Performance simulation for the highest PSB beam intensity at intermediate energy

M. Martini

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Simulation scenario

CASE 1 (high intensity beam)

- **CNGS-like beam (9.0 $\times 10^{12}$ protons) single turn injection with Accsim into a PSB ring on a 160 MeV plateau for emittance growth studies**
  - 99999 macro-particles were injected and stored for 13000 turns ($\approx$13 ms). This corresponds to the present maximum intensity beams (9 $\times 10^{12}$ real particles). The initial horizontal and vertical normalized rms emittances are 11.0 μm and 3.7 μm.
  - The phase and energy half-widths of limiting injected bunch ellipse (100% of particles) are 102.0 deg and 0.86 MeV for longitudinal matching. The bunch length is about 560 ns.

CASE 2 (high brightness beam)

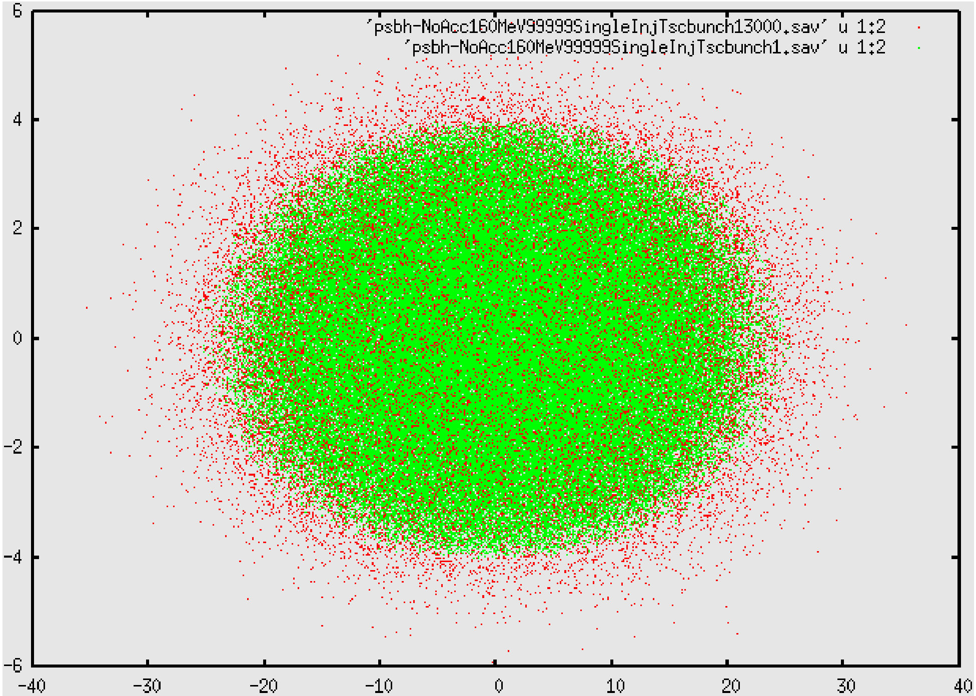
- **LHC nominal beam (3.25 $\times 10^{12}$ protons) single turn injection with Accsim into a PSB ring on a 160 MeV plateau for emittance growth studies**
  - 99999 macro-particles were injected and stored for 15000 turns. This is the LHC nominal single batch PSB intensity per ring (3.25 $\times 10^{12}$ real particles) for lossy transmission to LHC (cf. CERN-AB-2006-084 ABP/RF, Table 1.1 p 5). The initial transverse normalized rms emittances are 2.5 μm.
  - The phase and energy half-widths of limiting injected bunch ellipse are 100.2 deg and 1.03 MeV. The bunch length is about 550 ns.

Simulation scenario

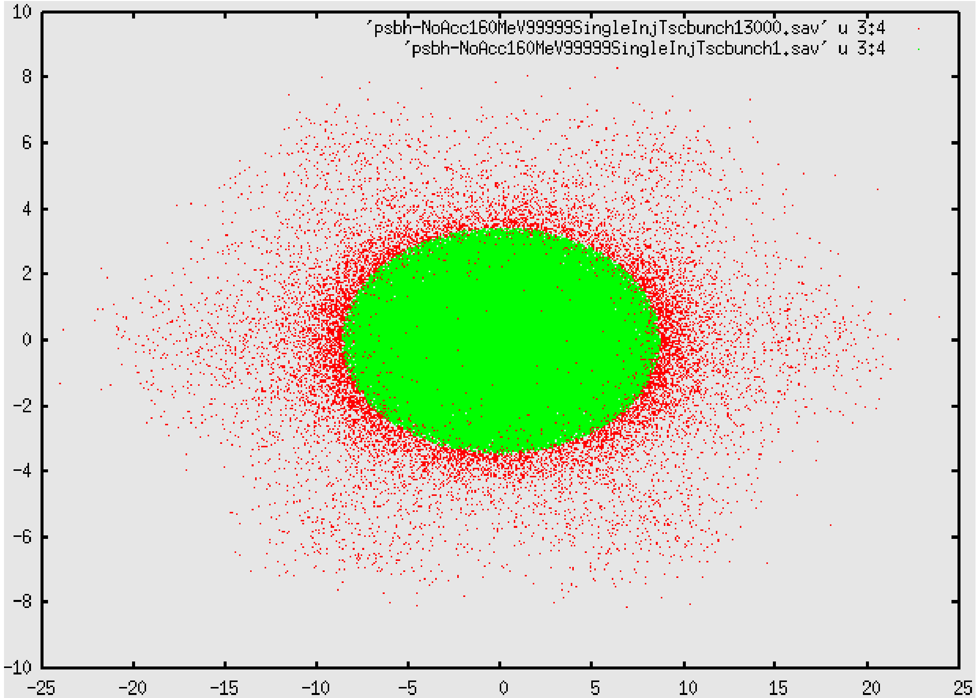
Common for both cases

- No H^- injection took place, the total proton beam intensity is injected on the 1^{st} turn onto an 8 kV bucket.
- The proton beams were injected in the middle of the PSB-ring section L1 where $\alpha_{H,V}$=0 to avoid transverse mismatch and subsequent emittance blow-up. Likewise, the short closed orbit bump (BS1-BS4) was disabled to avoid optics distortions.
- The simulation was made using the working point Q_H=4.28, Q_V=5.47.
- The simulations were done with the keyword TSCBUNCH=True in Accsim (which enables to scale the transverse space charge force in line with the local longitudinal charge density in the bunch). The transverse space charge fields were calculated using grid arrays with 0.75 mm (Case 1) and 0.5 mm (Case 2) spacing of grid points.
- All simulations were carried out using the August, 4, 2006 Accsim version.

Case 1 (high intensity beam): CNGS-like beam



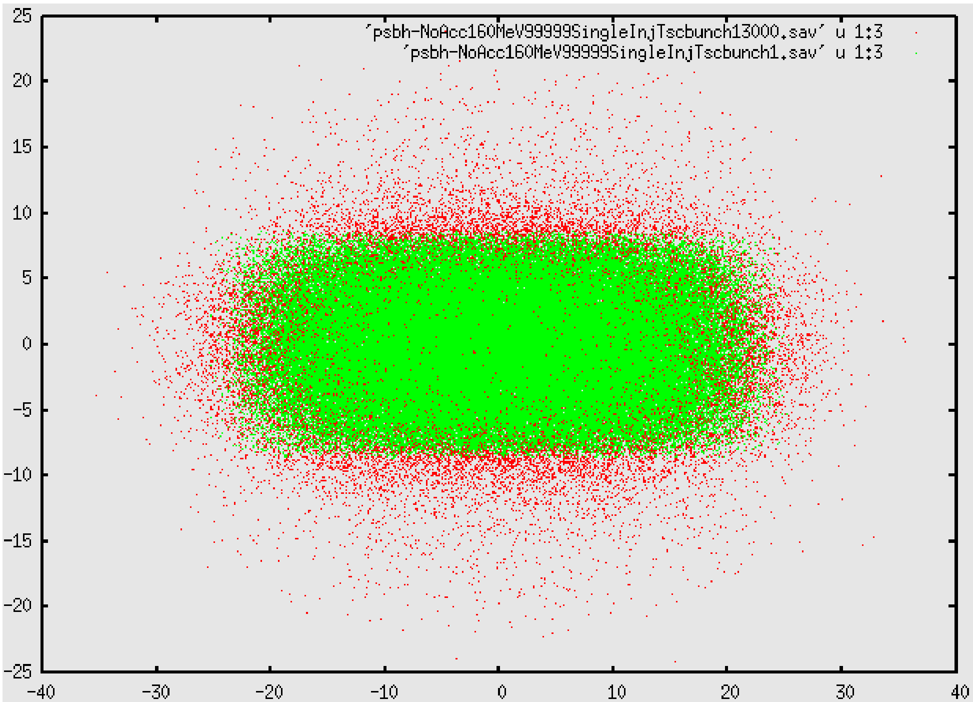
X-X' scatter-plot [mm-mrad] at turns 1 & 13000



Y-Y' scatter-plot [mm-mrad] at turns 1 & 13000

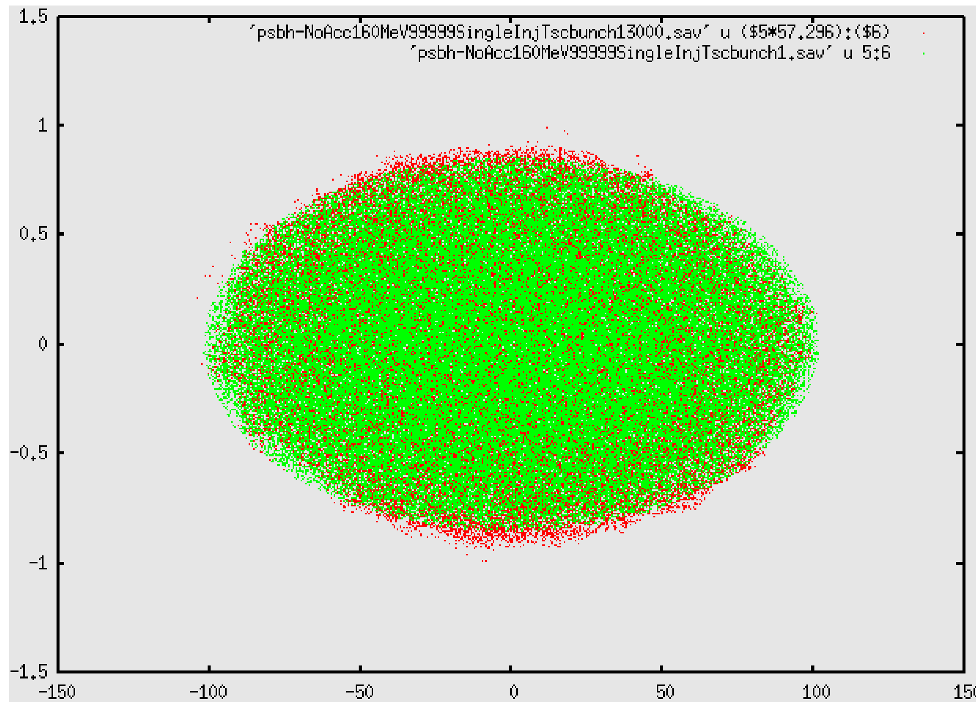
Q_H=4.28 Q_V=5.47 N=9×10^{12} protons (99999 macro-particles)

Case 1 (high intensity beam): CNGS-like beam



X-Y scatter-plot[1] [mm-mm] at turns 1 & 13000

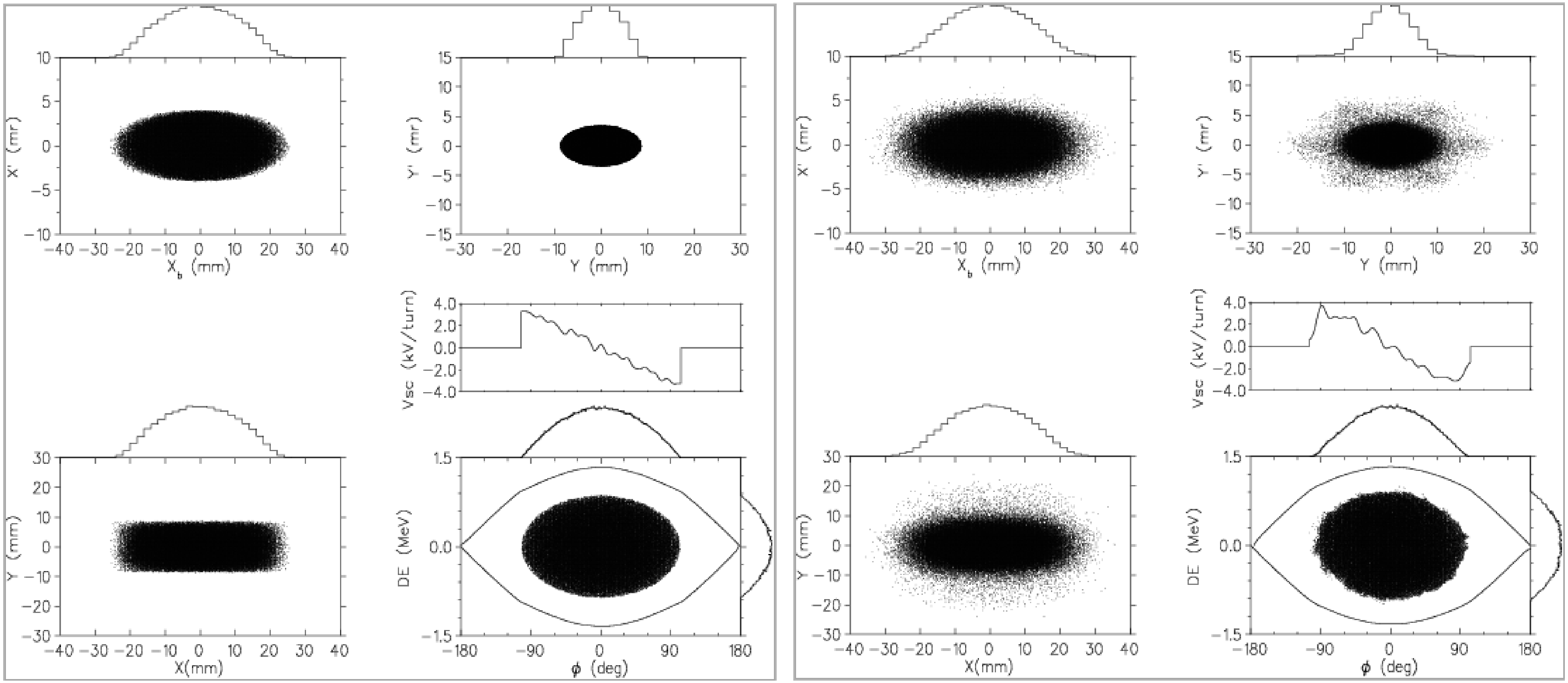
[1] *The physical cross-section of the injected beam is rectangular as no correlation is assumed between horizontal and vertical planes*



ϕ-ΔE scatter-plot [deg-MeV] at turns 1 & 13000

Q_H=4.28 Q_V=5.47 N=9$\times$10^{12} protons (99999 macro-particles)

Case 1 (high intensity beam): CNGS-like beam

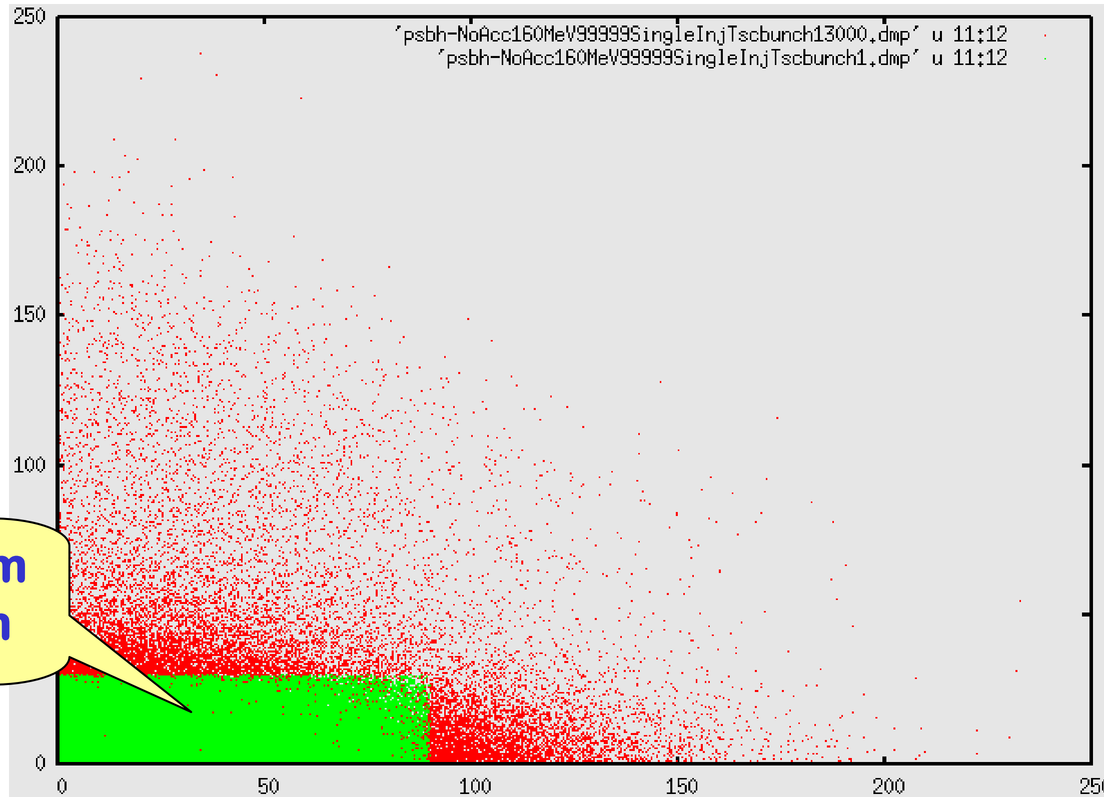


Q_H=4.28 Q_V=5.47 N=9×10^{12} protons (99999 macro-particles)

Scatter-plots at the 1st-13000th turns in the planes X-X', Y-Y' , X-Y, ϕ-ΔE

Case 1 (high intensity beam): CNGS-like beam

$\varepsilon^*_H(1\sigma) \approx 11.0\ \mu m$
$\varepsilon^*_V(1\sigma) \approx 3.7\ \mu m$



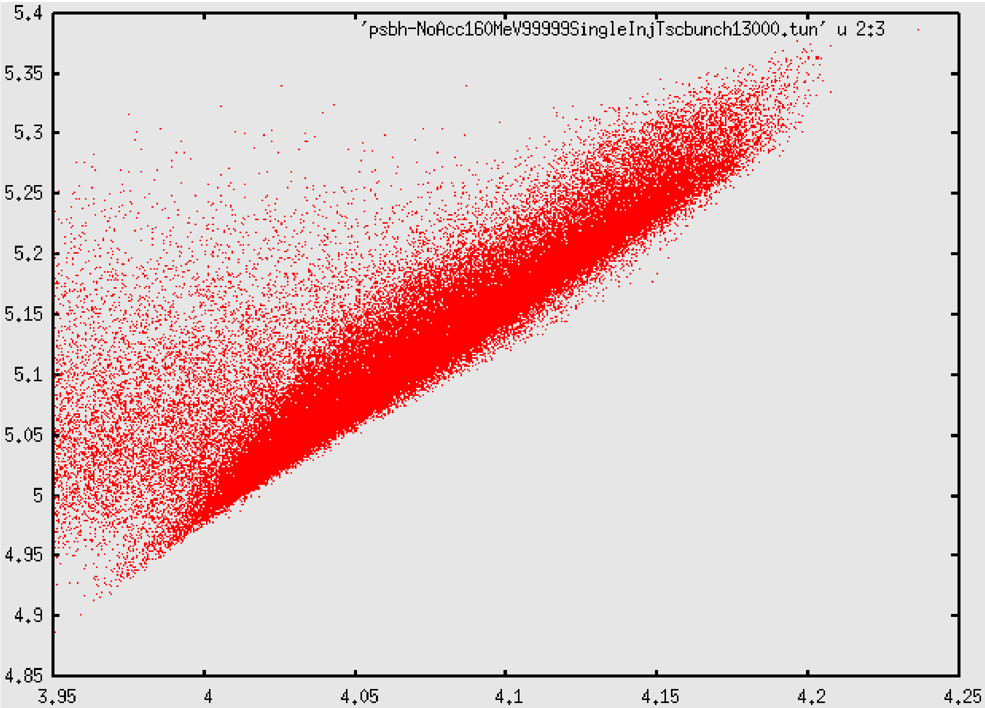
Physical emittance[(1)(2)] [μm] scatter-plot at turns 1 and 13000

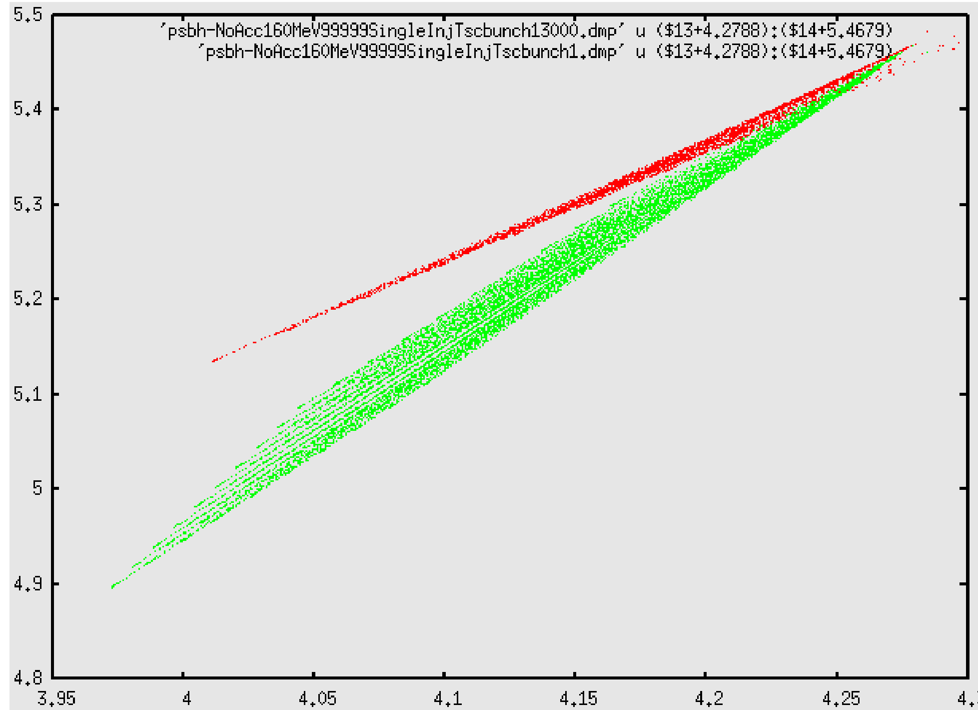
(1) Calculated Courant-Snyder invariants for individual particles

(2) The limiting 90 μm (H) and 30 μm (V) physical emittances correspond to 10.95 μm (H) and 3.65 μm (V) normalized rms emittances

Q_H=4.28 Q_V=5.47 N=9$\times 10^{12}$ protons (99999 macro-particles)

Case 1 (high intensity beam): CNGS-like beam





Particle tunes[(1)] at turn 13000

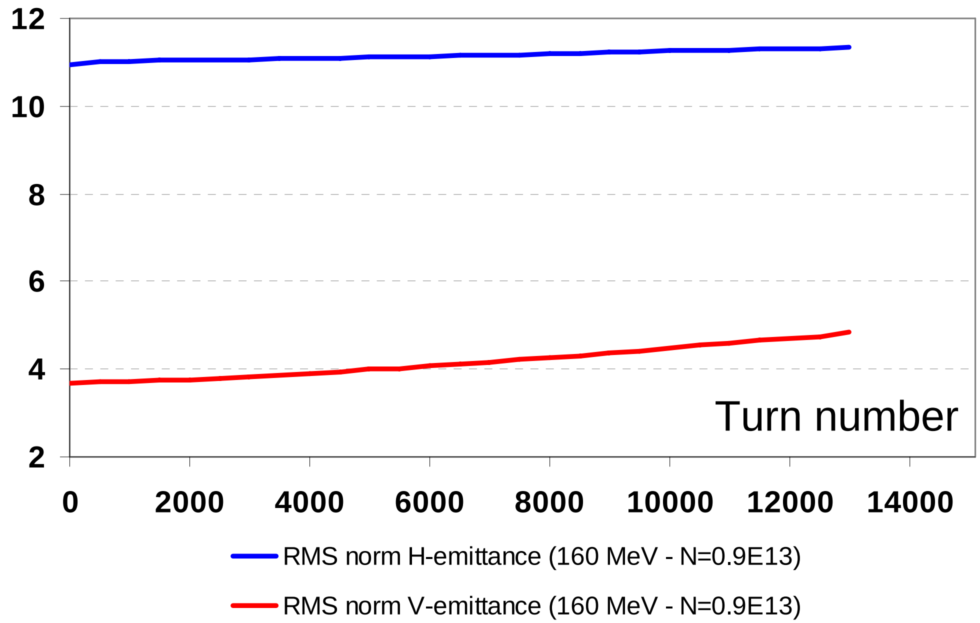
[(1)] Individual particle betatron tunes derived by counting particle zero-crossings in phase plane (the accuracy increases with the number of turns)

Particle tune shifts[(1)] at turns 1 and 13000

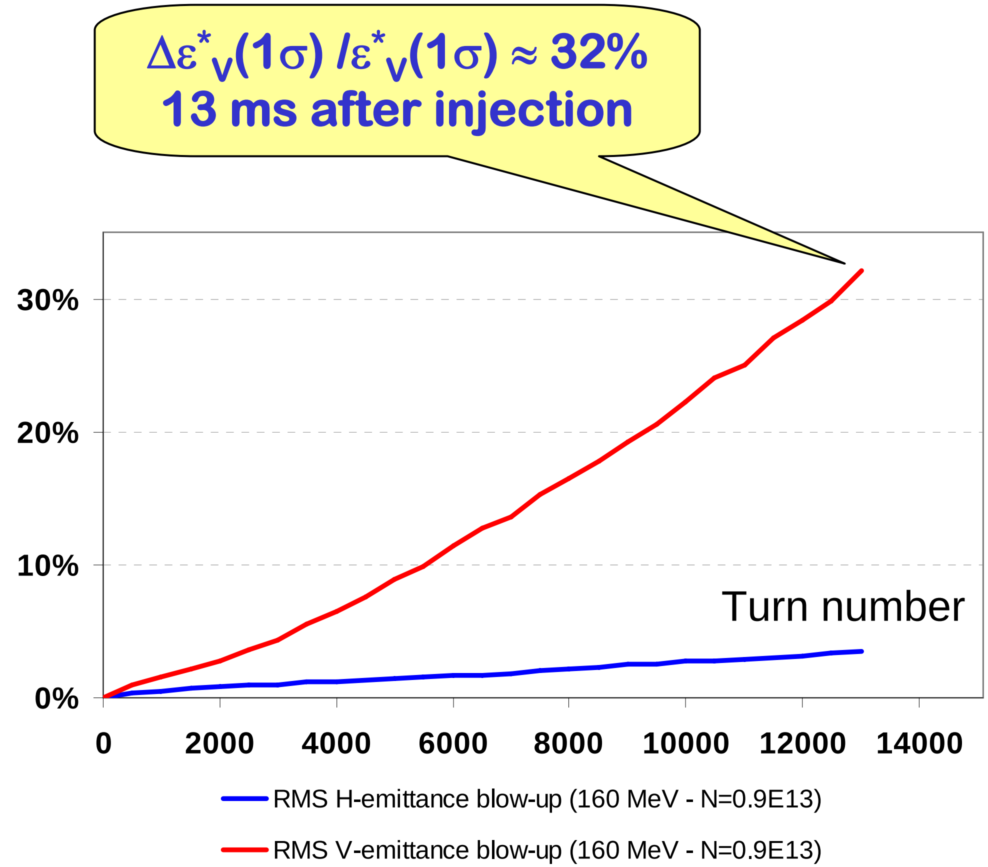
[(1)] Calculated individual particle tune shifts based on the generalized Laslett formula

Q_H=4.28 Q_V=5.47 N=9$\times 10^{12}$ protons (99999 macro-particles)

Case 1 (high intensity beam): CNGS-like beam

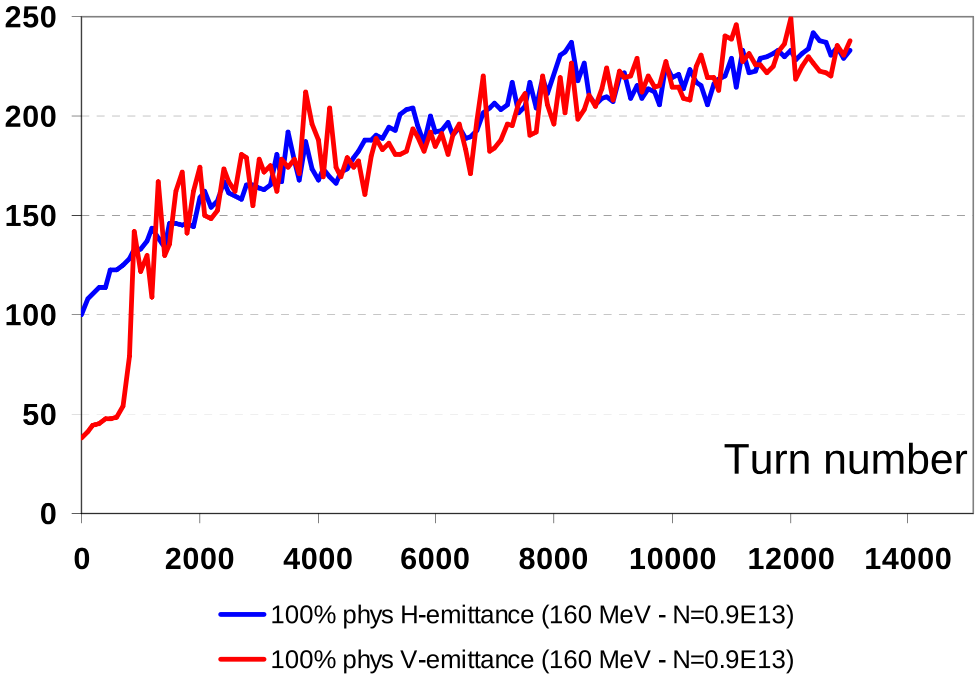


Evolution of rms normalized emittances [μm]

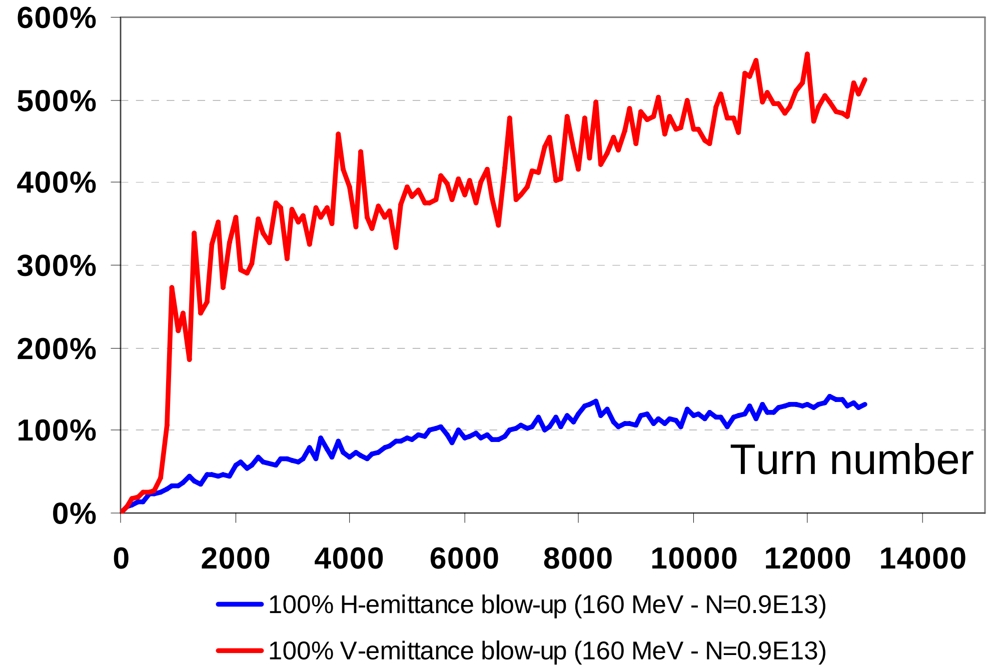


Evolution of rms normalized emittance blow-ups [%]

Case 1 (high intensity beam): CNGS-like beam

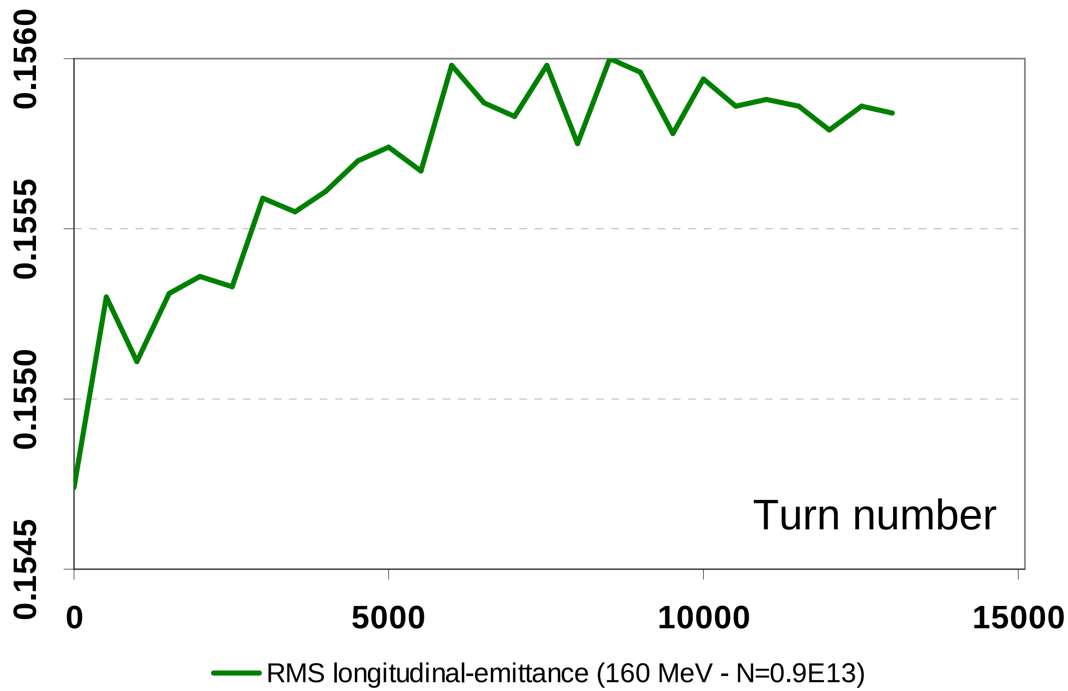


Evolution of 100% physical emittances [μm]



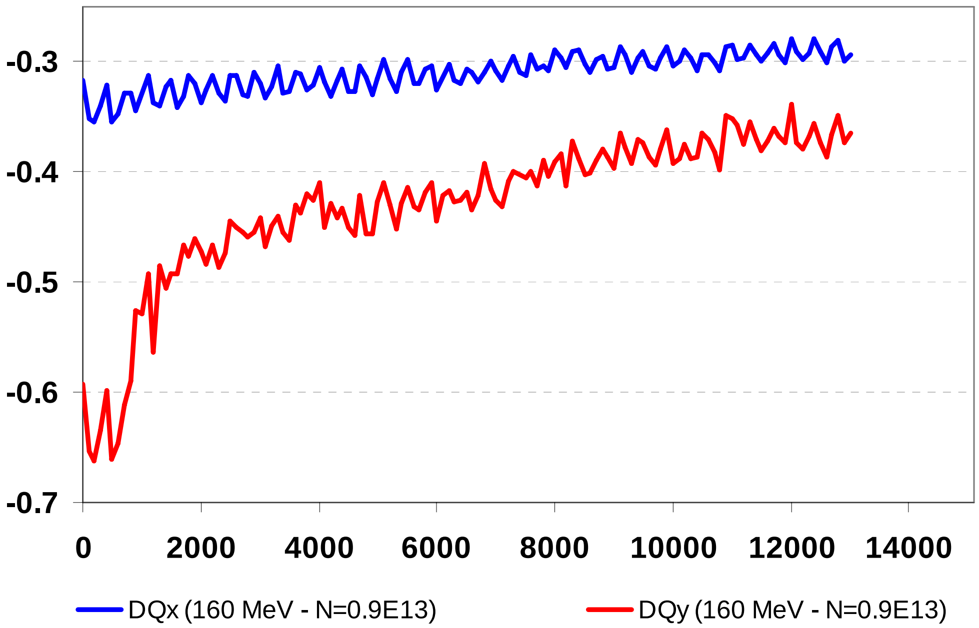
Evolution of 100% physical emittance blow-ups [%]

Case 1 (high intensity beam): CNGS-like beam



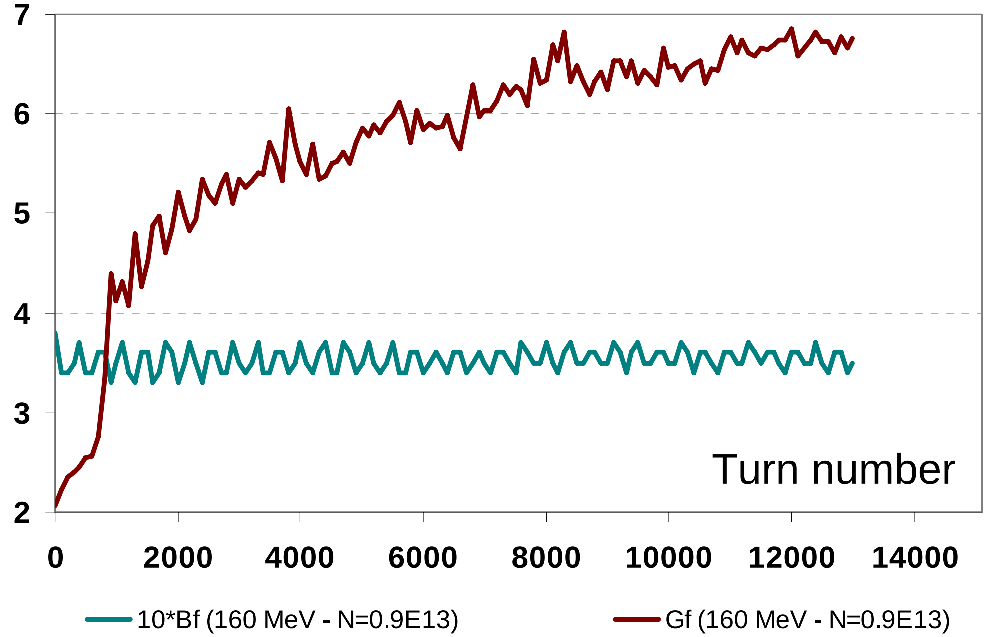
Evolution of rms longitudinal emittances [eVs]

Case 1 (high intensity beam): CNGS-like beam



Evolution of space charge tune shifts[(1)]

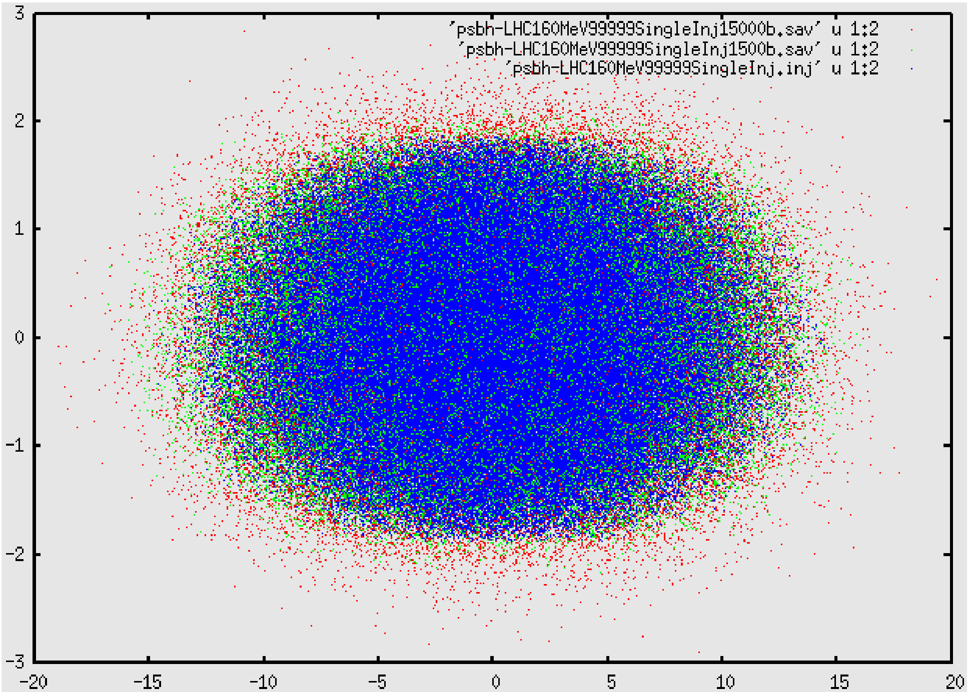
[(1)] Maximum tune shifts for the beam center



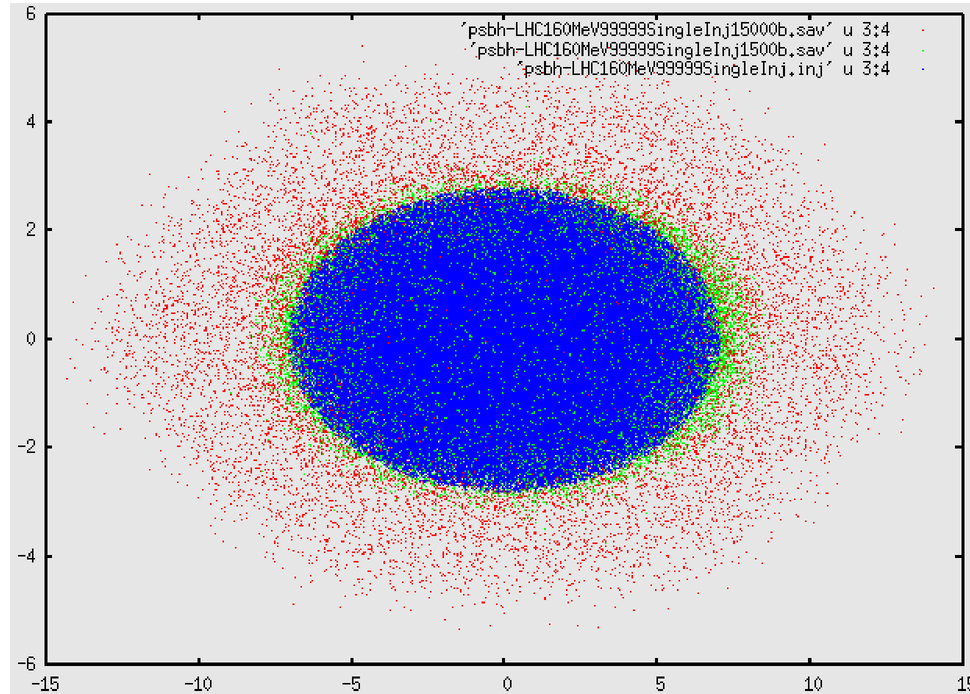
Evolution of bunching factor (×10) and form factor[(1)]

[(1)] Ratio of peak to average density for the transverse two dimensional distribution

Case 2 (high brightness beam): LHC nominal beam



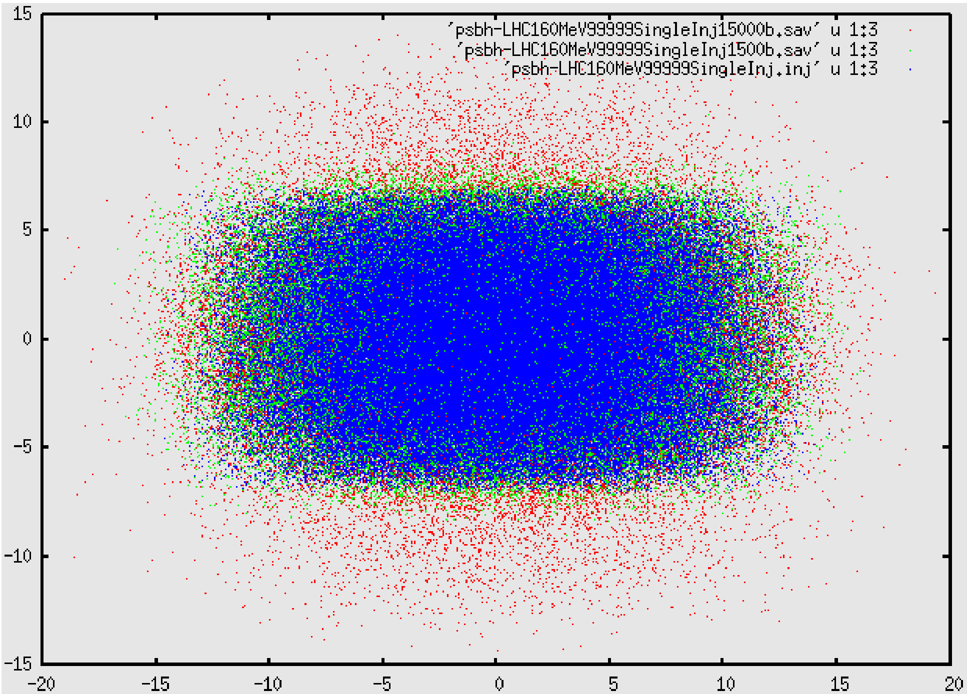
X-X' scatter-plot [mm-mrad] at turns 1, 1500 and 15000

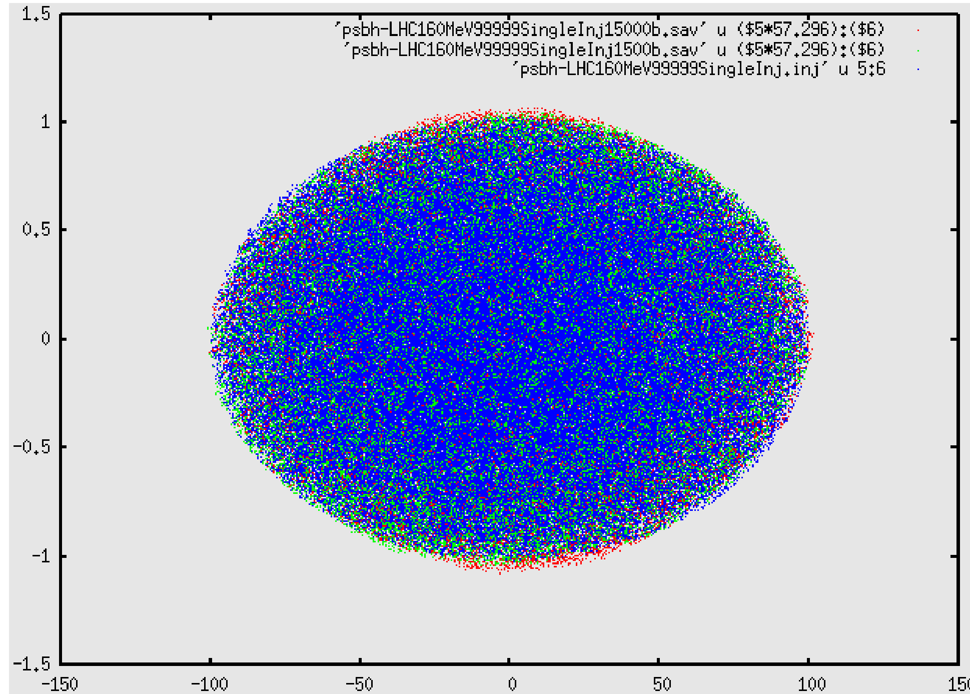


Y-Y' scatter-plot [mm-mrad] at turns 1, 1500 and 15000

Q_H=4.28 Q_V=5.47 N=3.25×10^{12} protons (99999 macro-particles)

Case 2 (high brightness beam): LHC nominal beam





X-Y scatter-plot[(1)] [mm-mm] at turns 1, 1500 and 15000

[1)] ***The physical cross-section of the injected beam is rectangular as no correlation is assumed between horizontal and vertical planes***

ϕ-ΔE scatter-plot [deg-MeV] at turns 1, 1500 and 15000

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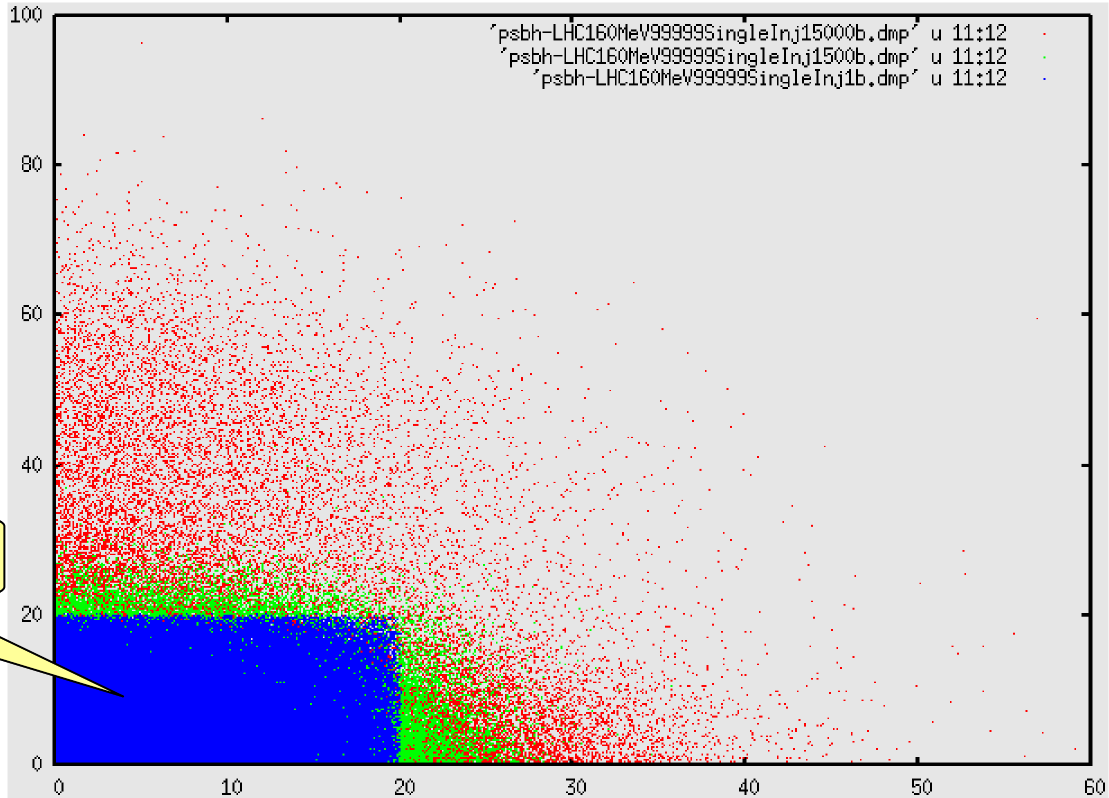

$\varepsilon^*_{H,V}(1\sigma) \approx 2.5\ \mu m$

Physical emittance(1)(2) [μm] scatter-plot at turns 1, 1500 and 15000

(1) Calculated Courant-Snyder invariants for individual particles

(2) The limiting 20 μm physical emittances correspond to 2.43 μm normalized rms emittances

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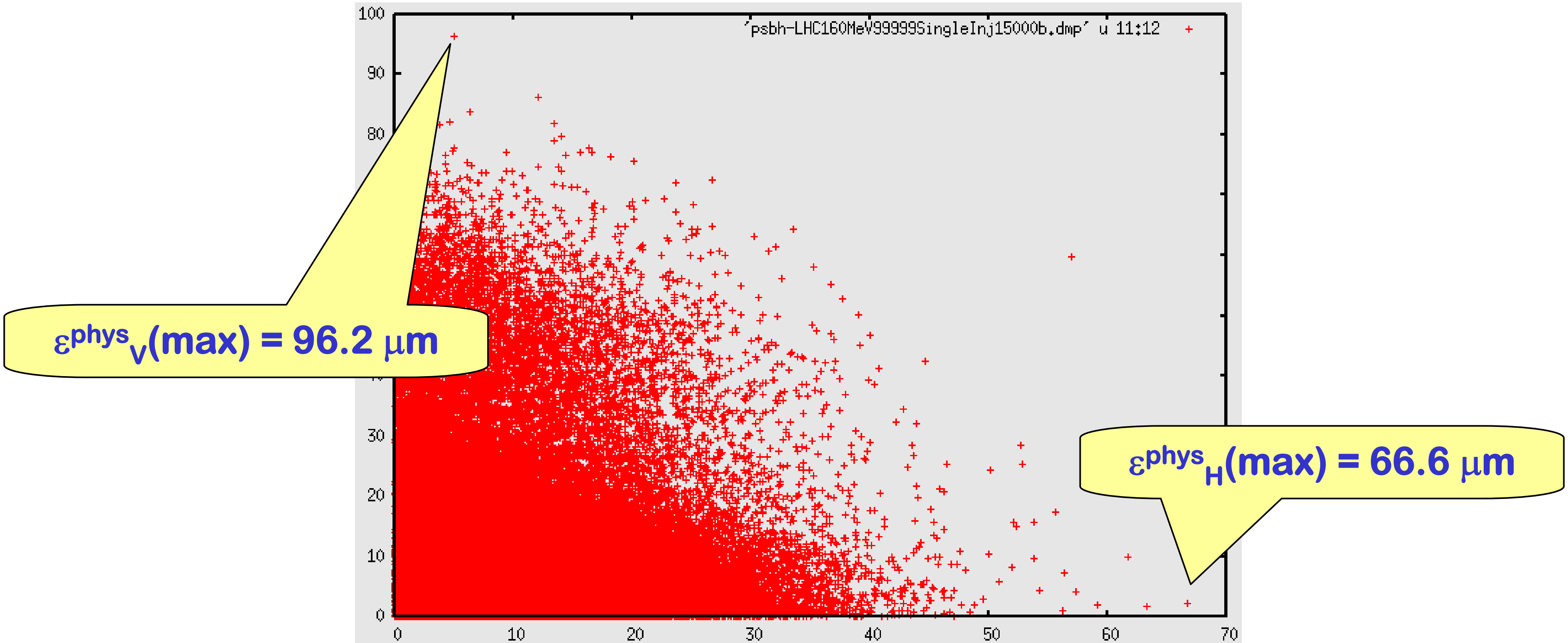
Case 2 (high brightness beam): LHC nominal beam

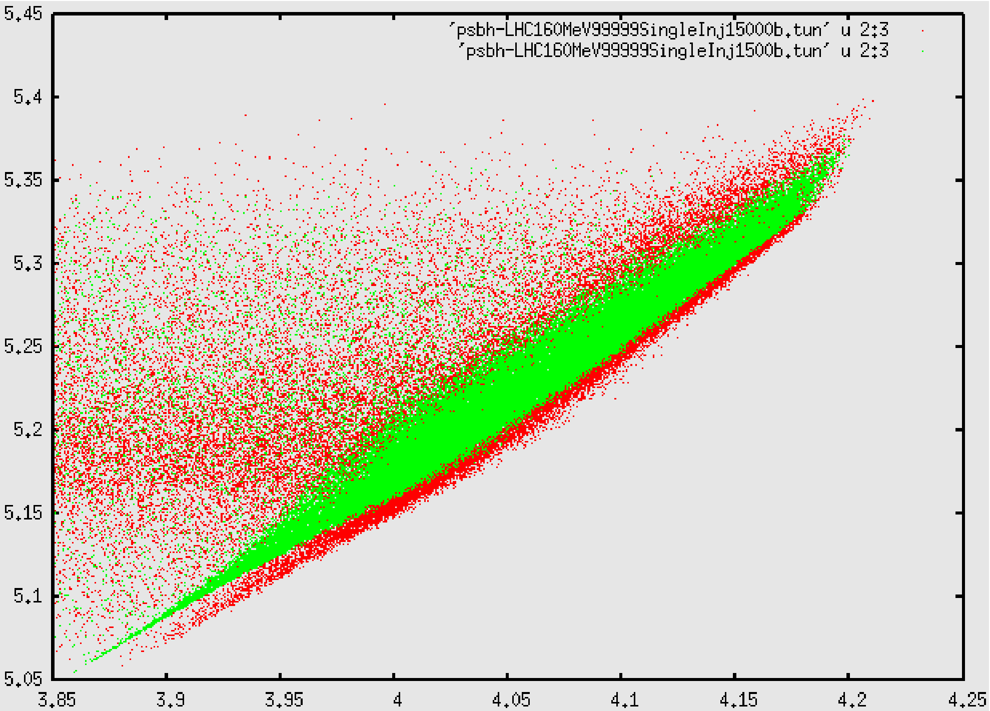


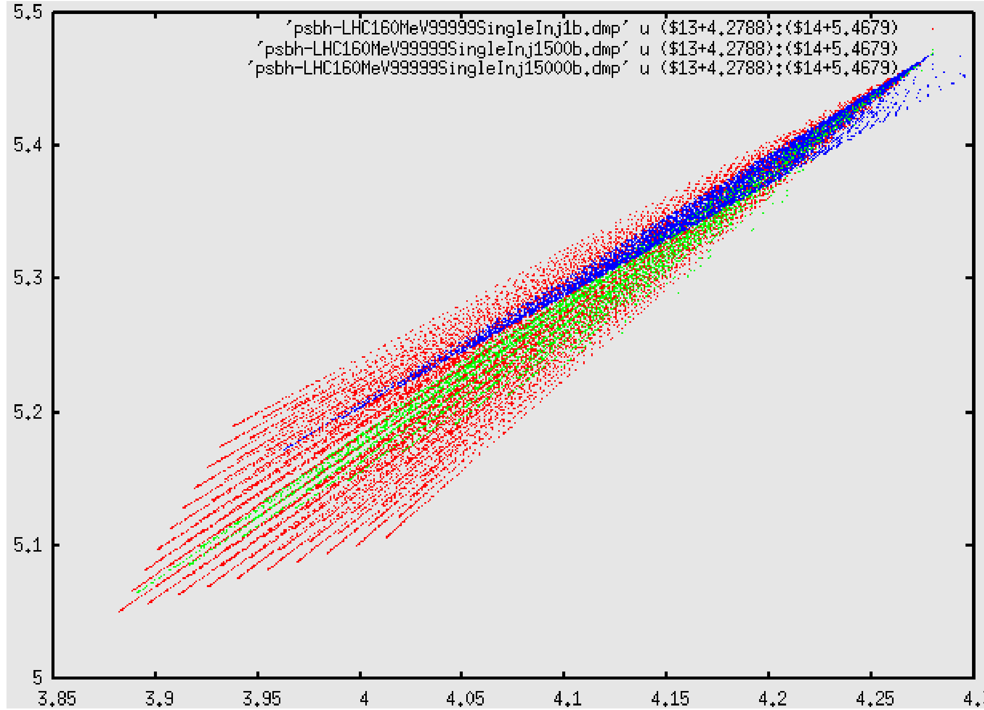
Physical emittance [(1)] [μm] scatter-plot at turn 15000

(1) **$\varepsilon^{phys}_{H,V,}$(max) define the 100% physical emittances**

Q_H=4.28 Q_V=5.47 N=3.25×10^{12} protons (99999 macro-particles)

Case 2 (high brightness beam): LHC nominal beam





Particle tunes[1] at turns 1500 and 15000

[1] *Individual particle betatron tunes derived by counting particle zero-crossings in phase plane (the accuracy increases with the number of turns)*

Particle tune shifts[1] at turns 1, 1500 and 15000

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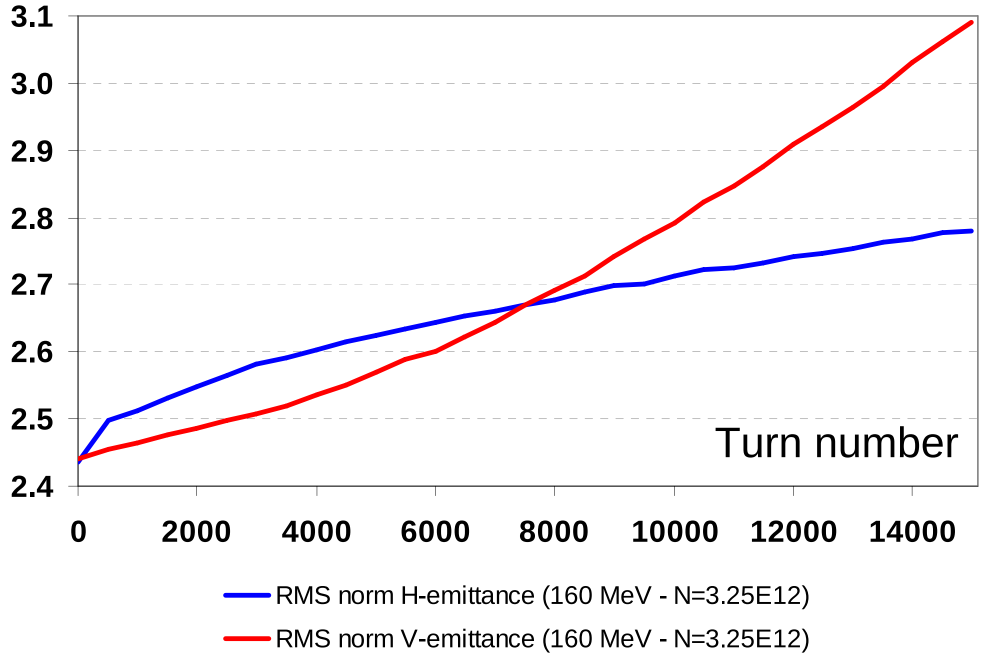
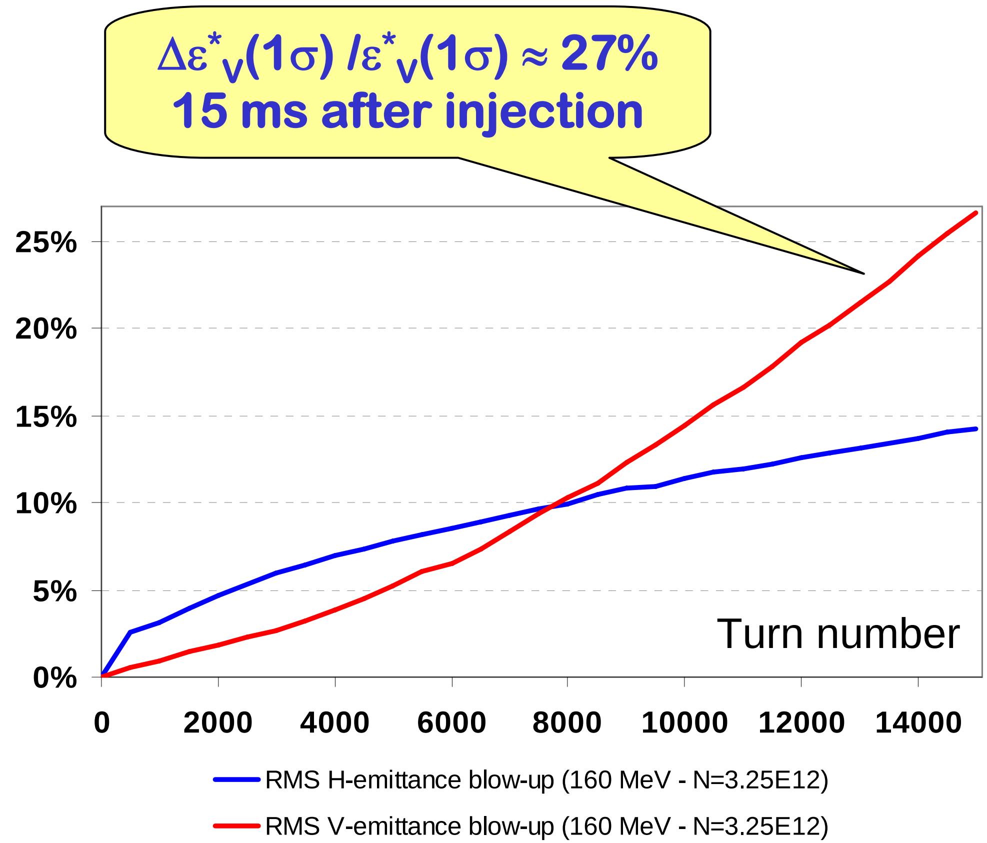
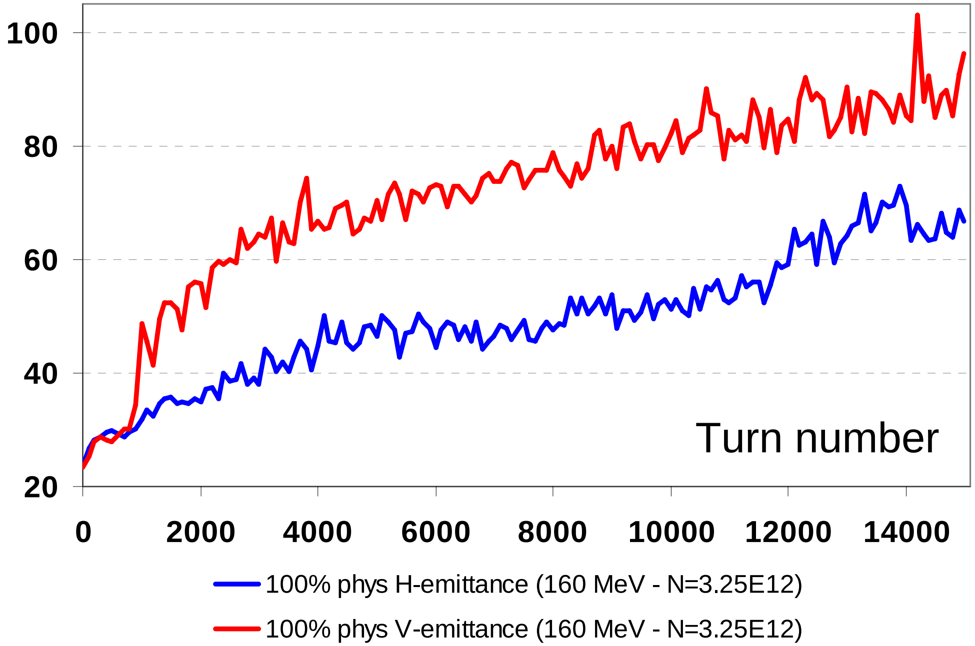


Evolution of rms normalized emittances [μm]

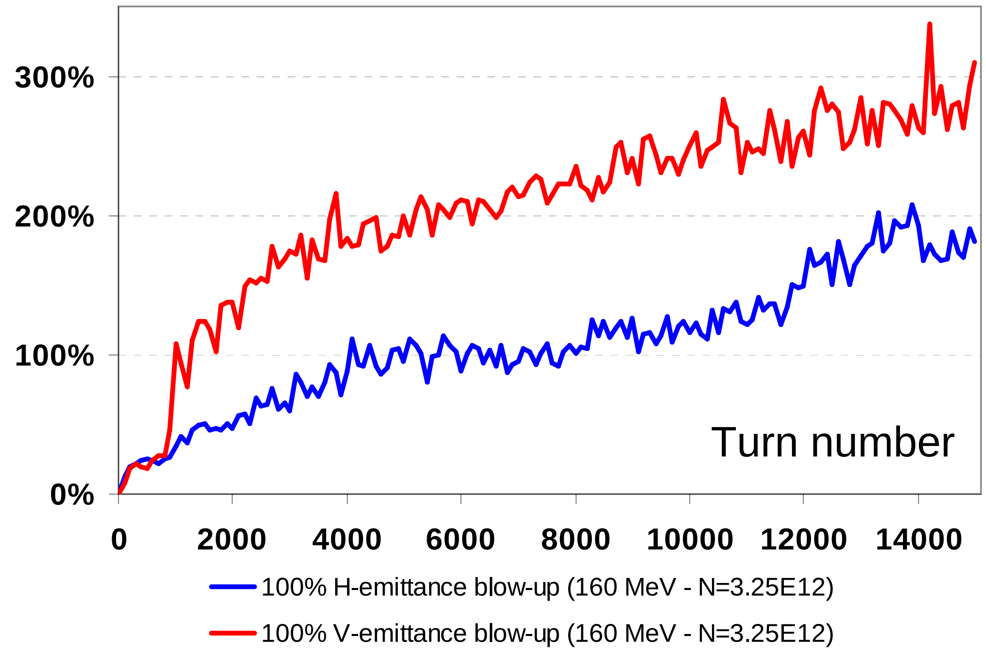


Evolution of rms normalized emittance blow-ups [%]

Case 2 (high brightness beam): LHC nominal beam

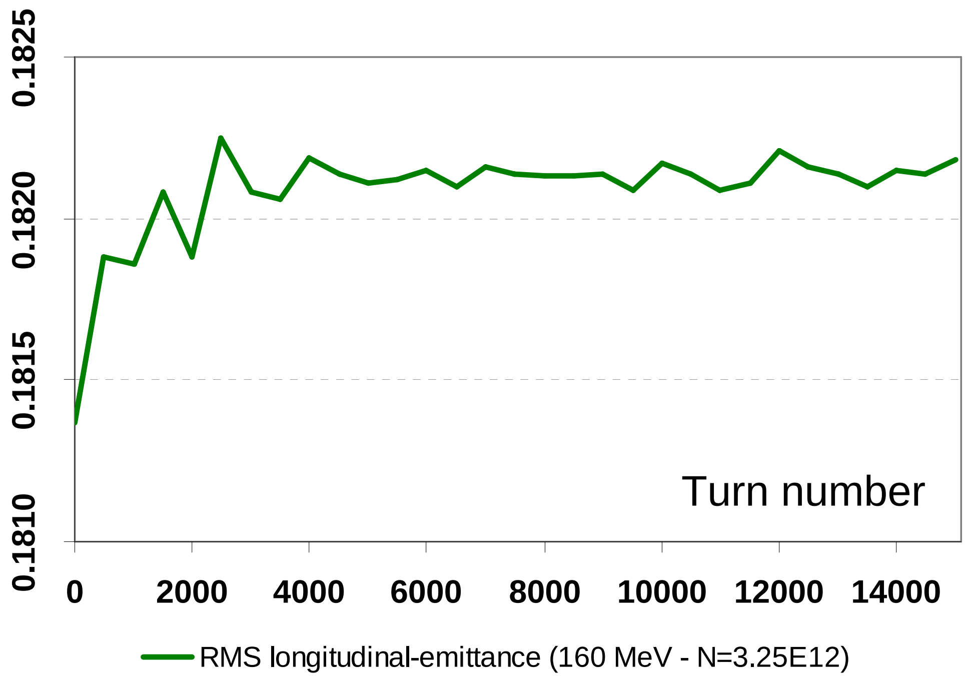


Evolution of 100% physical emittances [μm]



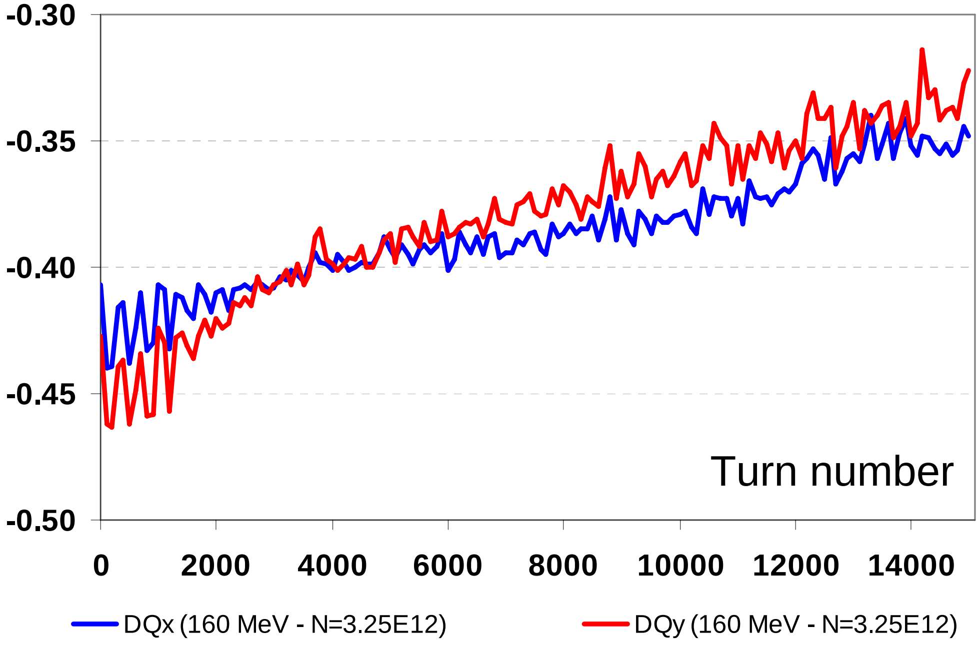
Evolution of 100% physical emittance blow-ups [%]

Case 2 (high brightness beam): LHC nominal beam



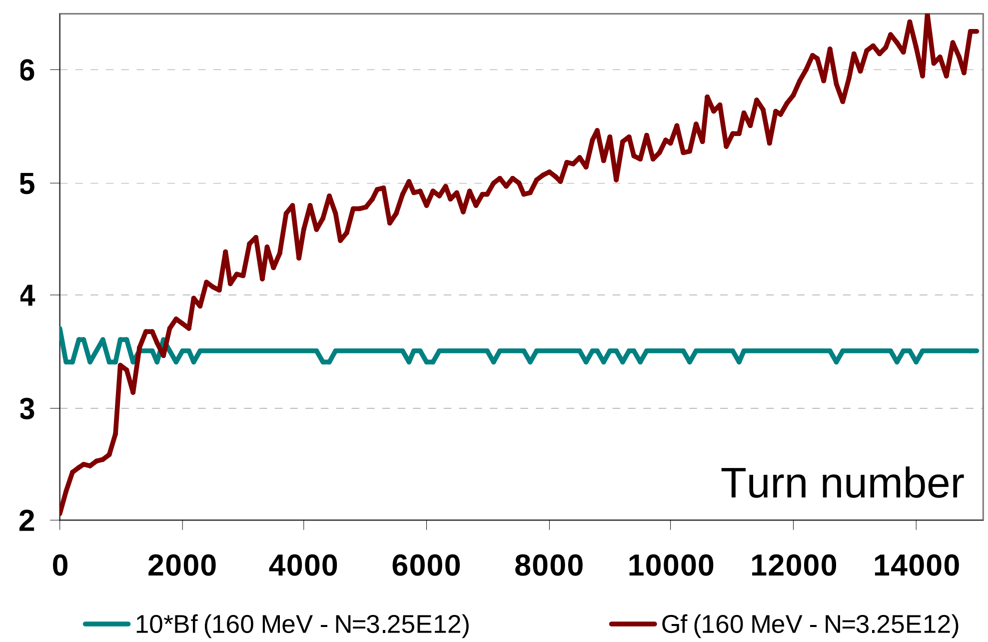
Evolution of rms longitudinal emittances [eVs]

Case 2 (high brightness beam): LHC nominal beam



Evolution of space charge tune shifts(1)

(1) Maximum tune shifts for the beam center



Evolution of bunching factor (×10) and form factor(1)

(1) Ratio of peak to average density for the transverse two dimensional distribution

Appendix: Injected beam distributions in Accsim

LHC nominal injected beam parameters

- **Transverse and longitudinal beam distribution specifications in Accsim**
  - IDISTX=3 (binomial horizontal phase plane distribution)
  - AMX=1.5 (elliptical distribution, parabolic profile)
  - ALPHX=0.0 BETX=5.59 (horizontal Twiss parameters of ellipse)
  - EPSLX=20.0 (horizontal physical emittance containing 100% of the beam; the area of limiting ellipse is $\pi\times$EPSLX)

    ...*Vertical beam distribution parameters not shown*...
  - IDISTL=3 (binomial longitudinal phase plane distribution)
  - AML=1.5 (elliptical distribution, parabolic profile)
  - PHIL=100.2 (phase half-width (deg) of limiting ellipse containing 100% of the beam)
  - DEL=1.03 (energy half-width (MeV) of limiting ellipse containing 100% of the beam)

Appendix: Injected beam distributions in Accsim

Beam parameter list

- **Binomial transverse phase plane distribution**
  - When the emittance specifies the limiting ellipse that encloses 100% of the beam

$$f(u,u') = \begin{cases} \dfrac{m}{\pi\varepsilon_u}\left(1-\dfrac{1}{\varepsilon_u}\left(\gamma_u u^2 + 2\alpha_u uu' + \beta_u u'^2\right)\right)^{m-1} & \text{for } \gamma_u u^2 + 2\alpha_u uu' + \beta_u u'^2 \le \varepsilon_u \\ 0 & \text{elsewhere} \end{cases}$$

m= AMX (Y), α_u= ALPHX (Y), β_u= BETX (Y), ε_u= EPSLX (Y), the ellipse area is $\pi\times\varepsilon_u$

  - When the emittance specifies the ellipse that encloses 2 standard deviations of the beam

$$f(u,u') = \begin{cases} \dfrac{2m}{(m+1)\pi\varepsilon_u}\left(1-\dfrac{2}{(m+1)\varepsilon_u}\left(\gamma_u u^2 + 2\alpha_u uu' + \beta_u u'^2\right)\right)^{m-1} & \text{for } \gamma_u u^2 + 2\alpha_u uu' + \beta_u u'^2 \le \left(\dfrac{m+1}{2}\right)\varepsilon_u \\ 0 & \text{elsewhere} \end{cases}$$

m=1 uniform m=1.5 elliptical m=2 parabolic m✹◎ gaussian

  - ε_u= EPSX (Y) (in Accsim), the ellipse area is $\pi\times\varepsilon_u$

Appendix: Injected beam distributions in Accsim

- **Binomial longitudinal phase plane distribution**
  - When the phase and energy half-widths specify the limiting ellipse enclosing 100% of the beam

$$f(\Delta\phi,\Delta E)=\begin{cases}\dfrac{m}{\pi\Delta\phi_{\max}\Delta E_{\max}}\left(1-\left(\dfrac{\Delta\phi}{\Delta\phi_{\max}}\right)^2-\left(\dfrac{\Delta E}{\Delta E_{\max}}\right)^2\right)^{m-1} & \text{for}\quad \left(\dfrac{\Delta\phi}{\Delta\phi_{\max}}\right)^2-\left(\dfrac{\Delta E}{\Delta E_{\max}}\right)^2\leq 1\\ 0 & \text{elsewhere}\end{cases}$$

$\Delta\phi_{max}$= PHIL, ΔE_{max}= DEL (in Accsim).

The longitudinal emittance (eVs) containing 100% of the beam is

$$\varepsilon_{\mathrm{L}}=\pi\Delta\phi_{\max}\Delta E_{\max}\frac{t_{\mathrm{rev}}}{360\mathrm{h}}$$

where t_{rev} is the revolution period, h the RF harmonic

Cf. “F.W. Jones, Accsim Reference Guide, Version 3.5s, June 1999” and “W. Joho, Representation of Beam Ellipses for Transport Calculations, SIN-Report TM-11-14 May 1980”.