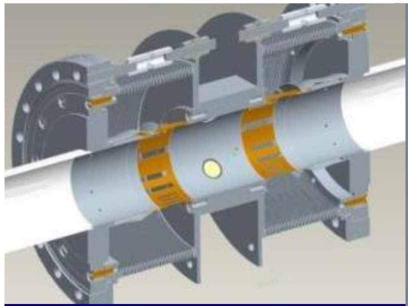

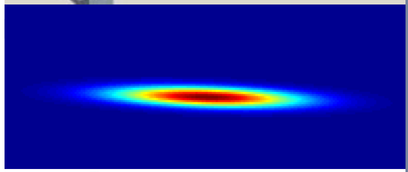

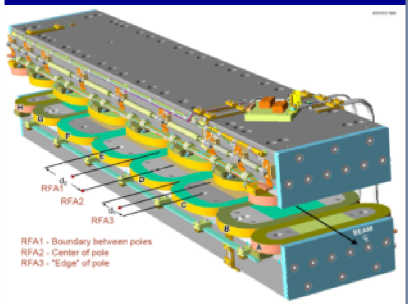

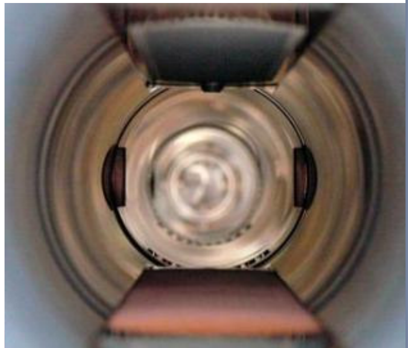

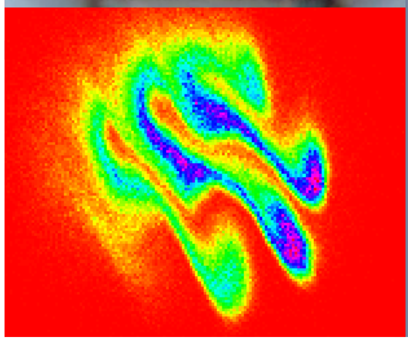

UNIVERSITY OF LIVERPOOL

The Cockcroft Institute
of Accelerator Science and Technology

Low-emittance tuning studies at CesrTA

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The Cockcroft Institute
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James Jones

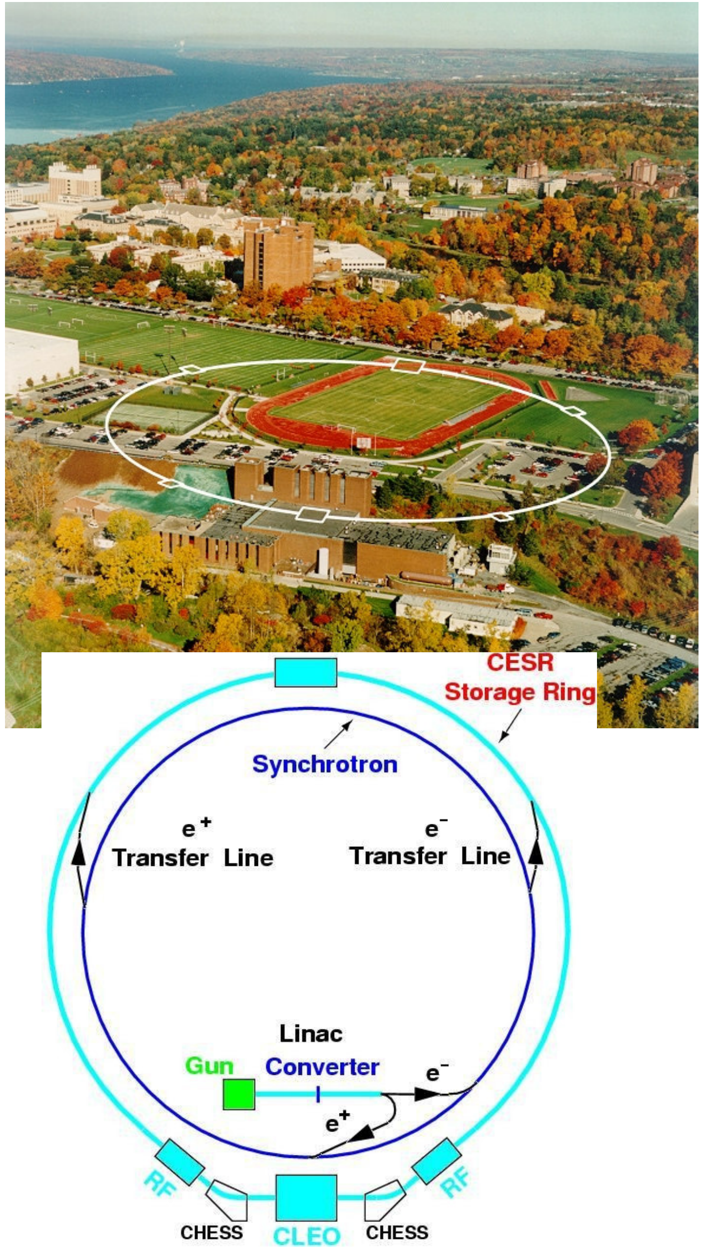
ASTeC

CI/University of Liverpool Group Meeting

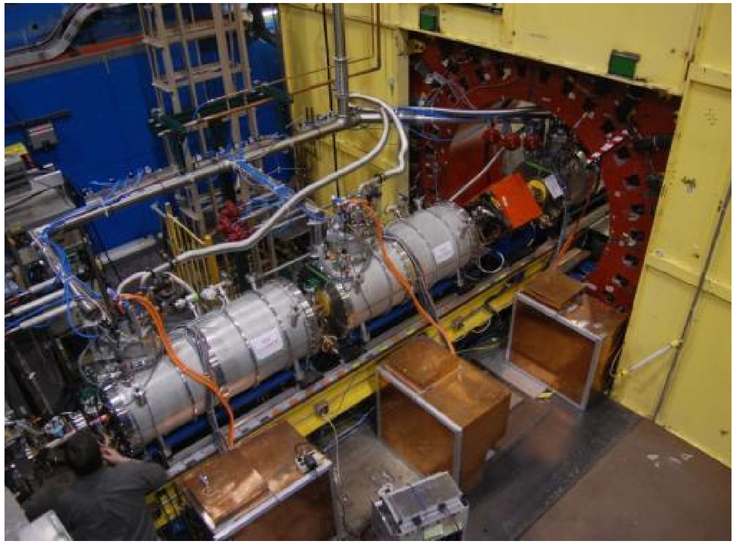
27 January 2009

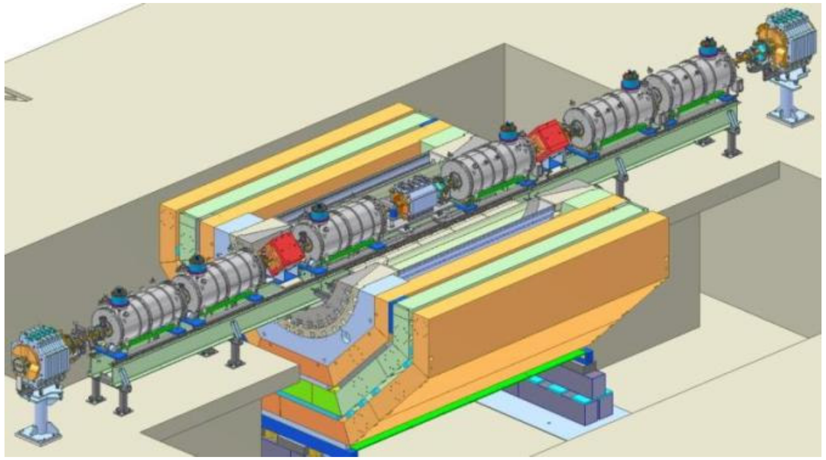
Cornell Electron Storage Ring (CESR)

- Designed to operate as an e+e- collider with centre of mass energies in range 3.5 GeV – 12 GeV.
- Operating (in various incarnations) since 1979.
- Also includes synchrotron radiation beamlines (Cornell High Energy Synchrotron Source: CHESS).
- Converted in 2008 to operate as a facility for studies of electron cloud in the parameter regime of linear collider damping rings.



CESR-c to CesrTA



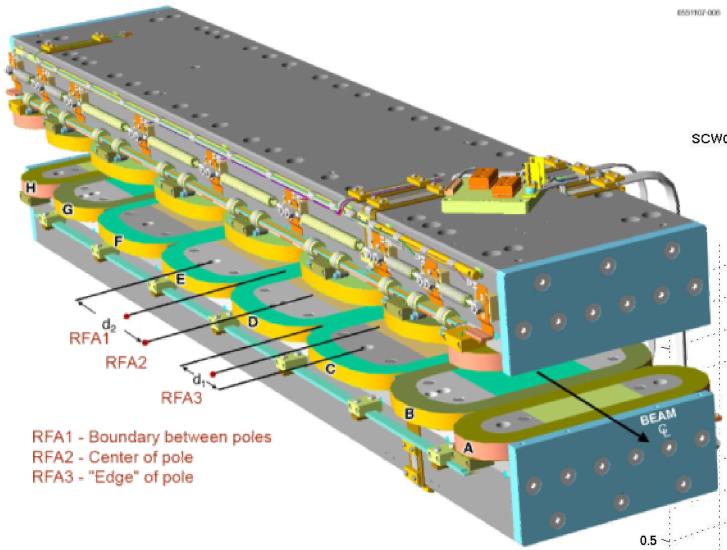


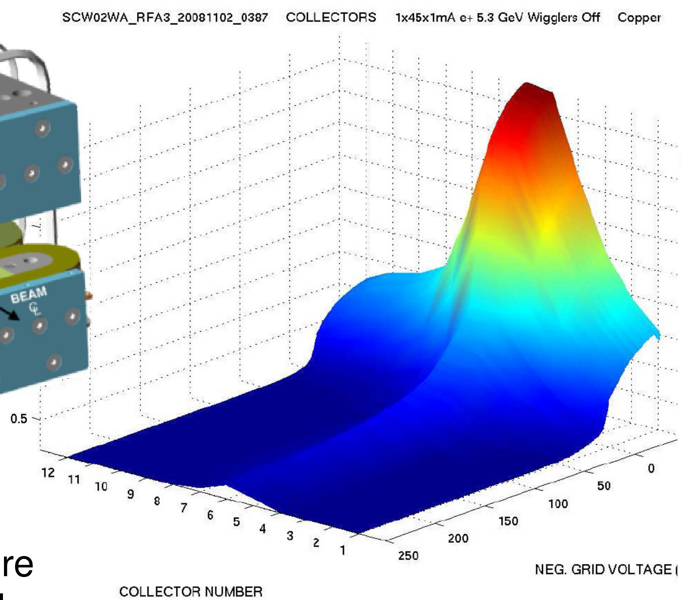
- Removal of CLEO detector, and relocation of six (out of twelve) wigglers to zero-dispersion straight (L0).
- New low-emittance optics at 2 GeV.
- Upgrade to alignment, BPMs and feedback system.
- Fast x-ray monitor, for bunch-by-bunch vertical beam size measurements with micron resolution.

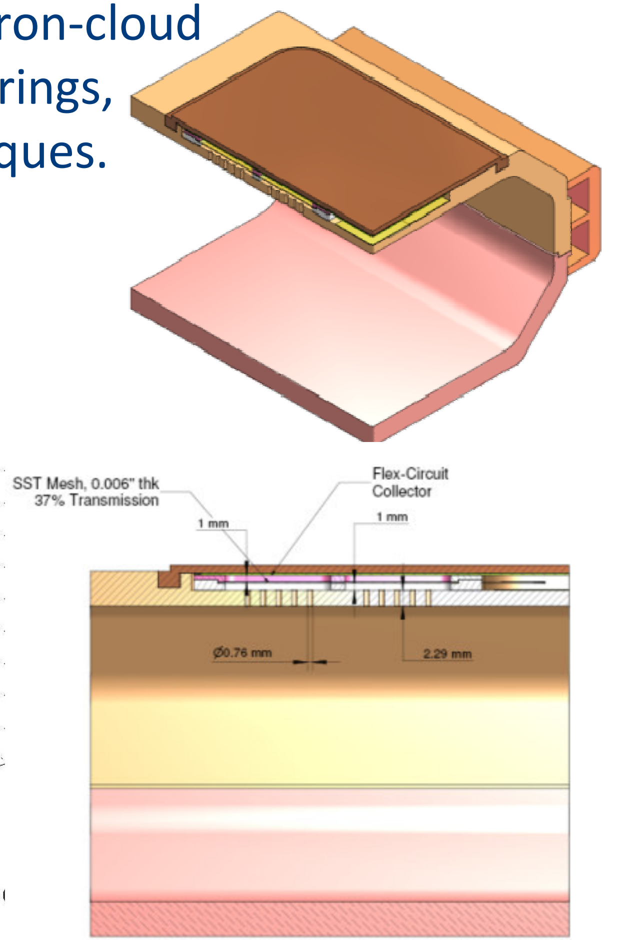
	CesrTA	ILC DR
Circumference	768 m	6476 m
Energy	2 GeV	5 GeV
Particles/bunch	2×10^{10}	2×10^{10}
Bunch spacing	4 ns	3 ns
Natural emittance	2.3 nm	0.5 nm
Vertical emittance	< 20 pm	2 pm
Bunch length	7 mm	6 mm
Damping time	47 ms	21 ms
Wiggler peak field	2.1 T	2.1 T
Wiggler period	400 mm	400 mm
Total wiggler length	19 m	230 m

Electron cloud studies at CesrTA

- Effect of electron cloud on ultra-low emittance beams is a critical issue for the ILC (and CLIC) damping rings.
- Suppression of electron cloud in wigglers presents challenges.
- CesrTA will allow experiments to characterise electron-cloud effects in the parameter regime of the LC damping rings, and provide opportunity to test suppression techniques.







Wigglers are instrumented with retarding-field analysers to measure spatial and energy distribution of the electron cloud.

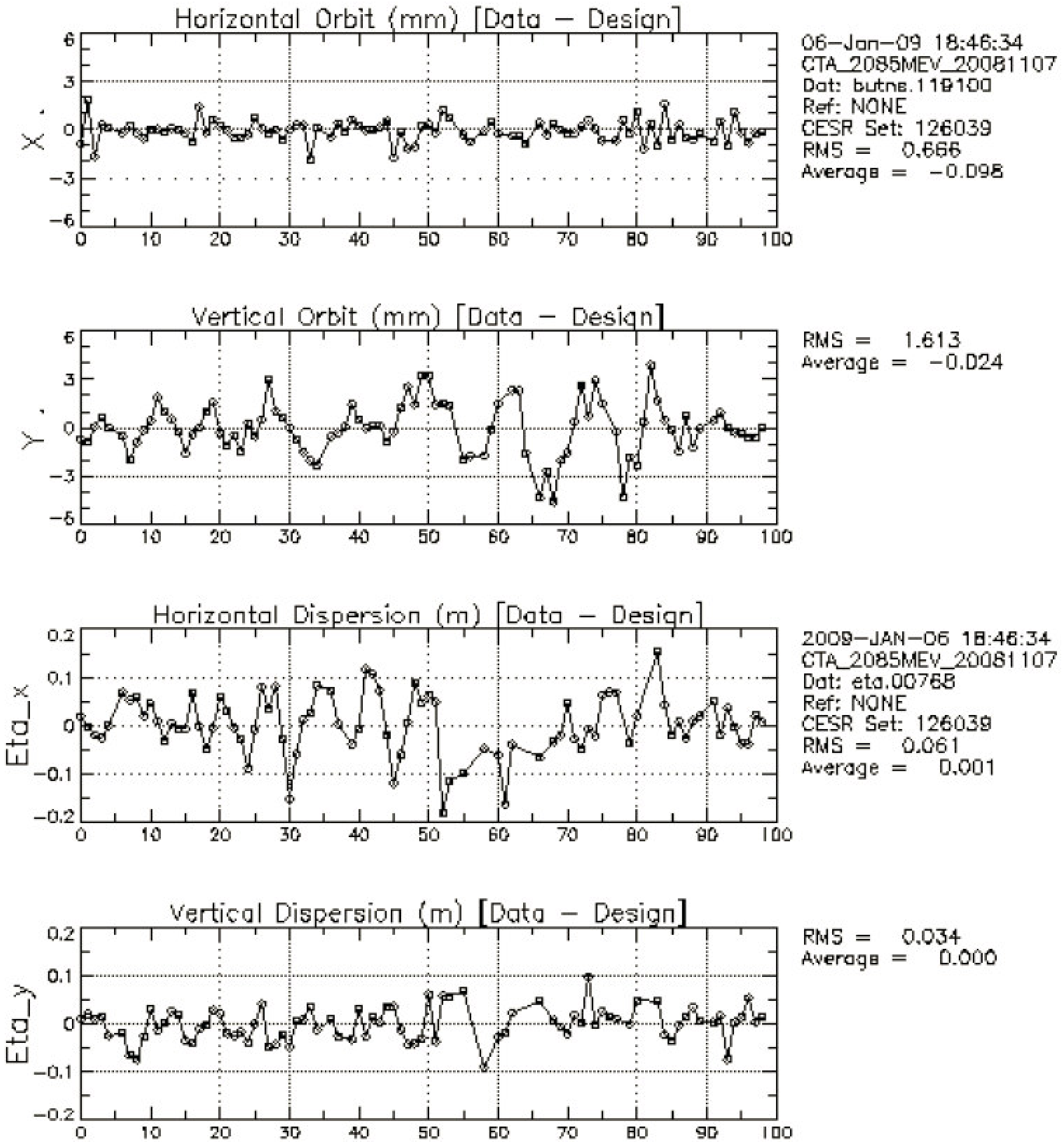
Low-emittance studies require low-emittance beam

- Natural emittance is essentially determined by beam energy and the optics of the lattice.
- Vertical emittance is dominated by alignment and tuning errors.
- Several electron storage rings have achieved vertical emittance < 5 pm: KEK-ATF, SLS, DLS…
- Achieving the vertical emittance goal will require:
  - precise alignment of magnets (quadrupoles < 100 μm);
  - high-performance, well-calibrated instrumentation;
  - precise correction of optics errors (dispersion and coupling).
- The goal for CesrTA is to achieve a vertical emittance < 20 pm, i.e. an emittance ratio $\varepsilon_y/\varepsilon_x$ less than 1%.

Alignment and optics correction at CesrTA

- "Routine" correction methods include:
  - survey and alignment of magnets;
  - orbit and dispersion correction;
  - measurement and correction of betatron phase-advance errors (using quadrupole strengths) and betatron coupling (using skew quadrupoles).
- A range of techniques for characterising errors are starting to be used regularly, or are in development:
  - alignment analysis based on zero-corrector orbits;
  - "detector calibration", i.e. beam-based bpm alignment;
  - AC dispersion measurements, i.e. measurement of dispersion by recording orbits while exciting synchrotron oscillations;
  - bpm gain mapping (comparing the signal measured one bpm button with that calculated from the signals on the other three bpm buttons);
  - analysis of the orbit response matrix.

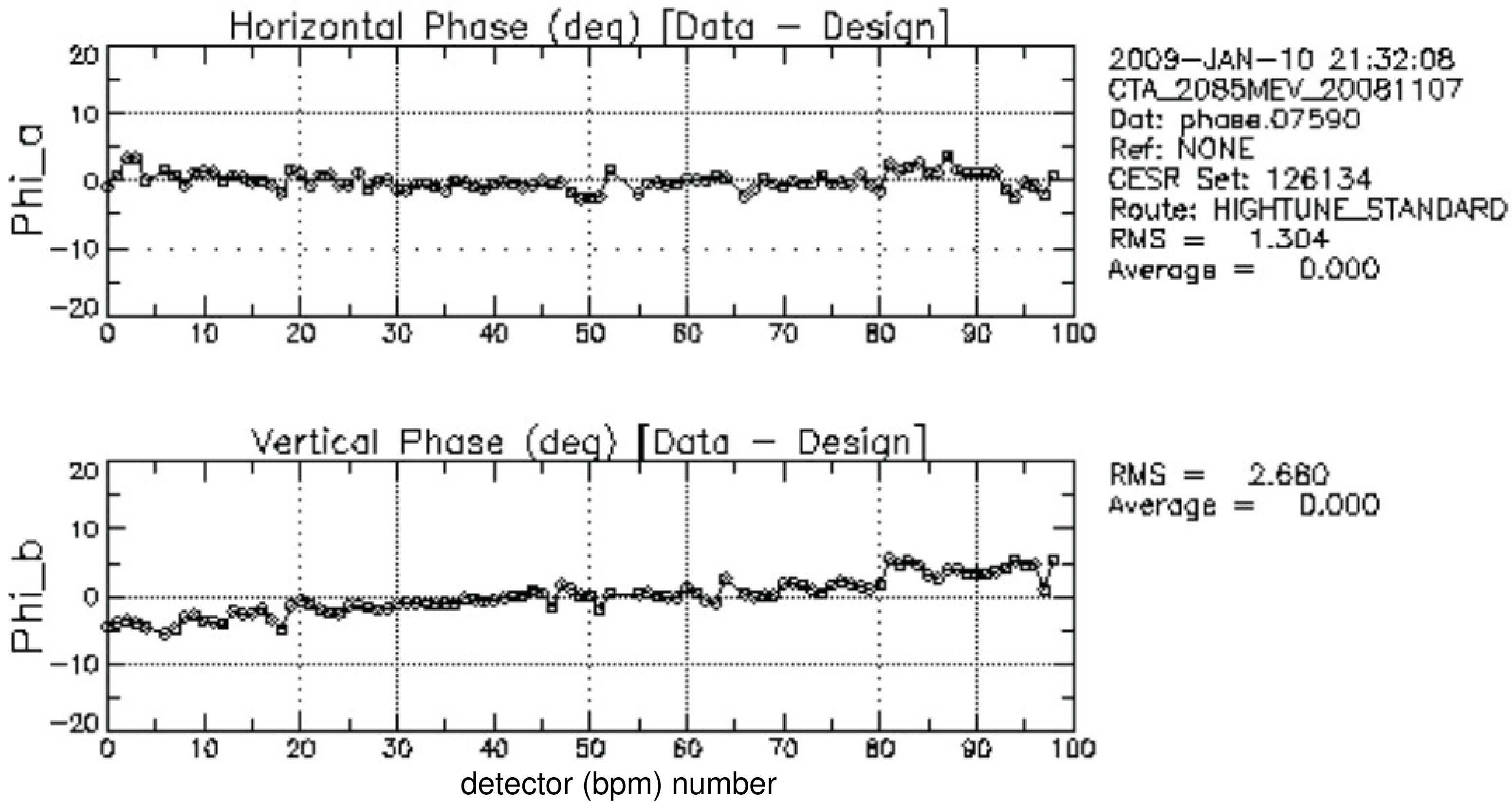
Example: orbit and dispersion correction



Note:

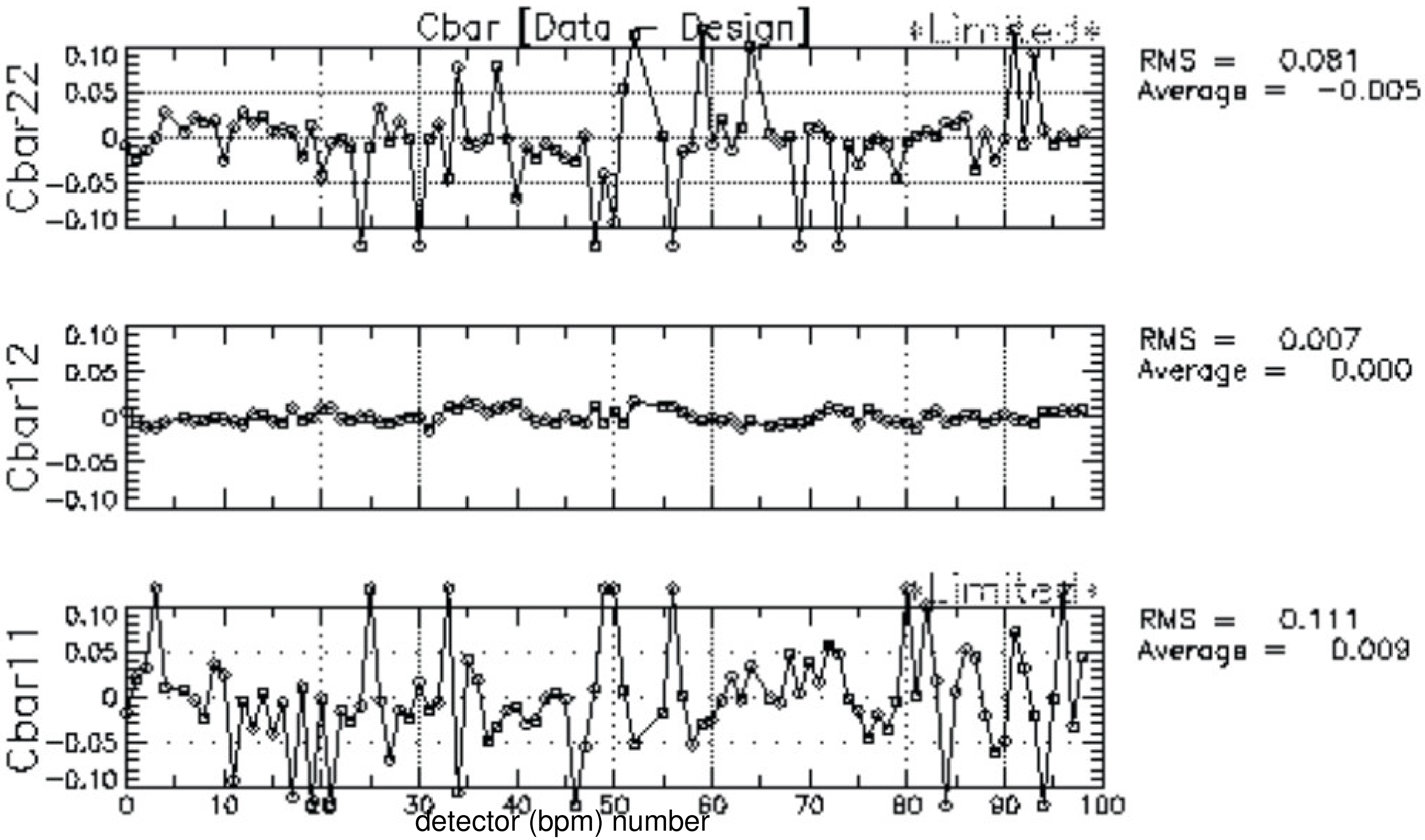
- Resolution of bpms in the present system is typically around 35 μm.
- Dispersion measurement made with: $\Delta f_{RF}/f_{RF}$ = 10 kHz/500 MHz.
- Momentum compaction: $\alpha_p = 6.4\times10^{-3}$.
- Resolution on the dispersion measurement is around 1 cm…

Example: betatron phase advance analysis



Example: betatron coupling analysis

$$\frac{\varepsilon_y}{\varepsilon_x} \approx 0.7\%$$



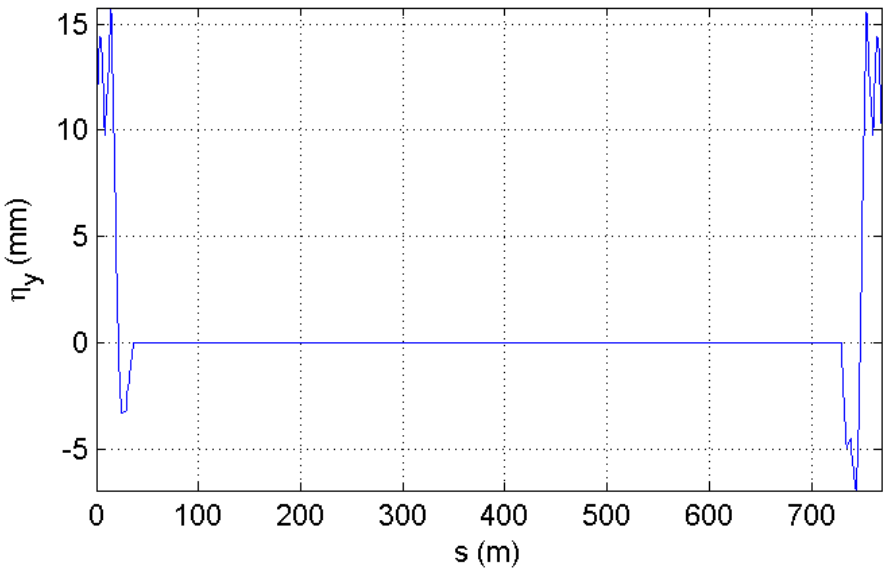
Correcting the vertical emittance

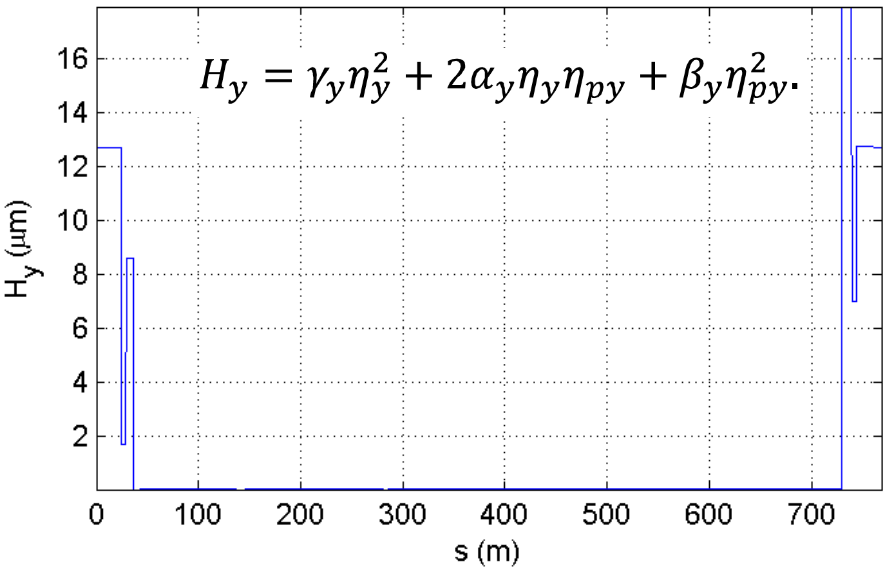
- Vertical emittance is generated by:
  - vertical dispersion;
  - betatron coupling.
- We can measure the vertical dispersion with a precision of around 1 cm (limited by bpm resolution).
- 1 cm rms vertical dispersion will generate an emittance:

$$\varepsilon_y \approx 2J_z \frac{\langle \eta_y^2 \rangle}{\langle \beta_y \rangle} \sigma_\delta^2 \approx 20\,\mathrm{pm}$$

- This leaves no margin for betatron coupling! What can we do?
- One possible solution is to generate "dispersion bumps" targeted on the wiggler sections, and tune directly on beam size.

Dispersion bumps

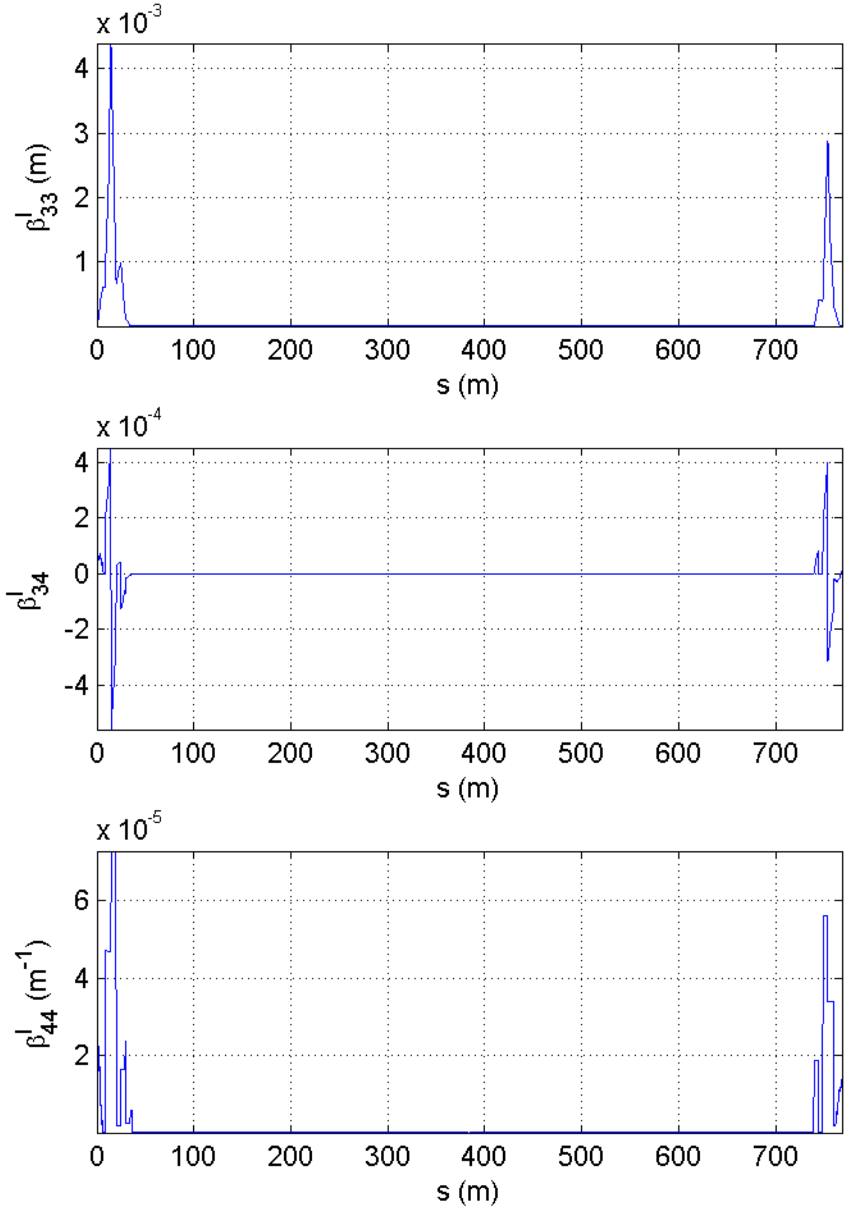




- L0 (wiggler straight) has four skew quads on either side.
- This allows for control of:
  - η_y, η_{py} to take specified values at centre of straight;
  - $\eta_y = 0$, $\eta_{py} = 0$ at exit of straight;
  - closed "coupling", i.e. set the four coupling components of the transfer matrix across the bump to zero.
- In principle, there should be no effect on the orbit.
- Note that the vertical emittance contribution from dispersion in the wigglers is given by:

$$\varepsilon_y = C_q \gamma^2 \frac{\oint \frac{H_y}{|\rho^3|} ds}{\oint \frac{1}{\rho^2} ds}.$$

Dispersion bumps: closing the coupling

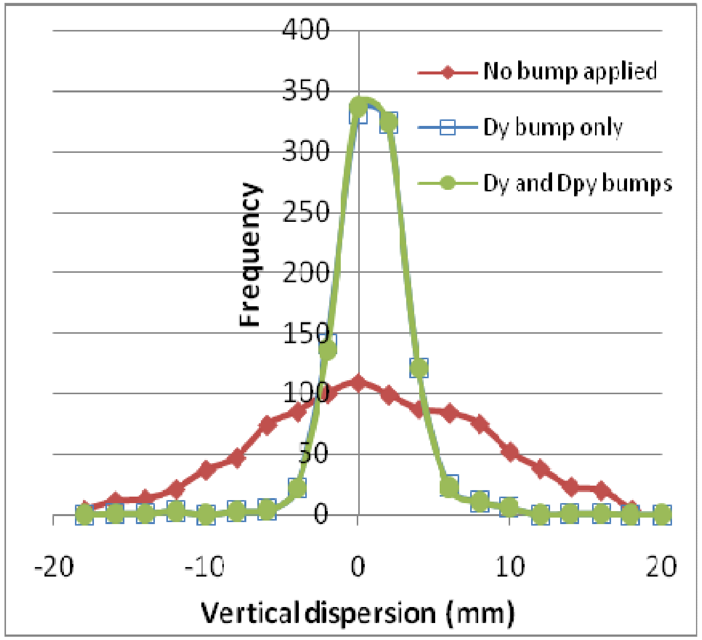


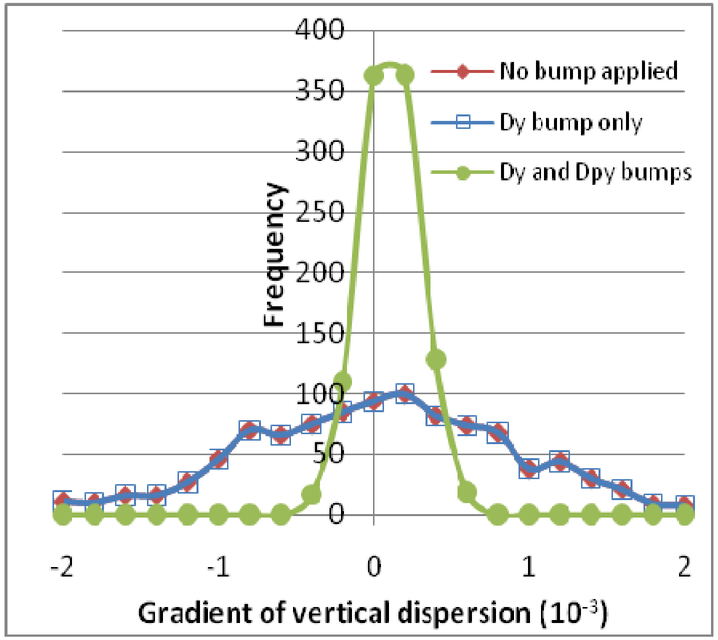
- Note: coupling can be characterised by a generalisation of the lattice functions:

$$\langle x_i x_j \rangle = \sum_{i,j,k} \beta_{ij}^k \varepsilon_k$$

Testing the dispersion bumps in simulation

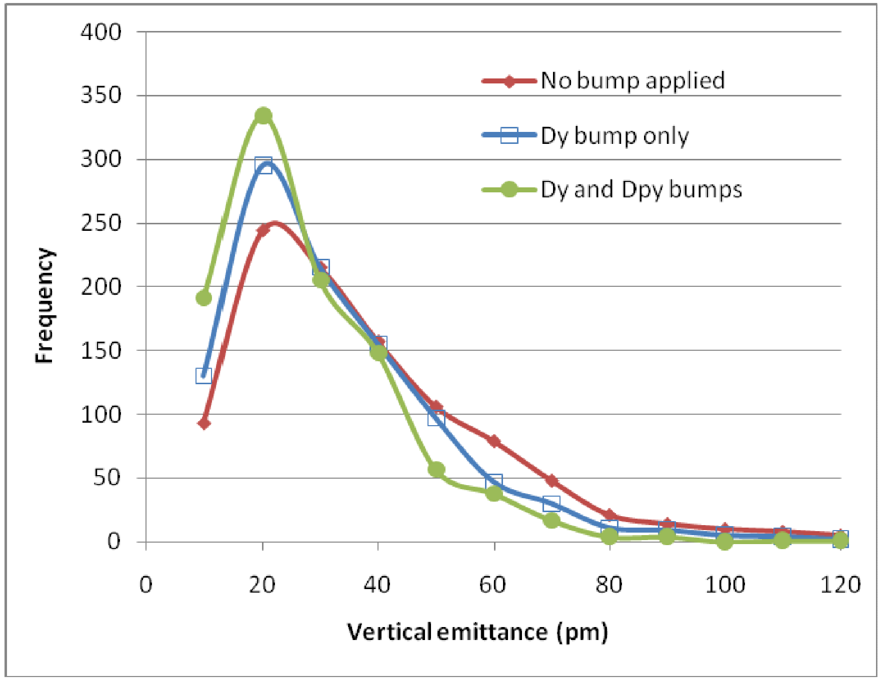
- We apply a random set of alignment errors to the quadrupoles and sextupoles.
- We apply dispersion bumps in L0 to minimise the emittance: note that we do not tune directly on dispersion.
- We repeat for many different sets of alignment errors, and collect the statistics on the dispersion, and the emittance.
- The dispersion bumps have the expected effect.

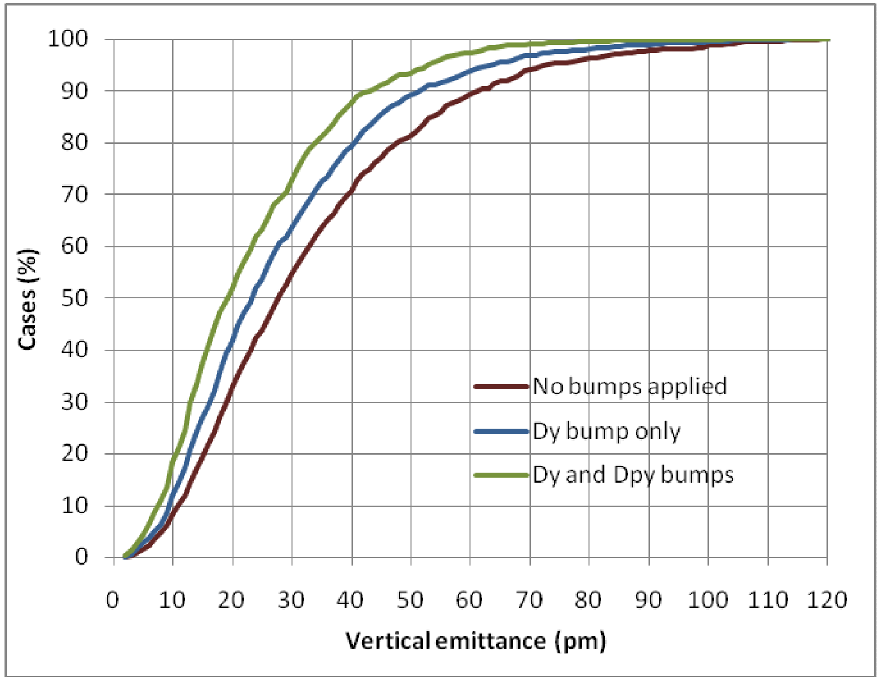




Testing the dispersion bumps in simulation

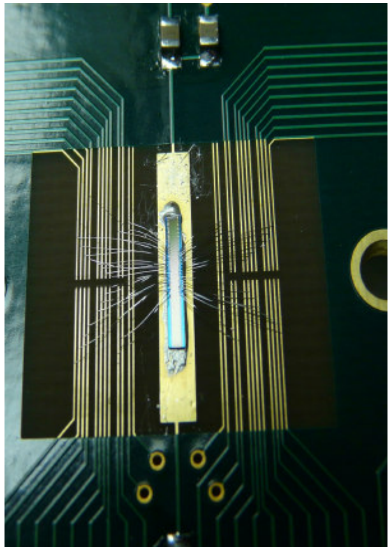
- By applying dispersion bumps only in L0, the fraction of cases with emittance below 20 pm increases from 30% to 50%.
- Typically, there is a reduction in the vertical emittance of around 30%: some cases show a much larger reduction, others show a very small reduction.
- The L0 dispersion bumps are very "local". There may be similar benefits from applying dispersion bumps in the arcs, though in these cases, the correction will be less local, because the skew quads are not ideally located.





Fast x-ray beam size monitor

- The goal is to provide an instrument for bunch-by-bunch vertical beam size measurements, with resolution of a few microns.
- This is still an R&D project.

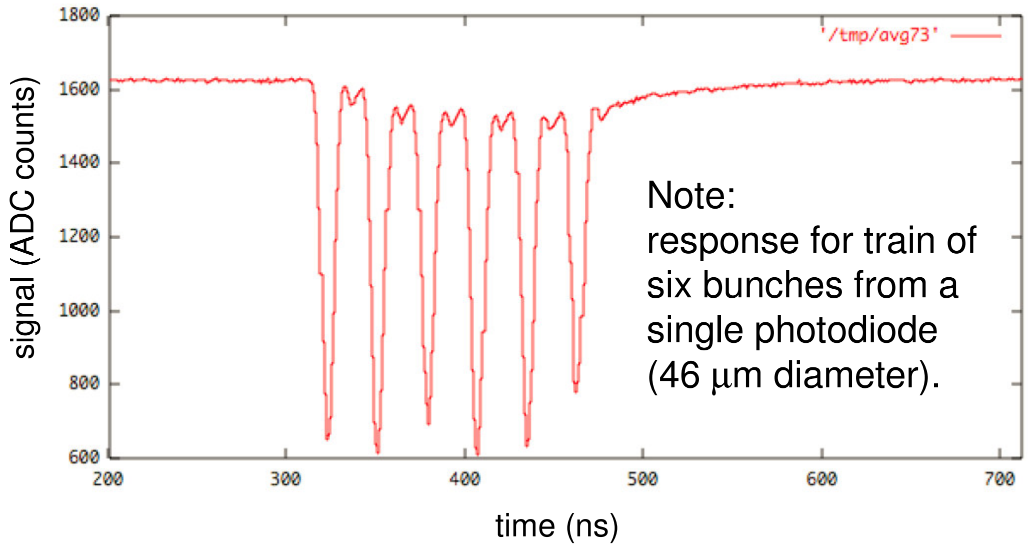


Photodiode array for fast x-ray beam size monitor:

512 photodiodes,

25 μm pitch.

Jim Alexander, et al.



Can we estimate the beam size without direct measurement?

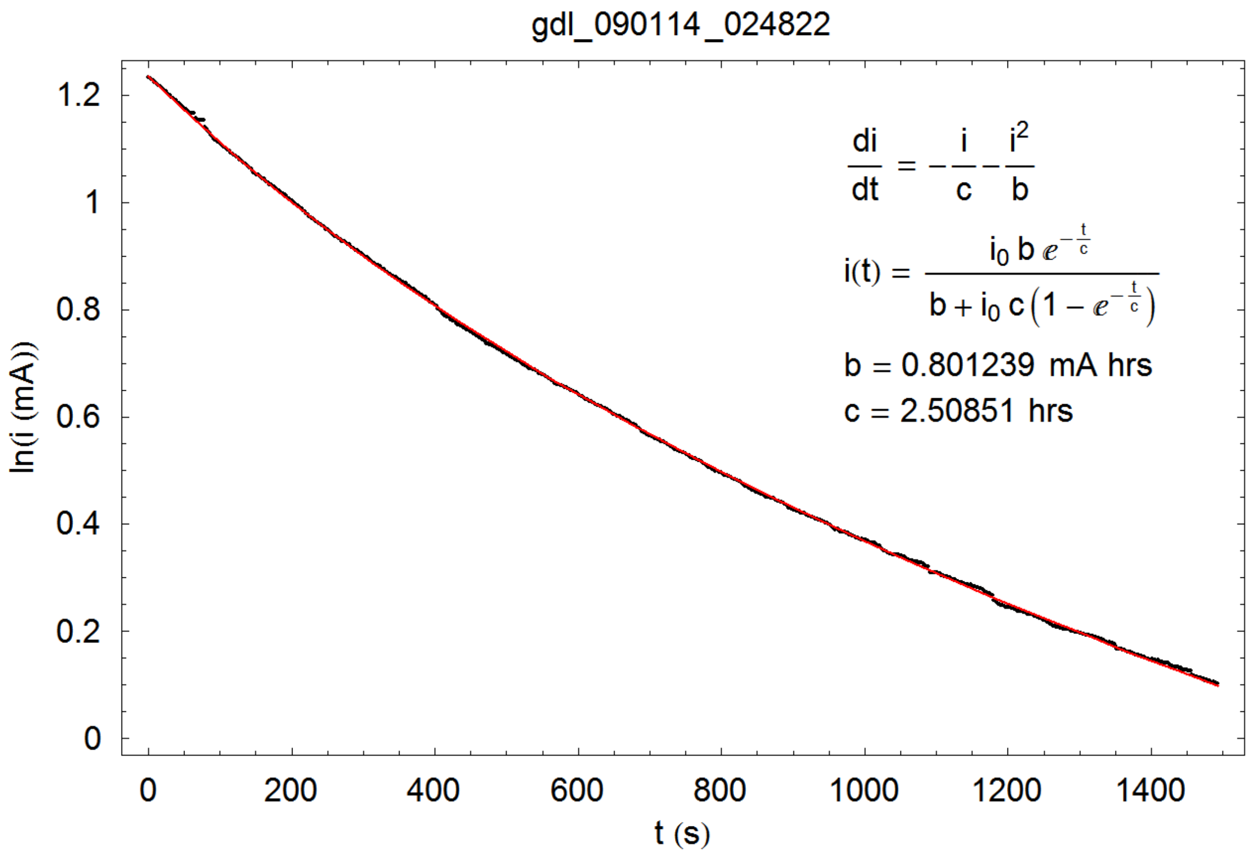
- Various phenomena that are sensitive to the beam size have effects that are (in principle) measurable.
- A technique that is commonly used, is to measure the Touschek lifetime.
- Advantages:
  - has reasonable sensitivity to the beam size in the parameter regime of interest;
  - measurements are easy to make using standard instrumentation (beam current monitor, and a clock).
- Disadvantages:
  - Touschek scattering is a complicated effect that involves many parameters that may not be well known;
  - collecting enough data for a reasonable estimate of the vertical emittance can be a slow process.

$$\frac{1}{\tau} = \frac{N r_e^2 c}{8\pi\sigma_z\gamma^2}\left\langle \frac{D(\epsilon)}{\delta_{max}^3\sigma_x\sigma_y} \right\rangle, \qquad \epsilon = \left(\frac{\delta_{max}\beta_x}{\gamma\sigma_x}\right)^2,$$

$$D(\epsilon) = \sqrt{\epsilon}\left(-\frac{3}{2}e^{-\epsilon} + \frac{\epsilon}{2}\int_\epsilon^\infty \frac{e^{-u}\ln u}{u}du + \frac{1}{2}(3\epsilon - \epsilon\ln\epsilon + 2)\int_\epsilon^\infty \frac{e^{-u}}{u}du\right).$$

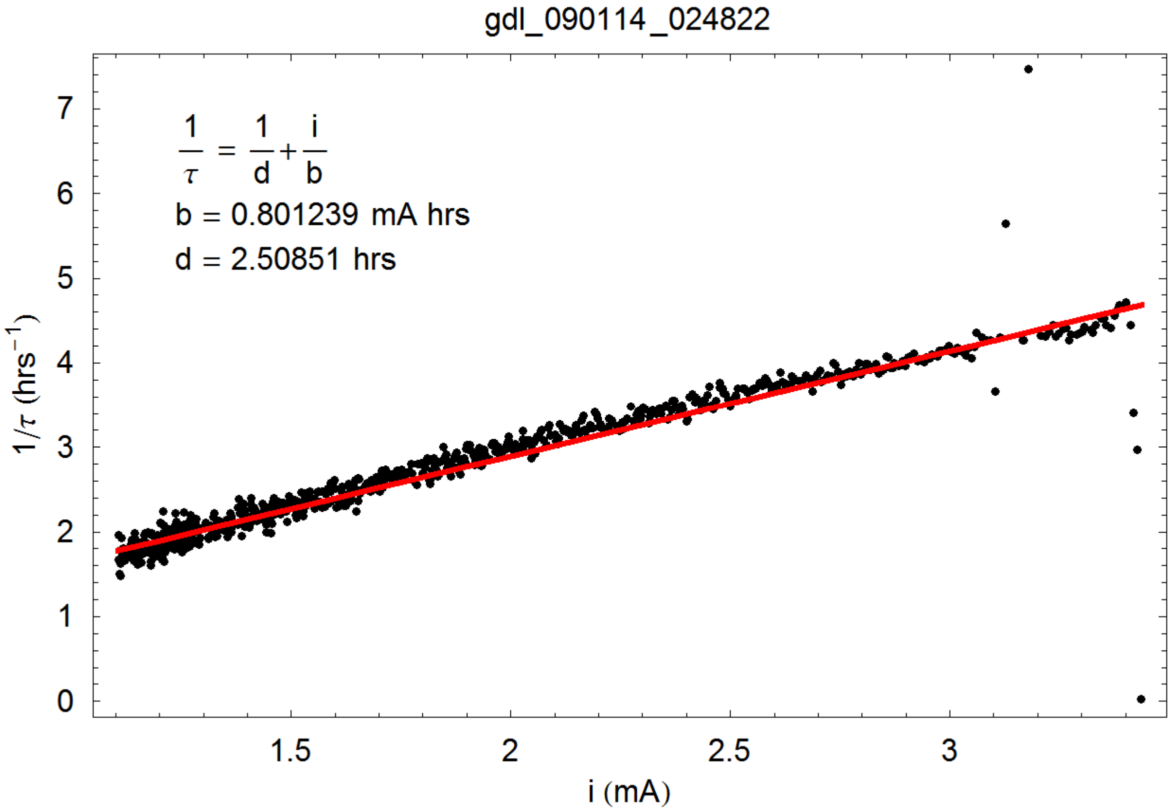
Estimating the emittance from Touschek lifetime

- Since the lifetime depends on the bunch charge, the decay of the beam current is not exactly exponential…



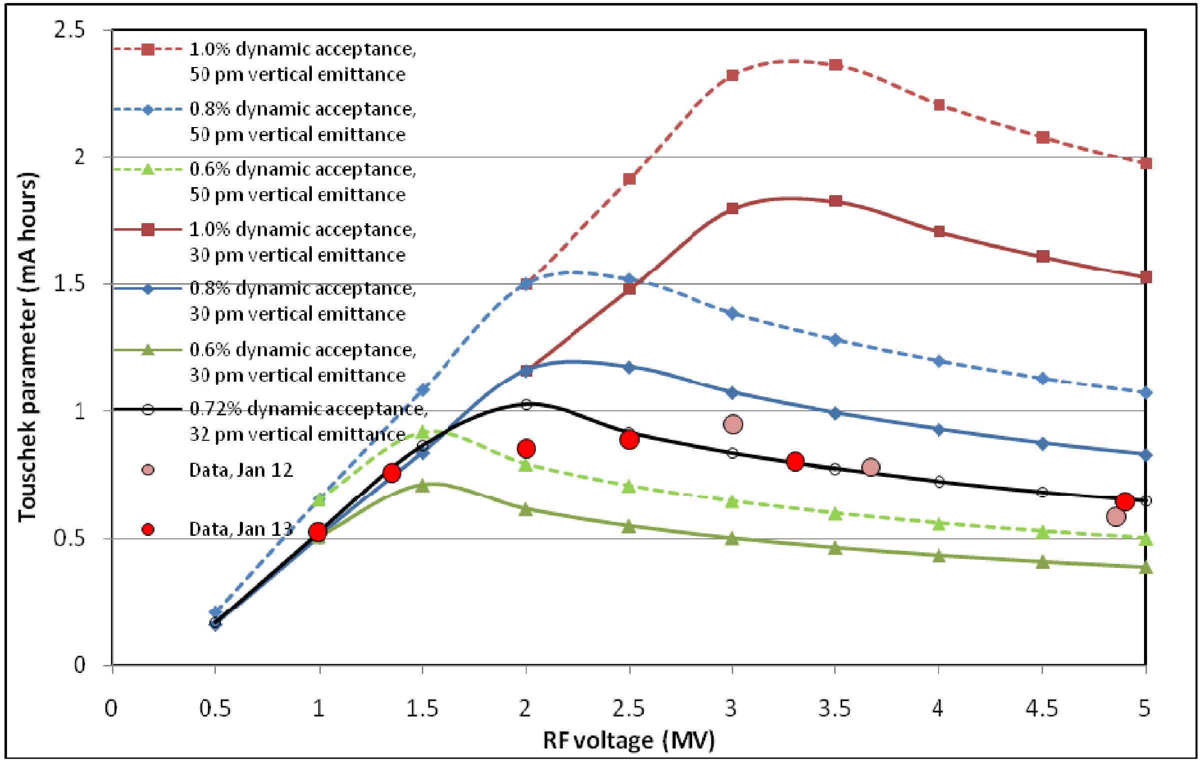
Estimating the emittance from Touschek lifetime

- We can compare two estimates of the lifetime:
  1. lifetime from an analytical fit of the curve of current vs time over a long (20 minute) time scale;
  2. lifetime from a "control system" estimate, based on rate of current decay over a short (few second) time scale.
- The comparison hints at additional effects we are not taking into account. Potential well distortion? Intrabeam scattering? Electron cloud?



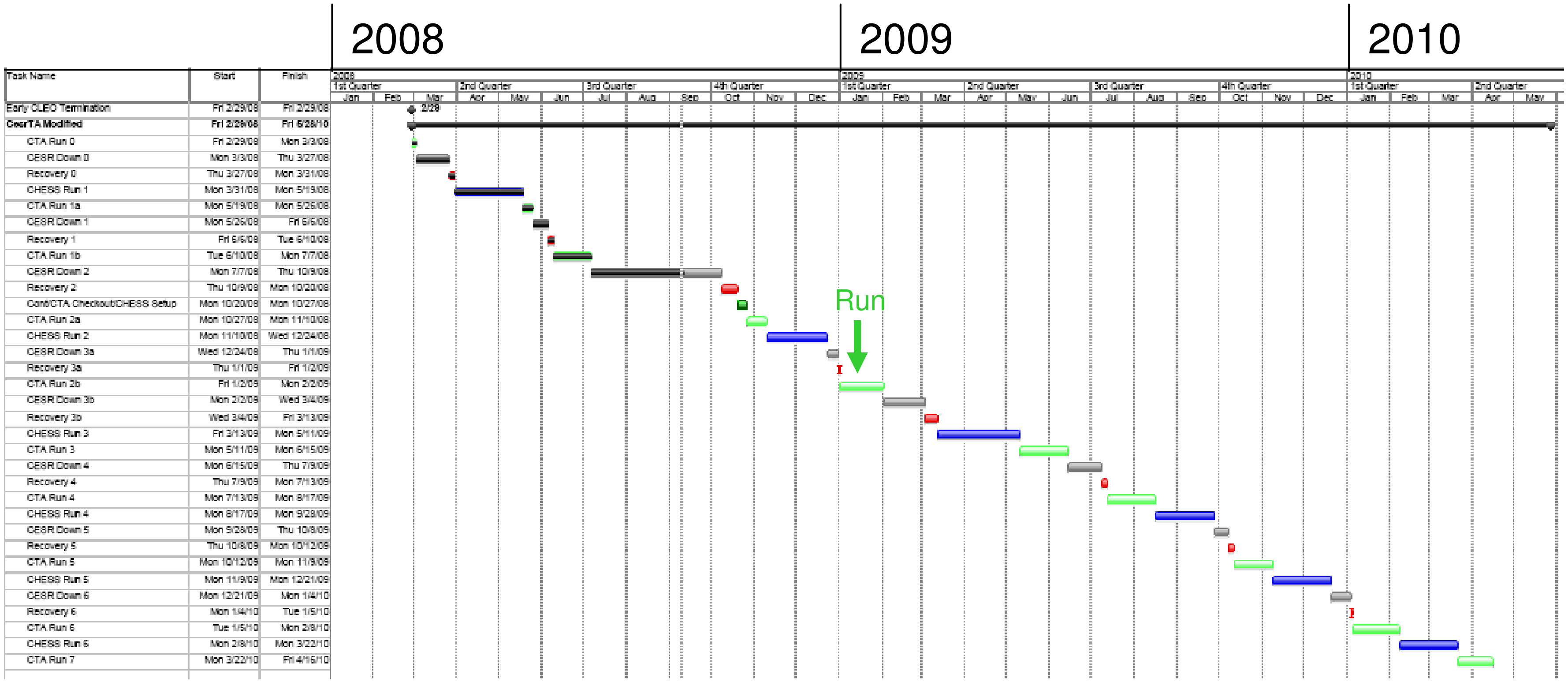
Estimating the emittance from Touschek lifetime

- Measuring the Touschek lifetime as a function of rf voltage allows us to estimate the vertical emittance and the energy acceptance.
- From data collected in January 2009, it appears that:
  - the energy acceptance is around 0.7% (much smaller than nominal);
  - the vertical emittance is in the range 30 – 40 pm (better than expected at this stage, and probably optimistic).



Final remarks

- CesrTA has made a good start:
  - January 2009 was the first proper period for studies of electron cloud and ultra-low emittance tuning.
  - The program will continue to April 2010, with five more "run" periods of about a month each.



Final remarks

- Collection and analysis of data on electron cloud, and development of mitigation techniques, is the top priority.
- Ultra-low emittance is needed to minimise the extrapolation of the electron cloud data to the linear collider damping rings.
- The experience in January 2009 was interesting and useful for developing tools, techniques and procedures:
  - dispersion bumps in the wigglers: tested but not used for tuning;
  - lifetime data: tested as a technique for estimating emittance;
  - orbit response matrix analysis: data collected…
  - bpm gain mapping: data collected…
  - zero-corrector orbits, beam-based alignment…
- A determined effort to achieve 20 pm vertical emittance will require instrumentation upgrades:
  - new bpm electronics (few μm resolution): much of the hardware is in place, but switching over will be non-trivial;
  - fast x-ray beam size monitor is needed for tuning and measurement of beam with emittance of 20 pm (or less!)

Acknowledgements

Many thanks to our colleagues at LEPP:

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- Jim Shanks
- CesrTA operators