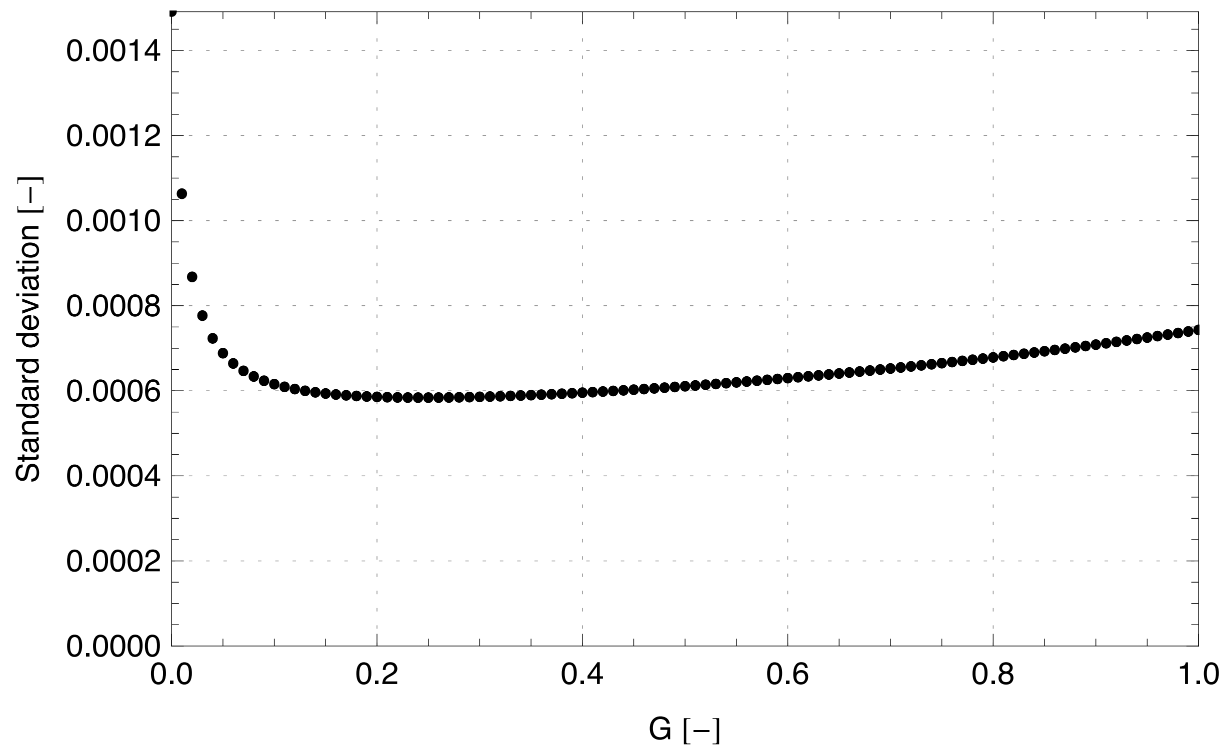
- Dynamic charge variation from one pulse slcie to the next seems better than BPM resolution

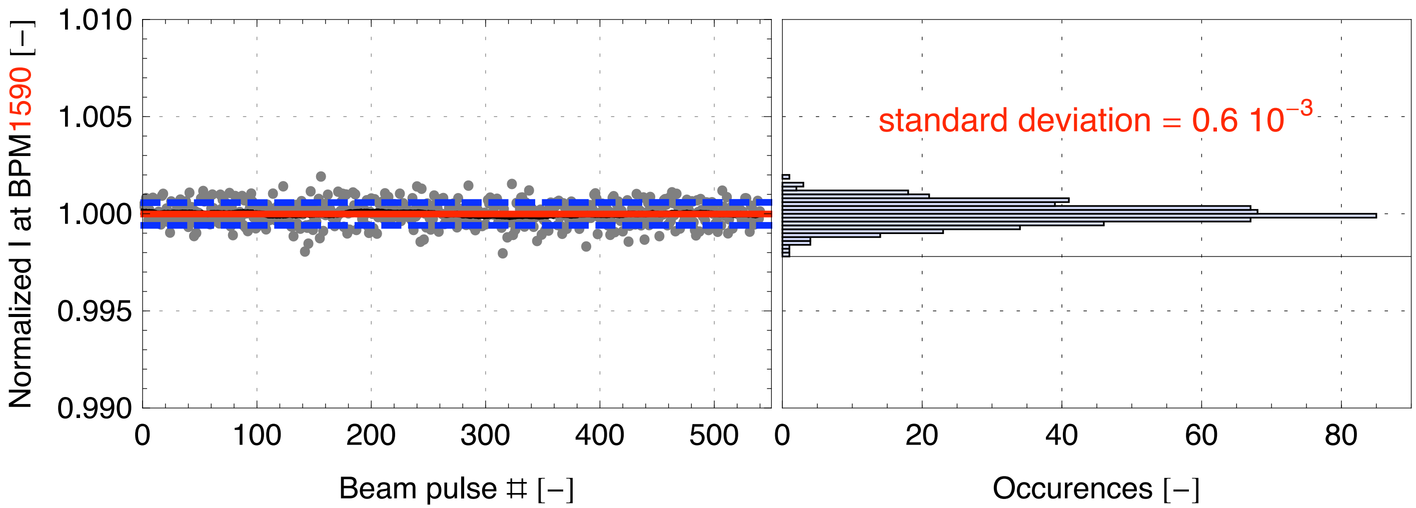


Improvement with Simulated Feedback

- Assume a pulse to pulse feedback on the current and use measured data

  $\Rightarrow$ current stability would improve to 0.06%



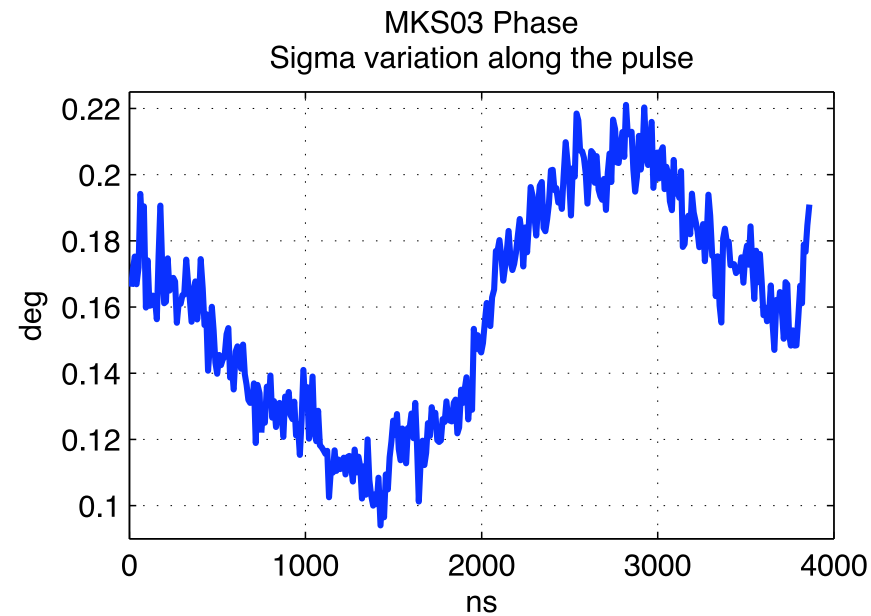


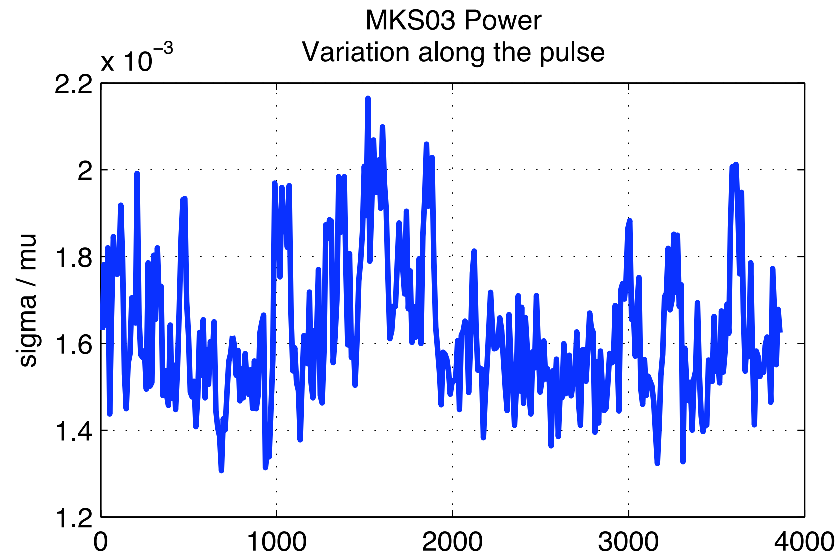
Phase and Power Measurement in CTF3

- Measurements of phase and power of CTF3 klystron indicate
  - phase stability of $0.2°$
  - power stability of $< 0.2\%$
    $\Rightarrow$ gradient stability $\leq 0.1\%$

$\Rightarrow$ Corresponds to drive beam needs

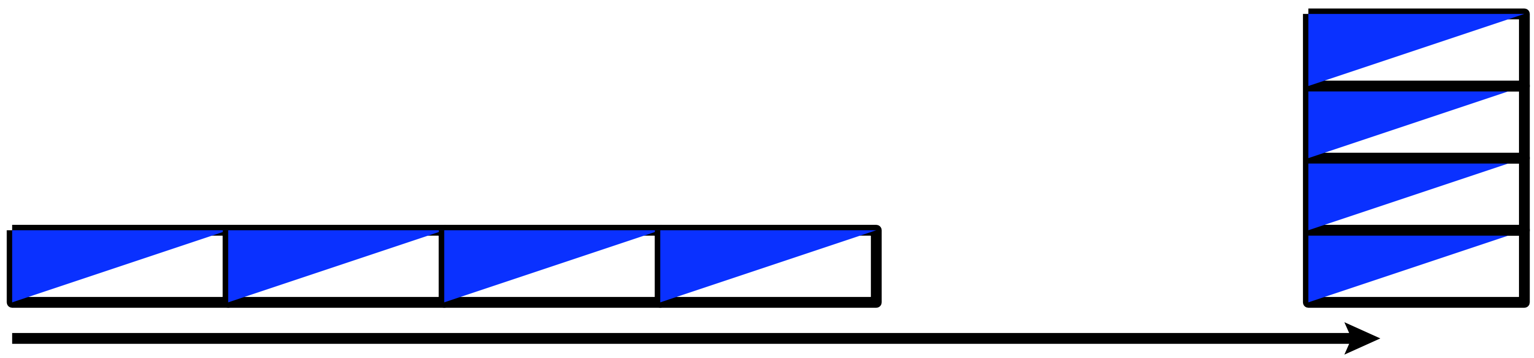
- Improvements appear possible





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



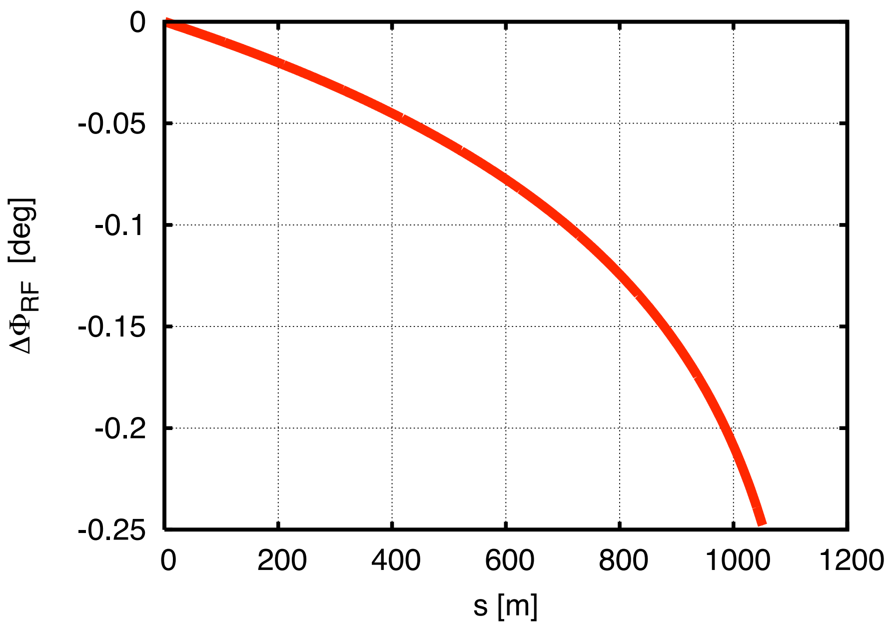
- Also design of sequence of acceleration and bunch compression for drive beam can help to achieve required performance
  - but still need to beam able to measure final jitter

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

Transverse Drive Beam Jitter



- 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

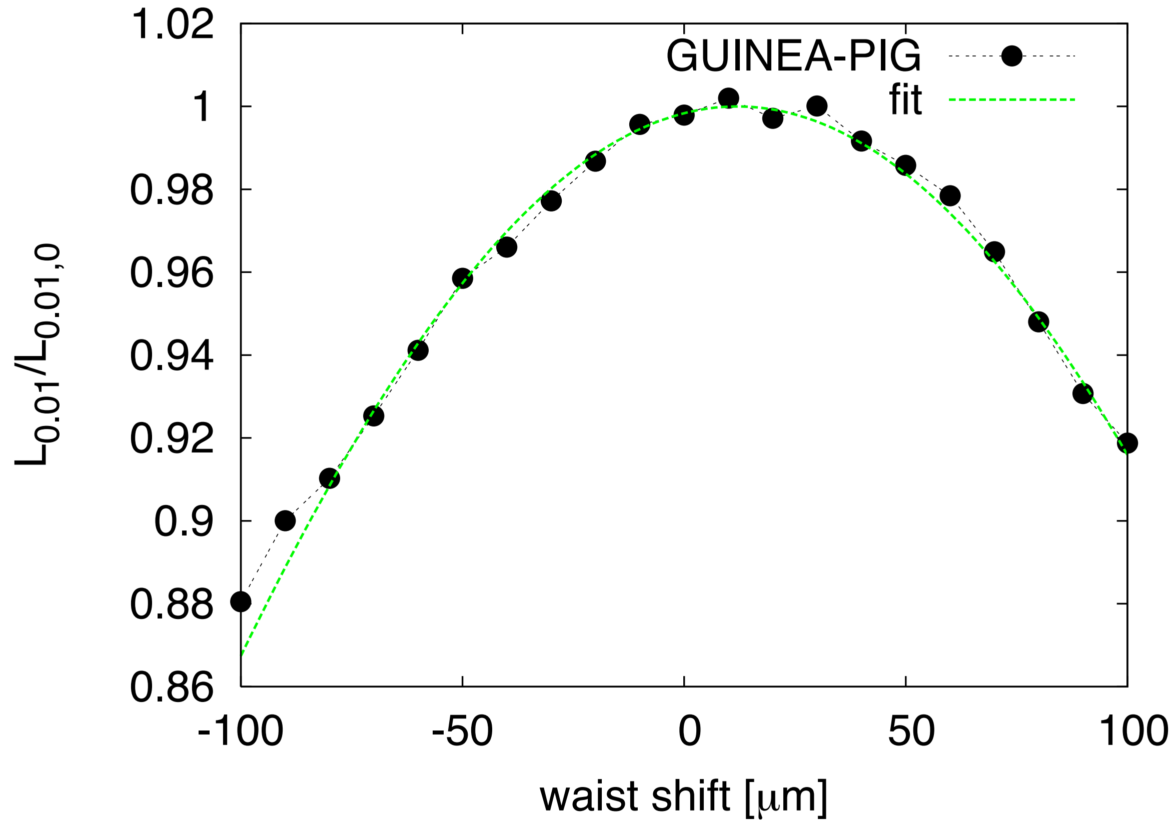
$$\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta x'}{\sigma_{x'}}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2 + \left(\frac{\Delta y'}{\sigma_{y'}}\right)^2 \leq 1^2$$

Main Beam to Main Beam Phase Tolerance

- RMS collision timing shift

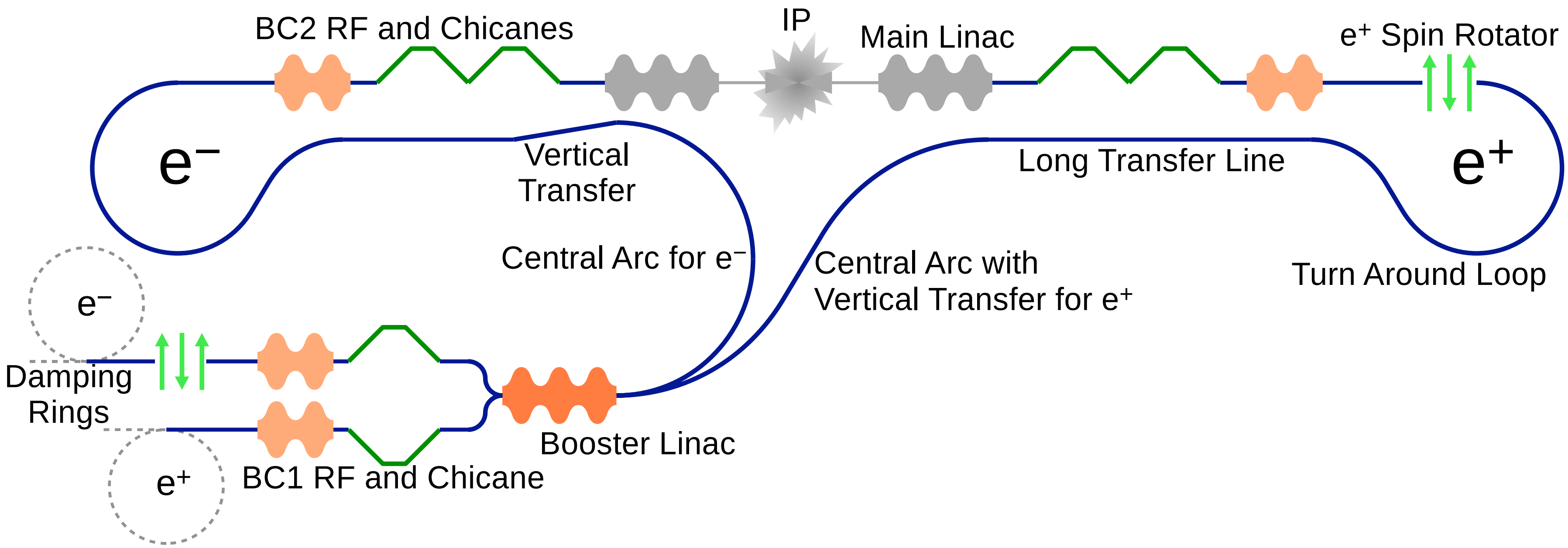
  1% loss per beam for $21\,\mu\mathrm{m}$

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



- Shift of beam waist in one beam

Main Beam Phasing



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

Main Beam Phasing

- Measure phase and energy error in damping ring and correct with BC1 at extraction
  - needs to be worked out
  - energy and phase stabilisation in damping ring needs to be studied
- Before beams are sent to main linacs could measure and correct phase
  - no design exists for now, exploration required

Resulting IP Beam-Beam Phase Error

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

$$\sigma_{BB} \approx \sqrt{2}\left(\frac{6}{7}\sigma_{MB\to RF} \oplus \sigma_{MB}\right)$$

  σ_{MB}: Timing error of outgoing main beam

  $\sigma_{MB\to RF}$: 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 $\leq 21\,\mu\mathrm{m}$

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

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

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

  $\sigma_{ref\to RF}$: 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 $\leq 21\,\mu\mathrm{m}$

- Energy error also leads to main beam phase jitter

Beam Waist Feedforward

- If we measure the relative phase errors of the outgoing main beams we can move the waist longitudinally with a feedforward
  - Could have fast quadrupoles
  - Kick beams in sextupoles
  - Could accelerate/decelerate beam just before the final doublet, where the chromaticity is uncorrected
- Details need to be worked out

RTML Tolerance

- Gradient error in booster linac (without energy feedforward): 4×10^{-4}
  - could be relaxed to 1×10^{-3} but large beam energy jitter at main linac
- Phase error of first bunch compressor (BC1) at $4\,\mathrm{GHz}$:
  - 0.04° for main beam as timing reference
  - 0.26° for X-FEL scheme
- Coupling of RF for both main beams would help
  - but currently different time slices are used
- Phase errors from the damping rings can be cured in BC1
- Relative phase of electron and positron beam can be measured after booster linac
  - feedback for phase tuning appears possible
  - feedforward is not obvious before BC2
  - could correct at BC2 and ship phase error signal to all turn-arounds
- Better solution may be to measure beam energy and phase before BC1 and correct with feeforward

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

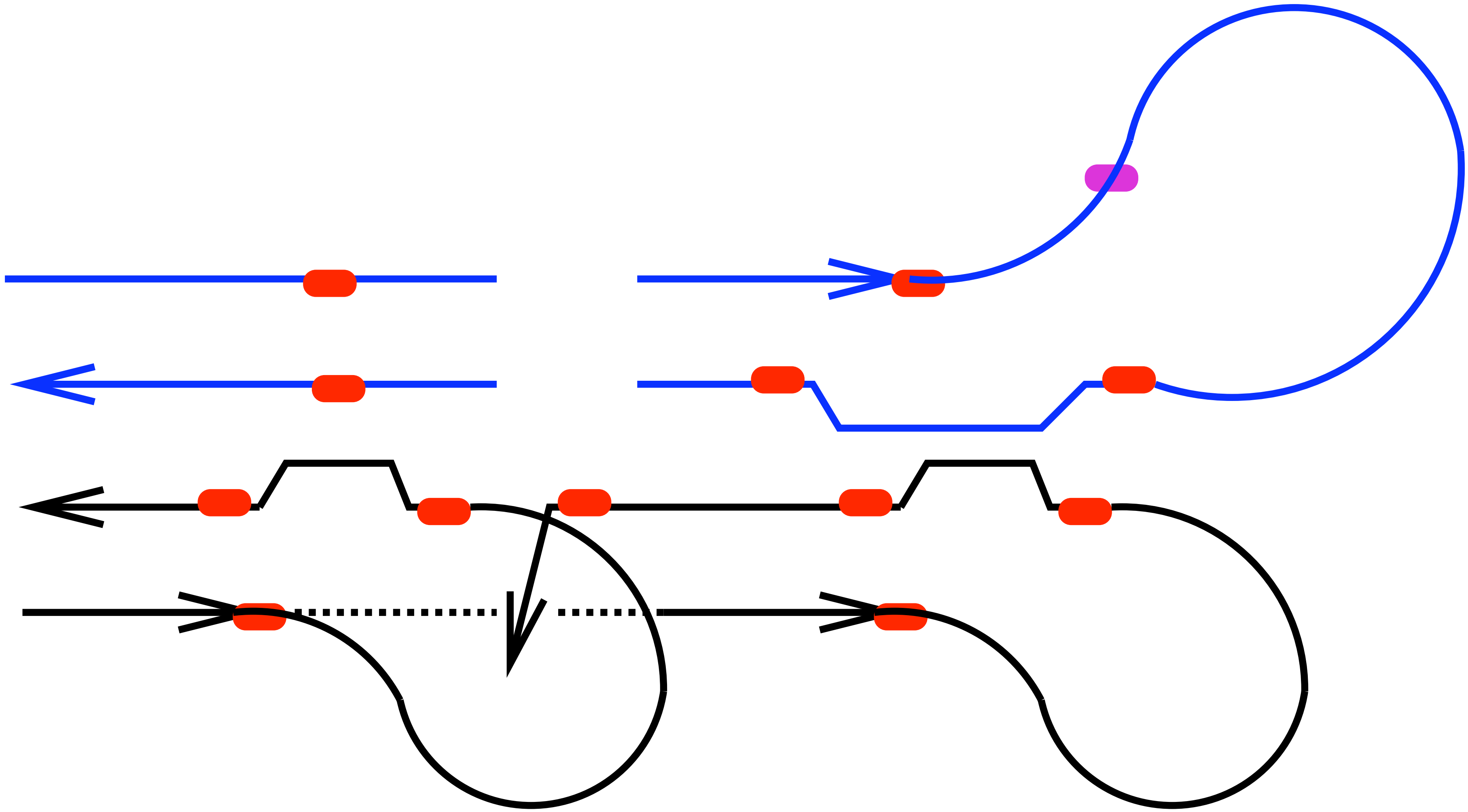
$$\sigma_{MD} \approx \sigma_{ref\to RF} \oplus \sqrt{2}\sigma_{ref} \oplus \sigma_{DB\to corr} \oplus a\sigma_{DB} \oplus \frac{1}{7}\sigma_{MB}$$

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

$\Rightarrow$ Slow drifts of relative phasing of the beams do not appear to be an feasibility issue

Feedforward and Feedback Layout



Some Open 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
- We seem to have a concept for drive beam generation and transport complex that leads to acceptable tolerances
  - demonstration of hardware

  $\Rightarrow$ 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 again into effects within the drive beam accelerator pulse
- The missing systems need to be studied
  - and detailed layouts for the conceptual systems
- Should review module phase stability strategy

Reserve

Single Stage Bunch Compressor Option

- Total compression after drive beam accelerator or just before decelerator
  - not clear that this yields a small enough energy spread
- Energy chirp is limited to at most 0.5–0.6% per $\sigma_z = 3\,\mathrm{mm}$
  - Due to combiner rings and turn-around loops
- Required R_{56} can be estimated (excluding overcompression) as

$$\frac{\sigma_{z,0} - \sigma_{z,1}}{\Delta E(\sigma_z)/E} \leq R_{56} \leq \frac{\sigma_{z,0}}{\Delta E(\sigma_z)/E}$$

- For the given energy spread and initial bunch length and the final target of $\sigma_{z,1} = 1\,\mathrm{mm}$ we find

$\Rightarrow$ Requires $R_{56} = 333$–$600\,\mathrm{mm}$

$\Rightarrow$ relative energy error tolerance is 2–4×10^{-4} $\Rightarrow$ relative gradient tolerance is 1–2×10^{-4} $\Rightarrow$ relative charge tolerance is 2–4×10^{-4}

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