
CERN

Longitudinal painting requirements

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Acknowledgements: J. Abelleira, A. Lombardi, G. Rumolo, R. Wegner

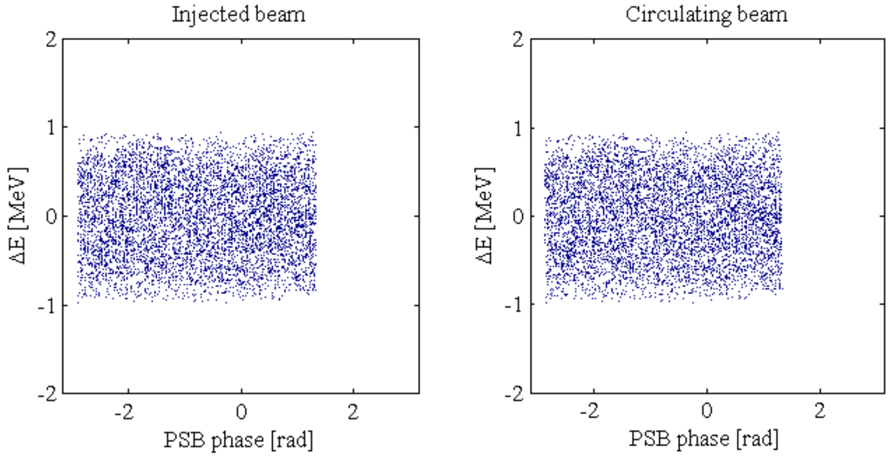
Outline

- Longitudinal painting vs. un-modulated energy injection
    - The processes
    - Physical parameters
    - Present hardware limitations
    - Simulations set-up and comparison for
        - Transverse emittance
        - Losses
        - Transverse space charge
- Longitudinal painting optimization process
- Summary and conclusions

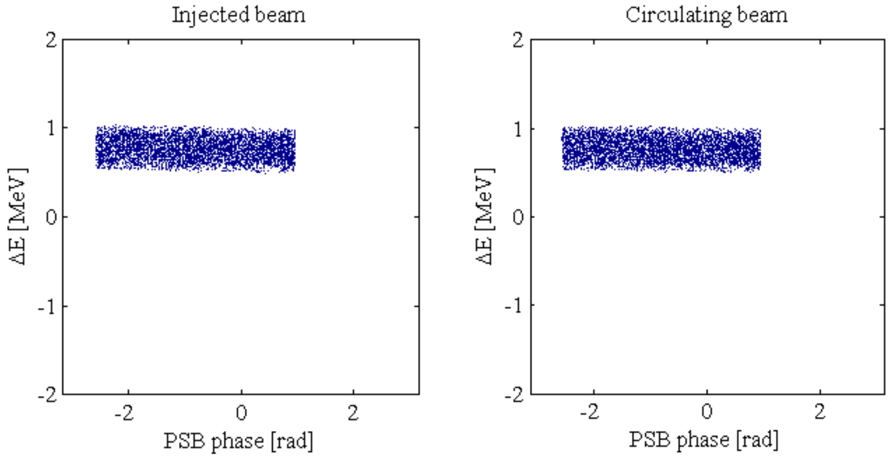
The processes

- Multi-turn un-modulated energy injection
  - The L4 bunch trains arrive to the PSB with **the same central energy E_0 = 160 MeV**
  - The **rms energy spread δE is** usually **large (~400-450 keV)** to compensate peaks of line density

    → bad for space charge
  - The **chopping factor is fixed (~60%)**

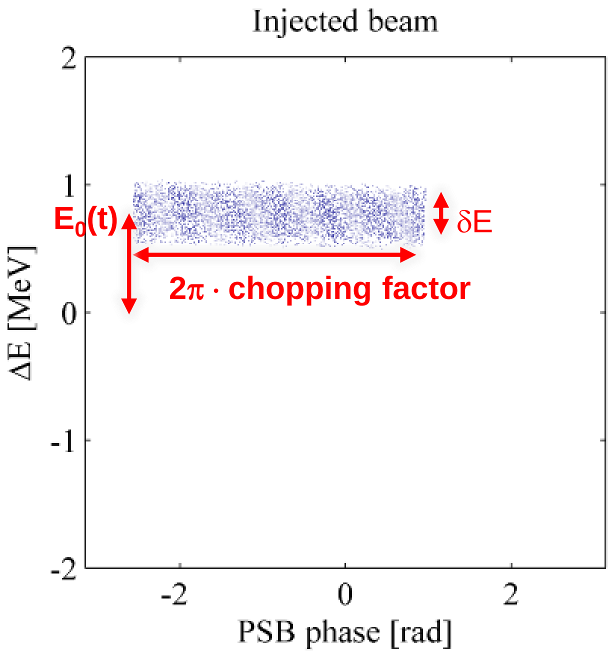


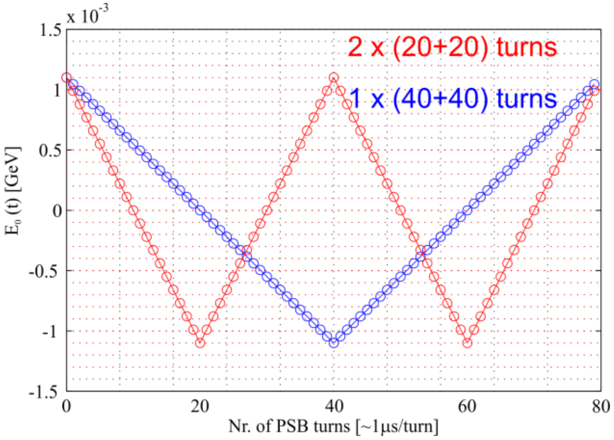
- Multi-turn longitudinal painting
  - The **L4 bunch trains** arrive to the PSB **with different (turn-by-turn) central energy around E_0 = 160 MeV**
  - The **rms energy spread δE is fixed (120-250 keV)**
  - The **chopping factor is varying** to follow the longitudinal iso-Hamiltonian contours for a given longitudinal emittance.



Physical parameters

- The rms energy spread **δE**
  - Imposed **by the de-buncher**
  - **Fixed** during the injection process
- The central energy **$E_0(t)$**
  - Imposed **by the last two PIMS**
  - **Can be swept turn-by-turn** at injection
- The central energy sweeping rate **$dE_0(t)/dt$**
  - Imposed by the last two PIMS → **change of phase and, thus, power requested to the de-buncher**
- The chopping factor **(≤1)**
  - Imposed **by the chopper**
  - **Rations the effective current/turn** at the PSB entrance
    - **$I_{eff}(t)$ = chop. factor × unchopped current = chop. factor × 40 mA**
  - **Can be modulated** turn-by-turn at injection
  - **Determines the number of turns to be injected** for any given target intensity
- The number of injectable turns
  - **Is limited** by the BI.DIS **at <150 per PSB ring**





A possible energy sweep through the PIMS

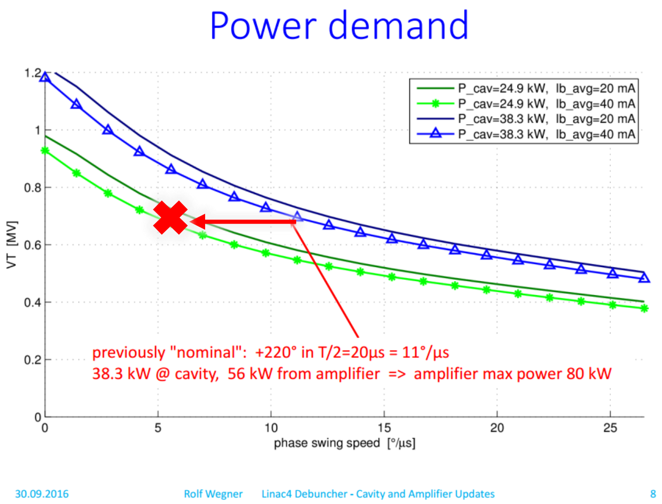
Present hardware limitations

- **The present de-buncher power supply has power limitations → cavity power limited to 24.9 kW**
  - <u>δE =120 keV rms (historical reference value for energy spread)</u> can be reached **with a maximum of ~5.5 °/μs at 40 mA → sweeping with the PIMS between ±1.2 MeV in 40+40 turns (or ±0.8 MeV in 20+20 turns)**

    → Previous expectations were **11 °/μs sweeping** with the PIMS **between ±1.2 MeV in 20+20 turns** → **to be obtained cavity power must increase to ~38.3 kW** → **<u>Upgrade of the de-buncher amplifier would be needed!</u>**

    →With **present performances the rms energy spread at the PSB entrance** will reasonably vary in between **80 keV ÷ 450 keV** with **~5.5 °/μs (1 sweeping period in 80 turns (40+40)** turns

- **Can we relax some injection parameters to avoid the power amplifier upgrade? We need longitudinal painting simulations vs. un-modulated injection simulations…**
  - **Is a slower sweeping rate acceptable? → 1x(40+40) vs. 2x(20+20) turns**
  - **Could we think to sweep in a more limited range? → ±0.8 MeV vs. ±1.2 MeV**
  - **Is the natural energy spread (~250 keV, de-buncher OFF) acceptable?**
  - **Can we survive without longitudinal painting in a first phase?**

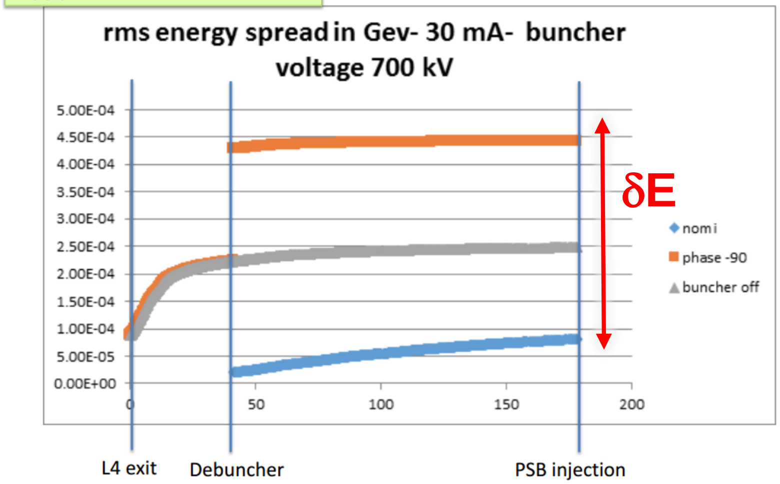


Power demand

previously "nominal": +220° in T/2=20μs = 11°/μs
38.3 kW @ cavity, 56 kW from amplifier => amplifier max power 80 kW

30.09.2016 Rolf Wegner Linac4 Debuncher - Cavity and Amplifier Updates 8

copy-paste of Alessandra's email…

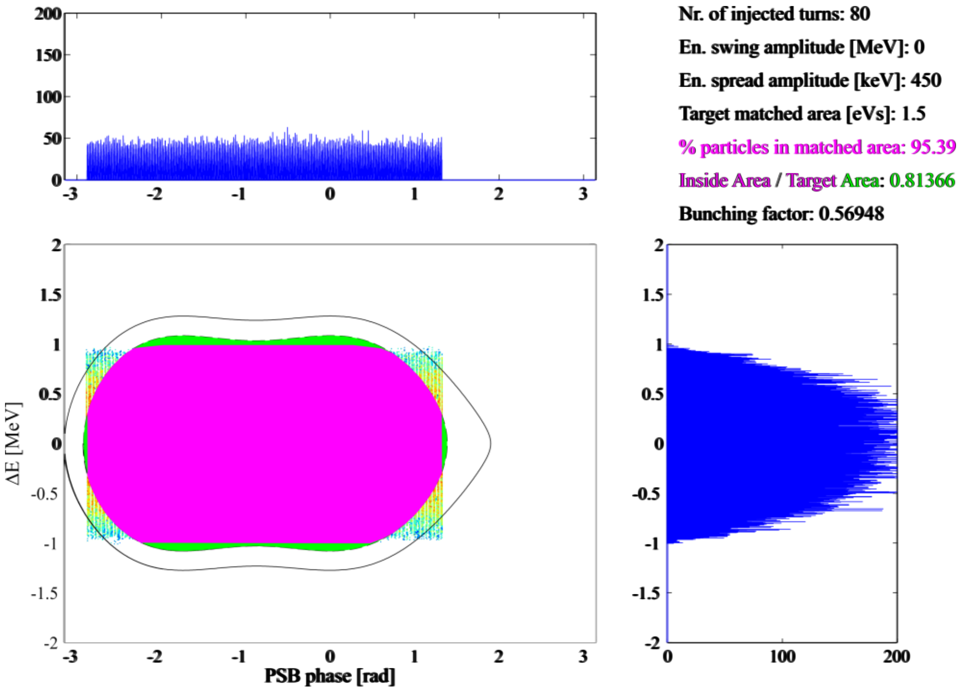


Plots from E. Benedetto, A. Lombardi, R. Wegner presentations at LIU-PSB Injection Meeting #23

Longitudinal distribution optimization

- **An optimized painting is necessary both in un-modulated and modulated conditions**
  - A **numerical optimization process for the most uniform fill of the target matched area** has been prepared
  - **The optimization is based on a "uniformity index" (U.I.) which has been chosen, in frozen conditions (i.e. no tracking), as the product of:**
  - **The choice of the 'best' fill is** the one correspondent to **the highest uniformity index**

U.I. = (**Particles inside matched area / Total particles**) × (**Inside area / Target matched area)**



Nr. of injected turns: 80
En. swing amplitude [MeV]: 0
En. spread amplitude [keV]: 450
Target matched area [eVs]: 1.5
% particles in matched area: 95.39
Inside Area / Target Area: 0.81366
Bunching factor: 0.56948

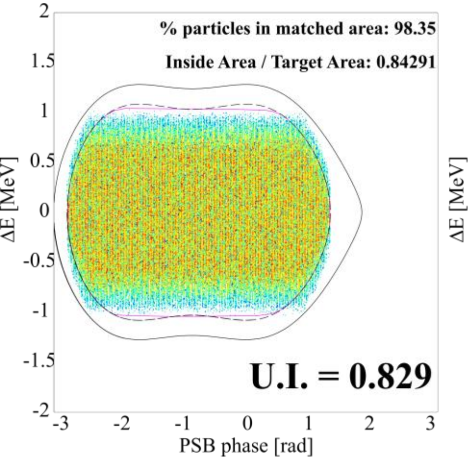
U.I. = 0.776

Un-modulated injection

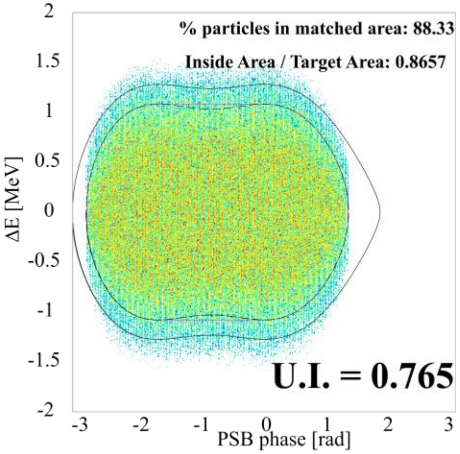
δE [keV rms]	Chop. Factor [-]	Matched area [eVs]	Particles inside matched	Inside area/target area	U.I.
400	0.69	1.5	0.95172	0.74752	0.711
450	0.69	1.5	0.93807	0.81418	0.764
400	0.68	1.5	0.9544	0.74222	0.708
450	0.68	1.5	0.941	0.81528	0.767
400	0.68	1.5	0.95944	0.74299	0.713
450	0.68	1.5	0.94548	0.81357	0.769
400	0.67	1.5	0.96345	0.7405	0.713
450	**0.67**	**1.5**	**0.95387**	**0.81366**	**0.776**
400	0.66	1.5	0.97166	0.73602	0.715
450	0.66	1.5	0.96276	0.80601	0.776
400	0.65	1.5	0.97807	0.7327	0.717
450	0.64	1.5	0.97167	0.79778	0.775
400	0.64	1.5	0.98565	0.72328	0.713
450	0.63	1.5	0.98012	0.78465	0.769
400	0.62	1.5	0.9913	0.71242	0.706
450	0.6	1.5	0.98772	0.76563	0.756
400	0.6	1.5	0.99563	0.69656	0.694
450	0.58	1.5	0.99372	0.7448	0.740
400	0.58	1.5	0.99854	0.67563	0.675
450	0.55	1.5	0.99763	0.71126	0.710
400	0.55	1.5	0.99984	0.64264	0.643
450	0.5	1.5	0.9997	0.66541	0.665

Longitudinal distributions optimization

- **An optimized painting is necessary both in un-modulated and modulated conditions**
  - The uniformity index U.I. **is usually higher in longitudinal painting conditions** → reason behind the painting itself !
  - **The number of modulations influences very little the uniformity**.
  - The higher the peak energy sweep amplitude **ΔE_0 , the smaller the minimum chopping factor** for a given longitudinal emittance contour
  - **A smaller energy spread helps to be more precise in painting** the contour **for a given energy sweep**.



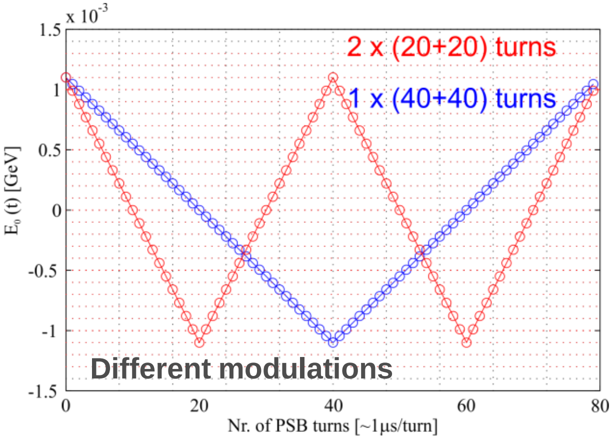
Painting with smaller energy spread



Painting with larger energy spread

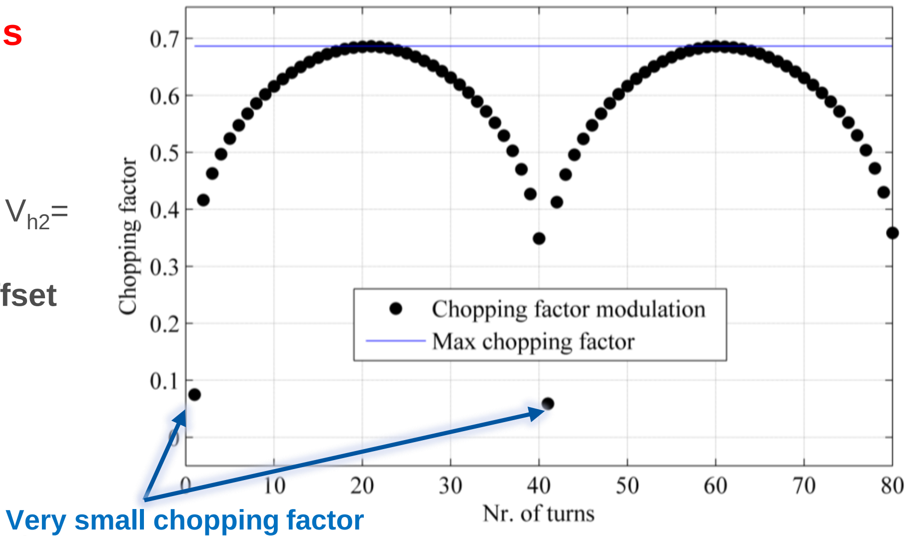
Longitudinal painting

Nr. of modulations [-]	ΔE_0 [MeV]	δE [keV rms]	Matched area [eVs]	Particles inside matched area	Inside area/target area	Min. chopping factor	U.I.
1	**0.8**	**120**	**1.5**	**0.98353**	**0.84291**	**0.55**	**0.829**
1	1.1	120	1.5	0.94151	0.86583	0.06	0.815
1	0.8	250	1.5	0.94259	0.86532	0.55	0.816
1	**1.1**	**250**	**1.5**	**0.88329**	**0.8657**	**0.06**	**0.765**
2	0.8	120	1.5	0.98368	0.83807	0.56	0.824
2	1.1	120	1.5	0.93647	0.8658	0.36	0.811
2	0.8	250	1.5	0.94405	0.86568	0.56	0.817
2	1.1	250	1.5	0.87876	0.86584	0.36	0.761

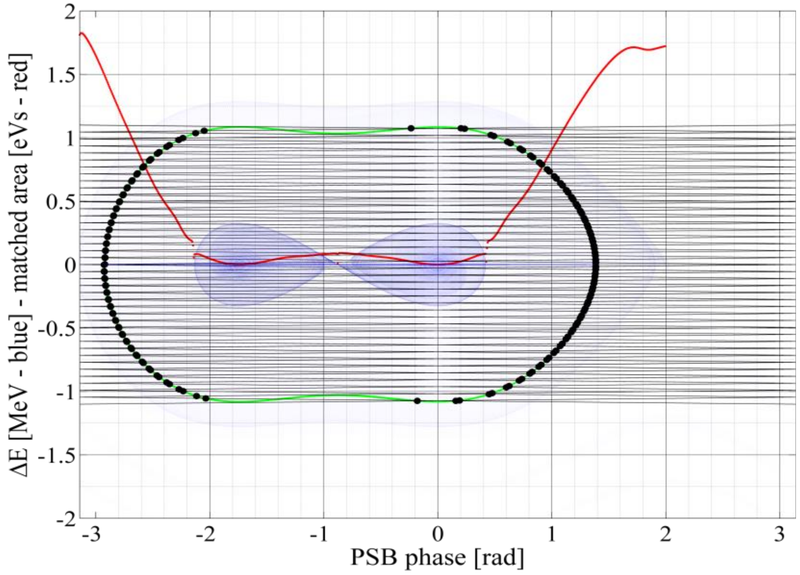


Simulations set-up

- **Simulations set for future NORMGPS/HRS beams (target 1.3e13 p. and $\varepsilon_x/\varepsilon_y$= 13(15) / 6(8) um)**
  - The multi-turn capture process (~10 ms from injection) has been simulated in PTC-Orbit
  - **'Usual' double RF bucket** with V_{h1}= 8 kV and V_{h2}= 6 kV with $\Delta\phi$=220 deg
  - **Fixed KSW painting function** and **vertical offset** for transverse emittance tailoring as in PSB-MKKSW-EN-0001
  - **Transverse + longitudinal space charge**
  - **80 turns imposed** in **1x(40+40) or 2x(20+20) turns sweep** or **without sweep**
  - **±0.8 MeV** and **±1.1 MeV** sweeping max amplitude
  - **80 keV and 120 keV rms** for the longitudinal painting
  - **450 keV rms (after optimization)** for the un-modulated injection
  - **Variable chopping factor patterns for longitudinal painting** depending on selected target long. emittance contour
- **Figures of merit of the simulation results:**
  - **Transverse emittance**
  - **Losses** for activation reasons
  - **Line density / bunching factor** for tr. space charge



Very small chopping factor



Longitudinal painting
± 1.1 MeV sweep - 1 x (40+40) turns

Simulations set-up

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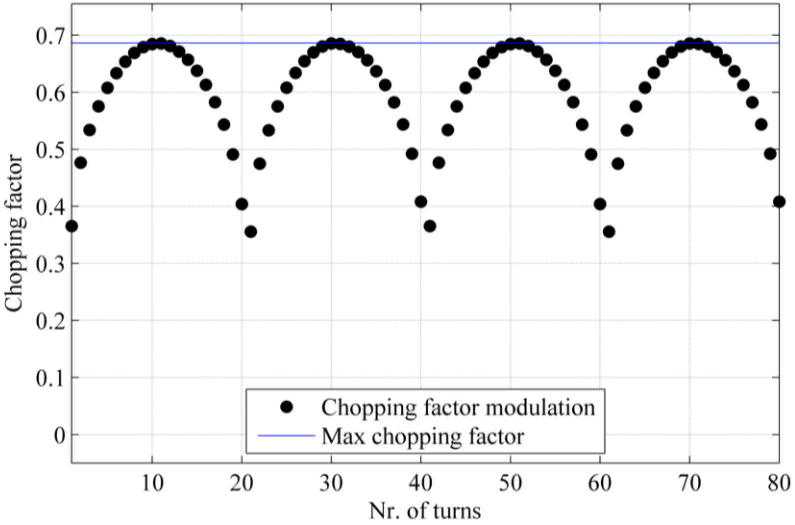

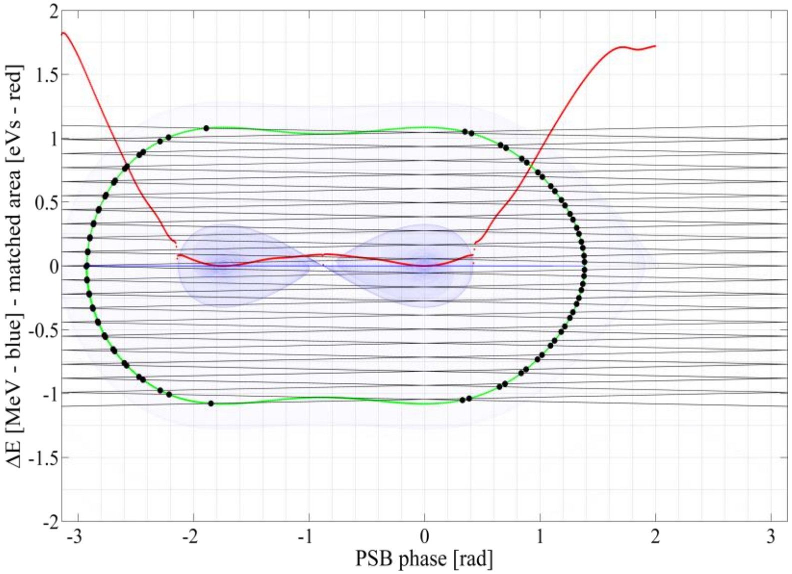

Longitudinal painting
± 1.1 MeV sweep - 2 x (20+20) turns

Simulations set-up

- **Simulations set for future NORMGPS/HRS beams (target 1.3e13 p. and $\varepsilon_x/\varepsilon_y$= 13(15) / 6(8) um)**
  - The multi-turn capture process (~10 ms from injection) has been simulated in PTC-Orbit
  - **'Usual' double RF bucket** with V_{h1}= 8 kV and V_{h2}= 6 kV with $\Delta\phi$=220 deg
  - **Fixed KSW painting function** and **vertical offset** for transverse emittance tailoring as in PSB-MKKSW-EN-0001
  - **Transverse + longitudinal space charge**
  - **80 turns imposed** in **1x(40+40) or 2x(20+20) turns sweep** or **without sweep**
  - **±0.8 MeV** and **±1.1 MeV** sweeping max amplitude
  - **80 keV and 120 keV rms** for the longitudinal painting
  - **450 keV rms (after optimization)** for the un-modulated injection
  - **Variable chopping factor patterns for longitudinal painting** depending on selected target long. emittance contour
- **Figures of merit of the simulation results:**
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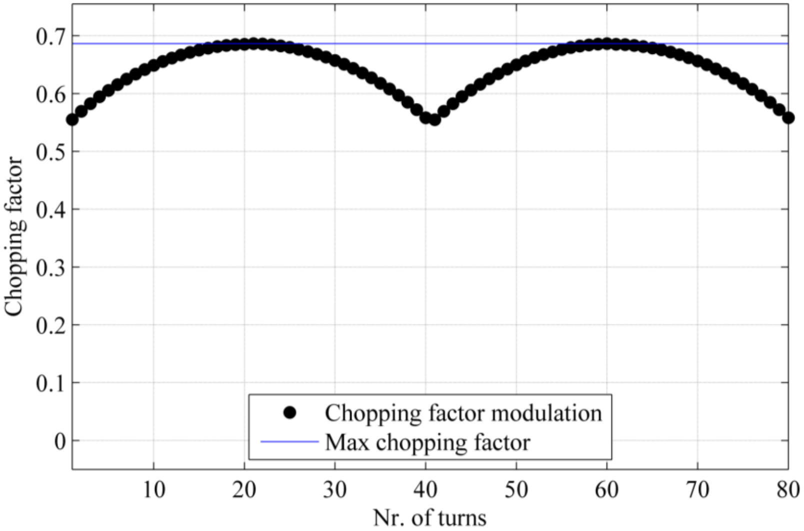
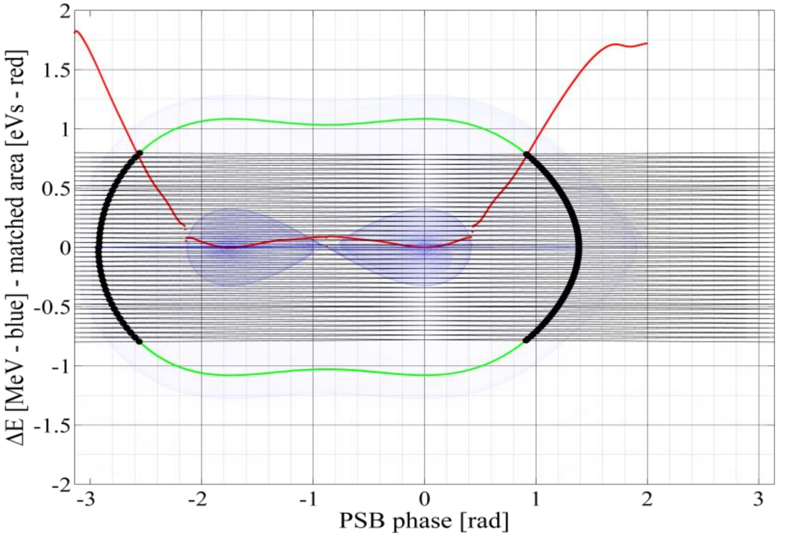
  - **Losses** for activation reasons
  - **Line density / bunching factor** for tr. space charge





Longitudinal painting
± 0.8 MeV sweep - 1 x (40+40) turns

Simulations set-up

- **Simulations set for future NORMGPS/HRS beams (target 1.3e13 p. and $\varepsilon_x/\varepsilon_y$= 13(15) / 6(8) um)**
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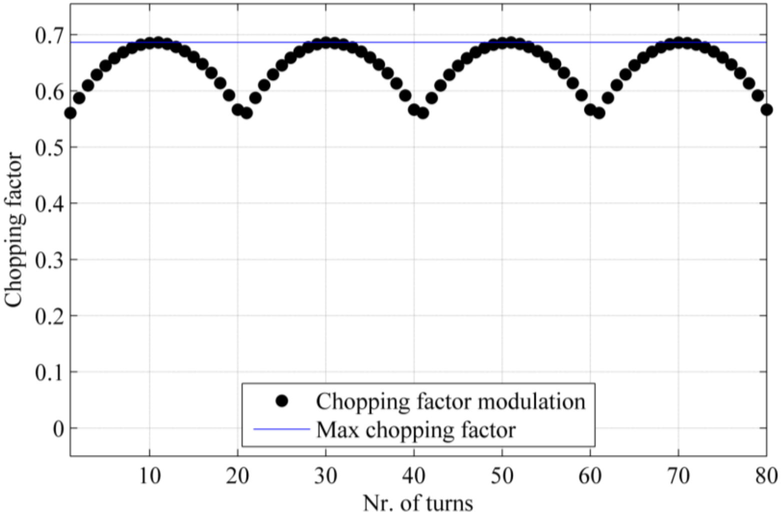
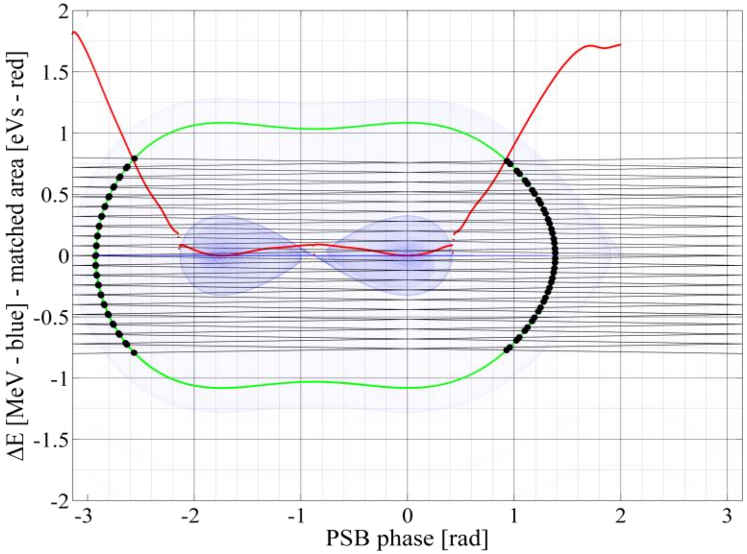


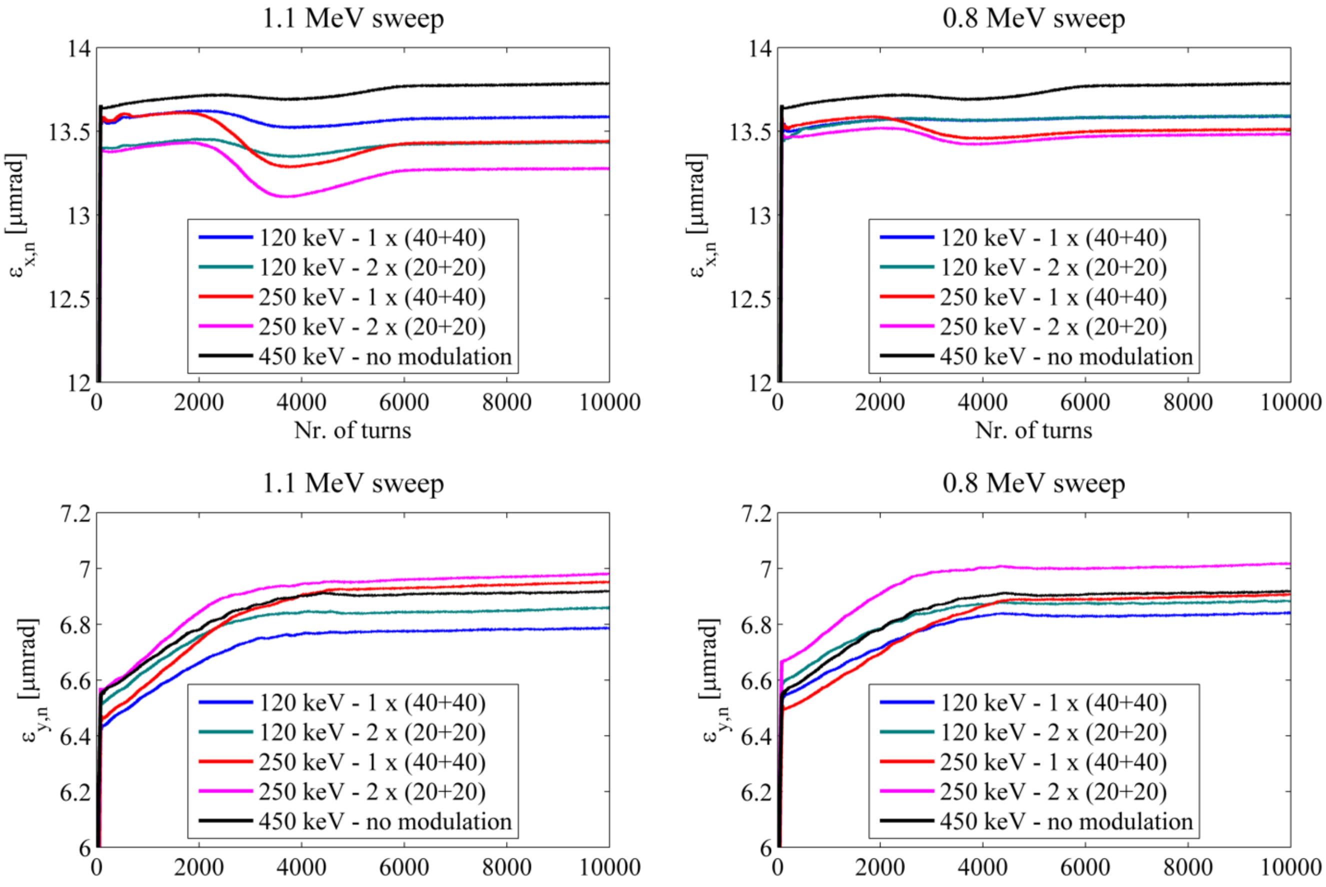


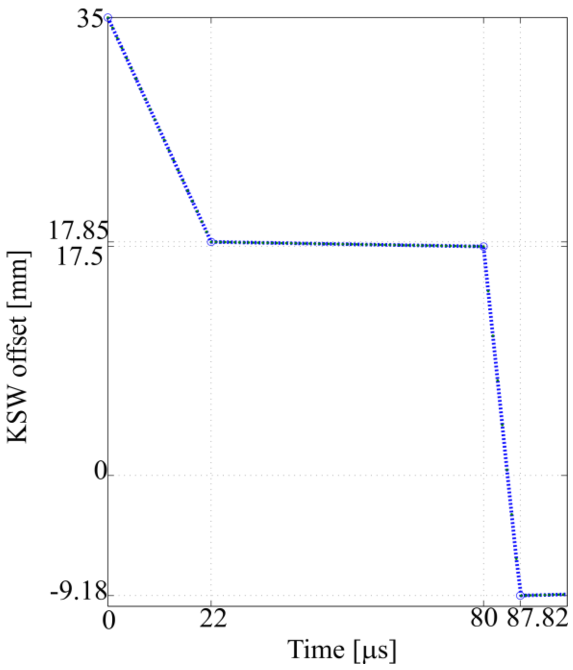
Longitudinal painting
± 0.8 MeV sweep - 2 x (20+20) turns

Simulation results

Transverse emittance

- The NORMGPS beam (I=1.3e13 p.) has **target emittance** of **$\varepsilon_x/\varepsilon_y$= 13(15) / 6(8) μmrad**
- The **transverse emittance is created by the transverse painting** process through the **KSW** (fast) and **BSW** (slow) decay waveforms.
- **The emittances are similar** for the cases **with and without longitudinal painting and in agreement with the required specifications**.

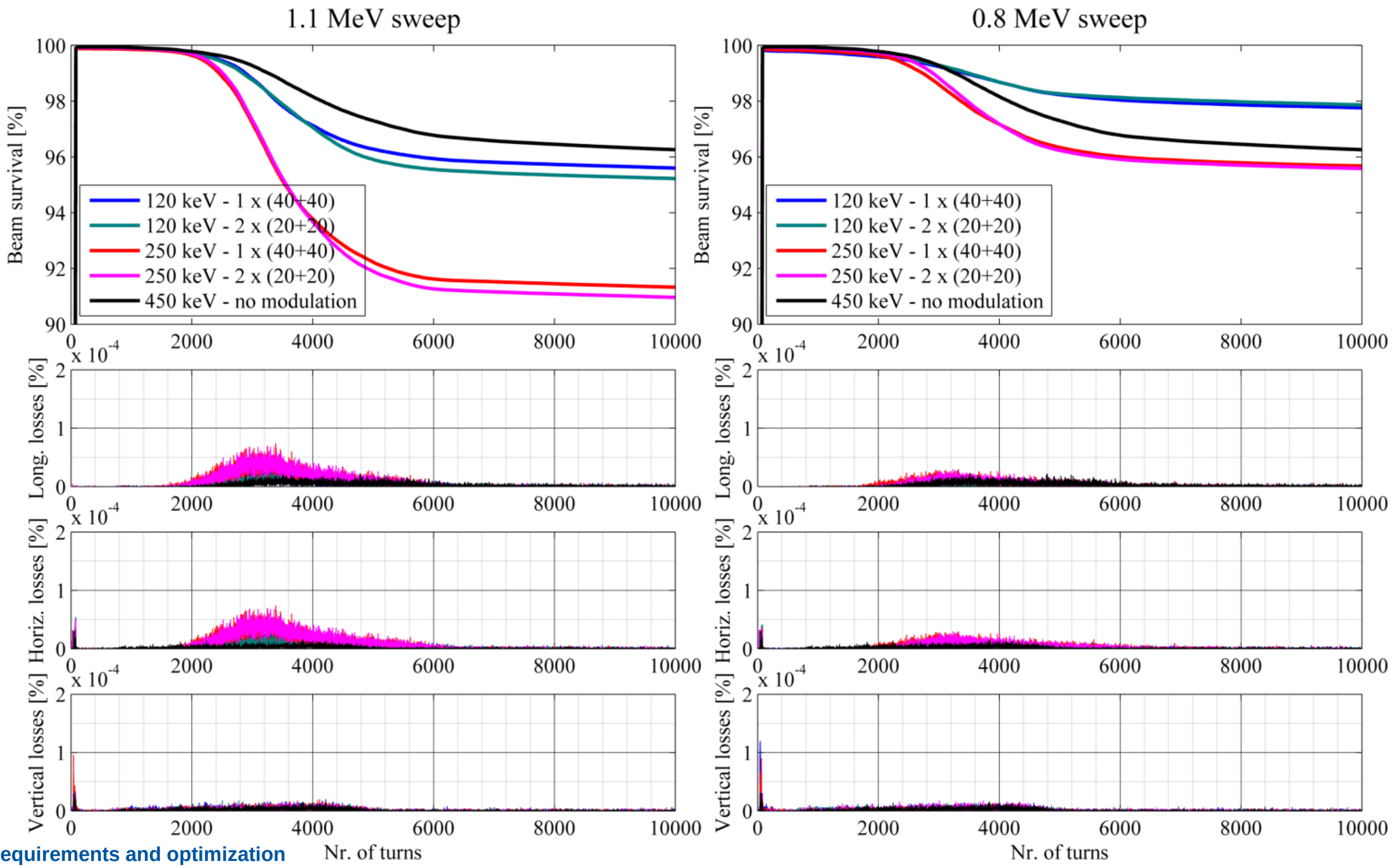




KSW decay waveform adapted for 1 x (40+40) turns (ref. PSB-MKKSW-EN-0001)

Simulation results

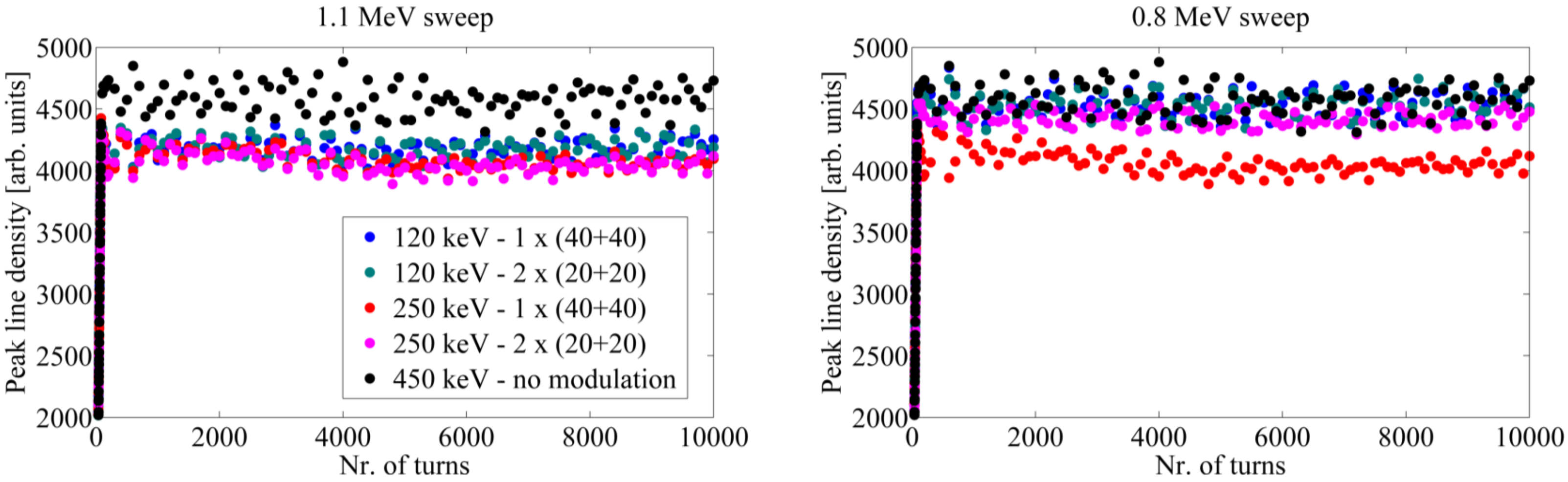
- **Losses**
  - The NORMGPS beam (I=1.3e13 p.) is a high intensity beam → Already few percents of losses (in the machine) can cause RP issues
  - Losses in the simulations are mainly caused by exceeding the longitudinal acceptance and beam loading induced by longitudinal space charge.
  - The results show **an improvement for a reduced amplitude of the sweep** (**0.8 MeV**)



Simulation results

- **Peak line density**
  - An **advantage of the longitudinal painting** is to **lead to a <u>SMALLER</u> peak line density (10%)**, compared to the un-modulated energy case.

$$\Delta Q_y = -\frac{r_0 \lambda}{2\pi e \beta^2 \gamma^3} \oint \frac{\beta_y(s)}{\sigma_y(s)\left[\sigma_x(s)+\sigma_y(s)\right]} ds$$



* See also C. Carli, R. Garoby, Active Longitudinal Painting for the H^- Charge-Exchange Injection of the Linac4 Beam into the PS Booster, CERN, AB-Note-2008-011 ABP

Summary

- Main purpose of the painting is a uniform fill of the iso-Hamiltionian contour for a given matched area. **The longitudinal painting is**, for the PSB, foreseen **for beam intensities ≥ 6e12 ppr.**

- A **'uniformity index'** has been introduced **to optimize** the longitudinal phase space fill.

- **Comparative (full capture) simulations** for the high intensity NORMGPS/HRS beams in the PSB (1e13 ppr) have been performed **for longitudinal painting and un-modulated injection**.

- A parametric scan has been performed for the longitudinal painting for **different sweeping amplitudes rates (0.8 MeV and 1.1 MeV)** , **E_0 change rate (1x(40+40) turns and 2x(20+20 turns))** and **rms energy spreads (120 keV and 250 keV)**

- **The longitudinal painting, compared to the un-modulated injection, for the NORMGPS/HRS beams has shown**:
    - **Transverse emittances in specs → less relevant for ISOLDE beams**
    - **Reduced losses for a reduced sweeping amplitude** with smaller sensitivity with respect to the central energies change rates, but **contour area not fully filled**
    - **Reduced line densities especially for larger sweep → GOOD for space charge mitigation**
    - **Smaller sensitivity of the parameters to the E_0 change rate (**except for a reduced peak line density case 1 x (40+40) and δE=120 keV rms).

Conclusions

- **The longitudinal painting can be an important tool for the PSB: it helps to have more control of the longitudinal phase space**, as done for the transverse painting.

- **The E_0 change rate has shown no major influence in the analysed cases** high intensity ISOLDE beams.
  - **A fast change rate might be needed** if one wants to use the painting **in future for low intensity beams and higher brightness**

- **The energy sweep amplitude depends on the RF bucket shape and on the target longitudinal emittance** that one wants to paint at injection.

- **A small energy spread δE is always helpful (~100 keV rms). A larger one could lead to losses if not associated to a reduced energy sweep amplitude, with risk of un-uniform painting→ trade-off**

- **The difference between longitudinal painting and no energy modulation depends on the iso-Hamiltonian shapes → Triple RF** (idea from E. Benedetto and S. Albright) **could furtherly help with un-modulated injection or** also **in combination with longitudinal painting.**
  - Promising first tests in the PSB

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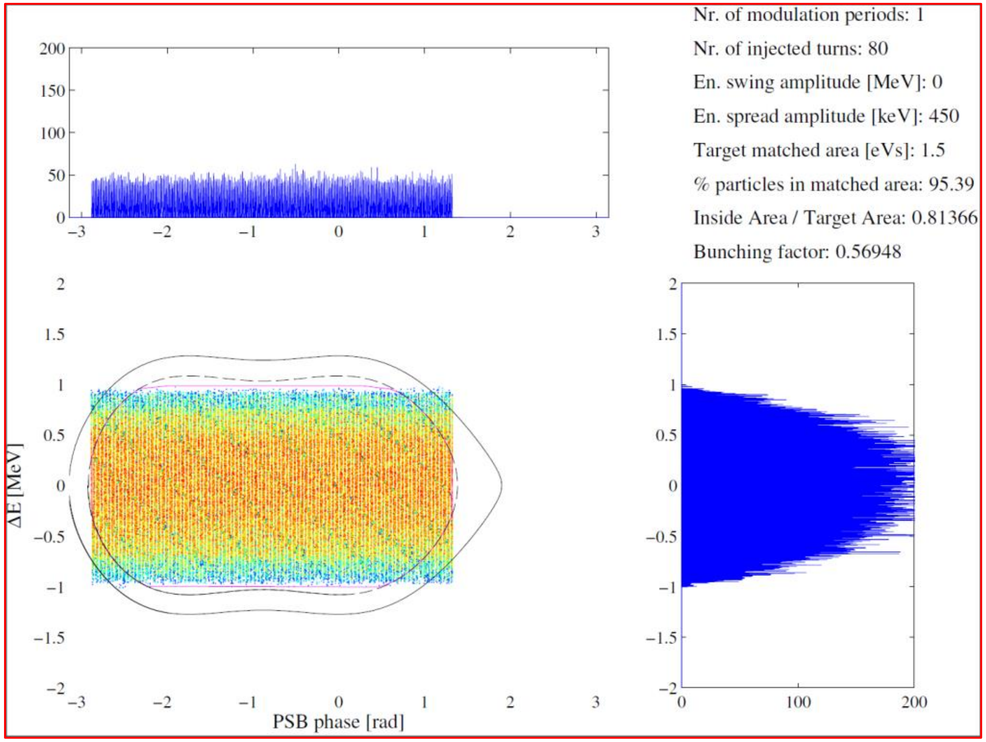
Appendix – total longitudinal distributions used in simulations

- **Un-modulated**



Nr. of modulation periods: 1

Nr. of injected turns: 80

En. swing amplitude [MeV]: 0

En. spread amplitude [keV]: 450

Target matched area [eVs]: 1.5

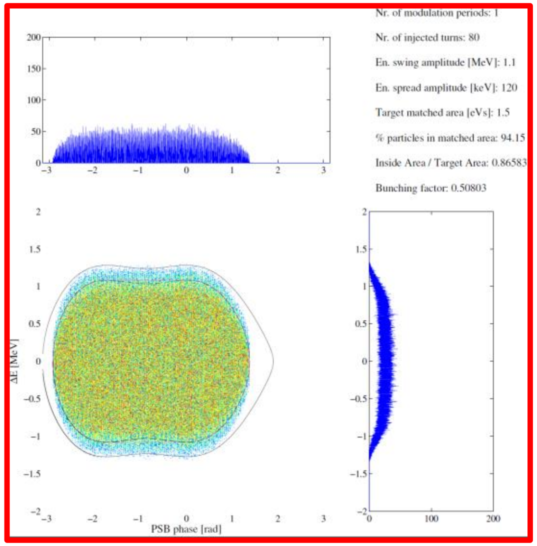
% particles in matched area: 95.39

Inside Area / Target Area: 0.81366

Bunching factor: 0.56948

Appendix – total longitudinal distributions used in simulations

Modulated 1.1 MeV sweep amplitude



Nr. of modulation periods: 1

Nr. of injected turns: 80

En. swing amplitude [MeV]: 1.1

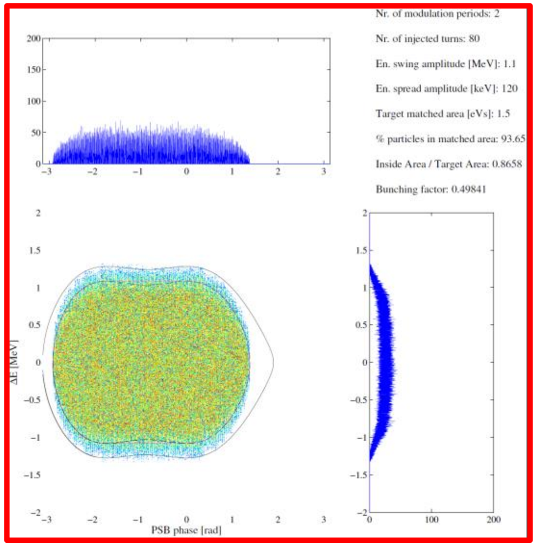
En. spread amplitude [keV]: 120

Target matched area [eVs]: 1.5

% particles in matched area: 94.15

Inside Area / Target Area: 0.86583

Bunching factor: 0.50803



Nr. of modulation periods: 2

Nr. of injected turns: 80

En. swing amplitude [MeV]: 1.1

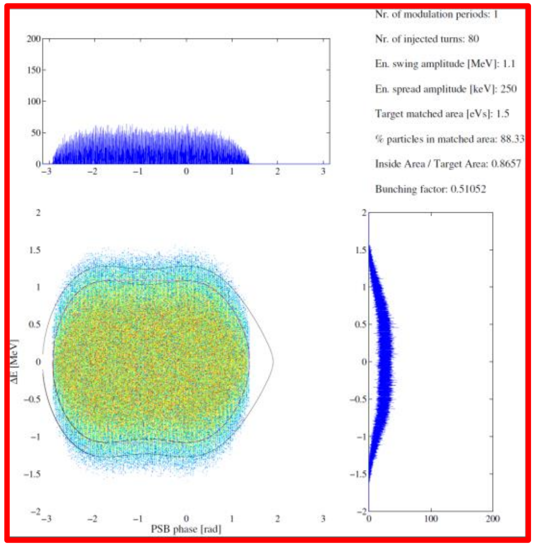
En. spread amplitude [keV]: 120

Target matched area [eVs]: 1.5

% particles in matched area: 93.65

Inside Area / Target Area: 0.8658

Bunching factor: 0.49841



Nr. of modulation periods: 1

Nr. of injected turns: 80

En. swing amplitude [MeV]: 1.1

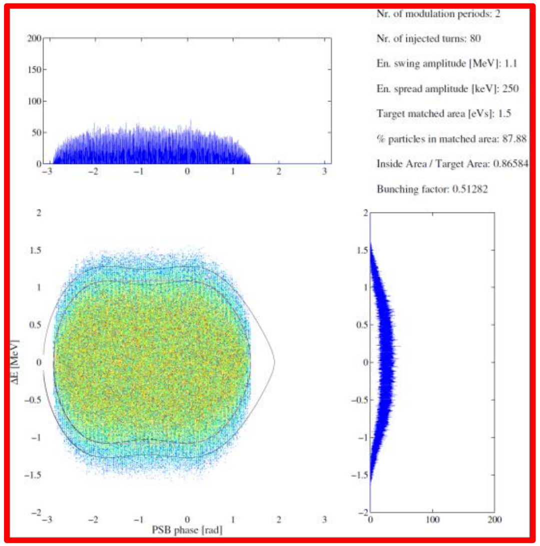
En. spread amplitude [keV]: 250

Target matched area [eVs]: 1.5

% particles in matched area: 88.33

Inside Area / Target Area: 0.8657

Bunching factor: 0.51052



Nr. of modulation periods: 2

Nr. of injected turns: 80

En. swing amplitude [MeV]: 1.1

En. spread amplitude [keV]: 250

Target matched area [eVs]: 1.5

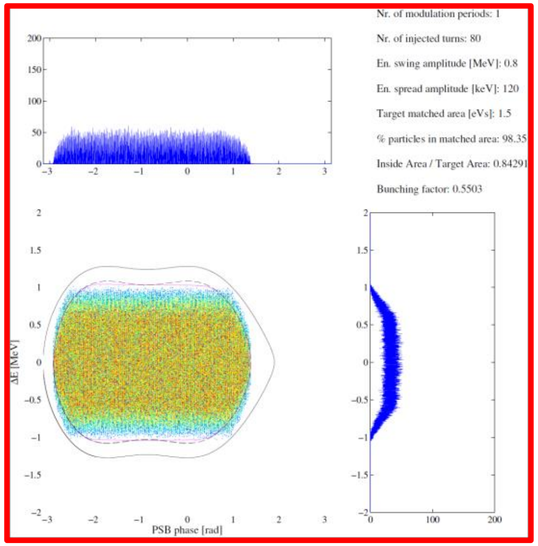
% particles in matched area: 87.88

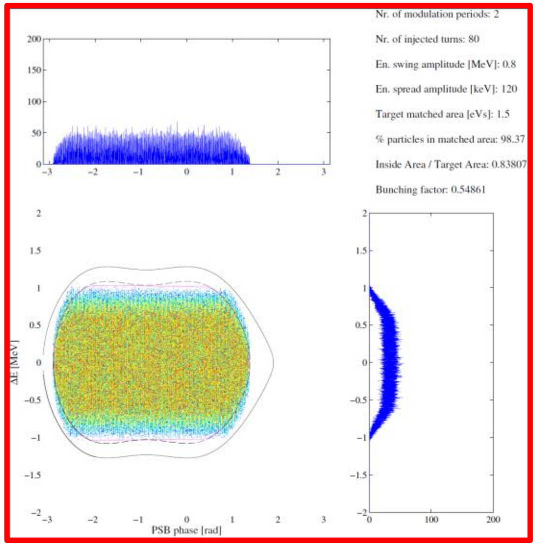
Inside Area / Target Area: 0.86584

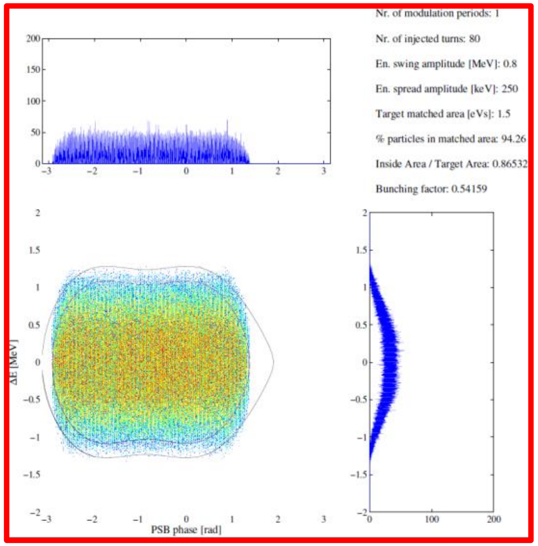
Bunching factor: 0.51282

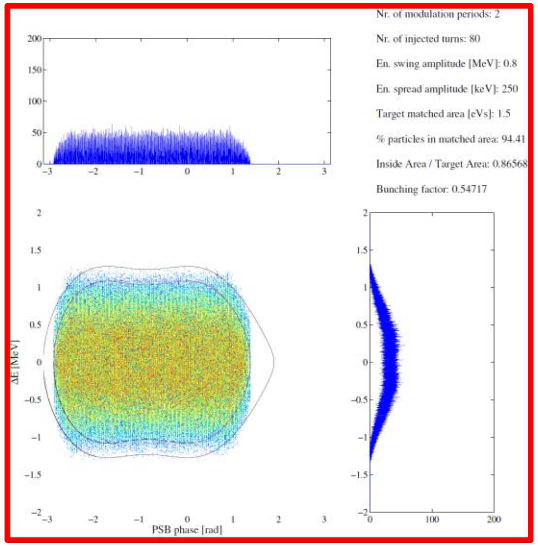
Appendix – total longitudinal distributions used in simulations

- **Modulated 0.8 MeV sweep amplitude**


Nr. of modulation periods: 1
Nr. of injected turns: 80
En. swing amplitude [MeV]: 0.8
En. spread amplitude [keV]: 120
Target matched area [eVs]: 1.5
% particles in matched area: 98.35
Inside Area / Target Area: 0.84291
Bunching factor: 0.5503


Nr. of modulation periods: 2
Nr. of injected turns: 80
En. swing amplitude [MeV]: 0.8
En. spread amplitude [keV]: 120
Target matched area [eVs]: 1.5
% particles in matched area: 98.37
Inside Area / Target Area: 0.83807
Bunching factor: 0.54861

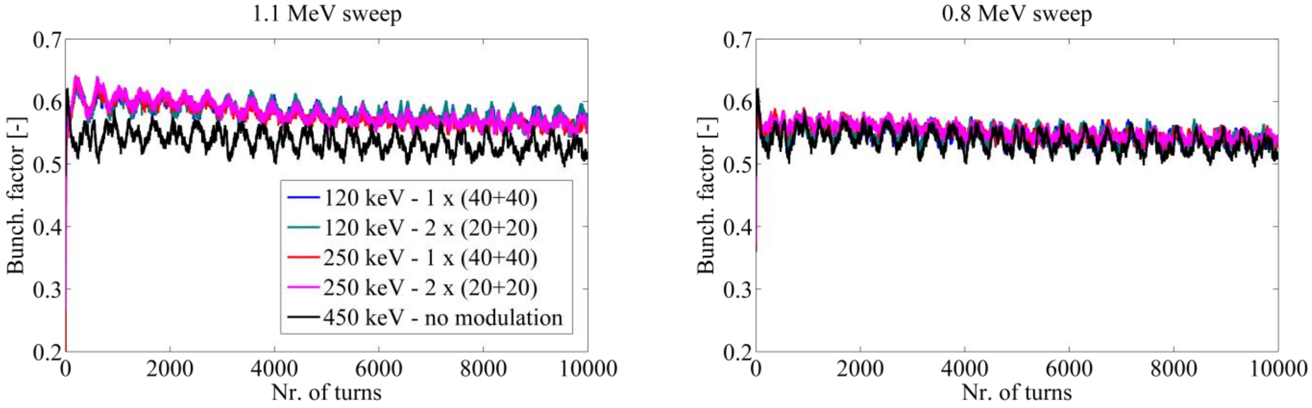

Nr. of modulation periods: 1
Nr. of injected turns: 80
En. swing amplitude [MeV]: 0.8
En. spread amplitude [keV]: 250
Target matched area [eVs]: 1.5
% particles in matched area: 94.26
Inside Area / Target Area: 0.86532
Bunching factor: 0.54159

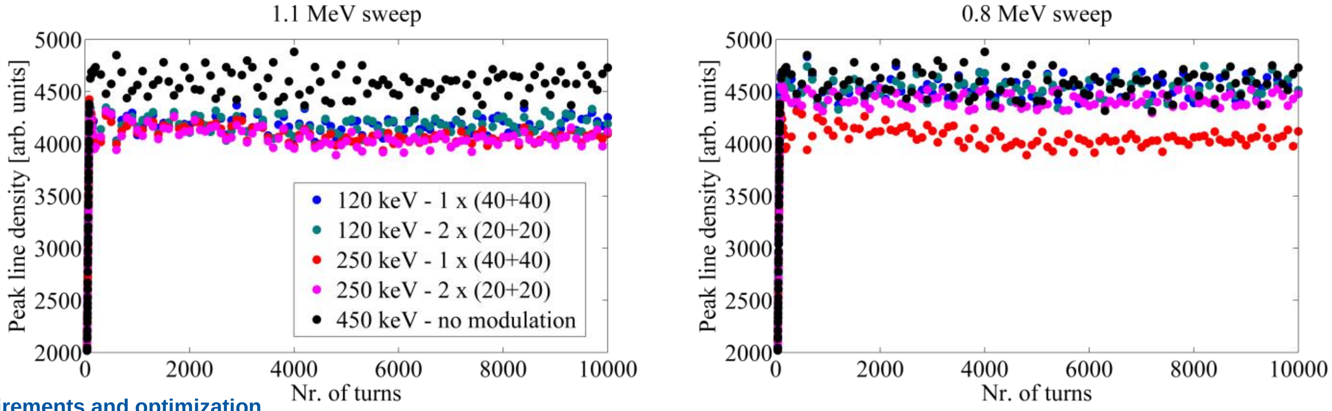

Nr. of modulation periods: 2
Nr. of injected turns: 80
En. swing amplitude [MeV]: 0.8
En. spread amplitude [keV]: 250
Target matched area [eVs]: 1.5
% particles in matched area: 94.41
Inside Area / Target Area: 0.86568
Bunching factor: 0.54717

Simulation results

- **Bunching factor and peak line density**
  - An **advantage of the longitudinal painting** is to **lead to an higher bunching factor**, **with reduced beating**, and **a smaller peak line density**, compared to the un-modulated energy case.
  - Simulations showed an increase of the bunching factor (and a decrease of the peak line density λ) of a factor **up to ~10% for large sweeps (1.1 MeV) *→ Potential benefit for reduced space charge tune spread in higher brightness beams.**

$$\Delta Q_y = -\frac{r_0 \lambda}{2\pi e \beta^2 \gamma^3} \oint \frac{\beta_y(s)}{\sigma_y(s)\left[\sigma_x(s)+\sigma_y(s)\right]} ds$$





* See also C. Carli, R. Garoby, Active Longitudinal Painting for the H$^-$ Charge-Exchange Injection of the Linac4 Beam into the PS Booster, CERN, AB-Note-2008-011 ABP

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