Intensity Increase in the LER

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FNAL

- ***Motivation***
- ***Slip stacking in the Main Injector***
- ***Constraints on LER slip stacking***
- ***Preliminary slip stacking simulations (ESME)***
- ***Preliminary conclusions***

Special thanks to Jim MacLachlan (FNAL)

Motivation

SPS upgrade - allows an increase in injection energy and intensity.

LER - increases the injection energy. Intensity?

Intensity Increase

- SPS is intensity limited to the present value due to impedances, electron cloud, space charge, …
- LHC is very sensitive to beam losses, rules out the possibility of intensity increase in the LHC.
- Is it possible to increase the bunch intensity in the LER ?

Benefit

$$\text{Luminosity} \sim M N_b^2$$

Methods to increase bunch intensity

- *Bunch coalescing*

  Used to coalesce 2 or more bunches in adjacent buckets. The LHC bunch structure has a 10 bucket gap between bunches – lots of "white space" to be filled in

- *Momentum stacking*

  Used in the Accumulator to increase pbar intensity. Requires a large momentum aperture – beam is injected away from the reference orbit and then accelerated to the reference orbit.

- *Slip stacking*

  Used in the FNAL Main Injector. 2 batches at slightly different energies are brought together into 1 batch.

Slip stacking schematic

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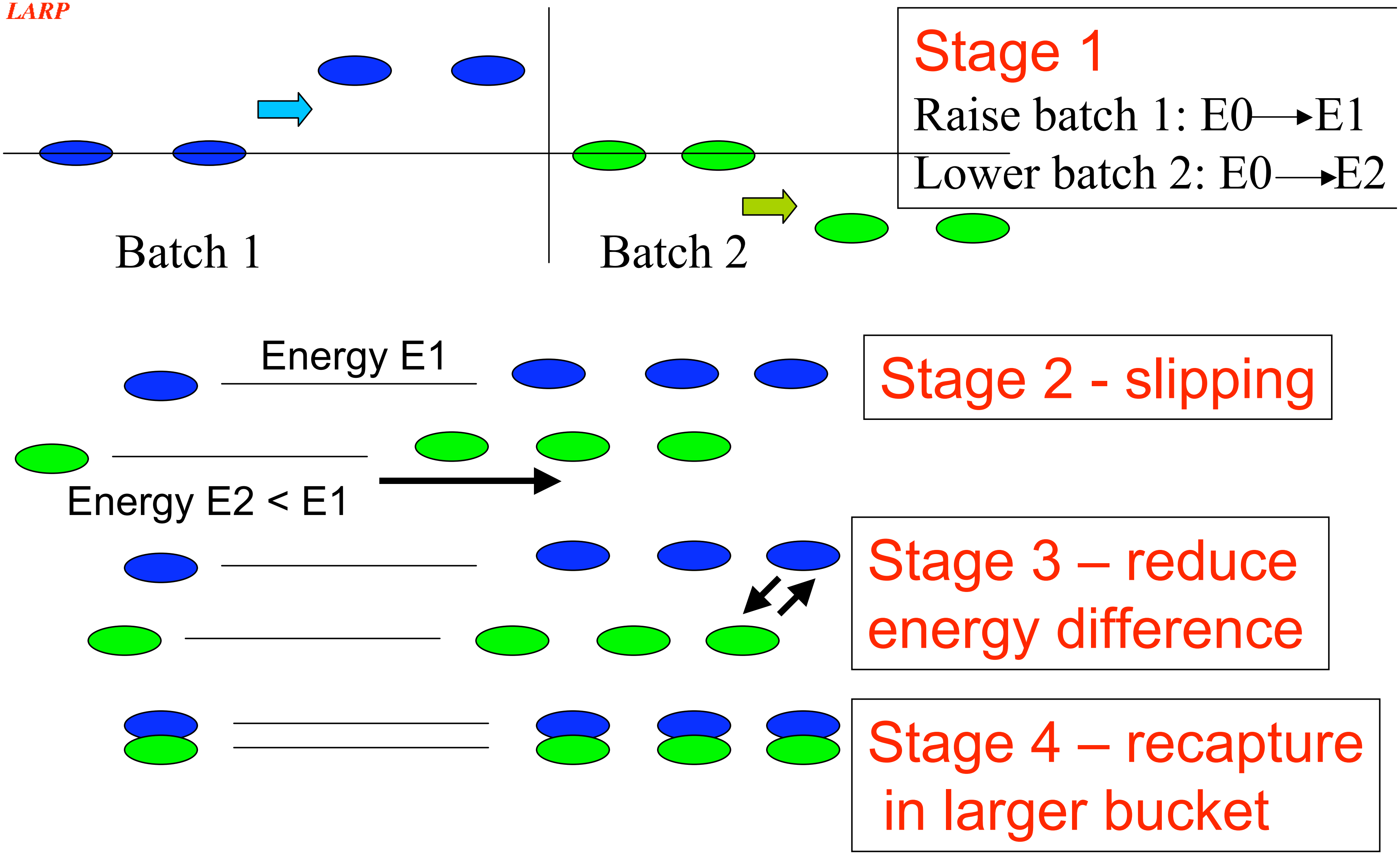


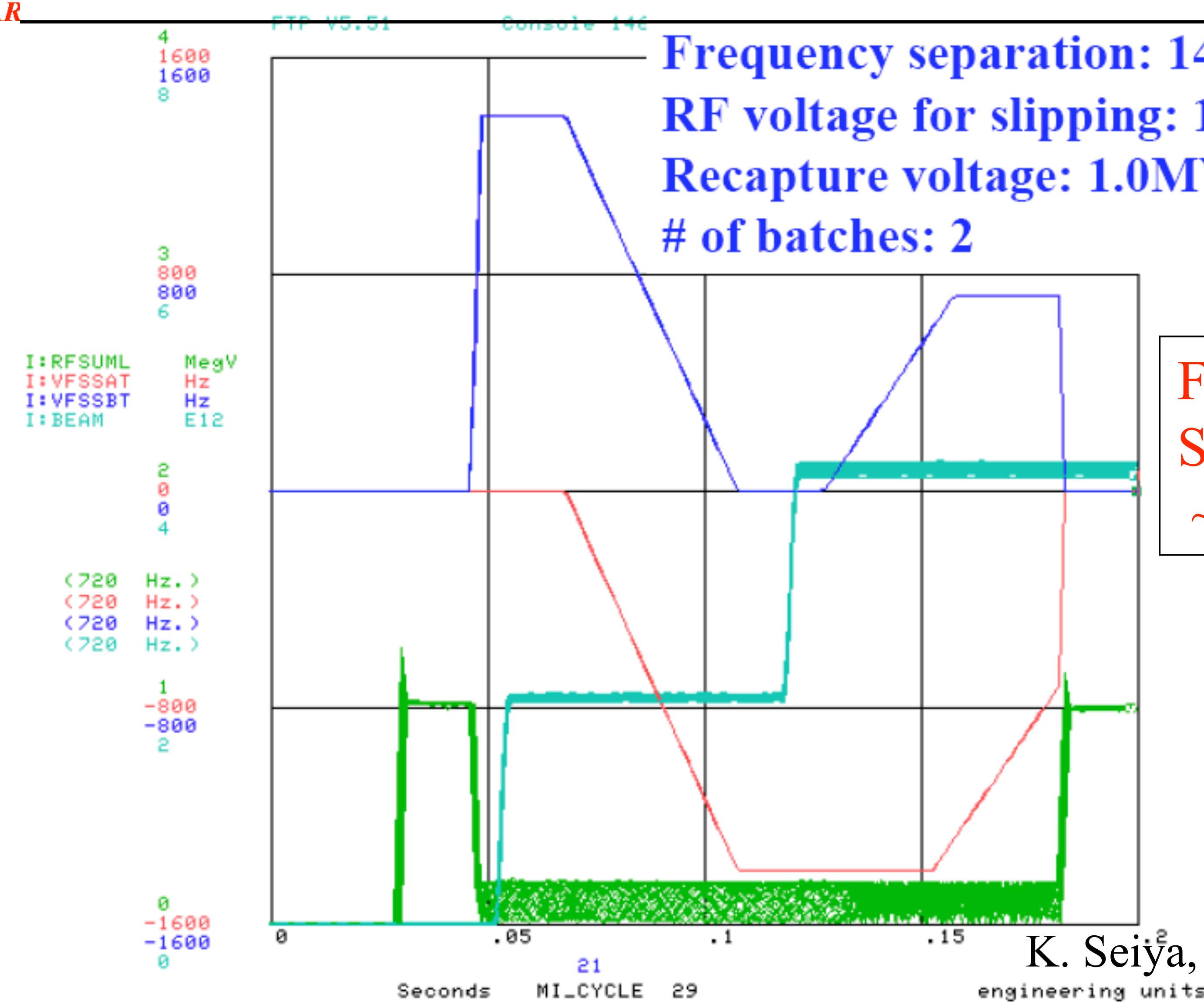
Frequency Curves - FNAL Main Injector

Frequency separation: 1400Hz

RF voltage for slipping: 110kV for each

Recapture voltage: 1.0MV

# of batches: 2



Frequency Separation ~ 5 fs

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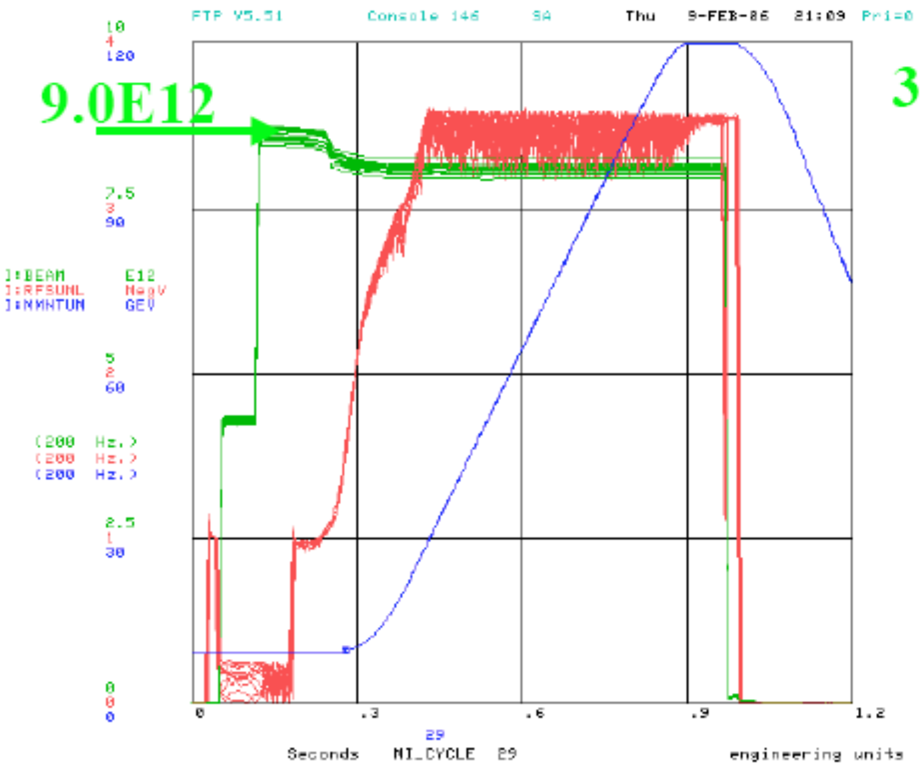
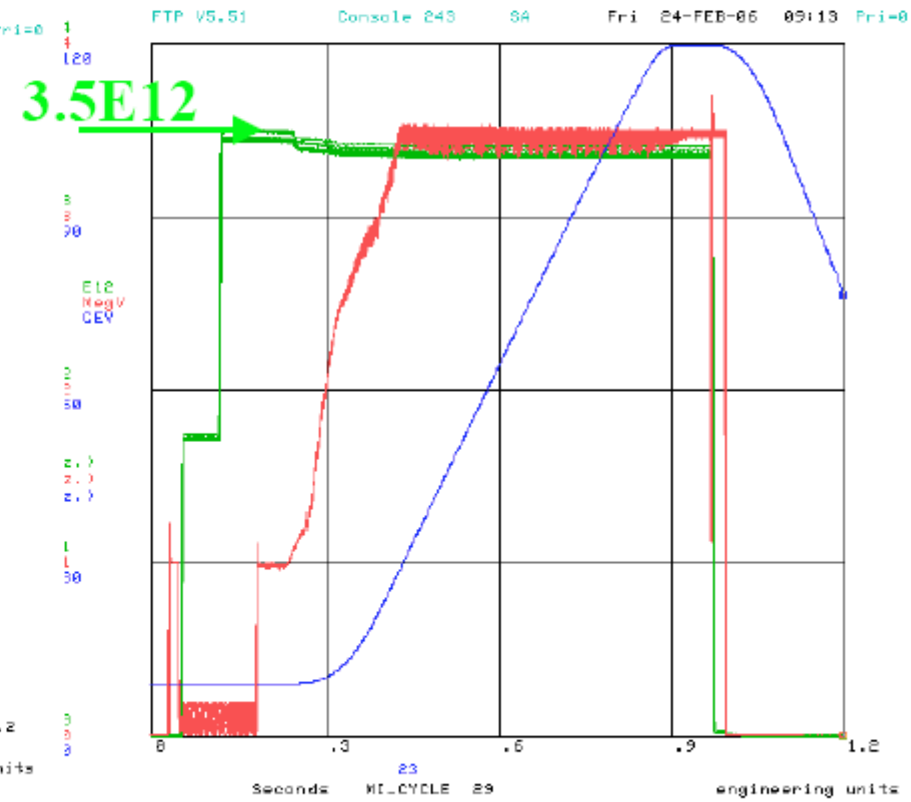
Losses during slip stacking (FMI)

High intensity(~6.5%Loss)	Low intensity(~2.5%Loss)





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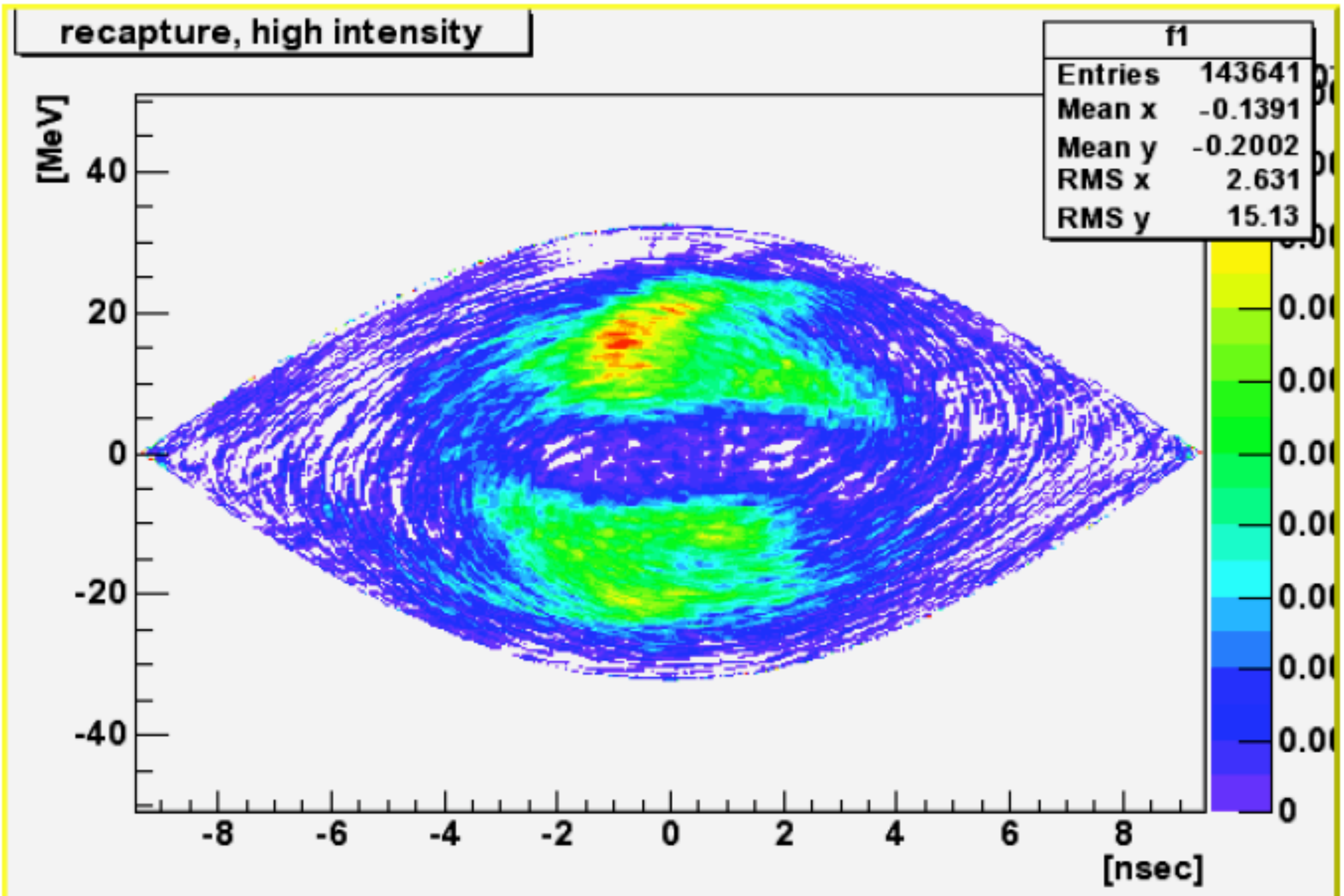
Beam capture in the FMI

Beam at recapture (1MV)



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Tomographic reconstruction

Constraints on slip stacking in the LER

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- Beam can be injected only once from the LER into the LHC – rings are Siamese Twins
- Slip stacking can be done only at injection energy – batches have to be at different energies
- The two beams must have different rf systems in the LER
- Second beam has to be slip stacked while the first beam is circulating – constraints on aperture in the common areas
- Losses in the LER must be absorbed in the LER

Slip stacking in the LER

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2 adjacent batches will be slip stacked.

Assume: same bunch structure as at present. 234 bunches per batch, 10 bucket spacing between adjacent bunches and 38 bucket spacing between batches.

1st batch: accelerate to slightly higher energy.

2nd batch: decelerate to slightly lower energy.

Time for the 2nd batch to catch up with the 1st batch

$$t_{slip} = \Delta t/(\eta\ \Delta E/E)$$

Δt = time interval from 1st to 2nd batch, $\Delta E/E$= relative energy difference between batches.

During the slipping both rf systems act on both batches – energy separation should be large to minimize impact but needs to be chosen carefully.

Energy difference between batches

Larger ΔE reduces

- the slipping time
- the interference of other rf system
- beam-beam forces between beams. But these are small at high energy ~ $1/\gamma^3$

But larger ΔE increases

- the required aperture of machine
- the emittance growth after recapture.

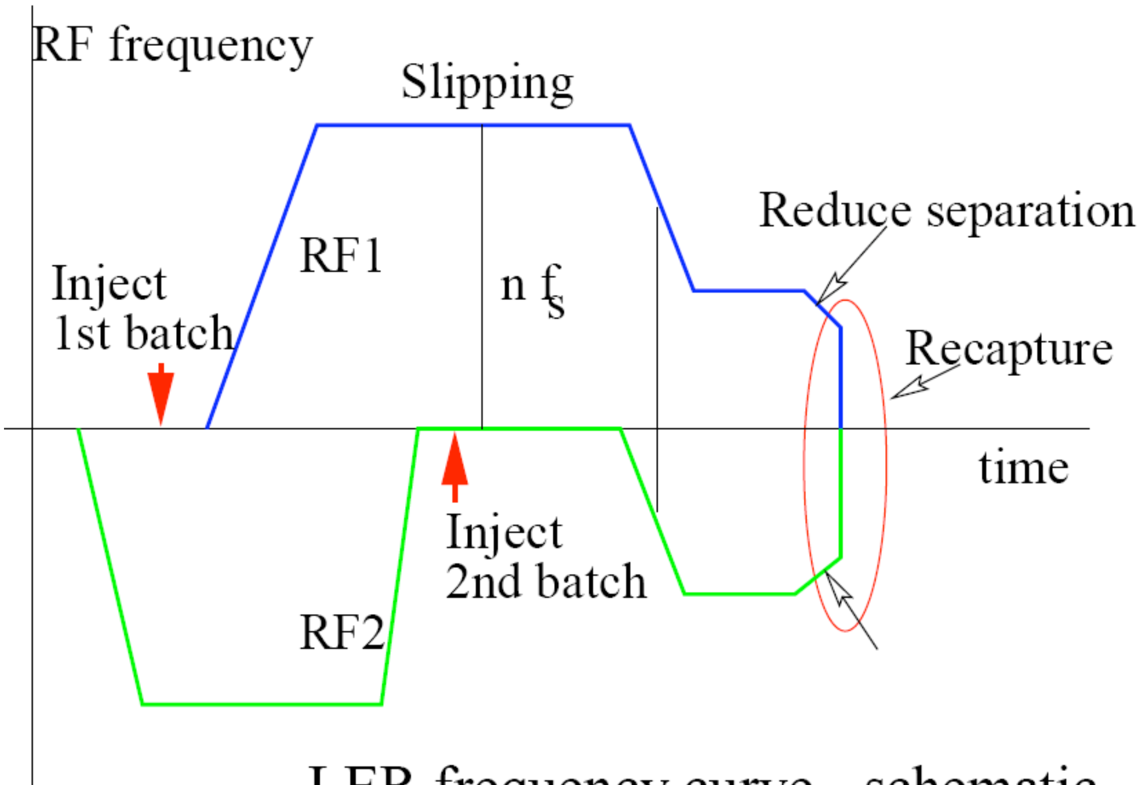
Recapture process

Emittance growth and possibly beam loss can occur if voltages, energy difference and time for recapture are not properly chosen.

Parameters for ESME simulations

PARAMETER	
Injection Energy in the LER	450 GeV
Longitudinal emittance (95%)	0.7 eV-sec
Initial rf voltage	2.7 MV
Rf frequency	400 MHz
Bucket Area	0.83 eV-sec
Bunch spacing	25 nano-sec
Batch length	234 bunches or 6.4 μsec
Batch spacing	38 buckets or 95 nano-sec
Synchrotron frequency	37 Hz
Slip factor	3.18×10^{-4}
Energy difference during slipping	1.8×10^{-3} (rel)/ 0.81 GeV (abs)
Slipping time	11.3 sec (between consecutive batches)

LER RF frequency curve



LER frequency curve - schematic

- Estimate required momentum aperture $\Delta E/E \sim 1.8 \times 10^{-3}$ if n=6
- RF voltage could be decreased while bunches are slipping to reduce interference
- Final capture voltage depends on energy difference.

Slipping at constant energy difference

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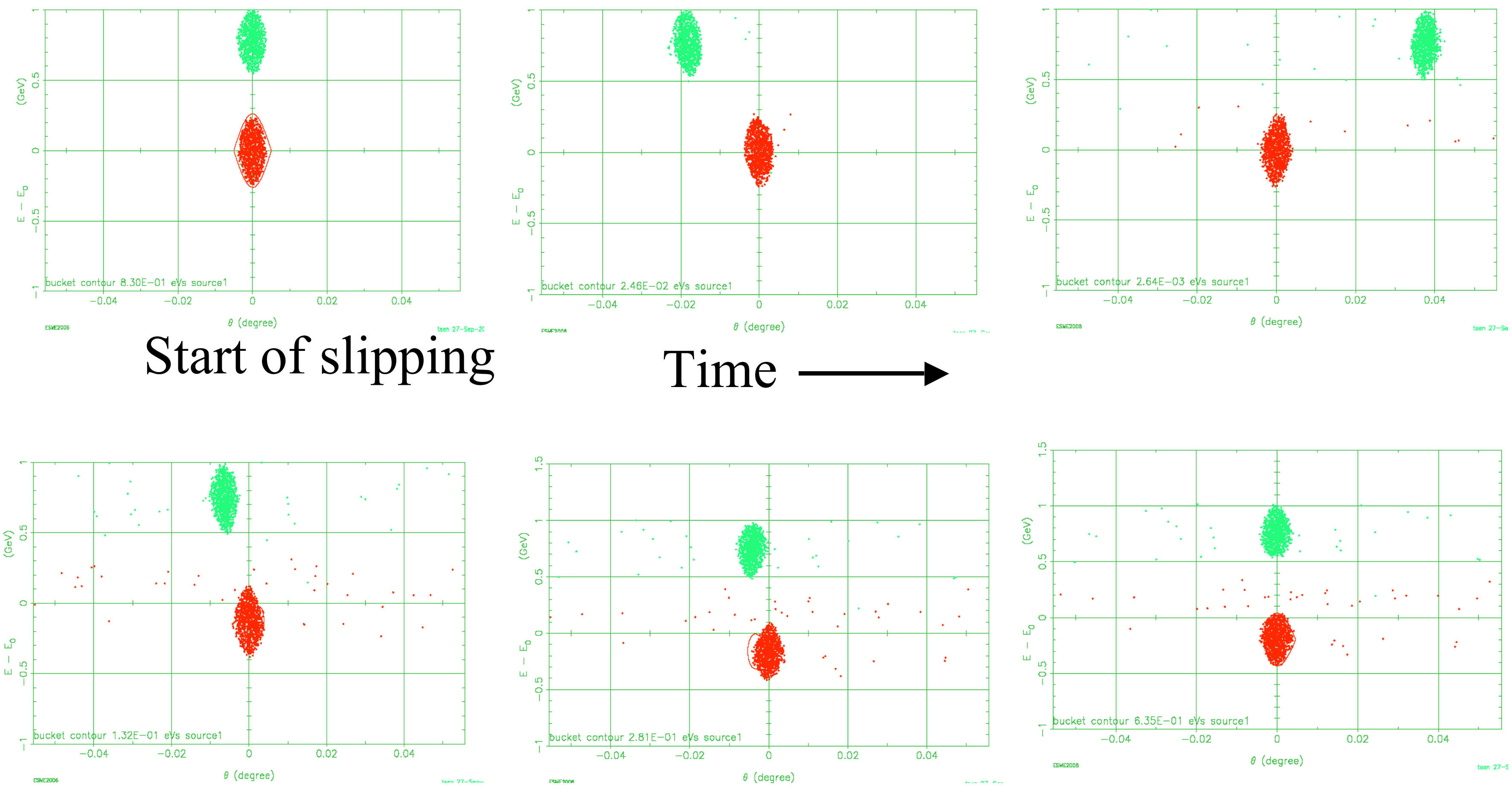


Start of slipping

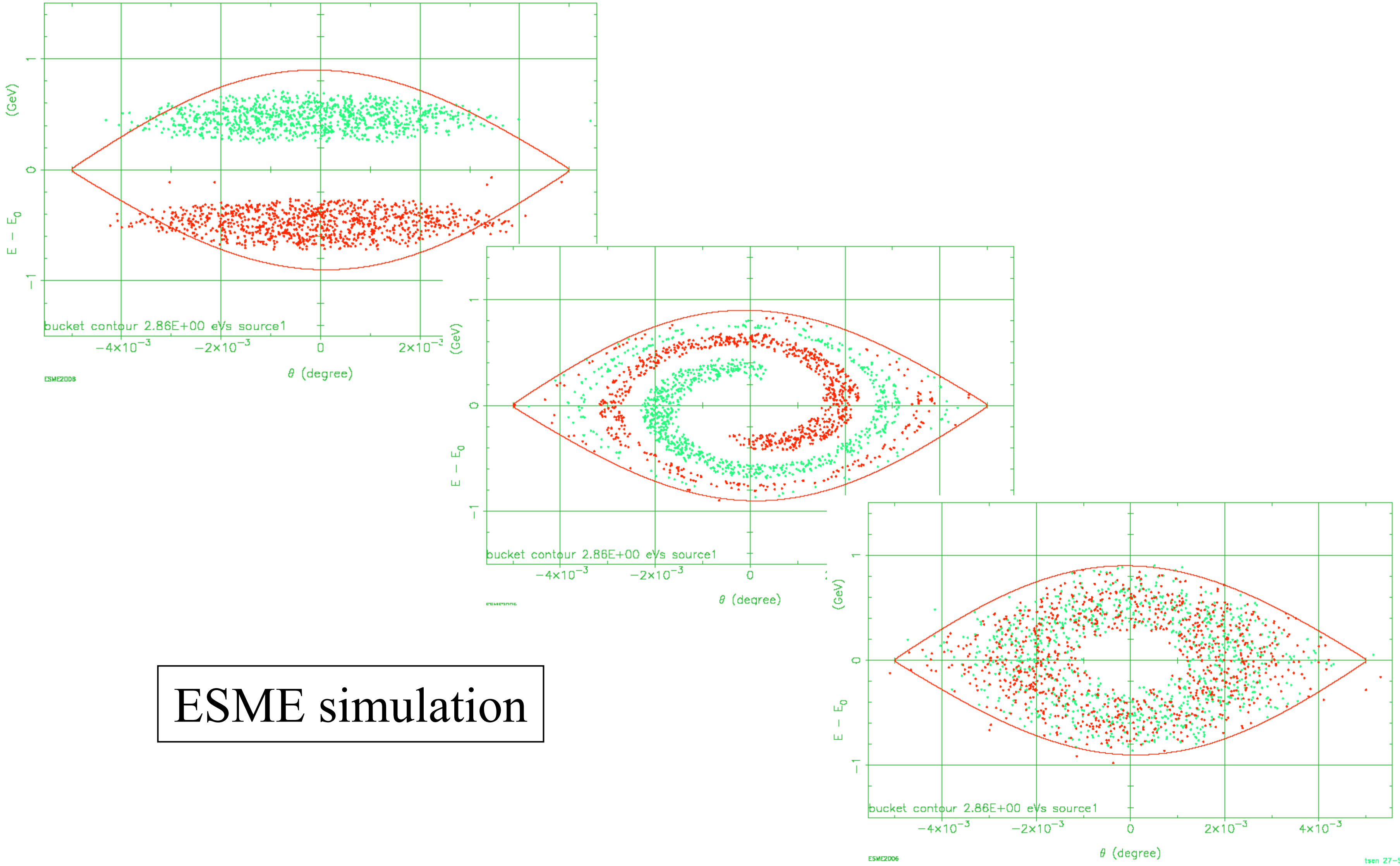
Time ⟶

ESME simulation

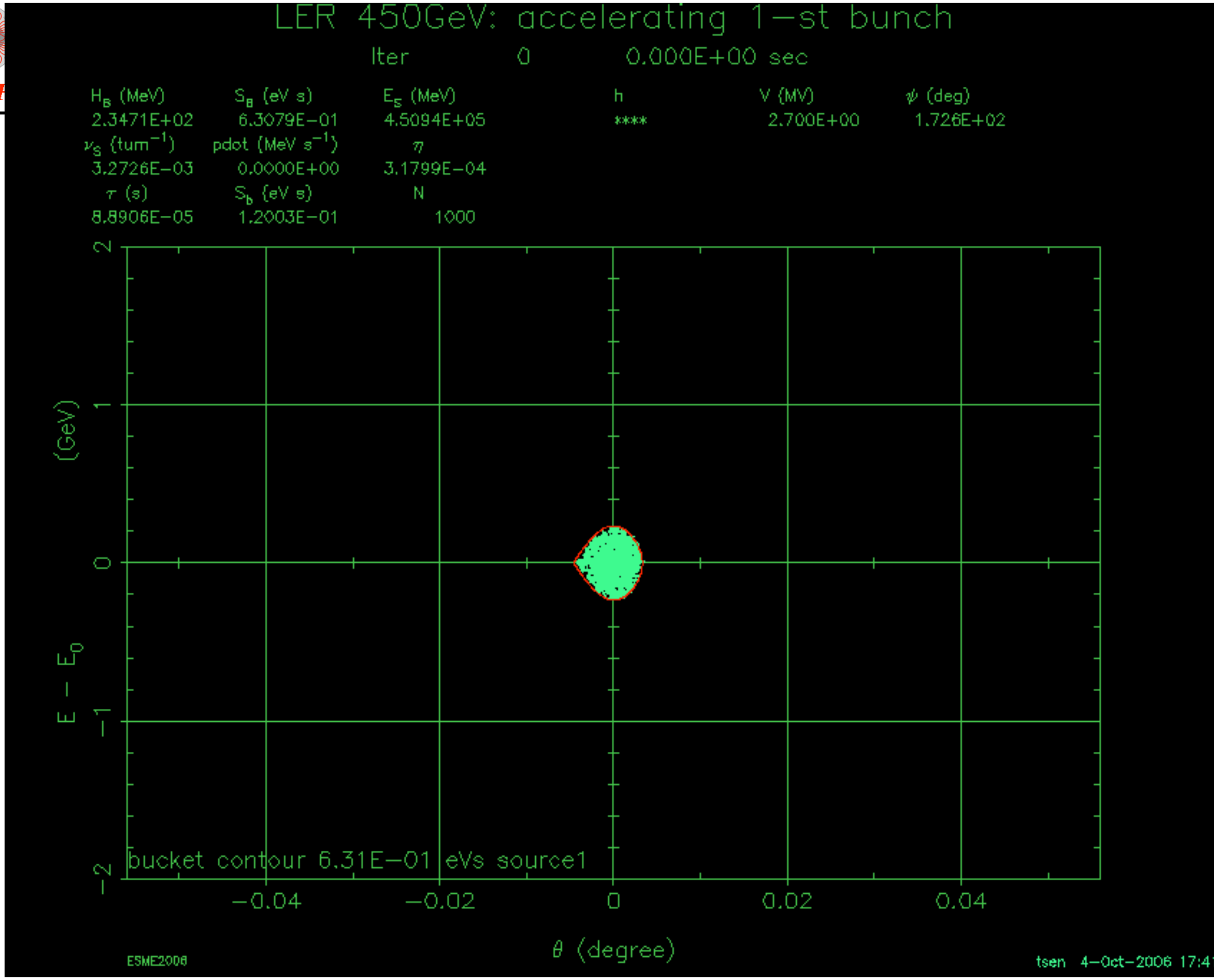
End of slipping

Frequency separation = $6f_s$

Capture of both bunches



ESME simulation


LER 450GeV: accelerating 1−st bunch
Iter 0 0.000E+00 sec
H_B (MeV) 2.3471E+02
S_B (eV s) 6.3079E−01
E_S (MeV) 4.5094E+05
h ****
V (MV) 2.700E+00
ψ (deg) 1.726E+02
ν_S (turn^−1) 3.2726E−03
pdot (MeV s^−1) 0.0000E+00
η 3.1799E−04
τ (s) 8.8906E−05
S_b (eV s) 1.2003E−01
N 1000
E − E_0 (GeV)
θ (degree)
bucket contour 6.31E−01 eVs source1
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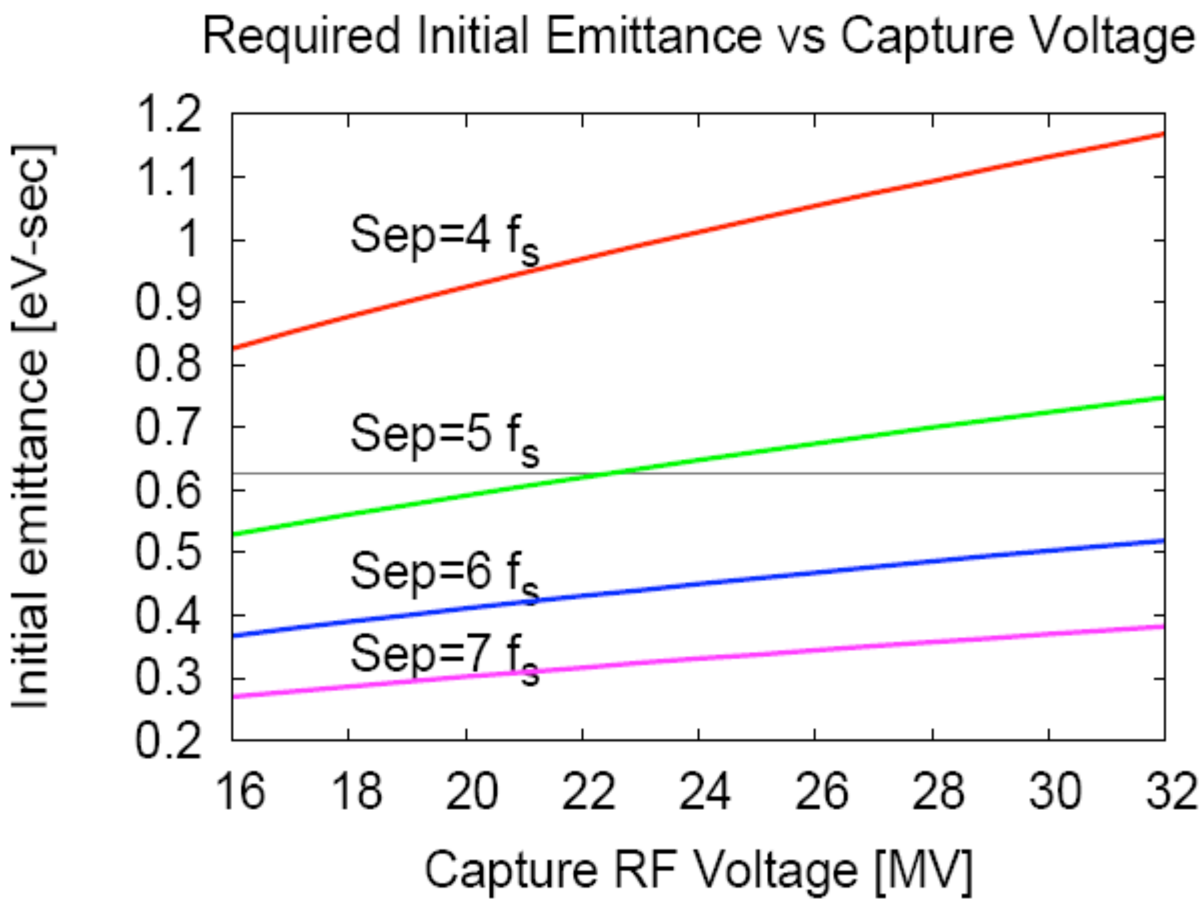
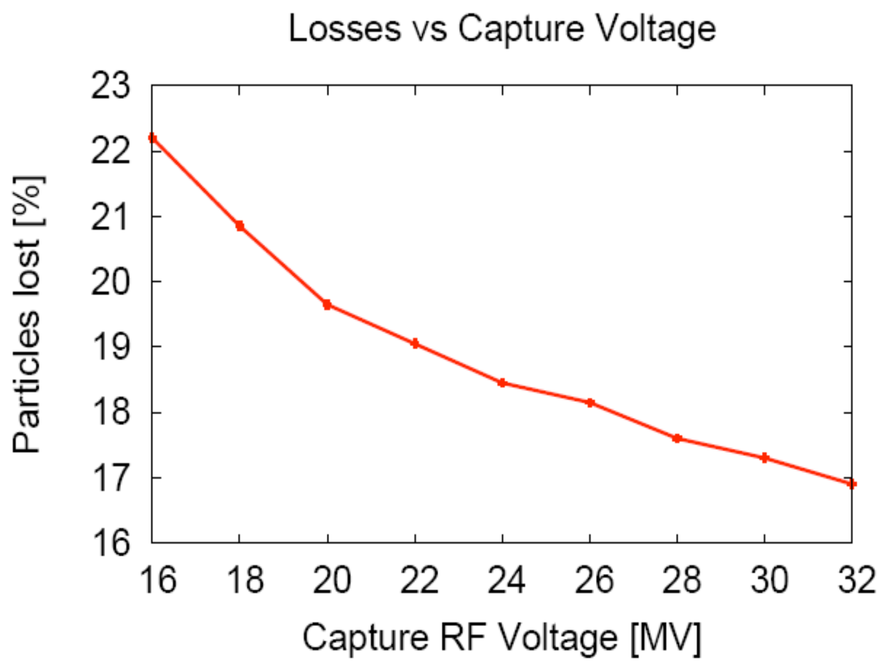
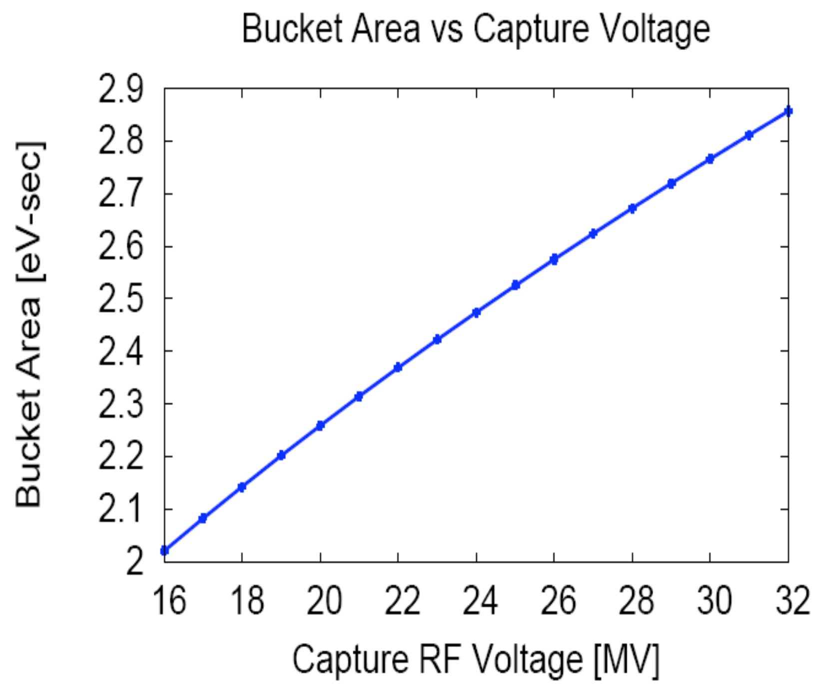
Capture Voltage and Initial Emittance



- Present emittance is sufficient if the final separation can be 4 f_s
- Losses increase with smaller separation
- Emittance of captured bunch increases with larger separation
- Larger capture voltage increases final emittance.

Losses, Emittance vs Capture Voltage

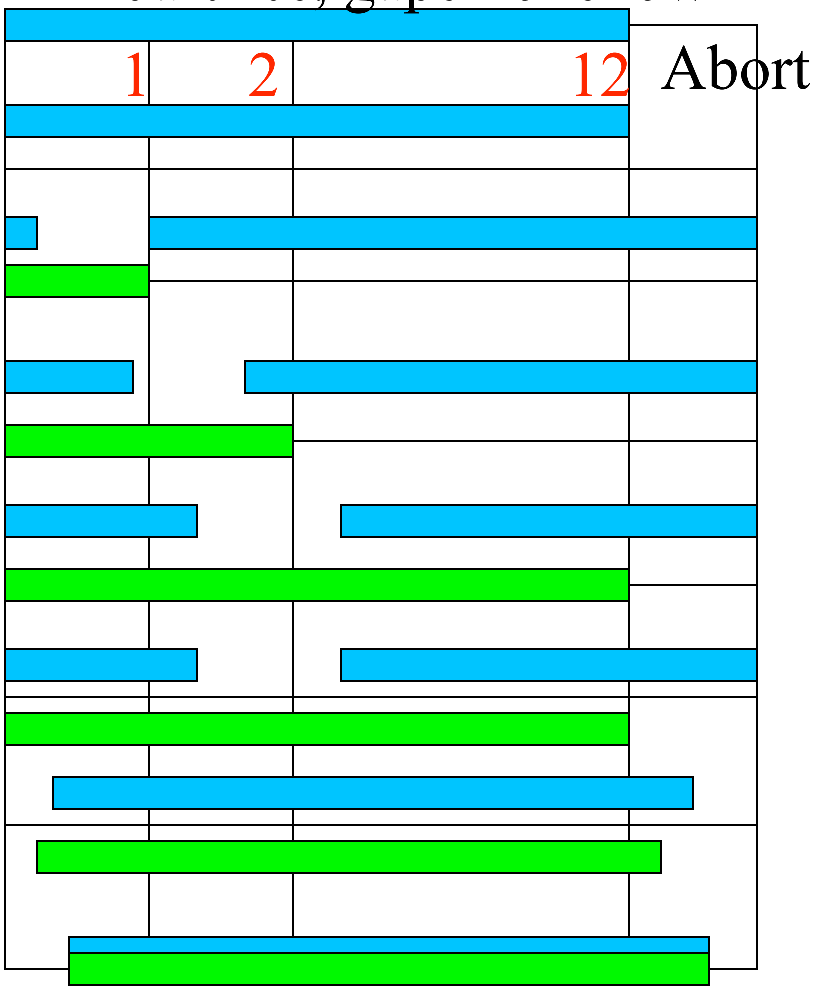




- Loss results are **very** preliminary – intended only to show variation with Vrf. This level of losses is **not** acceptable.
- Largest fraction of losses occur as beams are brought closer just before recapture
- Better control of the rf phases will reduce losses - losses in FMI < 7%

Filling the LER and Slip stacking

12 batches, gaps not shown



- Inject 12 batches from the SPS into the LER at reference energy
- Accelerate these batches to ΔE. These batches will slip before next SPS injection
- Inject the next 12 SPS batches at reference energy
- Decelerate both sets of 12 batches by 0.5 ΔE. Batches will be slip at constant energy difference.
- Capture when batches are aligned.

Adapted from proposed slip stacking in Recycler (I. Kourbanis)

Slip stacking Issues

- Beam loading compensation
- Instabilities during recapture. Intensity limits in LER.
- Final emittance after recapture – resulting requirement of capture voltage in the LHC
- Time taken to inject and slip stack both beams in the LER
- Robustness of the LER to losses – what fraction of the beam can be lost without quenching?
- Shorter batches from the SPS would reduce the slipping time. This needs to be balanced against the total number of bunches – gaps are limited by the injection kicker rise and fall time.

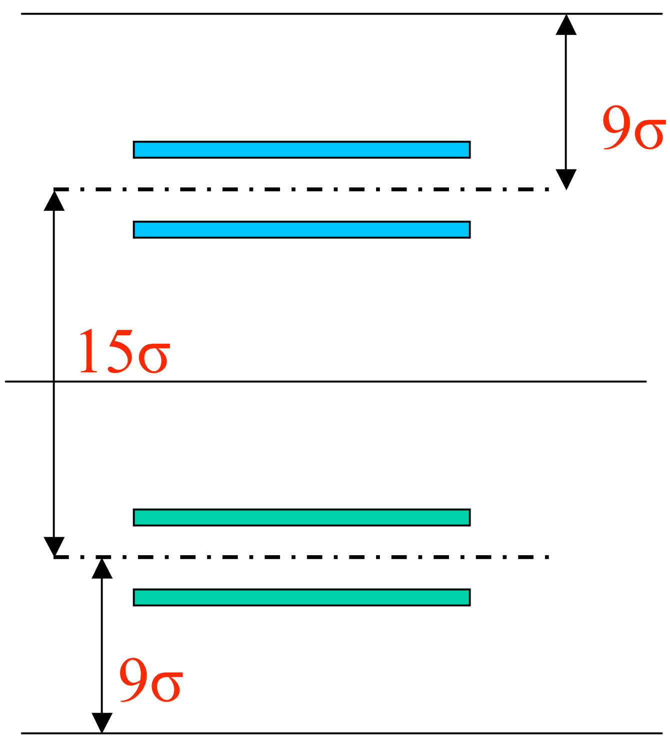
Preliminary Conclusions

- The likely robustness of the LER to beam loss makes it a candidate to consider increasing the intensity in this machine.
- Slip stacking will have to be done at injection energy.
- Preliminary simulations show that there is little emittance increase during slipping and the beam loss during slipping is not excessive if frequency separation is kept at 6 f_s.
- The capture process requires detailed simulations and reducing losses.
- Capture voltage of 16MV is sufficient if the frequency separation between batches just before capture is reduced to 4 f_s.
- A possible (plausible?) LER filling scenario with slip stacking will increase the bunch intensity (~2 fold). Luminosity increase N_b^2 or ~ 4 fold. Other filling scenarios may be possible.
- Detailed analysis of other slip stacking issues (beam loading compensation, final emittance,…) is necessary.

LARP

Backups

Horizontal Aperture

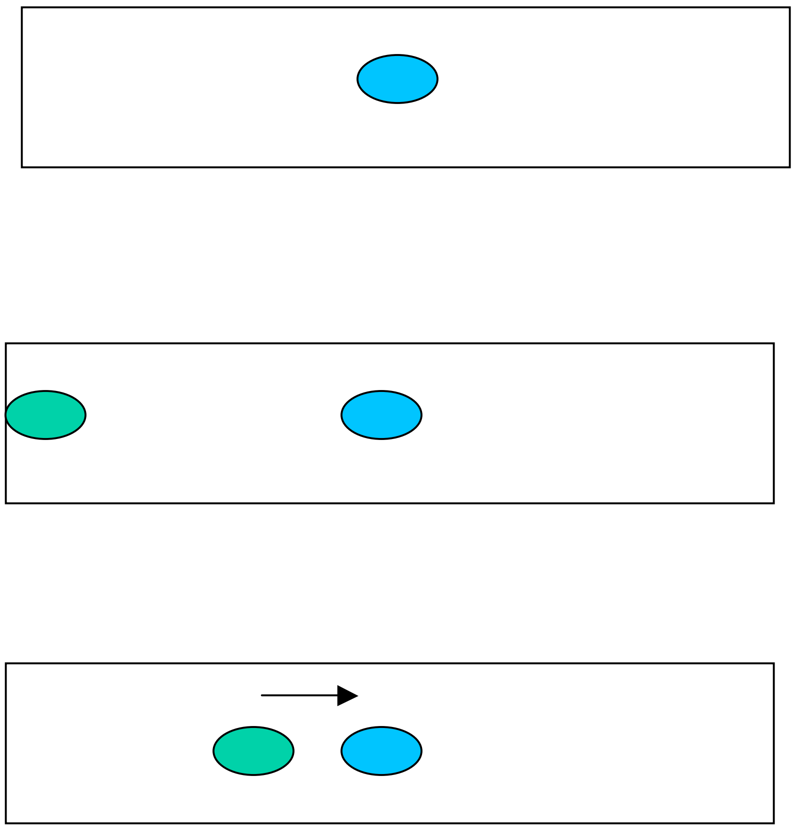


Relative energy separation = 1.8×10^{-3}

- Hor. Space between slipping batches = 3.6mm at Dx = 2m
- Average transverse displacement between beams ~ 15σ.
- Clearance of ~ 9σ for each beam to limiting aperture
- Total space required = 33 σ + 3.6mm
- At β^{max} = 185m in arc cell,

  σ = 0.35mm
- Required space = 15.1mm

Mechanics of momentum stacking



- Circulating beam on central orbit
- Inject beam onto off-momentum closed orbit. Requires a special kicker
- Decelerate off-momentum beam to central orbit
- Capture both beams in a larger RF voltage. Dynamics of the final capture process is the same as in slip stacking.

Filling the LER and Slip stacking

Alternate scenario

- Inject odd numbered batches 1, 3, …. 11 for the 1st beam from the SPS. Raise energy of these odd batches
- Inject even numbered batches 2, 4, … 12 from the SPS. Lower energy of these even batches
- Let batches slip until (1,2), (3,4), … (11,12) align. This assumes spacing between batches is uniform.
- Turn on main RF capture voltage at this time.
- Bunch intensity is doubled, number of bunches is halved, spacing between batches is doubled.
- Repeat process with 2nd beam using its rf system. 1st beam is circulating
- Accelerate both beams to top energy. DC beam from losses at lower energy is dumped in absorbers.
- Extract both beams to the LHC