Courtesy of Jacobs Gibb / Crispin Wride Architectural Design Studio

Optimisation of Modern Light Source Lattices

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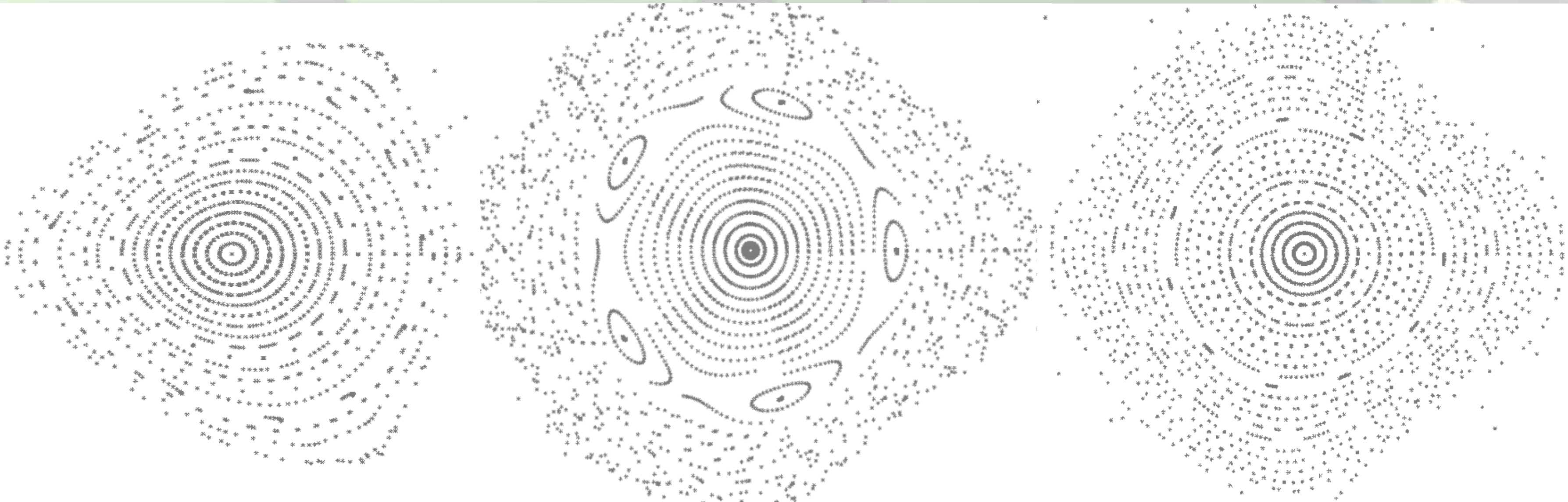


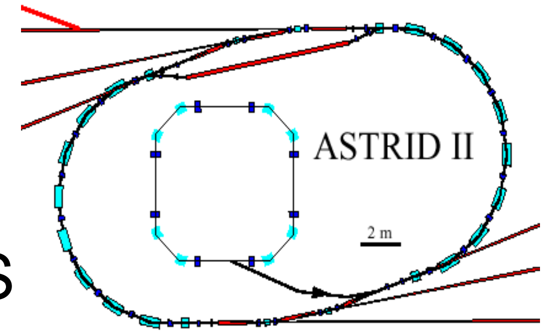
Content

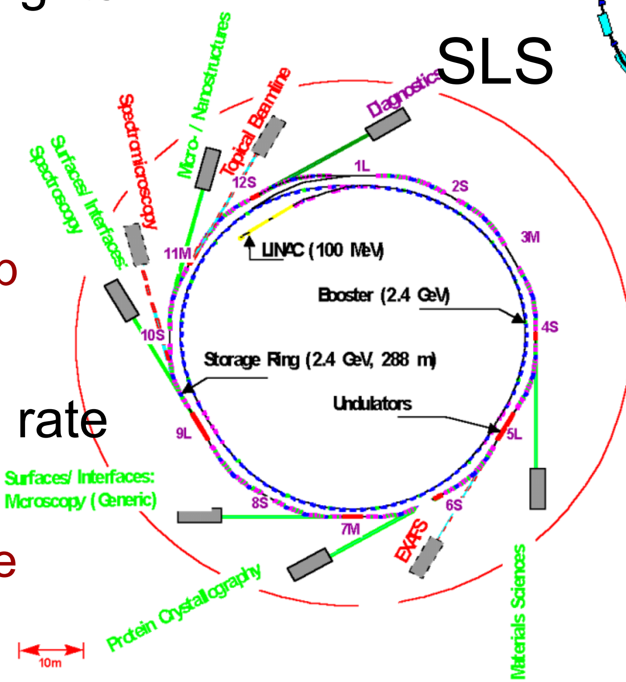
- Design
- Optimisation
  - » Evolution
  - » Linear
  - » Nonlinear
    - Issues
    - How its done
    - Examples
- Verification
- Conclusion

Aims of source design

Economically produce the "Best Light Source" for a give community

- Number of ID straights
- Length of straight
- Ratio of bends to straights
- Brightness
  - » Emittance
  - » Photon range
    - Minimum ID gap
- Flexibility
- Lifetime and injection rate
  - » Dynamic aperture
  - » Momentum aperture
- Stability
- Future proofing





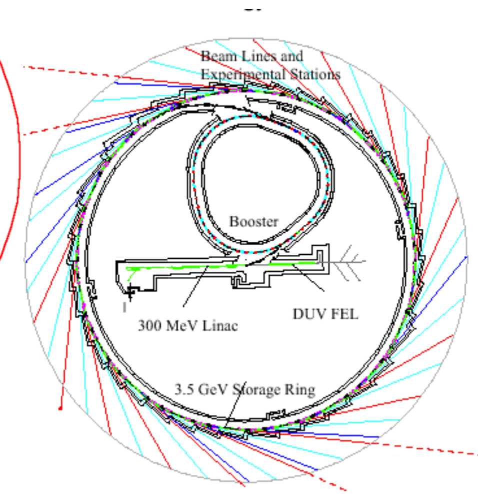


Fig.1 Layout of the SSRF

Choice of overall design

- TBA DBA or NBA
- Machine energy
- Minimum ID gap
- Numbers of cells
- Symmetry
- Lengths of ID straights
- Machine apertures
- Emittance
- Coupling
- Minimum lifetime
- Flexibility of tuning
- Circumference

No optimisation tools will tell you which lattice to build!!

But…………..

Medium energy DBA solutions of 8 to 24 cells appear very popular as "National" sources covering hard x-rays from small gap Ids

Intermediate energy machines

TEN- Intermediate energy DBAs proposed or under construction

Table 1 List of storage ring parameters for machines that are either proposed or under construction.

Name	E (GeV)	I (Amp)	ε_{x0} (nm·rad)	Tunes Q_x/Q_y	f_{RF} (MHz)	Lattice	Straights	Circum. (m)
BOOMERANG	3.0	200	11.5*	11.11/4.18	499.65	DBA	12	184.07
CANDLE	3.0	350	8.4*	13.22/4.26	499.65	DBA	16	216
CLS	2.9	500	18.1*	10.22/3.26	500	DBA	12	170.88
DIAMOND	3.0	300	2.0*	29.16/11.35	500	DBA	24	560.4
INDUS-II	2.5	300	58.1	9.2/5.2	505.81	DBA	8	172.47
MOSLA	2.0	300	54	7.1/3.15	500	DBA	8	119.88
SOLEIL	2.5	500	3.1*	18.28/10.26	352.20	DBA	24	354.10
SPEAR3	3.0	500	18	14.19/5.23	476.3	DBA	18	240
SSRF	3.5	300	4.8*-11.8	22.19/8.23	499.65	DBA	20	396
Super SOR	1.6		5.62*	14.26/12.19	500.09		12	249.39
TLS-II	3.0	400	9.8*-28.3	12.2/5.2	500	DBA	16	240

*Natural emittance of dispersion-distributed mode

*J Corbett, D.Einfeld, Z.T. Zhao, **SSILS 2001***

Evolution of optimisation strategy (1)

- **2nd Generation SR lattices**
  - » **Step 1 Linear lattice design FQ-DQ scans of stability neck-tie with attention given to chromaticity correction and avoidance of low order (1-5) structure resonances**
  - » **Step 2 Confirmation dynamic aperture >> physical aperture**

- **3rd Generation SR lattices**
  - » **Step 1 Linear lattice design, DBA Or TBA highly symmetric**
  - » **Step 2 Nonlinear optimisation by tuning small number of harmonic sextupole families**
  - » **Step 3 Confirmation of dynamic aperture by tracking and effects of errors**

Evolution of optimisation strategy (2)

- **3rd Generation "high performance" lattices, pushing for low emittance, large off momentum aperture requirement, often lower symmetry**
  - » **Phase requirements for minimisation of non-linearities particularly in lower symmetry machines**
  - » **Linear matching and optimisation**
  - » **Optimisation of larger number of sextupole families**
  - » **Non linear optimisation has impact on general lattice layout and linear design**
  - » **Detailed characterisation of on and off momentum behaviour**
  - » **Lifetime calc for nonlinear lattice**
- **Nonlinear optimisation and linear matching are now coupled and nonlinear optimisation impacts on linear lattice design.**

Linear matching

Typical linear matching criteria for lattice

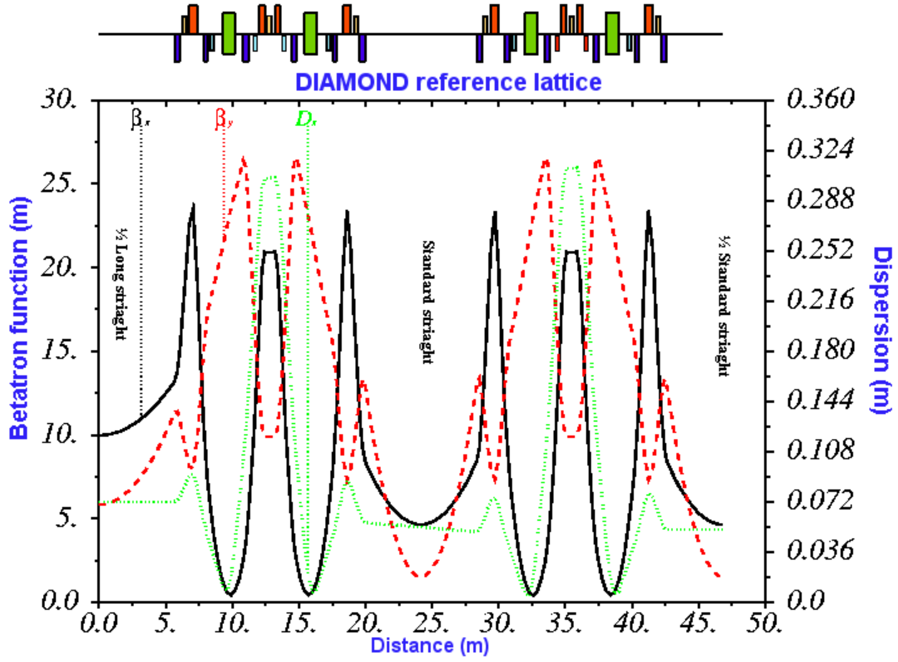
- Reasonable maximums for βr and βv $\leq$ 35 m (**sensitivity**)

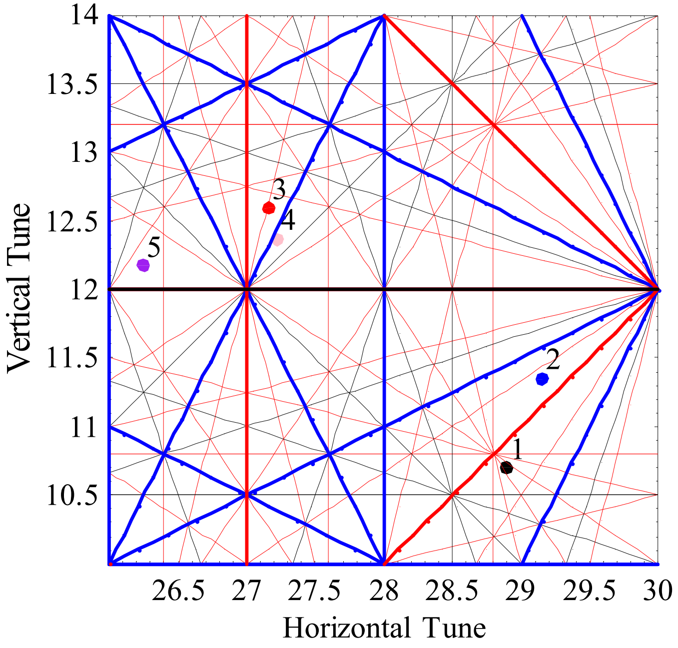
- **Reasonable beta split at the centre of the achromat**
- **Natural chromaticities ξr < -120, ξv < -50**
- **Reasonable dispersion at the centre of the achromat > 0.25 m**
- **Sextupoles in the high dispersion region $|K2|$<45 T/ m**

- Natural radial emittance < 3 nm-rad & > 1.5 nm-rad
- **Dispersion, centre of the standard straight > 0.04 m, $\leq$ 0.1 m**
- **βr**, **βv** at the centre of the standard straight $\leq$ **5m**, $\leq$ **2.5m** (**match ID lengths for small gap**)
- **βr**, **βv** at the centre of the long straight **> 10 m** (**injection**), $\leq$ **8 m**

Typical linear matching criteria for lattice

- αr, αv = 0 at the centre of "achromat" & ID straight sections
- Integer part of radial & vertical tune < 0.5 (**resistive wall**)
- Working point clear of systematic, structure resonances
- Working point clear of non-systematic resonances
- **Phase optimisation to minimise nonlinear effects.**





Nonlinear optimisation

Light source issues

Concerns

Beam lifetime

Injection rate/efficiency(top-up)

Nonlinearities

Sextupoles for chromaticity correction

(Magnet errors, IDs)

Mechanisms

Fast (<10^4 turns) diffusion

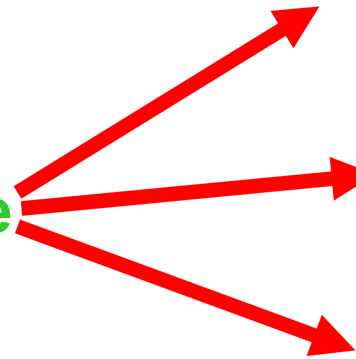
Touschek and gas scattering

Small transverse and longitudinal apertures

Lifetime and momentum aperture

Touschek Lifetime $\propto$ (Momentum acceptance)^2

Momentum acceptance



RF aperture

Physical aperture

Dynamic aperture

Several sources (ALS,ESRF,APS) measure dynamic momentum acceptance ~ 2%, less than the design study predictions!!

Medium energy, small emittance light sources require 4-6% aperture (SLS, SOLEIL,DIAMOND etc..)

Nonlinear optimisation

- **Problem**
  - » **Small emittance**
  - » **Strong quadrupoles**
  - » **Strong sextupoles**
  - » **Large nonlinear kicks**
  - » **Poor dynamic aperture**

- **Solution**
  - » **Cancellation of kicks**
    - **Choosing carefully phase between sextupoles**
    - **Adding additional sextupoles**

Nonlinear optimisation

Single particle motion: H $(x,p_x,y,p_y,t,\delta;s)$

No analytic solution so have two courses to follow

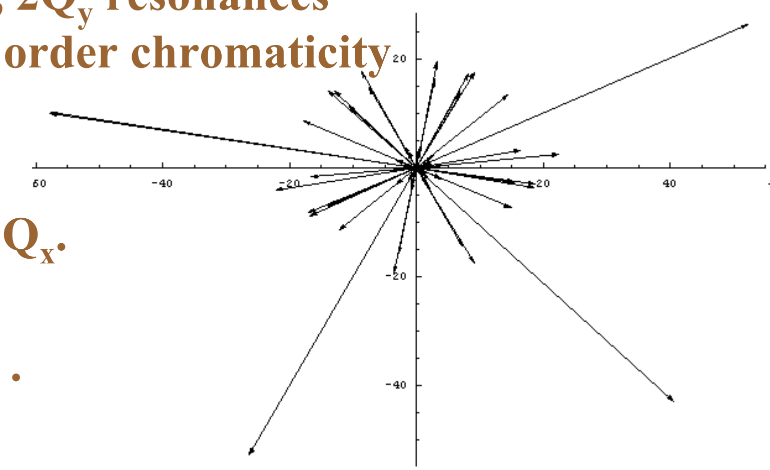
- Tracking (**Symplectic**) → Kick → Series of maps (formalised through Lie series)
  - » Accurate
  - » Works for strong and weak nonlinearities
  - » Gives little theoretical understanding of non-linear motion
  - » Can be slow and computer intensive
- Perturbation methods → Canonical perturbation theory → one turn maps /normal forms/ diff Algebra
  - » Provides information:- dynamic quantities, tuneshifts, resonance strengths, phase space distortions etc. that can be used as a basis for optimisation
  - » Approximate
  - » Limits on ranges of validity (strength of non-linearities, distance of resonances, amplitude of motion)

The sextupole Hamiltonian

$$h_{jklmp} \propto \sum_n^{N_{sext}} (b_3L)_n \beta_{xn}^{\frac{j+k}{2}} \beta_{yn}^{\frac{l+m}{2}} \eta_n^p e^{i[(j-k)\varphi_{xn}+(l-m)\varphi_{yn}]} - \left[\sum_n^{N_{quad}} (b_2L)_n \beta_{xn}^{\frac{j+k}{2}} \beta_{yn}^{\frac{l+m}{2}} \eta_n^p e^{i[(j-k)\varphi_{xn}+(l-m)\varphi_{yn}]} \right]_{p\neq 0}$$

4 Chromatic terms

h_{11001} & h_{00111} => chromaticities
h_{20001} & h_{00201} => off-momentum $2Q_x$, $2Q_y$ resonances
and cause betafunction beats and 2nd order chromaticity



5 Geometric terms

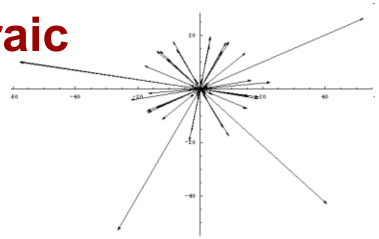
h_{21000} & h_{10110} => integer resonances , Q_x.
h_{30000} => 3rd integer resonances $3Q_x$.
h_{10200} & h_{10020} => coupling resonances .

13 terms in 2nd order of sextupole strength

3 terms giving linear tune shift with amplitude
8 octupole-like terms driving resonances $4Q_x$, $2Q_x \pm 2Q_y$ *etc.*
2 terms generating the second-order chromaticities.

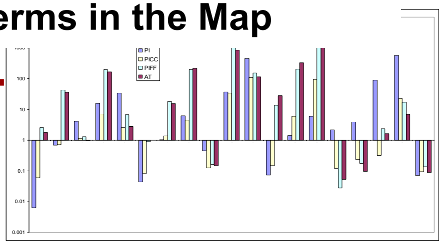
Codes

- **MAD, BETA, OPA, RACETRACK…**
  - » **BETA allows optimisation of sextupole driving terms and tune shifts with amplitude**
  - » **MAD, HARMON optimises tune shifts with amplitudes, generalised resonance strength term which is based around the first order resonance terms and higher order chromaticities, STATIC and DYNAMIC (Lie-algebraic analysis…)**
  - » **OPA, 9 first order terms and 2nd order terms**



- **MARYLIE etc..**
  - » **Lie algebraic analysis, one turn map, coefficients.**

Magnitude of nonlinear Terms in the Map



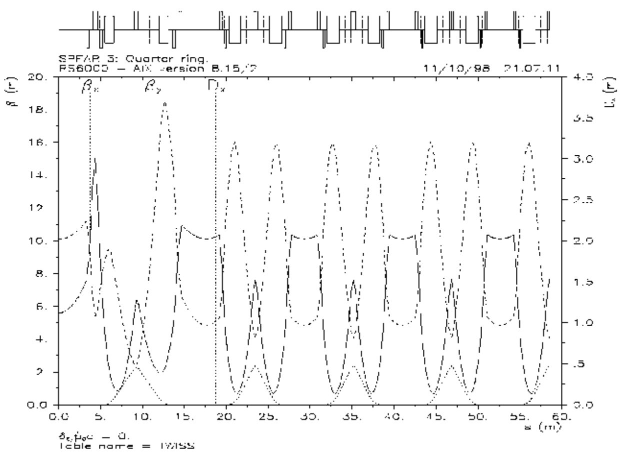
Two steps

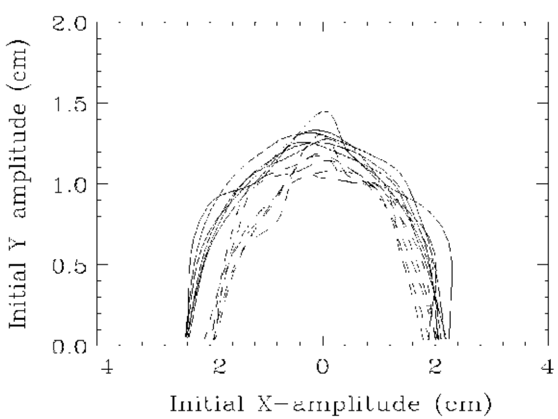
» **STEP 1** Cancellation/minisation of terms by setting tune or phase over sections of lattice

» **STEP 2** Optimisation of sextupole strengths, position, small variation in tune

Phase (1)

SPEAR 3

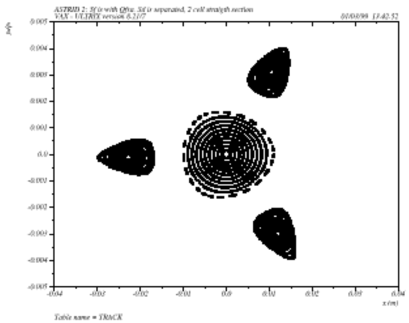


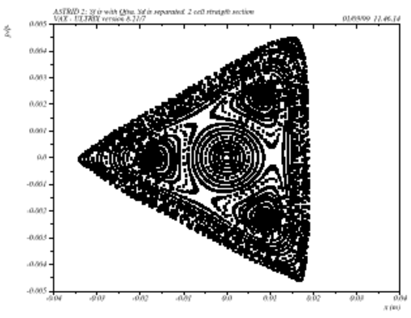


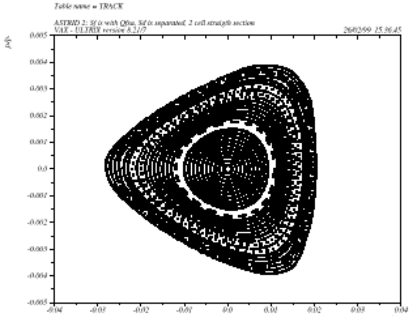
- 3 GeV, 18 cell, dba racetrack lattice
- 18 nm rad emittance
- phase advance in arc cells close to 0.75×2π horizontally, 0.25×2π vertically
- matching cells adjacent to long straights used to control the overall tune
- no harmonic sextupoles
  - » designs with harmonic correction tested and not found effective
- dynamic aperture in excess of 20 mm horizontally, 10 mm vertically
- stable with respect to field errors

J Corbett, Y Nosochkov, J Safranek, A Garren, ***PAC 99***

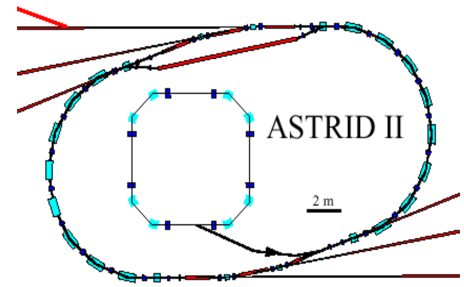
Phase (2)







ASTRID II

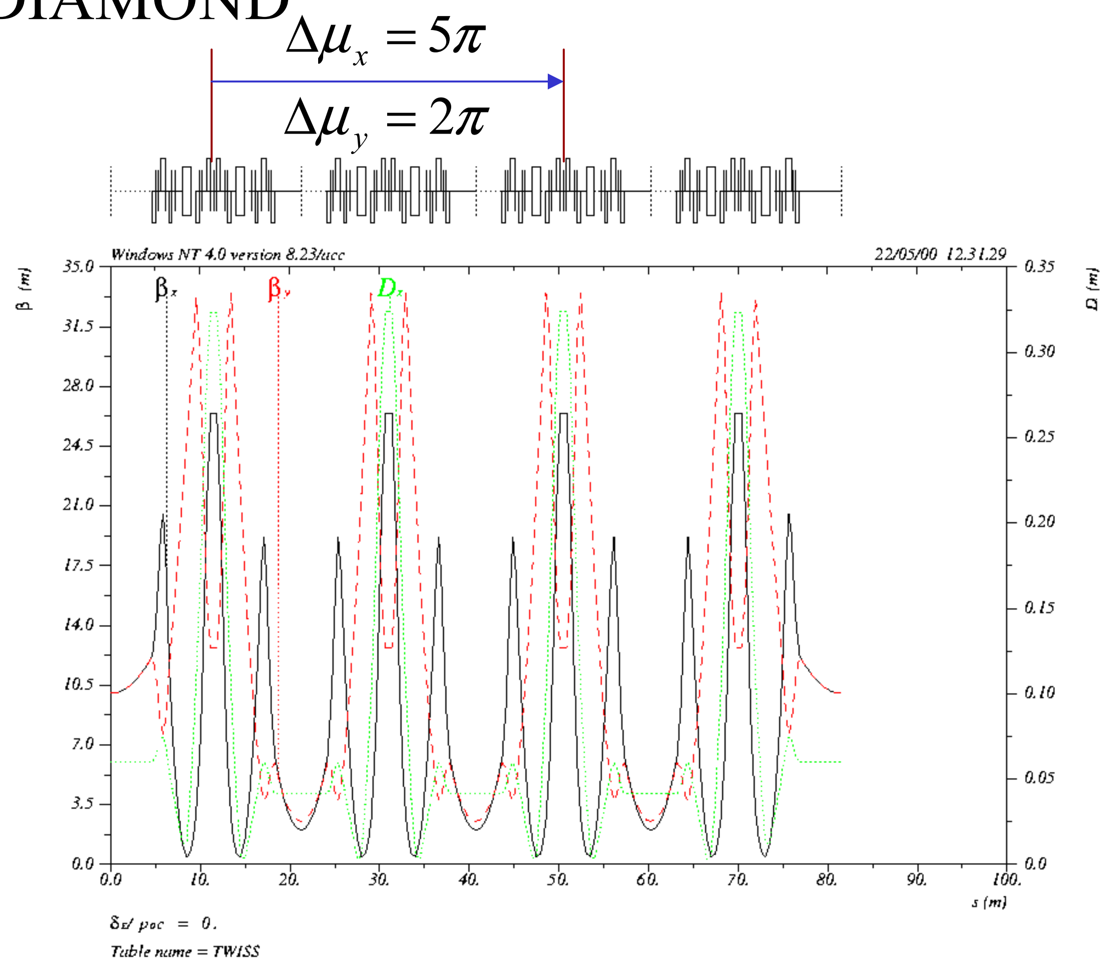


- Cells in the arcs have
  - » integer tunes
  - » sextupoles arranged to cancel geometric aberrations
  - » over-compensated chromaticity
- The long straight sections have
  - » tunes close to a third-integer
  - » no sextupoles (negative chromaticity)
- Large tune shift with amplitude controlled to minimise effects of terms in the map driving the resonance

*Yu Senichev, **PAC 99***

Phase (3)

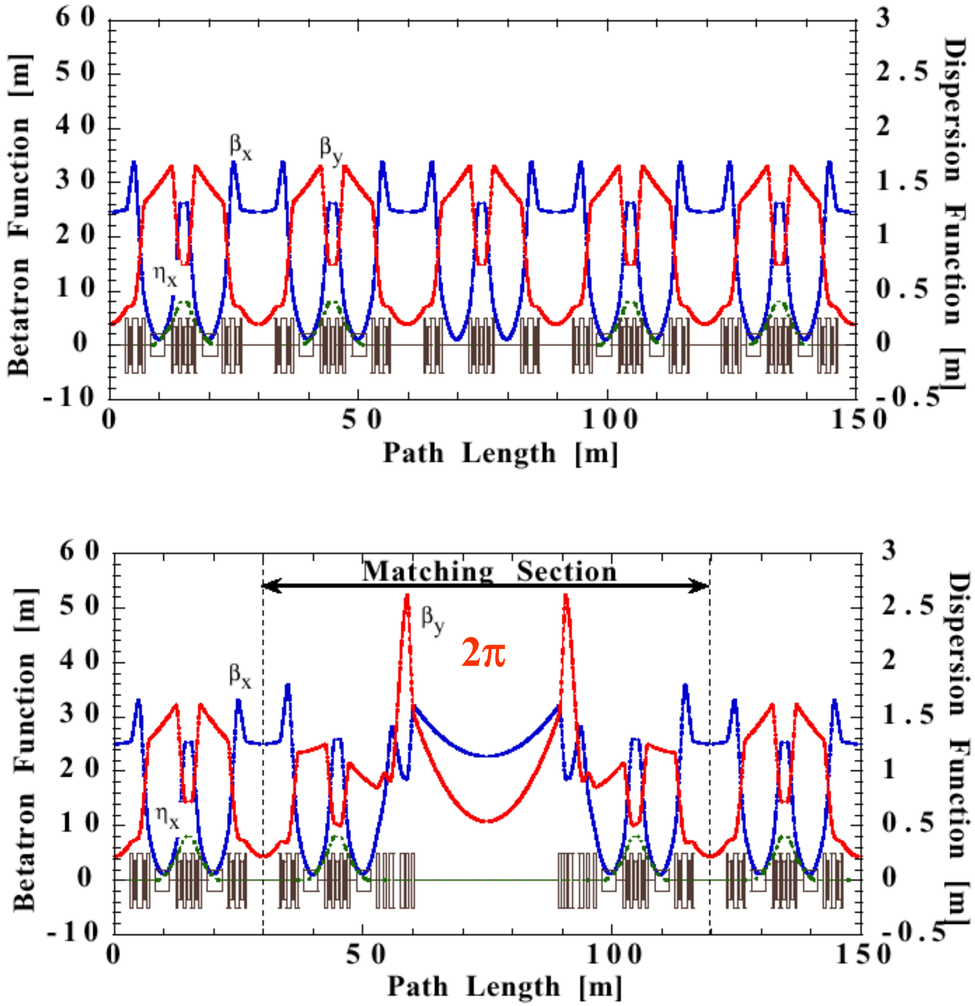
DIAMOND



- Phase advance over short straights carefully controlled.
- Phase advance over long straights allows control of overall tune
- Beta functions in short straights low to give high brightness from insertion devices
- Beta functions in long straights high for ease of injection
- Some dispersion allowed to reduce emittance

A Wolski EPAC 2000

Phase (4)

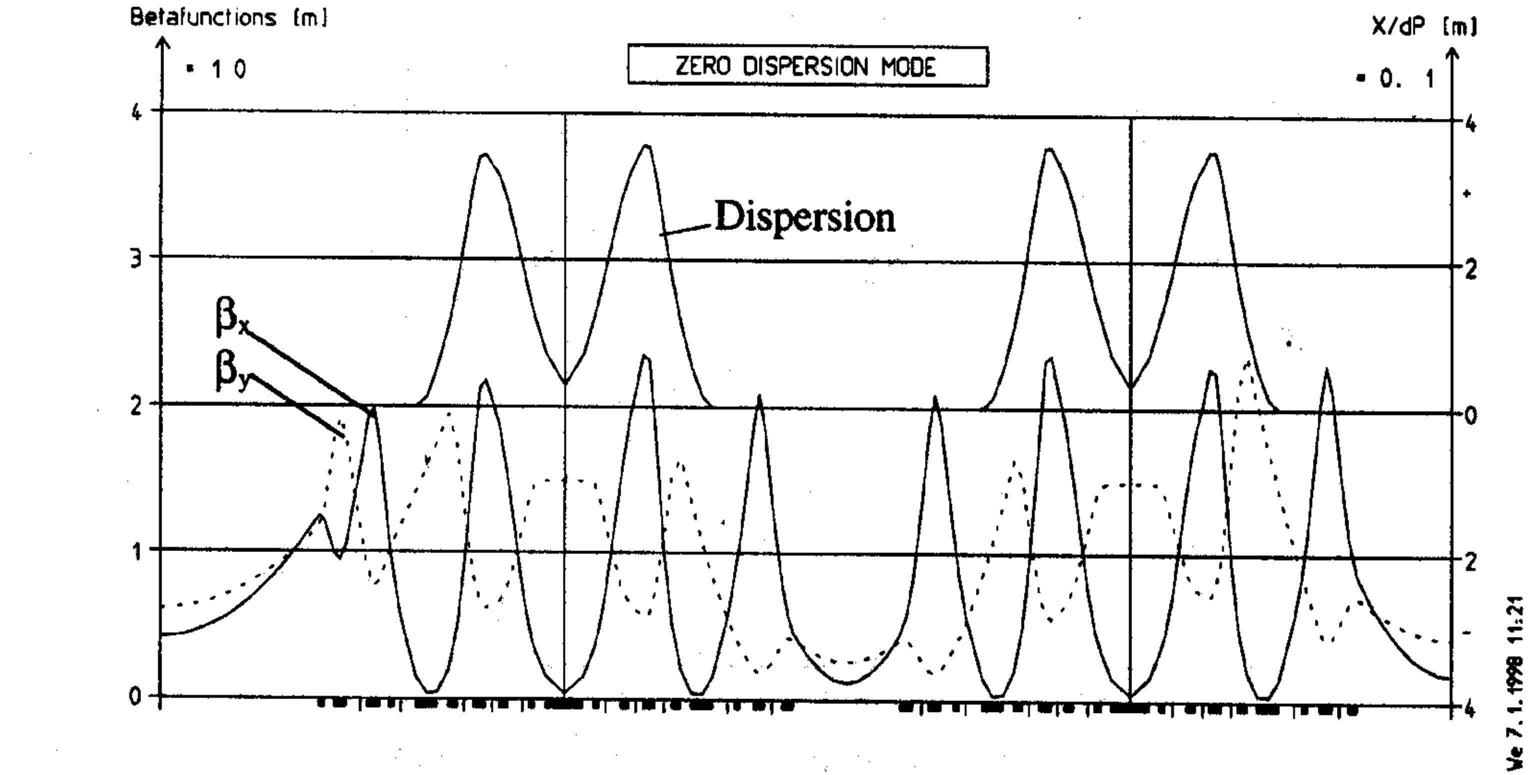


SPRING 8

- Symmetry restoration by "transparent" 2π insertion
- Matching is effective for on momentum particles only
- Need weak harmonic sextupoles
- Correct local chrom, in matching section
- Helps suppression of resonances
- Recovers stability of off momentum electrons

H TANAKA et al, ***EPAC 2000***

Phase (5)



SLS set ΔQx ~7/4 and ΔQy ~ 3/4 per cell
to cancel h_{2001} and h_{0201} between two TBA cells and
geometric modes between 2 TBA-pairs

Optimising sextupole families

- **Optimisation**
  - » **Delicate balance of cancellation and minimisation of various terms**
- **First order**
  - » **For Nsext sextupoles grouped into Msext families the 9 equations give 9xMsext linear system could be solved but degeneracy or nearly so requires optimisation of linear lattice phase to cancel some terms.**
- **Second order**
  - » **Large dynamic aperture requires that control is taken of some of these terms…tune shift with amplitude, higher order chromaticity etc.**

SLS statement... ***"eventually some skill in setting weight factors for the many terms, developed by systematic phenomenological studies"***

Procedure

- **Variables**
  - » **The knobs that are twiddled to achieve an optimum.**
- **Quality factors**
  - » **The quantities you evaluate to determine how well the optimisation is going.**

Should have a link to the ultimate machine performance !!!!

Variables

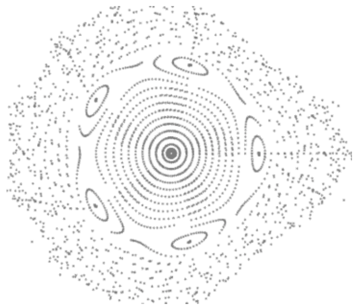
- **Phase over section of lattice**
- **Machine tune (fast small tune changes by special tune matrix elements)**
- **Number of sextupole families**
  - » **Lower symmetry and higher complexity requires increased numbers of "harmonic" sextupoles. SLS has 9 sextupole families, DIAMOND has 8 and SOLEIL with new arc ID straight, has 10 families.**
- **Sextupole positions**
  - » **Sensitive to <10 cm, have to be optimised within engineering constraints.**
- **Sextupole strengths**
- **Optimisation**
  - » **Method of optimisation**
  - » **Weights given to quality factors**
  - » **Target values of quality factors**

Analytic Quality factors

- Relatively quickly calculated
- Easily used to scan and optimise variables
- Often necessary but not sufficient for good machine performance
  - » Minimised/control values of 1st and 2nd order perturbation terms

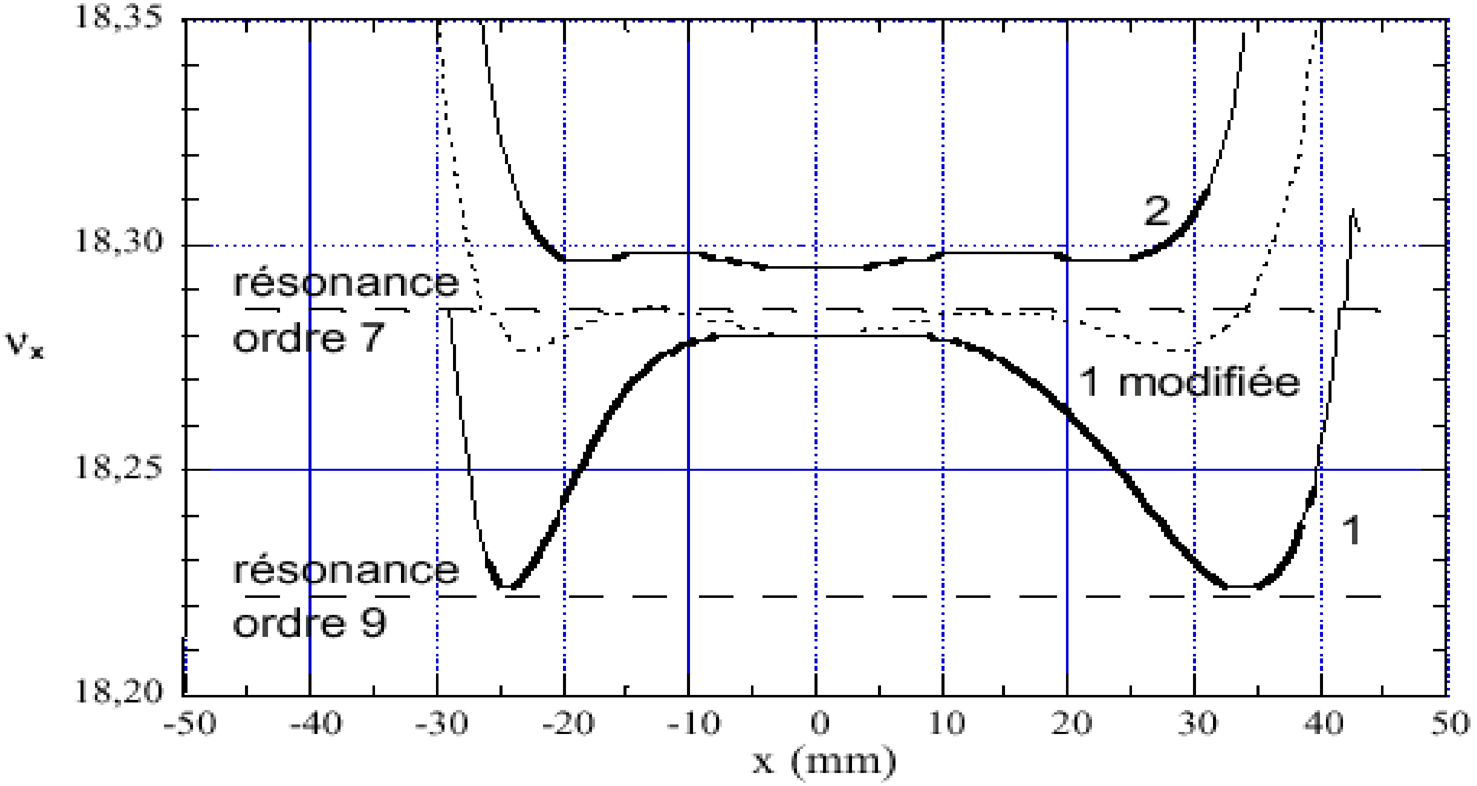
    MAP coefficients, tuneshifts with ampitude ,tune shifts with momentum, higher order chromaticity, resonance driving terms
  - » Off momentum lattice functions
  - » Maximum sextupole strengths

Numerical Quality factors



- Slow to calculate
- Difficult to use in optimisation
- Closer related to machine performance
- Numerical from tracking
  - » Phase space plots
  - » Tune shifts with amplitude and momentum
  - » Frequency maps analysis
- Dynamic aperture itself (short term, longer term, 1 to 6 dimensions)
  - » On and off momentum
  - » With errors (field and closed orbit)
  - » With physical apertures
  - » With typical realistic chromaticity values
  - » With IDs including vertical coupling

Tune shift control from SOLEIL (APD)



Control $(\partial Qx/\partial x)x = 0$ so that: when Qx (x=0) is above the 7th order resonance, Qx is curved upwards: when Qx (x=0) is below 7th order resonance, Qx is curved downwards

Frequency map analysis

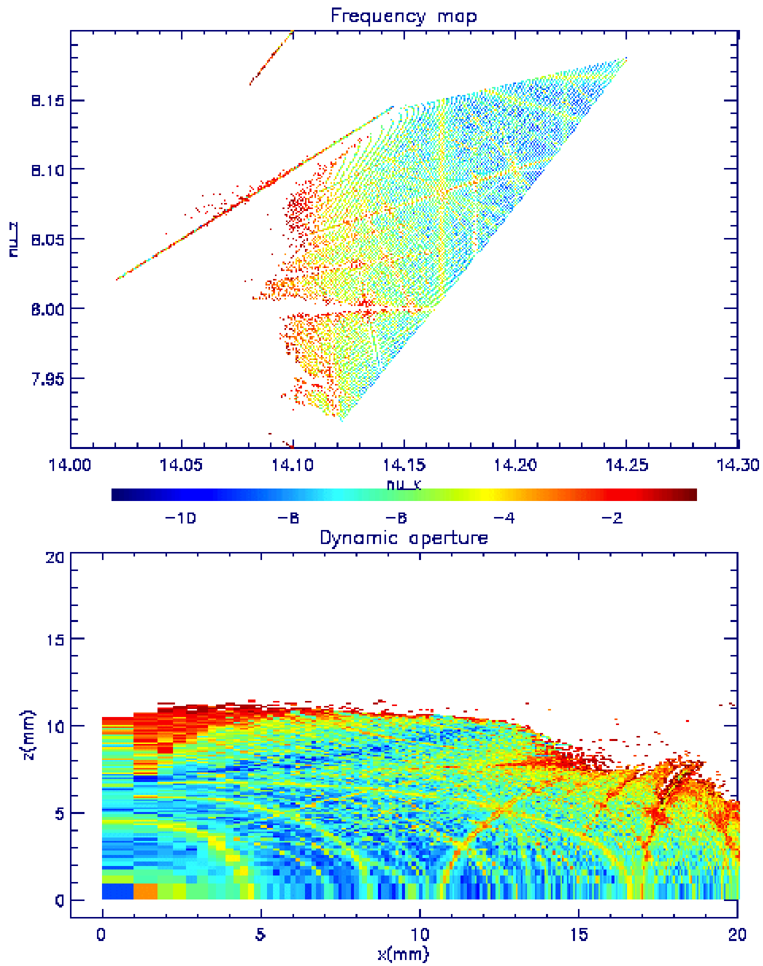
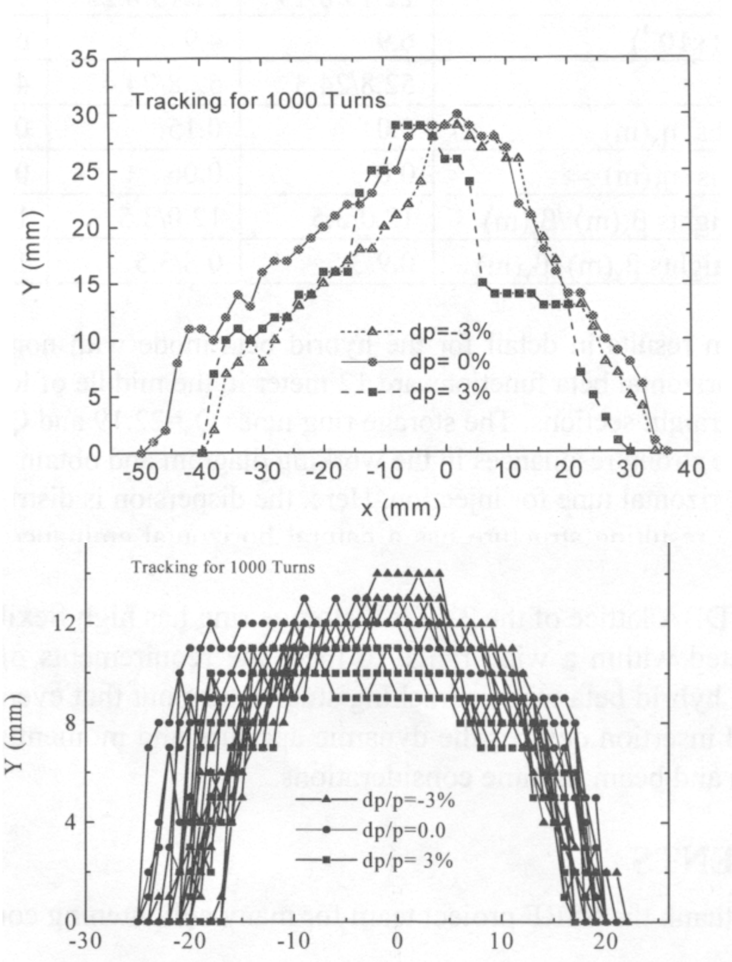


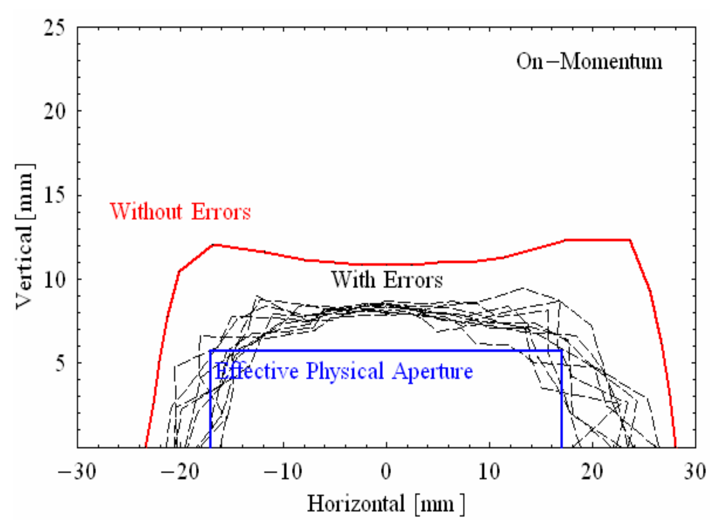
Figure 1: Frequency map of the ALS for an ideal lattice

launched particles over a fine X-Y grid plotting numerical “tunes”

highlighting, nonlinearity (diffusion rate).

Dynamic aperture with errors



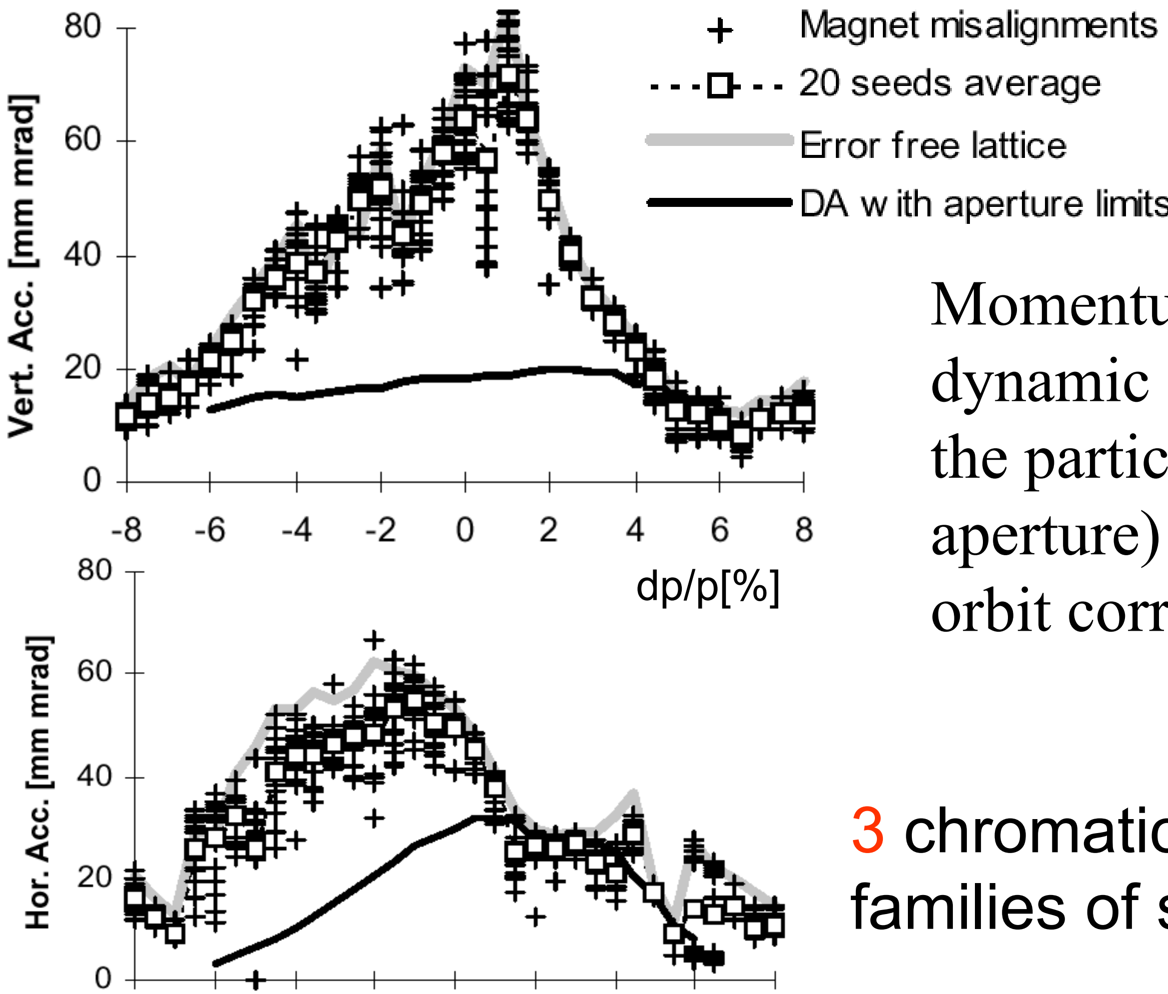


DIAMOND, Dynamic aperture including misalignments, field errors and systematic and random multipole errors and random field errors.

Rigidity of aperture with errors !

SSRF, Dynamic aperture without and with systematic and random multipole errors and random field errors.

Dynamic acceptance with momentum



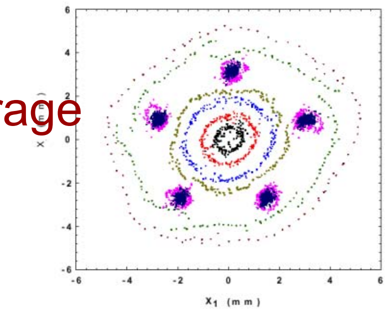
Momentum dependant dynamic acceptances the particle at dynamic aperture) after closed orbit correction

3 chromatic & 6 harmonic families of sextupole

A. Streun et al EPAC'98

Verification of tools and models in real machines

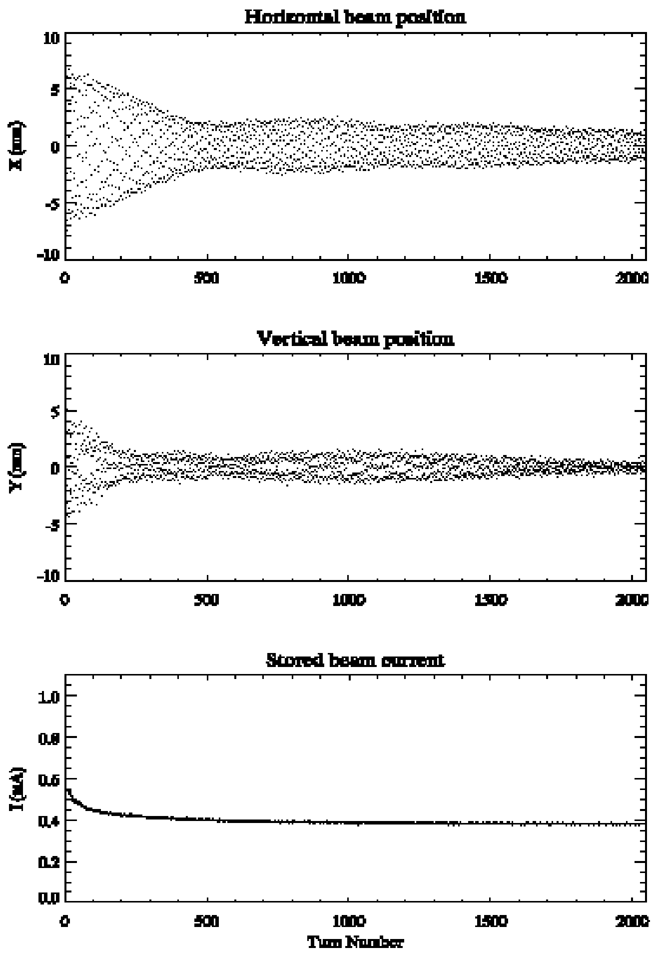
- Tracking
  - » Turn by turn tracking using **fast BPMs** and digital storage
    - Tuneshift with amplitude
    - “Phase space”
    - Measured frequency maps



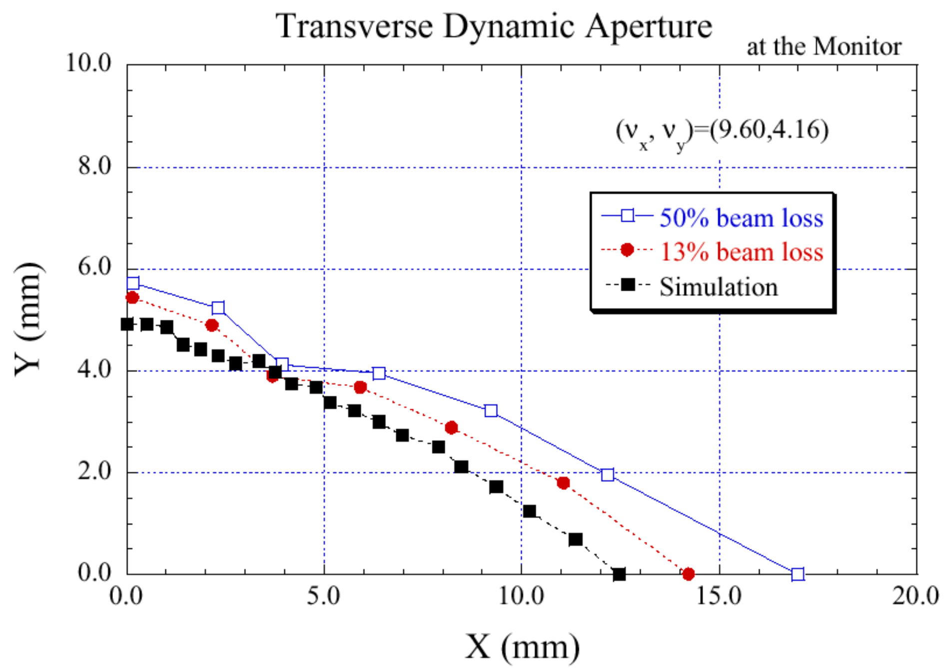
SSRC T.S. Ueng PAC’01

- Dynamic aperture measurements
  - » Lifetime and injection studies
  - » Kick experiments
- Momentum aperture
  - » Lifetime measurements
- Linear beam based modelling (LOCO, J. Safranek) (ALS, NLS, SRRC, SPEAR…...)
- Tuneshifts with momentum

Dynamic aperture measurements



Kick then measure on fast position monitors and loss rates



Photon Factory EPAC'00 **Y.Kobayashi and K. Haga**

Tuneshift with momentum

Change RF frequency and follow off energy orbit

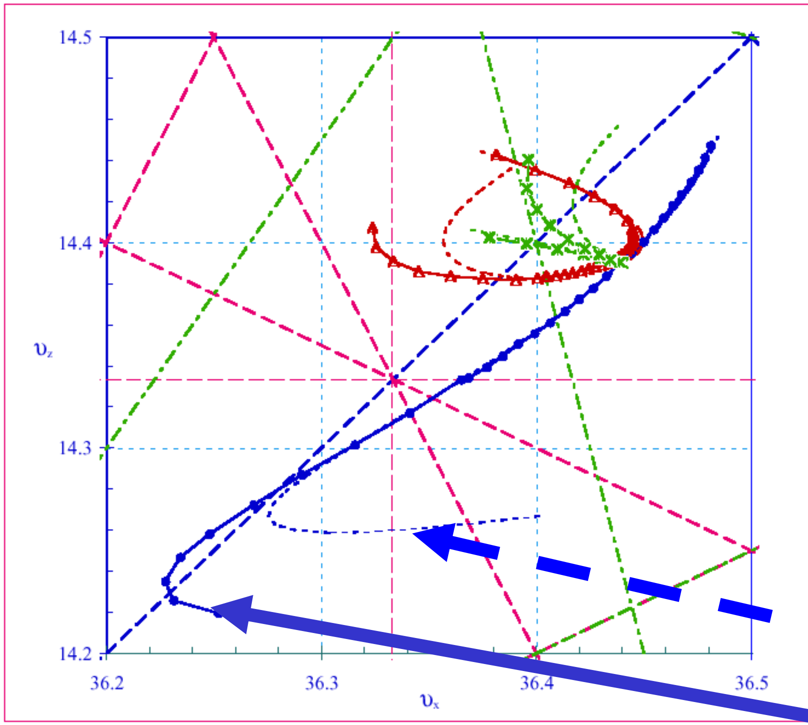


Figure 6: Measured and predicted (dashed) tune paths

- Thin sextupoles an issue
- Checked multipole contribution
- Fitted sextupole strengths to data

Predicted

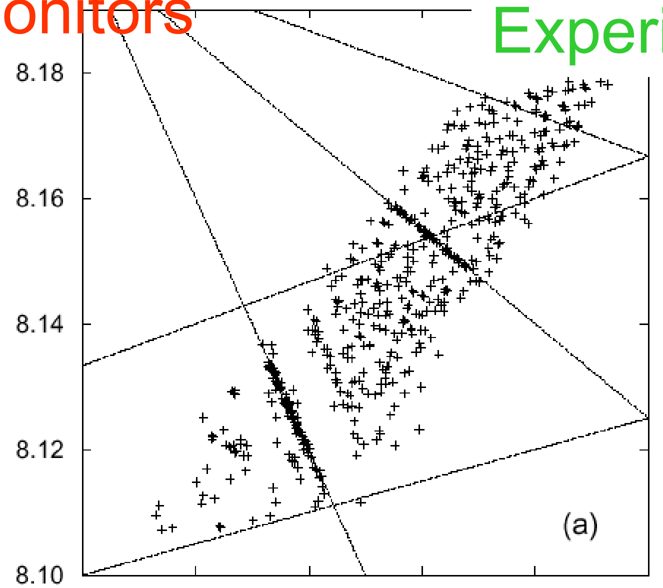
Measured

PAC 2001 **A. Ropert, L. Farvacque,**

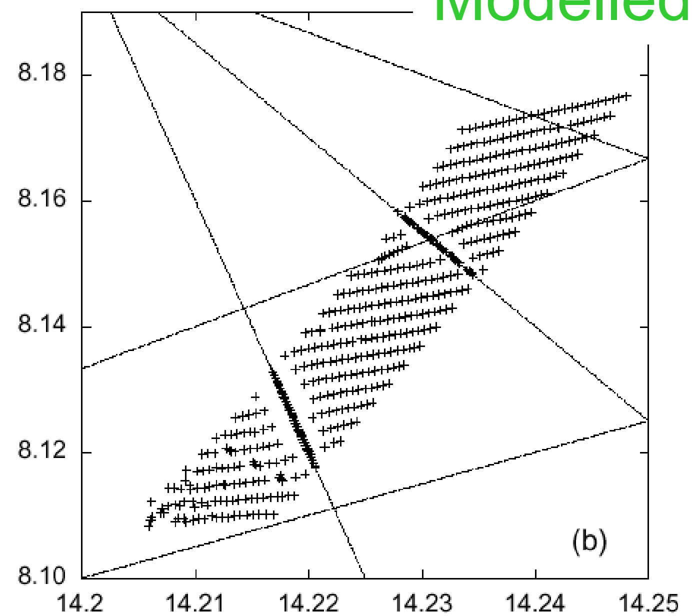
Frequency map

Kick then measure on fast position monitors

Experimental



Modelled



Frequency maps for ALS with a calibrated lattice (I.e. adjusted to match measured response matrix,**LOCO**)

Un-allowed resonances appear.

ALS EPAC'00 C. Steier, D. Robin

Summary/Conclusions (1)

- High performance **flexible** lattices demand more **complex** optimisations (SOLEIL **10 families** of sextupoles)
- **Nonlinear optimisation** now impacts significantly on the **linear design**
- Perturbation theory provides **quickly** derivable relevant “quality factors”, powerful techniques (lie algebra, normal forms and differential algebra) introduced over the last 15 years
- None of these factors guarantees good dynamic aperture. Both on and off momentum behaviour must be test directly by tracking. Eventually full characterisation requires **realistic** model.

Conclusion (2)

- Characterisation of tracking results e.g. through **frequency map analysis** etc. has provided additional input into optimisation of both new and existing lattices
- **Existing machines** with improved diagnostics and beam based error models have provide important **verification** of our tools and have allowed the determination of significant **missing factors** from our simplistic models, also……….

...proved optimisations can be highly successful !!!!

(ESRF, SLS, APS, ALS, SPRING-8 etc, etc, etc)

Thanks to

Hywel Owen, James Jones and Andy Wolski[1] for helping to develop our in-house lattice optimisation strategy and capability and my understanding of it during the **DIAMOND** design.

[1] Now at Berkeley Lab

And to

the band of "lattice optimisers", dispersed throughout the world, who have shared their knowledge, experience, expertise and tools with us.