SIS100 nonlinear dynamics and high intensity beam loss

G. Franchetti

MAC – 3 March 2009

Overview

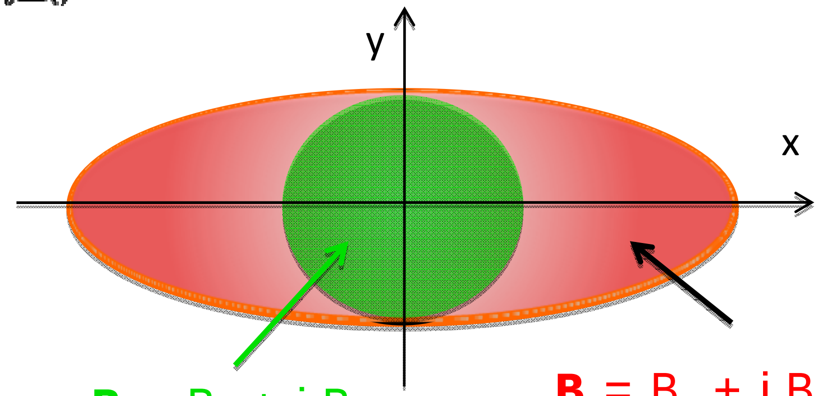
- Modeling of the nonlinear lattice
- Effect of random error / COD
- Long term effect of space charge
- Beam loss budget
- Remarks

Modeling nonlinear errors

Standard nonlinear dynamics in code uses multipole decomposition

$$B_y(x,y;s) + iB_x(x,y;s) = B_0 \sum_{n=0}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_0} \right)^n$$

Advantages:	Forces are conservative and well suited for long term tracking The interpretation of the resonance excited by each term is well established
``Disadvantages'':	This description is 2D
Applicability:	The series converges within the reference radius
Requirements:	In SIS100 beam size reach almost the beam pipe!



B = B_y + i B_x
Well described

B = B_y + i B_x
Is it the magnetic field well reconstructed ??

$$B_y + iB_x = A_0 + \sum_{m=1}^{\infty} \left[A_m \frac{\cosh(m\eta)}{\cosh(m\eta_0)} \cos(m\psi) \right]$$

P. Schnizer et. al., february 9th, 2007

Dipole multipoles in Cartesian frame

Computation of elliptic multipoles on the larger ellipse (very precise)

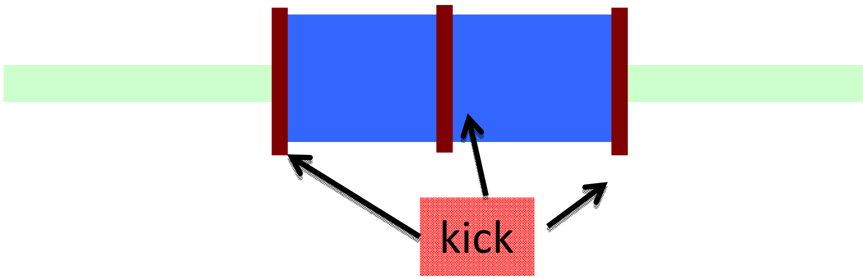
Conversion of the elliptic multipoles into Cartesian multipoles

Table 1 Multipolar components of the magnetic field in curved sc dipoles for I=658 A (T: integrated, C: center, - and |: edges) R=30 mm

658	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}
T	0.197	1.28	-0.46	0	2.75	0	-0.11	0	0.08	0	-0.03
C	0.151	0.11	4.09	0	-0.19	0	-0.15	0	0.06	0	-0.02
-	0.023	6.52	-10.83	0	12.95	0	0.05	0	0.16	0	-0.09
|	0.023	3.65	-19.87	0	11.84	0	-0.02	0	0.17	0	-0.09

P. Akishin, E. Fischer and P. Schnizer

Bending Magnet



Nonlinear components in Quadrupoles are taken from the Dubna magnets (measurements) R=40 mm

N	b_b	a_n
	Units 10^{-4}	Units 10^{-4}
1	9.00	10.75
2	6815.8	0.00
3	1.26	-3.41
4	0.68	-0.82
5	0.67	0.28
6	-13.05	2.78
10	4.98	-2.12

A. Kovalenko

The choice of the working point

Constrains:

Resistive wall instability

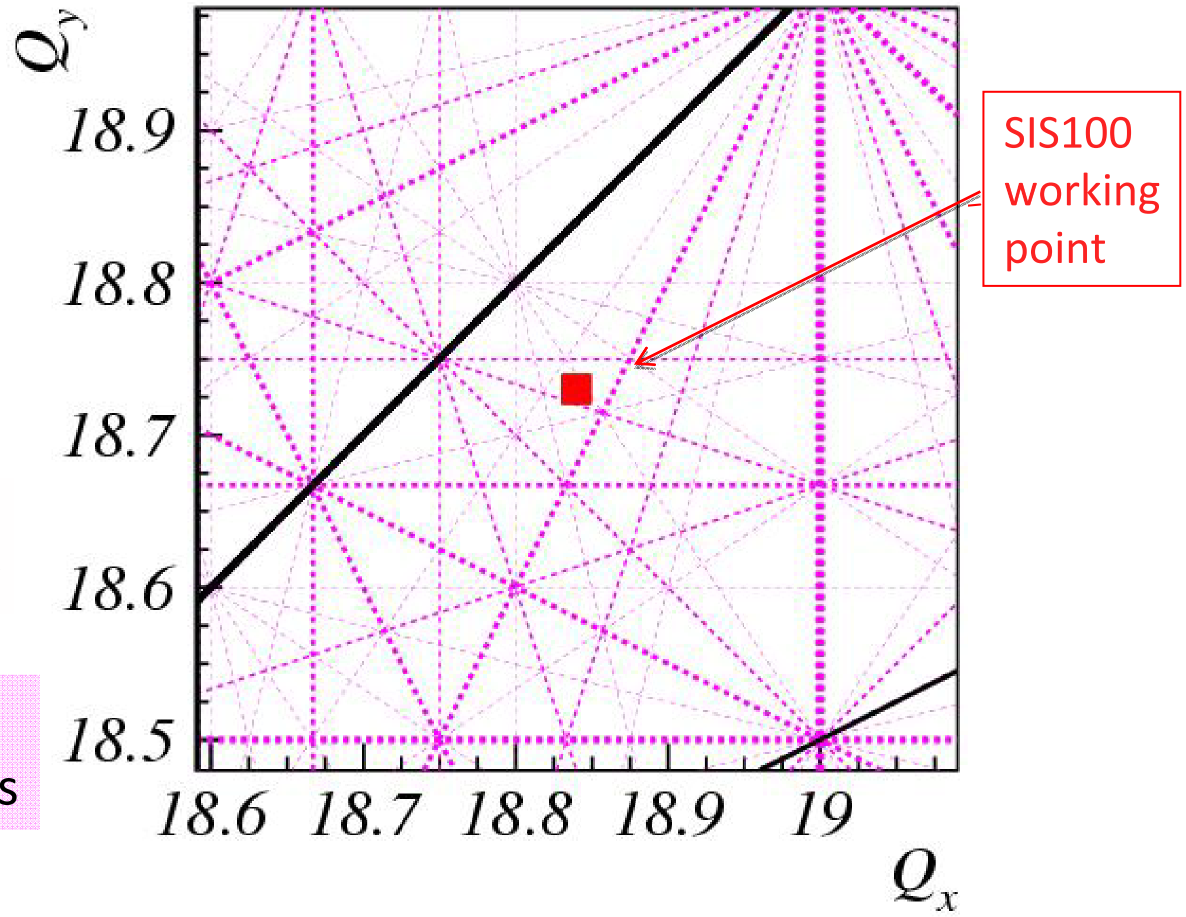
Montague stop-band must be avoided

Space charge induced periodic resonance crossing

Systematic resonances

Random resonances

Qx = 18.84, Qy = 18.73



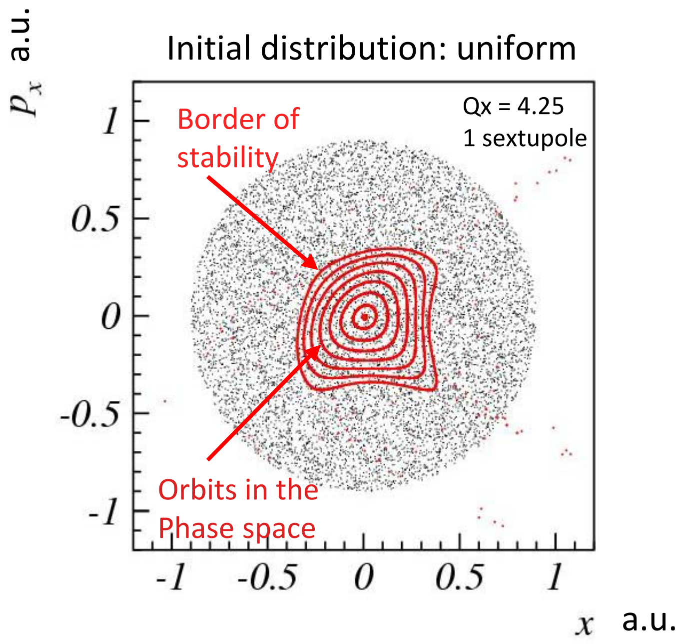
I.Hofmann,G. Franchetti, GSI report 2005
G. Franchetti et al., EPAC 2006

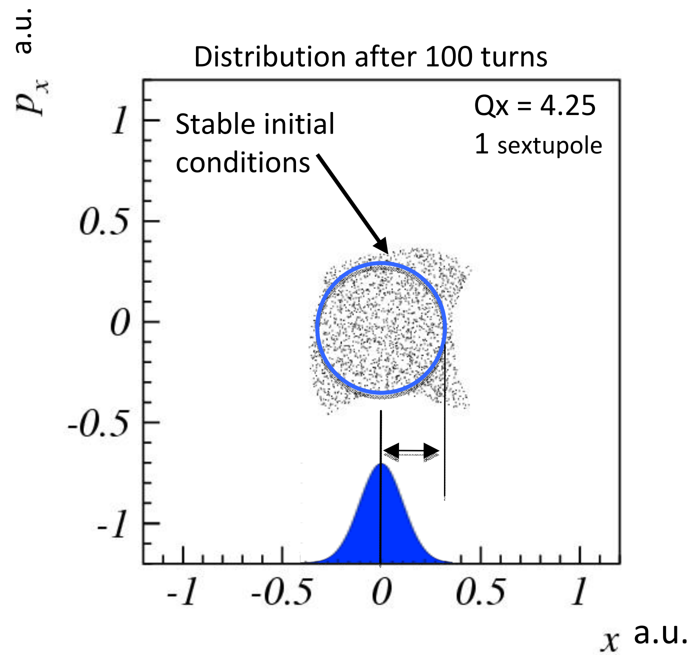
Short term dynamic aperture (ST DA) and its use

We use the ST DA to explore the main feature of the beam dynamics

Definition:	*The maximum circle of stable coordinates inscribed in the stability domain*

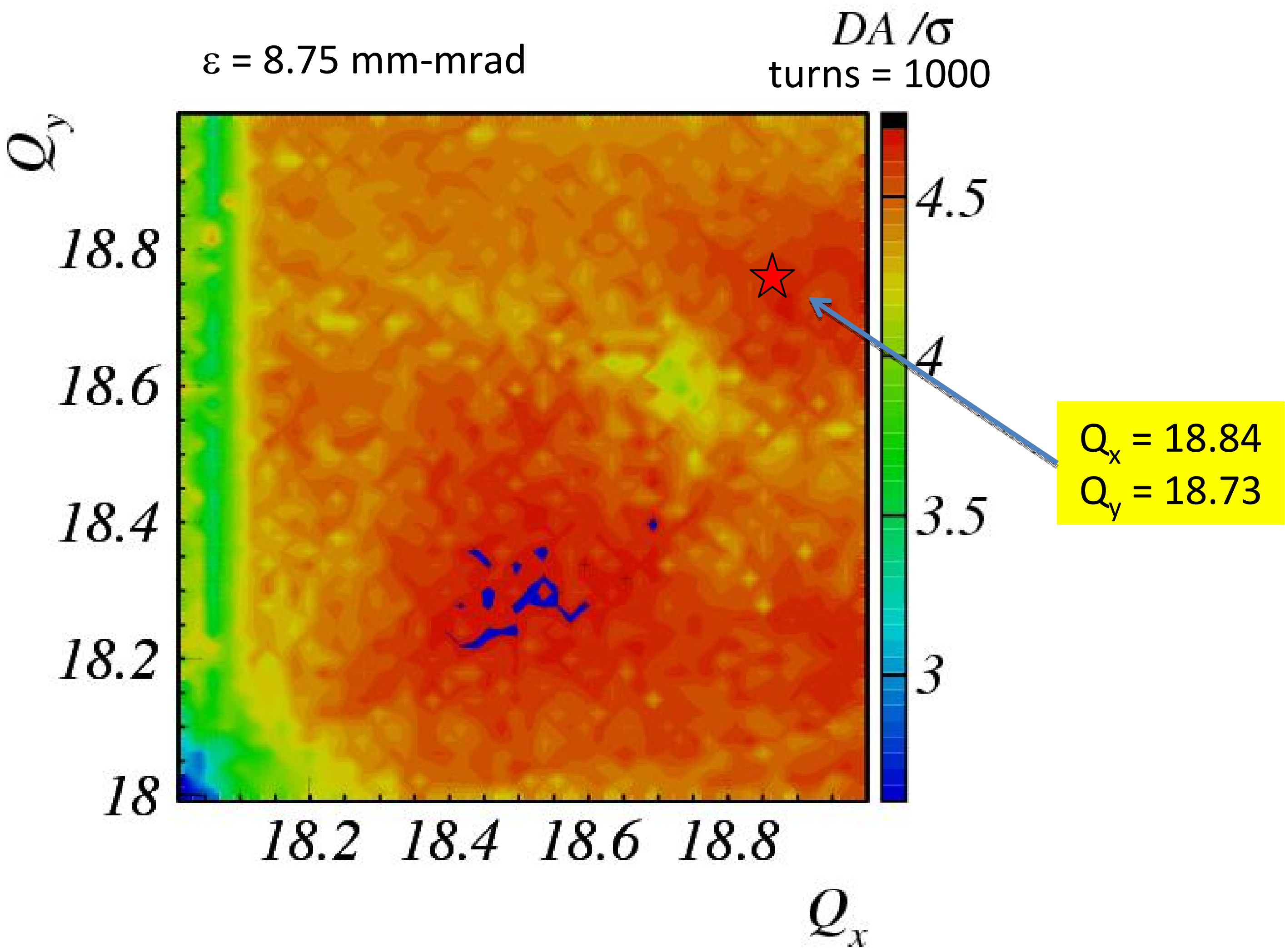
Rescaled DA: we define the DA with respect to the beam size





We use ST DA for first indicator of nonlinear beam dynamic problems

SIS100 dynamic aperture by magnet systematic components



Sources/effect of random errors

Intrinsic magnet errors

Sources of the error is in the magnet: imperfection in the geometry, etc..

Optics dependent induced nonlinear errors

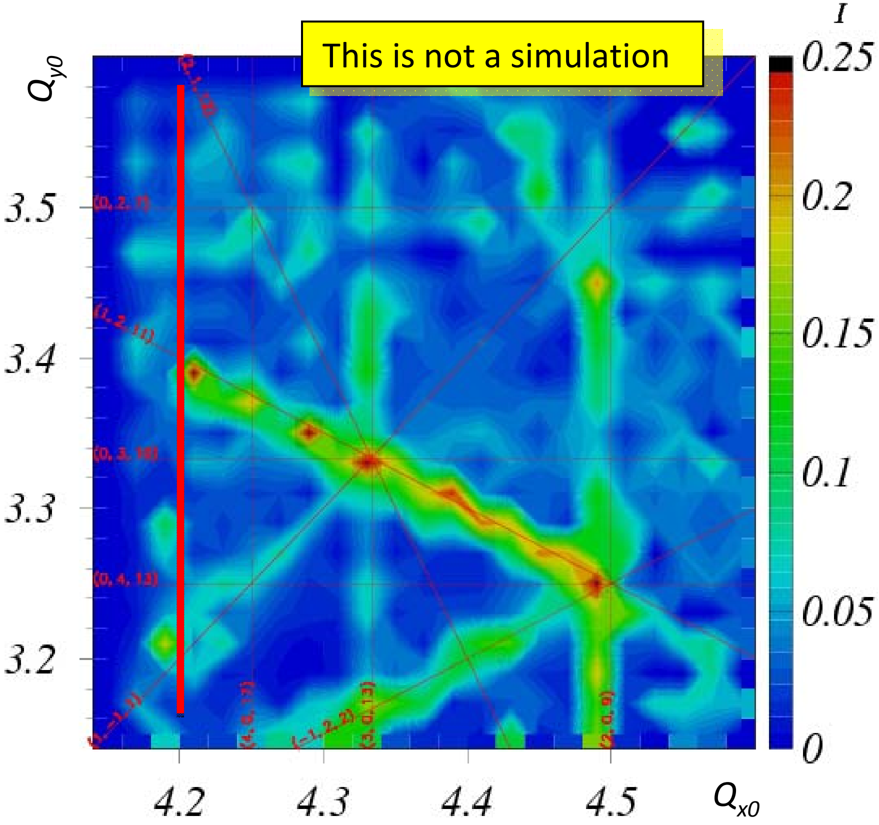
Magnet positioning errors → Closed orbit deformation

↓

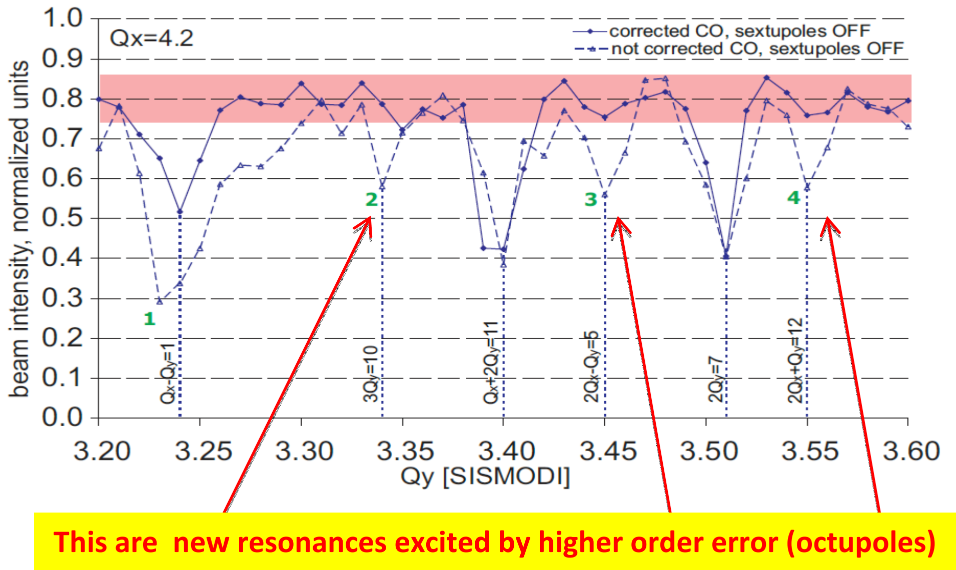
Feed down of intrinsic magnet errors

Experimental verification in SIS18

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



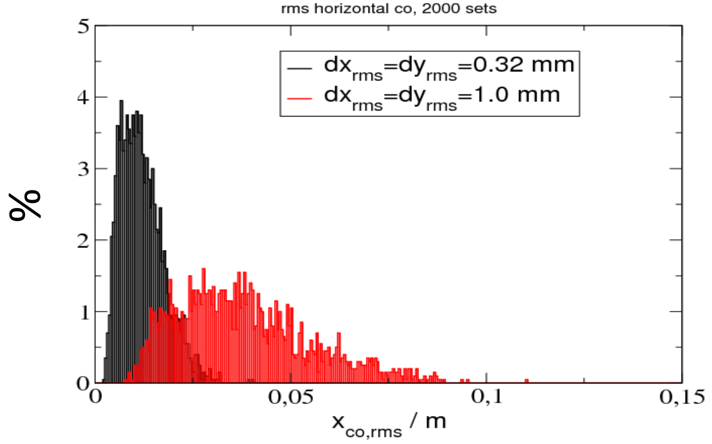
Closed orbit affect resonances and machine tune



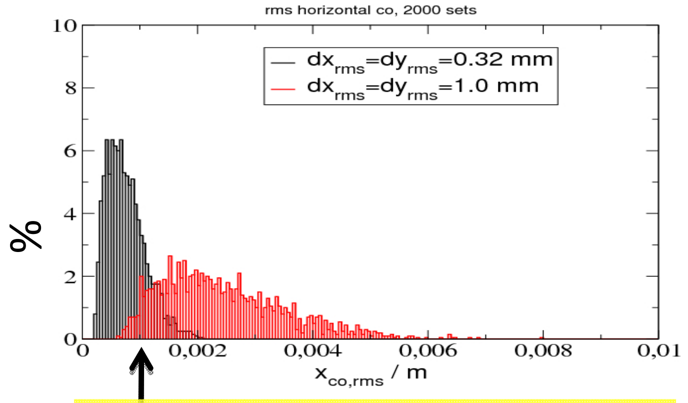
A.Parfenova et al., GSI Report 2008

Closed orbit distortion and DA

before CO correction

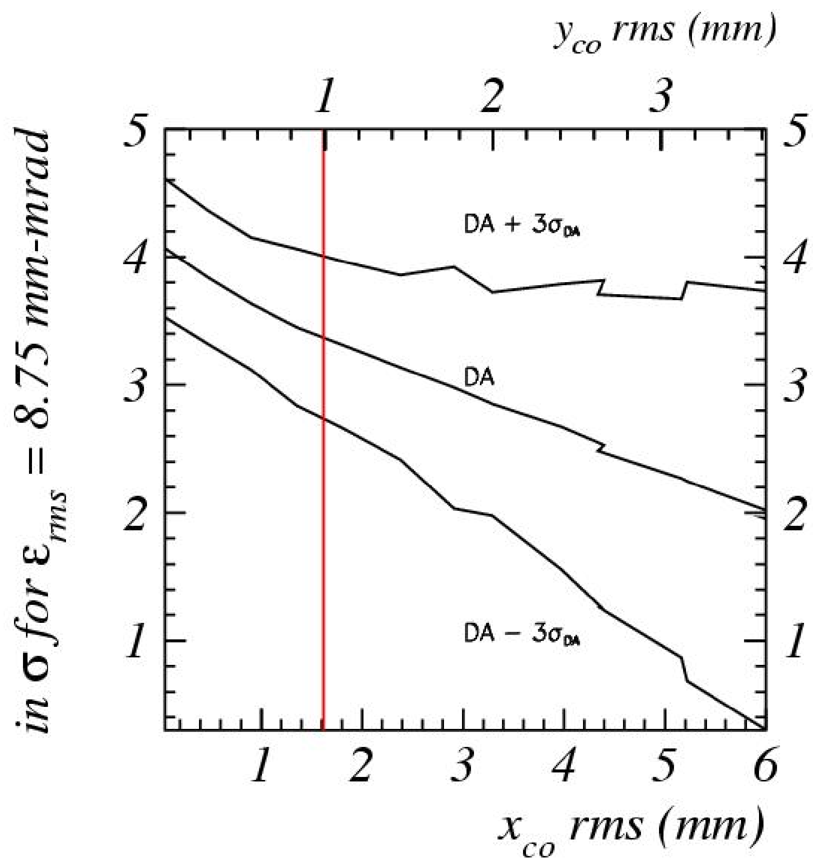


after CO correction



Residual closed orbit of 1-1.4 mm rms

S.Sorge, ACC-note-2009-002



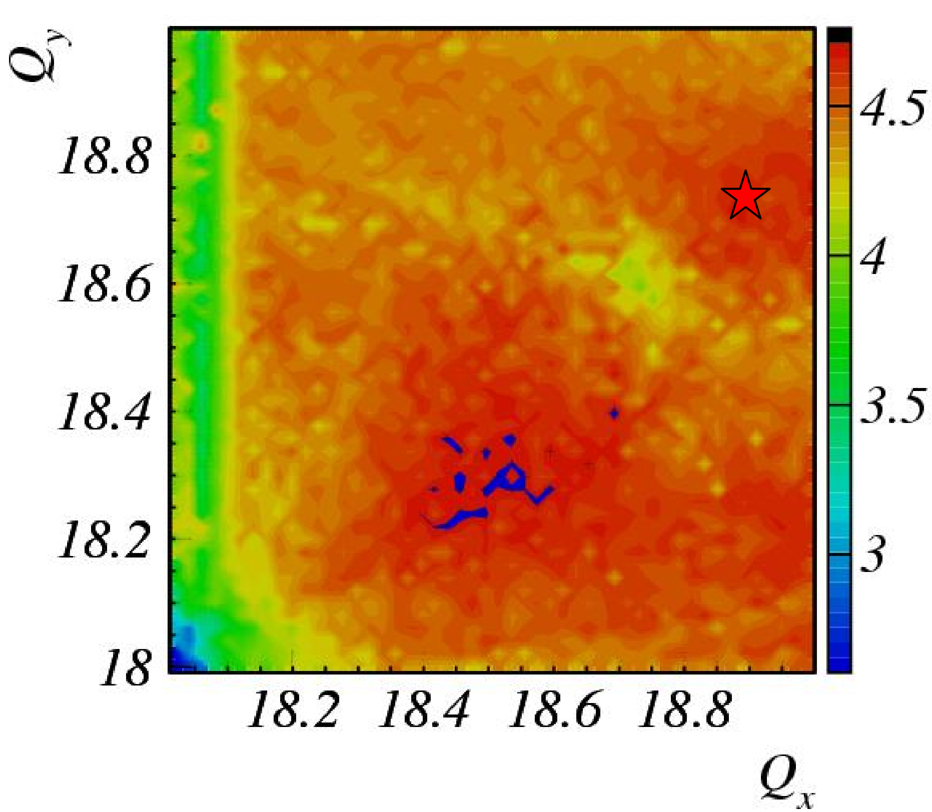
shift in quadrupoles
dipoles: systematic errors
quadrupoles: systematic errors

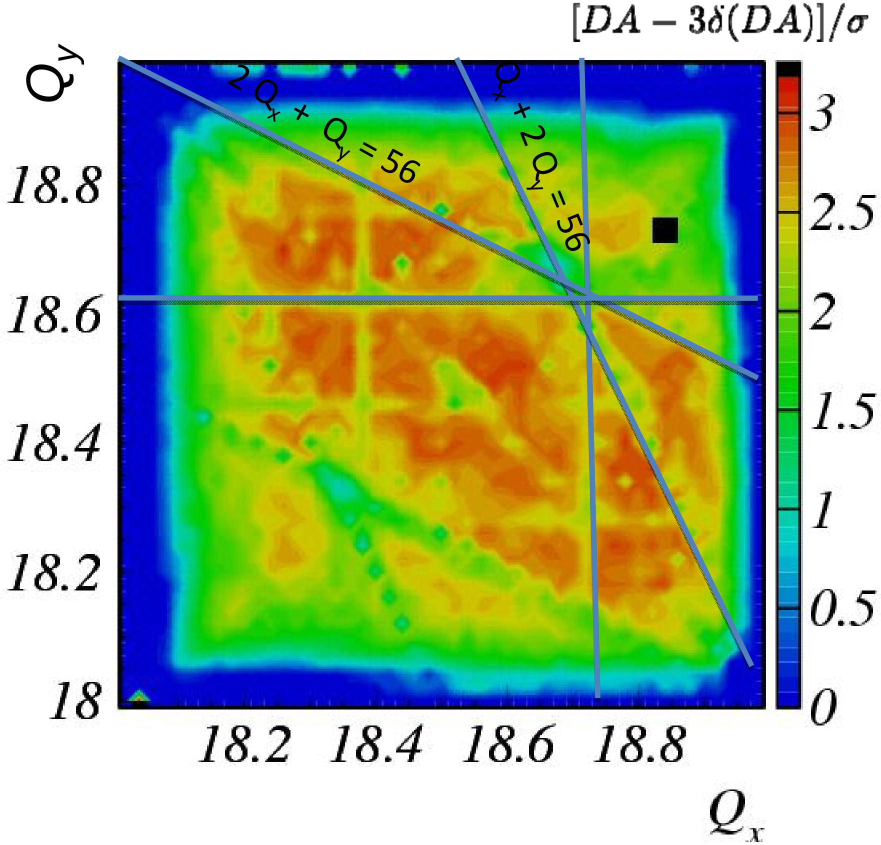
We select a COD of 1 mm rms as residual deformation after COD correction

Random error + COD on ST DA

10 DA scans: random error of 30% on magnet systematic nonlinear components

Only systematic errors





Beam loss without space charge

We make a study for two beams

Beam 1 (2σ): ε_x = 35 mm-mrad, ε_y = 15 mm-mrad
Beam 2 (2σ): ε_x = 50 mm-mrad, ε_y = 20 mm-mrad

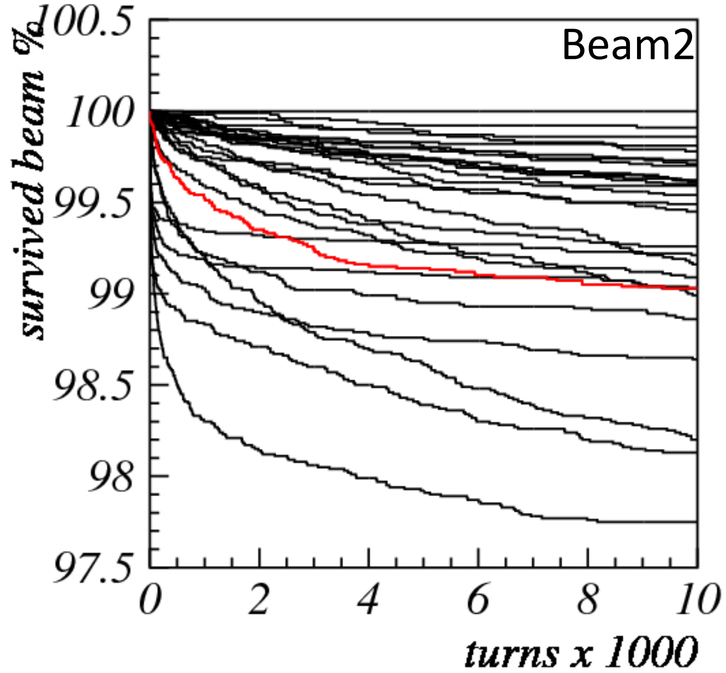
Beam1 edge → 2.5 σ
Beam2 edge → 2.98 σ

DA for systematic errors
DA = 4.7σ

NO beam loss

NO space charge

Beam 10^4 macroparticles coasting beam



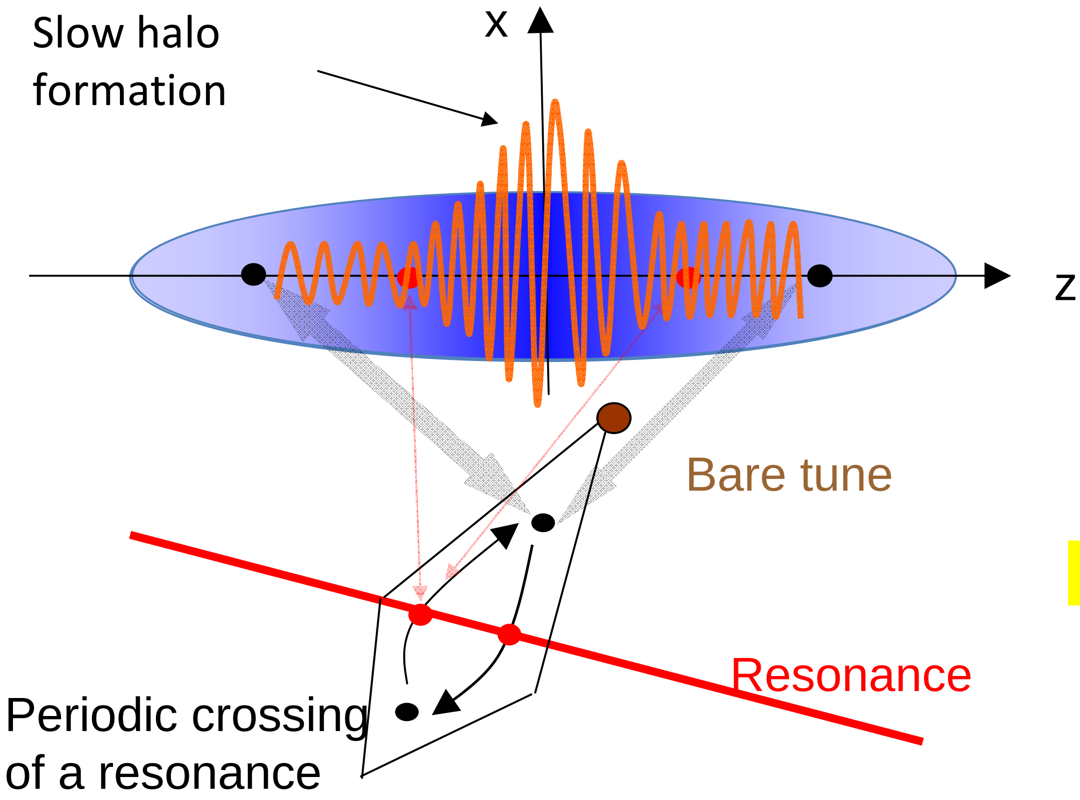
These are 27 simulations of a COD of 1 mm rms

We select one error seed + 1 COD as Standard error case

With Beam1 we find no relevant beam loss

The long term diffusional effects

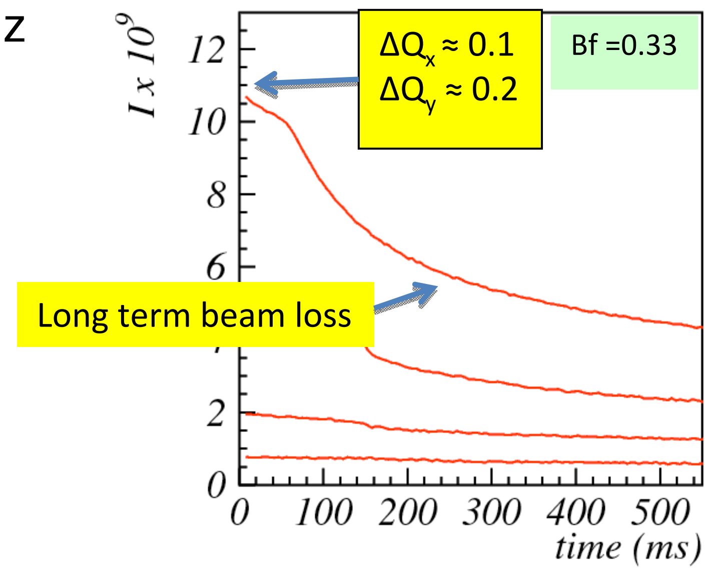
Bunched beams at high intensity stored for a second enhances the transverse-longitudinal coupling



Long term tracking requires frozen model to prevent algorithm noise to create artificial emittance growth

G. Franchetti, I. Hofmann, M. Giovannozzi, M. Martini, E. Metral, Phys. Rev. ST Accel. Beams 6, 124201 (2003). PDF

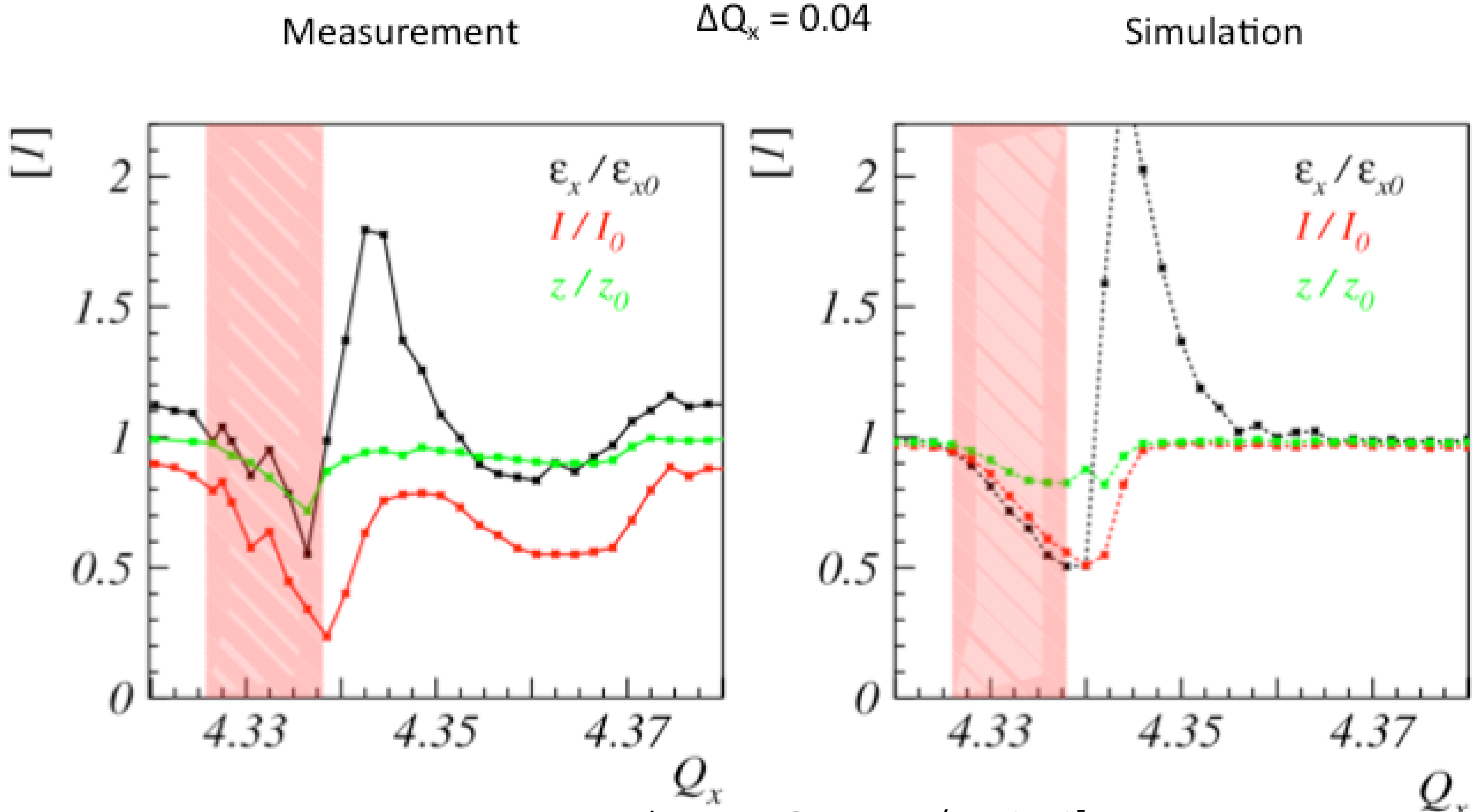
A. Orzhekhovskaya, G. Franchetti Proc. of ICAP 2006, TUPPP05. p. 106.



Code benchmarking with experiments (S317)

Periodic crossing of a 3-order resonance with space charge in SIS-18: Ar^{18+} bunch

Measurements vs. simulation: emittance growth, beam loss and bunch length



1 second storage @ 11.4 Me/u = 2×10^5 turns

G. Franchetti et al., to be published

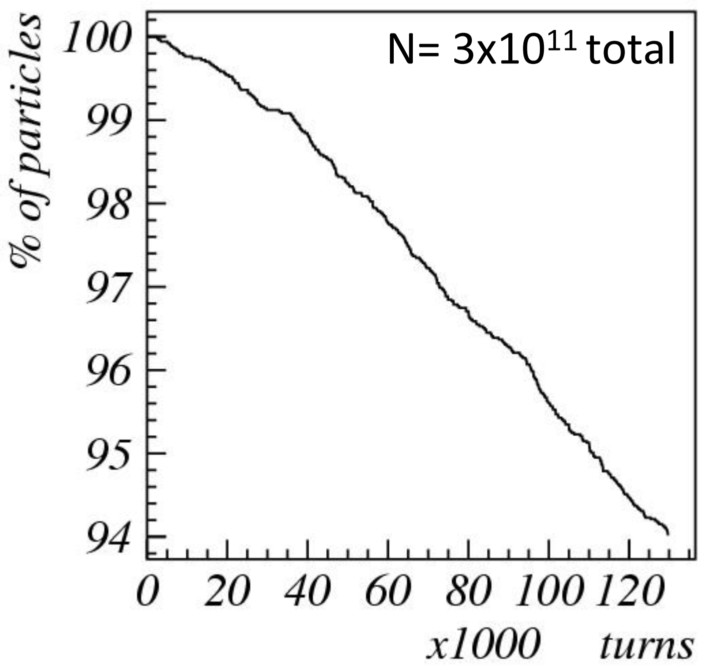
Simulation with space charge

Nominal intensity N = 6 x 10^{11}

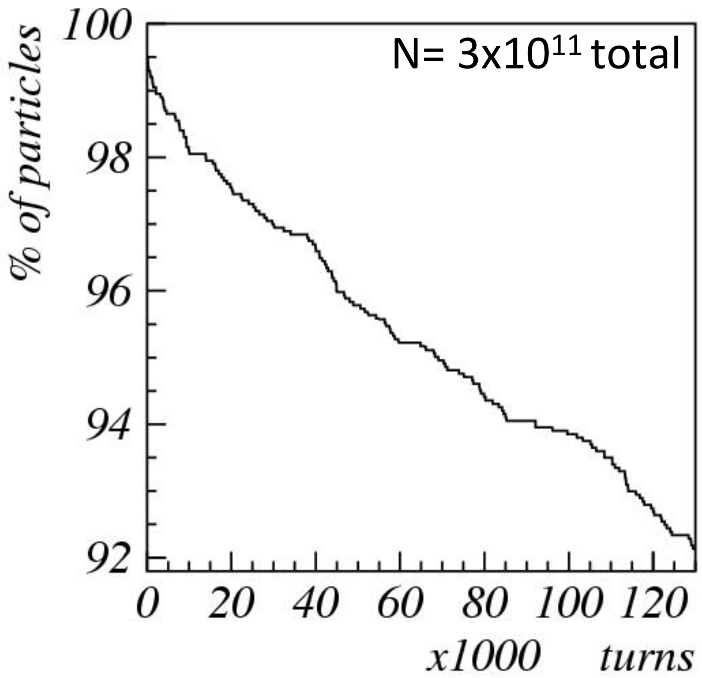
Beam 1: -0.26 / -0.40 (-0.31 / -0.47) @ 0.75 x 10^{11}
Beam 2: -0.18 / -0.29 (-0.21 / -0.34) @ 0.75 x 10^{11}

Chromaticity included
B_f = 0.33

Beam 1



Beam 2



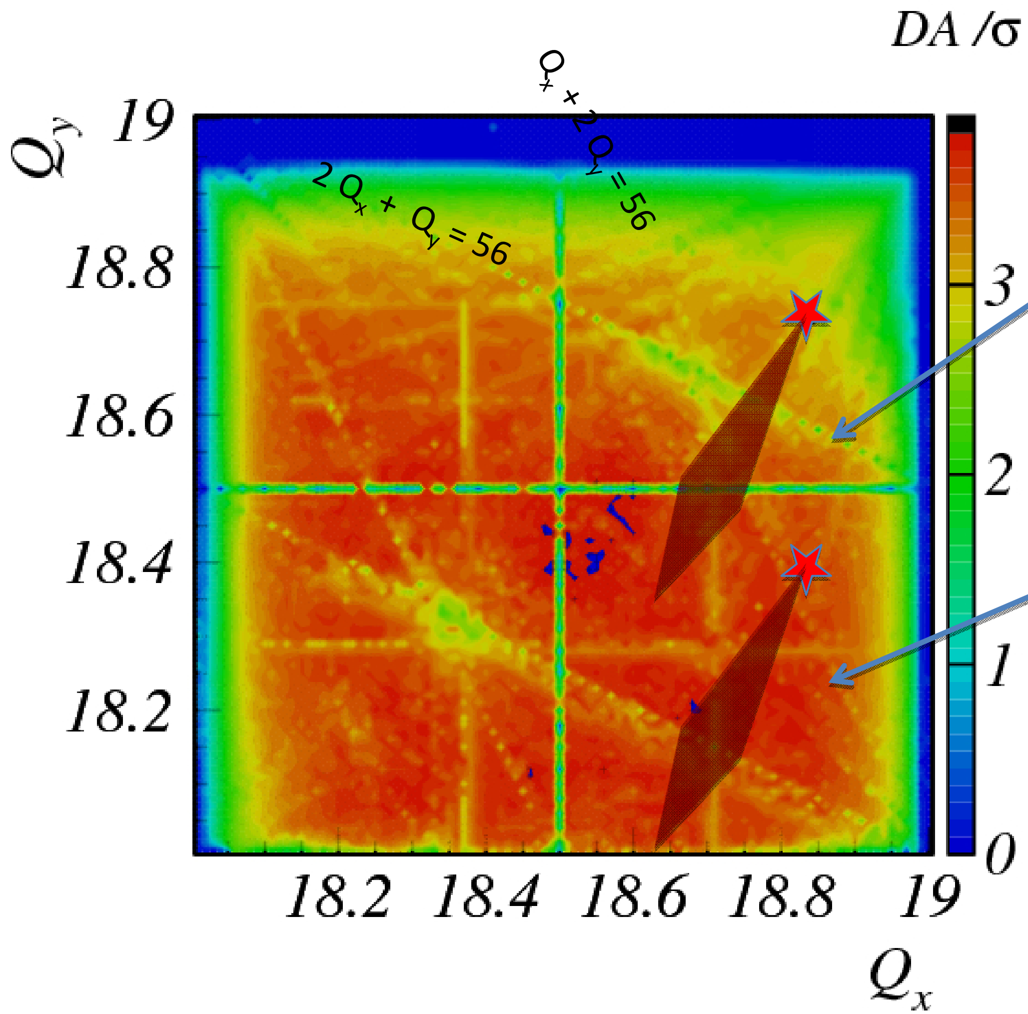
resonance driving beam loss $Q_x + 2\,Q_y = 56$

Summary of beam loss

For the "standard error case"

		WP1 Qx = 18.84 Qx=18.73		WP1- alternative Qx=18.84 Qy=18.40	
		Beam 1	Beam 2	Beam 1	Beam 2
	Emittances Ex/Ey	35/15	50/20	35/15	50/20
Full intensity	Total Particles	$6x10^{11}$	$6x10^{11}$	$6x10^{11}$	$6x10^{11}$
	Beam survival	75 %	78 %	87%	86%
Half intensity	Total Particles	$3x10^{11}$	$3x10^{11}$	$3x10^{11}$	$3x10^{11}$
	Beam survival	97%	96 %	95%	91%

DA for the "standard error case"



resonance affecting WP1

resonance affecting WP1-alternative

Conclusion

The challenge of the nonlinear dynamics for the high intensity beams in the SIS100 has required the development of unique tools for the understanding of a worldwide unique high intensity operation regime.

Experiments in SIS18 confirm and extend CERN-PS measurements and our understanding of the underlying mechanisms (S317)

These studies show that beam survival up to 90% is possible at half intensity and ≈85% for full intensity

Chromaticity correction – or partial – will improve beam loss budget: compensation scheme of relevant resonances is necessary

Full beam intensity requires flexibility on the choice of the working point to take into account the actual resonance strength

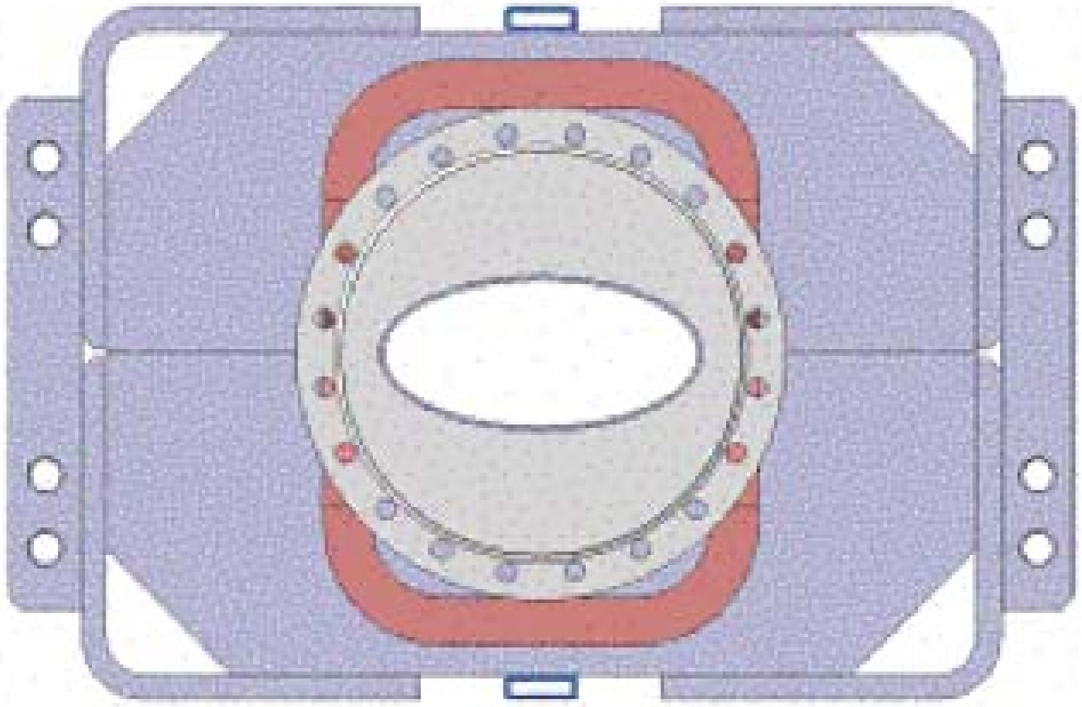
Double RF system for enhancing bunching factor for 0.333 to 0.5 should be foreseen: experimental tests in SIS18 are foreseen (S356)

Work in progress for SIS100

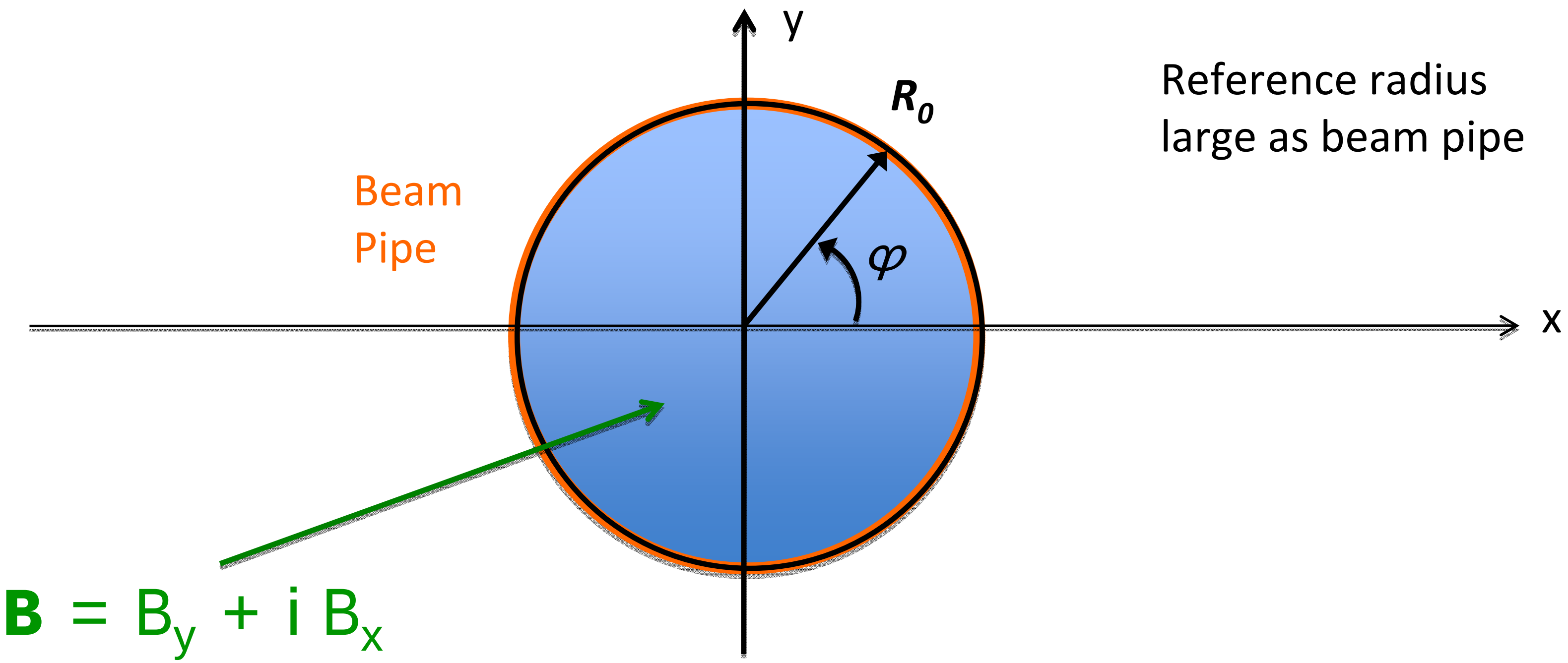
- Assess the space charge self-consistency on beam loss
- Studies on the effect of lattice nonlinearities and chromaticity correction system on slow extraction
- Effect of full random error and all misalignments on beam loss (machine resonances and space charge)
- Effect of the SIS100 nonlinear dynamics and high intensity on the efficiency of Halo scrapers
- Evaluation of dangerous field component and their level of compensation: studies on effect of space charge on the efficiency of resonance compensation in a resonance periodic crossing regime

The SIS100 dipole magnets

Magnets are characterized by an elliptic cross section



Calculation of multipoles

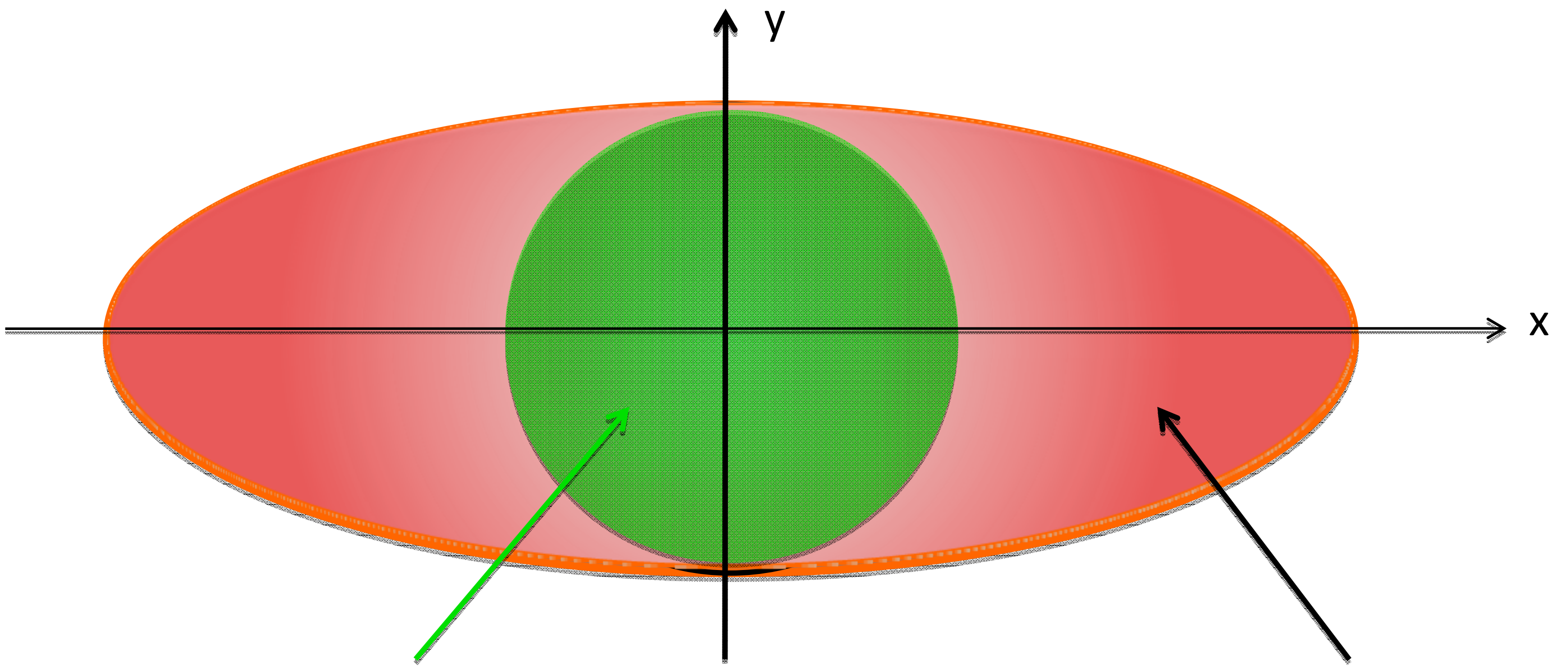


Reference radius
large as beam pipe

$$x_c = R_0 \cos\phi$$
$$y_c = R_0 \sin\phi$$

$$b_n + i a_n = \frac{1}{2\pi B_0} \int_0^{2\pi} d\phi (B_y + i B_x)|_{(x_c, y_c)} e^{-in\phi}$$

Limits of Cartesian multipoles



B = B_y + i B_x

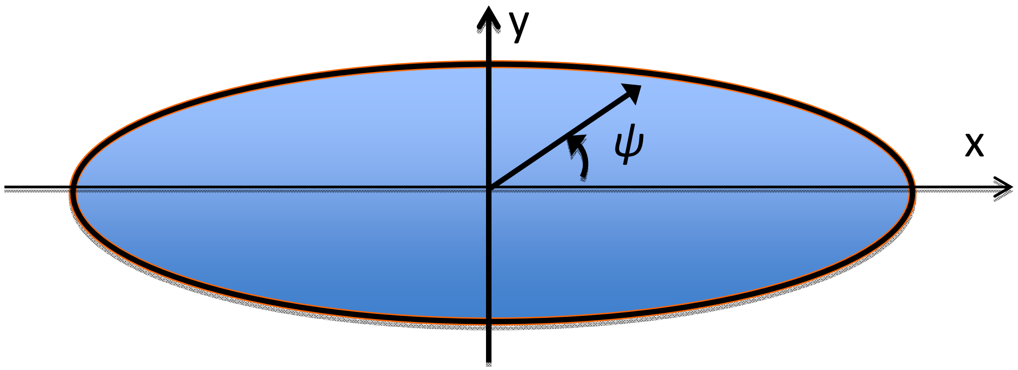
Well described

B = B_y + i B_x

Is it the magnetic field well reconstructed ??

Elliptic multipoles

Laplace equation can be solved in an elliptic reference frame



$$x = e \cosh \eta \, \cos \psi$$
$$y = e \sinh \eta \, \sin \psi$$

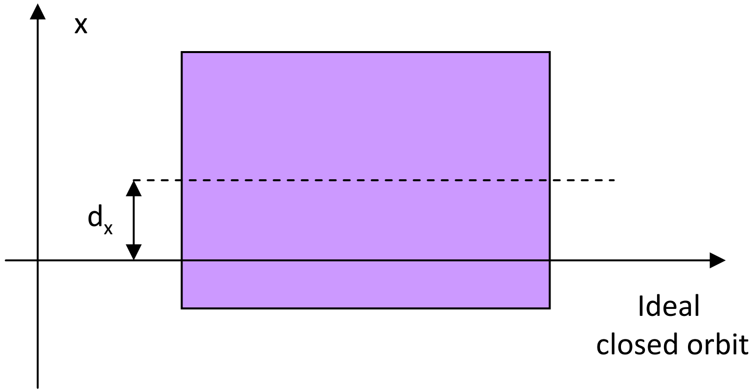
$$B_y + iB_x = A_0 + \sum_{m=1}^{\infty} \left[A_m \frac{\cosh(m\eta)}{\cosh(m\eta_0)} \cos(m\psi) + B_m \frac{\sinh(m\eta)}{\sinh(m\eta_0)} \sin(m\psi) \right]$$

$$A_m = \frac{1}{\pi} \int_0^{2\pi} d\psi (B_y + iB_x)|_{x_e, y_e} \cos(m\psi)$$
$$B_m = \frac{1}{\pi} \int_0^{2\pi} d\psi (B_y + iB_x)|_{x_e, y_e} \sin(m\psi)$$
$$D_m = \frac{1}{2\pi} \int_0^{2\pi} d\psi (B_y + iB_x)|_{x_e, y_e} e^{-m\psi}$$

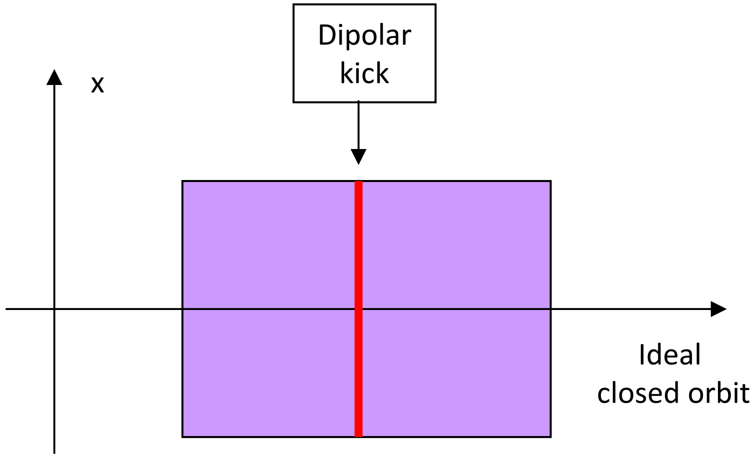
P. Schnizer et. al., february 9th, 2007

Effect of closed orbit deformations

A displacement of a quadrupole orthogonal to its longitudinal axes creates a **dipolar** component



Equivalent to



Integrated strength

Focusing plane $$K_0 = 2\sqrt{|k_x|}d_x \sin(\sqrt{|k_x|}L/2)$$

Defocusing plane $$K_0 = -2\sqrt{|k_x|}d_x \sinh(\sqrt{|k_x|}L/2)$$

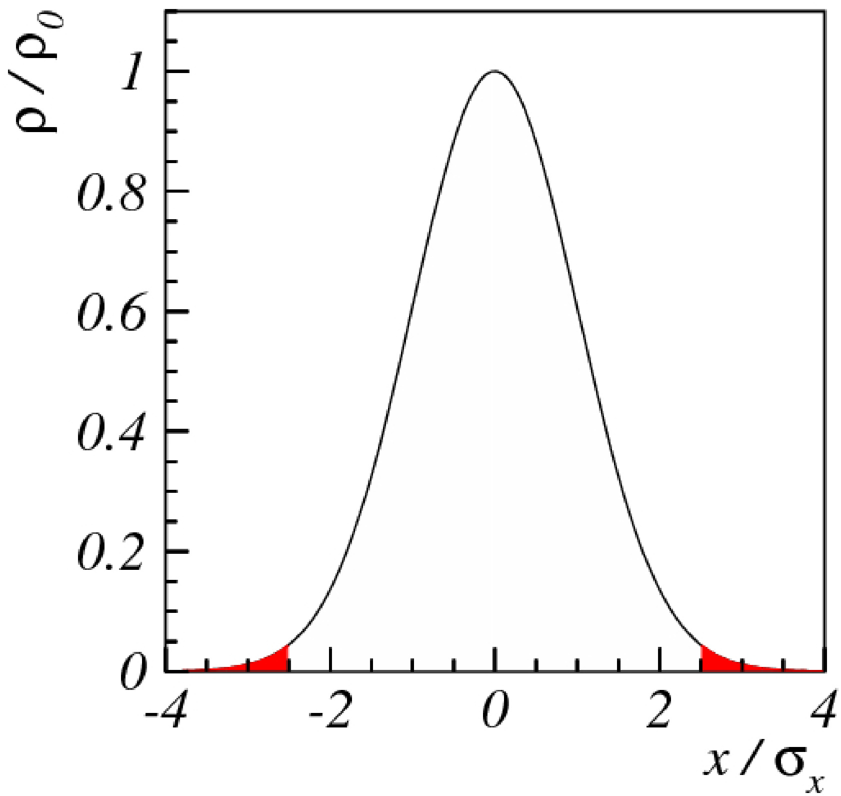
For d_x = 0.3 mm (rms)

K_0 ~ 8 x 10^{-5} rad (rms)

Closed Orbit Distortion

Beam distribution

The beam distribution is truncated Gaussian distribution



1 Create a full Gaussian distribution

2 cut the distribution at 2σ in energy

We speak of emittance of the un-cut distribution. The cut distribution has 15.6% smaller emittance

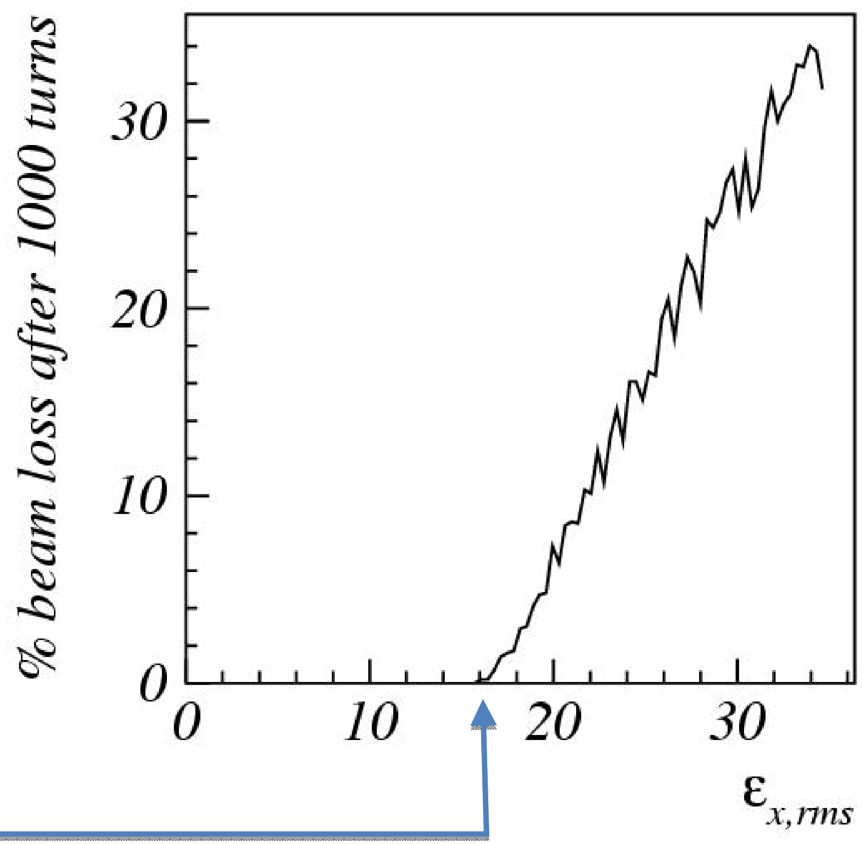
Test of linear acceptance

Control of the beam loss
vs acceptance

NO space charge
NO magnet nonlinear errors
NO closed orbit distortion

Constant ratio $\varepsilon_x / \varepsilon_y = 3$

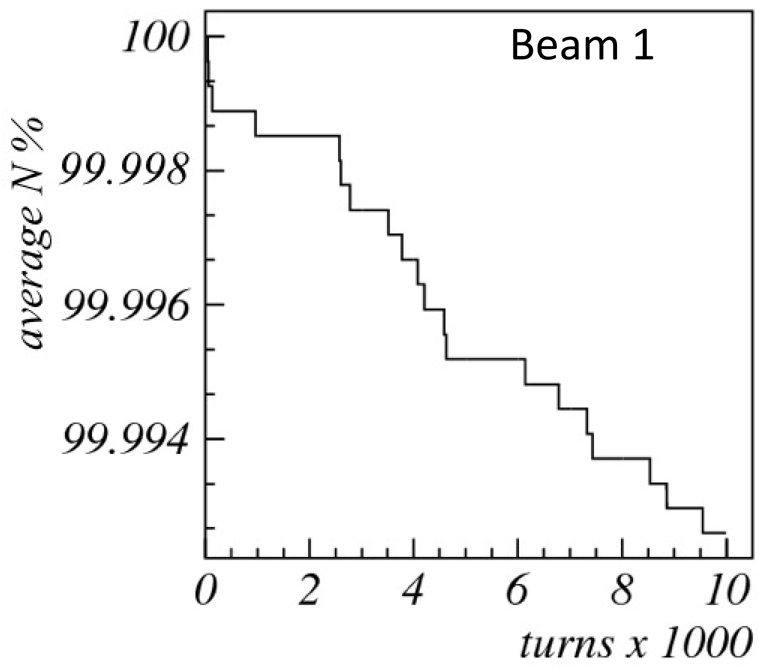
The edge emittance corresponds to $16 \times 2.5^2 = 103$ mm-mrad

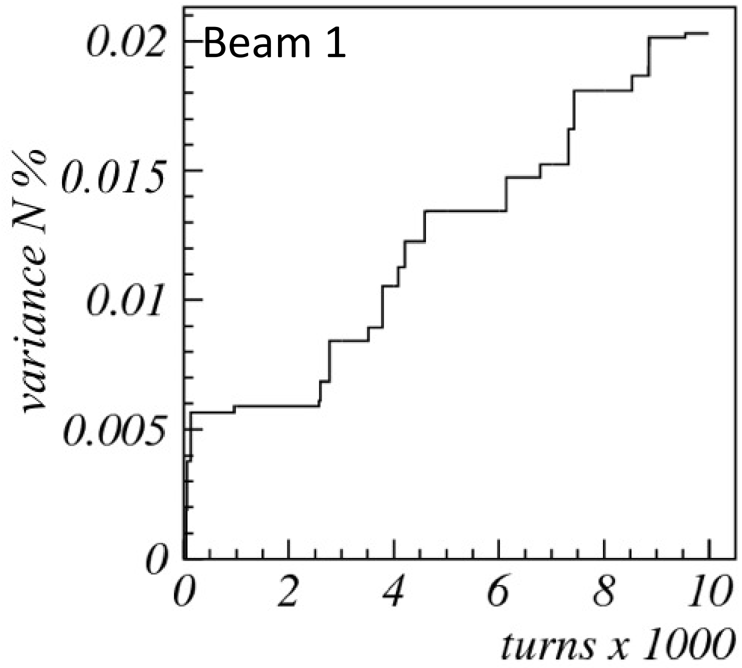


Study over 27 seeds for a fixed COD

Included magnet random error + quadrupole random transverse shift to create COD rms = 1 mm

No relevant beam loss are found

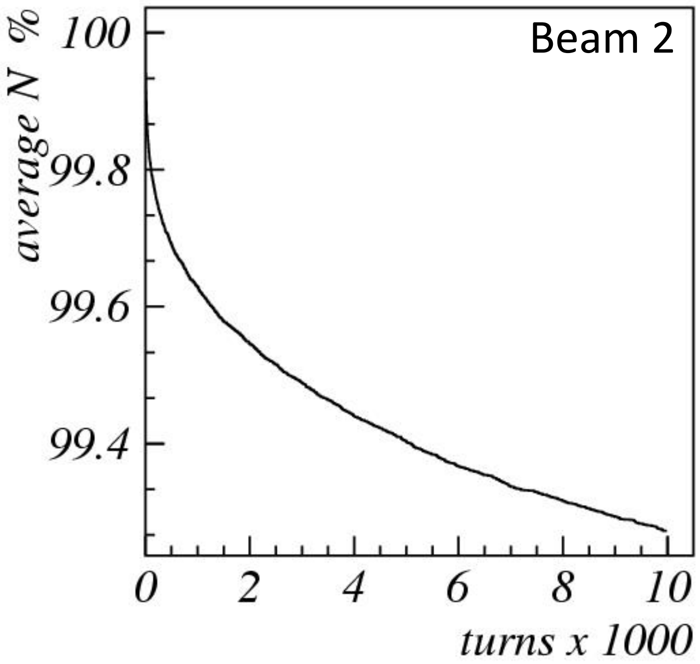




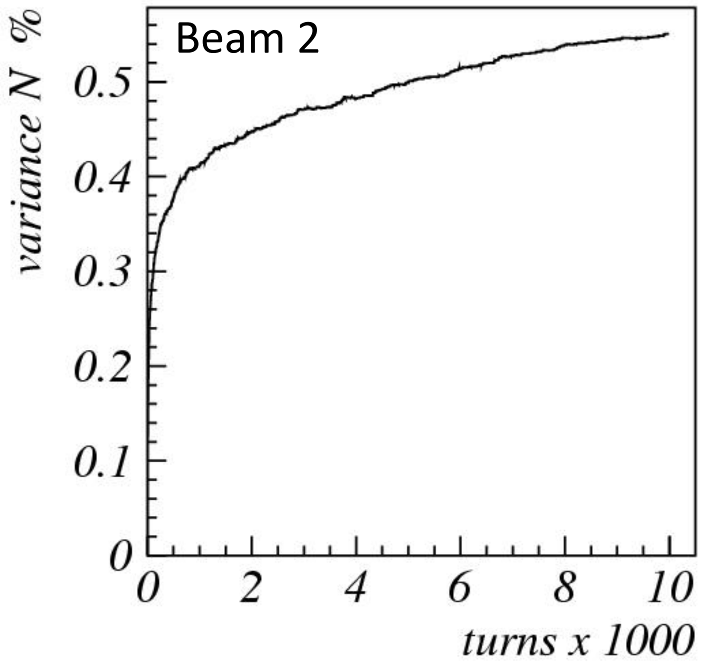
Study over 27 seeds for a fixed COD

No space charge
NO chromaticity

Average beam survival



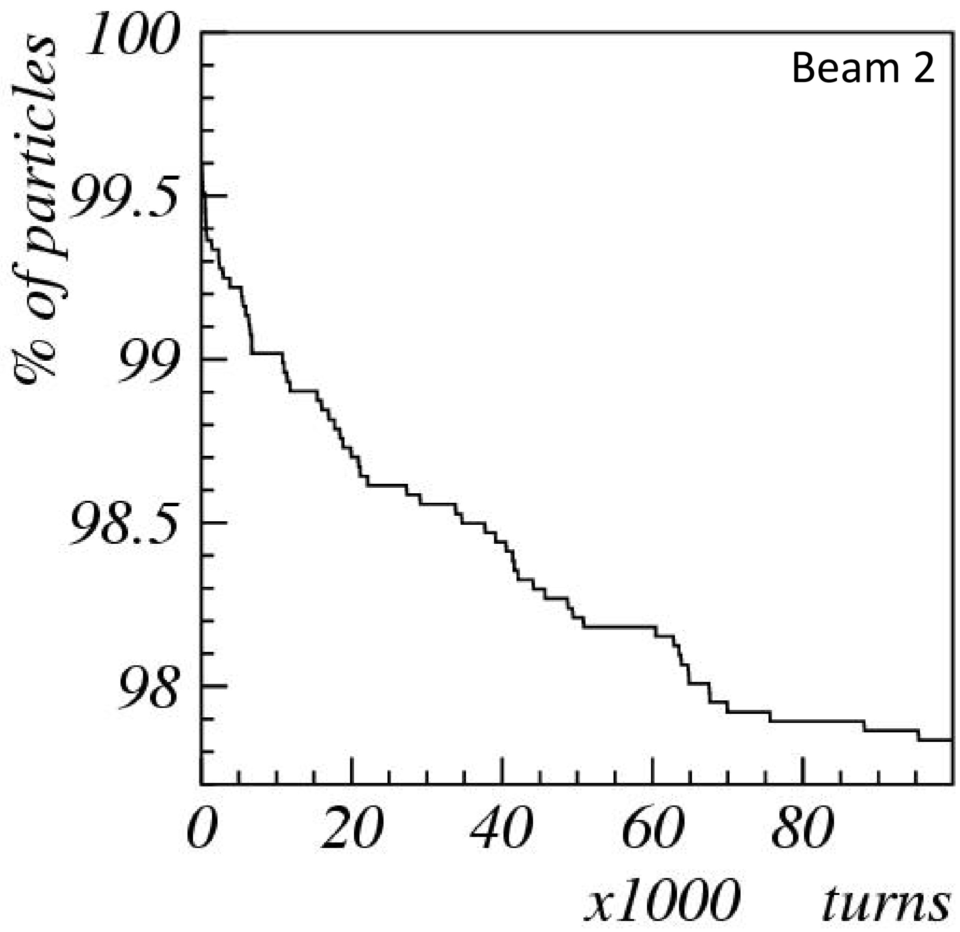
Variance



Test of long term beam loss for a bunched beam

NO space charge
NO chromaticity

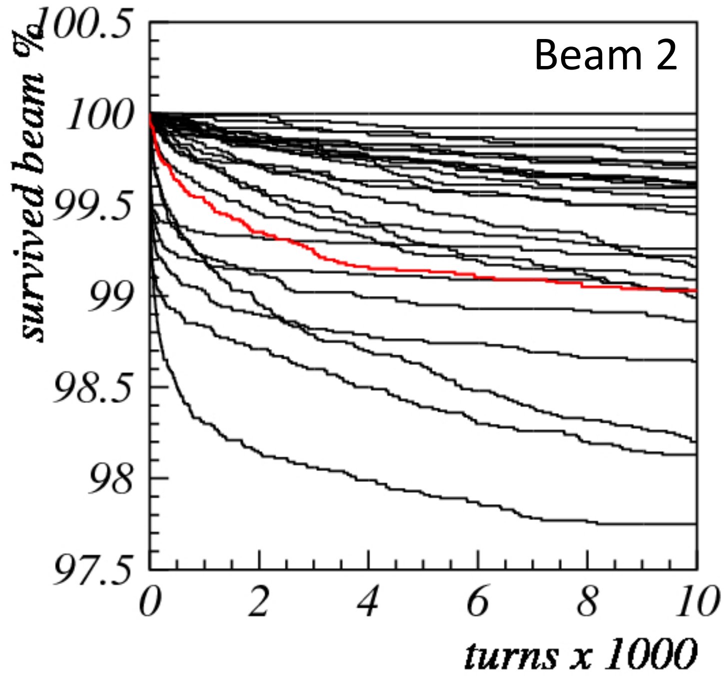
Test long term beam loss due to pure nonlinear dynamics



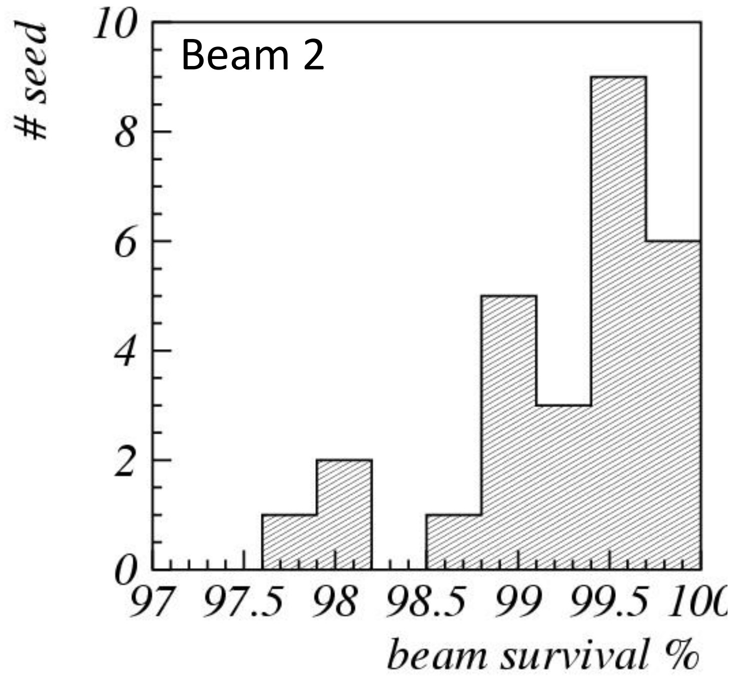
Beam2: Statistics

Long term beam loss/ emittance growth are very CPU time expensive when space charge is included

We select on error case which creates 1% beam loss: “standard error case”



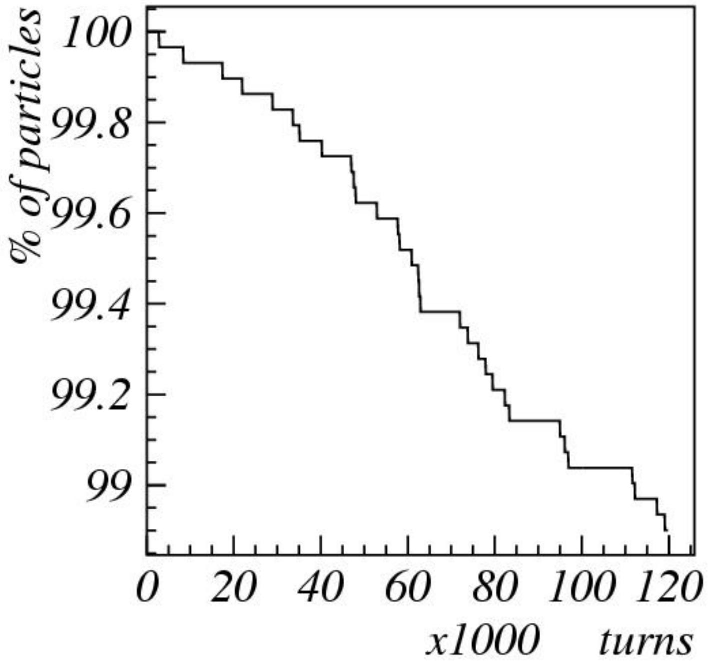
Beam loss distribution after 10^4 turns



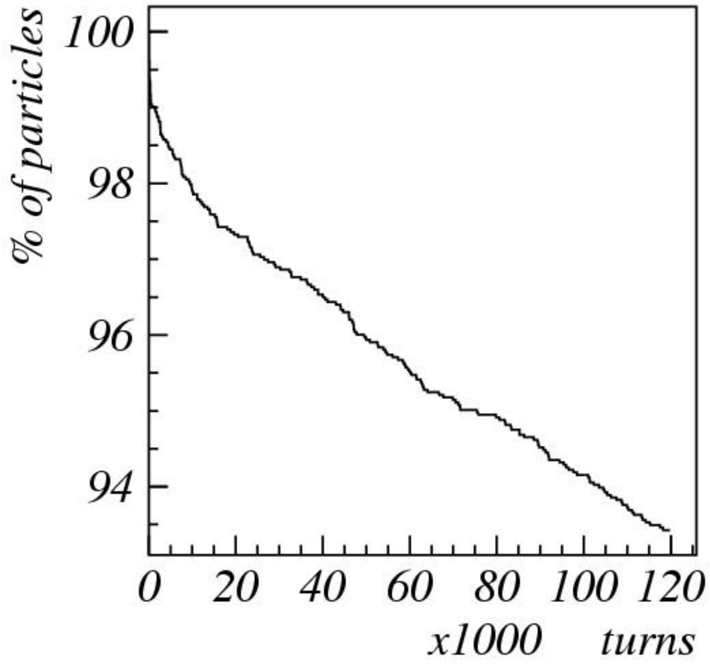
Beam loss including chromaticity effects

$B_f = 0.33$ Bunch length = +/- 90^0 $(\delta p/p)_{rms} = 5x10^{-4}$

Beam1



Beam2



WP1 alternative

Qx = 18.84 Qy = 18.40