Longitudinal Painting for a PSB H^- Injection

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- H^- injection at other places around the world
- Basic facts and considerations for Linac 4 and PSB
  - Bunching factor and d(Bρ)/dt
  - Painting and finite dispersion at PSB injection
  - Effect of d(Bρ)/dt energy of "synchronous particle"
- Schemes investigated:
  - Three energy slices
  - Painting with fast sinusoidal energy modulation
  - Painting with slow sinusoidal energy modulation
  - Triangular energy modulation
- Energy modulation
- Summary and Outlook

Acknowledgements:

Based on many discussions with R. Garoby, Frank, Giulia, Alessandra, Michel …

H^- injection at other places around the world

Collect information to avoid "re-inventing the wheel" !

- PDAC:
  - Injection lasts several (~9) synchrotron revolutions,
  - Synchrotron motion used for azimuthally smoothing,
  - Not applicable for PSB case (no way to inject over several synchroton periods).
- SNS:
  - Rather awkward longitudinal distributions in some papers (on transverse painting), but relatively smooth bunch shape,
  - Only $\frac{1}{4}$ of a synchrotron period for bunch shortening:
    - "Funny" bunch shape, but beam kept only very shortly (compared to pseudoadiabatic capture).
  - Though about a "energy spreader" cavity !.
- J-PARC:
  - First glance similarities with H- injection into the PSB (Injection energy, …),
  - Lasts several synchrotron oscillations (many turns, high RF voltage, harm.) !!

Conclusion:

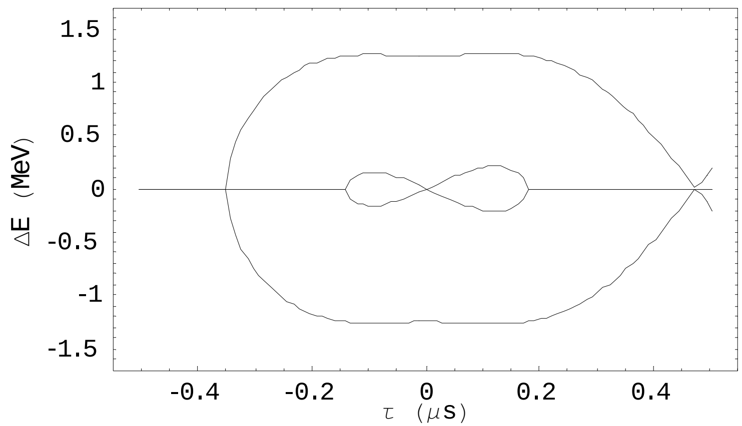
- H- injection into PSB: somehow unique case for painting:
  - No way to profit from synchrotron motion for longitudinal painting.

Basic Facts and Considerations

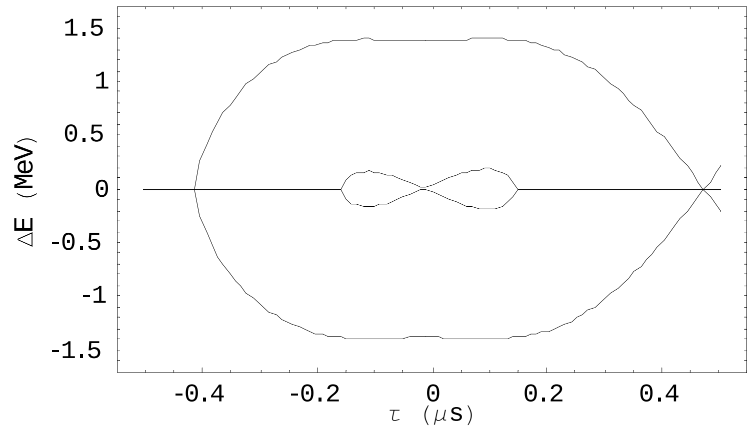
- Longitudinal acceptance, emittance …… (cf F. Pedersen):
  - Aim: Favorable (large) bunching factor for "small" tune spread
  - Acceleration with full bucket and maximum RF voltage (i.e. large emittance):
    - For a given emittance: best bunching factor with acceptance just sufficient for emittance
    - Larger emittance (and RF voltage) results in smaller φ_s, larger bunching factor and smaller tune spread
  - Bdot a compromise between bunching factor and time spent at low energy:
    - Small Bdot -> smaller tune spread, but long time at low energy,
    - Large Bdot -> larger tune spread during a shorter time.
- $\partial B\rho/\partial t$ at injection:
  - Present situation (protons injected at 50 MeV):
    - Injection on ramp with $\partial B\rho/\partial t$ = 4.0 Tm/s,
    - Passage at 160 MeV with $\partial B\rho/\partial t$ = 10 Tm/s,
    - Maximum ramp $\partial B\rho/\partial t$ > 16.0 Tm/s (higher for 900 ms cycle ?)
  - Expectation for H^- for Linac 4:
    - $\partial B\rho/\partial t$ = 10 Tm/s is upper limit,

Basic Facts and Considerations

- Bucket for maximum voltage ($V_{h=1}$ = 8kV, $V_{h=2}$ = 5kV) and expected $\partial B\rho/\partial t$:



$\partial B\rho/\partial t$ = 10 Tm/s $\Delta\varphi$ = 203 deg



$\partial B\rho/\partial t$ = 5 Tm/s $\Delta\varphi$ = 191 deg

- Little, but not negligible motion in longitudinal phase space:
  - No way to get painting for free from synchrotron motion,
  - ➢ "Active" (energy variation –amplitude ≈≥1.2MeV- and chopping) painting needed !
  - ➢ Necessary Amplitude of energy variation : ~± 1.2 MeV
  - ➢ Attention: Acceptance of the transfer line !!
  - Synchrotron motion may lead to local density increases/increases,
  - Avoid slow painting in one direction (e.g. energy monotonously increasing) only

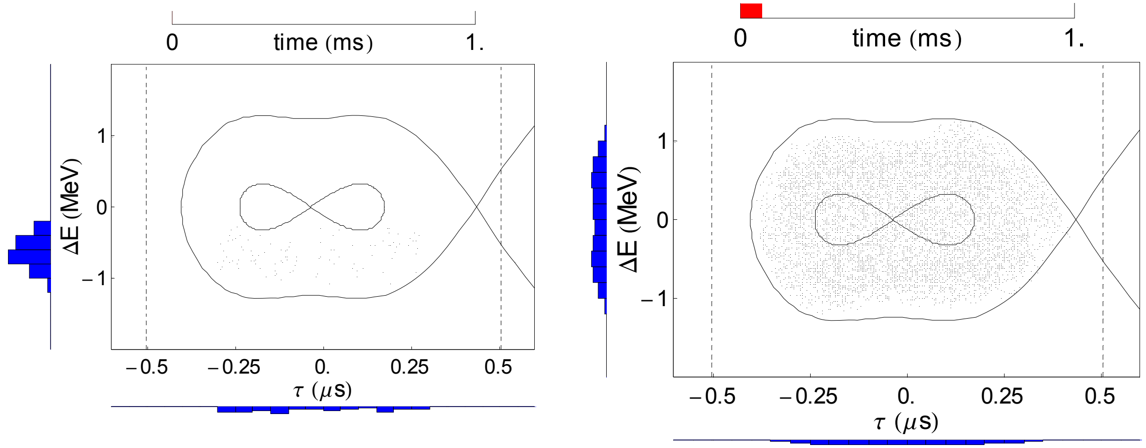
Basic Facts and Considerations

- Energy of "synchronous particle increases during injection:
  - During 100 turns (high intensity) with $\partial B\rho/\partial t$ = 10 Tm/s : ≈156 MeV
  - Adds to needs for energy modulation for injection inro one ring,
  - Ring to ring variations compensated with "Bdl"s (orbit perturbations ~1mm).
- Dispersion in injection straight section:
  - in case the injected beam arrives with D=0m (and D'=0):
    - full bucket height: ~2 MeV,
    - rms momentum spread after injection: $\frac{\sigma_p}{p} \approx \frac{1}{\beta_{rel}^2} \frac{2\,MeV/5}{(938.27+160)MeV} \approx 1.3 \bullet 10^{-3}$
    - horizontal emittance blow-up: $\Delta\varepsilon_{rms}^* \approx \beta_{rel}\,\gamma_{rel}\,\frac{1}{2}\frac{(D\,(\sigma_p/p))^2}{\beta_{Twiss}} \approx 0.2\,\mu\mathrm{m}$
    - May be acceptable (thus injected beam arriving with D=0m may be o.k.)
    - Better be careful (previous computation led to opposite result) !!
    - ➢ matched D at injection -> larger beam, more foil hits … !?
- Number of injected turns:
  - Painting in three phase spaces with only 9 injected turns (actual figure for LHC) ?
  - Are in-homogeneities (unavoidable painting with few turns) a problem ?
  - Lengthen injection (at least for low intensities) ?

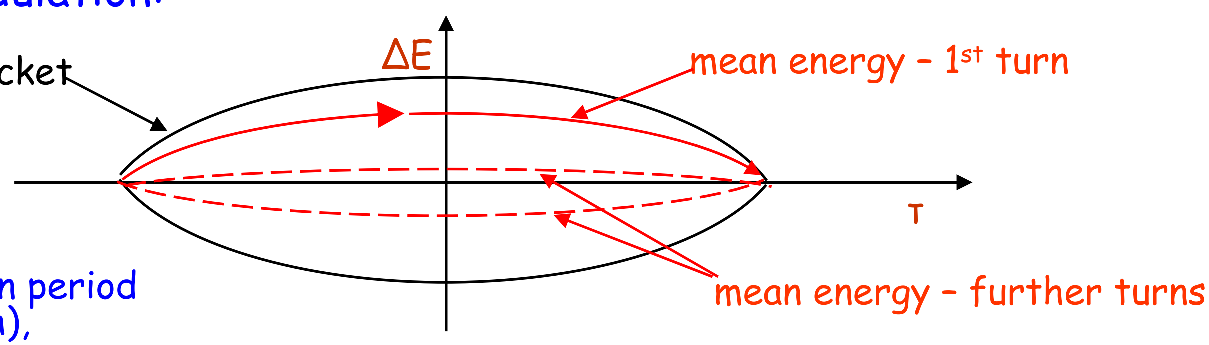
➢ Painting in all three phase spaces for H^- in PSB a non-trivial problem:
  - ➢ Keep conventional pseudo-adiabatic capture as plan B.

Schemes investigated

- Three energy slices:



  - Simple (robust) scheme:
  - Just three different energies to be delivered,
  - Reasonably smooth (better than pseudo-adiabatic bunching) filling of the bucket.
  - Abandoned: energy modulation out of reach for Linac 4
- Fast sinusoidal energy modulation:
  - Aimed at painting the bucket border,



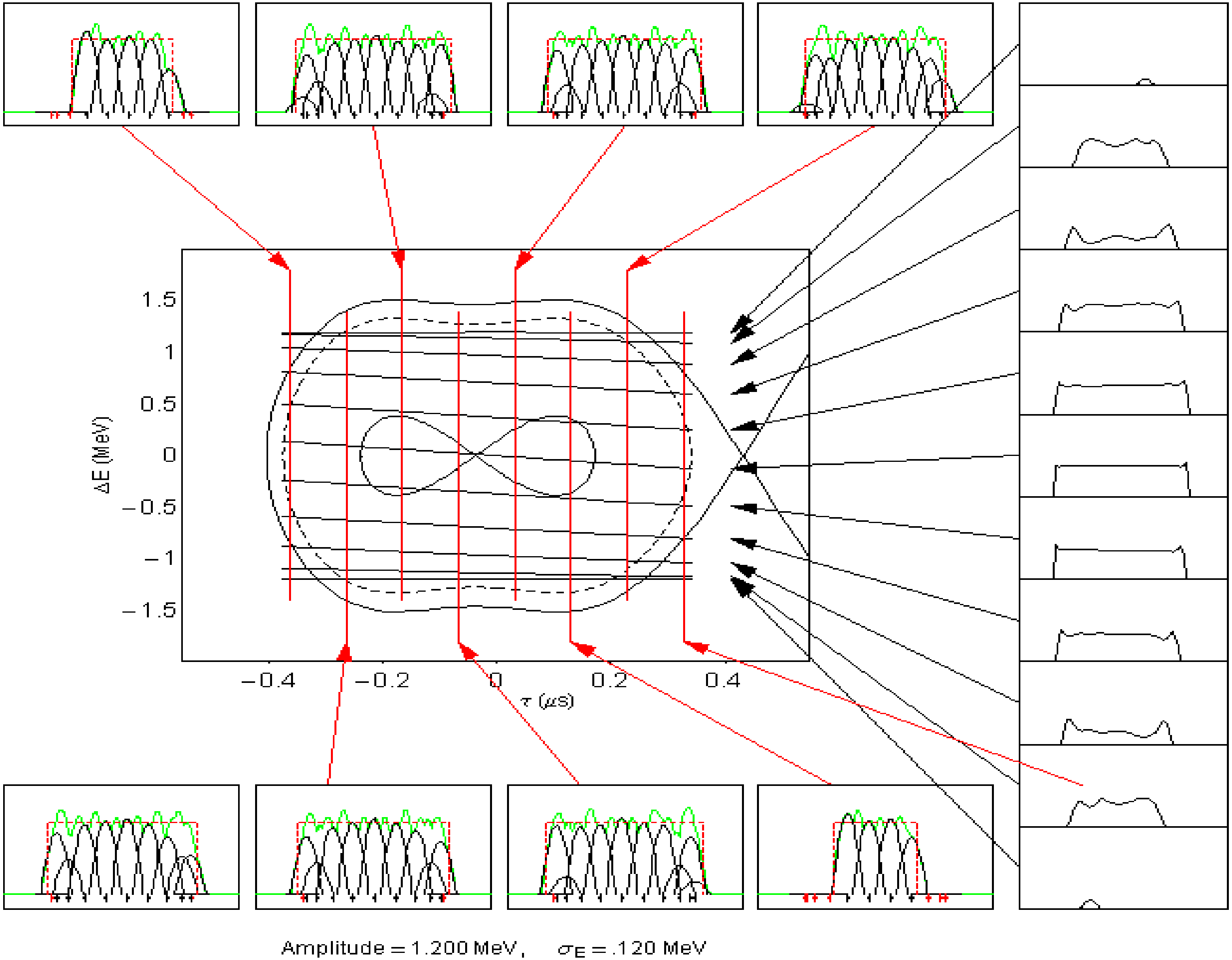
  - Abandoned:
    - Restrictive (modulation period matches bucket length),
    - Creation of the energy modulation

Schemes investigated

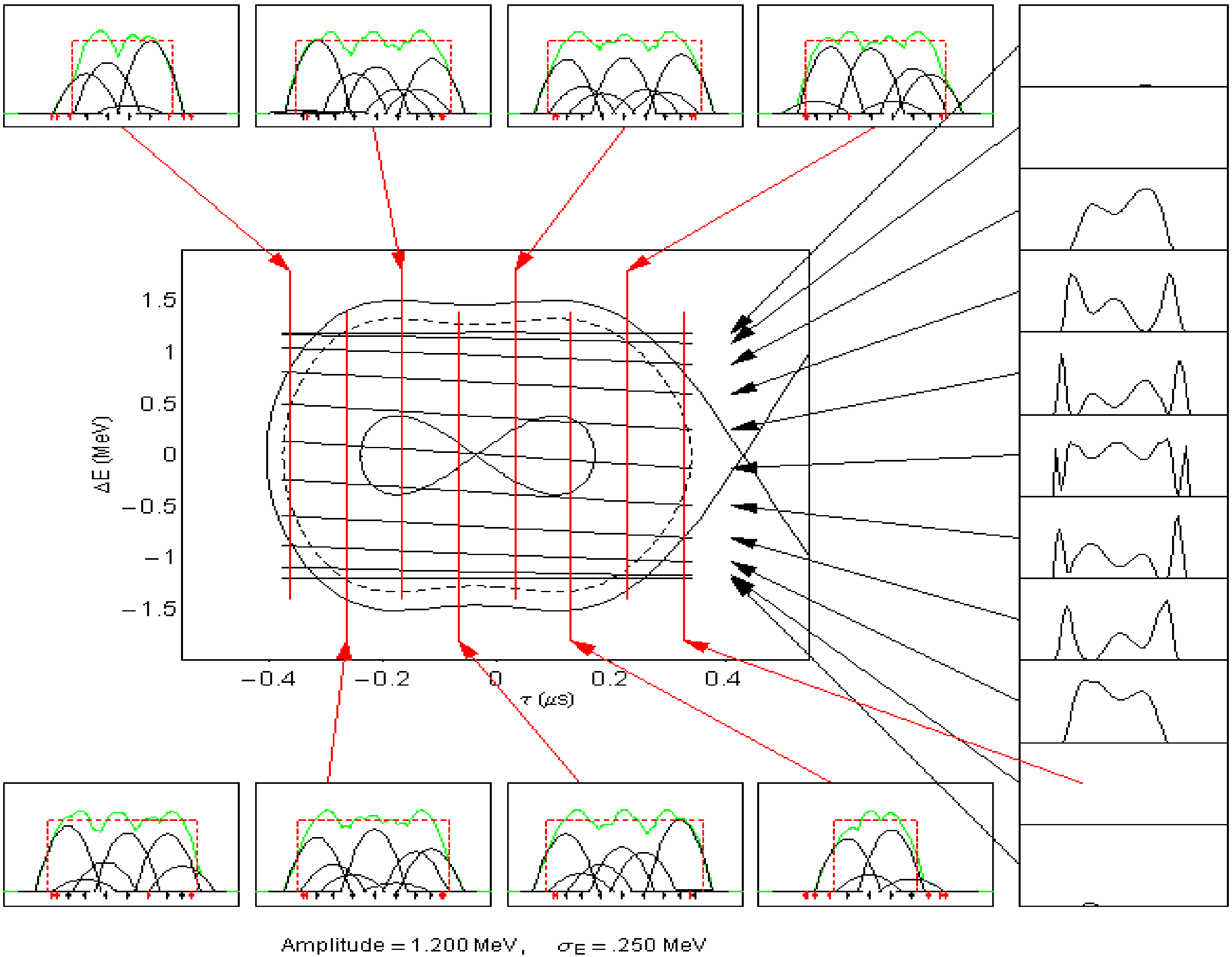
(Slow Sinusoidal energy modulation)

- Initial idea:
  - Slow sinusoidal energy modulation:
    - Say one modulation period takes 20 PSB revolutions (e.g. instead of 9 turns for LHC beams),
  - Algorithm to compute which bunches are taken and which are kicked out by chopper.
- Approach:
  - For fixed longitudinal position,
    - Energy offset at different turns given,
    - Aim at painting a given fraction (say 80%) of the acceptance homogeneously
  - First step: current versus time curves (to be translated into bunch structure –giving right mean current vs time- later)
- Result (plots on following pages):
  - Looks reasonable at a first glance:
    - critical at bucket borders and for large σ_E
- Abandoned
  - How to generate energy modulation?

Schemes investigated
(Slow Sinusoidal energy modulation)

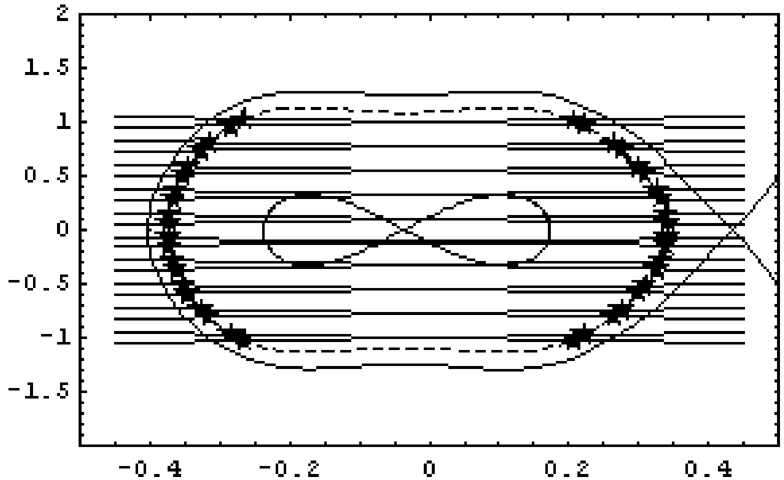


Schemes investigated
(Slow Sinusoidal energy modulation)



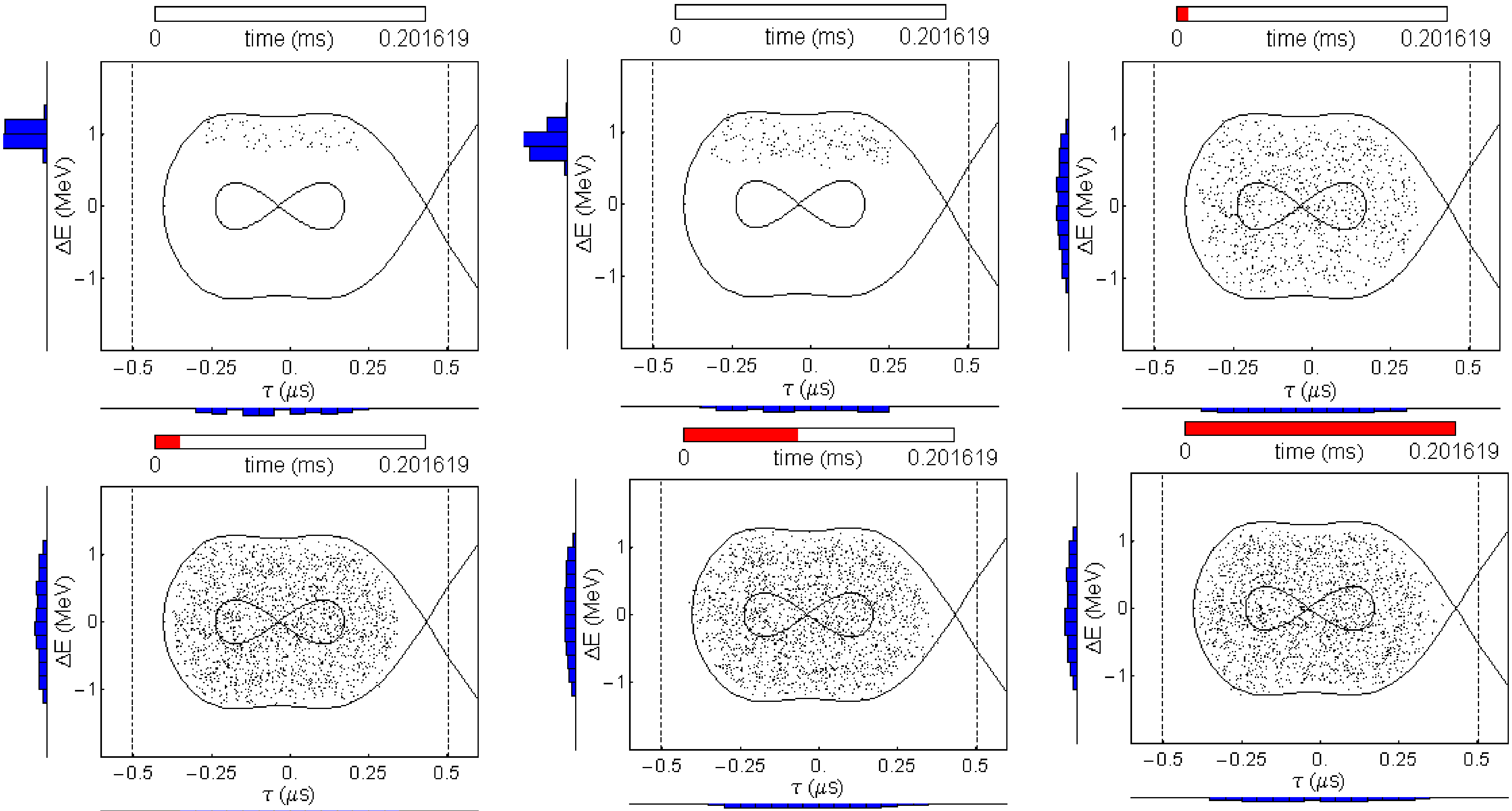
Schemes investigated
(Triangular)

- Motivation:
  - initial ideas (see below) on energy ramping ruled out,
  - linear ramp (energy vs time):
    - "simple" for generation of E modulation,
    - turn-by-turn equidistance.
  - Switching the beam on/off inside/outside a contour (for present simulations 80% of acceptance) in longitudinal phase space



- Result:
  - Only promising scheme (in simulations without direct space charge),
  - Further simulations (see last slide).

Schemes investigated
(Triangular Energy Modulation)



Longitudinal phase after 1, 2, 10, 20 (end of injection), ~100 and 200 revolutions

Energy Modulation

- Slow sinusoidal modulation based on:
  - Ramping just after Linac 4: Sinusoidal phase modulation at debuncher,
  - Ramping after debuncher: ramping disturbs debunching
  - ➢ No way – find another scheme !
  - ➢ Rule out envisaged painting schemes !
- Phase modulation (like Linac 3 ramping for LEIR):
  - Needs: ~1.2 MV in 10 μs (LEIR ~0.1 MV in 200 μs),
  - Energy modulation cavity:
    - Say cavity right after Linac with amplitude A_U = 2.4 MV,
    - ±1.2 MV corresponds to ±30 deg (60 deg phase shift in 10 μs),
    - Ramp up down corresponds to frequency offsets of $\Delta f \approx \pm 17$ kHz.
  - Debuncher (distance l downstream):
    - $\Delta E = \pm 1.2$ MV $\rightarrow \Delta t = (1.89 \cdot 10^{-11}$ s/m) l $\rightarrow \Delta\varphi = 2.39$ deg/m
    - Very likely to be a limitation (showstopper ?): compromise between distance and maximum phase excursion !!
    - Phase excursion $< \pm 60$ deg ($\Delta f < 35$kHz) -> $l < 20$m
  - Giulia and Alessandra are looking into this !

Summary and Outlook

- Summary:
  - H- injection into PSB somewhat unique for long. painting,
  - Injection with dispersion and (very likely) Bdot,
  - Several schemes investigated,
  - Slow triangular energy modulation most promising.
- Next:
  - How to generate energy modulation (is linear ramp feasible ?),
  - Include space charge (how ?, ESME suitable ? …),
  - Energy jitter:
    - Pulse to pulse or bunch to bunch (quantify with Energy modulation) ?
    - Can PSB phase loop compensate a pulse to pulse jitter ?
  - Add transverse phase space:
    - effect of dispersion (resulting emittance blow-up, correlation between horizontal and vertical phase space),
    - number of injected turns and painting in 6D phase space,
    - consequences for stripping foil … ,
  - Injection line with energy modulation:
    - acceptance,
    - dispersion (horizontal AND vertical), chromatic effects …