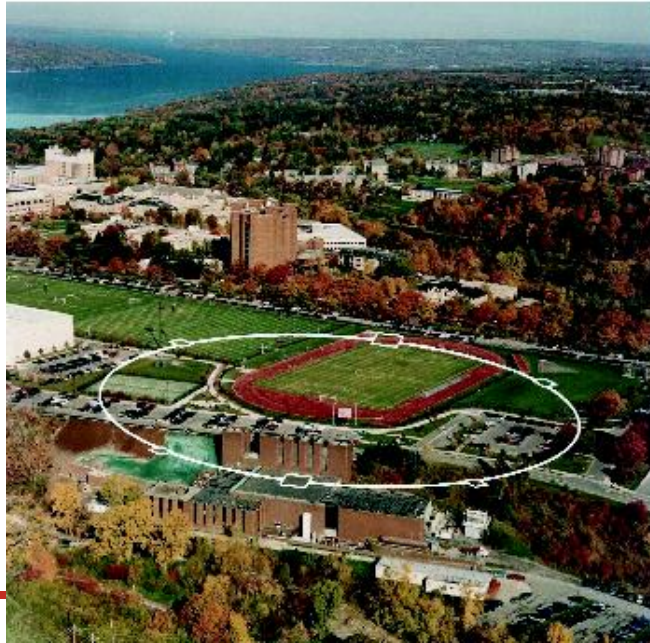


Cornell Laboratory for
Accelerator-based Sciences and
Education (CLASSE)

Ultra-Low Emittance Storage Ring

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- Much of our research is focused on the production and physics of ultra-low emittance beams.
 - Emittance is the phase space volume of the beam
 - For example horizontal emittance
- $$\epsilon = \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle + \langle xp_x \rangle^2}$$
- Emittance is roughly equivalent to temperature
 - Typically an electron bunch emitted from a photocathode has a relatively low emittance
 - Circulation in a storage ring heats up the beam as it equilibrates with its environment as defined by the magnetic lattice
 - The equilibrium temperature (emittance) is determined by the storage ring guide field



- Horizontal emittance is a function of the lattice focusing. Damping wigglers can be leveraged to increase the emittance of the lattice
 - 130 nm-rad at 2GeV for D-meson production for CLEO-c
- Or to decrease the emittance
 - to 2.5 nm-rad for investigations of the electron cloud in CEsrTA
(The minimum that can be achieved given the layout of the ring magnets)
- The vertical emittance is only indirectly dependent on the ring lattice. It is dominated by magnet misalignments and field errors
- Misalignments generate transverse coupling and vertical dispersion which in turn increase the equilibrium temperature of the vertical phase space
- The theoretical minimum vertical emittance (quantum limit) obtains when the magnets are perfectly aligned (or perfectly compensated) so that the residual vertical dispersion vanishes.

Our goal is to reach the quantum limit



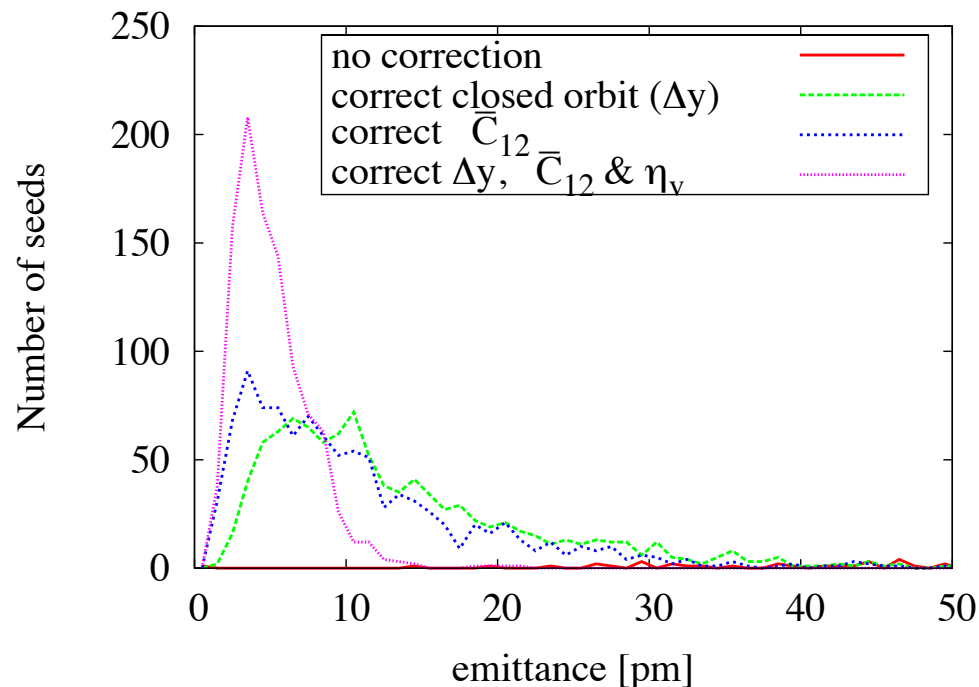
- CesrTA is meant to explore the dynamics of ultra-low vertical emittance beams. => Minimizing emittance is essential
- Strategy for reducing vertical emittance
 - Better survey and alignment of the guide field magnets
 - Improved stability of magnet power supplies
 - Techniques and instrumentation for beam based measurements to identify the sources of residual dispersion and coupling.
 - Compensation of the sources with corrector magnets
 - Beam based techniques to calibrate the instrumentation
- CesrTA instrumentation, especially the beam position monitor system, is designed with these objectives in mind, by providing precision measurements of dispersion and coupling



- During the last couple of years we have learned to use that instrumentation to identify and compensate the errors with corrector magnets
 - => from 50-100 pm-rad to as few as 3-5 pm-rad,
(lowest positron beam emittance ever measured, and very close to the world lowest for an electron beam.)
- The theoretical minimum vertical emittance is 0.25 pm-rad
- Another factor of 20 times smaller. To reach the quantum limit we will have to very significantly improve
 - Quality and stability of magnet survey
 - Stability of magnet power supplies
 - Our understanding of emittance diluting errors
 - Quality of the beam based measurements on which we depend for correction and compensation of those errors.



- As an illustration we use a simulation to evaluate the effectiveness of our correction procedure.
 - Depends on the resolution of the beam position monitors.

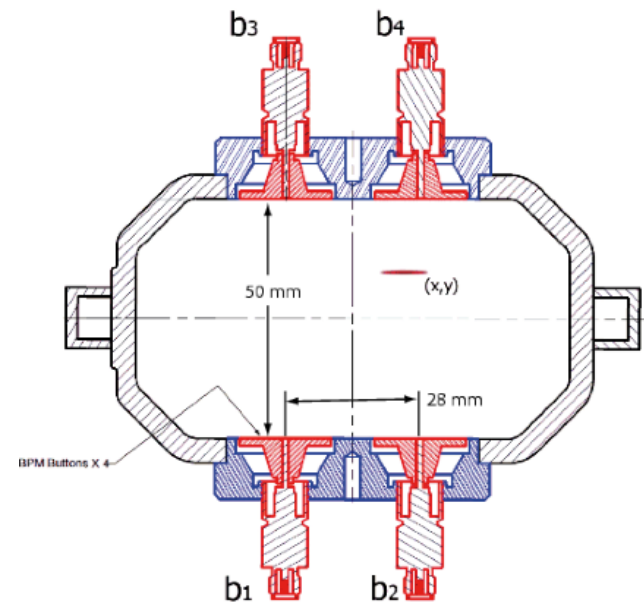


BPM precision

Absolute [μm]	200
Differential [μm]	10
Tilt [mrad]	22

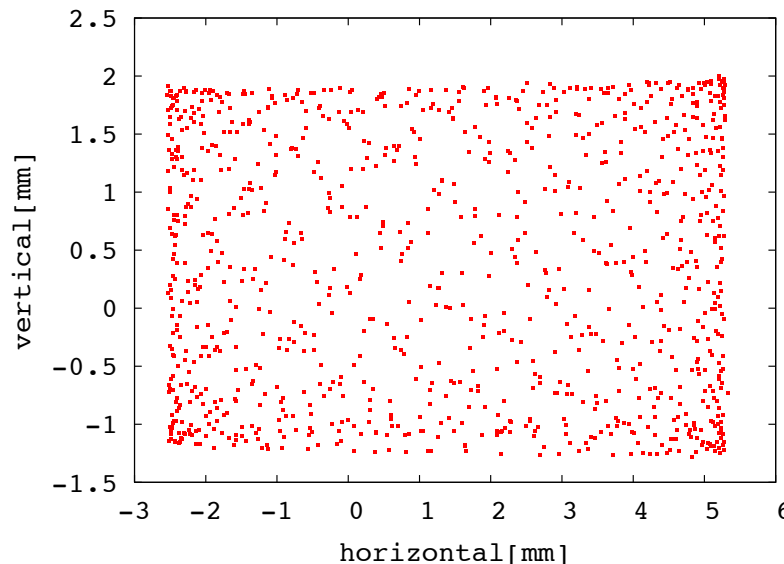
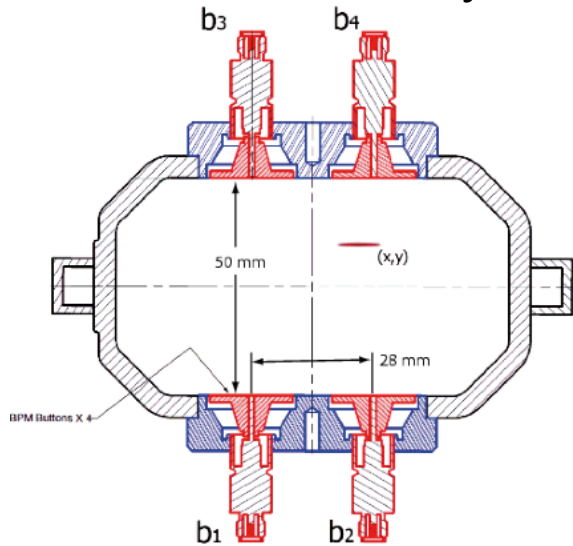
- We see that the model is a reasonably accurate representation of the machine as the results we achieve in the control room (typically 4-10 pm-rad) are in good agreement with simulation.

- The emittance scales as the square of the dispersion-
In order to reach the quantum limit (0.25 pm-rad)
 - => ~ need to reduce measurement error nearly 5 times
 - from 15mm (at present) to 3mm
 - => < 2 micron intrinsic position measurement resolution
 - => Better control of systematics such as:
 - variations in the response or gain of the four BPM buttons
 - and physical tilt of the BPM.





- Exploit the turn by turn capability of the BPM electronics for beam based calibration of button gains.
 - We note that 3 buttons determine the position of the bunch.
 - The fourth is redundant. There is a unique set of multipliers (gains) that render the four measurements self consistent.
 - Collect button data for a set of orbits that samples the entire active area of the detector
 - => Determine a set of multipliers with precision of a fraction of a percent.
 - Collect the turn by turn data in a few seconds => gain mapping is routine.



1024 turns
BPM 10



- **Beam based techniques for**
 - measuring the absolute offset of the BPM with respect to the adjacent quadrupole - (routine procedure)
 - Determining BPM rotation with mrad precision – (not yet routine).
- **These kinds of tools will be essential to reach the quantum limit. CsrTA provides a superb foundation for this effort.**



- As we achieve ever smaller emittance, sensitivity to the physics of colder and higher charge density beams is enhanced.
- IBS: Observable effect of intra beam scattering is current dependence of the beam size.
 - Intra-beam scattering increases with charge density.
 - Beam size, is the equilibrium between IBS and radiation damping, increases with bunch charge.
- Measurements of IBS will require higher resolution xray beam size monitor.
 - Vertical emittance of 5pm-rad => corresponding beam size is 5-15 microns.

At the quantum limit - 0.25 pm-rad, - vertical beam size is 1-3 microns.

- Measurement of IBS effects will require fraction of a micron resolution.
- => higher density photo diode detectors
- more magnification
- better control of the systematics (averaging)

The smallest beam size will only be realized with very little total charge and relatively few photons => All vacuum xray beam line.



We approach the **vertical** emittance limit with better alignment, and compensation of dispersion and coupling

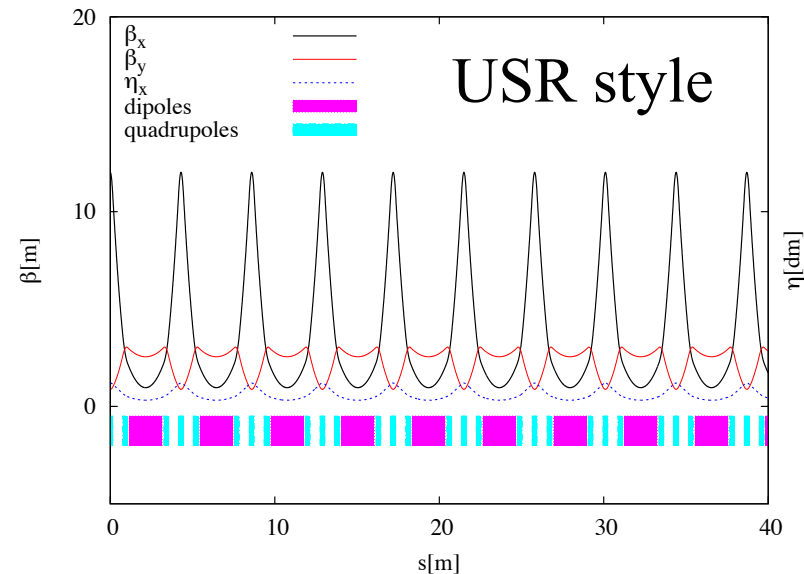
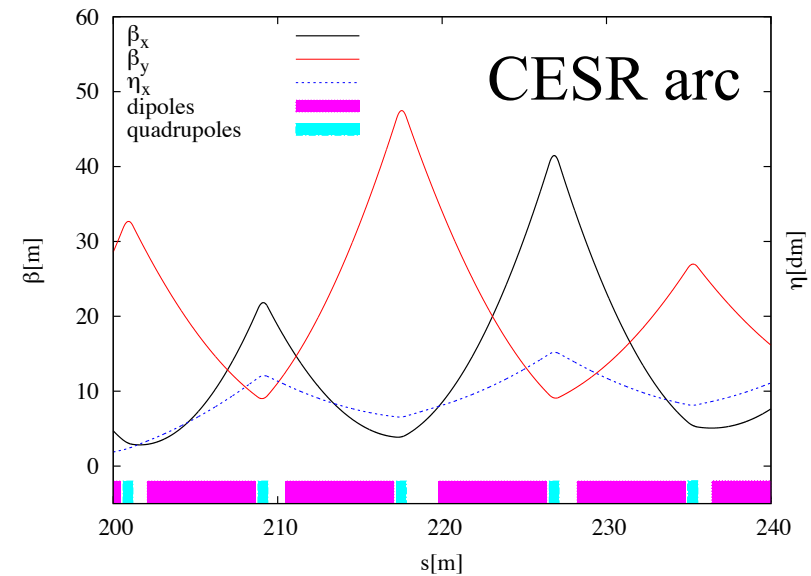
- **Horizontal** emittance depends on the distribution of quadrupole and dipole magnets.
- Rings that promise to reach the theoretical minimum horizontal emittance have
 - many short dipoles
 - a high density of quadrupoles and very strong focusing
- Such an “Ultimate Storage Ring” (USR) promises horizontal emittance 100 times smaller than anything ever achieved.

CESR layout

- long (6.6 m) dipoles
- widely spaced quadrupoles

CesrTA depends on damping
wigglers to reach 2.5 nm-rad

Ultimate Storage Ring concept
promises 100 times smaller
horizontal emittance with
closely spaced quadrupoles and
very strong focusing





- **Many challenges to the USR concept**
 - Extreme guide field nonlinearities due to the very strong focusing.
 - Instrumentation and techniques for the beam based measurements will be required to have extraordinary precision
 - Manipulating the beam to make the measurements will be constrained by the limited dynamic aperture
- **Design and operation of a prototype USR in the CESR tunnel ?**
 - Test our understanding of how the magnetic environment determines equilibrium temperature at extreme low horizontal and vertical emittances simultaneously
 - Test effectiveness of lattice symmetries, periodicity and tailored sextupole distributions for mitigating machine resonances
 - Laboratory for testing the instrumentation for manipulating such beams and investigating the physics of beams with ultra-low horizontal as well as vertical emittances.



- Theoretical minimum vertical emittance in CesrTA and exploration of cold vertical phase space (near)
- Ultimate storage ring – like lattice in the CESR tunnel (far)
 - Test our understanding of how the magnetic environment determines the equilibrium temperature in the extreme low emittance regime
 - Provide a laboratory for exploring the physics

Vision ?

A crowd of students in the control room staring at a monitor that is reporting 0.25pm-rad emittance and the thesis “Measurements of intrabeam scattering at the quantum limit”.



END