Design and Control of Ultralow Emittance Light Sources

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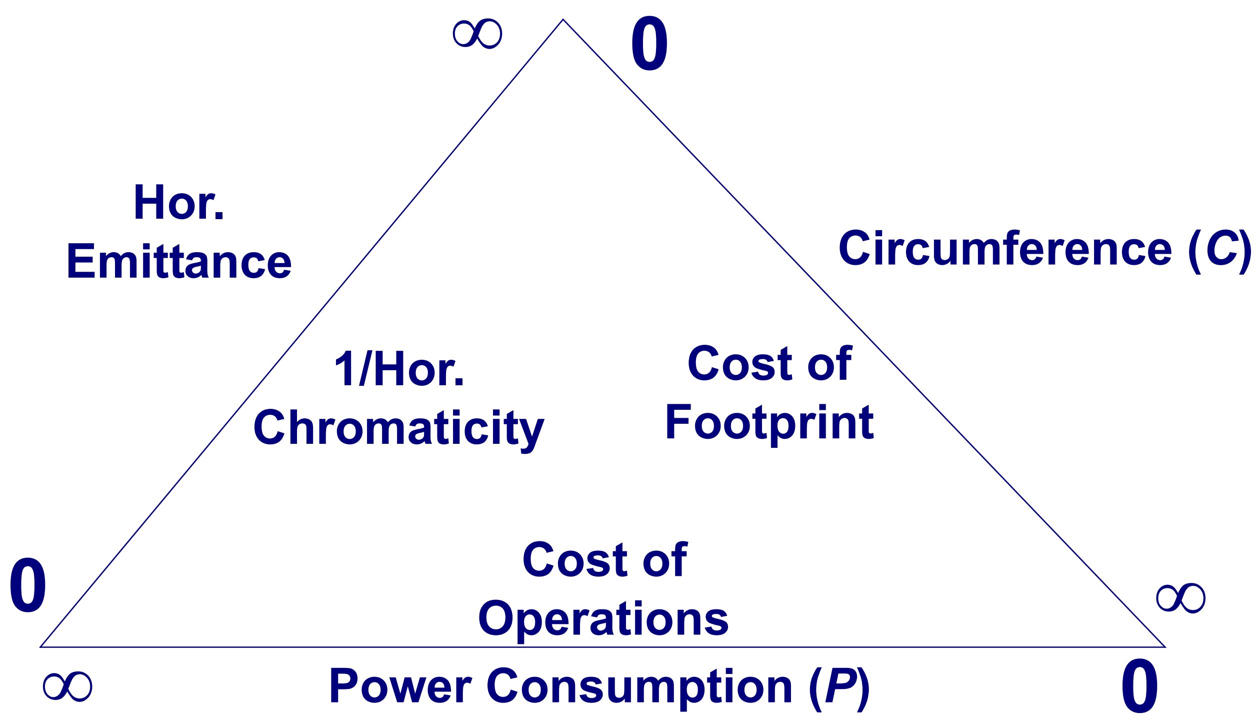
NSLS-II

Outline

- Trade-Offs.
- What's Known.
- What's New.
- Challenges.
- Lattice Parameters.
- Robust Design and Control.
- Modeling: Numerical- vs. Analytical methods.
- The NSLS-II "Wind Tunnel".
- Control of Dynamic Aperture.
- A Simulator.
- A Model Server with Thin Clients.
- Conclusions

Trade-Offs: Global Optimization

1. Horizontal emittance (natural): **damping ↔ diffusion** (fundamental limit is IBS).
2. Optimize (for Insertion Devices (IDs)):



$$\varepsilon_x \sim \frac{1}{R^2 \cdot P},$$

R bend radius

Optics guidelines:

- max chromaticity per cell,
- min peak dispersion,
- max values for the beta functions.

What's Known

- Dedicated third generation light sources: ~20 years of optimizations.
- The horizontal emittance (isomagnetic lattice) is given by

$$\varepsilon_x \,[\mathrm{nm \cdot rad}] \;=\; 7.84 \times 10^3 \cdot \frac{(E\,[\mathrm{GeV}])^2 F}{J_x N_b^3}$$

N_b is the number of dipoles, $0 < J_x < 3$, $F \geq 1$. No dipole gradients => $J_x \approx 1$.

- Generalized Chasman-Green Lattices: DBA, TBA, QBA, 7-BA.
- Effective emittance => chromatic cells.
- Increasing N_b reduces ε_x but also reduces peak dispersion, which makes the chromatic correction less effective => "chromaticity wall".
- Damping wigglers (DWs): damping rings and conversion of HEP accelerators.
- Mini-Gap Undulators (MGUs), Three-Pole-Wigglers (TPWs) inside DBA.

What's New

- Use of damping wigglers to reduce horizontal emittance and as high flux X-ray sources => achromatic cells and weak dipoles.
- Medium energy ring (3 GeV) with 30 DBA cells.
- Vertical orbit stability requirements.
- Generalized higher order achromat.

Challenges

Non-linear dynamics:

- Medium energy: control of Touschek life time and momentum aperture.
- 30 DBA cells: control of tune footprint.
- Control of impact of DWs and IDs: include leading order nonlinear effects from DWs in Dynamic Aperture (DA) optimizations.
- Optics requirements for IDs and top-up injection: introduce alternating straights with high- and low horizontal beta function <-> reduced symmetry (30 -> 15).
- DBA: momentum dependence of optics functions for => number of chromatic sextupole families.

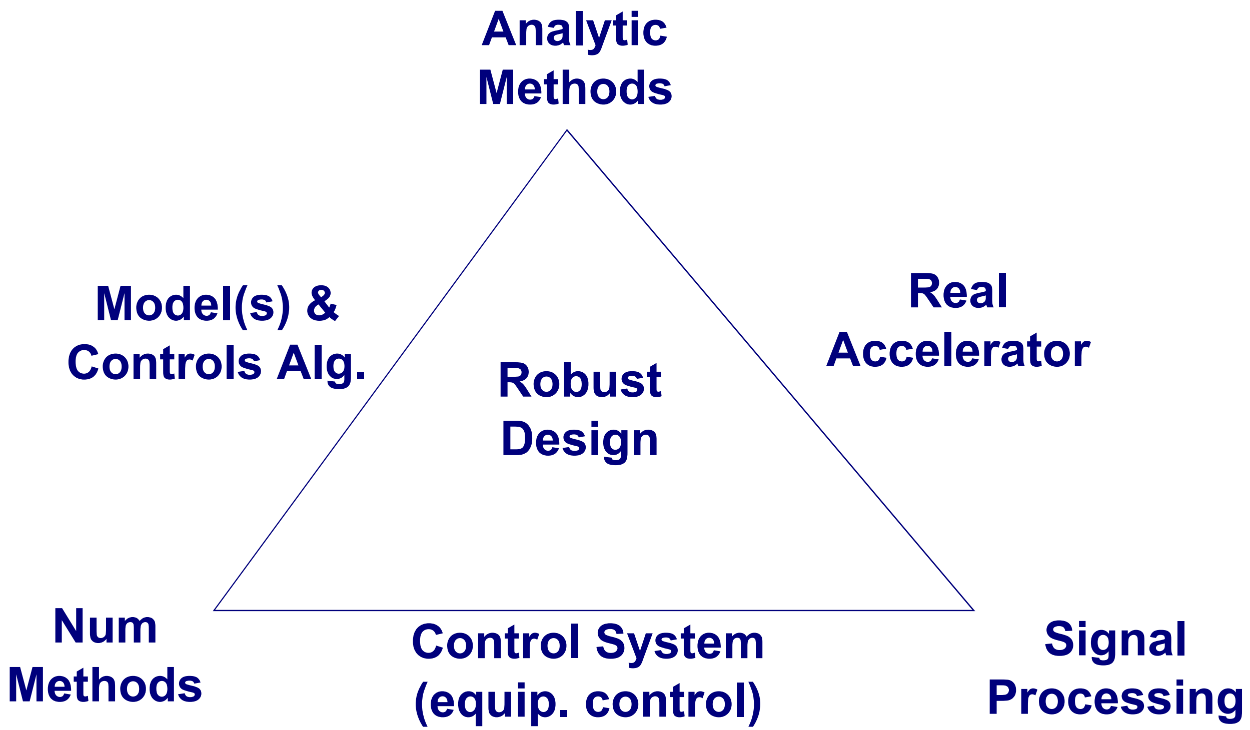
Technical

- Weak dipoles: introduce TPWs adjacent to the dipoles => control of peak beta functions and horizontal dispersion.
- Vertical orbit stability: sub micron => pushing the state-of-the-arts.

Lattice Parameters

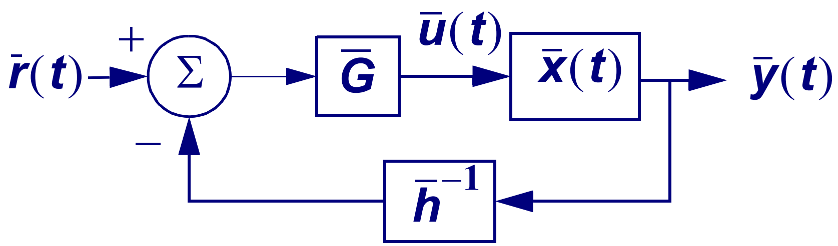
Energy	3 GeV
Circumference	791.5 m
Harmonic Number	1320
Bending Radius (R)	25.0 m
Dipole Energy Loss (U_0)	286.5 keV
Emittance (ε_x, ε_y): bare/w. 8 DWs	(2.1, 0.01)/(0.6, 0.01) nm·rad
Momentum compaction	0.00037
RMS Energy Spread: bare/w. 8 DWs	0.05/0.1%
Working point (ν_x, ν_y)	(32.4, 16.3)
Chromaticity (ξ_x, ξ_y)	(-100, -42)
Peak Dispersion ($\hat{\eta}_x$)	0.45 m
Beta Function (β_x, β_y): long/short straight	(18, 3)/(3, 3) m

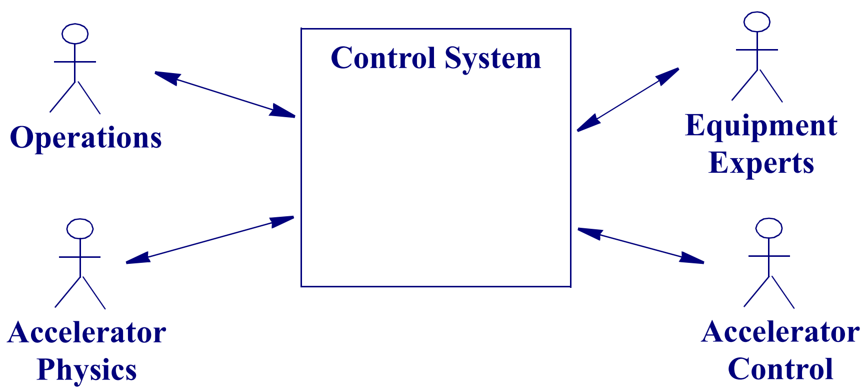
Robust Design and Control: Model Based



Challenge: re-use the design model for model based (on-line) control.

Systematic Approaches





"Closed-Loop" Control:

- lattice design,
- control of DA,
- guidelines for engineering tolerances, ring magnets, and insertion devices,
- correction algorithms,
- aka TQM in industry.

Use Case approach:

- model based control.

Modeling Considerations

- A confinement problem governed by the Lorentz force: $\frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$.
- The single particle dynamics is described by the relativistic Hamiltonian for a charged particle in an external electro-magnetic field (aka volume preserving flow). => Symplectic integrators.
- The residual beam size is a dynamic equilibrium between "cooling" from radiation damping (described by classical radiation), and "heating" due to diffusion from quantum fluctuations (i.e., recoil from the emitted photons). => Modified symplectic integrator.
- Need to model a realistic magnetic lattice, i.e., that includes mechanical misalignment- and magnetic field errors, and related correction algorithms.
- Must be able to compute- and optimize the global properties of a realistic lattice, e.g. the optics, diffusion coeffs, driving terms, tune foot print, etc.
- No theory of stability (for the general nonlinear case). => Perturbation theory. Hence, "analytic" results must be validated by numerical simulations.

Modeling Considerations cont.

- Control nonlinear effects by the: lattice symmetry, driving terms/resonances (Lie generators), and tune foot print; obtained either from Taylor maps, Lie series, and map normal form (analytically) or frequency maps (numerically).

Challenge: How to combine the numerical methods for modeling of a realistic lattice with the analytical techniques for analysis of its properties?

- Introduce a polymorphic number class for transparent floating point- and TPSA (Truncated Power Series Algebra) calculations; with object-oriented programming (Bengtsson, LBL 1994 => a Lagrangian object, aka PTC (with E. Forest)).

How to re-use the beam dynamics model and related correction algorithms developed during the design phase as an on-line model for the commissioning?

- Implement a well designed software library that can be re-used by e.g. the Controls Group.

Model

The Hamiltonian is (medium sized ring)

$$H = (1 + h_{\mathrm{ref}}(s))\left[-\frac{q}{p_0}A_s(s) + \frac{\left(p_x - \frac{q}{p_0}A_x(s)\right)^2}{2(1+\delta)} + \frac{\left(p_y - \frac{q}{p_0}A_y(s)\right)^2}{2(1+\delta)} - \delta + O(p_{x,y})^4\right] \qquad \text{(EQ 1)}$$

with the multipole expansion

$$\frac{q}{p_0}A_s(s) = -\mathrm{Re}\left\{\sum_{n=1}^{\infty}\frac{1}{n}(ia_n(s) + b_n(s))(x+iy)^n\right\} = -\mathrm{Re}\left\{\sum_{n=1}^{\infty}\frac{1}{n}(ia_n(s) + b_n(s))(re^{i\varphi})^n\right\} \qquad \text{(EQ 2)}$$

The map is obtained by splitting the Hamiltonian into two integrable parts
$H = H_{\mathrm{drift}} + H_{\mathrm{kick}}$ $(:f(\bar{x}):g(\bar{x}) \equiv [f(\bar{x}), g(\bar{x})])$

$$\mathcal{M}(\Delta s) = \exp\left(:-\int_0^{\Delta s} H ds:\right) = e^{:-H\Delta s:} = e^{:-H_{\mathrm{drift}}\Delta s/2:}e^{:-H_{\mathrm{kick}}\Delta s:}e^{:-H_{\mathrm{drift}}\Delta s/2:} + O(\Delta s^3)$$

$$= \mathcal{M}_{\mathrm{drift}}\left(\frac{\Delta s}{2}\right)\mathcal{M}_{\mathrm{kick}}(\Delta s)\mathcal{M}_{\mathrm{drift}}\left(\frac{\Delta s}{2}\right) + O(\Delta s^3) \qquad \text{(EQ 3)}$$

aka a 2nd order symplectic integrator. It can be generalized to e.g. 4th order.

Model cont.

For insertion devices, the vector potential can be obtained from the magnetic field (numeric model or measurements) by

$$A_x(s) = -\int_s B_y(z)dz, \qquad A_y(s) = \int_s B_x(z)dz, \qquad A_z(s) = 0$$

The corresponding kick map $\mathcal{M}_{\mathrm{kick}}$ is provided by e.g. RADIA.

For an analytic model (to leading order)

$$\frac{q}{p_0}A_x(s) = \frac{B_\mathrm{u}}{k_z(B\rho)}\cos(k_x x)\cosh(k_y y)\sin(k_z s), \qquad \frac{q}{p_0}A_y(s) = \frac{k_x B_\mathrm{u}}{k_y k_z(B\rho)}\sin(k_x x)\sinh(k_y y)\sin(k_z s)$$

with $k_z^2 = k_y^2 - k_x^2 = (2\pi/\lambda_\mathrm{u})^2$.

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Analytic Methods

Assuming a Taylor map (to arbitrary order) has been obtained from our dynamics model, it can be factored (Lie series)

$$\mathcal{M} = \mathcal{A}^{-1} \ldots \mathbf{e}^{:\boldsymbol{f}^{(4)}:} \mathbf{e}^{:\boldsymbol{f}^{(3)}:} \mathcal{R}\mathcal{A} \qquad \textbf{(EQ 1)}$$

The (Lie) generators (aka driving terms) provides a means to control the DA (Bengtsson, SLS, 1997). They can also be measured from turn-by-turn data and Fourier analysis (part of my thesis) => “closing-the-loop” (R. Bartolini, et al).

It can also (recursively) be transformed into normal form

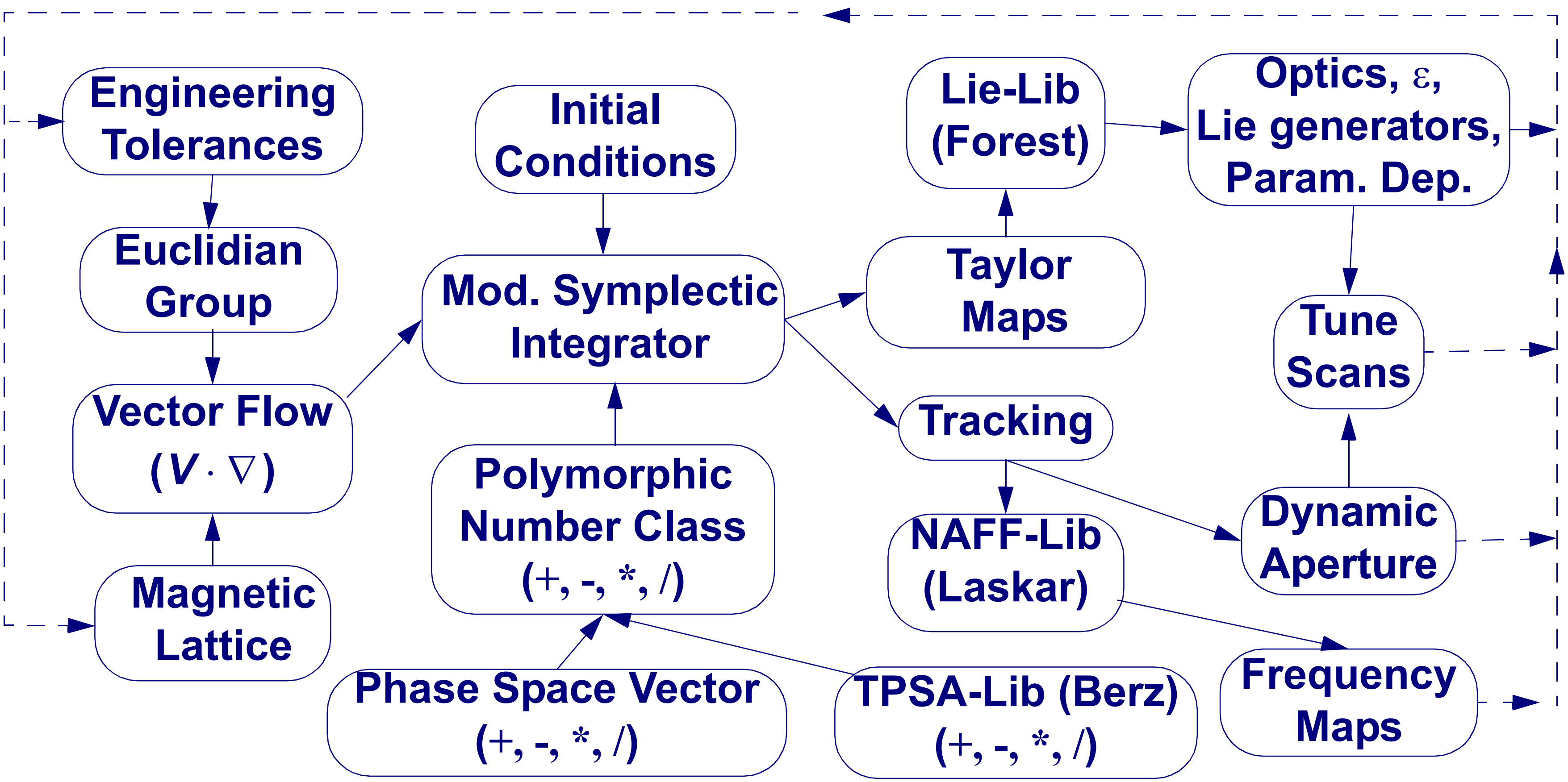
$$\mathcal{M} = \mathcal{A}^{-1} \ldots \mathbf{e}^{:\boldsymbol{f}^{(4)}:} \mathbf{e}^{:\boldsymbol{f}^{(3)}:} \mathcal{R}\mathcal{A} = \mathcal{A}^{-1} \mathbf{e}^{:-\boldsymbol{g}(\bar{\boldsymbol{J}}, \bar{\phi}):} \mathbf{e}^{:\boldsymbol{k}(\bar{\boldsymbol{J}}):} \mathbf{e}^{:\boldsymbol{g}(\bar{\boldsymbol{J}}, \bar{\phi}):} \mathcal{A} \qquad \textbf{(EQ 2)}$$

from which we obtain the global properties of the lattice, e.g. the tune shift

$$\bar{\nu}(\bar{\boldsymbol{J}}) = -\frac{1}{2\pi} \frac{\partial \boldsymbol{k}(\bar{\boldsymbol{J}})}{\partial \bar{\boldsymbol{J}}} \qquad \textbf{(EQ 3)}$$

The NSLS-II "Wind Tunnel"

(aka PTC (Polymorphic Tracking Code), Tracy-3)



=> self-consistent: numerical simulations/analysis and analytic techniques applied to the same (realistic) model.

Control of Dynamic Aperture: Requirements

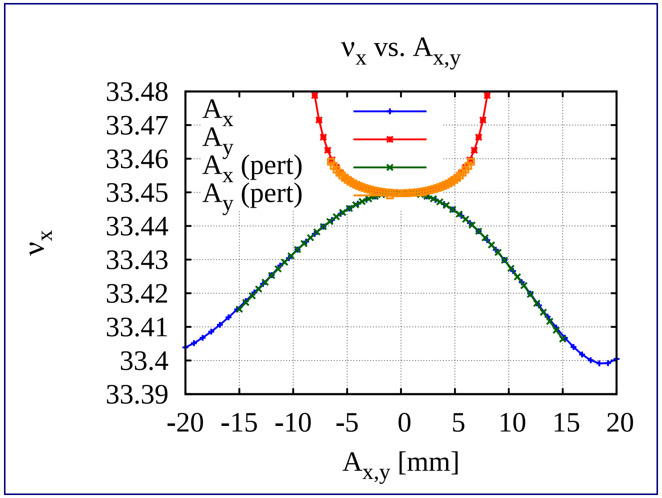
The requirements are:

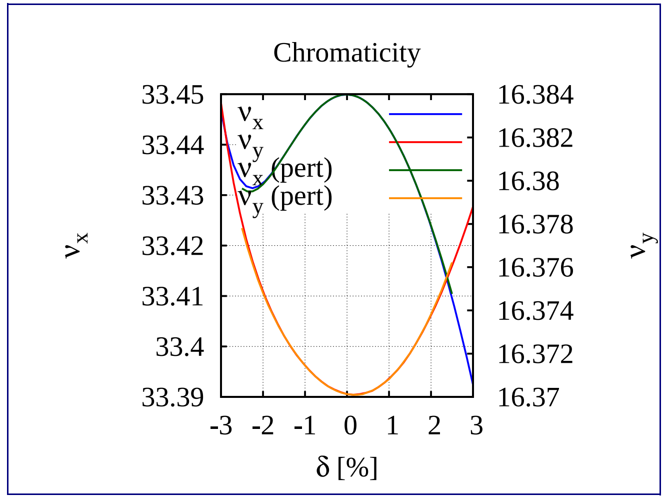
- On momentum Dynamic Aperture (DA): 11 mm (robust top-up injection),
- Off momentum Dynamic Aperture: 2.5% (Touschek life time),
- Tune footprint for the bare lattice (w/ DWs): ~0.05 (to accommodate eng. tol., IDs, etc.).

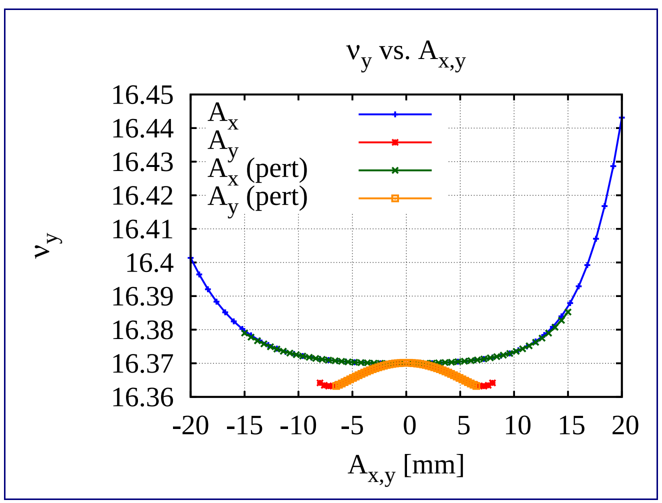
The last requirement is based on a (conservative) estimate of the tune footprint for stable beam in existing medium energy light sources, i.e., about ~0.1.

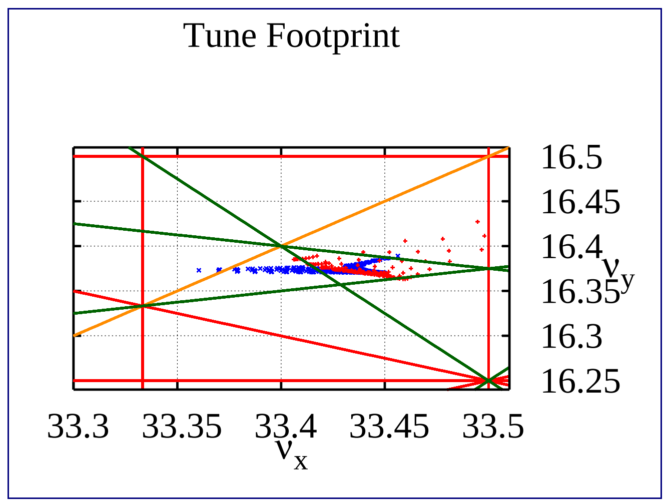
Note, due to the high number of DBA cells (30), as compared to existing medium energy synchrotron light sources, the control of the amplitude dependent tune shift per cell needs to be about 3 times better for a comparable nonlinear performance. Hence also the tight engineering tolerances.

Tune Footprint (w/ DWs)









After:

- **Optics correction (local/global control of symmetry & tune).**
- **And, sextupole re-optimization (to control the DWs' contribution).**

Analytic model to 6th order in the sextupole strength:

$$\bar{\nu} \equiv \bar{\nu}(\bar{\boldsymbol{J}}) + \boldsymbol{O}(\bar{\boldsymbol{J}}, \delta)^4$$

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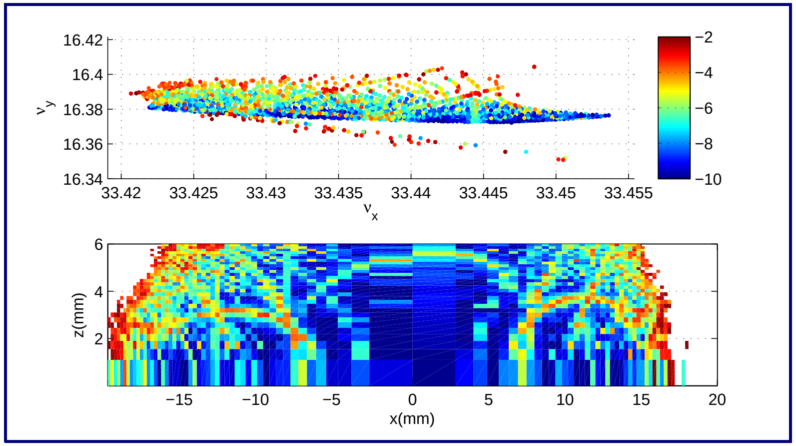
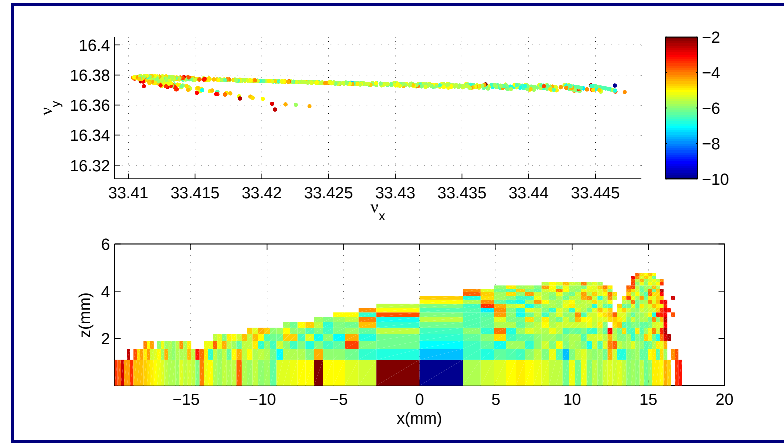
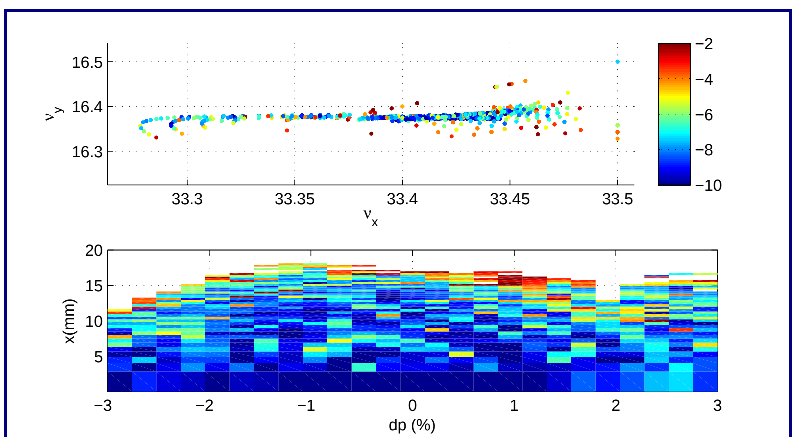
Impact of Eng. Tol. and DWs

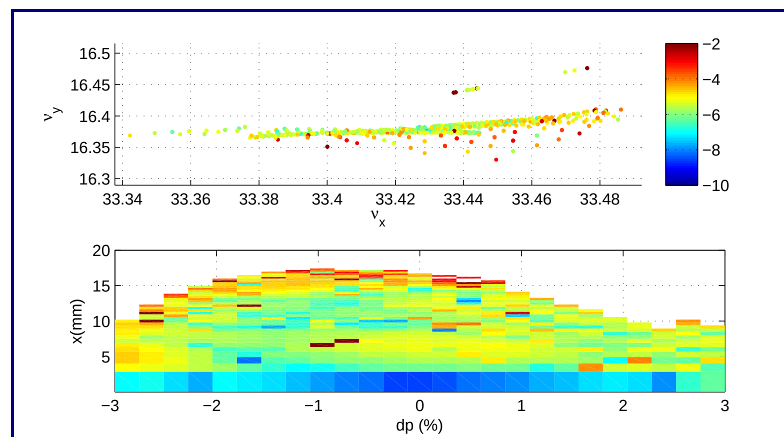




With misalign. (incl. girder correlations) and rand. and sys. multipole errors.

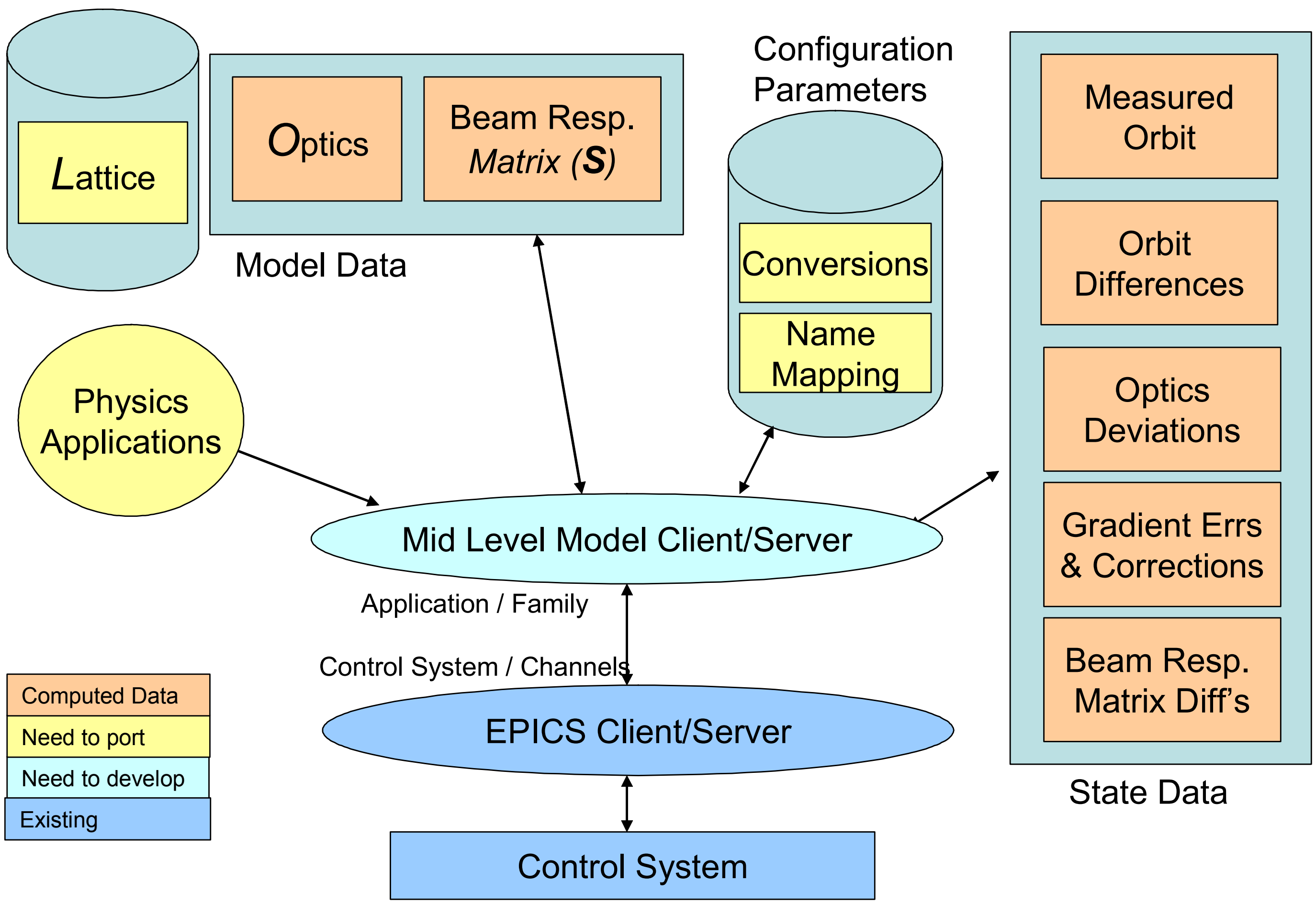
With eng. tol. and DWs.





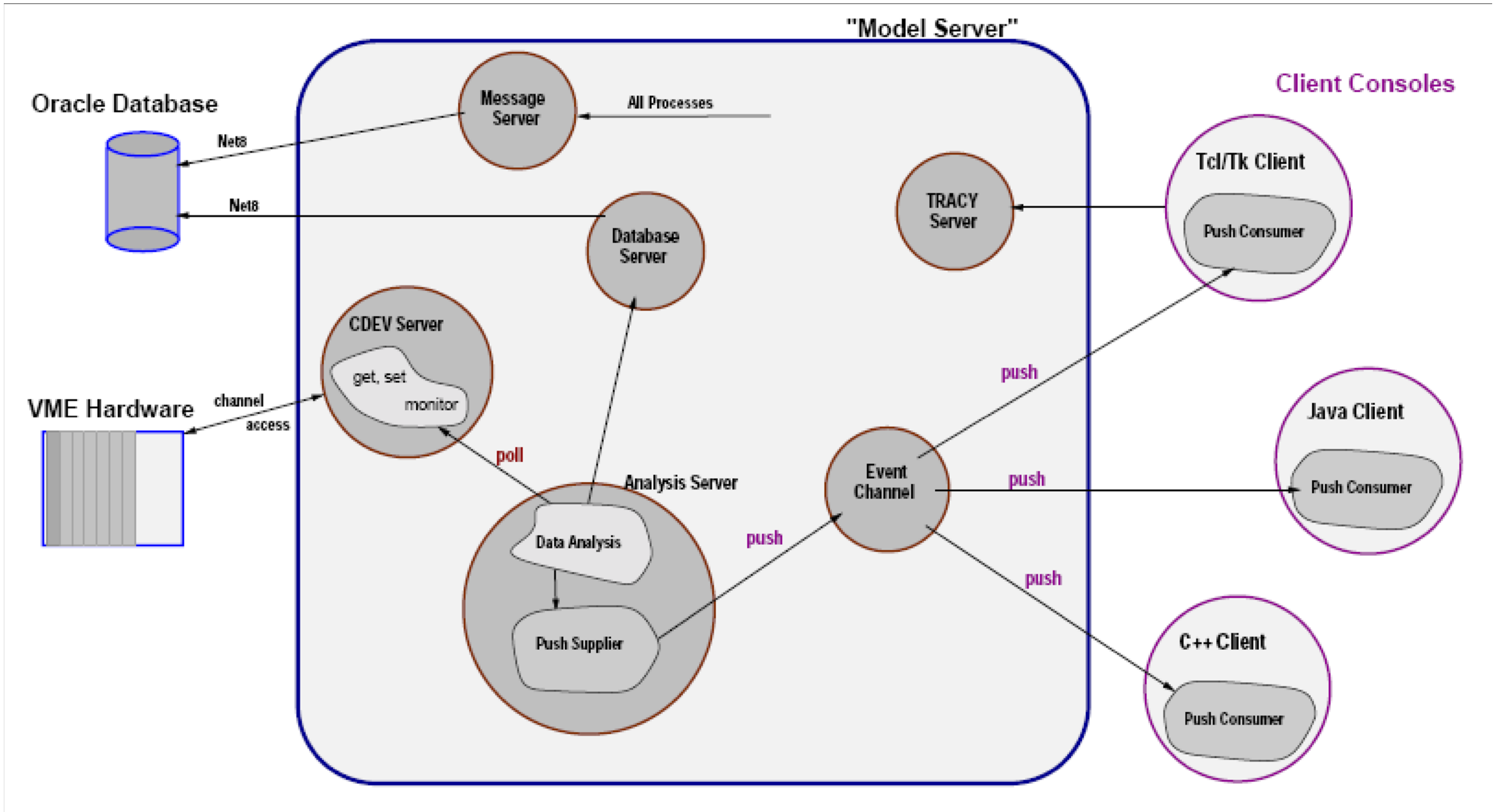
Model Based Control: A Client/Server Approach

(B. Dalesio, G. Shen, et al)



Proof-of-Concept: A (CORBA) Based Approach
(M. Böge, SLS, PAC01)

Re-use accelerator design model (Tracy-2) as on-line model (by machine translating ~10,000 lines of Pascal code to C with p2c).



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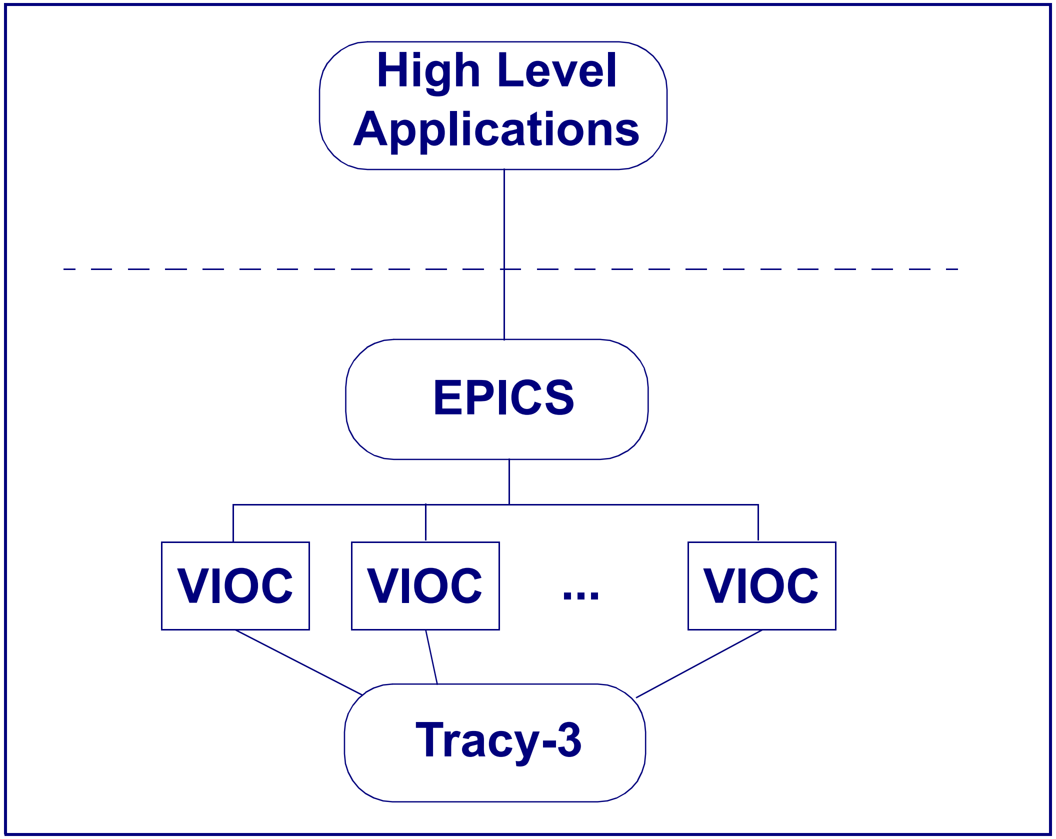
Simulator: A Virtual IOC (VIOC) Approach
(J. Rowland et al, DIAMOND, PAC05; G. Shen et al for NSLS-II)

Connect EPICS to a virtual accelerator simulated with Tracy-3 by Virtual IOCs.



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Conclusions

- By using modern methods, a self-consistent, realistic computer model has been implemented, i.e., where the same model is used for numerical simulations and analysis by analytic techniques.
- It has been used to guide the NSLS-II design. In particular, it has provided an effective framework to control the dynamic aperture, and to provide guidelines for engineering tolerances, and magnet- and insertion device design. In other words, "closing-the-loop".
- It is also being used by the Controls Group, as a simulator for the accelerator, by hooking it up to EPICS, for e.g. testing of high level applications & controls algorithms. Furthermore, it also provides for a transparent implementation of a model server with thin clients for the commissioning of the accelerator.

References

[1]