Linac4 to PSB H^- injection and acceleration studies for high-intensity beams

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Acknowledgments

S. Cousineau (ORNL), *F. Jones* (TRIUMF)

C. Carli, M. Chanel, H. Schönauer

The issue

Historic of the studies:

- **STEP 1: 2003-2004 (cf. EPAC' 04)**

  Simulations of 160 MeV Linac4 to PSB injection and beginning of acceleration for the high intensity beam for CNGS and the high brightness beam for LHC

  Results showed vertical emittance blow-ups during the first few thousand turns beyond the emittance figures compatible with the PS acceptance

  Were these blow-ups due to real physical emittance increase process or were they due artifact of the simulation code (ACCSIM code was used)?

- **STEP 2: 2006**

  Aim to crosscheck with another simulation code. Collaboration started with ORNL (ORBIT programme)

  High-intensity beam for CNGS was considered for the benchmarking study, using a simplified scenario <u>without adiabatic RF capture nor acceleration</u>

  The benchmarking results (ACCSIM, ORBIT) is not reported hereinafter because only preliminary data are available at present

The issue

The high intensity beam for CNGS :

- Single batch PS injection at 1.4 GeV
- PS: 5×10^{13} protons in 8 bunches
- PSB: 1.25×10^{13} protons per ring
- Normalized emittance figures:

$$\varepsilon^n_H(1\sigma) = 11.5\ \mu m,\ \varepsilon^n_V(1\sigma) = 4.6\ \mu m$$

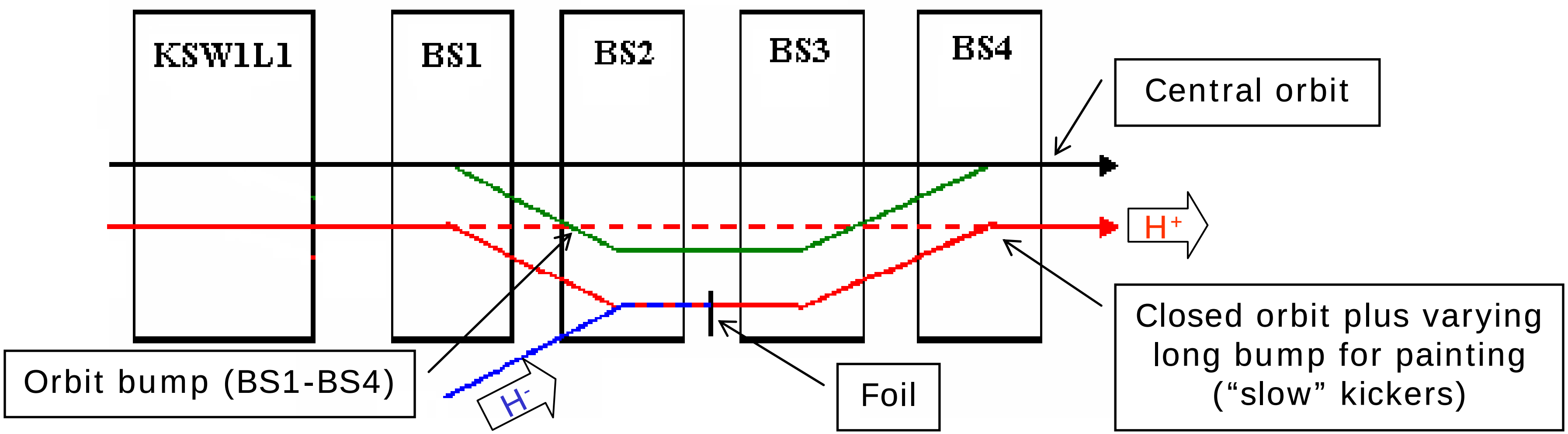
The emittance figures for the LHC & CNGS beams are the normalized rms emittances that yield about 1% beam losses (assuming gaussian beams) at PS entrance due to the aperture limitation (measured as A_H=60 μm and A_V=20 μm)

Linac4-PSB H^- injection scenario

PSB H^- injection: a possible scheme (K. Schindl, E. Troyanov)

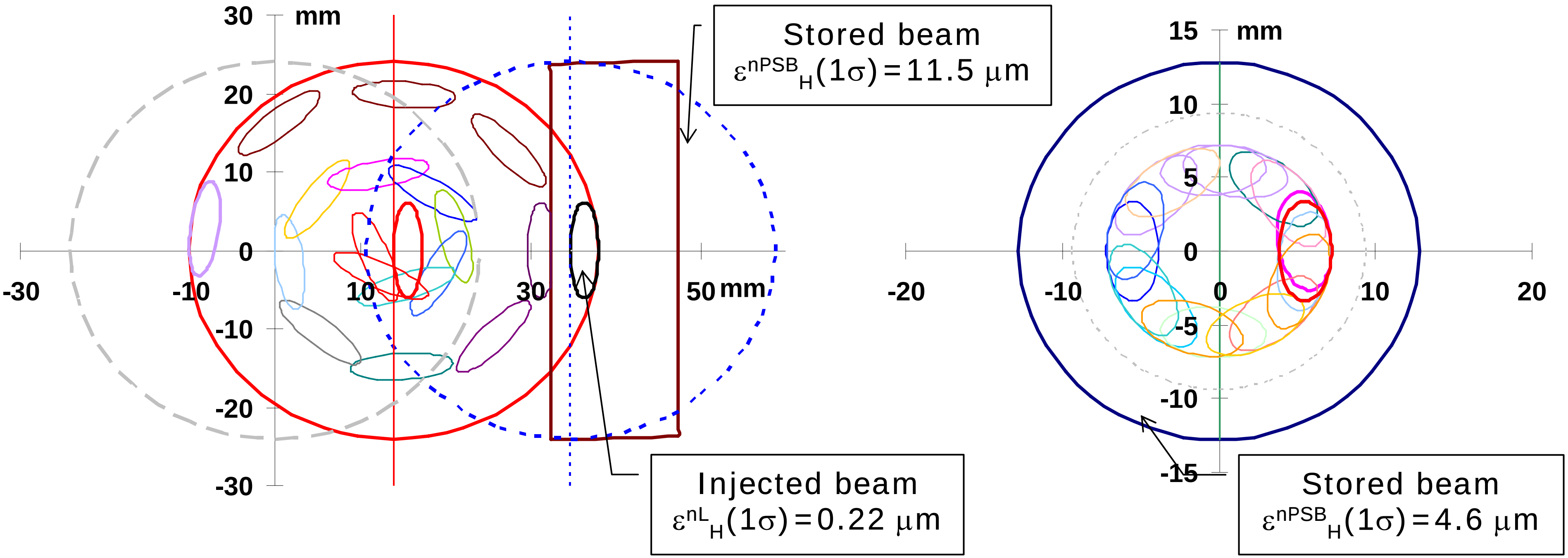
PSB H^- injection in section 1L1 of each of the 4 rings:

- Local (short) closed orbit bump in the injection area: 4 bends BS1- BS4 proposed
- Transverse painting using programmed orbit (long) bumps: “Slow” kickers: KSW1L1, KSW1L4, KSW2L1, KSW16L4 (maximum bump value ≈ 25 mm)
- Combination of closed orbit plus programmed orbit bumps for painting move circulating beam out to merge with incoming beam. Final beam is moved back onto the central orbit



Geometry of the proposed H^- injection into the PSB in the 2.5 m long straight section 1L1 of each of the four rings

A. PSB 160 MeV H⁻ inj: No adiabatic capture, no acceleration

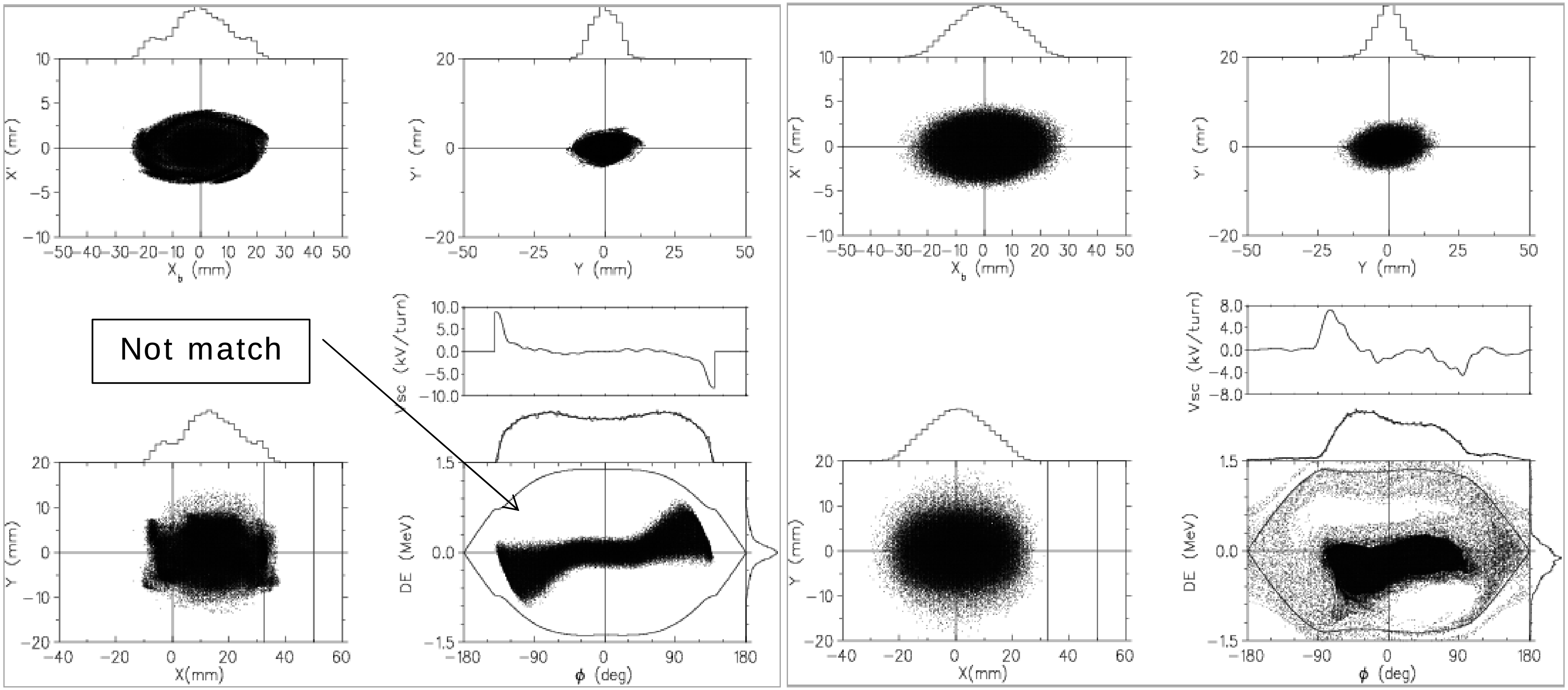


Transverse normalised phase-planes (no space charge): the circles show the stored beam ellipse contours on 1st injected turn, 66th (last) turn and at zero long-bump amplitude

- Horizontal phase-plane: circle painting
- Vertical phase-plane: no painting
- Injection completed in 66 turns (≈0.66 ms), 35 mm long-bump amplitude

Transverse distributions: elliptical (parabolic profile)
Longitudinal distribution: uniform (phase) gaussian (energy)

A. PSB 160 MeV H^- inj: No adiabatic capture, no acceleration

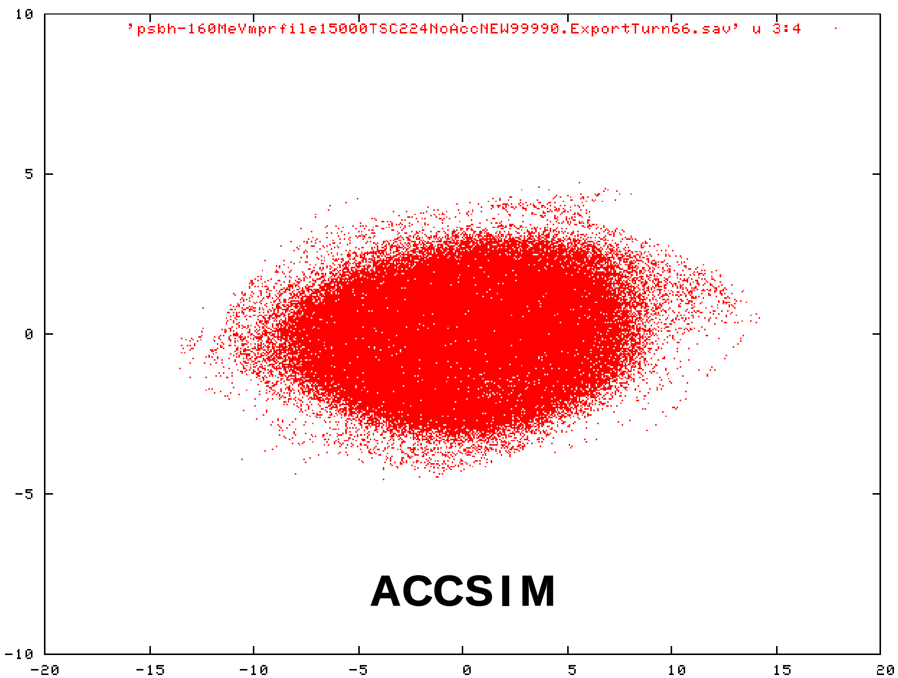


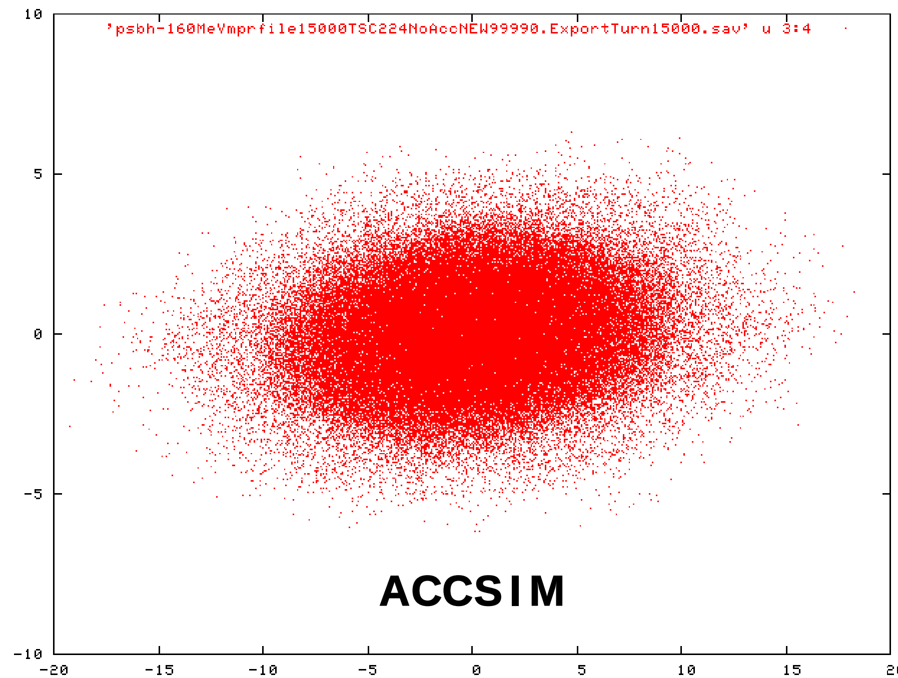
ACCSIM

Q_H=4.28 Q_V=5.47 N=1.25×10[13] H^+ (99990 macro-particles)

Scatter-plots at the 66th-15000th (15.1 ms) turns in the planes X-X', Y-Y' , X-Y, ϕ-ΔE
(No beam loss, 3 mean foil traversals per particle)

A. PSB 160 MeV H^- inj: No adiabatic capture, no acceleration

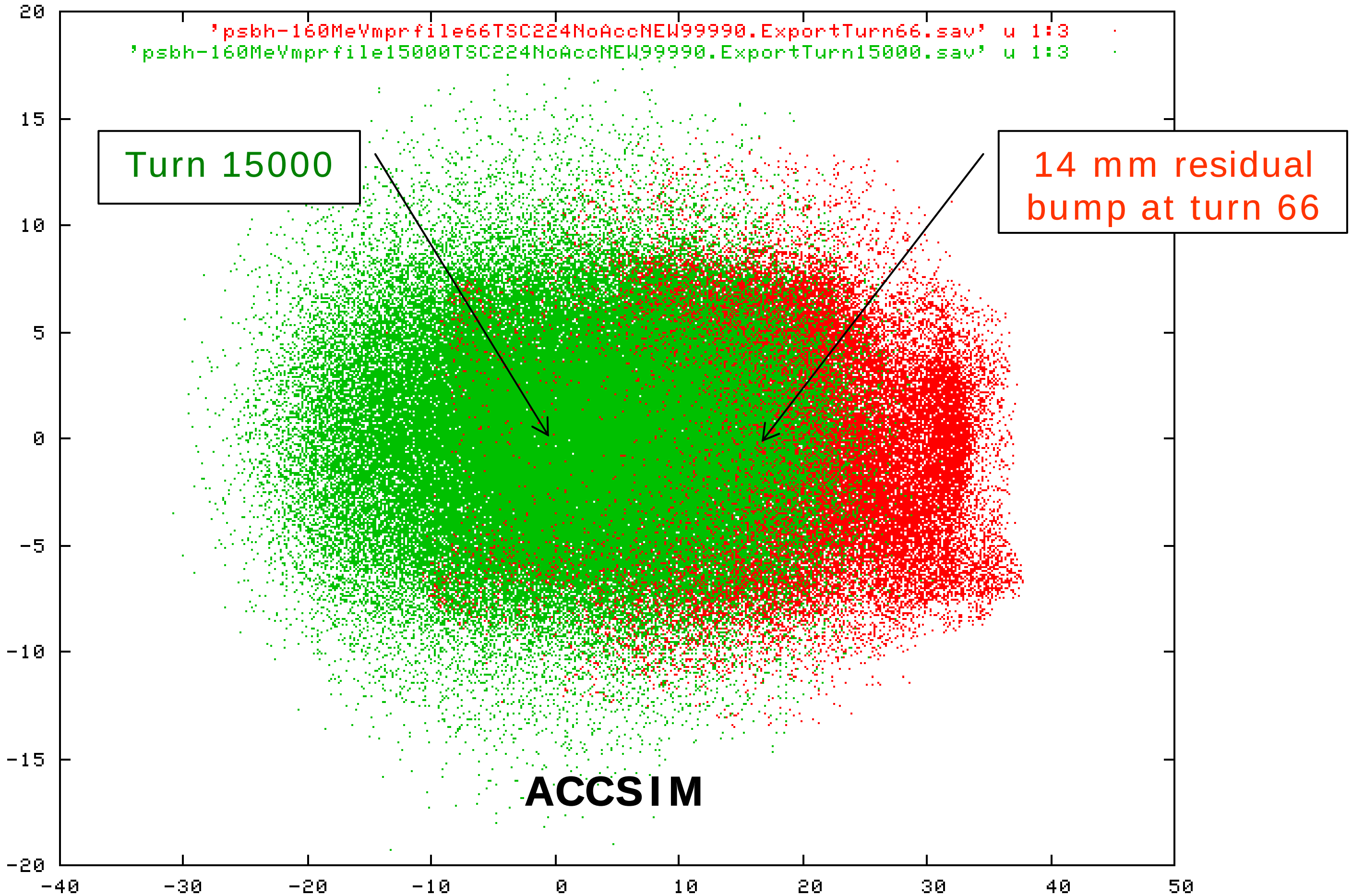




Q_H=4.28 Q_V=5.47 N=1.25×10^{13} H^+ (99990 macro-particles)

Scatter-plots at the 66th and 15000th turns in the plane Y-Y' [mm-mrad]

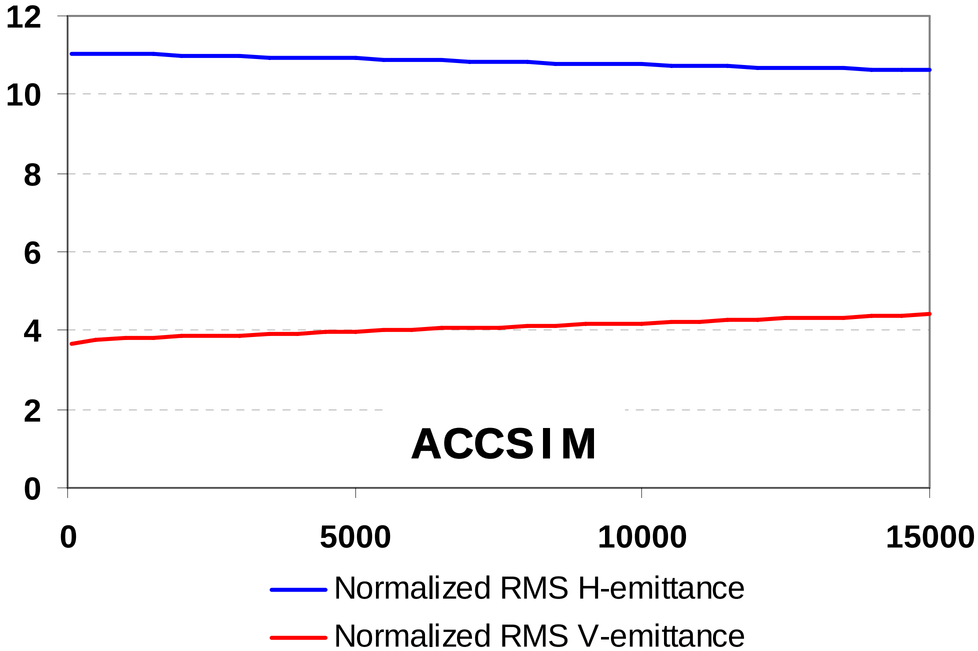
A. PSB 160 MeV H⁻ inj: No adiabatic capture, no acceleration



Q_H=4.28 Q_V=5.47 N=1.25×10^{13} H^+ (99990 macro-particles)

Scatter-plots at the 66th and 15000th turns in the planes X-Y [mm-mm]

A. PSB 160 MeV H^- inj: No adiabatic capture, no acceleration

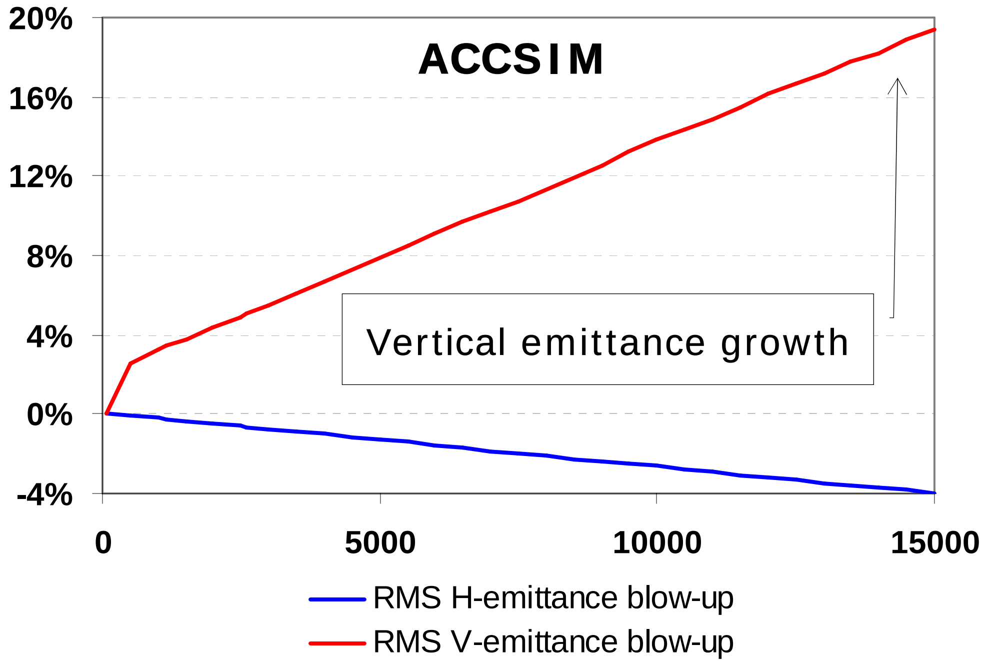


- Emittance budget:

$\varepsilon^n_H(1\sigma) = 11.5\ \mu m$, $\varepsilon^n_V(1\sigma) = 4.6\ \mu m$ (at PS entry)

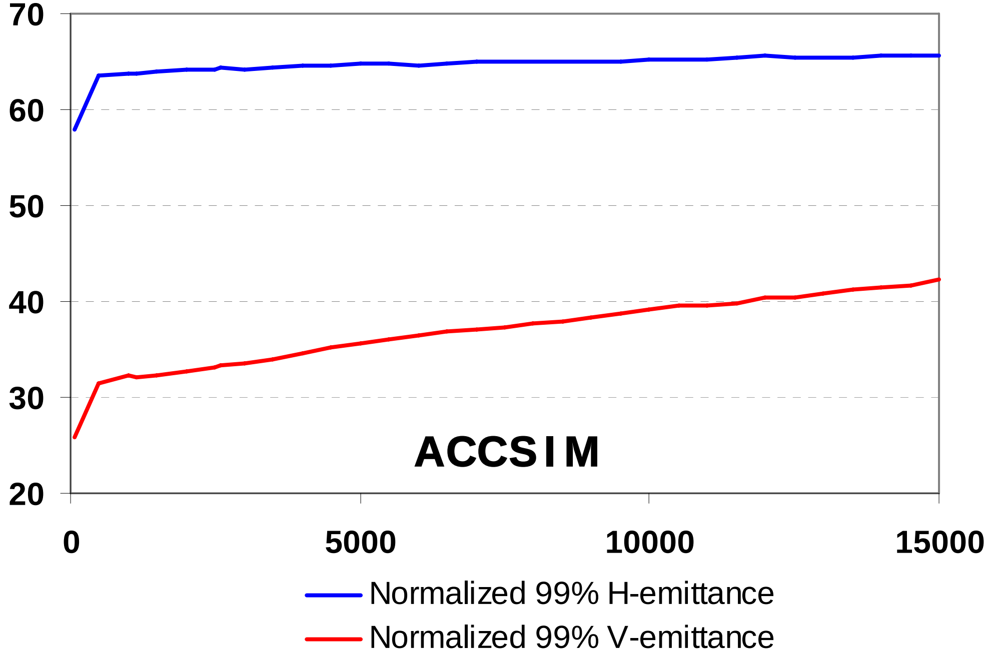
- Tracking results:

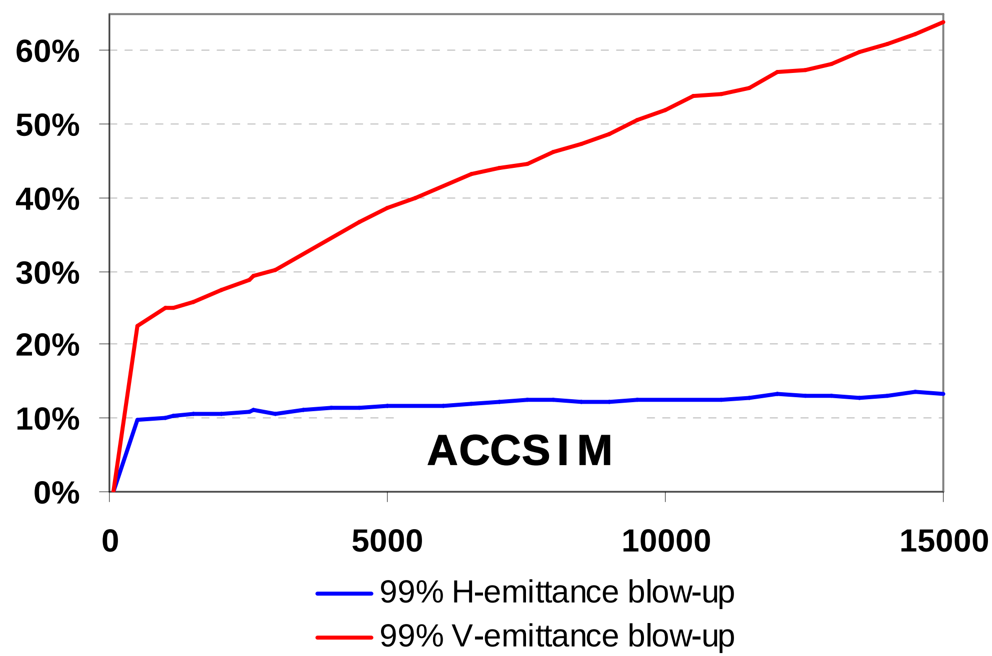
$\varepsilon^n_H(1\sigma) = 10.6\ \mu m$, $\varepsilon^n_V(1\sigma) = 4.4\ \mu m$ (turn 15000)

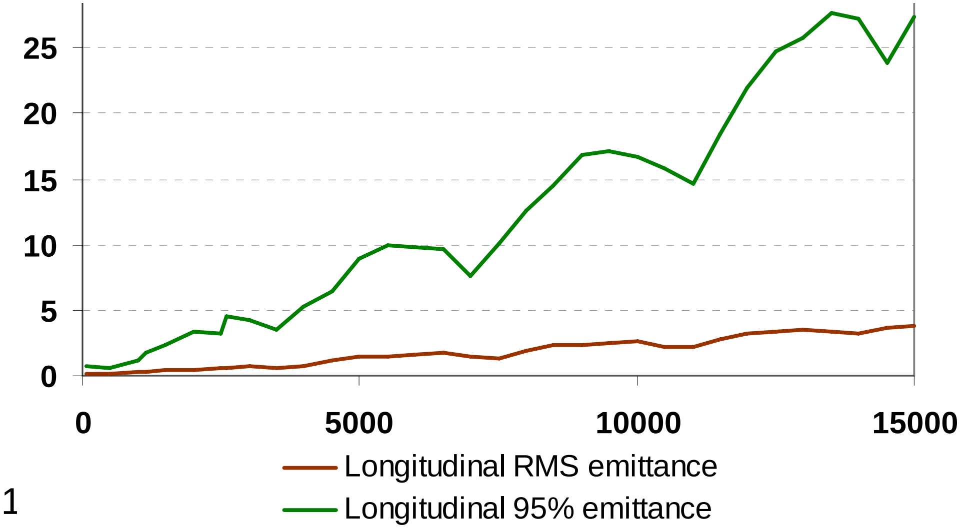


Evolution of the transverse normalized rms emittances [μm]

A. PSB 160 MeV H^- inj: No adiabatic capture, no acceleration





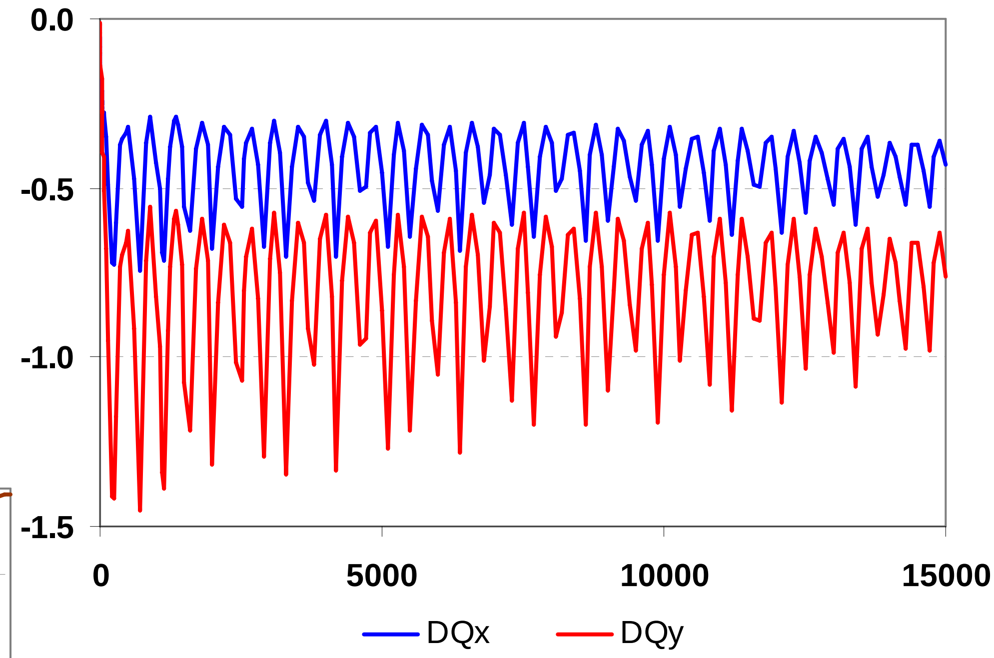


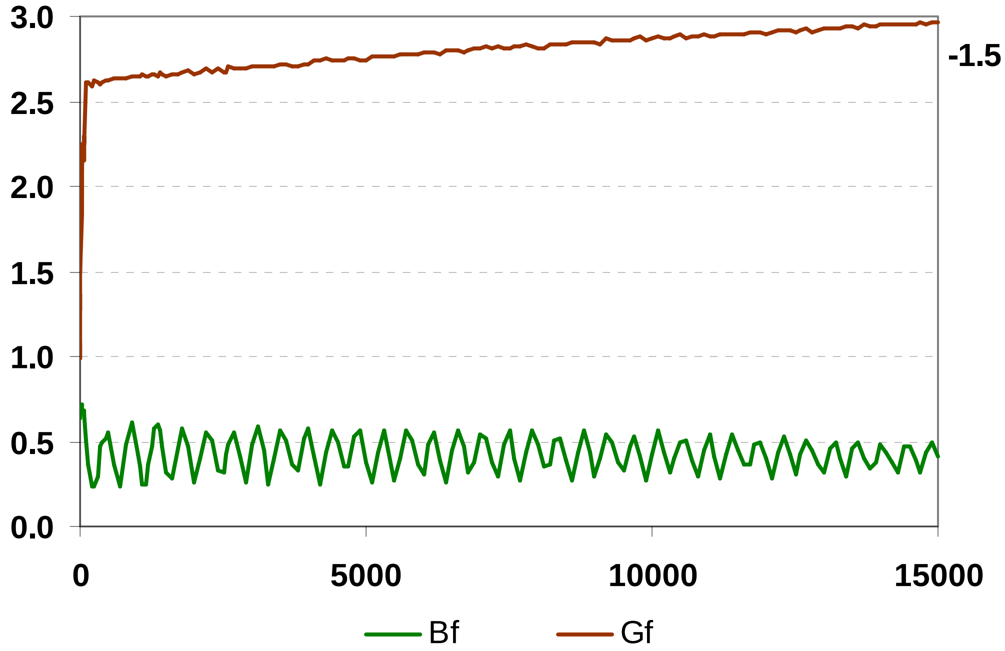
- Evolution of the transverse normalized emittances at 99% [μm]
- Evolution of the longitudinal rms and 99% emittances [eV.s]

A. PSB 160 MeV H^- inj: No adiabatic capture, no acceleration

ACCSIM quotes the zero amplitude tune shifts (Laslett):

- ❑ Computed turn by turn
- ❑ Considering the updated values of the bunching factor Bf, form factor Gf and beam emittances





- ❑ Evolution of the tunes shifts
- ❑ Evolution of the bunching B_f and form factors G_f

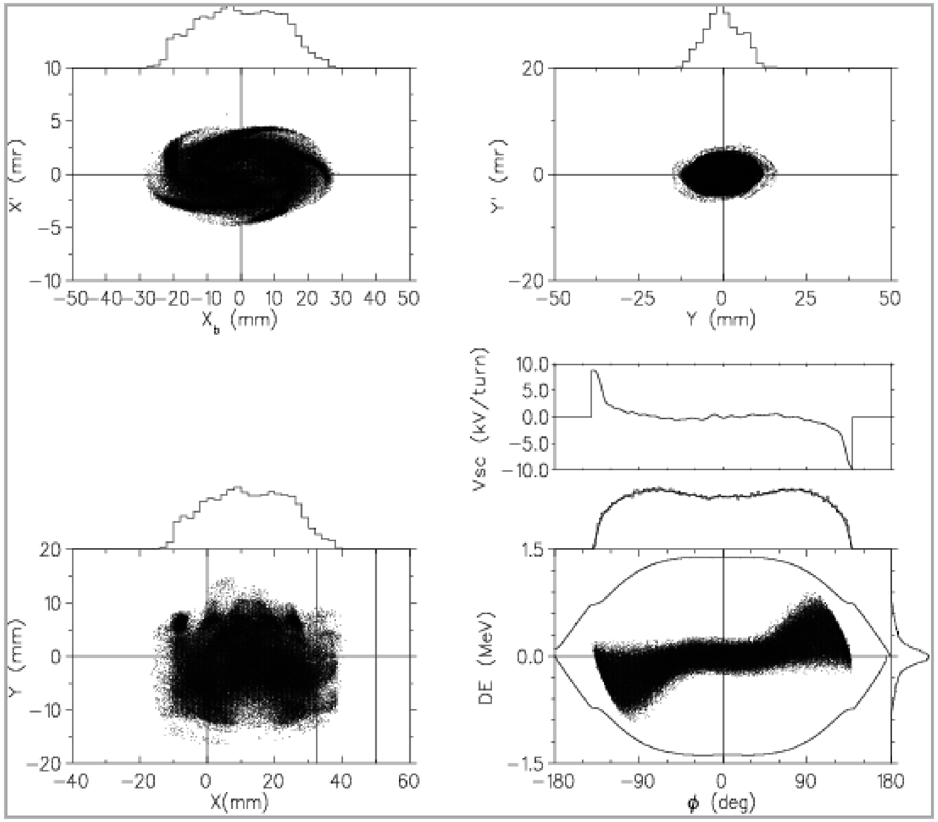
$r = Ax + b$

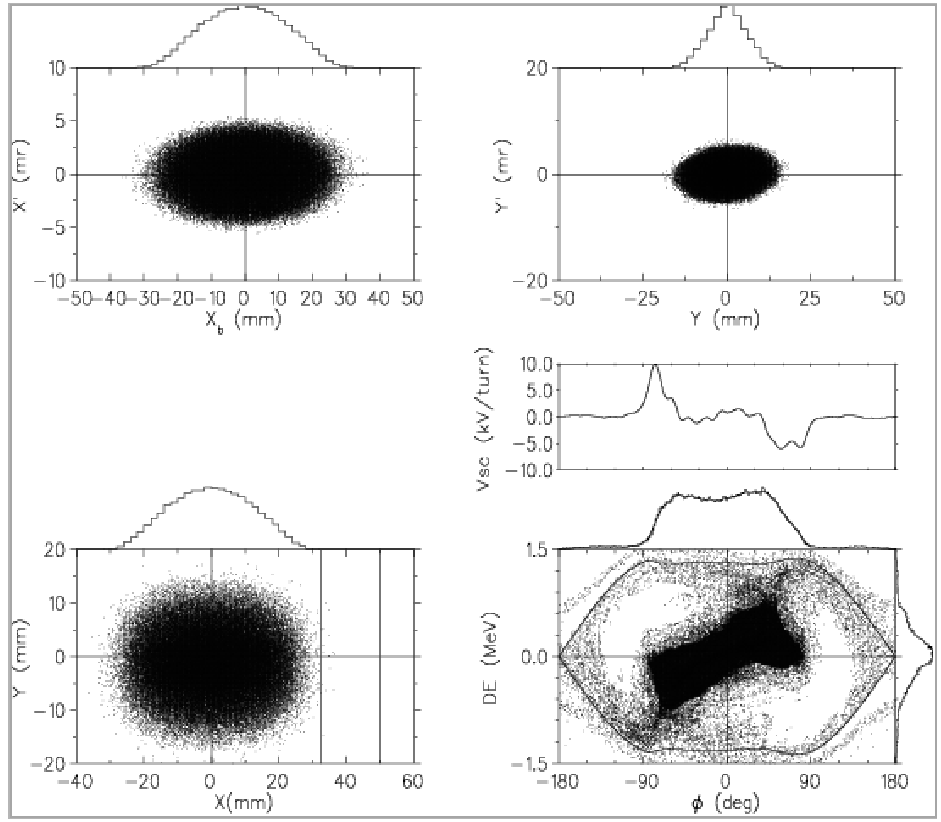
B. PSB 160 MeV H^- inj: No adiabatic capture, no acceleration, lattice errors

Aim

- Modeling of PSB lattice perturbations for studies of injection with high space charge detuning (cf. Ch Carli)
  - Study undertaken in the frame of simulation of the H^- injection into the PSB and time evolution of the beam during the beginning of the acceleration
  - **Dipolar errors**: the main source exciting the PSB closed orbit is the misalignment of quadrupoles (horizontal and vertical misalignments of 0.4 mm and 0.25 mm are considered to obtain closed orbit distortions similar to those measured)
  - **Quadrupolar errors**: individual particles may hit the resonance $2Q_V=11$ (working point $Q_V=5.47$) due to direct space charge tune shift
  - Additional thin dipole kicks and quadrupole strength errors are used to model the imperfections

B. PSB 160 MeV H^- inj: No adiabatic capture, no acceleration, lattice errors





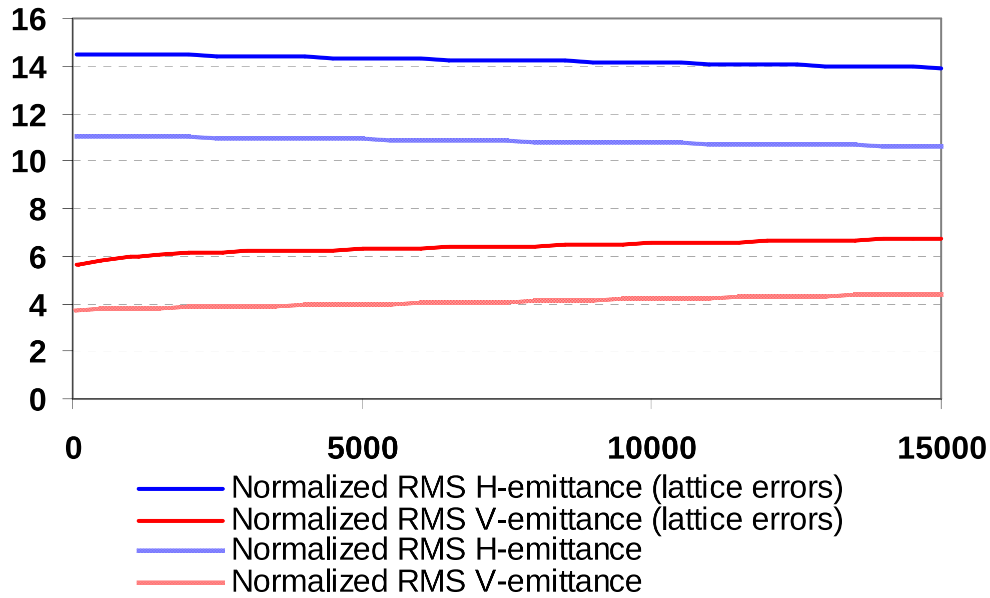
ACCSIM

Q_H=4.28 Q_V=5.47 N=1.25×10^{13} H^+ (99990 macro-particles)

Scatter-plots at the 66^{th}-12000^{th} (12.1 ms) turns in the planes X-X', Y-Y' , X-Y, ϕ-ΔE

B. PSB 160 MeV H$^-$ inj: No adiabatic capture, no acceleration, lattice errors

Results with and without lattice errors



Evolution of the transverse normalized rms emittances [μm]

Emittance budget:

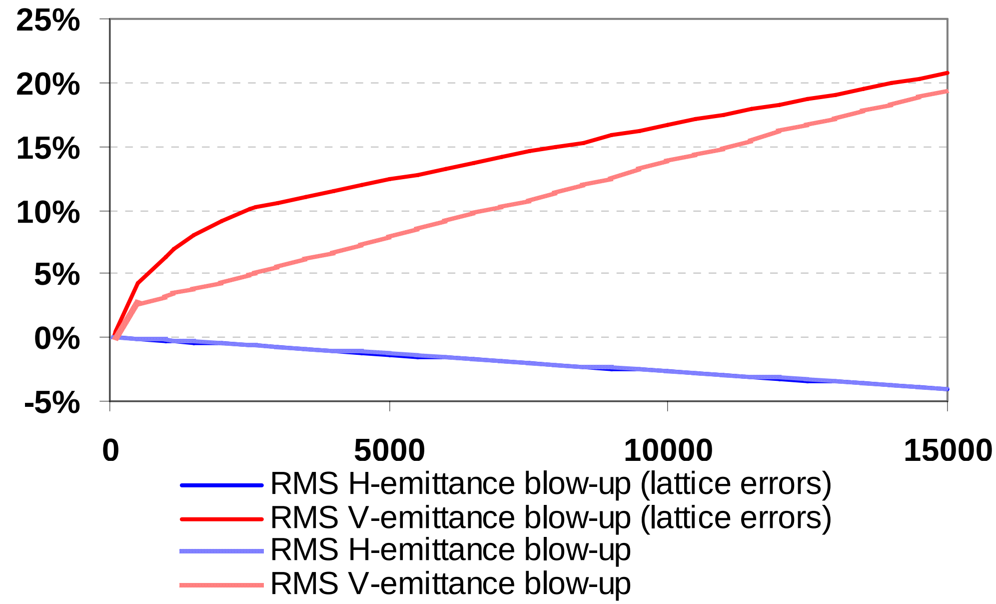
$\varepsilon^n_H(1\sigma)$ = 11.5 μm, $\varepsilon^n_V(1\sigma)$ = 4.6 μm

- no lattice errors: within the emittance budget

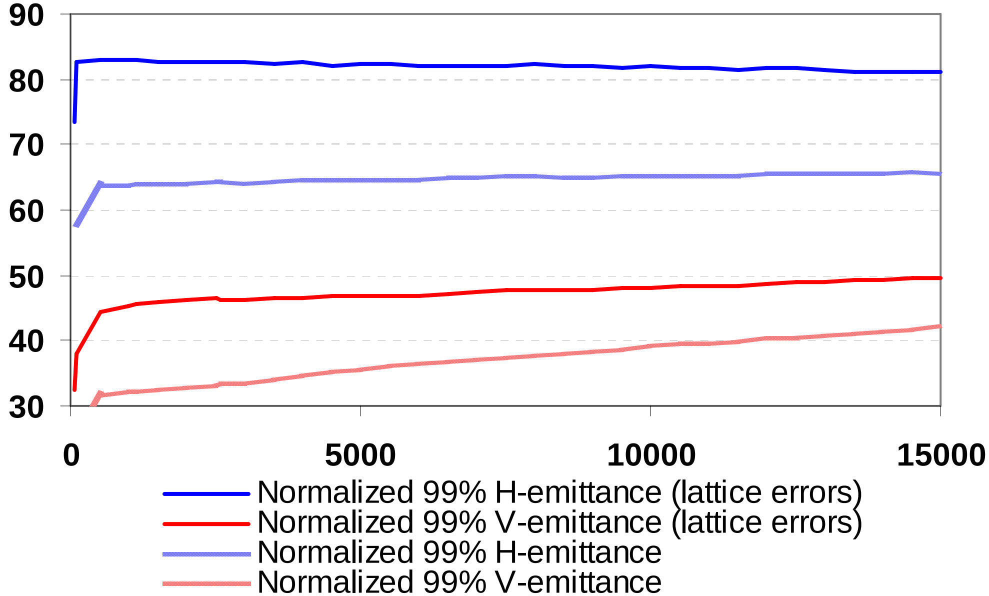
$\varepsilon^n_H(1\sigma)$ = 10.6 μm, $\varepsilon^n_V(1\sigma)$ = 4.4 μm (turn 15000)

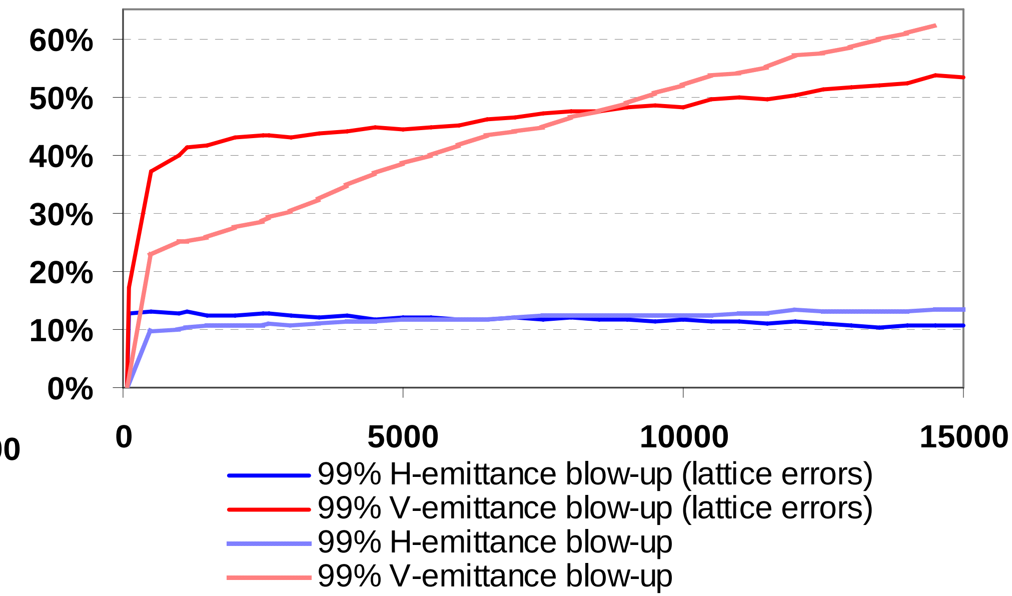
- with lattice errors: above the emiitance budget

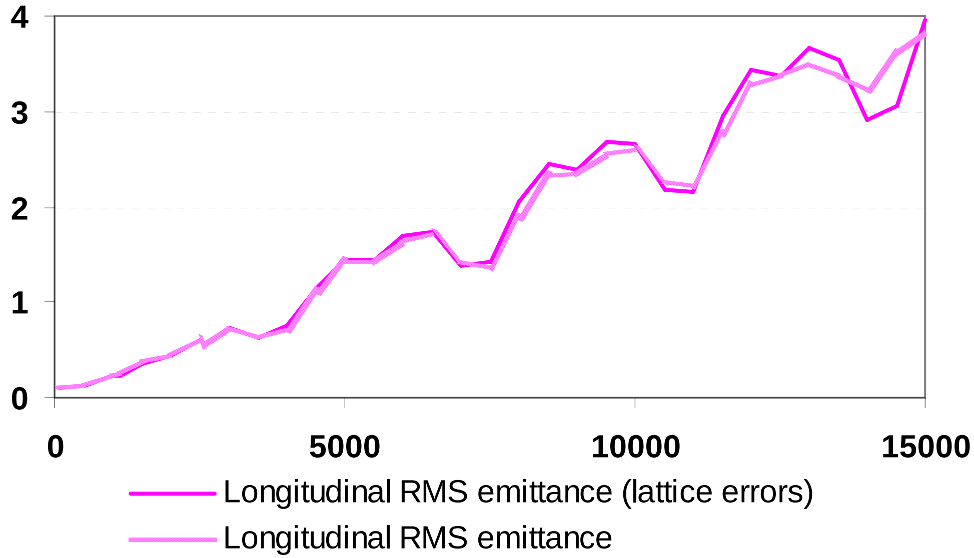
$\varepsilon^n_H(1\sigma)$ = 14.0 μm, $\varepsilon^n_V(1\sigma)$ = 6.6 μm (turn 12000)



B. PSB 160 MeV H⁻ inj: No adiabatic capture, no acceleration, lattice errors







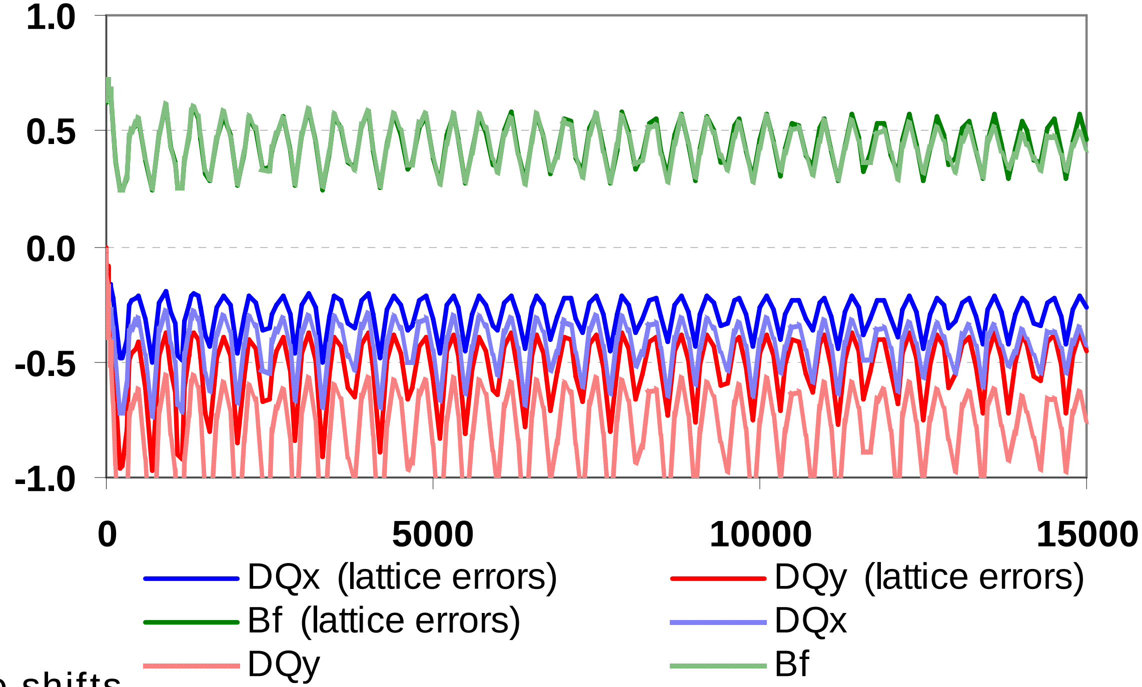
- Evolution of the transverse normalized emittances at 99% [μm]
- Evolution of the longitudinal rms emittance at 99% [eV.s]

B. PSB 160 MeV H⁻ inj: No adiabatic capture, no acceleration, lattice errors

Results with and without lattice errors

Particles with the lowest amplitudes (possibly zero) have the highest tune shift and may thus hit the integer resonance, grow in amplitude (i.e. emittance) and change the phase plane distribution

$$\Delta Q_{\mathrm{H,V}} = -\frac{k_b N_b r_p G_{\mathrm{f}}}{4\pi B_{\mathrm{f}} \beta\gamma^2 \varepsilon^n_{\mathrm{H,V}}}\left(1+\sqrt{\frac{\varepsilon_{\mathrm{V,H}} Q_{\mathrm{H,V}}}{\varepsilon_{\mathrm{H,V}} Q_{\mathrm{V,H}}}}\right)^{-1}$$



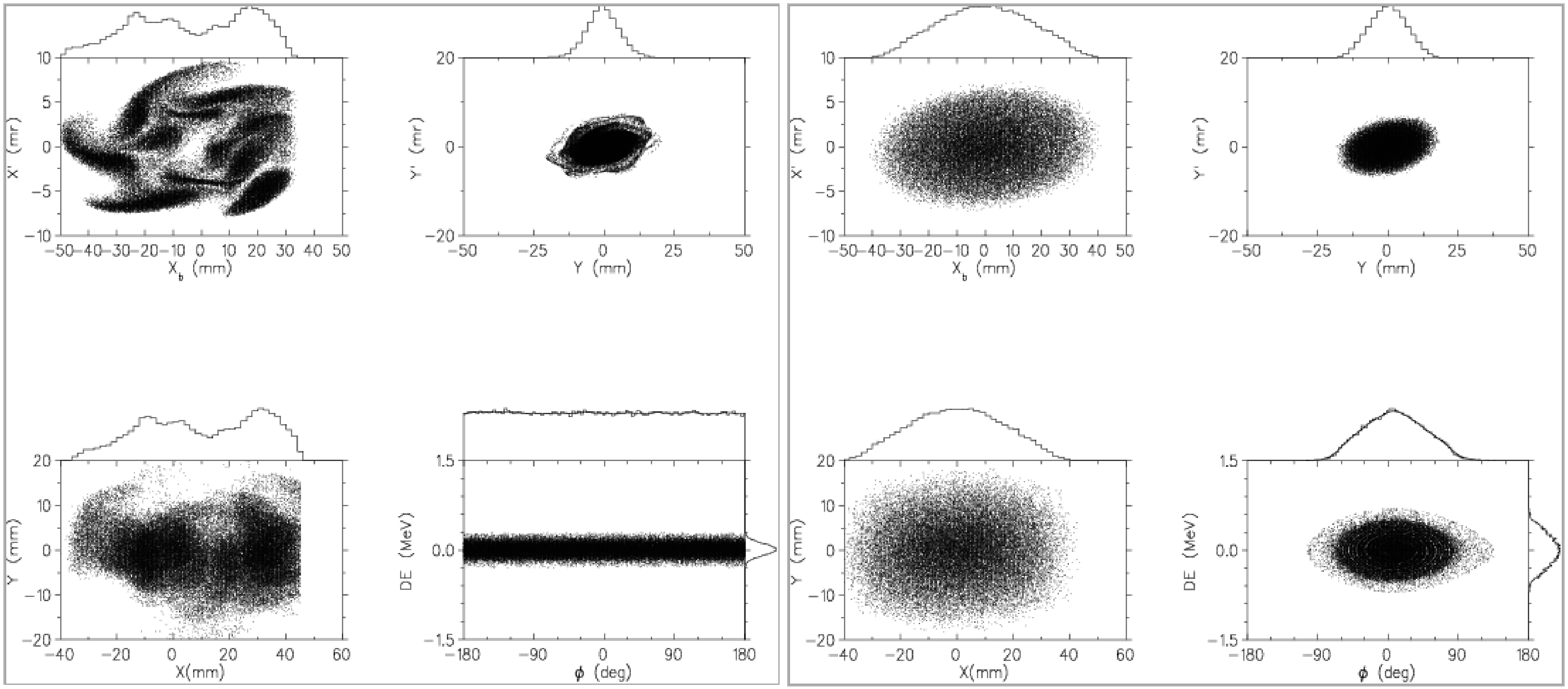
ACCSIM quotes the zero amplitude tune shifts (Laslett formula for incoherent tune shifts):

- Computed at each machine turn
- Considering the updated values of the bunching factor Bf, form factor G and beam emittances

$$\frac{\Delta Q_{\mathrm{V}}}{\Delta Q_{\mathrm{H}}} = \sqrt{\frac{\varepsilon_{\mathrm{H}} Q_{\mathrm{H}}}{\varepsilon_{\mathrm{V}} Q_{\mathrm{V}}}}$$

Evolution of the tunes shifts and bunching factor

C. PSB 50 MeV multi-turn H^+ inj: Capture, acceleration

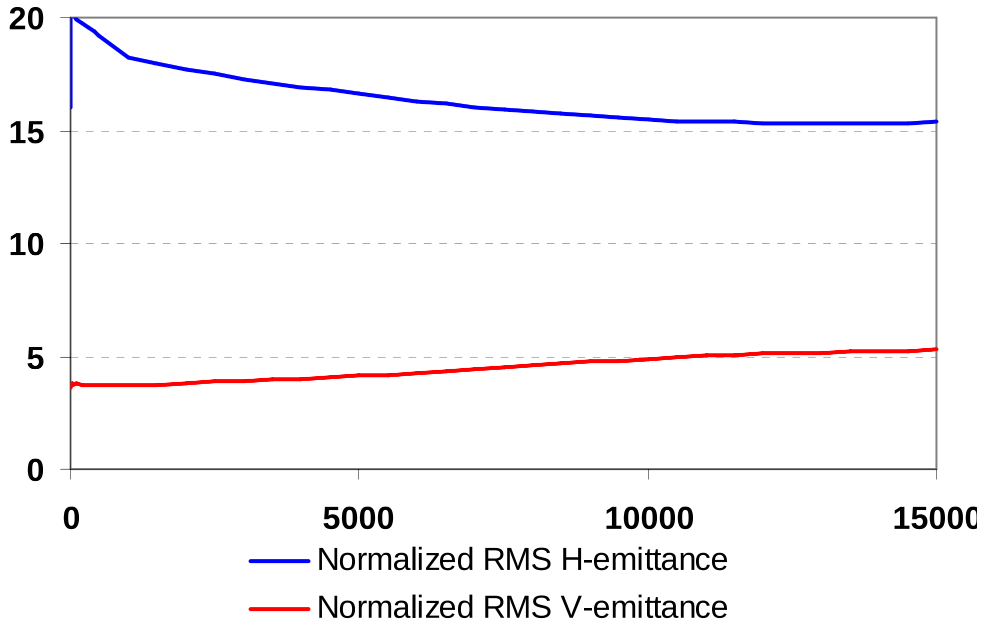


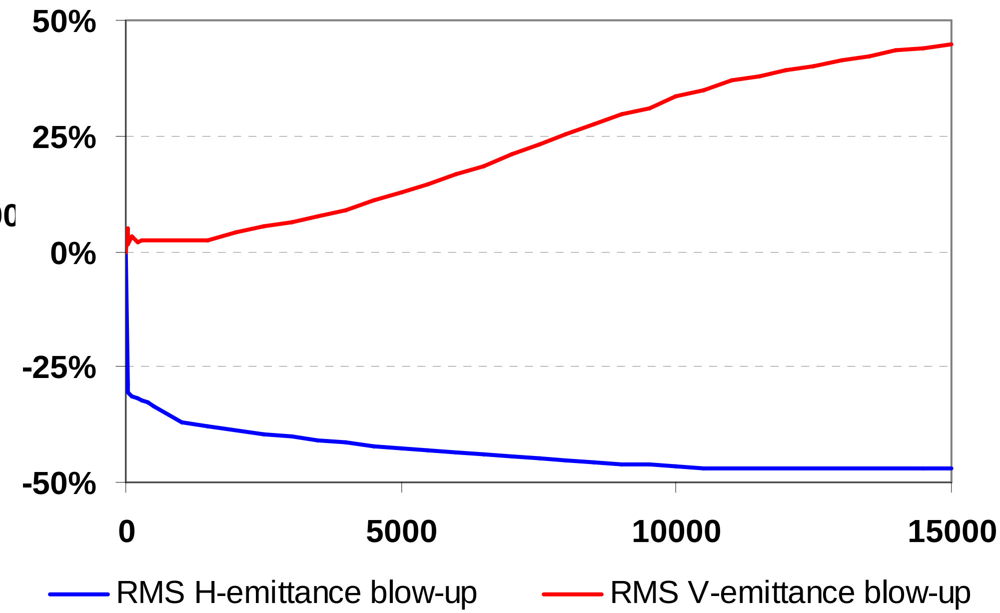
ACCSIM

Q_H=4.28 Q_V=5.55 N=2.23×10^{13} H^+ (99990 macro-particles)

Scatter-plots at the 13^{th}-15000^{th} (24.5 ms) turns in the planes X-X', Y-Y' , X-Y, ϕ-ΔE

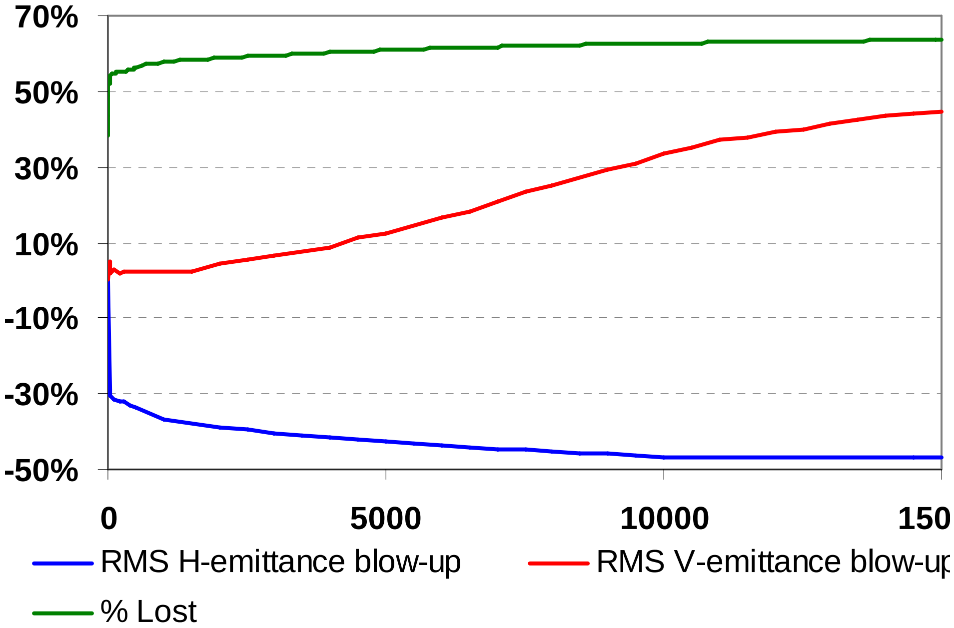
C. PSB 50 MeV multi-turn H^+ inj: Capture, acceleration

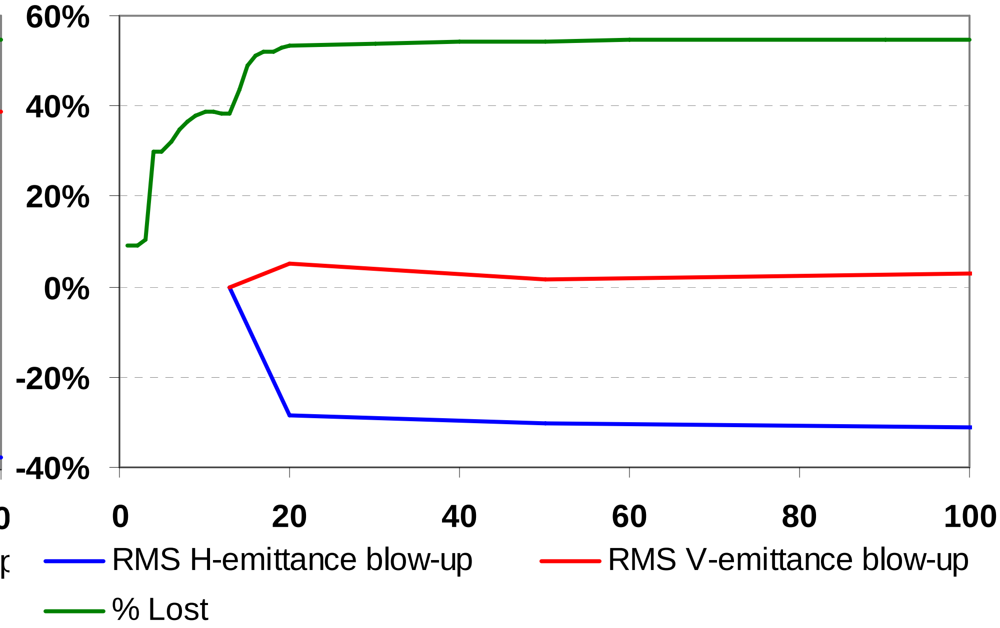


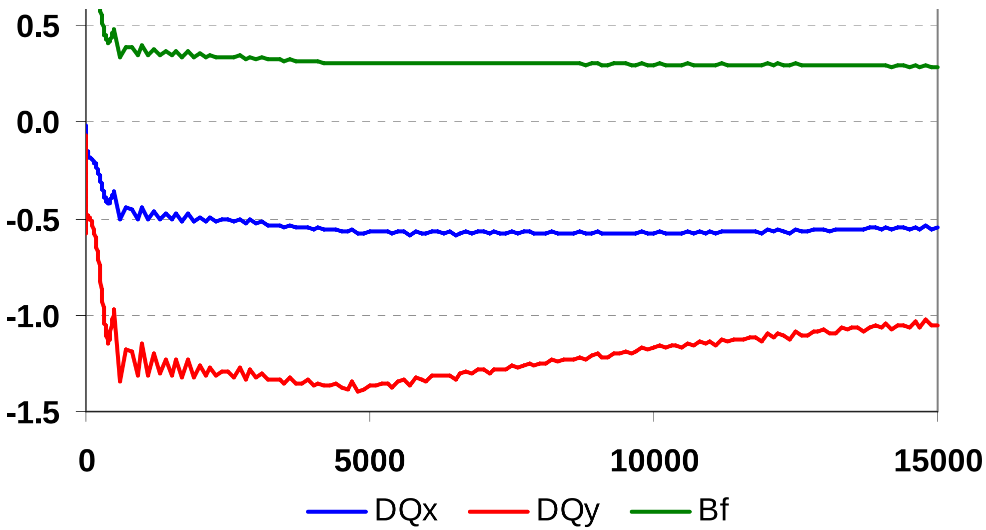


Evolution of the transverse normalized rms emittances [μm]

C. PSB 50 MeV multi-turn H⁺ inj: Capture, acceleration







- Evolution of the transverse normalized rms emittances [μm] and losses [%]
- Evolution of the tunes shifts and bunching factor B_f