Operational Beams for the LHC

(in the injector complex)

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LHC Performance Workshop

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Acknowledgements

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Outline

- LHC requirements for the injectors
- Single bunch beams
- 25 ns and 50 ns physics beams
- Doublet scrubbing beam and 8b+4e beam
- LHC Ion beam
- LHC beams' status and planning
- Conclusions

H. Bartosik and G. Rumolo, LBOC, 08/04/2014
H. Bartosik and G. Rumolo, Evian 2014
D. Manglunki, LIU-Ion LEIR review, 20/08/2014

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(Proposed) LHC start up in 2015

M. Lamont, LMC, 10/09/2014

450GeV

6.5 TeV ?

Commissioning (low intensity/luminosity)

Vacuum conditioning (50ns/short trains 25ns) (5-7 days)

Scrubbing with 25ns (2 days)

50ns (intensity ramp up + physics)

LHCPROBE
LHCINDIV
(Van der Meer)

LHC50 (std)
up to 1.5 x 10^{11} p/b *

LHC25 (std)
1.2 x 10^{11} p/b *

LHC50 (std/BCMS)
up to 1.7 x 10^{11} p/b *

450GeV

6.5 TeV ?

25ns scrubbing (5 days)

Scrubbing with doublet beams (≈ 5 days)

25ns test ramps + commissioning (≈ 5 days)

LHC25 (std)
1.2 x 10^{11} p/b *

LHC25doublet
1.6 x 10^{11} p/doublet *

LHC25 (std/BCMS)
up to 1.3 x 10^{11} p/b *

Intensity ramp up & physics with 25ns

LHC25 (std/BCMS)
up to 1.3 x 10^{11} p/b *

Or, if scrubbing not sufficient

Use of low e-cloud filling patterns

Possible alternative
LHC25 (8b+4e)
up to 1.8 x 10^{11} p/b *

* At LHC injection

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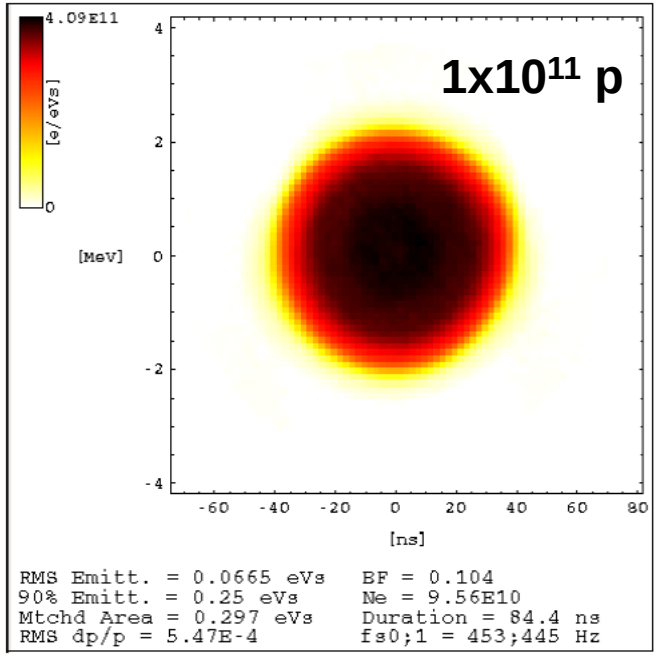
LHCPROBE & LHCINDIV – specs @LHC injection

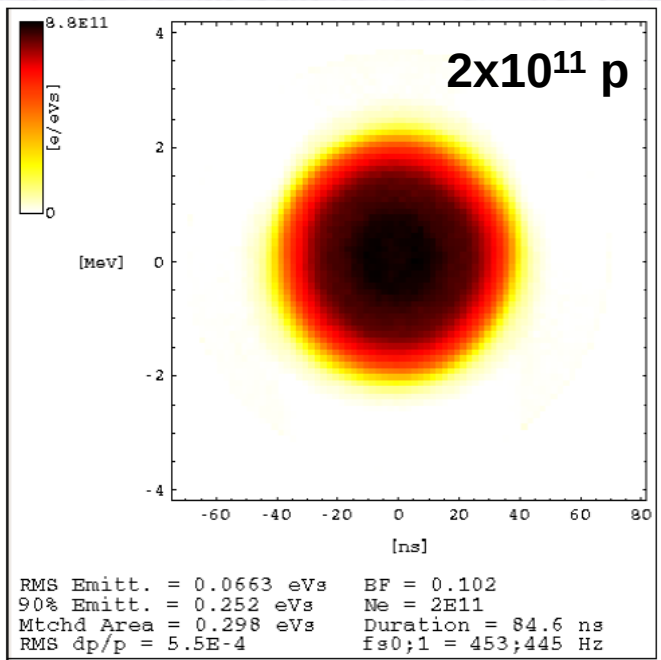
	LHCPROBE	LHCINDIV
Intensity [p/b]	$5 \times 10^9 - 2 \times 10^{10}$	$2 \times 10^{10} - 3 \times 10^{11}$
Transverse emittance, 1σ [μm]	1	< 2.5
Longitudinal emittance [eVs]	0.35	0.35 – 0.5

- LHCPROBE (=LHCPILOT) usually with intensities ≤ 10^{10} p/b, transverse emittance not critical (but anyhow small)
- LHCINDIV parameter range also extended in MDs to produce single bunches with up to 4×10^{11} p/b and/or with lower longitudinal emittances (down to 0.15 eVs) at SPS injection
  - High-intensity variants for possible impedance or beam-beam studies

LHCPROBE & LHCINDIV

- Production mechanism improved in PSB since 2013, covering parameter range for both type of beams **S. Hancock, CERN-ATS-Note-2013-040 MD**
  - Reworking of controlled longitudinal blow up (C16 and C02 parameters) during first part of PSB cycle
  - Unique knob (C16 voltage) for intensity control
  - Preserving the 6D phase space volume for different intensity values
  - Excellent shot-to-shot reproducibility and control of both intensity and longitudinal emittance





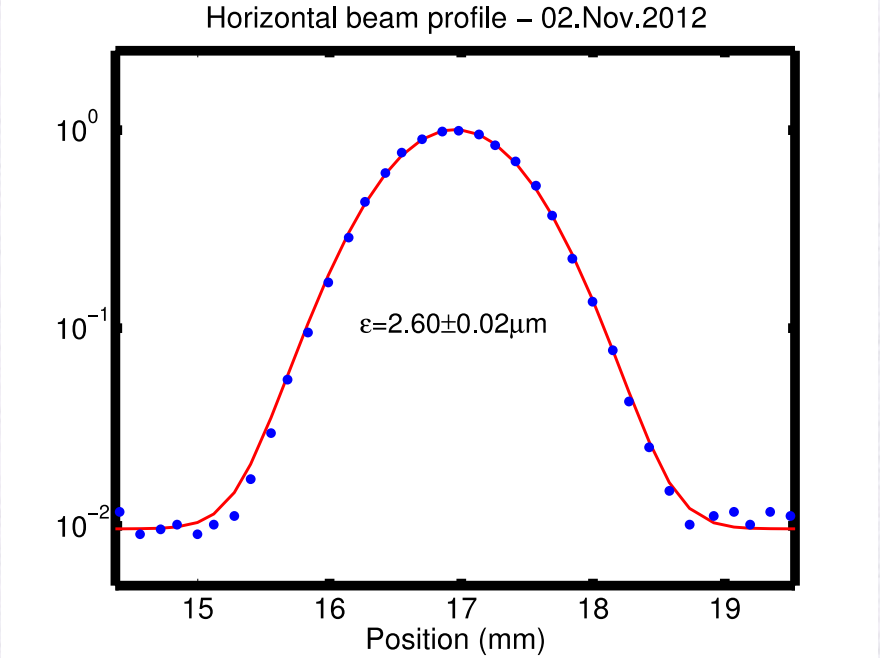
LHCINDIV for Van der Meer scans

Single bunch beam parameters	
Intensity [p/b]	7 – 9 x 10^{10}
Transverse emittance, 1σ [μm]	≥ 2.5
Transverse distribution	**Gaussian**

To be reproduced in 2014/15 …

H. Bartosik and G. Rumolo, CERN-ACC-NOTE-2013-0008 MD

- Procedure for producing Gaussian bunches for Van der Meer scans established in 2012
  - Based on longitudinal AND transverse shaving in the PSB to obtain “large” emittance single bunches with under-populated tails
  - Provides Gaussian bunches with the desired intensities in the SPS after scraping



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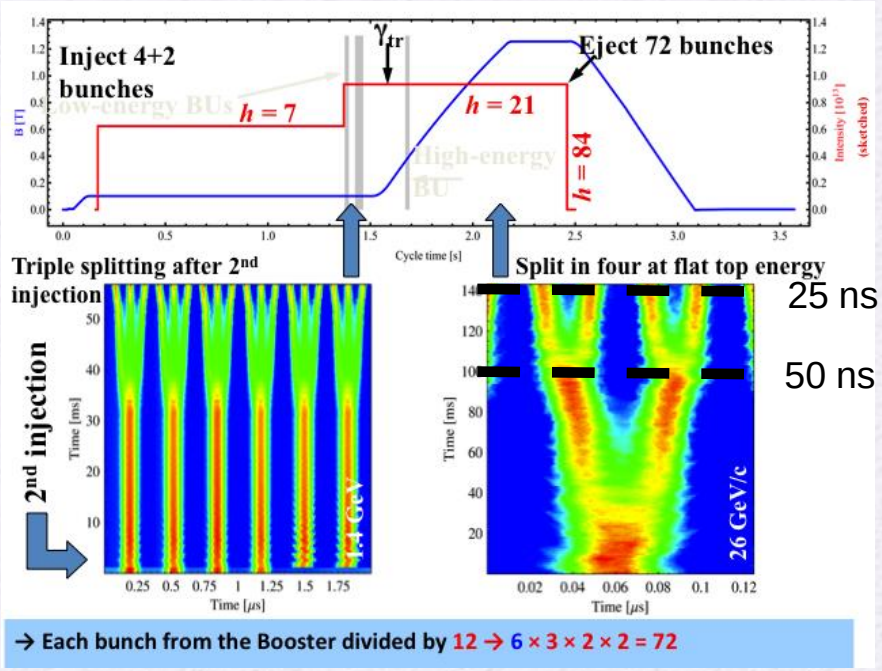
LHC25 and LHC50 (standard & BCMS)

Standard scheme:

(maximum number of bunches in LHC)

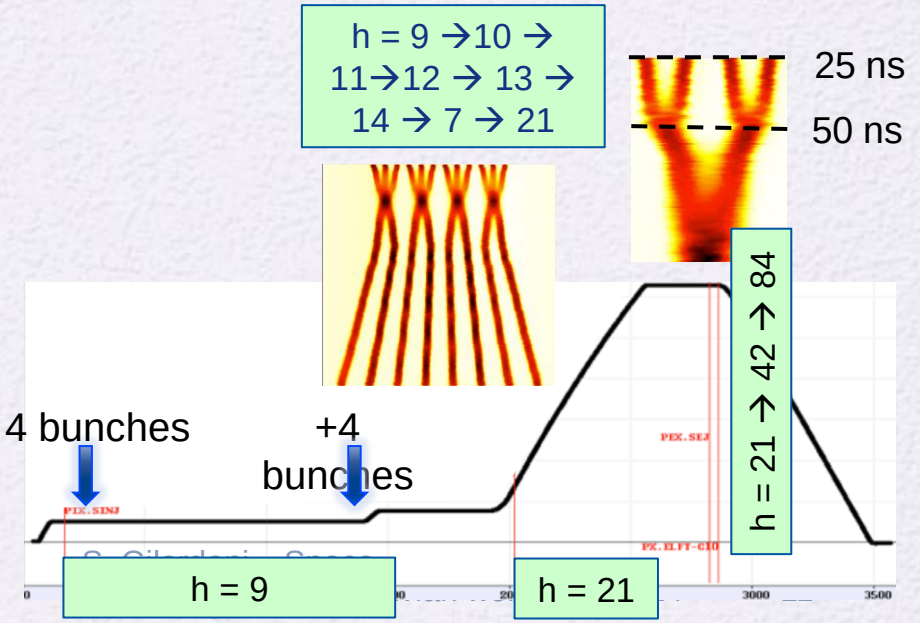


PS batches with 72 (36) bunches for 25ns (50ns)

Triple splitting up to 2013 at 1.4 GeV (moved to 2.5 GeV after LS1)

BCMS scheme:

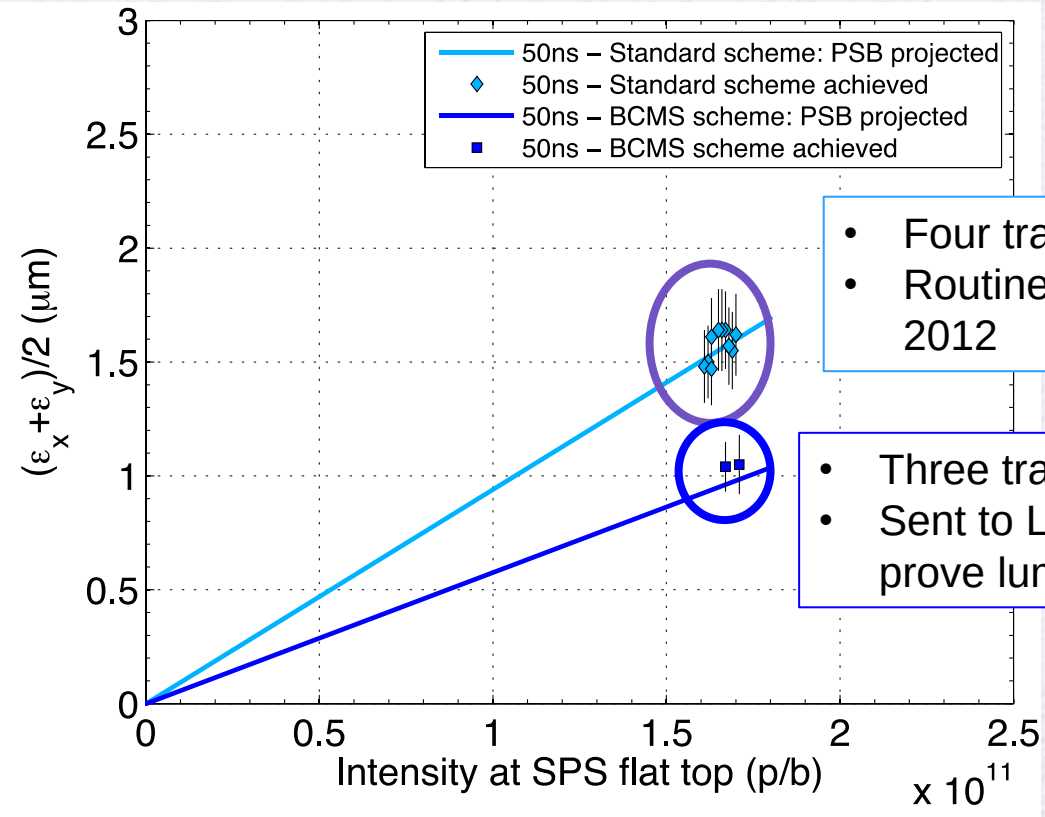
(less bunches in LHC but higher brightness)



PS batches with 48 (24) bunches for 25ns (50ns)

LHC50 (std & BCMS) – pre-LS1 status

- 50 ns beam at the **SPS extraction** in 2012/13 (Q20)
  - Combined wire-scans at end of **SPS flat bottom** (values cross-checked @ LHC)
    - Error bars include measurement spread, as well as systematic uncertainty (10%)
  - Intensity measured at SPS flat top after scraping
  - Transport through PS and SPS within intensity loss and emittance blow up budgets



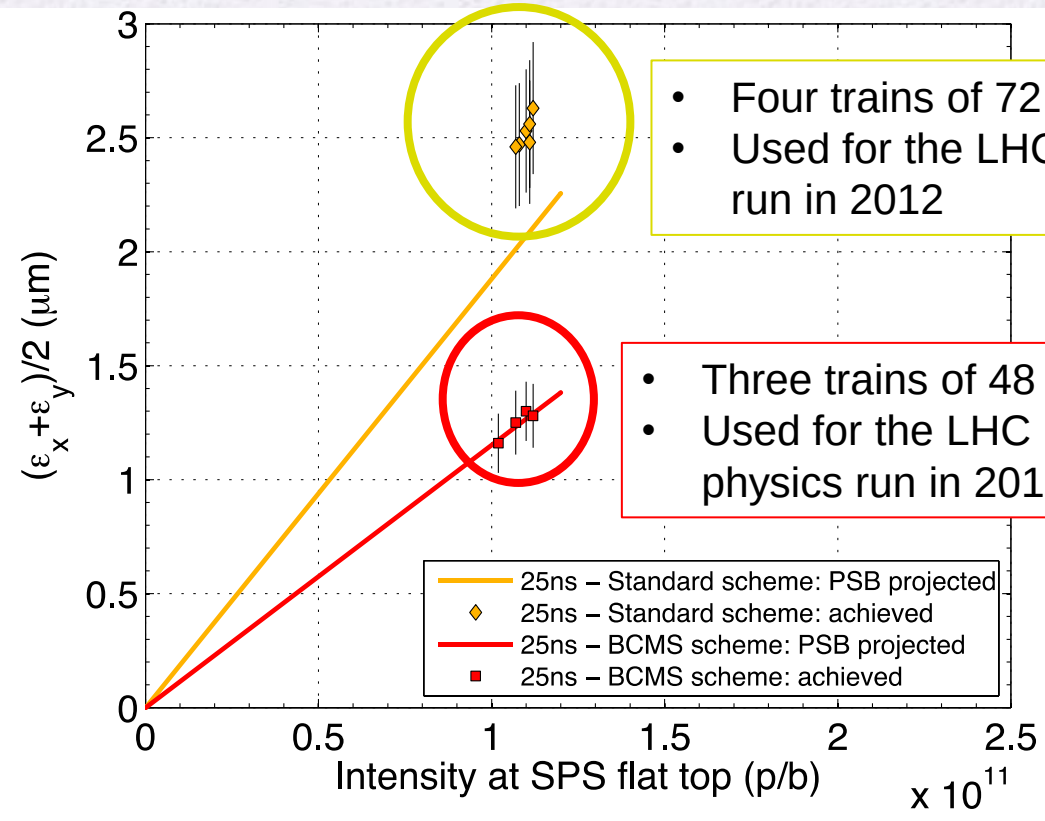
- Four trains of 36 bunches
- Routinely used for physics in 2012

- Three trains of 24 bunches
- Sent to LHC only for test to prove luminosity gain

Budget	PS	SPS
$\Delta\varepsilon_{x,y}/\varepsilon_{x0,y0}$	5%	10%
$-\Delta N/N_0$	5%	10%

LHC25 (std & BCMS) – pre-LS1 status

- 25 ns beam at the **SPS extraction** in 2012/13 (Q20)
  - Combined wire-scans at end of **SPS flat bottom** (values cross-checked @ LHC)
    - Error bars include measurement spread, as well as systematic uncertainty (10%)
  - Intensity measured at SPS flat top after scraping
  - Transport through PS and SPS 15% above budget for standard beam



- Four trains of 72 bunches
- Used for the LHC scrubbing run in 2012

- Three trains of 48 bunches
- Used for the LHC pilot physics run in 2012

Budget	PS	SPS
$\Delta\varepsilon_{x,y}/\varepsilon_{xo,yo}$	5%	10%
$-\Delta N/N_o$	5%	10%

Pre-LS1 performance limits

- Both standard production and BCMS beams already very close to the limits in injectors
- 50 ns beam
  - **Intensity/bunch:** close to the limit of longitudinal instability in the PS
  - **Brightness**: BCMS at the present space charge limit in the SPS
- 25 ns beam
  - **Intensity/bunch:** close to the limit of RF power and longitudinal instability in the SPS
  - **Brightness**: At the present space charge limit in the PS

LHC50/25 beam production after LS1

- Recover 2012 performance
  - Machines exposed to air → electron cloud → SPS scrubbing run
  - RF manipulations in the PS performed at 2.5 GeV instead of 1.4 GeV in all LHC cycles (regularly used with BCMS beams in 2012)
    - increases available bucket area
    - tuning groups of cavities have changed → allows for further increase of bucket area

- Potential for **higher bunch intensity**
  - Possible benefits in the PS from
    - upgraded 1-turn delay feedback for 10 MHz cavities (available at start-up 2014)
    - upgraded longitudinal coupled-bunch feedback (commissioning starting in 2014)
  - 25 ns up to 1.3 x 10^{11} p/b at SPS extraction as during 2012 MDs (limited by RF power and longitudinal instabilities in the SPS)

- Potential for **higher brightness** (as from RLIUP workshop)
  - PS: Alleviate space charge by longer bunches and larger momentum spread
    - need longitudinal blow-up on the PSB ramp to produce required emittance
    - use of h1+2 in phase at PSB extraction to keep these larger longitudinal emittance bunches within certain length (recombination kicker rise time constraint)
  - SPS : further working point optimization for 50 ns BCMS beam

Post-LS1: PSB – PS transfer

Recombination kicker rise time:

Kinetic energy, E_{kin}	Rise time
1.4 GeV	**105 ns**

	E_{kin}	Bucket length	Max bunch length
h=7 (std)	1.4 GeV	327 ns	220 ns
h=9 (BCMS)	1.4 GeV	255 ns	150 ns

Longitudinal emittance per bunch at PS injection should not exceed

- [Total Split Factor x 0.35 eVs]/1.1 (includes 10% margin for blow-up)
- About 3 eVs (h=7) and 2 eVs (h=9) for RF manipulations at E_{kin}=2.5 GeV
- [FB Split Factor x 1 eVs] for transition crossing in h=21
- Matched value in the PSB (h1+2) to obtain the above bunch lengths

Post-LS1: PSB – PS transfer

Recombination kicker rise time:

Kinetic energy, E_{kin}	Rise time
1.4 GeV	**105 ns**

	E_{kin}	Bucket length	Max bunch length	Bunch length (pre-LS1)
h=7 (std)	1.4 GeV	327 ns	220 ns	180 ns
h=9 (BCMS)	1.4 GeV	255 ns	150 ns	150 ns

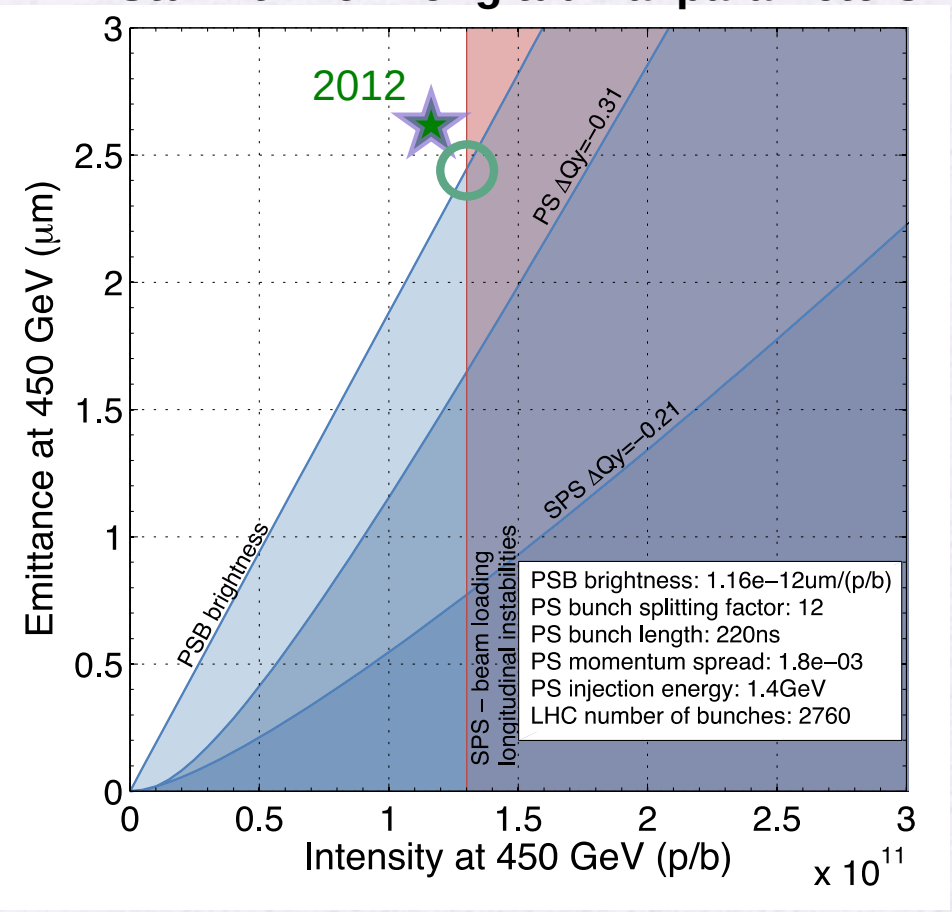
Longitudinal emittance per bunch at PS injection should not exceed

- [Total Split Factor x 0.35 eVs]/1.1 (includes 10% margin for blow-up)
- About 3 eVs (h=7) and 2 eVs (h=9) f
- [FB Split Factor x 1 eVs] for transit
- Matched value in the PSB (h1+2) t

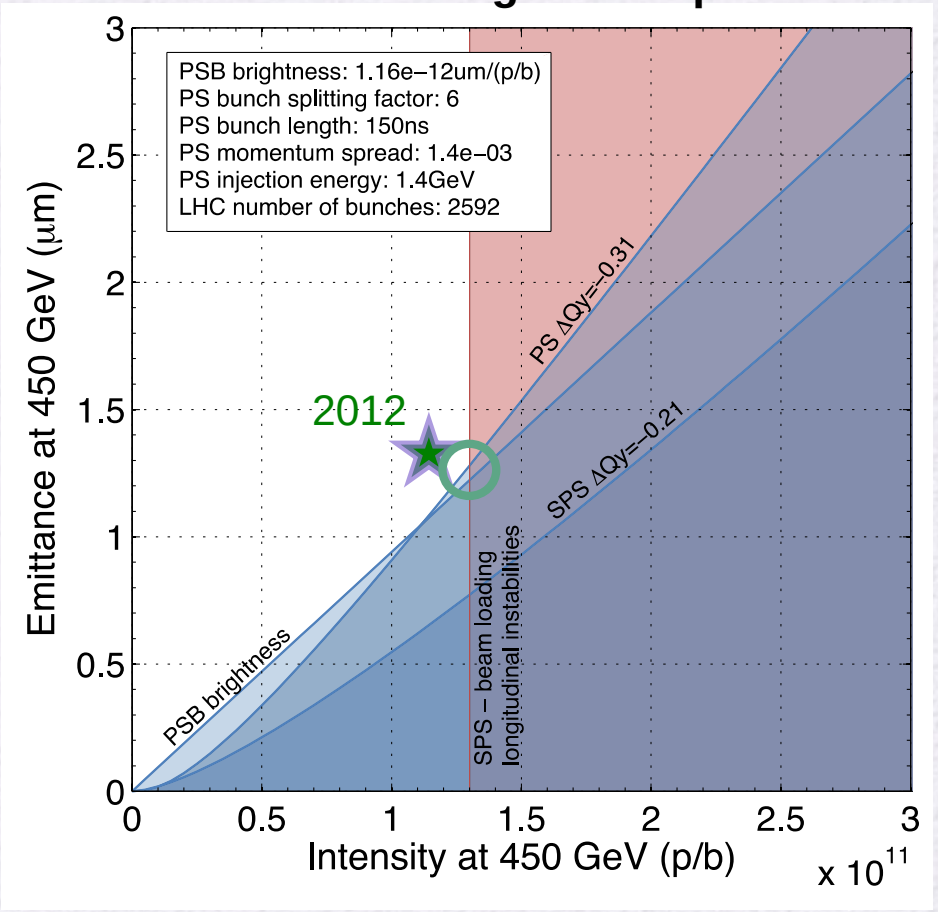
RF Manipulation:	@1.4 GeV	@2.5 GeV
50 ns (Std/BCMS)	1.2/0.9 eVs	1.9/0.9 eVs
25 ns (Std/BCMS)	1.2/0.9 eVs	2.8/1.5 eVs

Post-LS1: LHC25 (std & BCMS)

Std with new longitudinal parameters



BCMS with new longitudinal parameters



Beam parameters at LHC injection after LS1

2012 performance

25 ns	Intensity (p/b)	Emittance (μm)
Standard	1.2×10^{11}	2.6
BCMS	1.15×10^{11}	1.4

50 ns	Intensity (p/b)	Emittance (μm)
Standard	1.7×10^{11}	1.7
BCMS	1.7×10^{11}	1.1

- Assuming transport in the PS and SPS within budgets like in 2012
- **Requires successful SPS scrubbing !**
- All beams to be prepared in 2014!

Beam parameters at LHC injection after LS1

	2012 performance		with potential improvements from optimized PSB-PS transfer and intensity increase in SPS	
25 ns	**Intensity (p/b)**	**Emittance (μm)**	**Intensity (p/b)**	**Emittance (μm)**
Standard	1.2×10^{11}	2.6	1.3×10^{11}	2.4
BCMS	1.15×10^{11}	1.4	1.3×10^{11}	1.3

50 ns	**Intensity (p/b)**	**Emittance (μm)**	**Intensity (p/b)**	**Emittance (μm)**
Standard	1.7×10^{11}	1.7	1.7×10^{11}	1.6
BCMS	1.7×10^{11}	1.1	1.7×10^{11}	1.1

- Assuming transport in the PS and SPS within budgets like in 2012
- **Requires successful SPS scrubbing !**
- All beams to be prepared in 2014!

- Setup of longitudinal blow-up along PSB ramp and h1+2 transfer to the PS during commissioning and MDs
- Push SPS to intensity limit for 25 ns beams

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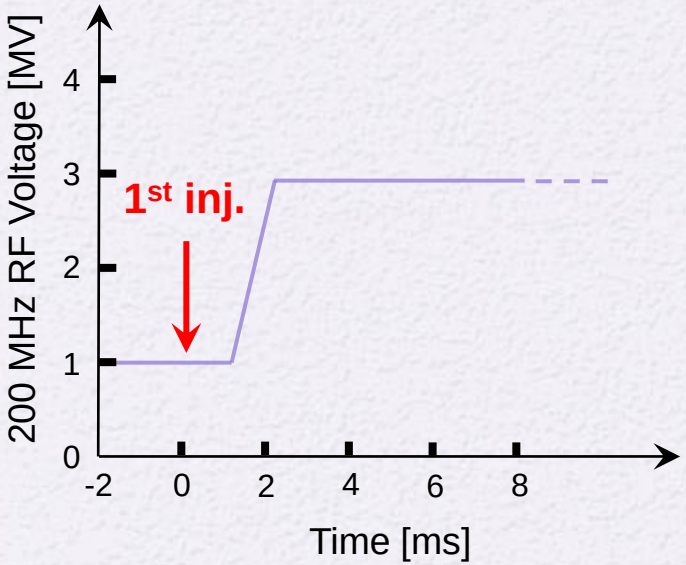
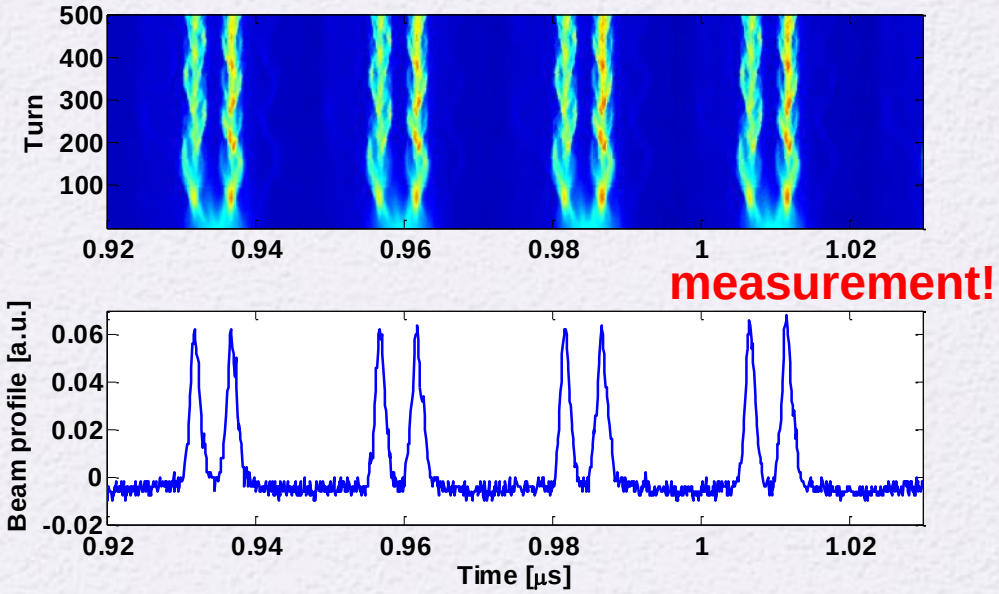
Doublet beam

- Injection of trains of 72 x 10 ns long bunches with 1.7e11 p/b on unstable phase and capture in two neighboring buckets in the SPS → **successfully tested (no acceleration to 450 GeV)** → **e-cloud enhancement observed in the SPS**



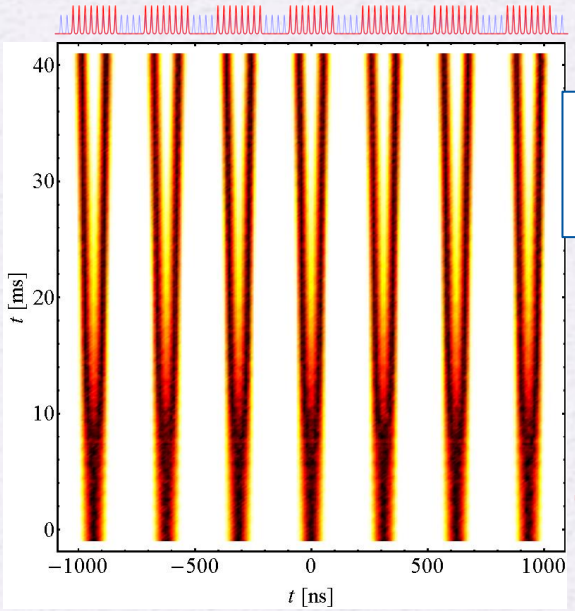


- Need to gain experience in the SPS with **dedicated MDs in 2014** for complete parameter list at flat top

For more info see H. Bartosik, Chamonix 2014

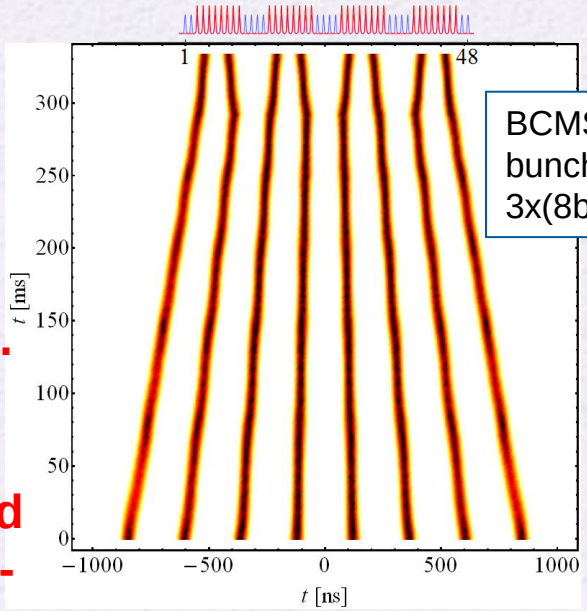
8b+4e scheme

- Trains with 4 missing bunches every 8 bunches **H. Damerau, RLIUP 2013**
  - Allows for larger intensity per bunch and expected to reduce e-cloud effects



Standard scheme bunch pattern: 6x(8b+4e) + 8b

Simulations shown. Recent successful tests in the PS. To be fully optimized in MDs during 2014-2015



BCMS scheme bunch pattern: 3x(8b+4e) + 8b

25 ns (8b+4e)	Intensity (p/b)	Emittance (μm)	Bunch pattern
Standard	1.8×10^{11}	2.3	6 x (8b+4e) + 8b
BCMS	1.8×10^{11}	1.4	3 x (8b+4e) + 8b

For more info see G. Rumolo, Chamonix 2014

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LHC ion performance in 2011

- Pb-Pb goal in 2011: 30-50 μb^{-1} in 4 weeks, with $\mathcal{L}_{peak}$ = $1.4x10^{26}$ Hz/cm^2

- Achieved @ 3.5ZTeV : **150 μb^{-1}** with peak luminosity $5x10^{26}$ Hz/cm^2 (half of the nominal)
  - Increased LEIR brightness with nominal bunch population of $4.5x10^8$ Pb^{54+} ions/bunch but smaller emittances
  - Scaling with E^2, $\mathcal{L}_{peak}$ = $2x10^{27}$ Hz/cm^2 @ 7ZTeV (twice the nominal)
    - Good beam behaviour at low energy in PS due to excellent vacuum
    - Modified production scheme: No splitting in PS, i.e. half as many bunches with twice the intensity/bunch
    - Good behaviour of bunches on SPS flat bottom (RF Noise improved, IBS & space charge less critical than expected and with Q20 after 2013)

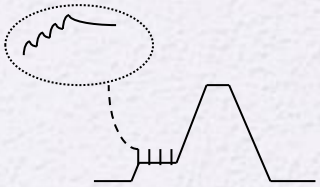
LHC ion performance in 2013 projected to 2015

- For p-Pb run in 2013, LEIR bunch intensity further increased to 5.5×10^8 Pb^{54+} ions/bunch (1.2 times the nominal)

- With same scheme as 2011, and performance of 2013, Pb-Pb peak luminosity of 3×10^{27} Hz/cm^2 @ 7ZTeV can be expected

- A 20% increase in peak luminosity (3.6×10^{27} Hz/cm^2 @ 7ZTeV) can be gained by squeezing 20% more bunches in LHC
  - Batch compression to 100ns in PS
  - Two-bunch batches separated by 225ns in SPS (12 injections, to be **optimised**)

LHC ion scheme in 2011



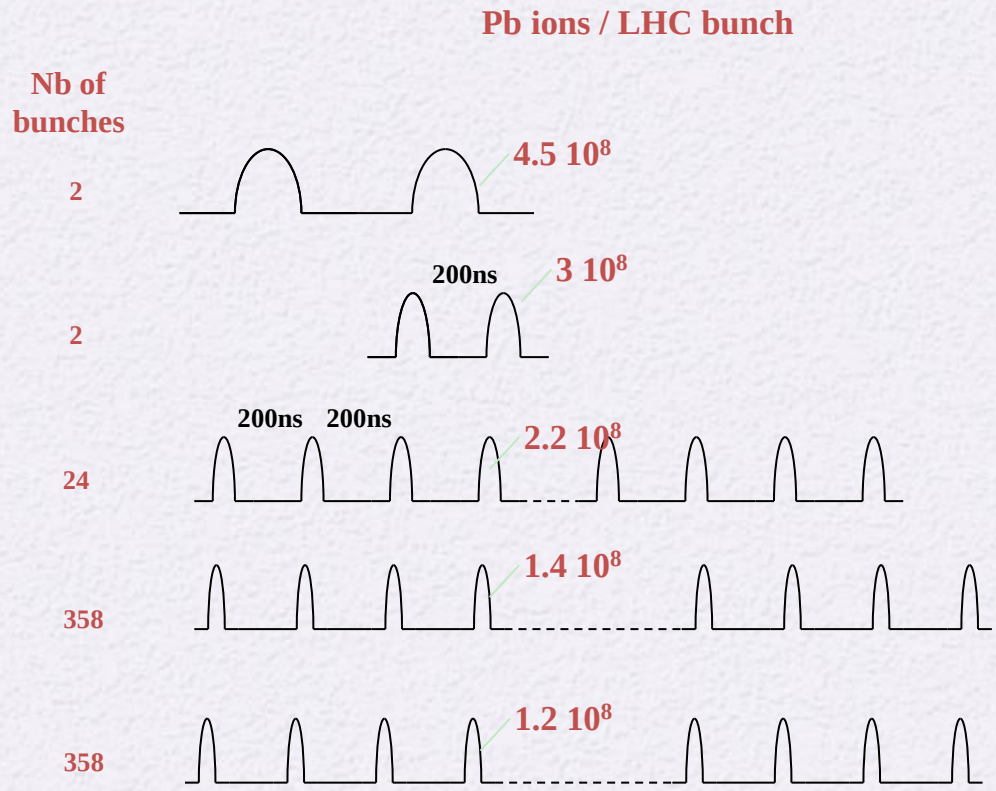
LEIR (9 10^8 Pb ions / 3.6 s)

PS (NO splitting)
bunch spacing = 200ns

SPS at extraction,
after 12 transfers from PS,
Batch spacing = 200 ns

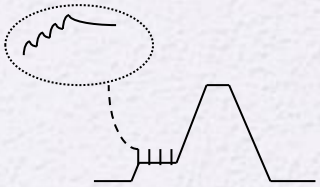
LHC at injection,
after 15 transfers from SPS

LHC in collision



$\beta^* = 1\ m \rightarrow L = 5.10^{26}\ cm^{-2}\ s^{-1}$

LHC ion scheme in 2015



7 injections

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

LHC in collision

Nb of bunches	Pb ions / LHC bunch	Harmonic number / Frequency
2		2
2	100ns	16–18-21 -169
24	100ns 225ns 2.2 10^8	200 MHz
432	1.6 10^8	400 MHz
432	100ns 225ns 1.4 10^8	

$\beta^* = 0.5$ m -> L = 3.6 10^{27} cm^{-2} s^{-1}

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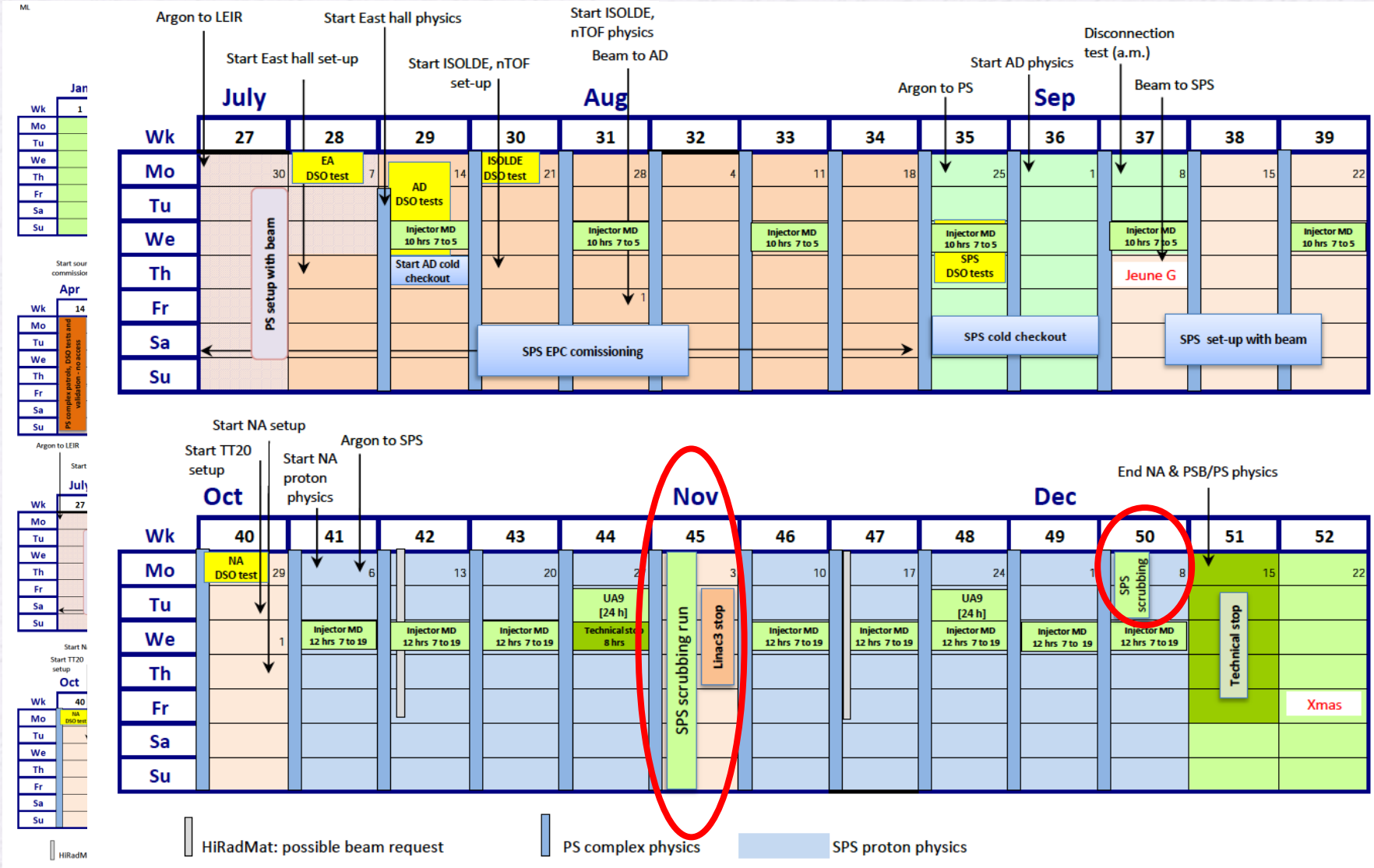
Revised Injector schedule 2014



LHC beam status and planning

K. Hanke, Chamonix 2014

- Recover 2012 performance
  - LHCPROBE (=LHCPILOT) and LHCINDIV
    - In good shape in PSB and PS, 12-24 bunches taken in SPS for realignment campaign and RF setting-up (energy matching)
  - LHC 25 and 50 ns standard
    - Produced in PSB and PS (triple splitting achieved), fine tuning in progress
    - Not taken yet in SPS (scrubbing in week 45)
  - LHC 25 and 50 ns BCMS not taken yet
- Pushing intensity of 25ns beam and production of doublet beam
  - To be established in (dedicated) MDs by the end of 2014 (scrubbing run II in 2015)
  - Many other concurrent MD requests and setting up of Ar for NA ion physics
- 8b+4e beam
  - Recent successful tests in the PS
  - Tests in the SPS probably not before 2015 due to limited MD time
- LHC ion beams not yet produced in LEIR but general problems solved
  - To be optimized in 2014-2015

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Conclusions

- Single bunch beams
  - New production scheme for better control of intensity and longitudinal emittance
- 25 ns and 50 ns beams
  - Recovering the 2012 performance relies on successful scrubbing of the SPS
  - Implementation of new beam production schemes for higher brightness in PSB and PS and higher intensity in SPS
  - Second SPS scrubbing run in 2015
- Doublet beam for LHC (and SPS) scrubbing
- 8b+4e beam as low e-cloud option
  - Successful measurements in the PS
  - Tests in SPS not before 2015 (limited MD time)

} lots of SPS MD time with very long cycle needed !!

- LHC ions
  - Pb performance in 2013 and PS batch compression (100ns)
- Injectors are already very busy: physics beams, LHC beams (old and new schemes!), ion beams in preparation for 2015, MDs …


Thank you for your attention