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

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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

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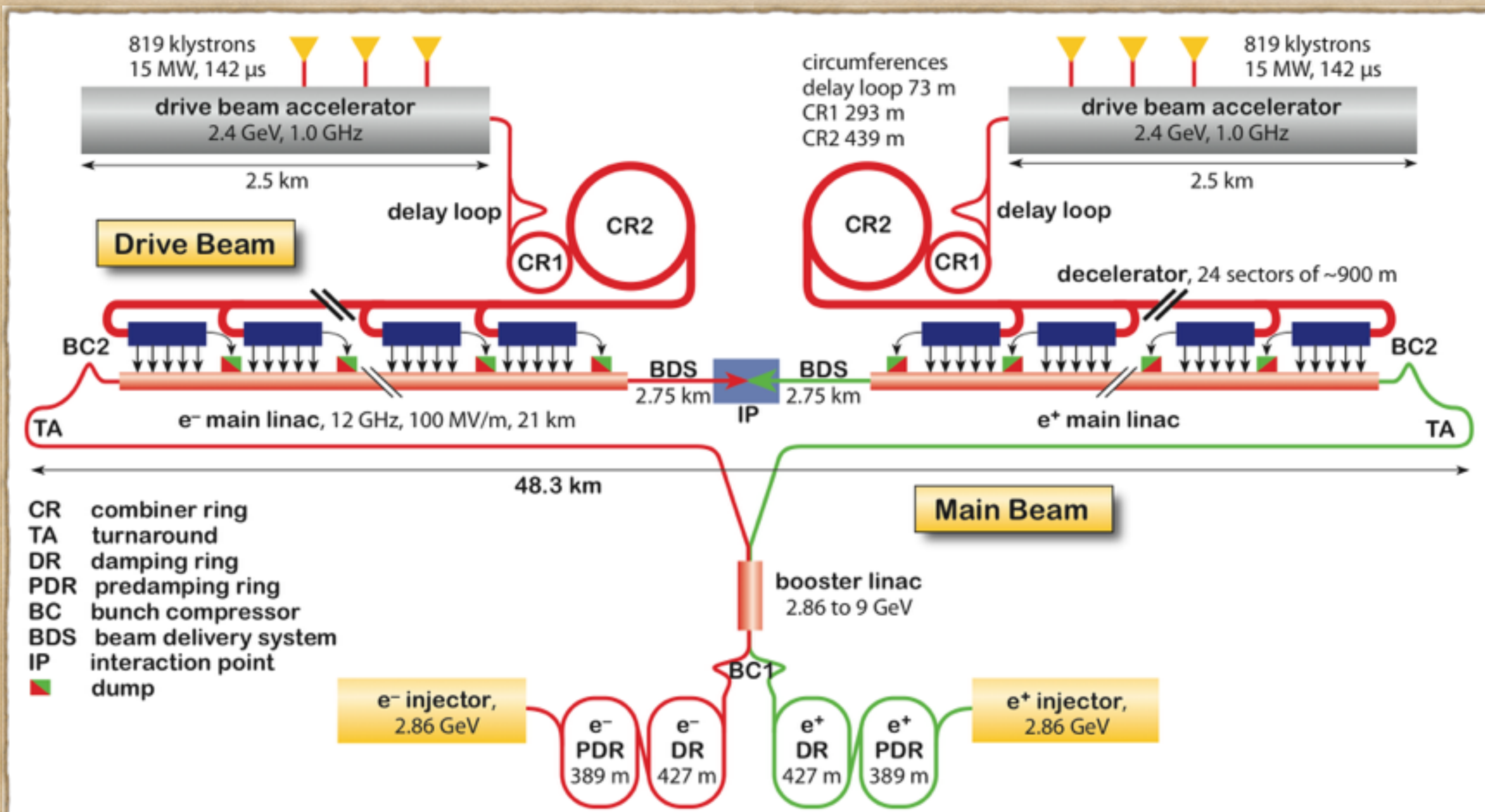
CLIC - Design of the Compact Linear Collider

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.



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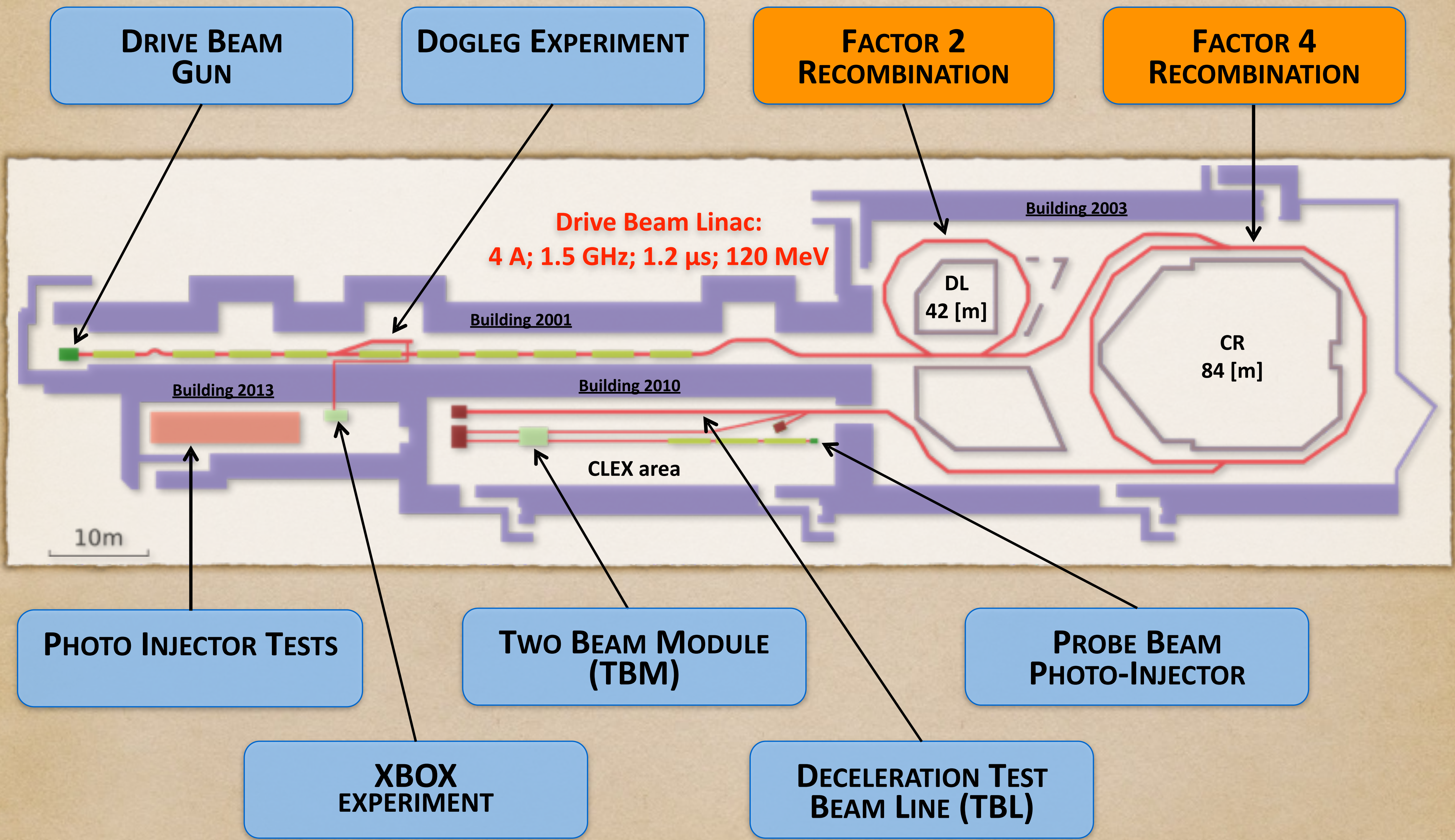
CTF3 - The CLIC Test Facility at CERN



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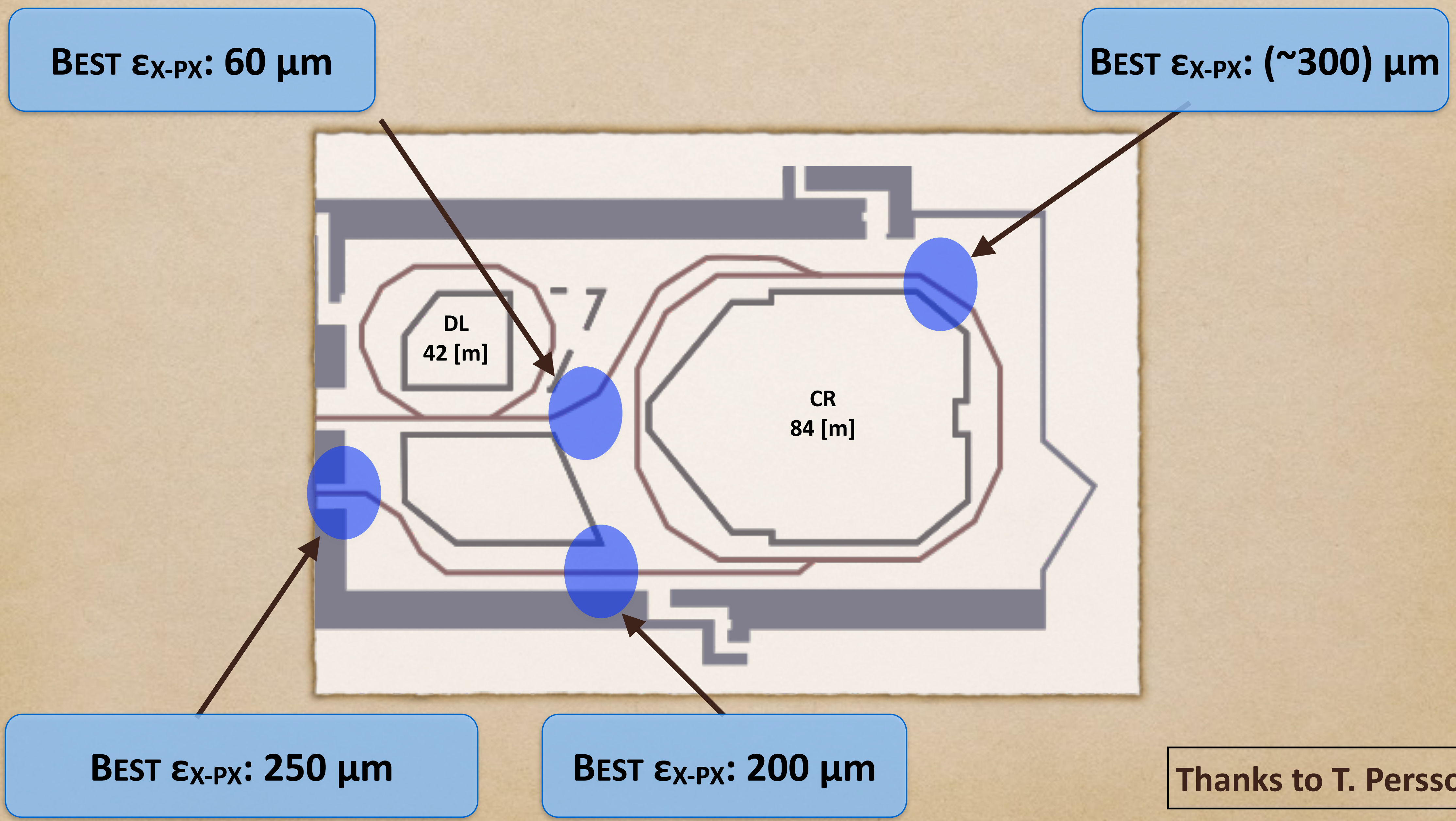
Emittance along the Drive Beam Recombination.

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



Thanks to T. Persson

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Sources of emittance growth

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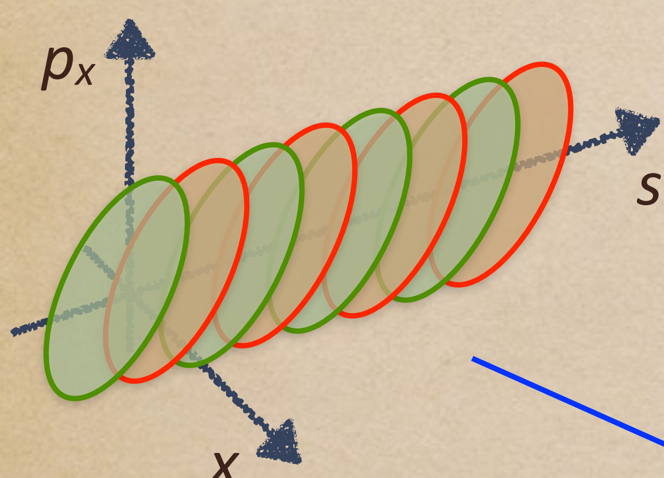
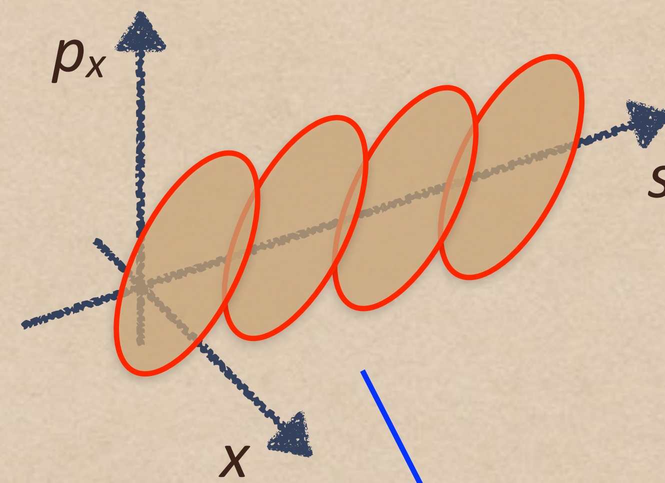
CTF3 Drive Beam Recombination

Incoming beam:

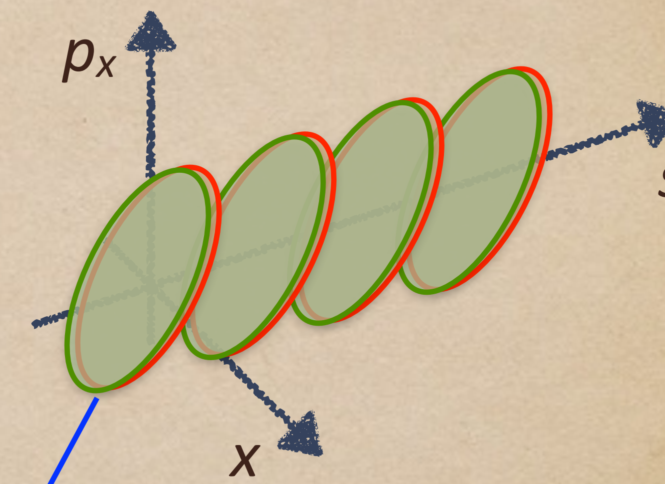
- **4 A; 1.5 GHz; 1.2 μs; 120 MeV**
- **divided in eight 140 ns sub-trains**

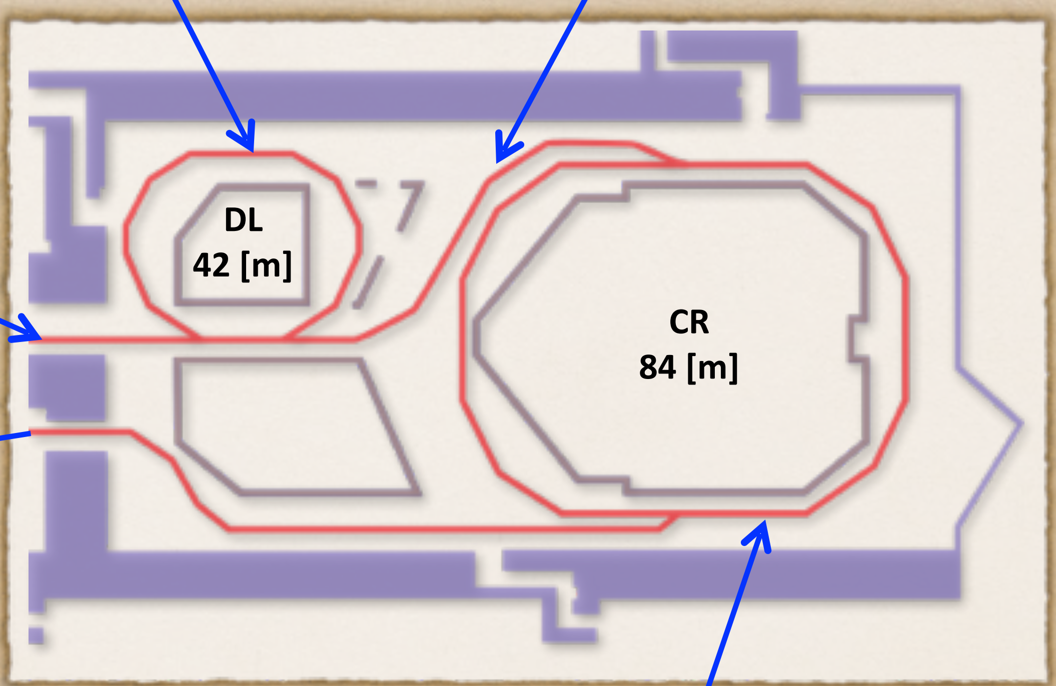


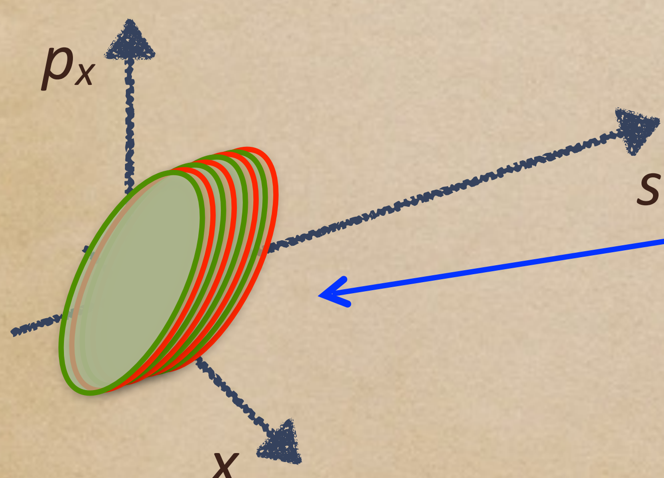
Every second sub-train is 'delayed' in the Delay Loop



'Odd' and 'Even' sub-trains are recombined into four 3 Ghz sub-trains







Outgoing beam:

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

The four 3 Ghz sub-trains are interleaved by performing different number of turns in the Combiner Ring.

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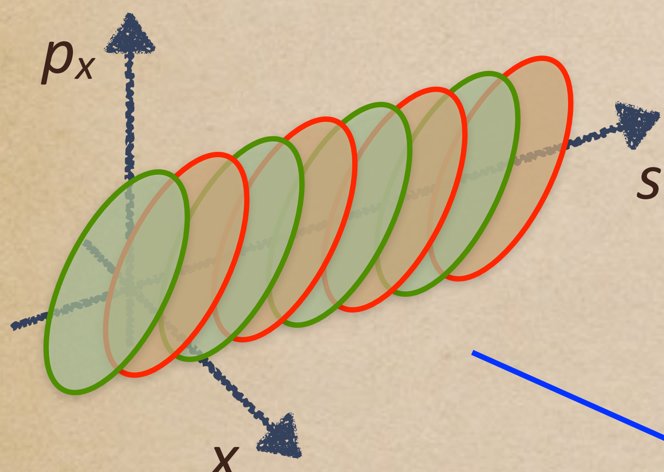
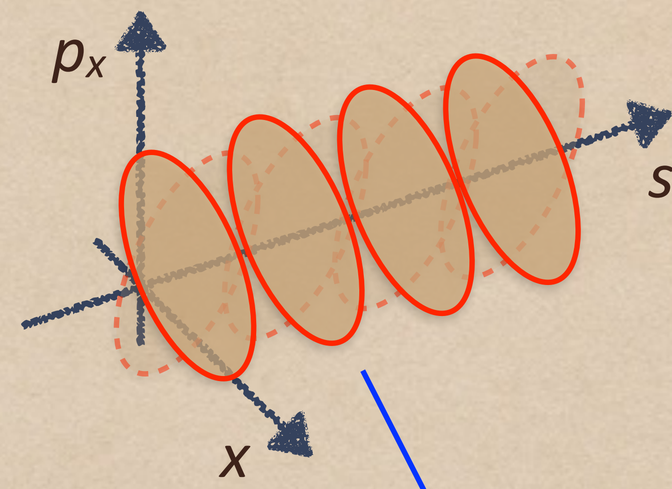
Recombination: everything can go wrong…

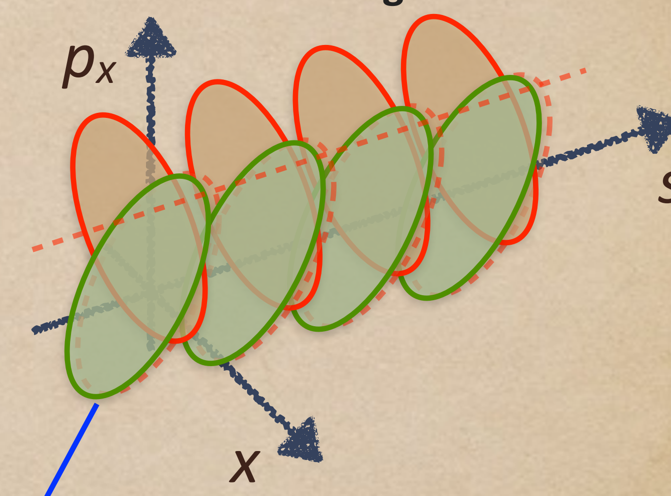
Incoming beam:
- **4 A; 1.5 GHz; 1.2 μs; 120 MeV**
- **divided in 140 ns sub-trains**

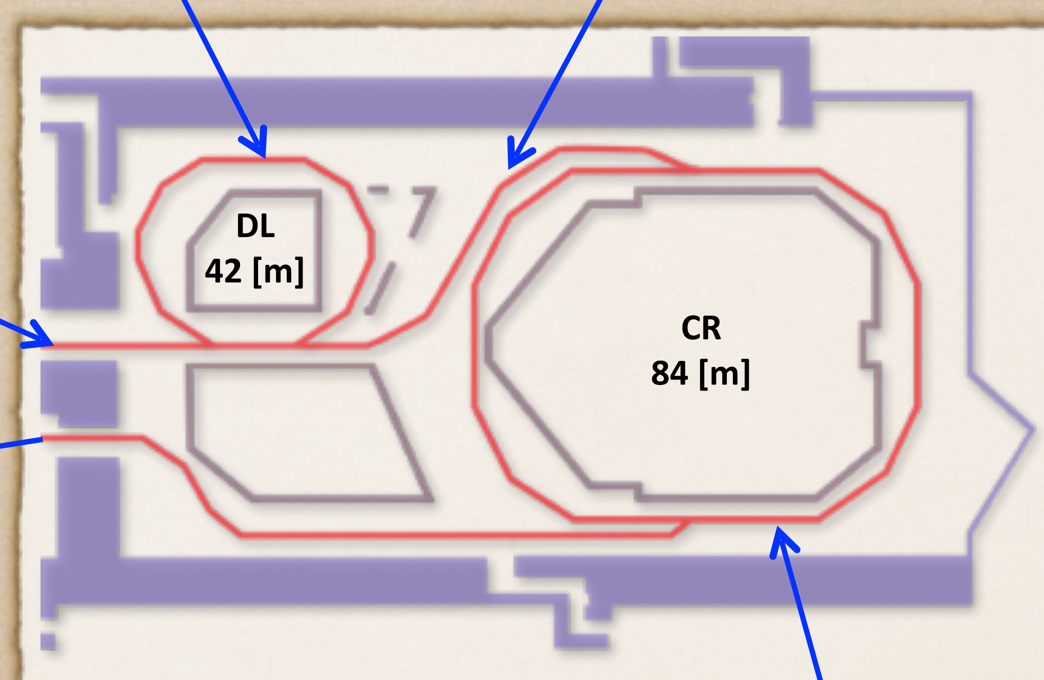


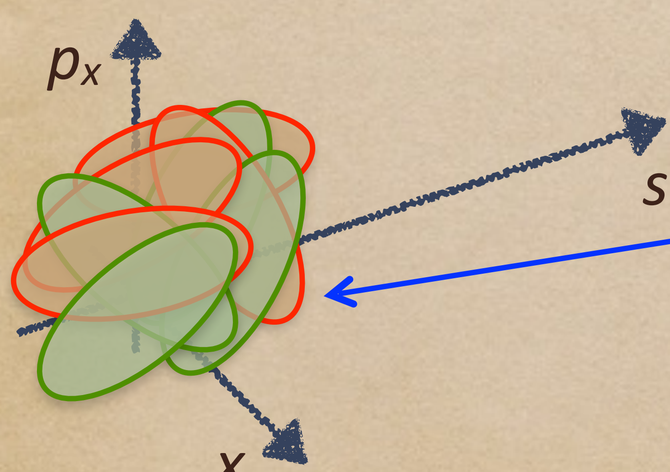
DL optics could be unmatched.



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







Outgoing beam:
- **Projected emittance growth.**

Same effects in the Combiner Ring: here all four sub-trains take different paths…

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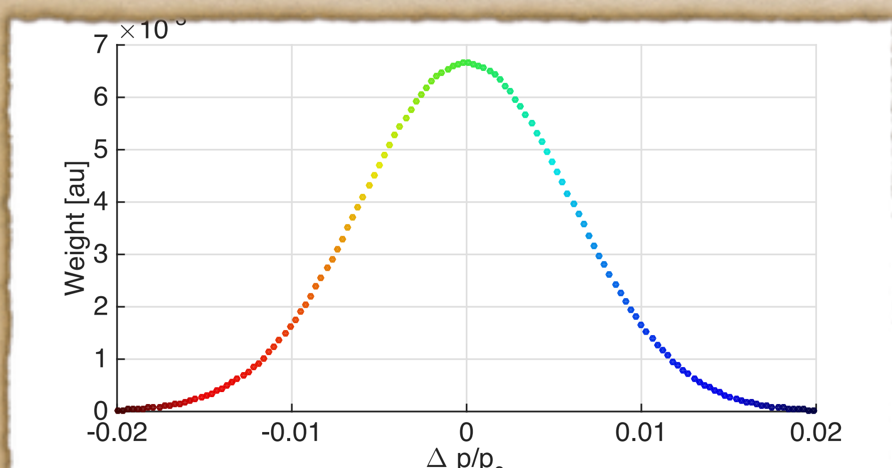
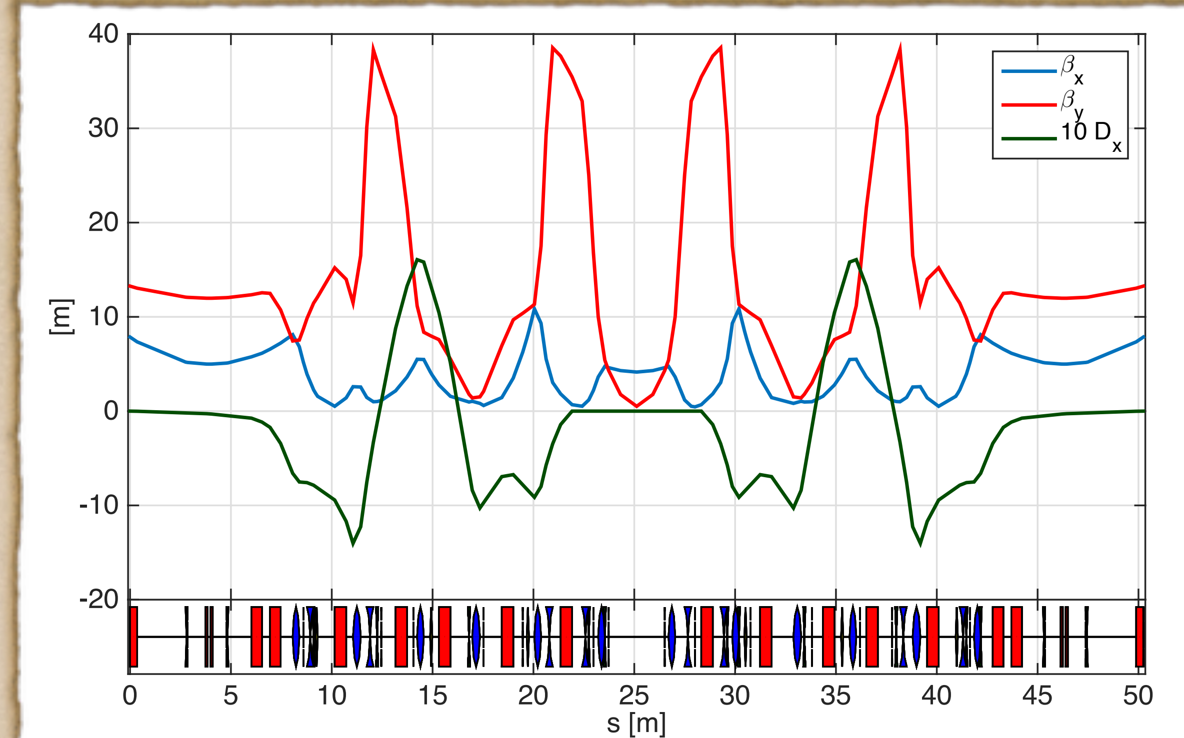
On top: energy spread...

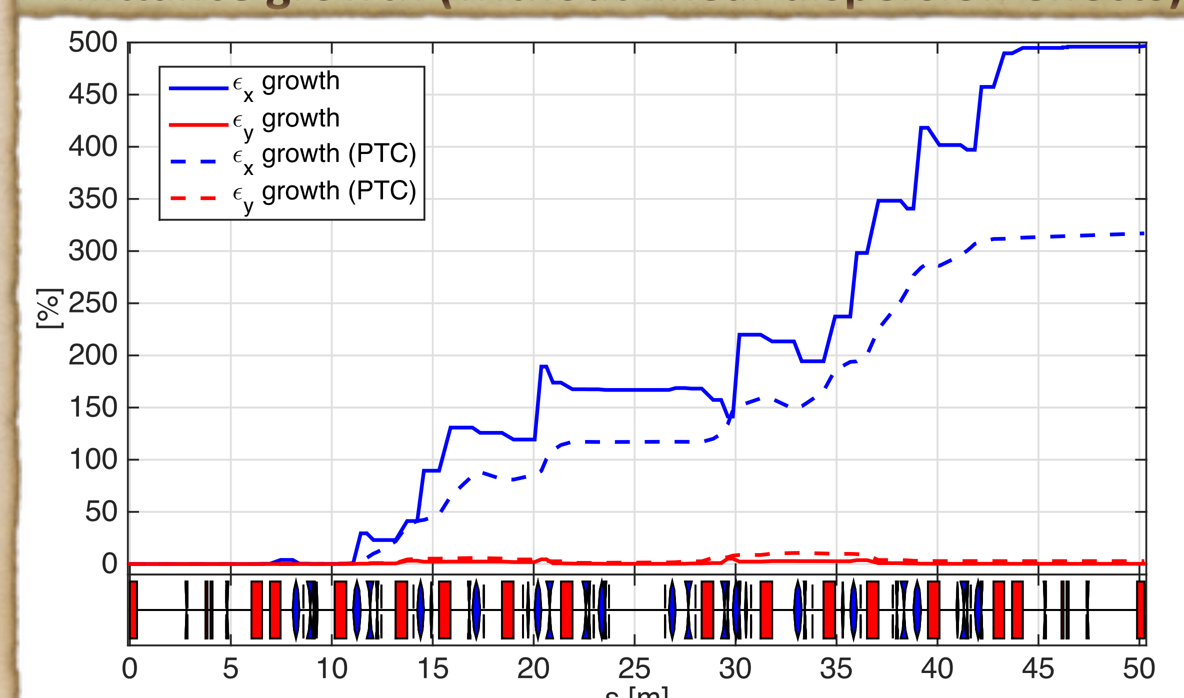
- Single passage in the Delay Loop.
- Assume perfect transverse matching.
- Typical incoming beam:
  - ε_x = 60 μm; ε_y = 100 μm;
  - $\Delta p/p_0$ = 0.6 % σ



Nominal Twiss functions and Dispersion



Emittance growth (without linear dispersion effects)



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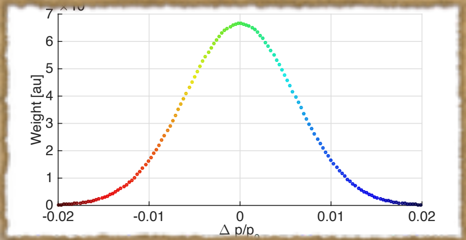
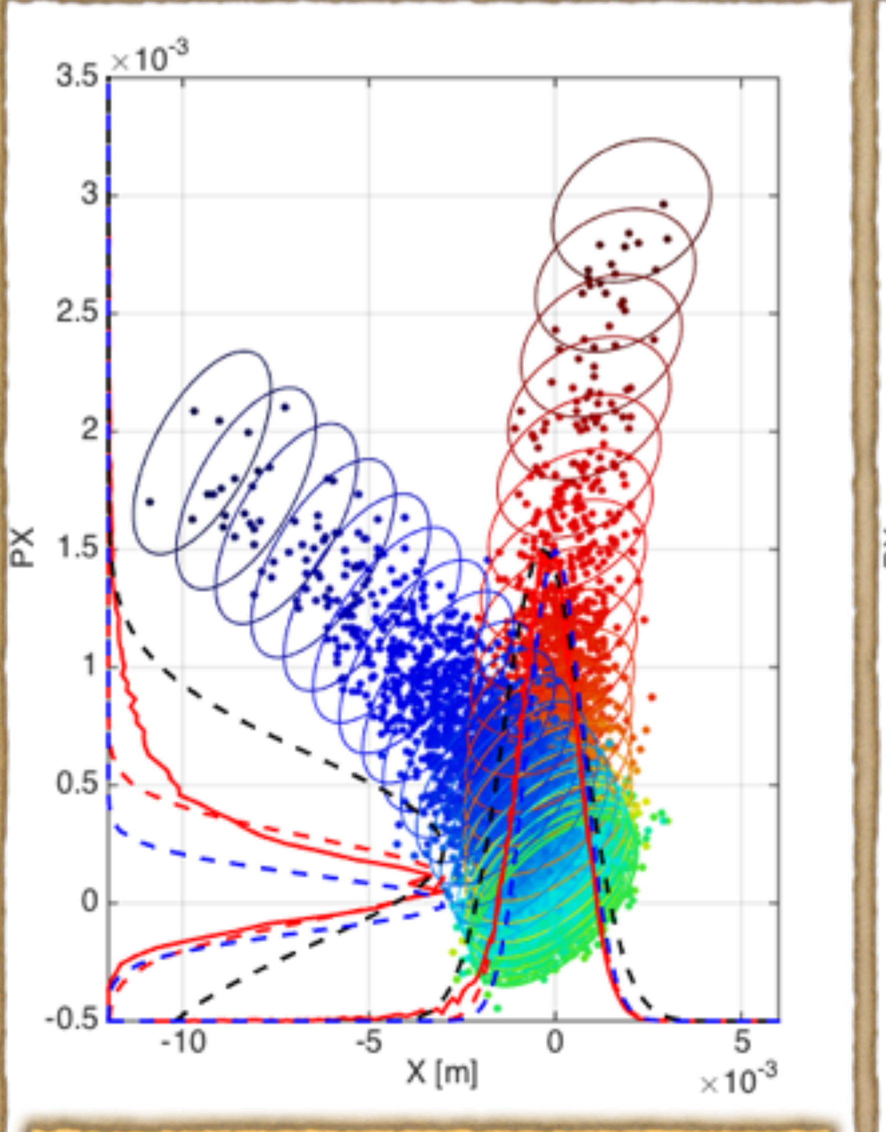
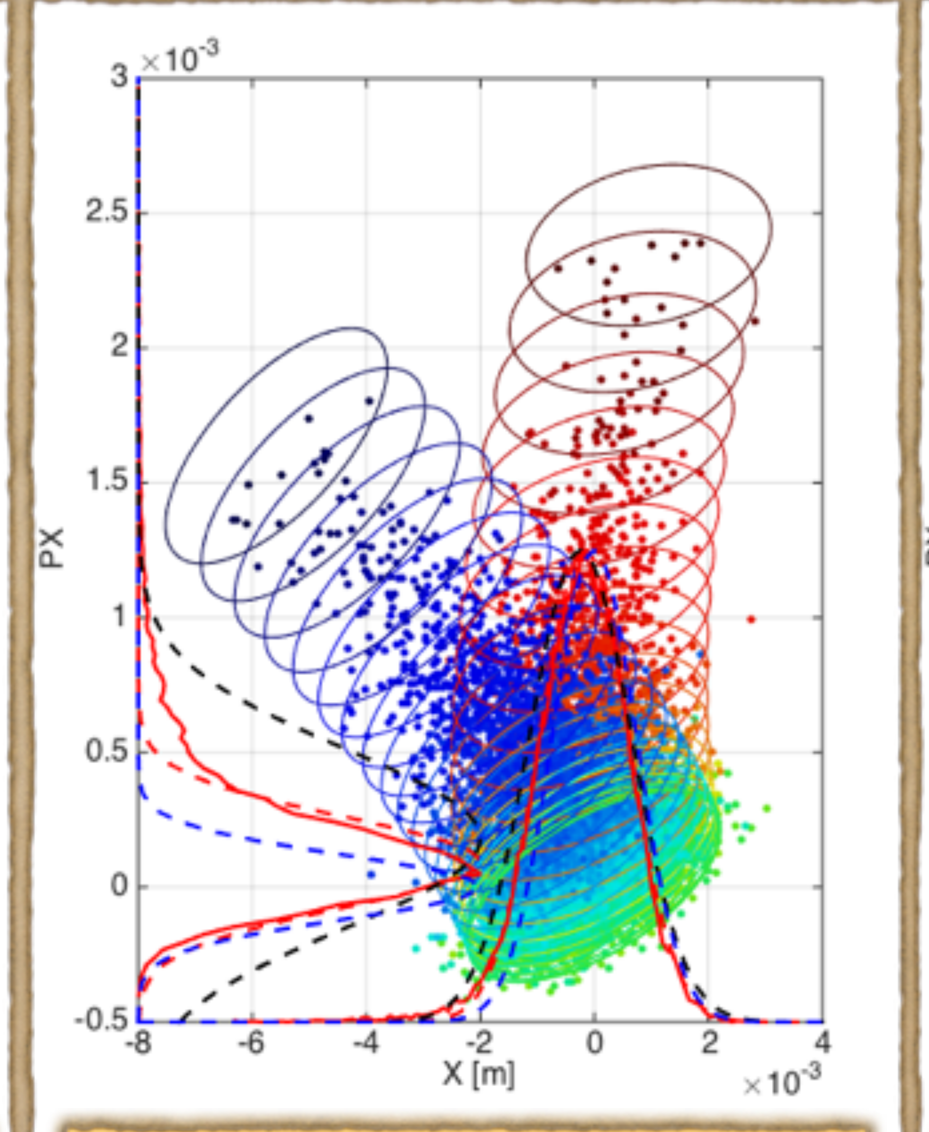
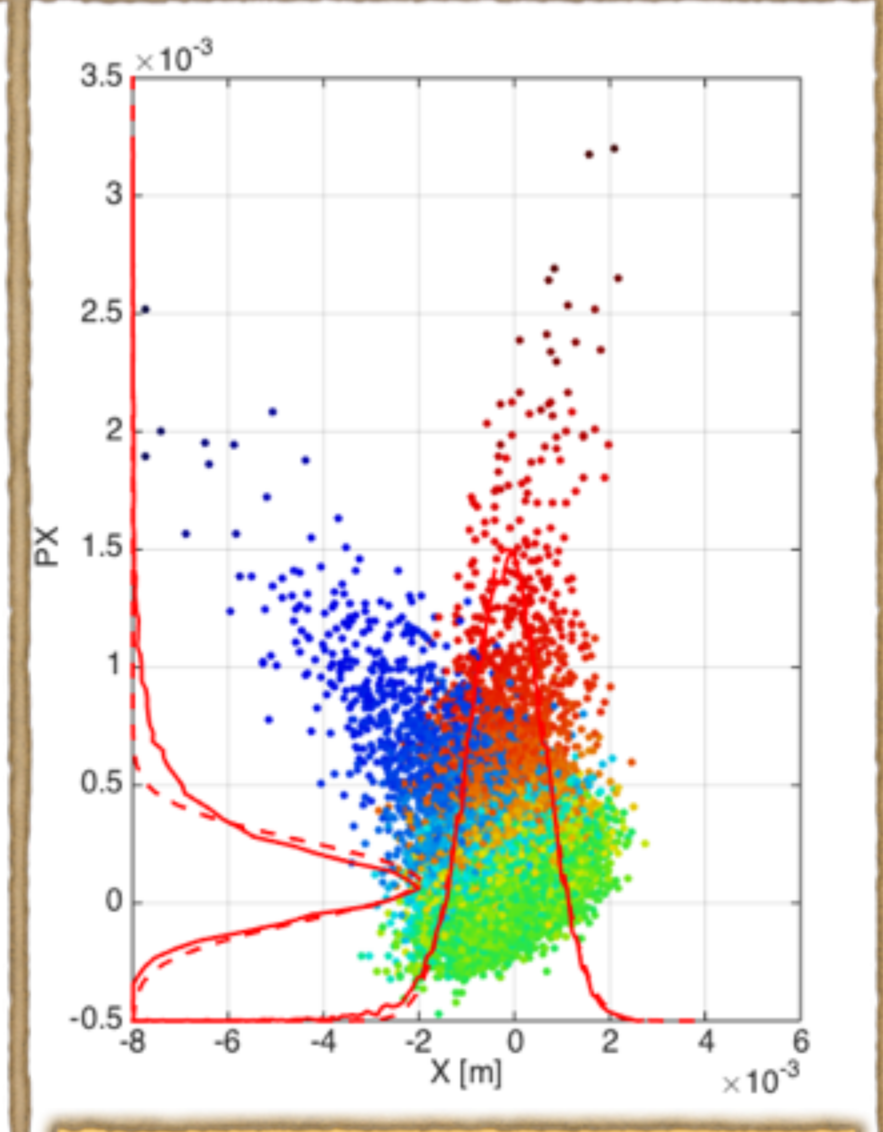
Energy spread simulations: X-PX









MAD-X simulation:

- ε_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:

- ε_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:

- **ε_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**

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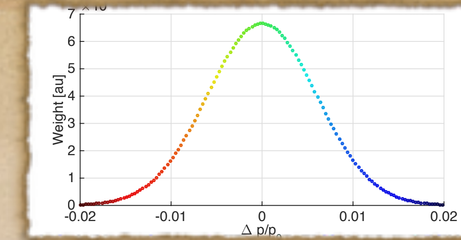
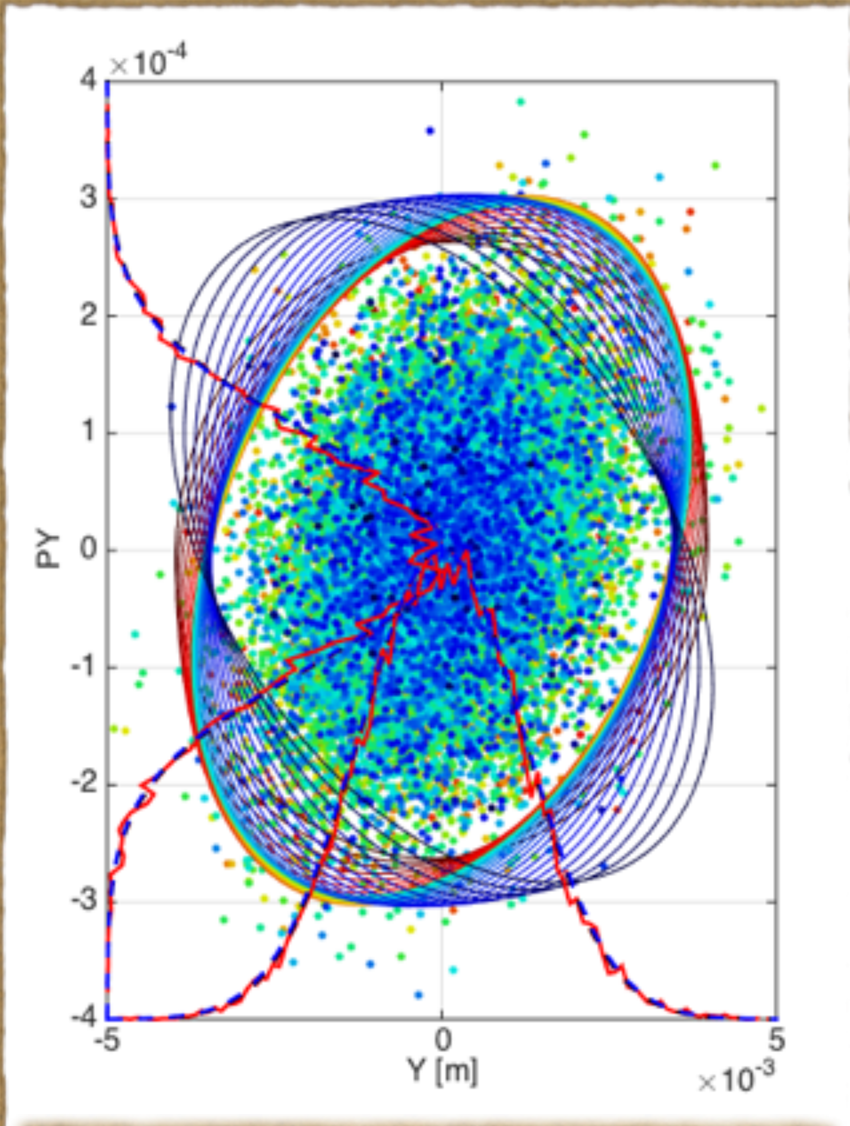
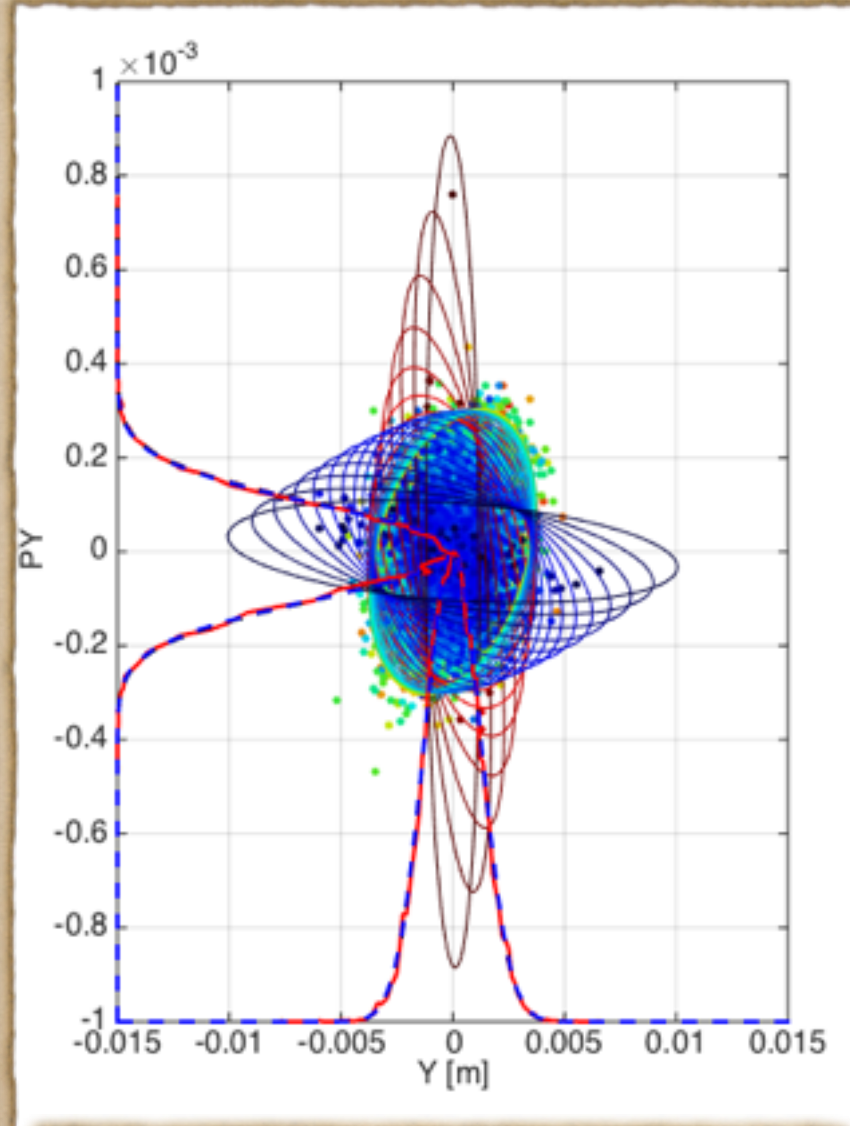
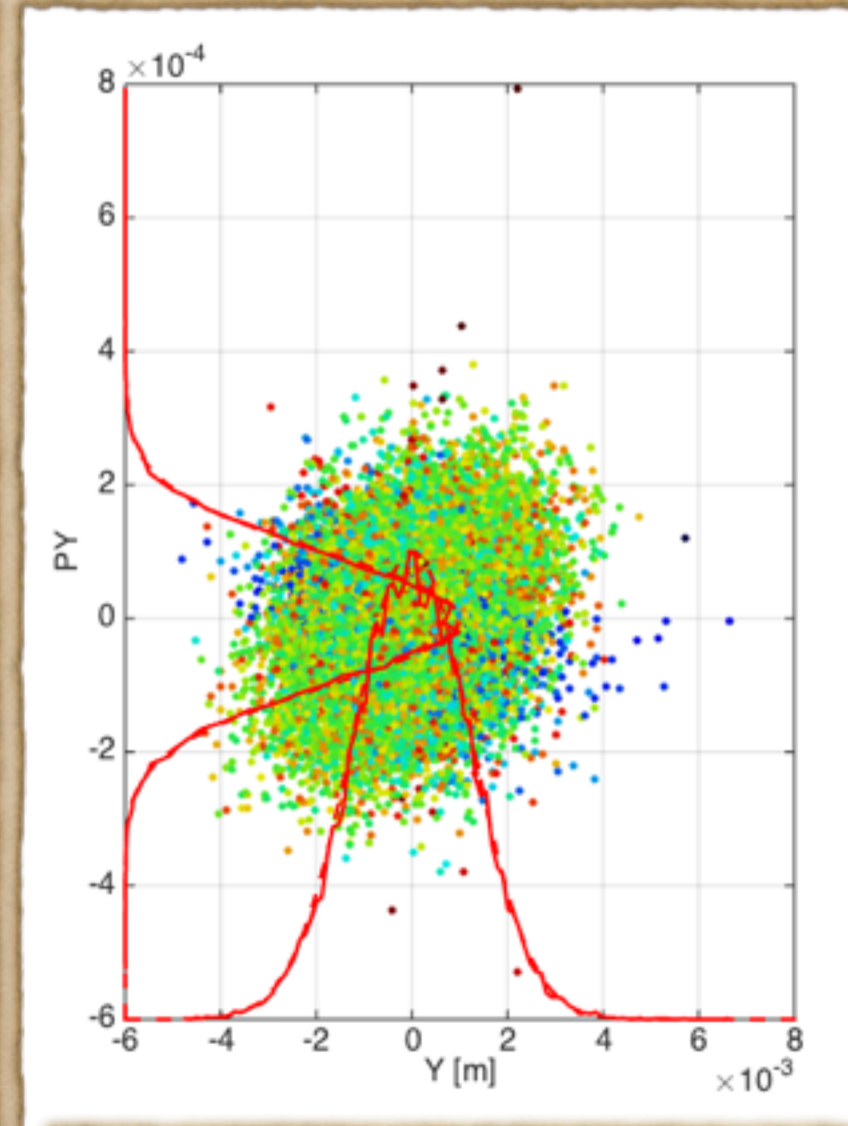
Energy spread simulations: Y-PY









MAD-X simulation:

- ε_y growth = ~ 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:

- ε_y growth = ~ 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:

- ε_y growth = ~ 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

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Implemented tools to diagnose and optimise the beam.
Some experimental results.

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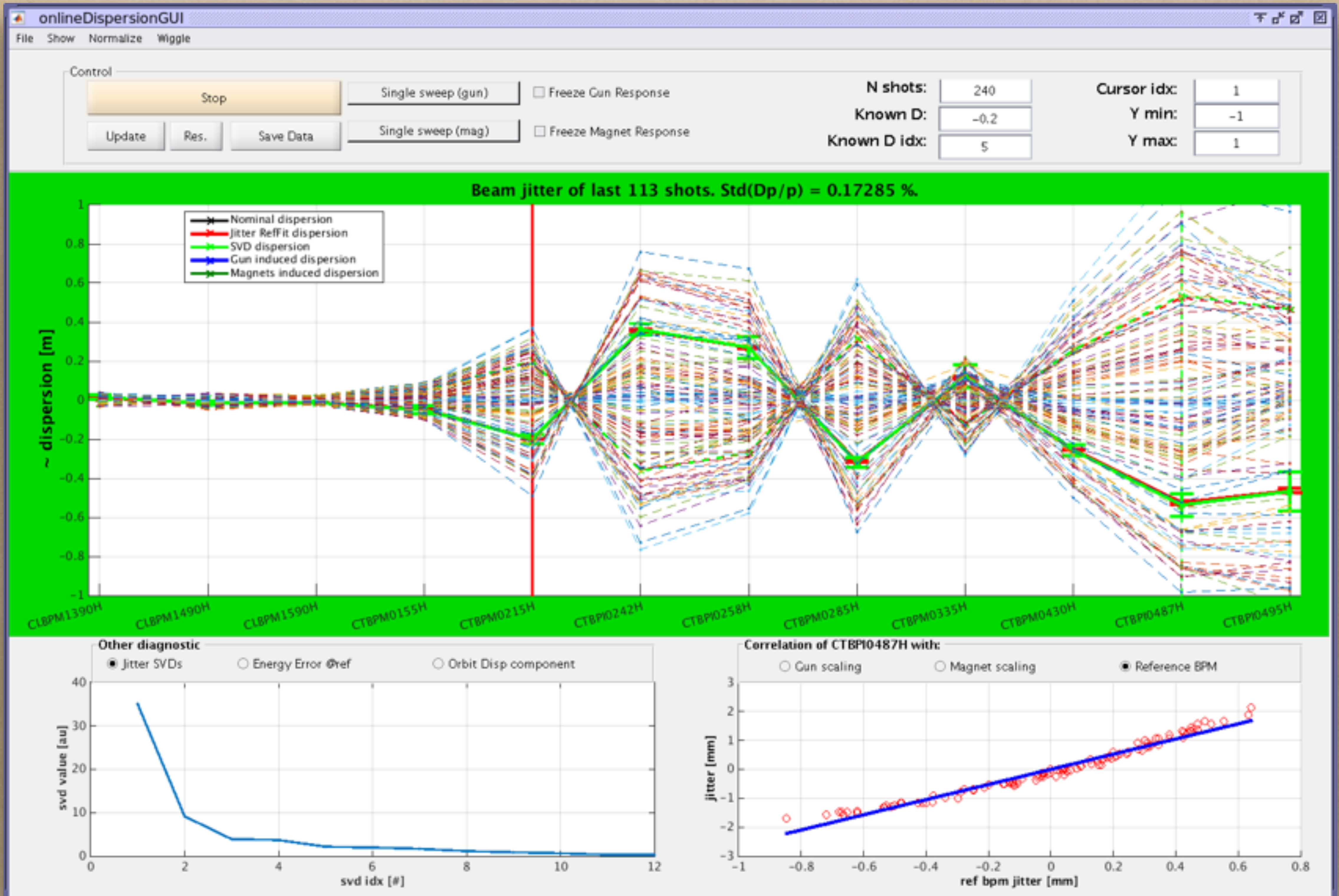
Dispersion measurements



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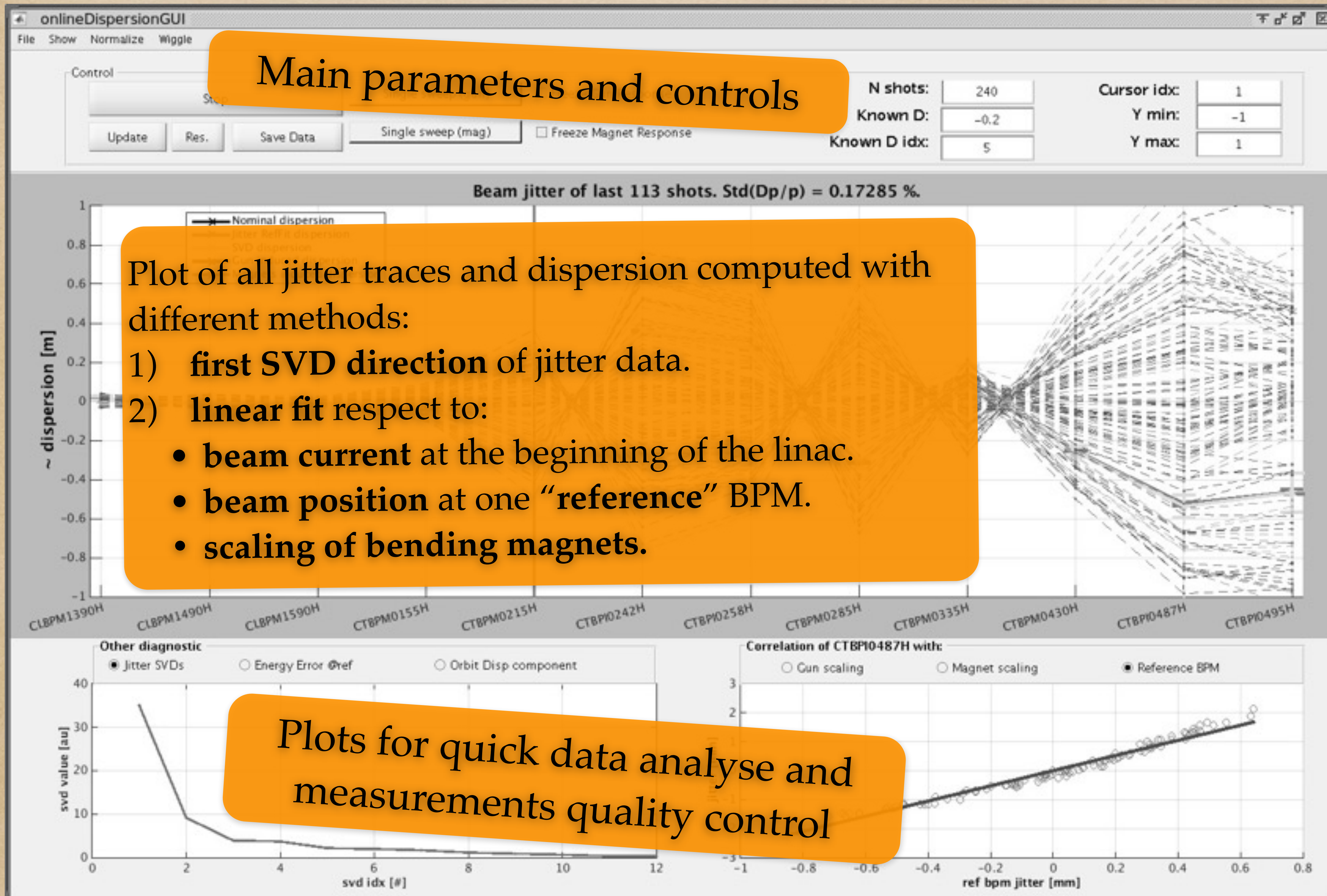
Dispersion measurements



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

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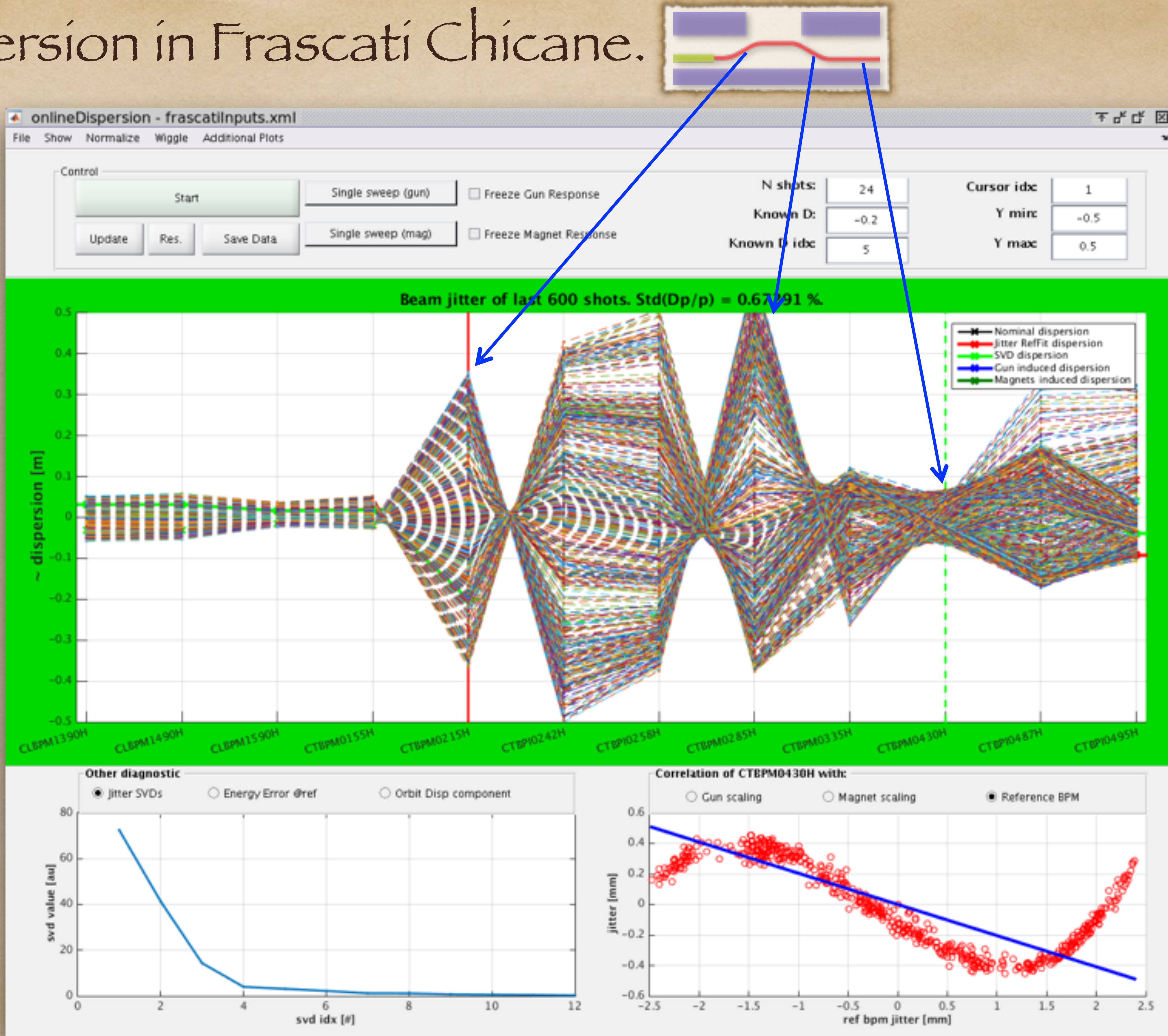
Dispersion in Frascati Chicane.



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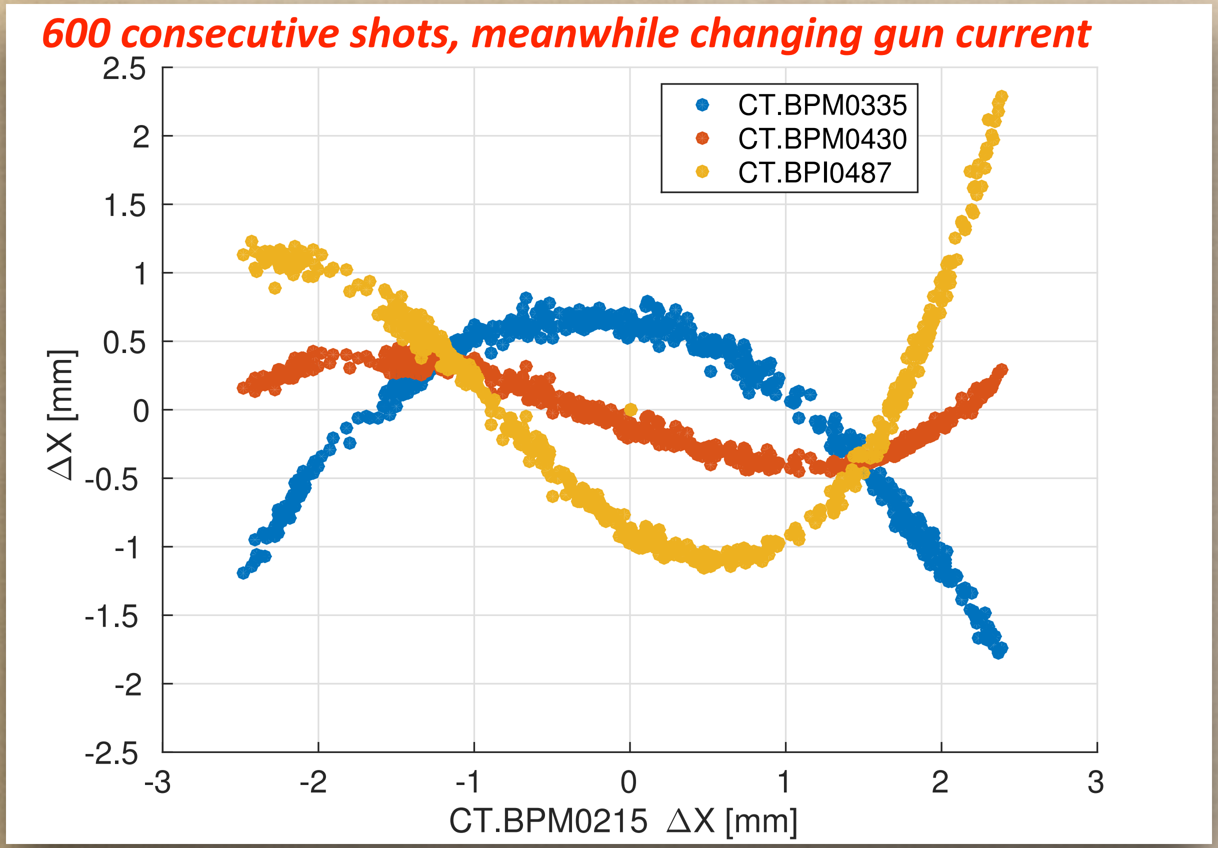
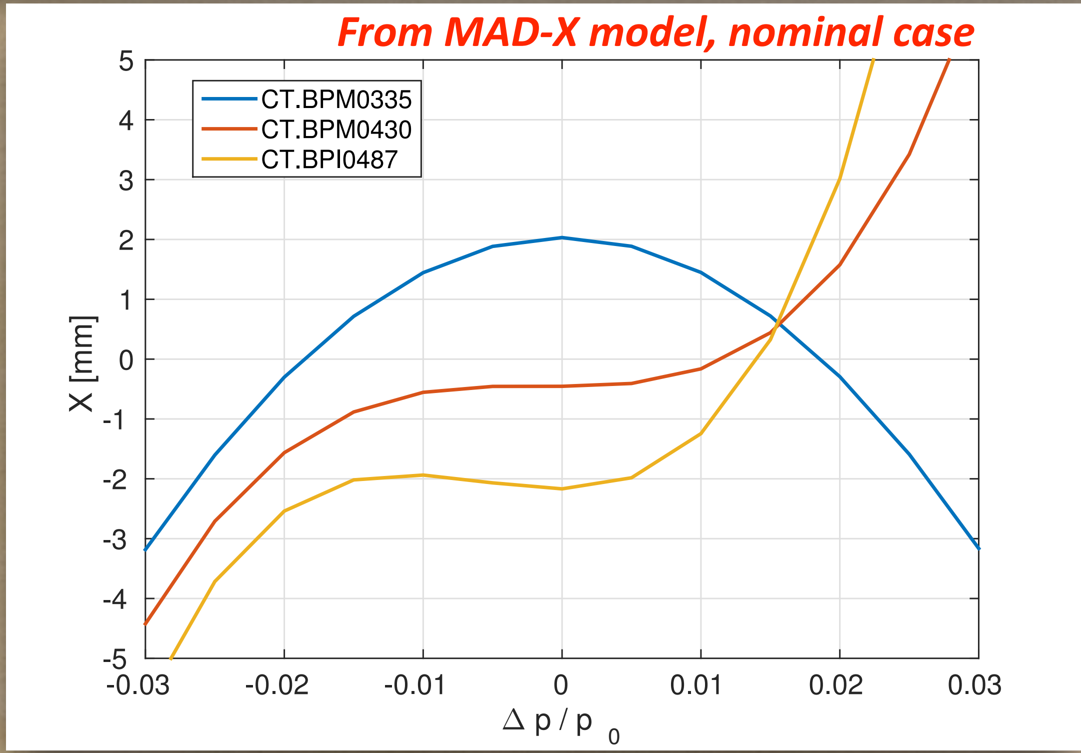
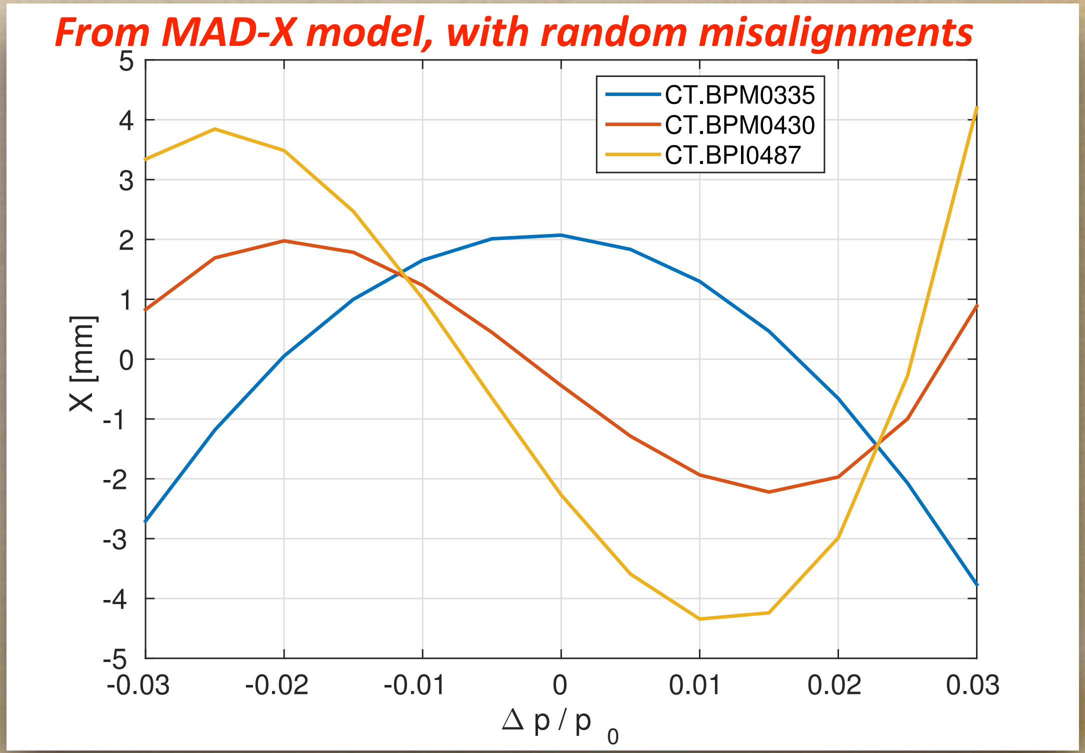
Dispersion in Frascati Chicane: a closer look.



- 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** (σ=0.2 [mm]).





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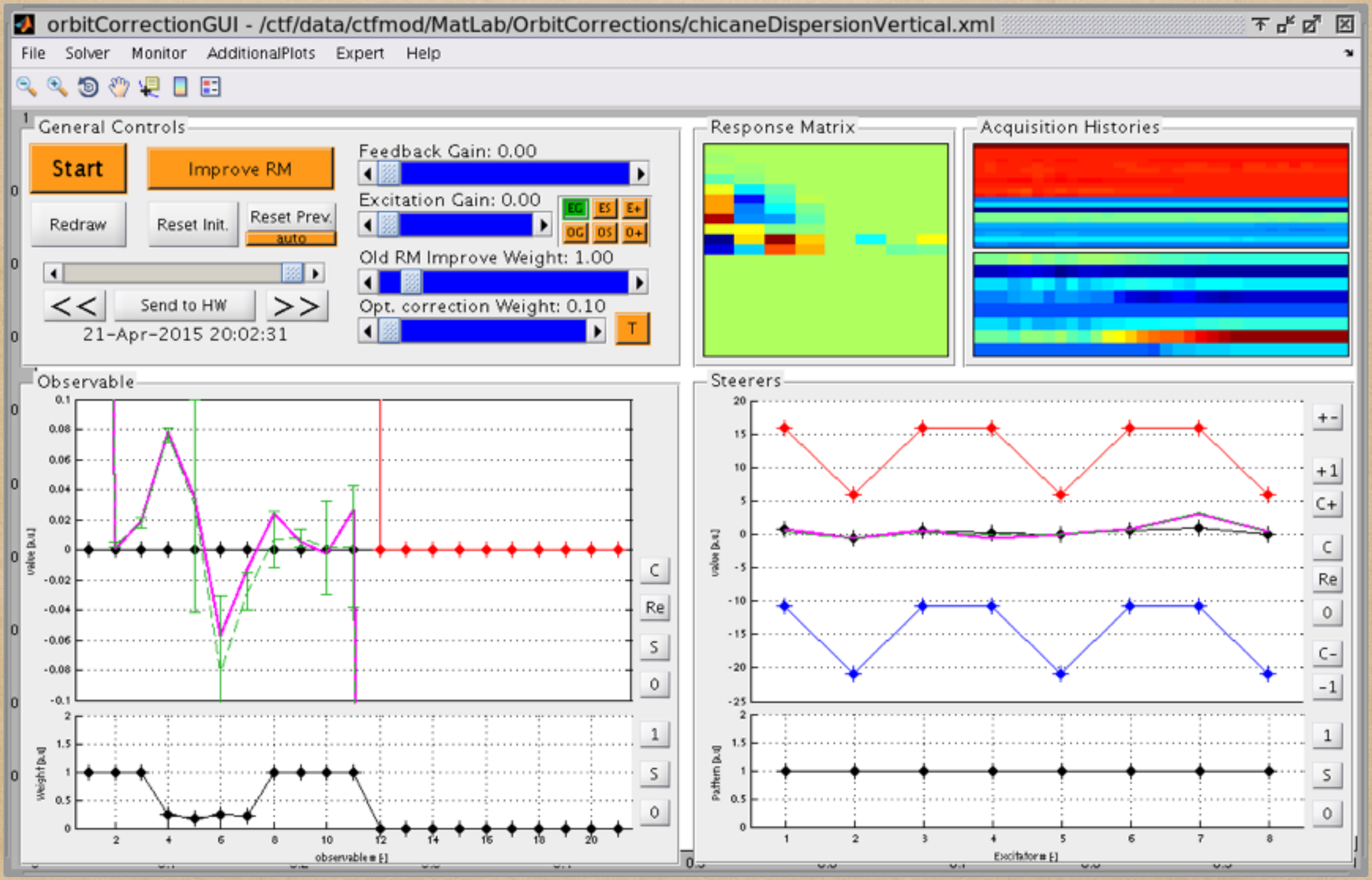
Slow feedback



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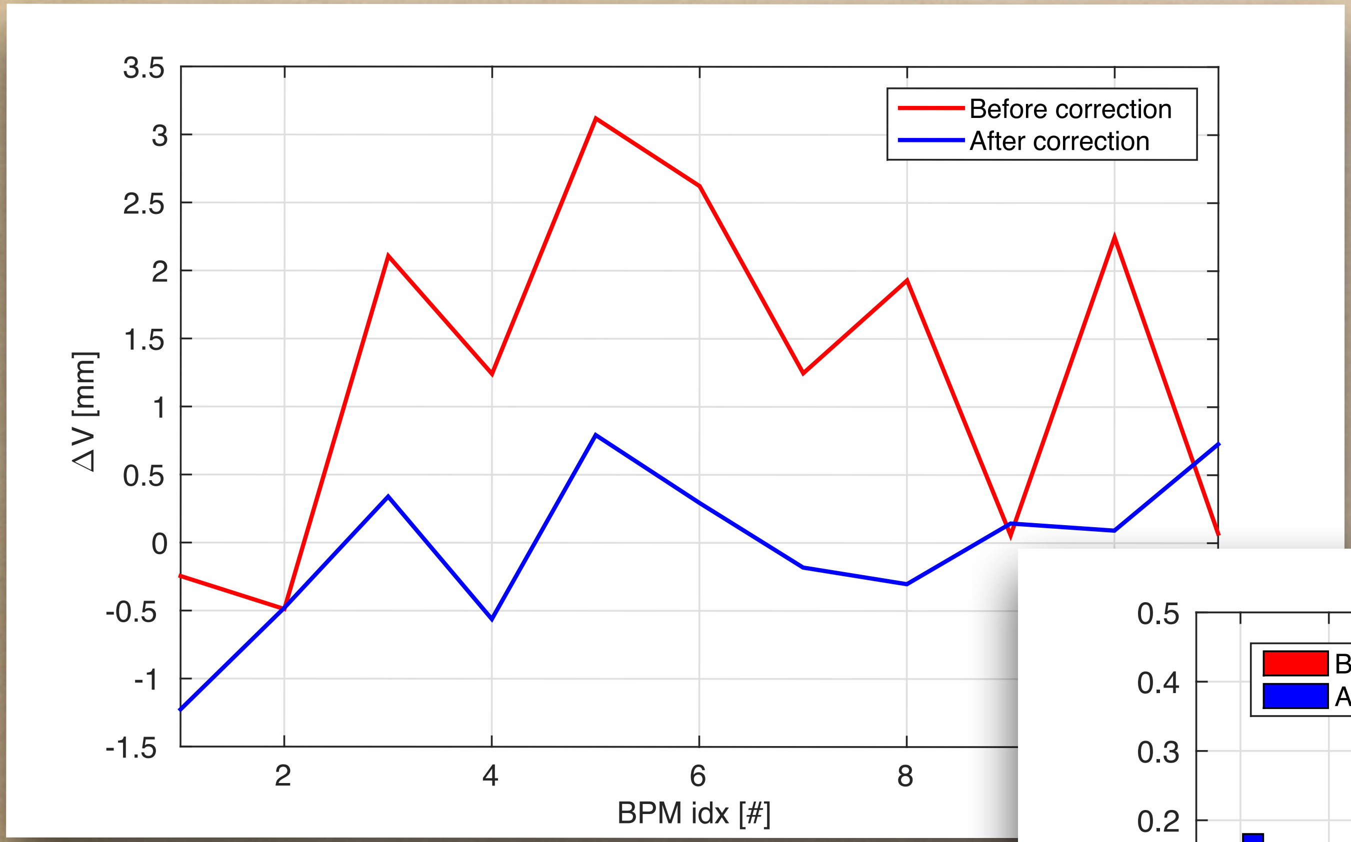
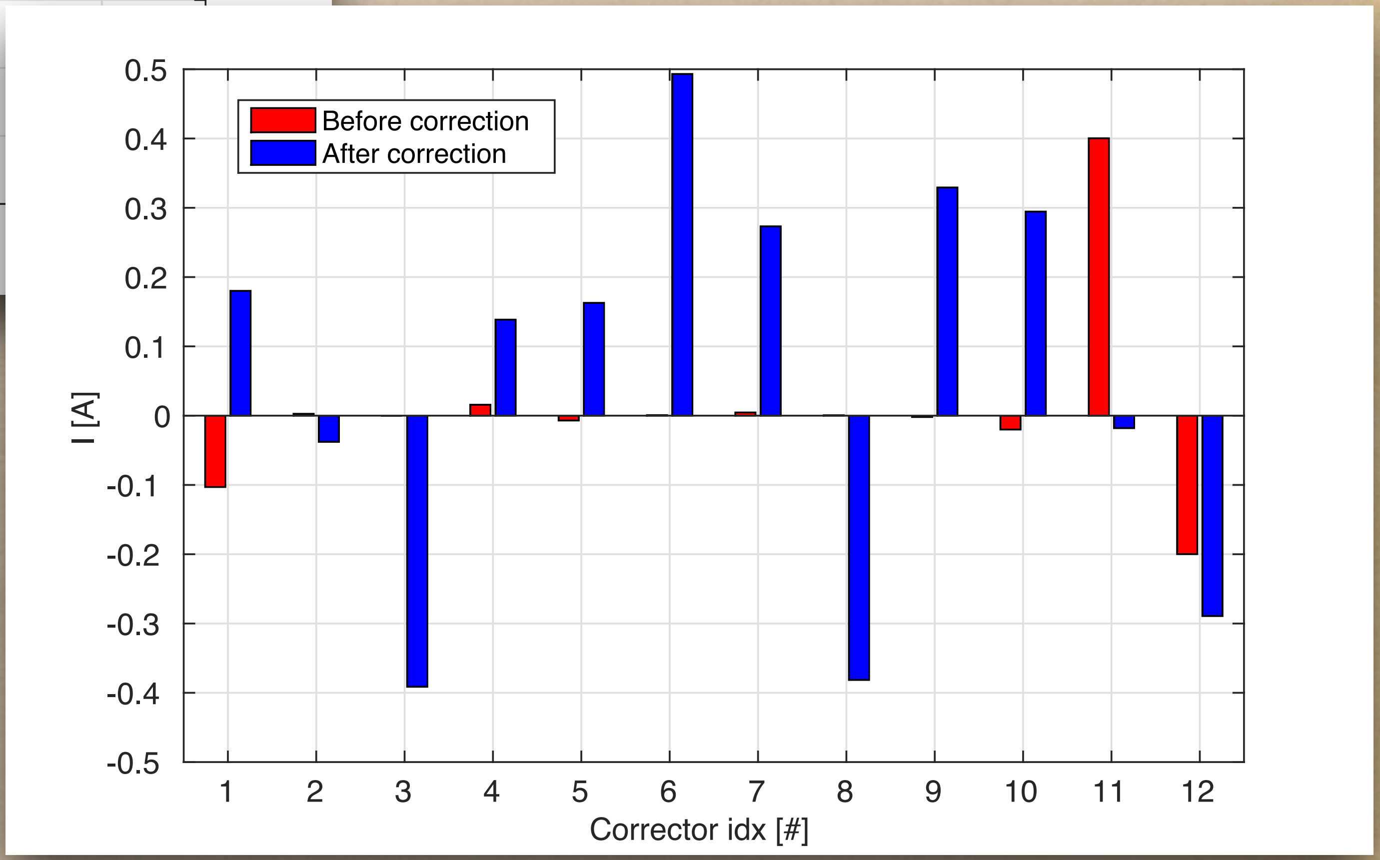
Orbit correction: vertical closure of CR.



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.**

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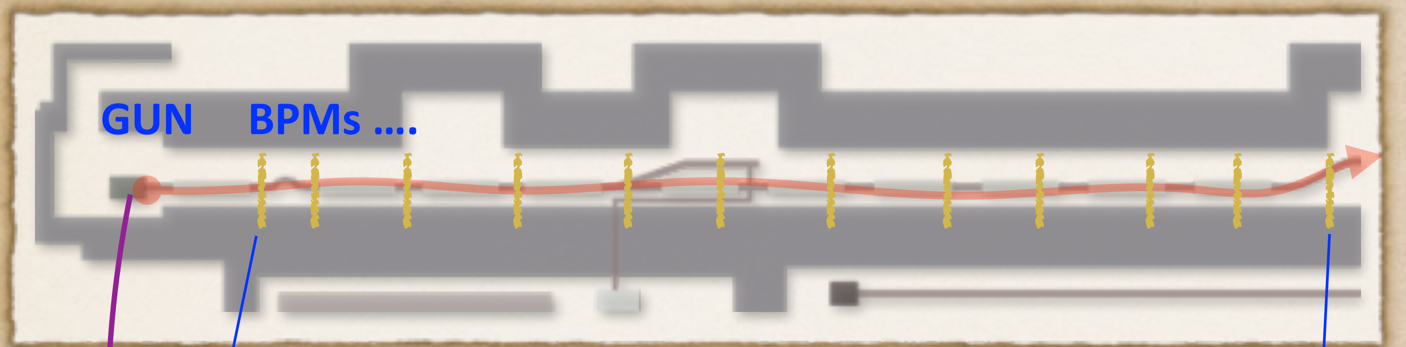
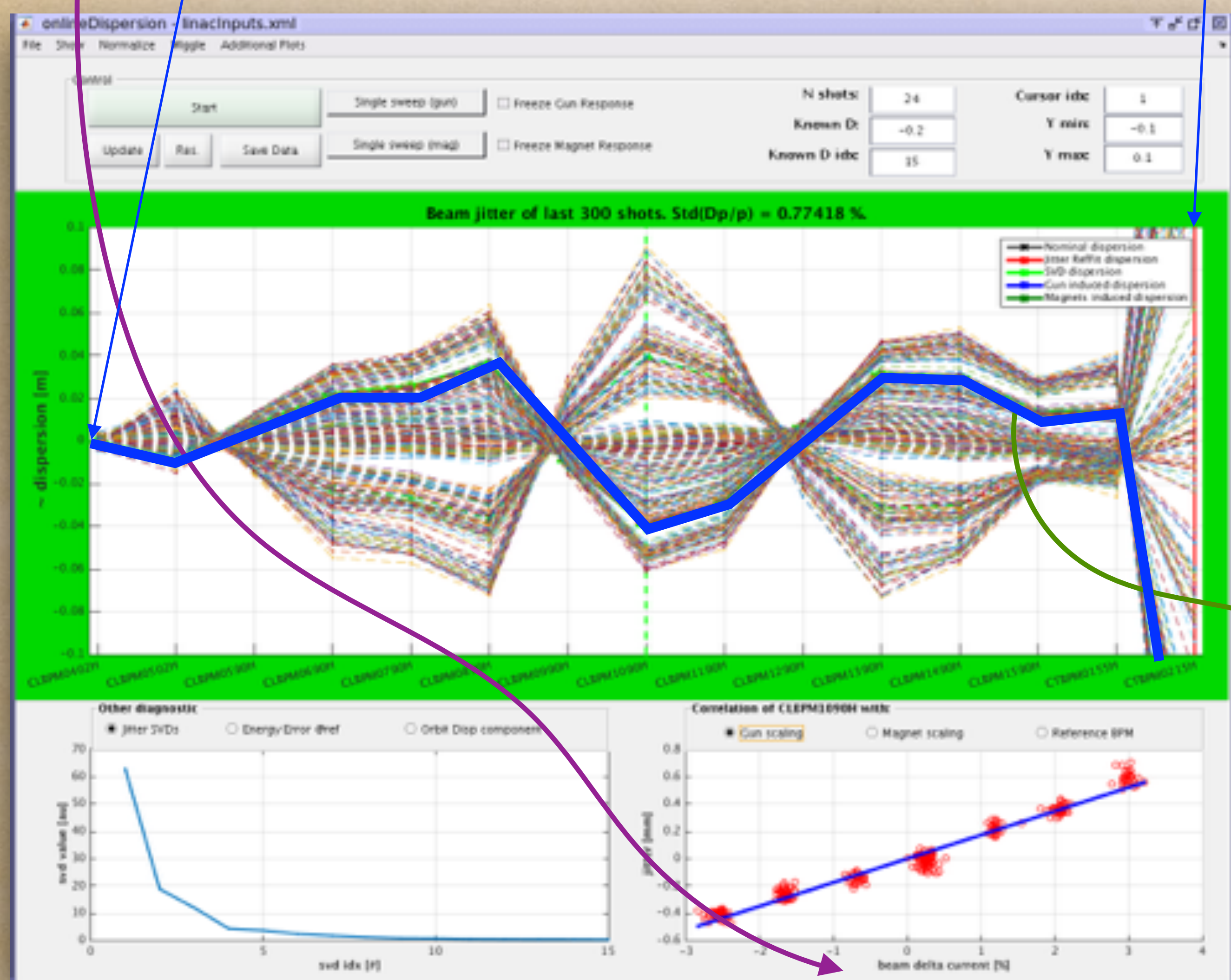
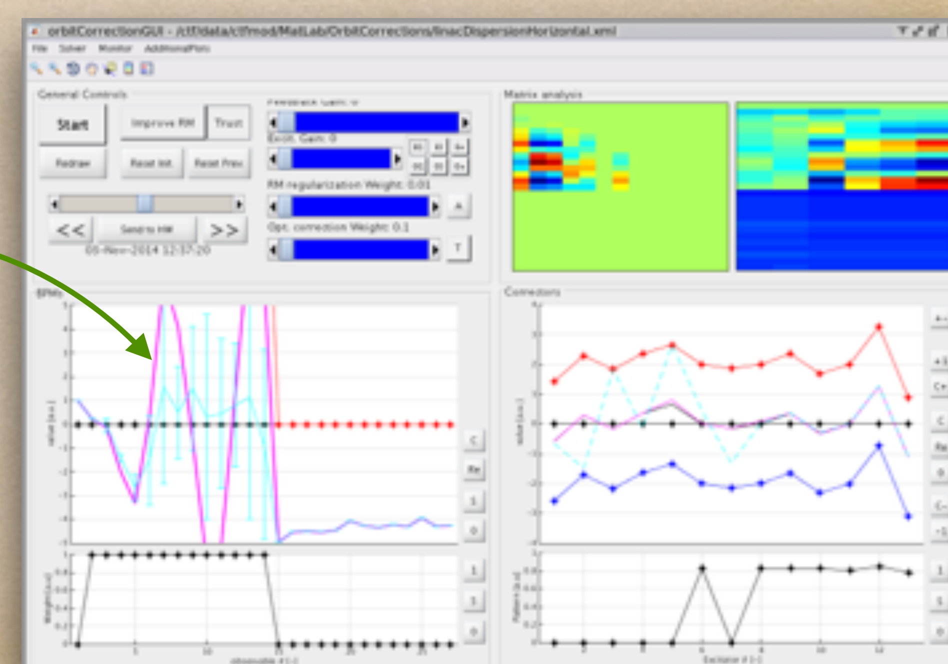
Dispersion free steering in the LINAC





- 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…**



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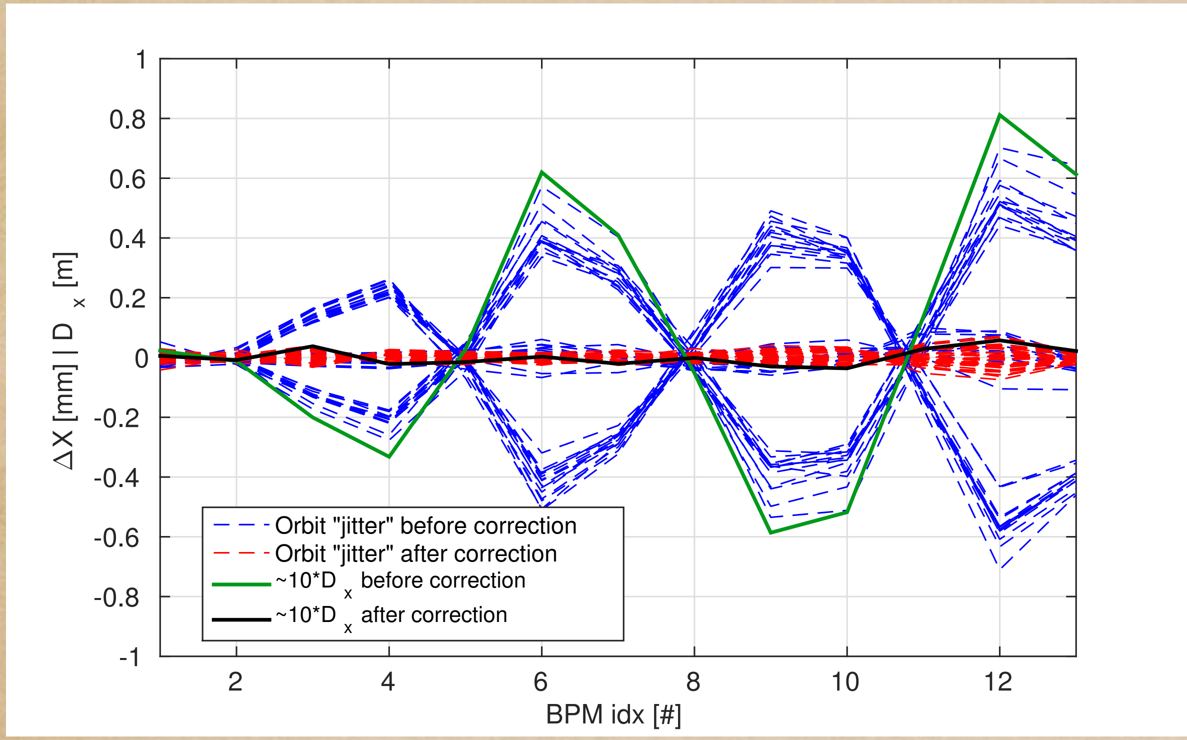
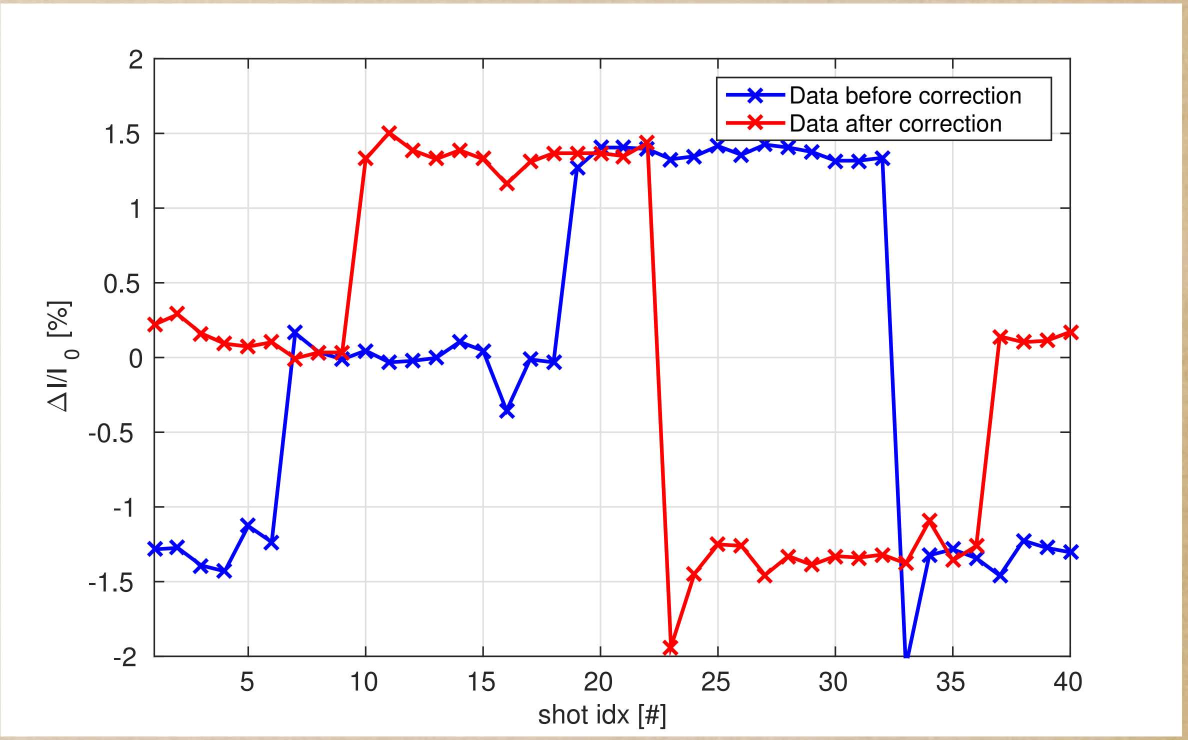
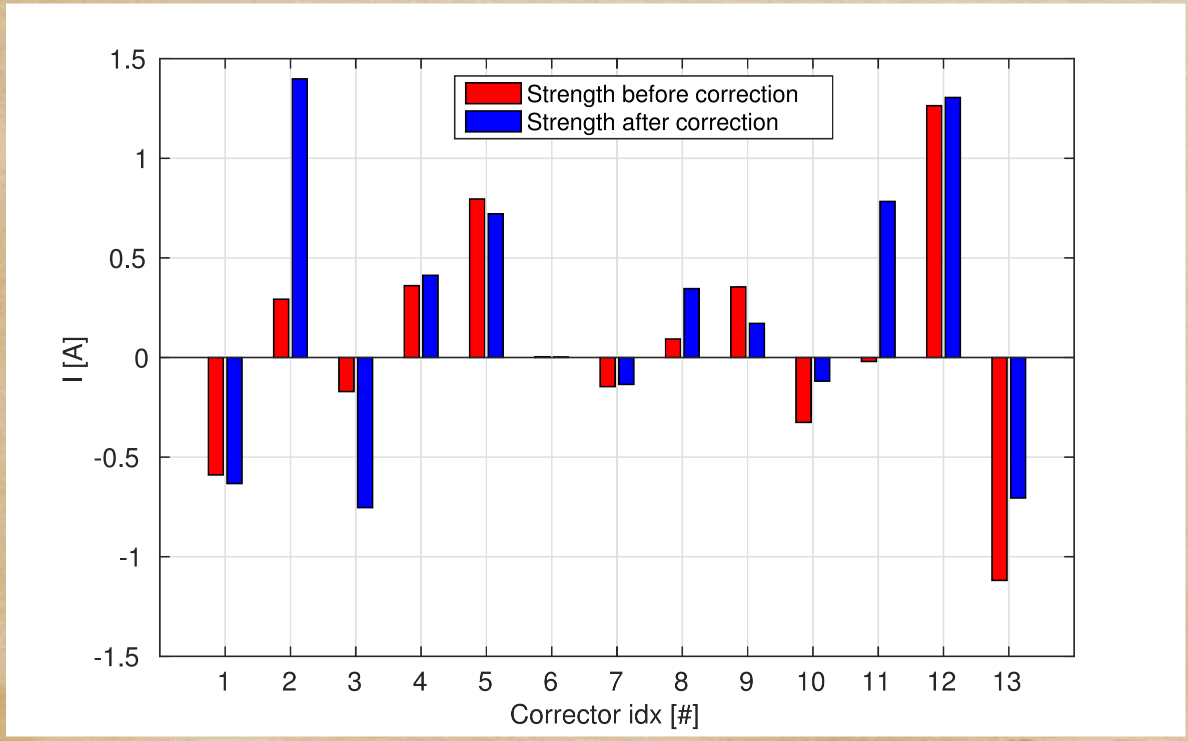
Dispersion free steering in the LINAC

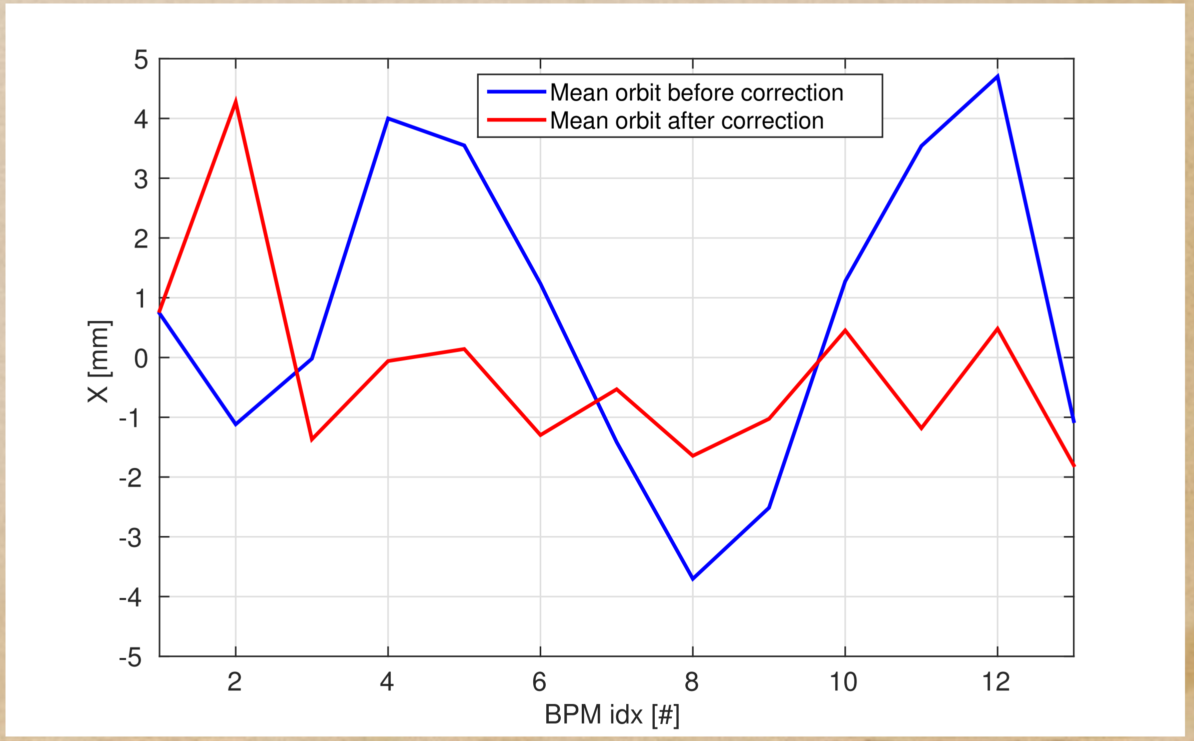
- **Observables: 40 consecutive shots at different GUN current settings (scaling up/down of ~1.5% than nominal).**





- **Main correction is at the beginning of the linac. This reduces not only the dispersion, but also the orbit.**





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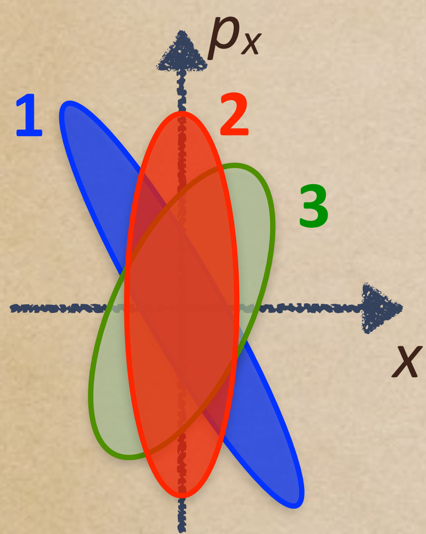
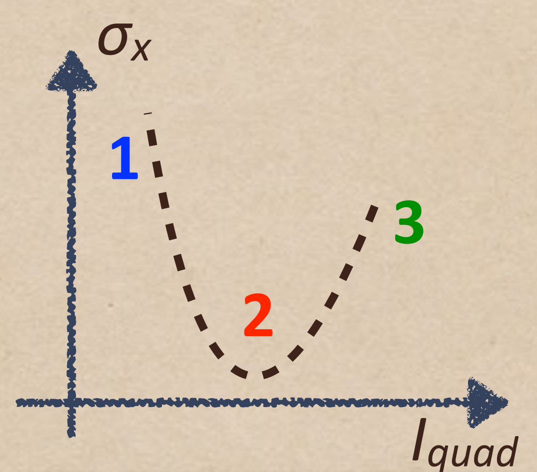
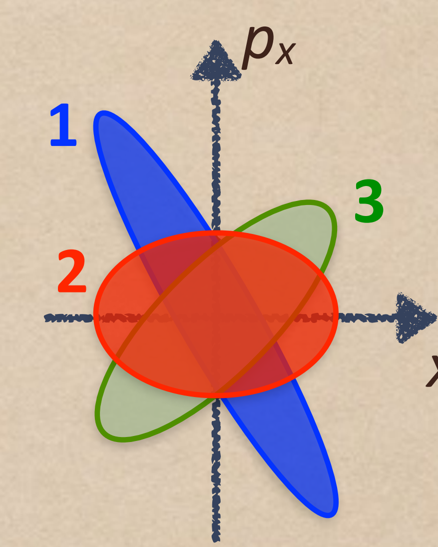
Work in progress: constant beam size Quadscan:

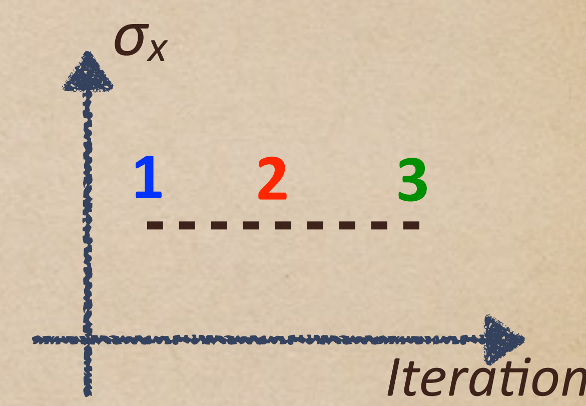
During a quadscan normally one quadrupole strength is varied and the beam size recorded on a screen…
… but one could use two quadrupoles and still “rotate” the beam, but keep the **beam size constant**!





Parabolic behaviour expected



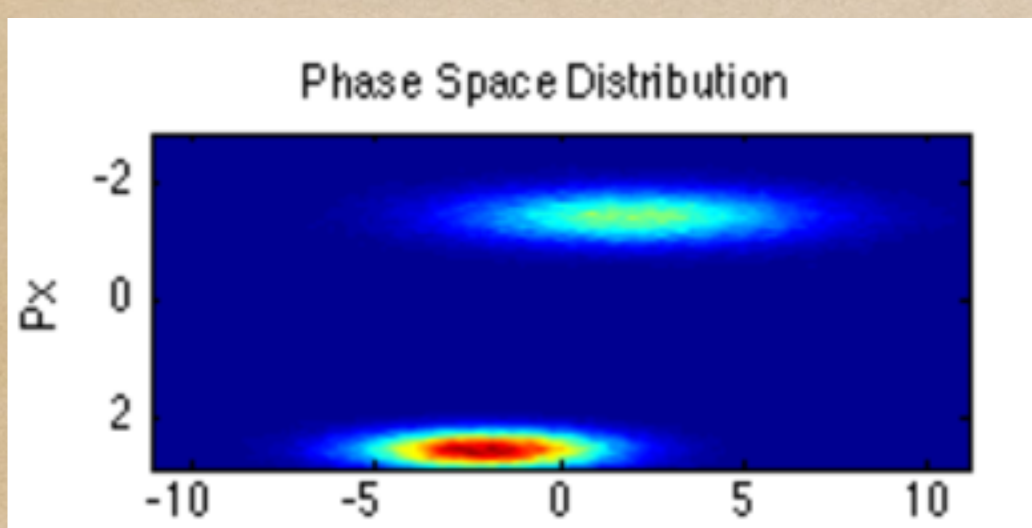


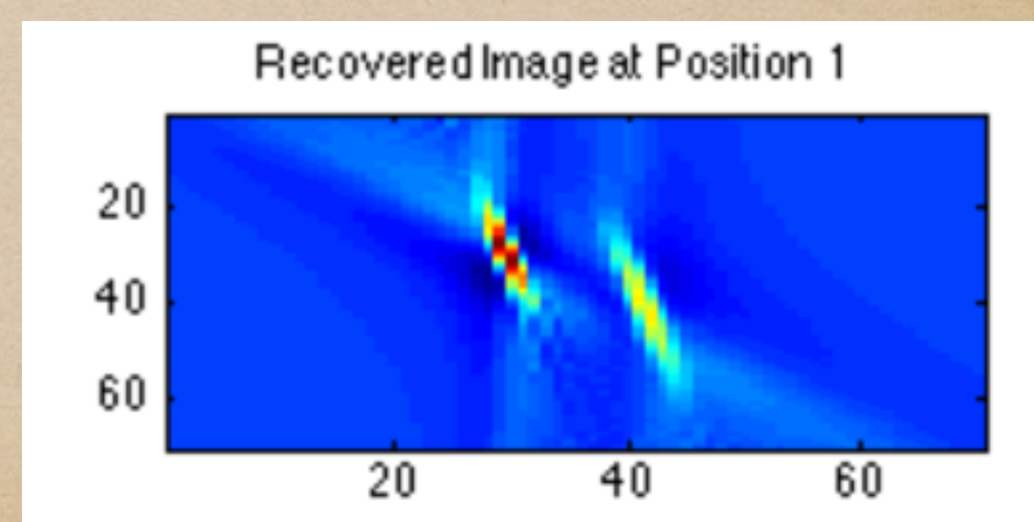
Constant beam size.
No effects from screen resolution.

Work in progress: phase-space tomography

A. Rollings;
L. Martin

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





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Summary

- The CTF3 Drive Beam recombination is affected by **emmitance 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.

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Thank you for your attention

CLIC - A possible Compact Linear Collider

- Some parameters:

Center of mass energy	E_{cm}	3000	GeV
Main Linac RF Frequency	f_{RF}	11.994	GHz
Luminosity	L	5.9×10^{34}	cm-2 s-1
Linac repetition rate	f_{rep}	50	Hz
No. of particles / bunch	N_b	3.72×10^9	
No. of bunches / pulse	k_b	312	
Bunch separation	Δt_b	0.5 (6 periods)	ns
Bunch train length	τ_{train}	156	ns
Beam power / beam	P_b	14	MW
Unloaded / loaded gradient	$G_{unl/l}$	**120 / 100**	**MV/m**
Overall two linac length	L_{linac}	42.16	km
Total site AC power	P_{tot}	415	MW
Length of PETS	L_{PETS}	0.213	m
Nominal output RF Power / PETS	P_{out}	136	MW
Wall plug -> RF efficiency	η_{ACRF}	58.6	%
RF -> drive beam efficiency	η_{bRF}	93	%
drive beam -> RF efficiency (HDS input)	η_{decRF}	65	%
RF -> main beam efficiency	η_{bRF}	27.7	%
Wall plug to main beam power efficiency	η_{tot}	7	%

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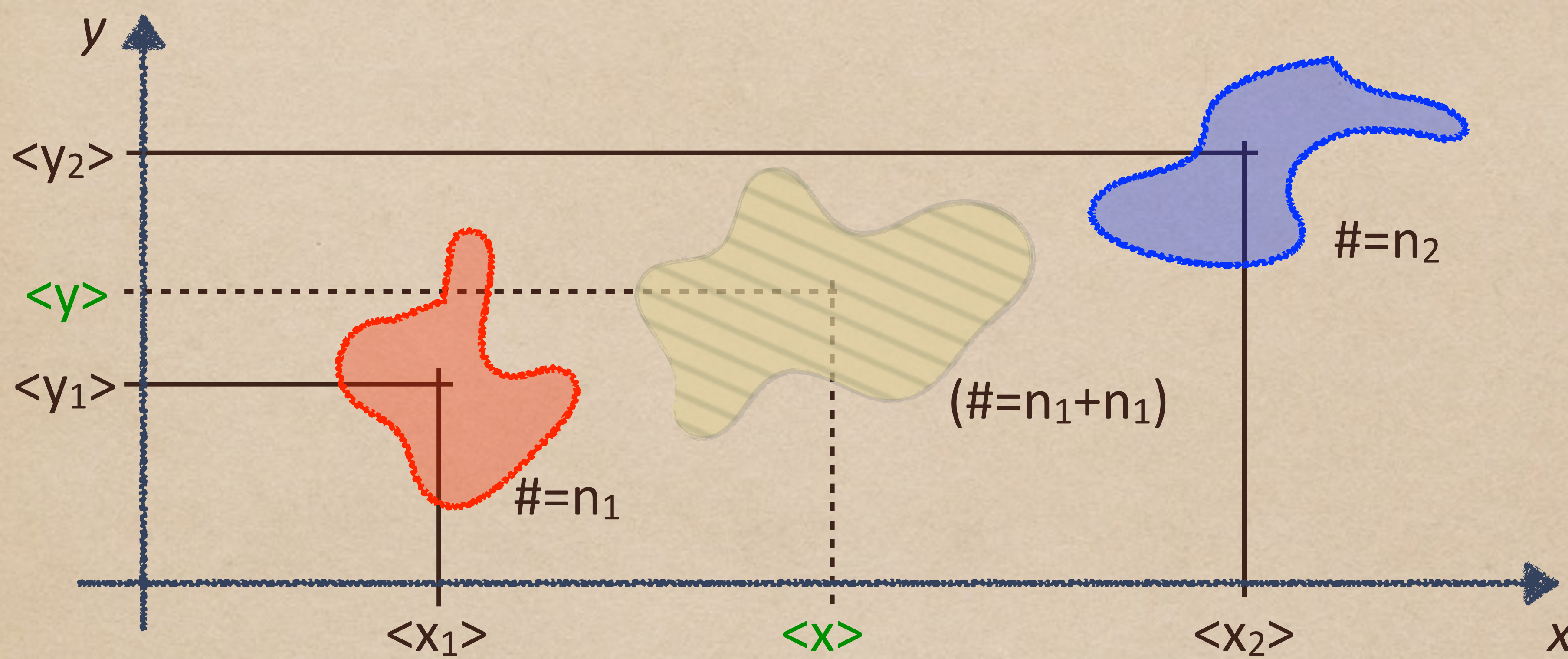
Simulation method: few details.

- Combine covariance matrices at one location:



$$\Sigma_1 = \begin{bmatrix} \sigma(\mathbf{x_1},\mathbf{x_1}) & \sigma(\mathbf{x_1},\mathbf{y_1}) \\ \sigma(\mathbf{y_1},\mathbf{x_1}) & \sigma(\mathbf{y_1},\mathbf{y_1}) \end{bmatrix}$$

$$\Sigma_2 = \begin{bmatrix} \sigma(\mathbf{x_2},\mathbf{x_2}) & \sigma(\mathbf{x_2},\mathbf{y_2}) \\ \sigma(\mathbf{y_2},\mathbf{x_2}) & \sigma(\mathbf{y_2},\mathbf{y_2}) \end{bmatrix}$$

$$\sigma(\mathbf{x_1},\mathbf{y_1}) = \langle \mathbf{x_1 y_1} \rangle - \langle \mathbf{x_1} \rangle \langle \mathbf{y_1} \rangle$$

$$\sigma(\mathbf{x_2},\mathbf{y_2}) = \langle \mathbf{x_2 y_2} \rangle - \langle \mathbf{x_2} \rangle \langle \mathbf{y_2} \rangle$$

$$\sigma(\mathbf{x},\mathbf{y}) = \langle \mathbf{xy} \rangle - \langle \mathbf{x} \rangle \langle \mathbf{y} \rangle$$

$$\langle \mathbf{x} \rangle = \frac{n_1 \langle \mathbf{x_1} \rangle + n_2 \langle \mathbf{x_2} \rangle}{n_1 + n_2}$$

$$\langle \mathbf{y} \rangle = \frac{n_1 \langle \mathbf{y_1} \rangle + n_2 \langle \mathbf{y_2} \rangle}{n_1 + n_2}$$

$$\langle \mathbf{xy} \rangle = \frac{n_1 \left(\sigma(\mathbf{x_1},\mathbf{y_1}) + \langle \mathbf{x_1} \rangle \langle \mathbf{y_1} \rangle\right) + n_2 \left(\sigma(\mathbf{x_2},\mathbf{y_2}) + \langle \mathbf{x_2} \rangle \langle \mathbf{y_2} \rangle\right)}{n_1 + n_2}$$

$$\Sigma = \begin{bmatrix} \sigma(\mathbf{x},\mathbf{x}) & \sigma(\mathbf{x},\mathbf{y}) \\ \sigma(\mathbf{y},\mathbf{x}) & \sigma(\mathbf{y},\mathbf{y}) \end{bmatrix}$$

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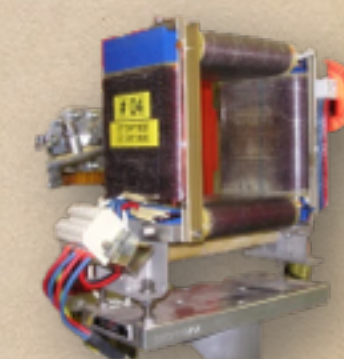
Feedback tool: what is behind

Wanted orbit

Classic response matrix

Correctors settings

$$\begin{pmatrix} \begin{pmatrix} b_1\\ b_2\\ \vdots\\ b_n\end{pmatrix} \\ \lambda \begin{pmatrix} t_1\\ t_2\\ \vdots\\ t_m\end{pmatrix}\end{pmatrix} = \begin{bmatrix} \begin{bmatrix} R_{1,1} & R_{1,2} & \dots & R_{1,m}\\ R_{2,1} & R_{2,2} & \dots & R_{2,m}\\ \vdots & \vdots & \dots & \vdots\\ R_{n,1} & R_{n,2} & \dots & R_{n,m}\end{bmatrix} \\ \lambda \begin{bmatrix} 1 & 0 & \dots & 0\\ 0 & 1 & \dots & 0\\ \vdots & \vdots & \dots & \vdots\\ 0 & 0 & \dots & 1\end{bmatrix}\end{bmatrix} \begin{pmatrix} c_1\\ c_2\\ \vdots\\ a_m\end{pmatrix}$$



Weighted Target correction

Weighted Identity matrix

- If **λ = 0**, we are back in the classical situation.
- If **λ != 0**, then the full Response Matrix is **always over-constrained**.
  - Solution cannot explode.
- If **λ >> 0**, then the classic response matrix is just “noise”. Solution will be identical to the target correction required.

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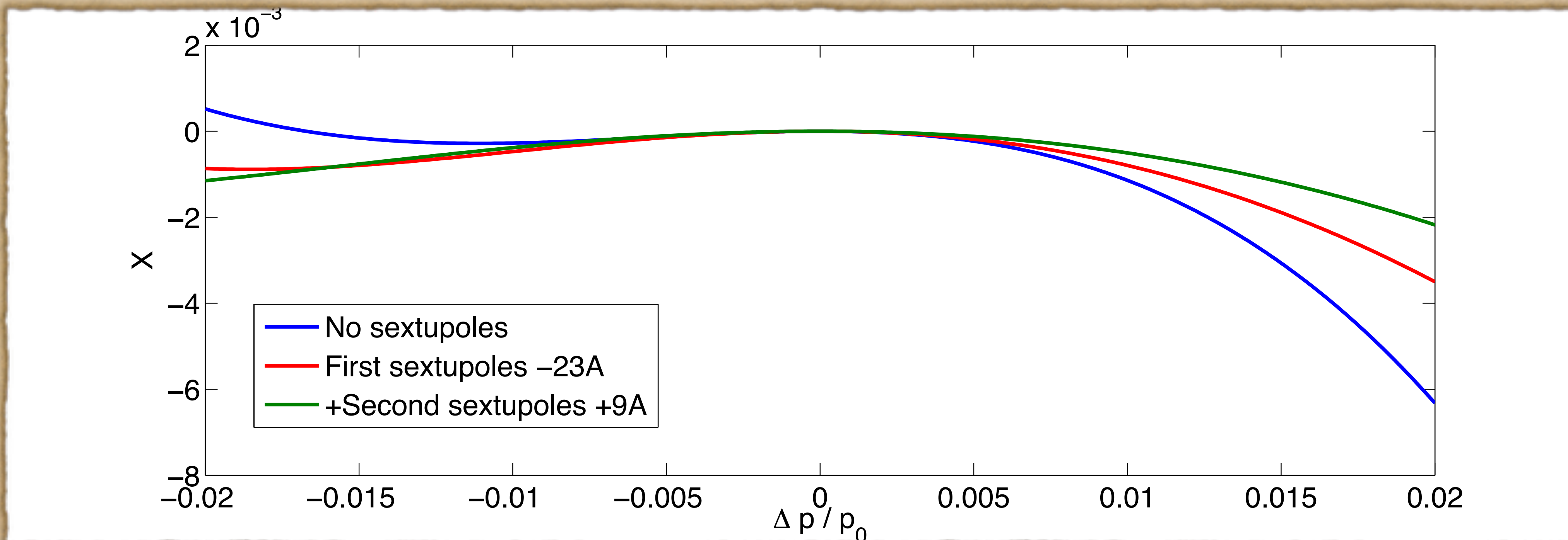
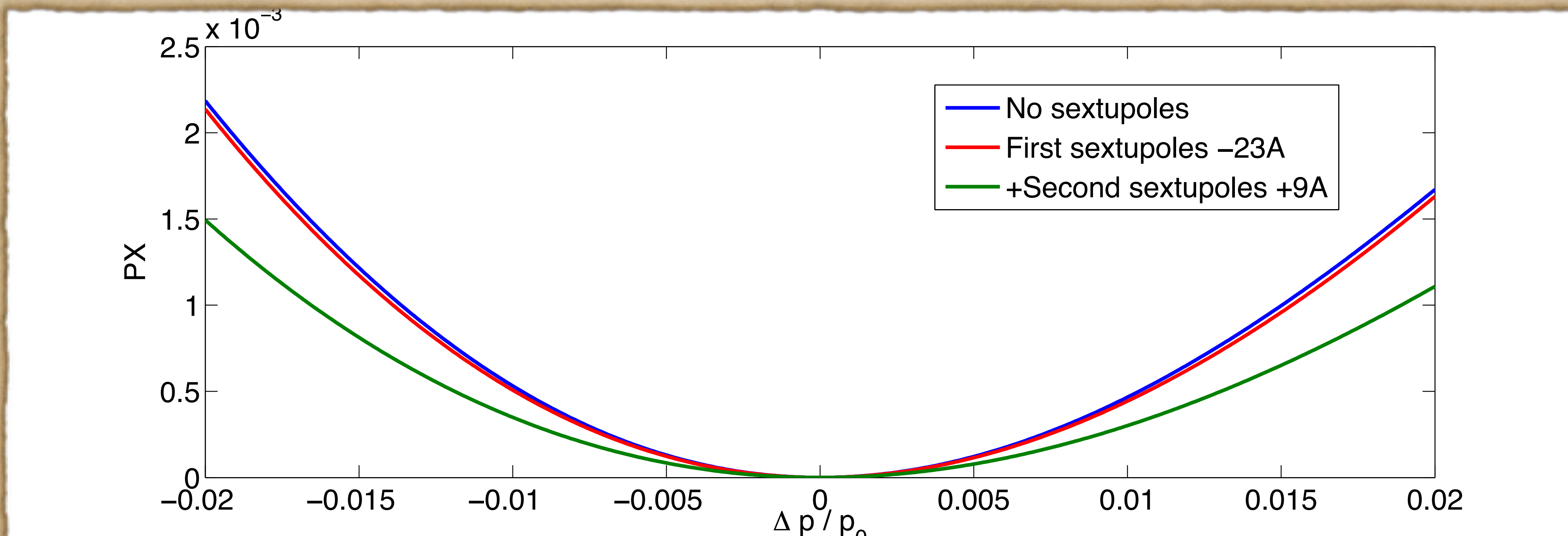
Experimental test: sextupolar dispersion correction

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





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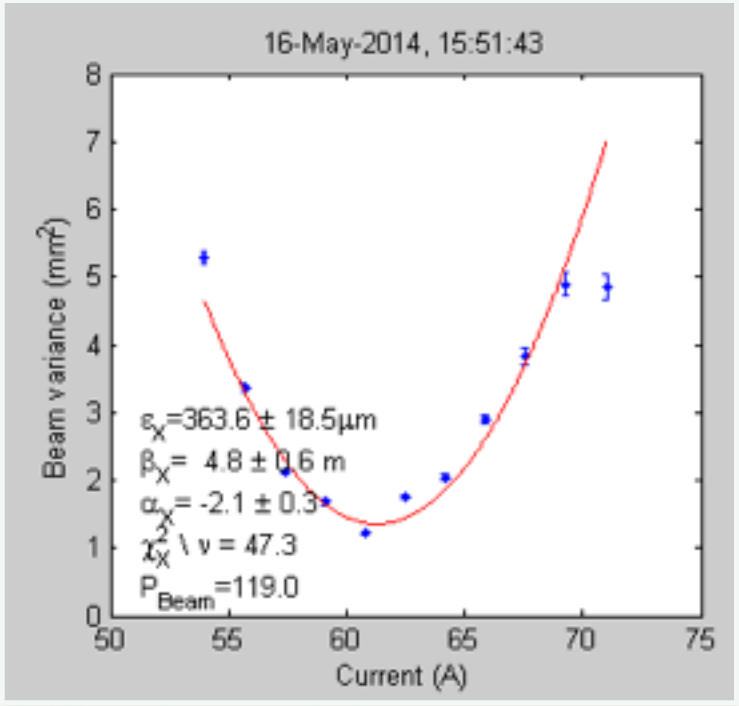
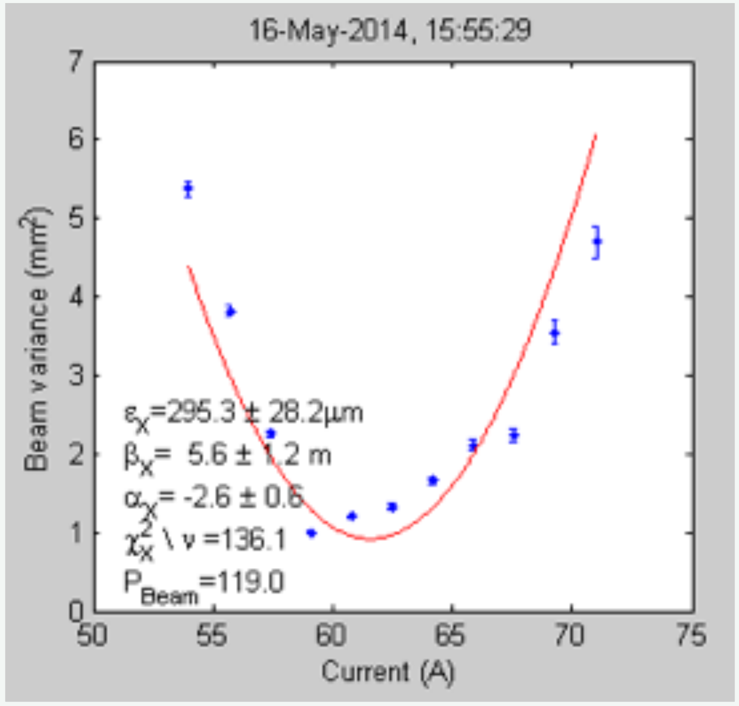
Experimental results

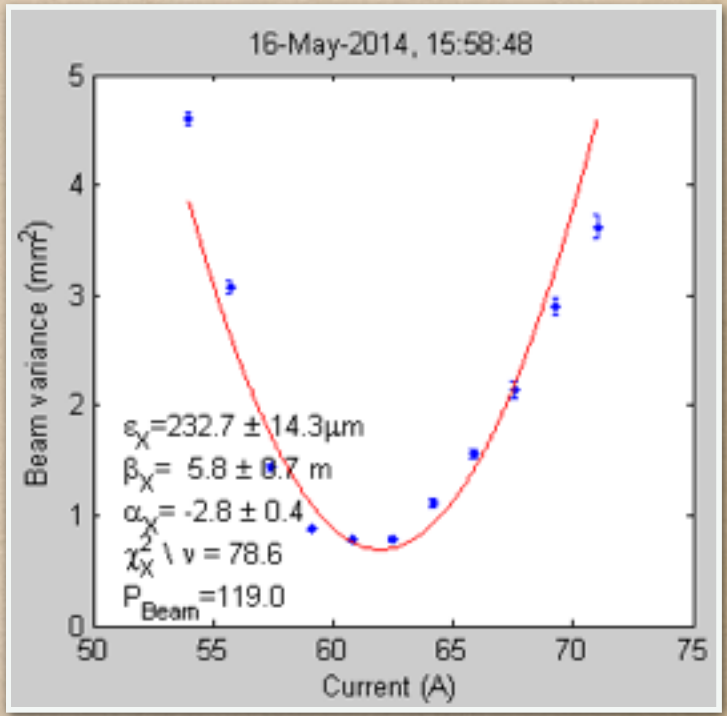
- Implementing sextupolar correction of second-order dispersion.
- Measuring emittance in downstream measurement line at different stages.



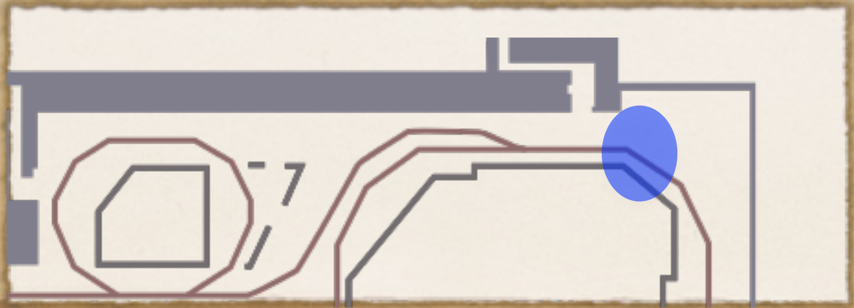
No sextupoles on.



First family at -23 A



First family at -23 A
Second family at +9 A



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