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Space charge simulation using MAD-X with account of longitudinal motion

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Contents

- Collaborations: MADX (ITEP & CERN),

  GSI (SIS18 & SIS100), FNAL (deb. mu2e)
- Approach & methods overview
- 4D & 6D benchmarking for SIS18 (GSI, 2009)
- Applications: DA & Beam losses (TWAC, SIS100)
- MADX-script algorithm for variable lattice with 6D
- Debuncher with ORBIT(6x6matr.)-lattice by VN
- Debuncher with MAD8 (SW)->MADX + BB

ITEP-CERN collaboration on MADX in 2004-2006

- MAD-X is the successor of MAD-8 (frozen in 2002).
- MAD-X has a modular organization => Team:
  custodian (F.Schmidt) + Module Keepers
- “PTC-TRACK module” is developed by V.Kapin (ITEP) & F.Schmidt (CERN)

MAD-X Home Page:
“http://mad.home.cern.ch/mad/”

Initial plans for S.C. in 2006

- Two options are discussed

I) **thin-lens-tracking** II) thick-lens (PTC-library):

I.a) usage a “linear” kick-matrix for Twiss parameters (b);

I.b) a space-charge kicks from "frozen beam" “BB-kicks” during tracking;

II) Model using a new PTC elements (many “Beam-Beam”)

Presently: BB are in PTC-library (done by E.Forest), but interfacing with MADX -> ??? (manpower required)

WE USE ONLY 1-st option for MADX with Sp.Ch. !!!

MADX+ sp.ch. chronology

- 2007-08 – 4D sp.ch. for DA in TWAC storage ring (ITEP); RuPAC'08 (FRCAU03 at JACOW)
- 2009 – 4D & 6D sp.ch benchmarking SIS18 (GSI) vs SIMPSONS, MICROMAP codes:
  report TH5PFP023 at PAC'09
- 2009 – 6D sp.ch beam-loss evaluations for SIS100 (GSI): report TH5PFP023 at PAC'09
- 2010 (Jan-Mar) at FNAL: GSI-MADX-script for variable lattice with 6D for FNAL debuncher (mu2e)
- 2010 -> (Apr-July) at GSI: SIS100 tracking with variable multipole contents due at different energies

2. Approaches & methods overview

Thin-lens (option I) "MADX+S.C."

- The whole idea is not a new one.

  For example, references below.

- Presented methods had been already implemented in other beam dynamics codes.
- Our task is a step-by-step adaptation some of them to MADX, which is presently *one of the most advanced code for* ***nonlinear beam dynamics*** *simulations* without space-charge.

M. Furman, 1987 PAC, pp. 1034-1036.

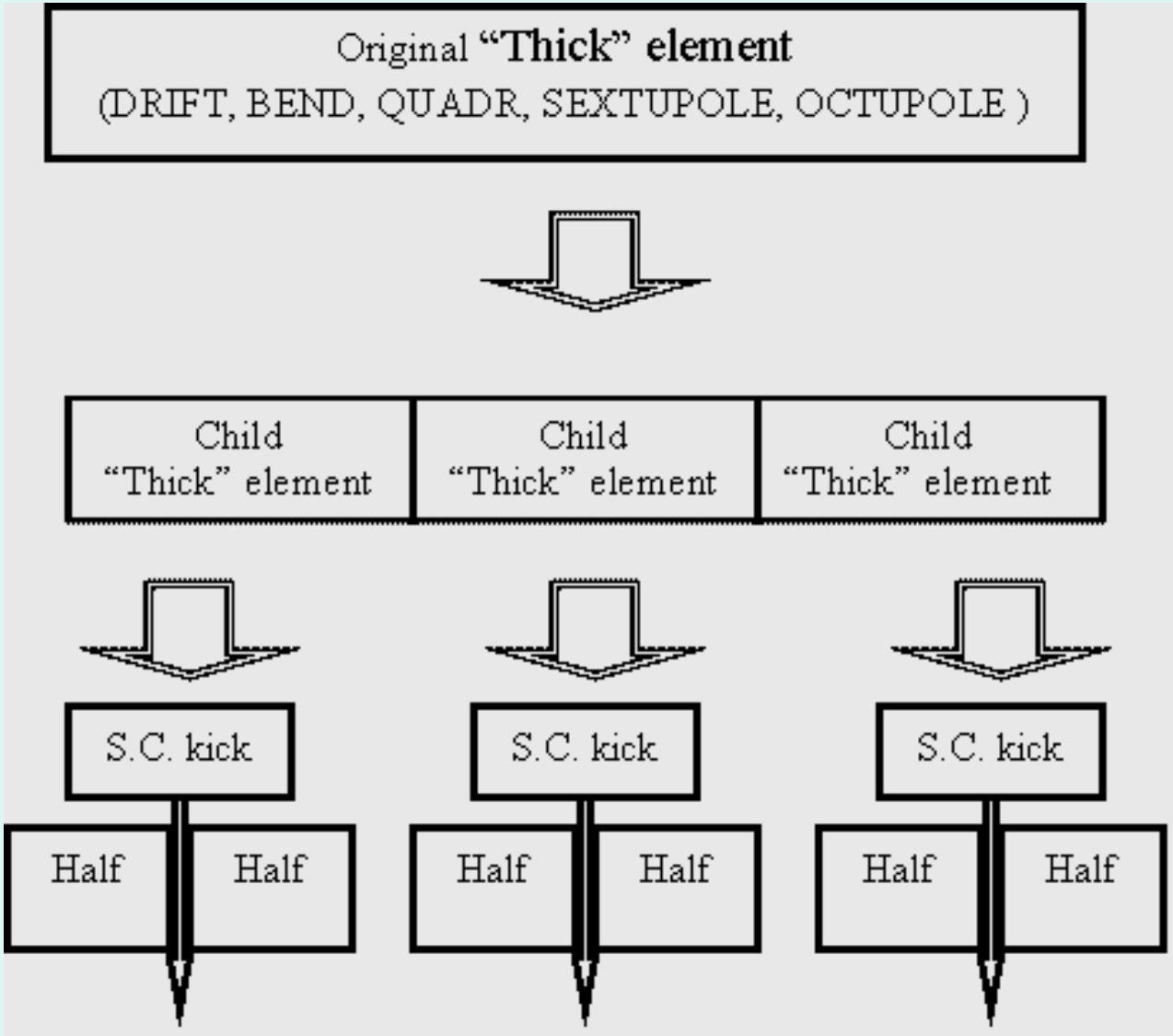
……

Y. Alexahin, 2007 PAC, report code THPAN105.

Features & Algorithm of Direct S.C Simulations with MADX for 4D (coasting beam)

- most work is done using macros of MADX input scripts
- Only 2D(transv.) space-charge fields
- "Frozen" charge distribution either linear (MATRIX) or Gaussian (BB);
- Several space-charge kicks within every thick element (bends, quads, drifts etc.);

The 2nd order ray tracing integrator for a number of S-C kicks



Remind about integrators

1) A. Chao, “Adv. Topics”, USPAS, 2000:

Thick element with the foc. strength S and the length L:

1st order “O(L)”:

a) drift(L)+kick(SL) ; b) kick(SL)+drift(L)

2nd order “O(L^2)”: drift(L/2) + kick(SL) + drift(L/2)

2) MAD-9 project (EPAC’00, TUP6B11):

Hamiltonian: $H=H_{ext}+H_{sc}$ => 2nd order map:

$M = M_{ext}(t/2)\, M_{sc}(t)\, M_{ext}(t/2)$

Ray Tracing: (L/2n)(SL/n)(L/2n) …. repeat n times

Y.Alexahin, A.Drozhdin, N.Kazarinov,
"direct space charge in Booster with MAD8", Beams-doc-2609-v1

1) direct space charge in MAD using set of BEAMBEAM (BB) elements.
Tune shift:

$$\Delta\nu = -\frac{1}{4\pi}\sum_{i=1}^{Nbb}\beta_i K_i$$

where β – the Twiss beta-function at BB location, K – kick acting on the particle, N_{bb} – number of BB elements.

2) The number of particle N' in fictitious colliding beam must be set as:

$$N' = B_f \frac{NL_i}{C(\gamma^2 - 1)}$$

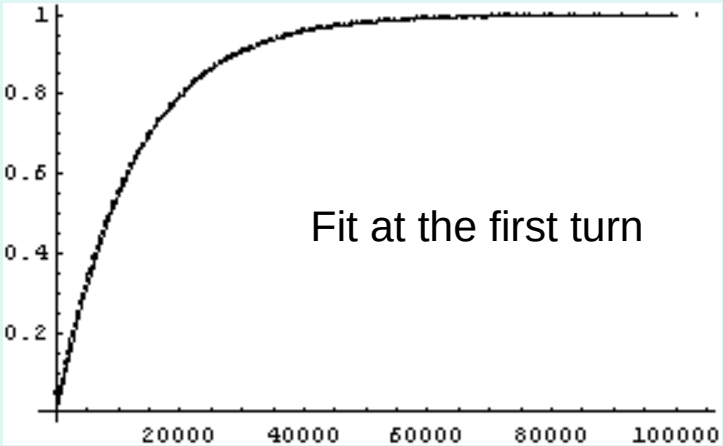
Here B_f – bunching factor, N – number of particle, C – circumference, L_i – distance between successive BB elements, γ – relativistic factor.

3) Simulation with changing emittance from turn to turn of the beam.

The emittance have been evaluated by fitting the integral of distribution function with:

$$F(I) = 1 - \exp(-I/\varepsilon)$$

where I – is action variable.



Self-consistent (linear) BB-sizes

- Space-charge kicks simulated by
  the 1st order MATRIX for
  linear TWISS calculations;
- Linearly self-consistent beam sizes calculated by iterations with the TWISS;
- Analytical Laslett's formula and numerical iterations provide near the same tune shifts (<u>for coasting beam</u> !!!)

$$\Delta\nu_{x,y} \approx -\frac{r_0^{\text{part}} N_{\text{part}}}{2\pi B}\frac{1}{\gamma^3\beta^2}\frac{\beta_{x,y}}{\sigma_{x,y}\left(\sigma_x+\sigma_y\right)}$$

$$\sigma_{x,y}^0 = \sqrt{\varepsilon_{x,y}\beta_{x,y}^0}$$

BB-sizes for 6D simulations

Conte & MacKay, “Intro to Phys. Part. Acc”, 1991,

5.5 Dispersion:

trajectories x(s) is composed of two parts:

a) betatron oscillations $x_\beta(s)$, and particular solution due to dispersion $x_D(s)=D(s)\delta_p$.

b) Statistically beam size is $\sigma^2_{tot}= \sigma^2_\beta + [D(s)\ \sigma_p]^2$

Beam size in bends ($D_x \neq 0$) is

increased for beam with σ_p

Tracking with many BB in 6D

- S.C. kicks by BB-elements for non-linear tracking; (C.O. shifts are included; a total number BB-elements is not limited);
- Thin-lens tracking with MADX (similar to MAD8) with lattice conversion by MAKETHIN command
- Transverse BB-forces are modulated according to longitudinal Gaussian distribution. Two versions:

  a) given “fake” harmonical oscillations (GSI- 2009)

  b) ΔT from real 6D tracking (FNAL-2010)

3. Benchmarking with 4D & 6D simulations using MADX + Sp.Ch. for SIS18 model (GSI, 2009)

vs.

G. Franchetti (GSI), MICROMAP
S. Machida (RAL), SIMPSON

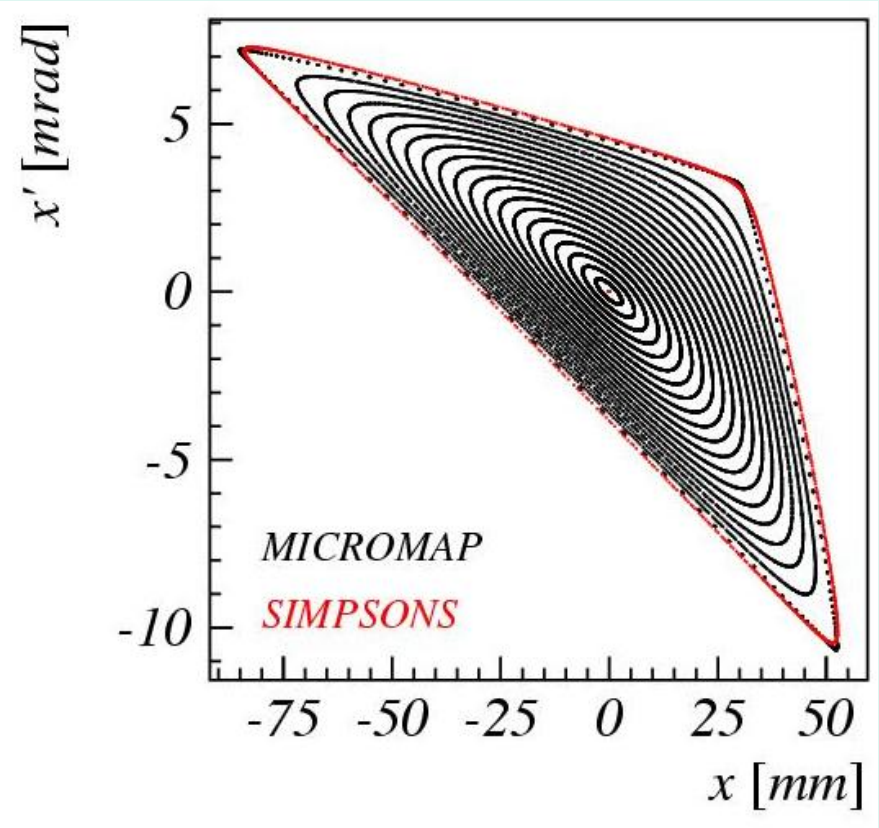
G. Franchetti,

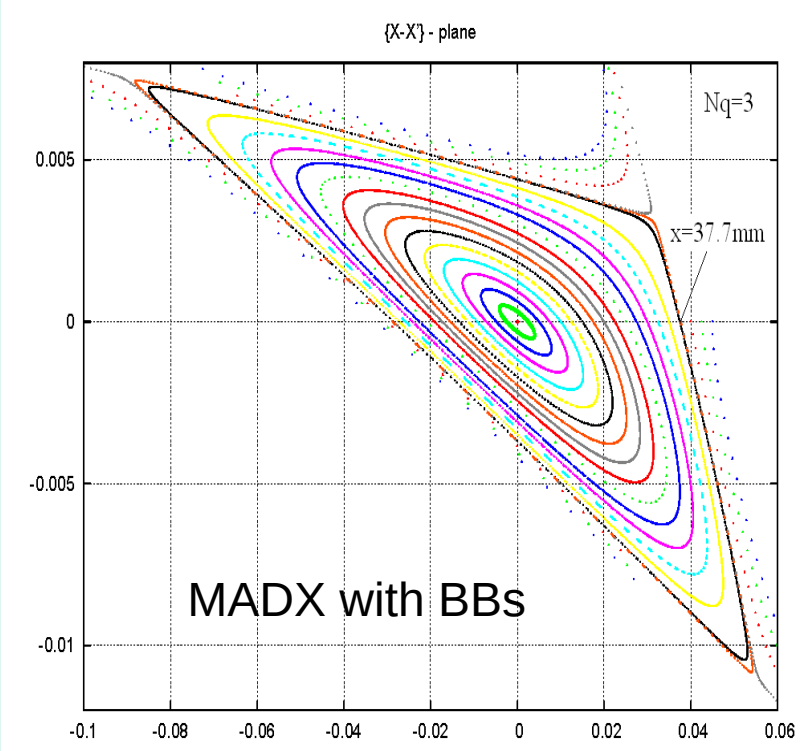
"**Code Benchmarking on Space Charge Induced Trapping":**

http://www-linux.gsi.de/~giuliano/

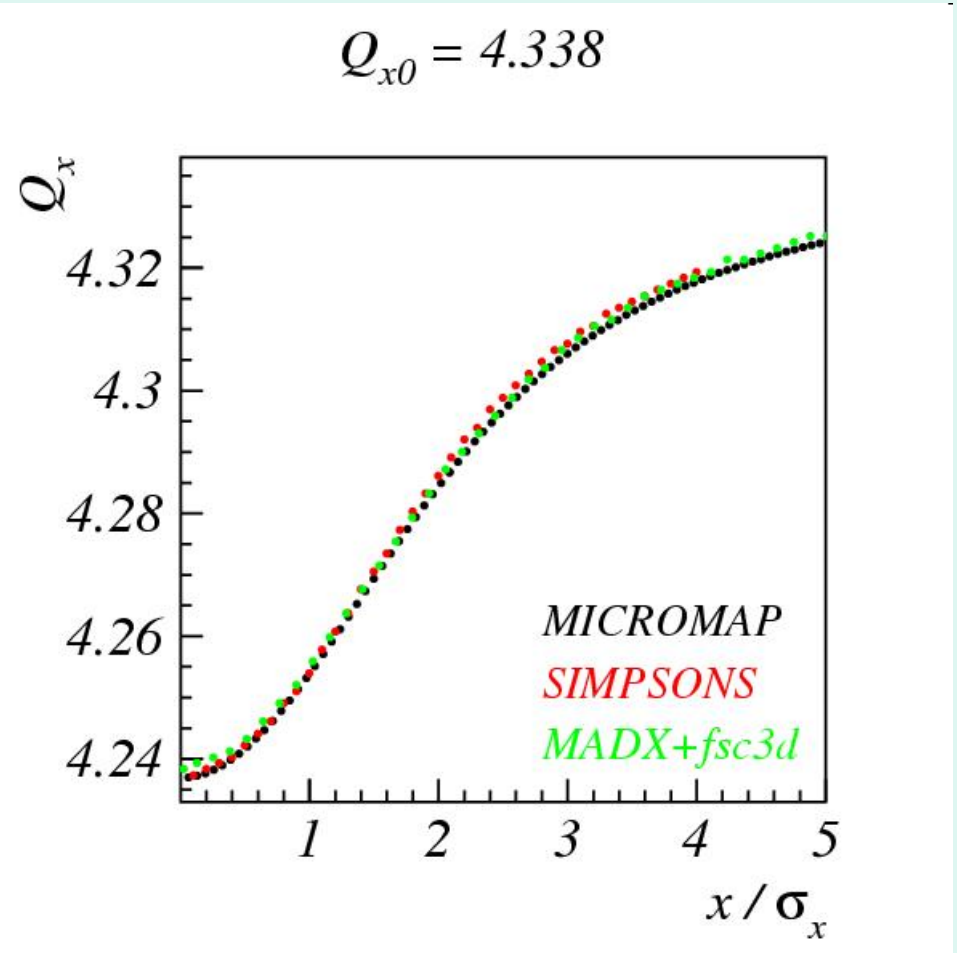
Benchmarking SIS18 steps 1-5 for 4D

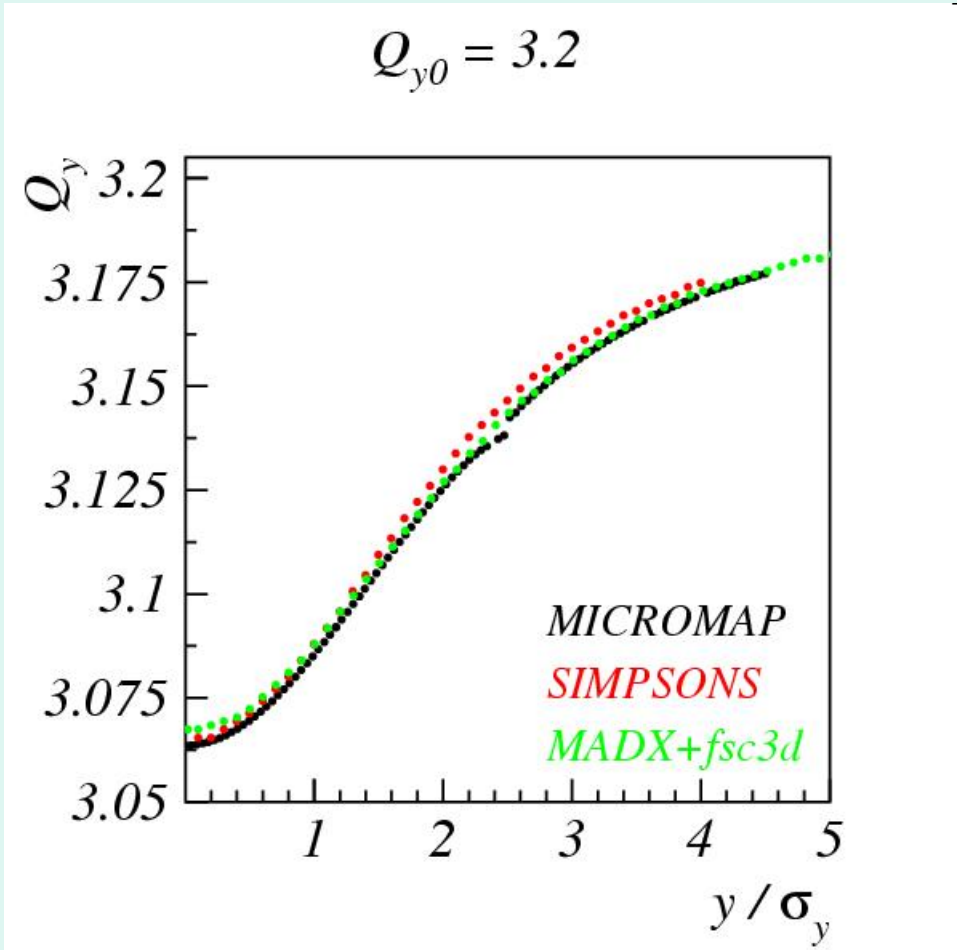
- **1) Benchmarking of the Phase Space**



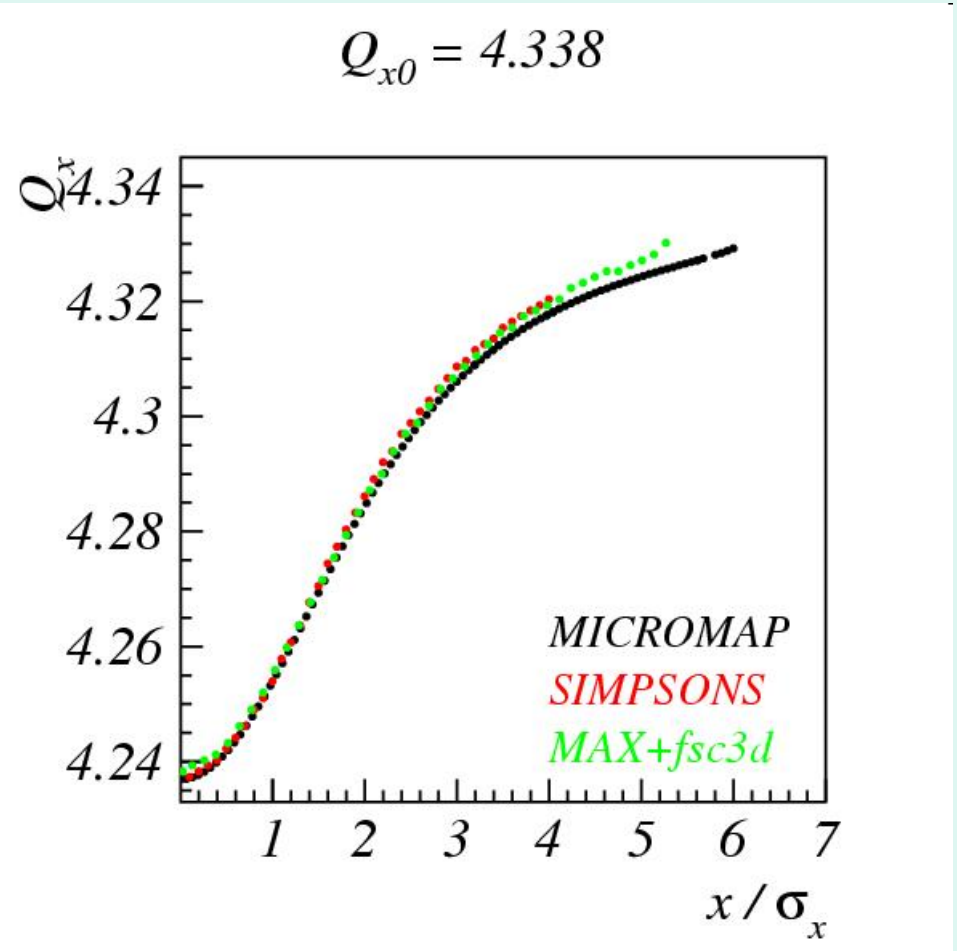


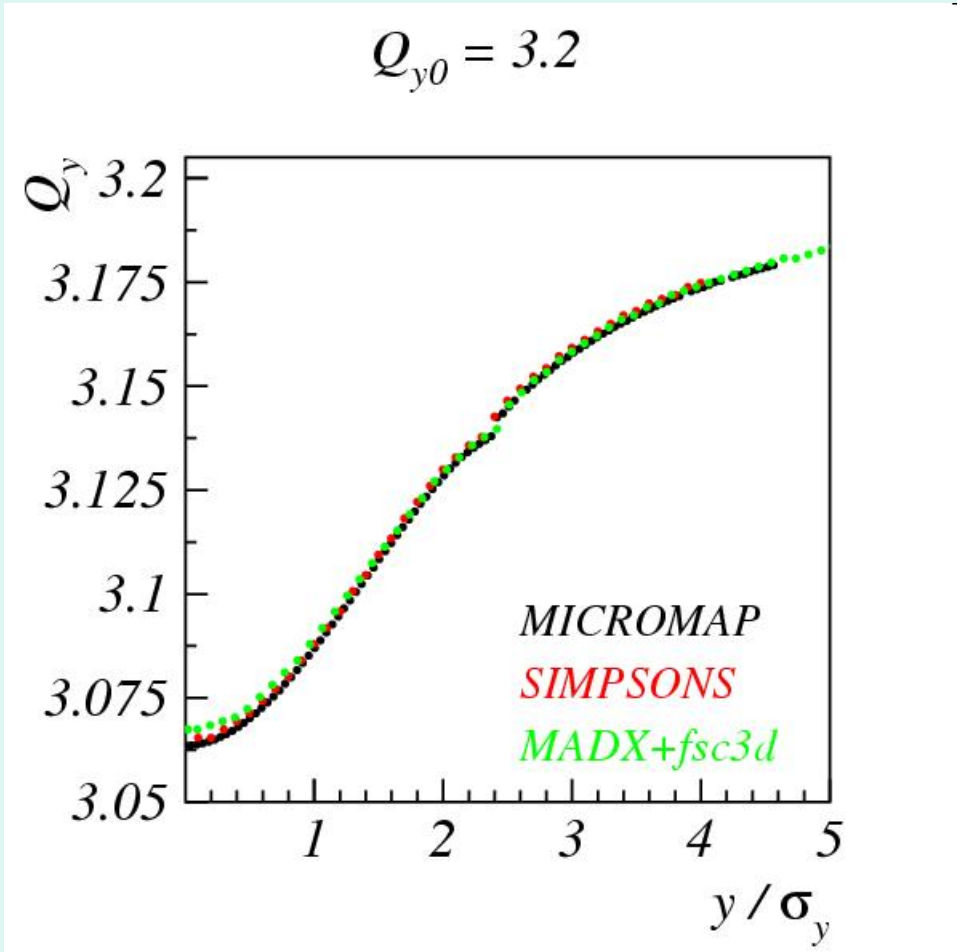
2) Benchmarking of the tunes versus particle amplitude. Sextupole OFF.



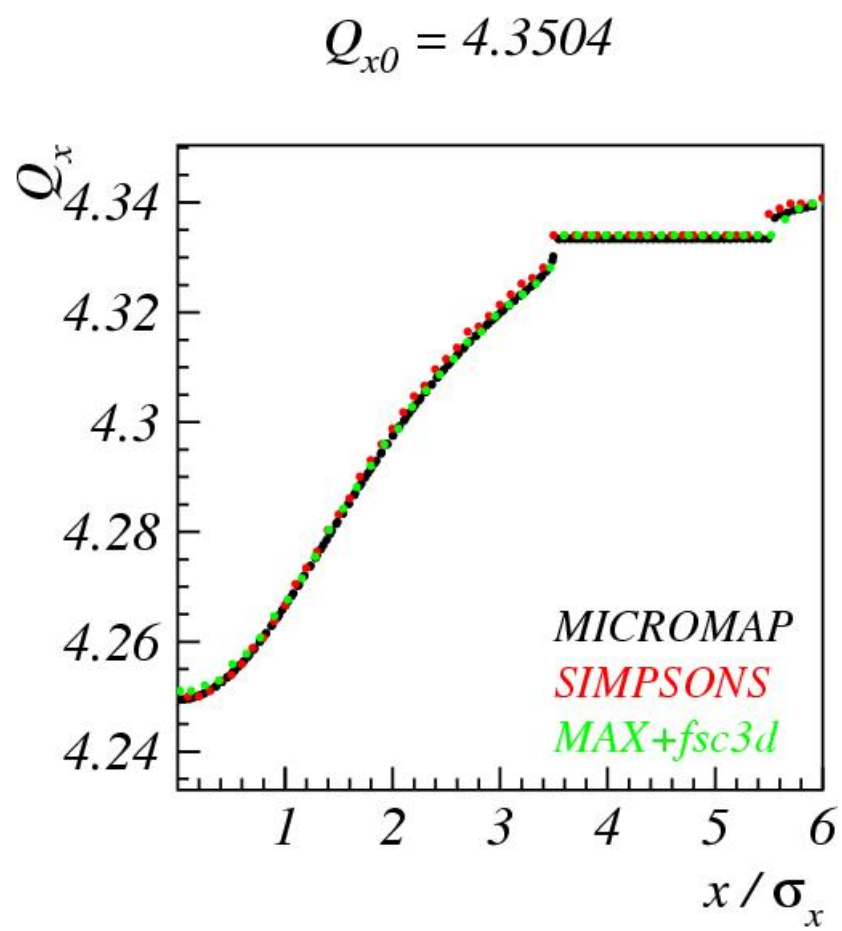


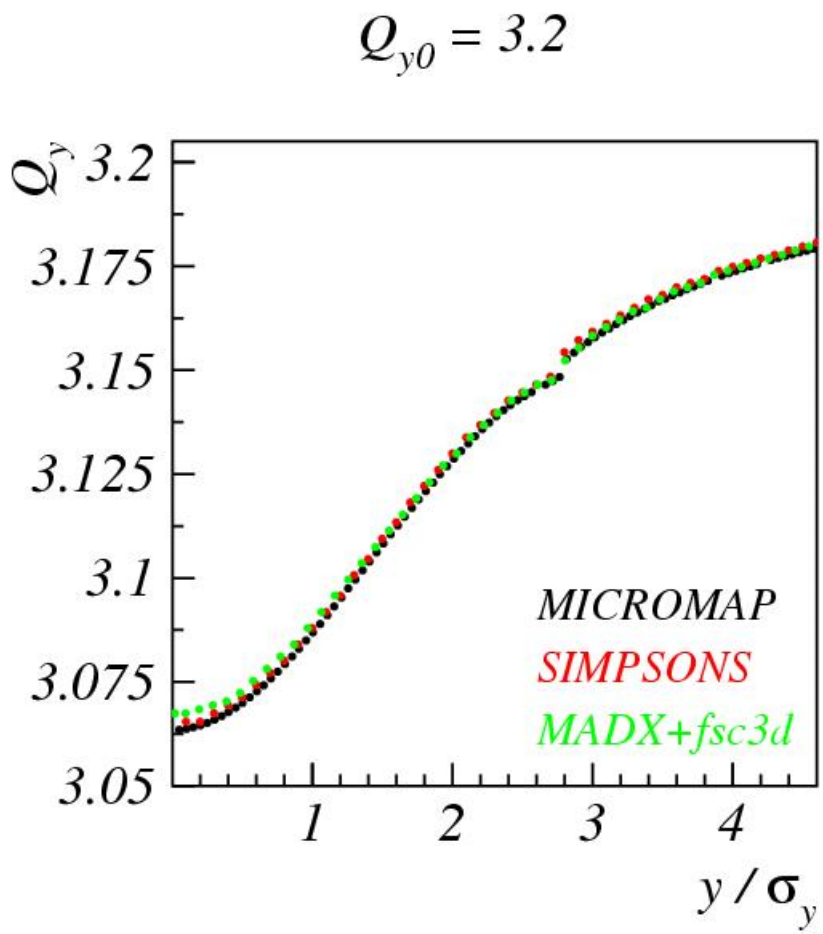
3) Benchmarking of the tunes versus particle amplitude, with sextupole ON.



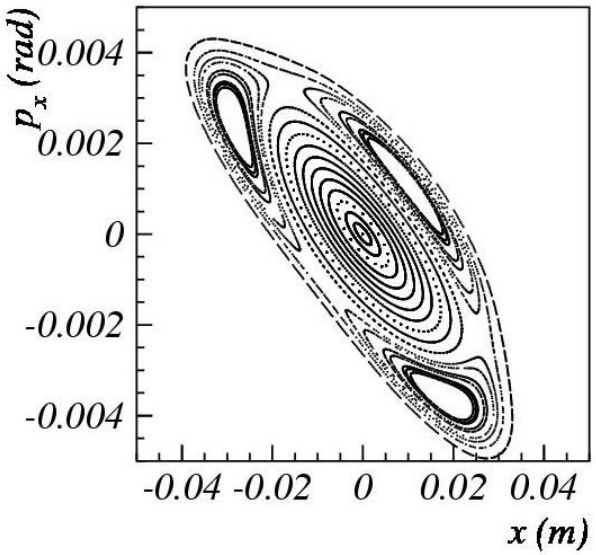


4) Benchmarking of the Tunes versus particle amplitude, with sextupole ON



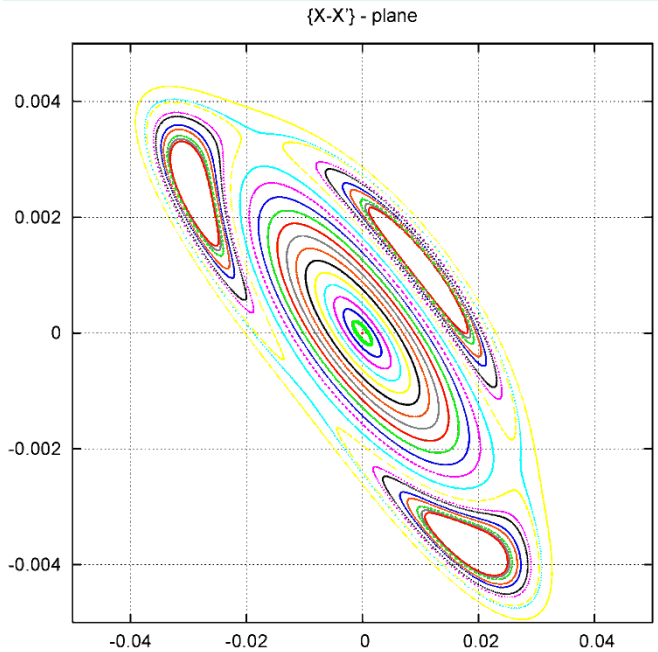


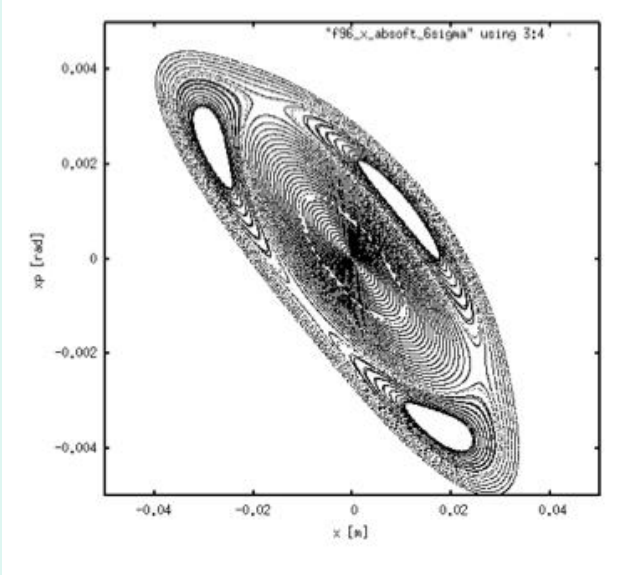
5) Benchmarking of phase space with space charge and sextupole on at Qx = 4.3504



MICROMAP

MAD-X with BB's

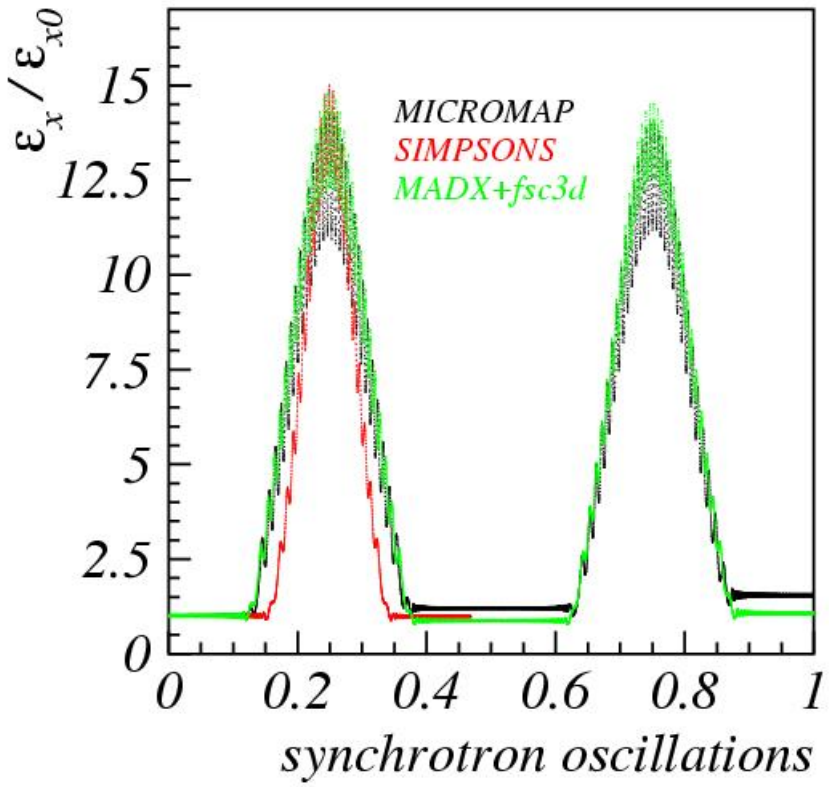




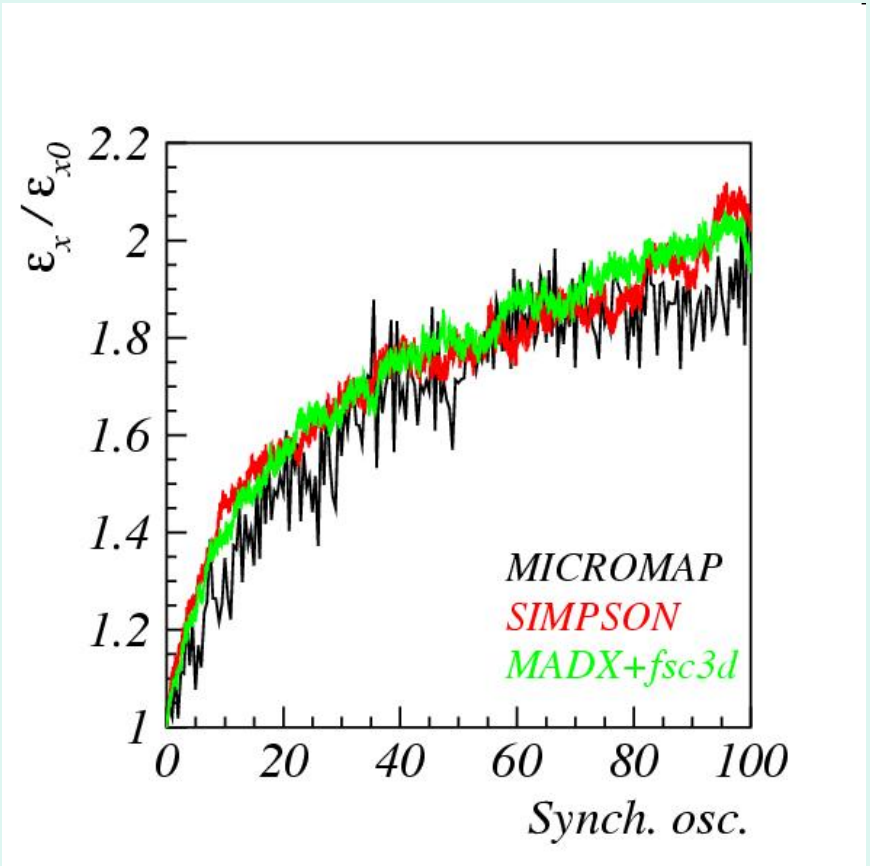
SIMPSONS

Benchmarking SIS18 for 6D (fake longitudinal motion)

BM-6: Trapping test particle during 1 synchrotron oscillation

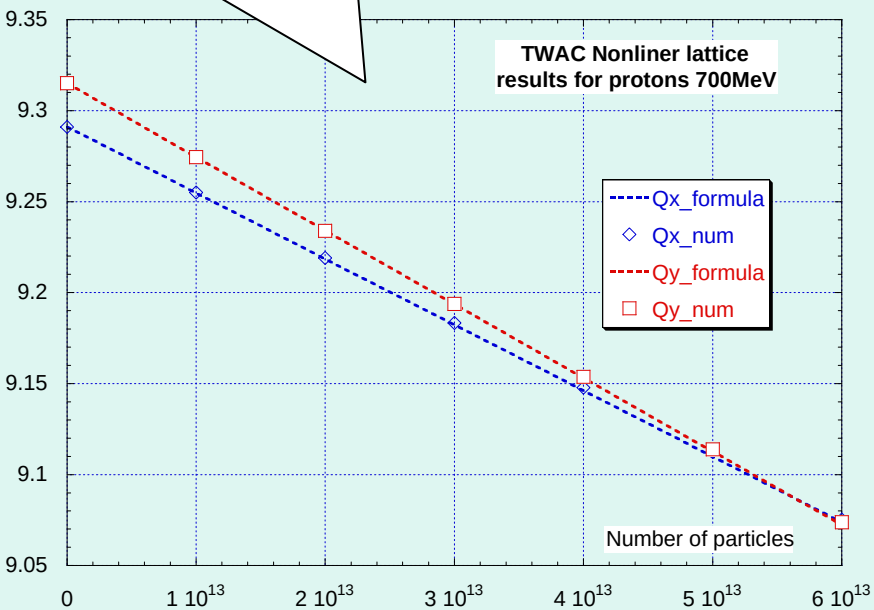


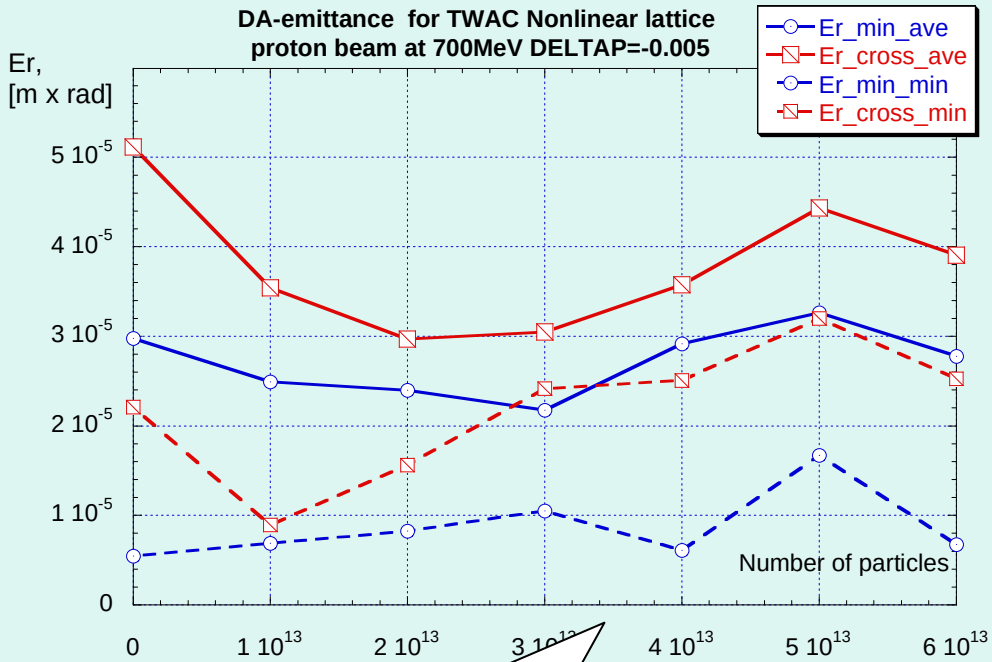
BM-9: evolution of the transverse rms emittance of a bunch (1000particles)



4. Applications: DA (4D) with Sp.Ch for ITEP's TWAC storage ring

Dependence of analytical (Laslett) and computed (MADX-> TWISS) betatron tunes on intensity.





Dependence of DA on the beam intensity for relative momentum offset DELTAP= -0.005

V. V. Kapin, A. Ye. Bolshakov, P. R. Zenkevich, "Influence of space charge on dynamical effects on dynamical aperture of TWAC storage ring", RuPAC'08 (at JACOW).

4. Applications: DA of SIS100 (GF-report) “benchmarking”

- Syst. & rand. errors
- RMS closed orbit – 1.5/1.0 mm

MICROMAP:

a) COD=0:

central DA=4.05 with 3-σ (3.5-4.6)

b) COD=1.5/1.0mm:

central 3.3 with 3-σ (2.7-4.0)

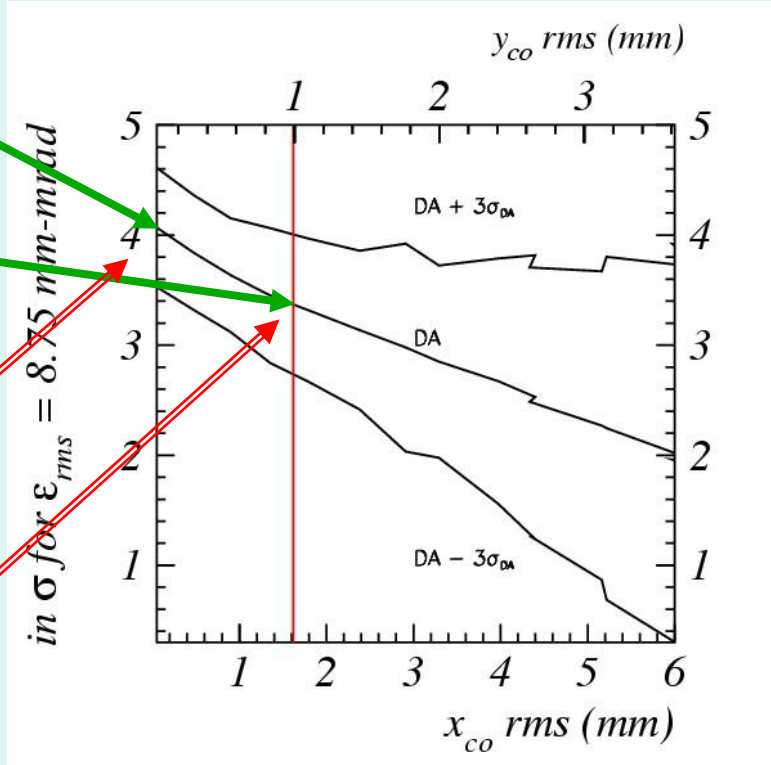
MADX:

a) COD=0:

DA=> (3.8-4.0)

b) COD=1.5/1.0mm:

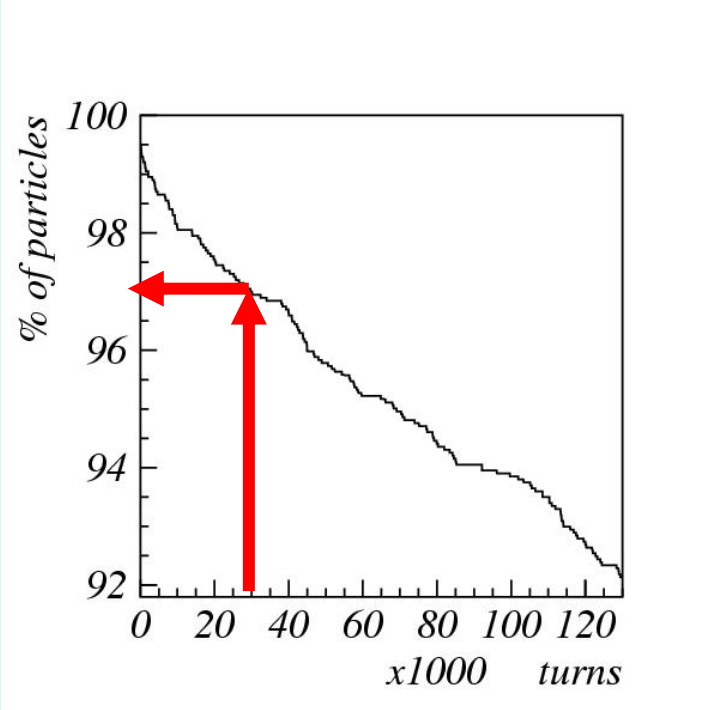
DA => (3.2-3.3)



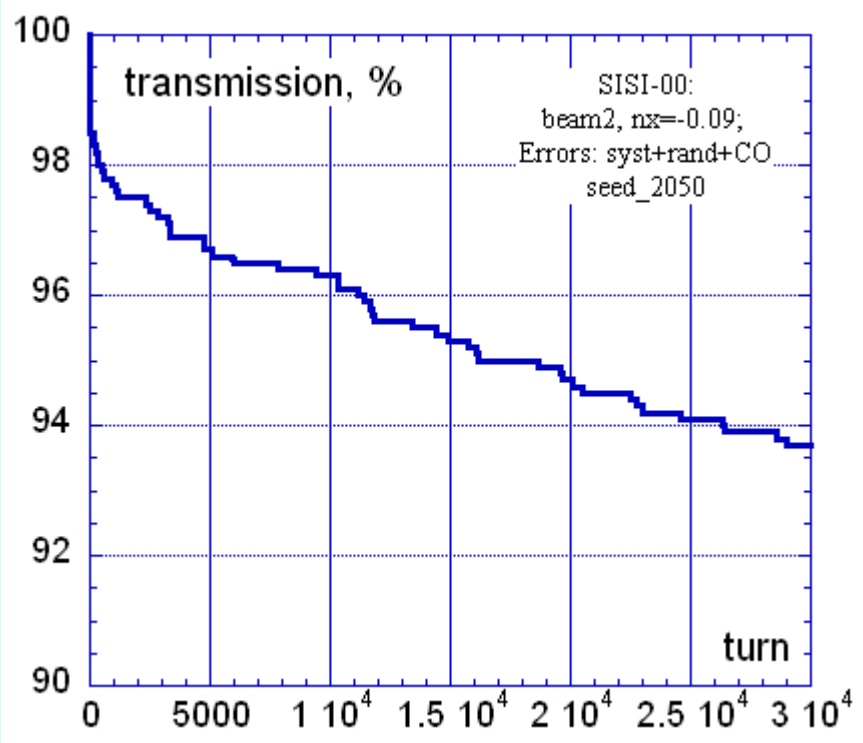
4. Applications: Beam loss in SIS100 (GSI)

MADX-Lattice with 840 BBs for Sp-charge

"BEAM2" for JF (nu_x=-0.090)



CDR-2008: Fig.11 Beam loss with space charge for Beam2 (2000 macroparticles).



97% vs 93.7% (?)

Initial Mismatching CO + other diff. (seed, sp-ch-center).

Initial loss->1.5% => 97% vs 95.2%

5. MADX-script algorithm for 6D-tracking in lattice with variable parameters

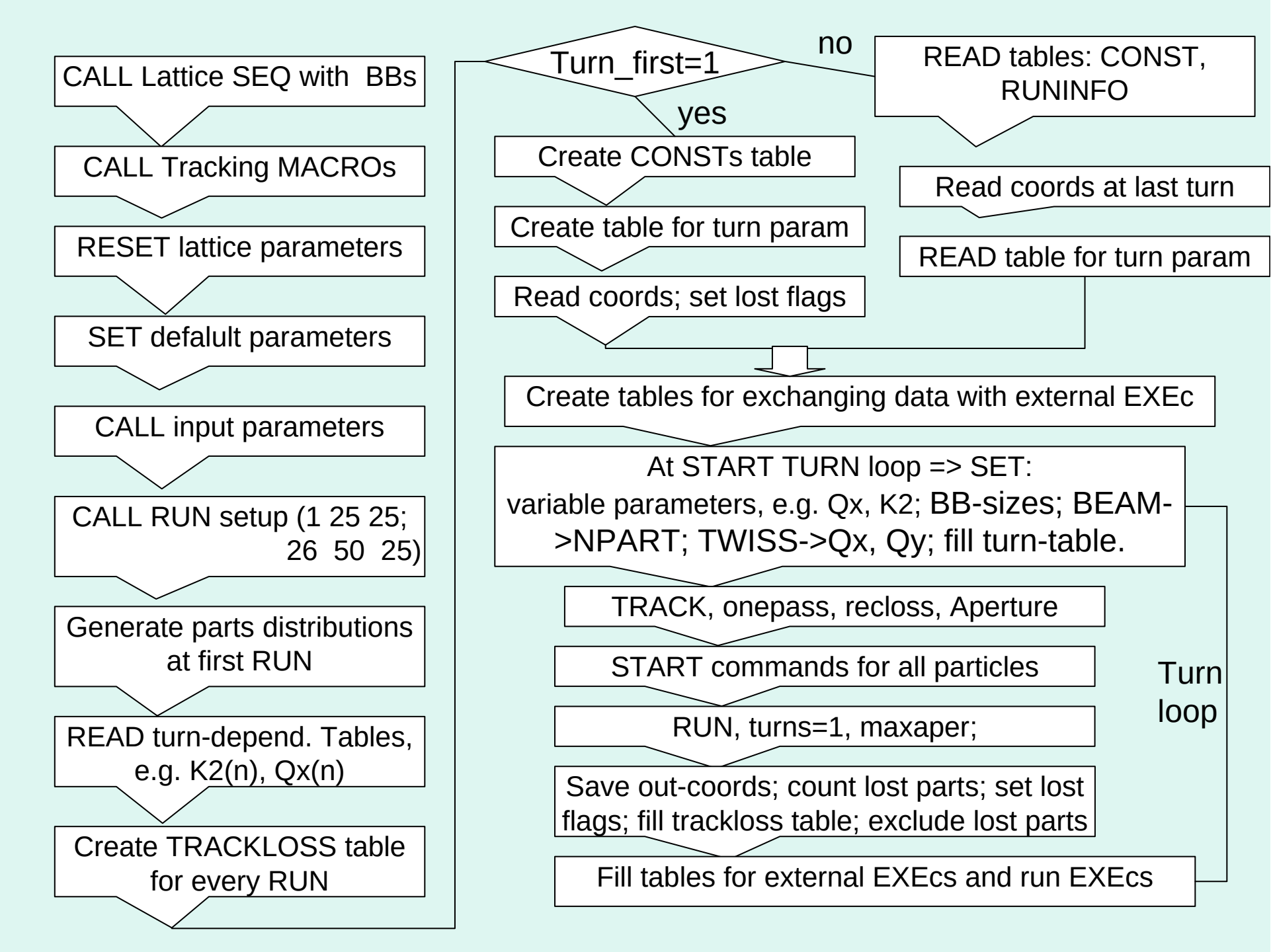
- Normally MADX used as multiturn tracking in lattice with constant parameters:
- `TRACK, recloss, aperture;`

```
  START, x, px, y, py, t, pt;
  RUN, turns;
ENDTRACK;
```

- => Need for multi-runs of one-turn tracking (`turns=1`), while varying lattice parameters after every turn.

5. MADX-script algorithm (continued)

- In more details for every turn:
  a) varying lattice parameters; b) collecting surviving particles and lost particles; c) calculating some “integral” beam parameters;
  d) reading and filling tables etc.
- Tool: madx-script language (C-like) with a quite poor set of commands (no manuals, only a few examples) =>
  a time consuming code developments;
  CPU memory consuming => run portions with only 25 turns (restarts with a simple external linux-script).
- The developed script has all attributes of a simple particle tracking code, which can be written and tested with a usual language like FORTRAN in a few weeks.
- It consists of main code with about 7 hundreds lines, plus macro file with 5 hundreds lines, while the lattice file (MADX-sequence) prepared separately.


CALL Lattice SEQ with BBs
CALL Tracking MACROs
RESET lattice parameters
SET defalult parameters
CALL input parameters
CALL RUN setup (1 25 25; 26 50 25)
Generate parts distributions at first RUN
READ turn-depend. Tables, e.g. K2(n), Qx(n)
Create TRACKLOSS table for every RUN
Turn_first=1
no
yes
READ tables: CONST, RUNINFO
Create CONSTs table
Create table for turn param
Read coords; set lost flags
Read coords at last turn
READ table for turn param
Create tables for exchanging data with external EXEc
At START TURN loop => SET:
variable parameters, e.g. Qx, K2; BB-sizes; BEAM->NPART; TWISS->Qx, Qy; fill turn-table.
TRACK, onepass, recloss, Aperture
START commands for all particles
RUN, turns=1, maxaper;
Save out-coords; count lost parts; set lost flags; fill trackloss table; exclude lost parts
Fill tables for external EXEcs and run EXEcs
Turn loop

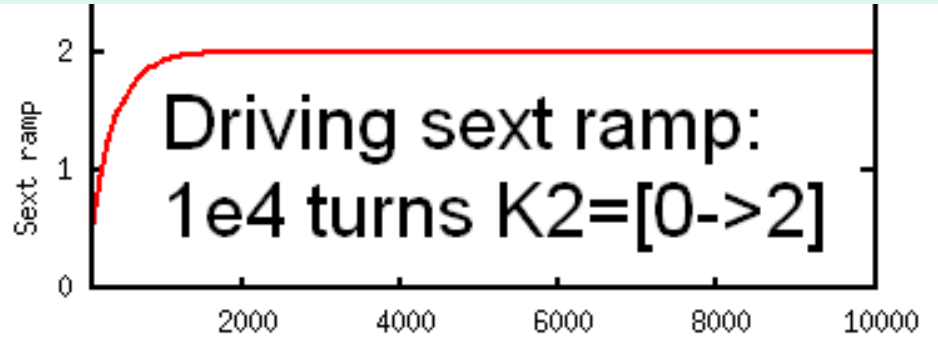
6. Debuncher with ORBIT(6x6matr.)-lattice by V.Nagaslaev

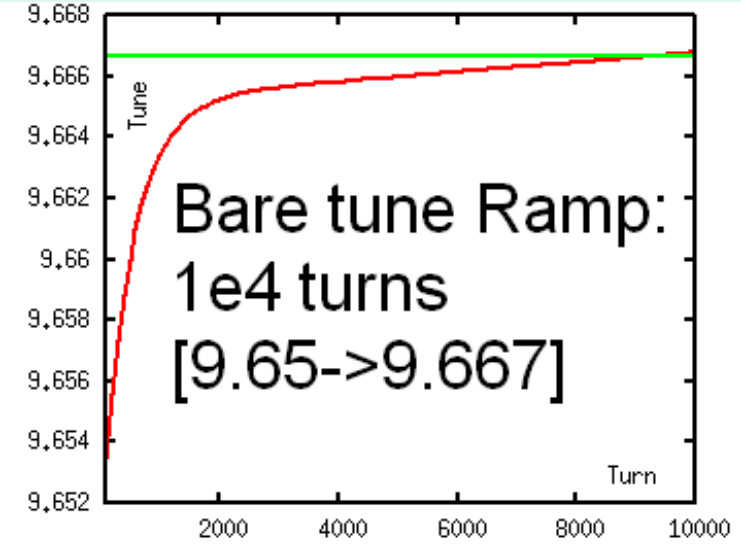
Lattice preparation:

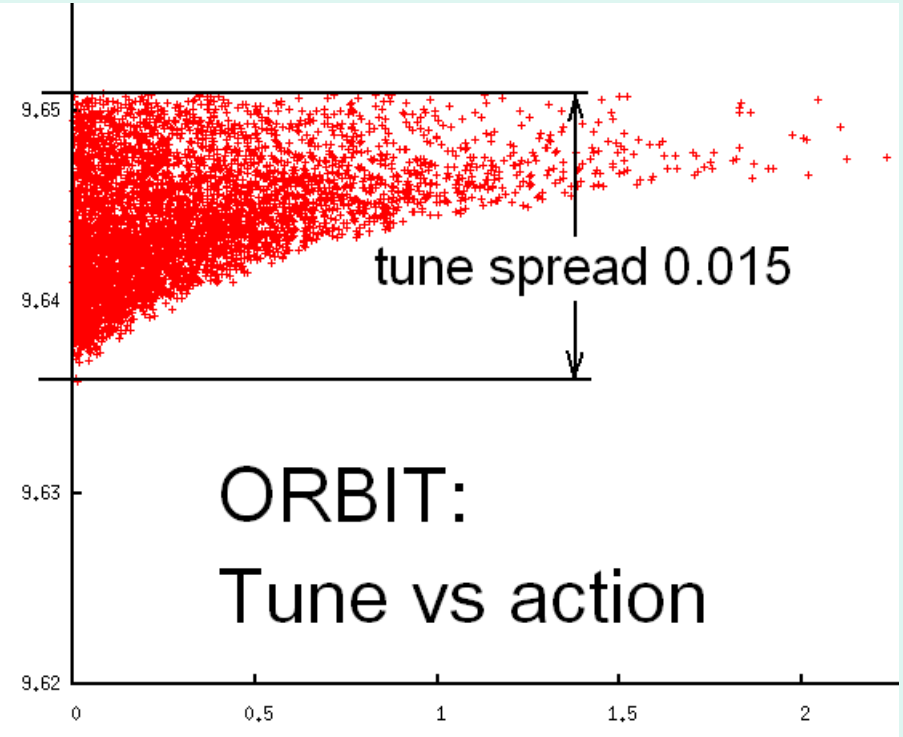
- a) accepting matrices (more 2 hundreds) with specially written FORTRAN code
- b) generating MAD-X lattice with matrices and special elements (apertures, driving and chr.-correcting sextupoles)
- c) inserting BB-elements in places between sector matrices => BB-locations (=> type of integrator!) and N_{BB}=213 are defined by VN
- d) Twiss parameters are compared (preserved!).

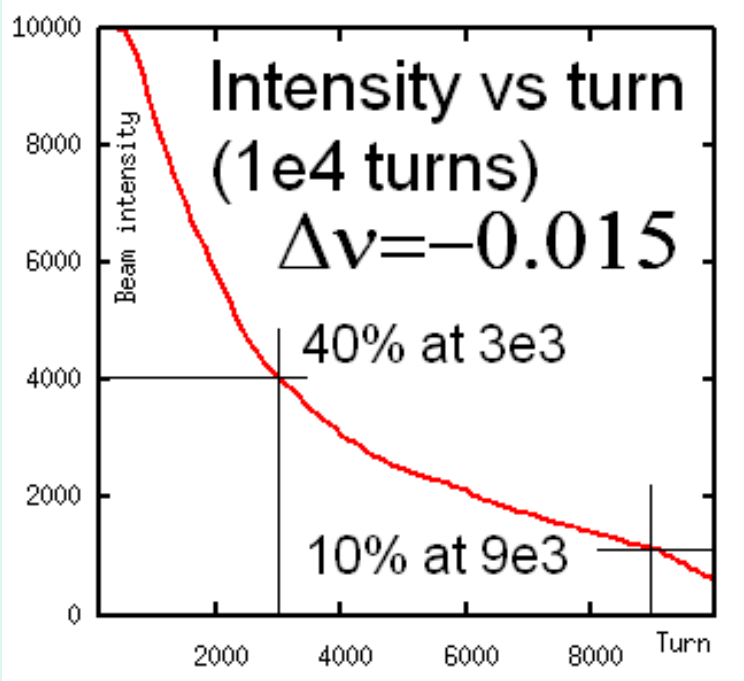
Simulations with ORBIT by VN

Ramps are given in tables;
Npart in bunch ~ 2.5e12

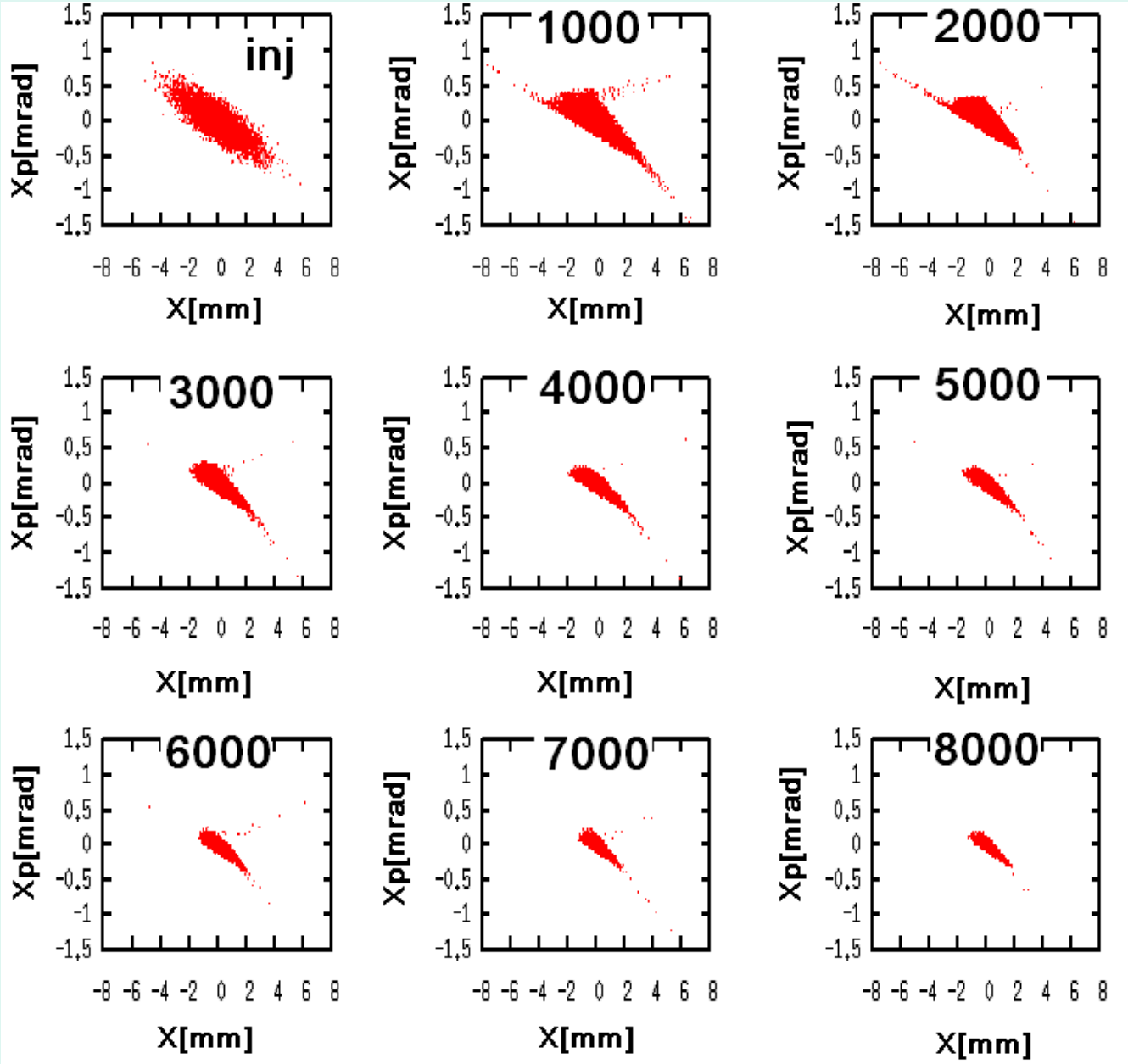




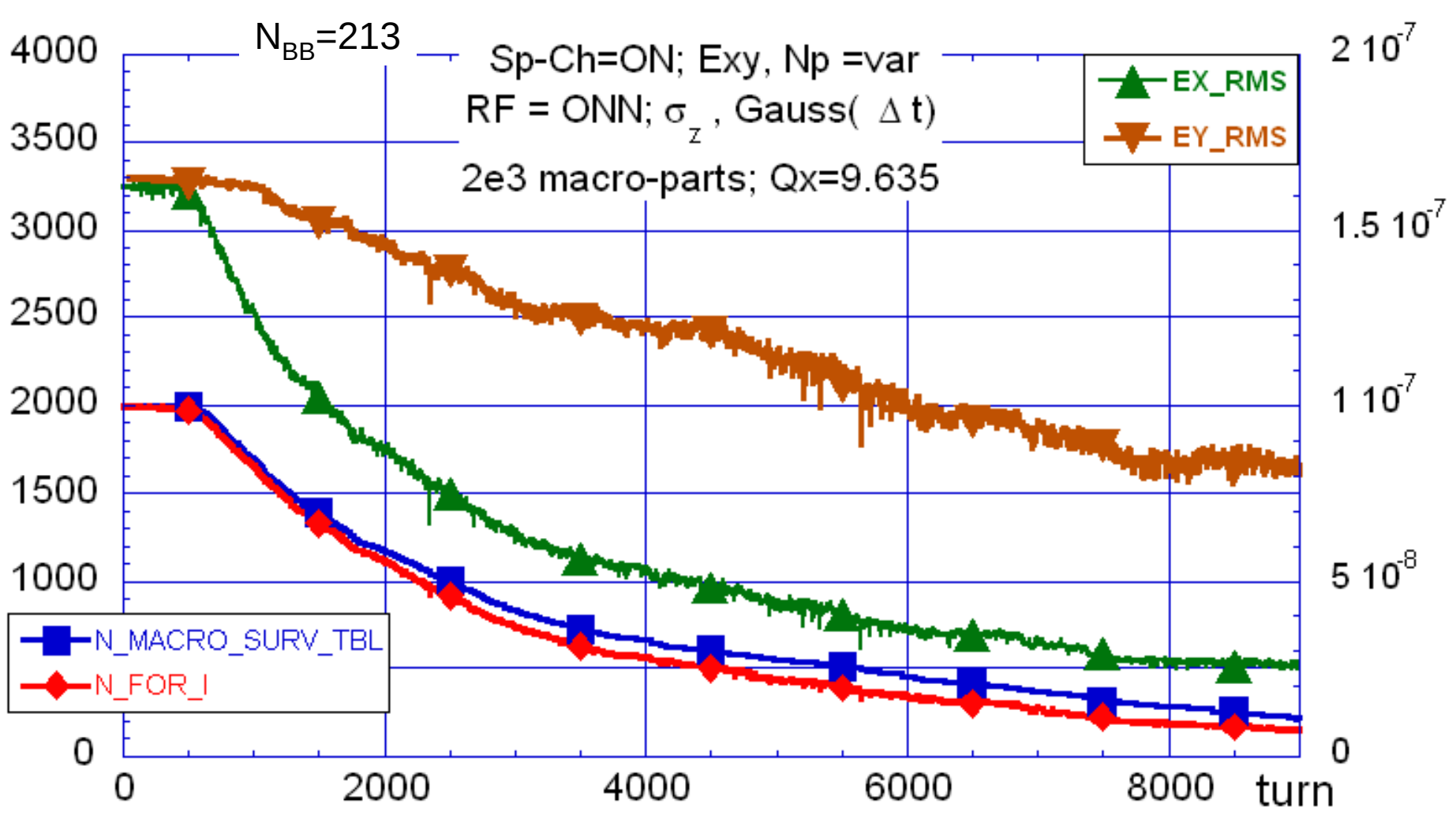




Orbit: X-X' phase space evolutions at tune shift 0.015)



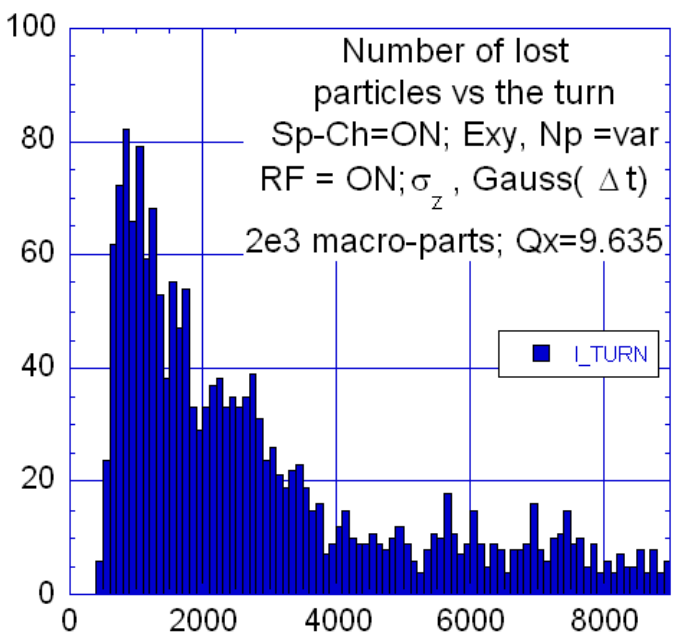
MADX (Orbit-lattice): Intensity vs turns ($\Delta\nu$=-0.015)

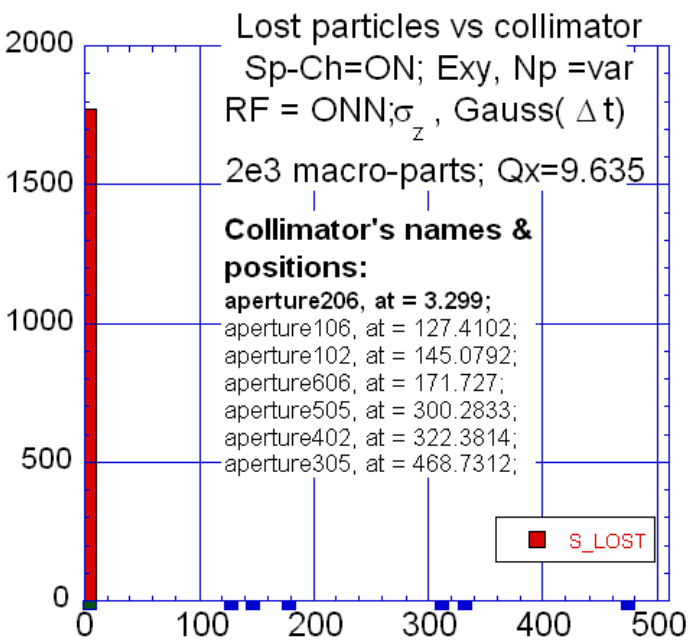


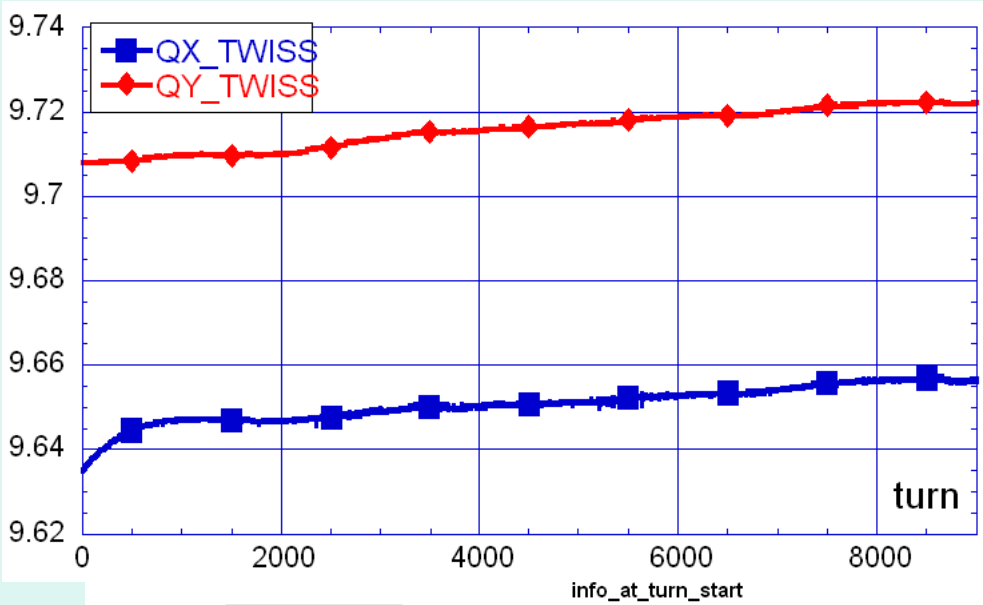
MADX: at turn=3000 Intensity=42%; at turn=9000 Intensity=11%
ORBIT: at turn=3000 Intensity~40%; at turn=9000 Intensity~10%

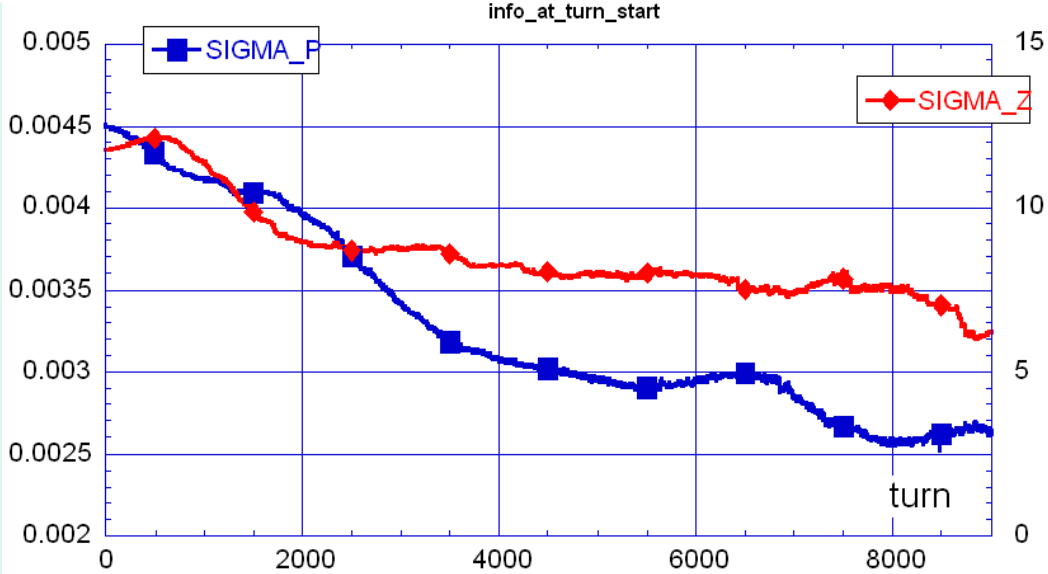
MADX: losses, tunes, sizes vs turns ($\Delta\nu$=-0.015)

Extraction rate decreased if tune shift is increased

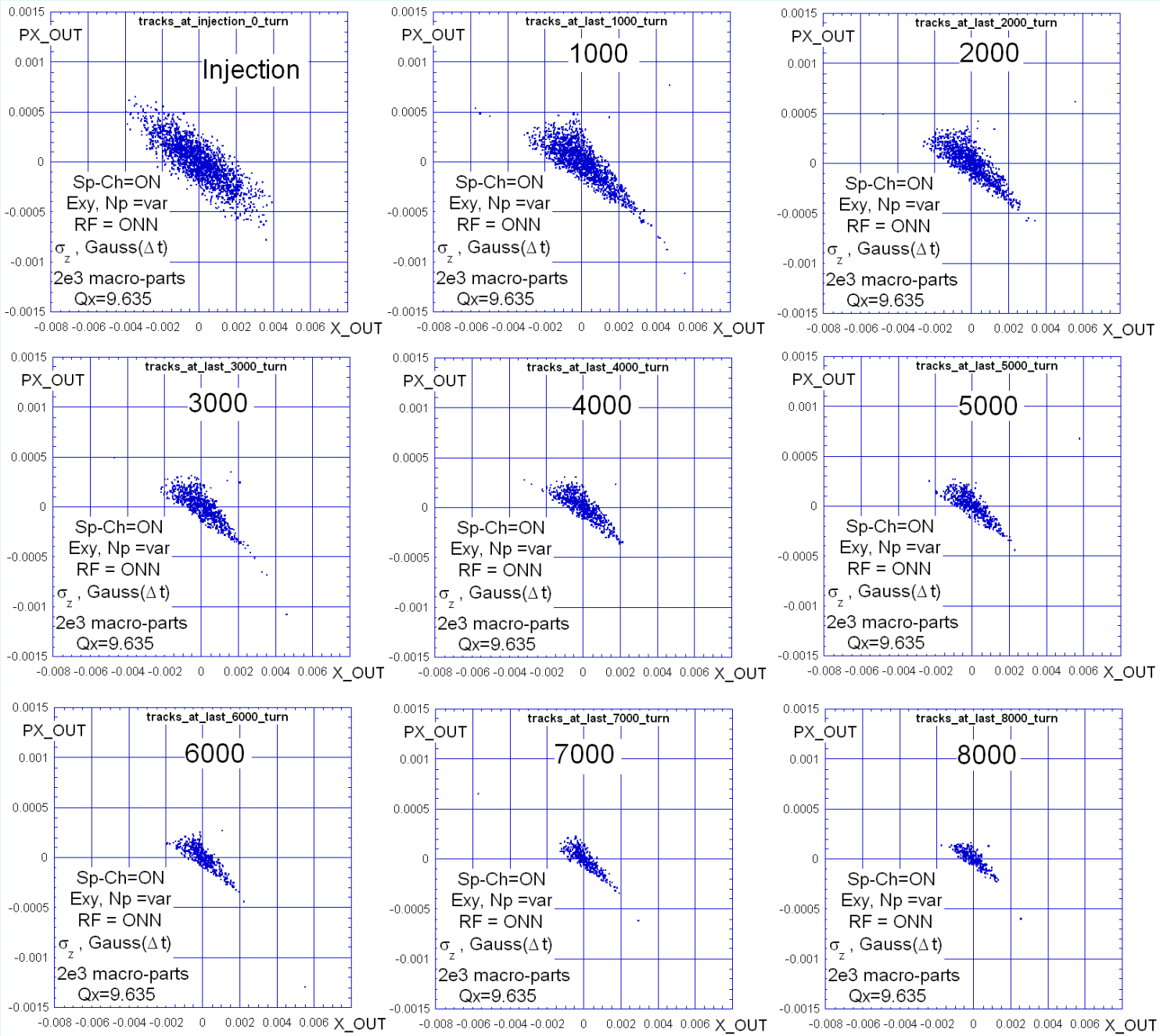








MADX: X-X' phase space evolutions ($\Delta\nu$=-0.015)



Remark on coasting to bunched beam transition

$$\sigma^2_{tot} = \sigma^2_{\beta} + [D_x(s)\,\sigma_p]^2$$

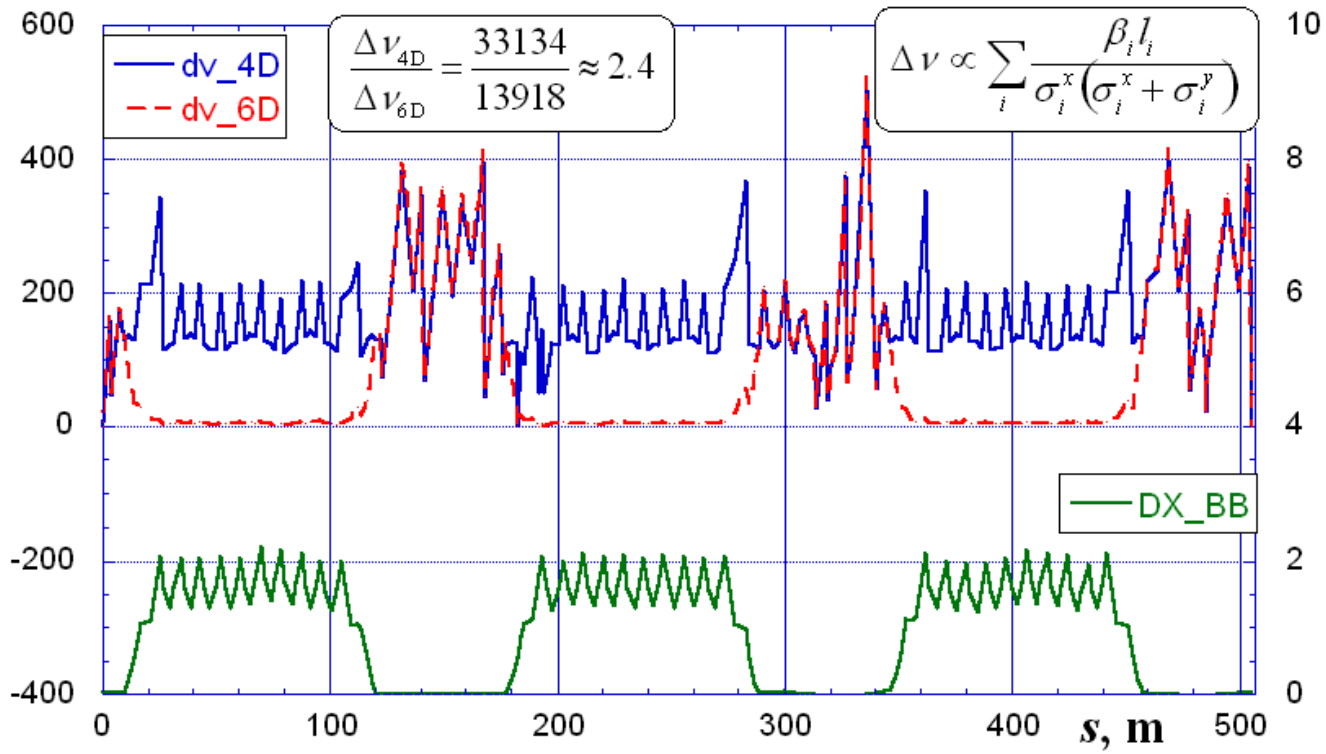
- For **coasting** 4D beam N=1.75e13 for the tune shift $\Delta\nu$=-0.015:
  A good agreement between analitical Laslett's and numerical TWISS

- For 6D beam (σ_z=12m; σ_p=4.5e-3) due to Dx => $\Delta\nu$=-0.0054

Calculated numerically MADX: a) TWISS; b) TBT tracking over 1024 turns

=> Increase Npart for BB-elements by factor $K_{4D\text{->}6D}$ =**2.7** (0.0148/0.054)

to reach $\Delta\nu$=-0.015 for bunched beam



Simple explanation:

by evaluating the sums for tune shifts 4D & 6D => $K_{4D\text{->}6D}$~**2.4**

Number particles in bunch

$N_{part}(6D)=N_{part}(4D)$ *

* $K_{4D\text{->}6D}$*(2.5σ_z/L_{ring})=

1.75e13*(2.4÷2.7)*

(2.5*12/505)=**(2.5÷2.8)e12**

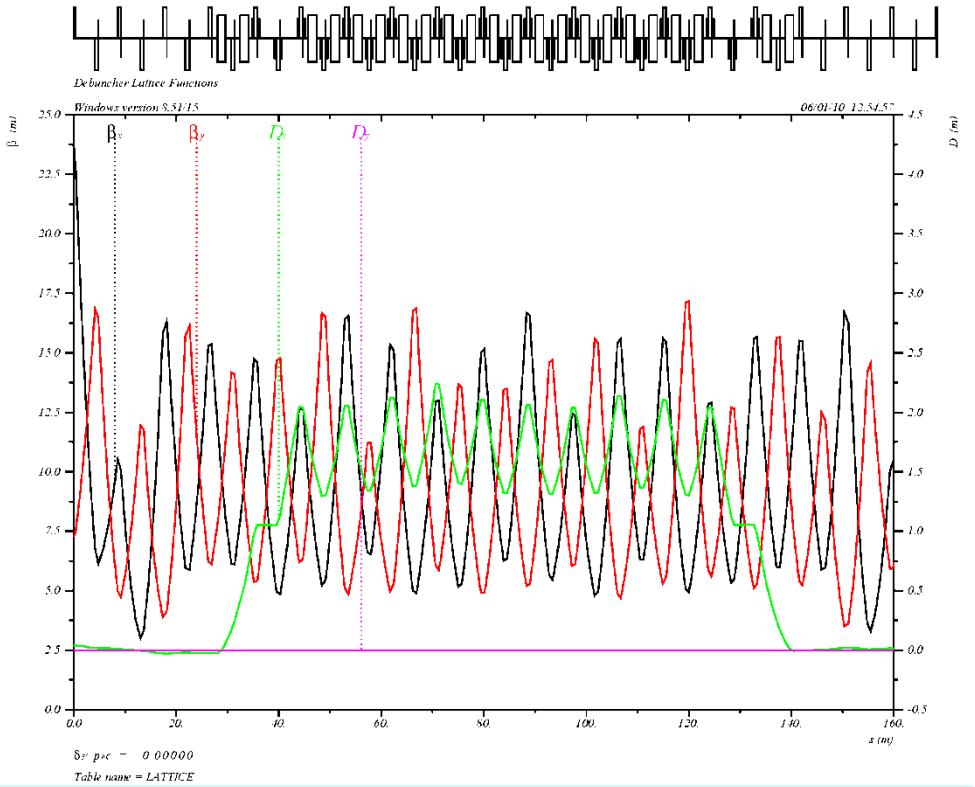
(Orbit: ~2.5e12)

7. Debuncher with MAD8 (S.Werkema)->MADX + BB

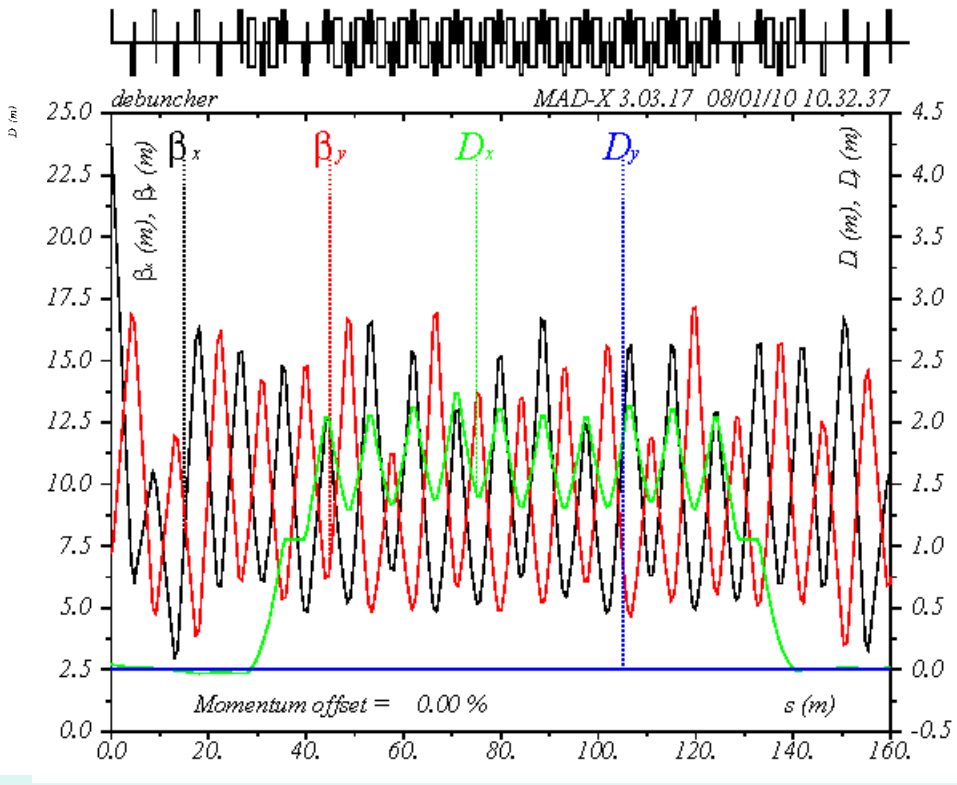
- Lattice preparation:
- a) converting MAD8 file to MADX format while preserving all relations for elements excitations created by SW
- b) inserting BB-elements in MADX lattice according to the 2nd order ray tracing integrator.
- c) global Twiss parameters are preserved well.

Twiss parameters for 1/3 of ring.

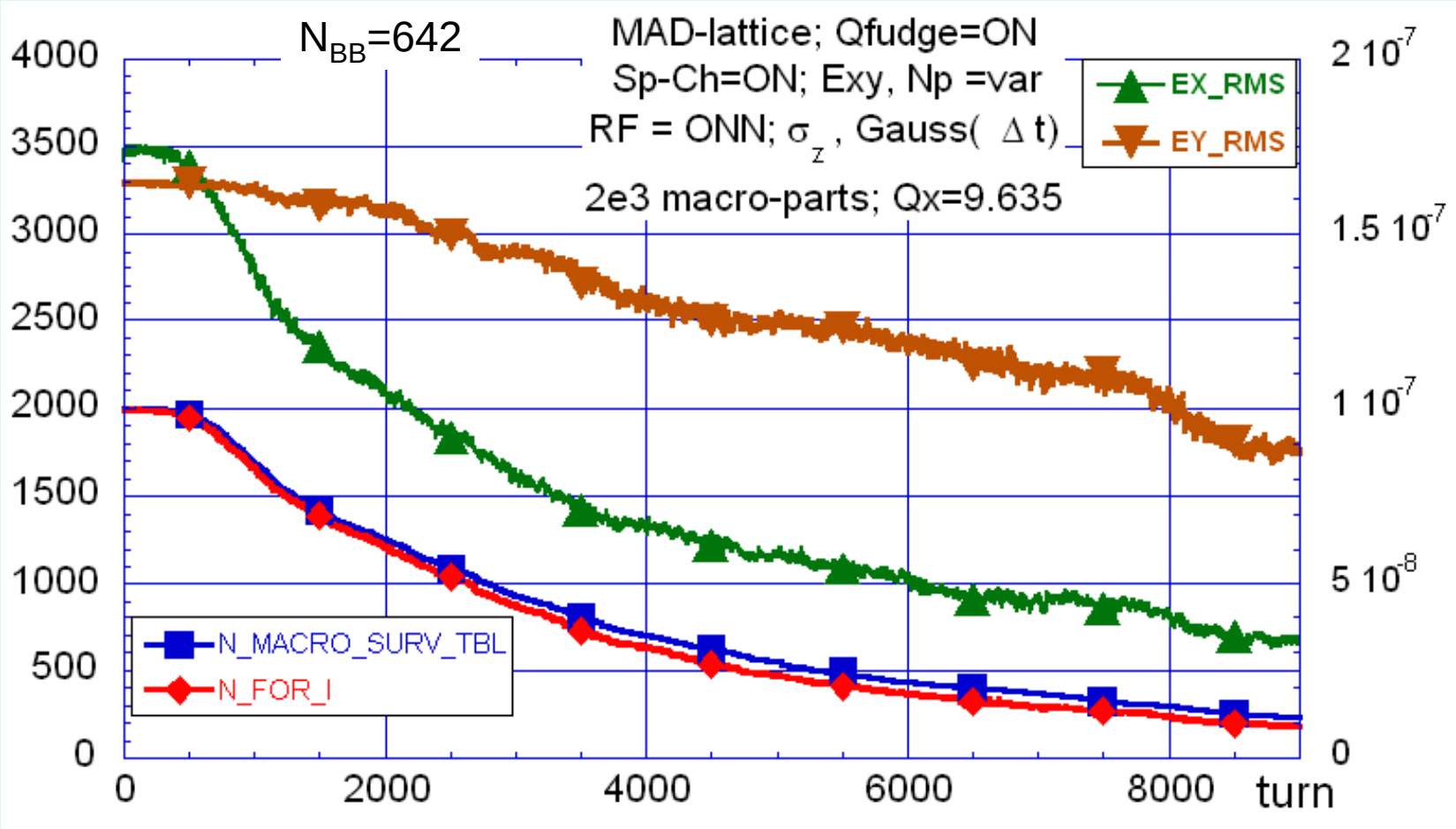
MAD8 version 51.15



MADX



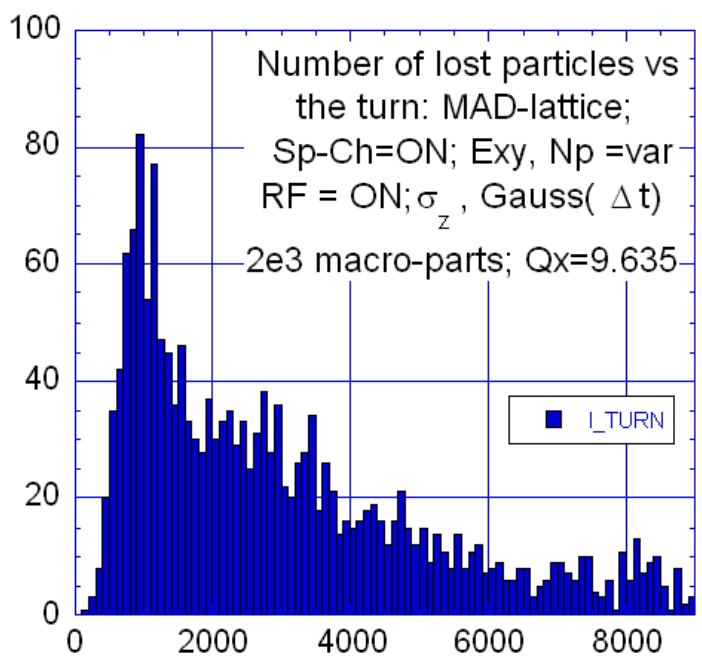
MADX (mad-lattice): Intensity vs turns ($\Delta\nu$=-0.015)

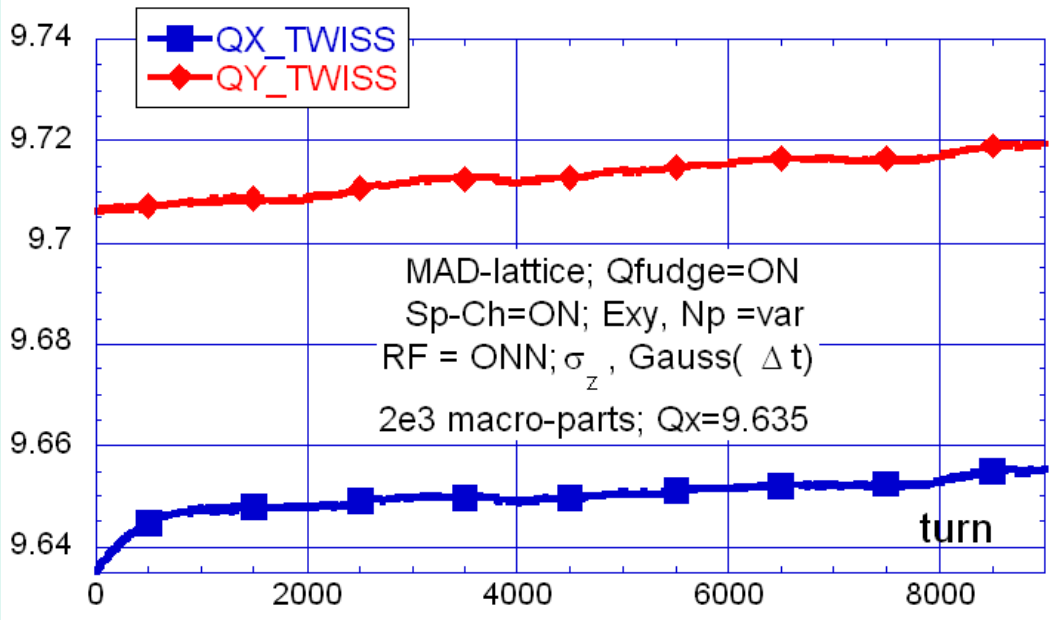


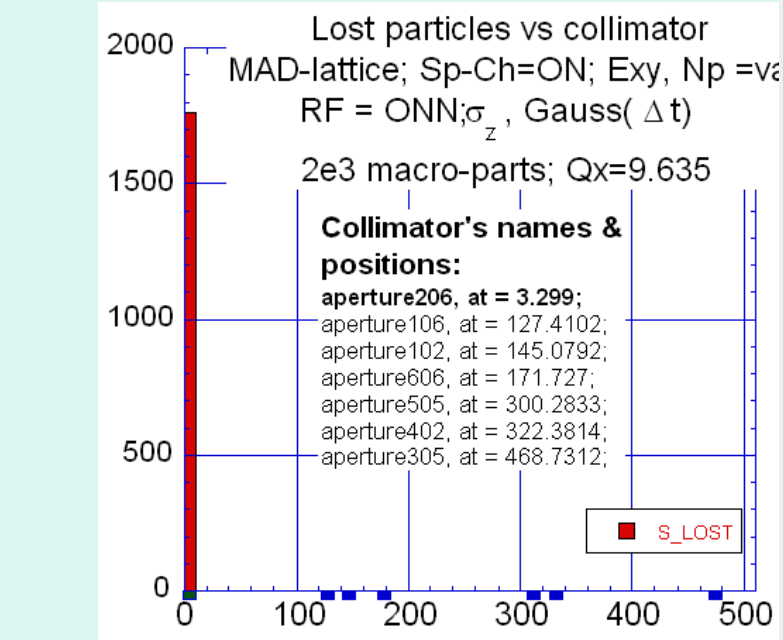
MADX: for MAD-lattice and ORBIT-matrices Intensity = 46% and ~40% at turn=3000, and Intensity=12% and ~10% at turn=9000, respectively.

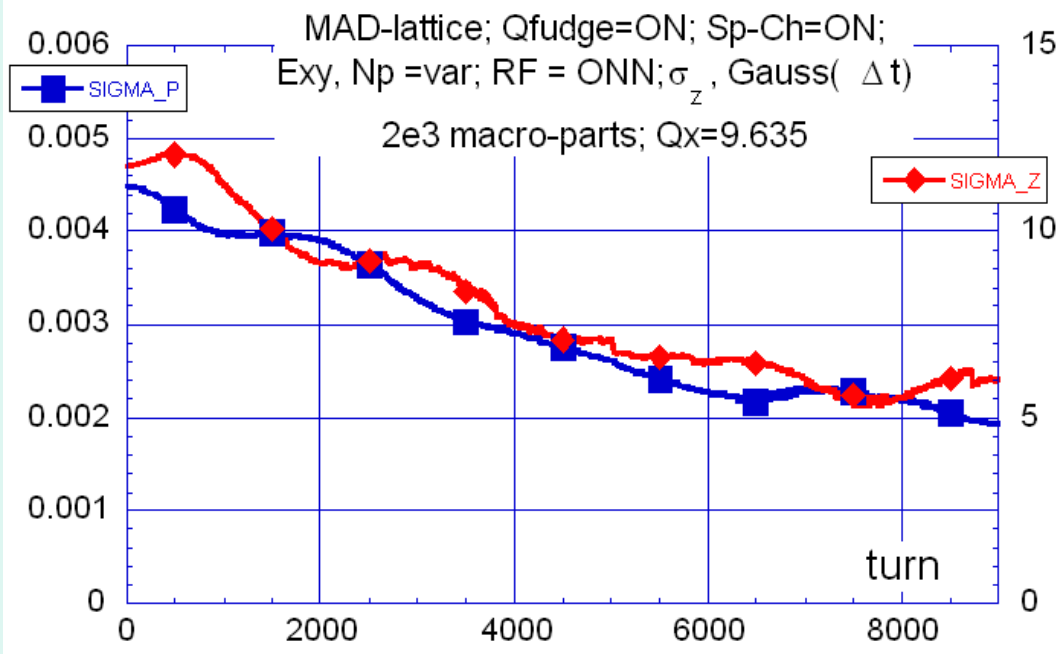
Increase Npart by factor $K_{4D\text{->}6D}$ =2.77 to reach $\Delta\nu$=-0.015 for bunched beam.
=> Number particles in bunch Npart(6D)~2.9e12
=>close to 2.8e12 for lattice with ORBIT matrices

MADX (mad-lattice): losses, tunes, sizes vs turns ($\Delta\nu$=-0.015)

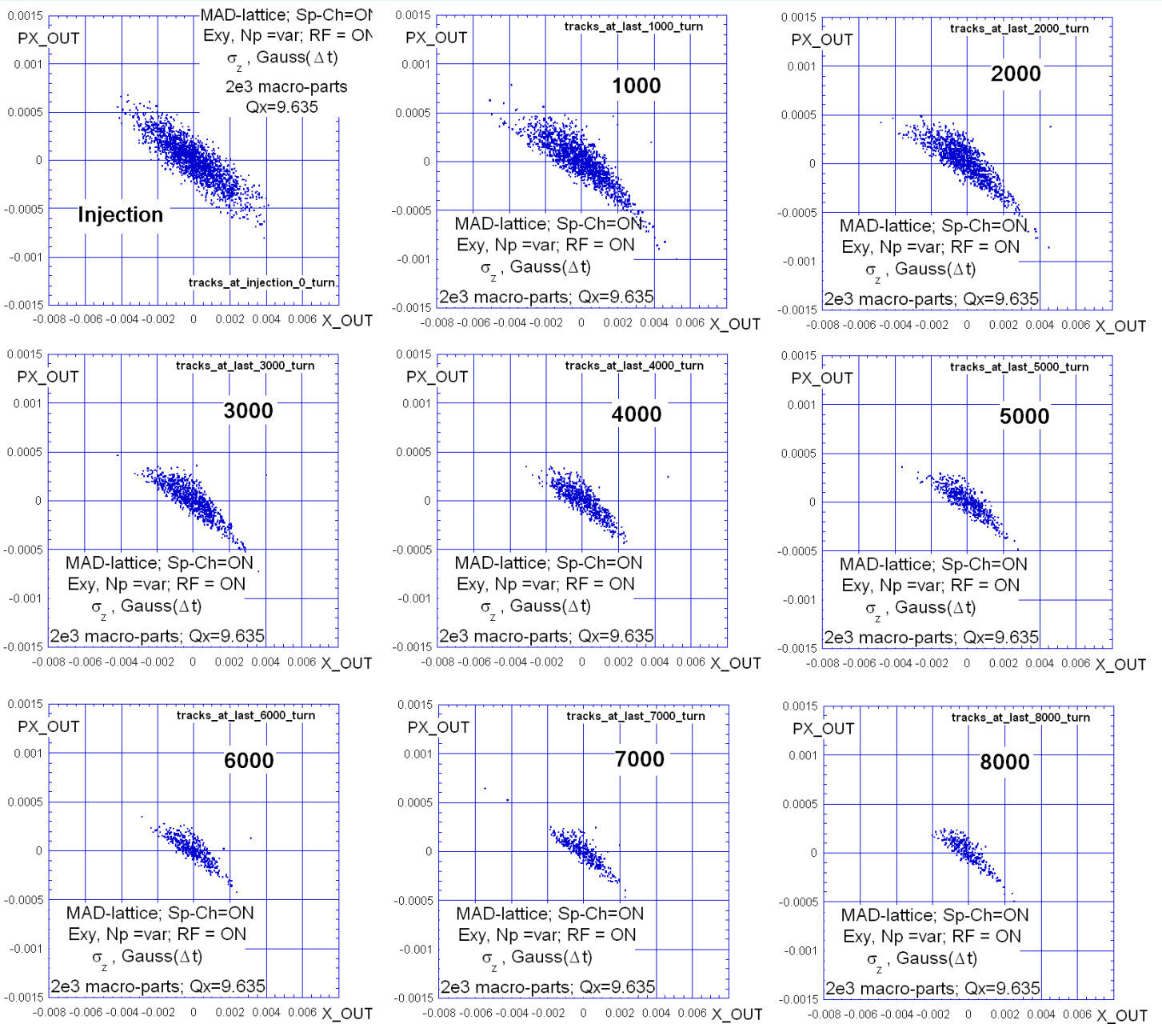








MADX (MAD-lattice): X-X' phase space evolutions ($\Delta\nu$=-0.015)



Conclusion

- MADX can be applied for sp-ch simulations for coasting and bunched beams
- Benchmarking test showed a good agreements with other codes
- Developed MADX-script for lattice with variable parameters can be used for slow-extraction simulations
- Preliminary comparison of results obtained by MADX and ORBIT allowed to correct bugs in initial data submitted to the codes
- Good agreement in final results between:
  a) ORBIT vs MADX using ORBIT-style lattice
  b) ORBIT-lattice vs MAD-lattice using MADX