Beam Loss Simulations at injection plateau

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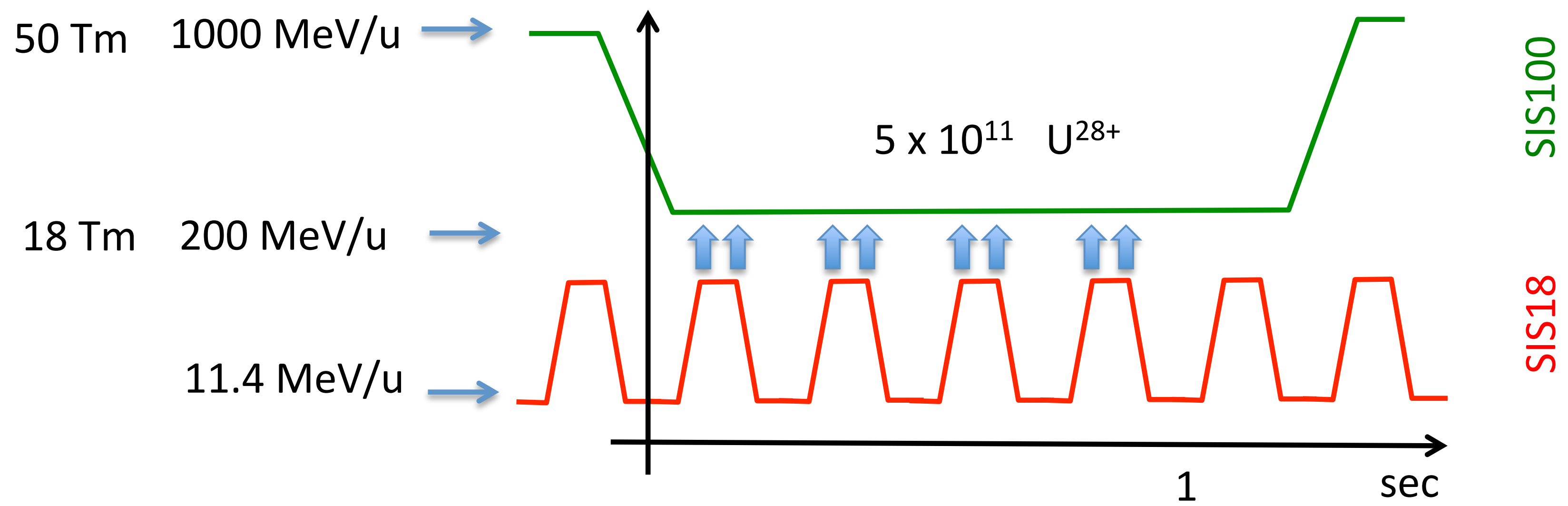
Overview

- **SIS100 injection plateau scenario**
- **Beam Loss Mechanism Mechanism**
- **Beam Loss Prediction for SIS100**
- **Improving Beam Loss**
- **Robustness of the correction scheme**
- **Next Step: Verification in SIS18**
- **Conclusion and Final Remarks**

SIS100 injection plateau scenario



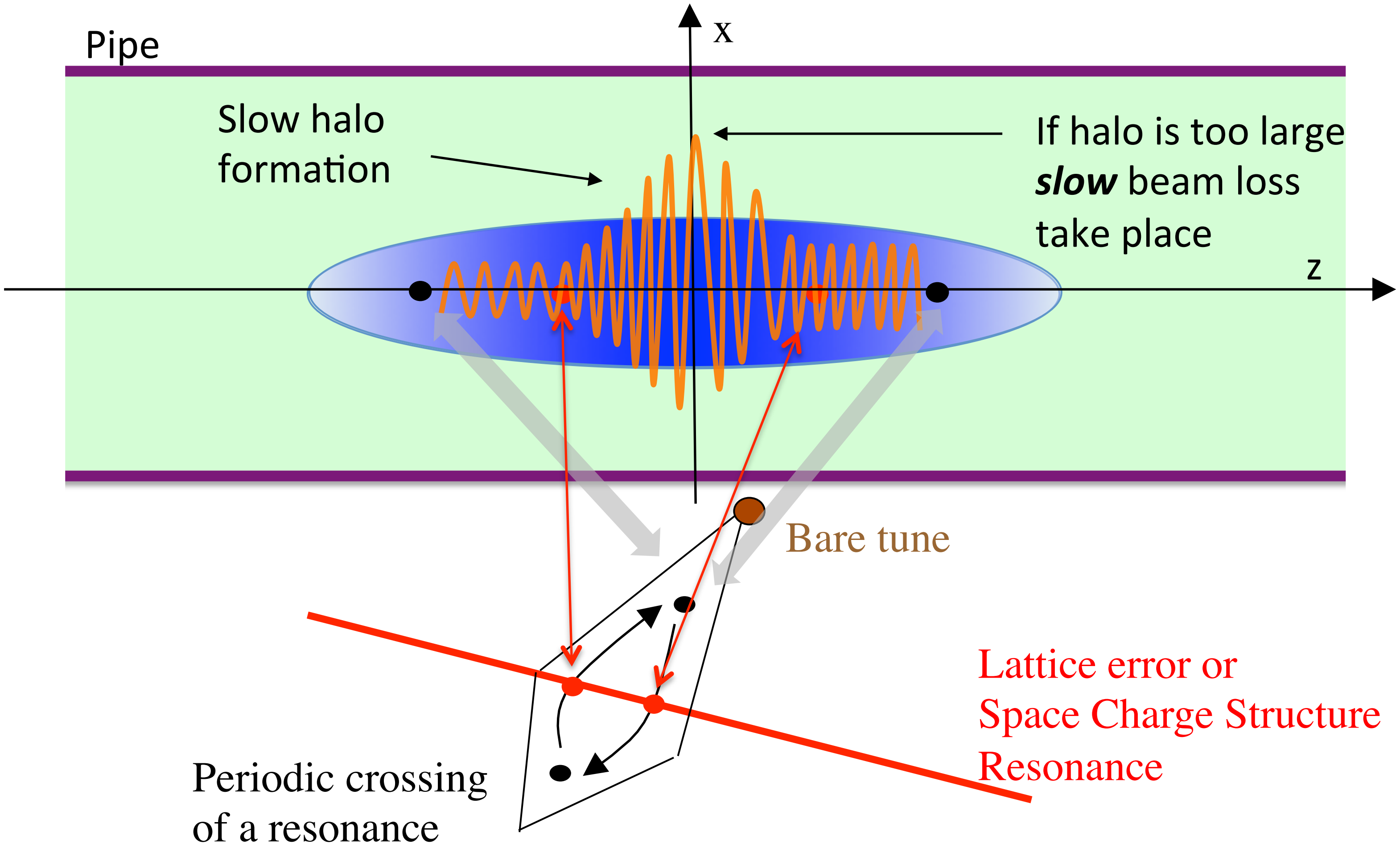
First bunch @ 200 MeV/u

Nominal N_{ions} = 6.25 x 10^{10}/bunch
Beam1: $\varepsilon_{x/y}$ = 35/15 mm-mrad (2σ) $\Delta Q_{x/y}$= -0.21/-033
Beam2: $\varepsilon_{x/y}$ = 50/20 mm-mrad (2σ) $\Delta Q_{x/y}$= -0.15/-0.24
Turns = 1.57 x 10^5 (1 sec.)

Problem of control of beam loss for the bunched beams in SIS100 during 1 second

BEAM LOSS MECHANISM

Mechanism of beam loss



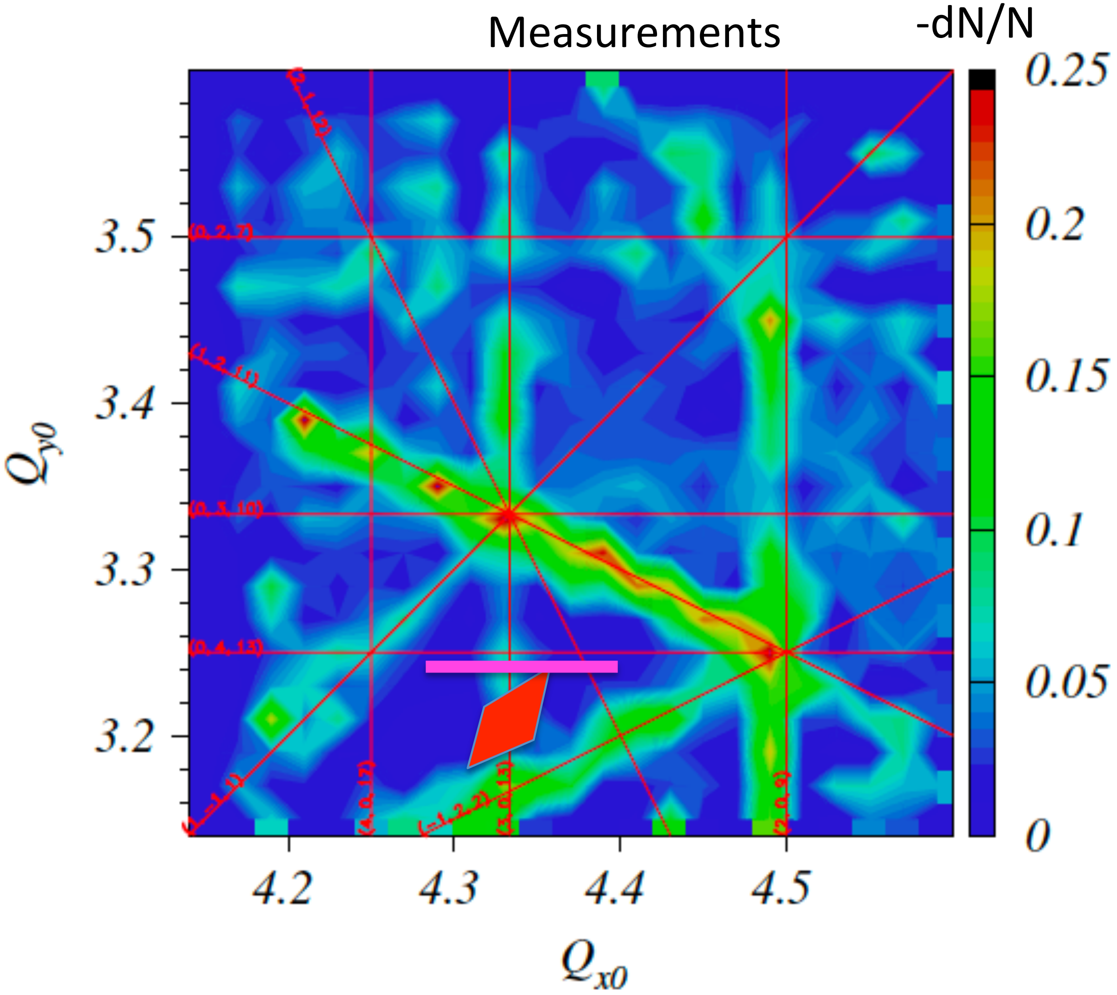
Key ingredients

1) Space charge tune-spread
2) Lattice Resonance
3) Longitudinal motion (bunched beam)

Halo amplitude and speed of halo formation has a complex dependence from

1) Space charge incoherent tune-shift
2) Position of bare tune with respect to the resonance
3) Strength of the resonance
4) Longitudinal profile

Experimental verification in SIS18



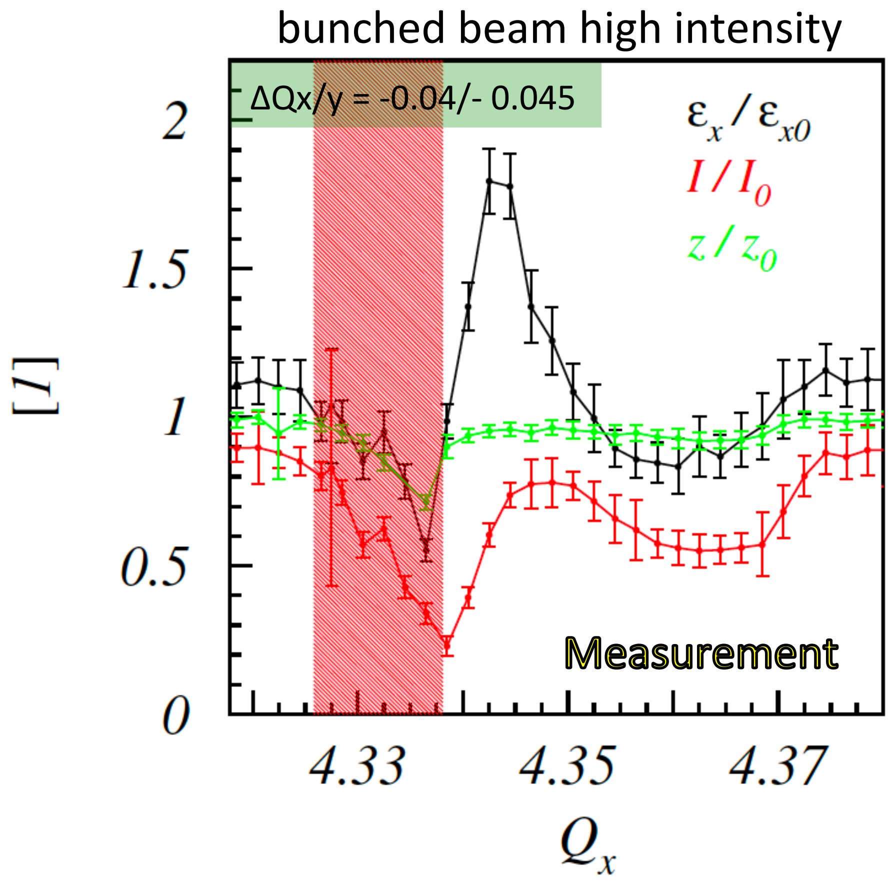
G. Franchetti et al., GSI-Acc-Note-2005-02-001

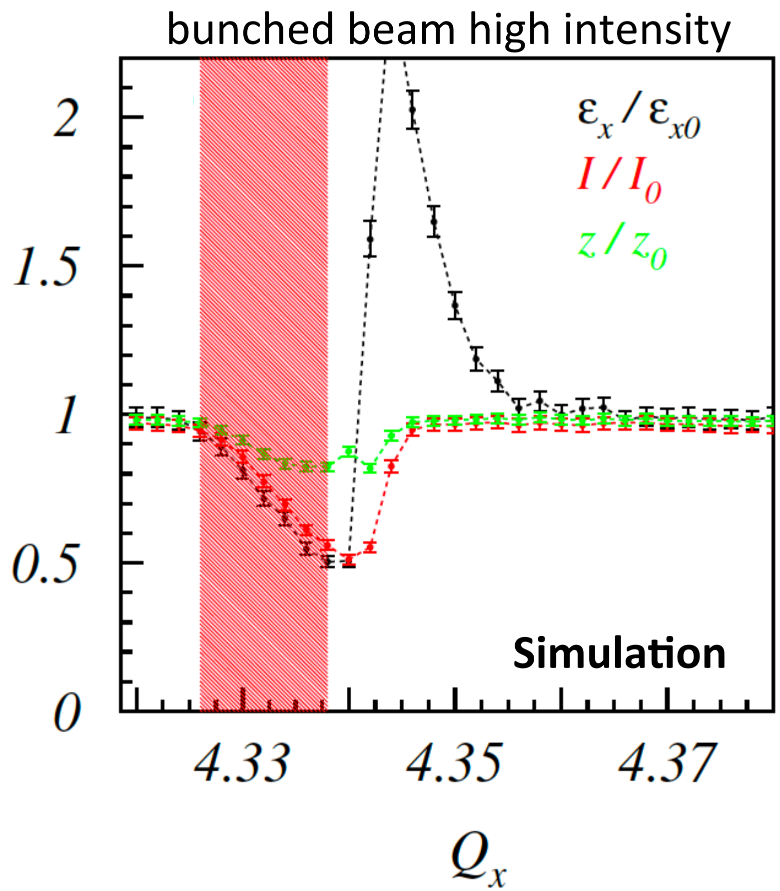
TABLE I. Typical parameters of SIS18 and of the ion beam used.

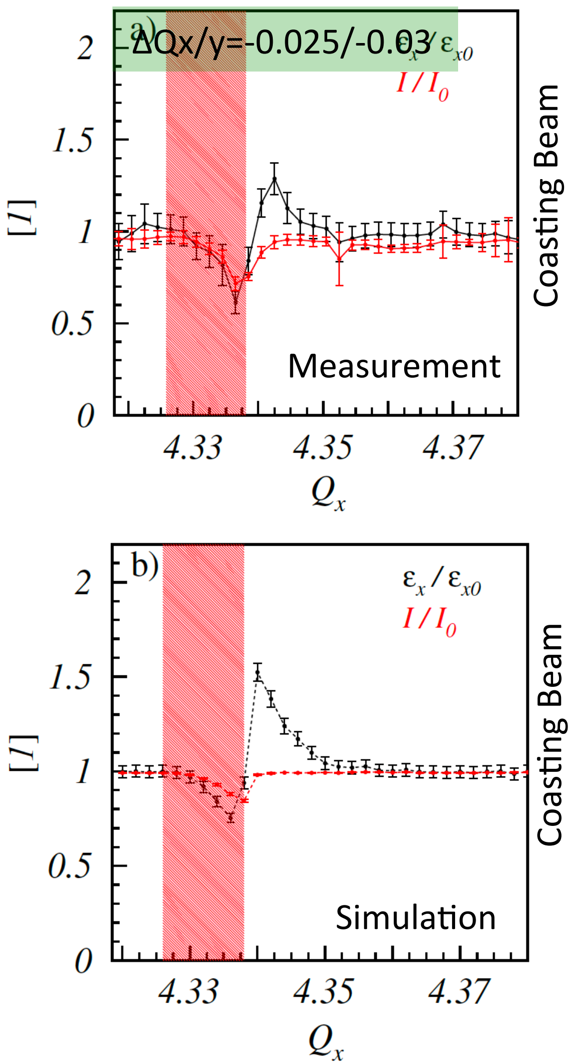
Parameter	Value	Units
Energy per nucleon	11.28	MeV/u
Ion mass number	40	
Ion charge state	18	
rf harmonics	4	
rf voltage	4	kV
Total particles per bunch	3.125×10^8	
Gamma transition	5.01	
Rigidity	1.077	Tm
SIS18 circumference	216.1	m
Average β_x	~8	m
Average β_y	~10	m
Revolution time	4.673	μs
Eta transition	0.9362	
Synchrotron tune	6.915×10^{-3}	
Bunching factor	0.3357	
Rms momentum spread	1.3×10^{-3}	
Bunch length 4σ	560	ns
Maximum $\delta p/p$ in the bucket	7.4×10^{-3}	
Horizontal emittance at 2σ	19	mm mrad
Vertical emittance at 2σ	14	mm mrad
Horizontal peak tune shift	-4×10^{-2}	
Vertical peak tune shift	-4.5×10^{-2}	

Experimental verification in SIS18

G. Franchetti, O. Chorniy, I. Hofmann, W. Bayer, F. Becker, P. Forck, T. Giacomini,
M. Kirk, T. Mohite, C. Omet, A. Parfenova, and P. Schuett PRSTAB **13**, 114203 (2010)







Simulations made with MICROMAP library

- Full linear and nonlinear optics;
- Symplectic tracking;
- Frozen space for long term tracking: analytic Model for a Gaussian Transverse-Longitudinal beam distribution;
- PIC available, but not used for 10^5 turns (!) for avoiding noise effects on beam.

The library has been tested against codes
for the self-consistent part
+
Tested against the SIS18 measurements (benchmarking)

SUMMARY

Experimental evidence show that slow beam loss takes place
only when the following 3 elements are simultaneously present

1) Space charge tune-spread
2) Lattice Resonance
3) Longitudinal motion (bunched beam)

MICROMAP predicts beam loss a factor 2 less than real beam loss

BEAM LOSS PREDICTION FOR SIS100

SIS100 Modeling

1) Linear Lattice
2) All insertions (i.e. each element sizes + all septums, NO Collimators)
3) Each magnet has nonlinear field modeled via 3 localized nonlinear kicks of the systematic errors
4) Displacement of quadrupoles is modeled by insertion of a dipolar kick in center of quadrupole
5) Inclusion of all magnet correctors: steerers and sextupole for chromatic correction and resonance corrector sextupoles (in addition with quadrupoles and octupoles)

Magnet design: CSLD *Pavel Akishin, Anna Mierau, Pierre Schnizer, Egbert Fischer 3. June 2010*

Magnet multipoles: V.Kapin, P. Schnizer, A. Mierau
Kapin, V.; Franchetti, G. ACC-note-2010-004

Lattice: J. Stadlmann, A. Parfenova, S.Sorge

SIS100 magnet nonlinearities

Multipoles in magnets up to order 15:
nonlinear kick in Entrance Body Exit

EXAMPLE

Dipole: Body

Quadrupole: Body

```
!================== the dipole model 25/6/2010 ==========================

!SIS100_Dipole_CSLD8b
!"Rogovsky_I1_1319kA_Cntr_Bpho_Tm_10.17_CO_xy_p0.0_p0.0_mm"
!"data_hdf/SIS100_Dipole_CSLD_Harmonics_20100609.h5:
! /Dipole/D3/Curved/CSLD8b/Rogovsky_Profile/"
MDC0   MULTIPOLE  -4.8321734468527902E-02  -8.0460622403658862E-11   0
MDC1   MULTIPOLE   1.3222876973075998E-06  -4.4286349322627113E-09   1
MDC2   MULTIPOLE  -1.5411882617349000E-02  -2.6132592908204184E-07   2
MDC3   MULTIPOLE  -3.7034493848285333E-03  -1.8587012098560845E-05   3
MDC4   MULTIPOLE   4.5506880778861124E+01   2.9261019441204273E-04   4
MDC5   MULTIPOLE  -6.2559995183645212E+00   2.3583431753596007E-01   5
MDC6   MULTIPOLE   7.3051033143311797E+04  -1.4162812922709435E+02   6
MDC7   MULTIPOLE  -1.4288951062831108E+05  -3.4965239042733432E+04   7
MDC8   MULTIPOLE   2.2831975374350262E+09   1.0324892588690210E+07   8
MDC9   MULTIPOLE   1.0564506501167362E+10   2.9113326625993242E+09   9
MDC10  MULTIPOLE  -1.6359949140068581E+14  -7.0591807199292908E+11   10
MDC11  MULTIPOLE  -6.9868819985378656E+13  -2.1251269228490359E+14   11
MDC12  MULTIPOLE   2.5207268897163274E+18   3.4255809404212480E+16   12
MDC13  MULTIPOLE   1.6101150642536155E+19   1.1090489334002389E+19   13
MDC14  MULTIPOLE  -2.2667622204271218E+23  -9.5935636945850047E+20   14
MDC15  MULTIPOLE  -8.9215833271142267E+22  -3.2804988706914617E+23   15
```

```
!====================== model of quadrupole 25/6/2010 ======================

!SIS100_Quadrupole6Turn
!"Quad6TurnsV1_I1_460kA_Cntr_Bpho_Tm_12.23_CO_xy_p0.0_p0.0_mm"
!"data_hdf/SIS100_Quadrupole6Turn_20100623.h5:
! /Quadrupole/Turns6/D3/OperaCalc/StaticCalculation/V1/"
Eqb0   MULTIPOLE  -2.6789881018894428E-14   5.5045898388867806E-14   0
Eqb1   MULTIPOLE   2.1717022154679769E-01   1.9856320529300420E-12   1
Eqb2   MULTIPOLE  -9.4521226576819973E-11   1.9401448718616971E-10   2
Eqb3   MULTIPOLE   3.7858283188846437E-03   1.0501181037334316E-08   3
Eqb4   MULTIPOLE   7.0414842692841817E-07  -1.4318783375984776E-06   4
Eqb5   MULTIPOLE   3.0194294633632222E+02  -2.8051263507461471E-04   5
Eqb6   MULTIPOLE  -7.8478544512944073E-02   1.6019533278747095E-01   6
Eqb7   MULTIPOLE  -1.8269515944715394E+06   2.5709785026550517E+01   7
Eqb8   MULTIPOLE   4.7775705574752483E+03  -9.7507153716628163E+03   8
Eqb9   MULTIPOLE   1.5853417177689340E+11  -1.7429770135777944E+06   9
Eqb10  MULTIPOLE  -2.5512932132258266E+08   5.2083611876728094E+08   10
Eqb11  MULTIPOLE  -6.9973814030639240E+15   9.9896489034391388E+10   11
Eqb12  MULTIPOLE   9.8111951662325020E+12  -2.0032780989903805E+13   12
Eqb13  MULTIPOLE   1.2725759662788647E+20  -4.1250219682152360E+15   13
Eqb14  MULTIPOLE  -2.1305597834814832E+17   4.3518970770377338E+17   14
Eqb15  MULTIPOLE  -8.7801330870650991E+23   9.4854103306132488E+19   15
```

SIS100 working point and lattice resonances

Resistive wall instability

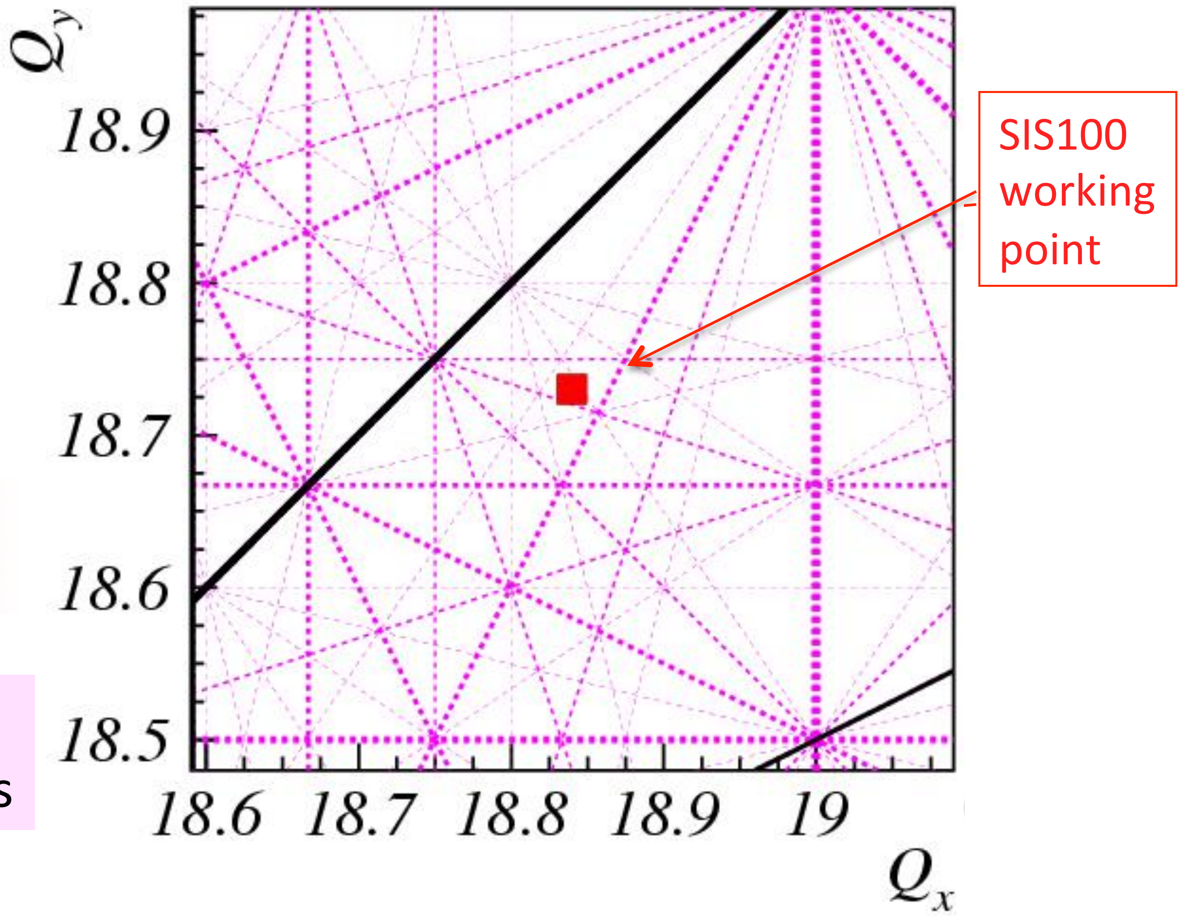
Montague stop-band must be avoided

Space charge induced periodic resonance crossing

Systematic resonances

Random resonances

Qx = 18.84, Qy = 18.73



I.Hofmann,G. Franchetti, GSI report 2005
G. Franchetti et al., EPAC 2006

Random Errors and COD

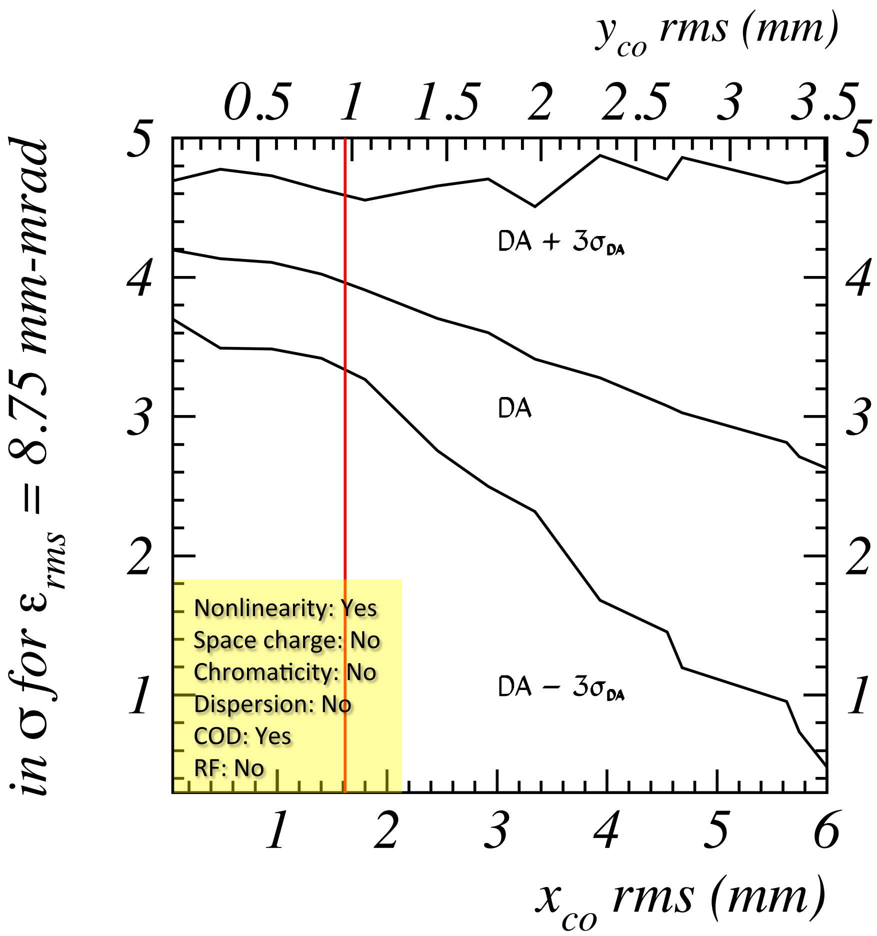
In order to predict beam loss we have to consider the effect of random deviation of systematic multipolar components in magnets

We call "seed" one sequence of random errors in SIS100 magnets + COD

Random error: Taken as 30% of the systematic component (Gaussian distribution)

COD: is obtained by adding a thin dipole in the quad of random strength δK_0 = 1.6 x10^{-5} rad.
This value is consistent with a rms COD of 1mm obtained after correcting the closed orbit deformation

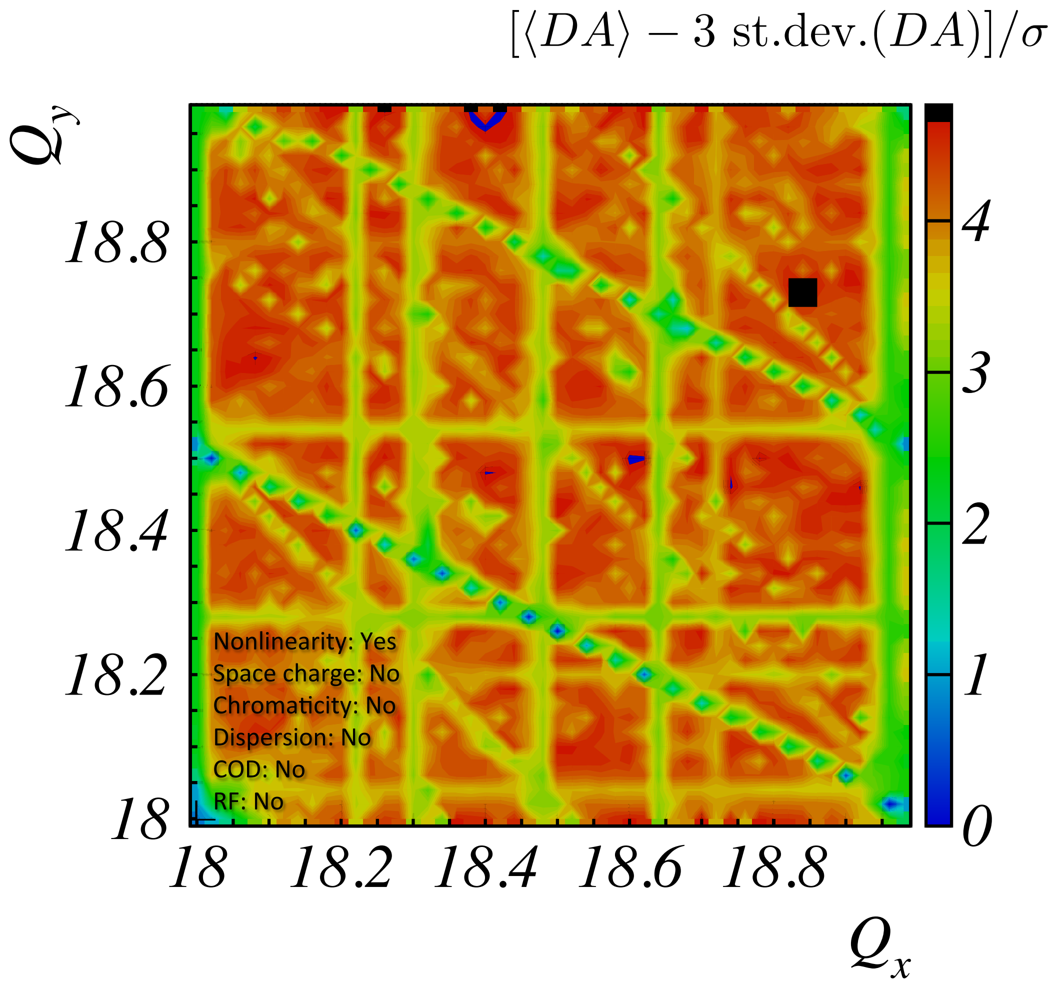
Effect of random error and COD



In absence of random error
DA = 4.8 σ

Random errors, DA, and Resonances

Statistical view of the possible resonances



Short term DA (1000 turns)

Average DA – 3 standard dev !

Statistics on 30 error seeds of random errors and quadrupoles displacement

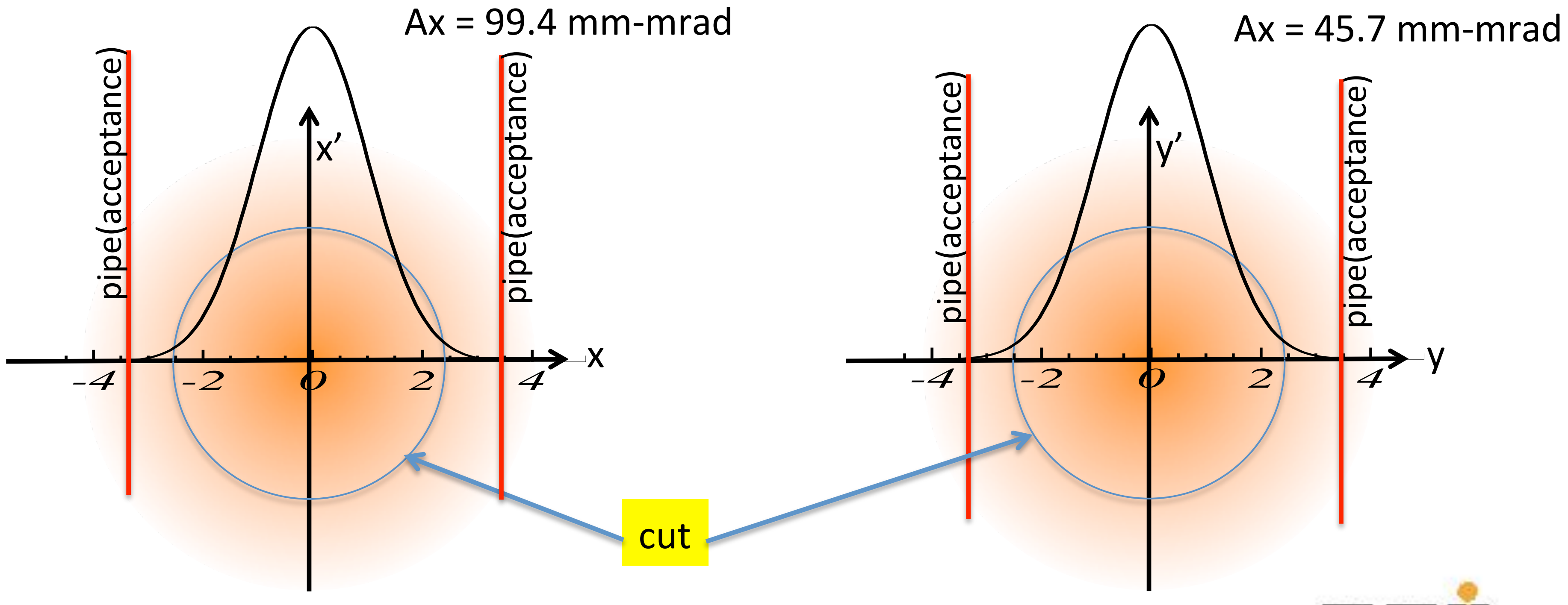
NO COD included in these simulations

Simulations: Beam Properties

The distribution is truncated in energy, in each plane, at 2.5 sigma

Beam1: $\varepsilon_{x2\sigma}$ = 35 mm-mrad, $\varepsilon_{y2\sigma}$ = 15 mm-mrad
Beam2: $\varepsilon_{x2\sigma}$ = 50 mm-mrad, $\varepsilon_{y2\sigma}$ = 20 mm-mrad

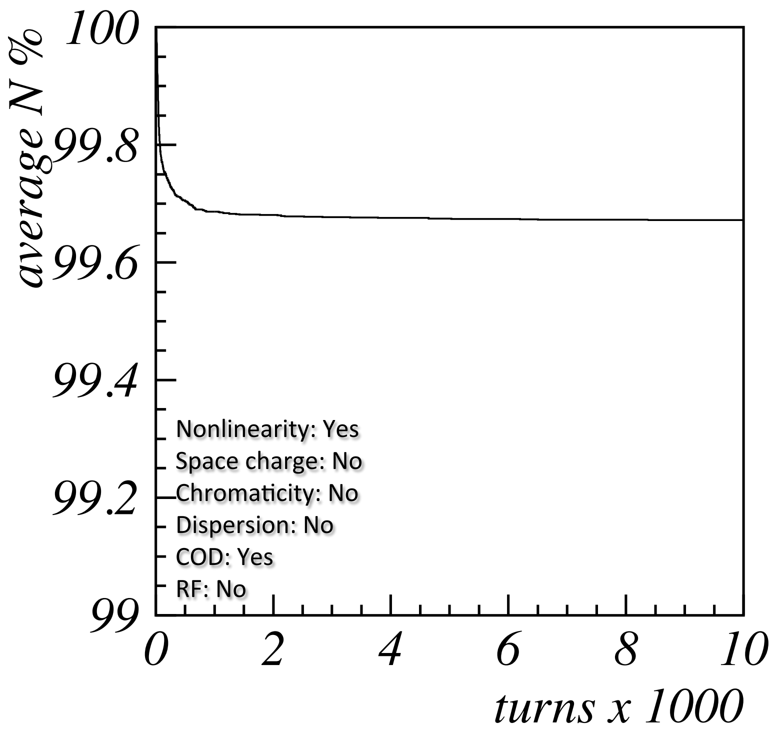
Particle distribution is Gaussian, matched with the lattice and injected 1mm off center

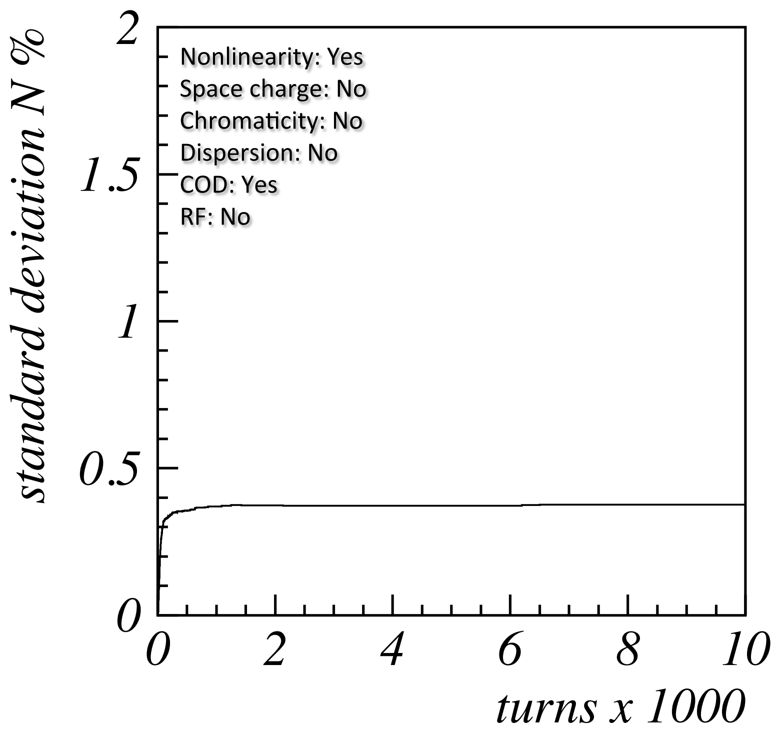


Identification of the "standard error seed"

Beam used: **Beam2**
5000 macro-particles
Statistics over 30 seeds

No Chromaticity
No Dispersion

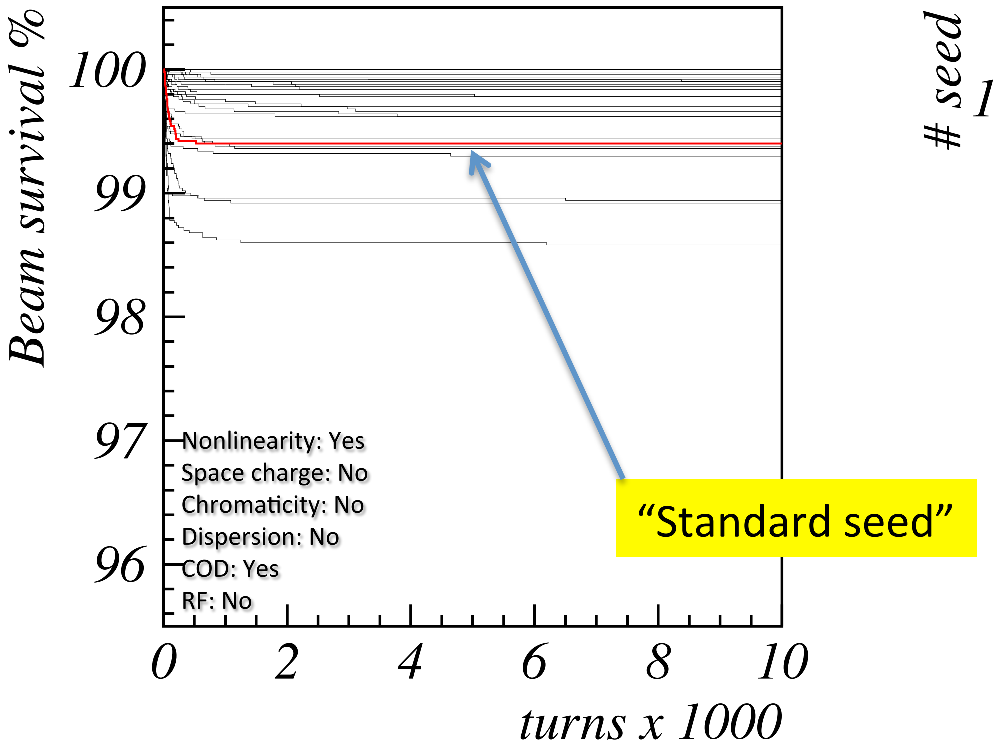




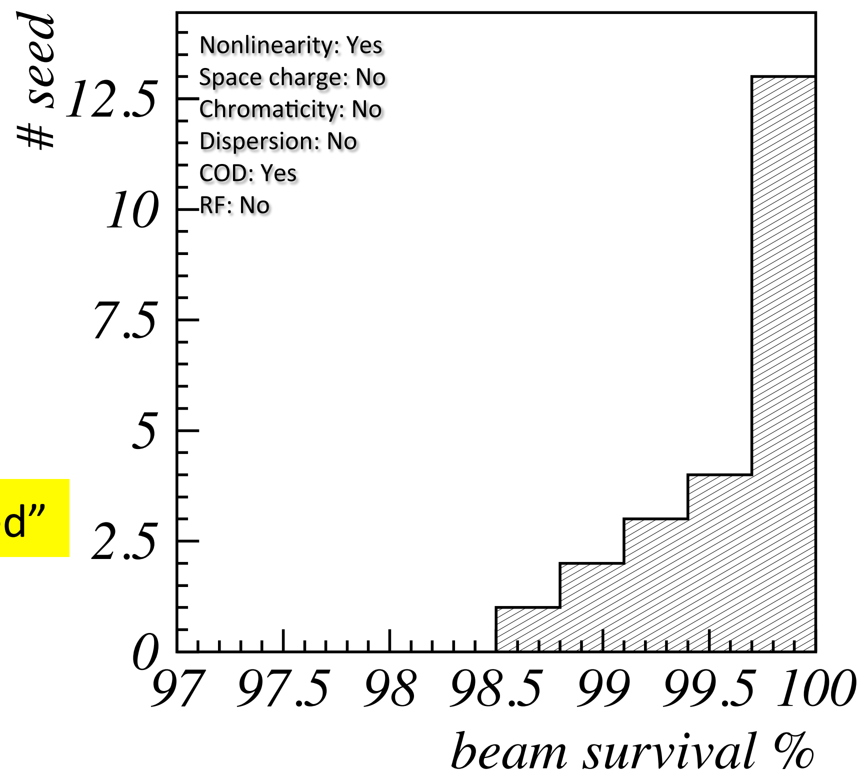
Choice of the "standard seed"

To select the error standard error seed we use the **Beam2** as a probe

Beam survival of all error seeds



Distribution of beam survival @ 10^4 turns

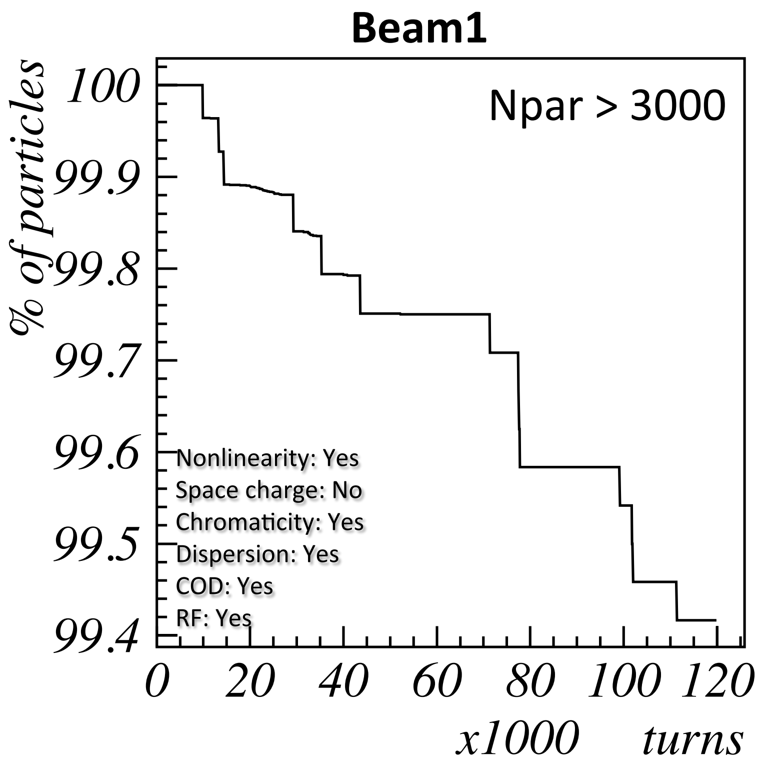


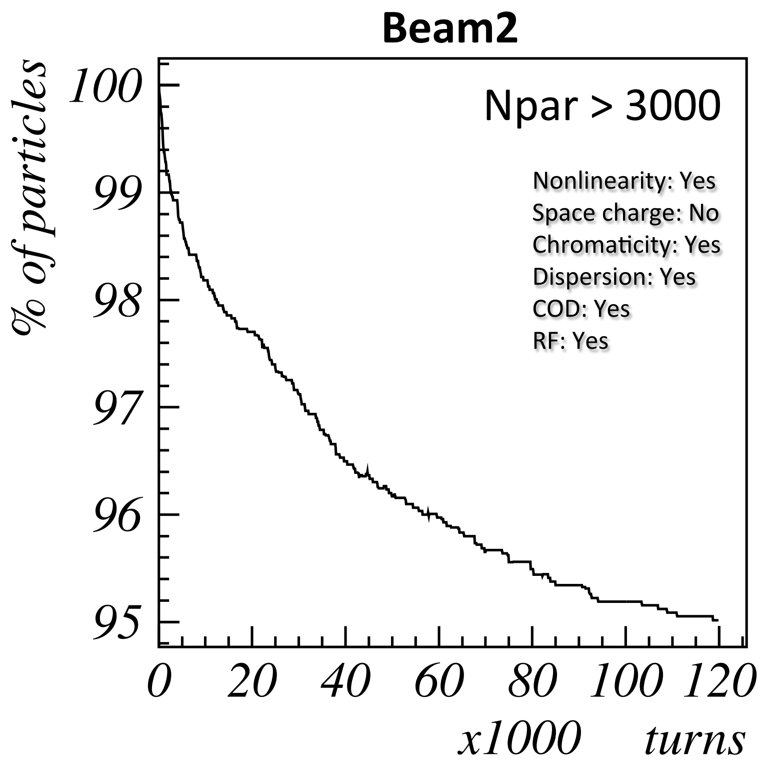
Check over full cycle length

bunch length +/- 90^0
Bf = 0.35

$(\delta p/p)_{rms}$ = +/- 5×10^{-4}
1/Qs = 233 turns

Simulation extended to 1.57×10^5 turns





Including space charge

We investigate here only Beam 1

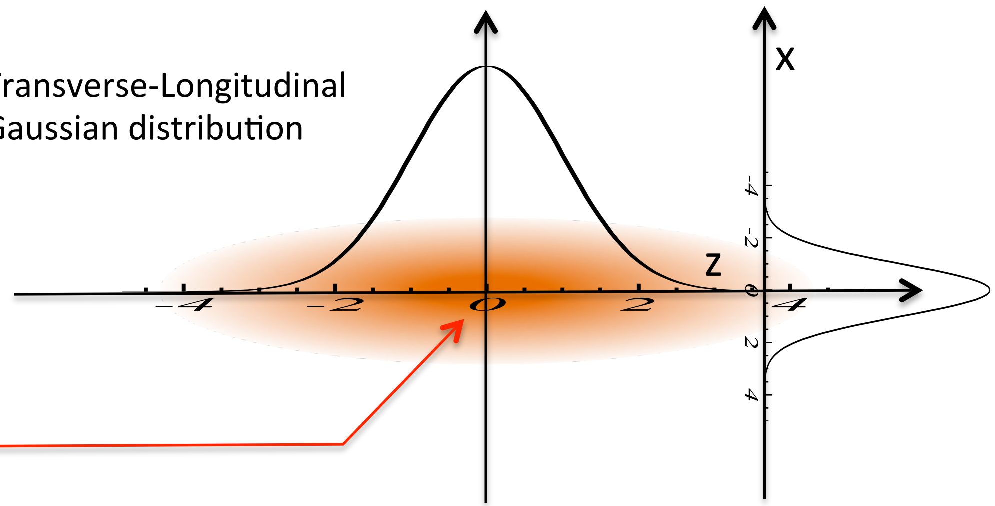
Beam1: $\Delta Q_{x/y}$ = -0.217 / -0.334 (-0.2106/ -0.371) @ 0.625x10^{11} particles per bunch
Beam2: $\Delta Q_{x/y}$ = -0.154 / -0.245 @ 0.625x10^{11} particles per bunch

From FFT in the code:
the difference stems from the effect of the optics on beam envelope

$$\Delta Q_{x,sc} = \frac{\bar{\beta}_x}{2} R_{acc} \frac{K_{peak}}{\sqrt{\bar{\beta}_x \epsilon_x}(\sqrt{\bar{\beta}_x \epsilon_x} + \sqrt{\bar{\beta}_y \epsilon_y})}$$

$$\Delta Q_{y,sc} = \frac{\bar{\beta}_y}{2} R_{acc} \frac{K_{peak}}{\sqrt{\bar{\beta}_y \epsilon_y}(\sqrt{\bar{\beta}_x \epsilon_x} + \sqrt{\bar{\beta}_y \epsilon_y})},$$

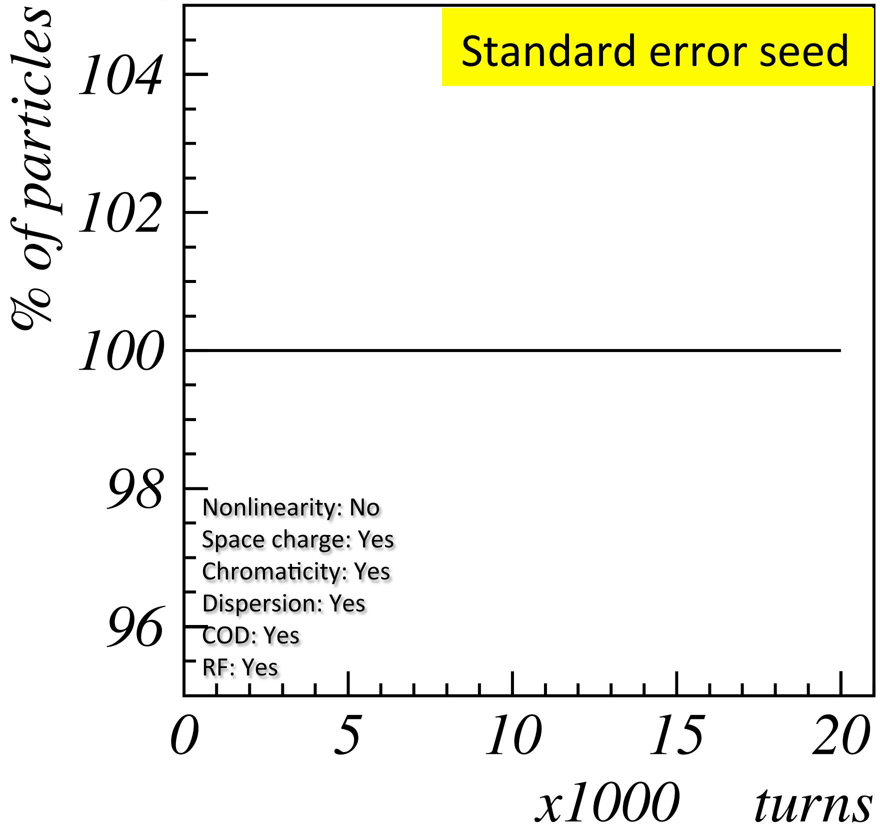
Transverse-Longitudinal Gaussian distribution



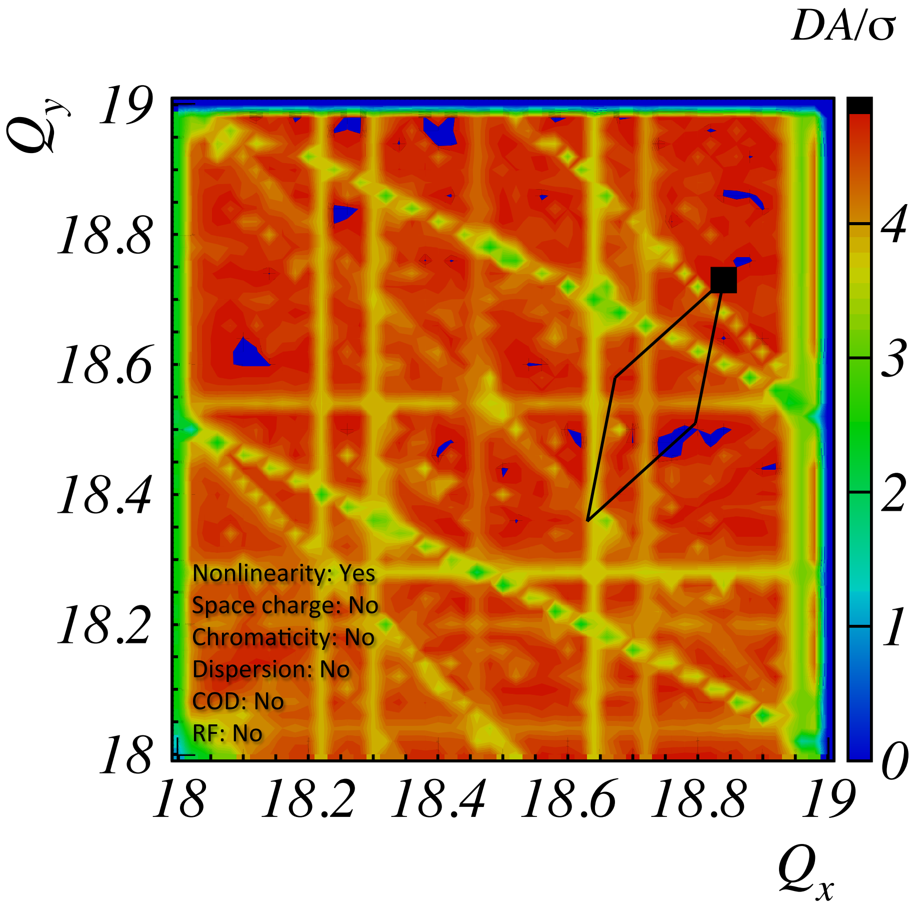
Tuneshift

Does the space charge create a trouble without nonlinearities ?

Answer: NO



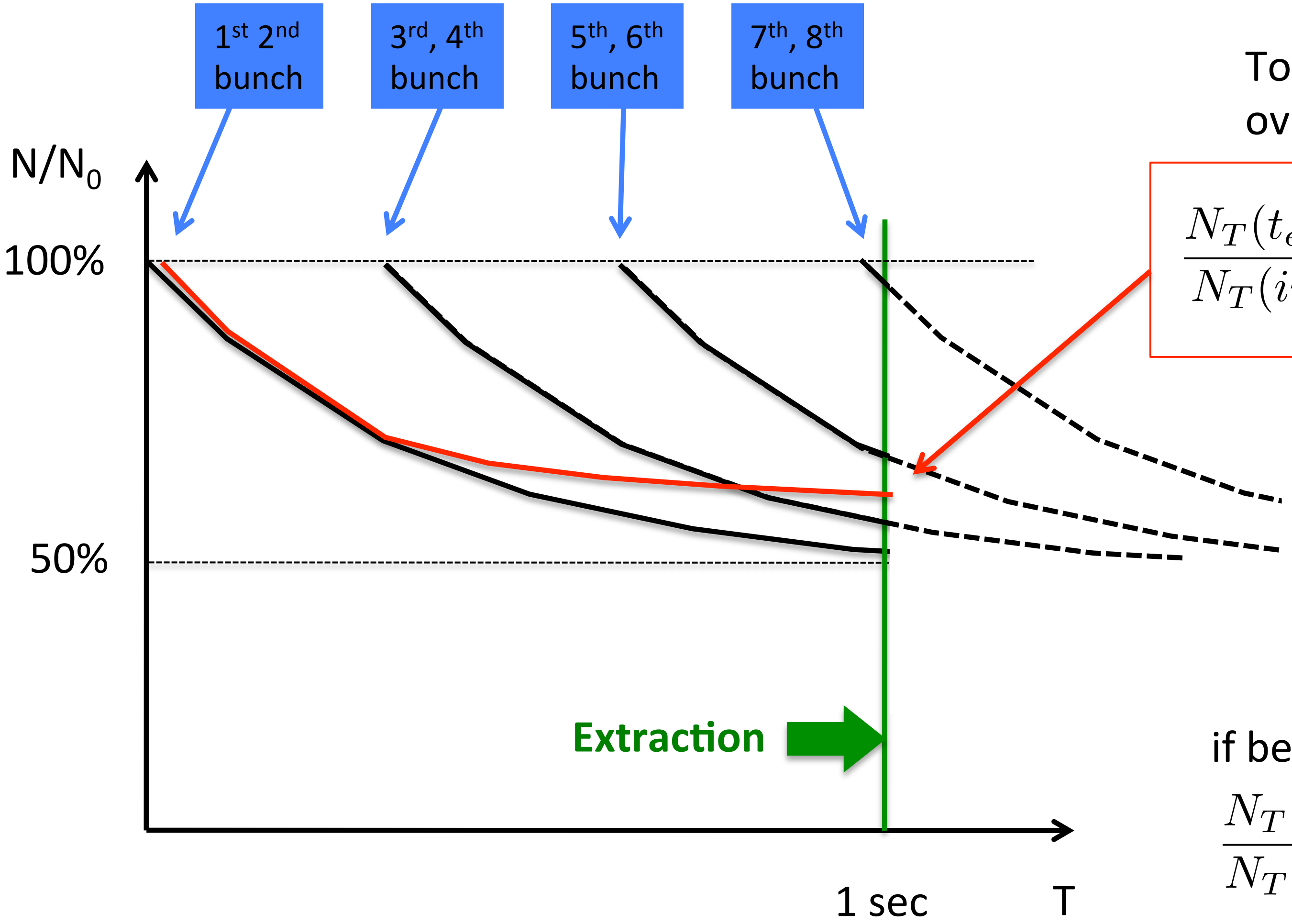
Resonances excited by the "standard seed"



Resonances crossing the space charge tune-spread

- 2 Qy = 37
- Qx + 2 Qy = 56
- 3 Qx = 56
- 2 Qx + 2 Qy = 75
- 4 Qx = 75

Relation between beam survival over full cycle and survival of 1st bunch



Total beam survival over full cycle

$$\frac{N_T(t_{end})}{N_T(inj)} = \frac{1}{4}\sum_{i=1}^{4}\frac{N(t_i)}{N_0}$$

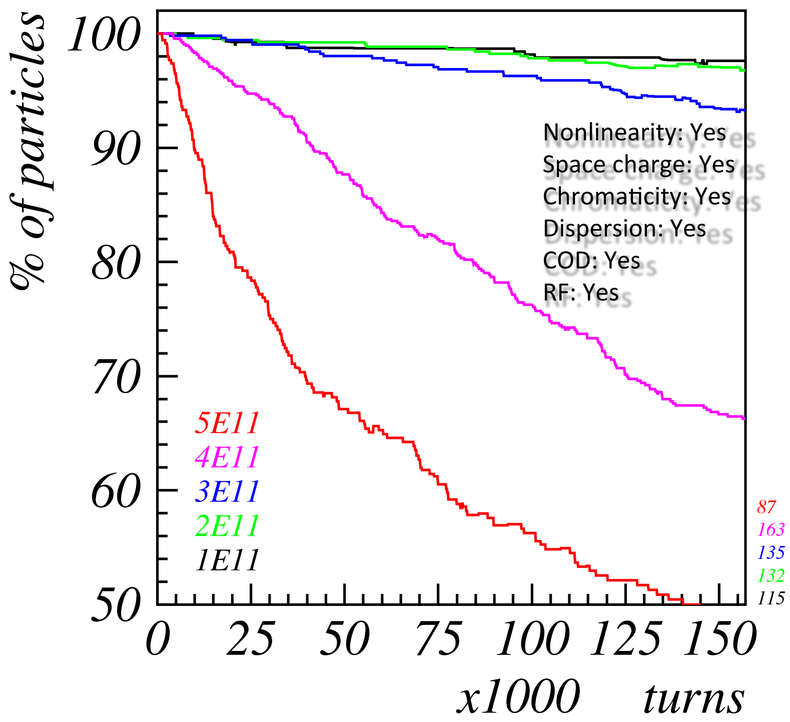
Guide line

if beam loss is linear in T

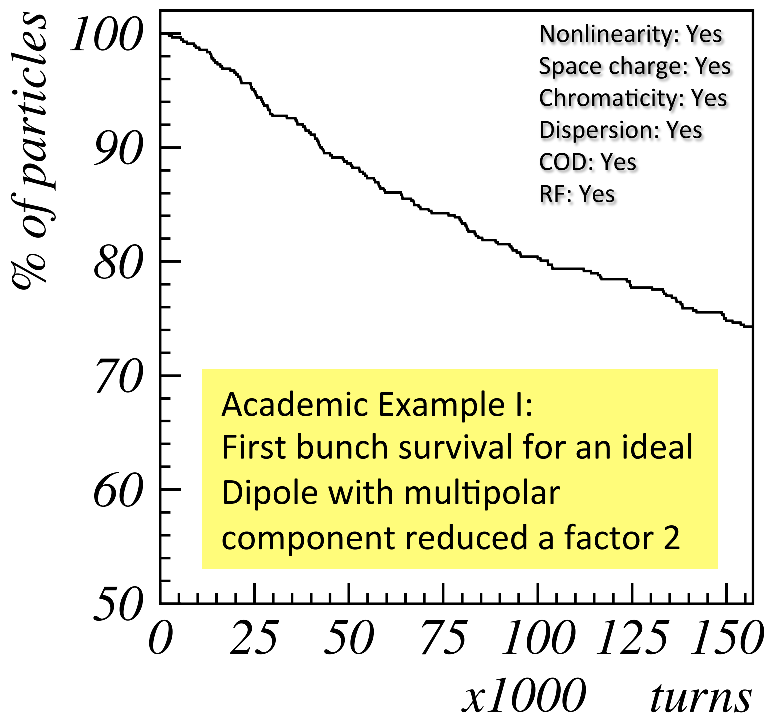
$$\frac{N_T(t_{end})}{N_T(inj.)} = \frac{1}{2}\frac{N(t_{end})}{N_0}$$

Beam loss versus beam intensity

First bunch



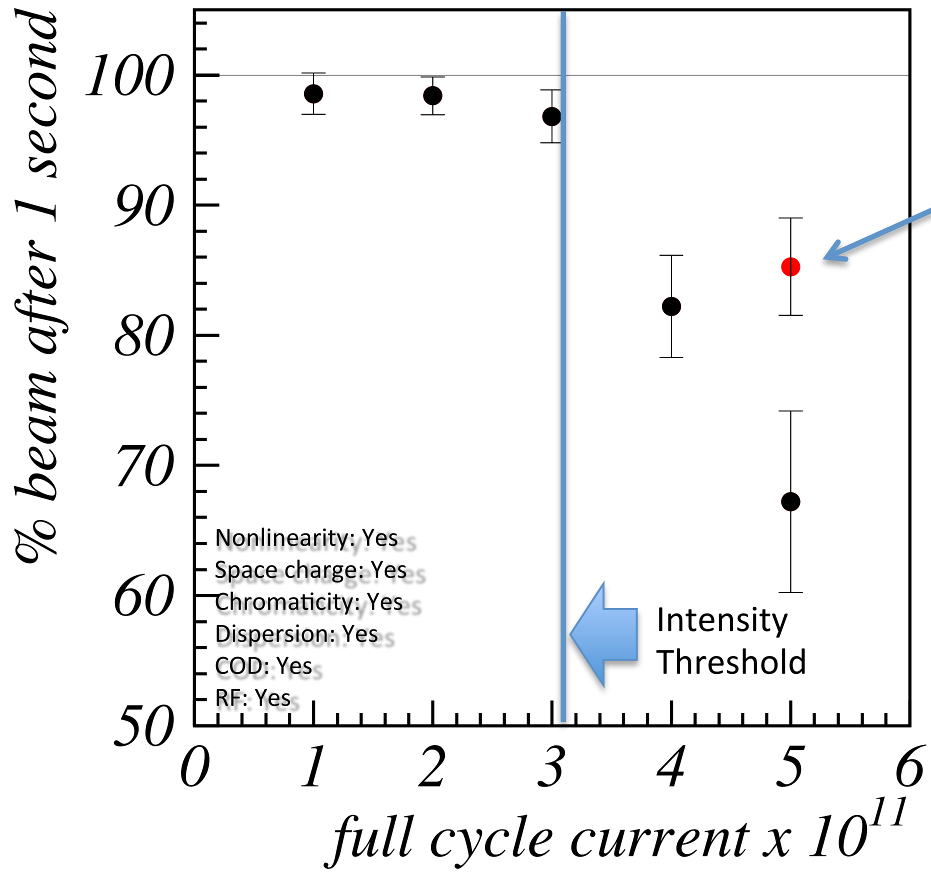
First bunch



Clear indication that beam intensity is relevant for beam survival but also that magnet nonlinearities are relevant in the beam loss budget

A global view: performances vs. intensity

$\varepsilon_{x/y,2\sigma} = 35/15$ mm-mrad



Academic example I

This results suggests that dipoles with better quality enhance beam lifetime

But

Using the physical understanding of the beam loss mechanism we can try to control beam loss

SUMMARY

For the "standard error" seed

Beam loss are strongly affected by space charge: for intensities below 3E11 beam loss are contained within 5%

At maximum beam intensity 5E11 beam loss over the full cycle is 35%

Improvement of all multipolar components improve beam loss to 15%

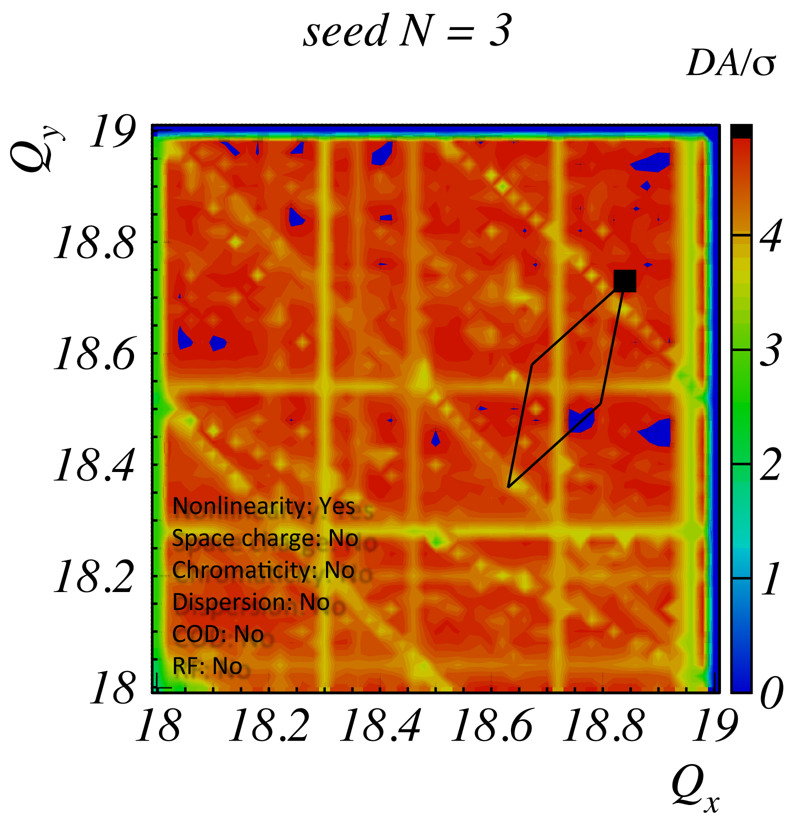
How do we use the understanding of the mechanism of beam loss to control them ?

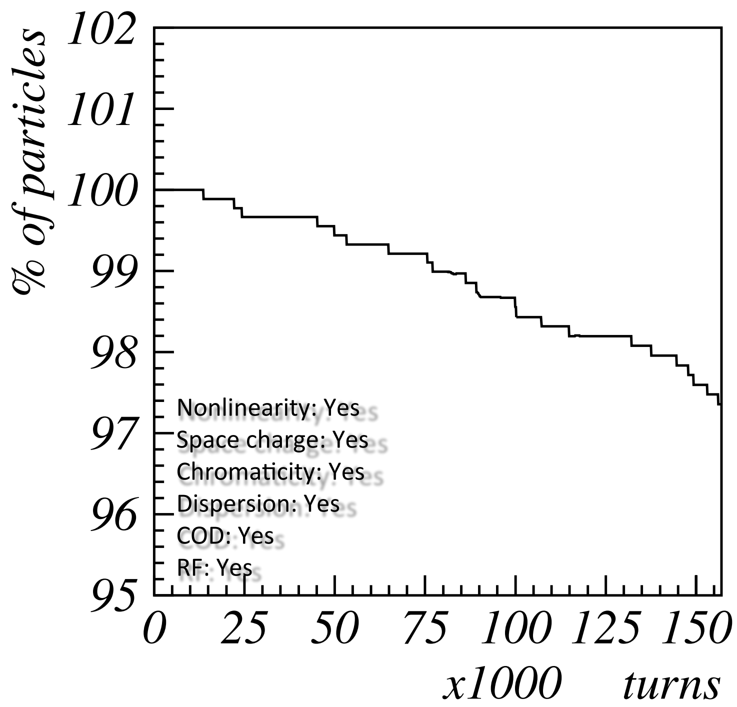
In TDR2008 it was suggested that Qx + 2Qy = 56 might be responsible of beam loss [also suggested in G.Franchetti et al. PRSTAB 12, 124401 (2009)]

IMPROVING BEAM LOSS

Academic example II

We remove the 3rd order components from dipoles

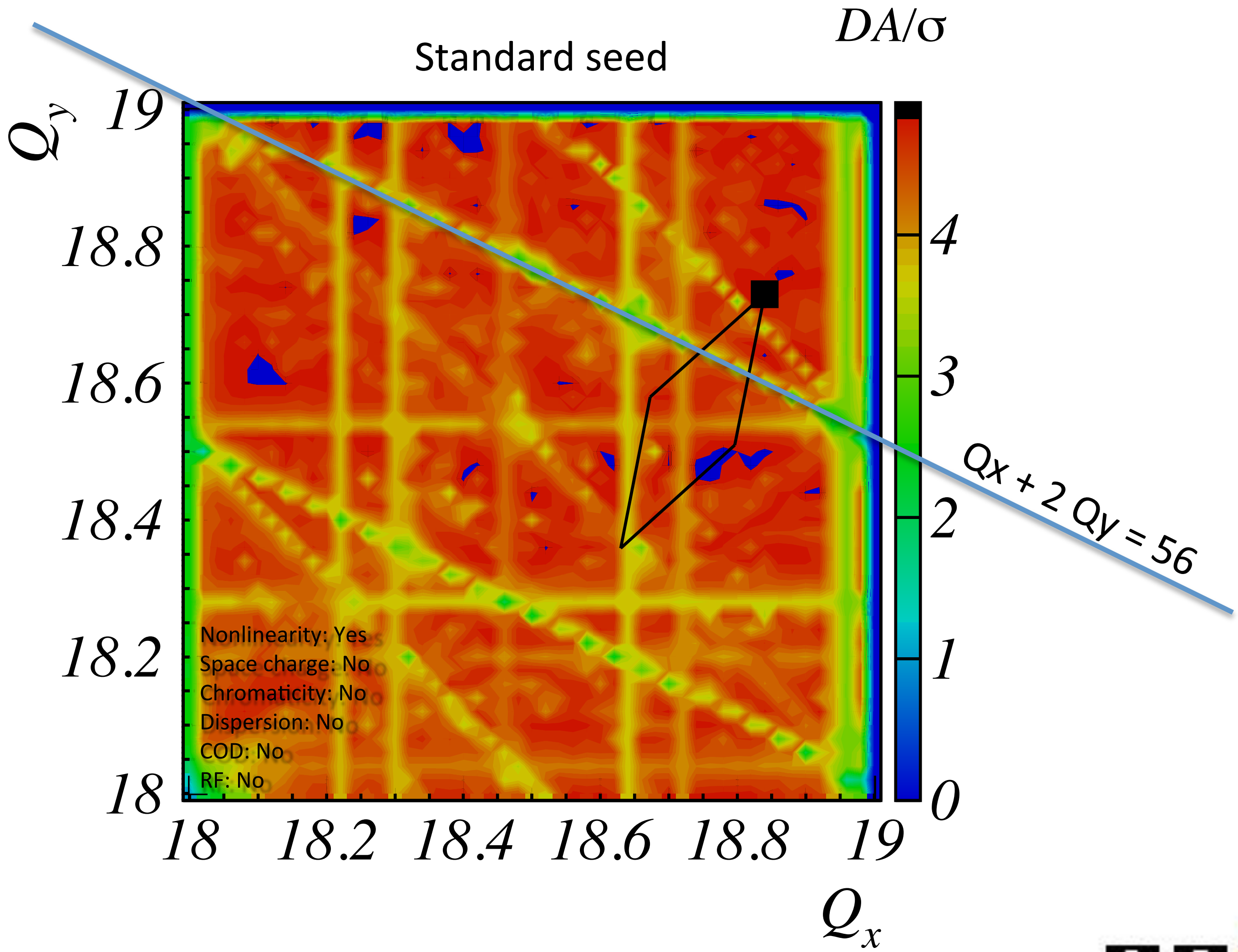




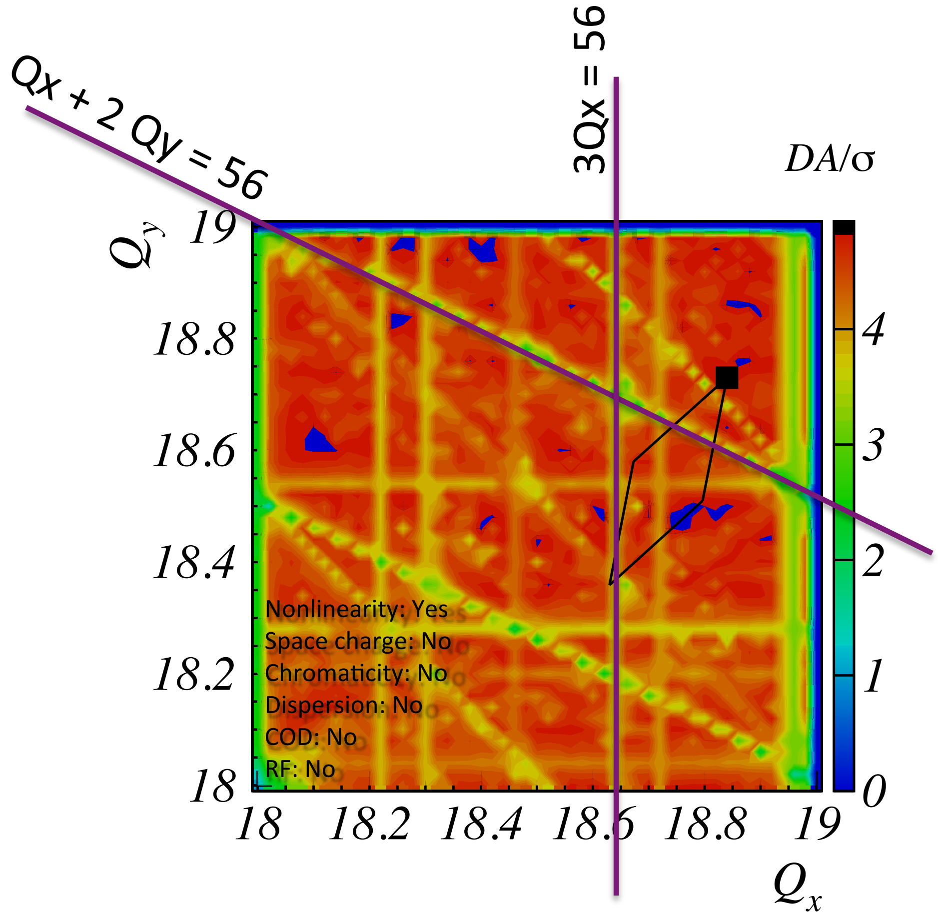
3rd order resonances are practically absent: only 4th order resonances dominates

First bunch beam survival is good, but this is an academic example

Does resonance compensation really mitigate periodic crossing diffusion ?



Compensation Strategy: A first approach



Compensate the resonance
Qx + 2 Qy = 56
without exciting the resonance
3 Qx = 56

Compensation strategy

Cancellation of the driving terms of
Qx + 2 Qy = 56 and 3 Qx = 56
at the crossing of the two resonances
that we call "cancellation working point"

WPC: Qxc = 18.66, Qyc = 18.66

Analysis of the driving terms

General expression of the driving terms

G. Guignard CERN 78-11 10 November 1978

$$h = \frac{R}{2\pi(2R)^{N/2}|n_x!||n_y!|} \sum_j \beta_{xj}^{|n_x|/2} \beta_{yj}^{|n_y|/2} \times e^{i[n_x\phi_{xj}+n_y\phi_{yj}-(n_xQ_x+n_yQ_y-p)s_j/R]} \begin{cases} (-1)^{(|n_y|+2)/2} K_{N,j} \text{for } n_y \text{ even} \\ (-1)^{(|n_y|-1)/2} J_{N,j} \text{for } n_y \text{ odd} \end{cases}$$

We define $k_{N,j}$ to be associated to $K_{N,j}$

$$k_{N,j} = \frac{R}{2\pi(2R)^{N/2}|n_x!||n_y!|} \beta_{xj}^{|n_x|/2} \beta_{yj}^{|n_y|/2} \times e^{i[n_x\phi_{xj}+n_y\phi_{yj}-(n_xQ_x+n_yQ_y-p)s_j/R]} \begin{cases} (-1)^{(|n_y|+2)/2} \text{for } n_y \text{ even} \\ (-1)^{(|n_y|-1)/2} \text{for } n_y \text{ odd} \end{cases}$$

$$h = \sum_l k_{2,l} K_{2,l} + \sum_j k_{2,j} K_{2,j}$$

This term depends only on the nonlinear errors: we call it k_{error}

This term depends only on the correctors

We consider only normal sextupolar components

Correction system normalized driving terms

The normalized resonance driving terms $k_{2,j} = |k_{2,j}| e^{i\theta}$ at the ''cancellation point'' Qxc = Qyc = 18.66 follow the symmetry of the optics

WPC: Qxc = 18.667 Qyc = 18.667

Resonance **3 Qx = 56**

Kerr = **-3.53E-03 + i5.30E-04**

Nele	$\|k_{2,j}\|$	$\vartheta/(2\pi)$
1	1.02E-02	0.5
535	5.36E-02	1.3963
2494	1.02E-02	1.8333
3028	5.36E-02	2.7297
4987	1.02E-02	3.1667
5513	5.36E-02	4.063
7472	1.02E-02	4.5
7998	5.36E-02	5.3963
9957	1.02E-02	5.8333
10483	5.36E-02	6.7297
12442	1.02E-02	7.1667
12986	5.36E-02	8.063

WPC: Qxc =18.667 Qxc = 18.667

Resonance **Qx + 2 Qy = 56**

Kerr = **9.63E-03 + i 3.26E-03**

Nele	$\|k_{2,j}\|$	$\vartheta/(2\pi)$
1	8.93E-02	0
535	5.28E-02	0.89866
2494	8.93E-02	1.3333
3028	5.28E-02	2.232
4987	8.93E-02	2.6667
5513	5.28E-02	3.5653
7472	8.93E-02	4
7998	5.28E-02	4.8987
9957	8.93E-02	5.3333
10483	5.28E-02	6.232
12442	8.93E-02	6.6667
12986	5.28E-02	7.5653

Full scheme of assigning 4 independent strengths

We have created 4 knobs, b_1,b_2,b_3,b_4 assigning to the 12 sextupoles the following values

Nele	Name strength	Name object	*value*
1	$K^2_{2,1}$	corr_oct1	b_3
535	$K^1_{2,1}$	corr_oct2	b_1
2494	$K^2_{2,2}$	corr_oct3	b_3
3028	$K^1_{2,2}$	corr_oct4	b_1
4987	$K^2_{2,3}$	corr_oct5	$-b_3$
5513	$K^1_{2,3}$	corr_oct6	$-b_1$
7472	$K^2_{2,4}$	corr_oct7	b_4
7998	$K^1_{2,4}$	corr_oct8	b_2
9957	$K^2_{2,5}$	corr_oct9	$-b_4$
10483	$K^1_{2,5}$	corr_oct10	$-b_2$
12442	$K^2_{2,6}$	corr_oct11	b_4
12986	$K^1_{2,6}$	corr_oct12	b_2

EFFECT on Chromaticity

$$\left|\frac{\partial Q_{x/y}}{\partial(\delta p/p)}\right| < \frac{1}{\pi}\beta_{x,max} D_{x,max} |b_i|_{max}$$

This strategy allows the minimization of the strength to be applied to the 12 strength in order to control DA

Application to the "standard error seed"

Therefore the simultaneous compensation of Qx + 2 Qy = 56 and 3 Qx = 56 reads

$$\left\{\begin{array}{l} -0.35349\times 10^{-2}+i0.52999\times 10^{-3}+ \\ +(k^1_{2,1}+k^1_{2,2}-k^1_{2,3})b_1+(k^1_{2,4}-k^1_{2,5}+k^1_{2,6})b_2 \\ +(k^2_{2,1}+k^2_{2,2}-k^2_{2,3})b_3+(k^2_{2,4}-k^2_{2,5}+k^2_{2,6})b_4 \quad =0 \\ \\ 0.96308\times 10^{-2}+i0.32631\times 10^{-2}+ \\ +(k^1_{2,1}+k^1_{2,2}-k^1_{2,3})b_1+(k^1_{2,4}-k^1_{2,5}+k^1_{2,6})b_2 \\ +(k^2_{2,1}+k^2_{2,2}-k^2_{2,3})b_3+(k^2_{2,4}-k^2_{2,5}+k^2_{2,6})b_4 \quad =0 \end{array}\right.$$

with ${k^l}_{2,I}$ computed for 3 Qx = 56 @ WPC

with ${k^l}_{2,I}$ computed for Qx + 2 Qy = 56 @ WPC

This is a system of 4 equation in the 4 unknown b_1,b_2,b_3,b_4

For the seed #3 we find

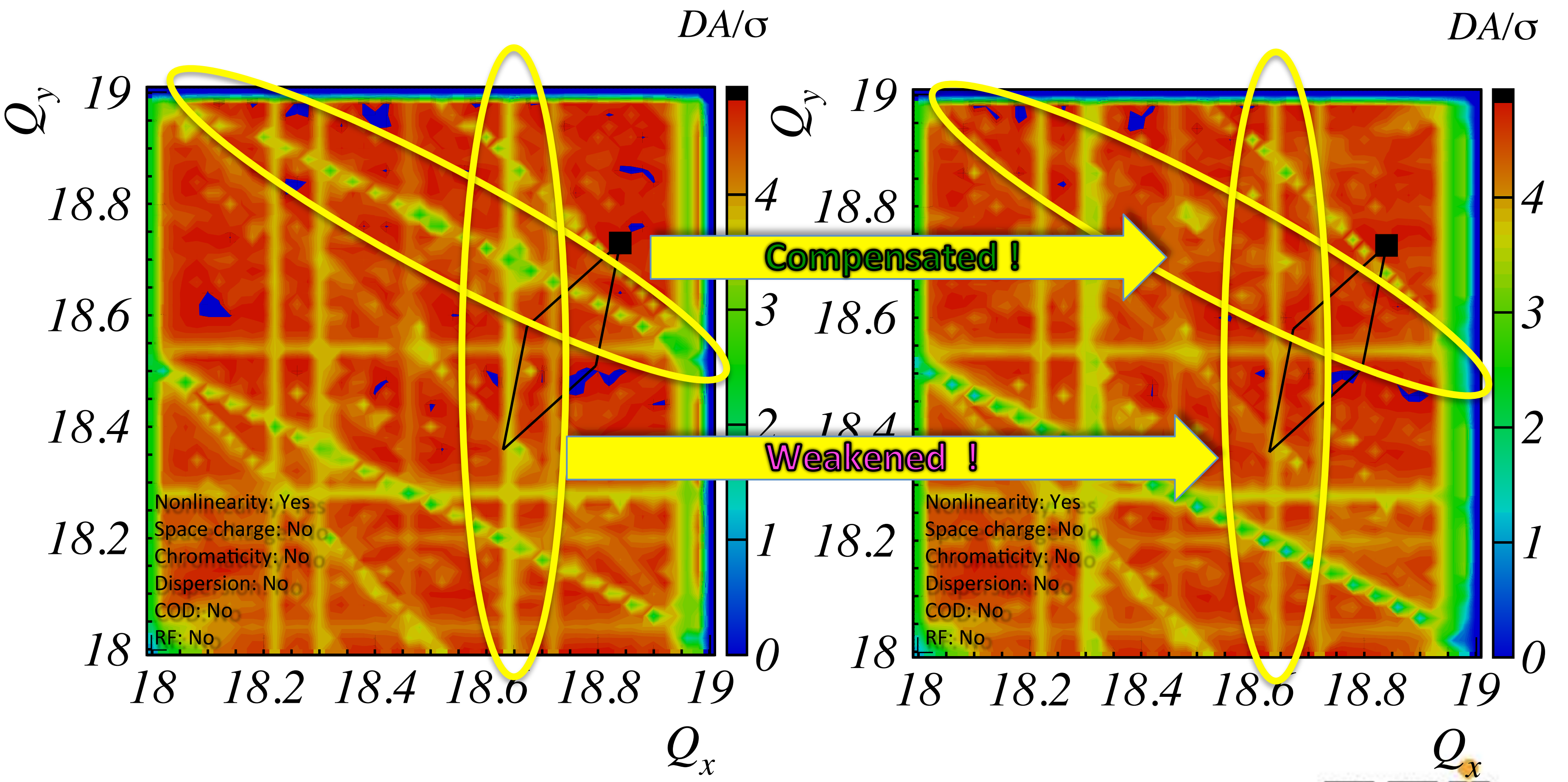
$$\begin{aligned} b_1 &= -0.0523366015 \quad m^{-3} \\ b_2 &= -0.0250475799 \quad m^{-3} \\ b_3 &= -0.0307216893 \quad m^{-3} \\ b_4 &= -0.0214847964 \quad m^{-3} \end{aligned}$$

Negligible effect on chromaticity

$$\left|\frac{\partial Q_{x/y}}{\partial(\delta p/p)}\right| < 0.04$$

DA scan verification

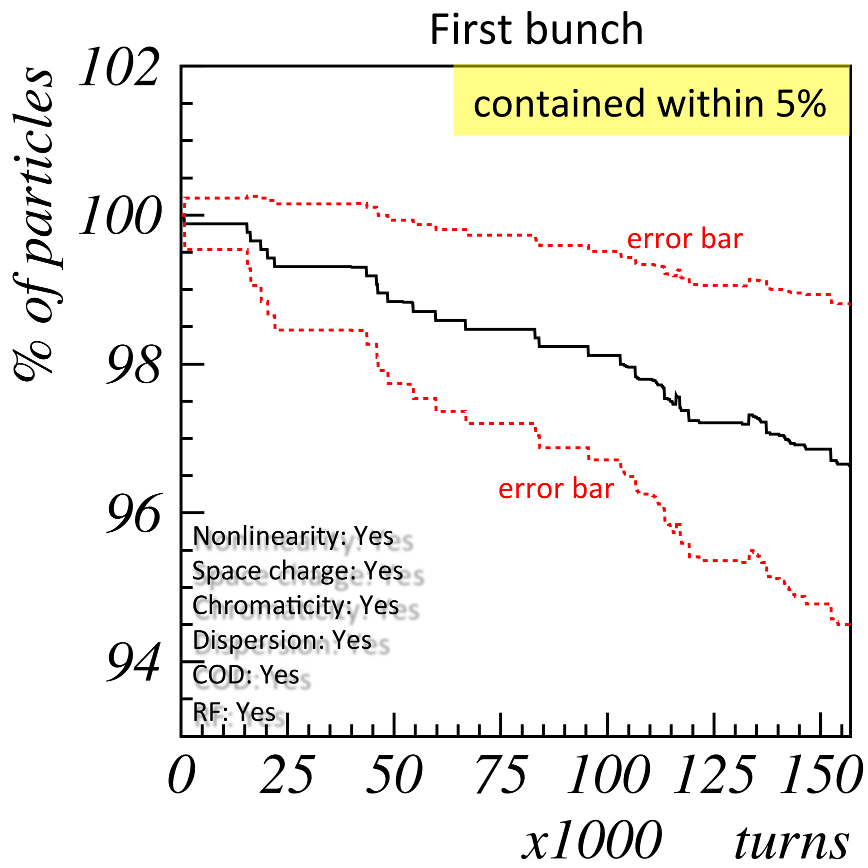
Resonances from standard error seed | including compensation compensation



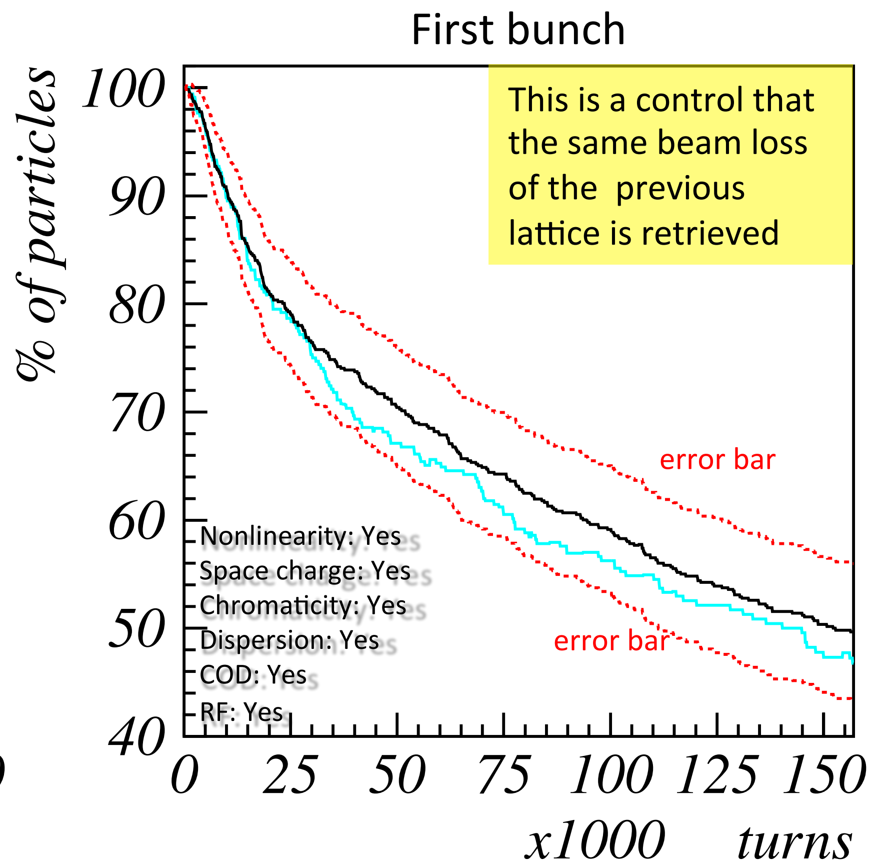
Beam loss prediction

Standard seed

Compensated



Un-Compensated



SUMMARY

For the "standard error seed"

Elimination of 3rd order components cut beam loss to ~3% (academic example II)

Successful implementation of a compensation strategy for removing
Qx + 2Qy = 56 without exciting other resonances

Multi-particle simulations confirm that beam loss are cut to 2.5% +/- 2%
No periodic resonance crossing can happen without a resonance to be crossed ;-)

Note that 2Qx + 2 Qy=56 does not give any problem!! :
Quite consistent with present understanding of periodic resonance crossing…

These results are theoretically valid for the standard error seed:
what happen with the other seeds ?

ROBUSTNESS OF THE CORRECTION SCHEME

Robustness of the correction scheme: first analysis

We corrected the resonance Qx + 2 Qy = 56 for the "standard error seed'' (seed #3)

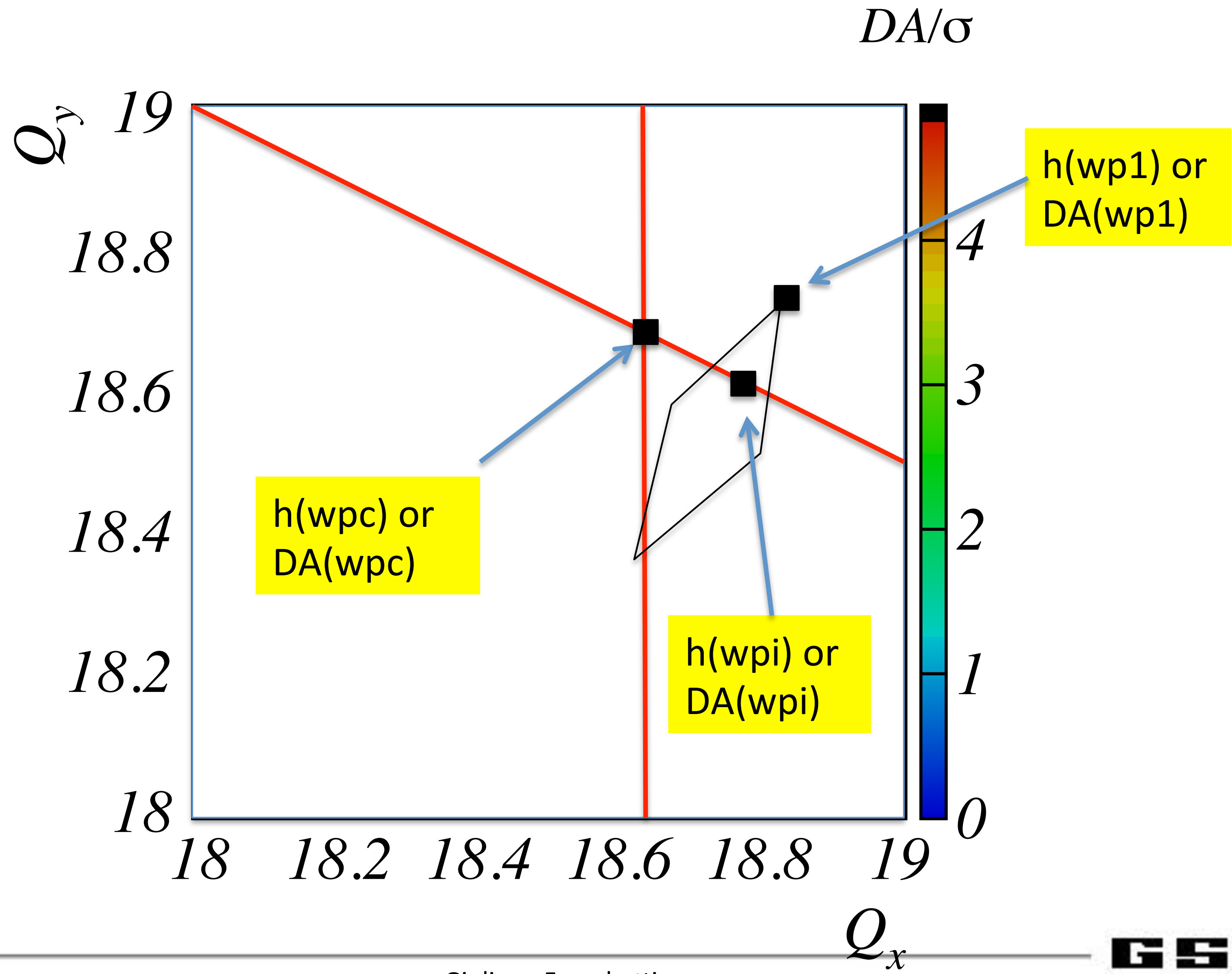
What happen with the other 29 seeds ?

Can we make a compensation without reducing too much DA ?

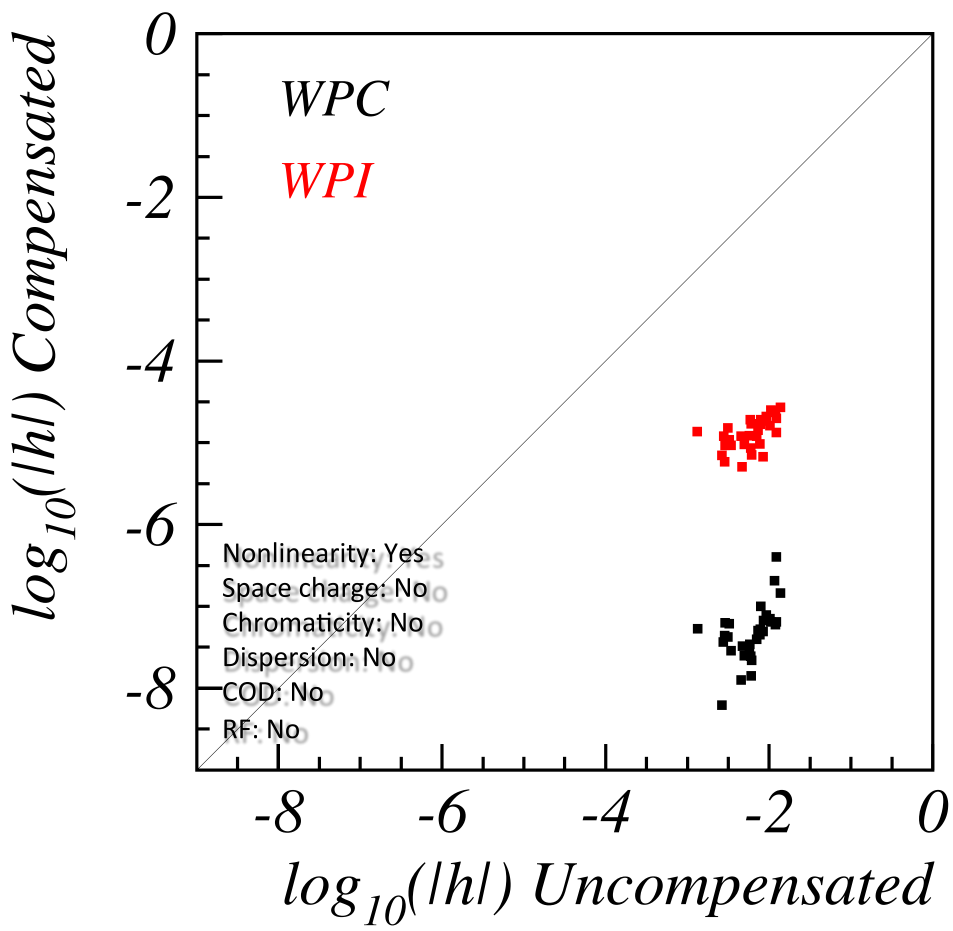
New Issues

1) Does space charge affect the resonance compensation scheme?
2) At what level the compensation has to be carried out ?

Definitions of the Compensation Indicators



Statistic analysis with driving terms

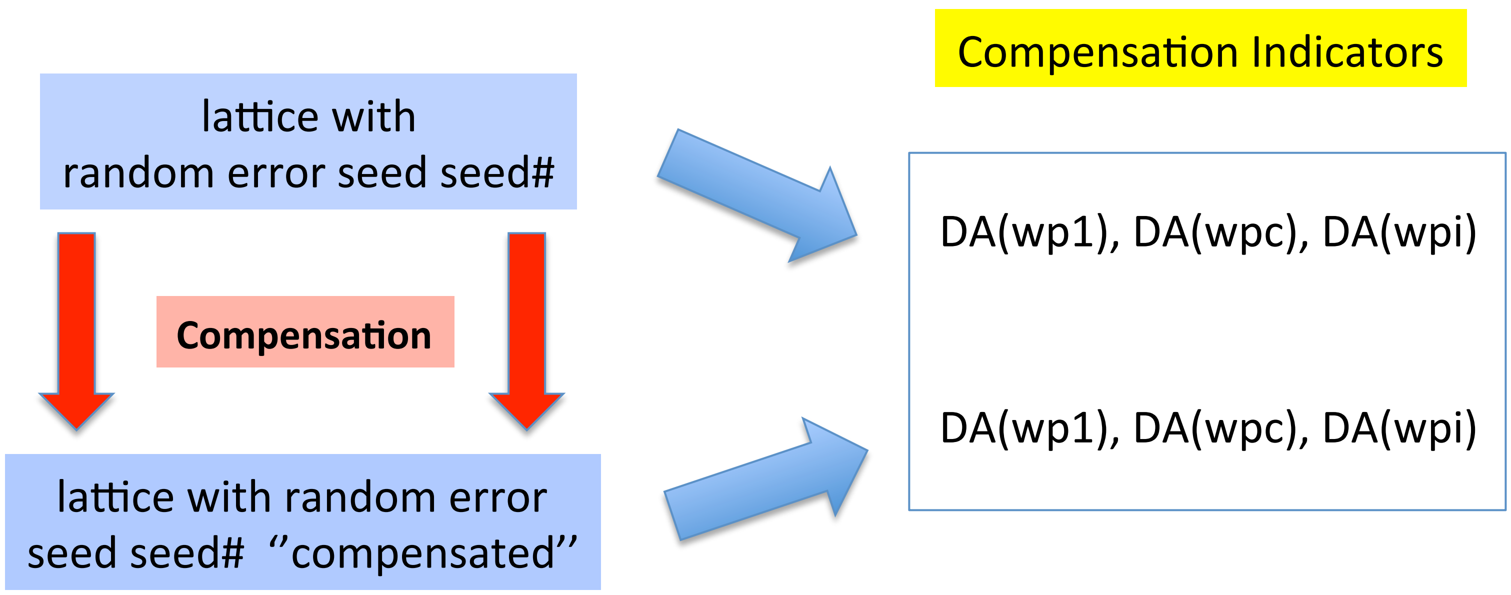


h(wpc) is reduced ~5 orders
h(wpi) is reduced of ~3 orders

Apparently good

Statistic analysis with beam dynamics based Compensation Indicators

For each of the 30 seeds we compute the compensation indicators
with and without compensation



Statistical results

Compensation indicators for the "standard error seed"

	DA(wp1) /σ	DA(wpc) /σ	DA(wpi) /σ	b_1 [m^{-3}]	b_2 [m^{-3}]	b_3 [m^{-3}]	b_4 [m^{-3}]
uncompensated	4.76	2.93	3.64	0	0	0	0
compensated	4.68	3.96	4.66	-0.05	-0.025	-0.0307	-0.0214

Statistical analysis of the Compensation Indicators

	DA(wp1) /σ	DA(wpc) /σ	DA(wpi) /σ	b_1 [m^{-3}]	b_2 [m^{-3}]	b_3 [m^{-3}]	b_4 [m^{-3}]
uncompensated	4.64 +/- 0.10	3.18 +/- 0.45	4.03+/- 0.30	0	0	0	0
compensated	4.64 +/- 0.09	3.94 +/- 0.23	4.39 +/- 0.14	0 +/-0.03	0 +/-0.03	0 +/-0.02	0 +/-0.02

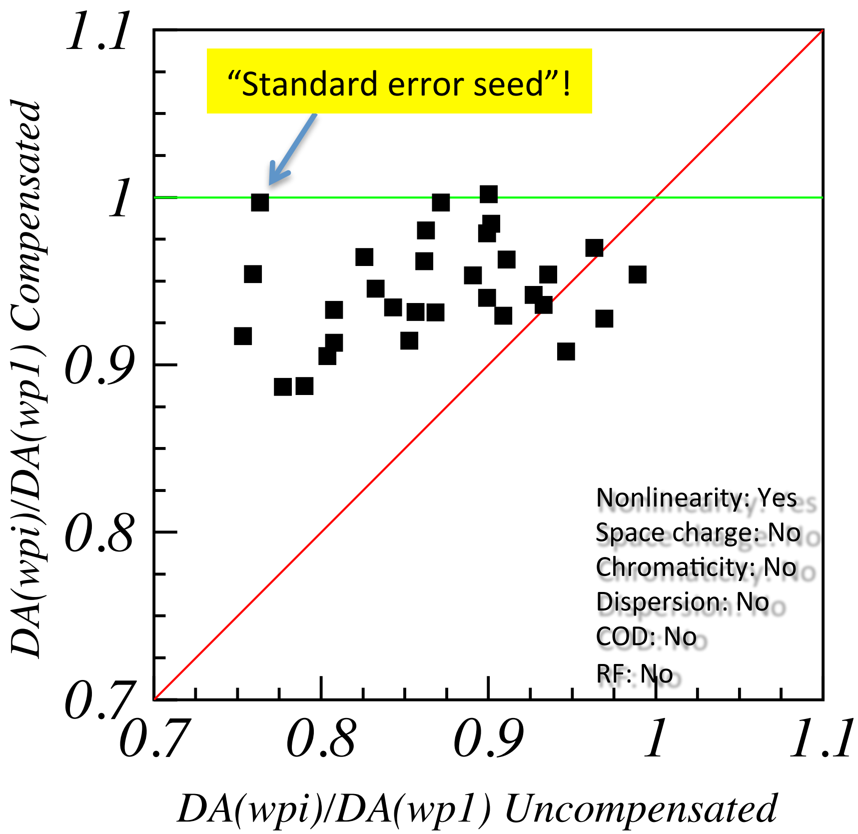
(Notation: average +/- standard deviation)

maximum effect on chromaticity → $$\left|\frac{\partial Q_{x/y}}{\partial(\delta p/p)}\right| < 0.08$$

Existence of Residual Resonances

From the statistic we find that DA(wp1) is not affected by the correction scheme

We take DA = 4.7/σ as a reference value



For most cases there exists a residual resonance after compensation

The effect of the residual resonance on beam survival is not tested yet…

SUMMARY

The method of controlling of $Q_x + 2Q_y = 56$ on the cancellation working point reduces the driving terms of a factor larger than 100

BUT

Verification with beam dynamics shows that some residual resonance at WPI is still found

Multiparticle tracking should be carried out for other seeds to confirm the dependence (or absence) of beam loss performance from residual resonances

-> Development of further more complex schemes of resonance control

Are we sure the effect of space charge does not affect the resonance compensation scheme ?

NEXT STEP
EXPERIMENTAL VERIFICATION ON SIS18

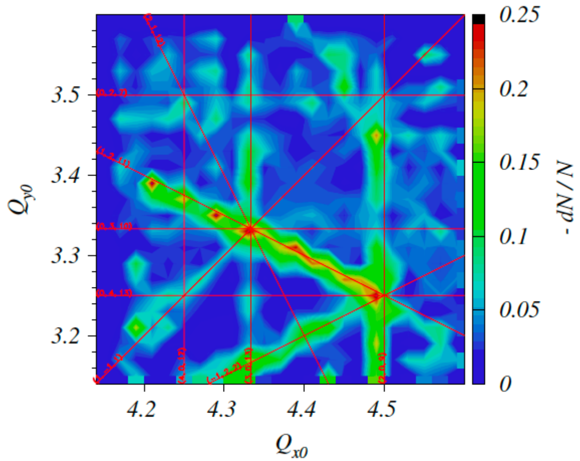
Relevant issues for experiments

It becomes then necessary to develop a measurement strategy of nonlinear error

1) Measurement in magnets
2) Beam Based Measurements

SIS18 becomes a "test accelerator" for the high intensity beam dynamics issues of SIS100

Resonances in SIS18



Reconstruction of sextupolar components in SIS18 with the nonlinear tune response matrix method

Simultaneous 2 BPM acquisition

Comparing with magnet measured data

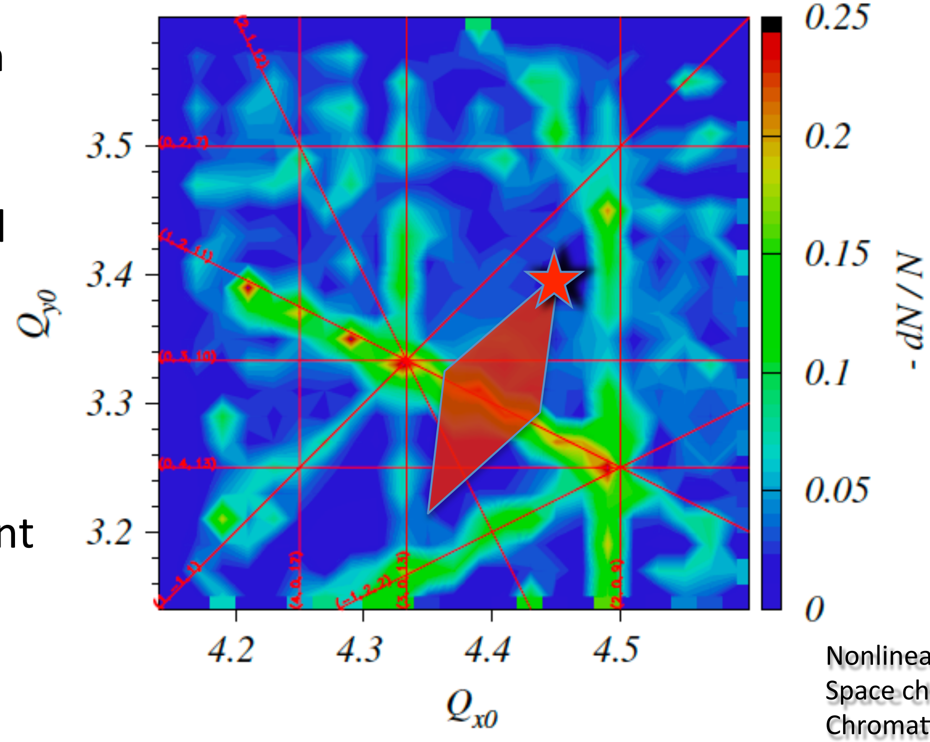
Experimental verification in SIS18

Test on SIS18 if the compensation scheme of a 3rd order resonance

Qx + 2 Qy = 11

works for a space charge bunched beam

1) Equivalent to the S317 experiment
2) Part of the SIS18 upgrade 2 FAIR



Nonlinearity: Yes
Space charge: No
Chromaticity: Yes
Dispersion: Yes
COD: Yes
RF: No

Conclusion

1) Space charge incoherent effect are responsible of beam loss;
2) A dedicated measurement campaign gave us confidence that we understand the main ingredients of the space charge and resonance driven beam loss;

3) In order to control beam loss in a high intensity bunched beam we have to:
   1) Optimize the location of the working point;
   2) Control of the relevant resonances;
   3) Flatten longitudinal bunch distribution;

4) We have implemented for moderate error seed the compensation of the resonance Qx + 2 Qy = 56 leaving the other resonances unchanged:
   We find a reduction of the beam loss of a factor 10 on the first injected bunch
   Therefore @5E11 beam loss ~5% to be doubled to 10% (factor 2 from benchmarking)

Over the full cycle @5E11 after correction of Qx + 2 Qy = 56 beam loss expected of ~5% for the "standard error seed"

Conclusion

5) **There is no prove that we are able to compensate any error seed induced resonance: further multi-particle simulations are necessary to clarify which level of residual resonance is allowed;**
6) Development of more efficient compensation schemes;
7) **It is mandatory to perform an experimental campaign in SIS18 for testing these findings.**

Final Remarks

The simulations here presented are in some case unfinished because of several computer crash in the central system: GSI needs to power more the computer center and renew the PROCESSOR-PARK

GSI needs to form and keep the competences apt to face this class of problems for the time SIS100 will be constructed

Optics at the location of the correction system

Corrector elements: 12 group of correctors each formed by 1 quadrupole, 1sextupole, 1 octupole

Optics at the position of the corrector sextupoles for the "cancellation WP"

Nele	Label	Position	βx	αx	ψx/(2π)	Dx	D'x	βy	αy	ψy/(2π)
1	corr_oct1	0	5.89921	0.07827	0	0.02449	-0.00179	17.1682	-1.39403	0
535	corr_oct2	56.6	17.78347	1.42584	0.96545	0.04476	-0.0039	5.84209	-0.03965	0.96661
2494	corr_oct3	180.6	5.89921	0.07827	3.11111	0.02449	-0.00179	17.1682	-1.39403	3.11111
3028	corr_oct4	237.2	17.78346	1.42584	4.07656	0.04476	-0.0039	5.84209	-0.03965	4.07772
4987	corr_oct5	361.2	5.89921	0.07827	6.22222	0.02449	-0.00179	17.1682	-1.39403	6.22222
5513	corr_oct6	417.8	17.78347	1.42584	7.18767	0.04476	-0.0039	5.84209	-0.03965	7.18883
7472	corr_oct7	541.8	5.89921	0.07827	9.33333	0.02449	-0.00179	17.1682	-1.39403	9.33333
7998	corr_oct8	598.4	17.78347	1.42584	10.29878	0.04476	-0.0039	5.84209	-0.03965	10.29994
9957	corr_oct9	722.4	5.89921	0.07827	12.44444	0.02449	-0.00179	17.1682	-1.39403	12.44444
10483	corr_oct10	779.0	17.78347	1.42584	13.40989	0.04476	-0.0039	5.84209	-0.03965	13.41105
12442	corr_oct11	903.0	5.89921	0.07827	15.55555	0.02449	-0.00179	17.1682	-1.39403	15.55556
12986	corr_oct12	959.6	17.78347	1.42584	16.521	0.04476	-0.0039	5.84209	-0.03965	16.52216

We split the 12 sextupoles into 2 families

$K^1_{2,1}, K^1_{2,2}, K^1_{2,3}\ K^1_{2,4}, K^1_{2,5}, K^1_{2,6}$ -> β_x = 17.7 m

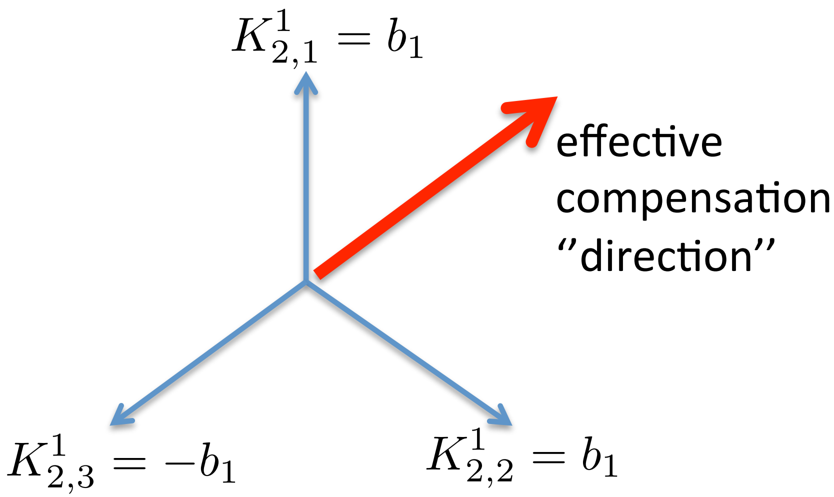
$K^2_{2,1}, K^2_{2,2}, K^2_{2,3}\ K^2_{2,4}, K^2_{2,5}, K^2_{2,6}$ -> β_x = 5.8 m

Assigning the strength in each sub-family

Minimum DA disturbance criteria:
we require to keep the strength of the sextupoles as low as possible

Optics considerations:

Subfamily $K^1_{2,1}, K^1_{2,2}, K^1_{2,3}$ ⇒ At WPC each sextupole has $\Delta\theta = 120^0$ + a multiple of *360°* form the next of the same sub-family



With this configuration the sub-family

$K^1_{2,1}, K^1_{2,2}, K^1_{2,3}$

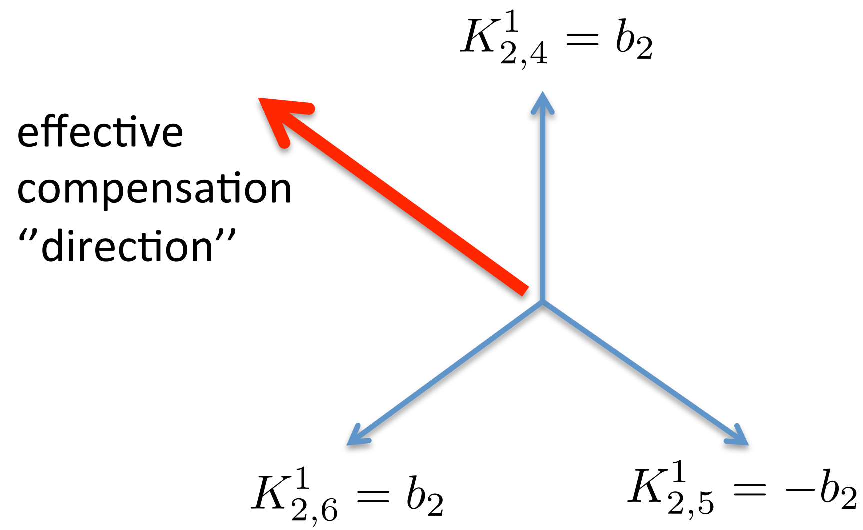
creates a driving term

$\propto b_1 e^{i\pi/6}$

The 3 sextupoles creates an effective strength $\propto 2b_1$

2^{nd} sub-family

Subfamily $K^1_{2,4}, K^1_{2,5}, K^1_{2,6}$ → At WPC each sextupoles is $\Delta\theta = 120^0$ + a multiple of 360° form the next



With this configuration the sub-family

$K^1_{2,4}, K^1_{2,5}, K^1_{2,6}$

creates a driving term

$\propto b_1 e^{i\pi 5/6}$

Therefore $K^1_{2,1}, K^1_{2,2}, K^1_{2,3}$ and $K^1_{2,4}, K^1_{2,5}, K^1_{2,6}$ creates two independent direction in the complex plane 120° degree apart

The same strategy is applied to the 2 sub-families $K^2_{2,1}, K^2_{2,2}, K^2_{2,3}$ $K^2_{2,4}, K^2_{2,5}, K^2_{2,6}$

Definition of sub-families

The simultaneous compensation of 2 resonances require 4 "knobs"

We divide each sub-family into 2 sub-families

Nele	Name strength	Name object
1	$K^2_{2,1}$	corr_oct1
535	$K^1_{2,1}$	corr_oct2
2494	$K^2_{2,2}$	corr_oct3
3028	$K^1_{2,2}$	corr_oct4
4987	$K^2_{2,3}$	corr_oct5
5513	$K^1_{2,3}$	corr_oct6
7472	$K^2_{2,4}$	corr_oct7
7998	$K^1_{2,4}$	corr_oct8
9957	$K^2_{2,5}$	corr_oct9
10483	$K^1_{2,5}$	corr_oct10
12442	$K^2_{2,6}$	corr_oct11
12986	$K^1_{2,6}$	corr_oct12

$\beta_{x,\,max}$ = 17.7 m

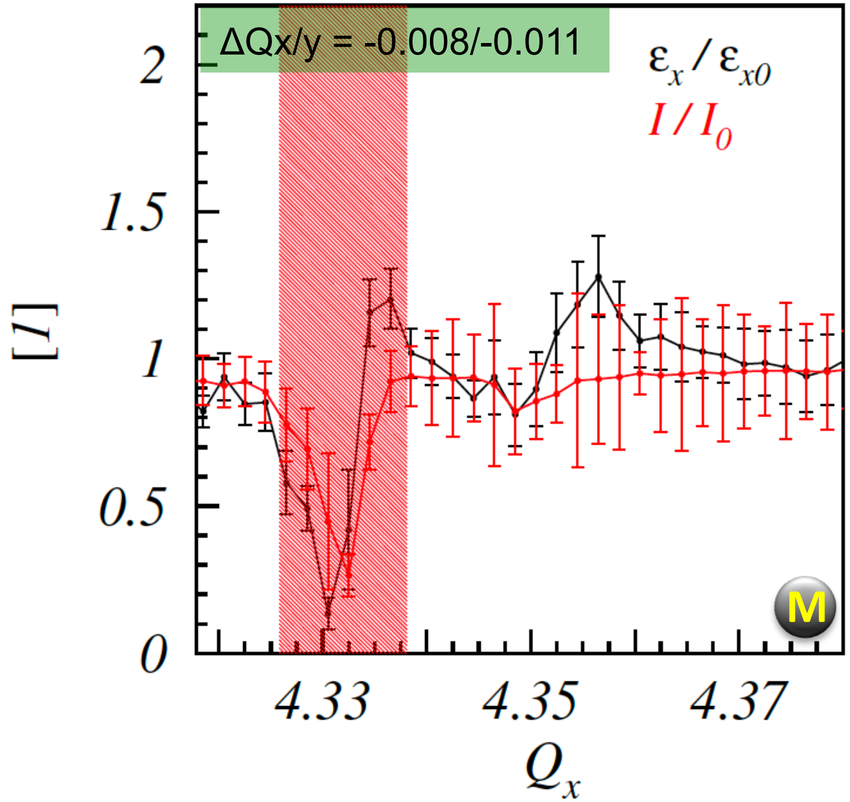
$K^1_{2,1}, K^1_{2,2}, K^1_{2,3}$ $K^1_{2,4}, K^1_{2,5}, K^1_{2,6}$

$\beta_{x,min}$ = 5.8 m

$K^2_{2,1}, K^2_{2,2}, K^2_{2,3}$ $K^2_{2,4}, K^2_{2,5}, K^2_{2,6}$

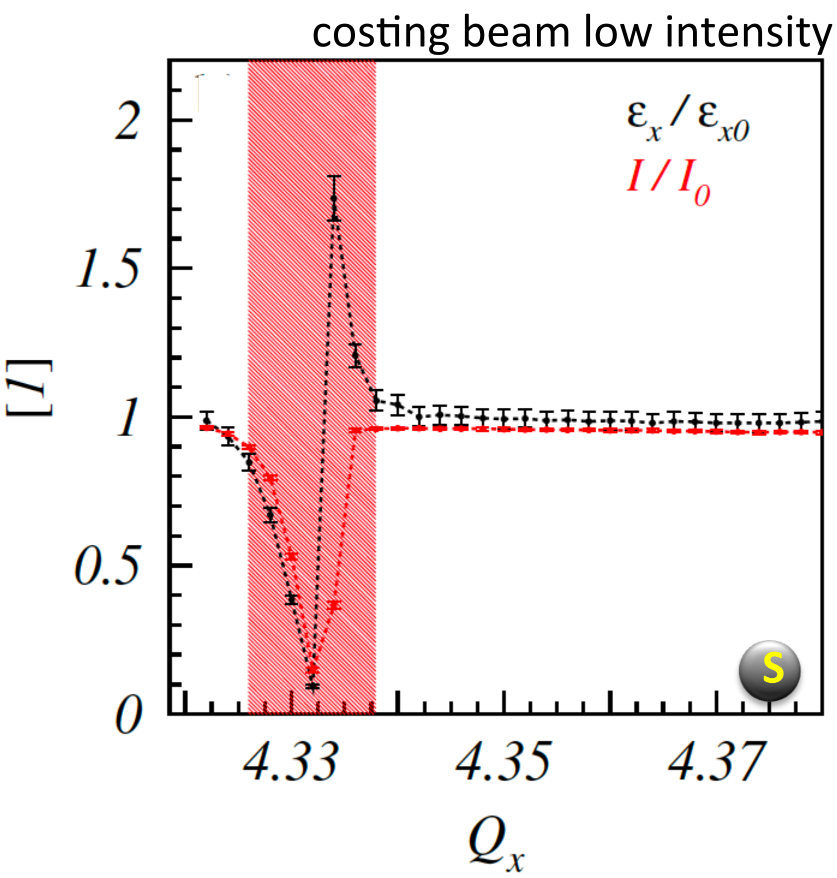
Strategy: each sub-family provides a degree of freedom in the complex plane

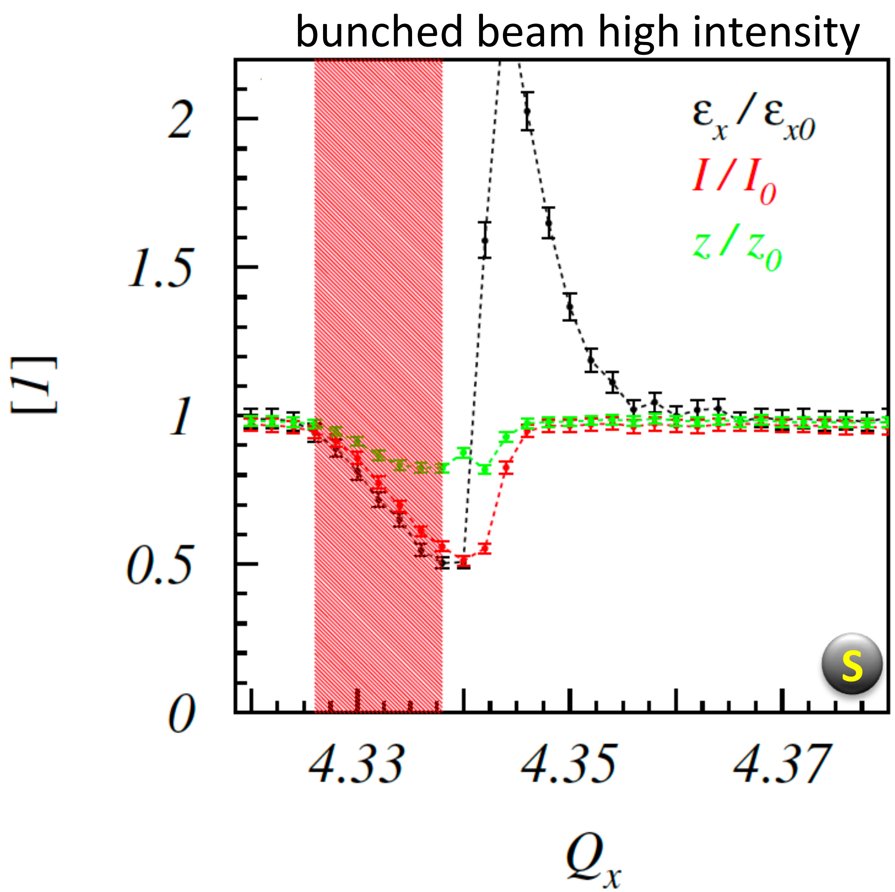
Optimal requirement: each family is a combination of elements which provides a 90 degree phase from the next sub-family costing beam low intensity



Simulation benchmarking

Weak modeling of the SIS18 nonlinear dynamics close 3rd order resonance





SIS100 multipoles

DIPOLE

```
!================== the dipole model 25/6/2010 ==========================

!SIS100_Dipole_CSLD8b
!"Rogovsky_I1_1319kA_Entr_Bpho_Tm_10.17_C0_xy_p0.0_p0.0_mm"
!"data_hdf/SIS100_Dipole_CSLD_Harmonics_20100609.h5:
! /Dipole/D3/Curved/CSLD8b/Rogovsky_Profile/"
MD+0    MULTIPOLE  -4.7163399758317062E-03  -1.0547373696328898E-11   0
MD+1    MULTIPOLE   3.0785055973603015E-05  -5.8053823331158389E-10   1
MD+2    MULTIPOLE  -2.6366697311469640E-02  -3.4256536267695576E-08   2
MD+3    MULTIPOLE   7.3195053029524795E-02  -2.4365230674135484E-06   3
MD+4    MULTIPOLE  -1.2439243085057312E+02   3.8357509219972509E-05   4
MD+5    MULTIPOLE   1.5378080000548240E+02   3.0914907235399965E-02   5
MD+6    MULTIPOLE  -8.6451329022645557E+04  -1.8565663052472367E+01   6
MD+7    MULTIPOLE  -3.0816832178552798E+05  -4.5835022334820633E+03   7
MD+8    MULTIPOLE  -1.4944190003612607E+09   1.3534633120010719E+06   8
MD+9    MULTIPOLE  -2.8271535894108959E+10   3.8163902568321079E+08   9
MD+10   MULTIPOLE   1.1525179718432939E+14  -9.2536963799966492E+10  10
MD+11   MULTIPOLE   1.2805569617742790E+15  -2.7857736036314035E+13  11
MD+12   MULTIPOLE  -2.1999264938605724E+18   4.4905049474379860E+15  12
MD+13   MULTIPOLE  -5.0851929146109133E+19   1.4538233978336215E+18  13
MD+14   MULTIPOLE   2.0686832547682220E+22  -1.2575953096211676E+20  14
MD+15   MULTIPOLE   7.3450854860770844E+23  -4.3003206361307635E+22  15
```

Entrance

```
!SIS100_Dipole_CSLD8b
!"Rogovsky_I1_1319kA_Cntr_Bpho_Tm_10.17_C0_xy_p0.0_p0.0_mm"
!"data_hdf/SIS100_Dipole_CSLD_Harmonics_20100609.h5:
! /Dipole/D3/Curved/CSLD8b/Rogovsky_Profile/"
MDC0    MULTIPOLE  -4.8321734468527902E-02  -8.0460622403658862E-11   0
MDC1    MULTIPOLE   1.3222876973075998E-06  -4.4286349322627113E-09   1
MDC2    MULTIPOLE  -1.5411882617349000E-02  -2.6132592908204184E-07   2
MDC3    MULTIPOLE  -3.7034493848285333E-03  -1.8587012098560845E-05   3
MDC4    MULTIPOLE   4.5506880778861124E+01   2.9261019441204273E-04   4
MDC5    MULTIPOLE  -6.2559995183645212E+00   2.3583431753596007E-01   5
MDC6    MULTIPOLE   7.3051033143311797E+04  -1.4162812922709435E+02   6
MDC7    MULTIPOLE  -1.4288951062831108E+05  -3.4965239042733432E+04   7
MDC8    MULTIPOLE   2.2831975374350262E+09   1.0324892588690210E+07   8
MDC9    MULTIPOLE   1.0564506501167362E+10   2.9113326625993242E+09   9
MDC10   MULTIPOLE  -1.6359949140068581E+14  -7.0591807199292908E+11  10
MDC11   MULTIPOLE  -6.9868819985378656E+13  -2.1251269228490359E+14  11
MDC12   MULTIPOLE   2.5207268897163274E+18   3.4255809404212480E+16  12
MDC13   MULTIPOLE   1.6101150642536155E+19   1.1090489334002389E+19  13
MDC14   MULTIPOLE  -2.2667622204271218E+23  -9.5935636945850047E+20  14
MDC15   MULTIPOLE  -8.9215833271142267E+22  -3.2804988706914617E+23  15
```

Body

```
!SIS100_Dipole_CSLD8b
!"Rogovsky_I1_1319kA_Exit_Bpho_Tm_10.17_C0_xy_p0.0_p0.0_mm"
!"data_hdf/SIS100_Dipole_CSLD_Harmonics_20100609.h5:
! /Dipole/D3/Curved/CSLD8b/Rogovsky_Profile/"
MD-0    MULTIPOLE  -4.7138405749040302E-03  -1.2991132072721643E-11   0
MD-1    MULTIPOLE   8.2298425078906093E-05  -7.1504519323945776E-10   1
MD-2    MULTIPOLE  -2.5429816100754250E-02  -4.2193554515923325E-08   2
MD-3    MULTIPOLE   1.8570007483834530E-01  -3.0010497284566724E-06   3
MD-4    MULTIPOLE  -1.1505080048691593E+02   4.7244696421450073E-05   4
MD-5    MULTIPOLE   4.9635167510791450E+02   3.8077691609973333E-02   5
MD-6    MULTIPOLE  -4.1068310345945916E+04  -2.2867207296236053E+01   6
MD-7    MULTIPOLE   7.4381818310866482E+05  -5.6454701035899407E+03   7
MD-8    MULTIPOLE  -2.3694572786783257E+09   1.6670520215659430E+06   8
MD-9    MULTIPOLE  -3.4309559893775809E+08   4.7006232355151188E+08   9
MD-10   MULTIPOLE   1.4223443489744228E+14  -1.1397718076645877E+11  10
MD-11   MULTIPOLE  -1.1221740140895050E+15  -3.4312193588405953E+13  11
MD-12   MULTIPOLE  -2.9902753171154821E+18   5.5309259468893420E+15  12
MD-13   MULTIPOLE   5.8658711948882985E+19   1.7906648912458665E+18  13
MD-14   MULTIPOLE   2.8992131756741854E+22  -1.5489720220994719E+20  14
MD-15   MULTIPOLE  -2.9914139190013502E+24  -5.2966771587902469E+22  15

!=========================================================================
```

Exit

QUADRUPOLE

```
!====================== model of quadrupole 25/6/2010 ======================

!SIS100_Quadrupole6Turn
!"Quad6TurnsV1_I1_460kA_Cntr_Bpho_Tm_12.23_C0_xy_p0.0_p0.0_mm"
!"data_hdf/SIS100_Quadrupole6Turn_20100623.h5:
! /Quadrupole/Turns6/D3/OperaCalc/StaticCalculation/V1/"
Eqb0    MULTIPOLE  -2.6789881018894428E-14   5.5045898388867806E-14   0
Eqb1    MULTIPOLE   2.1717022154679769E-01   1.9856320529300420E-12   1
Eqb2    MULTIPOLE  -9.4521226576819973E-11   1.9401448718616971E-10   2
Eqb3    MULTIPOLE   3.7858283188846437E-03   1.0501181037334316E-08   3
Eqb4    MULTIPOLE   7.0414842692841817E-07  -1.4318783375984776E-06   4
Eqb5    MULTIPOLE   3.0194294633632222E+02  -2.8051263507461471E-04   5
Eqb6    MULTIPOLE  -7.8478544512944073E-02   1.6019533278747095E-01   6
Eqb7    MULTIPOLE  -1.8269515944715394E+06   2.5709785026550517E+01   7
Eqb8    MULTIPOLE   4.7775705574752483E+03  -9.7507153716628163E+03   8
Eqb9    MULTIPOLE   1.5853417177689340E+11  -1.7429770135777944E+06   9
Eqb10   MULTIPOLE  -2.5512932132258266E+08   5.2083611876728094E+08  10
Eqb11   MULTIPOLE  -6.9973814030639240E+15   9.9896489034391388E+10  11
Eqb12   MULTIPOLE   9.8111951662325020E+12  -2.0032780989903805E+13  12
Eqb13   MULTIPOLE   1.2725759662788647E+20  -4.1250219682152360E+15  13
Eqb14   MULTIPOLE  -2.1305597834814832E+17   4.3518970770377338E+17  14
Eqb15   MULTIPOLE  -8.7801330870650991E+23   9.4854103306132488E+19  15
```

Body

```
!SIS100_Quadrupole6Turn
!"Quad6TurnsV1_I1_460kA_End_Bpho_Tm_12.23_C0_xy_p0.0_p0.0_mm"
!"data_hdf/SIS100_Quadrupole6Turn_20100623.h5:
! /Quadrupole/Turns6/D3/OperaCalc/StaticCalculation/V1/"
Eqf0    MULTIPOLE  -2.7060318826655702E-13   1.1626213256498432E-13   0
Eqf1    MULTIPOLE   3.1164889913266550E-02   3.7901786032567582E-12   1
Eqf2    MULTIPOLE  -9.5477779762820312E-10   4.0969260285906951E-10   2
Eqf3    MULTIPOLE  -1.4490292439969379E-01   2.0044610087550655E-08   3
Eqf4    MULTIPOLE   7.1127170011828505E-06  -3.0181254972048956E-06   4
Eqf5    MULTIPOLE   3.7933624599308937E+03  -5.3544165092945964E-04   5
Eqf6    MULTIPOLE  -7.9272672909384778E-01   3.3791339547476712E-01   6
Eqf7    MULTIPOLE   3.2031177498768162E+07   4.9074727624193621E+01   7
Eqf8    MULTIPOLE   4.8259166343405115E+04  -2.0567353101754215E+04   8
Eqf9    MULTIPOLE  -1.4378359763176462E+12  -3.3269865841298578E+06   9
Eqf10   MULTIPOLE  -2.5771111689094310E+09   1.0986636546656621E+09  10
Eqf11   MULTIPOLE  -2.9558496053583675E+15   1.9068195721472757E+11  11
Eqf12   MULTIPOLE   9.9104811140321641E+13  -4.2259100934876094E+13  12
Eqf13   MULTIPOLE   1.0139123133611631E+21  -7.8738228587503470E+15  13
Eqf14   MULTIPOLE  -2.1521204668226107E+18   9.1809992911089267E+17  14
Eqf15   MULTIPOLE  -2.5358360899375195E+25   1.8105707307445312E+20  15

!=========================================================================
```

Entrance\Exit

V. Kapin visit Summer 2010