A Moment with Tracy-2,3: Completing the Circle!

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Synchr. Modeling with Tracy-2,3: Overview

- **Tracy (ALS, LBL, EPAC 1988): Pascal-S Compiler/Interpreter (a strongly typed language, first compiler written in its native language => portable, courtesy N. Wirth et al, ETH, Zürich, in the early 1970s) extended with "standard" procedures for beam dynamics. A "recursive approach"; i.e., user procedures, after prototyping, could be ported to the internal model/code. However, the beam dynamics "model" was based on a "two times 2×2 matrix" formalism with thin kicks for multipoles, i.e., assuming mid-plane symmetry and zero engineering tolerances. Hence, not suitable for an on-line model.**
- **Tracy-2 (Center for Beam Physics, LBL, 1990): Pascal-S Compiler/Interpreter extended with "standard" procedures with: 4th order symplectic integrator for multipoles and generating function for Insertion Devices, 6-D radiation effects, modeling of the impact from eng. tolerances, and linked to Numerical Recipes Library for (extensive) support of numerical optimizations.**
- **6-D phase-space tracking of dipole moments for bunched beams to model collective phenomena and related bunch-by-bunch feedback systems (PAC 1993, EPAC 1994).**

Synchr. Modeling with Tracy-2,3: Overview (cont.)

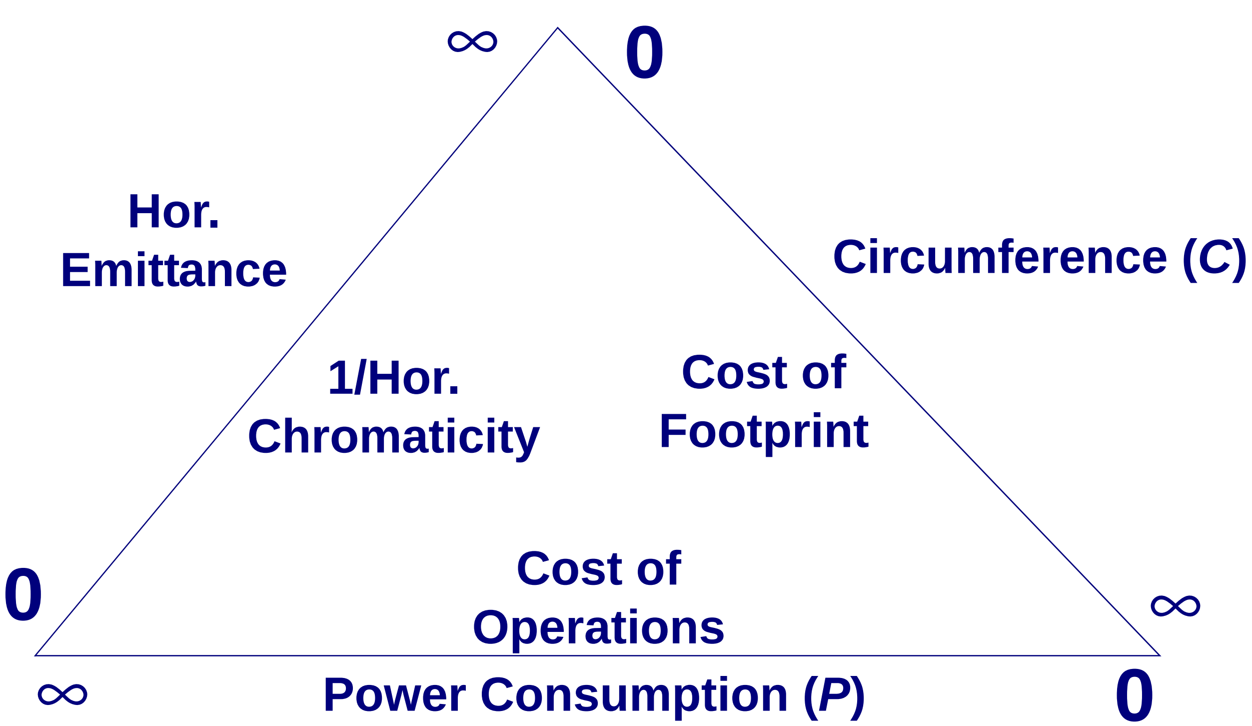
- Polymorphic Tracking Code (in C++, Center for Beam Physics, LBL, 1994): polymorphic number class with reference counting for floating point and Truncated Power Series Algebra, aka "Thor" vs. the ("object oriented") "Classic Project", CERN (AIP Conf. Proc., 1997); which, eventually, stalled.
- Eventually, E. Forest, 2000, then at KEK, re-implemented the concept/approach in Fortran-90: aka PTC.
- Machine translation of the Tracy-2 beam dynamics library from Pascal to C (by using p2c, courtesy M. Böge, SLS); for on-line model (client/server architecture and Python scripts, PAC 2001) for model based control.
- Radia Kick Maps (for precision modeling of Insertion Devices) and Frequency Maps (courtesy L. Nadolski, SOLEIL, (EPAC 2004).
- Virtual Accelerator (client/server architecture, i.e., EPICS VIOC, courtesy J. Rowland, PAC 2005); aka J.M.S. (James' Model Server). He also prototyped a Python interface for the scripting.
- The NSLS-II "Wind Tunnel", 2006.
- Tracy-3 = Tracy-2 + Thor, 2008 => one code vs. two to develop & maintain.
- Replacement of Numerical Recipes with GSL (courtesy P. Pietr, B. Sulkowski, SOLARIS, 2014).

A Systematic Approach to Lattice Design: Overview

- **Global optimization of ring-based synchrotron light sources: trade-offs.**
- **A Measure for Stiffness of Chromatic Control.**
- **The OFODOFO Cell (Bengtsson, LER 2014).**
- **Similarly, and more complete; F. Antoniou "Optics Design of Intrabeam Scattering Dominated Damping Rings" CERN, thesis 2012.**
- **Lessons Learnt.**
- **Tracy-2,3: Use Cases.**
- **Conclusions**

Trade-Offs: Global Optimization (EPAC 2008)

1. Horizontal emittance (natural): damping $\leftrightarrow$ 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.

Chasman-Green Lattices

[1] R. Chasman, G.K. Green, E.M. Rowe "Preliminary Design of a Dedicated Synchrotron Radiation Facility" PAC 1975.

[2] M. Sommer "Optimization of the Emittance of Electrons (Positrons) Storage Rings" LAL/RT/83-15 (1983).

[3] L. Teng "Minimum Emittance Lattice for Synchrotron Radiation Storage Rings" ANL LS-17 (1985).

[4] G. Vignola "The Use of Gradient Magnets in Low Emittance Electron Storage Rings" SRI 1985 (-> ALS).

[5] H. Wiedemann "An Ultra-Low Emittance Mode for PEP Using Damping Wigglers" Nucl. Instr. Meth. 266A, 24-31 (1988).

[6] S. Ozaki et al "Philosophy for NSLS-II Design with Sub-Nanometer Horizontal Emittance" PAC 2007.

Already 1985 Teng noted that (p. 18):

"This theoretical minimum should be at least a factor 2 smaller than the desired emittance because when one gets to the later steps, it is unlikely that one can attain and then maintain optimum values for all the parameters."

i.e., a *system approach*.

A Measure for Stiffness of Chrom. Ctrl (ICFA 57, 2012)

3.6.5 The Chromatic Control Problem: A Measure for Stiffness

It is known that (fixed ρ_b) [36]

$$\varepsilon_x[\text{nm}\cdot\text{rad}] = 1470 \cdot \frac{(E\,[\text{GeV}])^2 \langle \mathcal{H}_x \rangle^{\min}}{\rho_b J_x} = 1470 \cdot \frac{(E\,[\text{GeV}])^2 (2\pi)^3 F}{12\sqrt{15} J_x N_b^3} \qquad (2)$$

where N_b is the total number of dipoles and [37]

$$F_{\text{CB}} = 1, \quad F_{\text{EB}} = 3, \quad F_{N\text{-BA}} = \left(\frac{N}{2 + (N-2)\cdot 3^{1/3}} \right)^3 F_{\text{EB}} \qquad (3)$$

for a "center bend", "end bend", and N-BA, respectively.

As a measure for the *stiffness* of the chromatic control problem, we introduce

$$S \equiv \frac{|\xi_x|}{\nu_x \sqrt{\langle \mathcal{H}_x \rangle}} \sim \frac{1}{\text{DA}}. \qquad (4)$$

Note that the DA has a minimum for the $\langle \mathcal{H}_x \rangle^{\min}$-cell. A survey of F_{rel} (= 1 for $\langle \mathcal{H}_x \rangle^{\min}$) vs. S is summarized in Tab. 1. For the operating facilities we find: $S = 49 \pm 23$.

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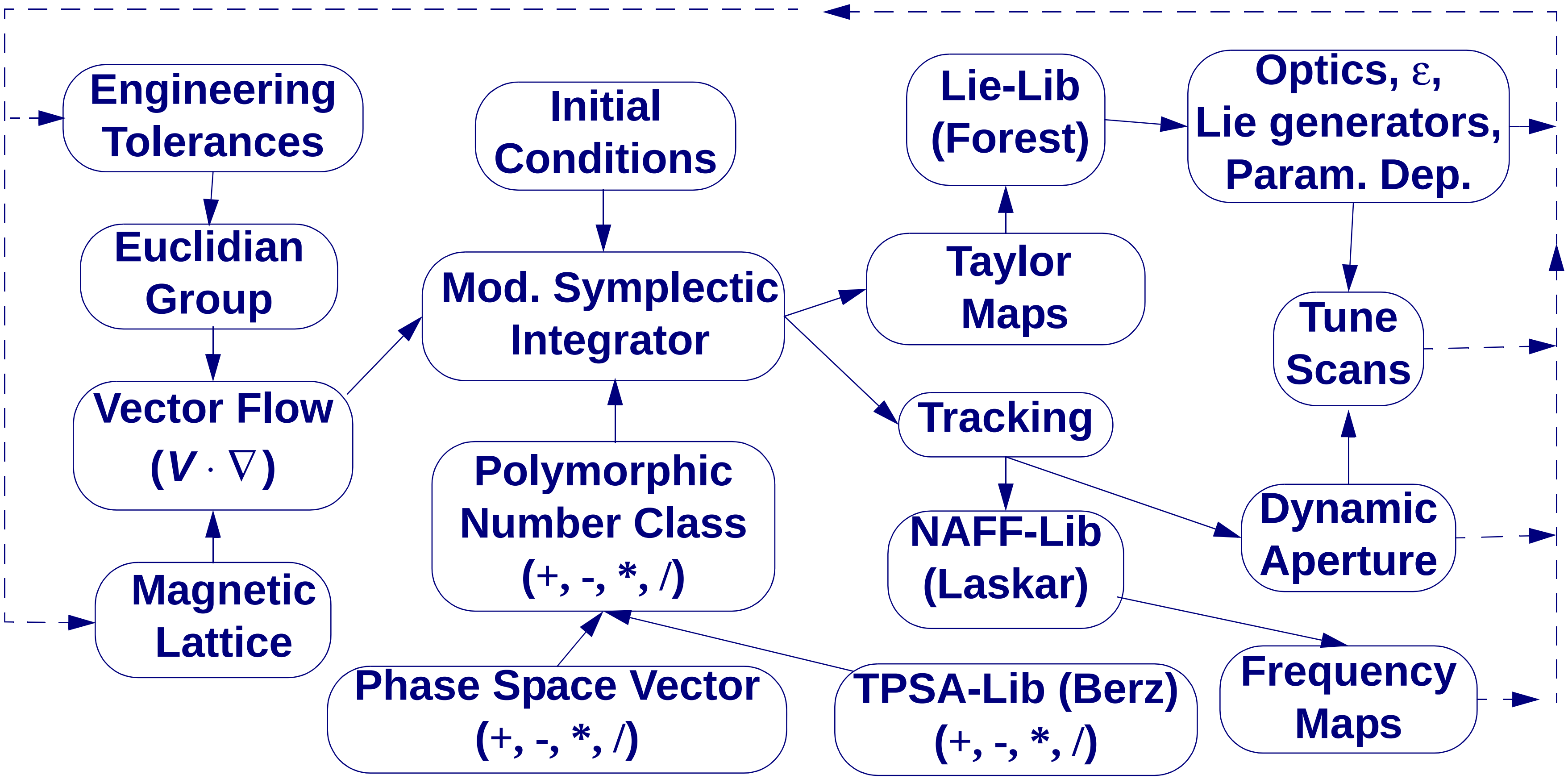
A Measure for Stiffness of Chrom. Ctrl (cont)

Table 1: Survey of F_{rel} vs. Stiffness S for some Storage-Ring Light Sources.

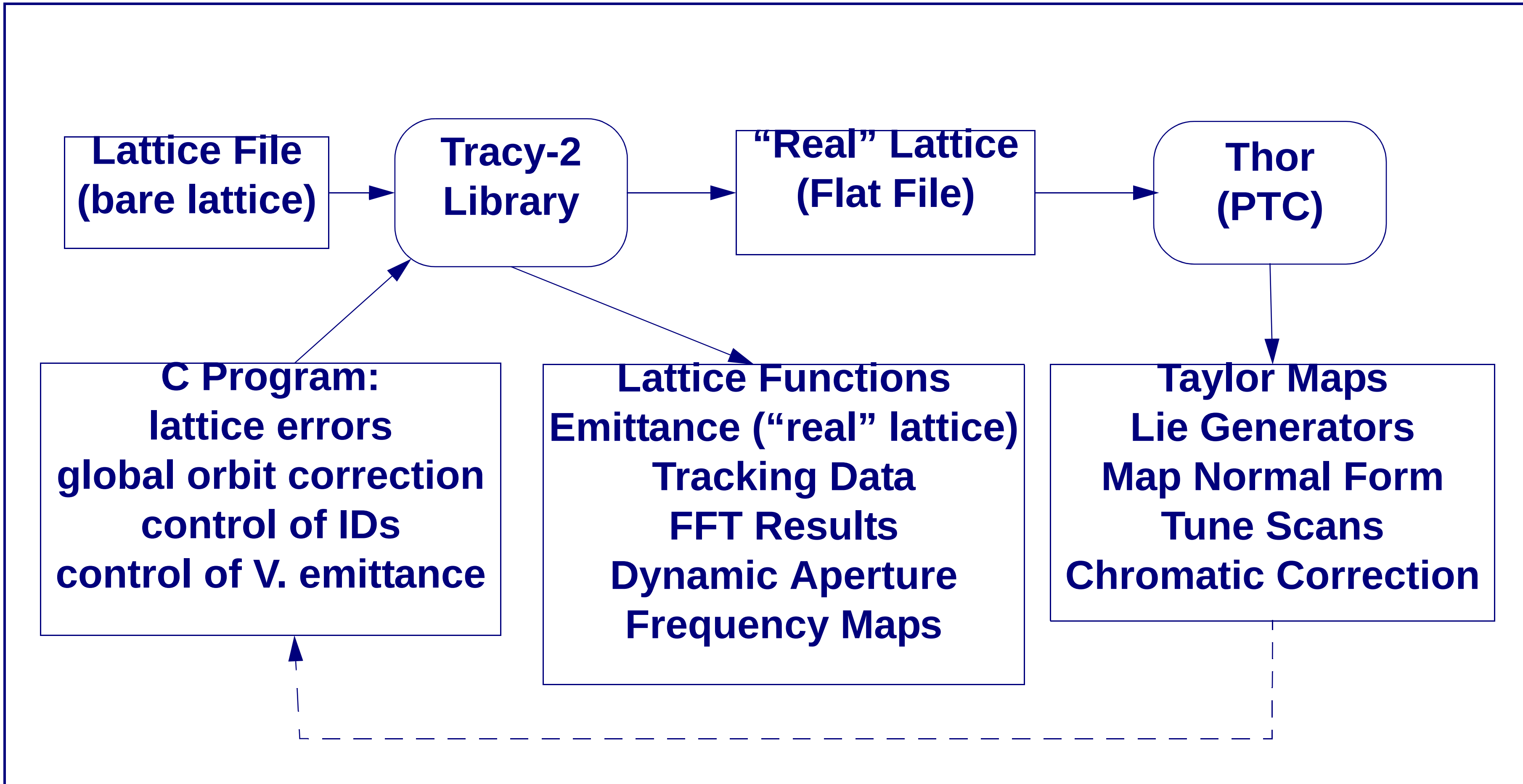
Lattice	Type	E [GeV]	ε_x [nm·rad]	ε^*_x [nm·rad]	J_x	$<\mathcal{H}_x>$ [$\times 10^{-3}$]	F_{rel}	ξ_x/ν_x	S
SPring-8	11×DB-4	8	3.4	3.7	1.0	1.42	4.6	2.2	58
ESRF	DB-32	6	3.8		1.0	1.68	3.5	3.6	89
APS	DB-40	7	2.5	3.1	1.0	1.35	3.3	2.5	69
PETRA III	Mod. FODO	6	1		1.0	3.62	39.8	1.2	20
SPEAR3	DB-18	3	11.2		1.0	5.73	7.4	5.5	73
ALS	TB-12	1.9	6.3	6.4	1.0	4.99	10.4	1.7	24
BESSY II	TBA-10	1.9	6.1		1.0	4.83	2.9	2.8	40
SLS	TBA-12	2.4	5		1.0	3.38	2.6	3.2	56
DIAMOND	DB-24	3	2.7		1.0	1.46	4.2	2.9	76
ASP	DB-14	3	7		1.4	5.60	3.0	2.1	28
ALBA	DB-16	3	4.3		1.3	2.96	2.6	2.1	39
SOLEIL	DB-16	2.75	3.7	5.5	1.0	1.79	2.0	2.8	67
CLS	DBA-12	2.9	18.3		1.6	16.79	2.0	1.3	10
ELETTRA	DBA-12	2	7.4		1.3	9.12	1.4	3.0	31
TPS	DB-24	3	1.7		1.0	1.08	2.7	2.9	87
NSLS-II	DBA-30	3	2		1.0	3.78	2.0	3.1	50
MAX-IV	7BA-20	3	0.33		1.9	0.40	18.1	1.2	59
PEP-X (TME)	4×8TME-6	4.5	0.095		1.0	0.34	3.3	1.7	90
PEP-X (USR)	8×7BA-6	4.5	0.029		1.0	0.10	5.3	1.4	145
TeVUSR	30×7BA-6	11	0.0031		2.4	0.02	12.0	1.4	360
TeVUSR	30×7BA-6	9	0.0029		2.7	0.02	18.4	1.4	281

The NSLS-II "Wind Tunnel" (BNL, 2006)



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

The NSLS-II “Wind Tunnel” (cont.)



Implementation (~50,000 lines of C++, C, and FORTRAN code; two different codes, C and C++, at the time).

Lessons Learnt: ALS

EPAC 1988

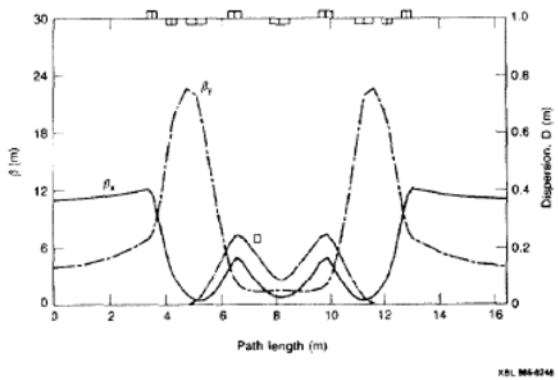


Fig. 3. Lattice functions through one unit cell of the TBA structure.

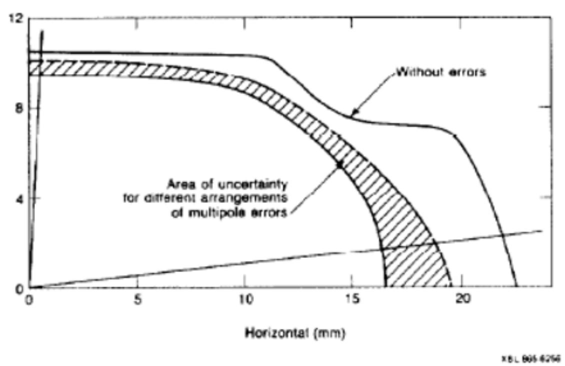


Fig. 5. Dynamic aperture in the presence of multipole errors.

For the linear optics see G. Vignola SRI 1986.

D. Robin et al (EPAC96)

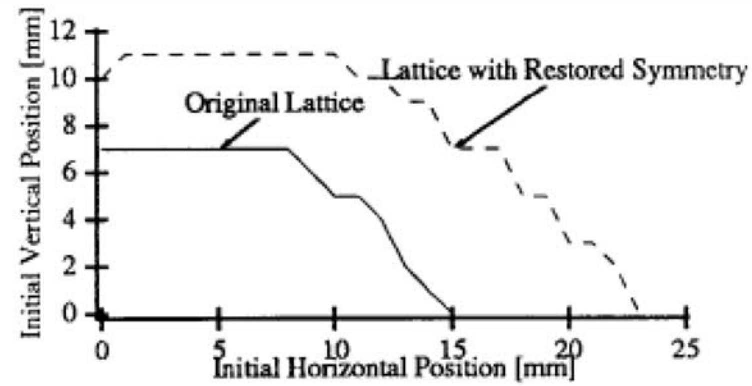


Figure 6: Comparison of dynamic aperture for the original and restored symmetry lattices.

- **Only 2 sextupole families.**
- **Orbit correction not robust; not "tied down" in the sextupoles (BPM placement based on linear optics).**
- **For the "48-Knob Scheme" see AIP Conf. Proc. 255 (1991).**
- **For validation of the nonlinear model (Tracy-2), see J. Bengtsson et al (PAC94).**

Lessons Learnt: M-BA -> SLS

EPAC 1994

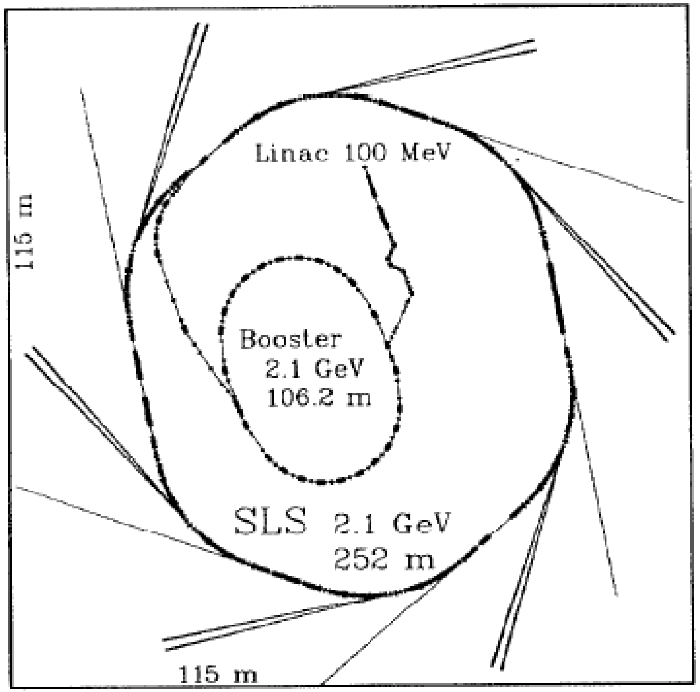


Figure 2: Layout of the SLS facility with linac, booster and storage ring. Shown are the photon beamlines from insertion devices and the twin beamlines from the six superconducting bending magnets.

EPAC 1996

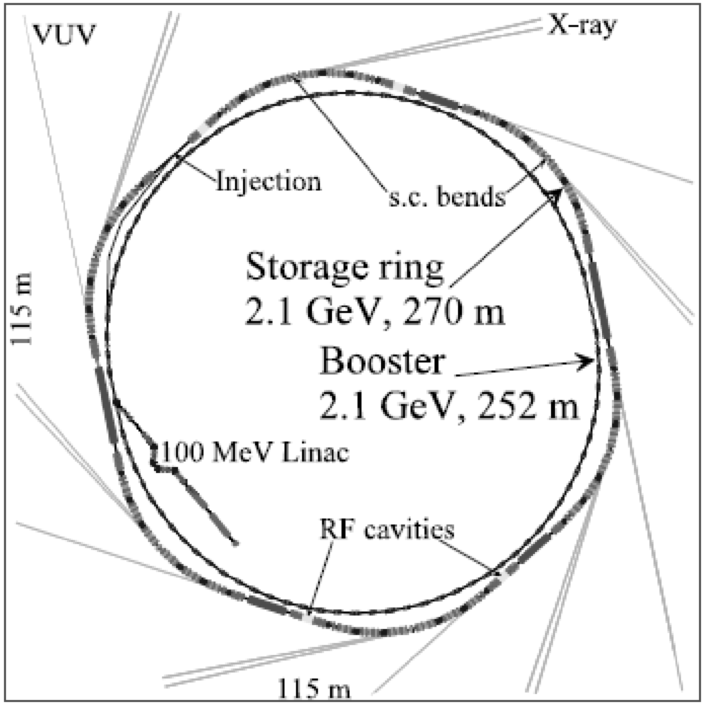
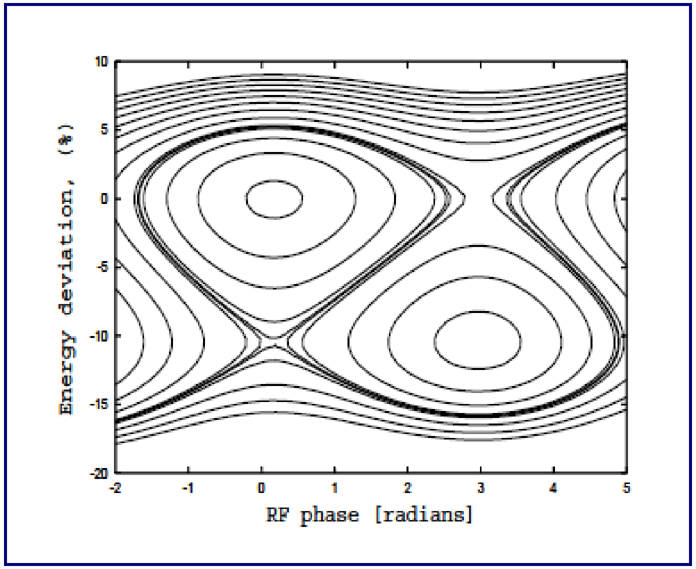


Figure 1: Layout of the SLS facility with linac, booster and storage ring. Shown are the possible photon beamlines from insertion devices and the possible twin beamlines from the six superconducting bending magnets.

For a perspective see:

1. **A. Streun "Nonlinear Dynamics at the SLS Storage Ring" LER 2010 (4 phase tromb. and 33 sext. fam.).**
2. **P. Kaltchev et al "Lattice Studies for a High Brightness Light Source" PAC 1995.**

Lessons Learnt: SOLEIL -> Alpha Buckets



SOLEIL PAC 1999.

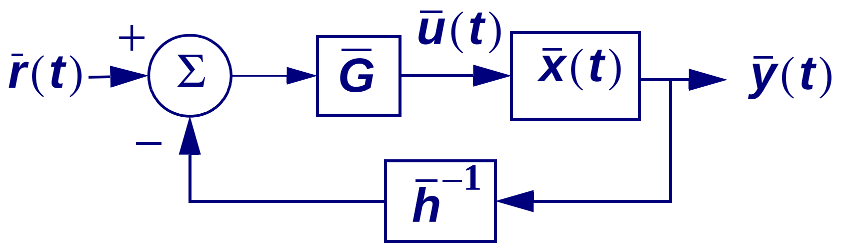
D. Robin, E. Forest, C. Pellegrini, A. Amiry "Quasi-Isochronous Storage Rings" Phys. Rev. E 48, 2149-2156 (1993).

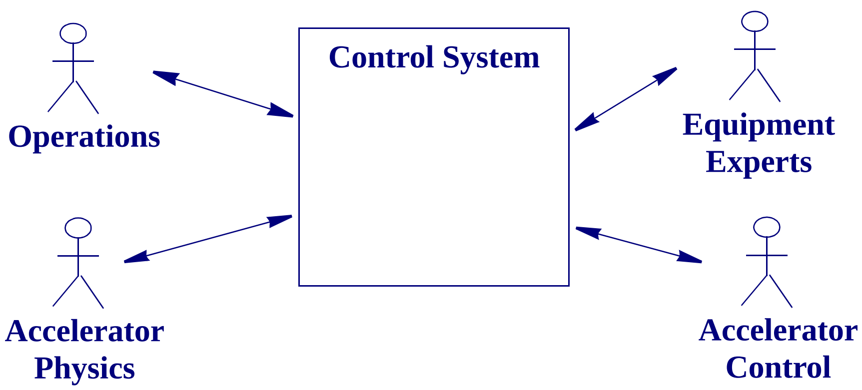
$$\alpha_c^{(1)} \sim \frac{1}{\nu_x^2}$$

$$H(\phi, \delta; s) = \frac{\eta^{(1)} h\omega_0}{2c_0}\delta^2 + \frac{\eta^{(2)} h\omega_0}{3c_0}\delta^2 + \frac{\omega_0 eV_{rf}}{2\pi c_0 E_0}(\cos(\phi + \phi_s) + \phi\sin(\phi_s))$$

$$\phi' = \partial_\delta H = \frac{h\omega_0\eta^{(1)}}{c_0}\delta + \frac{h\omega_0\eta^{(2)}}{c_0}\delta^2, \qquad \delta' = -\partial_\phi H = \frac{\omega_0 eV_{rf}}{2\pi c_0 E_0}(\sin(\phi + \phi_s) - \sin(\phi_s))$$

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.**

Tracy-2: Use Cases

Use Cases:

- **ALS:**

  A recursive approach (based on the Pascal-S compiler/interpreter; courtesy N. Wirth et al, ETH, Zürich, early 1970s).

  Fourier analysis of betatron spectrum (CERN 88-05, EPAC 1988).

  Integration of a super conducting wiggler by global symmetry restoration; aka "48-knob scheme" (AIP Conf. Proc. 255, 1991).

  Modeling of realistic lattice; incl. evaluation of vertical emittance.

  Touschek tracking.

  Validation of nonlinear model (EPAC 1994).

  Using Taylor maps for modeling of a realistic lattice the digital bunch-by-bunch feedback system proposed by SLAC (PAC 1993, EPAC 1994).

- **Duke FEL Storage Ring**

  Dynamic aperture (PAC 1993).

Tracy-2: Use Cases (cont.)

- **BESSY-II**

  Touschek tracking (EPAC 1994).

- **SPEAR**

  Octupoles (PAC 1995).

- **SLS:**

  Robust conceptual design,

  The driving terms (Nucl. Instr. Meth.).

  Client/server on-line model and machine translation to C (PAC 2001a, PAC 2001b).

- **SOLEIL:**

  Alpha-buckets (PAC 1999).

  RADIA kick maps,

  Frequency Maps (EPAC 2004).

Tracy-2: Use Cases (cont.)

- **DIAMOND:**

  Client/server Virtual Accelerator (James Rowland, PAC 2005); aka J.M.S. (James' Model Server).

  Python interface (James Rowland).

- **NSLS-II:**

  Robust conceptual design.

  Integration of Insertion Devices.

  Virtual Accelerator and on-line model: J.M.S. (James' Model Services, ICA-LEPS 2013).

  On-line model for model based control; re-using controls algorithms developed for the conceptual design.

- **MAX-IV:**

  Dynamic Aperture and Touschek life time (PR ST-AB, 2012).

  Interplay of Touschek scattering, IBS, and RF cavities (PR ST-AB, 2014).

Tracy-2: Use Cases (cont.)

- **SOLARIS:**

  Replacement of Numerical Recipes library with GSL.

  Client/server Virtual Accelerator (ICAP 2012).

- **New developments:**

  Python interface (first prototyped by J. Rowland, DIAMOND, 2004).

  Replacement of lattice parser to LEX/YACC based (based on Unix/Linux compiler generating tools -> recursive; provided by L. Yung).

  Modeling of collective phenomena by moment tracking.

  Modeling of bunch-by-bunch feedback systems.

  Evaluation of impact of e.g. linear chromaticity on such systems.

  Beam Line Struct (Pascal -> C) -> Beam Line Class (C++).

  Multiple model instances (for model based control w/ Python Notebooks).

  Modeling of small rings (e.g. chromaticity).

  Modeling of ERLs.

Tracy-2: Use Cases (cont.)

Model of leading order space charge effects?

LINAC modeling?

...?

SCSI: Self-Consistent Symplectic (or vector flow) Integrator.

[1] A. Adelmann "3D Simulation of Space Charge Effects in Particle Beams" PSI Bericht 02-20 (2002).

[2] M.G. Minty, A.W. Chao, W.L. Spence "Emittance Growth due to Decoherence and Wakefields" PAC 1995.

Tracking of Moments

The Hamiltonian for the longitudinal dynamics is

$$H(\bar{x};s) = \frac{1}{2}(p_x^2 + K_x x^2) + \frac{qE}{p_0 c_0} x \sin(\omega_0 s / c_0 + \varphi)\delta(s - s_0) \qquad (1)$$

and the equations of motion

$$x' = p_x, \qquad p'_x = -Kx - A\sin(\omega_0 s / c_0 + \varphi)\delta(s - s_0) \qquad (2)$$

where

$$A = \frac{qE}{p_0 c_0}. \qquad (3)$$

The equations of motion for the linear moments are

$$\langle x \rangle' = \langle x' \rangle = \langle p_x \rangle, \qquad \langle p_x \rangle' = \langle p'_x \rangle = -K\langle x \rangle - A\sin(\omega_0 s / c_0 + \varphi)\delta(s - s_0) \qquad (4)$$

Tracking of Moments (cont.)

with the solution

$$\langle \bar{x} \rangle = 0. \qquad (1)$$

For the quadratic moments we obtain

$$\begin{aligned}
\langle x^2 \rangle' &= 2\langle xx' \rangle = 2\langle xp_x \rangle, \\
\langle xp_x \rangle' &= \langle x'p_x \rangle + \langle xp'_x \rangle = \langle p_x^2 \rangle + \langle xp_x' \rangle \\
&= \langle p_x^2 \rangle - K\langle x^2 \rangle - \langle x \rangle A \sin(\omega_0 s / c_0 + \varphi)\delta(s - s_0), \\
\langle p_x^2 \rangle' &= 2\langle p_x p_x' \rangle = -2K\langle xp_x \rangle - 2\langle p_x \rangle A \sin(\omega_0 s / c_0 + \varphi)\delta(s - s_0)
\end{aligned} \qquad (2)$$

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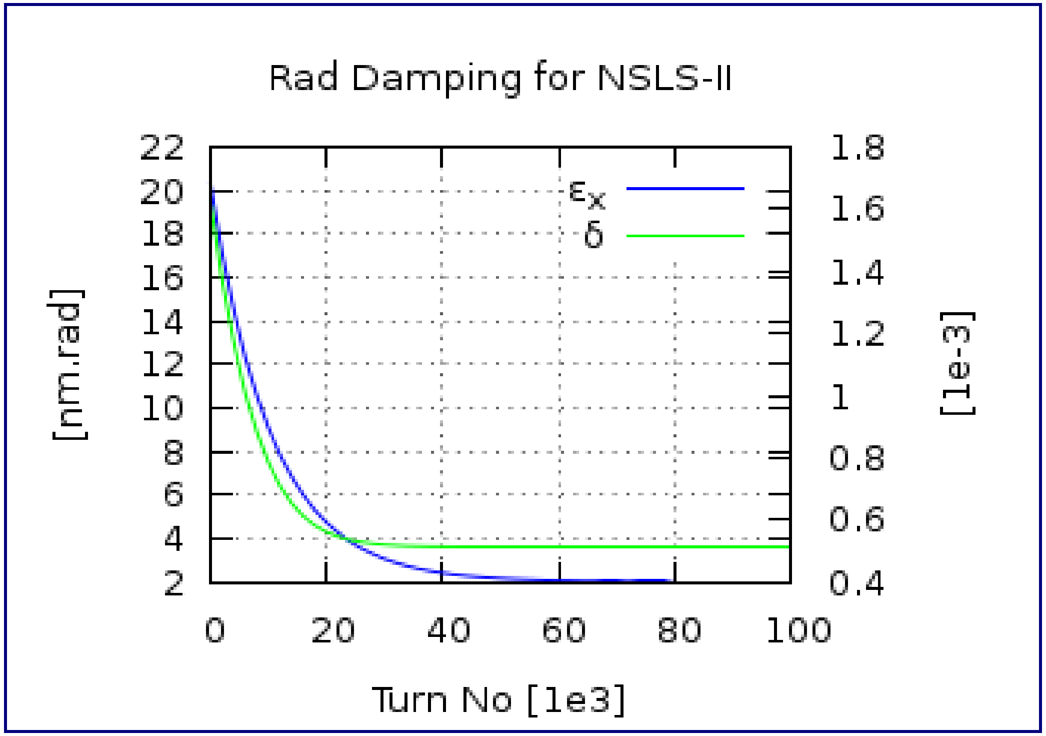
Tracking of Moments (cont.)



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“Outside the Box”: MAX User Meeting 2008 (M. Eriksson)

MAX IV – Swedish / Nordic / Baltic SR facility

1. Small magnets => strong lenses => short magnets
But: How to do it? Never done before.

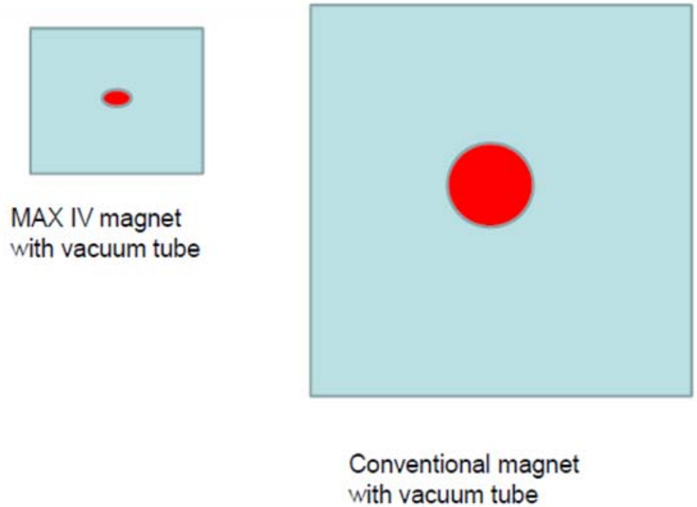
Ask Lars Johan Lindgren and Bengt Anderberg!

2. But you need new types of lattices?

Ask Simon Leeman, Johan Bengtsson (Brookhaven) and Andreas Streun (PSI) to develop codes and number-crunch!

3. The vacuum chamber bore is to small for pumping?

Ask Erik Wallén, Magnus Berglund. Anders Hansson and Roberto Kersevan (ESRF) to develop and characterize a linear pumping system (NEG-coated)!



4. Ultra-small emittance=>no beam life-time!

Ask Lars Malmgren, Per Lilja, Robert Nilsson, Åke Andersson to make 100 MHz RF system with huge energy acceptance!

MAX-lab

MAX User Meeting 2008

Question: What’s fundamentally different to previous designs?

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The KTH Great Prize 2011

“Eriksson describes the early efforts of building a world-famous physics laboratory as surprisingly modest.

‘When we were working on the first technology to generate the light source, one of my colleagues brought in his mother’s old washing machine [w/ a manual wrangler] so we could jury-rig some transformer plates,’

he says.

...

Eriksson says his innovative design solutions were partly inspired by his uncle, KTH Professor Hannes Alfvén, who received the 1970 Nobel Prize in Physics.”

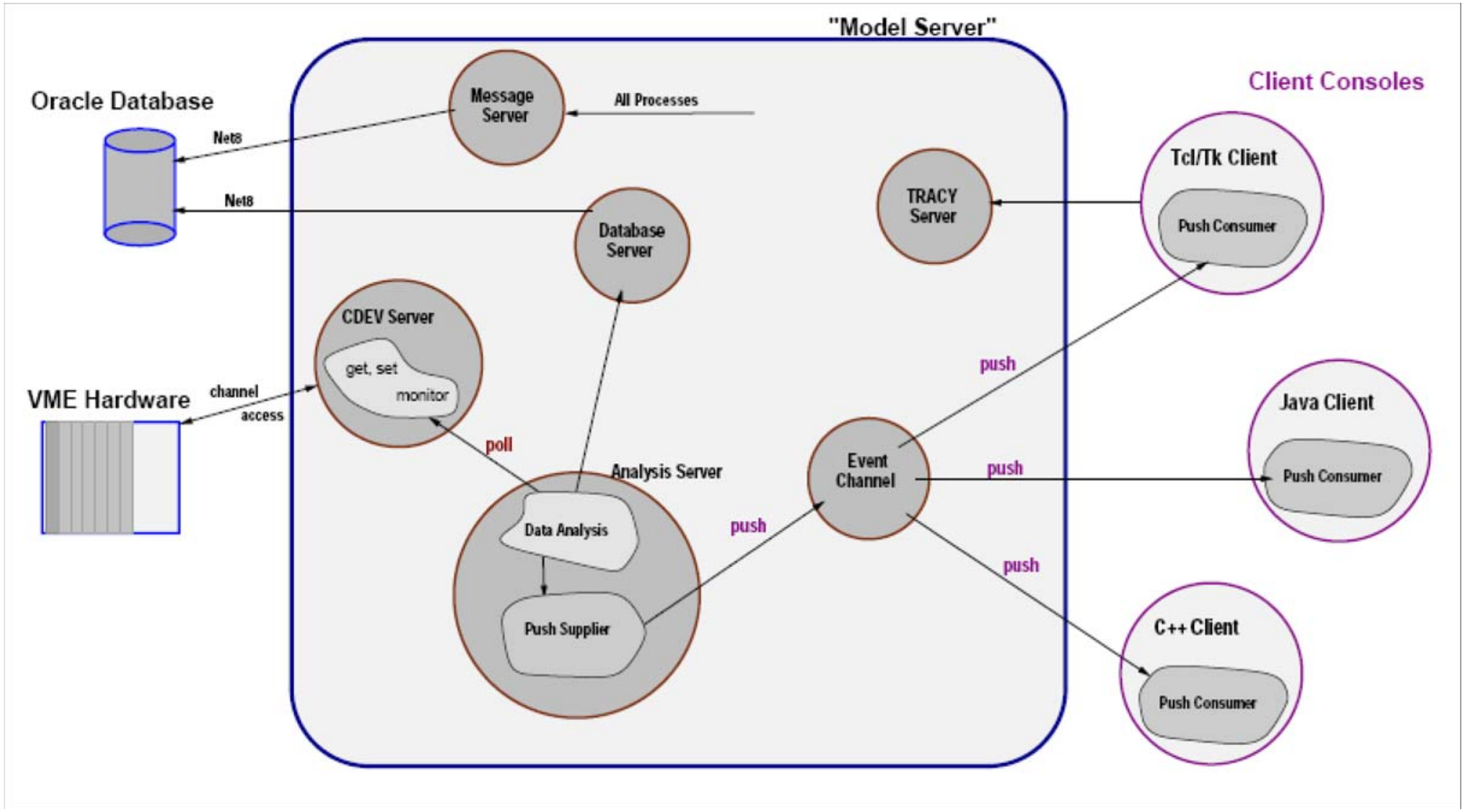
In particular, instead of following the beaten path, aka “TME” (“Theoretical” Minimum Emittance Cell), an academic “guideline” which has resulted in a scrap heap of paper designs (when engineering tolerances are included) he ignored it.

Quantitatively, $\varepsilon_r = 13 \Rightarrow \varepsilon_x = 0.615, C = 500\ \mathrm{m}$ **nm·rad @3 GeV for the MAX-IV unit cell; for *robust design*.**

Actually, $\varepsilon_x = 0.334$ **but** $J_x \approx 2$**; i.e., the Qd gradient is integrated into the dipole.**

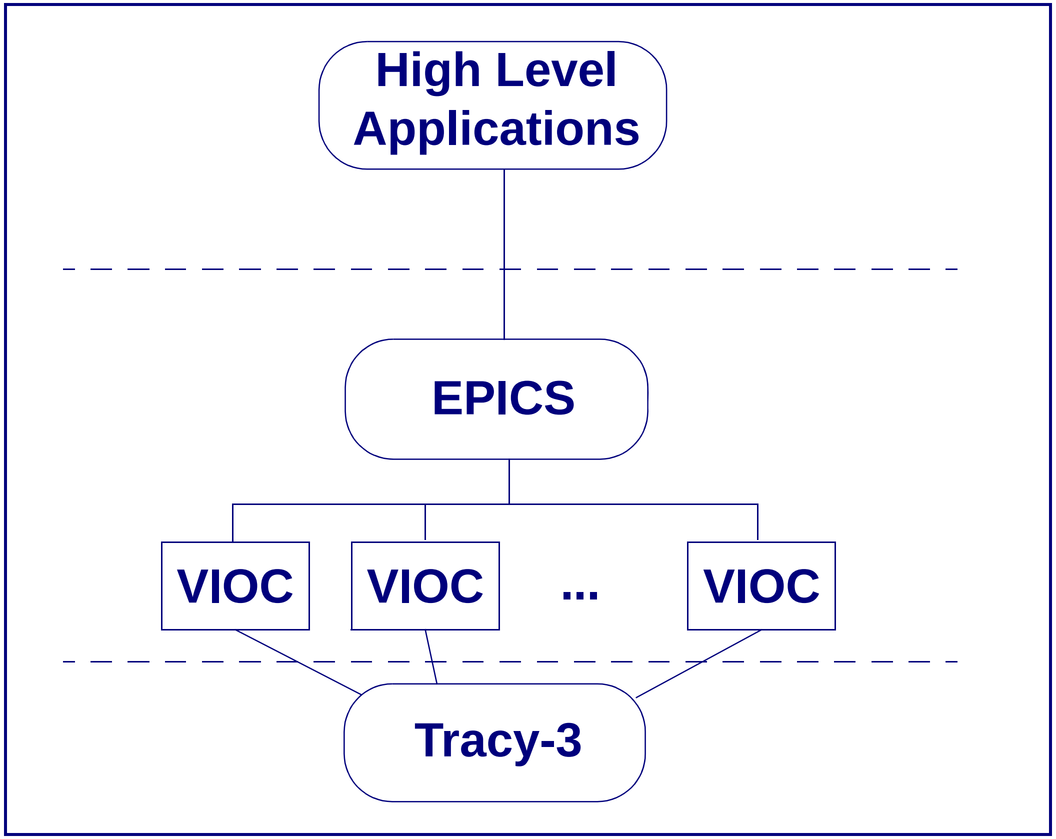
A Client/Server Approach (M. Böge, SLS, PAC 2001)

- **Re-use accelerator design model (Tracy-2) as on-line model: by machine translating (with p2c) ~10,000 lines of Pascal code to C.**
- **Feasible because the code is organized as a library and the internal beam dynamics model is: architectured, layered, and recursive.**



Simulator: A EPICS Virtual IOC (J. Rowland, DIAMOND, PAC05)

Connect EPICS to a virtual accelerator simulated with Tracy-3 by Virtual IOCs; aka J.M.S. (James' Model Server).



Conclusions