Frequency maps for designing proton accelerators

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Outline

- Non-linear dynamics in proton accelerators
- Dynamics of the LHC and frequency maps
  - Detrimental effects of dipole errors
  - Diffusion maps as quality factor for correction schemes
  - Beam-beam effect
  - Super-bunches and crossing schemes for LHC upgrade
  - Frequency for understanding collective non-linear beam dynamics (the e-cloud effect)
- Dynamics of the SNS
  - Off-momentum frequency maps for working point choice

Non-linear dynamics studies in proton accelerator

Accelerator design focuses on high **performance**

- Colliders ⟶ Luminosity (number of events/second) $L = N^2 k_b \gamma / (4\pi\epsilon_n \beta^*)$, with N number of particles, k_b number of bunches, γ relativistic factor, ϵ_n normalized emittance, β^* betatron function at the I.P.
- High-intensity machines ⟶ Average beam power $\bar{P} = \bar{I}E = f_N N e E$, with $\bar{I}$ the average current

Non-linear effects limit the performance ⟶ beam loss

- Colliders ⟶ Reduced lifetime
- High-intensity machines ⟶ Radio-activation

↓

Identification of non-linearities and correction

Dynamics of the LHC

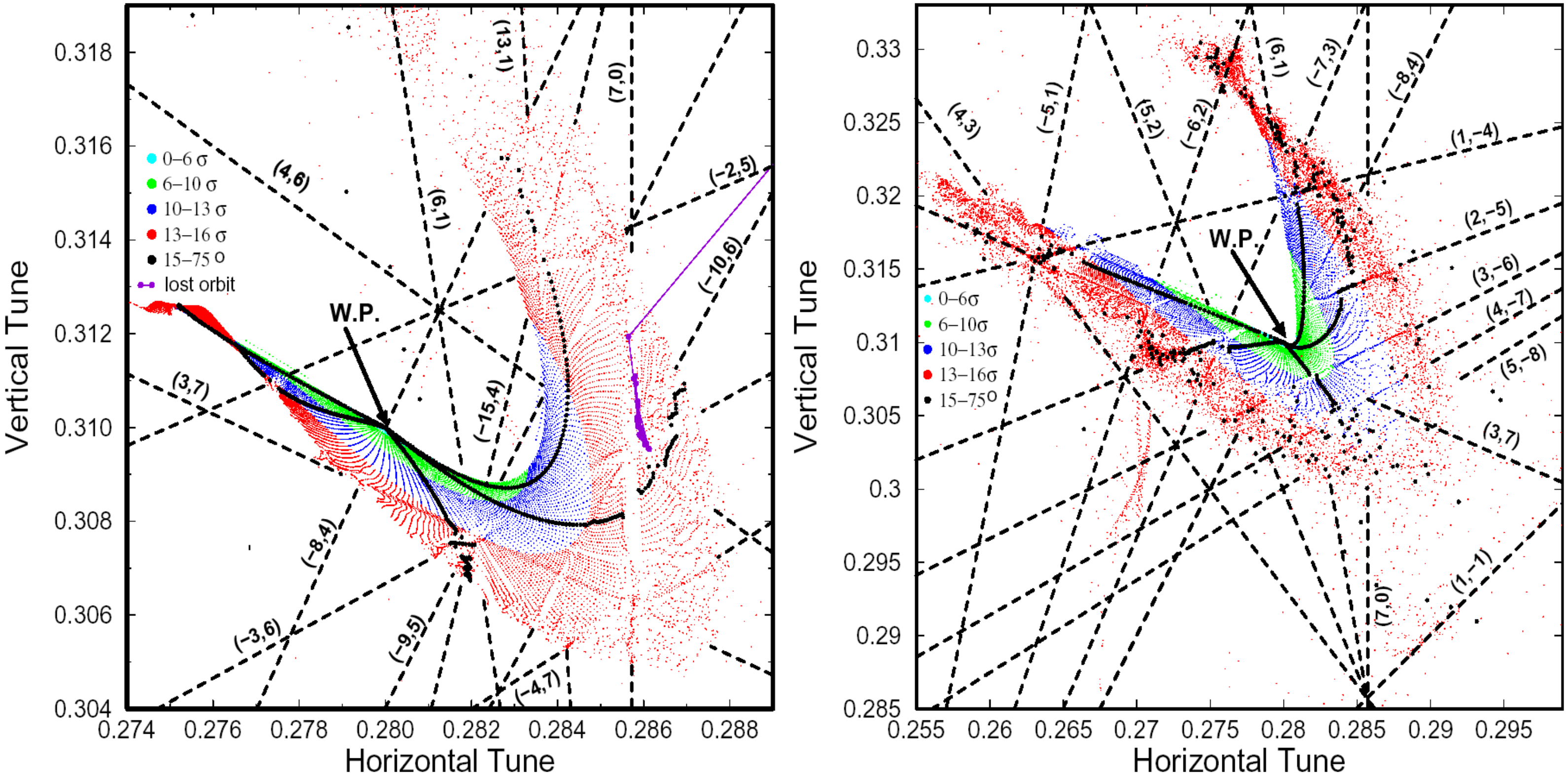
Long-term stability of the beam (e.g. Injection period → 10^7 turns) limited by

- Errors in super-conducting magnets (main dipoles, IR quadrupoles)
- Magnet misalignments and rolls
- Power supplies' ripple and tune-modulation
- Beam-beam effect
- Wall effects - wake fields (impedances)
- Electron cloud and other collective instabilities

Measure of beam stability → Dynamic Aperture (DA)

- Impossible to track full injection/ramping/collision period
- No insight in structure of phase space
- Use of analytical and numerical non-linear dynamics methods (normal form construction, frequency maps, etc.)

Frequency maps for the LHC



Frequency map for the LHC optics version 5 using the target error table (left) and an increased a_4 error in the main dipoles (right).

Diffusion Maps

Calculate tune for two equal and successive time spans and compute diffusion vector:

$$\boldsymbol{D}|_{t=\tau} = \boldsymbol{\nu}|_{t\in(0,\tau/2]} - \boldsymbol{\nu}|_{t\in(\tau/2,\tau]} \ ,$$

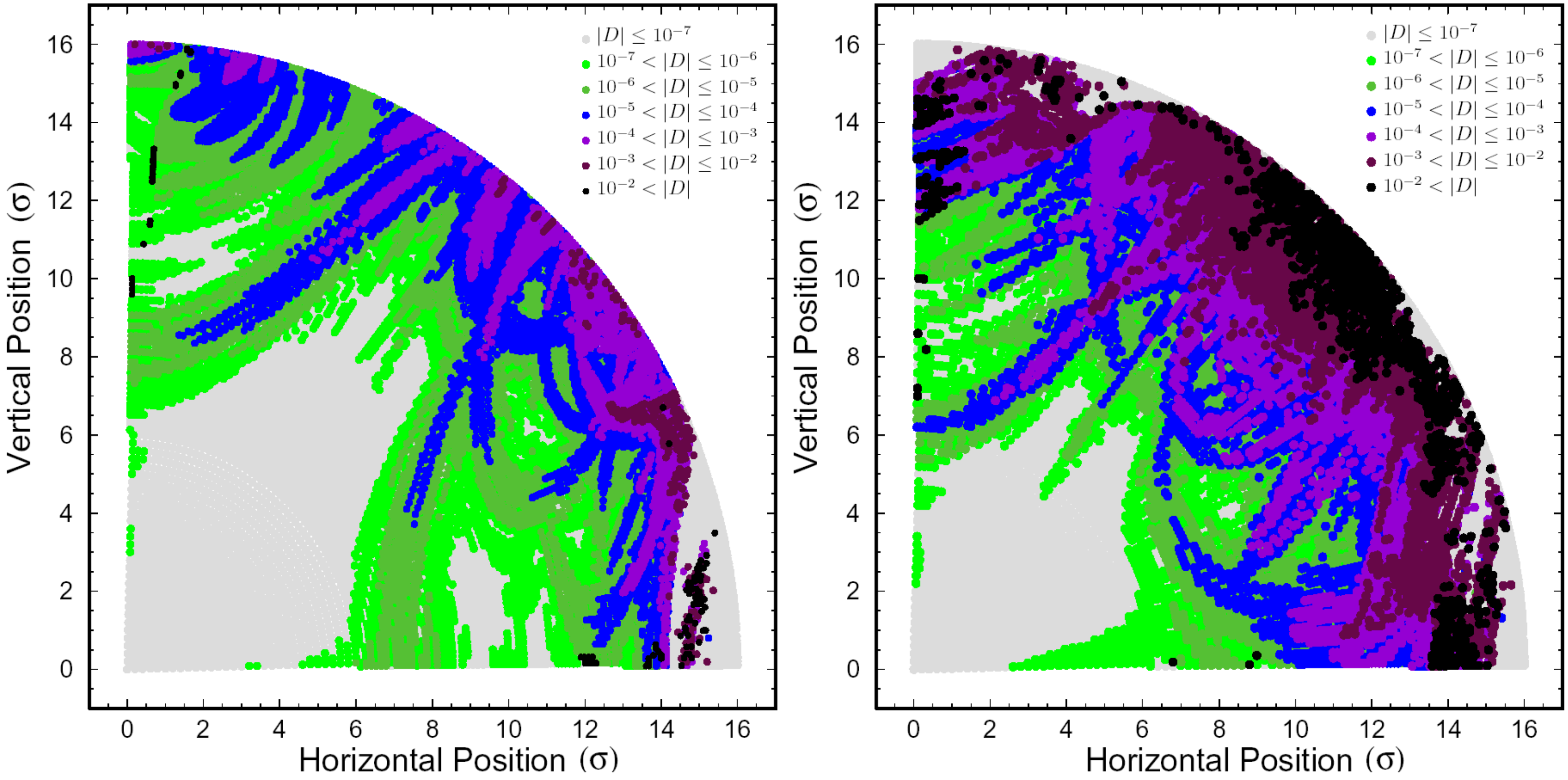
Plot the points in (I_{x0}, I_{y0})–space with different colors

- grey for stable ($|\boldsymbol{D}| \leq 10^{-7}$) to
- black for strongly chaotic particles ($|\boldsymbol{D}| > 10^{-2}$).

Diffusion quality factor:

$$D_{QF} = \left\langle \frac{|\boldsymbol{D}|}{(I_{x0}^2 + I_{y0}^2)^{1/2}} \right\rangle_R \ .$$

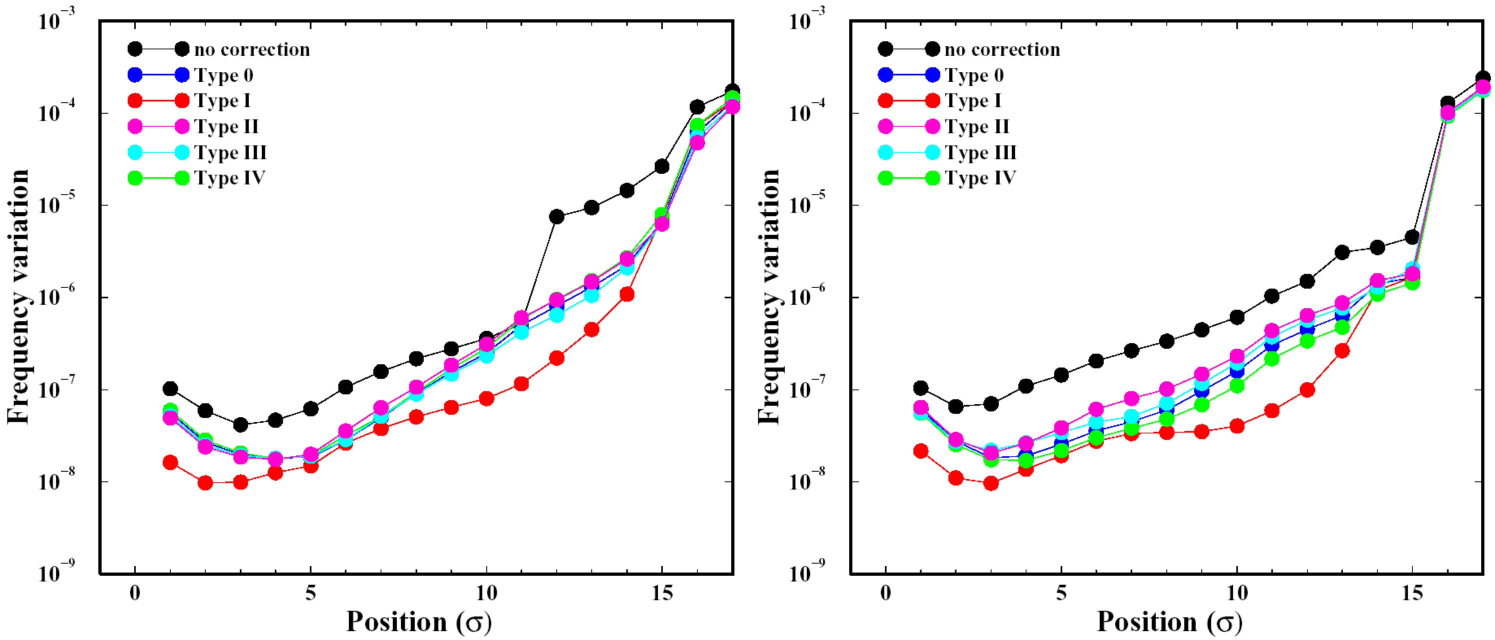
Diffusion Maps for the LHC



Diffusion maps for the LHC optics version 5 using the target error table and an increased a_4 error in the main dipoles (right).

Efficiency of LHC correction schemes

suggested by J.P.Koutchouk

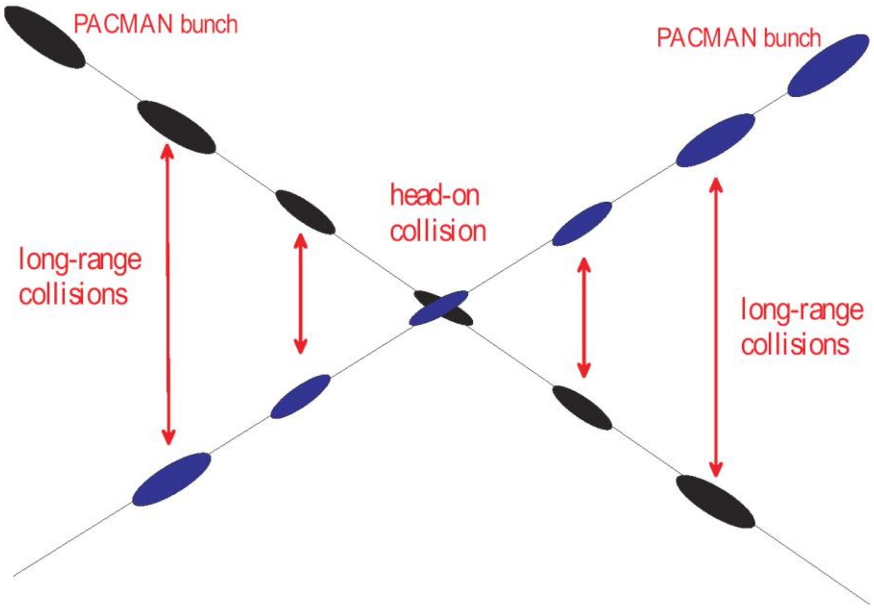


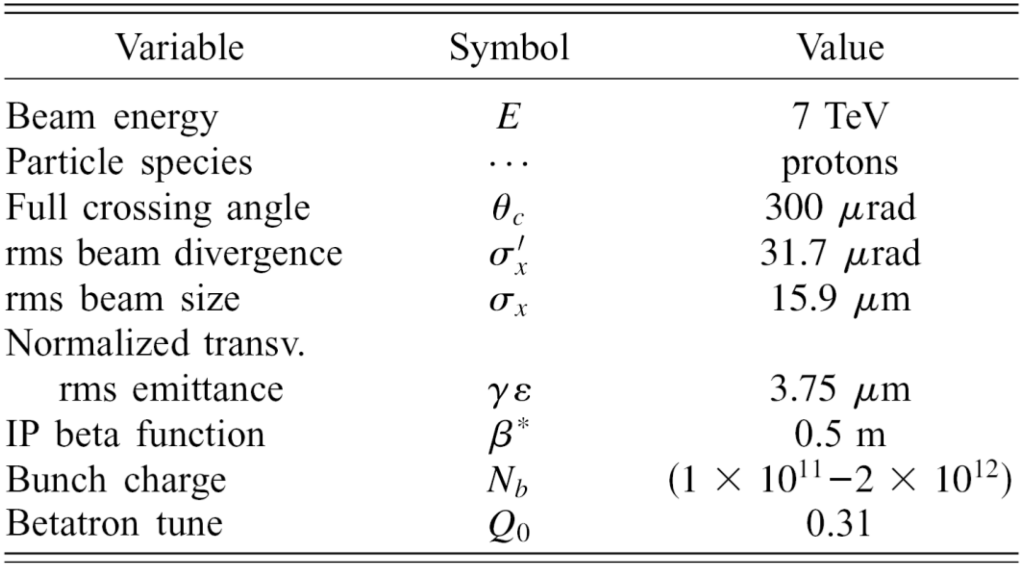
Efficiency of 5 different correction schemes for the b_4 and b_5 error in the main dipoles using frequency diffusion as a quality factor. Average tune variation vs. particles' amplitude with $\delta p/p = 7 \times 10^{-4}$ and for $(Q_x, Qy) = (0.28, 0.31)$ (top) and $(Q_x, Qy) = (0.21, 0.24)$ (bottom).

Beam-beam effects in the LHC

with F.Zimmermann

Schematic of long-range collisions experienced by closely spaced short bunches on either side of the primary head-on interaction point (IP).





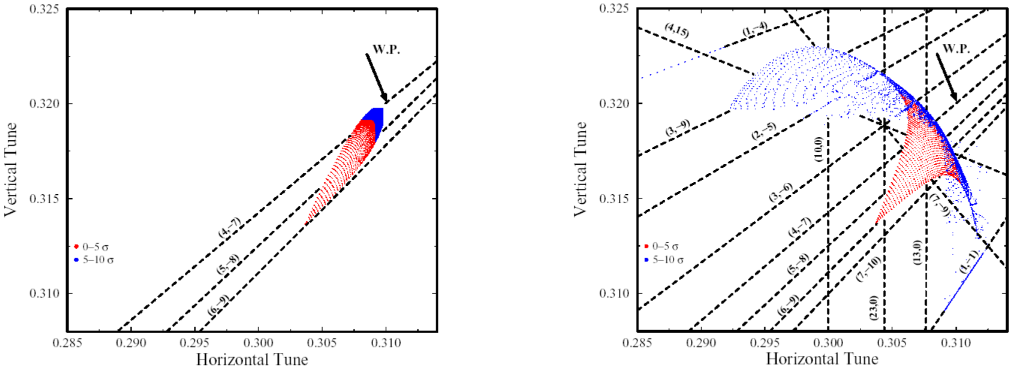
Variable	Symbol	Value
Beam energy	E	7 TeV
Particle species	$\cdots$	protons
Full crossing angle	θ_c	300 μrad
rms beam divergence	σ'_x	31.7 μrad
rms beam size	σ_x	15.9 μm
Normalized transv. rms emittance	$\gamma\varepsilon$	3.75 μm
IP beta function	β^*	0.5 m
Bunch charge	N_b	$(1 \times 10^{11} - 2 \times 10^{12})$
Betatron tune	Q_0	0.31

LHC parameters used in weak-strong beam-beam simulations

Beam-beam effects in the LHC

Head−on collisions

Head−on + long−range collisions



Head−on + long−range collisions
+ KEK triplet errors

Long−range collisions
+ KEK triplet errors

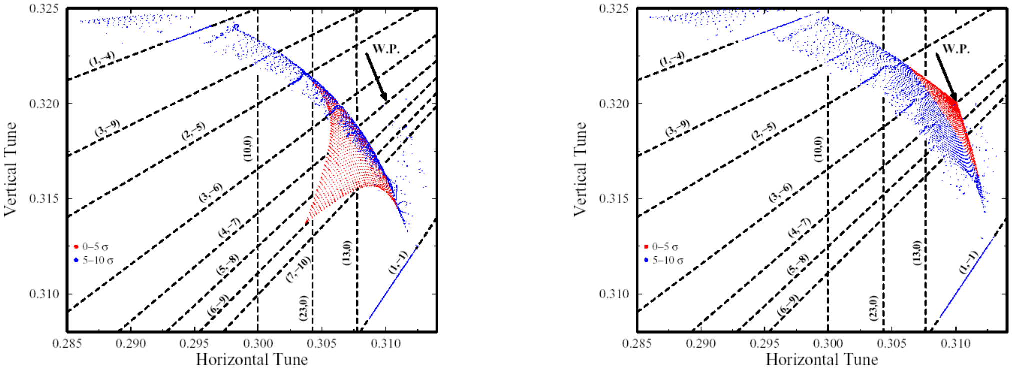
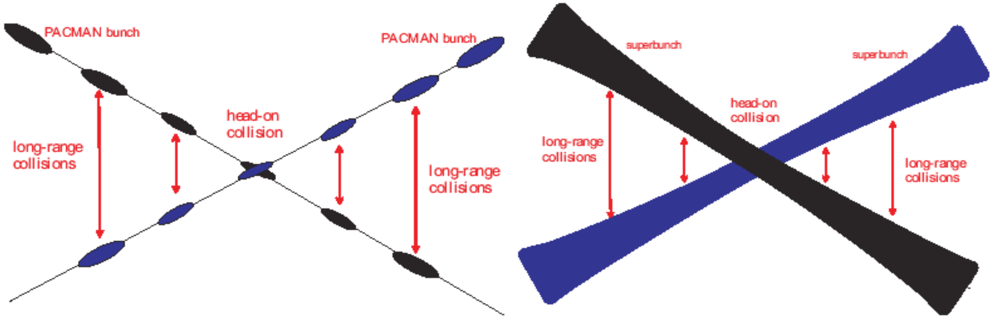


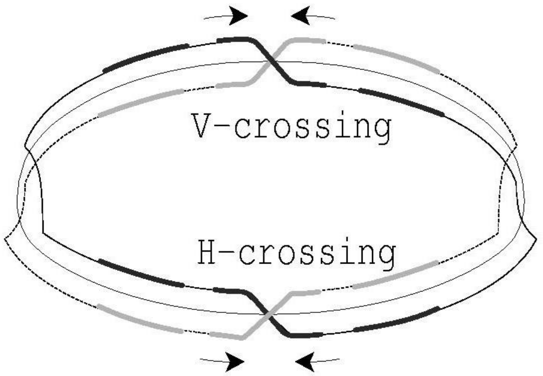
Figure 8: LHC tune footprints obtained with head-on and long-range collisions and triplet errors.

LHC luminosity upgrade: super-bunches and alternative crossing schemes

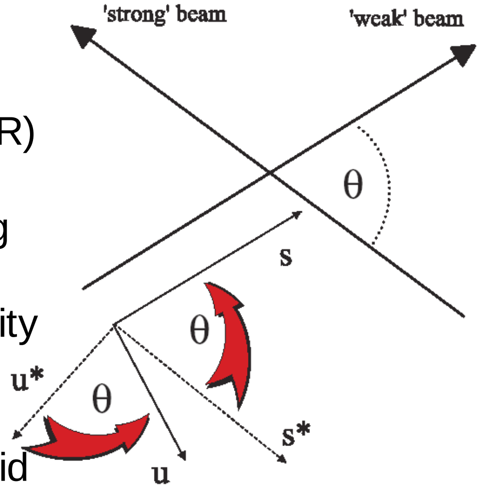
with F.Ruggiero, G. Rumolo and F.Zimmermann



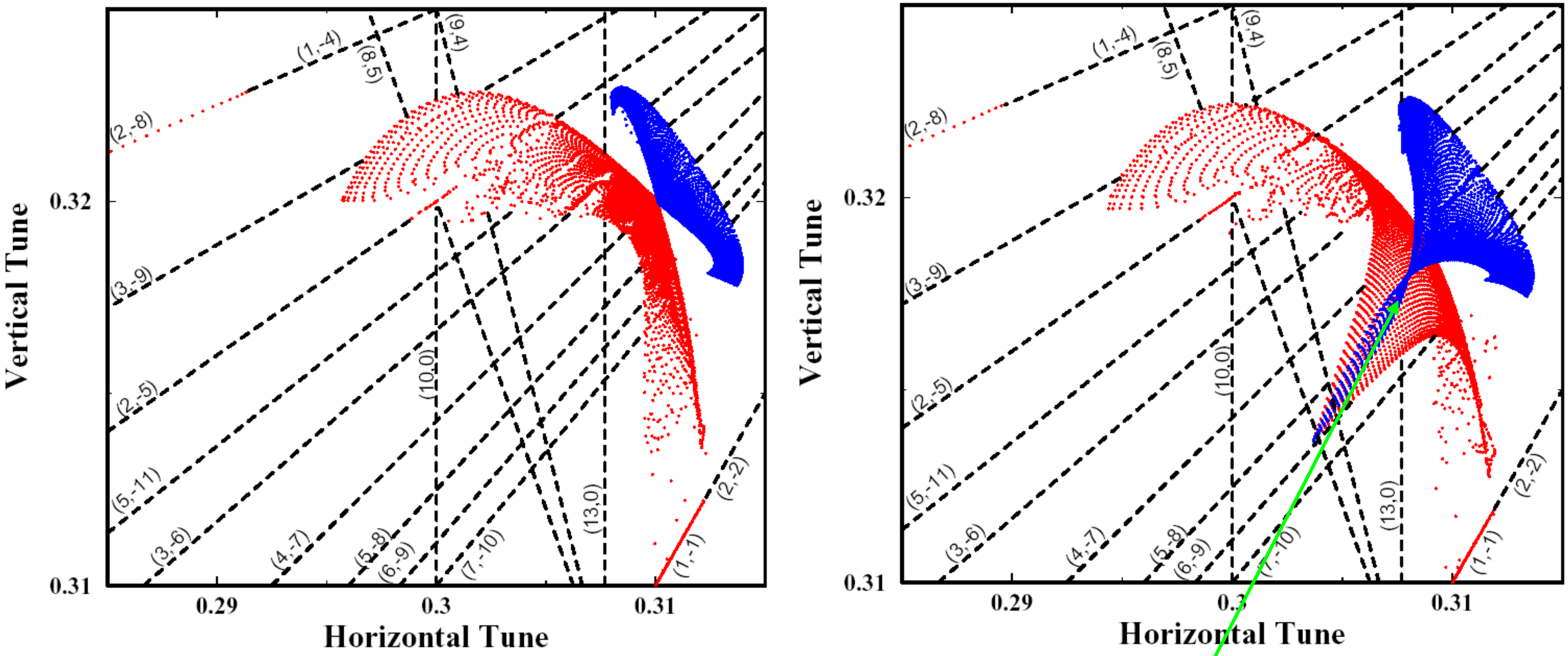
Left: Gaussian bunches (LHC); right: superbunches (LHC-II?)



- Luminosity increases by increasing the product of bunch length and crossing angle
- Second option: the use of long super-bunches (almost coasting beams, e.g. ISR)
- Advantages: i) Cancellation between head and long-range components of the beam-beam tune-shift, ii) Absence of PACMAN bunches iii) possibility of avoiding multipacting and e-cloud built up
- Disadvantages: enhanced radiation damage of the detector (increased luminosity and higher rate of reactions during the bunch crossing)
- Essential ingredient the alternating crossing of beams between the IPs i) Horizontal / vertical (LHC nominal) ii) 45º/135º between the planes (inclined hybrid crossing, foreseen for Tevatron RunIIb)&&

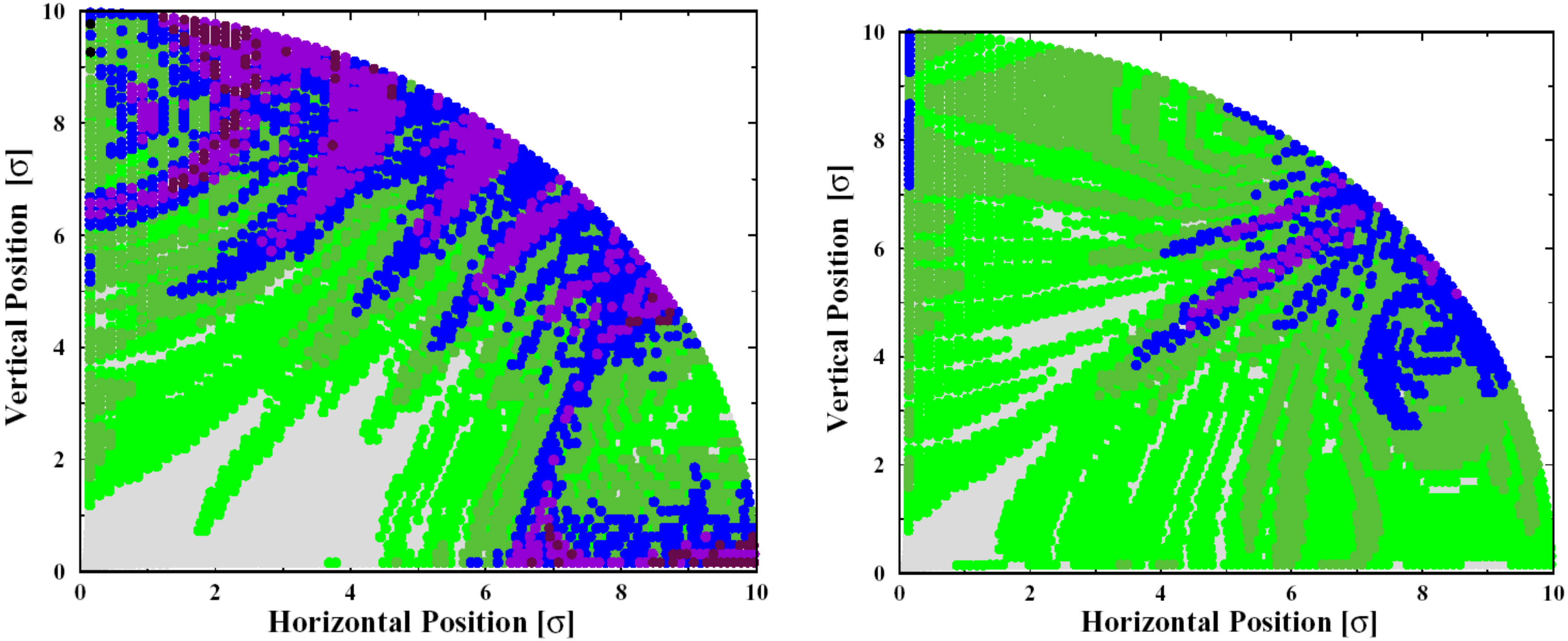


Frequency maps for inclined hybrid crossing



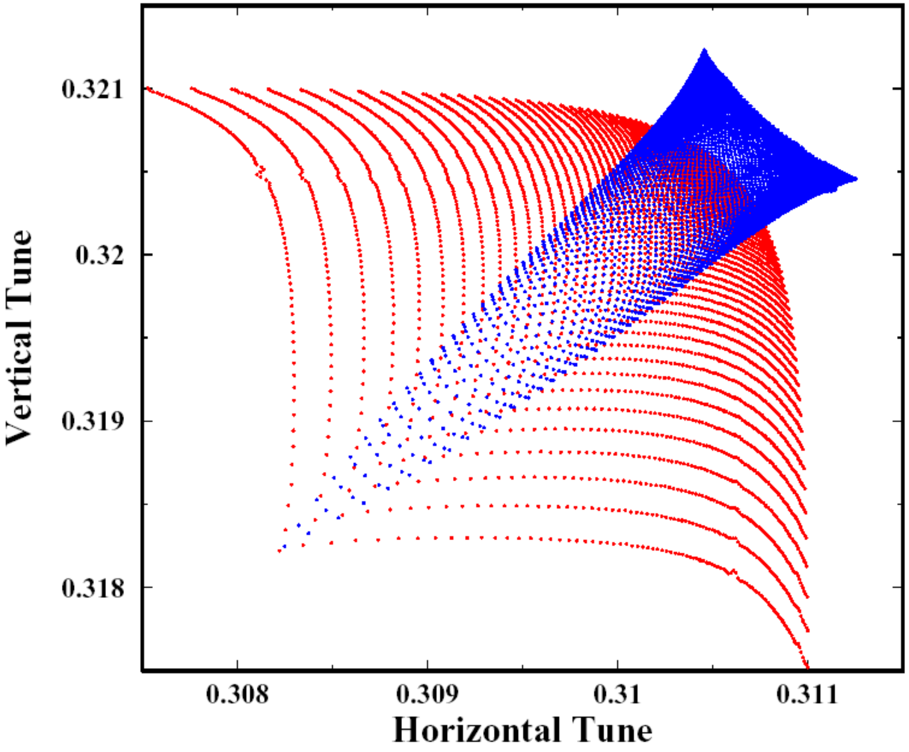
- The tune-shift with amplitude is much reduce with the inclined hybrid scheme (much less resonance crossing)
- Question about the change in the tune-shift direction

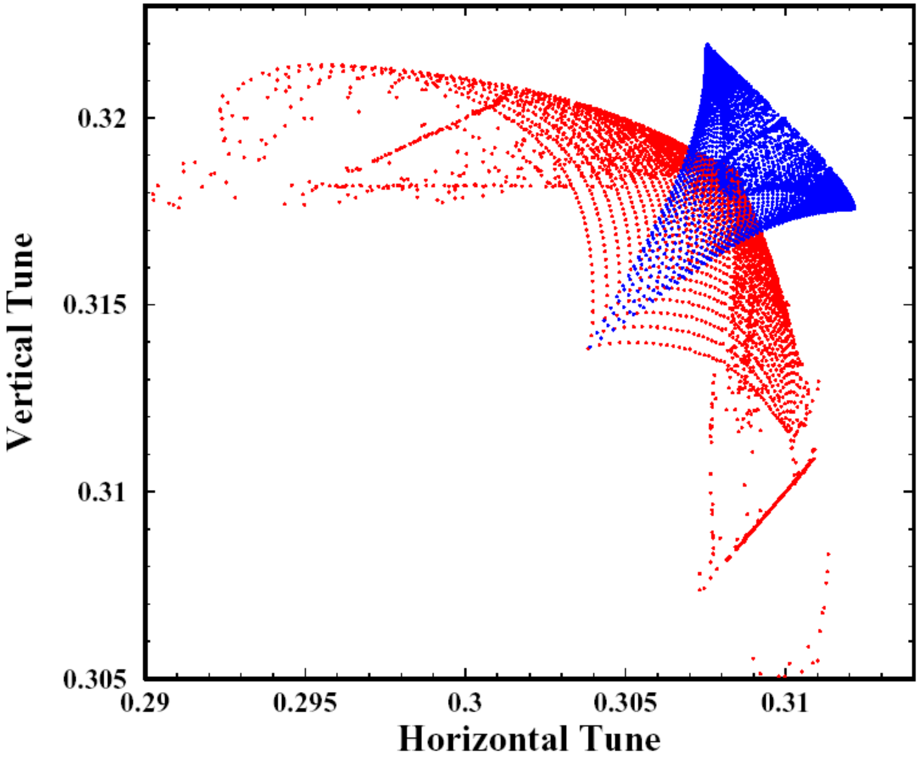
Diffusion maps comparison



- Diffusion maps confirm that the inclined hybrid crossing is better with respect to non-linear beam dynamics

Diffusive aperture and frequency maps for super-bunches





- The tune-shift with amplitude is much reduce with the inclined hybrid scheme (much less resonance crossing).
- Crossing angle of 1000µrad much better than 423µrad

Frequency maps and collective beam dynamics: the e-cloud effect

with E.Benedetto et al.

- E-cloud can lead to emittance blow up
- Understand the non-linear dynamics of protons under the influence of the electron potential
  - Freeze the electron potential issued by a multi-particle simulation
  - Integrate the equations of motions of protons under the influence of this potential

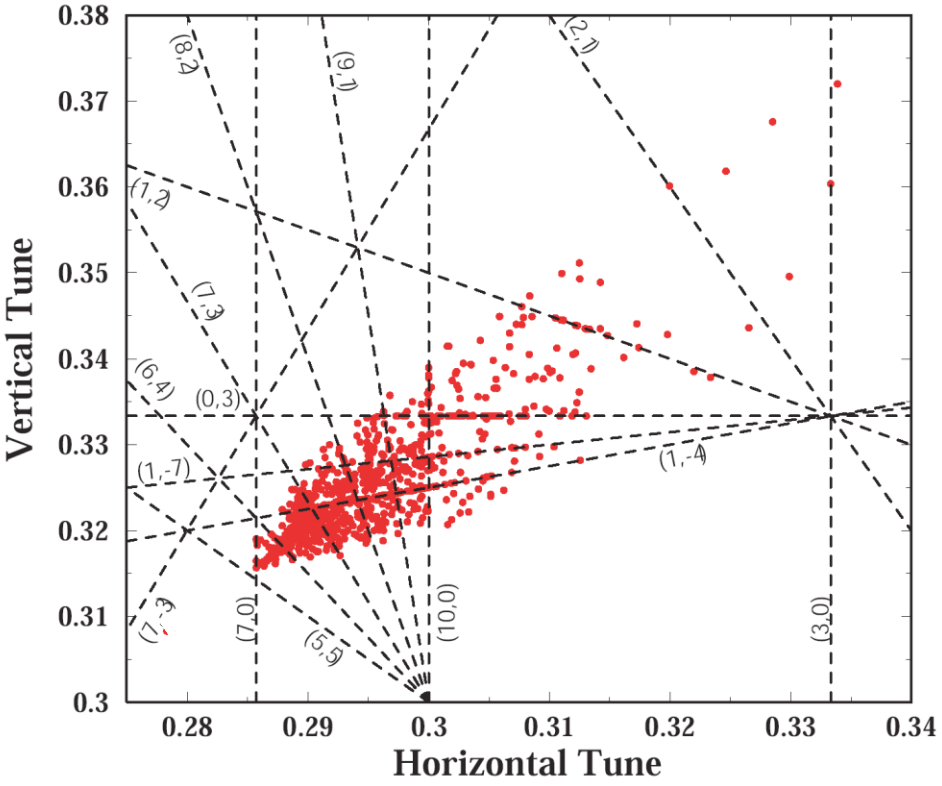


Figure 8: Tune footprint obtained from tracking through a frozen electron potential with 1 IP per turn by a frequency-map analysis [8].

SNS Performance Goal

Average Beam Power to the target (2MW)

Key Issue: Low losses for reducing radio-activation

Combination of

Collective instabilities (space-charge, electron cloud,…)

Intensity dependent

Magnet non-linearities (chromaticity, fringe-fields, magnet errors)

Emittance, mom. spread dependent

Expected Tune-shifts

Mechanism	**Tune-shifts**
Space Charge (2MW beam)	0.15-0.20
Chromaticity ($\delta p/p=1\%$)	±0.08
Quadrupole fringe-field	0.025
Uncompensated magnet errors	±0.02
Compensated magnet errors	±0.002
Chromatic Sextupoles	±0.002
Fixed injection chicane	0.004
Injection painting bump	0.001

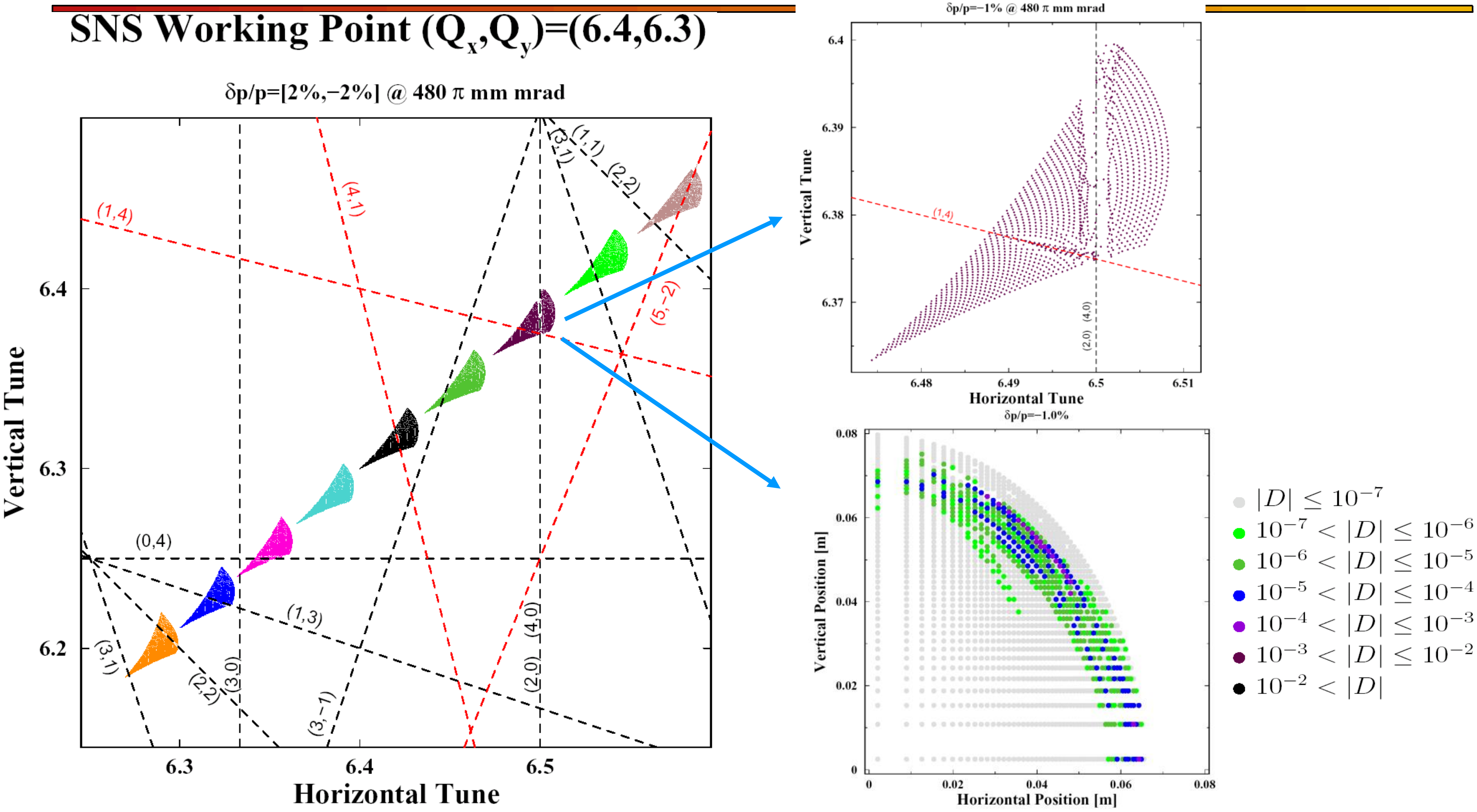
480 π mm mrad

Frequency and Diffusion Maps for the SNS Ring

- Model includes
  - Magnet fringe-fields (5th order maps)
  - Magnet systematic and random errors (10^{-4} level)
  - 4 working points, with and without chromaticity correction
  - No RF, no space-charge
- Single particle tracking using FTPOT module of UAL
  - 1500 particles uniformly distributed on the phase space up to 480 π mm mrad, with zero initial momentum, and 9 different momentum spreads (-2% to 2%)
  - 500 turns

$$\mathcal{F}_\tau \; : \begin{array}{ccc} \mathbb{R}^2 & \longrightarrow & \mathbb{R}^2 \\ (I_x, I_y)|_{p_x, p_y = 0}, & \longrightarrow & (\nu_x, \nu_y) \end{array}$$

Working point (6.4,6.3)

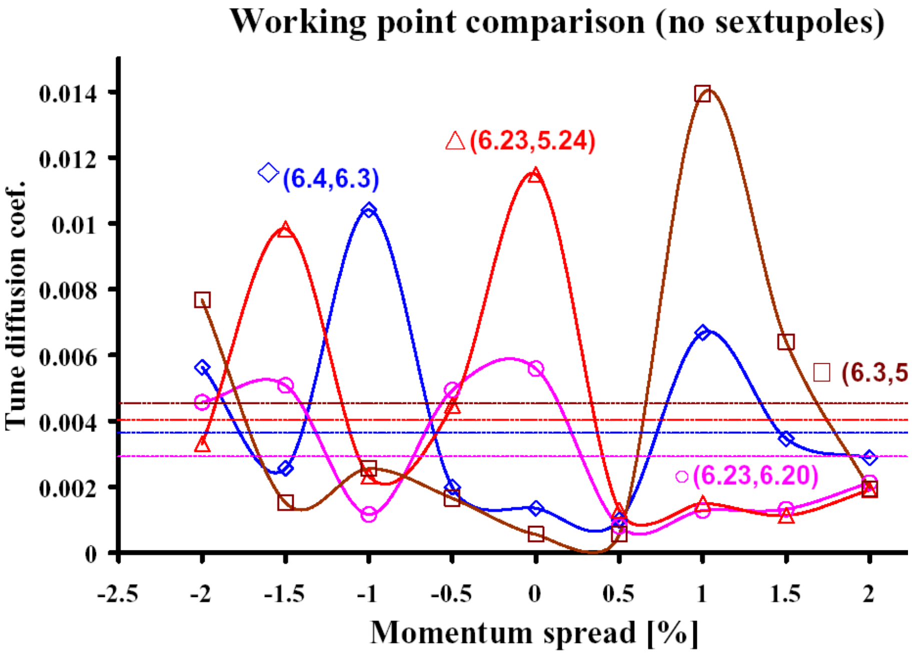


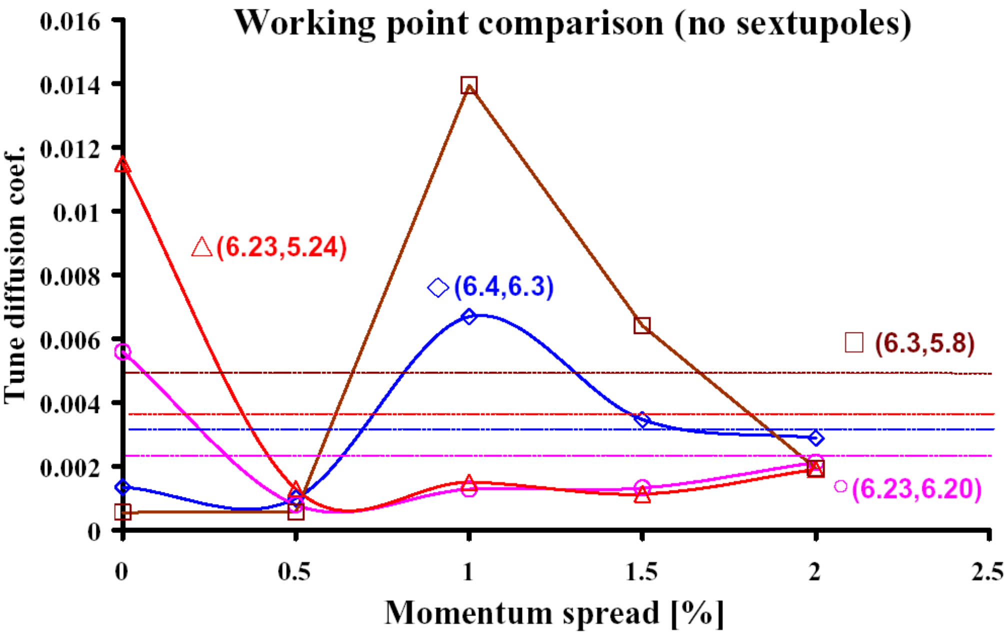
SNS Working Point $(Q_x,Q_y)=(6.4,6.3)$

Working Point Comparison

Tune Diffusion quality factor

$$D_{QF} = \left\langle \frac{|D|}{(I_{x0}^2 + I_{y0}^2)^{1/2}} \right\rangle_R$$



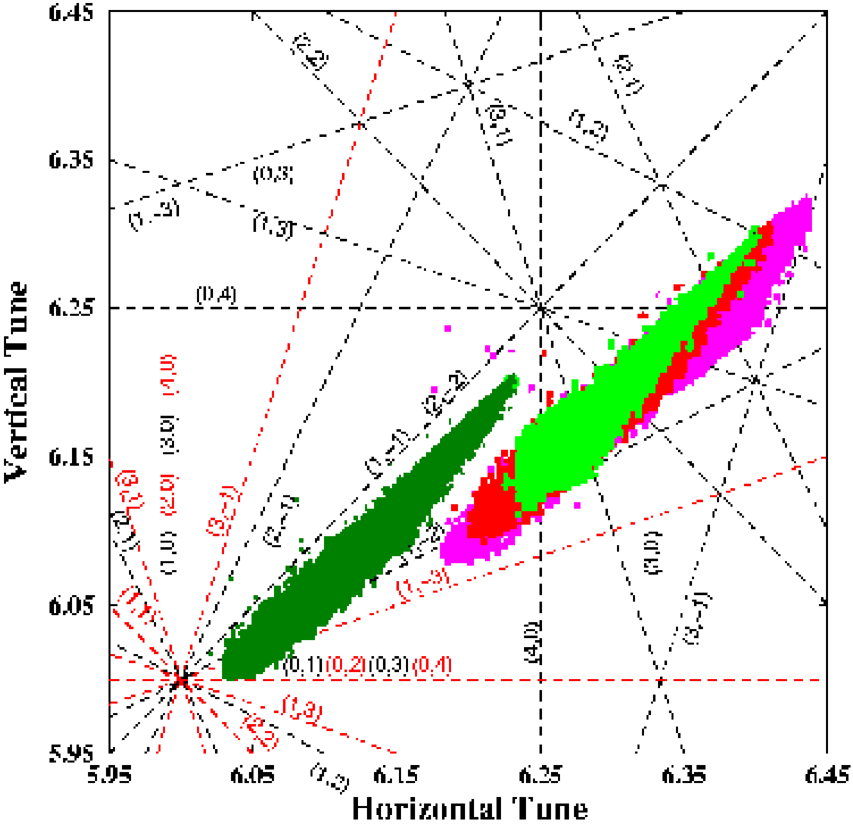


Working Points (6.40,6.30) - (6.23,6.20)

with A.Fedotov et al.

Identification of resonances for new working points

SNS Working Points



N	Resonances	Type	Perturbation	Correction
2	(2,0) (0,2)	Normal quadrupole	Quadrupole errors & misalignement	Quad TRIMS
2	(1,-1)	Skew quadrupole	Magnet Tilt - Space charge	Skew Quad. round beam
3	(3,0) (1,2) (1,-2)	Normal sextupole	Sextupole errors in dipoles	Sextupoles
3	(2,1) (2,-1) (0,3)	Skew sextupole	Magnet skew sextupole error	Skew Sext.
4	(4,0) (2,2) (2,-2) (0,4)	Normal octupole	Quadrupole fringe-fields, space-charge	Octupoles
4	(3,1) (3,-1) (1,3) (1,-3)	Skew octupole	Magnet errors	None