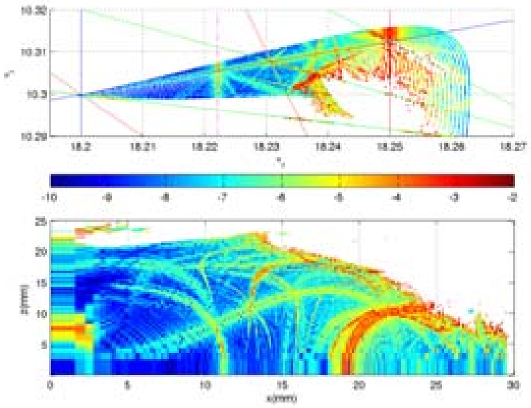
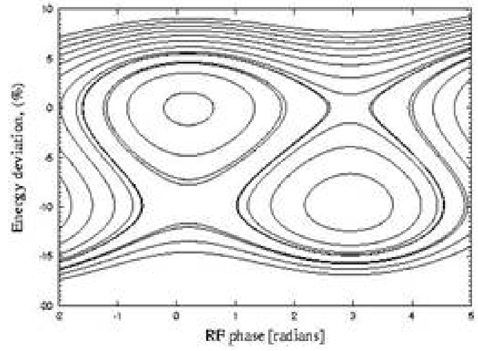
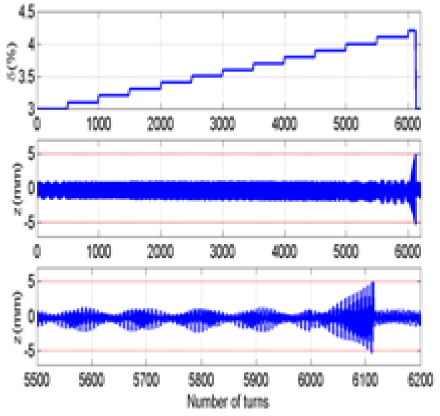
Version 2.0

SOLEIL SYNCHROTRON

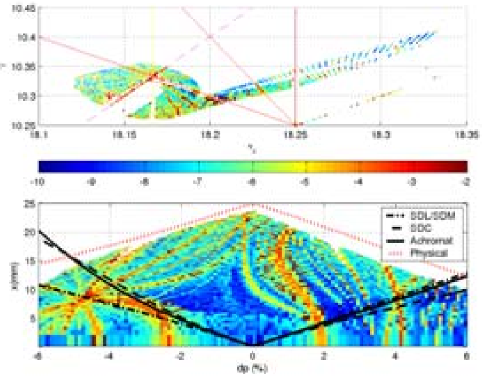
Tools for Modeling Dynamics Apertures, Touschek Lifetime and Insertion Devices at SOLEIL







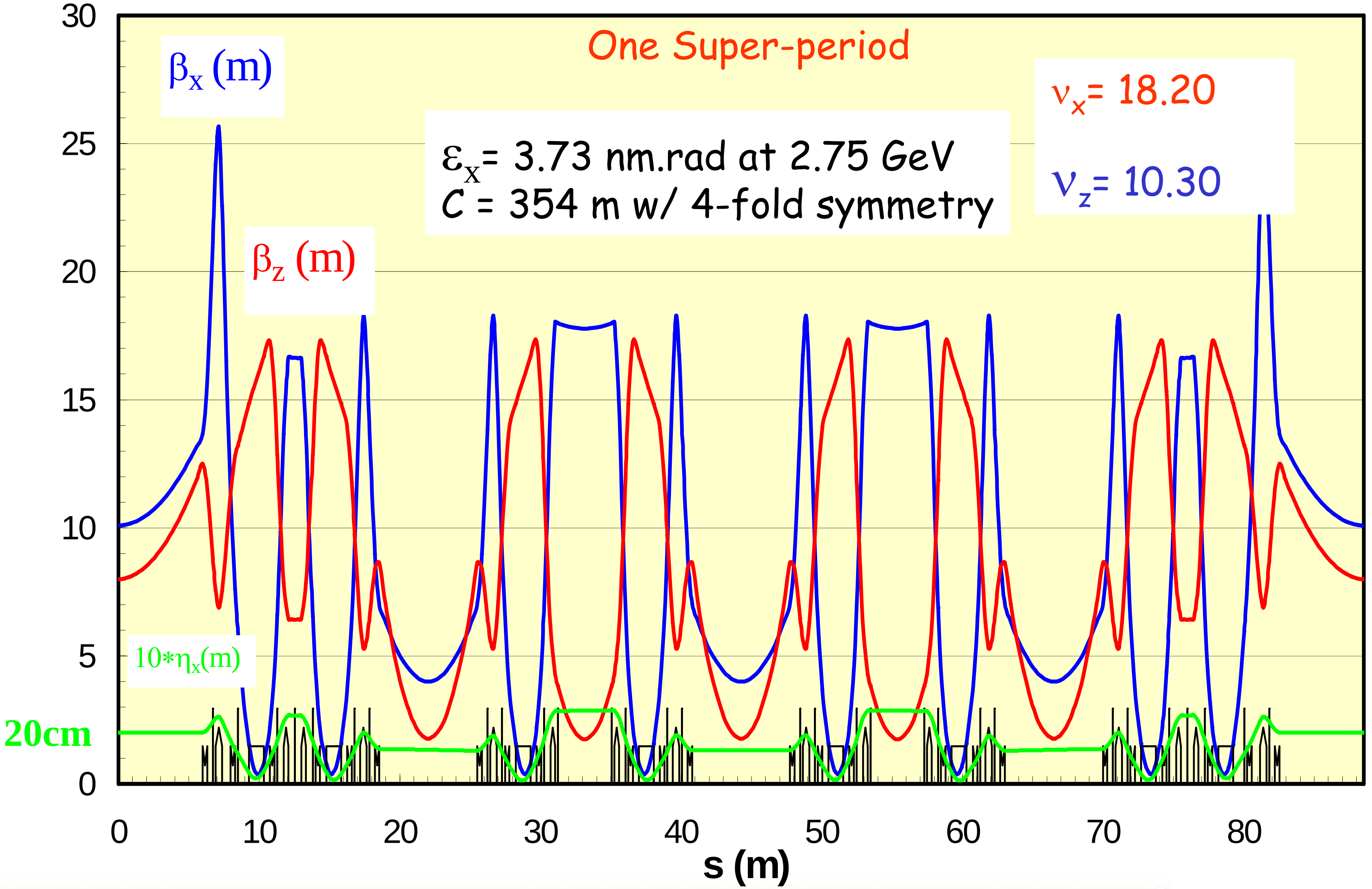
Laurent S. Nadolski
On behalf of the
Accelerator Physics Group
Synchrotron SOLEIL



Layout

- Non-linear dynamics optimization
  - Criteria for optimization
  - Modeling
  - Philosophy adopted at SOLEIL
- Numerical Tools through examples
  - Tracking codes
  - Frequency map analysis
  - Off momentum dynamics
  - Touschek lifetime computation
  - Insertion device modeling
- Conclusion

Linear Optics based on DBA lattice with distributed dispersion



Criteria for optimization non-linear dynamics

- Large on momentum dynamic aperture (DA)
  - Ensure 100% injection efficiency (beam stay clear, top-up operation)
  - Large enough (safe margin, robustness)
    - To anticipate small energy mismatch, orbit errors
    - To anticipate non-linearities from multipoles, insertion devices which will reduce furthermore the DA

- Large off-momentum dynamic aperture
  - Ensure **large Touschek lifetime** (33h @ 500 mA, 4 MV, κ =1%, multibunch)
    →Ensure stability for off-momentum particle (up to ±6%)
  - Margin of stability for ID effects

- Tune footprint in an area almost free of low order resonance
  - Tune shifts with amplitude constrained between resonance lines
  - Tune shifts with energy constrained between resonance lines
  - Minimizing the first order amplitude distortions of sextupolar resonances
    - Small enough sextupole strength
    - Based of analytical formulae where only first order quantities are involved.

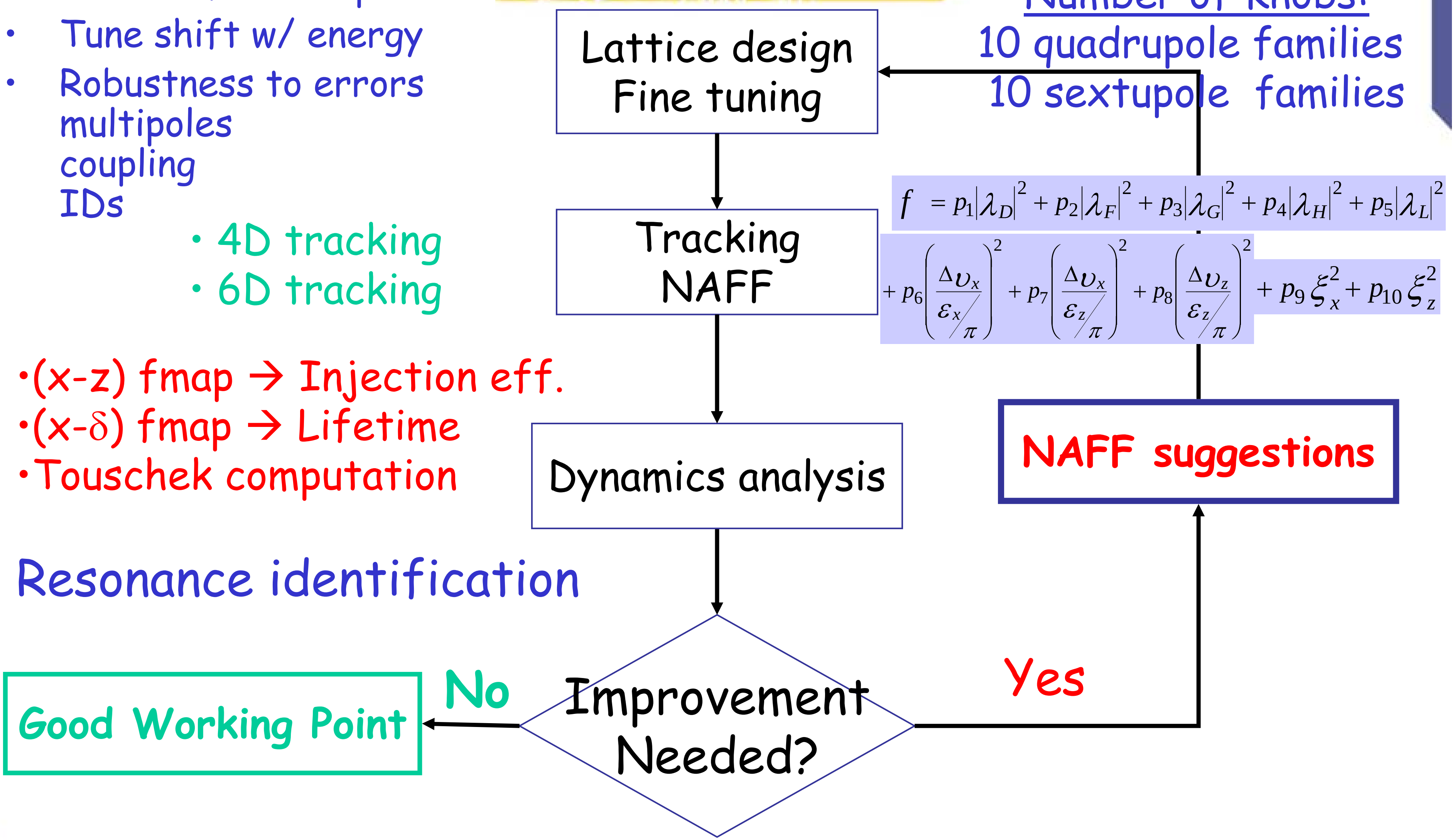
- Linear and non-linear dynamics are **strongly entangled** (back & forth)
  - No use of automatic procedure for full optimization

Optimization Method

- Tune shift w/ amplitude
- Tune shift w/ energy
- Robustness to errors
  multipoles
  coupling
  IDs
    - 4D tracking
    - 6D tracking

- (x-z) fmap → Injection eff.
- (x-δ) fmap → Lifetime
- Touschek computation

Resonance identification



Lattice design
Fine tuning

Tracking
NAFF

Dynamics analysis

Improvement
Needed?

No

Good Working Point

Yes

NAFF suggestions

Number of Knobs:
10 quadrupole families
10 sextupole families

$$f = p_1|\lambda_D|^2 + p_2|\lambda_F|^2 + p_3|\lambda_G|^2 + p_4|\lambda_H|^2 + p_5|\lambda_L|^2 + p_6\left(\frac{\Delta\upsilon_x}{\varepsilon_x/\pi}\right)^2 + p_7\left(\frac{\Delta\upsilon_x}{\varepsilon_z/\pi}\right)^2 + p_8\left(\frac{\Delta\upsilon_z}{\varepsilon_z/\pi}\right)^2 + p_9\,\xi_x^2 + p_{10}\,\xi_z^2$$

What is included in the Model?

- Systematic multipole errors
  - large δ-acceptance, large η–function → high order required
  - Dipole: up to 14-poles
  - Quadrupoles: up to 28-poles
  - Sextupoles: up to 54-poles
  - Correctors (steerers): up to 22-poles
    - Secondary coils in sext. → strong 10-pole term (large δ)
    - Typical set of current for orbit correction (model/reality)

- From magnetic measurements: anticipation of effects
  - Add true m-poles (both systematic and non systematic)
  - Dipole: fringe field, gradient error, edge tilt errors
  - Quad.: fringe field (to be done), octupole (banana effect for QL)

- Coupling errors (random rotation of quadrupoles)

- Insertion devices (destroy often Acc. Physicists' work!)

Codes used at SOLEIL

- **BETA-SOLEIL (fast, user friendly)**
  - Lattice design
  - Error settings and corrections (alignment, m-poles, …)
  - Sextupole optimization
  - Tune shifts, on/-off DA (limitation for large amplitude of 2nd order matrix code)
  - 4+2D Touschek lifetime computation

- **Tracy II (AT) → long term tracking code**
  - Full symplectic code
    - 4th order Ruth and Forest integrator, Laskar's scheme integrator
    - Inclusion of arbitrary m-poles, validity for large off-momentum oscillation amplitudes
  - True 6D tracking code
  - Frequency map analysis (NAFF package)
  - 4D or 6D energy acceptance computation, Touschek lifetime

- **Turn number selections for DA, FMA: @ SOLEIL 1026 turns is enough**
  - Choice dictated by
    - A good convergence near resonances
    - Beam damping times
    - 4D/6D
  - Use of diffusion coefficient to extrapolate dynamics for high number of turns

Mapped IDs à la ESRF

- IDs with complex EM-field (polarization, low gap, quasi-periodic mode)
  - Halbach formalism does not work!

- Nonlinear 2D maps of IDs are generated using the 3D RADIA code.

- BETA-SOLEIL and TRACYII have been modified in order to read the IDs maps.

- <u>Thin lens model (2nd order integrator):</u>
  - choice of number of lenses fixed by tune convergence
  - full ID, full ID + end poles

- Good agreements with e-beam meas.

See my second talk on Tuesday

- **The angular kicks experienced by the particle are derived from the function:**

$$\phi(x,z,s)=\left(\int_{-\infty}^{s} B_x\,ds'\right)^2+\left(\int_{-\infty}^{s} B_z\,ds'\right)^2$$

- **ϕ is integrated over 1 period resulting in a potential function U:**

$$U(x,z)=\int_{1\,period}\phi(x,z,s)\,ds$$

- **The angular kick experienced by a particle over the undulator period is:**

$$\boxed{\begin{aligned}\Delta x' &= -\frac{1}{2(p/e)^2}\frac{\partial U}{\partial x}(x,z)\\ \Delta z' &= -\frac{1}{2(p/e)^2}\frac{\partial U}{\partial z}(x,z)\end{aligned}}$$

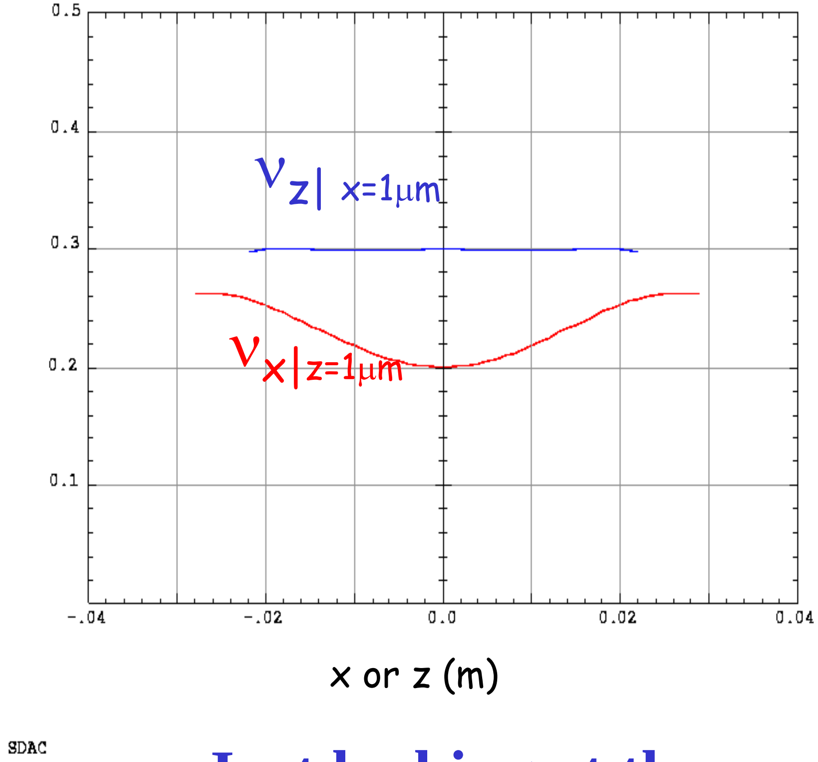
Frequency map analysis

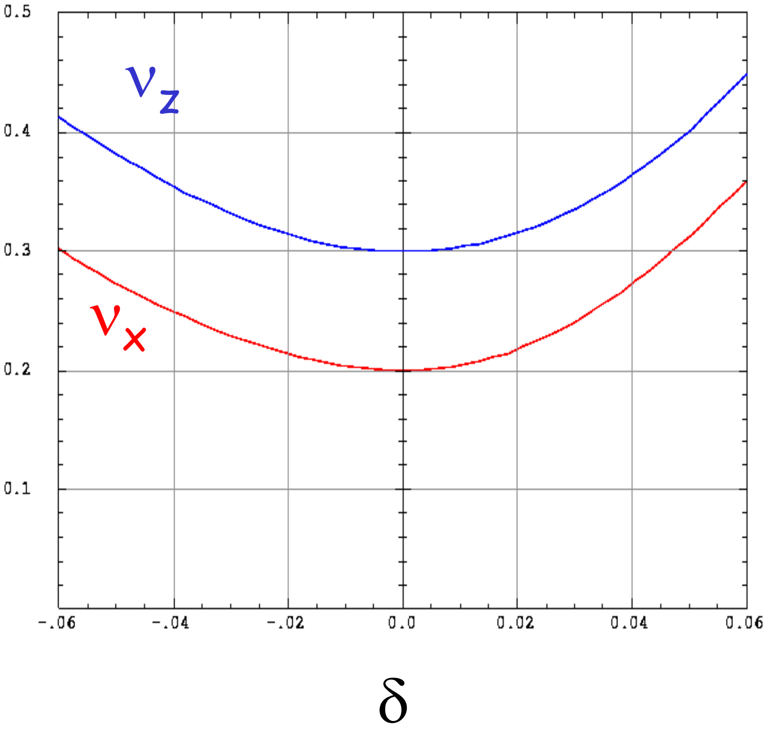
FMA at design stage for the SOLEIL lattice

- A numerical method based on a refined FFT (J. Laskar)
  - Convergence as $1/N^4$ using a Hanning windows (1/N for FFT)
  - Use of diffusion index
    - Predict orbit diffusion
    - Identify resonance
    - Show stable to strongly non linear areas in dynamic aperture and tune space
- Gives us a global view of the dynamics (footprints, DA contents & limitations)
- Shows dynamics sensitivity to quadrupoles, sextupoles and insertion devices
- Reveals nicely effect of coupled resonances, specially cross term $\nu_z(x)$
- Enables us to modify the working point to avoid resonances or regions in frequency space
- Importance of coupling correction to small values (below 1%)
- 4D/6D …

Nominal working point (18.2, 10.3)

No coupling resonance crossing
$\nu_x - \nu_z = 8$ ($\Delta\nu$ = 0.1).



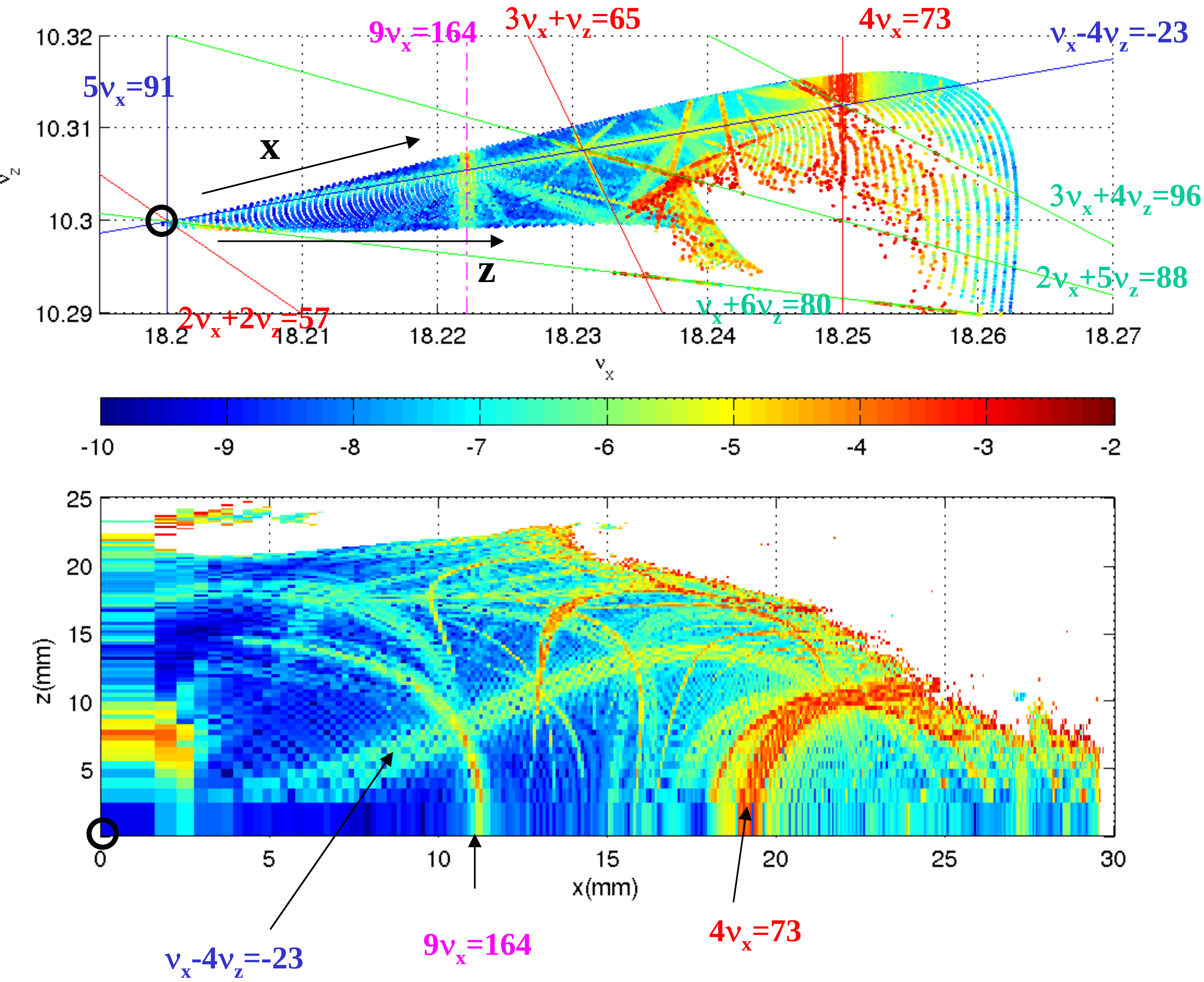


SDAC

Just looking at these curves, dynamics seems very clean …

On-momentum Dynamics --Working point: (18.2,10.3)

Bare lattice (no errors)



WP sitting on resonance node

$\nu_x + 6\nu_z = 80$

$5\nu_x = 91$

$\nu_x - 4\nu_z = -23$

$2\nu_x + 2\nu_z = 57$

Ok if low amplitude

Beware of tune shifts from IDs!

On-momentum dynamics with 1.9% coupling

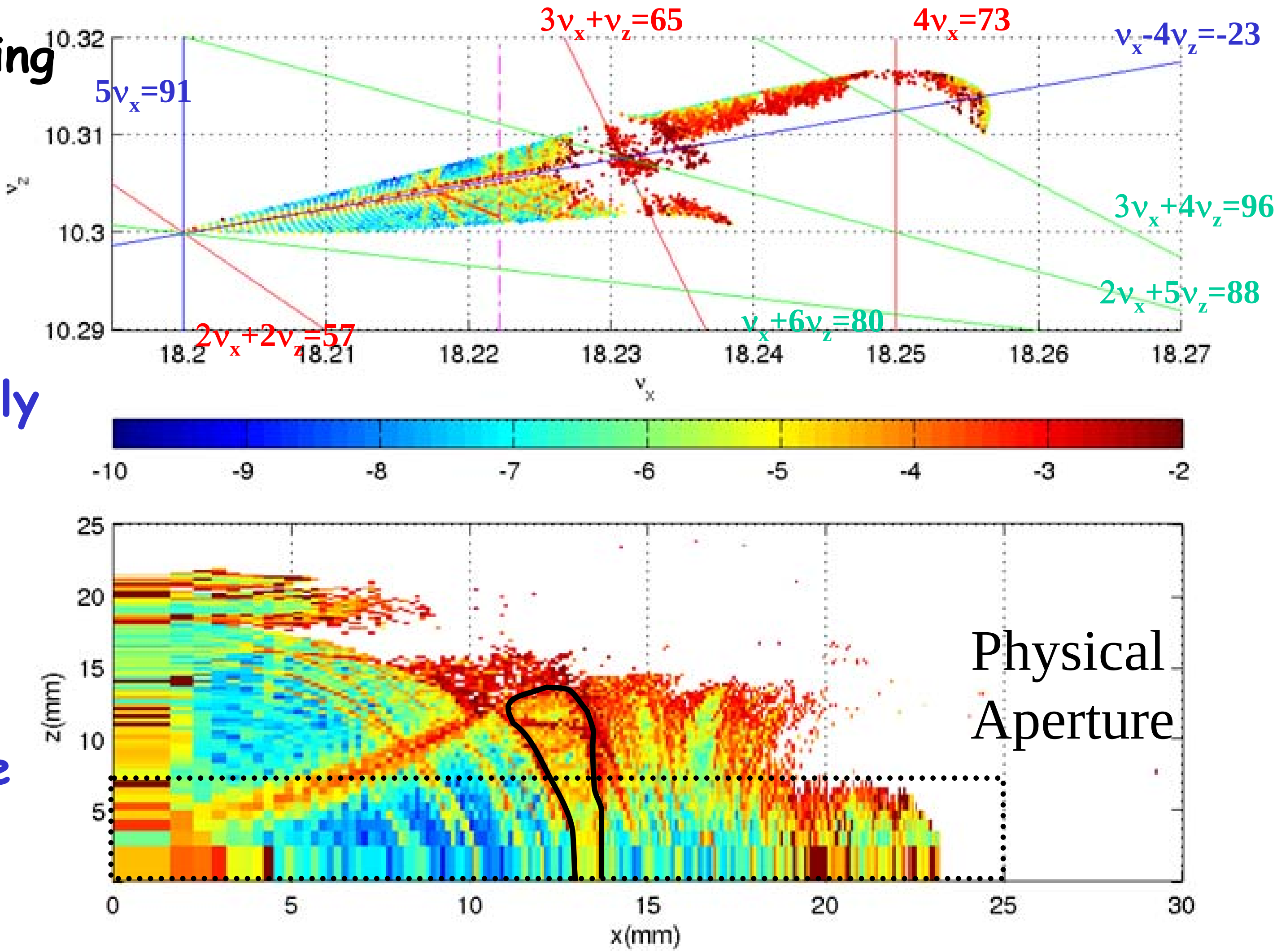
Randomly rotating 160 Quads

- **Map fold Destroyed**

- **Coupling strongly impacts**

$3\nu_x + \nu_z = 65$

- **Resonance node excited**



Resonance island
$3\nu_x+\nu_z=65$

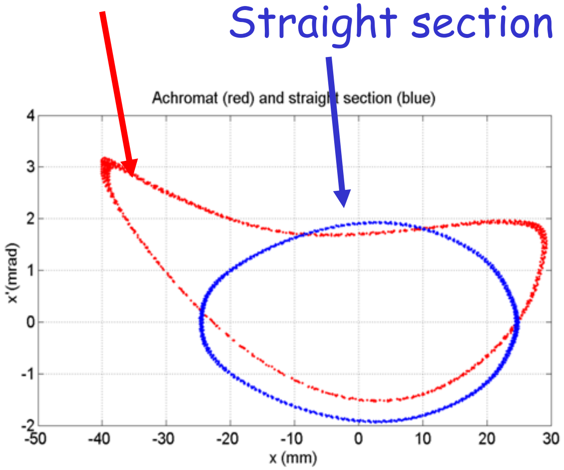
Physical Aperture limitations Included at early stage

Need to introduce into the code real vacuum chamber dimensions all around the ring (no sufficient to check only at a single s-position: cf phase space distortions)

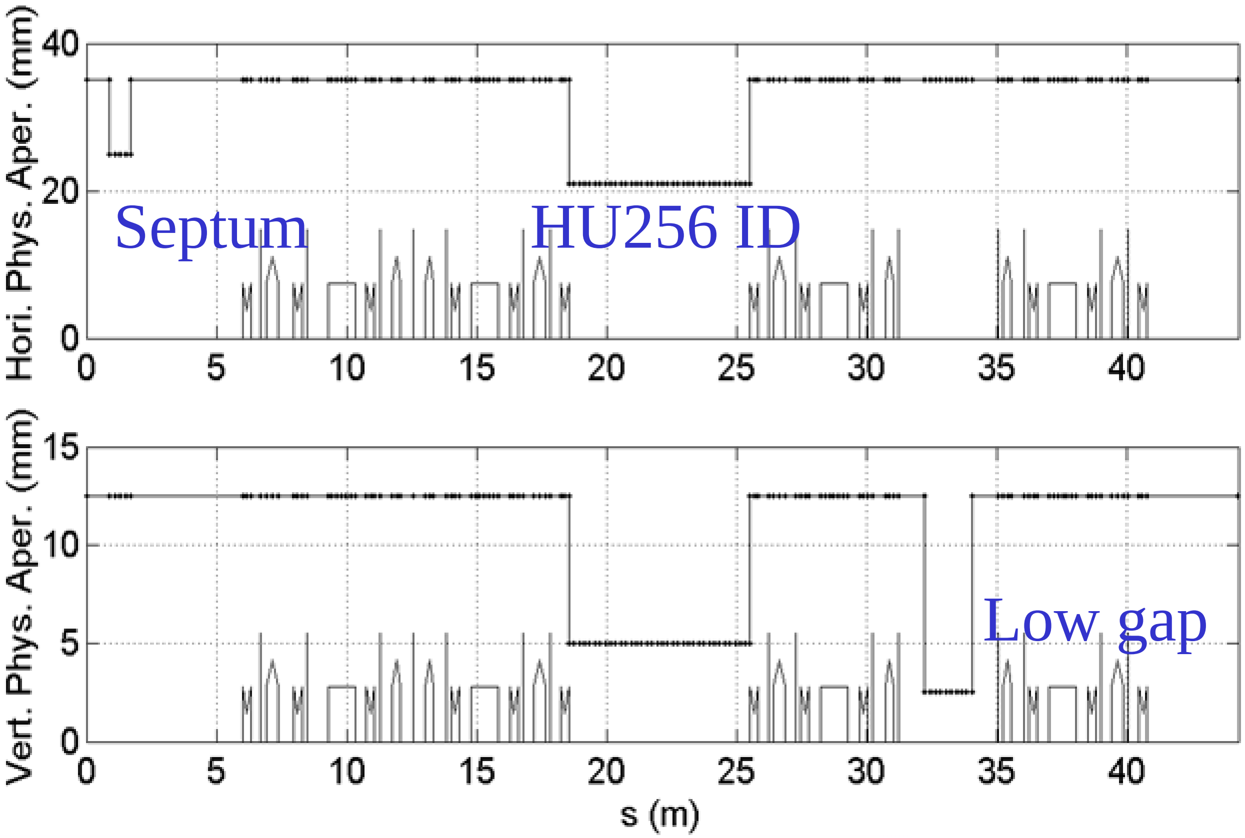
- H-plane: Absorbers, septum, etc…
- V-plane: Absorbers, small gaps, etc…

Achromat

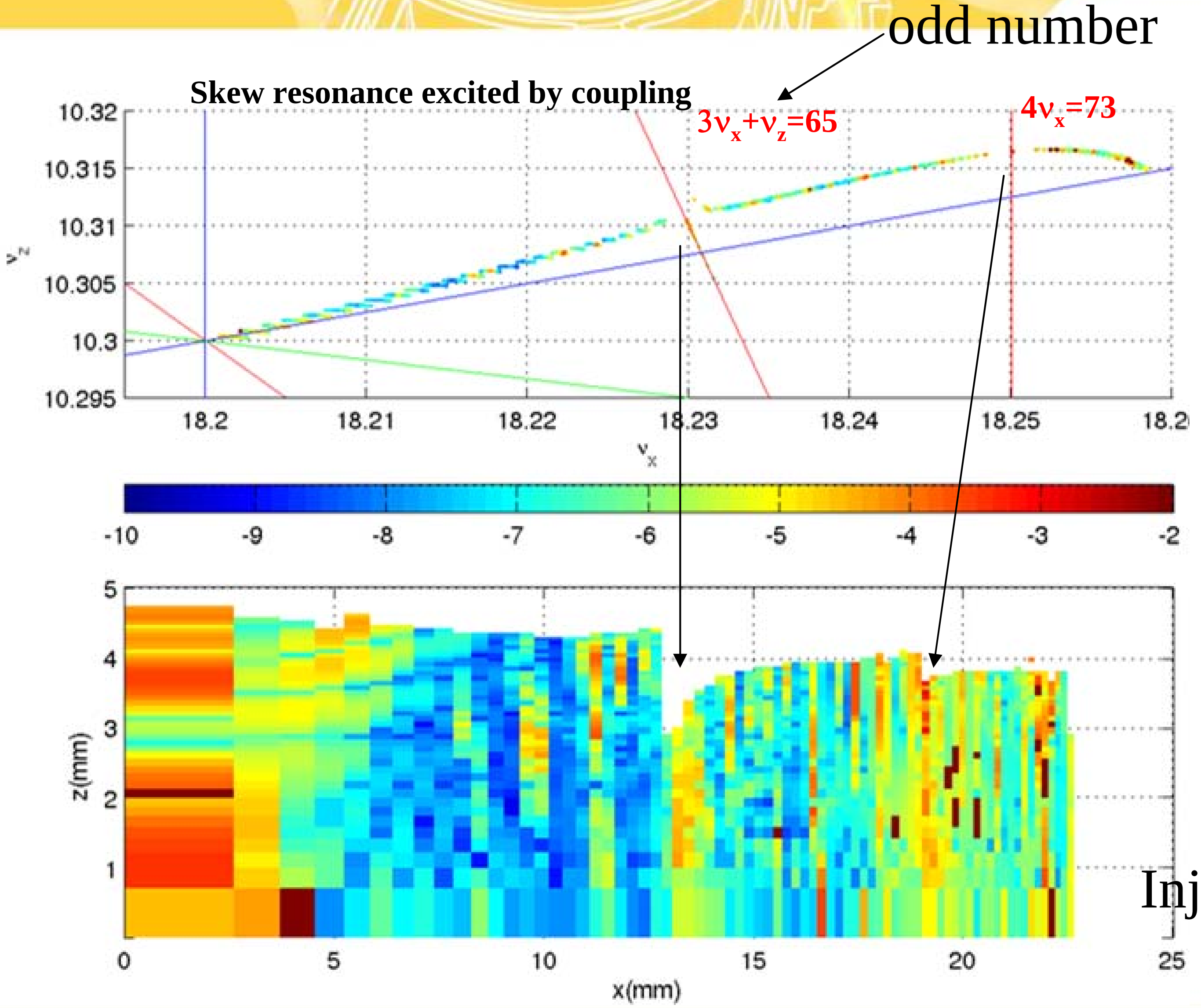
Straight section



H-phase space



Importance of including Vacuum Chamber Entanglement with Beam Dynamics



odd number

Skew resonance excited by coupling

$3\nu_x+\nu_z=65$

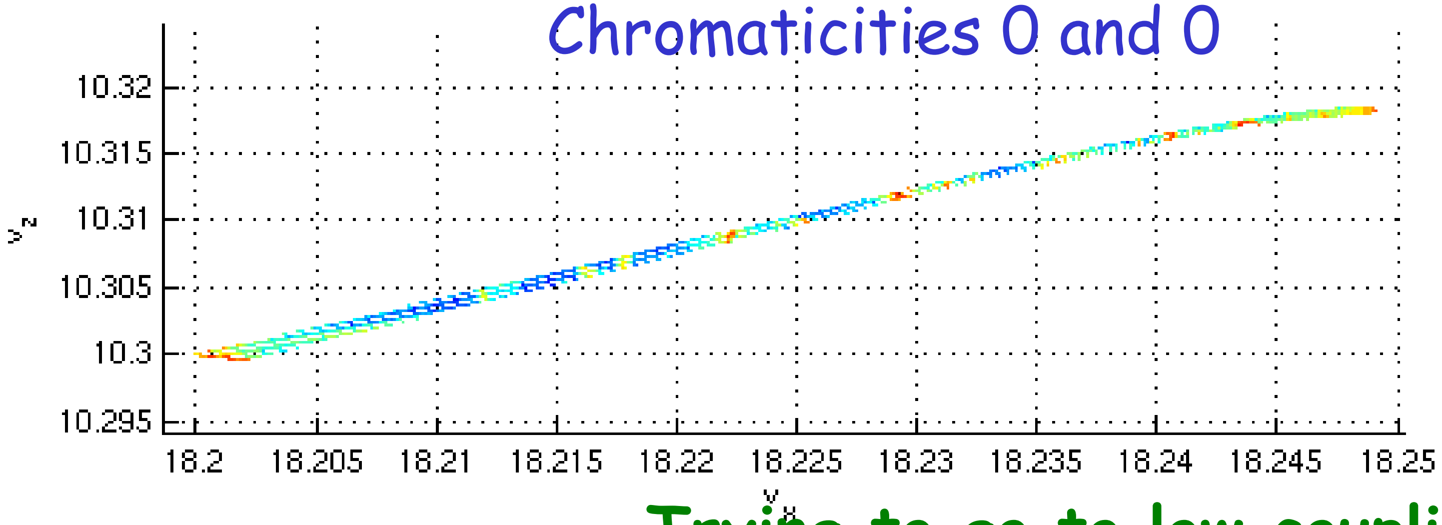
$4\nu_x=73$

1% linear coupling

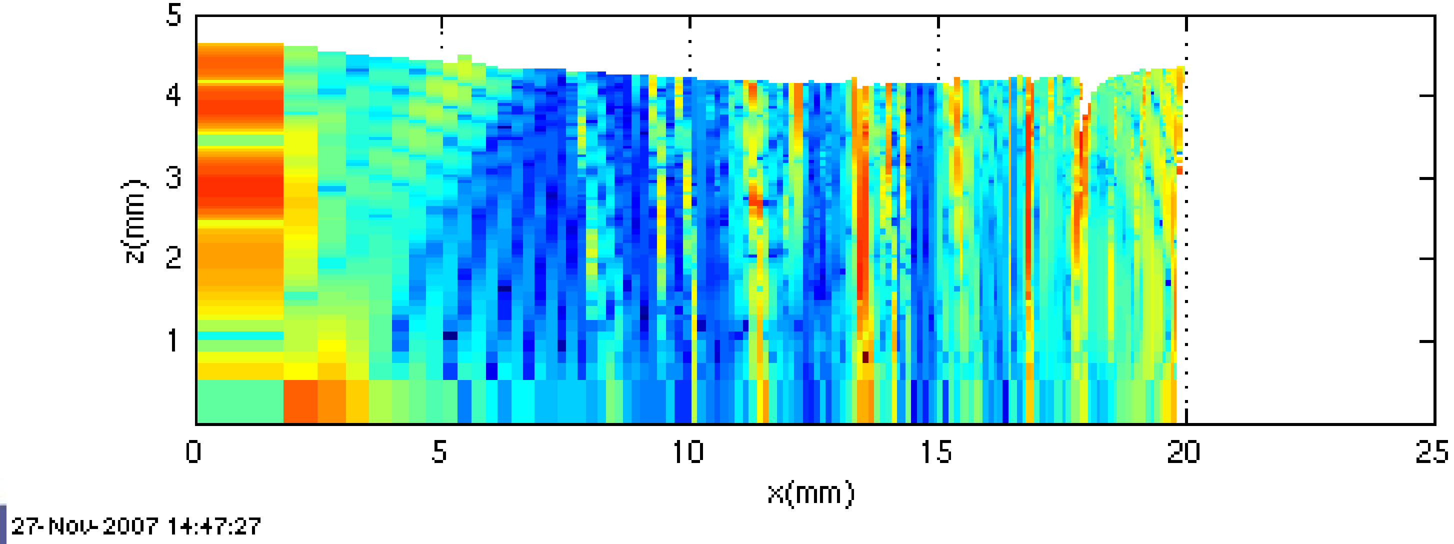
Injection @ 12mm

FMA 18.20 10.30 couplage 0.5%

Chromaticities 0 and 0



Trying to go to low coupling value



Effect of the H-Corrector Decapolar Component (1)

- Reduction of Touschek lifetime from 35 h to 25-30h
- Correction of H&V closed orbit and coupling.

❖ The 3D calculations of the dipole field of the correctors located in the sextupoles indicated that the best field generates a decapolar component of:

$$\frac{\Delta B_4}{B_0} = 0.43 \quad @\ x = 35mm$$

❖ We get the following integrated decapolar strength:

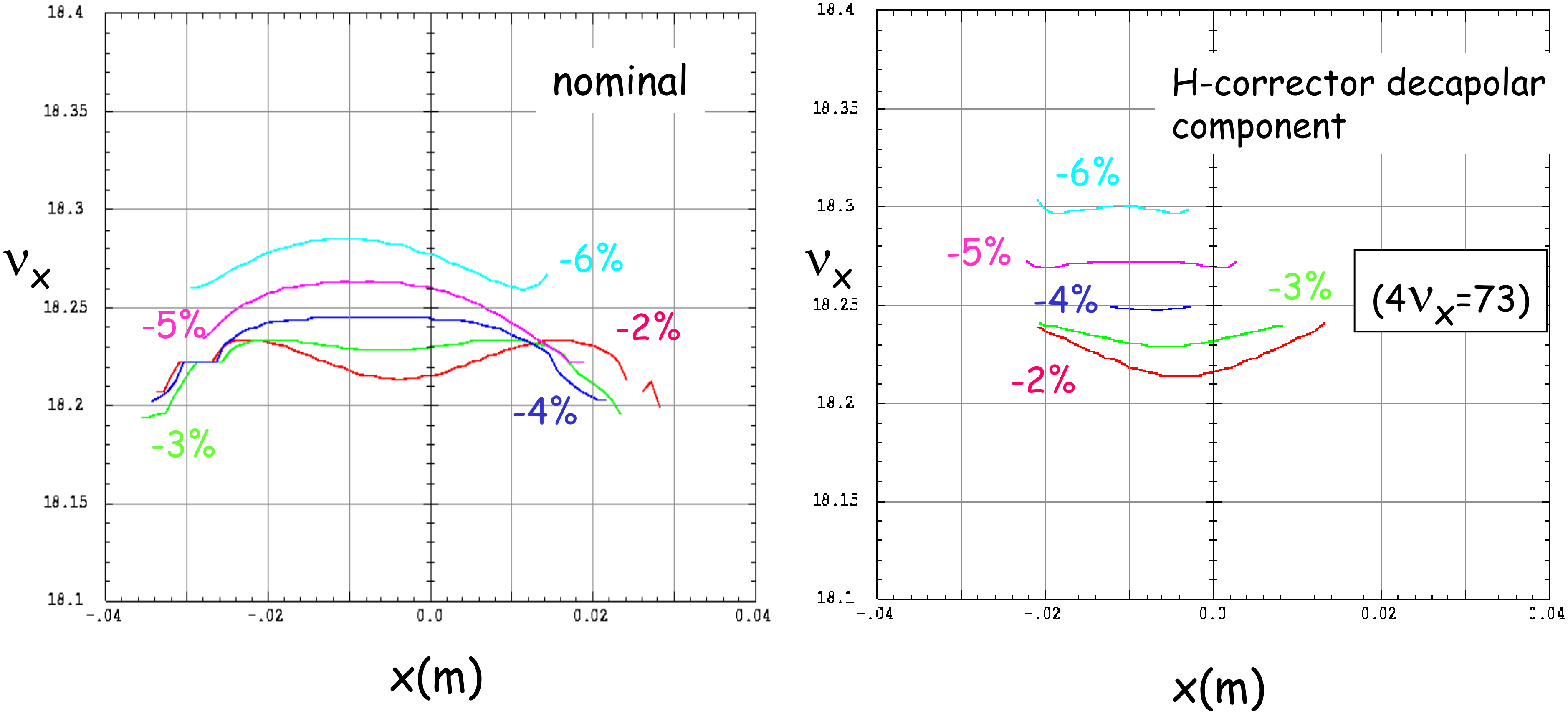
$$D_4 = \Theta \times 0.43 \times (0.035)^{-4}$$

Θ is the kick given by the correctors

$$B = D_4 x_0^4 + \boxed{4 D_4 \eta\delta x_0^3} + 6 D_4 \eta^2 \delta^2 x_0^2 + 4 D_4 \eta^3 \delta^3 x_0 + D_4 \eta^4 \delta^4$$

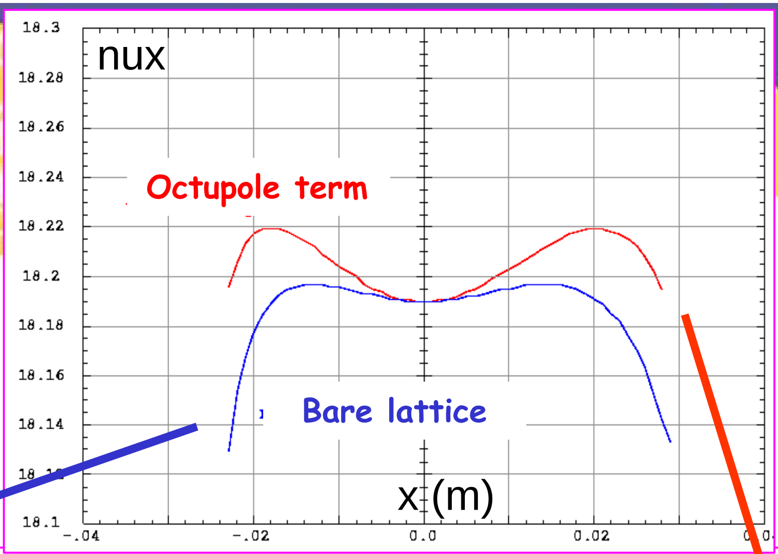
Feed-down effect: Off-momentum particles see octupole field $4\nu_x$ resonance

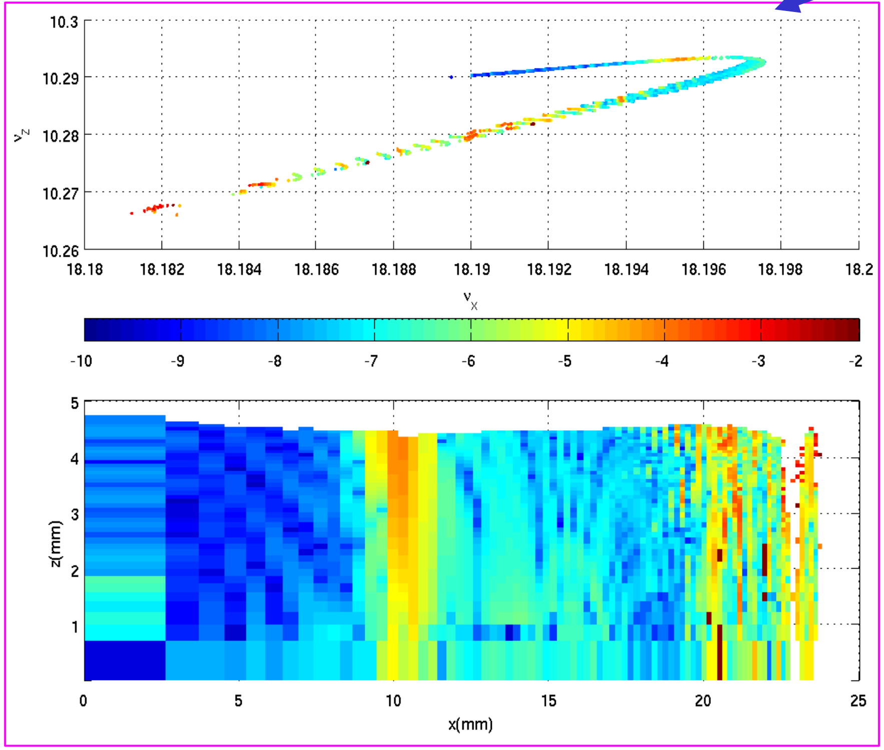
Effect of the H-Corrector Decapolar component (2)

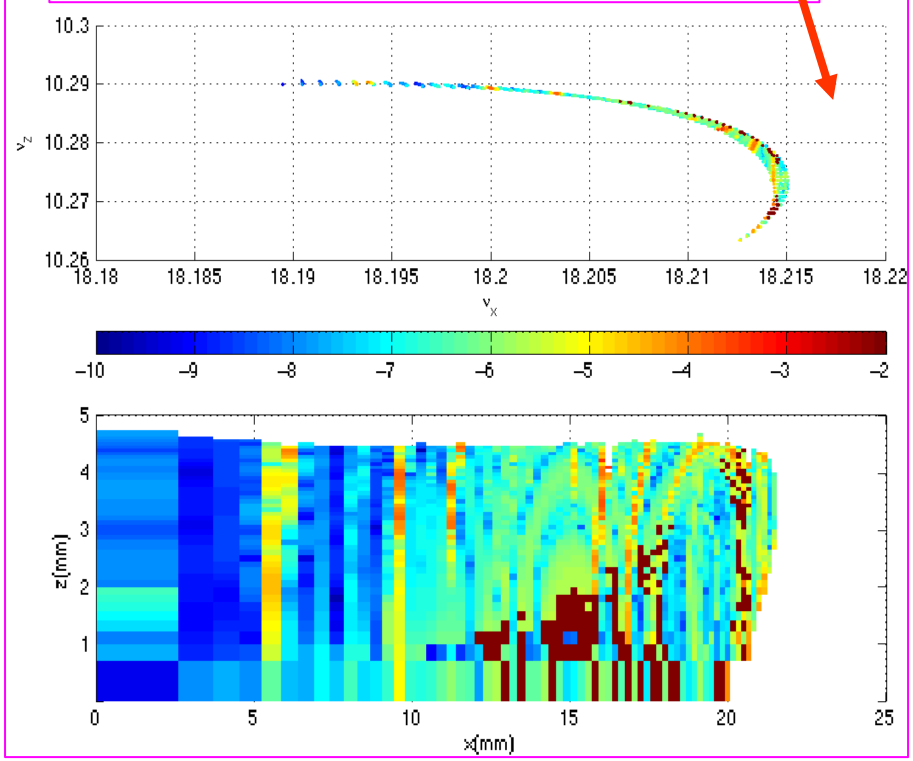


Dependent amplitude off-momentum tunes

Effect of large non systematic octupole in Long Quadrupoles Example of WP 18.19 / 10.29 → retrofit with sextupoles

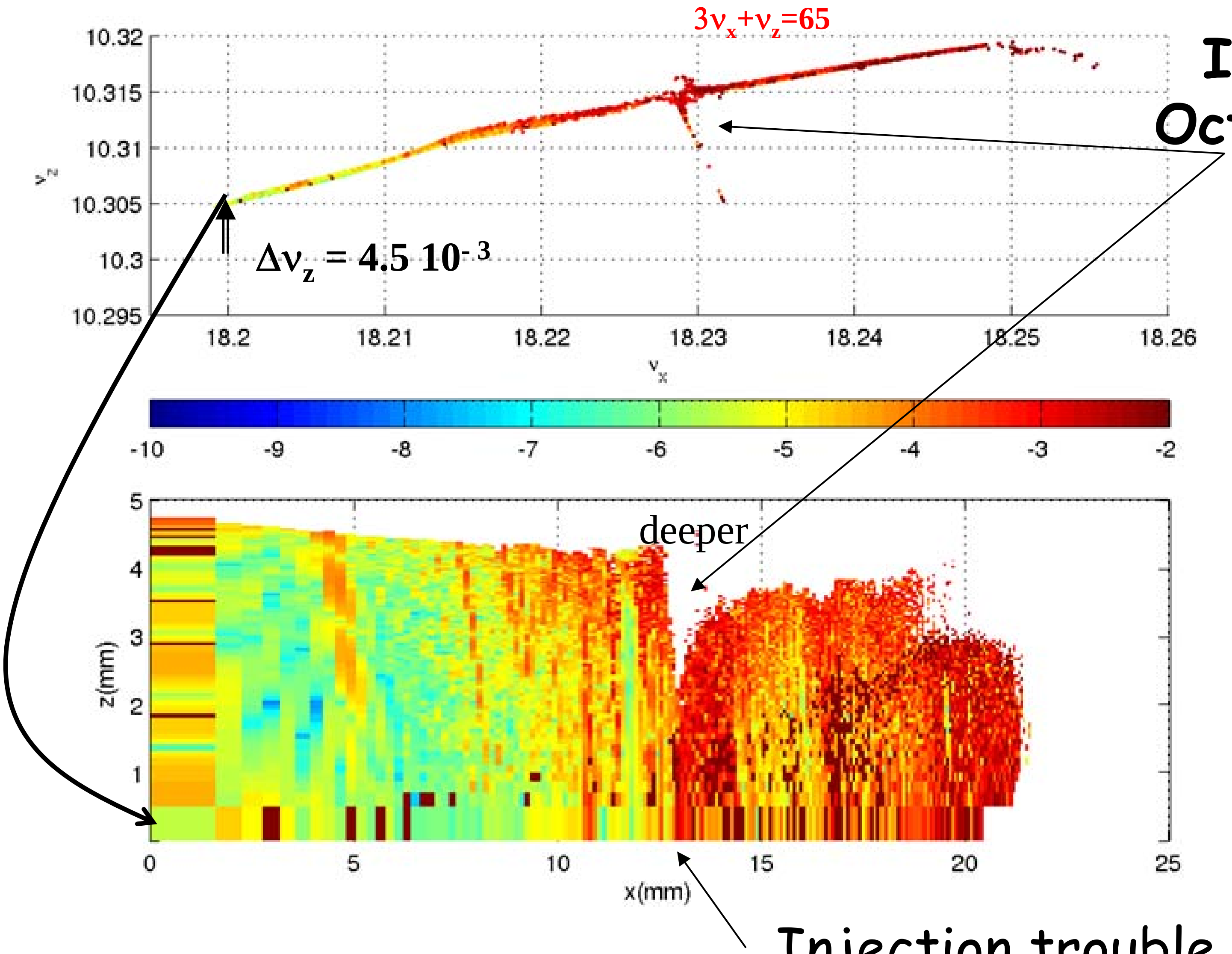






Adding effect of 3 in-vacuum IDs

Note: 1 single U20 → negligible effect



ID excites Octupole term

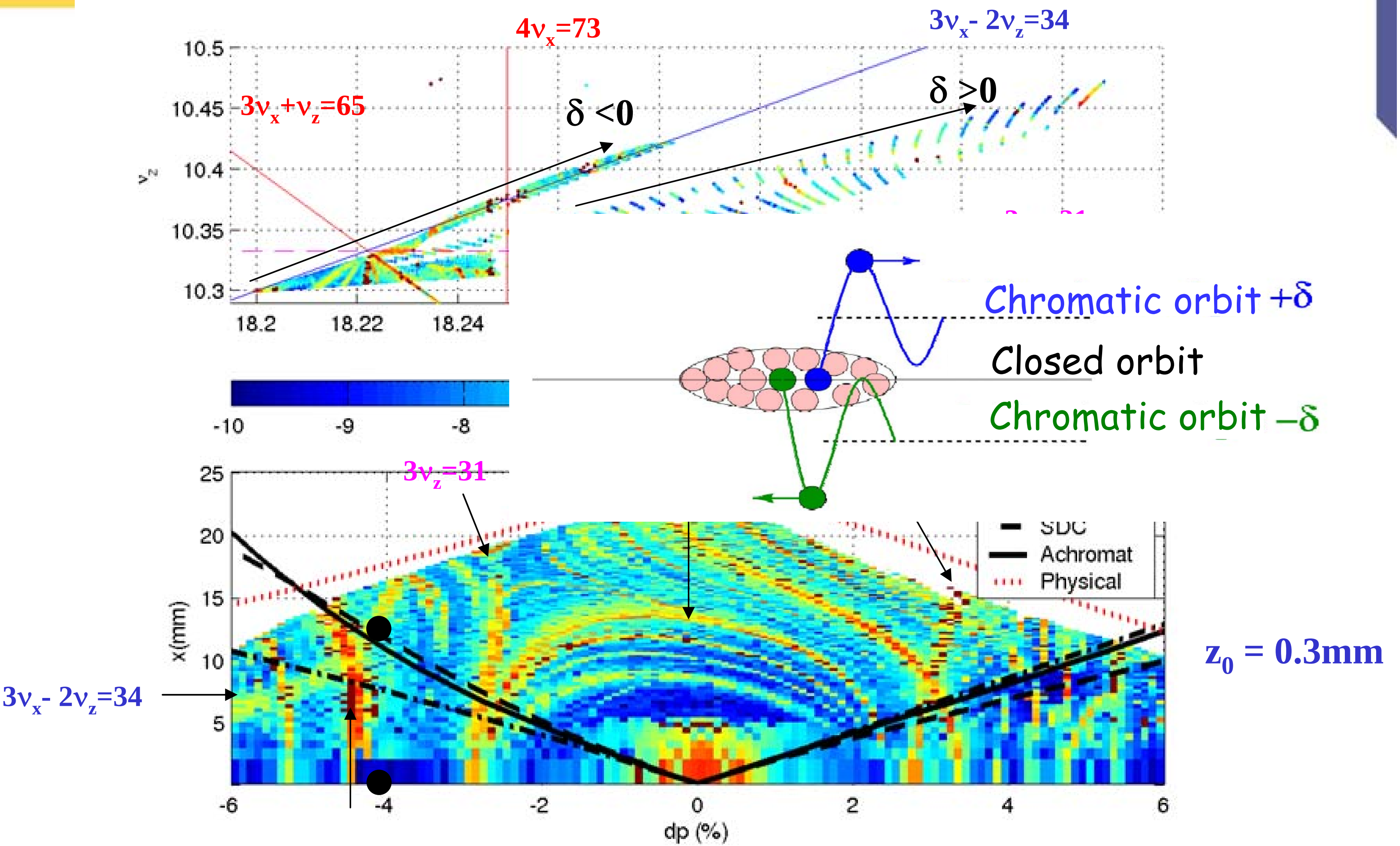
Injection trouble if stronger

Off-momentum dynamics exploration

Several approaches:

- Off-momentum frequency maps
- Energy/betatron-amplitude frequency maps
  - Very rich and concise
  - Static and dynamic information at the same time
- Touschek lifetime – momentum acceptance
  - 4D tracking
  - 6D tracking

Off momentum dynamics w/o IDs



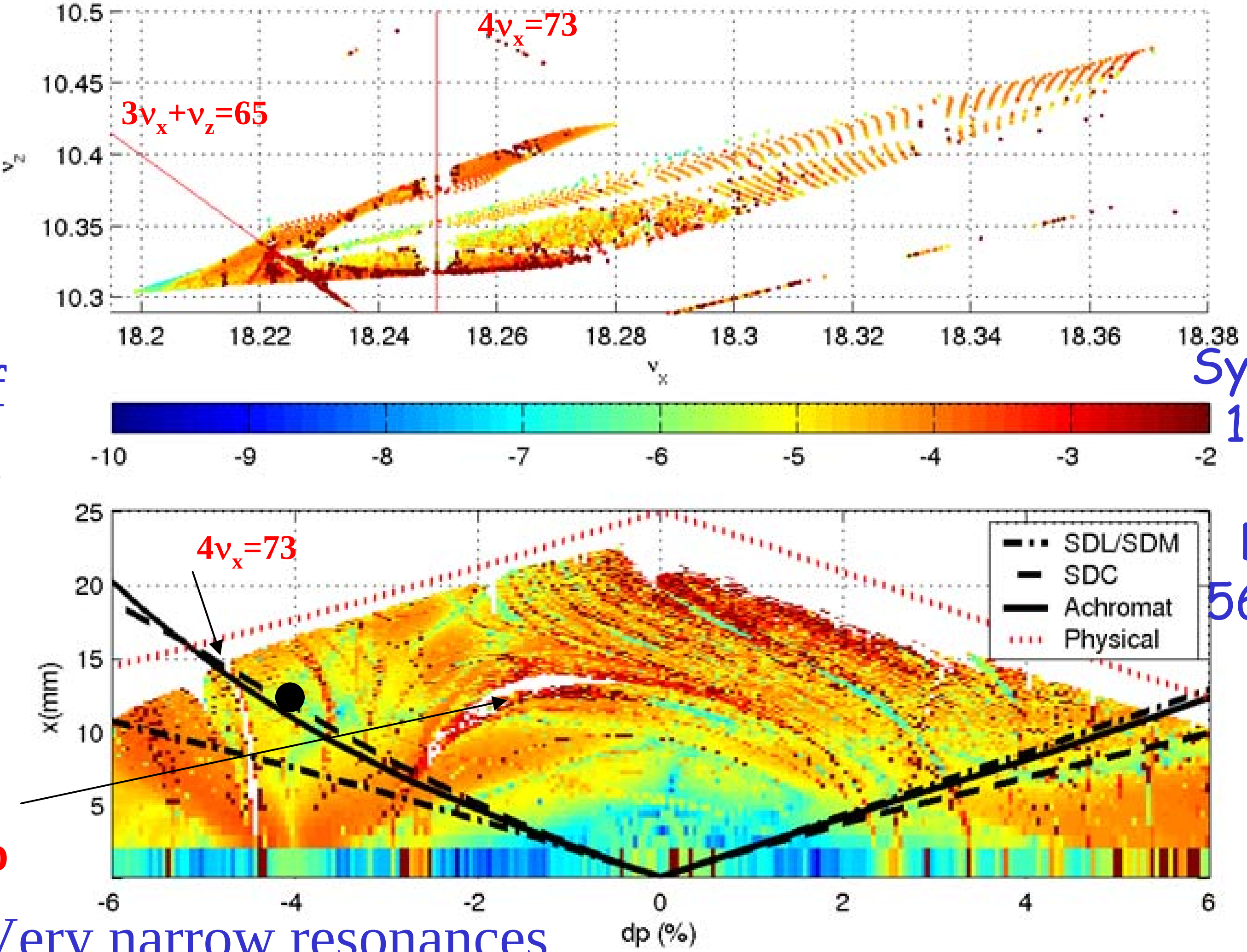
z_0 = 0.3mm

Off momentum dynamics w/ 3 x U20

What's about Effect of synchrotron radiation and damping?

U20

B-Roll off
β_x = 18 m
g = 5mm



Synchrotron
140 turns

Damping
5600 turns

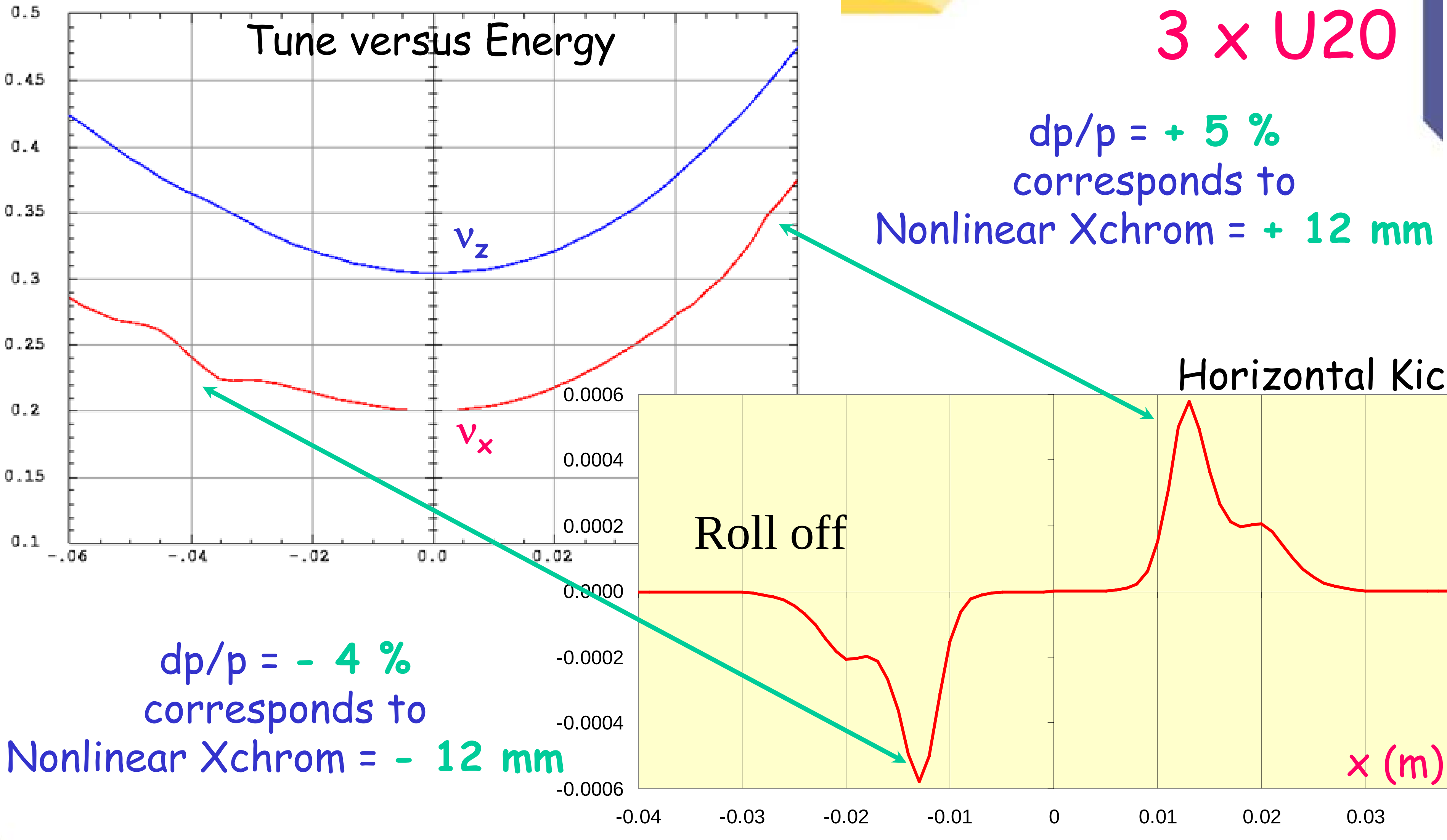
$3\nu_x+\nu_z=65$
Loss over
>400 turns
Stable in 6D

Very narrow resonances

Tune Shift with Energy

3 x U20

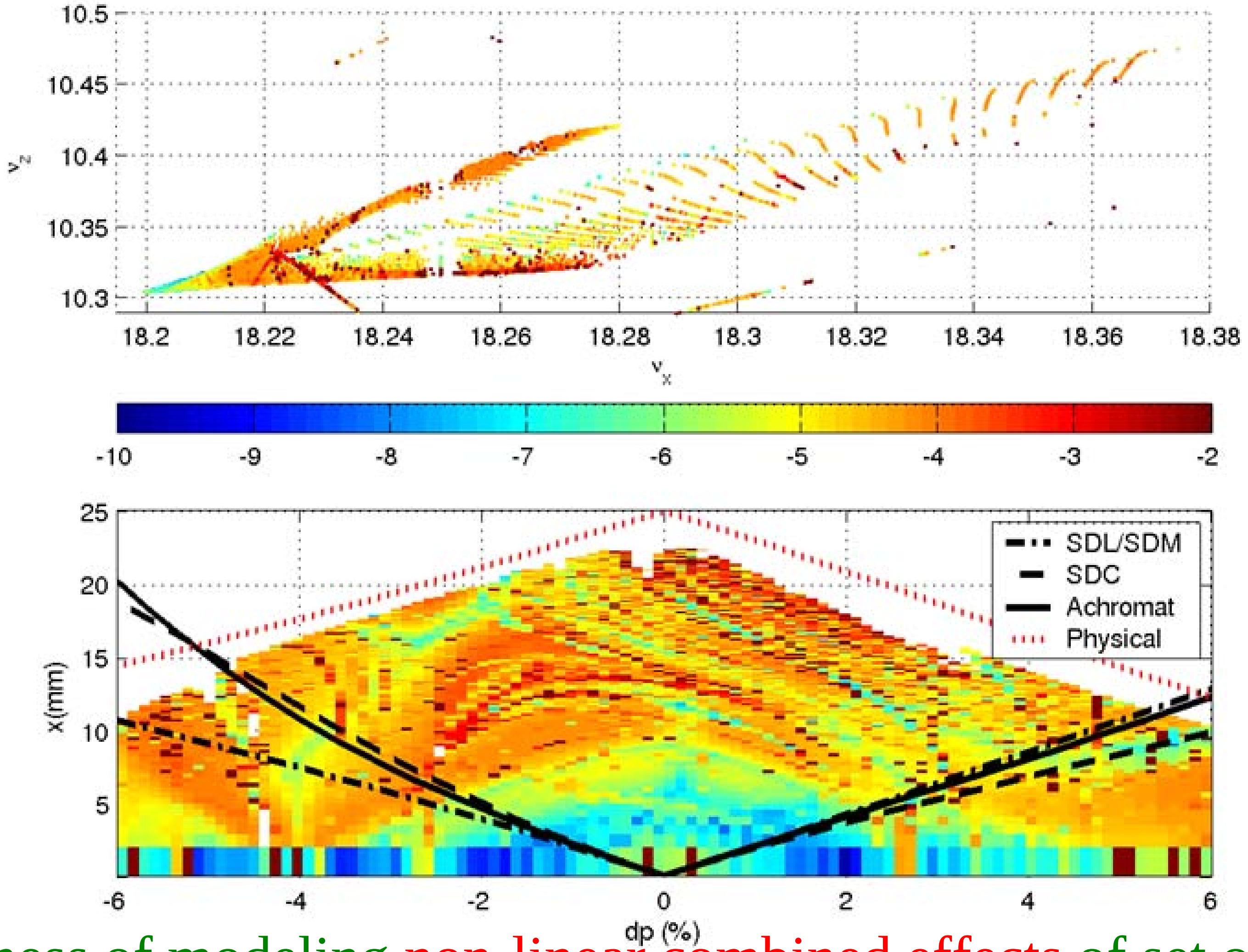
dp/p = + 5 %
corresponds to
Nonlinear Xchrom = + 12 mm



dp/p = - 4 %
corresponds to
Nonlinear Xchrom = - 12 mm

Coupling reduction by a factor 2 with 3 x U20

Usefulness to go to low coupling value



Usefulness of modeling non-linear combined effects of set of IDs

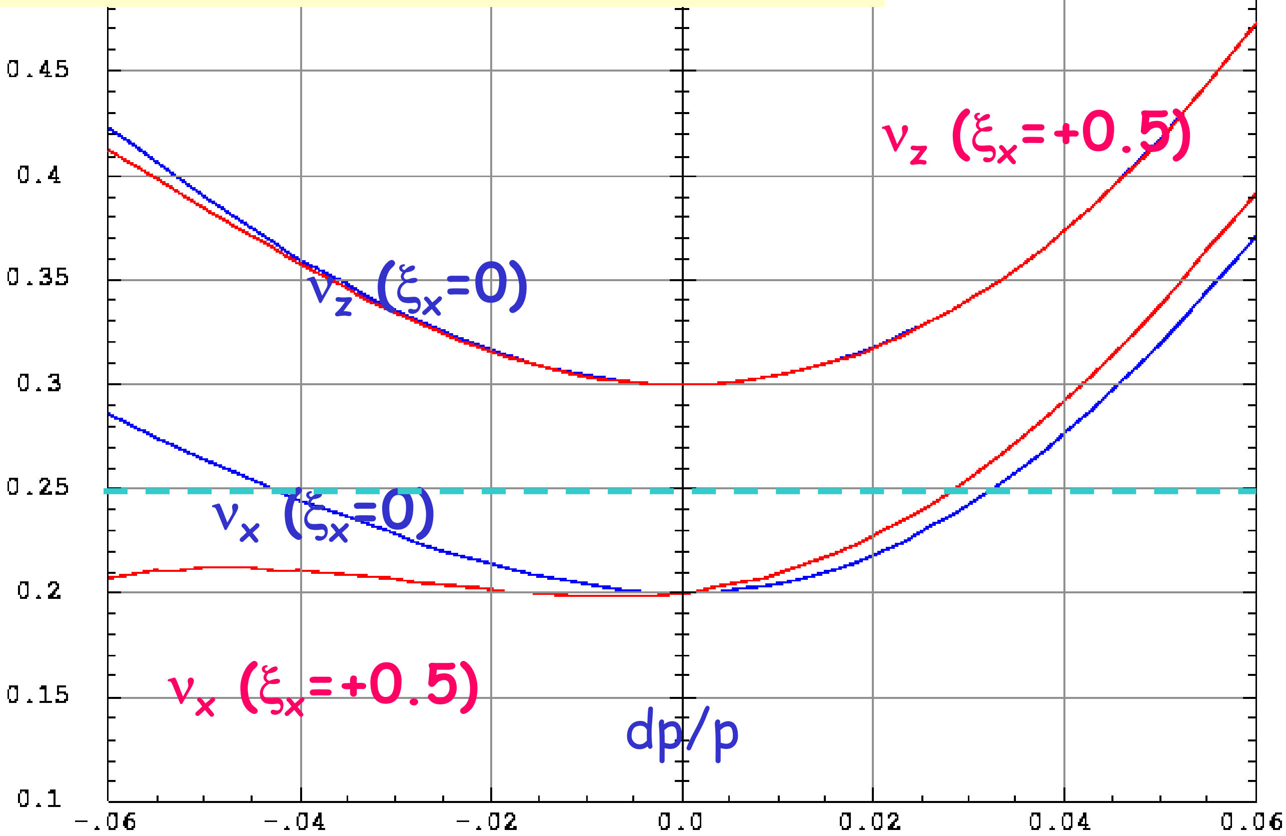
Optimization of a New Point Enhanced philosophy

- On momentum
  - **$3\,\nu_x + \nu_z = 65$** to be avoided (not shown w/o FMA)
  - WP to be shifted from resonance node
  - Control of tune shift with amplitude using sextupole knobs
    - $\nu_x(J_x, J_z) = a\,J_x + b\,J_z$
    - $\nu_z(J_x, J_z) = \mathbf{b}\,J_x + c\,J_z$
- Off momentum $\nu_x(\delta)$
    - Large energy acceptance
    - Control of the tune shift with energy using sextupoles
    - The $4\,\nu_x = 73$ resonance has to be avoided for insertion devices

~~Going to 100 mm magnet pole width?~~

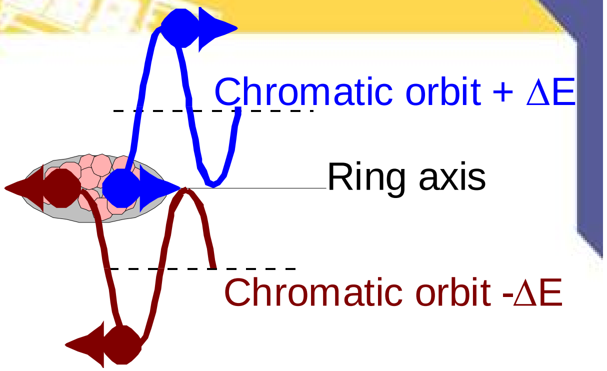
One solution : ξ_x = + 0.5 to avoid $4\nu_x = 73$ at dp/p = - 4.4 %

Using only 2 sextupole families : S9 and S10



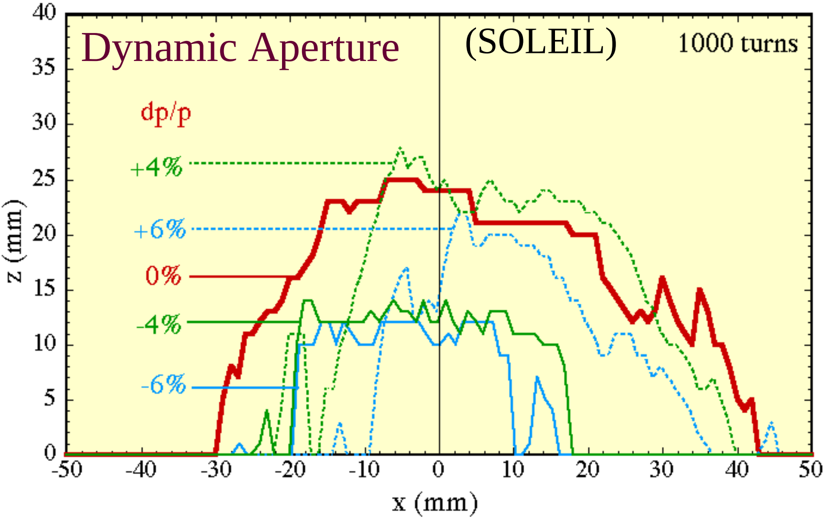
Tune shift w/ energy optimized with sextupoles to avoid in addition the $4\nu_x = 73$ resonance for negative energy offsets

Touschek Beam Lifetime



Touschek Effect: scattering within the bunch

$$\frac{1}{\tau_{T_{1/2}}} = \left(\frac{r_e^2 c N}{8\pi \gamma^3 \sigma_l}\right) \cdot \frac{1}{L} \int_0^L \frac{C\left[\left(\frac{\varepsilon_{acc}(s)}{\gamma \sigma'_x(s)}\right)^2\right]}{\sigma_x(s)\sigma_z(s)\sigma'_x(s)\varepsilon_{acc}^2(s)} ds$$



High density-Touschek scattering of particles - large longitudinal transfers of energy - loss unless large acceptance: RF acceptance, physical aperture, dynamic aperture for large energy deviations

$$\tau_T \propto \varepsilon_{acc}^{>2}$$

(SOLEIL: ε_{acc} = 4 to 6%)

Induced amplitude in a non zero dispersion location:

$$x = \sqrt{A_x \beta_{x1}} + \eta_1 \delta = (\sqrt{H_0 \beta_{x1}} + \eta_1).\delta \quad A_x = \gamma_{x0}(\eta_0 \delta)^2 + 2\alpha_{x0}(\eta_0 \delta)(\eta'_0 \delta) + \beta_{x0}(\eta'_0 \delta)^2 = H_0 \delta^2$$

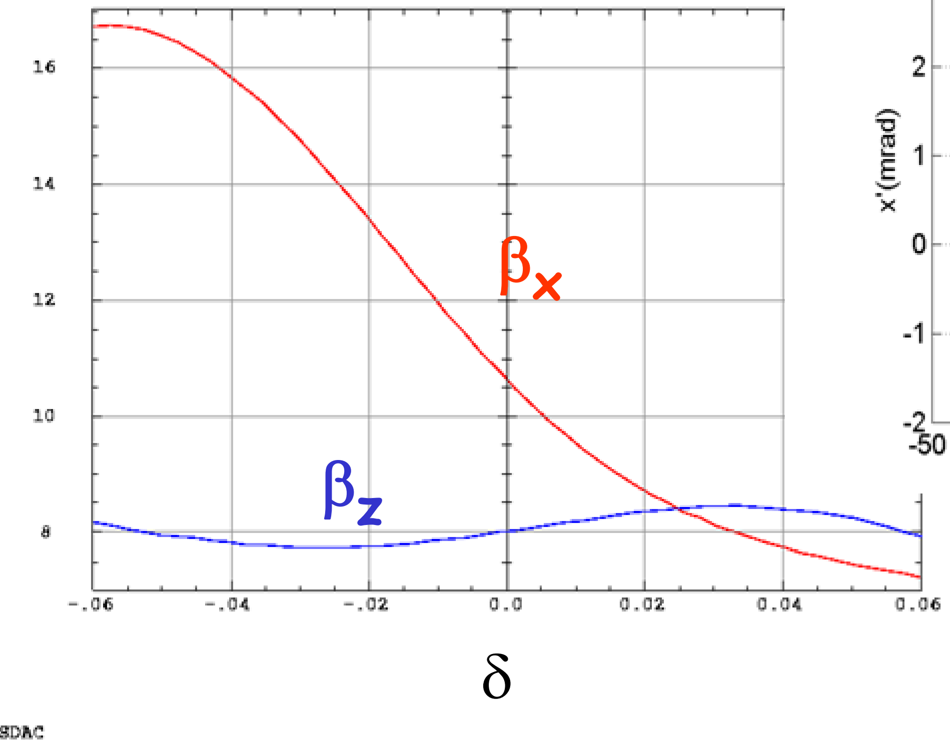
Transverse Energy Acceptance

- Some other effects have to be considered:
  - non-linear betatron motion, i.e., transverse phase space distortion,
  - non-linear synchrotron motion, i.e., effects of higher order chromaticities and higher order momentum compaction factors (already partly implemented in BETA),
  - synchrotron radiation: to follow the amplitude variation of the particles during the damping process (diffusion, resonance crossing),
  - coupling from horizontal to vertical plane:
    - induces also a vertical betatron amplitude from Touschek scattering:
      - ⇨ ε_{acc} limitations from small vertical gaps,
    - possible diffusion process in the vicinity of skew resonances
      - ⇨ Vertical amplitude growing,
  - higher order multipole effects.

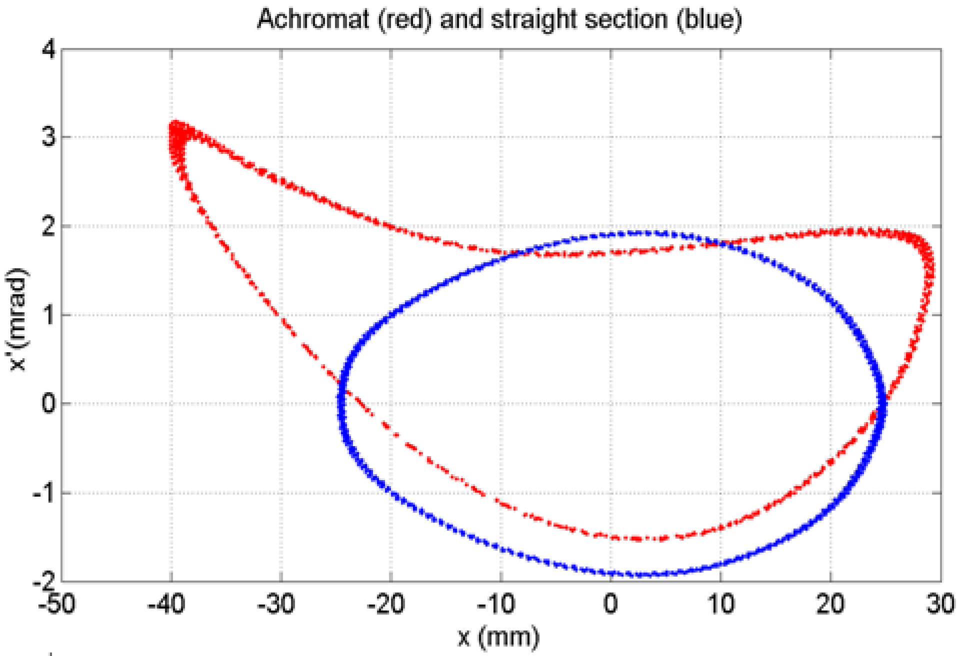
Twiss function variations

Betatron function variations with energy

Center of the long straight section



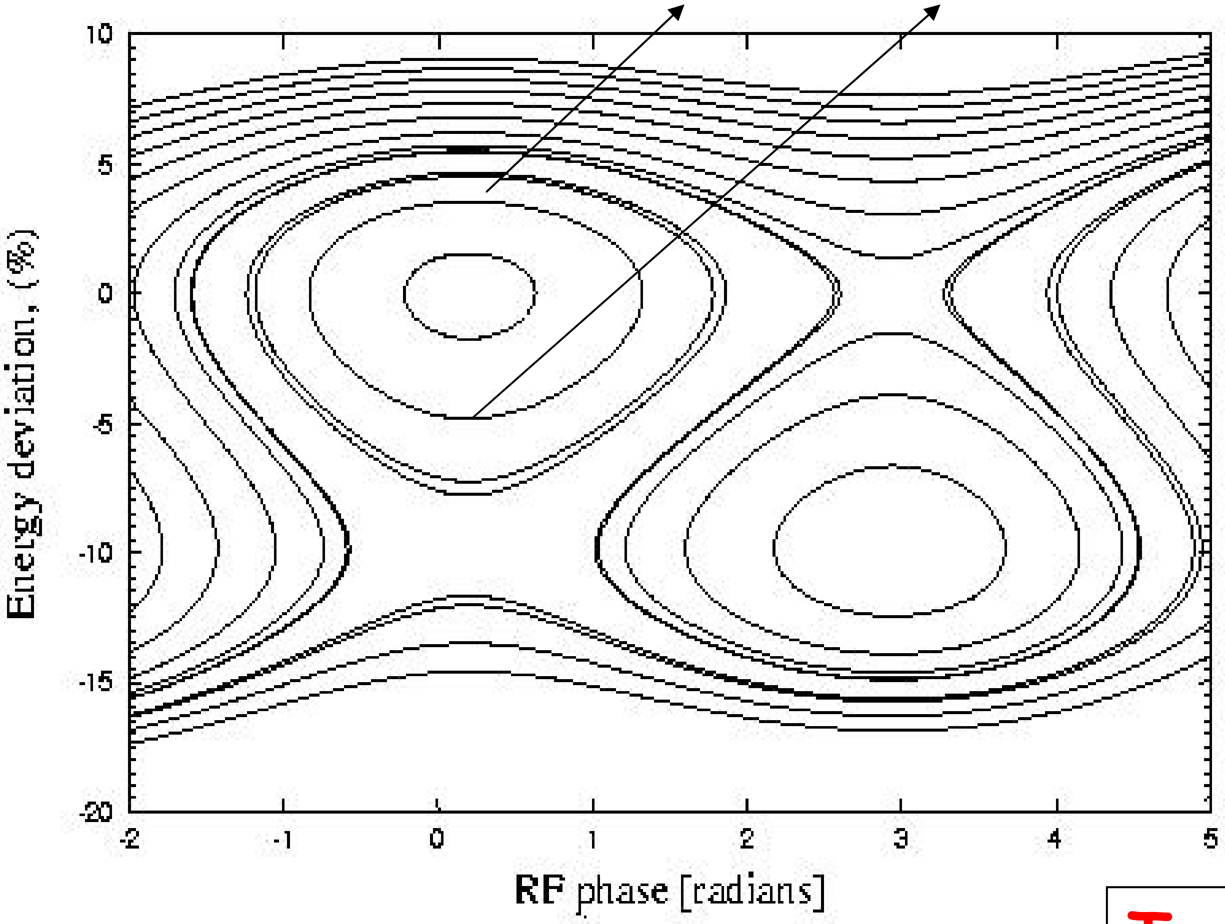
Non-linear betatron motion with amplitude



NB: Other reason for having the vacuum vessel defined everywhere for the tracking

Non-linear synchrotron motion

+3.8% ↔ -6%



$\alpha_1 = 4.38\ 10^{-4}$

$\alpha_2 = 4.49\ 10^{-3}$

$$\alpha_1 = \oint \frac{\eta_1}{\rho} ds$$

$$\alpha_2 = \oint \left(\frac{\eta_1'^2}{2} + \frac{\eta_2}{\rho} \right) ds$$

Tracking 6D required

Touschek Tracking

- One way to take into account these effects all together is to perform a 6D tracking.
- The energy acceptance calculation problem is then reduced to the very simple question:

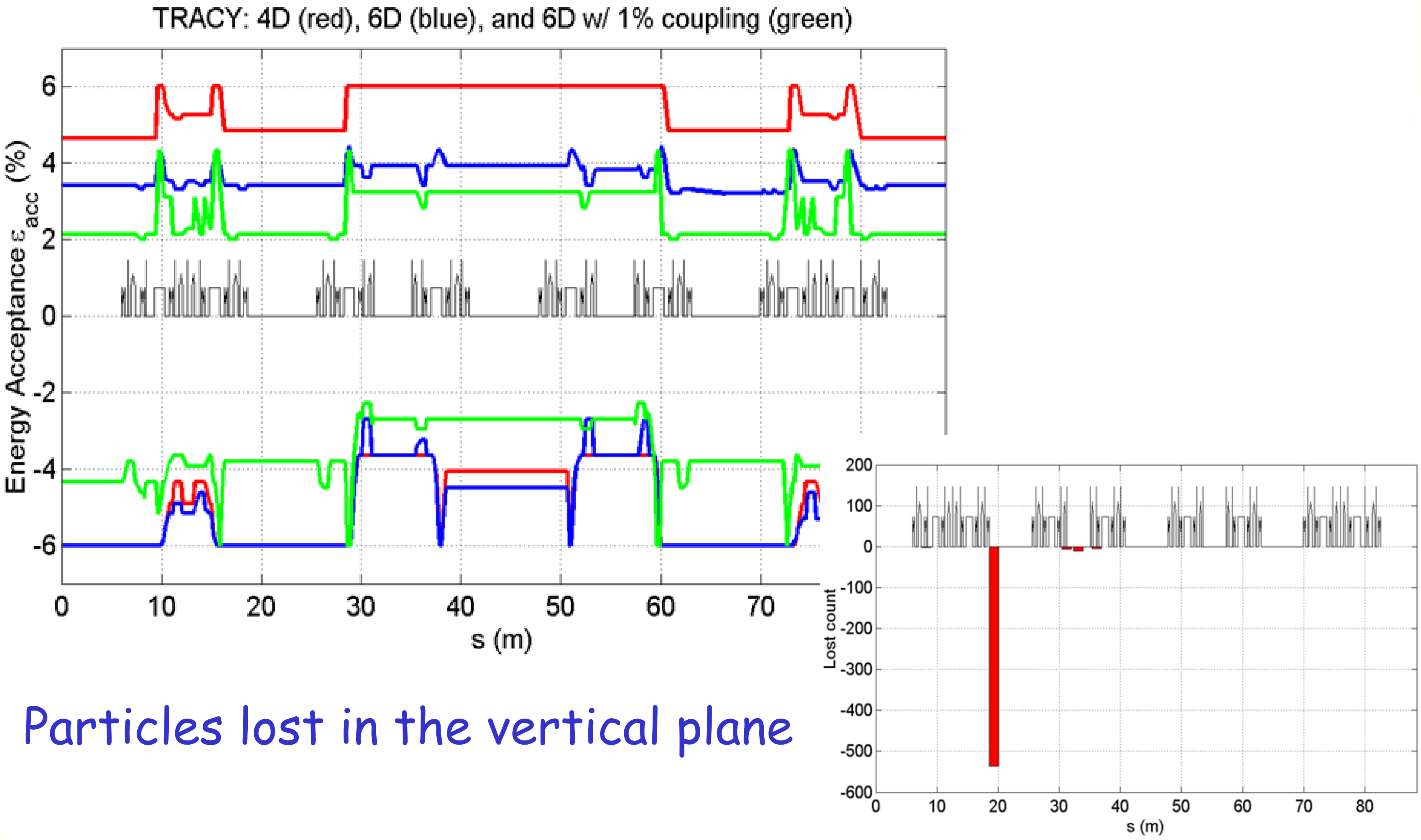
Is the particle with starting coordinates (0,0,0,0, ±δ,0) stable or not?

⇨ Particles tracking using the TRACY II code— Ruth and Forest's fourth order symplectic integrator.

Particles are tracked:

- ✓ over 1026 turns
- ✓ with a starting vertical amplitude of 0.3 mm
- ✓ with a given energy deviation δ: from -6% to 6% by steps of 0.1%.
- ✓ Understand where (s-location, plane) and why particles are lost?
  → Provide hints for improving/changing the working point

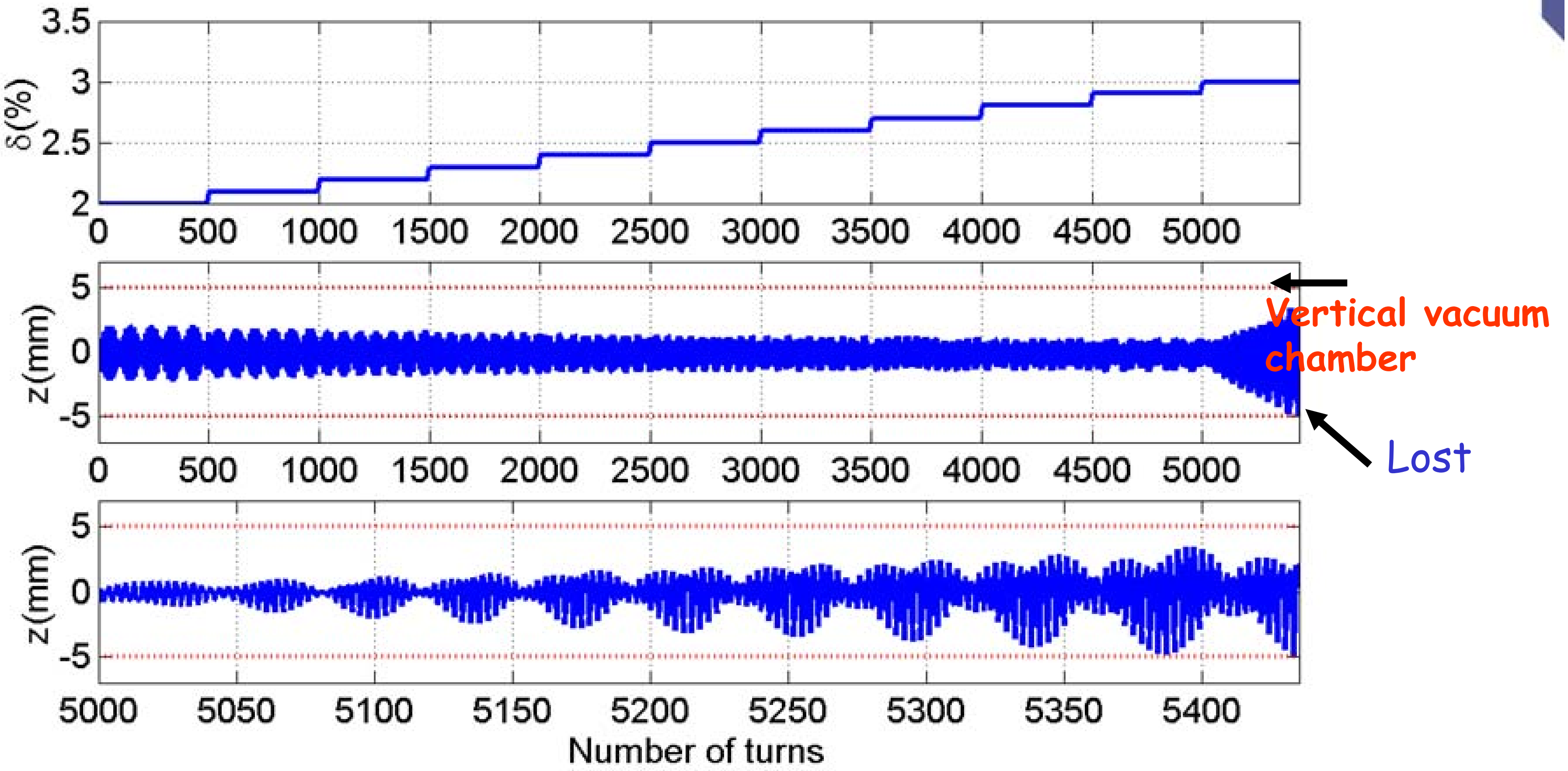
Example of working point 18.30 & 10.27


TRACY: 4D (red), 6D (blue), and 6D w/ 1% coupling (green)

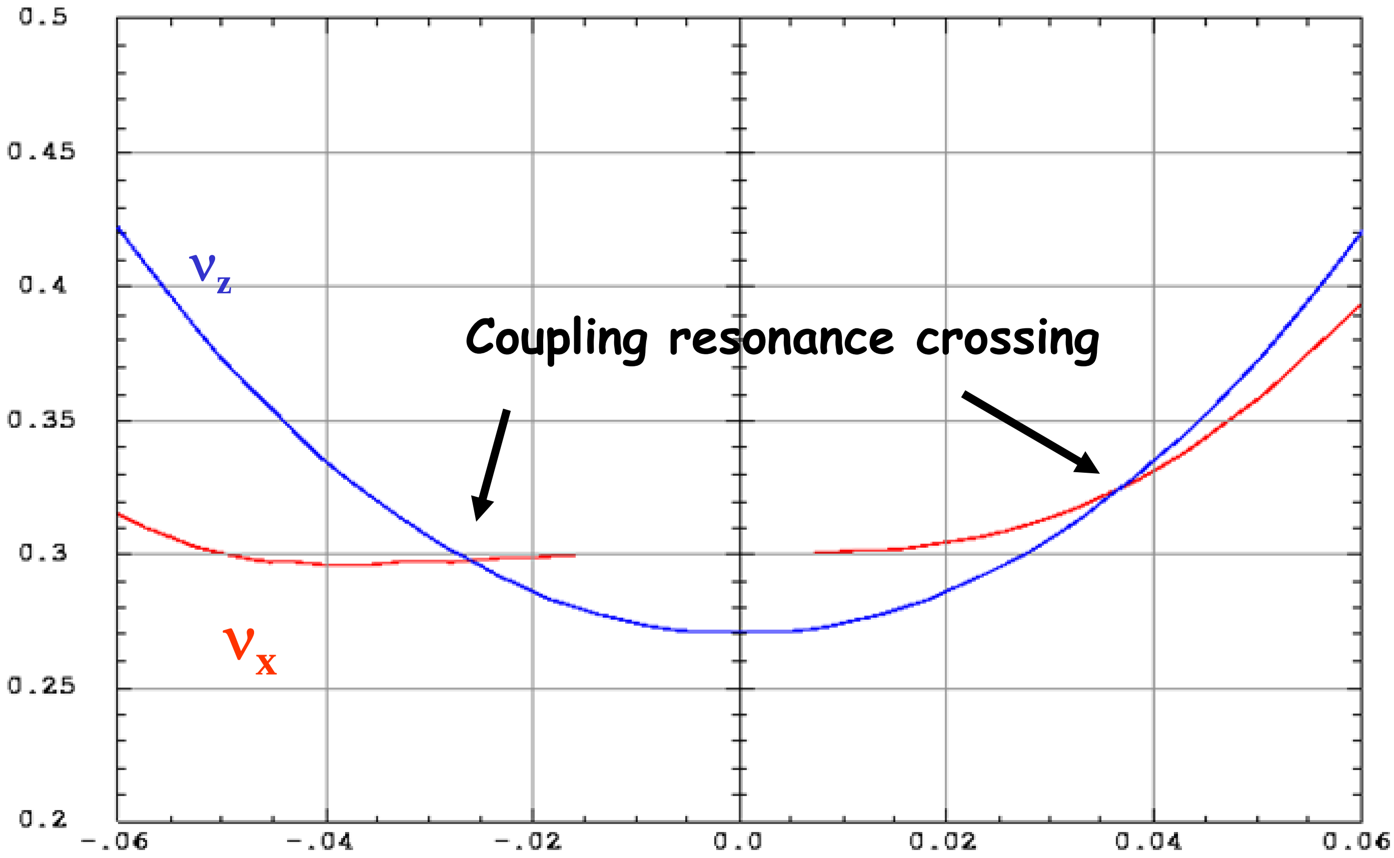
Particles lost in the vertical plane

Hitting the vertical chamber by diffusion

Understanding the physics of losses …



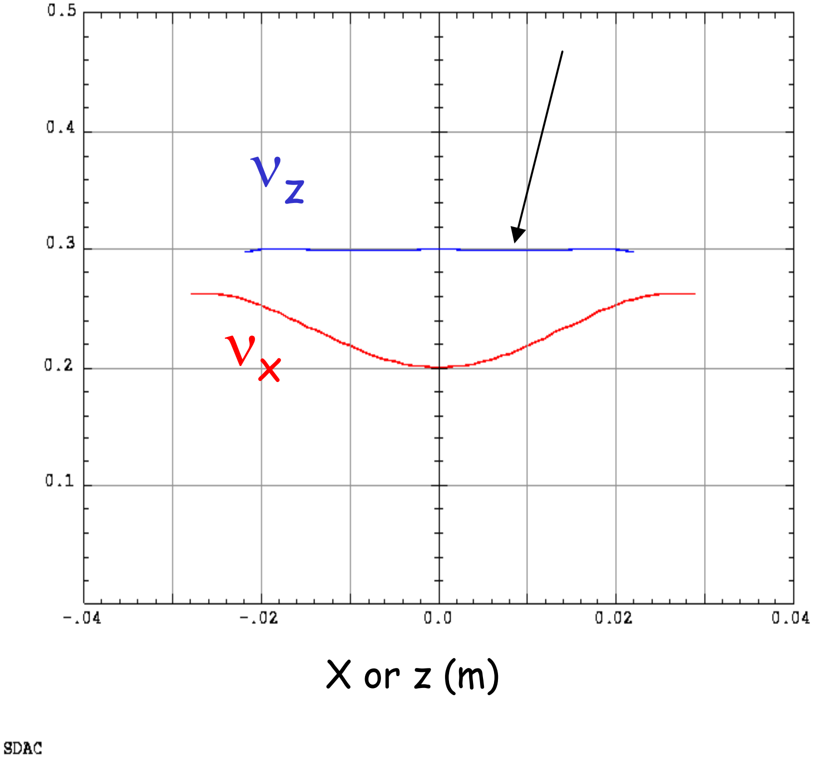
Tune shift with energy: 18.30 & 10.27



Linear coupling induced non-linear effects
Ensure that the linear coupling resonance is not crossed off-momentum

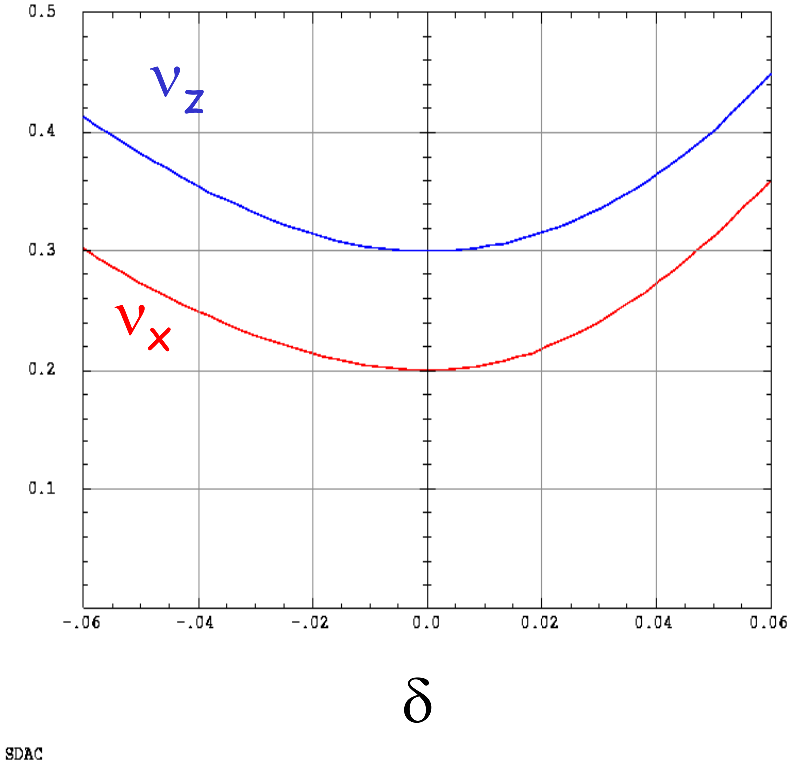
Nominal working point (18.2, 10.3)

Flat vertical tune



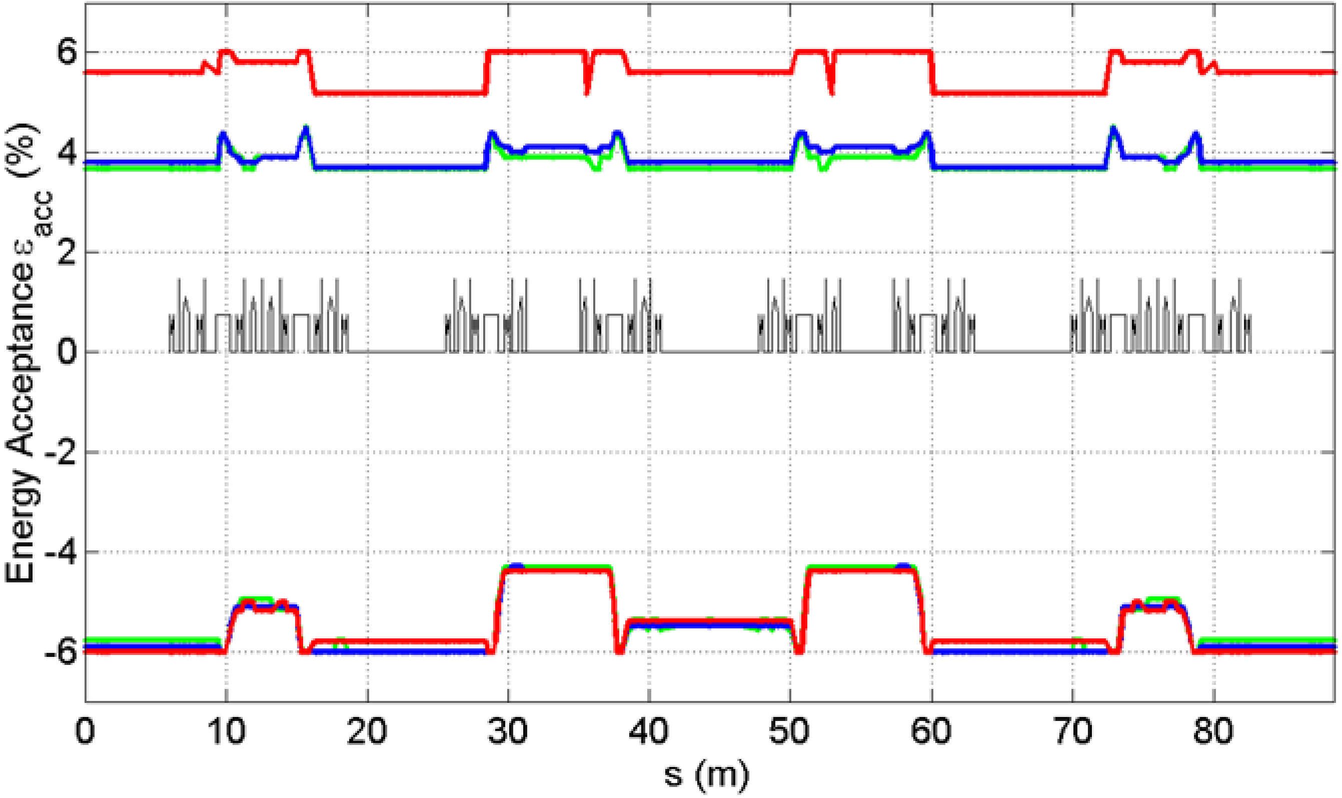
Non coupling resonance crossing

$\nu_x - \nu_z = 8$ ($\Delta\nu = 0.1$).



Nominal working point
18.20 & 10.30 ($\Delta\nu$=0.1)

TRACY: 4D (red), 6D (blue), and 6D w/ 1% coupling (green)



Touschek beam Lifetime calculation

$$\frac{1}{\tau_{T1/2}(s)} = \frac{1}{2}\left[\frac{1}{\tau^{+}_{T1/2}(\varepsilon^{+}_{acc}(s))} + \frac{1}{\tau^{-}_{T1/2}(\varepsilon^{-}_{acc}(s))}\right]$$

- Optics with 18.2 and 10.3:
- 6D Tracking with 1% coupling, mini gap (±2.5 mm in short straight section)
- natural bunch length (500 mA in 416 bunches, 4MV)

Example of local energy acceptance

Long Straight section: +3.8% -5.8%

Short Straight section: +4.0% -4.3%

$\tau^{-}_{T\,1/2}$ = 66h $\tau^{+}_{T\,1/2}$ = 22h

$\tau_{T\,1/2}$ = **33h**

- Combined with a gaz lifetime of 24h, this gives a total beam lifetime of approximately 16h.

Conclusion

- Model used for giving magnet multipole tolerances, for validating the design of the IDs. With modern tools: realistic estimations
- Modeling improvement
  - Fringe field quadrupole
  - Full 6D ID tracking + radiation
  - Retrofit from real IDs
  - Robustness for non zero chromaticity (few bunch operation, TFB)
- Sextupole families
  - 2 families for chromaticity correction
  - n families: chromaticity + nonlinearity compensation
  - Individual sextupoles:
    - Increase number of families: 13 at SOLEIL enable us to reduce α_2
    - Flexibility for local compensation (slicing exp., local focusing for BLs)
- See measurements with e-beam and how is the agreement with the model (Tomorrow's talk) .

SOLEIL SYNCHROTRON

References

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