# 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 $\sigma_y << \sigma_x$.
- Minimum value of $\beta_y^*$ is limited by the hour-glass effect… so we need $\varepsilon_y$ as small as possible.

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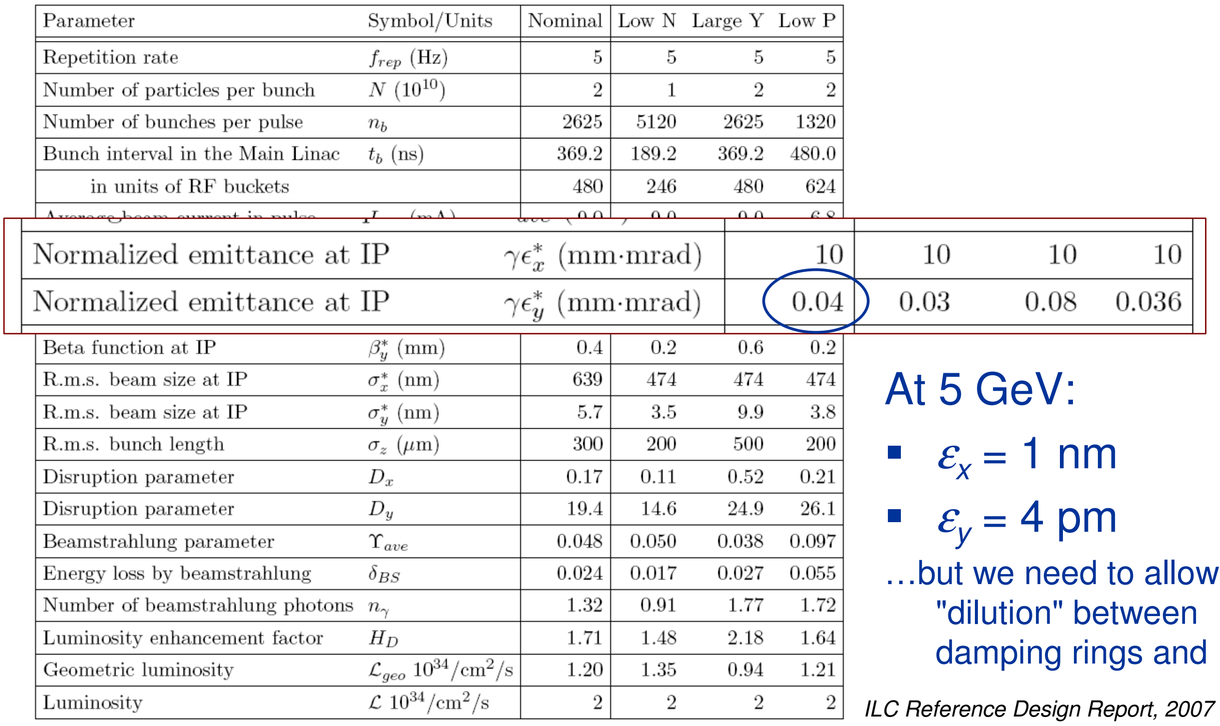
# Baseline ILC specifications



| 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 pulse | $I_{ave}$ (mA) | [illegible] | [illegible] | [illegible] | [illegible] |
| 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 | $\beta_y^*$ (mm) | 0.4 | 0.2 | 0.6 | 0.2 |
| R.m.s. beam size at IP | $\sigma_x^*$ (nm) | 639 | 474 | 474 | 474 |
| R.m.s. beam size at IP | $\sigma_y^*$ (nm) | 5.7 | 3.5 | 9.9 | 3.8 |
| R.m.s. bunch length | $\sigma_z$ ($\mu$m) | 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 | $\Upsilon_{ave}$ | 0.048 | 0.050 | 0.038 | 0.097 |
| Energy loss by beamstrahlung | $\delta_{BS}$ | 0.024 | 0.017 | 0.027 | 0.055 |
| Number of beamstrahlung photons | $n_\gamma$ | 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:

- $\varepsilon_x$ = 1 nm
- $\varepsilon_y$ = 4 pm

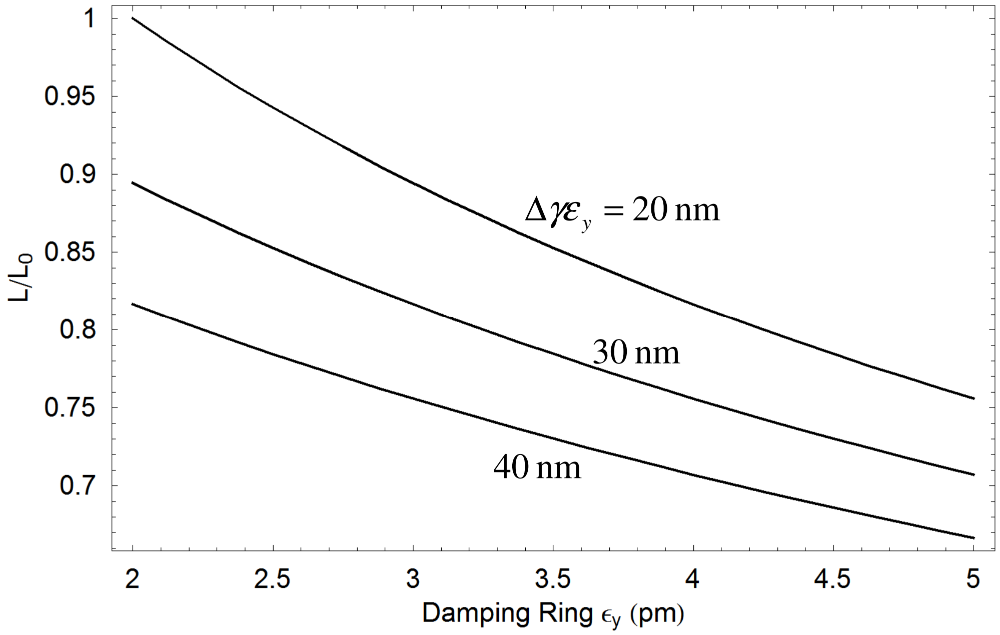
…but we need to allow for "dilution" between damping rings and IP.

*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 $\Delta\gamma\varepsilon_y < 20$ nm (expected to be roughly additive).
- The geometric emittance ($\varepsilon_y$) in the damping rings should be less than 2 pm, at full beam current (400 mA), with minimal tuning requirements over days and weeks.

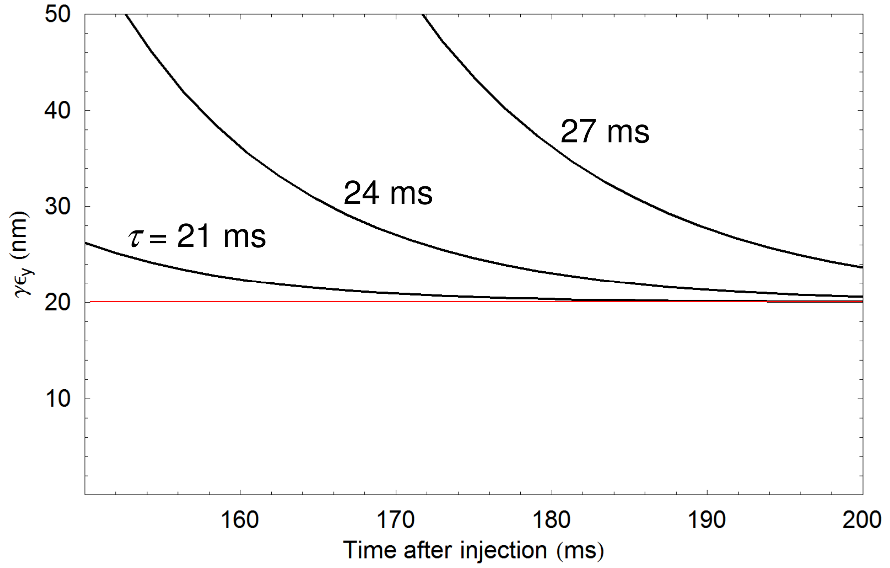
# Luminosity is sensitive to DR emittance



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.

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# 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 | $\varepsilon_x$ | $\varepsilon_y$ | 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?

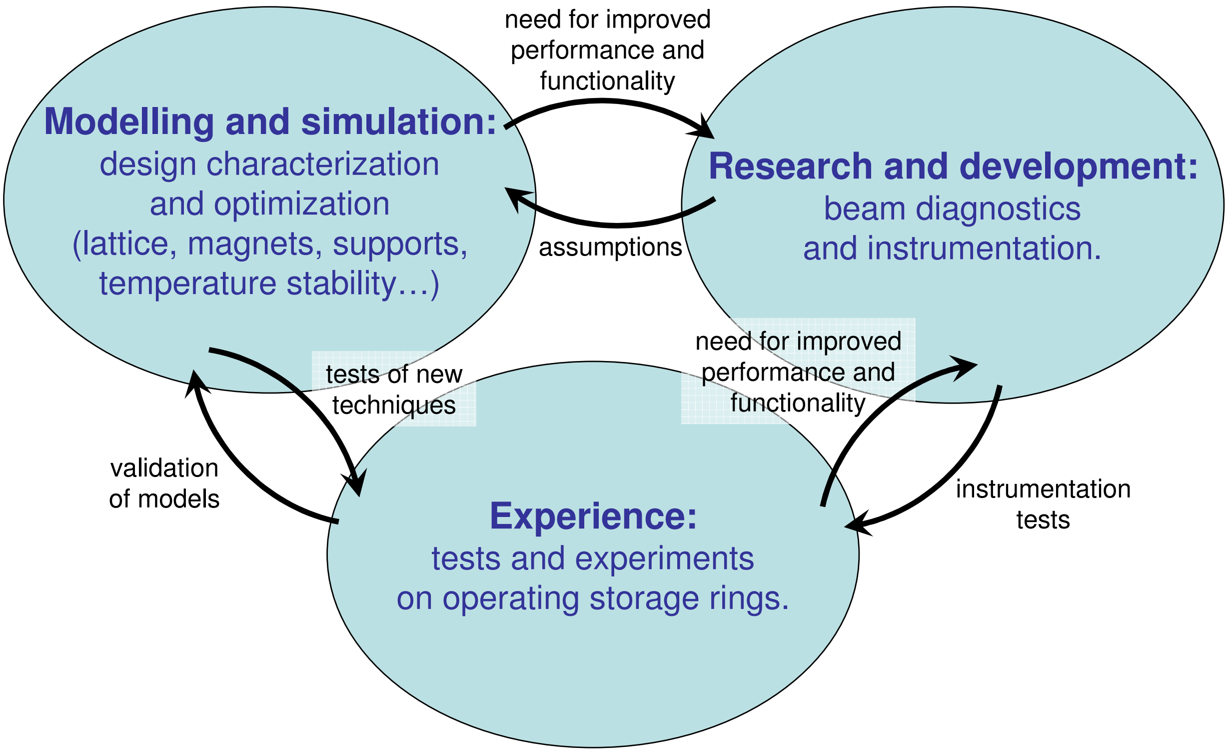
| Machine | Energy | $\varepsilon_y$ | $\gamma\varepsilon_y$ |
|---|---|---|---|
| SPring-8 | 8 GeV | ~ 5 pm | 80 nm |
| DIAMOND | 3 GeV | < 5 pm | 29 nm |
| SOLEIL | 2.75 GeV | < 5 pm | 27 nm |
| ILC DR (specified) | 5 GeV | 2 pm | 20 nm |
| ALS | 1.9 GeV | 4 - 7 pm | ~ 15 nm |
| SLS | 2.4 GeV | 3.2 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



**Modelling and simulation:**
design characterization
and optimization
(lattice, magnets, supports,
temperature stability…)

need for improved
performance and
functionality

assumptions

**Research and development:**
beam diagnostics
and instrumentation.

tests of new
techniques

validation
of models

need for improved
performance and
functionality

instrumentation
tests

**Experience:**
tests and experiments
on operating storage rings.

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# 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.

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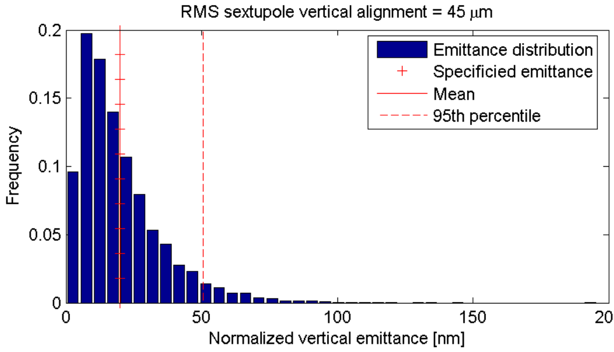
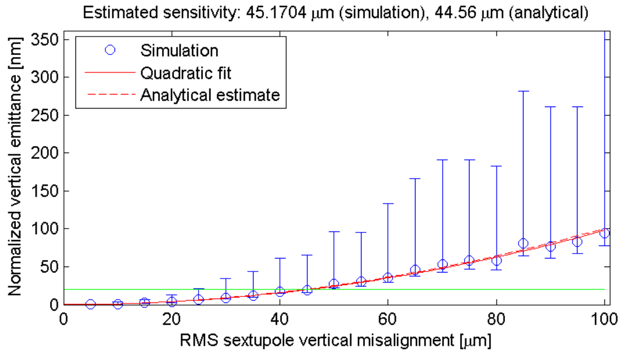
# Goals of low-emittance tuning simulations

An example from the Configuration Studies Report (2006):

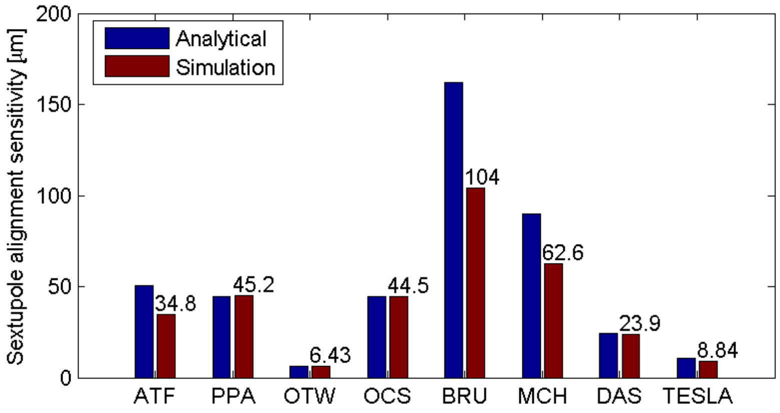
Sensitivity of the PPA lattice to random vertical misalignments of the sextupoles.





$$\frac{\epsilon_y}{\langle y^2_{sext}\rangle} \approx \frac{J_x\left[1-\cos 2\pi\nu_x \cos 2\pi\nu_y\right]}{\cancel{4}J_y\left[\cos 2\pi\nu_x - \cos 2\pi\nu_y\right]^2}\epsilon_x \sum_{sexts}\beta_x\beta_y\left(k_2L\right)^2 + \frac{J_z\sigma_\delta^2}{\cancel{4}\sin^2\pi\nu_y}\sum_{sexts}\beta_y\eta_x^2\left(k_2L\right)^2$$

# 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?

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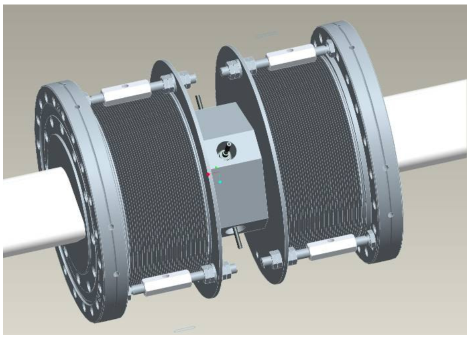
# Goals of low-emittance tuning simulations

- 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?

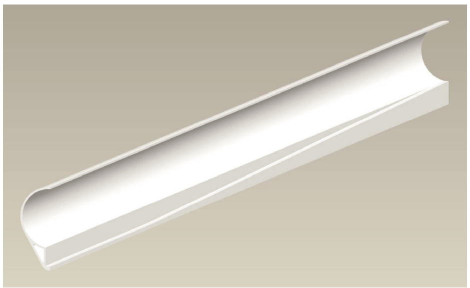
# Instrumentation research and development

- 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.

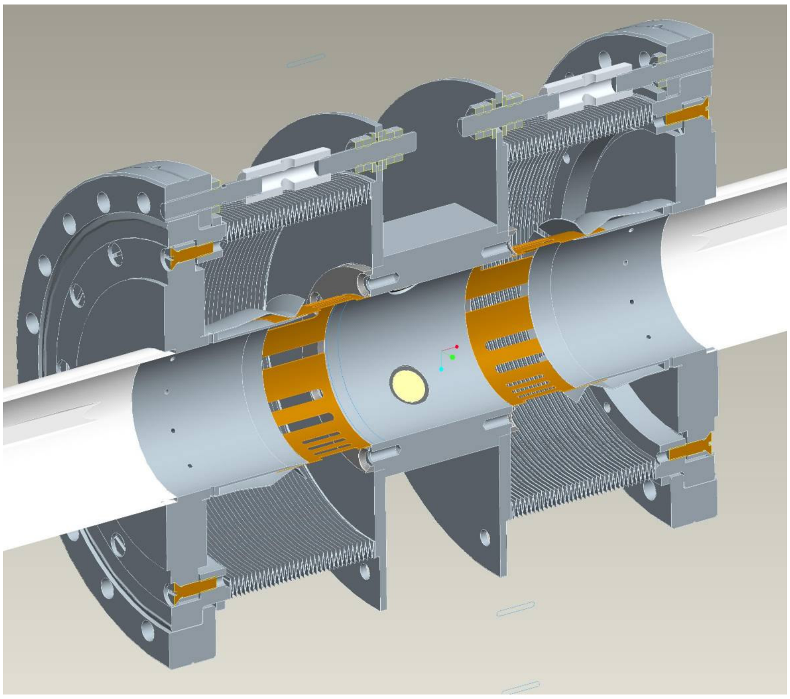
# Preliminary technical design: BPM insertion



Bellows/BPM external view



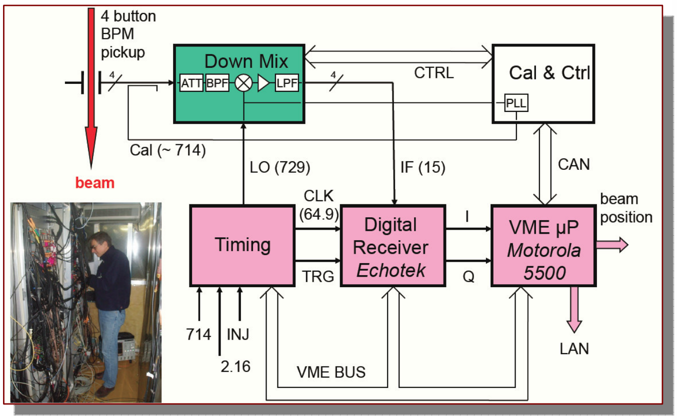
Antechamber taper (into BPM chamber)

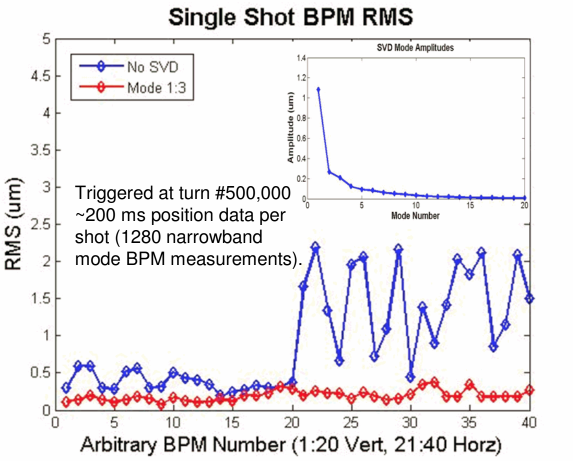


Bellows/BPM internal view

# 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.





Triggered at turn #500,000 ~200 ms position data per shot (1280 narrowband mode BPM measurements).

*Manfred Wendt (FNAL), et al*

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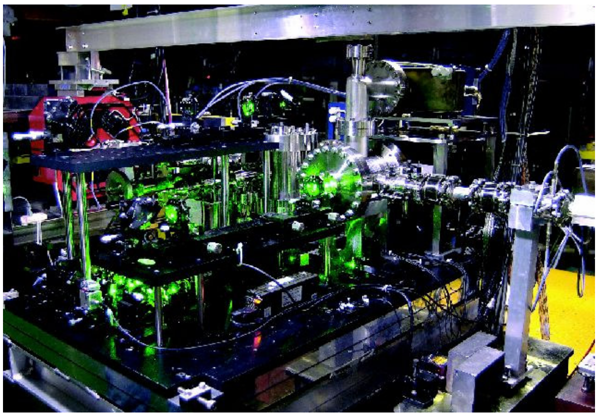
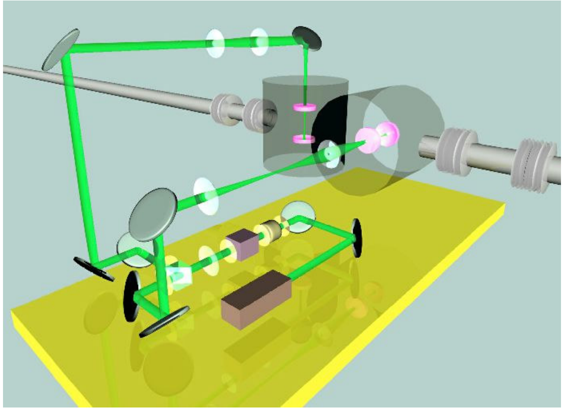
# Laser wire beam size monitor at KEK-ATF





*Y. Honda (KEK)*

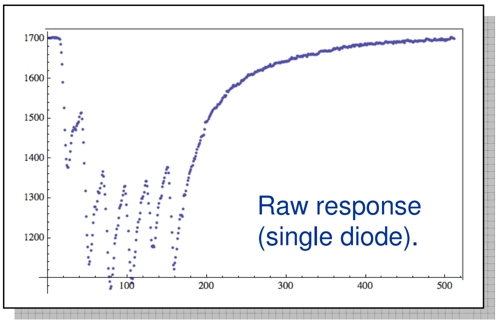
- Laser wire provides very high resolution measurement, but…
- …measurement times can be slow. A beam size monitor with fast (turn-by-turn) time resolution could improve tuning efficiency and allow observation of jitter, instabilities etc.

# Fast x-ray beam size monitor R&D at CesrTA

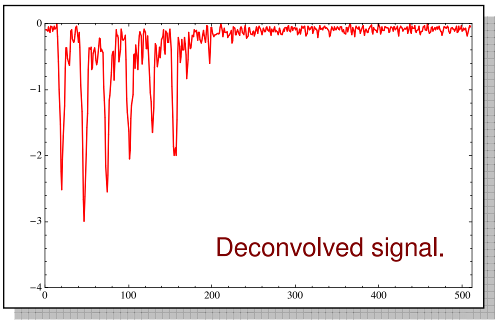
1-D array GaAs/InGaAs photodiodes.
512 diodes, 25µm x 500µm; time resolution ~ 1 ns.

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.

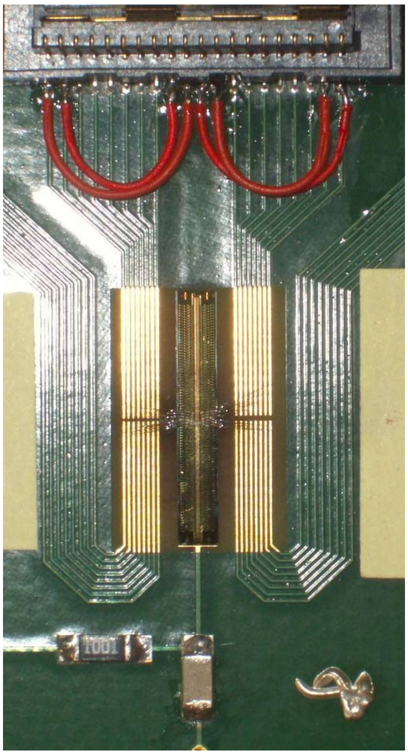
*Jim Alexander (CLASSE)*



Raw response (single diode).



Deconvolved signal.



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# 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. Zimmermann[5]

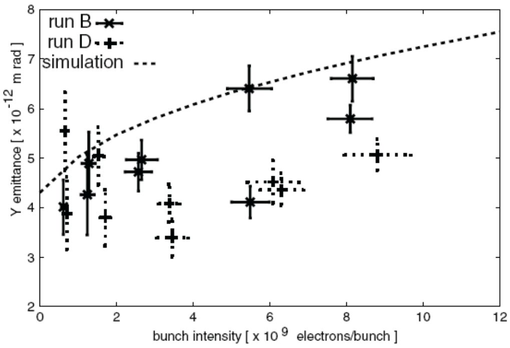


FIG. 2. Current dependence of the vertical emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

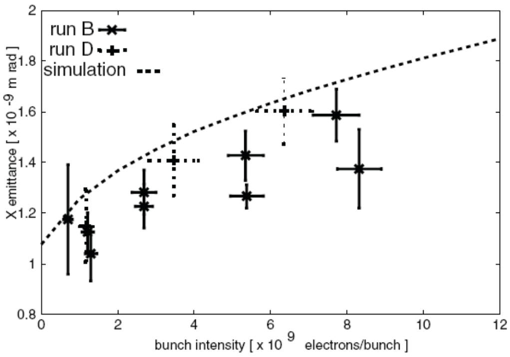
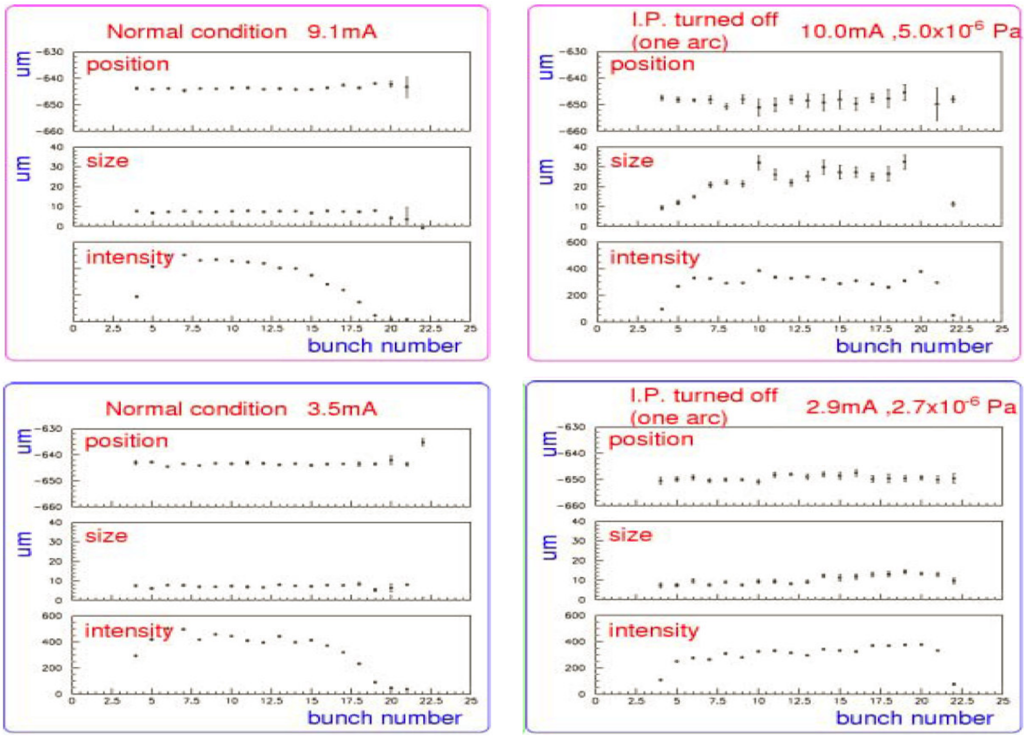


FIG. 3. Current dependence of the horizontal emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

# Machine experience: KEK-ATF



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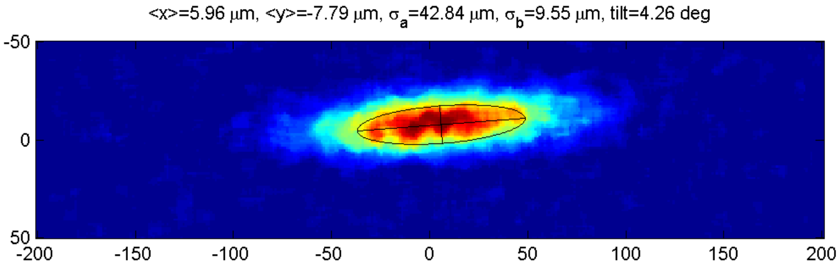
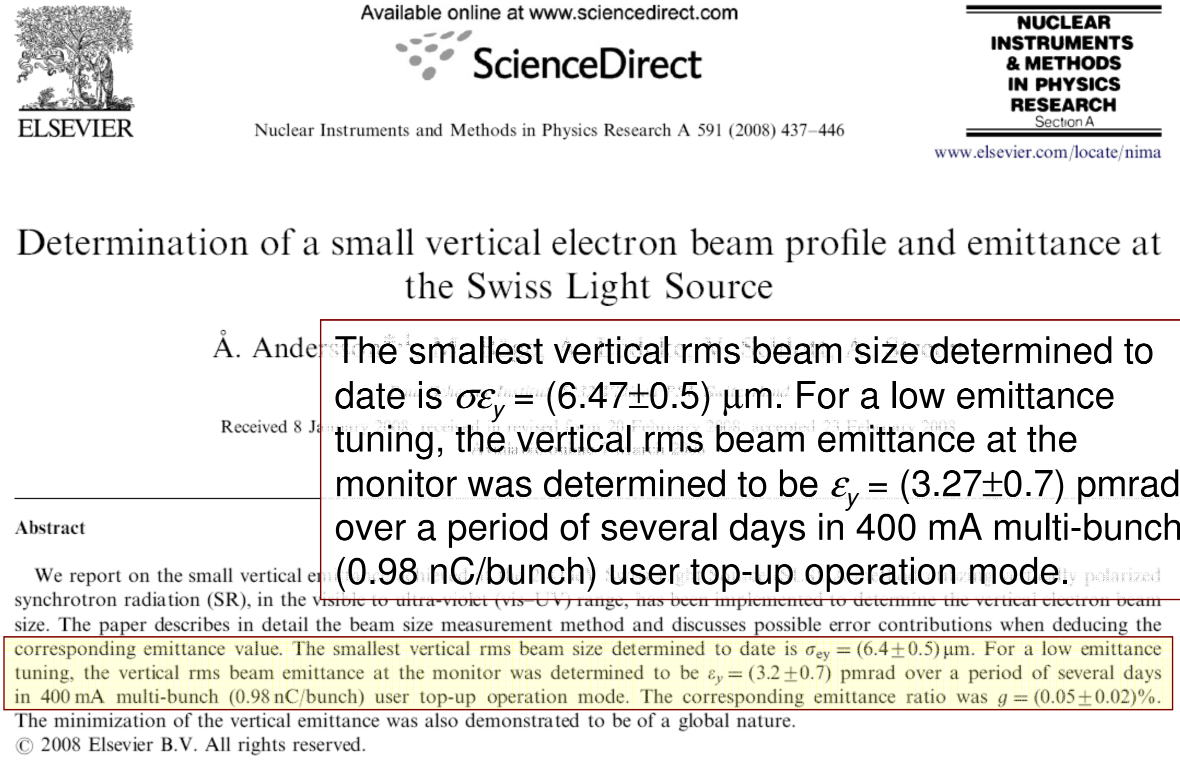
# Machine experience: KEK-ATF



- 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



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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. Ande

Received 8 Ja

**Abstract**

We report on the small vertical e polarized 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 $\sigma_{ey} = (6.4 \pm 0.5)\,\mu m$. For a low emittance tuning, the vertical rms beam emittance at the monitor was determined to be $\varepsilon_y = (3.2 \pm 0.7)$ 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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The smallest vertical rms beam size determined to date is $\sigma\varepsilon_y = (6.47 \pm 0.5)$ µm. For a low emittance tuning, the vertical rms beam emittance at the monitor was determined to be $\varepsilon_y = (3.27 \pm 0.7)$ pmrad over a period of several days in 400 mA multi-bunch (0.98 nC/bunch) user top-up operation mode.

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# Machine experience: the Swiss Light Source

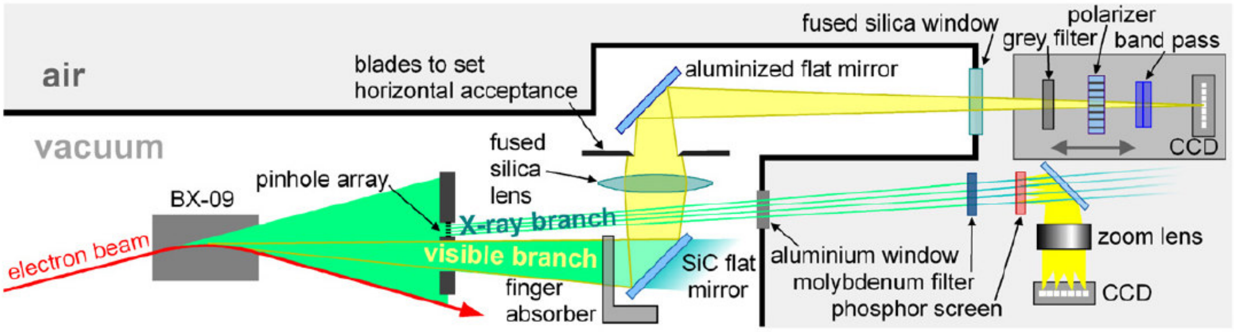

Fig. 1. Top view of the diagnostic beamline, showing the X-ray branch with pinhole array and the vis–UV branch.

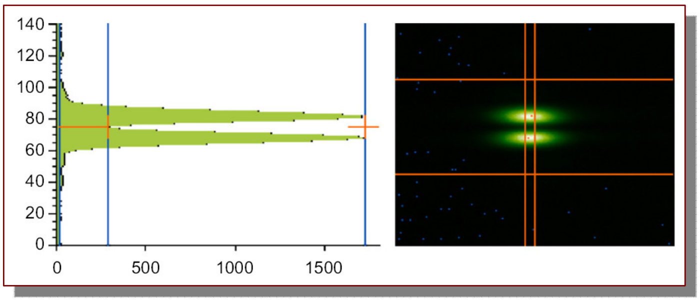

Fig. 4. Image from the vis–UV branch using vertically polarized light at 364 nm wavelength and 3.9/9.0 mrad horizontal/vertical acceptance angle. The scales are in pixel units, while the X_sig and Y_sig values are the derived rms electron beam sizes. Machine conditions: 350 mA in user top-up operation.

# 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.

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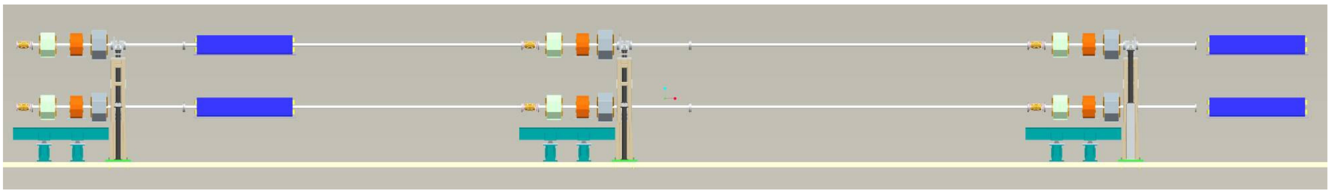
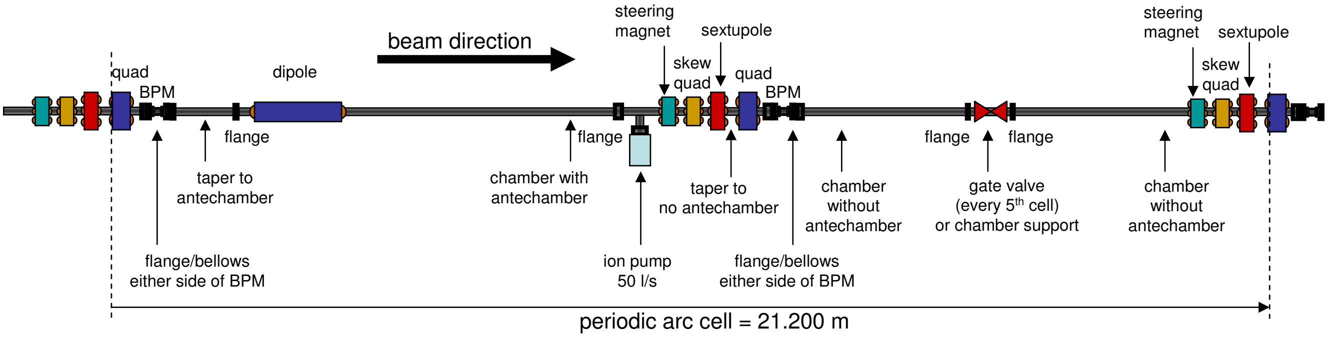
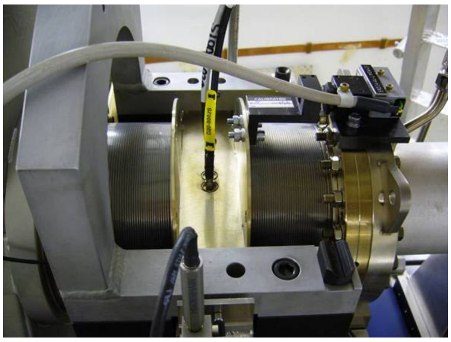
# Baseline lattice includes correction elements

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



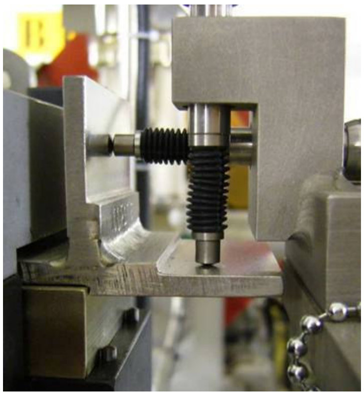


# Design work: building on experience



BPM and bellows chamber

Reference pillar supporting linear encoders



Linear encoders to monitor BPM position with respect to reference pillar

*Courtesy,*
*DIAMOND Light Source*

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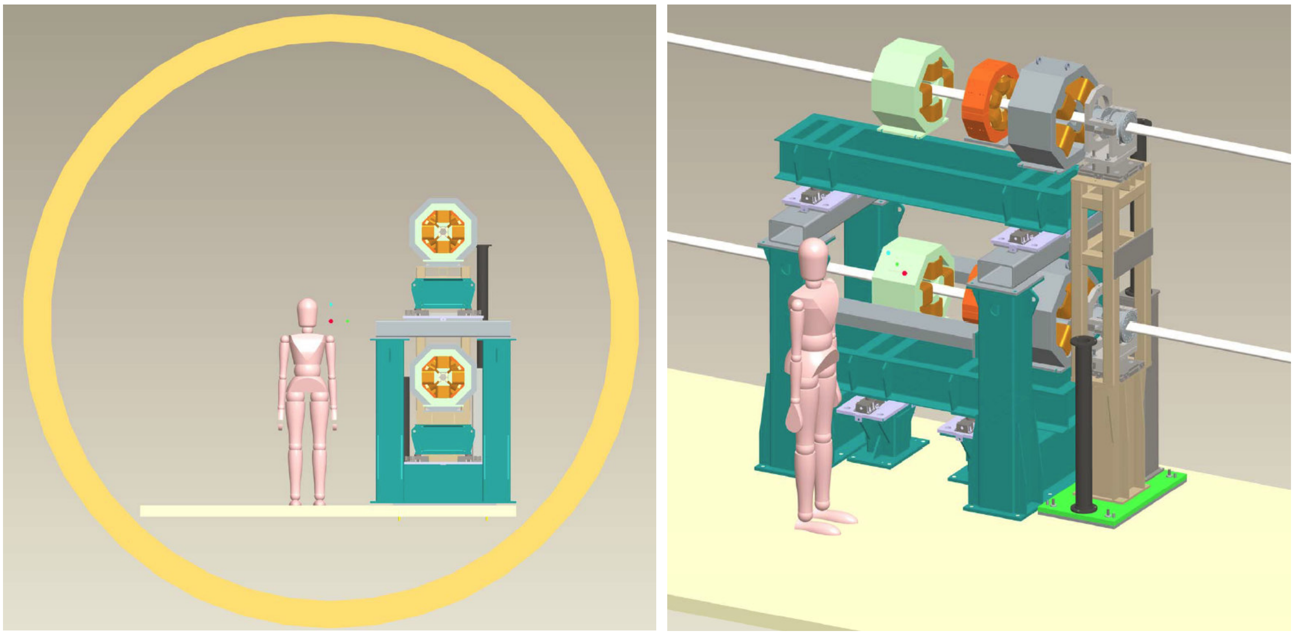
# Design work: building on experience



*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.

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# Workshop: Working Group Schedule

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