Experimental considerations on emittance growth in the Drive Beam recombination at CTF3
Outline

- CLIC and the CLIC Test Facility (CTF3)
- Drive Beam Recombination
  - Projected Emittance as a figure of merit
  - Sources of emittance growth
- Tools to control and optimise the beam
  - Dispersion measurements
  - Generic feedback application
  - Optics measurements
- Summary
CLIC - Design of the Compact Linear Collider

**Based on two-beam acceleration scheme:**

- Besides the two colliding beams, it requires two parallel high intensity Drive Beam for RF power production.
- Loaded accelerating gradient **100 MV/m**.
- 12 GHz RF generated from a **12x recombined** Drive Beam.
Experimental considerations on emittance growth in the Drive Beam recombination at CTF3

CTF3 - The CLIC Test Facility at CERN

Drive Beam Linac: 4 A; 1.5 GHz; 1.2 μs; 120 MeV

Drone Beam Linac: 4 A; 1.5 GHz; 1.2 μs; 120 MeV

Building 2001
Building 2010
Building 2013
CLEX area

Cr 84 [m]
DL 42 [m]

PHOTO INJECTOR TESTS
TWO BEAM MODULE (TBM)
DECELERATION TEST BEAM LINE (TBL)

XBOX EXPERIMENT
PROBE BEAM PHOTO-INJECTOR

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EAAC Workshop 2015 - La Biodola (IT)
Emittance along the Drive Beam Recombination.

- Experimentally measured by means of quadrupole scan: seen inconsistencies...
- It might be some optics/setup problems, but also a measurement related issue.

**Best $\varepsilon_{x-px}$:** 60 $\mu$m

**Best $\varepsilon_{x-px}$:** (~300) $\mu$m

**Best $\varepsilon_{x-px}$:** 250 $\mu$m

**Best $\varepsilon_{x-px}$:** 200 $\mu$m

Thanks to T. Persson
Sources of emittance growth
**CTF3 Drive Beam Recombination**

**Incoming beam:**
- 4 A; 1.5 GHz; 1.2 μs; 120 MeV
- divided in eight 140 ns sub-trains

**Outgoing beam:**
- ~30 A; 12 GHz; 140 ns; 120 MeV

**Every second sub-train is ‘delayed’ in the Delay Loop**

**‘Odd’ and ‘Even’ sub-trains are recombined into four 3 Ghz sub-trains**

**The four 3 Ghz sub-trains are interleaved by performing different number of turns in the Combiner Ring.**
Recombination: everything can go wrong…

Incoming beam:
- 4 A; 1.5 GHz; 1.2 μs; 120 MeV
- divided in 140 ns sub-trains

Outgoing beam:
- Projected emittance growth.

DL optics could be unmatched.

Delayed trains orbit could be different than the “straight” trains.

Same effects in the Combiner Ring: here all four sub-trains take different paths…
On top: energy spread...

- Single passage in the Delay Loop.
- Assume perfect transverse matching.
- Typical incoming beam:
  - $\varepsilon_x = 60 \mu m; \varepsilon_y = 100 \mu m$;
  - $\Delta p/p_0 = 0.6 \% \sigma$
**Energy spread simulations: X-PX**

**MAD-X simulation:**
- $\varepsilon_x$ growth = \(~ 496.5\) [%]
- nominal FWHM X = 1.7424 [mm]
- nominal FWHM PX = 0.2781e-3
- Gaussian fit FWHM X = 1.8925 [mm]
- Gaussian fit FWHM PX = 0.41397e-3

**PTC TWISS simulation:**
- $\varepsilon_x$ growth = \(~ 317\) [%]
- nominal FWHM X = 1.7424 [mm]
- nominal FWHM PX = 0.2781e-3
- Gaussian fit FWHM X = 1.8437 [mm]
- Gaussian fit FWHM PX = 0.39237e-3

**PTC TRACK simulation:**
- $\varepsilon_x$ growth = \(~ 257.8\) [%]
- nominal FWHM X = 1.7424 [mm]
- nominal FWHM PX = 0.2781e-3
- Gaussian fit FWHM X = 1.8595 [mm]
- Gaussian fit FWHM PX = 0.39229e-3
Experimental considerations on emittance growth in the Drive Beam recombination at CTF3

Energy spread simulations: Y-PY

MAD-X simulation:
- $\varepsilon_y$ growth $\sim 0.2$ [%]
- nominal FWHM Y= 2.9228 [mm]
- nominal FWHM PY = 0.23193e-3
- Gaussian fit FWHM Y = 2.8701 [mm]
- Gaussian fit FWHM PY = 0.23448e-3

PTC TWISS simulation:
- $\varepsilon_y$ growth $\sim 2.8$ [%]
- nominal FWHM Y= 2.9228 [mm]
- nominal FWHM PY = 0.23193e-3
- Gaussian fit FWHM Y = 2.8947 [mm]
- Gaussian fit FWHM PY = 0.23522e-3

PTC TRACK simulation:
- $\varepsilon_y$ growth $\sim 3$ [%]
- nominal FWHM Y = 2.9228 [mm]
- nominal FWHM PY = 0.23193e-3
- Gaussian fit FWHM Y = 2.9099 [mm]
- Gaussian fit FWHM PY = 0.23317e-3
Implemented tools to diagnose and optimise the beam.

Some experimental results.
Dispersion measurements

Experimental considerations on emittance growth in the Drive Beam recombination at CTF3

Beam jitter of last 113 shots. Std(Dp/p) = 0.17285 %.

Correlation of CTBPM0487H with:
- Gun scaling
- Magnet scaling
- Reference BPM

Other diagnostic:
- Jitter SVDs
- Orbit Disp component

Correlation with:
- Energy Error @ref

Other diagnostic:
- SVD dispersion
- Gun induced dispersion
- Magnets induced dispersion

Value [ads]

svd idx [#]

10 20 30 40

1 2 3 4 5 6 7 8 9 10 11 12

Correlation with:

svd value [ads]

ref bpm jitter [mm]

3 2 1 0 -1 -2 -3

0.2 0.4 0.6 0.8

CTBP0487H

CTBPM0431H

CTBPM0285H

CTBPM0353H

CTBPM0155H

CTBPM0215H

CTBPM0242H

CTBPM0258H

CTBPM0150H

CTBPM0140H

CTBPM0130H

Nominal dispersion
Jitter Refit dispersion
SVD dispersion
Gun induced dispersion
Magnets induced dispersion

N shots: 240
Known D: -0.2
Known D idx: 5
Cursor idx: 1
Y min: -1
Y max: 1
Dispersion measurements

Main parameters and controls

Plot of all jitter traces and dispersion computed with different methods:

1) **first SVD direction** of jitter data.
2) **linear fit** respect to:
   - **beam current** at the beginning of the linac.
   - **beam position** at one “reference” BPM.
   - **scaling of bending magnets.**

Plots for quick data analyse and measurements quality control
Experimental considerations on emittance growth in the Drive Beam recombination at CTF3

Dispersion in Frascati Chicane.

Beam jitter of last 600 shots. Std(Dp/p) = 0.67%.
Dispersion in Frascati Chicane: a closer look.

- Clear non-linearities visible on the dispersion free BPMs after the chicane.
- **Similar results** can be obtained by simulating different beam energies with MAD-X in the **nominal case** and with *(lucky)* random quadrupoles **misalignments** \( \sigma = 0.2 \text{ [mm]} \).

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**From MAD-X model, nominal case**

- **From MAD-X model, with random misalignments**
Experimental considerations on emittance growth in the Drive Beam recombination at CTF3

Slow feedback
Experimental considerations on emittance growth in the Drive Beam recombination at CTF3

**Observables** (i.e. differences between one turn and the next one on the mostly trusted BPMs of CR) before and after correction.

Further improvements mainly limited by losses.

Strength of the vertical correctors in the CR before and after the correction.

- Similar results has been obtained for horizontal closure, as well as general orbit correction in other parts of CTF3.
Dispersion free steering in the LINAC

- Zero dispersion expected.
- The small chicane after the injector might leave some unclosed dispersion.
- We have big aperture, so we can afford to heavily scale the beam current without losses.
- If we can measure something reasonable, we can correct it...
Dispersion free steering in the LINAC

- Observables: 40 consecutive shots at different GUN current settings (scaling up/down of ~1.5% than nominal).

- Main correction is at the beginning of the linac. This reduces not only the dispersion, but also the orbit.
Work in progress: constant beam size Quadscan:

During a quadscan normally one quadrupole strength is varied and the beam size recorded on a screen... but one could use two quadrupoles and still “rotate” the beam, but keep the beam size constant!

Work in progress: phase-space tomography

In a similar way to quadscan, we can reconstruct the phase-space using the quadscan projections and applying tomography algorithms.
Summary

• The CTF3 Drive Beam recombination is affected by emittance growth due to:
  • Orbit mismatch of the single sub-trains once recombined.
  • Transverse optics mismatch (less critical).
  • High beam energy spread and non-linear dispersion.

• We have a series of implemented tools to diagnose and correct (some) effects:
  • Dispersion measurements.
  • Generic slow feedback tool that has been demonstrated over a wide range of corrections. (here only discussed orbit and dispersion, but also energy, bunching, gun current,...)

• We are working on new methods to enhance our understanding of the leading sources of emittance growth:
  • Constant beam size based quadscan.
  • Transverse beam size tomography.
Thank you for your attention
**CLIC - A possible Compact Linear Collider**

- Some parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of mass energy</td>
<td>$E_{cm}$</td>
<td>3000 GeV</td>
</tr>
<tr>
<td>Main Linac RF Frequency</td>
<td>$f_{RF}$</td>
<td>11.994 GHz</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$</td>
<td>$5.9 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Linac repetition rate</td>
<td>$f_{rep}$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>No. of particles / bunch</td>
<td>$N_b$</td>
<td>$3.72 \times 10^9$</td>
</tr>
<tr>
<td>No. of bunches / pulse</td>
<td>$k_b$</td>
<td>312</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>$\Delta t_b$</td>
<td>0.5 (6 periods) ns</td>
</tr>
<tr>
<td>Bunch train length</td>
<td>$\tau_{train}$</td>
<td>156 ns</td>
</tr>
<tr>
<td>Beam power / beam</td>
<td>$P_b$</td>
<td>14 MW</td>
</tr>
<tr>
<td>Unloaded / loaded gradient</td>
<td>$G_{unl/l}$</td>
<td>120 / 100 MV/m</td>
</tr>
<tr>
<td>Overall two linac length</td>
<td>$L_{linac}$</td>
<td>42.16 km</td>
</tr>
<tr>
<td>Total site AC power</td>
<td>$P_{tot}$</td>
<td>415 MW</td>
</tr>
<tr>
<td>Length of PETS</td>
<td>$L_{PETS}$</td>
<td>0.213 m</td>
</tr>
<tr>
<td>Nominal output RF Power / PETS</td>
<td>$P_{out}$</td>
<td>136 MW</td>
</tr>
<tr>
<td>Wall plug -&gt; RF efficiency</td>
<td>$\eta_{ACRF}$</td>
<td>58.6 %</td>
</tr>
<tr>
<td>RF -&gt; drive beam efficiency</td>
<td>$\eta_{BRF}$</td>
<td>93 %</td>
</tr>
<tr>
<td>drive beam -&gt; RF efficiency (HDS input)</td>
<td>$\eta_{decRF}$</td>
<td>65 %</td>
</tr>
<tr>
<td>RF -&gt; main beam efficiency</td>
<td>$\eta_{BRF}$</td>
<td>27.7 %</td>
</tr>
<tr>
<td>Wall plug to main beam power efficiency</td>
<td>$\eta_{tot}$</td>
<td>7 %</td>
</tr>
</tbody>
</table>
Simulation method: few details.

- Combine covariance matrices at one location:

\[
\Sigma_1 = \begin{bmatrix}
\sigma(x_1, x_1) & \sigma(x_1, y_1) \\
\sigma(y_1, x_1) & \sigma(y_1, y_1)
\end{bmatrix}
\]

\[
\Sigma_2 = \begin{bmatrix}
\sigma(x_2, x_2) & \sigma(x_2, y_2) \\
\sigma(y_2, x_2) & \sigma(y_2, y_2)
\end{bmatrix}
\]

\[
\Sigma = \begin{bmatrix}
\sigma(x, x) & \sigma(x, y) \\
\sigma(y, x) & \sigma(y, y)
\end{bmatrix}
\]

\[
\begin{align*}
\sigma(x_1, y_1) &= \langle x_1 y_1 \rangle - \langle x_1 \rangle \langle y_1 \rangle \\
\sigma(x_2, y_2) &= \langle x_2 y_2 \rangle - \langle x_2 \rangle \langle y_2 \rangle \\
\sigma(x, y) &= \langle xy \rangle - \langle x \rangle \langle y \rangle \\
\langle x \rangle &= \frac{n_1 \langle x_1 \rangle + n_2 \langle x_2 \rangle}{n_1 + n_2} \\
\langle y \rangle &= \frac{n_1 \langle y_1 \rangle + n_2 \langle y_2 \rangle}{n_1 + n_2} \\
\langle xy \rangle &= \frac{n_1 (\sigma(x_1, y_1) + \langle x_1 \rangle \langle y_1 \rangle) + n_2 (\sigma(x_2, y_2) + \langle x_2 \rangle \langle y_2 \rangle)}{n_1 + n_2}
\end{align*}
\]
Feedback tool: what is behind

\[
\begin{pmatrix}
    b_1 \\
    b_2 \\
    \vdots \\
    b_n \\
    t_1 \\
    t_2 \\
    \vdots \\
    t_m
\end{pmatrix}
\begin{pmatrix}
    R_{1,1} & R_{1,2} & \cdots & R_{1,m} \\
    R_{2,1} & R_{2,2} & \cdots & R_{2,m} \\
    \vdots & \vdots & \ddots & \vdots \\
    R_{n,1} & R_{n,2} & \cdots & R_{n,m}
\end{pmatrix}
\begin{pmatrix}
    c_1 \\
    c_2 \\
    \vdots \\
    a_m
\end{pmatrix}
\]

- If \( \lambda = 0 \), we are back in the classical situation.
- If \( \lambda \neq 0 \), then the full Response Matrix is always over-constrained.
  - Solution cannot explode.
- If \( \lambda >> 0 \), then the classic response matrix is just “noise”. Solution will be identical to the target correction required.
Experimental test: sextupolar dispersion correction

- Simulated end of DL X/PX as a function of DELTAP (MAD-X simulations)
Experimental results

- Implementing sextupolar correction of second-order dispersion.
- Measuring emittance in downstream measurement line at different stages.

No sextupoles on.  
First family at -23 A  
Second family at +9 A

Thanks to P. Skowronski and T. Persson