Evolution beam parameters during injection and storage of the high brightness beams envisaged for the Linac4 injection into the CERN PS Booster

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Acknowledgements

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S.M. Cousineau (ORNL), F.W. Jones (TRIUMF)

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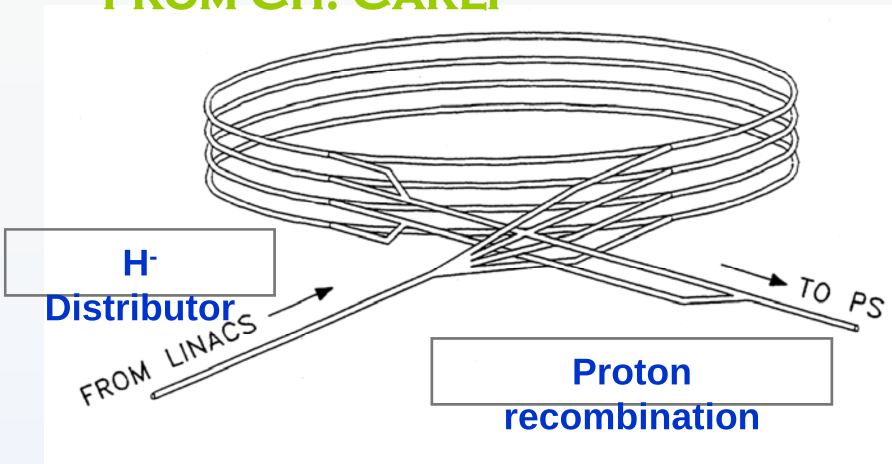
Agenda

- ✓ Studies of the injection and storage of the 160 MeV Linac4 beam for LHC into the CERN PS Booster (PSB)
  - Simulations with the Orbit code of the H^- charge exchange injection and following beam emittance evolution at 160 MeV
  - Injection done via a painting scheme for optimal shaping of the initial particle distribution
- ✓ Benchmarking of the Orbit and Accsim simulations with measurements performed in the PSB on the actual high intensity beam stored at 160 MeV

Motivation for the upgrade of the PSB with Linac4:
Deliver beams for the LHC, CNGS and ISOLDE of higher intensity or brightness than presently achieved

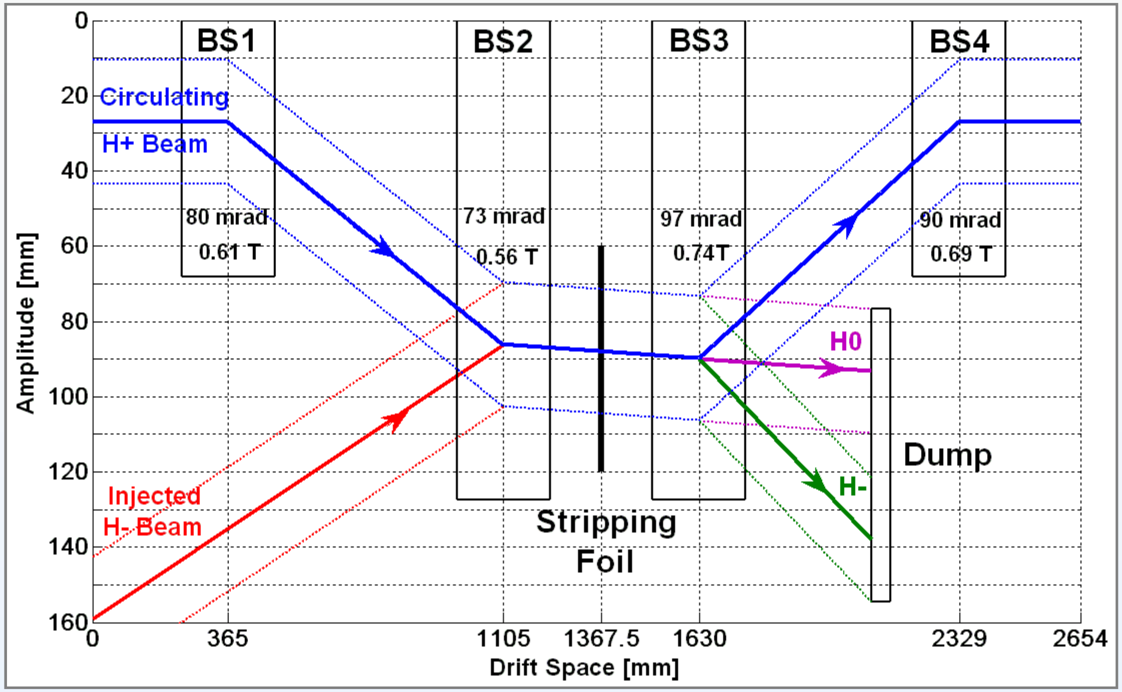
PS Booster overview

FROM CH. CARLI



- ✓ Actual PS Booster (PSB)
  - 4 superimposed rings (16 triplet cells, $\Delta\phi \gtrsim 90^\circ$ per period)
  - Multi-turn injection at 50 MeV with betatron stacking and septum
  - Large acceptances of $A_{H,V}$=180/120 μm
  - Acceleration to 1400 MeV in ~500 ms, double harmonic RF (h=1, h=2)
  - High space charge regime up to ~0.5 tune spreads at 50 MeV
- ✓ Upgrade PS Booster with Linac4 at 160 MeV
  - 10^{14} particles per pulse of 0.4 ms, 1.1 Hz repetition rate
  - Increase of intensity within given normalized emittances by a factor 2
  - Increase of PS Booster injection energy from 50 MeV to 160 MeV
    - $(\beta\gamma^2)_{160MeV}/(\beta\gamma^2)_{50MeV}$~2 (space charge decreased by a factor 2 within equal normalized emittance)
  - H^- charge exchange injection, Linac4 beam chopping

PSB injection – Hardware layout



W. WETERINGS ET AL.

PSB injection region

Injected & circulating 1st turn beam envelopes of $\pm 4\sigma$ with partly-stripped H^0 and un-stripped H^-

✓ 160 MeV H^- Linac4 beam injection system

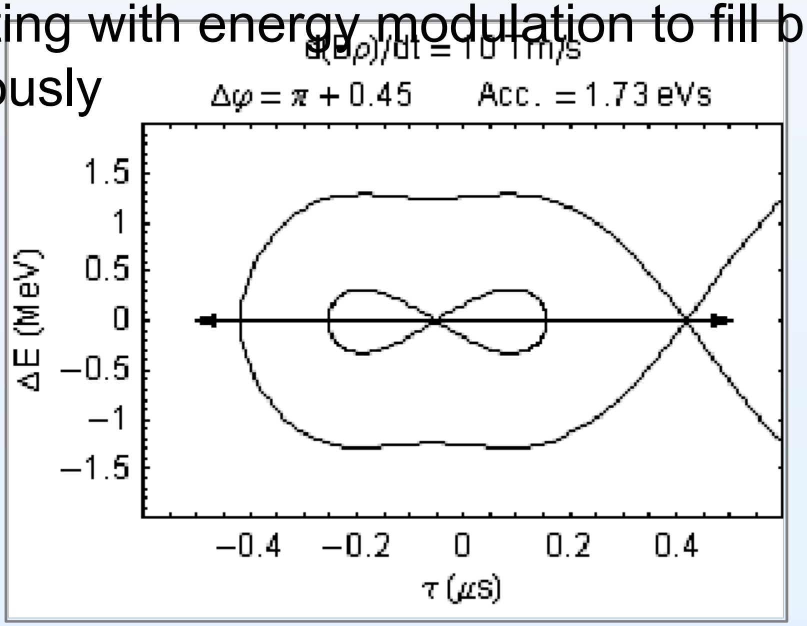
- Two independent closed orbit bump systems
  - Injection "chicane", 4 pulsed dipole magnets (BS), yielding ~61 mm beam offset throughout the injection process
  - Painting bump, 4 horizontal kickers (KSW, outside the injection region), giving a ~28 mm closed orbit bump with falling amplitude during the injection for horizontal phase space painting
- Stripping efficiency of ~98% expected (through a graphite stripping foil)

PSB injection – Longitudinal painting scheme

FROM CH. CARLI

✓ PSB with Linac4: similar RF system than at present

- Double harmonic
  - fundamental h=1 & h=2, systems to flatten bunches and reduce tune shifts
- Injection with $\partial(B\rho)/\partial t=10$ Tm/s
- Little but not negligible motion in longitudinal phase space
- Active painting with energy modulation to fill bucket homogeneously

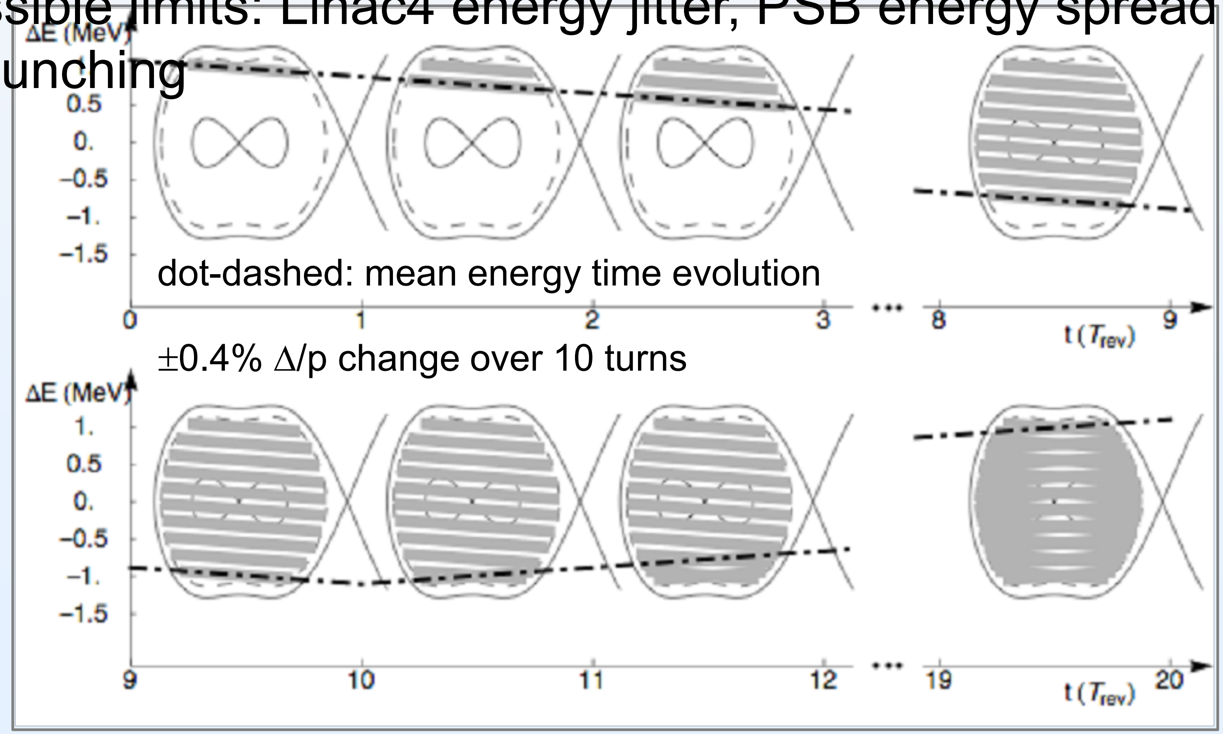


Accelerating RF bucket for a beam in a double harmonic system (h=1& h=2)

PSB injection – Longitudinal painting scheme

FROM CH. CARLI

- Principle of longitudinal painting
  - Triangular Linac4 energy modulation (slow, ~20 turns for LHC, ~41mA peak, 3.25×10^{12} p/ring)
  - Beam on if mean energy inside a contour ~80% of acceptance, off if mean energy outside (via a chopper, chopping factor ~62%)
  - Higher intensities: several and/or longer modulation periods (~41mA)
  - Possible limits: Linac4 energy jitter, PSB energy spread due to debunching



PSB injection –Painting and tracking with ORBIT

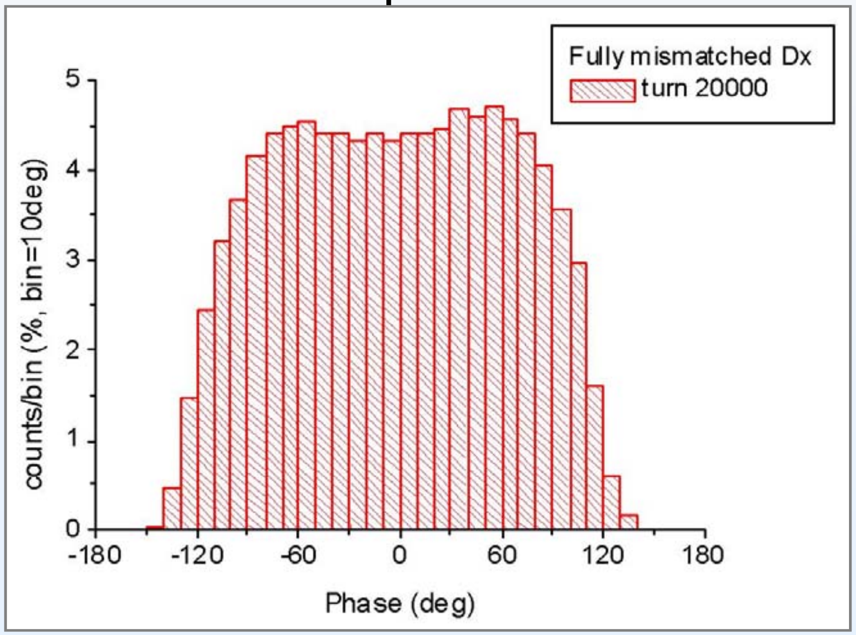
- ✓ Nominal LHC beam with Linac4
  - – Single batch PSB transfer: 3 out of 4 rings used, 6 bunches from 3 rings delivered (2 bunches per ring)
  - – PSB intensity per ring at 1.4 GeV for loss-free / lossy transmission to LHC: 2.76×10^{12} / 3.25×10^{12} particles
  - – Required PSB transverse normalized emittances: $\varepsilon^{n}_{H,V}(1\sigma)=2.5\ \mu m$

- ✓ ORBIT model (without acceleration) **FROM M. AIBA**
  - – Injection particle distribution
    - • 20 beam files (12000 particles per injected turn), containing the 6D particle distributions at the end of the transfer line (**FROM B. GODDARD**)
    - • The longitudinal painting process with proper chopping was implemented during the building of the above particle distributions
  - – ORBIT simulations
    - • The injection "chicane" and transverse painting bumps are implemented (thin lens approximation) (~400 turns BS dipole fall time)
    - • Beam files are injected turn by turn (over 20 turns, ~20μs)
    - • Bucket "filling up" via double harmonic RF system: 8 kV (h=1), 6 kV (h=2)
    - • Foil heating $\Delta T\sim500^{\circ}K$, ~9.5 foil hits per proton

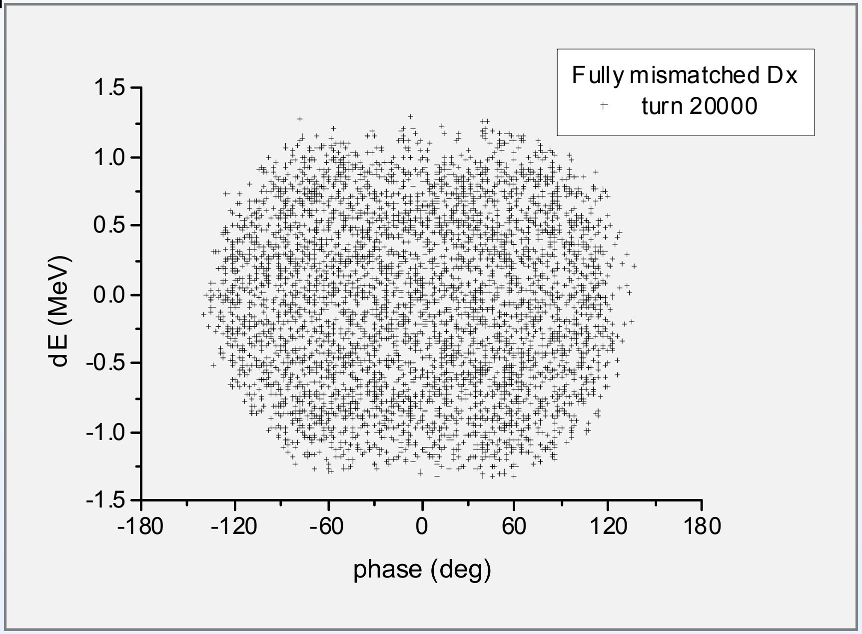
PSB injection –Painting and tracking with ORBIT

- ✓ Nominal LHC beam at 160 MeV PSB injection
  - – Mismatched dispersion at injection (end line: D_{Linac4}=0m, D_{PSB}≈-1.4m)
  - – Bunching factor ~0.60
  - – No impressive effect of dispersion mismatch

FROM M. AIBA



ORBIT : Longitudinal profile (flat) (2.2×10⁵ macro-particles)

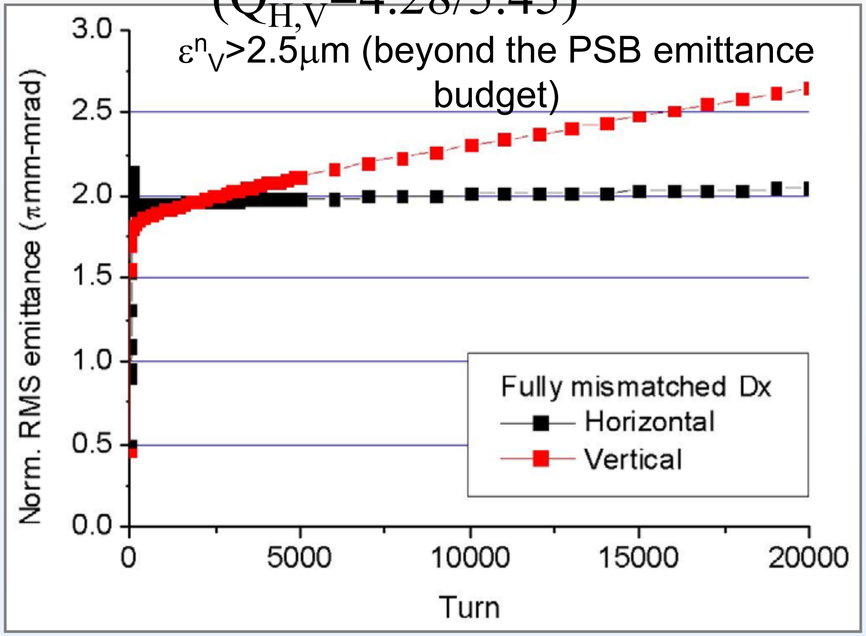


ORBIT : Longitudinal phase-space plot ϕ-ΔE [deg-MeV] (2.2×10^5 macro-particles)

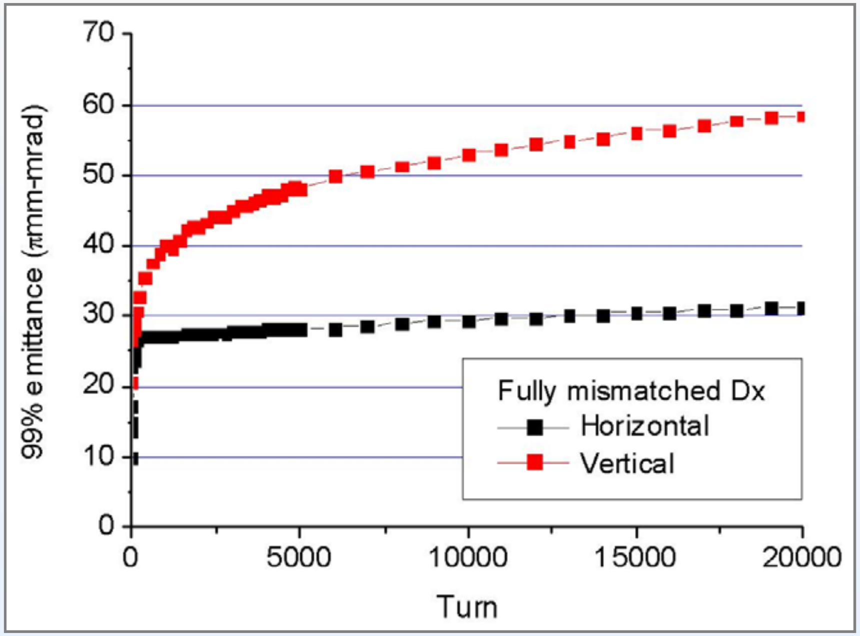
PSB injection –Painting and tracking with ORBIT

FROM M. AIBA

- ✓ Emittance evolution on a 160 MeV energy plateau
  - – Painting and subsequent tracking up to 2×10^4 turns
  - – Simulation done with space charge, $\Delta Q_{H,V}$~-0.27/-0.32 ($Q_{H,V}$=4.28/5.45)



ORBIT : Emittances after injection
$\varepsilon^n_{H,V}(1\sigma)$ [µm] (2.2×10^5 macro-particles)

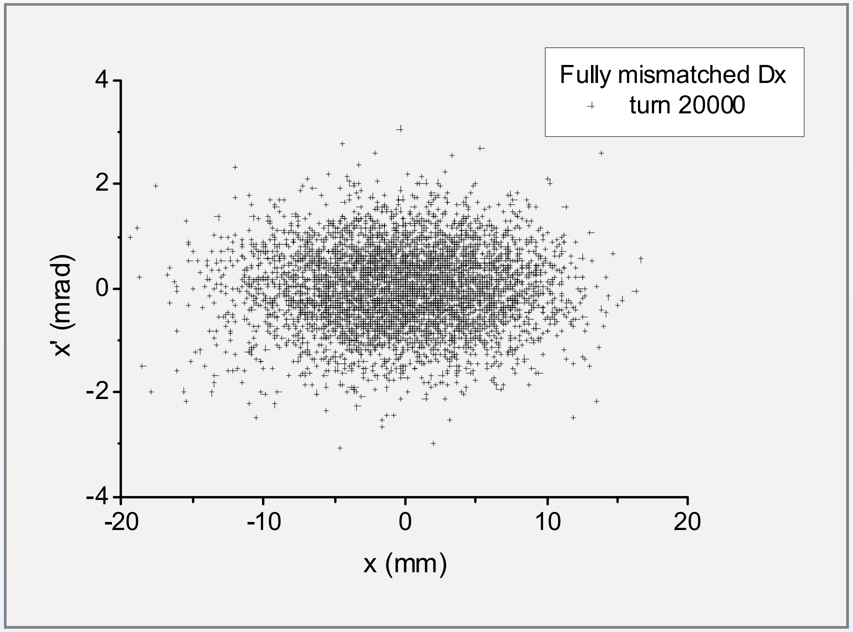


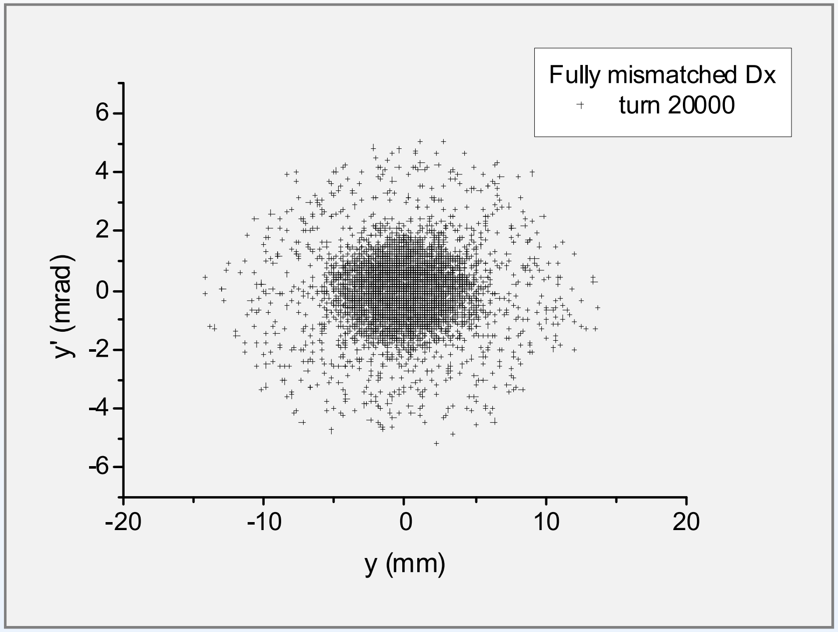
ORBIT : Emittances after injection
$\varepsilon^n_{H,V}(99\%)$ [µm] (2.2×10^5 macro-particles)

Remark: ~8% rms vertical emittance blow-up reduction after 10^4 turns when using 4 times more macro-particles (~9×10^5)

PSB injection –Painting and tracking with ORBIT

FROM M. AIBA





ORBIT : Transverse phase-space scatter plots X-X' & Y-Y' [mm-mrad] (2.2×10^5 macro-particles) (some halo develops in vertical plane)

Benchmark – ORBIT/ACCSIM vs. measurements

- ✓ PSB actual high-intensity beam on a 160 MeV energy plateau
  - Benchmark ORBIT & ACCSIM
  - High intensity beam (~10^{13} protons in one ring) on a 160 MeV energy plateau
  - Two sets of benchmark measurements were made (M. Chanel)

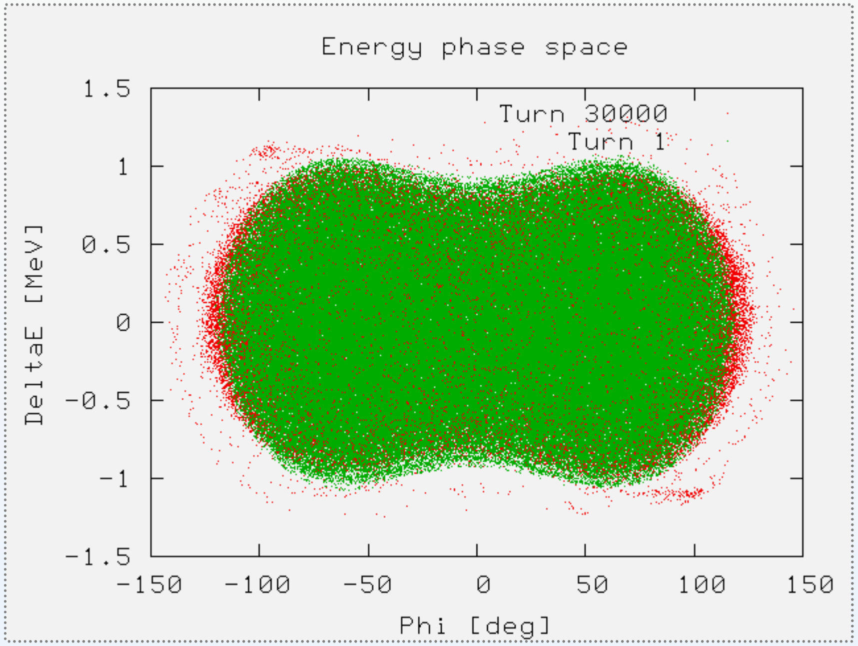
1. Long bunches – PSB working point $Q_{H,V}$=4.21/4.35
   - 1^{st} & 2^{nd} harmonic cavities at 8 kV in anti-phase
   - t=0 ms: 1.05×10^{13} p, $\varepsilon^n_{H,V}(1\sigma)$=13.7/6.8 μm, $\varepsilon_L(1\sigma)$~0.25 eVs
   - t=200 ms: 1.03×10^{13} p, $\varepsilon^n_{H,V}(1\sigma)$=13.1/7.5 μm, $\varepsilon_L(1\sigma)$~0.25 eVs
2. Short bunches – PSB working point $Q_{H,V}$=4.21/4.45[1]
   - 1^{st} & 2^{nd} harmonic cavities at 8 kV in phase
   - t=0 ms: 1.03×10^{13} p, $\varepsilon^n_{H,V}(1\sigma)$=19.2/7.1 μm, $\varepsilon_L(1\sigma)$~0.20 eVs
   - t=200 ms: 0.96×10^{13} p, $\varepsilon^n_{H,V}(1\sigma)$= 20.4/7.3 μm, $\varepsilon_L(1\sigma)$~0.20 eVs

(1) The vertical working point had to be changed to minimize the particle losses

Benchmark – ORBIT/ACCSIM vs. measurements

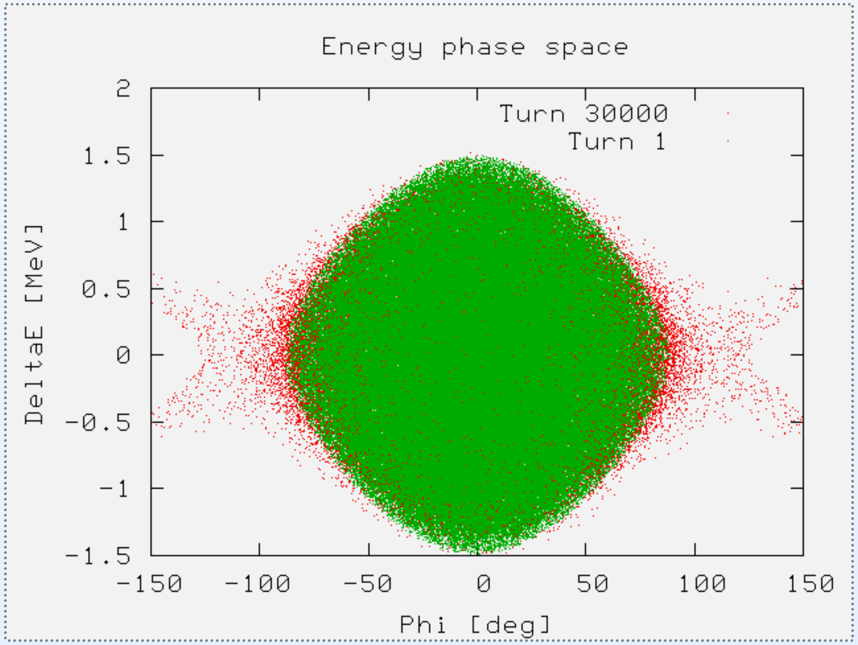
- ✓ ORBIT simulation
  - – 1 beam file (single injection 2×10^5 of macro-particles) holding the “steady” 6D particle distribution at 160 MeV with the right initial longitudinal/transverse emittances (PSB measurement)
  - – Subsequent simulation performed with space charge
  - – Tracking up to 3×10^4 turns
  - – No acceleration considered
  - – Parallel processing using 7 CPUs (crashes when using more CPUs!)
  - – Computation time ~proportional to the macro-particle numbers
    - ~1370 turns/h with 2.5×10^4 macro-particles
    - ~160 turns/h with 2×10^5 macro-particles (3×10^4 turns in ~8 days)
    - ~32 turns/h with 10^6 macro-particles? (3×10^4 turns in ~39 days?)

Benchmark – ORBIT/ACCSIM vs. measurements



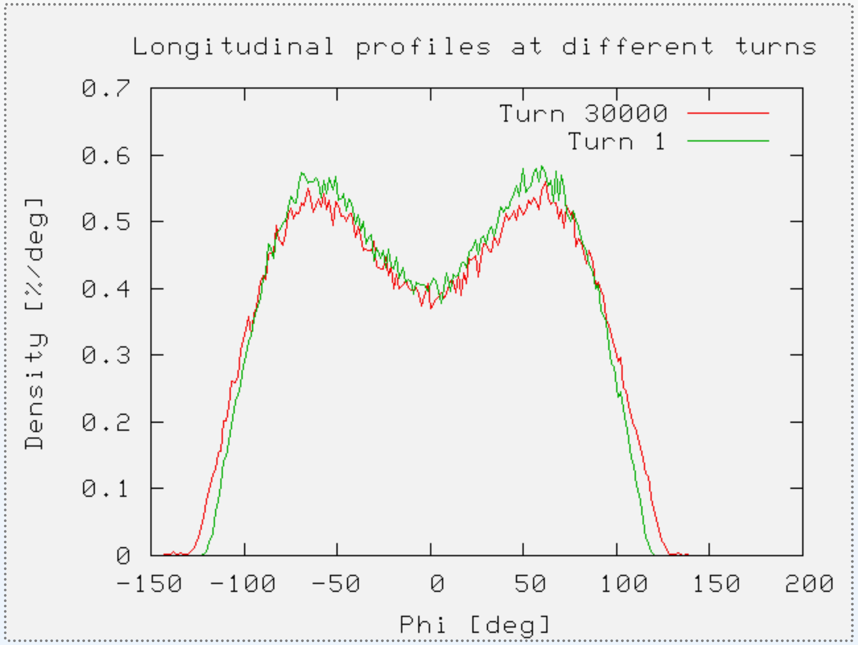
Longitudinal phase-space plots ϕ-ΔE [deg-MeV] (2×10^5 macro-particles) (green: at turn 1, red: at turn 30000)

✓ ORBIT $Q_{H,V}$=4.21/4.45
Short bunches



✓ ORBIT
$Q_{H,V}$=4.21/4.35
Long bunches

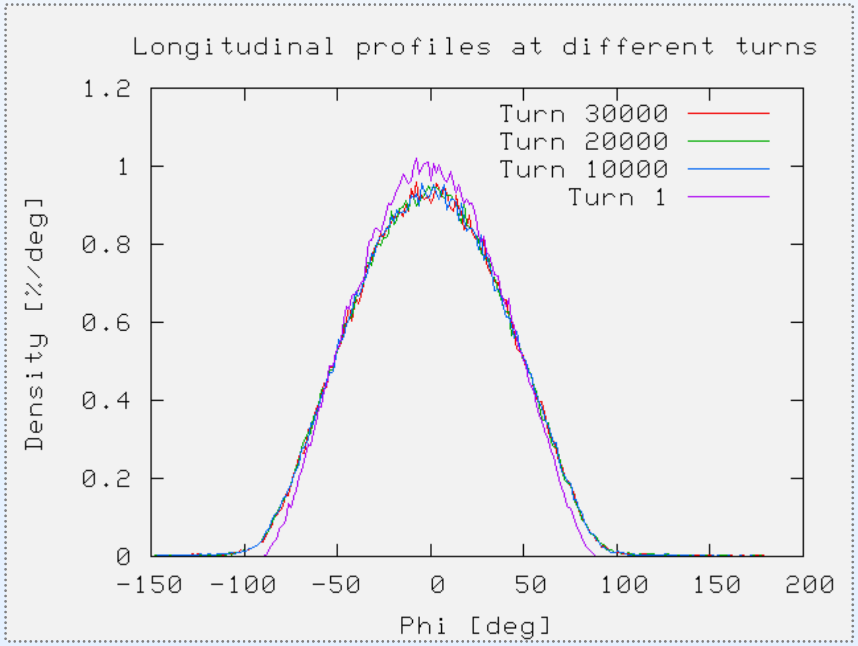
Benchmark – ORBIT/ACCSIM vs. measurements



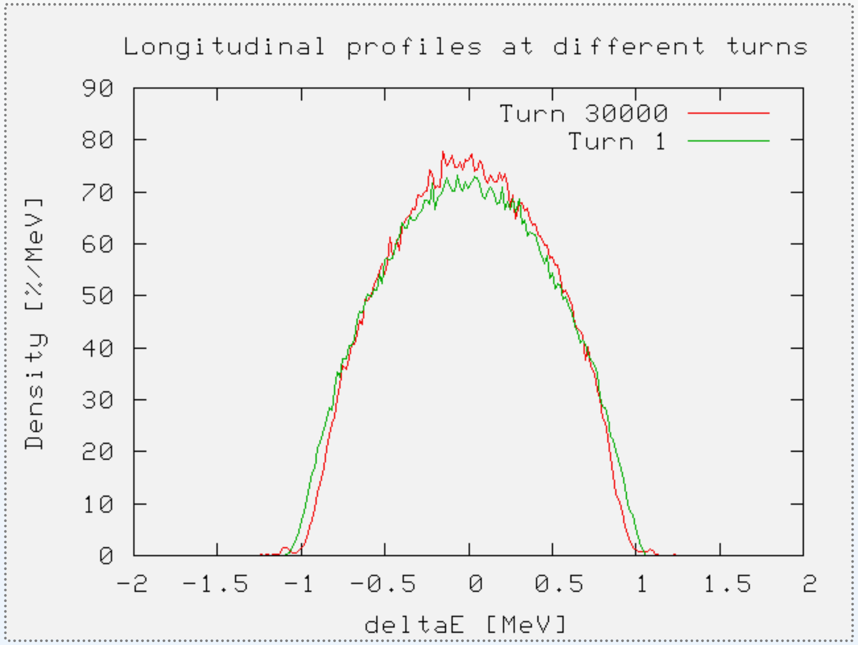
✓ ORBIT $Q_{H,V}$=4.21/4.35
Long bunches

Longitudinal profiles
$\partial \mathrm{Prob}\{\varphi \leq \phi\}/\partial \phi$ [%/deg] vs. ϕ [deg]
(φ single particle phase)
(2×10^5 macro-particles)

✓ ORBIT $Q_{H,V}$=4.21/4.45
Short bunches



Benchmark – ORBIT/ACCSIM vs. measurements



Energy distributions

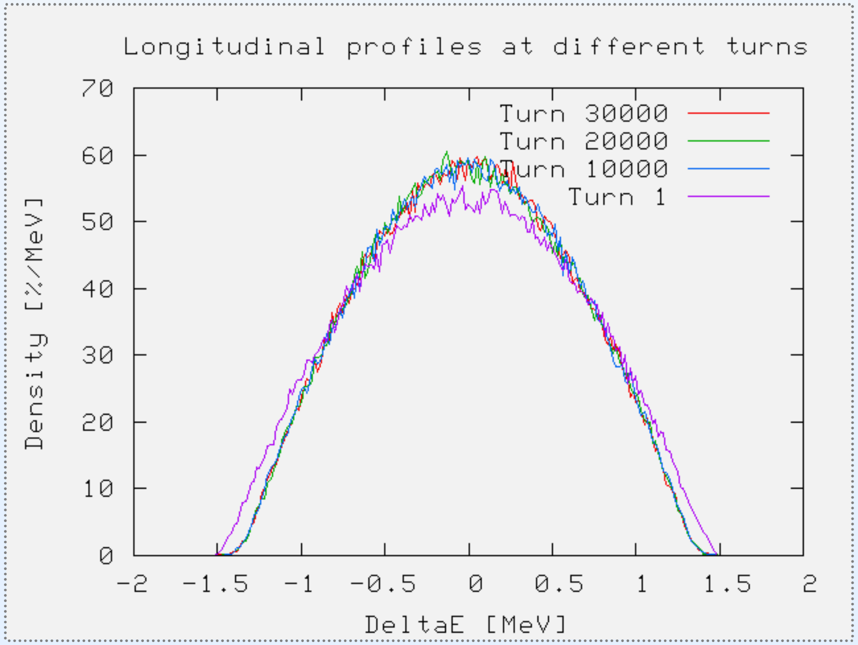
∂Prob{δE$\leq\Delta$E}/$\partial\Delta$E [%/MeV] vs. ΔE [MeV]

(δE single particle energy variation)

(2×10^5 macro-particles)

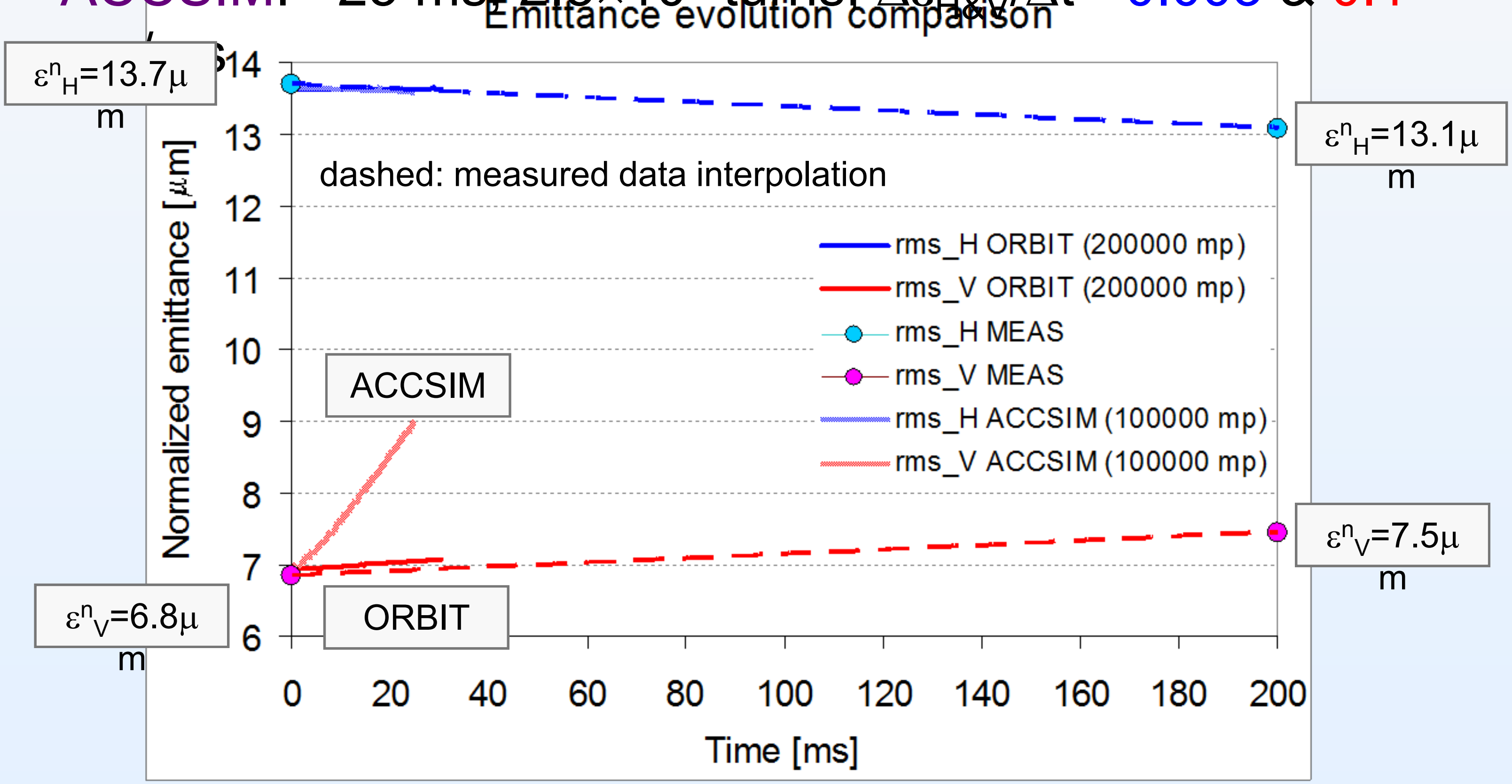
✓ ORBIT $Q_{H,V}$=4.21/4.45
Short bunches

✓ ORBIT
$Q_{H,V}$=4.21/4.35
Long bunches



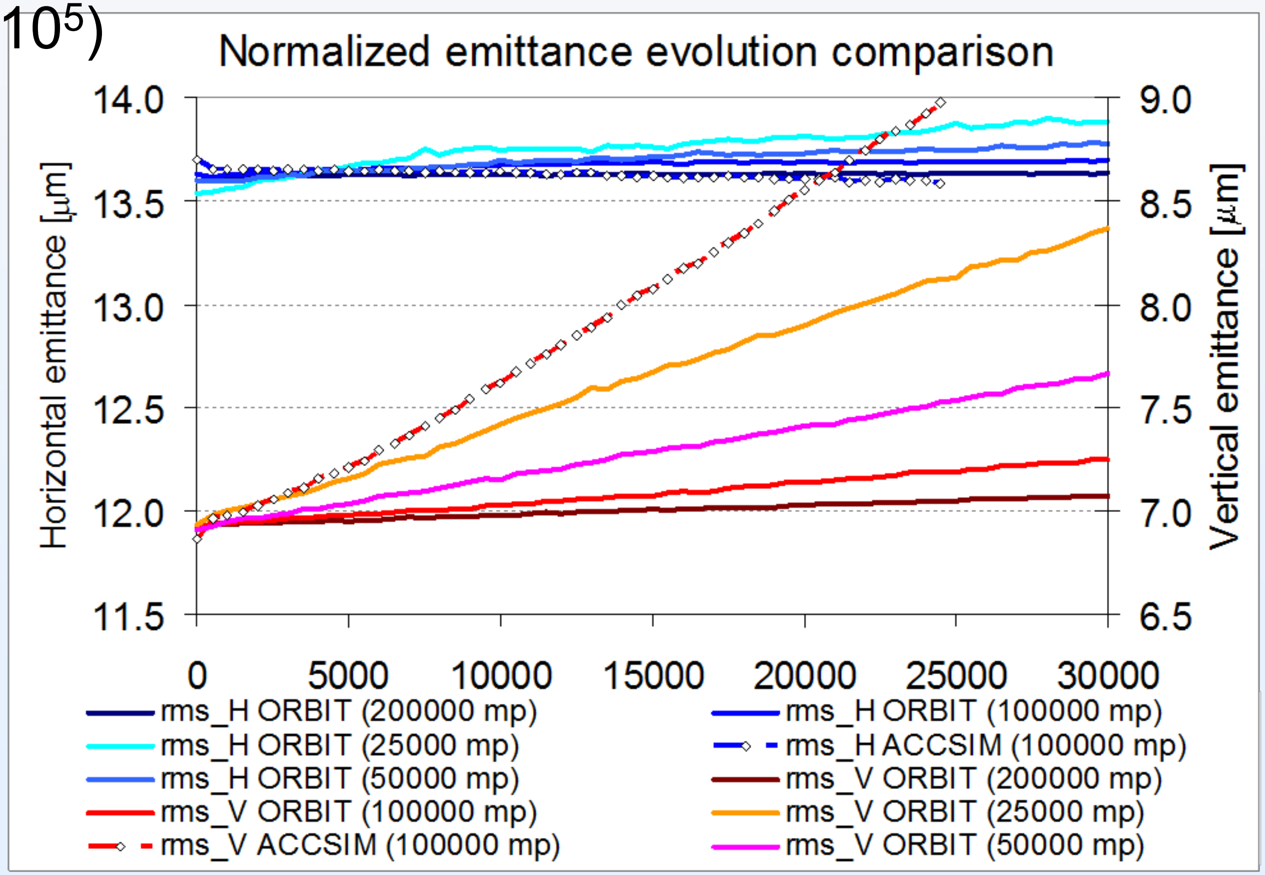
Benchmark – ORBIT/ACCSIM vs. measurements

- ✓ ORBIT and ACCSIM : Long bunches – $Q_{H,V}$=4.21/4.35
  - – 2nd harmonic cavity in anti-phase
  - – ORBIT: ~30 ms, 3×10^4 turns, $\Delta\varepsilon_{H\&V}/\Delta t$~$5\times10^{-4}$ & 5×10^{-3} µm/ms
  - – ACCSIM: ~25 ms, 2.5×10^4 turns, $\Delta\varepsilon_{H\&V}/\Delta t$~-0.003 & 0.1



Benchmark – ORBIT/ACCSIM vs. measurements

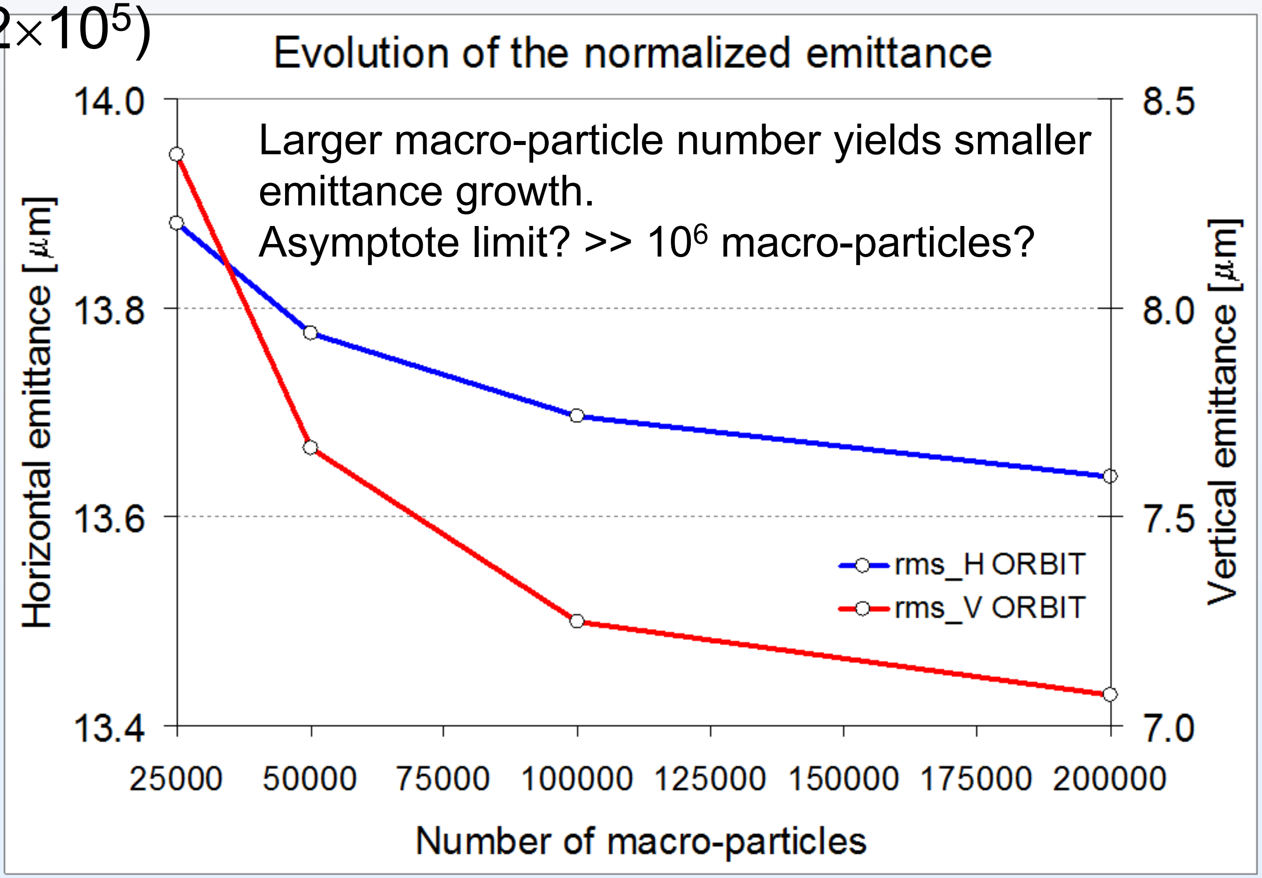
- ✓ ORBIT and ACCSIM : Long bunches – $Q_{H,V}$=4.21/4.35
  - – 2nd harmonic cavity in anti-phase
  - – Transverse emittance evolution $\varepsilon^{n}_{H,V}(1\sigma)$ [μm] versus number of turns for various number of macro-particles (2.5×10^{4} to 2×10^{5})



Benchmark – ORBIT/ACCSIM vs. measurements

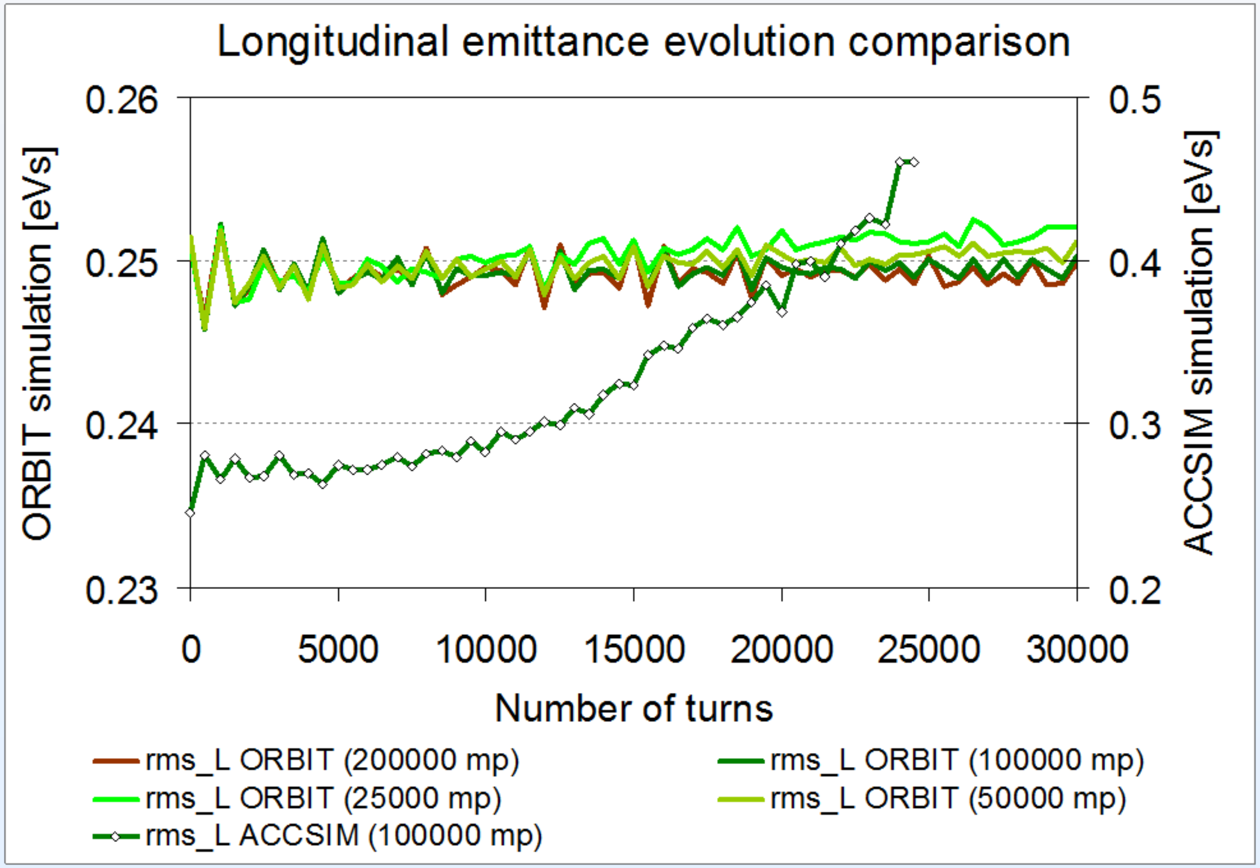
✓ ORBIT and ACCSIM : Long bunches – $Q_{H,V}$=4.21/4.35

- 2nd harmonic cavity in anti-phase
- Transverse normalized emittance evolution $\varepsilon^{n}_{H,V}(1\sigma)$ [μm] (at turn 3×10^4) versus number of macro-particles (from 2.5×10^4 to 2×10^5)



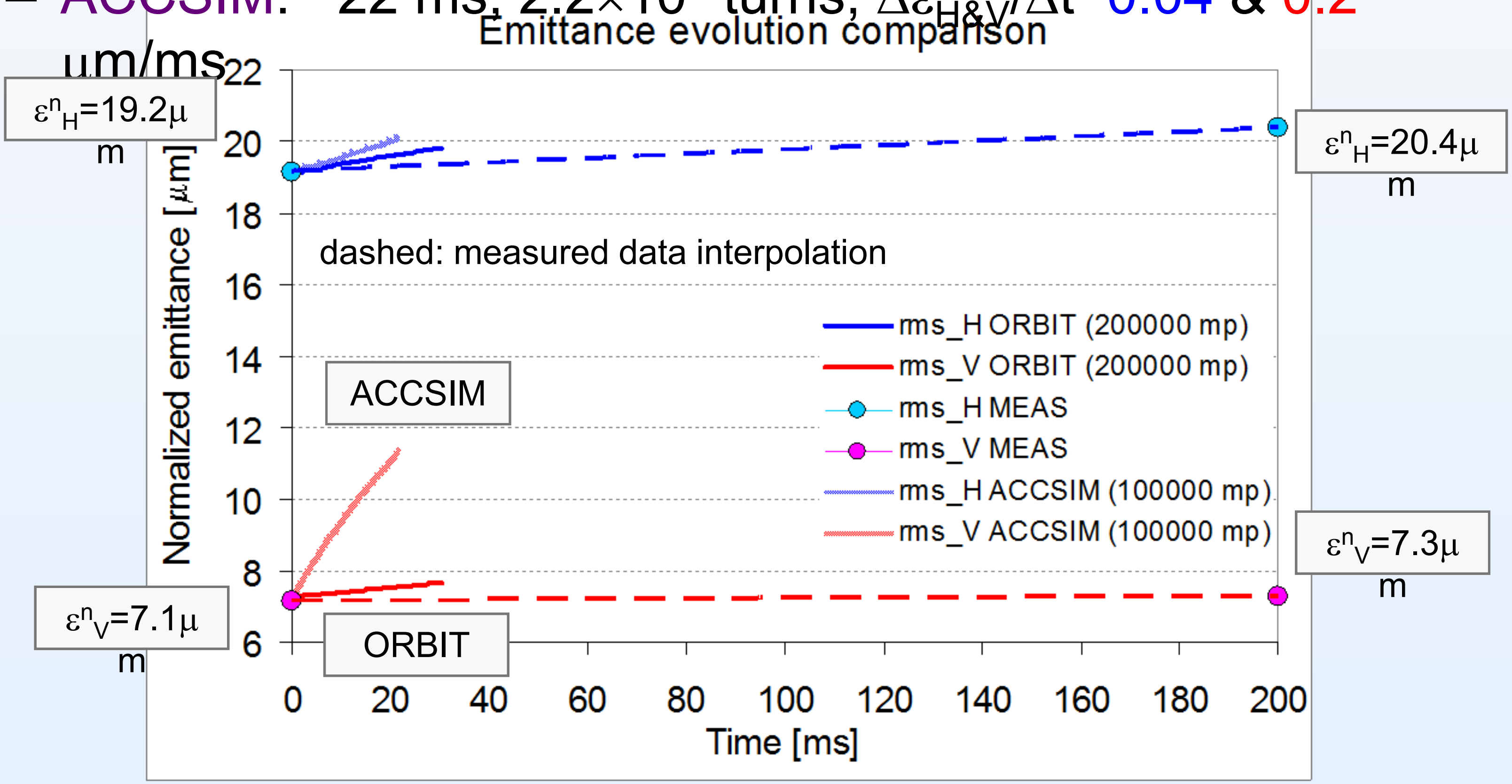
Benchmark – ORBIT/ACCSIM vs. measurements

- ✓ ORBIT and ACCSIM : Long bunches – $Q_{H,V}$=4.21/4.35
  - – 2^{nd} harmonic cavity in anti-phase
  - – Longitudinal remittance evolution $\varepsilon^n{}_L(1\sigma)$ [eVs] for various number of macro-particles (2.5×10^4 to 2×10^5)



Benchmark – ORBIT/ACCSIM vs. measurements

- ✓ ORBIT and ACCSIM : Short bunches – $Q_{H,V}$=4.21/4.45
  - 2nd harmonic cavity in phase
  - ORBIT: ~30 ms, 3×10^4 turns, $\Delta\varepsilon_{H\&V}/\Delta t$~0.024 & 0.013 μm/ms
  - ACCSIM: ~22 ms, 2.2×10^4 turns, $\Delta\varepsilon_{H\&V}/\Delta t$~0.04 & 0.2 μm/ms

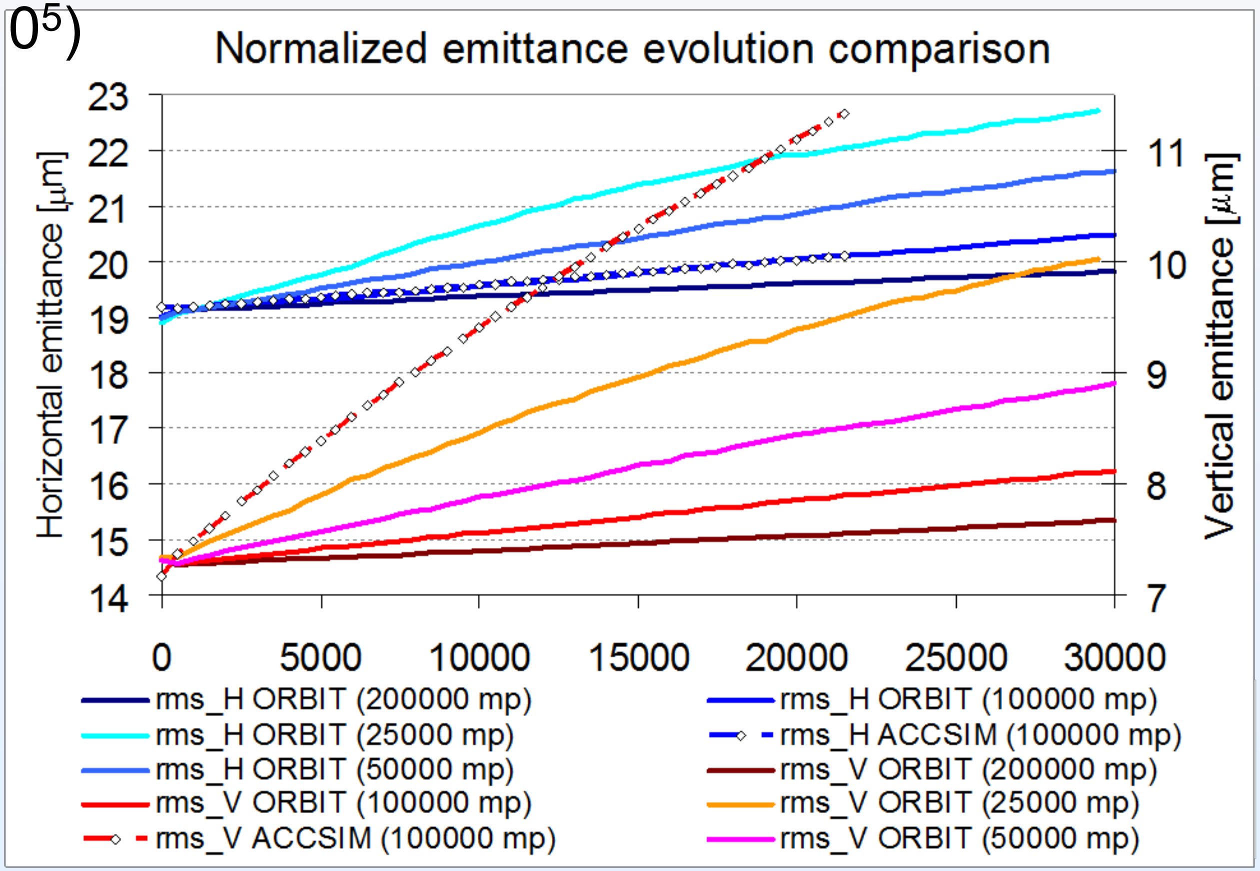


Benchmark – ORBIT/ACCSIM vs. measurements

- ✓ ORBIT and ACCSIM : Long bunches – $Q_{H,V}$=4.21/4.35
  - Only short simulation duration (time consuming)
  - ORBIT: Fairly good estimation of growth rates in both planes
  - ACCSIM: Overestimation / fairly good estimation of growth rates in the vertical / horizontal planes
- ✓ ORBIT and ACCSIM : Short bunches – $Q_{H,V}$=4.21/4.45
  - Only short simulation duration (computation time ~200 turns/h)
  - ORBIT: Slight overestimation of growth rates in both planes
  - ACCSIM: Overestimation / slight overestimation of growth rates in the vertical / horizontal planes
  - Insufficient statistics?
    - More emittance measurements set equally apart? (along the 200 ms)

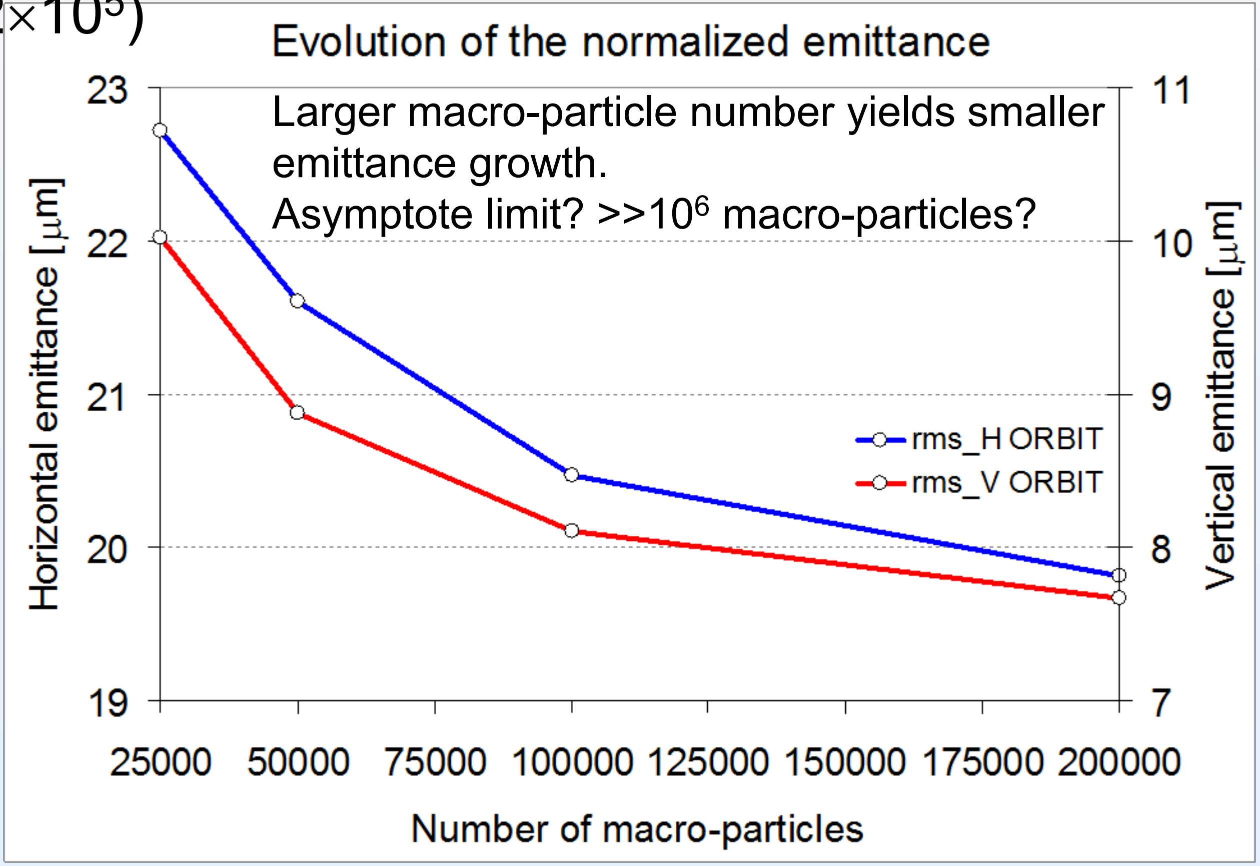
Benchmark – ORBIT/ACCSIM vs. measurements

- ✓ ORBIT and ACCSIM : Short bunches – $Q_{H,V}$=4.21/4.45
  - – 2^{nd} harmonic cavity in phase
  - – Transverse emittance evolution $\varepsilon^n_{H,V}(1\sigma)$ [μm] versus number of turns for various number of macro-particles (2.5×10^4 to 2×10^5)



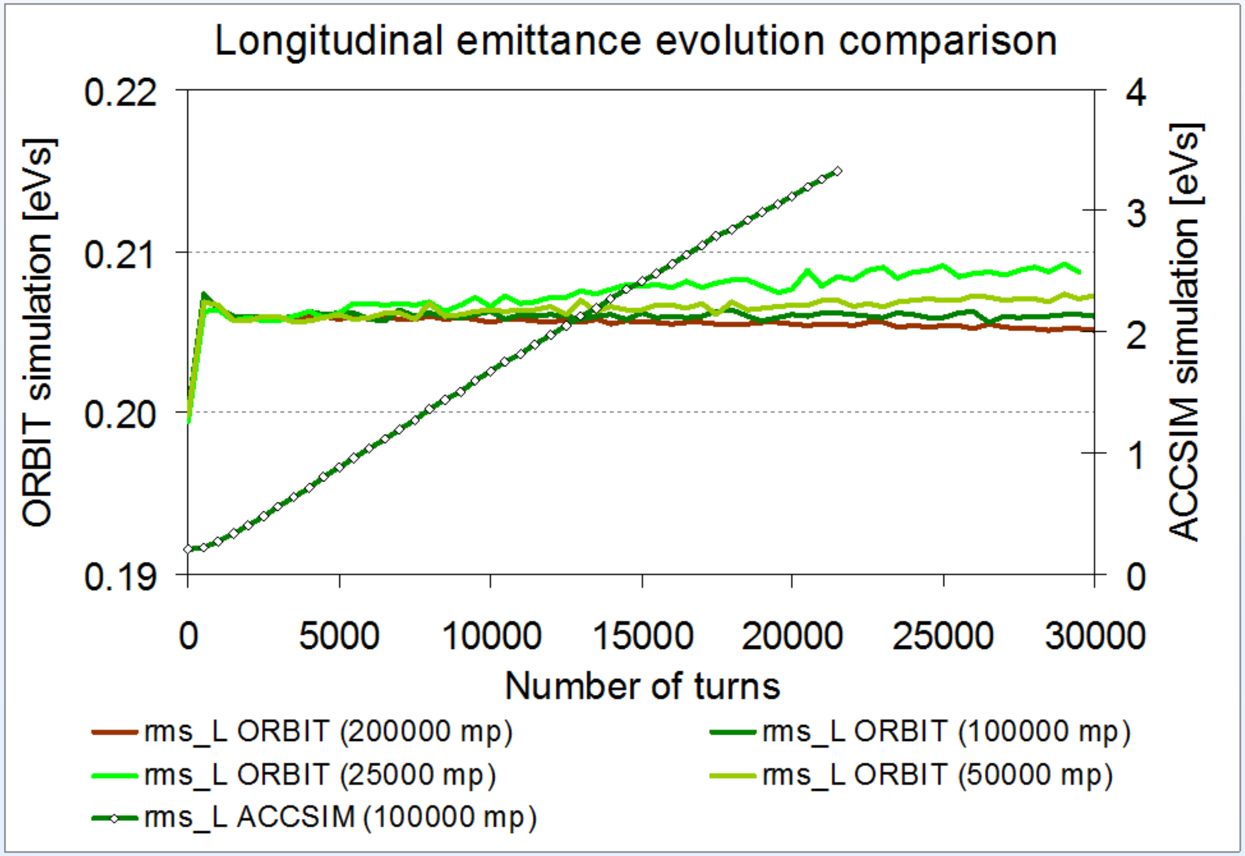
Benchmark – ORBIT/ACCSIM vs. measurements

✓ ORBIT and ACCSIM : Short bunches – $Q_{H,V}$=4.21/4.45
- 2nd harmonic cavity in phase
- Transverse normalized emittance evolution $\varepsilon^n_{H,V}(1\sigma)$ [μm] (at turn 3×10^4) versus number of macro-particles (from 2.5×10^4 to 2×10^5)

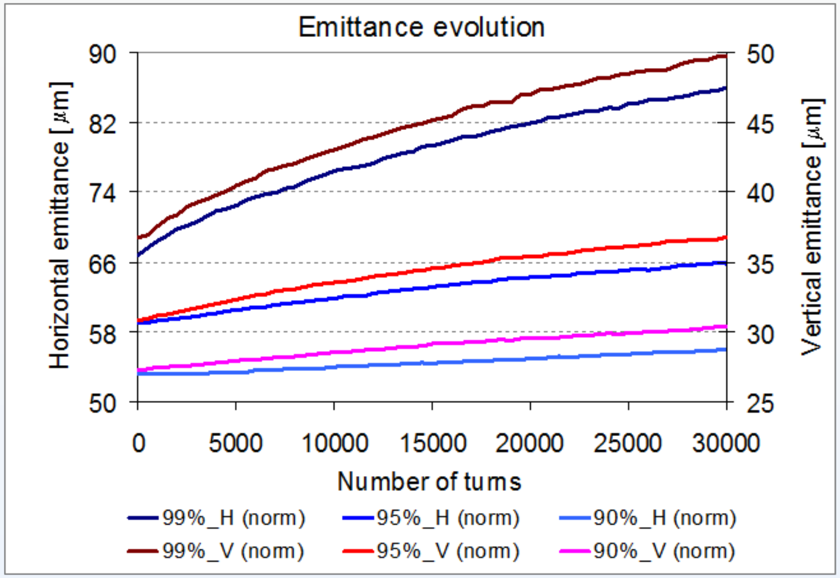


Benchmark – ORBIT/ACCSIM vs. measurements

- ✓ ORBIT and ACCSIM : Short bunches – $Q_{H,V}$=4.21/4.45
  - – 2^{nd} harmonic cavity in phase
  - – Longitudinal emittance evolution $\varepsilon^{n}_{L}(1\sigma)$ [eVs] for various number of macro-particles (2.5×10^4 to 2×10^5)
    - ACCSIM: particles escape the bucket (initial density not quite matched)



Benchmark – ORBIT/ACCSIM vs. measurements



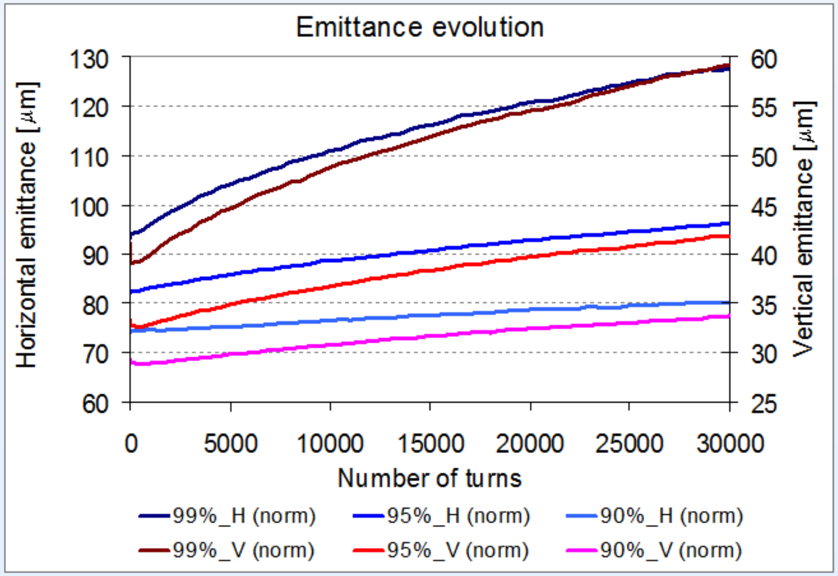
Transverse emittances

$\varepsilon^{n}_{H,V}(99, 95, 90\%)$ [µm]

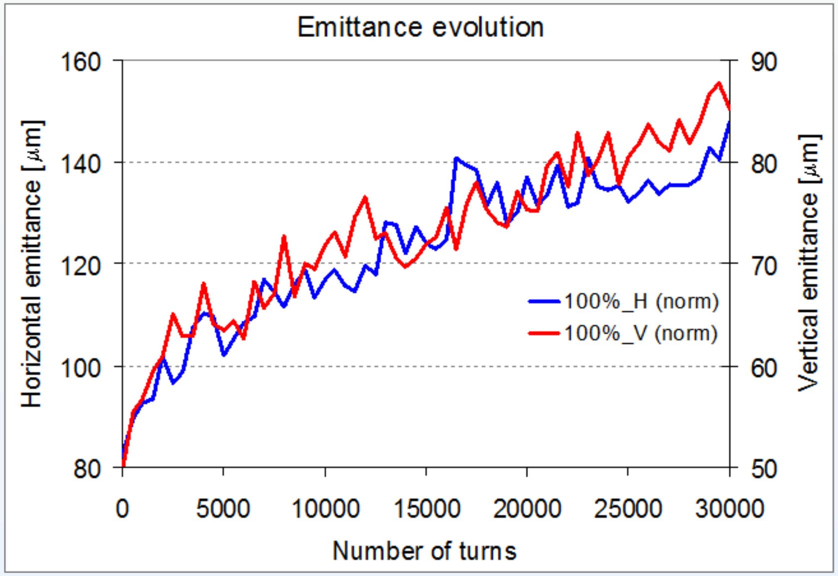
(2×10^{5} macro-particles)

✓ ORBIT $Q_{H,V}$=4.21/4.45
Short bunches

✓ ORBIT
$Q_{H,V}$=4.21/4.35
Long bunches



Benchmark – ORBIT/ACCSIM vs. measurements



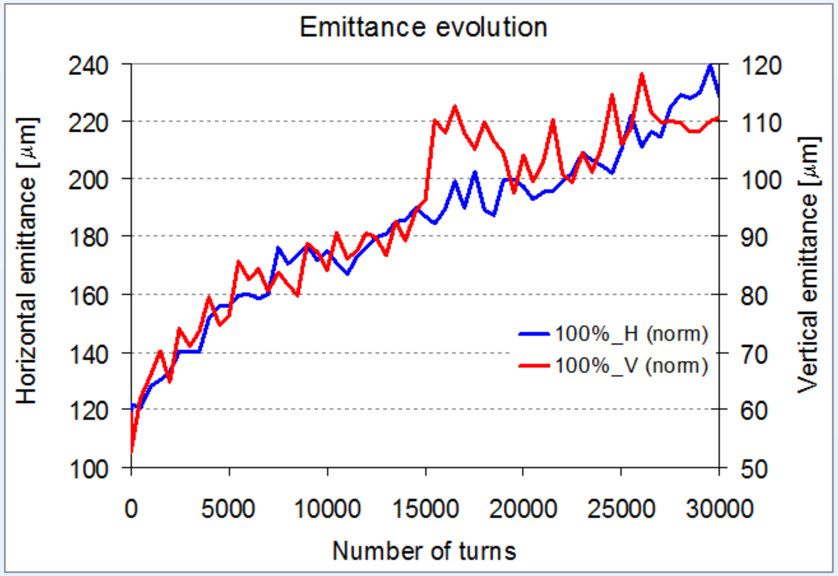
Transverse emittances

$\varepsilon^n_{H,V}(100\%)$ [μm]

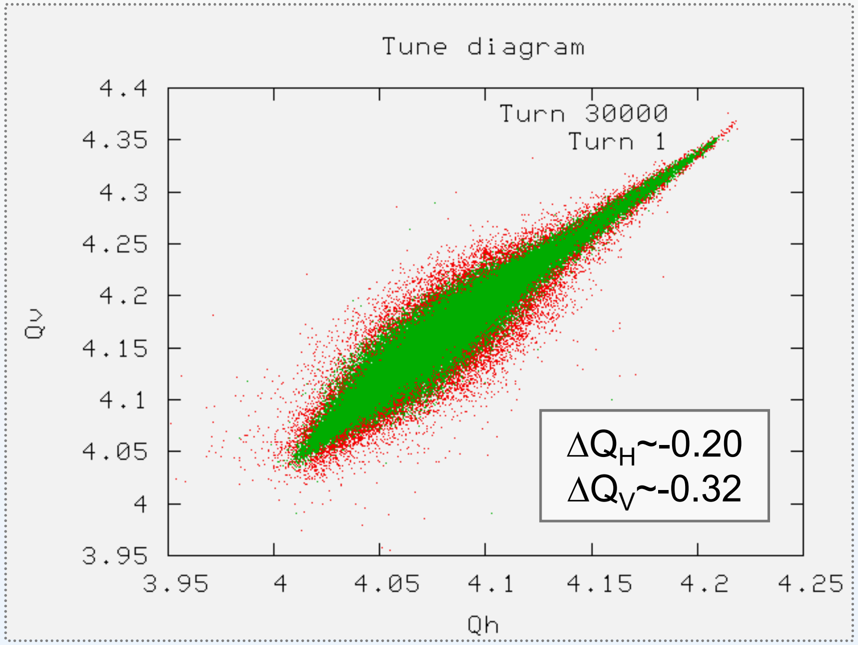
(2×10^5 macro-particles)

✓ ORBIT $Q_{H,V}$=4.21/4.35
Long bunches

✓ ORBIT $Q_{H,V}$=4.21/4.45
Short bunches



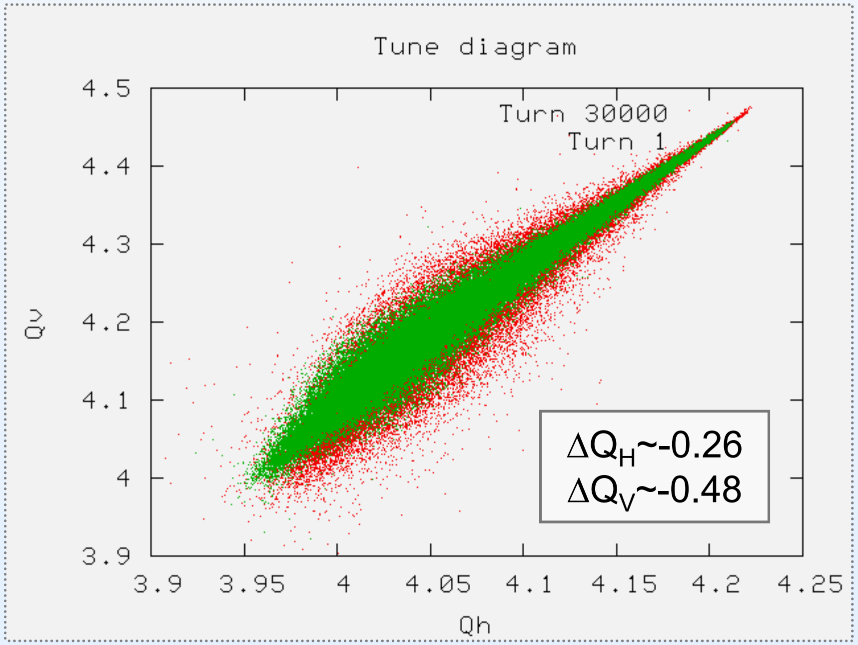
Benchmark – ORBIT/ACCSIM vs. measurements



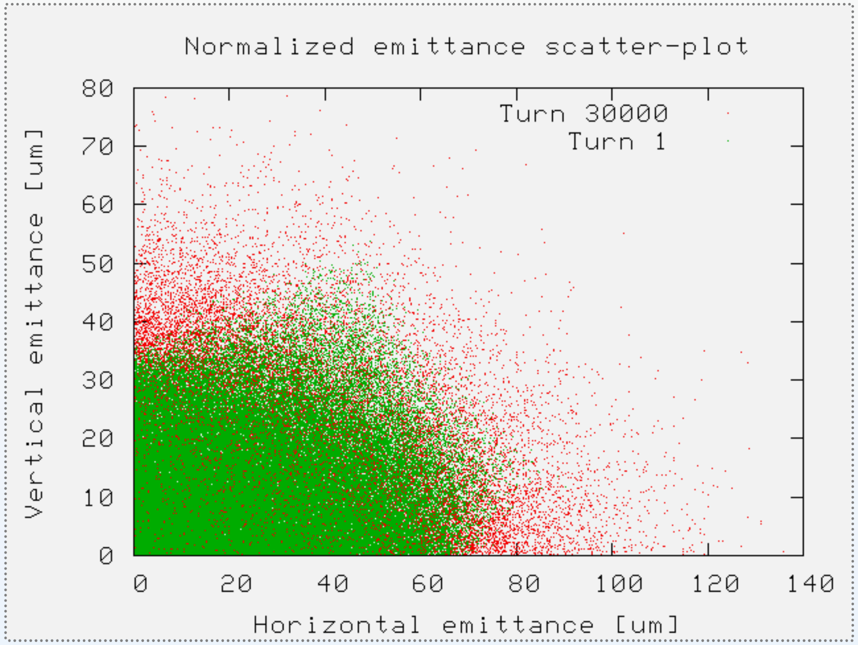
✓ORBIT $Q_{H,V}$=4.21/4.35
Long bunches

Tune diagrams
(2×10^5 macro-particles)
(green: at turn 1, red: at turn 30000)

✓ORBIT $Q_{H,V}$=4.21/4.45
Short bunches



Benchmark – ORBIT/ACCSIM vs. measurements



✓ ORBIT

$Q_{H,V}$=4.21/4.35

Long bunches

Transverse emittances scatter plots E^n_H- E^n_V [μm-μm] (2×10^5 macro-particles)

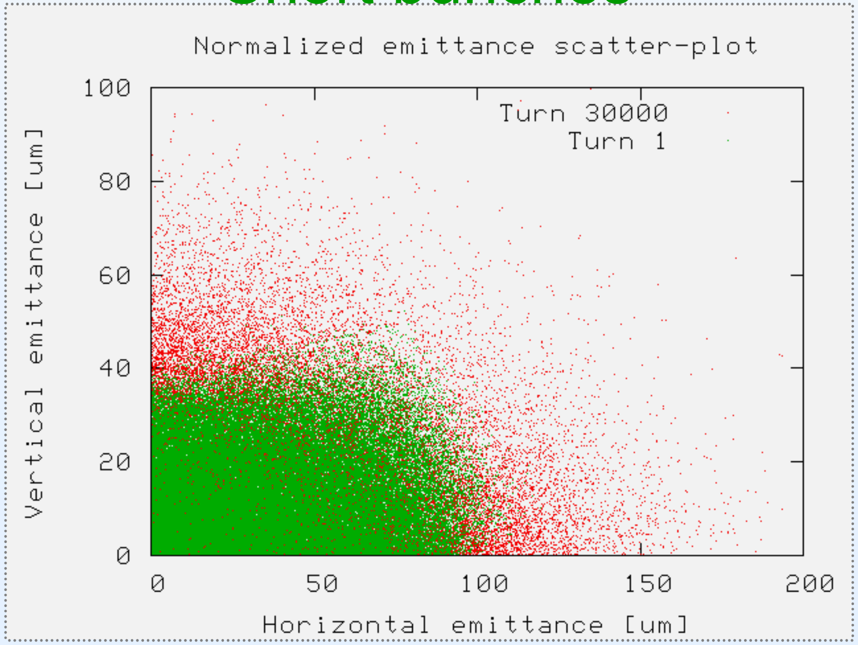
(particle emittance distribution)

($E^n_{H,V}$ single particle emittance)

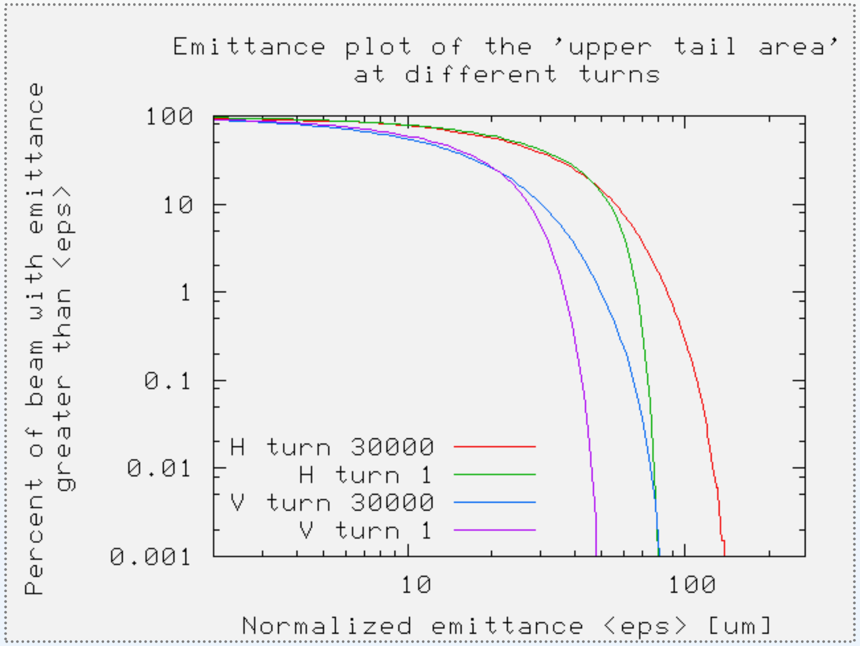
(green: at turn 1, red: at turn 30000)

✓ ORBIT $Q_{H,V}$=4.21/4.45

Short bunches



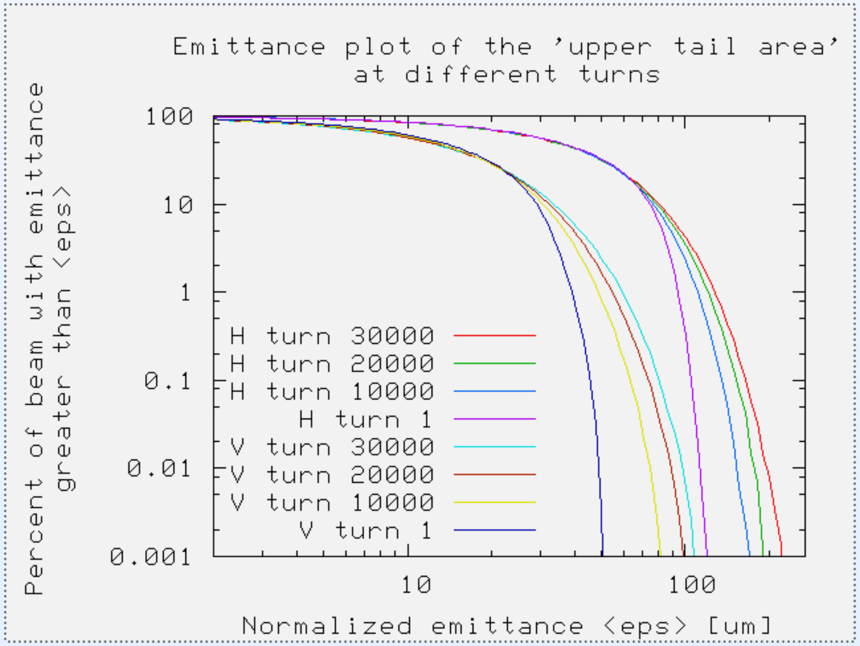
Benchmark – ORBIT/ACCSIM vs. measurements



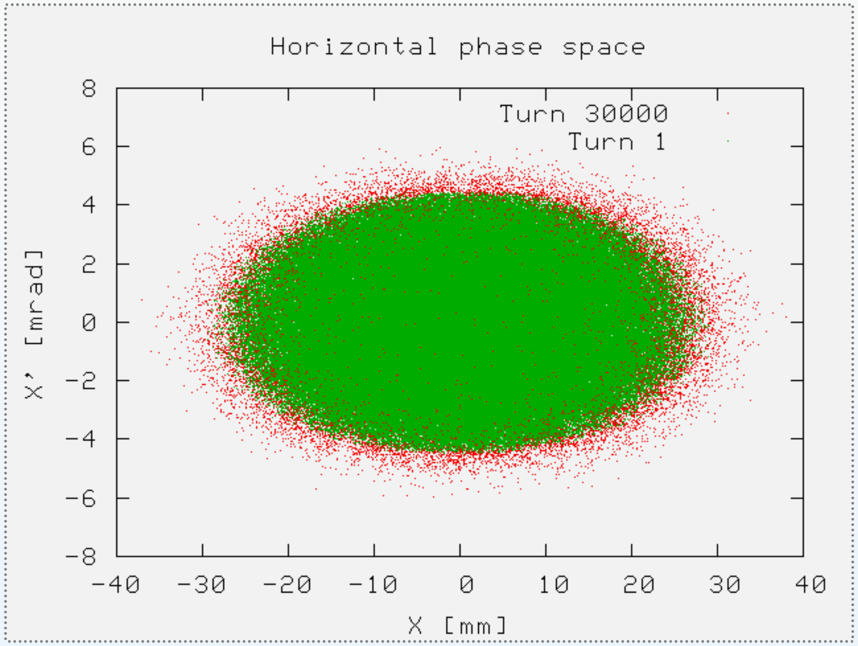
✓ ORBIT $Q_{H,V}$=4.21/4.35
Long bunches

Log-log "upper tail area" plot
Prob$\{E^n_{H,V} > \varepsilon^n_{H,V}\}$ [%] vs. $\varepsilon^n_{H,V}$ [μm]
($E^n_{H,V}$ single particle emittance)
(2×10^5 macro-particles)

✓ ORBIT $Q_{H,V}$=4.21/4.45
Short bunches



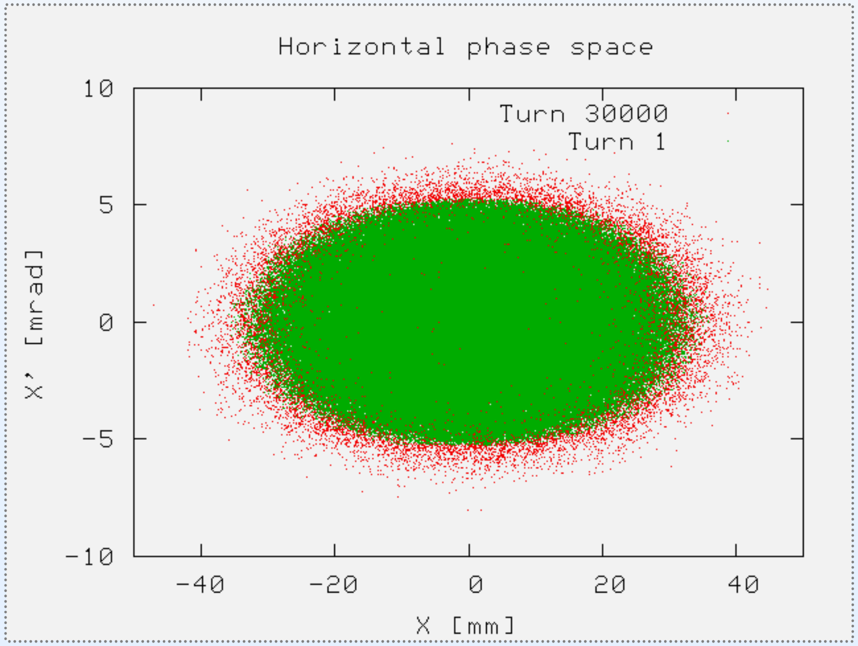
Benchmark – ORBIT/ACCSIM vs. measurements



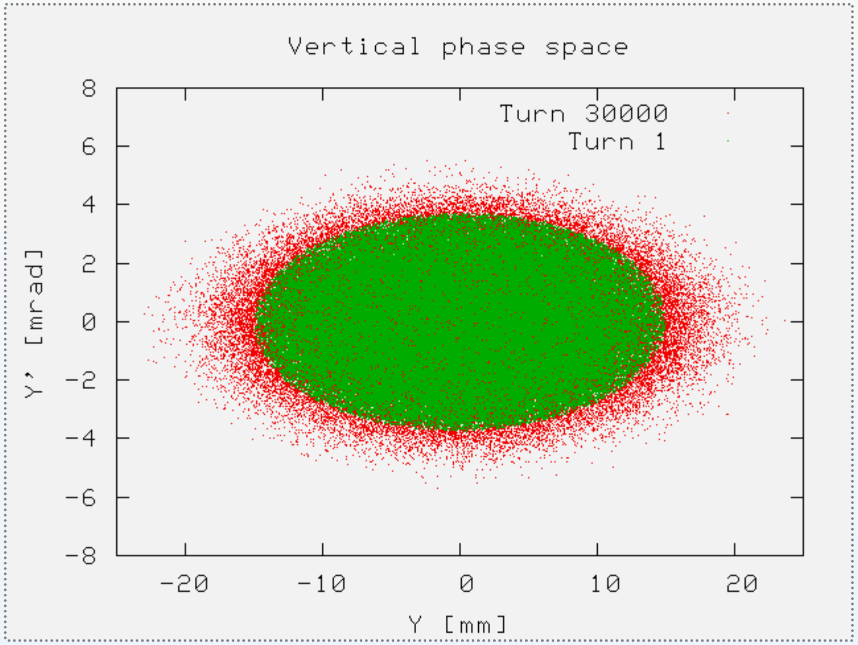
✓ ORBIT
$Q_{H,V}$=4.21/4.35
Long bunches

Horizontal phase-space scatter plots X-X' [mm-mrad] (2×10^5 macro-particles)
(green: at turn 1, red: at turn 30000)

✓ ORBIT $Q_{H,V}$=4.21/4.45
Short bunches



Benchmark – ORBIT/ACCSIM vs. measurements

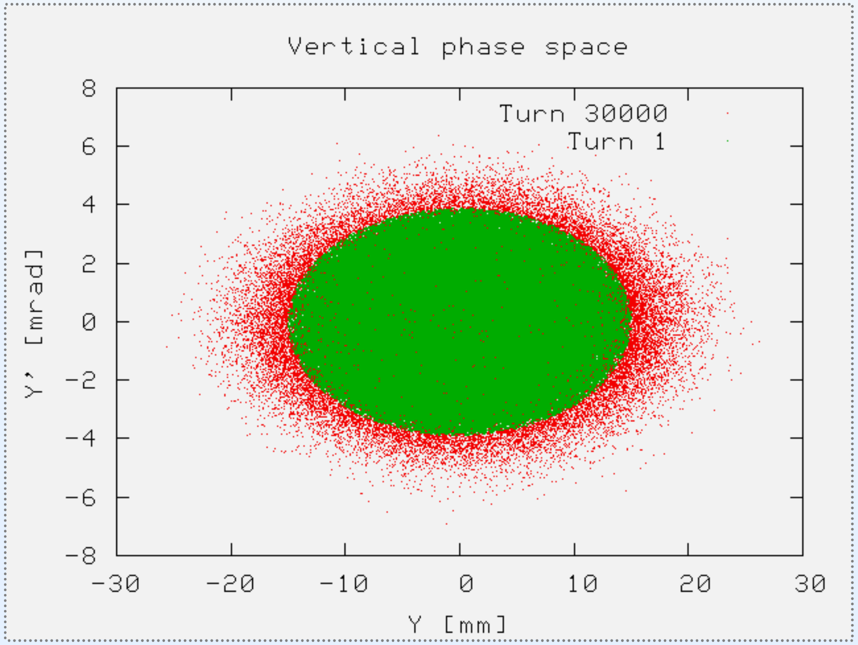


Vertical phase-space scatter plots Y-Y' [mm-mrad] (2×10^5 macro-particles)

(green: at turn 1, red: at turn 30000)

✓ORBIT $Q_{H,V}$=4.21/4.45
Short bunches

✓ORBIT
$Q_{H,V}$=4.21/4.35
Long bunches



Summary

✓ PSB injection simulations

- Controlled longitudinal injection painting scheme based on a triangular modulation of the Linac4 output energy examined
- Tailoring of the longitudinal and transverse distributions to minimize peak densities is effective in lessening the transverse emittance blow-up

✓ PSB benchmarking simulations

- Benchmark of the simulations with experiments at 160 MeV seems to indicate that the simulations done with Orbit are hopeful (i.e. emittance growth rates ~similar to measurements) while those conducted with Accsim are rather pessimistic (i.e. overestimation of growth rates but horizontal plane and long bunches)

Appendix: ORBIT/ACCSIM space charge modeling

- ✓ ORBIT transverse space charge routines (parallel processing)
  - 2½D space charge model ("mixed 2D & 3D models: space charge force on macro-particles scaled according to the longitudinal charge density). 3D space charge model exists too
  - Transverse space charge tracking calculation (applied at each space charge kick "nodes" inserted around the ring)
    - Pair-wise sum: "Particle-Particle" method. Computes the Coulomb force on one particle by summing the force over all other particles
    - Brute Force Particle-In-Cell (PIC): "Particle-Mesh" method. Bins the macro-particles on a grid, computes the force at each grid point and on each particle by linear interpolation from the grid (grid size automatically fitted to the beam extent)
    - FFT-PIC: Alike to the brute-force PIC but a FFT computes the force on the grid via the binned particle distribution (the fastest solver)
- ✓ ORBIT chromaticity (for Teapot based tracking)
  - Chromatic tune shift generated by the transfer matrix considering the $\Delta p/p$ (particle kicks at lattice elements depend on $\Delta p/p$)

Appendix: ORBIT/ACCSIM space charge modeling

- ✓ ACCSIM transverse space charge routines (non-parallel processing)
  - 2½D space charge model (similar as in ORBIT)
  - Transverse space charge tracking calculation (made at user-specified intervals in the ring)
    - Fast Multipole Method (FMM): "Particle-Particle Tree-code" method (lumping charges together). The force on each particle is derived from field calculation and kicks denoting the force integral are applied
    - Hybrid Fast Multipole (HFM): FMM is combined with elements of PIC-style methods by overlaying a proper grid on the densely-populated beam core region, assigning compound charges to the grid points, and letting FMM solve the whole system of core grid + halo charges (handle correctly large-amplitude beam halos)
- ✓ ACCSIM chromaticity (MAD8 based tracking)
  - Chromatic tune shift generated by extra particle betatron phase space rotation ($2\pi\Delta Q_{H,V}$) once or more per turn, driven by the first-order chromaticity $\xi_{H,V}$ and $\Delta p/p$