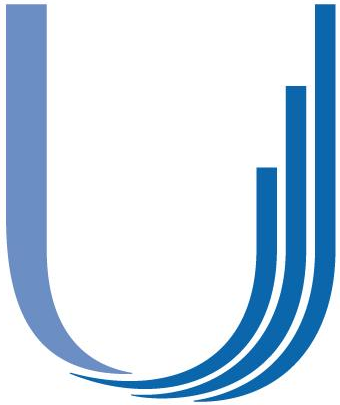


LHC Injectors Upgrade

LHC Injectors Upgrade

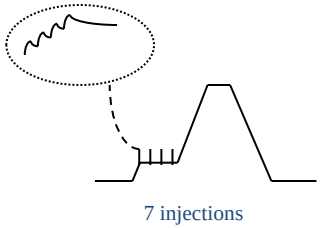
Performance of the injectors with ions after LS1

D.Manglunki
for the LIU-Ions team,
and with lots of help from
T.Argyropoulos, T.Bohl, E.Chapochnikova, H.Damerau,
R.Garoby, J.M.Jowett, J.B.Lallement, B.Mikulec, M.Schaumann.

Outline

- Reference: achieved performance of the ion injector chain
- Baseline upgrade scheme
  - 100ns batch compression in the PS
  - 100ns batch spacing into the SPS
- Additional improvements
  - Splitting and/or additional batch compression in the PS
  - Momentum Slip Stacking in the SPS
- Expectations for 2015
  - Alternating 100ns/225ns
- Possibility for different ions species
- Schedules (with and without LS1.5)
- Conclusions

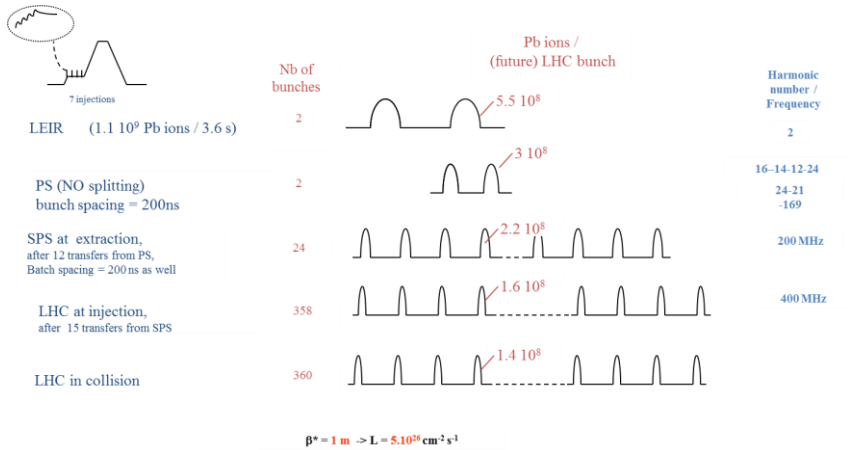
Current scheme
(“intermediate” in 2011, with 2013 performance)

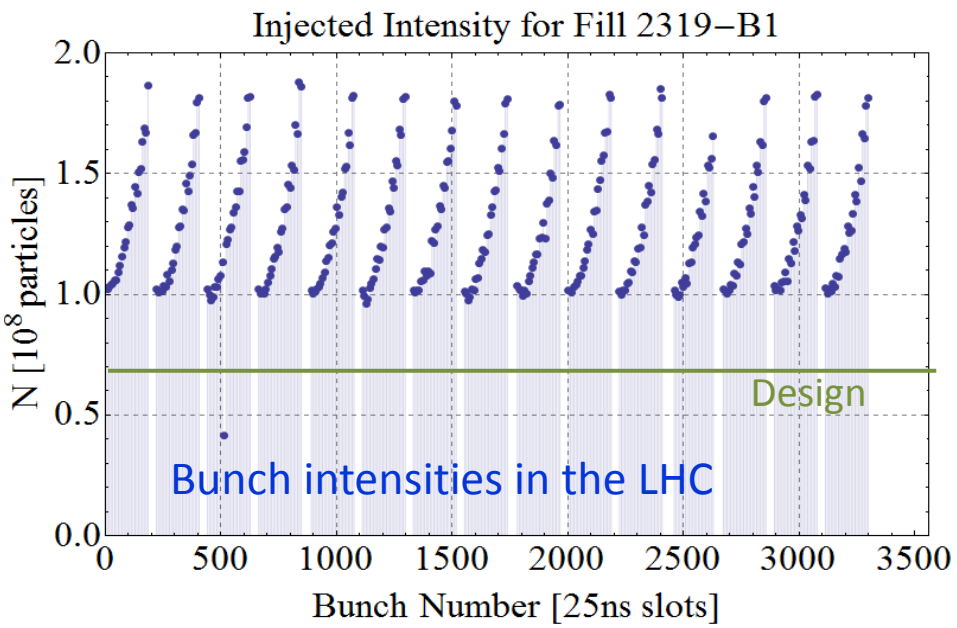


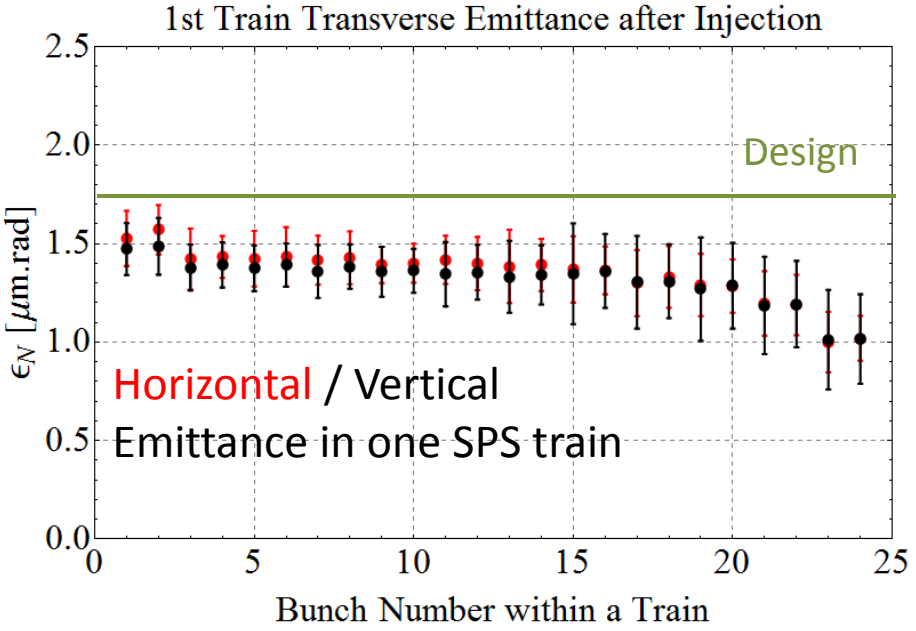
	Nb of bunches	Pb ions / (future) LHC bunch	Harmonic number / Frequency
LEIR (1.1 10^9 Pb ions / 3.6 s)	2	5.5 10^8	2
PS (NO splitting) bunch spacing = 200ns	2	3 10^8	16–14-12-24 / 24-21 -169
SPS at extraction, after 12 transfers from PS, Batch spacing = 200 ns as well	24	2.2 10^8	200 MHz
LHC at injection, after 15 transfers from SPS	358	1.6 10^8	400 MHz
LHC in collision	360	1.4 10^8	

β^* = 1 m -> L = 5.10^{26} cm^{-2} s^{-1}

Current scheme (2011) & performance (2013)



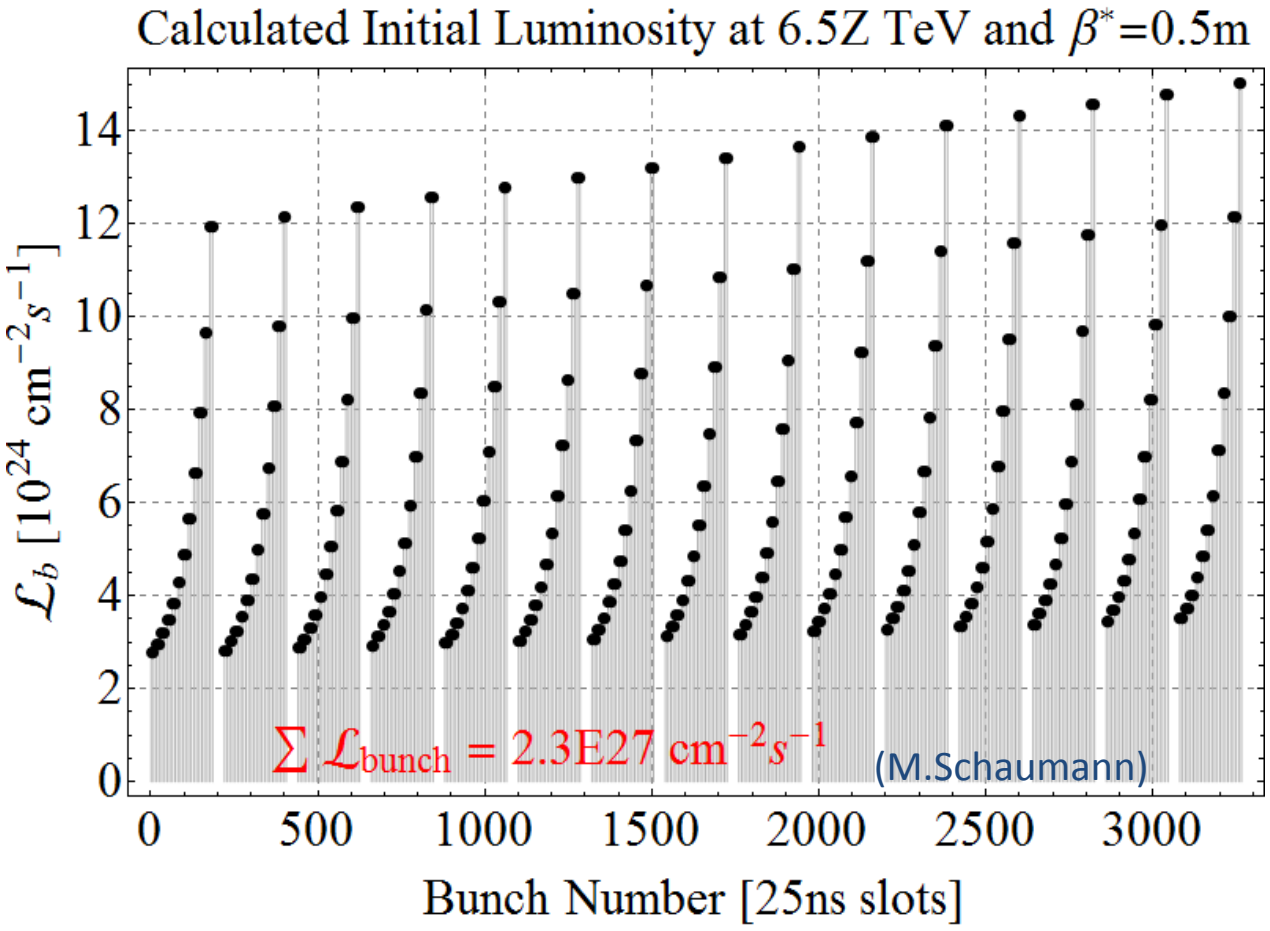




(M.Schaumann)

Current scheme performance

- Extrapolating to 6.5 TeV/c/charge, $\mathcal{L}_{peak}$= 2.3x10^{27}cm^{-2}s^{-1}



How to reach a higher $\mathcal{L}$? Increasing the total bunch number

- WHY?

The average bunch brightness is already twice nominal

  - Increasing it (if even possible) leads to more IBS in SPS and LHC, and also increases $\mathcal{L}$ burnoff.

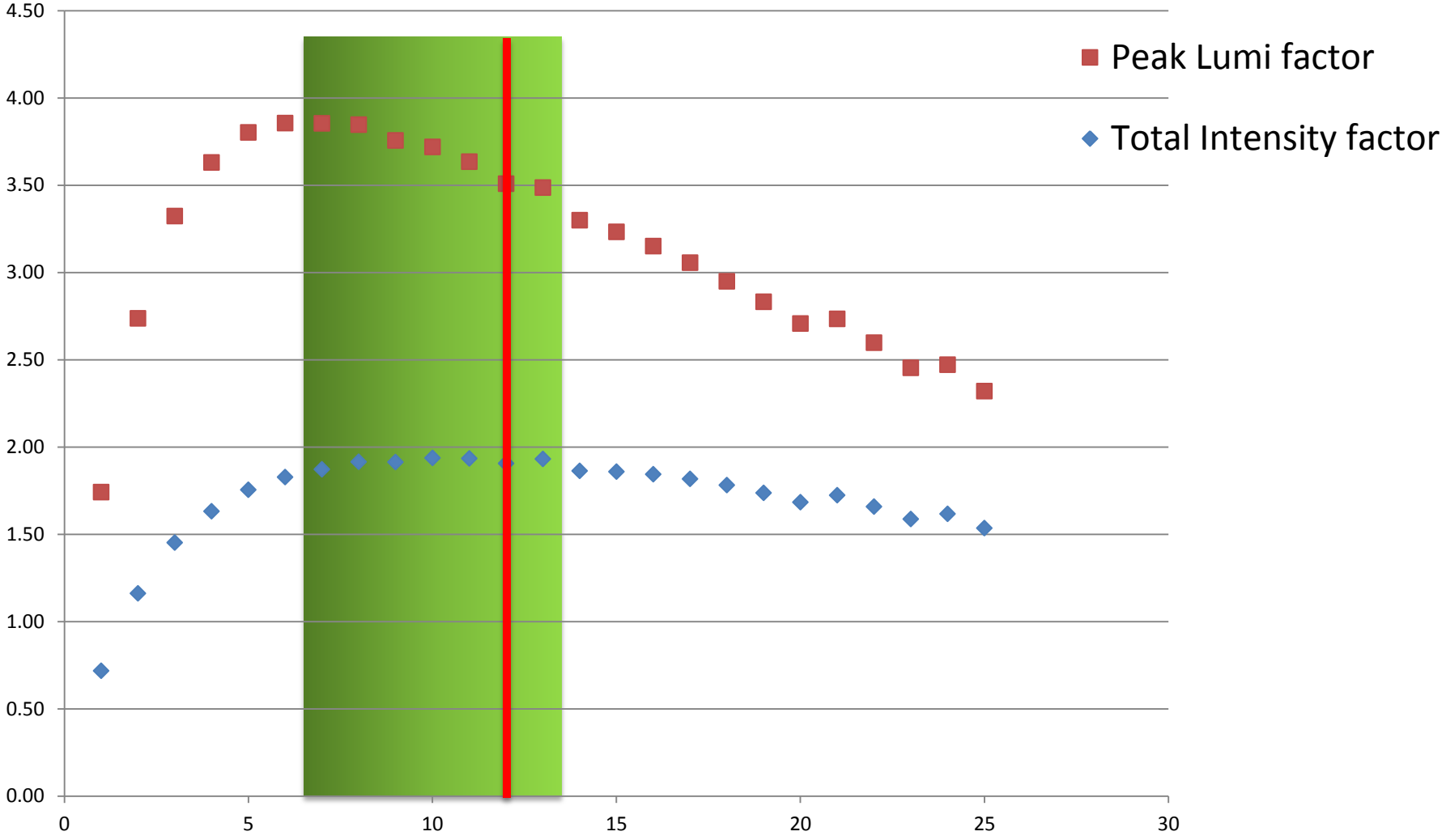
- HOW? Reducing average bunch spacing in the LHC

  - Reducing bunch spacing to 100ns by batch compression in the PS
  - Increasing number of injections into SPS as its injection kicker rise time is shorter than the LHC's, but a longer SPS flat bottom leads to losses and emittance blowup (IBS)
  - Decreasing batch spacing to 100 ns in SPS (Shorter injection kicker rise to get batches closer, but needs a new injection system)

- The LHC filling time will likely be longer

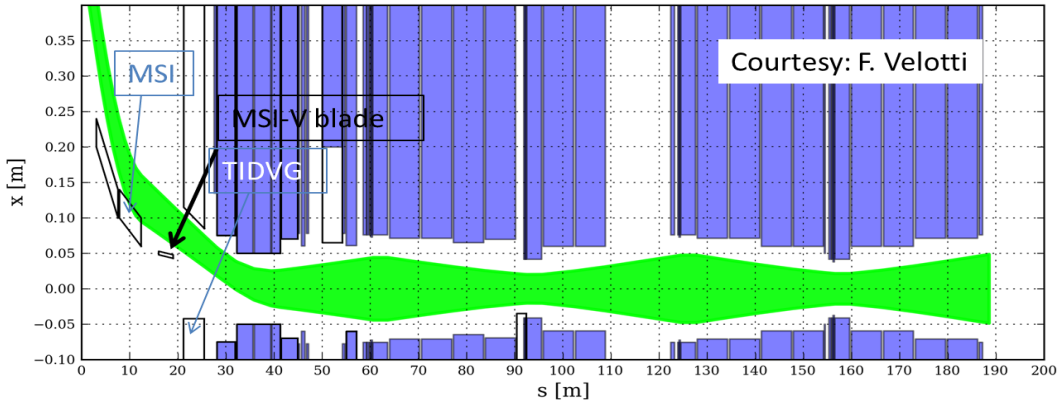
Optimum number of PS injections in the SPS

with current bunch behaviour on the SPS flat bottom (Q20, RF noise, intensity…)



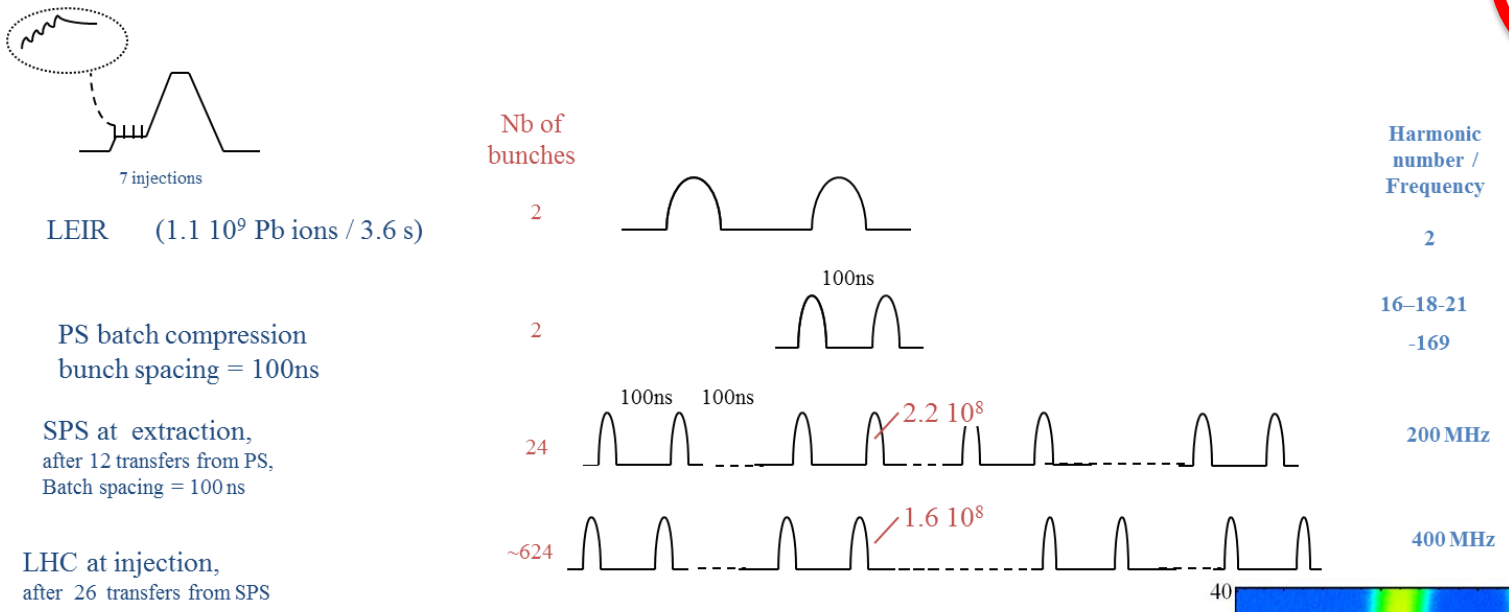
SPS injection system upgrade “option IV”: 100 ns
Review LIU-SPS, 4/10/2013
https://indico.cern.ch/conferenceDisplay.py?confId=263338

- Install a faster pulser & switch on MKP-S system in parallel to the present one
- Supplement septum by new MSI-V

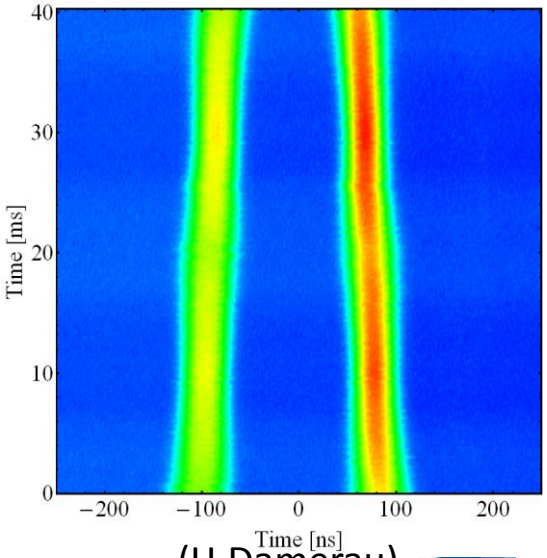


- No additional kicker magnets to be installed in the tunnel
- Maximum voltage of 40 kV
- Installation of MSI-V, recuperated from PSB recombination septa, one winter shutdown after LS2 (but spares can be used)
- With the MSI-V one can run at low voltages on the MKP-S and MSI-V, very comfortable, and no problems with Q20 optics
- Development time and lab tests needed

Baseline scheme and parameters



β* = 0.5 m -> L = 4x10²⁷ cm⁻² s⁻¹

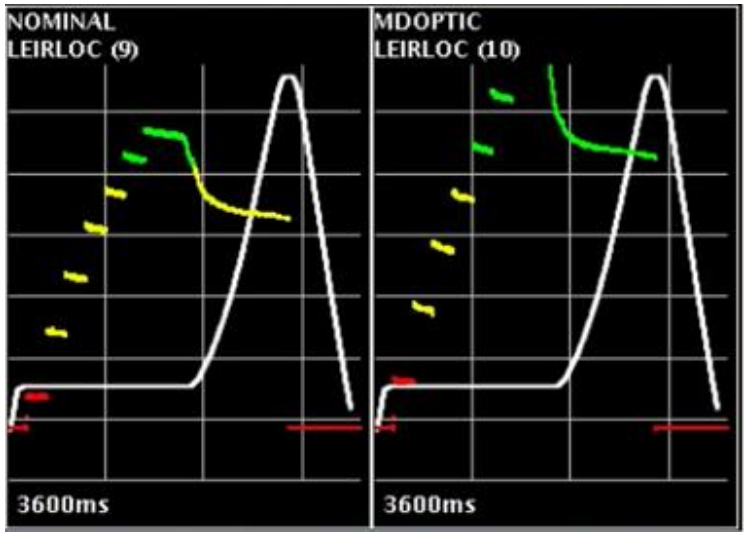


(H.Damerau)

- Modified RF gymnastics in PS
  - Batch compression (h = 16 – 18 – 21) -> 2 bunches spaced by 100 ns
- 12 (to be confirmed/optimized) injections into SPS spaced by 100 ns
  - 2.3μs trains of 24 bunches spaced by 100 ns
- 26 injections/ring into LHC
  - 624 bunches/ring (factor ~1.74)
  - >25' filling time per ring on paper
- From number of bunches: Pb-Pb $\mathcal{L}_{peak} = 4.0 \times 10^{27} cm^{-2} s^{-1}$

Additional improvements: Splitting and/or batch compression in PS

- Increasing number of bunches from PS to SPS:
  - Reintroduce splitting: needs even higher bunch density from LEIR, already above design, and currently limited – investigations ongoing, need time



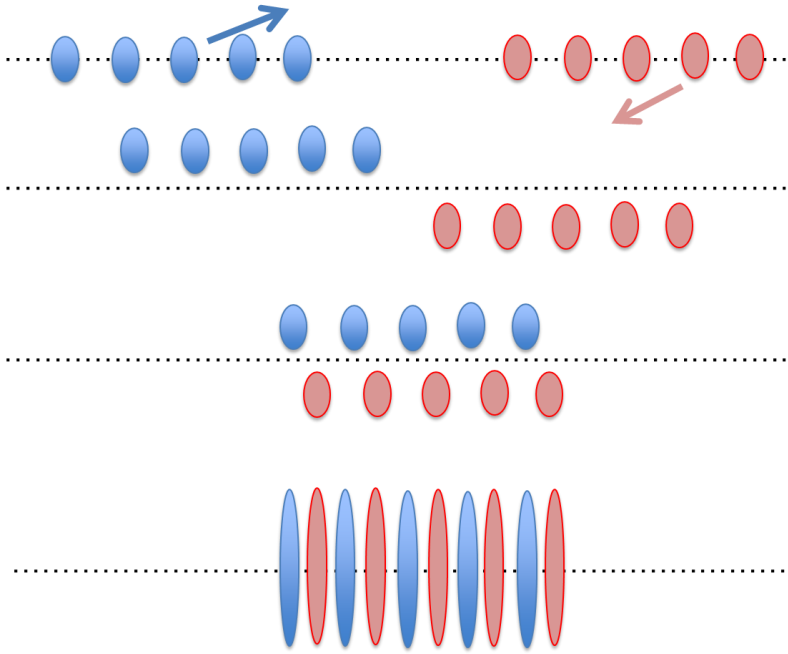
  - Reducing bunch spacing in PS to 50ns by batch compression at high energy, close to transition:
    - if more than 2 bunches (i.e. splitting), needs transition distortion optics and additional Finemet cavity (h = 21 -> 25 -> 30 -> 36 -> 42)
    - unsplit case (2 bunches) probably needs no additional HW and can be tested with Ar in 2014 (h = 21 -> 21+7 -> 42)
  - Splitting + batch compression: breakeven at +40% intensity as $1.4^2 / 2 = 1$
  - Note: smaller bunches suffer less from IBS on SPS flat bottom

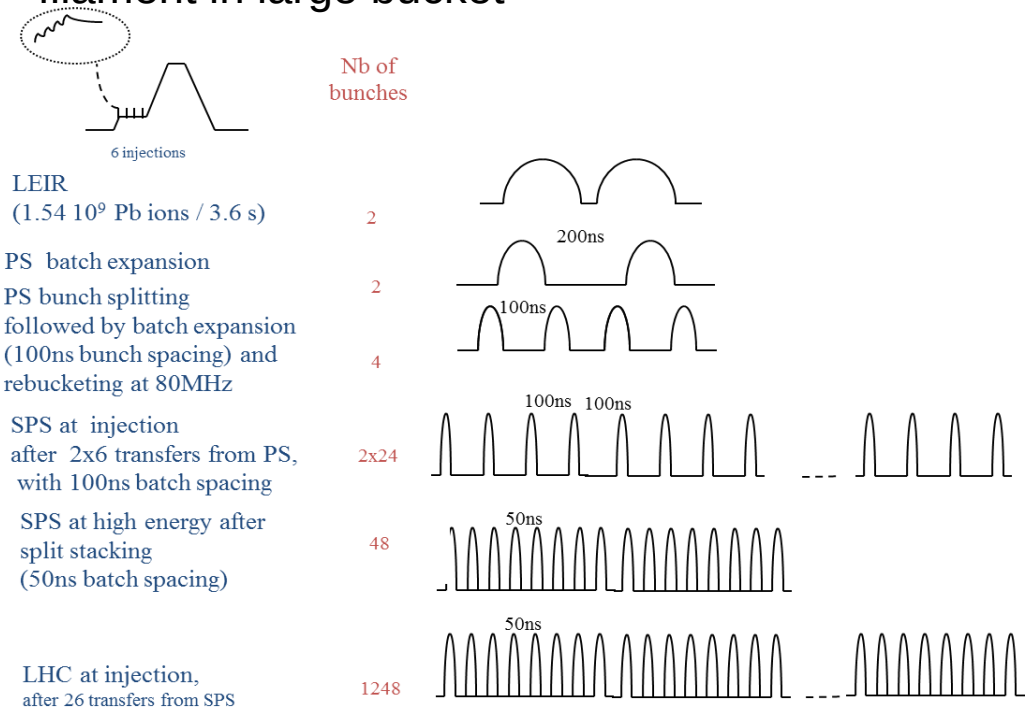
Additional improvements: Slip stacking in the SPS

- Further decreasing spacing in SPS: Slip stacking to get bunches closer [R.Garoby]

Example: 2x6 transfers of 4 bunches spaced by 100ns from PS, batch spacing 100ns

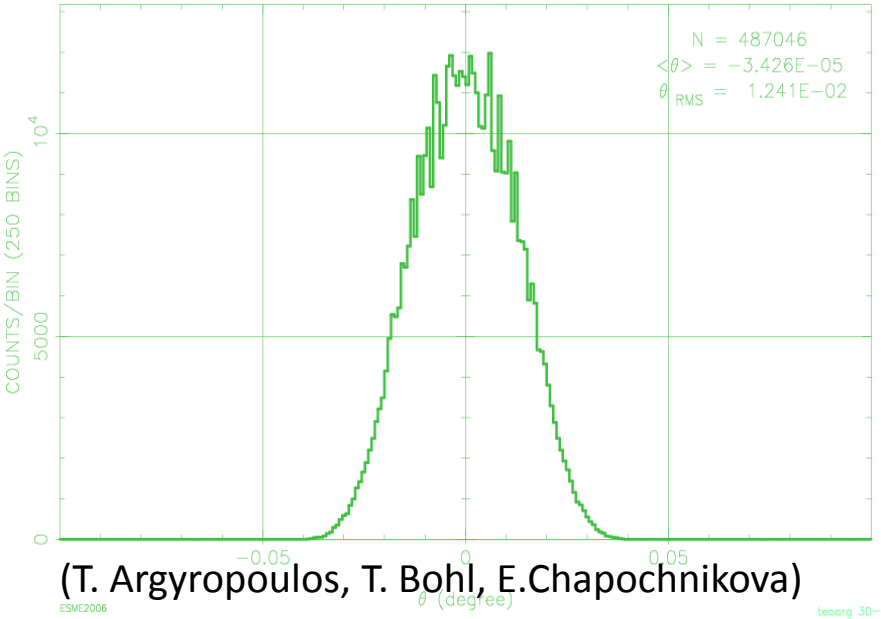
- The 2 trains are detuned in momentum, one up, one down, they start slipping
- Once the bunches are interleaved they are recaptured at average frequency and filament in large bucket





Slip stacking in the SPS

- Potential feasibility based on
  - Large bandwidth of the SPS Travelling Wave RF system
  - Relatively small initial emittances
  - Low ion intensity (no need of FB, FF, 800 MHz, …)
- Confirmation by particle simulations
- Conditioned by 200 MHz LLRF modification
  - independent control of 2 groups of cavities
- Slipping near but not at top energy
  - Far enough from transition
  - avoid transfer of uncaptured particles to the LHC
- 12mm maximum separation between beams
- ~1.0 second required for manipulations:
  - 0.45 s (slipping) + 0.2 s (up-down) + 0.35 s (filamentation)
- Beam parameters:
  - ~3% loss
  - emittance blow-up by ~ factor 2.5 => OK for extraction to LHC after 200 MHz upgrade in the SPS (or 200 MHz in LHC)



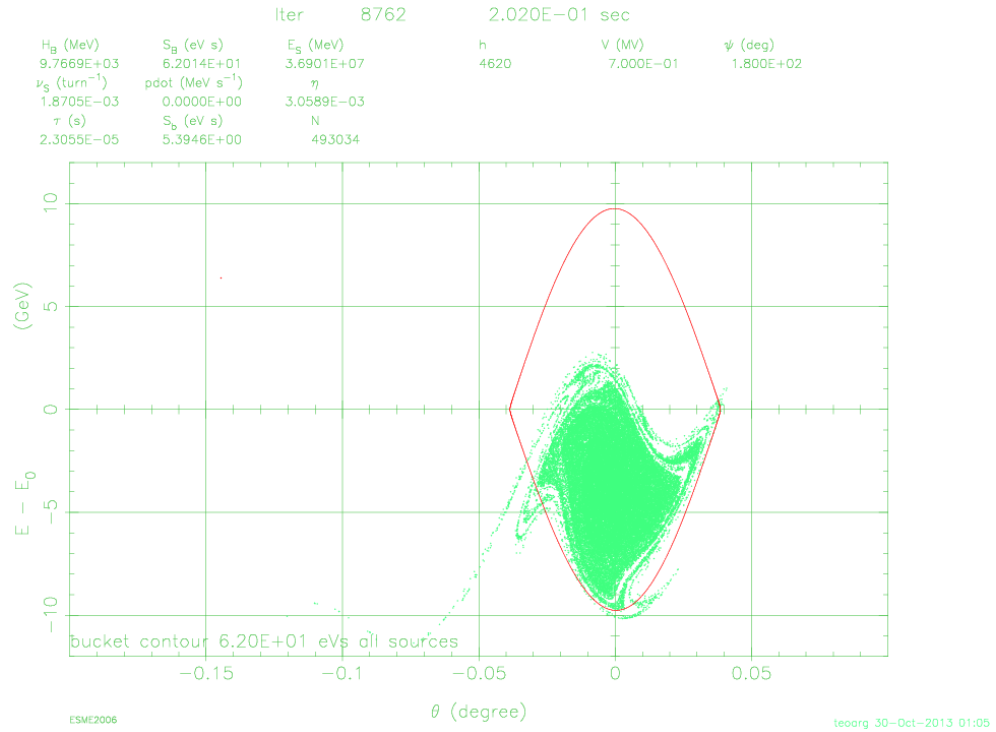
(T. Argyropoulos, T. Bohl, E.Chapochnikova)

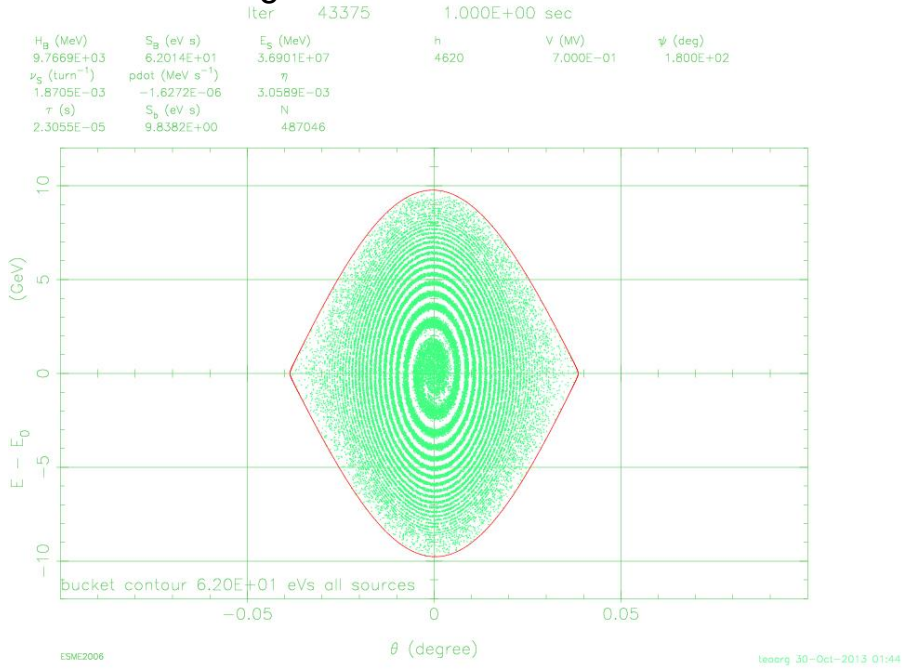
Slip stacking in the SPS: Preliminary results of ESME simulations

τ = 3.19 ns

ε_{fin} = 0.19 eVs/A

(ε_0 = 0.092 eVs/A)

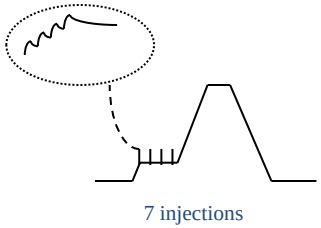




After slipping and just before recapture

After recapture (~0.8 s)

What can we do today (i.e. in 2015 assuming performance of 2013)? 100ns out of PS, 225 ns batch spacing in SPS



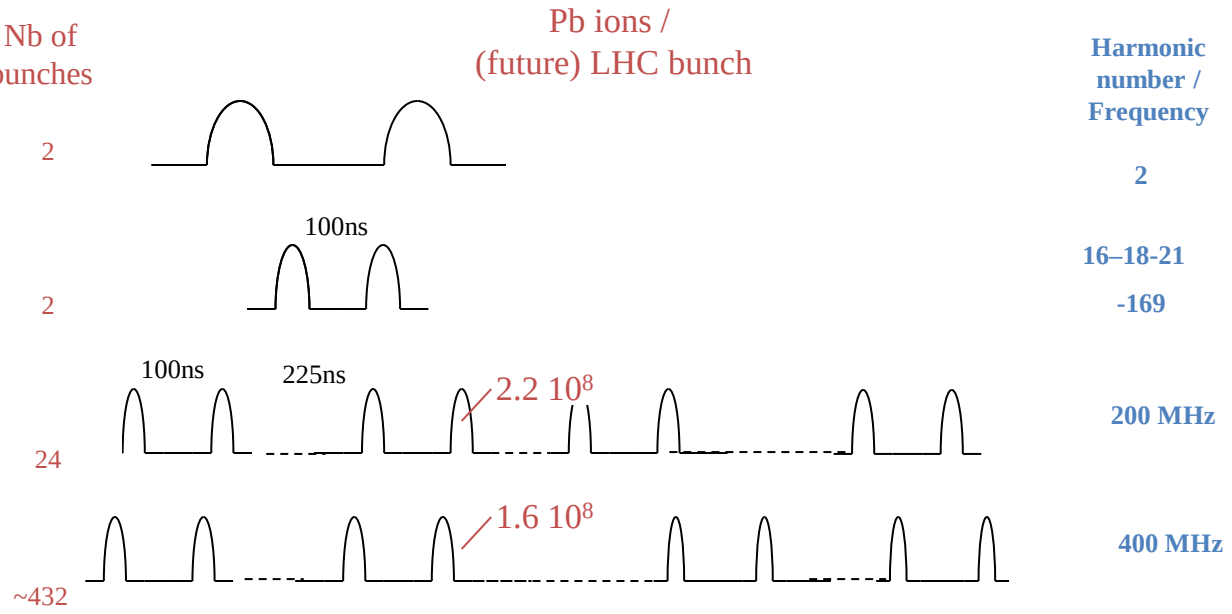
LEIR 1.1 10^9 Pb ions / 3.6 s)

PS batch compression

bunch spacing = **100ns**

SPS at extraction,
after 12 transfers from PS,
Batch spacing = 225 ns

LHC at injection,
after 18 transfers from SPS

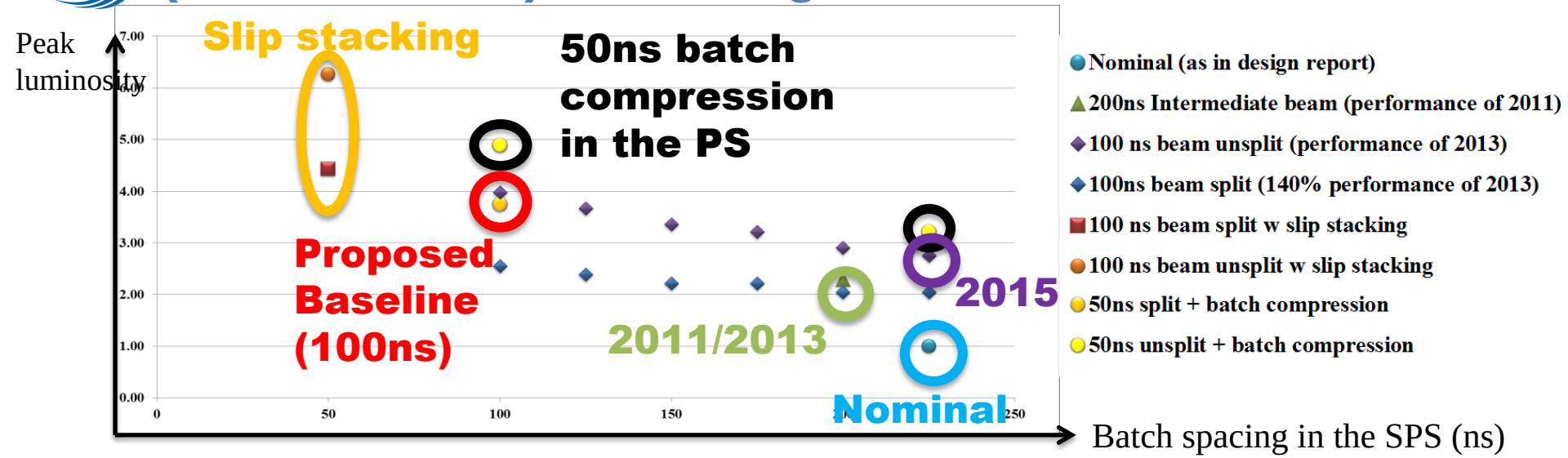


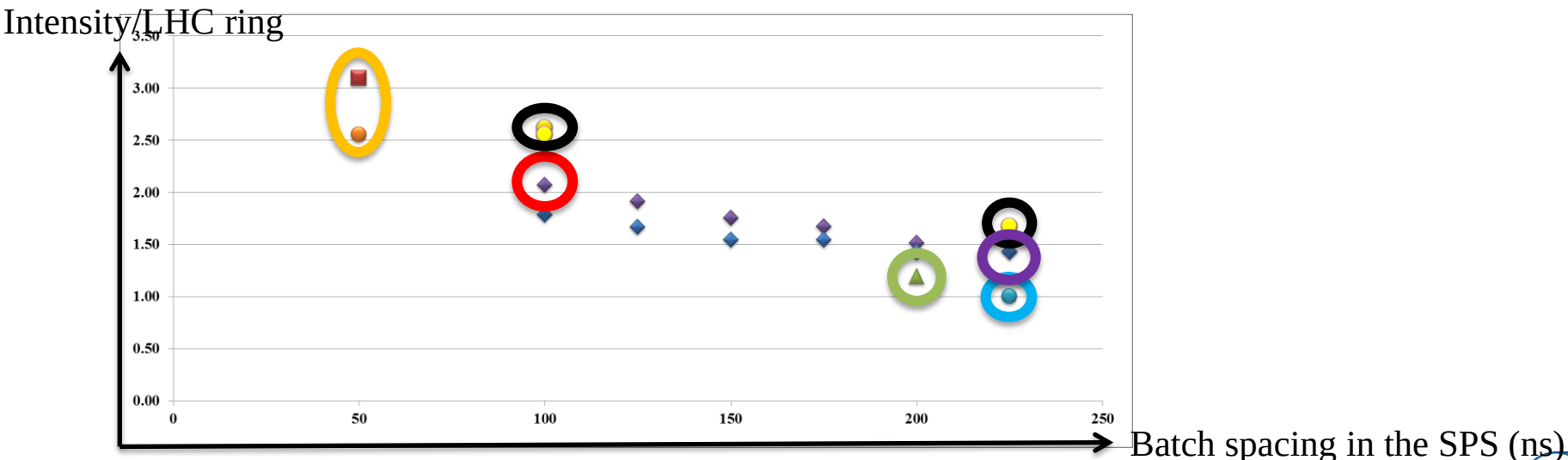
- 432 bunches of 1.6 x10^8 Pb^{82+} per LHC ring in 18 (!) injections from SPS
- Luminosity increase ~21% or $\mathcal{L}_{peak}$= 2.8x10^{27}cm^{-2}s^{-1}
- With additional batch compression to 50ns, $\mathcal{L}_{peak}$= 3.2x10^{27}cm^{-2}s^{-1}

Upgrades and studies

- Linac 3: increase intensity
  - ✔ 10Hz pulsing (included in consolidation - PIC)
  - ? multiple charge acceleration (unsure of benefit for LEIR)
- LEIR: Intensity limitation
  - ? ~+40% needed for additional splitting, but cause presently unknown
- PS: 50ns splitting or batch compression near transition
  - ✔ Tests of 2-bunch batch compression to 50ns with Ar
  - ? New cavity (Finemet)
  - ? Transition-distortion optics; imperfections?
- SPS
  - ✔ PFL on MKP + MSI-V septum for 100ns rise time injection / batch spacing
  - ✔ New beam control allowing RF gymnastics for slip-stacking
  - ? Are resulting imperfections after slip stacking acceptable by the LHC?
  - ✔ Improvement of beam behaviour on flat bottom (RF noise…)

Pb-Pb Summary: Peak luminosity & intensity (w.r.t. nominal) according to different schemes





Other ions

- CMS & ATLAS have expressed interest in Ar-Ar, but no requested luminosity defined

High intensity lighter ions than Pb would need shielding over LEIR, currently not foreseen (not needed for fixed target programme)

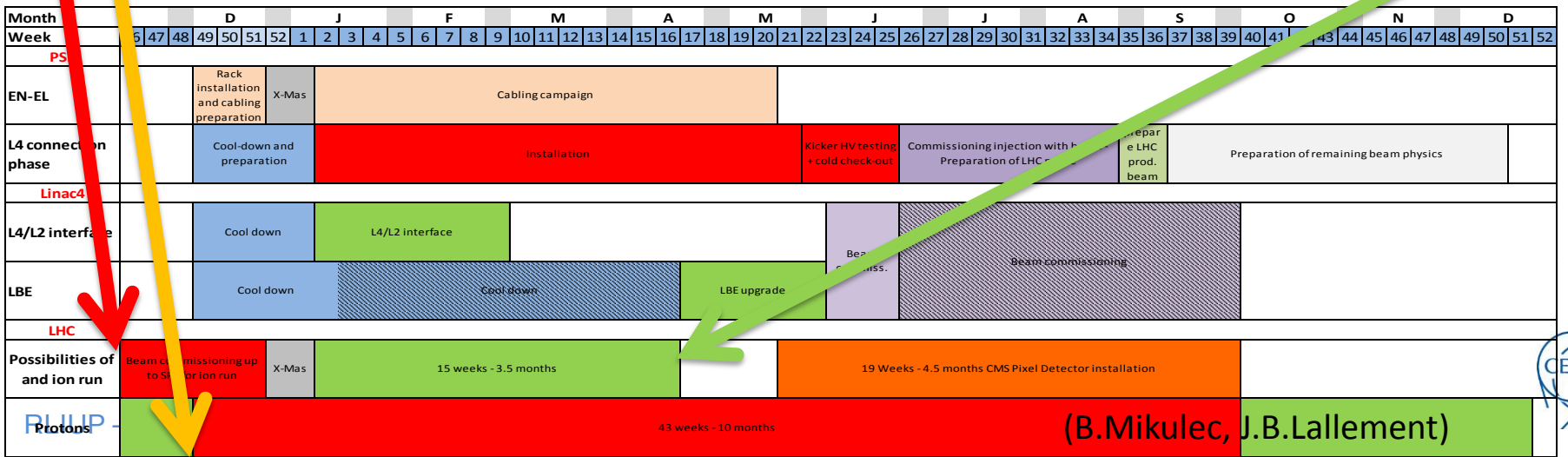
- LHCf has expressed interest in N-O, O-O, N-N, Fe-O, p-O, etc… at “very low luminosity”
- No official request for other ions
- Currently there is only one ECR source (may change with BioLEIR)
- Ar 2014-2015, then Xe 2016-2017 for fixed target programme in SPS
  - these two species could be available for collisions in LHC after LS2 (scheduling needed)
- O-O or p-O could be available for tests runs as early as before LS2, since O_2 is used as support gas for Pb

Schedule without LS1.5

- Ar commissioning in 2014, FT run in February-March 2015
- Switch to Pb in May 2015, for a first Pb-Pb run in November 2015
  - Note: A lot of MD time needed to retrieve 2013 performance 
- Xe commissioning begins (Linac3/LEIR/PS) in 2016
- Switch to Pb in Summer 2016, Pb-Pb run in LHC November 2016
- Xe end of commissioning (PS/SPS) + FT Run February-June 2017
- Switch to Pb in Summer 2017 for p-Pb run in November 2017 (+ 6 months?), followed by LS2

Schedule with LS1.5

- Ar 2014-2015 … first Pb-Pb run in November 2015 same as baseline
- Xe commissioning (Linac3/LEIR/PS/SPS) start early 2016 + FT Run in September 2016
- Switch to Pb November 2016, recommission Pb ion chain
- Stop protons 3 weeks before Xmas break
- Pb source standby during Xmas (cf Xmas 2012)
- Restart Pb ion chain in January
- 3.5 (max) months Pb run:
  - Ion MDs in chain
  - Primary Pb in NA
  - 8+ week LHC Pb-Pb run (grouping of 2016 & 2017 “November” runs)
- Restart with protons, next Pb ion run as p-Pb just before LS2 (2019?)



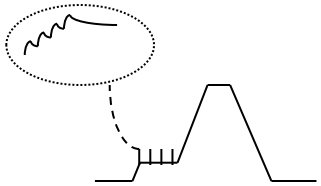
(B.Mikulec, J.B.Lallement)

Conclusions

- With the current scheme, the present injector performance would deliver $\mathcal{L}_{peak}$= 2.3x10^{27}cm^{-2}s^{-1} at 6.5ZTeV
- A robust baseline scheme is presented, which ensures bringing the peak Pb-Pb luminosity at 6.5ZTeV to $\mathcal{L}_{peak}$= 4.0x10^{27}cm^{-2}s^{-1} with feasible upgrades in the injectors.
- The main investment consists in an upgrade of the SPS injection scheme, using a septum recuperated from the PSB extraction line, after its upgrade to 2GeV, and a new pulser which had already been foreseen at the time of design.
- Until the SPS injection is upgraded, new RF gymnastics in the PS (demonstrated in 2012) already bring a 22% increase to $\mathcal{L}_{peak}$= 2.8x10^{27}cm^{-2}s^{-1}
- 2-bunch 50ns batch compression RF gymnastics under study could increase this figure to $\mathcal{L}_{peak}$= 3.2x10^{27}cm^{-2}s^{-1}
- A promising slip stacking scheme is being investigated, which would bring the performance to the experiments expectations
- Other ions such as Ar, Xe, or even O can be envisaged but are currently neither scheduled, nor specified
- Connecting the LINAC4 to the PSB during a 9 month proton stop “LS1.5” in the middle of Run2 could be used for a (maximum) 3.5 month Ion run
(Pb-Pb in LHC + FT for North Area + **MDs in injector chain, in view of HL-LIC**)
and would move other species (i.e. Xe) out of the way.

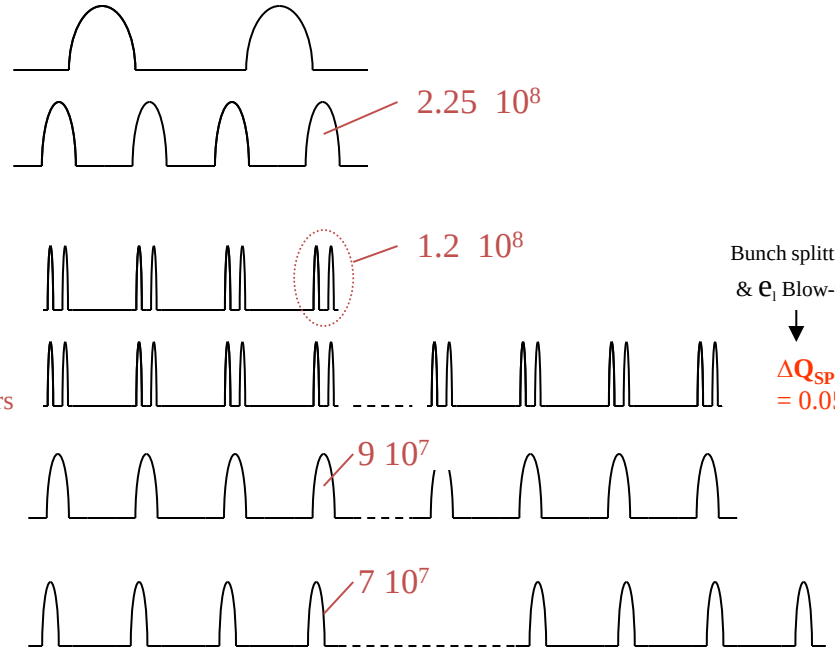
THANK YOU FOR YOUR ATTENTION!

Nominal scheme



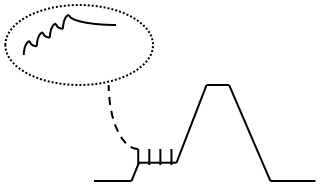
4 injections

	Nb of bunches	Pb ions / (future) LHC bunch	Harmonic number / Frequency
LEIR (9 10^8 Pb ions / 3.6 s)	2		2
PS after 1st splitting	4	2.25 10^8	16–14-12-24
PS after 2nd splitting	4 pairs	1.2 10^8	24-21 -169-423
SPS at injection (43.2 s flat-bot), after 13 (12, 8) transfers from PS	52 (32, 8) pairs	Bunch splitting & ϵ_l Blow-up → ΔQ_{SPS} = 0.05	200 MHz
SPS at extraction	52 (32, 8)	9 10^7	100 MHz + 200 MHz
LHC at injection, after 12 transfers from SPS	592	7 10^7	400 MHz



β^* = 0.5 m -> L = 10^{27} cm^{-2} s^{-1}

Baseline scheme: 100 ns

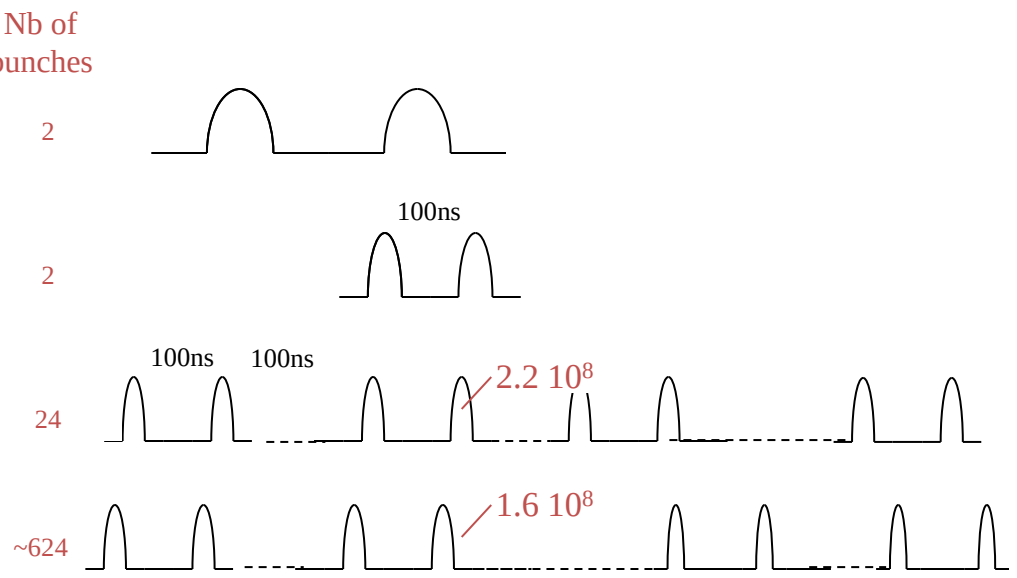


LEIR (1.1 10^9 Pb ions / 3.6 s)

PS batch compression
bunch spacing = 100ns

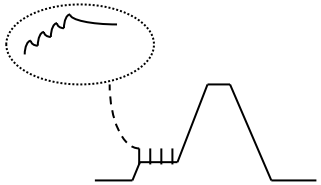
SPS at extraction,
after 12 transfers from PS,
Batch spacing = 100 ns

LHC at injection,
after 26 transfers from SPS



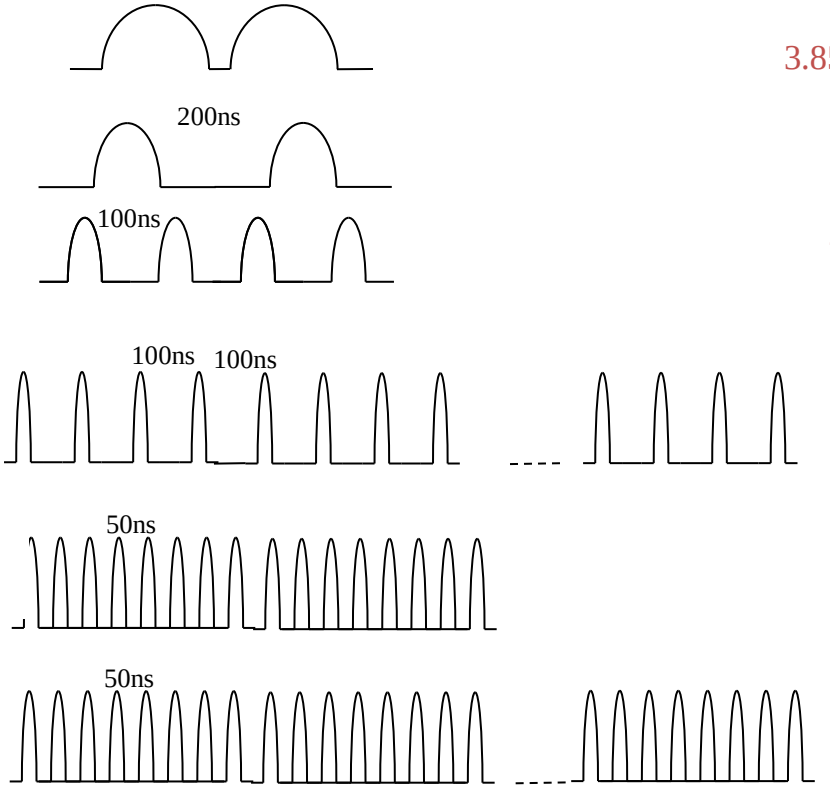
β* = 0.5 m -> L = 4x10^{27} cm^{-2} s^{-1}

50 ns slip-stacking scheme

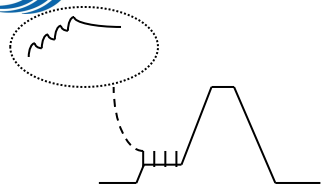


6 injections

	Nb of bunches	Pb ions / (future) LHC bunch	Harmonic number / Frequency
LEIR (1.54 10^9 Pb ions / 3.6 s)	2	3.85 10^8	2
PS batch expansion	2		16 – 14 – 12
PS bunch splitting followed by batch expansion (100ns bunch spacing) and rebucketing at 80MHz	4	2.7 10^8	12-24-21 169
SPS at injection after 2x6 transfers from PS, with 100ns batch spacing	2x24		200 MHz
SPS at high energy after split stacking (50ns batch spacing)	48		
LHC at injection, after 26 transfers from SPS	1248	1.2 10^8	400 MHz

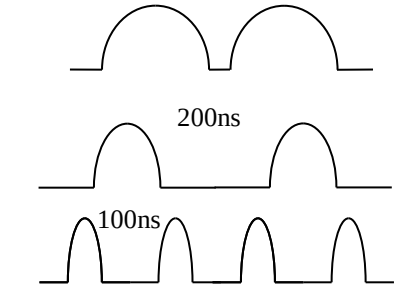


p-Pb scheme using slip-stacking

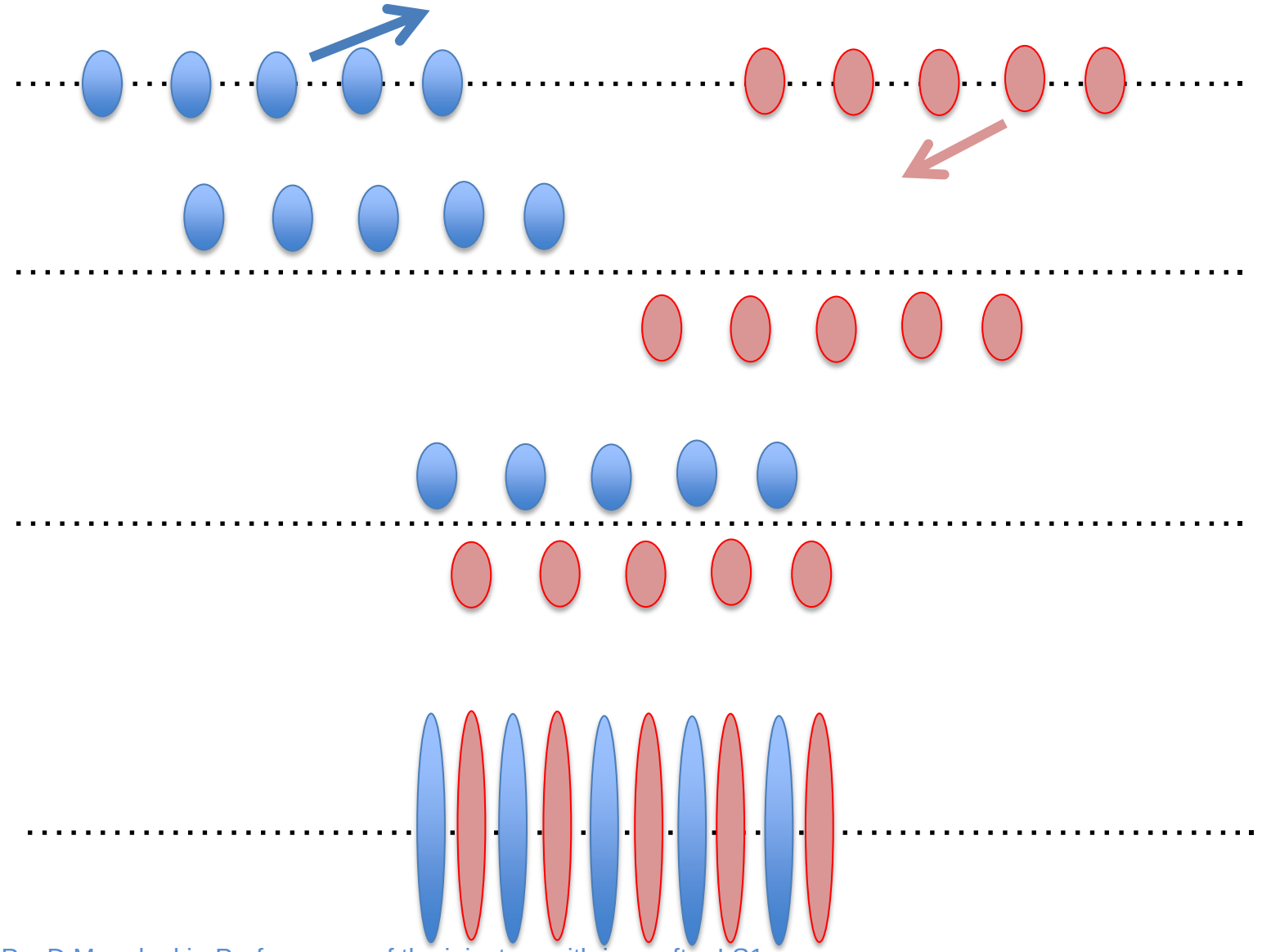


6 injections

	Nb of bunches	Pb ions / (future) LHC bunch	Harmonic number / Frequency
LEIR (1.3 10^9 Pb ions / 3.6 s)	2	3.2 10^8	2
PS batch expansion	2		16 – 14 – 12
PS bunch splitting followed by batch expansion (100ns bunch spacing) and rebucketing at 80MHz	4	2.7 10^8	12-24-21 / 169
SPS at injection after 4+5 transfers from PS, with 100ns batch spacing	16+20	2 10^8	200 MHz
SPS at high energy after split stacking (50ns batch spacing, similar pattern as 50ns protons but different)	36	1.6 10^8	

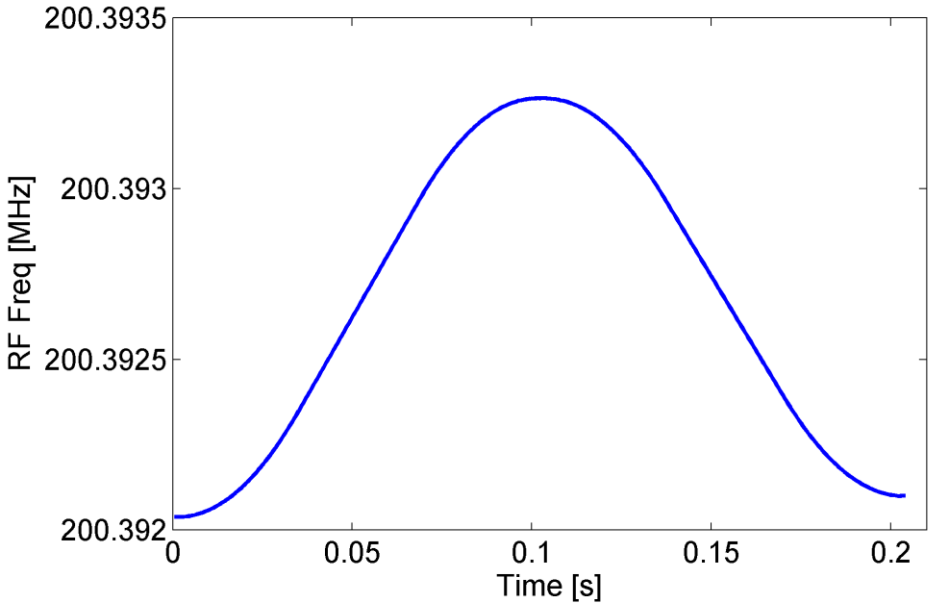


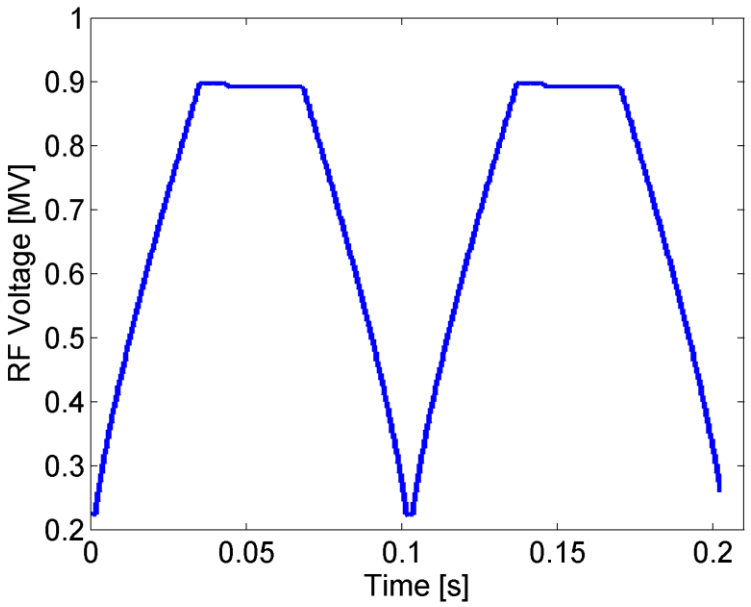
Slip stacking



RF (f_{rf} and V) programs

- 1st group of the 200 MHz RF: frequency and voltage programs

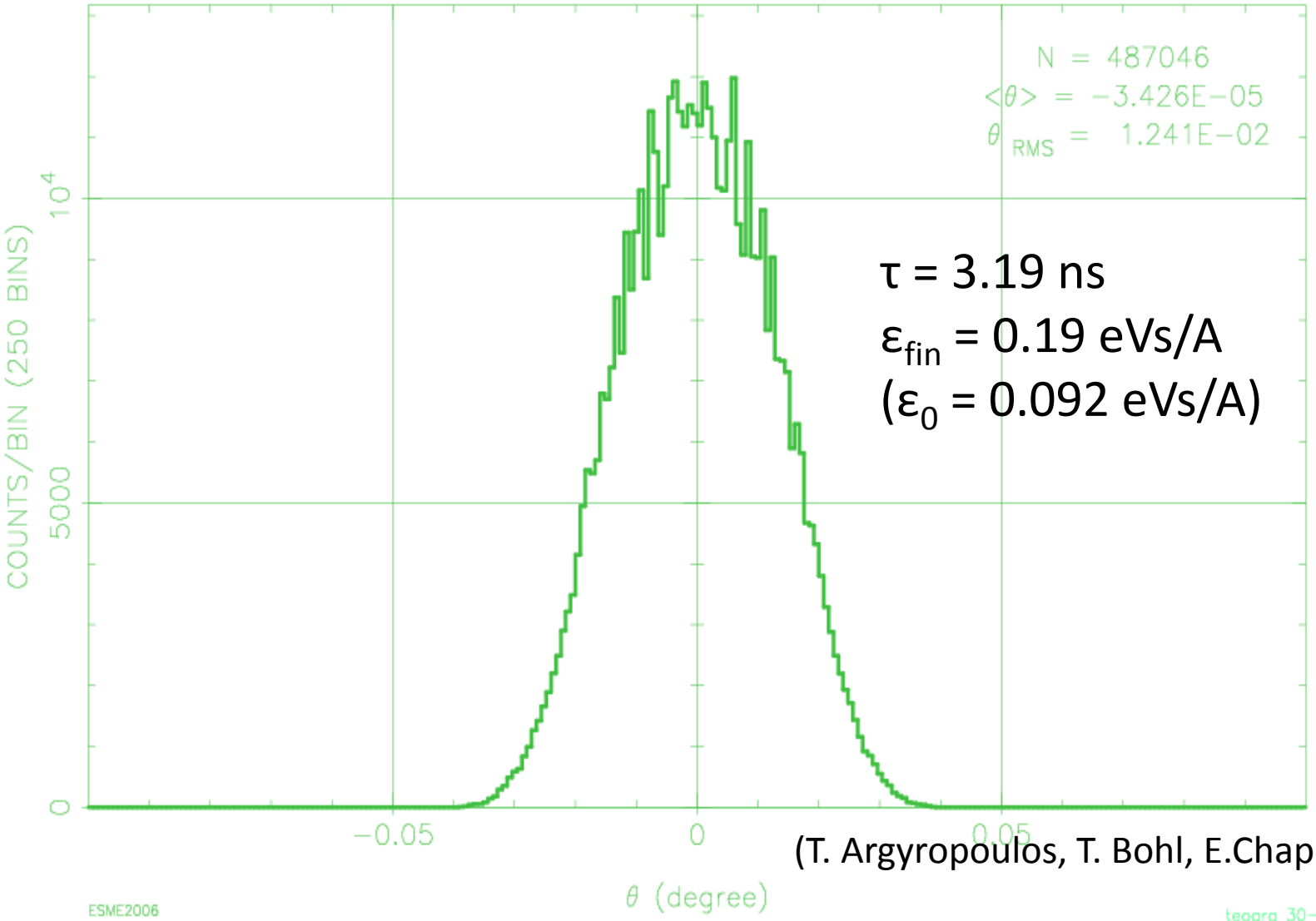




2nd group of RF: constant voltage of 0.225 MV and f_{RF2}=200. 39197748 MHz)

(T. Argyropoulos, T. Bohl, E.Chapochnikova)

After recapture (~0.8 s)



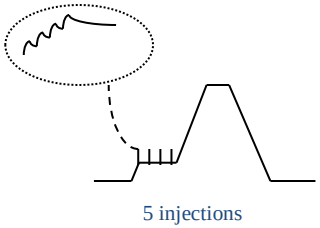
τ = 3.19 ns

ε_{fin} = 0.19 eVs/A

(ε_0 = 0.092 eVs/A)

(T. Argyropoulos, T. Bohl, E.Chapochnikova)

100/225 ns scheme for 2015



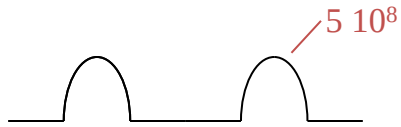
LEIR (10^9 Pb ions / 3.6 s)

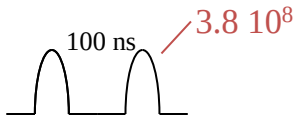
PS batch compression
bunch spacing = 100ns

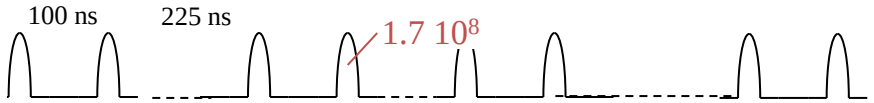
SPS at extraction,
after 12 transfers from PS,
Batch spacing = 225 ns

LHC at injection,
after 18 transfers from SPS

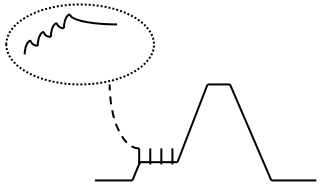
Nb of bunches	Pb ions / (future) LHC bunch	Harmonic number / Frequency
2	$5\ 10^8$	2
2	$3.8\ 10^8$	16–18-21 -169
24	$1.7\ 10^8$	200 MHz
432	$1.5\ 10^8$	400 MHz







Alternative scheme: 50/100 ns



6 injections

	Nb of bunches		Pb ions / (future) LHC bunch	Harmonic number / Frequency
				2
LEIR (1.54 10^9 Pb ions / 3.6 s	2		3.85 10^8	
PS batch expansion	2	200ns		16 – 14 – 12
PS bunch splitting followed by batch expansion (100ns bunch spacing)	4	100ns		12-24-21
PS acceleration on h=21 followed by batch compression (50ns bunch spacing)	4	50ns		21 – 25-30-36 -42
SPS at injection after 10 transfers from PS, with 100ns batch spacing	40	50ns 100 ns		200 MHz
LHC at injection, after 25 transfers from SPS	1000	50ns 100ns	1.3 10^8	400 MHz