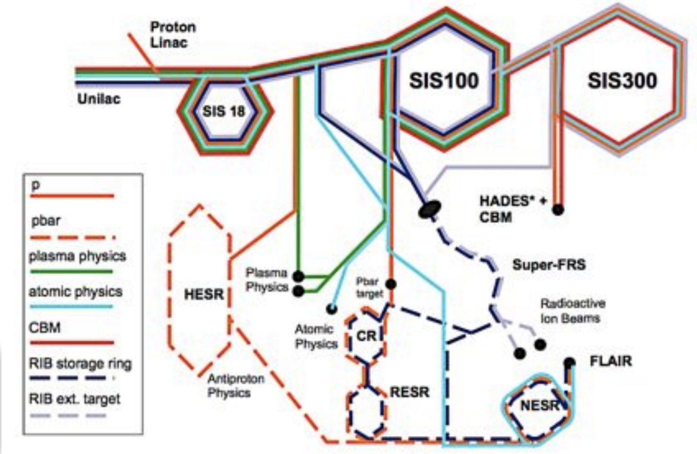
Libera

Instrumentation Requirements for Accelerators

Carlo J. Bocchetta, Libera Workshop, October 2010, Solkan, Slovenia

Introduction

- Modern accelerators have challenging “figures of merit”
  - Brilliance (SR 10^{22}, FEL 10^{34} ph/(s.mm^2.mrad^2.0.1% bw))
  - Luminosity (10^{34} cm^{-2}s^{-1}, nano-beams, …) -> 10^{36} proposed B-factories
  - High Power (ESS 5 MW) or Stored Energy (LHC 724 MJ [~173 kilograms of TNT!])
- Costly construction (100-1000’s M€)
  - Costly operation (10-100 M€/yr)
  - Cost of downtime (~2-20 k€/hr)
  - Cost of controls & diagnostics <10% of total machine cost
- Need to have high operational performance
  - Long MTBF, High availability & reliability (Medical), Short MTTR
  - Safety, …
  - Standardization (complexity of machines e.g., FAIR, …)

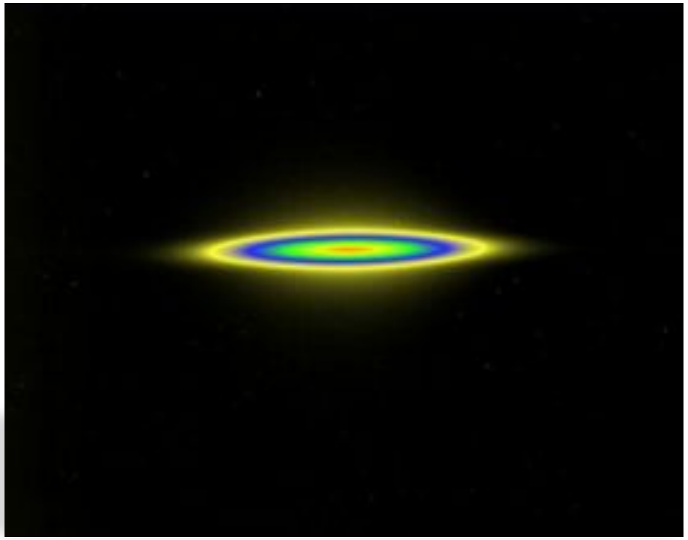


Introduction - II

- Instrumentation required for:
  - Operations (maintaining the “figures of merit”)
  - Improvement of “figures of merit”
  - New concepts
- Increasing need for “smart” instrumentation
  - Forms part of a more complex “sensor” (does not work alone)
  - Is part of an active system (feedback, feedforward)
  - Is highly integrated into the control system
  - Augments the machine model
- Examples in this talk: Storage ring light sources and FELs
  - Concepts are applicable to all accelerators (colliders, linacs, ERLs, FFAGs, …)

Synchrotron Light Sources – Storage Rings

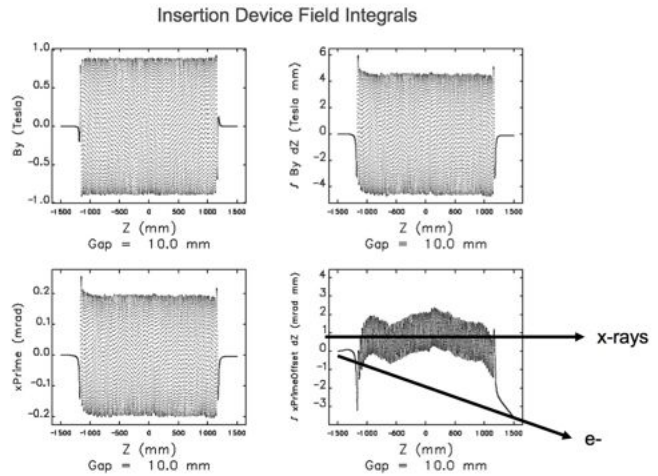
- Mature field
  - > 30 years experience
  - High % of diffraction limited light
  - Camshaft fills assisted by top-up mode
- Many User facility
- Many radiation sources
  - Bending Magnets
  - Undulators (PPM, IV, SCW, Cryo-undulators, … SCU)
  - IR, CIR, Slicing
  - FELO's, Seeding
- Figures of Merit
  - Brightness ~ 10^{22}
  - Reliability > 95% uptime
  - High stability <1/10 beam size, ~ few μrad pointing, at 100's Hz



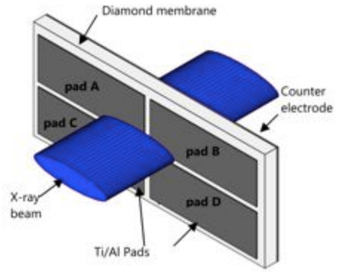
Recent record brilliance at ESRF: 5 pm vertical emittance
http://www.esrf.eu/news/spotlight/spotlight115/

Synchrotron Light Sources – Storage Rings

- Control of orbit and fast instabilities (smears the beam) well understood and implemented
- More difficult to control slow drifts (beam is shifted – strong effect on user)
  - Civil engineering (always) expensive
  - Auxiliary systems expensive for fraction of °C temperature control
- More work needed to limit slow drifts to <μm
  - Users control IDs – e-beam trajectory ≠ photon beam trajectory
  - Users can affect the optics – tune shifts, resonances, chromaticity,…
  - Need to monitor what's happening to the machine optics & act
  - Monitoring of BPMs – data integration
  - Increase use of photon beam in diagnostics (G. Decker, FLS2010)
  - Utilization of CVD diamond detectors close to the experiment

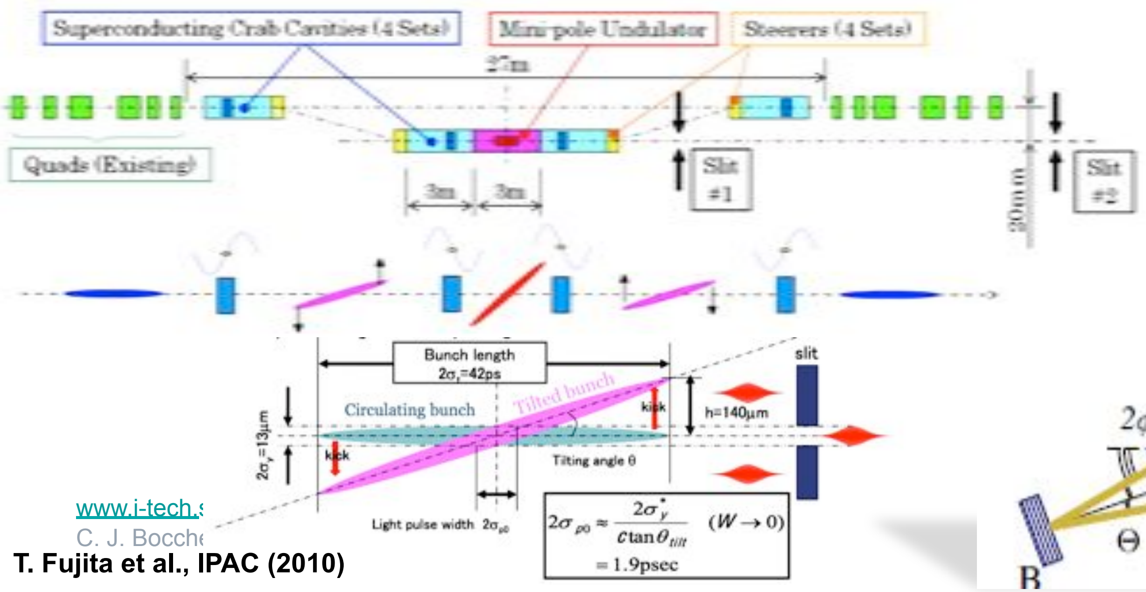


S. Krinsky and R. Hettel, Summary FLS2010, SLAC

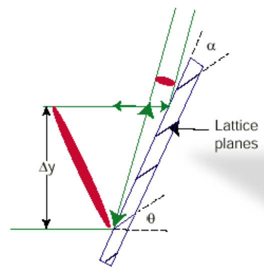


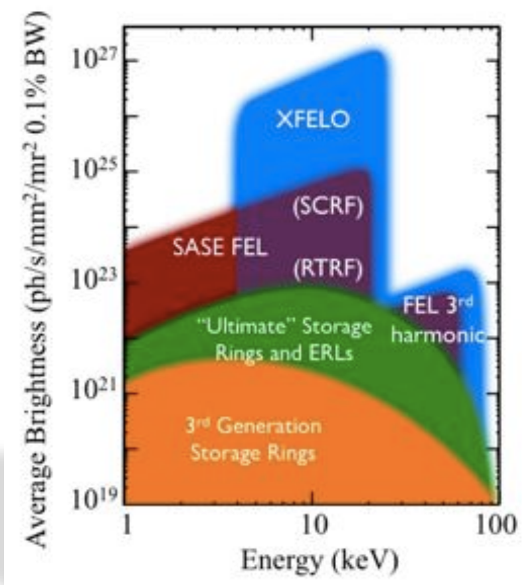
Synchrotron Light Sources – Storage Rings

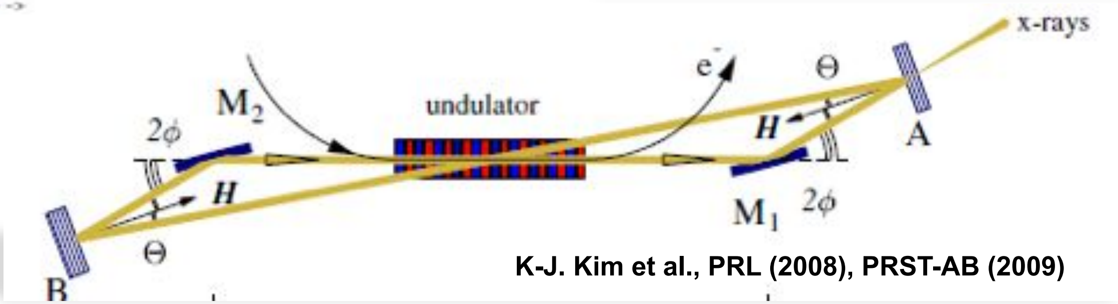
- Natural trend towards smaller emittance and shorter wavelengths for a given ring energy and for diffraction limited radiation.
- New developments pushing for short bunches: Slicing, Crab Cavities (SPring8; APS), XFELO (diamond crystal mirrors)
- Low alpha settings (CIR), **ultra-low emittance**



T. Fujita et al., IPAC (2010)







K-J. Kim et al., PRL (2008), PRST-AB (2009)

Ultra low emittance

- Optics – typically uses many bending magnets (with gradients), distributed dispersion, damping wigglers, strong focusing, many families of harmonic sextupoles, small dynamic aperture, hard to tune …
- Low dispersion, very strong sextuples, use families of octupoles, perhaps decapoles to increase dynamic aperture and tuneability.
- Lifetime dominated by IBS
- Low emittance – can lead to increased Touschek lifetime – important to maintain optics

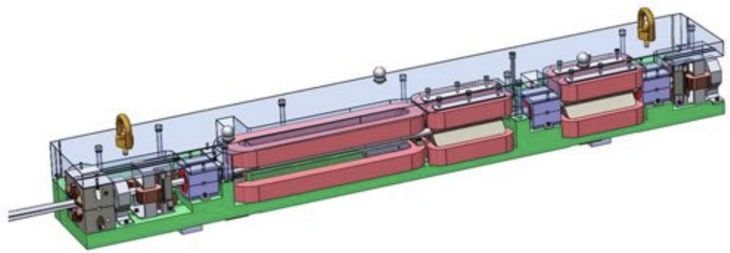
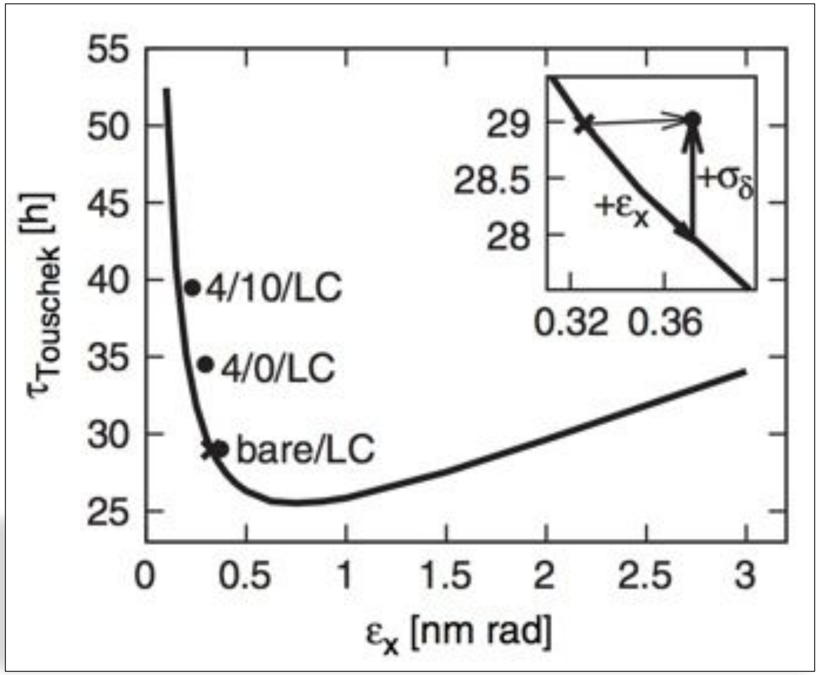


FIG. 7. (Color) Illustration of the matching cell magnet block. The common block integrates the 1.5° soft-end dipole, the final focusing quadrupole doublet, three octupoles, and two BPM/corrector pairs.

S. C. Leemann, et al., PRSTAB, 12, 120701 (2009)



Ultra low emittance - II

- Tracking and modelling codes are highly reliable – we build machines because of them
- It is mandatory to implement the model optics, necessitating measurement and correction of:
  - Linear Optics
  - Non-linear optics
  - Dispersion and spurious vertical dispersion
  - Coupling
  - Resonance excitation
  - Effects of Insertion devices
- Good orbit control is needed. Beam Based Alignment in quadrupoles and sextupoles
- Typical orbit correction to 100’s nm or less
- Instrumentation is required not only for routine operation (that includes fast feedbacks) but also for machine characterization and subsequent improvement.

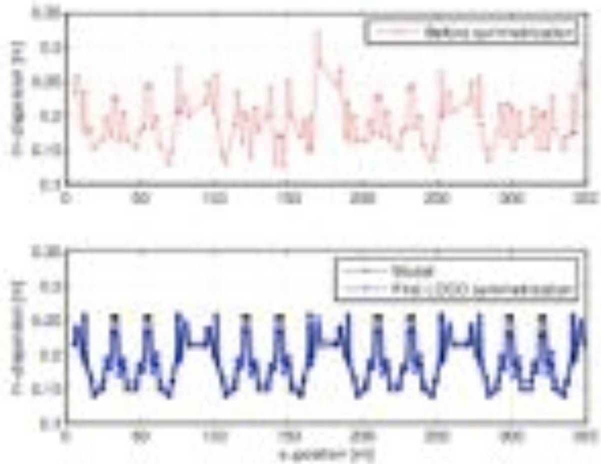
Characterizing the Machine

- Linear Optics from Closed Orbit – LOCO (J. Safranek, See ICFA Newsletter 44, 2007)
  - Determine the Orbit Response Matrix from the measured closed orbit
  - Widely used method to correct the linear optics
  - Well understood technique and used in light sources, damping rings and colliders

- Non-linear characterization
  - Experimental Frequency Map Analysis (FMA)
  - Use of Turn by Turn data from BPMs: Frequency analysis of motion
    (R. Bartolini, et al., PRSTAB, 11, 104002, (2008))
  - Determine non-linear resonances and update machine model
  - Transparent monitoring of optical functions – use of multibunch feedback systems on one bunch (G. Rehm, BIW2010)

LOCO – Linear Optics from Closed Orbit

- Measure closed Orbit Response Matrix (ORM)
- Least squares fit of model ORM to measured
  - Fitting Quadrupole gradients, BPM gains, Steering magnet calibrations, Skew quadrupole gradients, BPM coupling, Steering magnet rolls
  - Additionally: normal and skew gradients in sextupoles or insertion devices, steering magnet or BPM longitudinal positions, and steering magnet energy shifts
- Apply correction to model ORM
- Corrects linear optics asymmetries
- Improves injection efficiency, emittance, lifetime, coupling



$$\begin{pmatrix} x \\ y \end{pmatrix} = M \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}$$

$$M_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi\nu)} \cos(|\phi_i - \phi_j| - \pi\nu)$$

$$\chi^2 = \sum_{i,j} \frac{(M_{ij,\mathrm{model}} - M_{ij,\mathrm{meas}})^2}{\sigma_i^2}$$

$$M_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi\nu)} \cos(|\phi_i - \phi_j| - \pi\nu) + \frac{\eta_i \eta_j}{\alpha_c L_0}$$

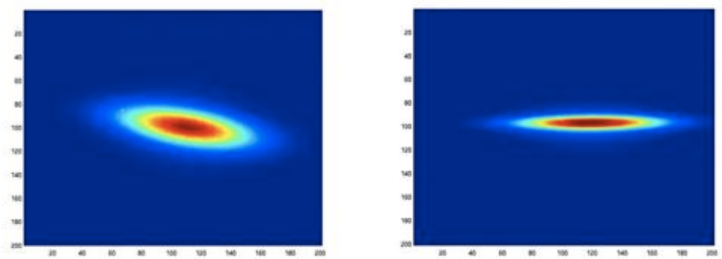
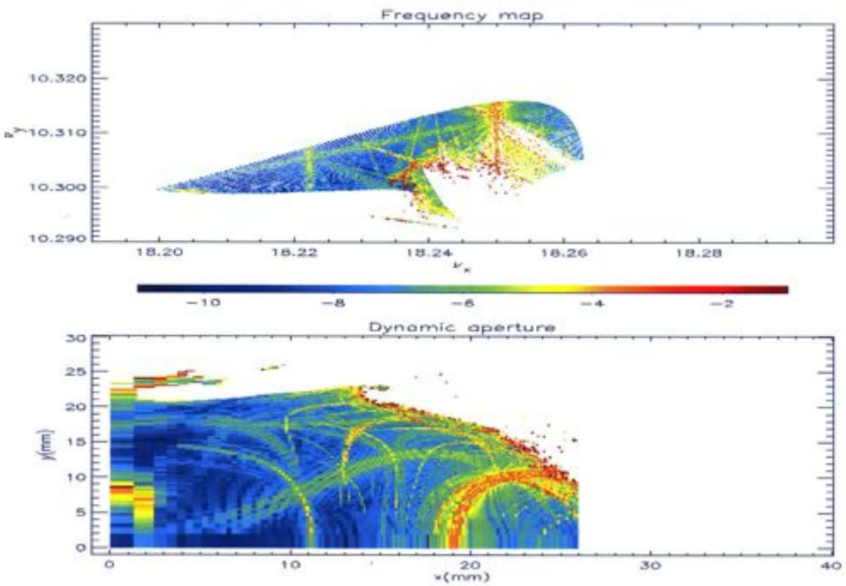


Figure 3: Beam size at the X-ray pinhole camera before (left) and after (right) coupling correction with LOCO.

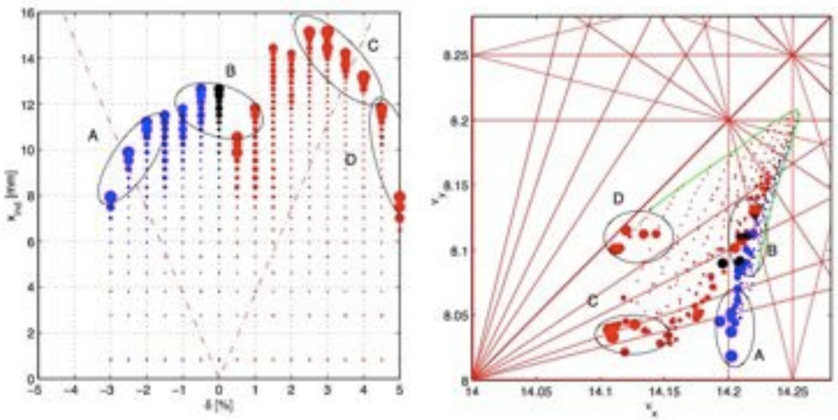
FMA from Turn-by-Turn BPM data

- Frequency Map Analysis - **Tracking**



unstable stable

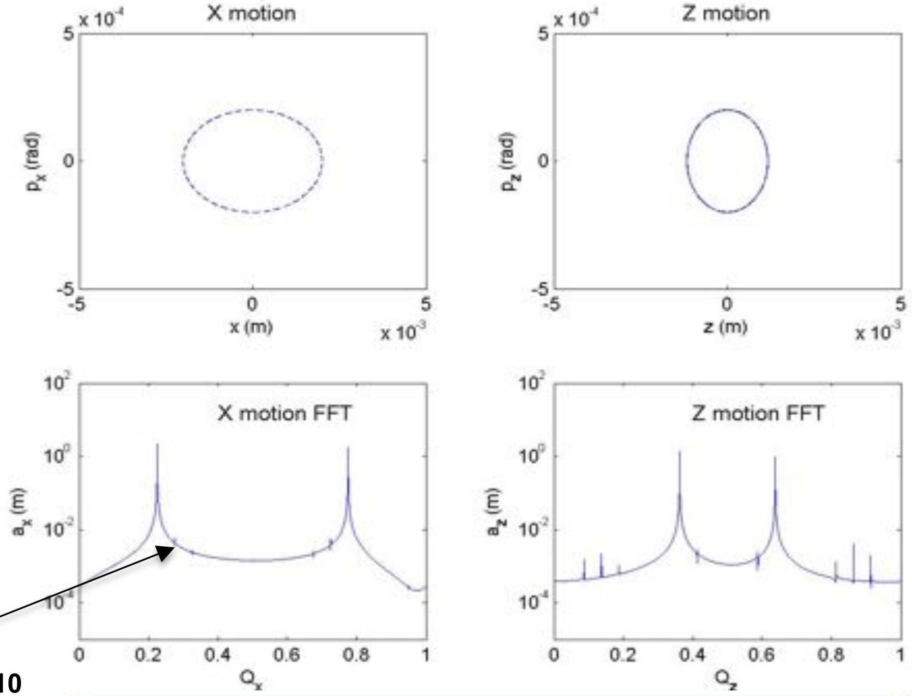
- **Measurement**
- Kick beam with fast pinger magnet
- Measure beam loss
- Extract tunes from TbT BPM data
- Model response to amplitude, energy



C. Steier, PAC2005

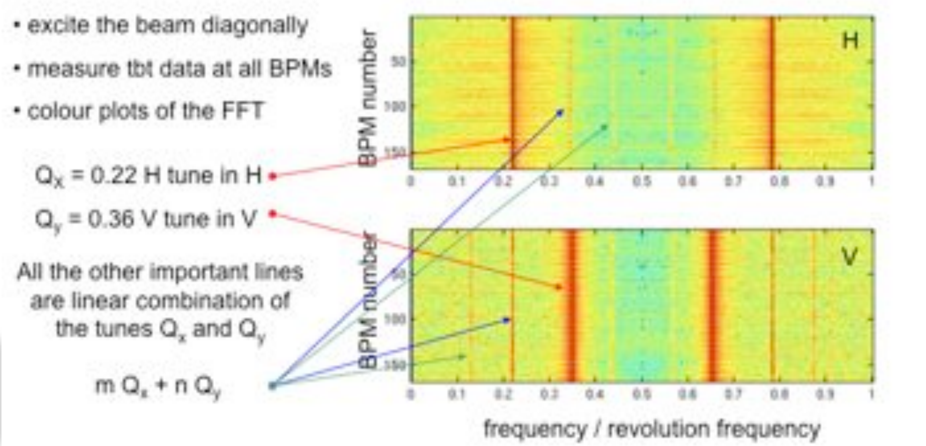
Spectral Line Analysis from Turn-by-Turn Data

- Has the potential to reconstruct the nonlinear machine model.
- Correction of multiple resonances and improvement in Touschek lifetime was achieved (DIAMOND & Soleil).
- Needs knowledge of multipole errors of magnets and fringe fields of dipoles and quadrupoles.



$$\nu_H(f_{jklm}) = (1-j+k)Q_x + (m-l)Q_y$$

R. Bartolini, LER Workshop 2010



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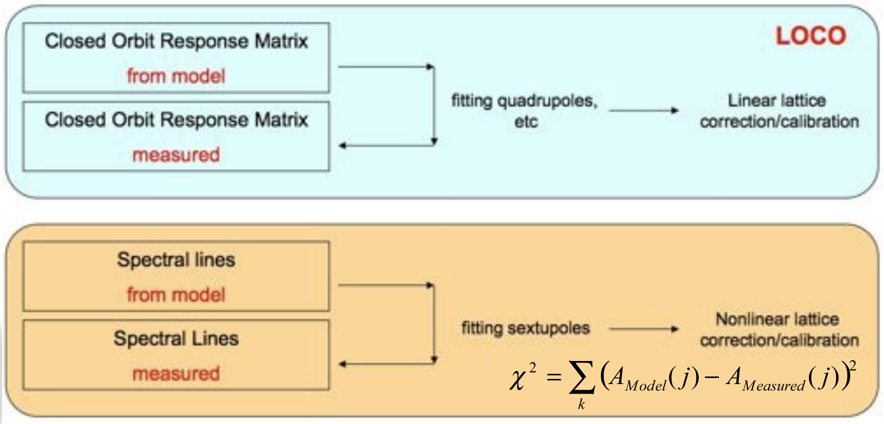
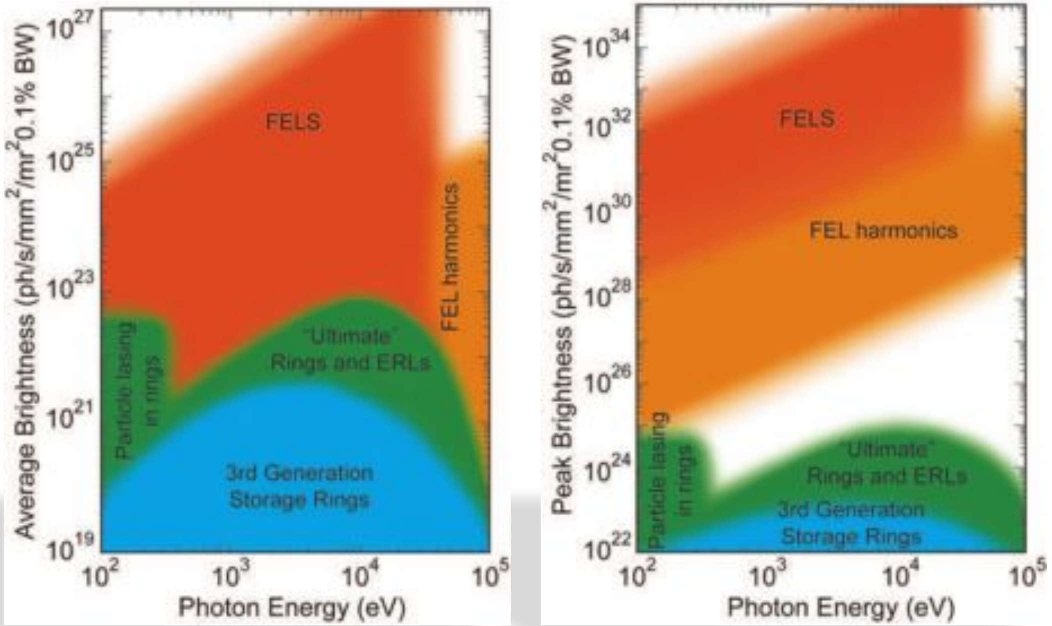


Minimize distance between the two vector of Fourier coefficients

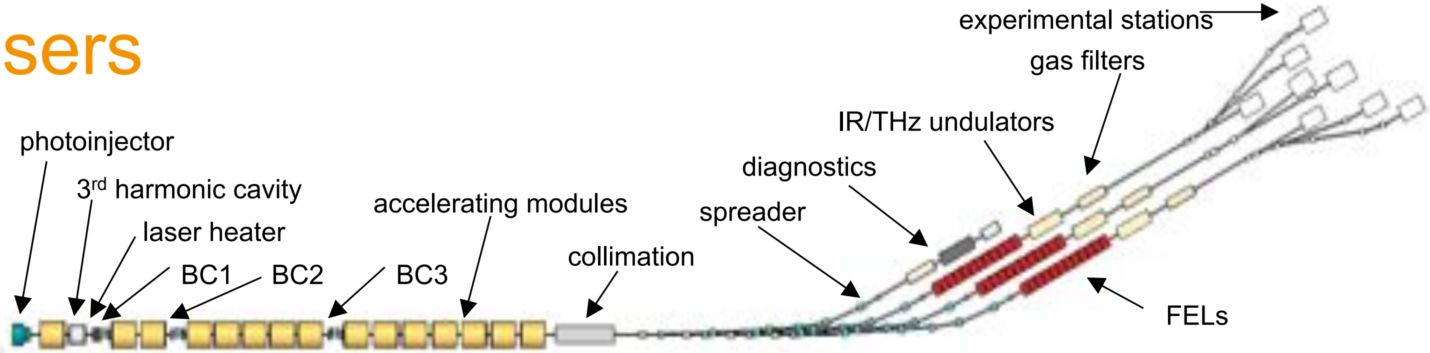
Free Electron Lasers - I

- Very challenging machines
  - Peak brightness ~10^{34}
  - Short Pulses (~ 10 fs)
  - Narrow Bandwidth
  - User and machine tightly linked
  - SC, NC, 10 Hz to MHz Rep rates
  - SASE, Seeded
- Expensive few user facility
  - Reliability is very important
  - Optimized beam transport



- Important parameters/features
  - Slice emittance < 1µmrad
  - Energy spread < 10^{-3}
  - Peak current ~10's kA
  - Timing (~10 fs)

Free Electron Lasers



NLS Deepa Angal-Kalinin
FLS 2010, ICFA Beam Dynamics Workshop, SLAC, 2010

- The trends
  - Shorter pulses – attoseconds and to zeptoseconds (A. Zholents, FEL2010)
  - Shorter wavelengths (J. Wu, FEL2010)
  - Novel Seeding (G. Stupakov IPAC2010)
  - Seeding at shorter wavelengths, higher harmonics (FLS2010, SLAC)
  - Increasing User Capacity

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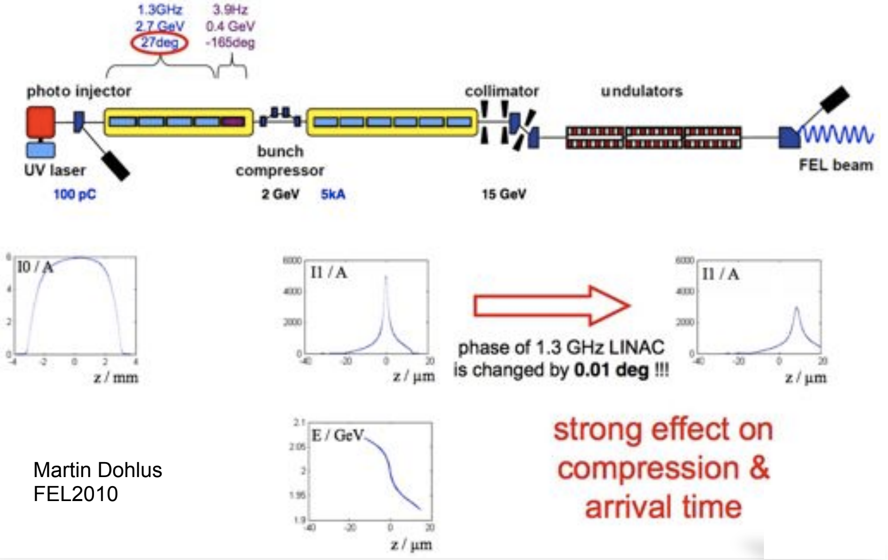
Free Electron Lasers - II

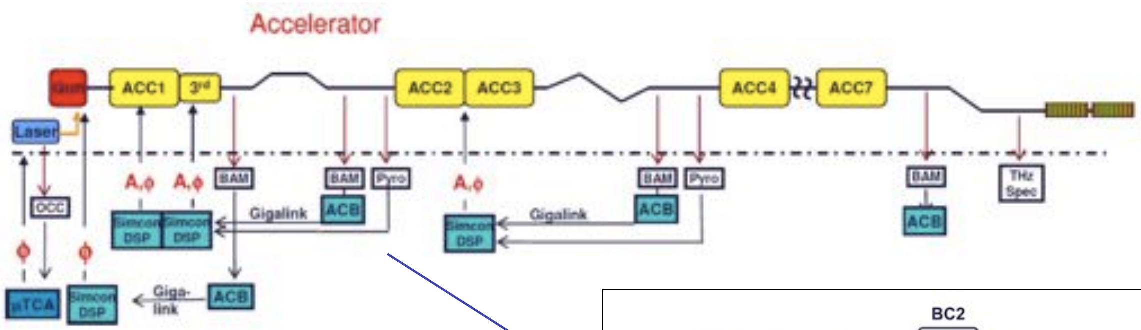
- Important Issues
  - Stability of systems (otherwise increased gain length and costly undulator or no lasing)
  - Potential coupling of feedback systems, diversity of sensors and actuators
  - Beam distribution
  - Synchronization between accelerator systems and experimental stations
  - Cascaded seeded systems place additional constraints on system stability
  - Beam dynamics (CSR, µbunching instabilities, wakefields, …)

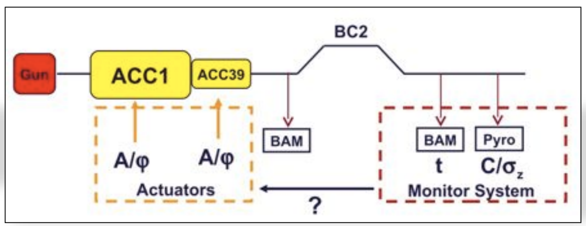


M. Dohlus, FEL2010

What has to be controlled in a FEL?

- Trajectory - through the linac (Laser heater, suppression of wakefields), the beam transport, the FEL modulators (seeding), the FEL radiators (lasing)
- Energy and Peak current - Linac phase & amplitude
- Charge - Gun laser
- Experimental Laser Systems





C. Behrens, DESY, FLS2010

- Many feedback/feedforward loops, can be global or local, slow and fast
- Accurate knowledge of the response matrix for successful implementation.
- Combined Beam Dynamics and Diagnostics Simulations for optimized compression schemes, sensitivities, working points

Machine Performance

- Good performance requires a good machine model
  - Knowledge comes from initial specifications and from measurement
- The model allows accurate prediction of behaviour.
- Good accelerator instrumentation eases characterisation of the model
- Leading to improvement in machine performance – optimal “figures of merit”
  - Brilliance, Flux, Luminosity, Availability, Lifetime

Thoughts for this meeting

- Accelerator instrumentation is increasingly part of active systems (LLRF, Orbit & MB control, timing, …)
- Instrumentation excels in performance when also conceived for use in physics programs
  - Improved performance
  - Improved operations

- Are there new emerging measurements to be conducted?
- Any thoughts for improvements to our instruments?
- Any additions to features to address new types of measurements and control of machine parameters?
- Any ideas about pre-processing data, distributed computing, data streams?
- Technologies and Standards?

Thanks for your attention