

Low Emittance Tuning in the ILC Damping Rings

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CesrTA Meeting/ILC Damping Rings Workshop

Cornell University, 8-11 July, 2008



Outline

- Motivation:
 - ILC luminosity;
 - electron cloud studies at CEsrTA.
- The three-pronged approach:
 - Modeling and simulation.
 - Research and development of instrumentation and diagnostics.
 - Experience at operating machines.
- Issues for damping rings design (and design status).
- Charge for the Working Group, and schedule.

Baseline ILC specifications

- Assuming Gaussian beam profiles, the luminosity in a linear collider is given by:

$$L = \frac{n_b N^2 f_{rep} H_D}{4\pi\sigma_x\sigma_y}$$

- To maximise the luminosity (minimise $\sigma_x\sigma_y$) while minimising beamsstrahlung (maximise $\sigma_x+\sigma_y$), we design for $\sigma_y \ll \sigma_x$.
- Minimum value of β_y^* is limited by the hour-glass effect... so we need ε_y as small as possible.

Baseline ILC specifications

Parameter	Symbol/Units	Nominal	Low N	Large Y	Low P
Repetition rate	f_{rep} (Hz)	5	5	5	5
Number of particles per bunch	N (10^{10})	2	1	2	2
Number of bunches per pulse	n_b	2625	5120	2625	1320
Bunch interval in the Main Linac	t_b (ns)	369.2	189.2	369.2	480.0
in units of RF buckets		480	246	480	624
Average beam current in pulses	I (mA)	0.0	0.0	0.0	0.8

Normalized emittance at IP	$\gamma\epsilon_x^*$ (mm·mrad)		10	10	10	10
Normalized emittance at IP	$\gamma\epsilon_y^*$ (mm·mrad)		0.04	0.03	0.08	0.036

Beta function at IP	β_y^* (mm)	0.4	0.2	0.6	0.2
R.m.s. beam size at IP	σ_x^* (nm)	639	474	474	474
R.m.s. beam size at IP	σ_y^* (nm)	5.7	3.5	9.9	3.8
R.m.s. bunch length	σ_z (μm)	300	200	500	200
Disruption parameter	D_x	0.17	0.11	0.52	0.21
Disruption parameter	D_y	19.4	14.6	24.9	26.1
Beamstrahlung parameter	Υ_{ave}	0.048	0.050	0.038	0.097
Energy loss by beamstrahlung	δ_{BS}	0.024	0.017	0.027	0.055
Number of beamstrahlung photons	n_γ	1.32	0.91	1.77	1.72
Luminosity enhancement factor	H_D	1.71	1.48	2.18	1.64
Geometric luminosity	\mathcal{L}_{geo} $10^{34}/\text{cm}^2/\text{s}$	1.20	1.35	0.94	1.21
Luminosity	\mathcal{L} $10^{34}/\text{cm}^2/\text{s}$	2	2	2	2

At 5 GeV:

- $\epsilon_x = 1 \text{ nm}$
- $\epsilon_y = 4 \text{ pm}$

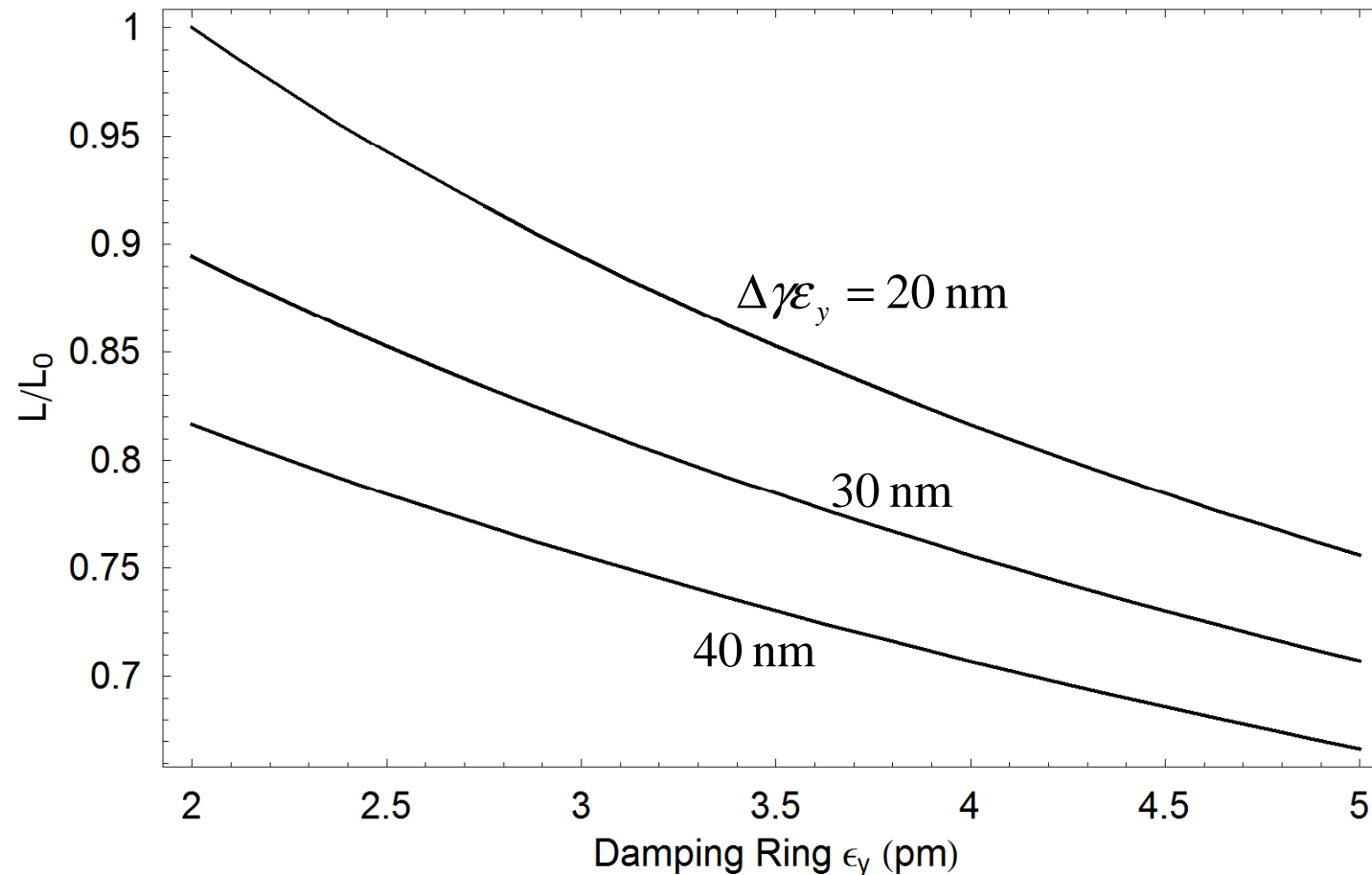
...but we need to allow for "dilution" between damping rings and IP.

ILC Reference Design Report, 2007

Baseline ILC specifications

- Between the damping ring and the interaction point, many effects will degrade the emittance.
 - dispersion; betatron coupling; single-bunch and multi-bunch wake fields; cavity tilts.
 - In the KEK-ATF, significant emittance growth has been observed in the extraction process itself.
- Extensive simulation efforts over the years have led to the goal of a maximum vertical emittance dilution $\Delta\gamma\epsilon_y < 20$ nm (expected to be roughly additive).
- The geometric emittance (ϵ_y) in the damping rings should be less than 2 pm, at full beam current (400 mA), with minimal tuning requirements over days and weeks.

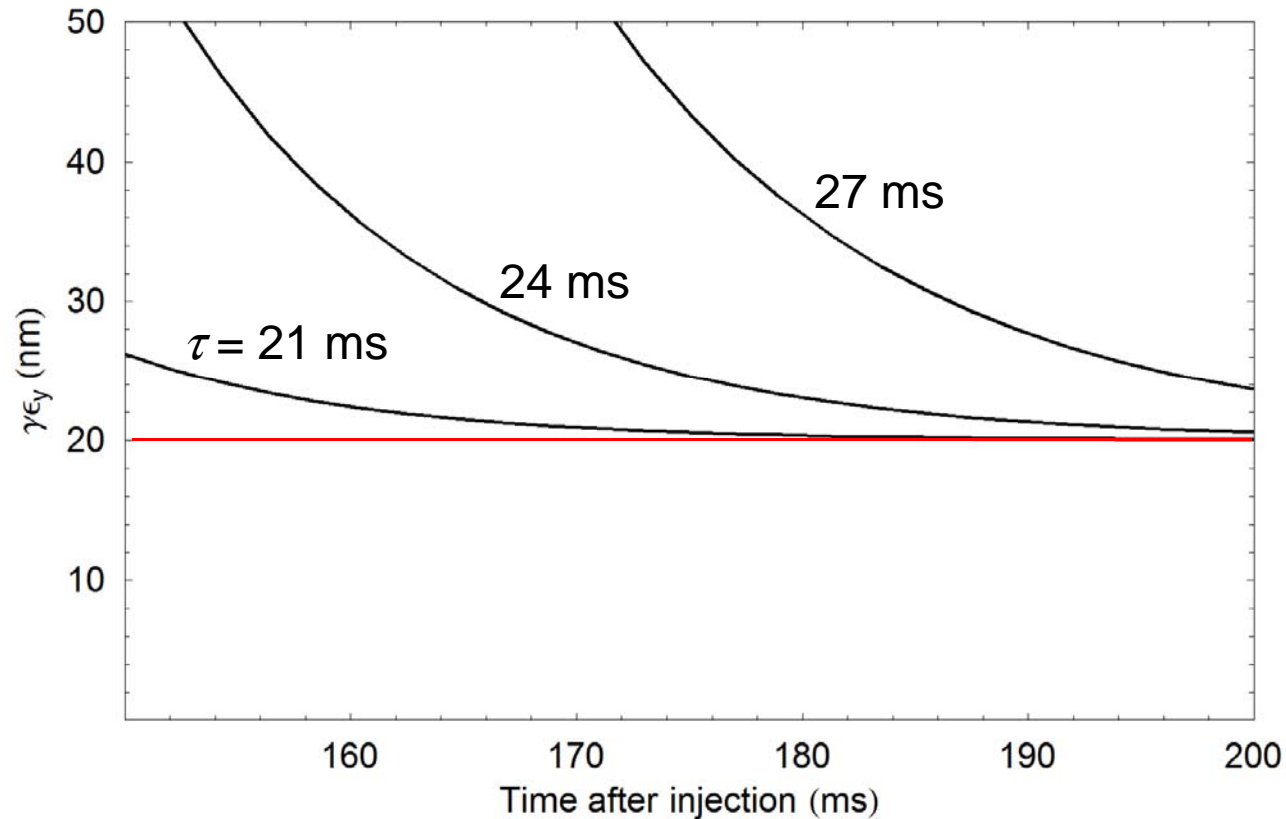
Luminosity is sensitive to DR emittance



Assumptions: L_0 is the Nominal luminosity; emittance dilution is purely additive; both beams have the same emittance; enhancement factor is constant.

Damping time ≤ 21 ms is needed

$$\varepsilon(t) = \varepsilon(0) \exp\left(-2\frac{t}{\tau}\right) + \varepsilon(\infty) \left[1 - \exp\left(-2\frac{t}{\tau}\right)\right]$$



Assumption: $\varepsilon(0) = 0.01$ m.

We need < 2 pm: how hard can it be?

- Storage rings generally do not push for the lowest possible emittance, since this reduces beam lifetime.
- Nevertheless, attempts are often made to minimize the coupling, as part of an overall strategy for machine tuning. Some examples:

Machine	Energy	Circumference	ϵ_x	ϵ_y	Reference
SPring-8	8 GeV	1436 m	6 nm	~ 5 pm	Tanaka et al, EPAC00
ALS	1.9 GeV	196 m	6.8 nm	4 - 7 pm	Steier et al, PAC03
DIAMOND	3 GeV	561 m	2.7 nm	< 5 pm	Martin et al, PAC07
SOLEIL	2.75 GeV	354 m	3.7 nm	< 5 pm	Nadji et al, PAC07
ATF	1.28 GeV	138 m	1 nm	~ 4 pm	Honda et al, PRL 81, 4388-4391 (2004)
SLS	2.4 GeV	288 m	6 nm	3.2 pm	Andersson et al, NIMPR-A, 591, 437-446 (2008)

Which emittance: geometric or normalised?

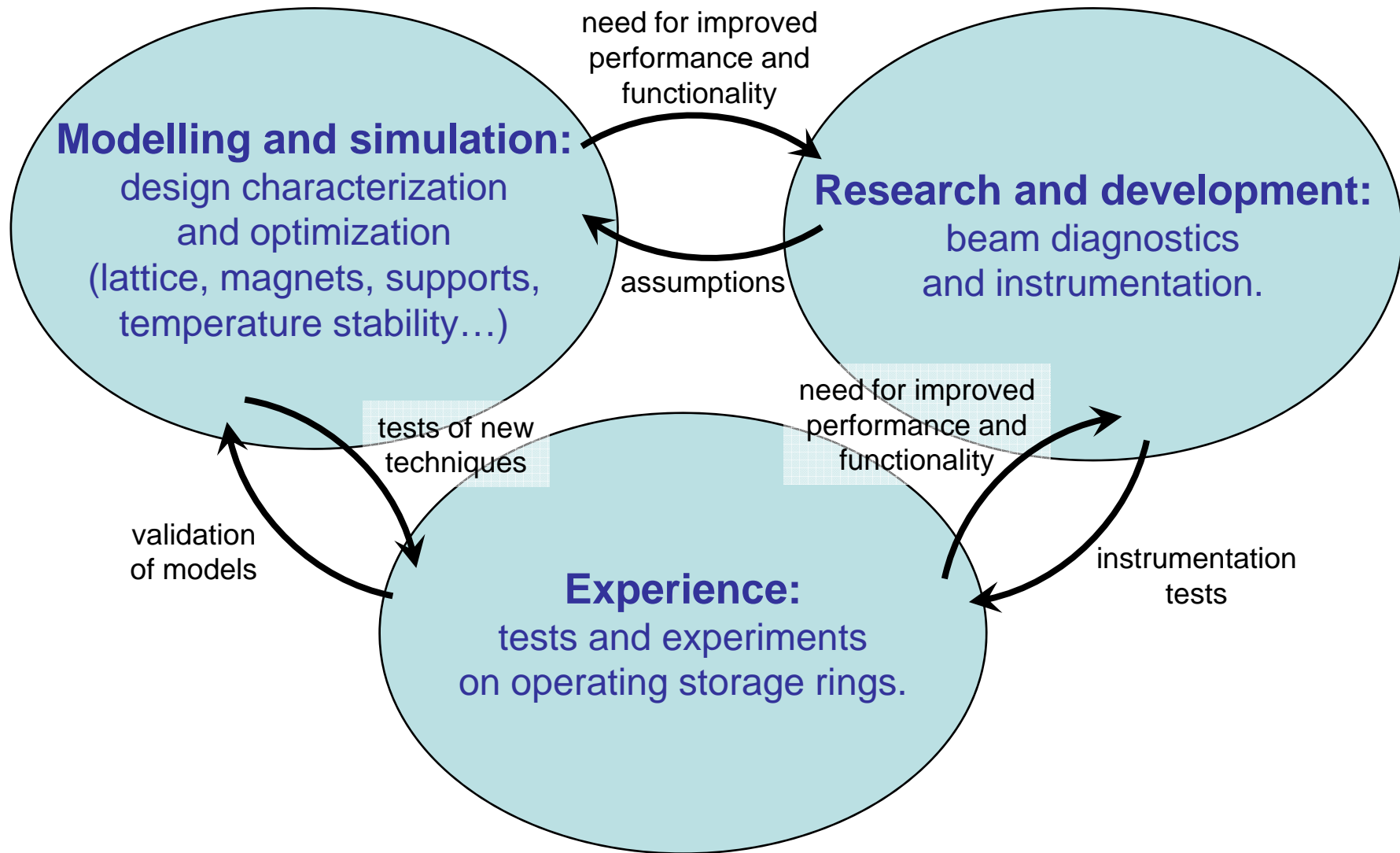
Machine	Energy	ϵ_y	$\gamma\epsilon_y$
SPring-8	8 GeV	~ 5 pm	80 nm
DIAMOND	3 GeV	< 5 pm	29 nm
SOLEIL	2.75 GeV	< 5 pm	27 nm
ILC DR (specified)	5 GeV	2 pm	20 nm
ALS	1.9 GeV	4 - 7 pm	~ 15 nm
SLS	2.4 GeV	3.2 pm	15 nm
ATF	1.28 GeV	~ 4 pm	10 nm
CLIC DR (specified)	2.4 GeV	0.7 pm	3.3 nm

- How do we fairly assess the level of difficulty of achieving a specified emittance in a storage ring design?

Vertical emittance in a storage ring

- The equilibrium vertical emittance depends on a wide variety of factors:
 - vertical steering, e.g. from quadrupole misalignments;
 - sextupole misalignments;
 - quadrupole tilts;
 - steering and skew quadrupoles designed to compensate for magnet misalignments;
 - magnet strengths and lattice optics;
 - beam energy, horizontal and longitudinal emittance, and tunes;
 - collective effects, such as wake fields, intrabeam scattering, space charge, electron cloud and ion effects...
- Every storage ring is unique, and all the above effects vary with time over different time scales.

The three-pronged approach



Modeling and simulation

- Computer models can include (nearly) all important effects.
 - Magnet alignment; instrumentation errors and performance limitations; coupling correction systems.
- Building a model that corresponds to some reality is often a challenge.
 - There are many important details: magnet girders and supports; BPM supports; ground motion...
- Some important effects are rarely included.
 - Temperature variations; collective effects.

Goals of low-emittance tuning simulations

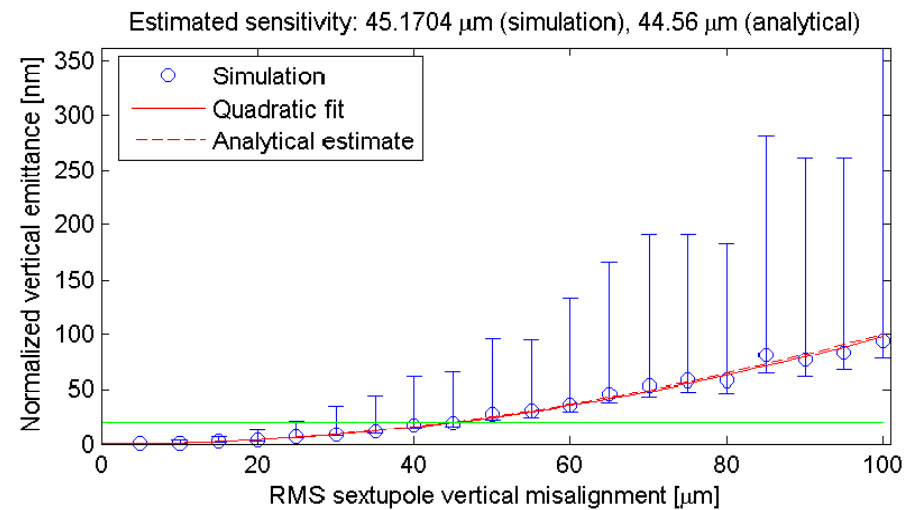
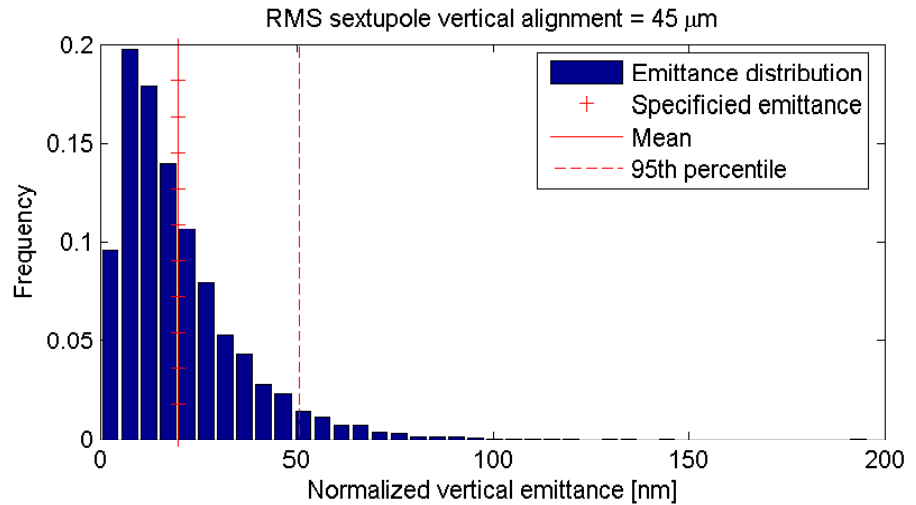
- To characterise the sensitivity of the vertical emittance in a given lattice to various errors.
- To compare different tuning techniques and specify the necessary conditions for each to achieve the specified vertical emittance.
- To help identify the requirements for further research and development.
- To indicate potential design improvements and cost savings.

Goals of low-emittance tuning simulations

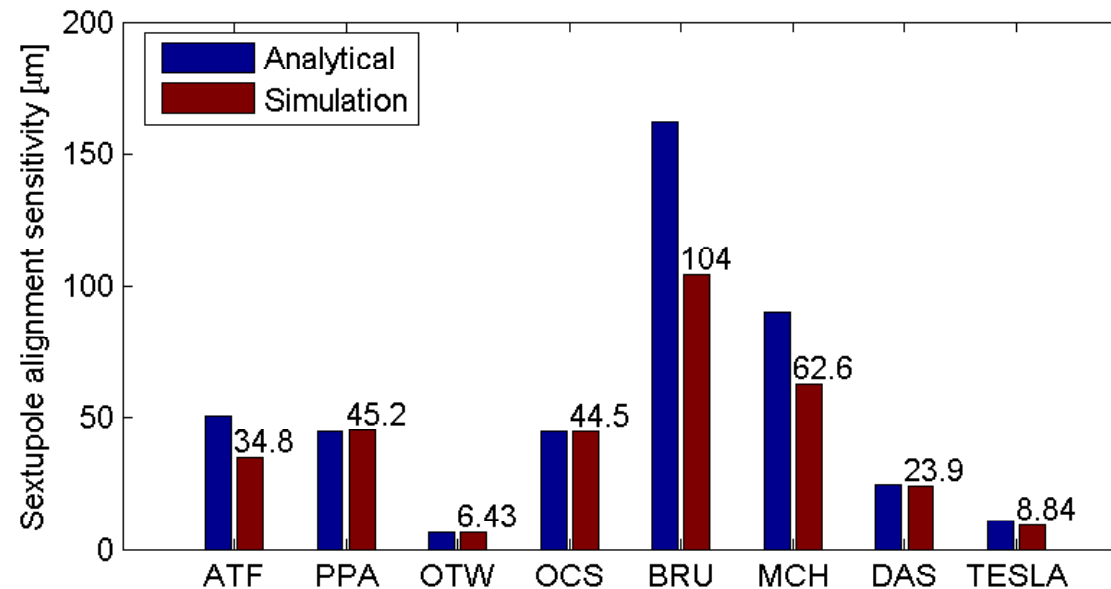
An example from the Configuration Studies Report (2006):

Sensitivity of the PPA lattice to random vertical misalignments of the sextupoles.

$$\frac{\epsilon_y}{\langle y_{sext}^2 \rangle} \approx \frac{J_x [1 - \cos 2\pi\nu_x \cos 2\pi\nu_y]}{4J_y [\cos 2\pi\nu_x - \cos 2\pi\nu_y]^2} \epsilon_x \sum_{sexts} \beta_x \beta_y (k_2 L)^2 + \frac{J_z \sigma_\delta^2}{4 \sin^2 \pi\nu_y} \sum_{sexts} \beta_y \eta_x^2 (k_2 L)^2$$



Goals of low-emittance tuning simulations



- The simulations allow us to compare the sensitivity of various lattice designs to errors of a particular kind...
- ...but are the results from such an "idealised" model meaningful?

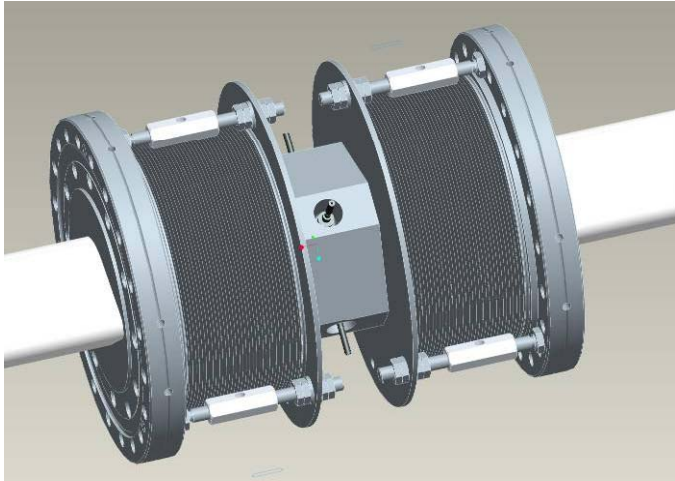
Goals of low-emittance tuning simulations

- There are many techniques in use for optics and coupling correction. Most of them are variations on:
 - orbit response matrix analysis: minimise the vertical orbit response to changes in horizontal steering, and vice-versa.
 - phase advance analysis: characterise the optics from turn-by-turn beam data collected simultaneously at a number of BPMs.
- Often, the techniques in use are tailored to some extent for a particular machine, to take into account special features of the optics or instrumentation.
- Which technique, or combination of techniques, will be most appropriate for use in the ILC damping rings? What are the requirements and optimal conditions for application of this technique? What are the practical limits?

Instrumentation research and development

- Performance of the instrumentation will be critical for achieving 2 pm vertical emittance.
- Issues include:
 - design of the BPM buttons: chamber aperture; shielding from radiation; trapped modes and HOM heating; impedance.
 - BPM electronics: modern digital receivers seem a promising solution, based on experience at ATF (good stability, good resolution in averaging and turn-by-turn modes).
 - instrumentation for fast measurement of micron-sized beams.

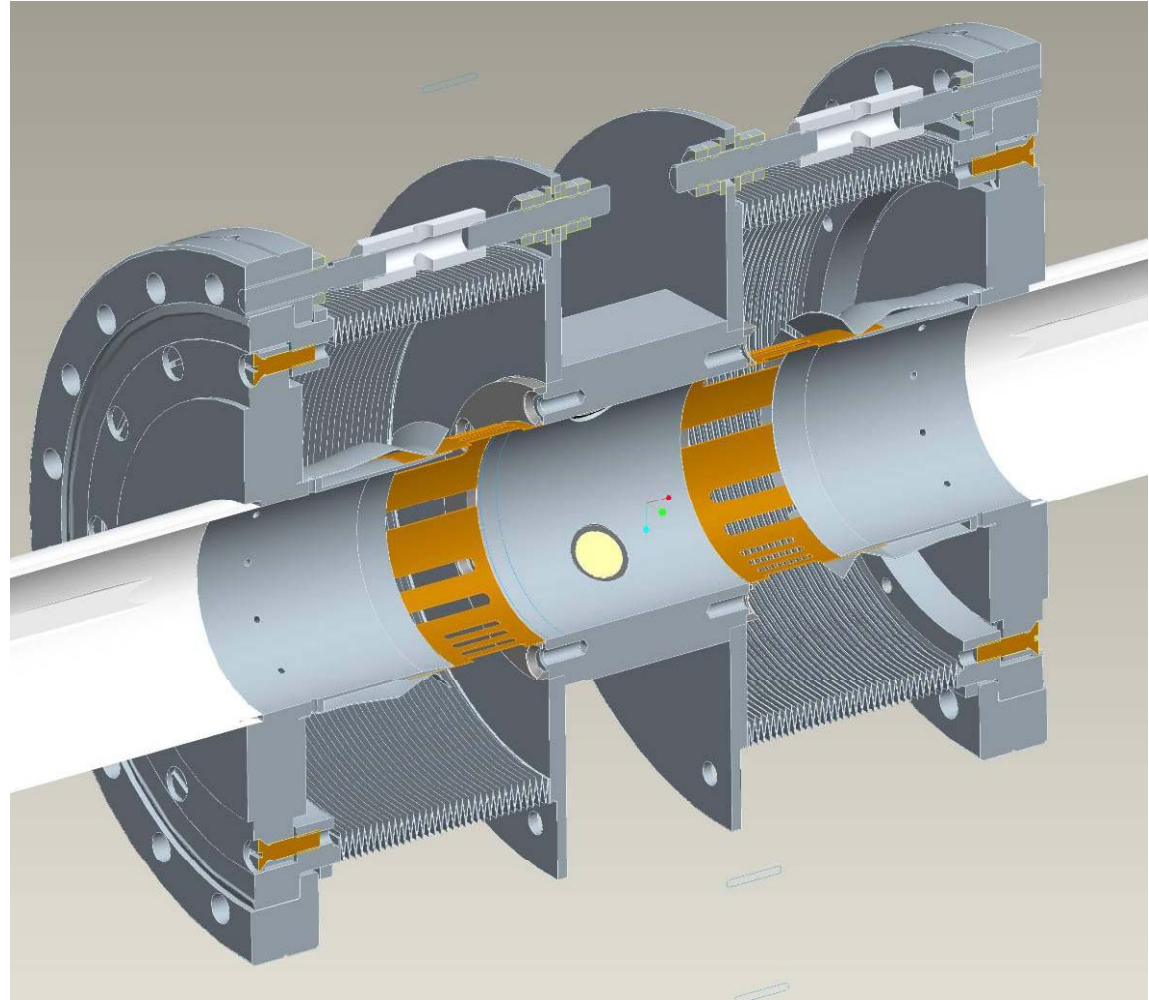
Preliminary technical design: BPM insertion



Bellows/BPM external view



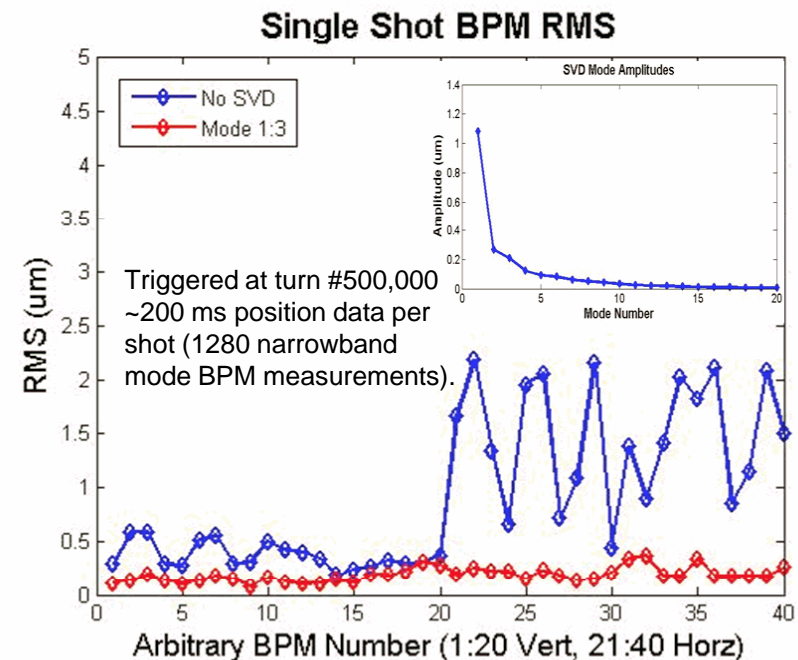
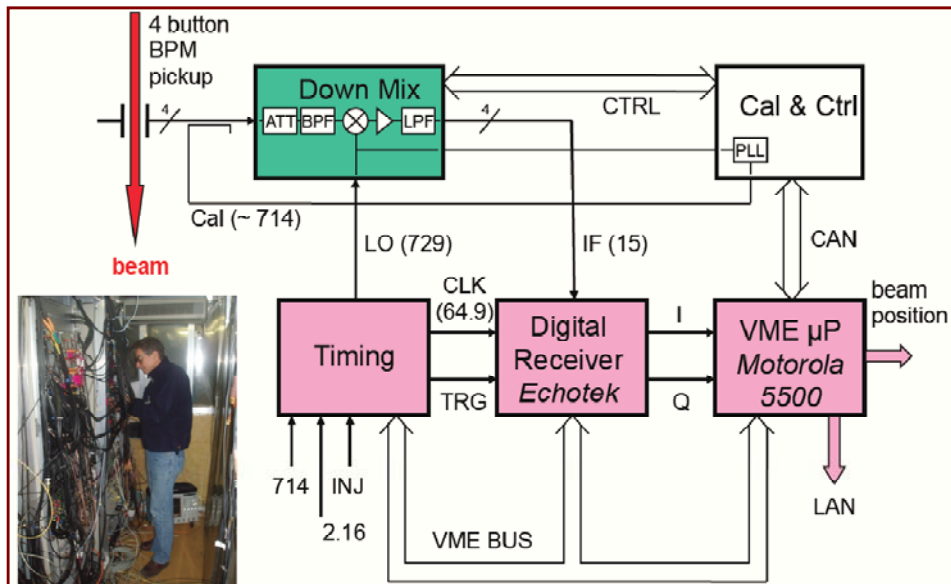
Antechamber taper (into BPM chamber)



Bellows/BPM internal view

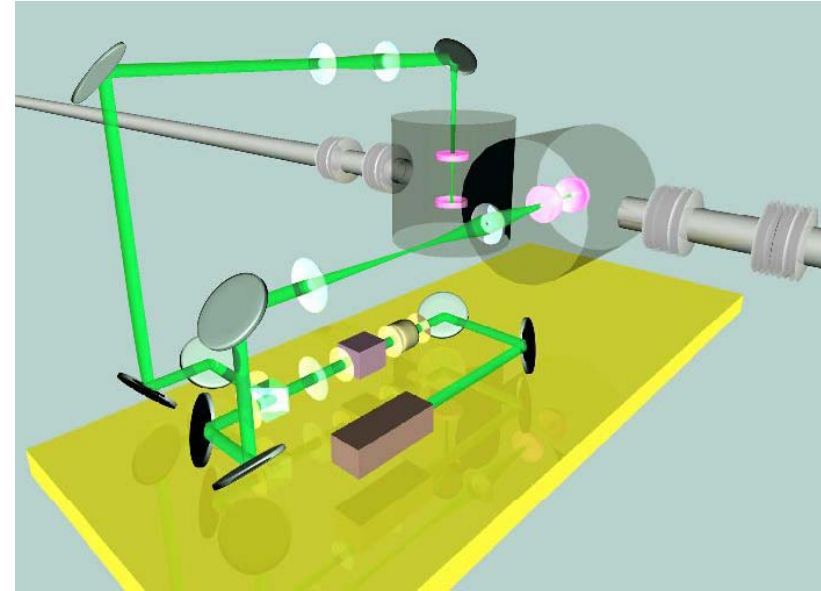
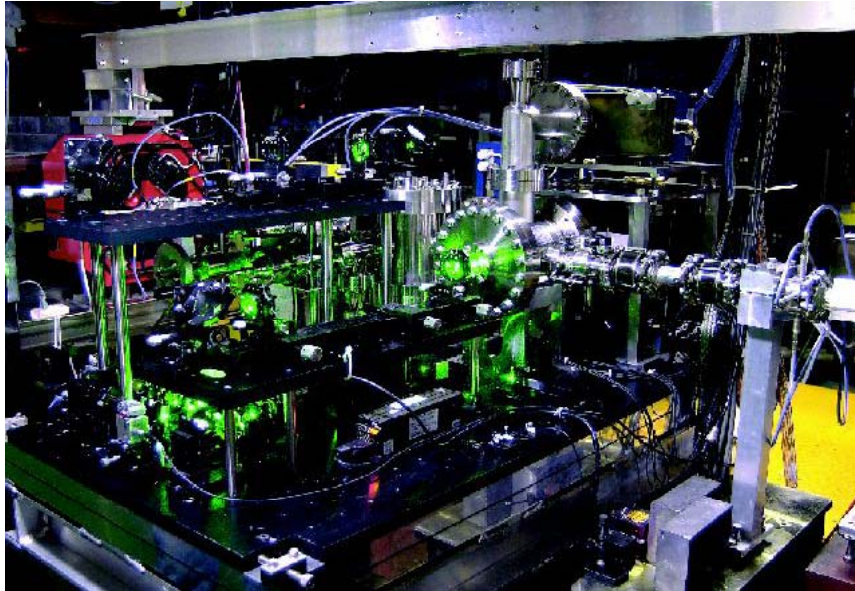
High performance electronics are available

- Digital receivers are becoming more widely used.
- Echotek modules are being tested at KEK-ATF, with very promising results so far.



Manfred Wendt (FNAL), et al

Laser wire beam size monitor at KEK-ATF



Y. Honda (KEK)

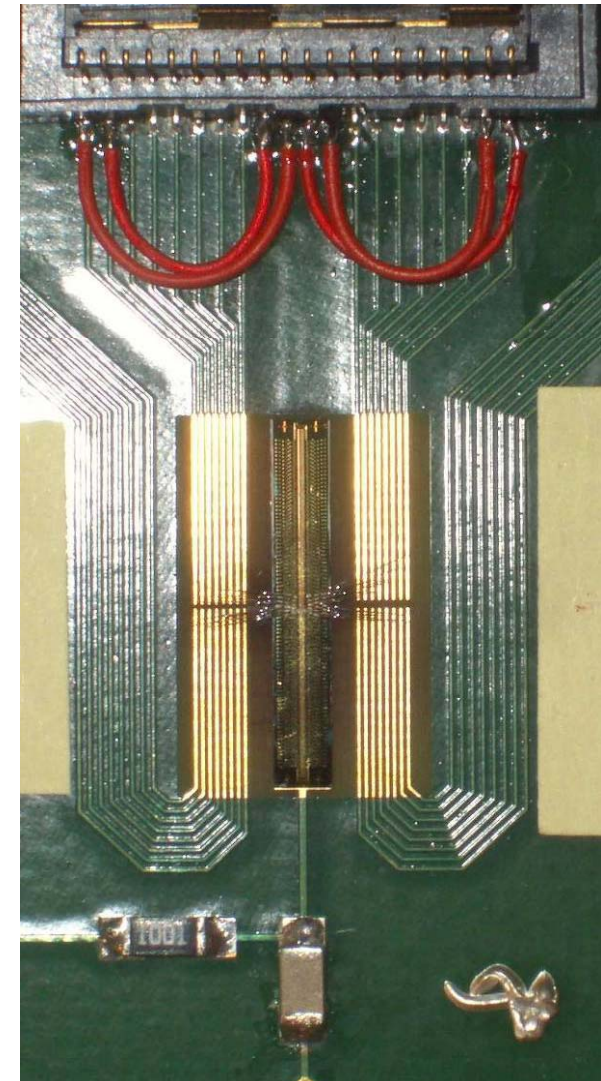
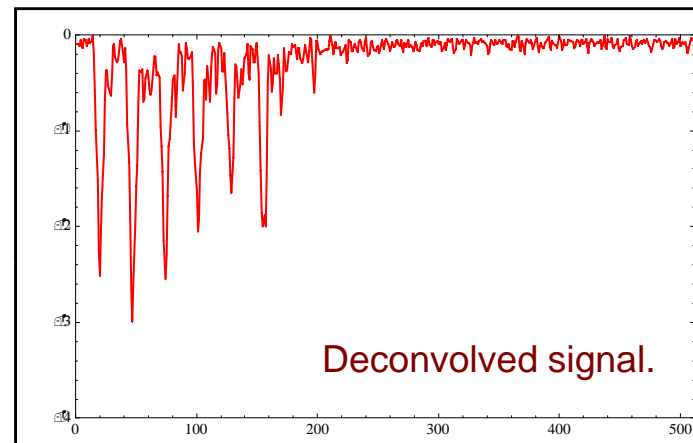
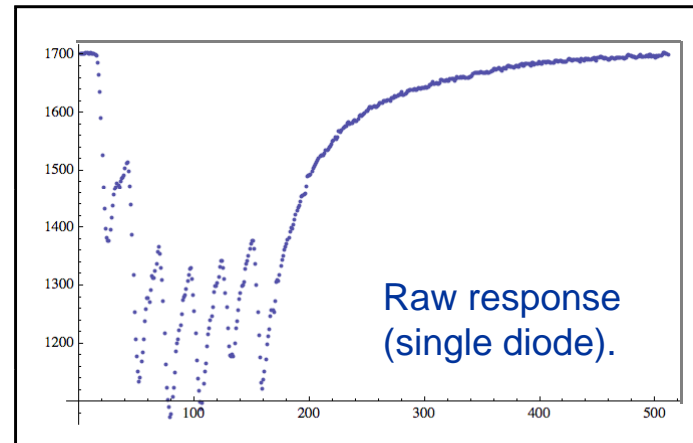
- Laser wire provides very high resolution measurement, but...
- ...measurement times can be slow. A beam size monitor with fast (turn-by-turn) time resolution could improve tuning efficiency and allow observation of jitter, instabilities etc.

Fast x-ray beam size monitor R&D at CEsrTA

1-D array GaAs/InGaAs photodiodes.
512 diodes, $25\mu\text{m} \times 500\mu\text{m}$; time resolution ~ 1 ns.

A turn-by-turn beam size monitor with micron resolution will provide capability for understanding and overcoming dynamical effects limiting emittance, such as intrabeam scattering, electron cloud and fast ion instability.

*Jim Alexander
(CLASSE)*



Machine experience: KEK-ATF

VOLUME 92, NUMBER 5

PHYSICAL REVIEW LETTERS

week ending
6 FEBRUARY 2004

Achievement of Ultralow Emittance Beam in the Accelerator Test Facility Damping Ring

Y. Honda,¹ K. Kubo,² S. Anderson,³ S. Araki,² K. Bane,³ A. Brachmann,³ J. Frisch,³ M. Fukuda,⁶ K. Hasegawa,¹⁴ H. Hayano,² L. Hendrickson,³ Y. Higashi,² T. Higo,² K. Hirano,¹³ T. Hirose,¹⁵ K. Iida,¹² T. Imai,⁹ Y. Inoue,⁷ P. Karataev,⁶ M. Kuriki,² R. Kuroda,⁸ S. Kuroda,² X. Luo,¹¹ D. McCormick,³ M. Matsuda,¹⁰ T. Muto,² K. Nakajima,² Takashi Naito,² J. Nelson,³ M. Nomura,¹³ A. Ohashi,⁶ T. Omori,² T. Okugi,² M. Ross,³ H. Sakai,¹² I. Sakai,¹³ N. Sasao,¹ S. Smith,³ Toshikazu Suzuki,² M. Takano,¹³ T. Taniguchi,² N. Terunuma,² J. Turner,³ N. Toge,² J. Urakawa,² V. Vogel,² M. Woodley,³ A. Wolski,⁴ I. Yamazaki,⁸ Yoshio Yamazaki,² G. Yocky,³ A. Young,³ and F. Zimmermann⁵

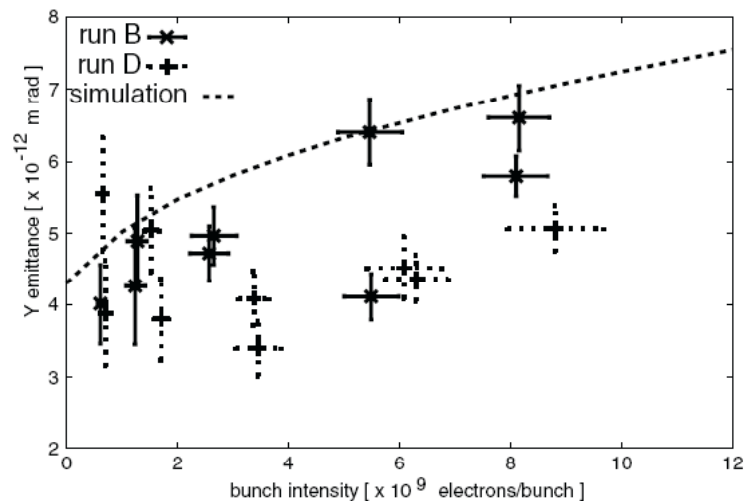


FIG. 2. Current dependence of the vertical emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

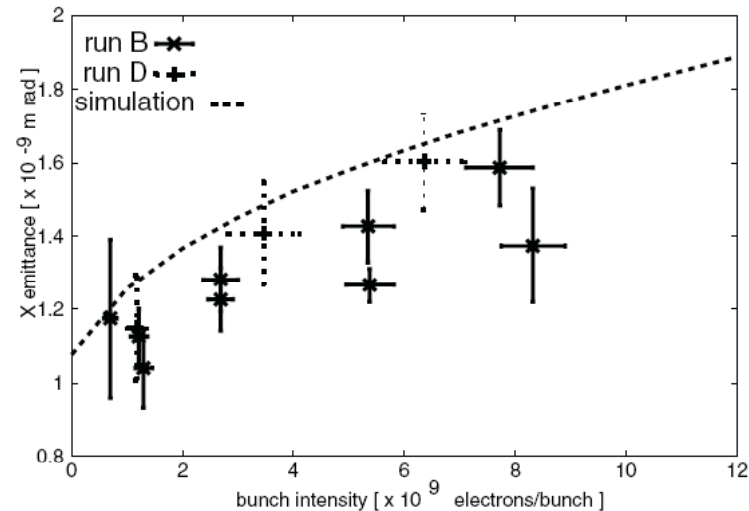
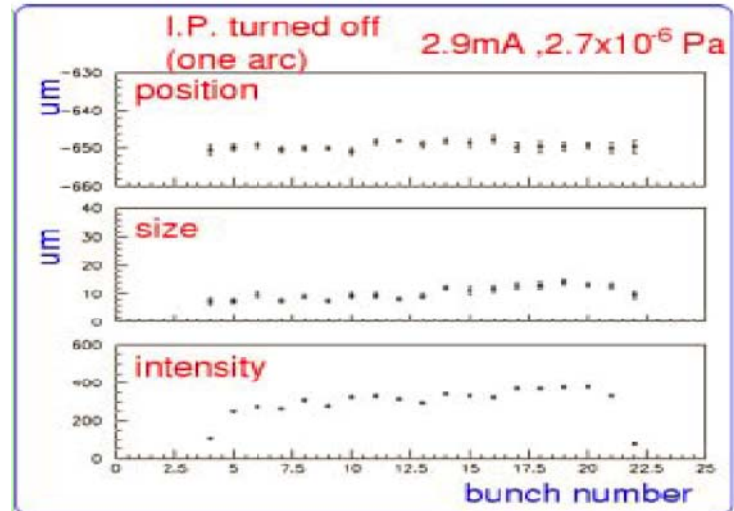
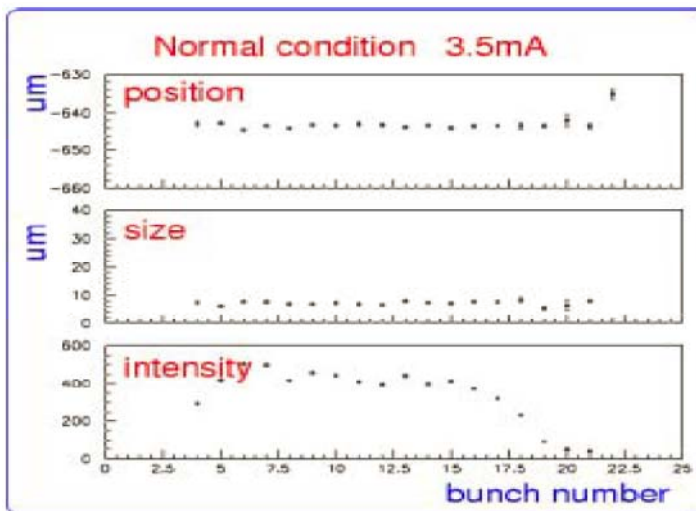
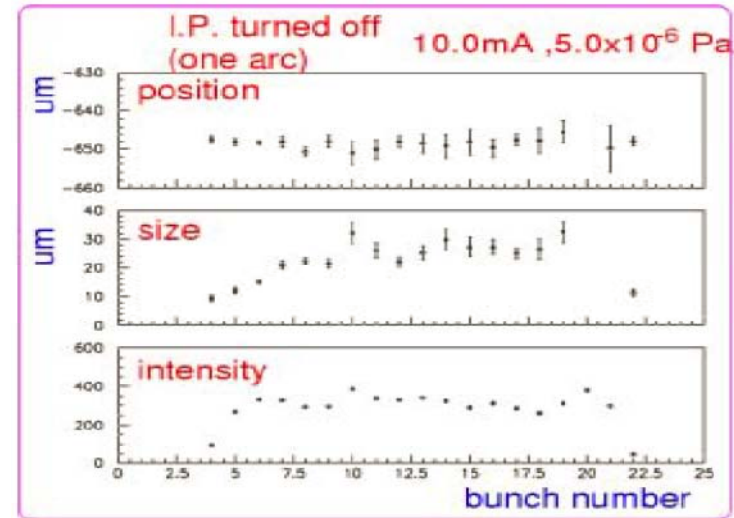
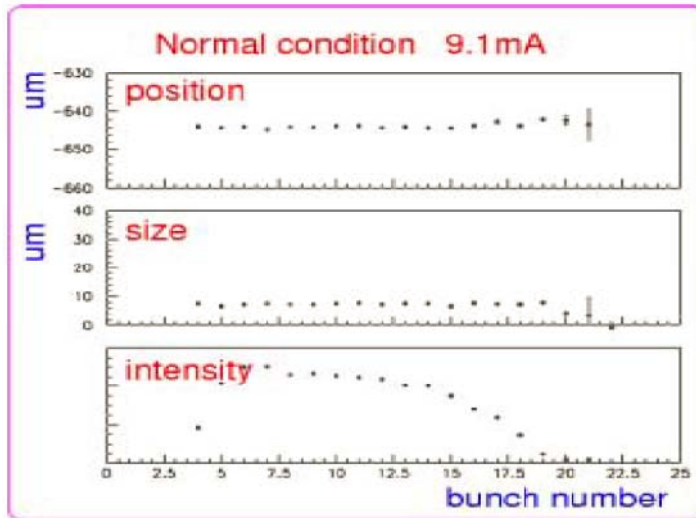
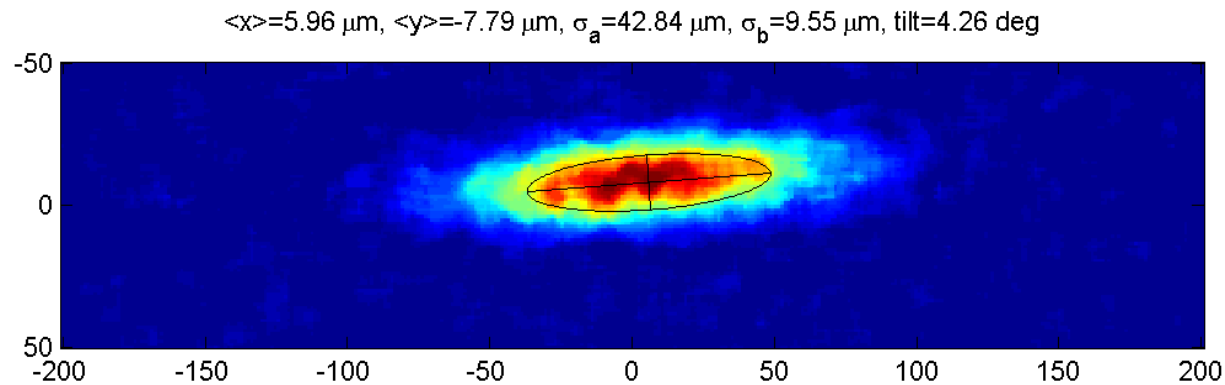


FIG. 3. Current dependence of the horizontal emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

Machine experience: KEK-ATF



Machine experience: KEK-ATF



- X-ray synchrotron radiation monitor image from ATF, May 2008.
- Vertical emittance 10 – 20 pm?
- Goals:
 - to demonstrate reliable operation with 2 pm vertical emittance;
 - to continue studies of fast ion effects.

Machine experience: the Swiss Light Source



Available online at www.sciencedirect.com



Nuclear Instruments and Methods in Physics Research A 591 (2008) 437–446

**NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH**
Section A

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Determination of a small vertical electron beam profile and emittance at the Swiss Light Source

Å. Anderjaska

Received 8 January 2008

The smallest vertical rms beam size determined to date is $\sigma_y = (6.47 \pm 0.5) \mu\text{m}$. For a low emittance tuning, the vertical rms beam emittance at the monitor was determined to be $\varepsilon_y = (3.2 \pm 0.7) \text{ pmrad}$ over a period of several days in 400 mA multi-bunch (0.98 nC/bunch) user top-up operation mode.

Abstract

We report on the small vertical electron beam profile and emittance at the Swiss Light Source (SLS) synchrotron radiation (SR), in the visible to ultra-violet (vis-UV) range, has been implemented to determine the vertical electron beam size. The paper describes in detail the beam size measurement method and discusses possible error contributions when deducing the corresponding emittance value. The smallest vertical rms beam size determined to date is $\sigma_{ey} = (6.4 \pm 0.5) \mu\text{m}$. For a low emittance tuning, the vertical rms beam emittance at the monitor was determined to be $\varepsilon_y = (3.2 \pm 0.7) \text{ pmrad}$ over a period of several days in 400 mA multi-bunch (0.98 nC/bunch) user top-up operation mode. The corresponding emittance ratio was $g = (0.05 \pm 0.02)\%$. The minimization of the vertical emittance was also demonstrated to be of a global nature.

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Machine experience: the Swiss Light Source

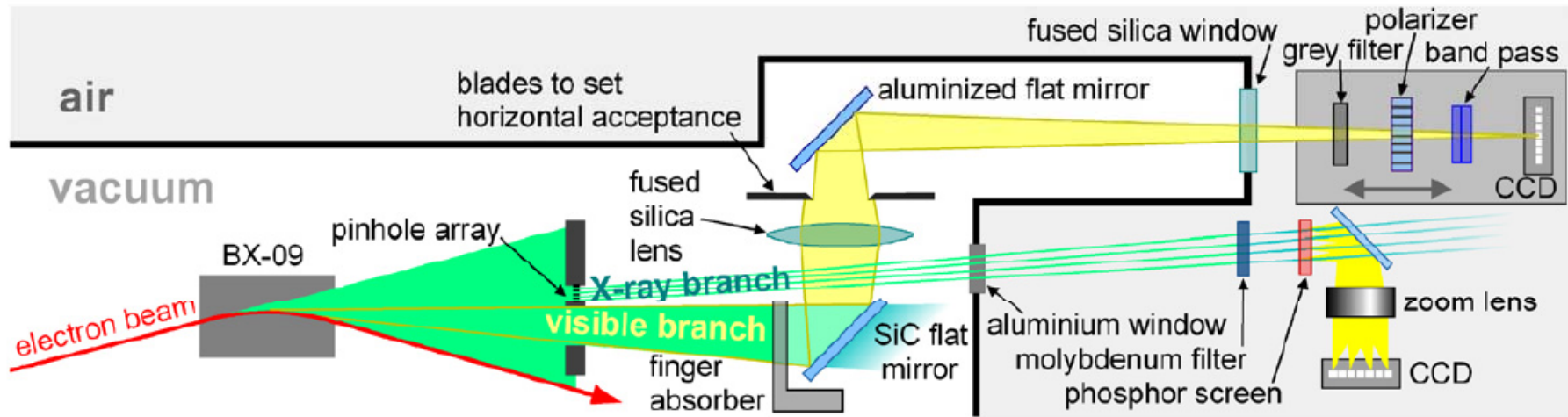


Fig. 1. Top view of the diagnostic beamline, showing the X-ray branch with pinhole array and the vis-UV branch.

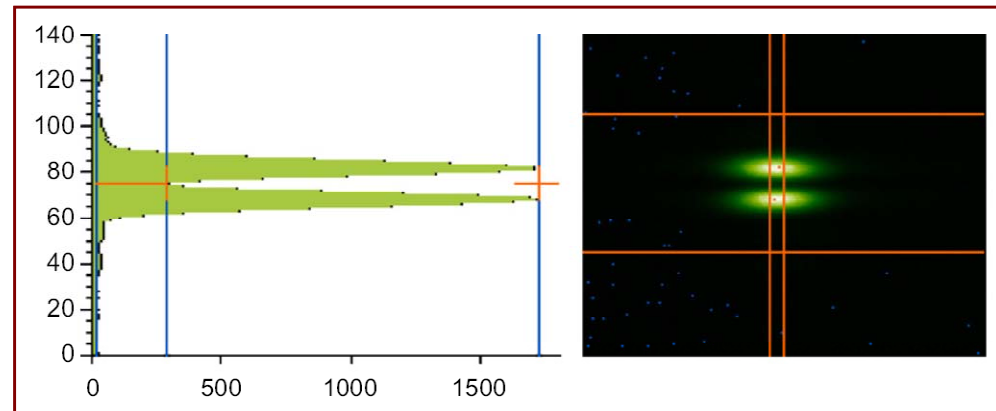


Fig. 4. Image from the vis-UV branch using vertically polarized light at 364 nm wavelength and 3.9/9.0 mrad horizontal/vertical acceptance angle. The scales are in pixel units, while the X_{sig} and Y_{sig} values are the derived rms electron beam sizes. Machine conditions: 350 mA in user top-up operation.

Machine experience: the Swiss Light Source

- “Several factors...are crucial to achieving a small emittance beam:
 - tight magnet alignment and roll tolerances due to a rigid mount on precision machined girders;
 - a reliable BPM system, providing sub-micron resolution;
 - refined and frequently repeated beam-based offset corrections of BPM readings (to within a few microns);
 - a large number of vertical BPMs and associated correctors;
 - a fast orbit feedback system;
 - frequent beta function measurements and corrections;
 - thermal stability due to top-up operation.”

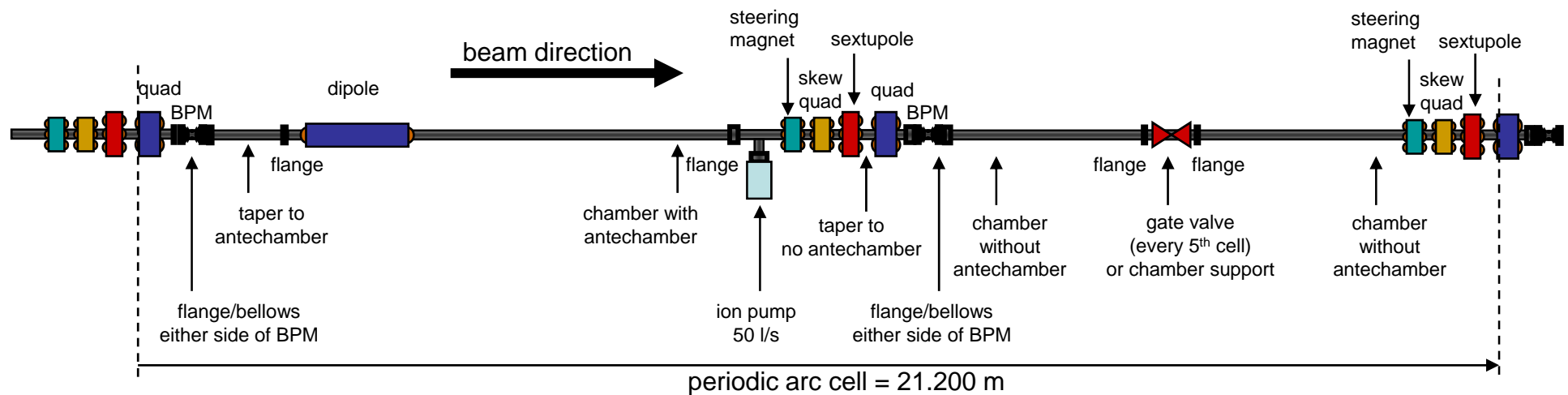
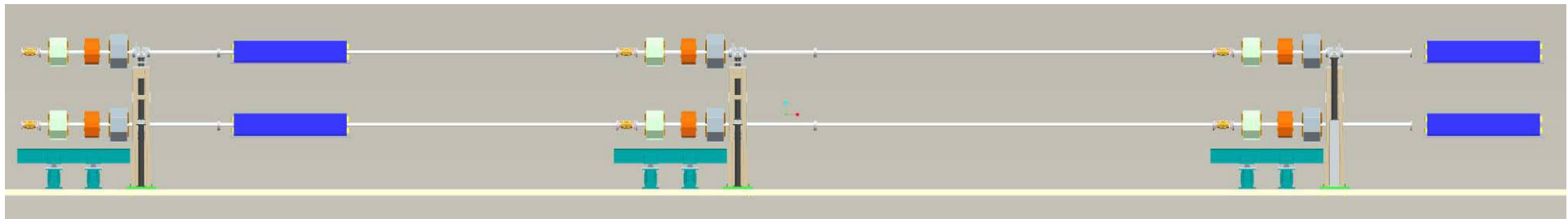
A. Andersson et al, Nucl. Inst. Meth. Phys. Res. A 591 (2008) 437-446.

Goals for the ILC Technical Design Phase

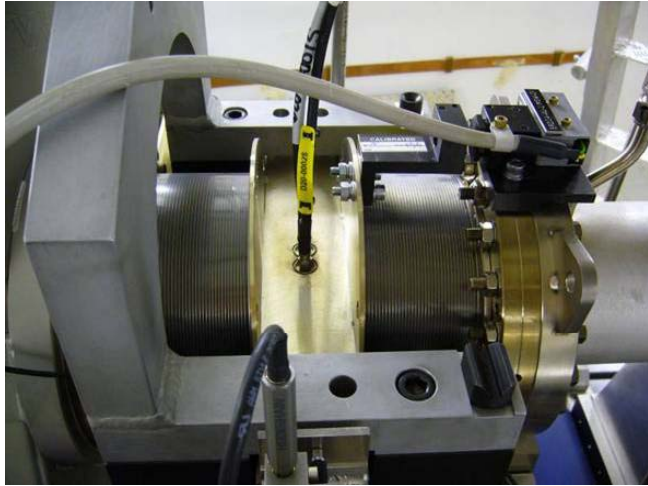
- To achieve reliable operation of CesrTA with vertical emittance < 10 pm, to allow studies of electron cloud in a regime directly relevant for the ILC damping rings.
- To demonstrate reliable operation of a storage ring with 2 pm vertical emittance.
- To specify and develop the instrumentation necessary for routine operation of the ILC damping rings with 2 pm vertical emittance.
- To specify and develop a technical design for the damping rings, capable of routine operation at 2 pm vertical emittance, for the lowest possible cost.

Baseline lattice includes correction elements

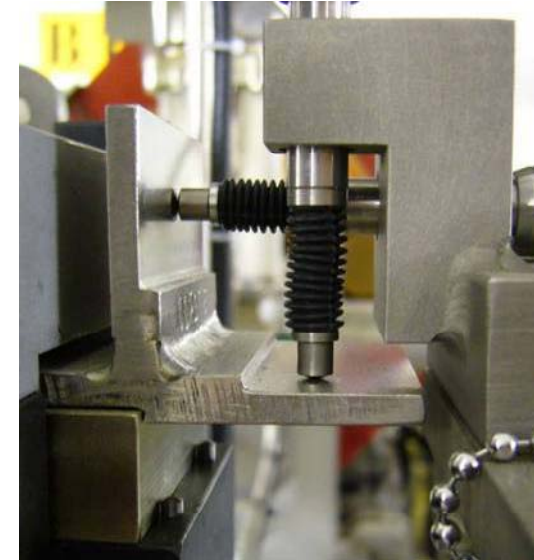
- Every quadrupole in the deck is accompanied by a BPM and a steering magnet (orbit correction).
- Every sextupole is accompanied by a skew quadrupole.



Design work: building on experience



BPM and bellows chamber

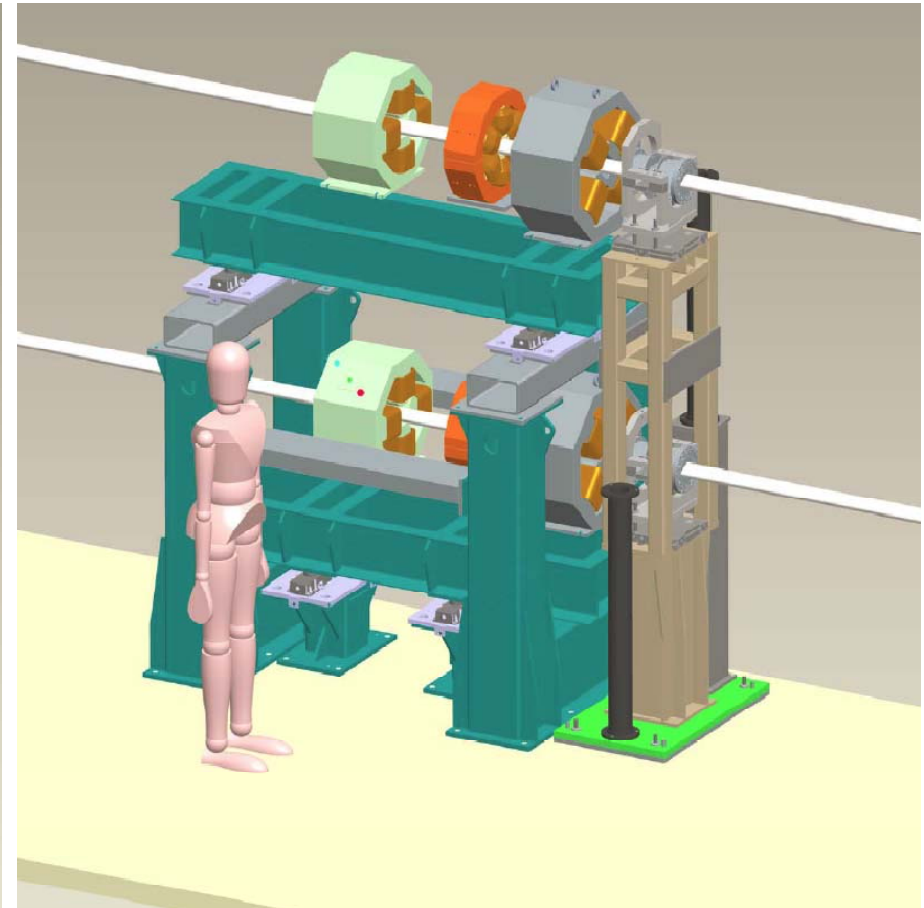
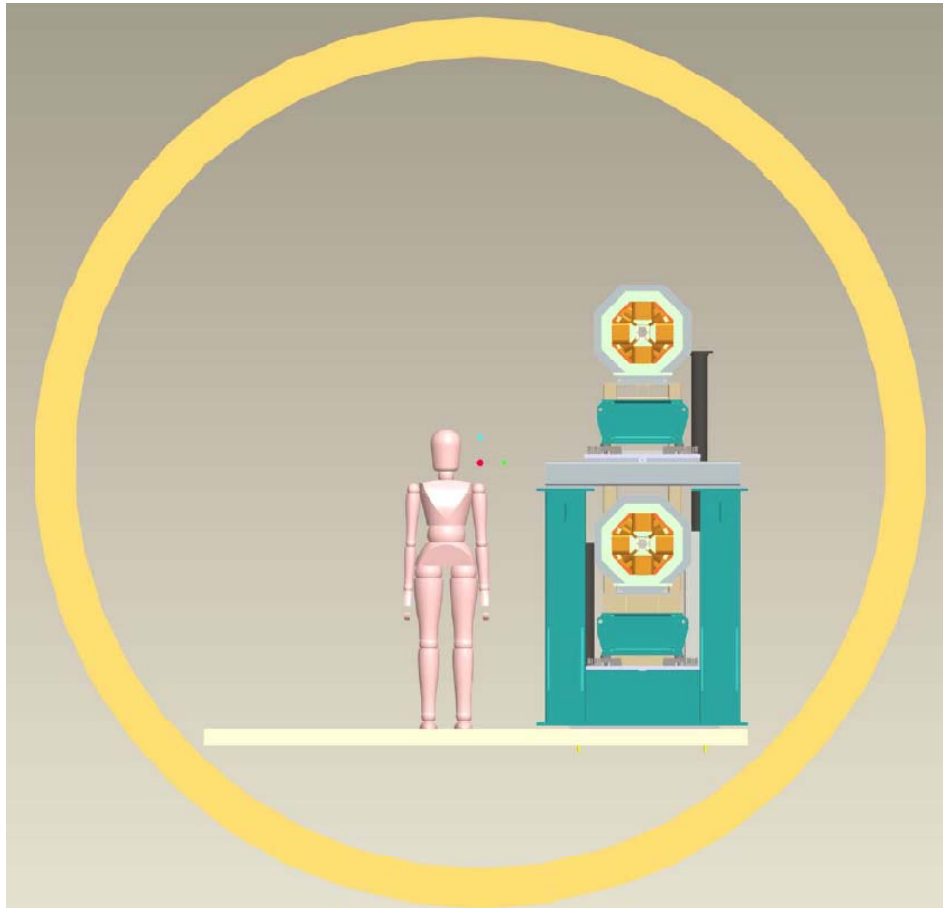


Linear encoders to monitor BPM position with respect to reference pillar

*Courtesy,
DIAMOND Light Source*

Reference pillar supporting linear encoders

Design work: building on experience



John Lucas, Alan Grant (STFC Technology), Oleg Malyshev (STFC ASTeC)

Workshop: Charge to the LET Working Group

The charge to the LET working group is to:

- evaluate the status of optics correction and emittance tuning techniques;
- to review emittance measurement techniques that will be needed for damping ring optimization;
- and to review the world-wide experimental program in low emittance tuning.

The group should, in particular, provide an evaluation of contributions that can be made as part of the CesrTA program and comment on how the efforts at various facilities world-wide can work together to provide confidence in the ILC and CLIC damping ring designs.

Workshop: Working Group Schedule

Wednesday 9:15 – 12:00	Instrumentation and measurement techniques	X-ray SR monitor at ATF AC dispersion measurement Beam-based survey and alignment of ring magnets Experience with Echotek digital receivers
Wednesday 14:00 – 15:30	Machine experience	Coupling correction at the Australian Synchrotron Optics modeling and low-e tuning: PEP-II experience Recent orbit response matrix studies at ATF
Thursday 9:15 – 9:45	Modeling and plans for future machines	Low-emittance tuning at NSLS-II Simulations of orbit and dispersion correction in the TDP baseline lattice
Thursday 11:00 – 12:30	Modeling and plans for CEsrTA	Optics modeling of CEsrTA Optics correction of CEsrTA Beam-based alignment of BPMs with ORM and coupling measurements at CEsrTA
Thursday 14:00 – 15:00	Discussion	Answering open questions