Benchmark of ACCSIM-ORBIT codes for space charge and e-lens compensation

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F. Gerigk, M. Martini, M. Meddahi, A. Shishlo and F. Zimermmann

Introduction: ACCSIM-ORBIT benchmark

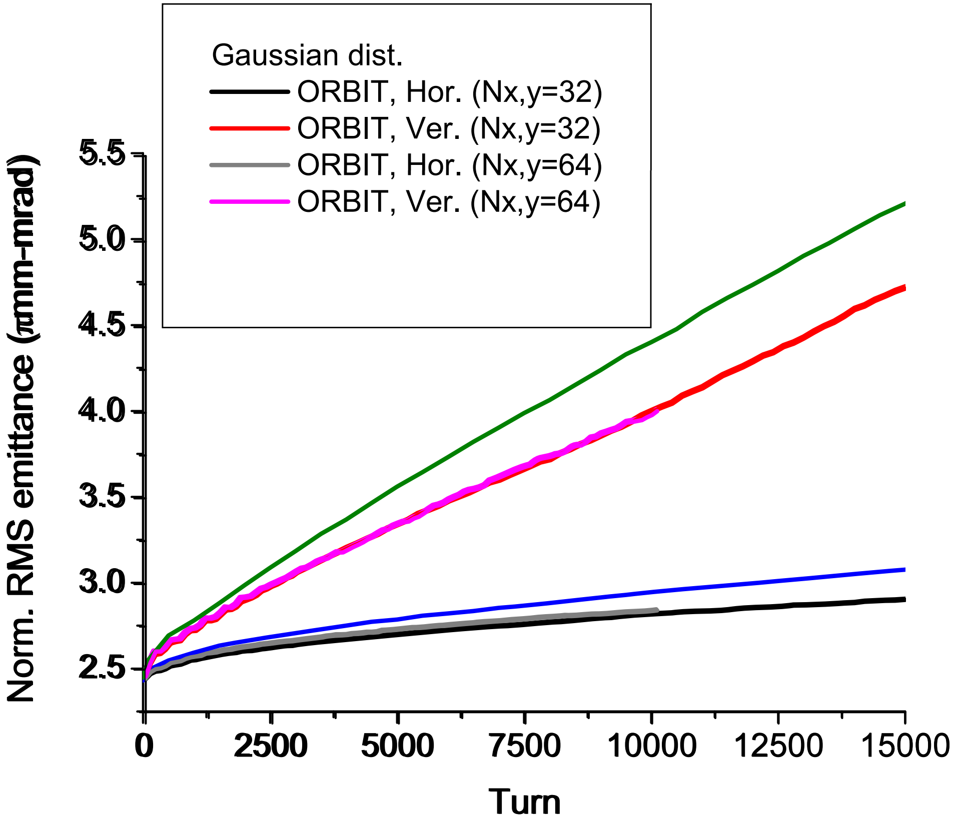
- Space charge codes
  - ACCSIM has been employed for space charge simulation at CERN
  - ORBIT was imported into CERN in 2006 by SNS team
- Benchmark
  - We started ACCSIM-ORBIT benchmark
  - In mind, to profit some advantages of ORBIT over ACCSIM
    - Parallel processing
    - Possibility of big simulation (large number of macro particles, large number of turns)

Ring & beam for benchmark

- CERN PS-Booster
  - Space charge effects are significant
  - Should be ready for 160 MeV injection
  - Simplified to 16 identical cells (w/o injection bumps)
  - Circumference ~157 m
- Proton beam for LHC with the coming LINAC4
  - 160 MeV
  - 3.25E12 protons / ring
  - 2.5 μm normalized r.m.s. emittance
  - Captured with 8 kV RF bucket (h=1)
  - Gaussian / Elliptic distribution

Emittance evolution (1)

- Gaussian distribution
  - 2.5 μm normalized r.m.s. emittance
  - Macro particles =99999 (limit in ACCSIM)
  - Flat bottom

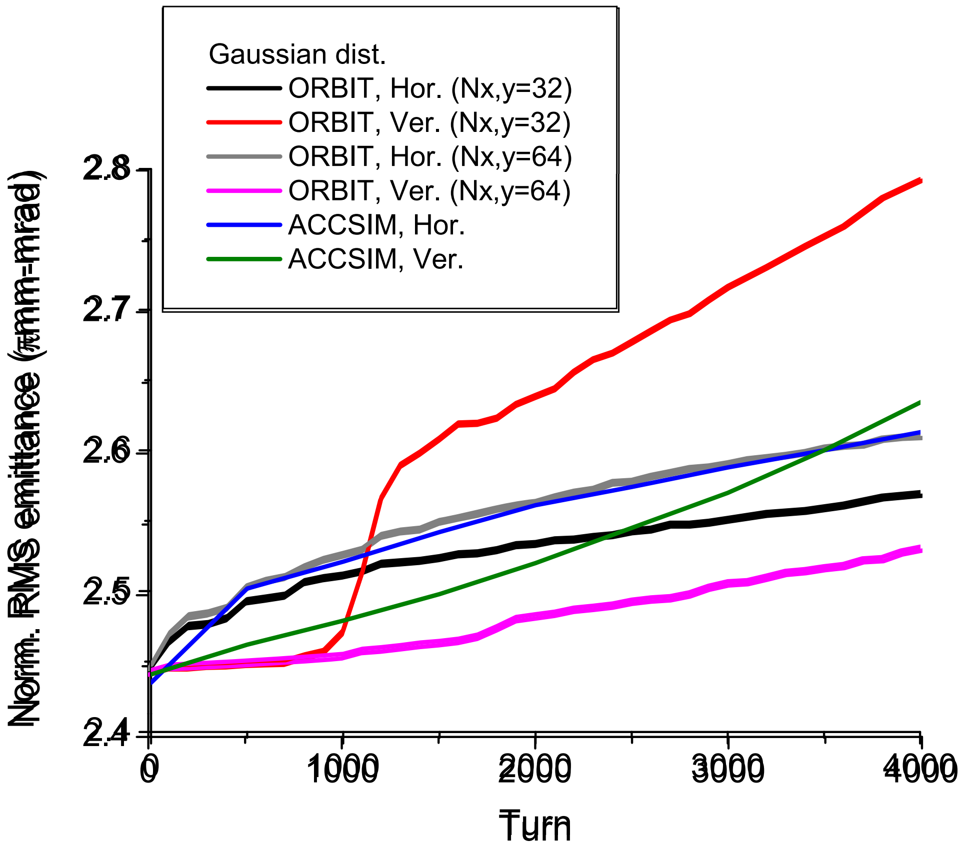


Rather good agreement

(ACCSIM simulation by M. Martini)

Emittance evolution (2)

- Elliptic distribution
  - 2.5 μm normalized r.m.s. emittance
  - Macro particles =99999 (limit in ACCSIM)
  - Flat bottom

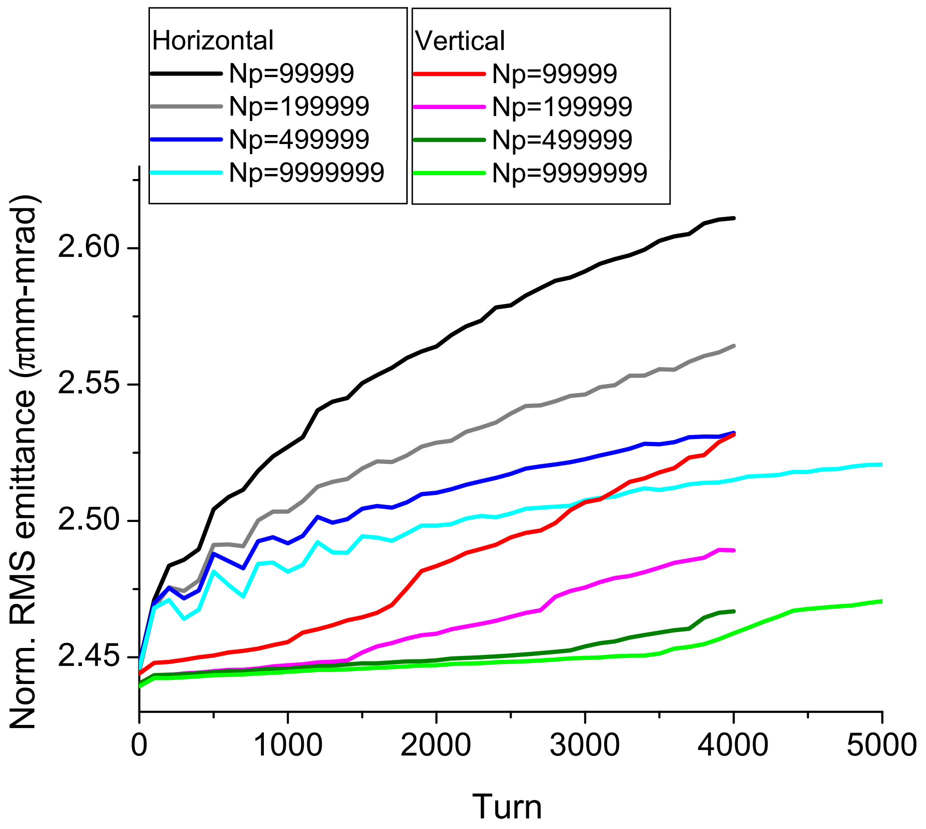


- Sensitive to number of grids
- Sudden blow-up in vertical (ORBIT)
- Rather good agreement in horizontal

(ACCSIM simulation by M. Martini)

Emittance evolution (3)

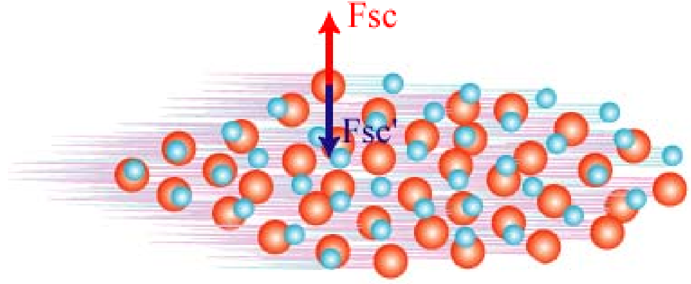
- Elliptic distribution
  - 2.5μm normalized r.m.s. emittance
  - Macro particles 99999~999999, Nx,y=64
  - Flat bottom



- Smaller blow-up with larger macro particles
- 99999 particles seem not enough statistically

Introduction: E-lens compensation

- E-lens compensation
  - Apply electron beam(s) to neutralize space charge force in proton beam



  - Reference: A.V.Burov, Q.W.Foster and V.D.Shiltsev, PAC01, P2896
- Simulation with ORBIT
  - New routine to install e-lens is under development and testing

General considerations

- Beam distribution
  - Ideally, the same transverse distributions both in proton beam and electron lens to compensate not only linear tune shift but also tune spread
  - Electron lens is localized longitudinally
- Neutralization of proton
  - $H^{+}+e^{-}\rightarrow H^{0}$ will be negligible because of different speeds between proton and electron beams

Compensation with localized lens

Compensation with localized lens

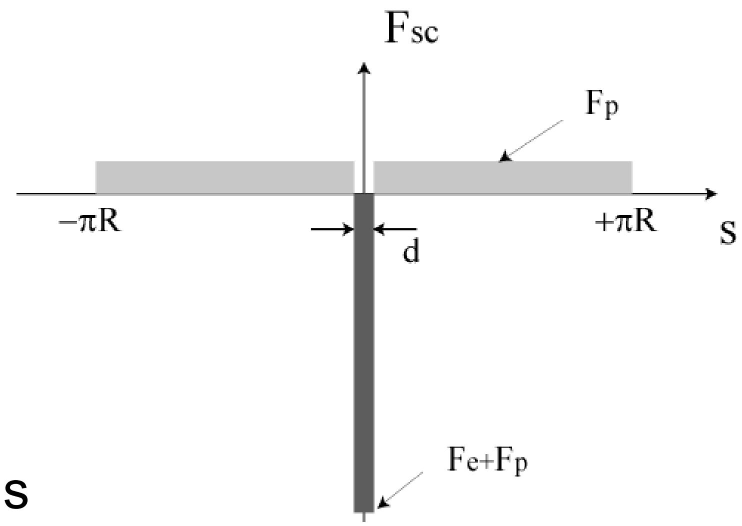
- Electron density for 100% compensation

$$\int_0^{2\pi R} (F_p + F_e) ds = 0$$

$$\rho_e(r) = A\rho_p(r)$$

$$\rightarrow \quad A = \frac{2\pi R}{d} \frac{1-\beta_p^{\,2}}{1 \pm \beta_e \beta_p}$$

Sign: + counter-direction lens
– forward-direction lens



- Resonances excited by electron lens

Newly developed routine in ORBIT

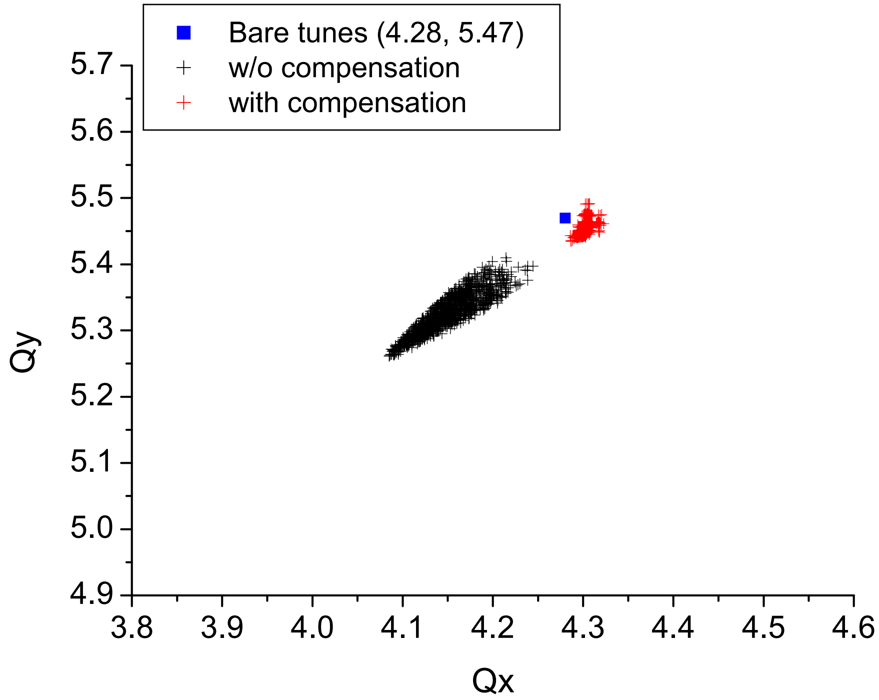
- Modeling of electron lens
  - Introduce electron lens like a lattice element
    - Size and current are constant
    - Transverse space charge forces due to lens are given by analytical forms
    - Longitudinal force (at the entrance and exit of lens) is ignored
  - Distribution and time structure
    - At this moment, Gaussian-DC lens is only available

$$E_x = \frac{Q}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\mathrm{Im}\left[\mathrm{erf}\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)-e^{\left(-\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right)}\mathrm{erf}\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

$$E_y = \frac{Q}{2\epsilon_0\sqrt{2\pi(\sigma_x^2-\sigma_y^2)}}\mathrm{Re}\left[\mathrm{erf}\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)-e^{\left(-\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right)}\mathrm{erf}\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

Compensation of tune spread (1)

- Simulation in PSB
  - Proton beam
    - Coasting beam
    - 3.25E12 protons / ring
    - Gaussian dist., 2.5 μm
  - Electron lens
    - DC localized, ~2 m * 4 lenses
    - 2.54 A, 10 keV
      (100% compensation)
    - Gaussian dist., 2.5 μm

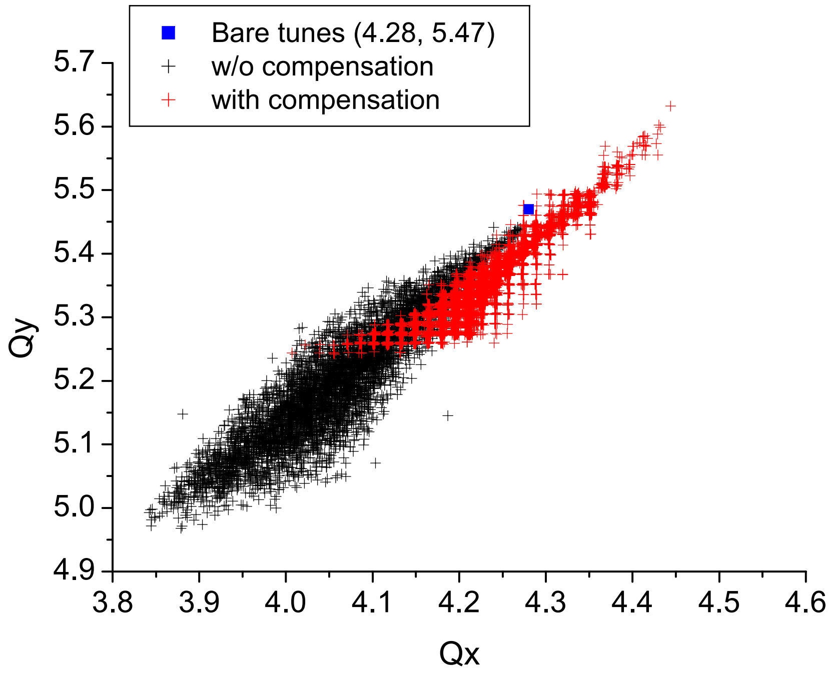


Tune spread is successfully compensated

Compensation of tune spread (2)

Simulation in PSB

- Proton beam
  - Bunched beam
  - 3.25E12 protons / ring
  - Gaussian dist., 2.5 μm
- Electron lens
  - DC localized, ~2 m * 4 lenses
  - 2.54 A, 10 keV
  - Gaussian dist., 2.5 μm

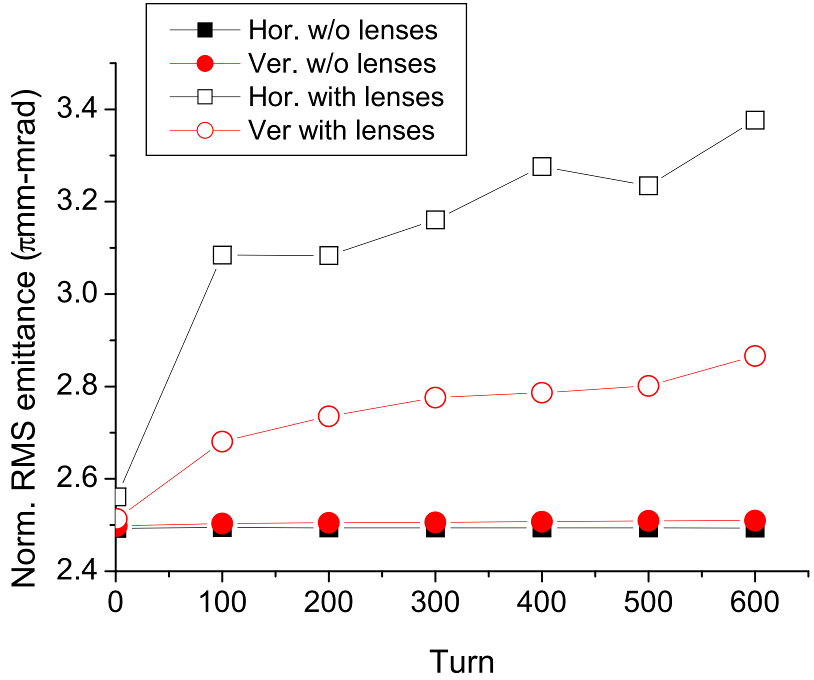


Over/Under compensation with DC lens

Emittance evolution (1)

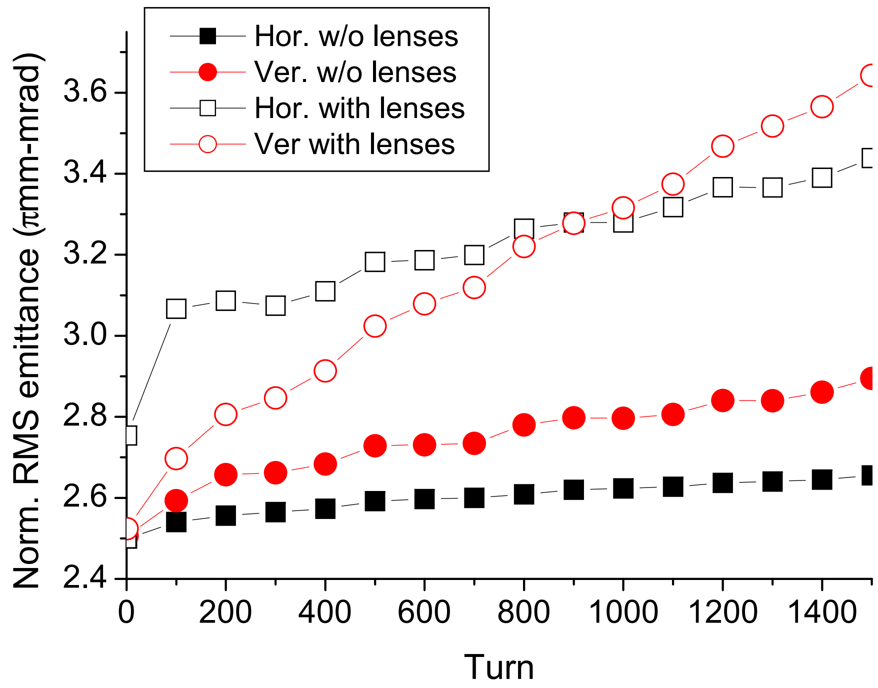
Simulation in PSB

- Proton beam
  - Coasting beam
  - 3.25E12 protons / ring
  - Gaussian dist., 2.5 μm
- Electron lens
  - DC localized, ~2 m * 4 lenses
  - 2.54 A, 10 keV (100% compensation)
  - Gaussian dist., 2.5 μm



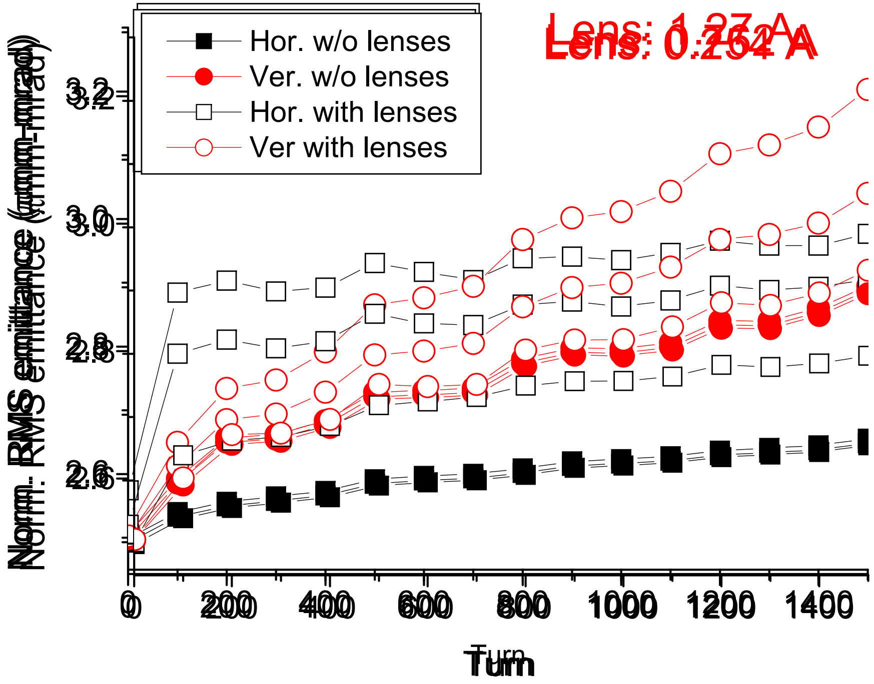
Emittance evolution (2)

- Simulation in PSB
  - Proton beam
    - Bunched beam
    - 3.25E12 protons / ring
    - Gaussian dist., 2.5 μm
  - Electron lens
    - DC localized, ~2 m * 4 lenses
    - 2.54 A, 10 keV
    - Gaussian dist., 2.5 μm



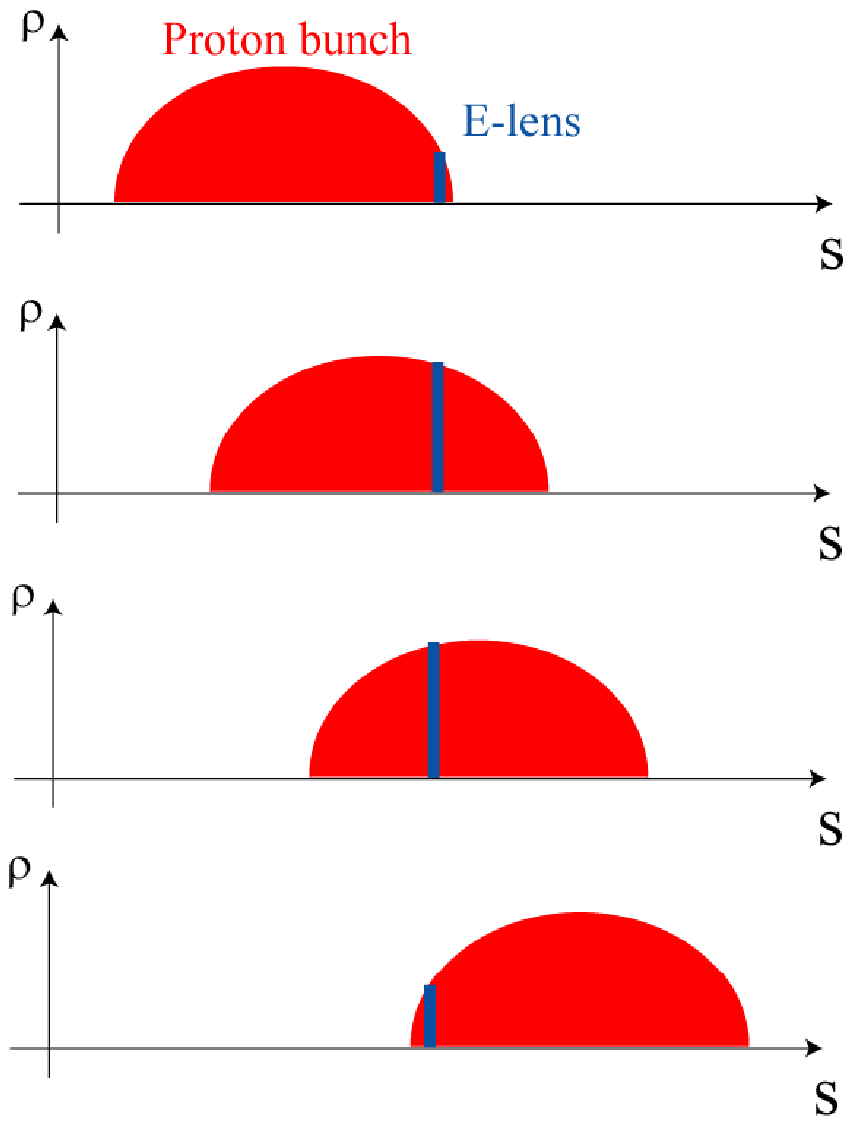
Emittance evolution (3)

- Simulation in PSB
  - Proton beam
    - Bunched beam
    - 3.25E12 protons / ring
    - Gaussian dist., 2.5 μm
  - Electron lens
    - DC localized, ~2 m * 4 lenses
    - Various currents, 10 keV
    - Gaussian dist., 2.5 μm



Pulse lens

- Bunch length vs.
  lens length
  - In PSB, proton bunch length is much larger than electron lens
  - Longitudinal profile could be followed with pulse lens



Summary

- Benchmark of ACCSIM-ORBIT codes
  - Benchmark with Gaussian distribution shows rather good agreement.
  - Elliptic distribution is sensitive to simulation parameters. We observe sudden blow-up in vertical emittance.
    - 99999 macro particles (limit in ACCSIM) seem not enough statistically.
- E-lens compensation
  - New routine to install e-lens into ORBIT is under development and testing
  - Tune spread could be compensated in principle
    - For bunched beam, pulse-lens would be needed
  - Emittance evolution
    - In any present results, electron lens enhances emittance growth.
  - Plans
    - Enrich the routine to have pulse-lens, other transverse shapes
    - Study various number of lenses, various operation points and so on.