CERN, 18 March 2013
ICFA Mini-Workshop
on Beam-Beam Effects in Hadron Colliders (BB2013)

Observations of beam-beam effects at the LHC

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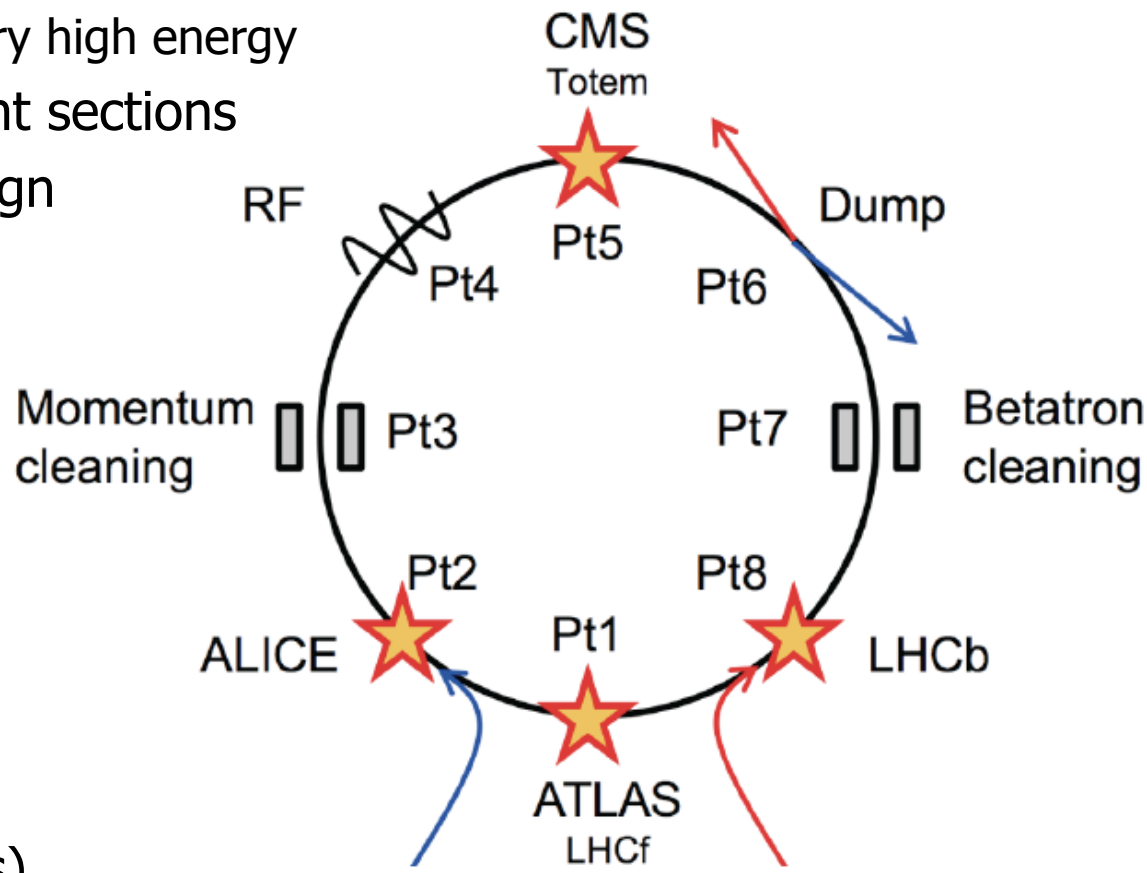
outline

- layout and filling scheme, numerology
  - collision pattern effects
  - potential loss of LD
- luminosity levelling with offset (IP2/8)
- HO tune shifts in MDs
- strong-strong effects: coherent modes and orbit
- scan of crossing angle
  - effect on losses and dynamic aperture
  - PACMAN observations

HO = Head-On
LR = Long-Range
LD = Landau Damping
MD = Machine Development
ppb = protons per bunch

LHC layout

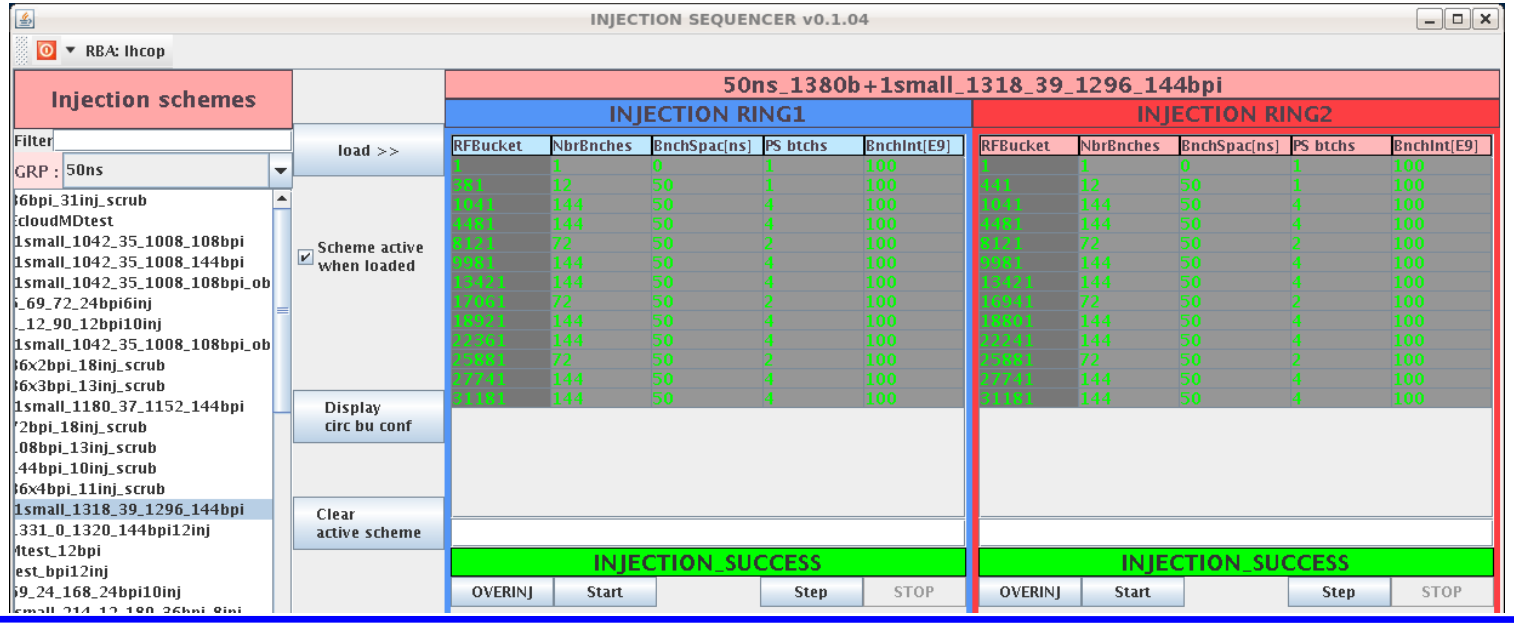
- Large Hadron Collider
  - very big, very cold, very high energy
- 8 arcs (~3km), 8 straight sections
- two-in-one magnet design



- IP2 and 8: injection
- IP6: beam dump region
- IP4: RF and BI
- IP3/7: collimators
- 4 Interaction Points (IPs)
  - IP 1 (ATLAS) and 5 (CMS): high luminosity experiments
  - 2 (Alice) and 8 (LHCb): with luminosity limitations

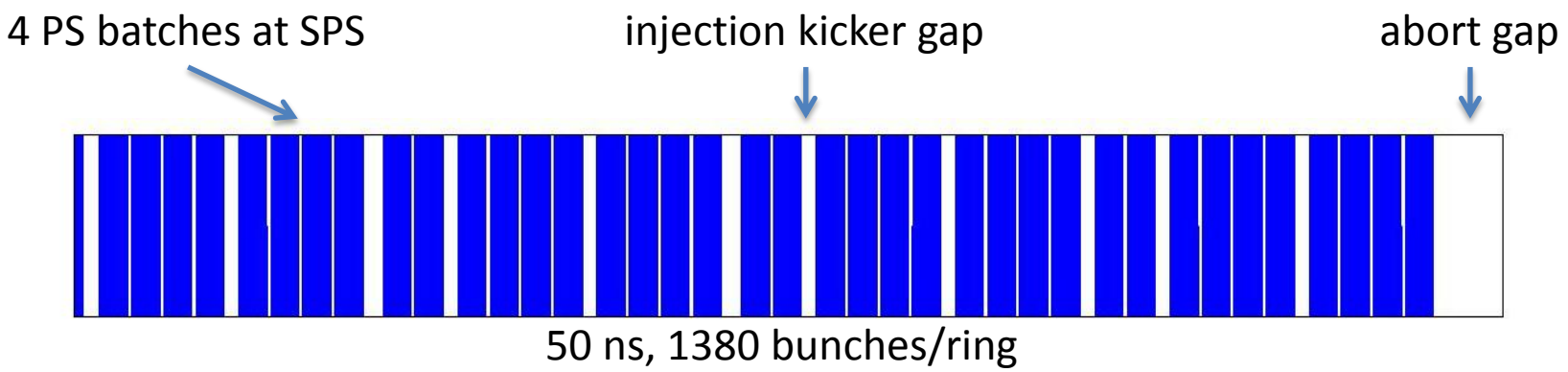
filling schemes

- motivation: different luminosity targets from the 4 experiments
  - filling schemes tailored to give different number of colliding pairs
    - ATLAS, Alice, CMS are located at the IP symmetry point, LHCb is 11.25 m away
  - techniques of luminosity levelling are operational
- 2.5 ns buckets, h = 35640, 25 ns minimum bunch spacing
- for a filling scheme we can chose:
  - bunch spacing: 25ns, 50ns, 75ns, 150ns, or >250ns
  - number of PS batches (1-4, dynamic), number of PSB rings
  - injection bucket



example for ring 1

INJECTION RING1				
RFBucket	NbrBnches	BnchSpac[ns]	PS btchs	BnchInt[E9]
1	1	0	1	100
381	12	50	1	100
1041	144	50	4	100
4481	144	50	4	100
8121	72	50	2	100
9981	144	50	4	100
13421	144	50	4	100
17061	72	50	2	100
18921	144	50	4	100
22361	144	50	4	100
25881	72	50	2	100
27741	144	50	4	100
31181	144	50	4	100



reminder on LHC performance

- 2010: inst. luminosity of $2x10^{32}$ $cm^{-2}s^{-1}$
- 2011: did 5.5 fb^{-1}
- 2012: did 23.2 fb^{-1}
  - ~nominal β^* thanks to excellent aperture and 'tight' collimators
  - very bright beams from injectors (note also SPS Q20 optics)

parameter	design	2012
beam injection energy (TeV)	0.45	0.45
beam energy (TeV)	7	4
number of bunches per beam (bunch spacing, ns)	2808 (25)	1380 (50)
β^* at IP1/5 (m)	0.55	0.6
number of particles per bunch (10^{11})	1.15	1.65
norm. transverse emittance (μm rad)	3.75	2.5
colliding beam size (μm)	16	19
luminosity ($cm^{-2}s^{-1}$)	1e34	0.77e34
stored beam energy (MJ)	362	145

why 50 ns and not 25 ns?

	# bunches	Nbunch (1e11 p)	ε SPS extr(μm)	ε LHC coll (μm)
25 ns	2760	1.15	2.8	3.75
50 ns	1380	1.6	1.7	2.3

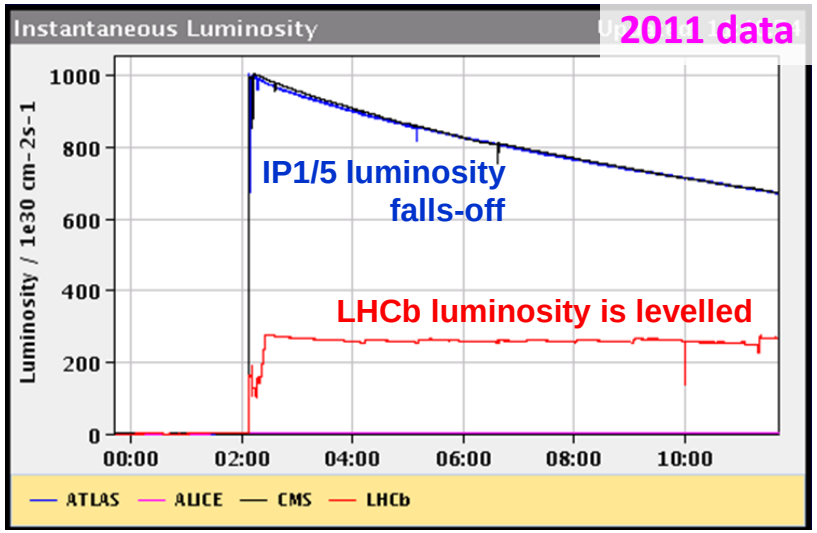
- 2012: 50 ns allowed more integrated luminosity while saving on scrubbing time
  - 50 ns beams are brighter from injectors
    - pile-up μ still manageable at 4 TeV (μ~30-35)
  - smaller emittance than for 25 ns allowed squeezing further
    - e.g. β^*_{50}=60 cm; β^*_{25}=80 cm;
  - 50 ns are much less affected by ecloud
    - thus less scrubbing time needed (3 days vs 2 weeks)
    - aim for more data for summer conference (July 2012)
- post LS1: 25 ns is default
  - too high pile-up with 50 ns (μ~80-120 vs μ~25-45 with 25 ns)
    - might need levelling even with 25 ns
  - "when" will depend on scrubbing efficiency
  - note: no more non-colliding bunches

pile-up: number of inelastic collisions per bunch crossing

R. Jacobsson, "*Needs and requirements from the LHC physics experiments*"

luminosity levelling with offset

- LHCb and Alice limited in pile-up μ
  - LHCb at μ~2.5
  - Alice at μ~0.02
    - ran also with main-satellite collisions (satellites at 25 ns)
- run with separated beams (transverse offset)
  - e.g. LHCb: running at constant L ~ $4 \cdot 10^{32}$ $cm^{-2}s^{-1}$
  - trimming down the offset in small steps during the fill
  - people worried at first, but no real showstopper found



R. Jacobsson, "*Needs and requirements from the LHC physics experiments*"

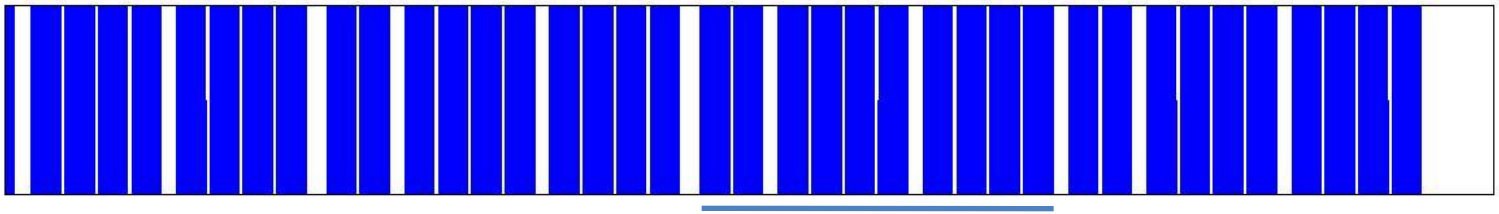
B. Muratori, "*Luminosity levelling techniques: implications for beam-beam interactions*"

D. Jacquet, "*Implementation and experience with luminosity levelling with offset beams*"

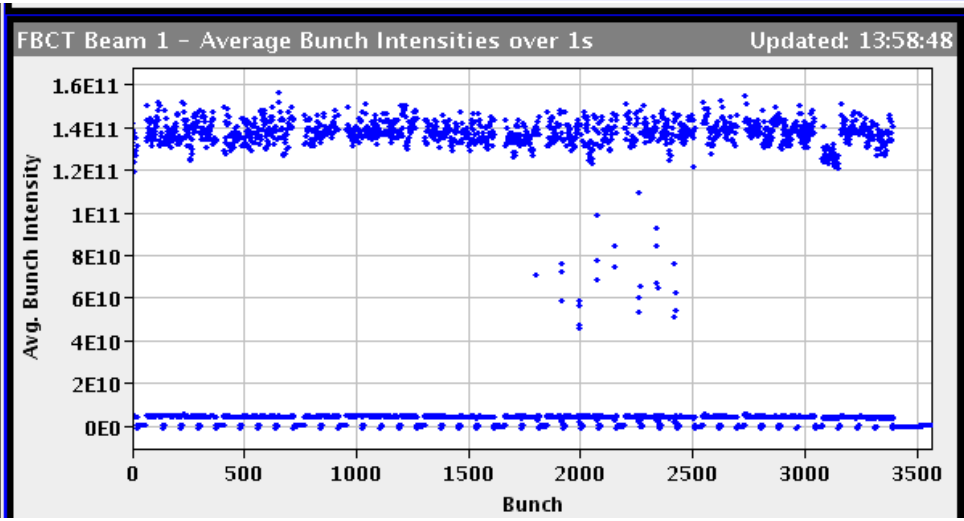
collision patterns

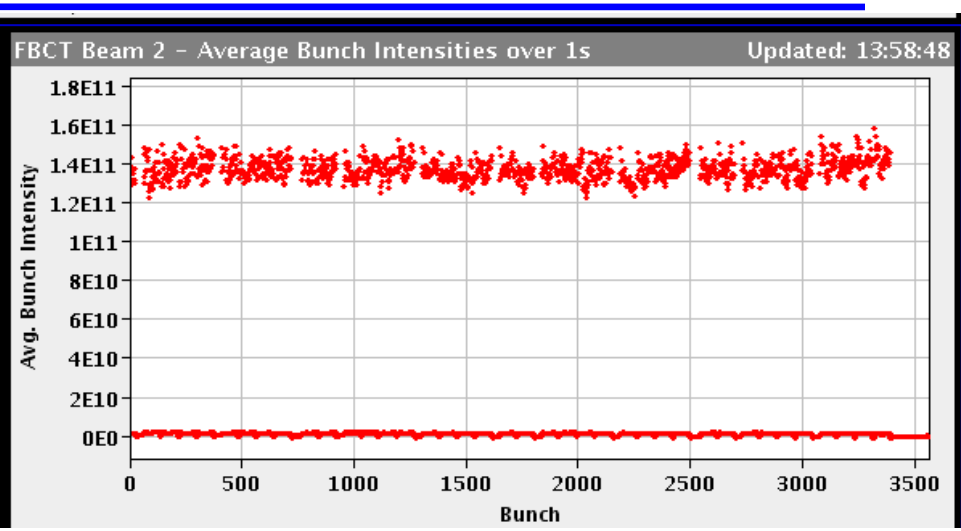
- provide different number of colliding pairs to different experiments by shifting the injection bucket
  - examples of filling schemes used in 2012 for physics production
    - 50 ns spaced beams, IP1/5 at $\beta^* = 0.6$ m
    - Alice running with main-satellite collisions, $\beta^* = 3$ m
    - LHCb running with levelling by offset ($\beta^* = 3$ m)
  - scheme 1 to 2: shift 4 injections

	total number of bunches	number of colliding pairs			comments
		IP 1 and 5	IP 2	IP 8	
scheme 1	1380	1331	0	1320	2012 initial
scheme 2	1380	1380	0	1274	to overcome loss of Landau damping
scheme 3	1380	1377	0	1274	3 non-colliding bunches in IP1/5



loss of Landau damping





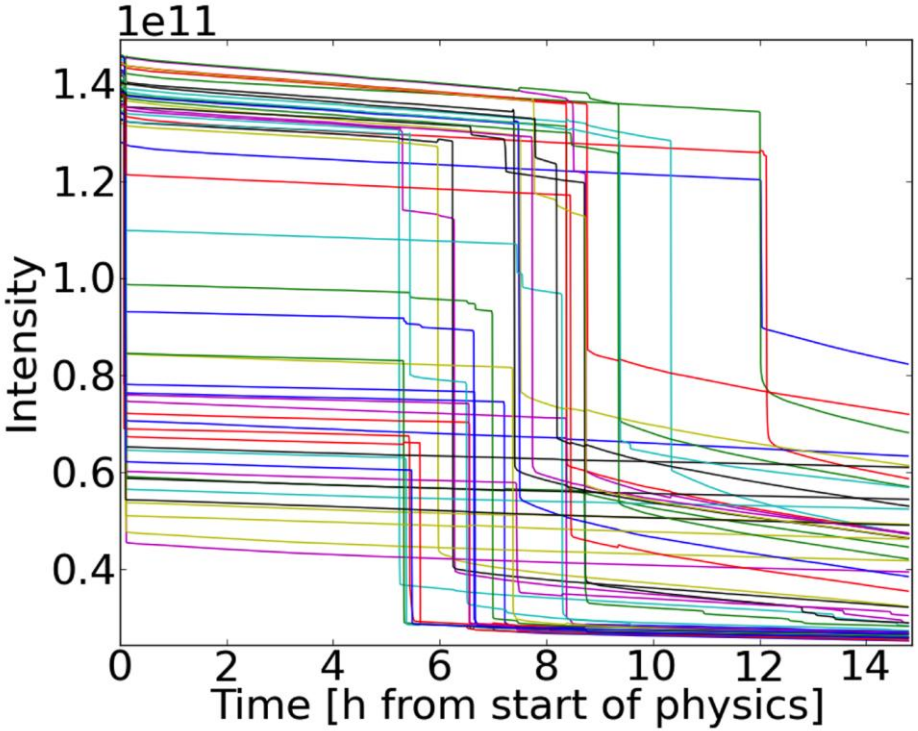
- some bunches in ring 1 were losing very quickly due to instabilities
  - interlock kicked in at ~4e10 ppb, and fills terminated prematurely
  - bunches colliding only in IP8 (levelled by separation)
- changed collision pattern to have head-on collisions in IP1/5 for all bunches
  - need the beam-beam tune spread
  - kept 3 non-colliding for background studies at IP1/5

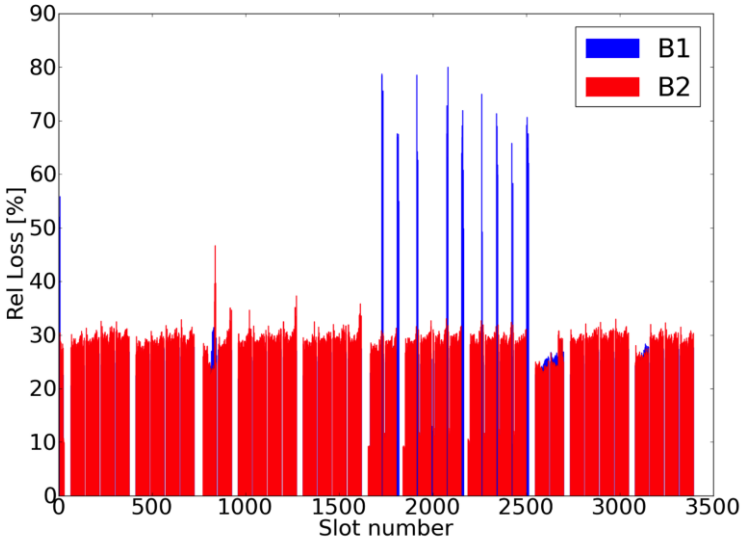
X. Buffat, "*Stability diagrams of colliding beams*"

X. Buffat, "*Consequences of missing collisions, beam stability and Landau damping*"

loss of Landau damping

- single bunches that become unstable
  - visible on losses, sometimes on emittance growth
  - need improvements on instrumentation for instabilities detection

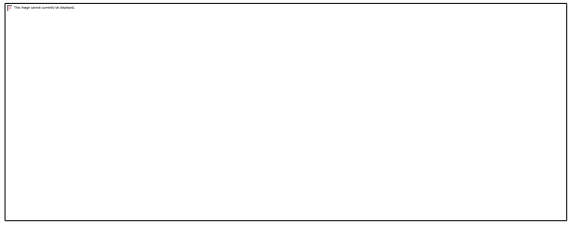




R. Giachino, "*Diagnostics needs for beam-beam studies and optimization*"

high HO tune shift in MDs

- performed several tests:
  - dedicated MDs on head-on limitations in 2011
  - high pile-up tests in 2011 and 2012



- head-on limit MD (2011):
  - N=1.9e11 ppb, ε=1.2-1.4 μm
  - linear head-on parameter: ξ=0.02/IP and ξ=0.034 total
    - design report: ξ=0.0033/IP for (3 IPs, +1 offset)
  - no significant losses nor emittance effects observed
    - tune adjustment needed to avoid emittance blowup: $Q_H=Q_V=0.31$

G. Trad, "*Beam-beam effects with a high pile-up test in the LHC*"

high pile-up in MDs

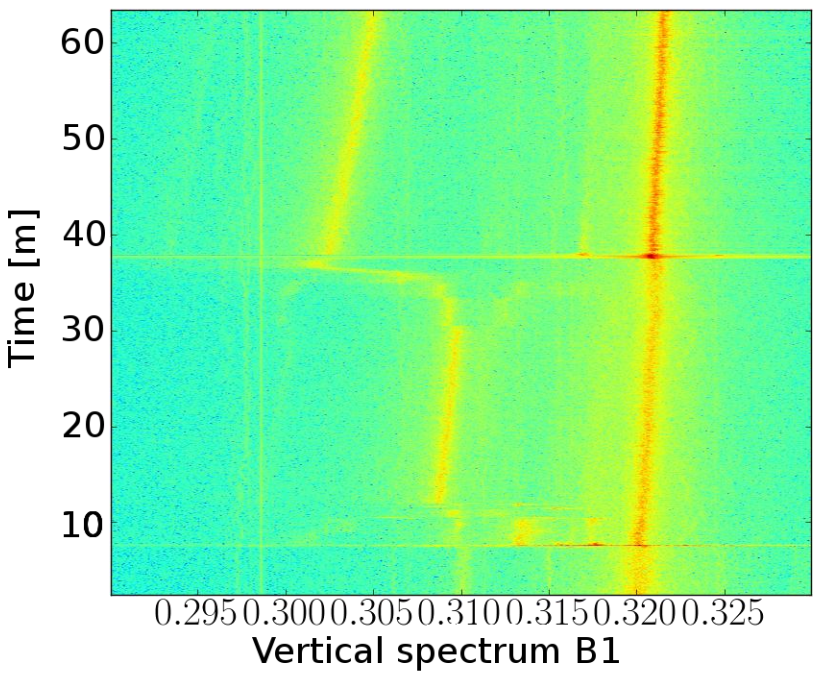
- design report: pile-up μ~19
- MD: high pile-up test (μ_{max}~31) in 2011
  - used by experiments to study their own limitations
- MD: high pile-up test (μ_{max}~70) in 2012
  - N=3e11 ppb, ε=2.2 μm
    - very bright single bunches with SPS Q20 optics
  - instabilities observed during ramp and squeeze
    - despite increased chromaticity and longitudinal size
    - one beam only into collisions cleanly
    - would have needed more time and iterations

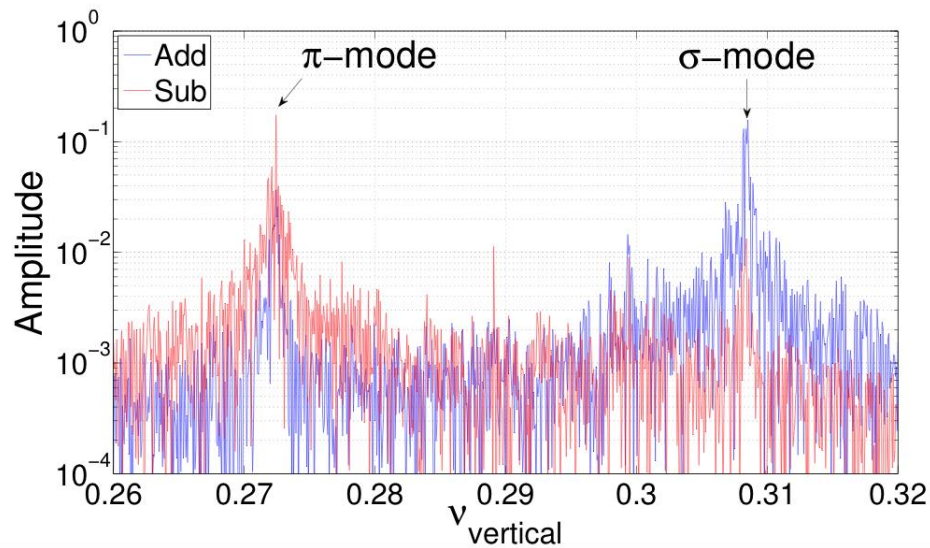
pile-up: number of inelastic collisions per bunch crossing

G. Trad, "*Beam-beam effects with a high pile-up test in the LHC*"

coherent modes

- observed during the head-on MDs in 2011
  - with individual bunches
- could measure σ and π modes

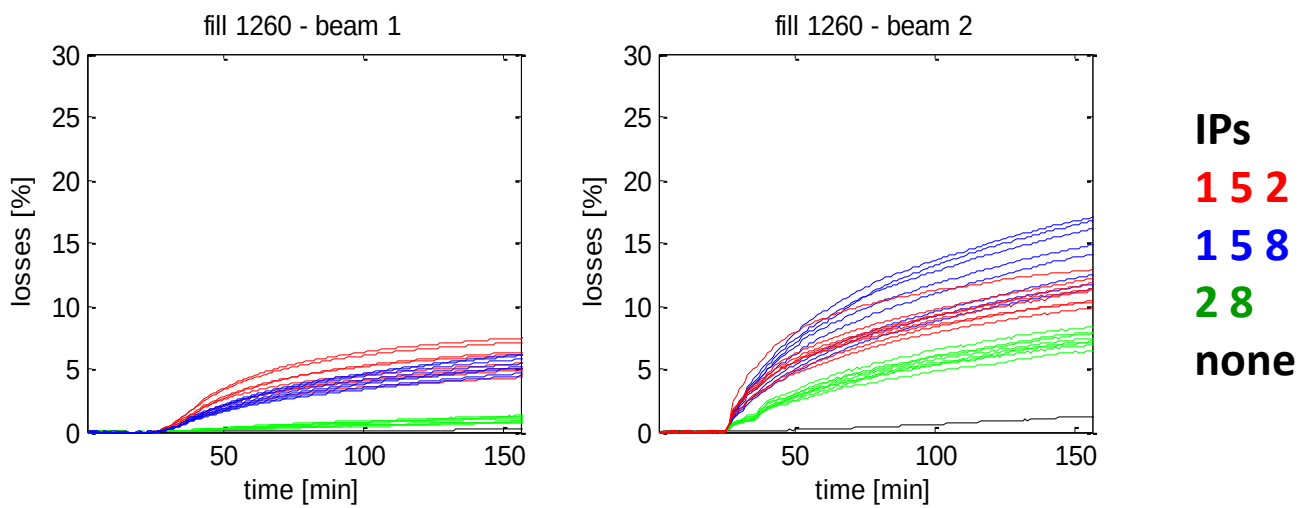




X. Buffat, "*Coherent beam-beam modes in the LHC*"

head-on collisions and losses

- 2010, ~0.9e11 ppb
- used to have a tune split
  - had problems initially, possibly with coherent modes
  - first: ΔQ1: -2.5e-3; ΔQ2: +2.5e-3
    - lifetime beam 1 worse than beam 2
  - here inverted: ΔQ1: +2.5e-3; ΔQ2: -2.5e-3
    - lifetime beam 2 worse
  - finally tune split removed



expected burn-off: ~0.5e9/collision after 500 minutes

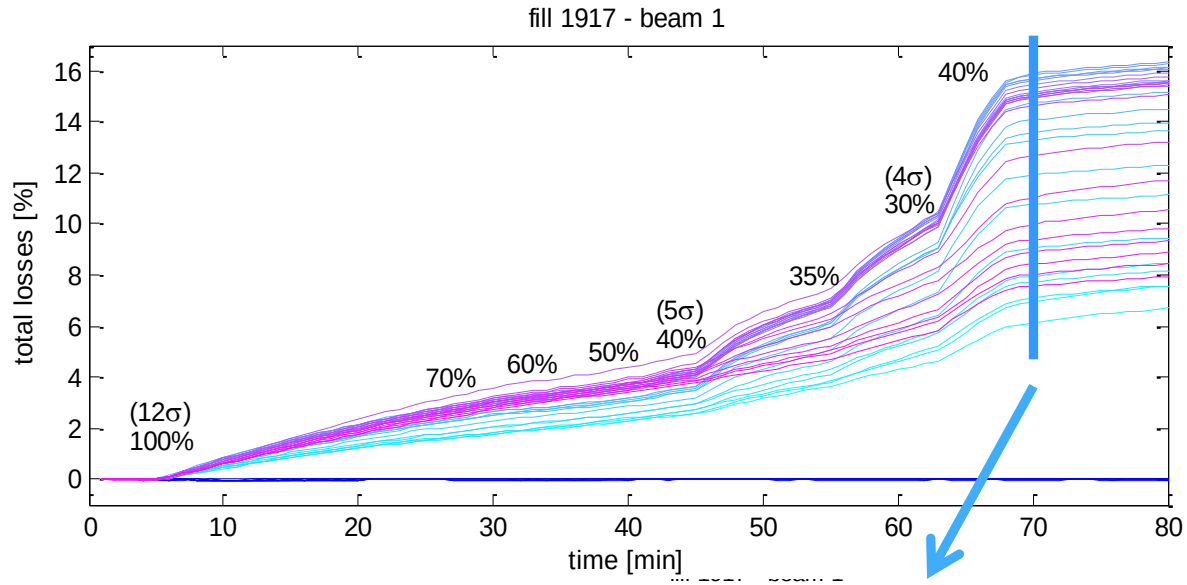
scans of crossing angle: settings

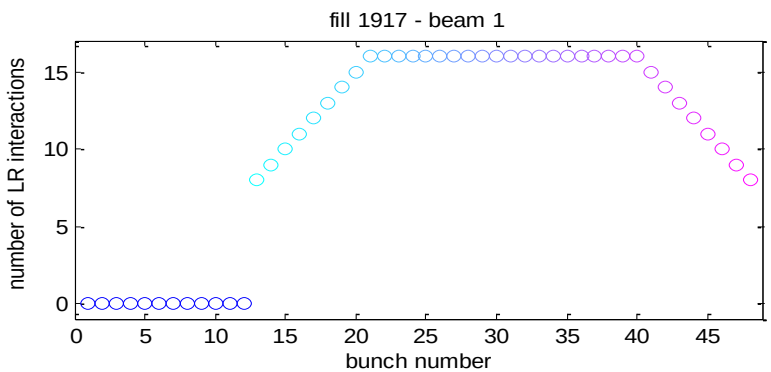
- crossing angle reduced in steps until losses or lifetime reduction is observed
  - in successive MD sessions, with different β^*, intensity and number of LR interactions
  - record separation for onset of losses
- results used to confirm simulations and predict required separation with future settings

scan	β^*	crossing angle	intensity	transverse emittance	bunch spacing	energy	IPs and comments
	m	μrad	10^{11} ppb	μm	ns	TeV	
1	1.5	120	1.2	2-2.5	50	3.5	IP1 then IP5
2	1.5	120	1.2	2-2.5	50	3.5	1-3 HO coll.
3	0.6	145	1.6	2-2.5	50	4	IP1 then IP5
4	0.6	145	1.2	2-2.5	50	4	IP1 then IP5
5	1	145	1.0	3.1	25	4	IP1+IP5

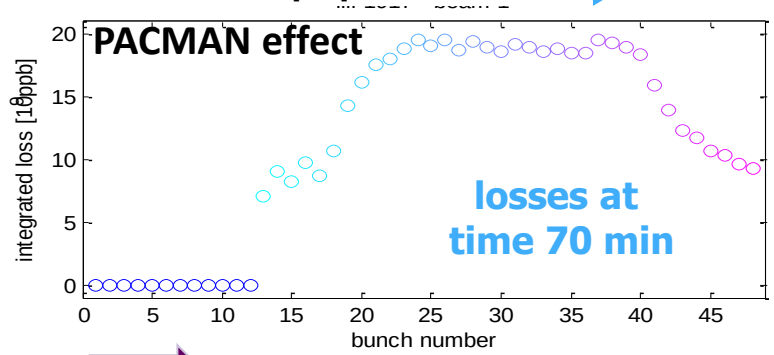
scan of crossing angle: losses

- scan 1
  - 3.5 TeV
  - β^*=1.5 m
  - xing angle=+-120 μrad
  - N=1.2e11 ppb
  - ε=2-2.5 μm
- scan of IP1 only





12 non-colliding +
50 ns train of 36

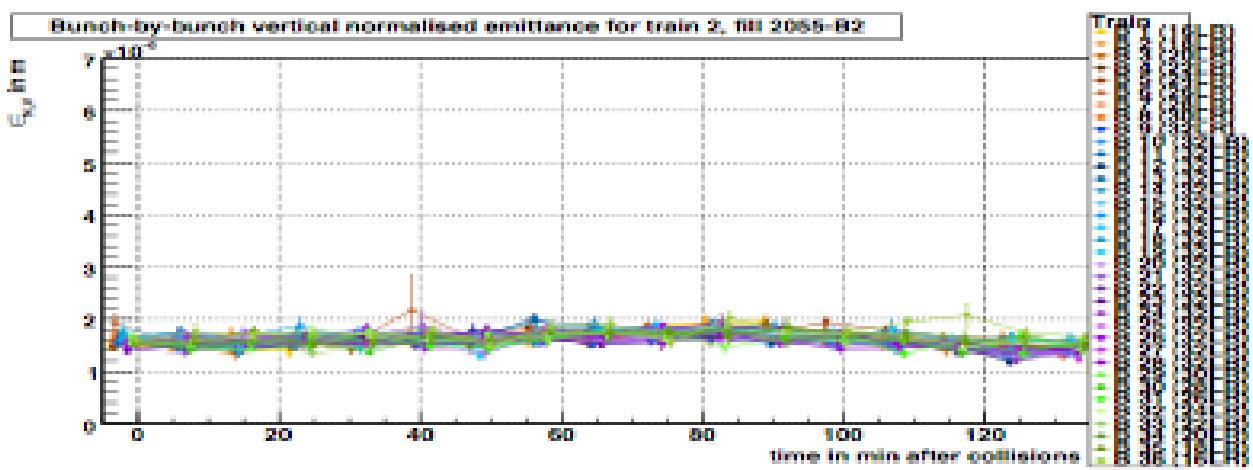


D. Kaltchev, "Analysis of long range studies in the LHC - comparison with the model"

W. Herr, "Long range beam-beam effects and experience in the LHC"

scan of crossing angle: results

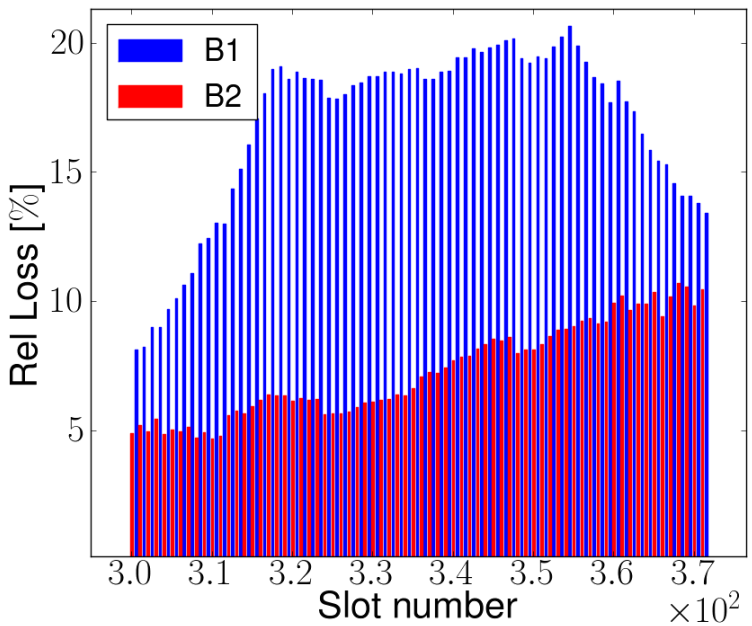
- clear dependence on bunch position in batch (anti-PACMAN)
  - dependence on number of head-on collisions highlighted also
- evidence for alternate crossing effectiveness
  - crossing plane: IP1 V, IP5 H (to compensate first order LR effects)
  - scan in IP5 after IP1: lifetime seemed best when separation and crossing angles are equal for the two IPs
- proven that it is a dynamic aperture effect
  - no effect on emittance
  - losses recover if wider crossing restored



emittance from scan 2

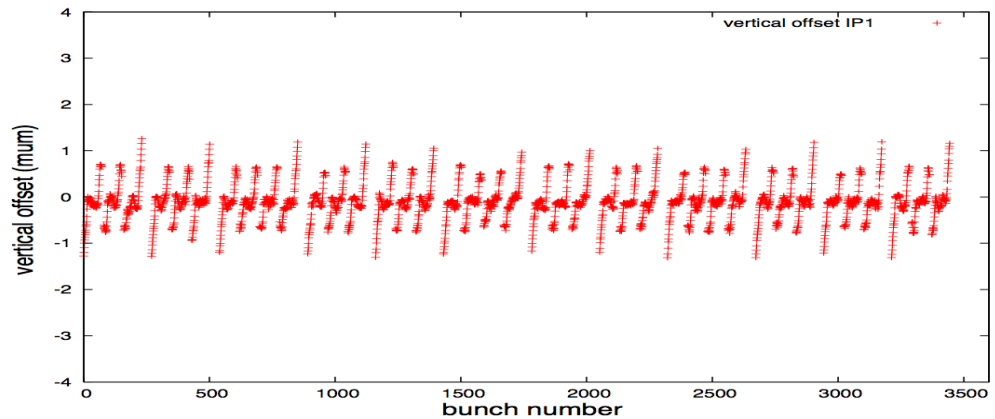
scan of crossing angle: 25 ns

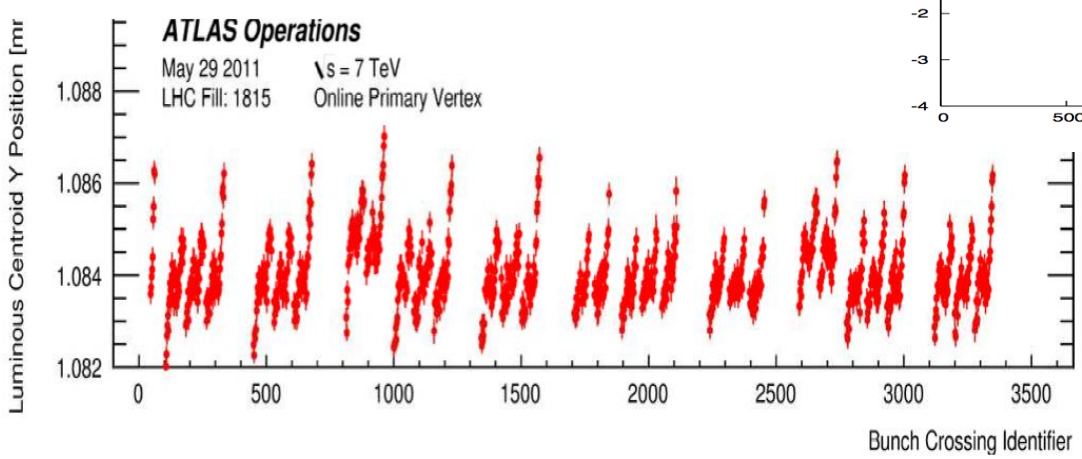
- 25 ns have twice the number of LR interactions
  - thus need bigger separation
- LR studies with 25 ns in 2012 (scan 5)
  - crossing reduced simultaneously in IP1/5
  - losses monitored
    - asymmetry B1/B2 not observed with 50 ns and to be understood
  - e-cloud effects visible



orbit effects

- different orbit due to LR collisions
  - fully self-consistent treatment developed
  - e.g. vertical offset in IP1
    - LHC orbit measurement cannot resolve these effects
    - qualitatively verified by ATLAS vertex centroid measurement
      - note the different filling scheme

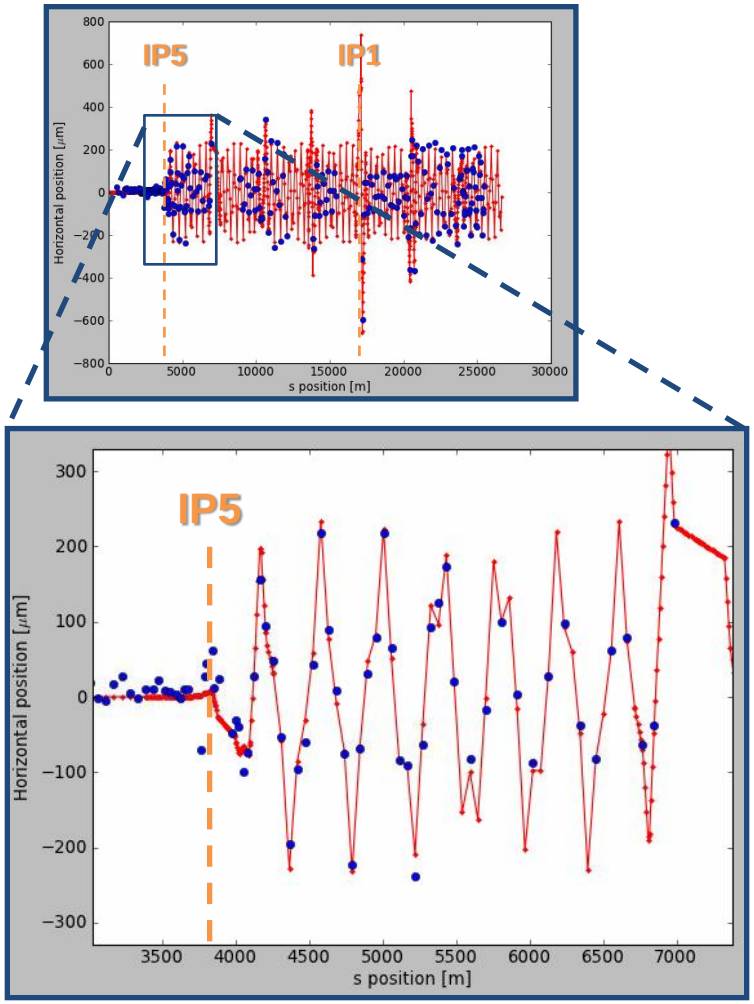




W. Herr, "Long range beam-beam effects and experience in the LHC"

M. Schaumann, "*Observed beam-beam induced orbit effects at LHC*"

missing LR deflection



single turn trajectory perturbation of B1H after dump of B2 for bunches with full LR (blue: BPM measurement, red: fit)

- beam dump of single beam in collisions leads to missing LR deflections
  - consequent single-turn trajectory perturbation of other beam
  - end-of-fill test on 13.12.2012
    - 25ns spacing, 72 bunches, ~1.1e11 ppb, ~65μrad crossing angle
  - B1H perturbation in the arc of ~230μm = 0.6σ 3.5μm·rad
- leads with physics beam to beam losses above BLM dump thresholds
  - effect observed throughout 2012

T. Baer, "*Beam-beam effects during the beam dump process*"

conclusions

- long list of observations
  - LR and HO, orbit, PACMAN, loss of Landau damping, coherent modes, …
- this was just a teaser, all details will come in the presentations in the next days
- enjoy this workshop!