Pb82+ Ions for LHC in the SPS 2015
- RF -

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LIU SPS BD WG 2016-01-07

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Introduction

Context

- start of heavy ion programme 1986 with D, O, S (FHA) for Fixed Target Physics
- since 1994 Pb82+ (later also In, Ar) beams in the SPS (FFA/FHA combined, FFA) for Fixed Target Physics
- Pb82+ Beams for UA9 coasts
- 2007 and 2009: commissioning, since 2010 operation of Pb82+ beams for LHC
- evolution since 2007: RF low level, working points, Q26, Q20, bunch spacing (Early Beam, Nominal Beam, Intermediate Beam), batch spacing
- LHC Beam requirements: better and more

Introduction

FFA

Synchronism of synchrotron:

- bunch encounters RF voltage at the same phase on each revolution independent of T_{rev}
- $f_{\mathrm{RF}} = h f_{\mathrm{rev}}$ with $h \in \mathbb{N}$ and const (FHA)
- for heavy ions this condition leads to an f_{RF} swing larger than BW of travelling wave cavities (TWC)

TWC filling time is 1 $\mu s \ll T_{\mathrm{rev}}$ and beam occupies fraction of circumference, i.e. phase between beam and cavity voltage is not constrained by f_{RF} and T_{rev}. Each passage of beam through TWC is a separate acceleration event for which the phase of the cavity voltage can be adjusted as required (FFA):

- FM or FSK at f_{rev} ($\eta = 0.5$)
  - $N(T_{\mathrm{RF}}) = N_{\mathrm{buckets}} = 4620$
  - $f_{\mathrm{RF}} = f_{\mathrm{RF,cav}} = const$ for $T_1 = \eta T_{\mathrm{rev}}$
  - $f_{\mathrm{RF}} = f_2 = f_2(T_{\mathrm{rev}}) \neq const$ for $T_2 = T_{\mathrm{rev}} - T_1$
- 100% AM
  - RF on during T_1 and off during T_2

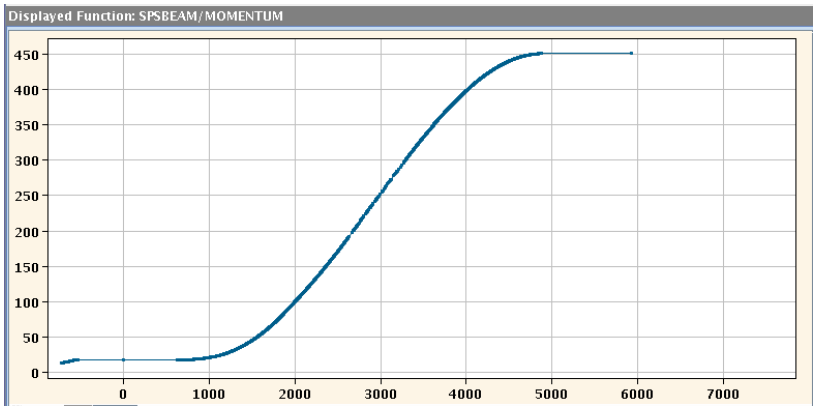
Introduction

Overview 2015

- first time Pb82+ beams for LHC since LS1
- new h/w, new s/w (RF, BQM)
- Early Beam, Nominal Beam (Intermediate Beam)
- LHCION1, LHCION2, ~~SFTION1, SFTION2, LHCION3~~
- beam related performance:
  - nothing substantially new related to beam physics
  - improved experience with Q20 (tuning in all planes)
  - better transmission than previously with Q20 (highest total intensity at Flat Top)
  - new: controlled emittance blow-up in CPS, transverse damper, smaller batch spacings, ...

Cycle LHCION1

Cycle Description



- FHA, SL, FFA, PL, $f_{\mathrm{RF,cav,inj}}$, inject 1 bunch/1 batch
- $f_{\mathrm{RF,cav,inj}}$ to $f_{\mathrm{RF,cav,acc}}$, SL to RL
- Start Ramp: $t_{\mathrm{StartRamp}} = 4\,880$ ms, $\dot{B} > 0.7$ T/s
- transition: FFA to FHA but still 100% AM
- Flat Top: RL to SL, 3-stage re-phasing
- Extraction: $t_{\mathrm{Extraction}} = 5\,825$ ms

Cycle LHCION1

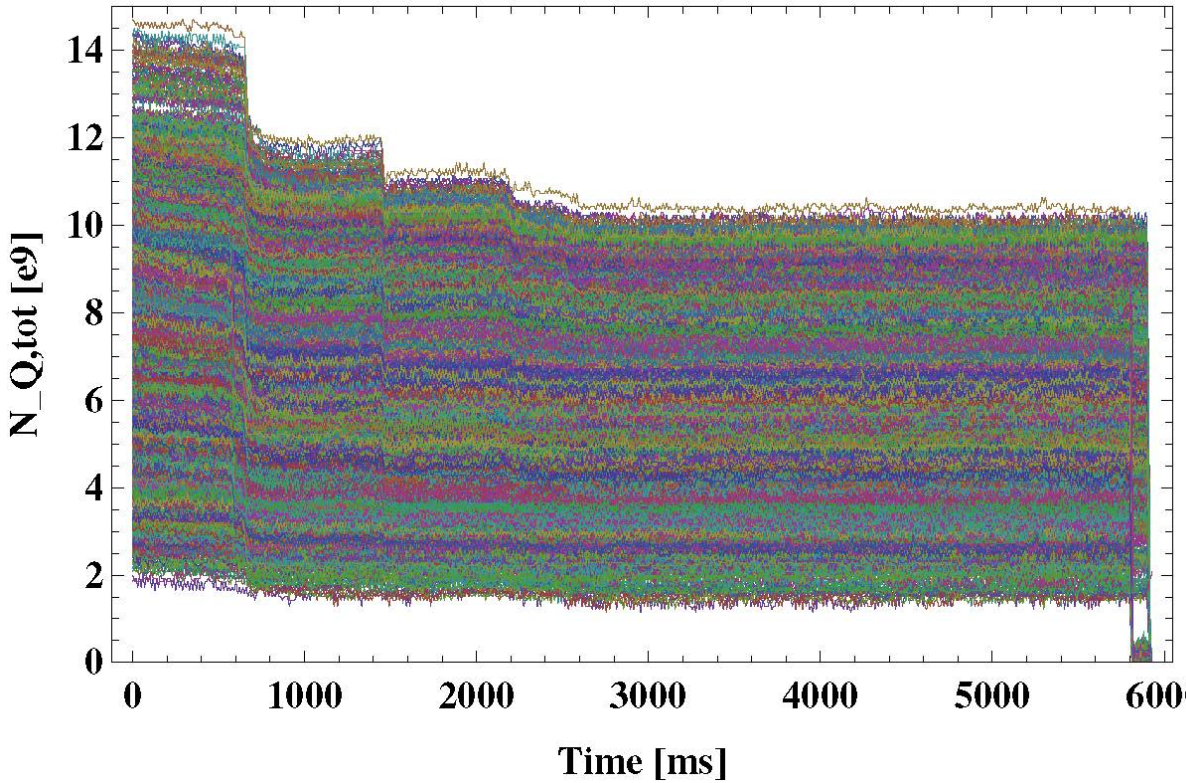
Cycle Description

Beam parameters at injection

- Early Beam, ~~Nominal Beam~~
- CPS extraction
  - $\lambda = 2.8$ ns: $\varepsilon/\mathrm{A} = 0.0235$ eVs
  - $\lambda = 4.0$ ns: $\varepsilon/\mathrm{A} = 0.0467$ eVs
- SPS injection
  - $\mathcal{A}_\mathrm{b}/\mathrm{A} = 0.031\ \mathrm{eVs}/\sqrt{1\ \mathrm{MV}}$ for $\gamma_\mathrm{t} = 17.95$

Cycle LHCION1

BCT Data and Transmission

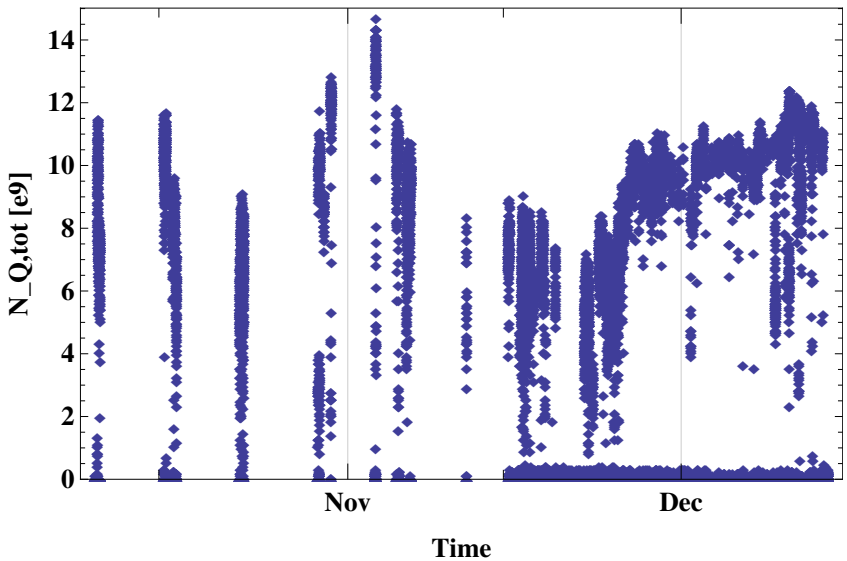


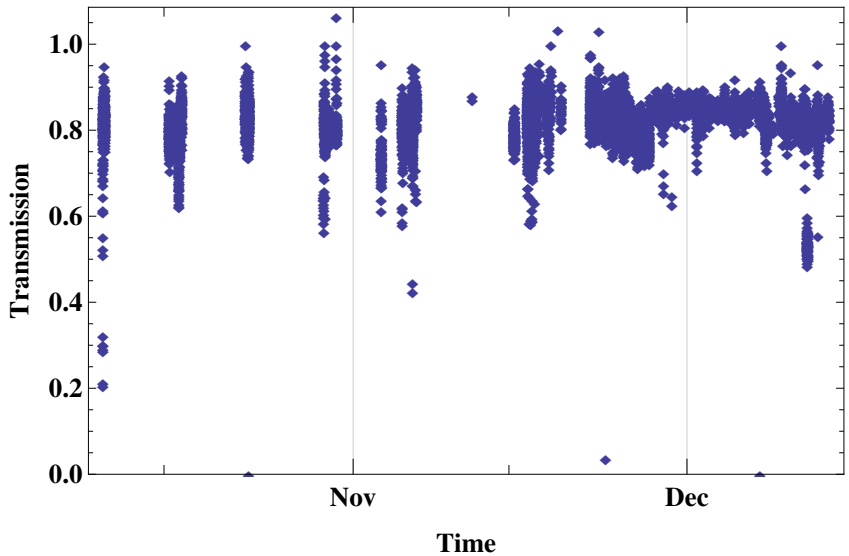
- variation of injected intensity
- transmission as function of injected intensity
- losses: capture, ramp, transition, post-transition

Cycle LHCION1

BCT Data and Transmission

Injected intensity and transmission versus date



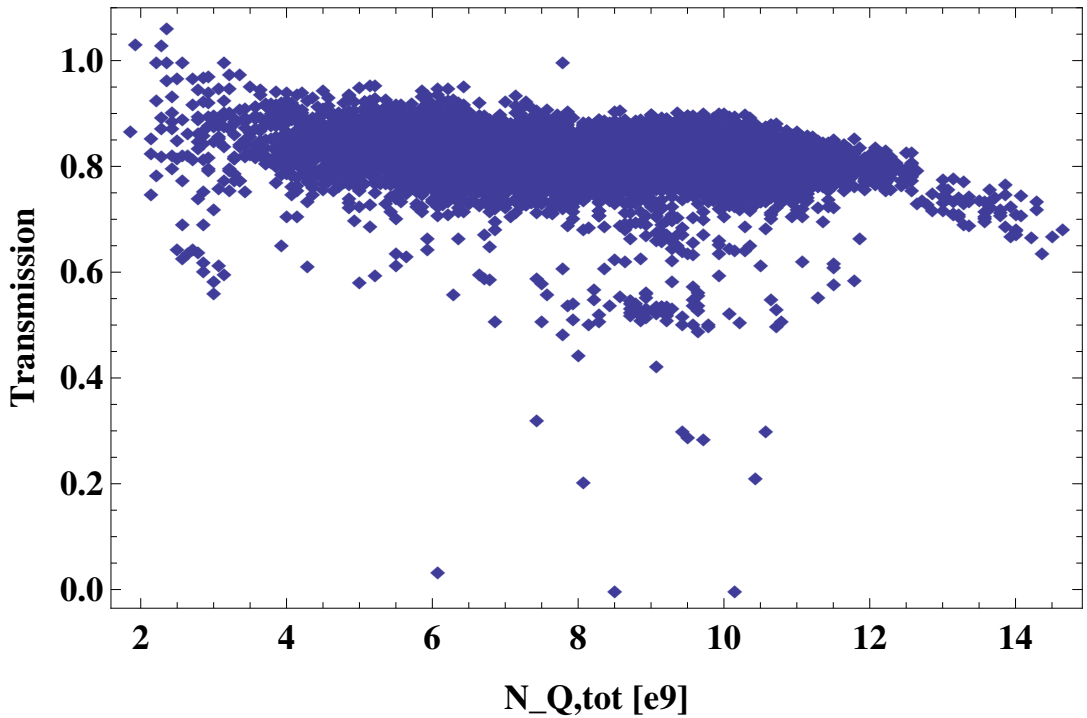


- end of November: transmission getting worse with increasing intensity then recovered, see also LHCION2

Cycle LHCION1

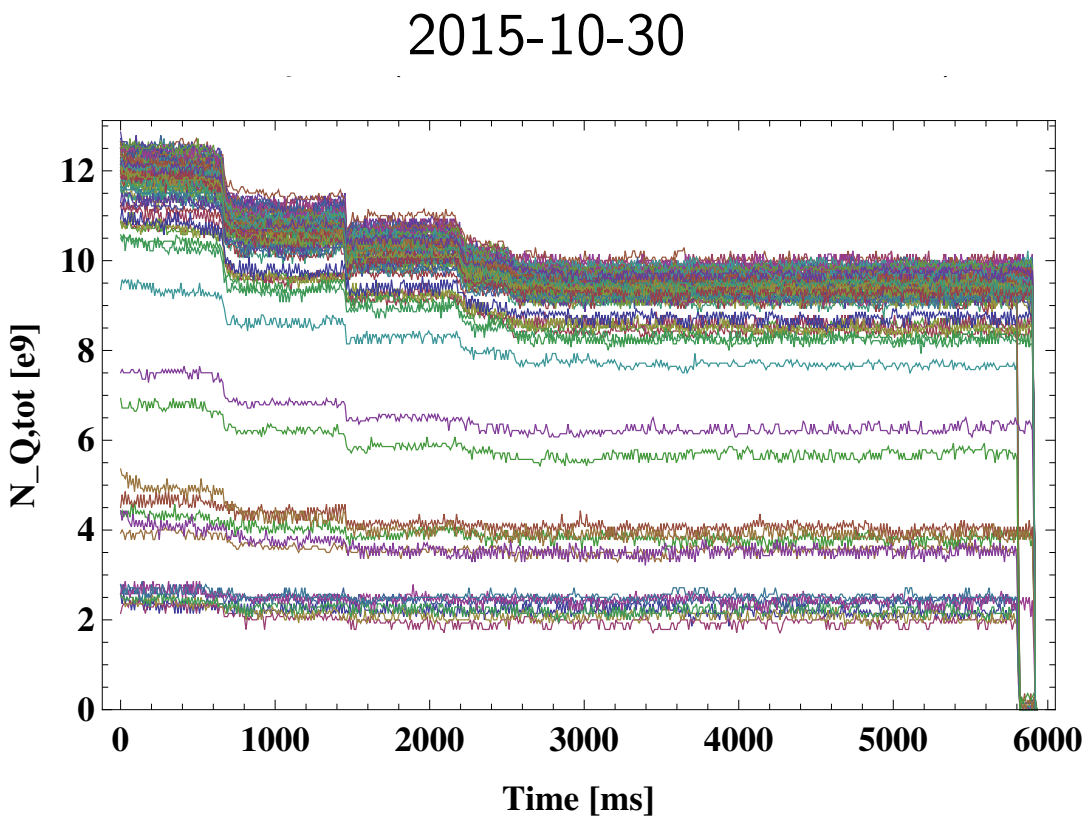
BCT Data and Transmission

Transmission versus injected intensity (October to December)



Cycle LHCION1

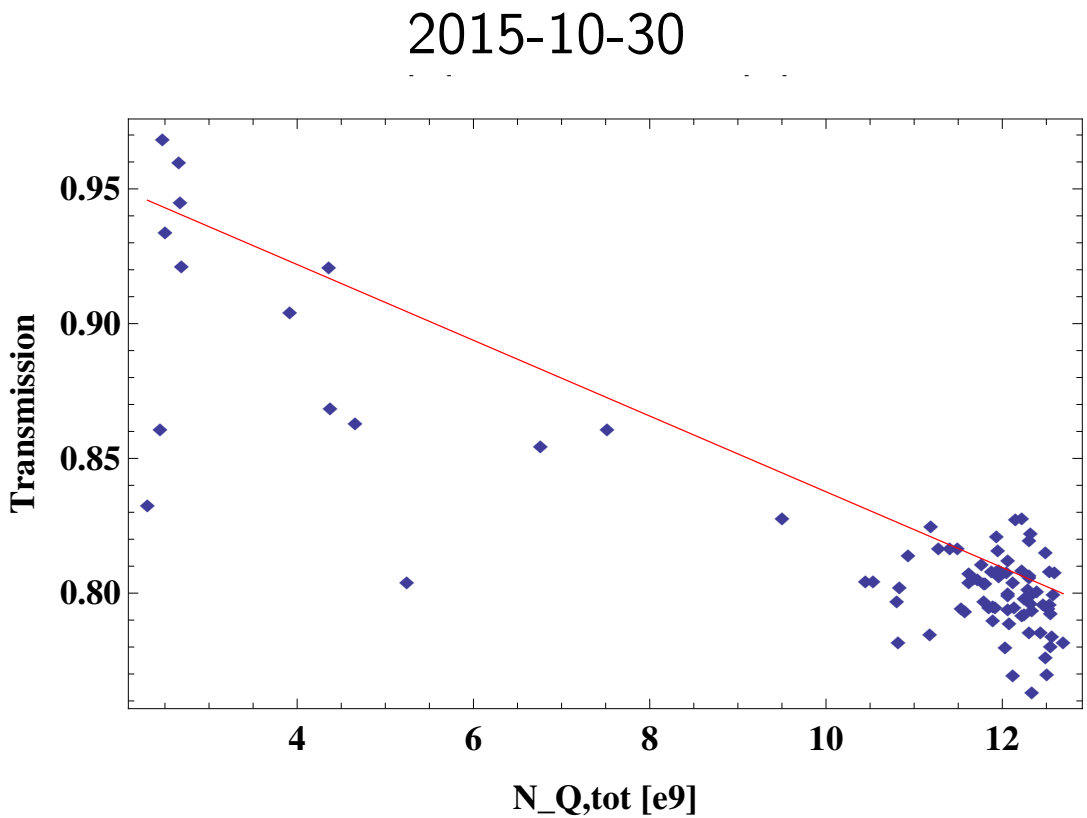
Injected Beam Parameters and Transmission



- transmission improves with lower injected intensity

Cycle LHCION1

Injected Beam Parameters and Transmission



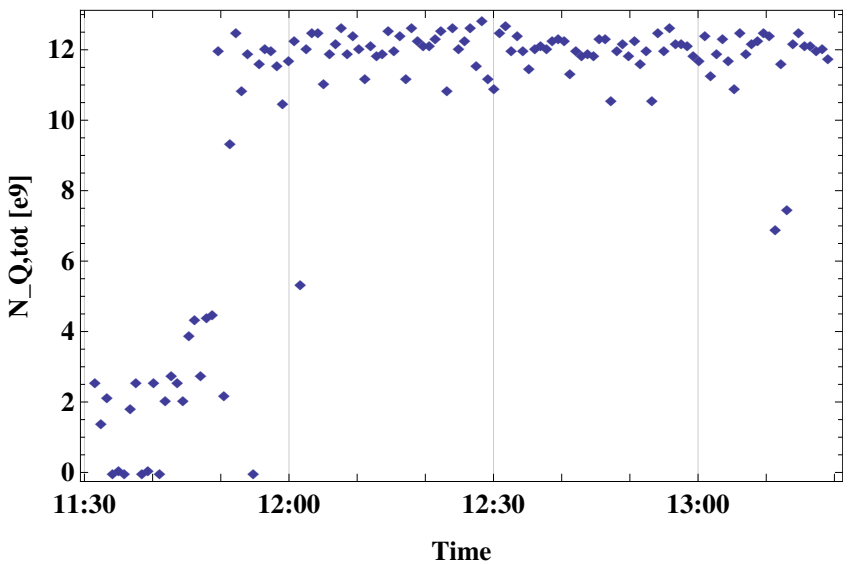
- transmission improves with lower injected intensity

Cycle LHCION1

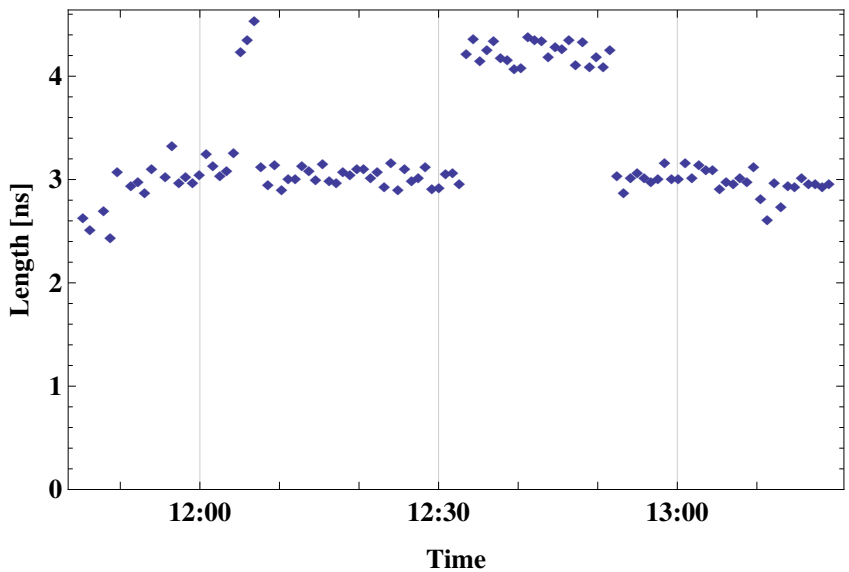
Injected Beam Parameters and Transmission

2015-10-30

$N_{\mathrm{Q,tot}}$



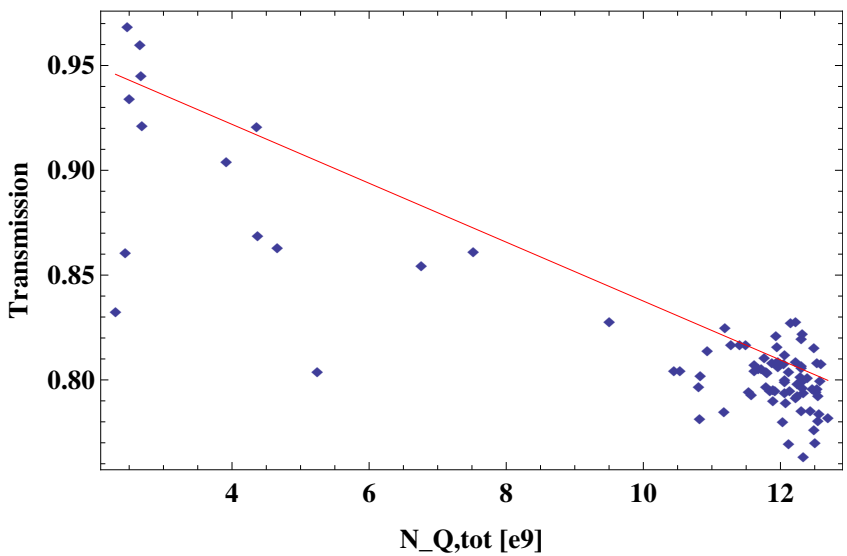
λ_{inj}

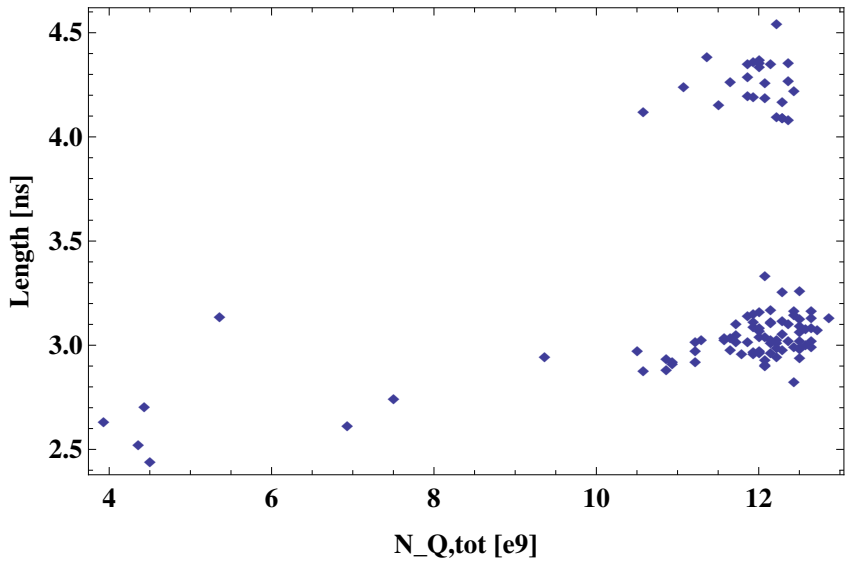


Cycle LHCION1

Injected Beam Parameters and Transmission

2015-10-30



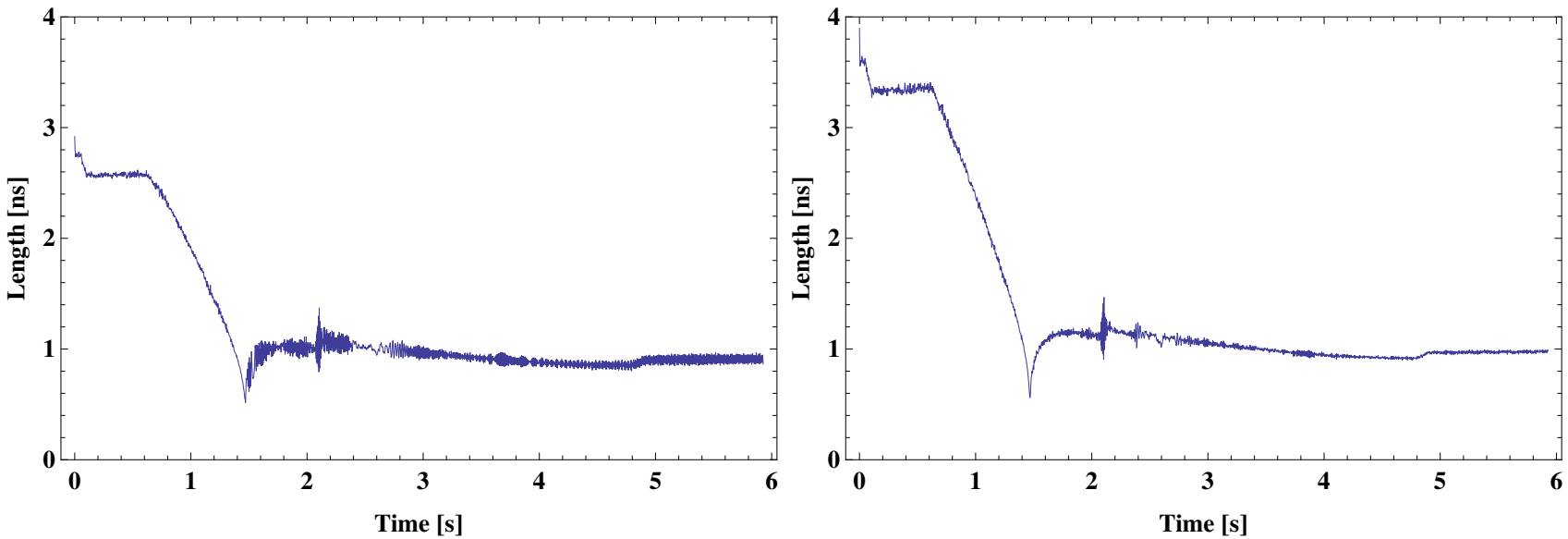


- better with lower injected intensity independent of λ_{inj}

Cycle LHCION1

Ramp and Flat Top

Controlled longitudinal emittance blow-up in CPS

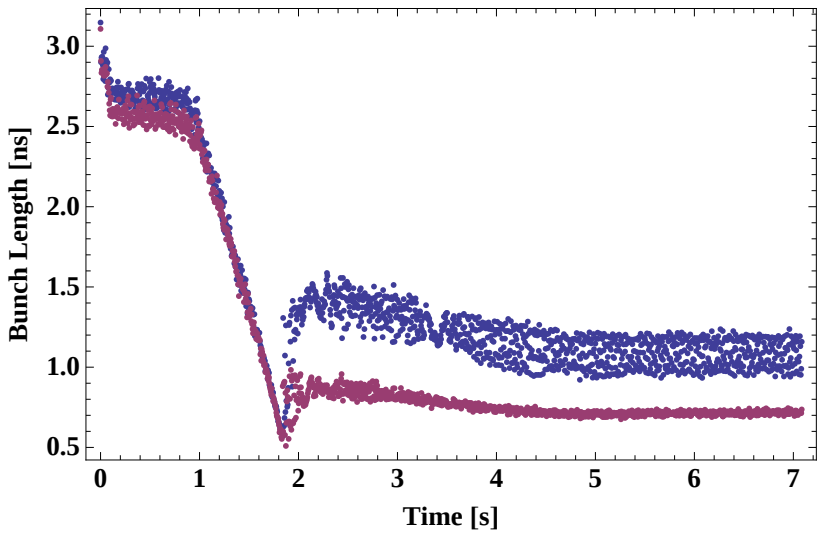


- $t_0 = 0$ ms

Cycle LHCION1

Ramp and Flat Top

2009-10-23, Q26, $N_Q = 1.5 \times 10^{10}$ (blue) , $N_Q = 0.7 \times 10^{10}$ (red)



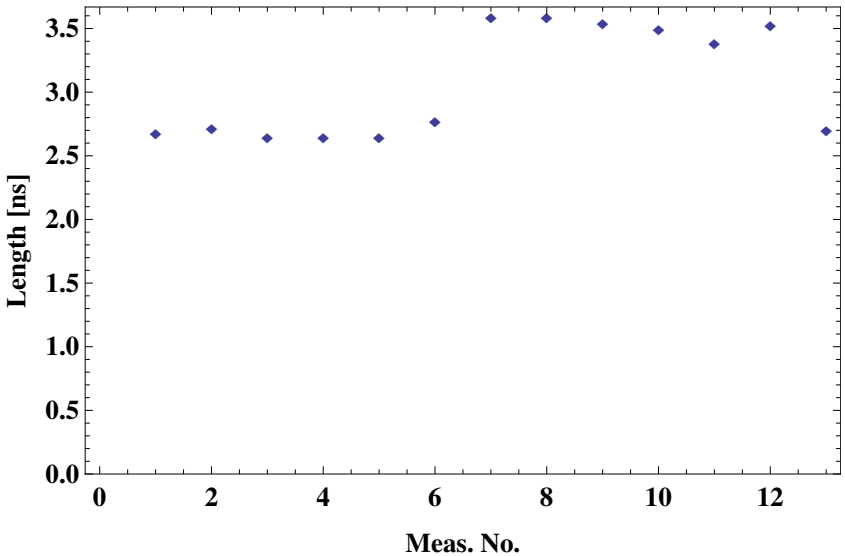
- $t_0 = 0$ ms

Cycle LHCION1

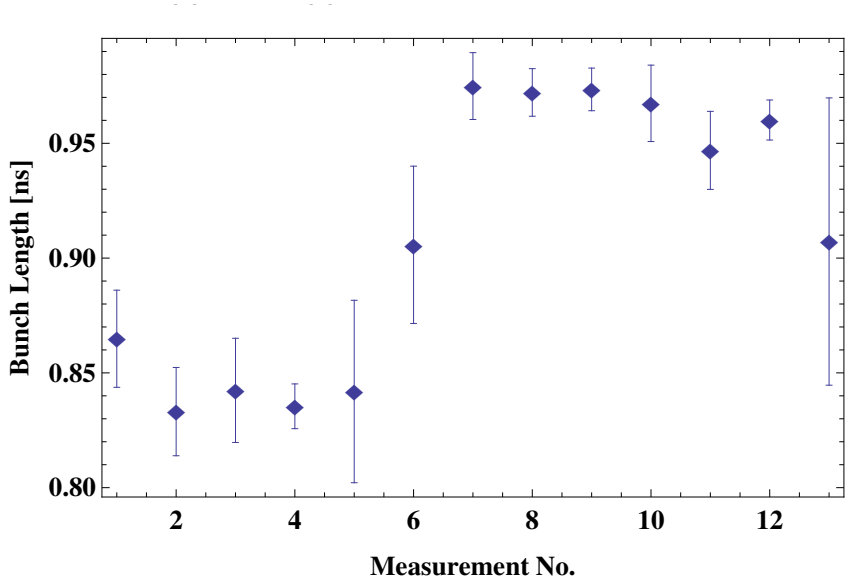
Ramp and Flat Top

Controlled longitudinal emittance blow-up in CPS and bunch length

Injection



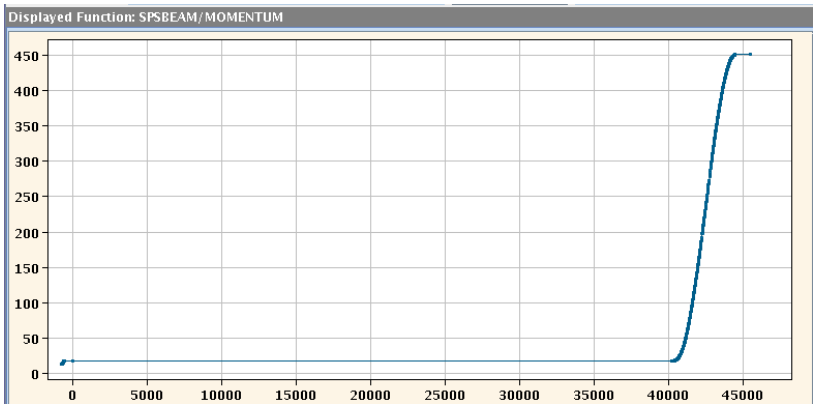
Flat Top



- Measurement No. 7 - 9
- absolute value and spread at Flat Top

Cycle LHCION2

Cycle Description

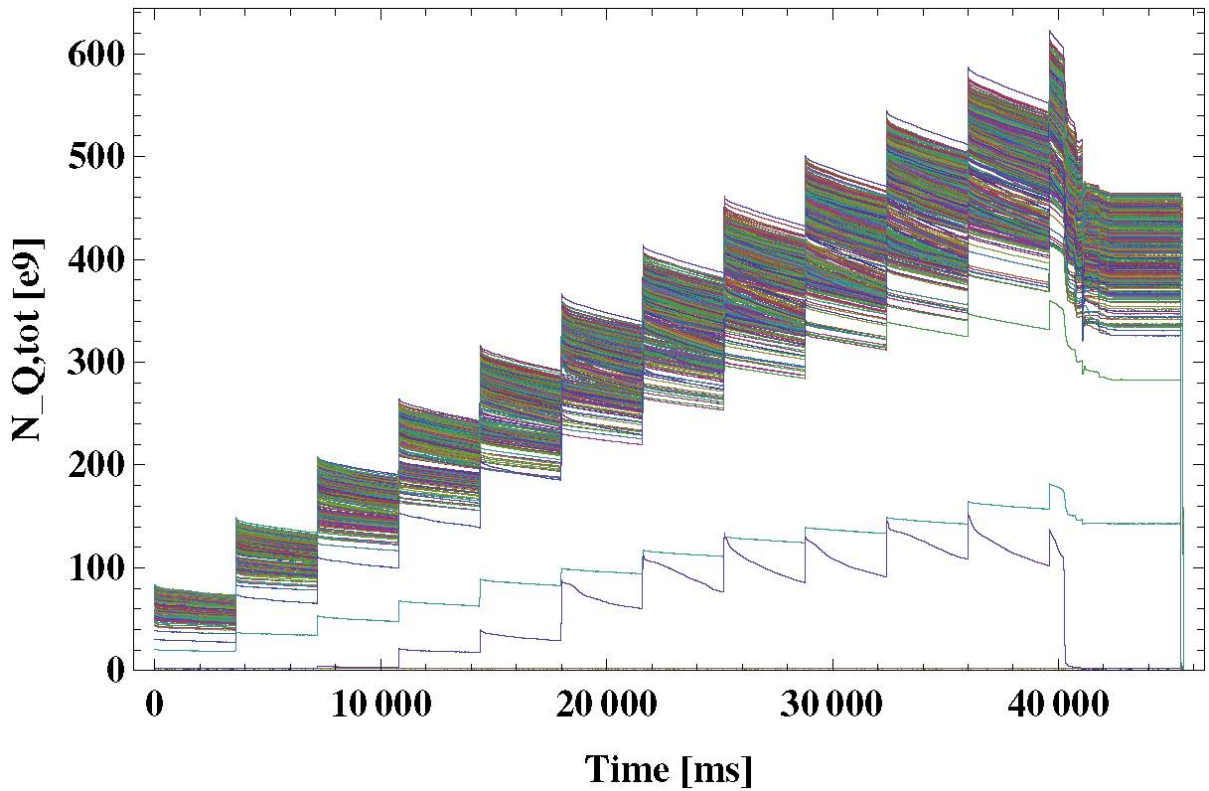


- FHA, SL, FFA, PL, $f_{\mathrm{RF,cav,inj}}$, inject up to 12 batches of Nominal Beam
- $f_{\mathrm{RF,cav,inj}}$ to $f_{\mathrm{RF,cav,acc}}$, SL to RL
- Start Ramp (LHCION2: $t_{\mathrm{StartRamp}} = 40\,220$ ms), $\dot{B} > 0.7$ T/s
- transition: FFA to FHA but still 100% AM
- Flat Top: RL to SL, 3-stage re-phasing
- Extraction: $t_{\mathrm{Extraction}} = 45\,425$ ms

Cycle LHCION2

BCT Data and Transmission

Example: 2015-12-07 00:00 and 2015-12-13 19:30, $N_{\mathrm{cycles}} = 674$

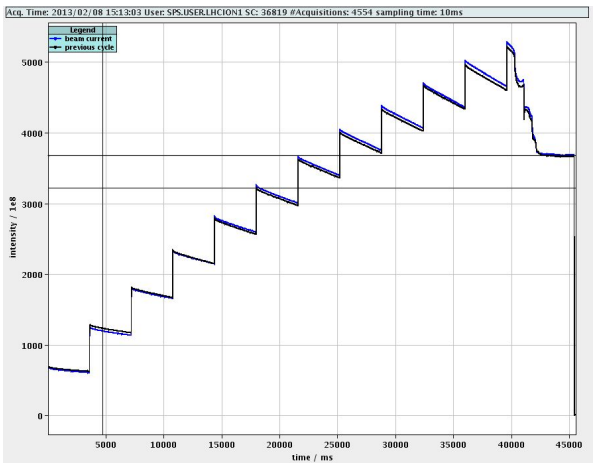


- variation of injected intensity
- transmission as function of injected intensity
- losses: capture, ramp, transition, post-transition

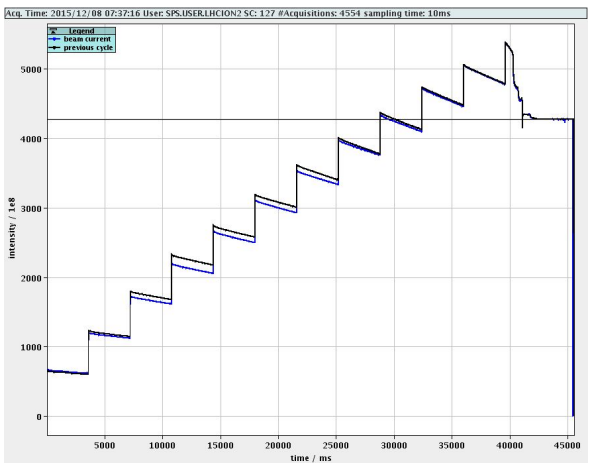
Cycle LHCION2

BCT Data and Transmission

End of Run 2013



End of Run 2015



2013

- Q20, $N_{\mathrm{Q,FT}} = N_{\mathrm{Q},7}$, $N_{\mathrm{Q,FT}} = 3.8 \times 10^{11}$

2015

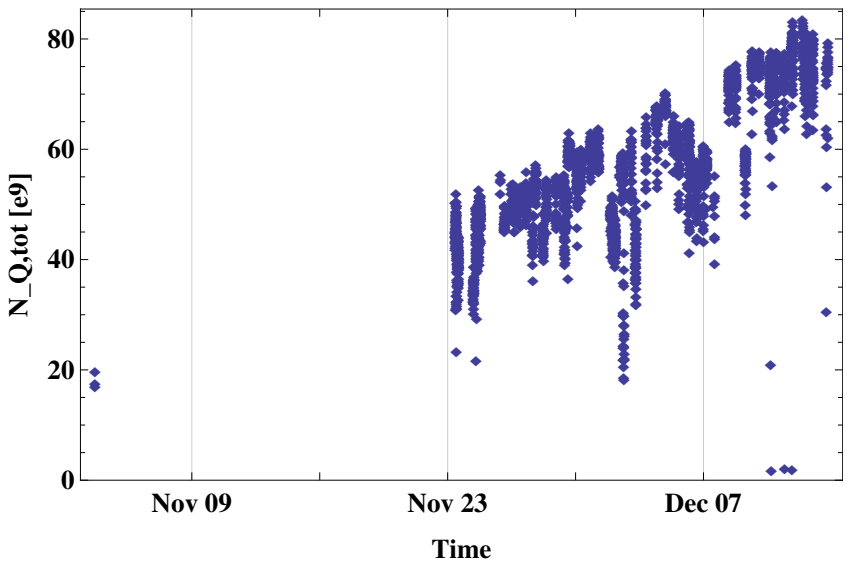
- example: screenshot with 175 ns batch spacing
- screenshots with 150 ns batch spacing worse
- Q20, $N_{\mathrm{Q,FT}} = N_{\mathrm{Q},9}$, $N_{\mathrm{Q,FT}} = 4.2 \times 10^{11}$

Cycle LHCION2

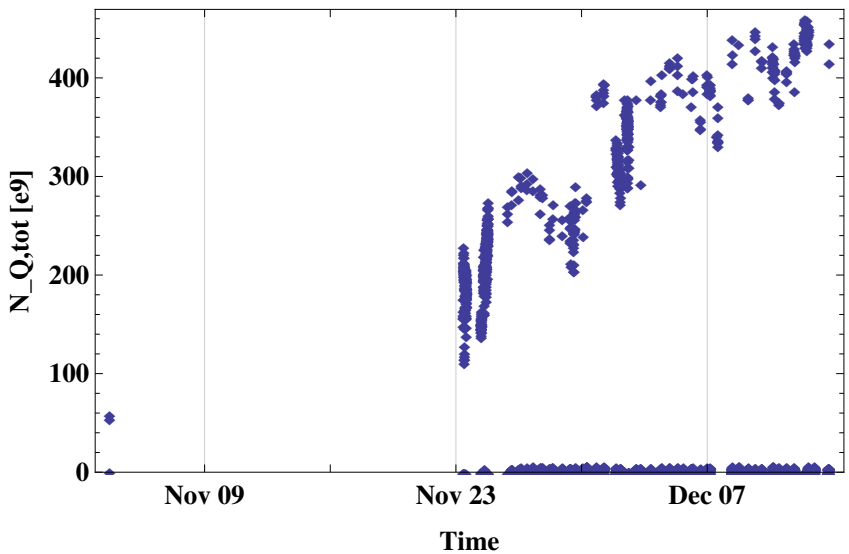
BCT Data and Transmission

All cycles with 12 batches, dynamic destination LHC, LHC Beam Mode INJPHYS and LHCION2 ($N_{\text{cycles}} = 2387$).

Injection



Extraction

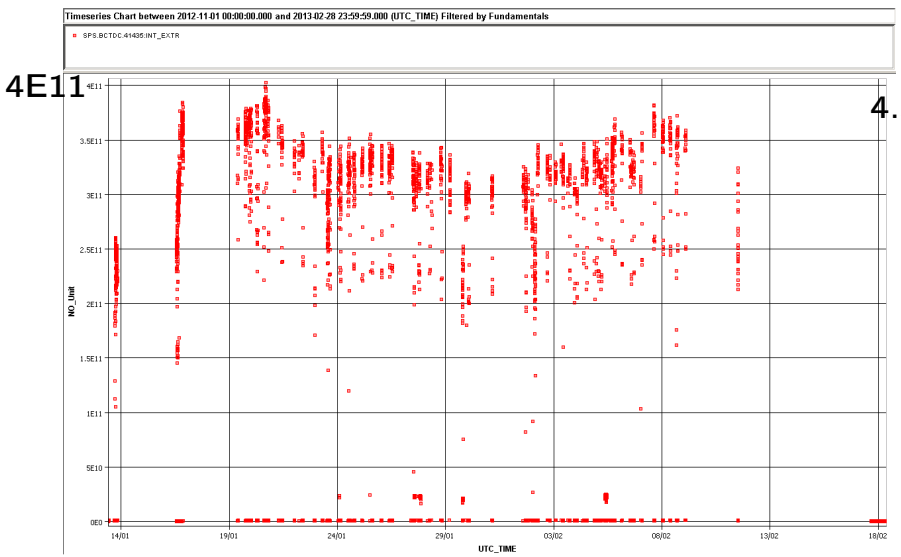


Cycle LHCION2

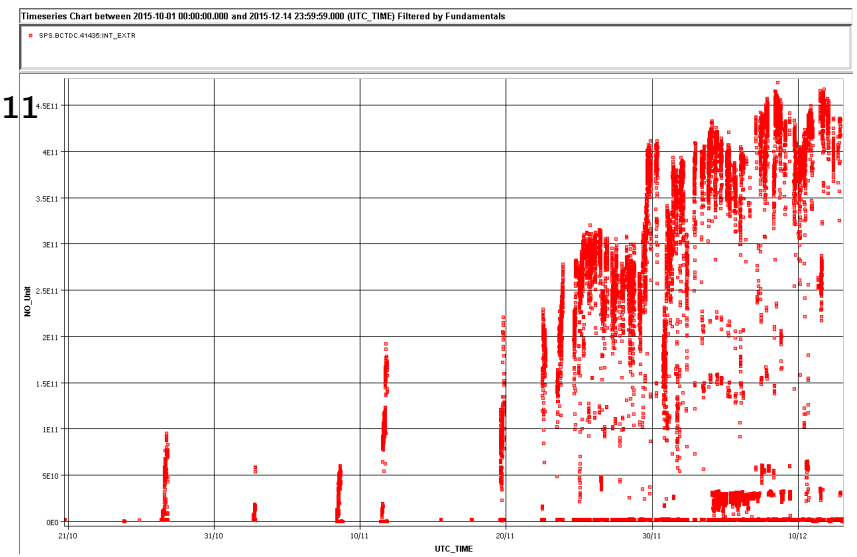
BCT Data and Transmission

BCTDC.41435:INT_EXTR for all cycles with up to 12 batches

Run 2013 Q20



Run 2015

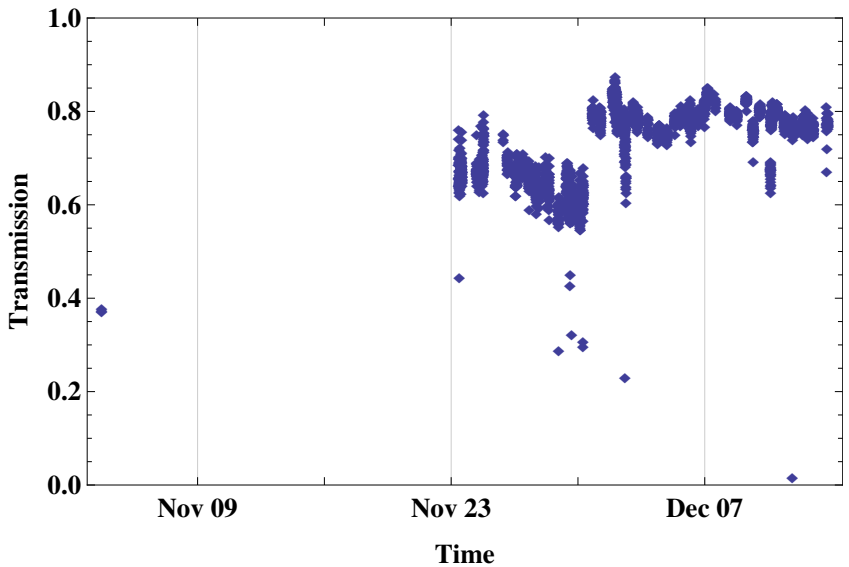


Cycle LHCION2

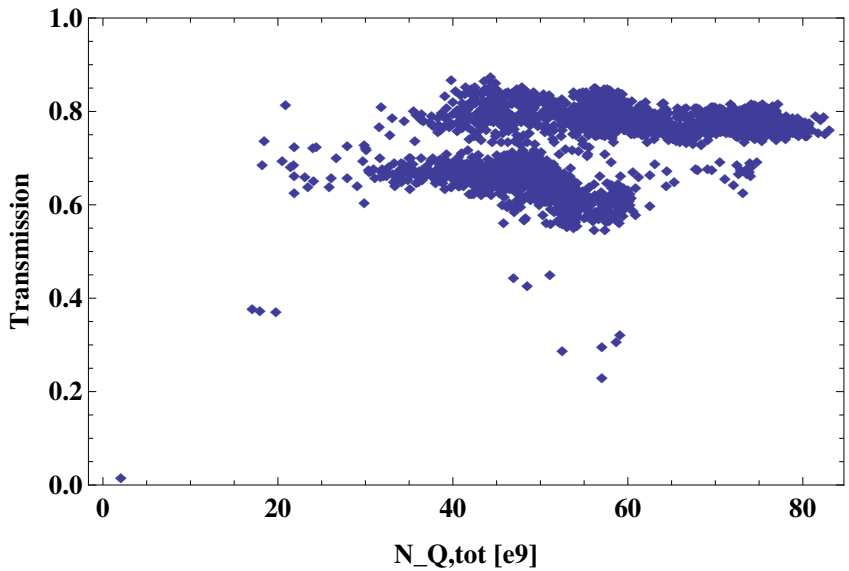
BCT Data and Transmission

Transmission ($t_1 = 40\,190$ ms, $t_2 = 45\,375$ ms)

Transmission vs Date



Transmission vs Injected Intensity



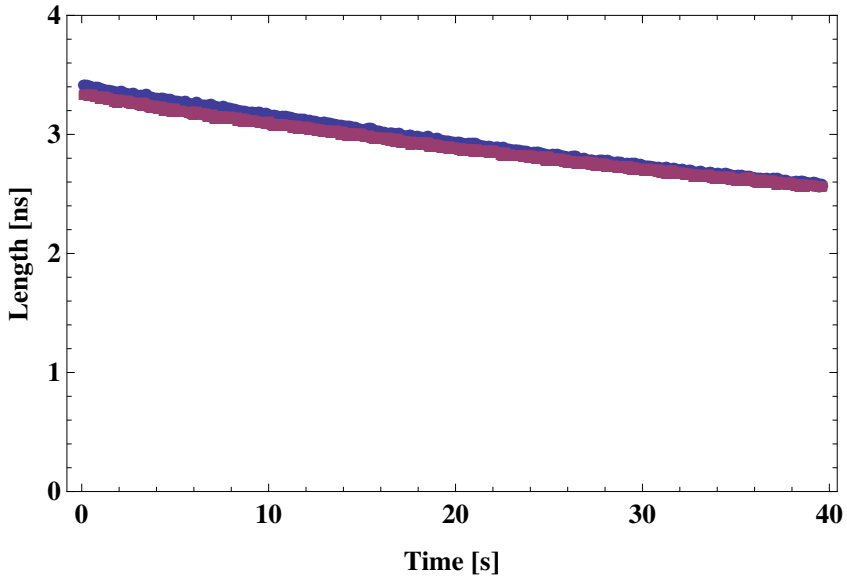
- end of November: getting worse with increasing intensity then recovered, see also LHCION1

Cycle LHCION2

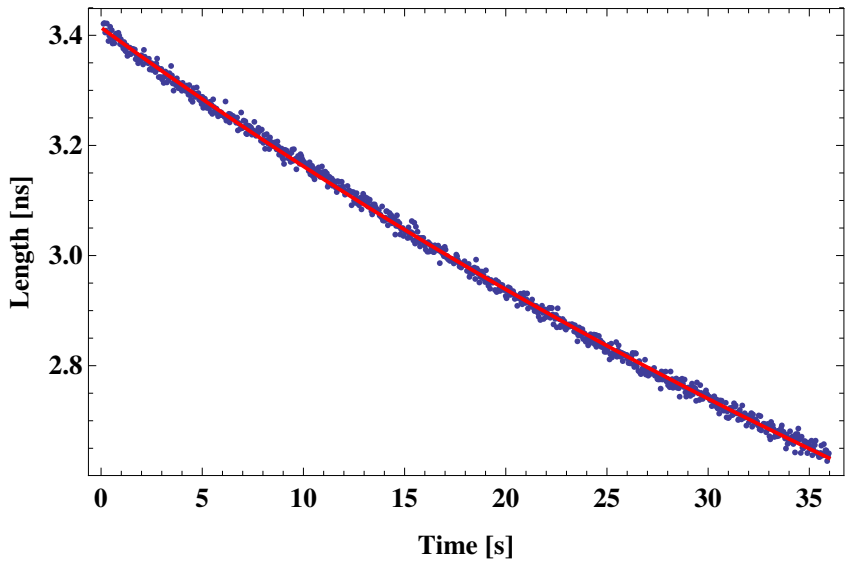
Beam Quality at Flat Bottom

Bunch Length, Batch Spacing: 175 ns (2015-12-07)

Bunch 1 & Bunch 2



Bunch 1



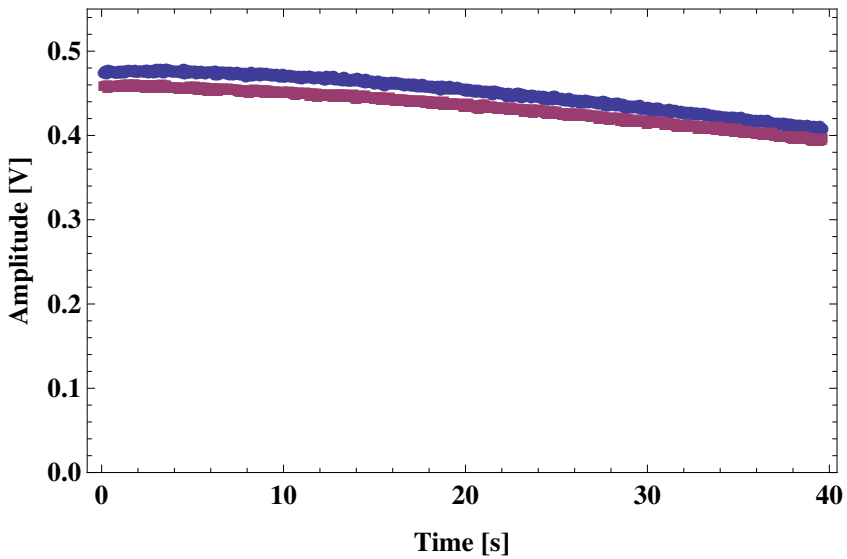
- $60\ \mathrm{s} \leq \tau_{\mathrm{aef}} \leq 85\ \mathrm{s}$ (asymptotic exponential fit: $\lambda = \lambda_\infty - (\lambda_0 - \lambda_\infty)\exp\left(-(t - t_0)/\tau_{\mathrm{aef}}\right)$
- $1.20\ \mathrm{s} \leq \lambda_\infty \leq 1.55\ \mathrm{ns}$ (asymptotic exponential fit)
- $125\ \mathrm{s} \leq \tau_{\mathrm{sef}} \leq 155\ \mathrm{s}$ (simple exponential fit)
- τ_{aef} about $2\times$ better than 2013-01-28 (no s.e.f. possible)

Cycle LHCION2

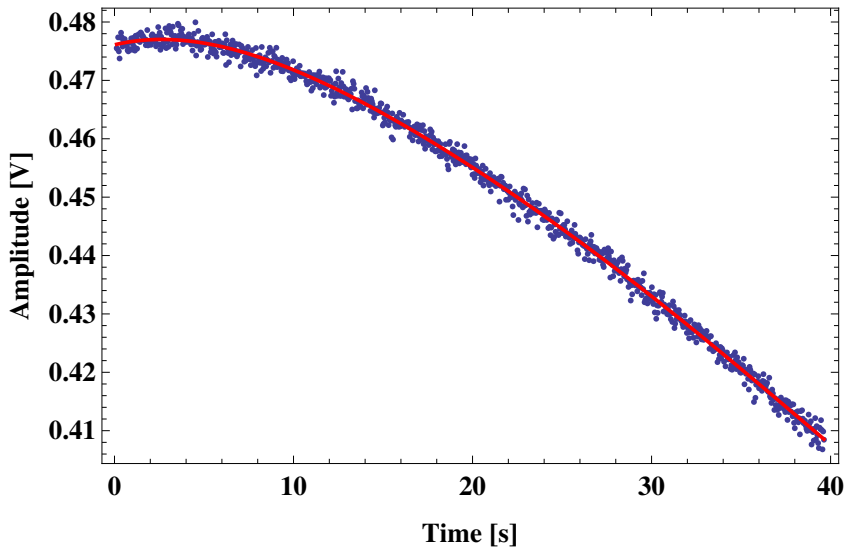
Beam Quality at Flat Bottom

Bunch Peak Amplitude, Batch Spacing: 175 ns (2015-12-07)

Bunch 1 & Bunch 2



Bunch 1

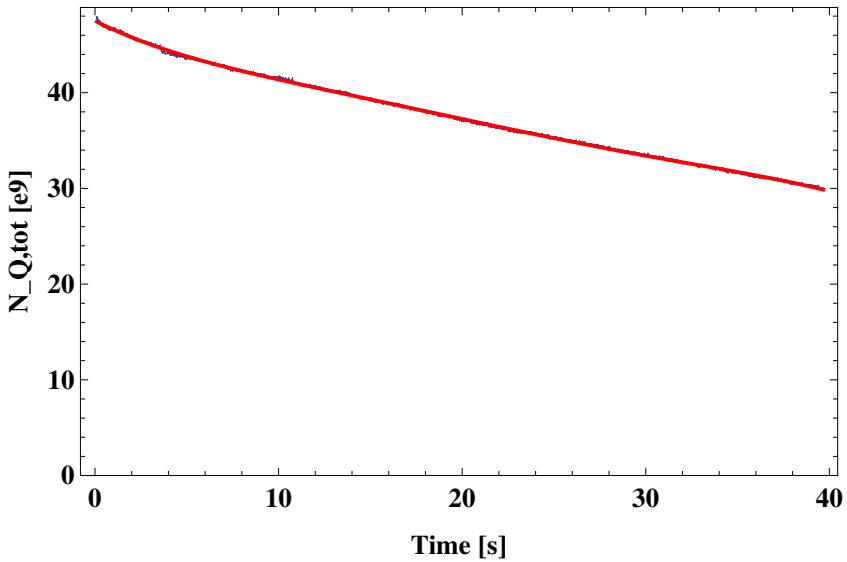


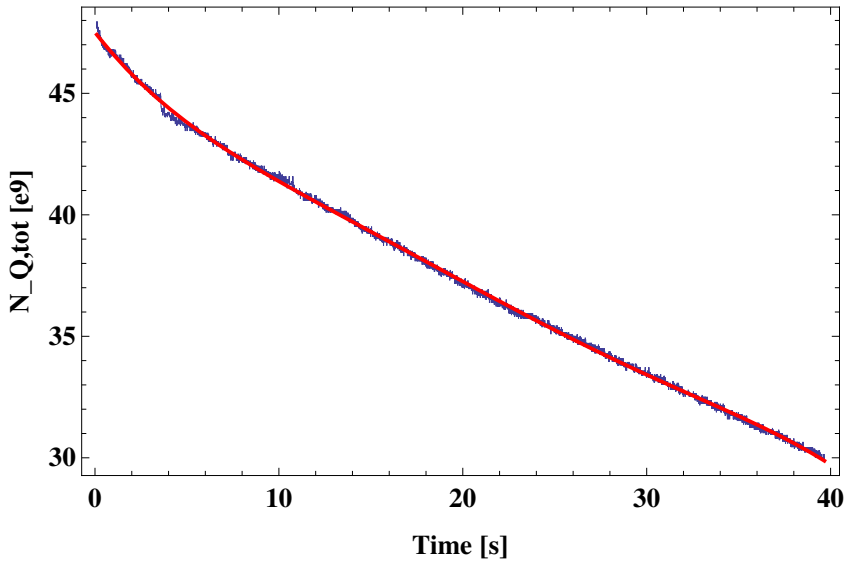
- no typical fit (Q20) possible (same as 2013): use 5th order polynomial
- average slope -3.5‰/s for $t_{\mathrm{obs}} = 40$ s
- $145\ \mathrm{s} \leq \tau \leq 200\ \mathrm{s}$ (amplitude reduction to 1/e) for $t_{\mathrm{obs}} = 40$ s
- about $2\times$ better than 2013-01-28

Cycle LHCION2

Beam Quality at Flat Bottom

BCT (2015-12-07)



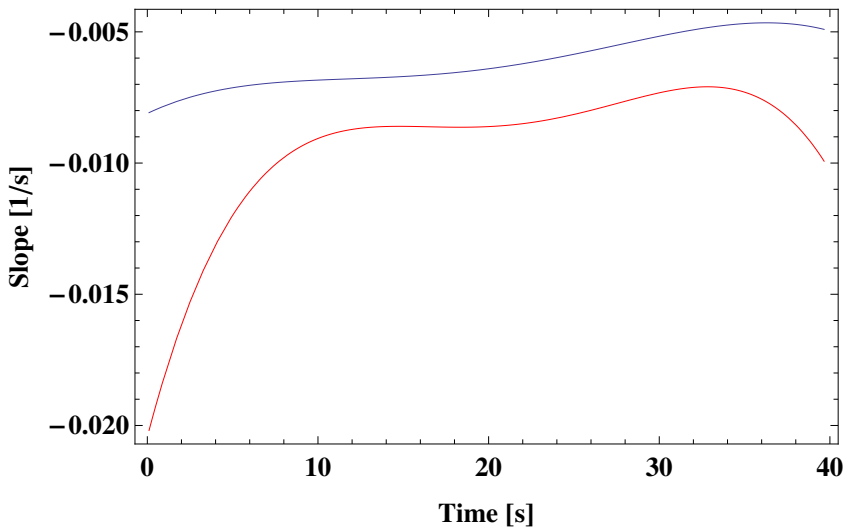


- no typical fit: use 5th order polynomial
- average slope -9.3‰/s for $t_{\mathrm{obs}} = 40$ s
- $\tau \approx 68$ s (amplitude reduction to 1/e) for $t_{\mathrm{obs}} = 40$ s
- about 2× worse than for Bunch Peak Amplitude

Cycle LHCION2

Beam Quality at Flat Bottom

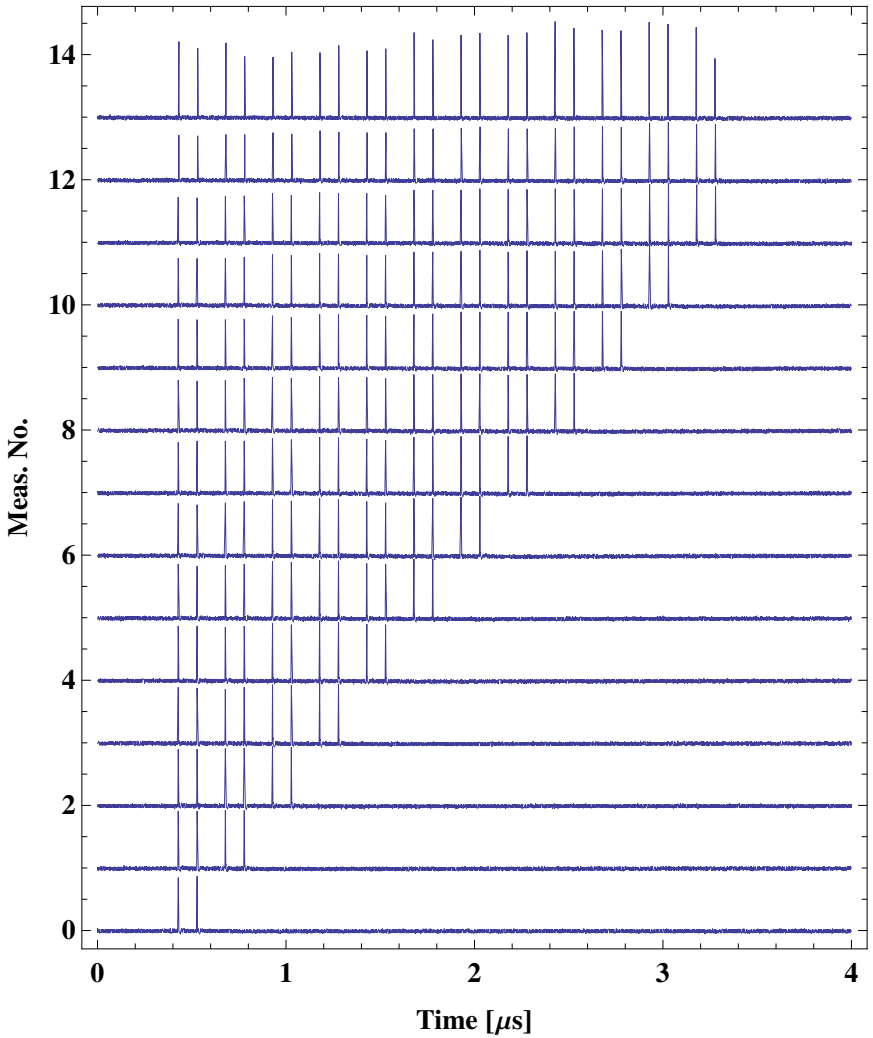
Bunch Peak Amplitude and BCT (2015-12-07)



- normalised to initial values
- $d(\text{Bunch Peak Amplitude})/dt$ (blue)
- $d(BCT)/dt$ (red)

Cycle LHCION2

Beam Quality at Flat Bottom

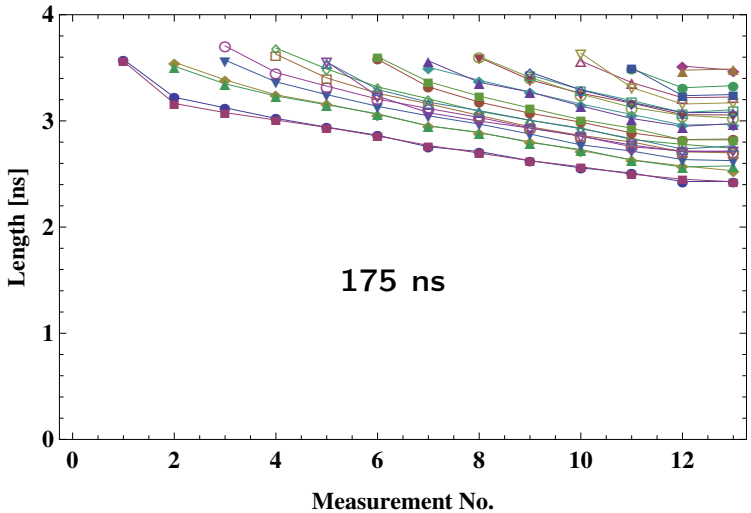


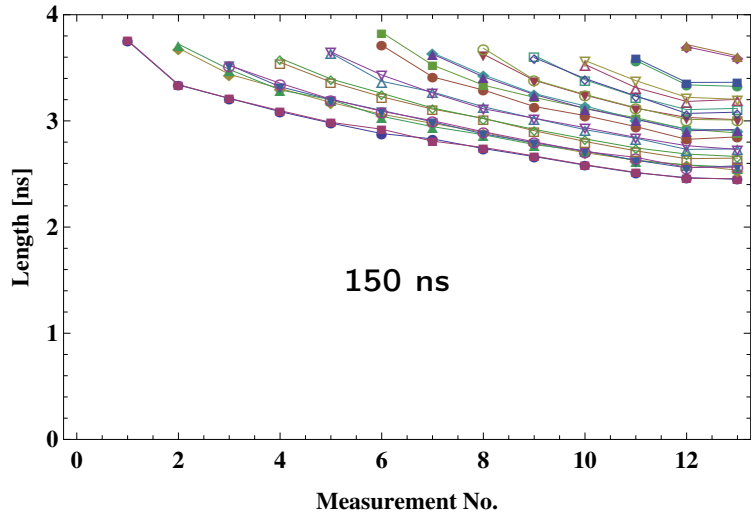
- batch spacing: 150 ns
- meas. after each injection (0 - 11), end Flat Bottom (12) & Flat Top (13)
- similar for other batch spacings, exception last batch

Cycle LHCION2

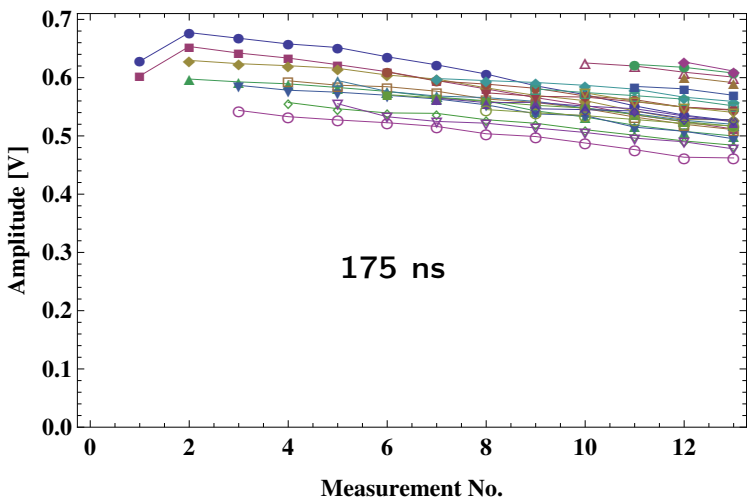
Beam Quality at Flat Bottom

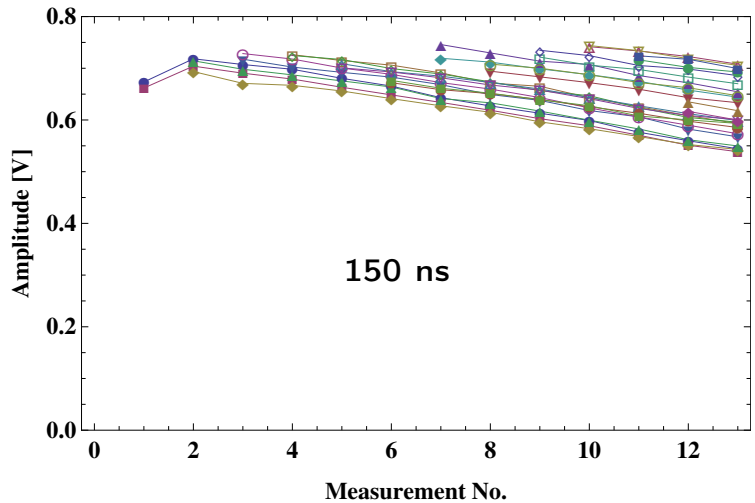
Bunch Length





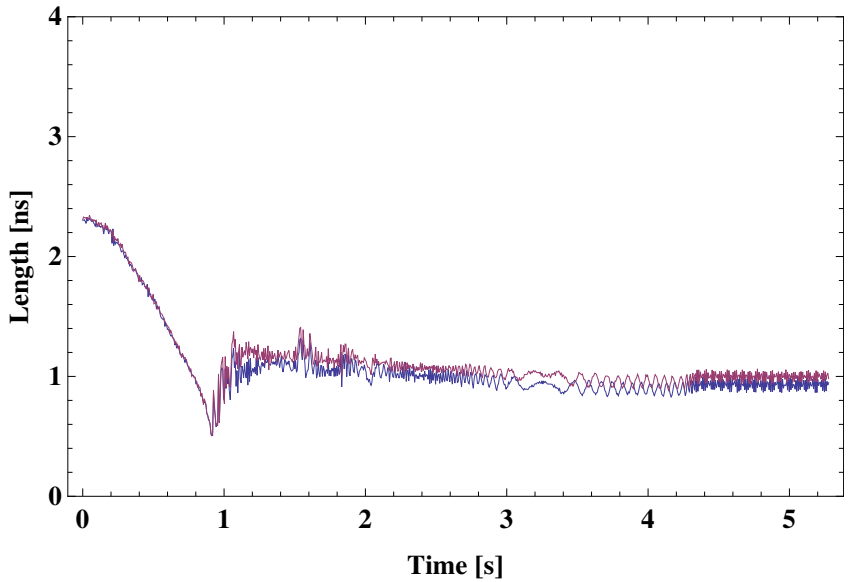
Bunch Peak Amplitude





Cycle LHCION2

Ramp



- $t_0 = t_{\mathrm{StartRamp}} - 60$ ms
- similar to LHCION1 case

Cycle LHCION2

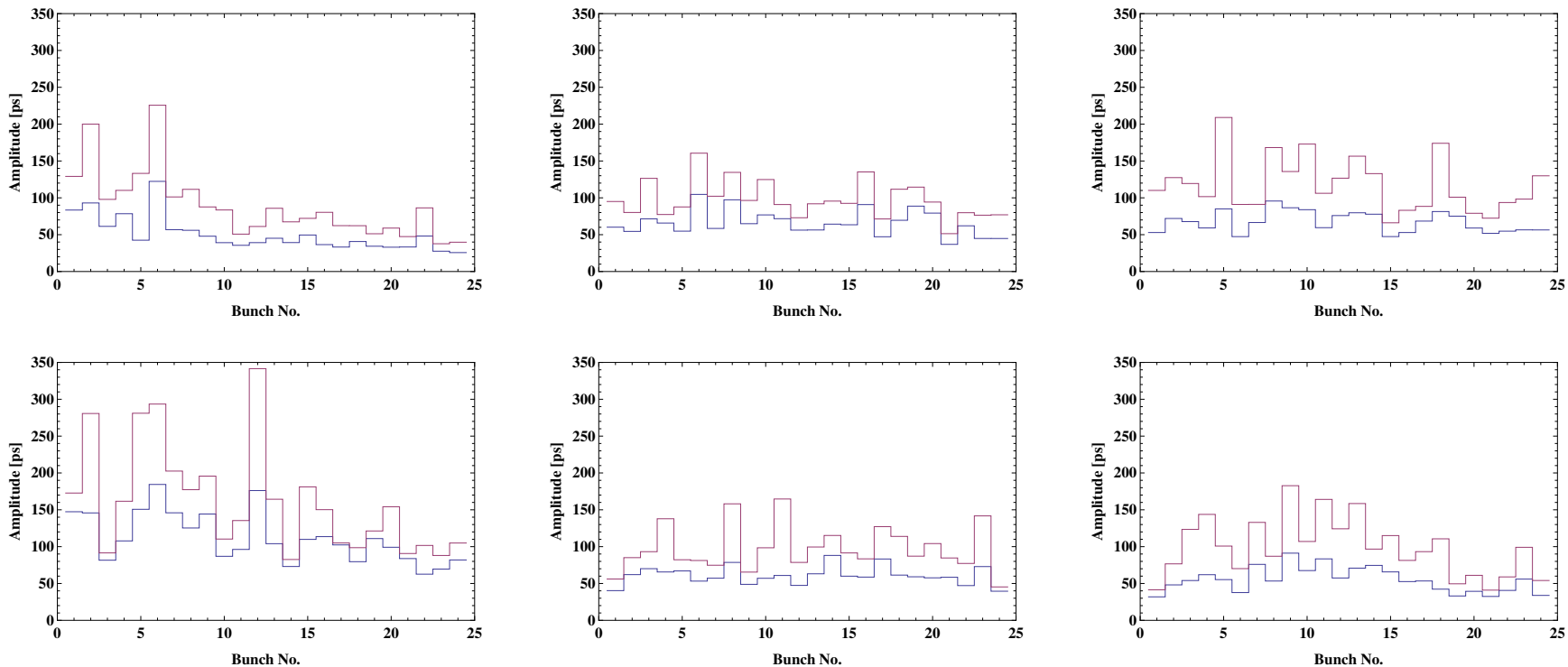
Flat Top

- bunch length oscillation, bunch position oscillation
- comparison with proton beam
- impedance
- controlled emittance blow-up in CPS
- in 2015: no problem delivering physics beam

Cycle LHCION2

Flat Top

Bunch Length Oscillation Amplitude: 2015-11-24, 2015-11-24, 2015-11-24, 2015-11-25, 2015-12-09, 2015-12-11

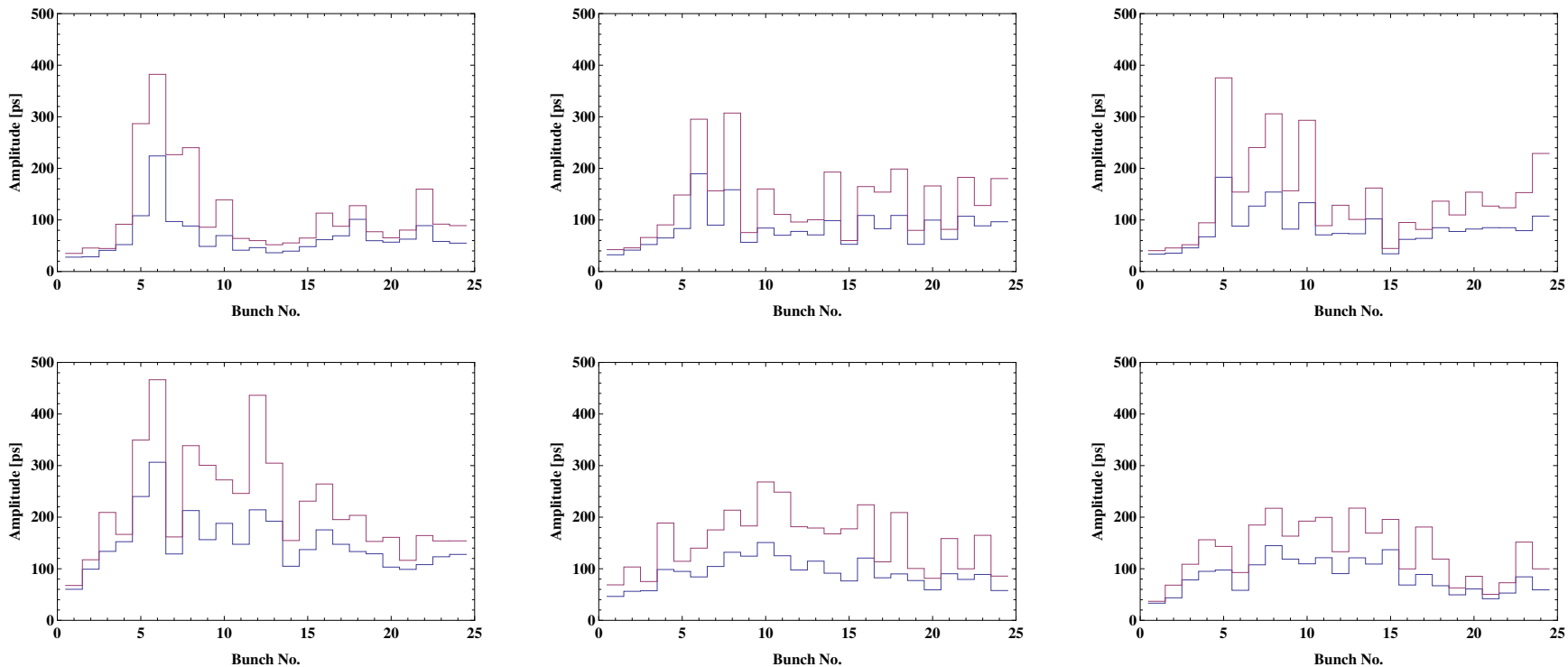


- max (red), average (blue)
- improvement with time

Cycle LHCION2

Flat Top

Bunch Position Oscillation Amplitude: 2015-11-24, 2015-11-24, 2015-11-24, 2015-11-25, 2015-12-09, 2015-12-11

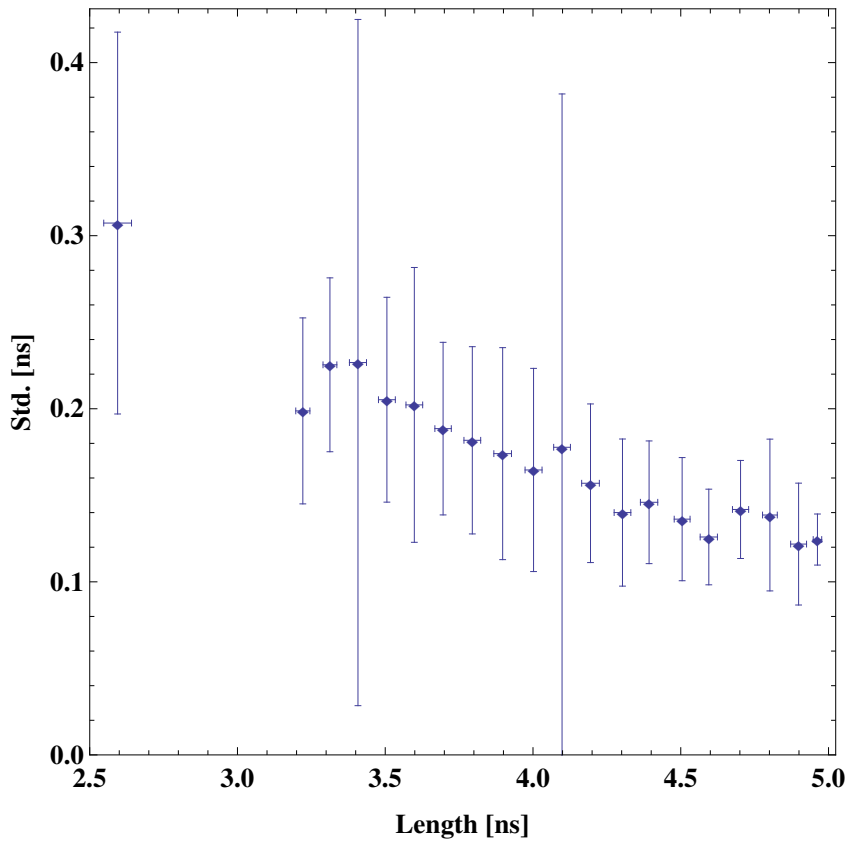


- max (red), average (blue)
- improvement with time

Cycle LHCION2

Flat Top

BUNCH_LENGTH_INJ_MEAN, BUNCH_LENGTH_STDDEV, 2015-11-23/2015-11-30

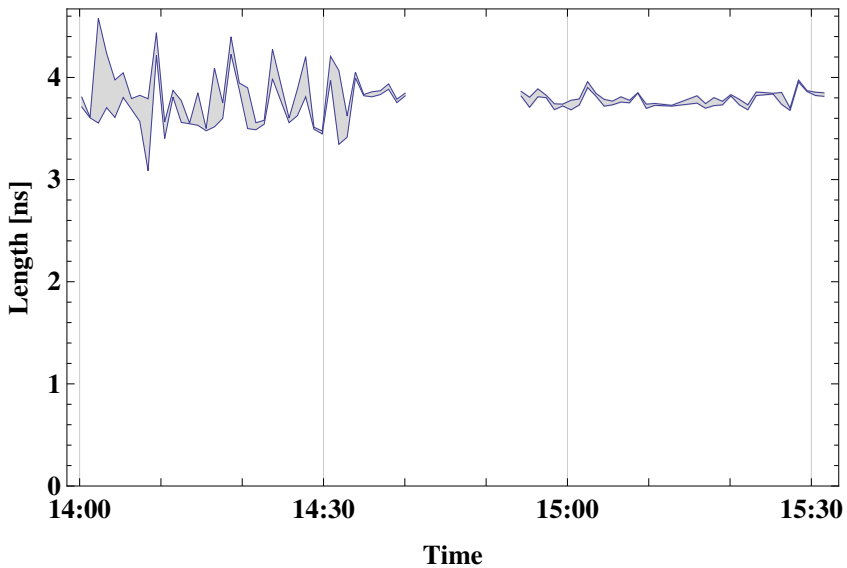


Cycle LHCION2

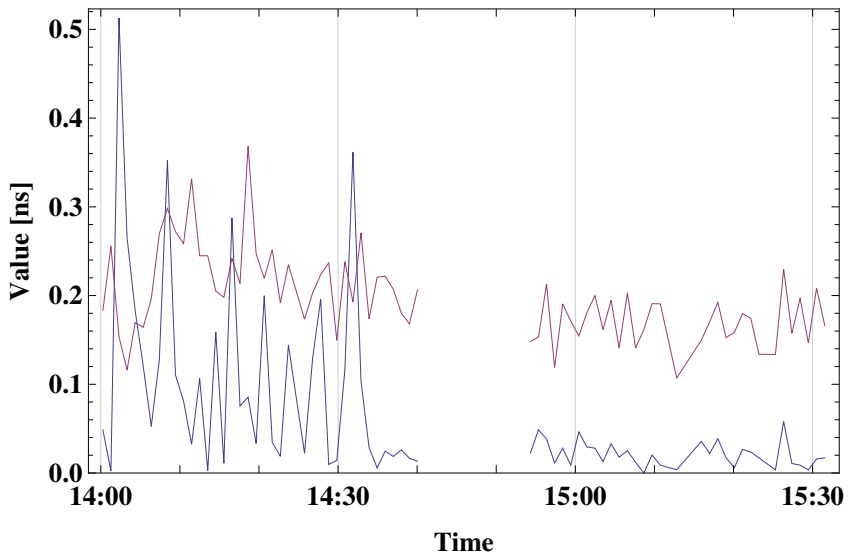
Flat Top

Controlled emittance blow-up in CPS 2015-12-02

$\lambda_{\mathrm{inj,min}}$, $\lambda_{\mathrm{inj,max}}$



$\Delta\lambda_{\mathrm{inj}}/2$ (blue), $std(\lambda_{\mathrm{EXT}})$ (red)

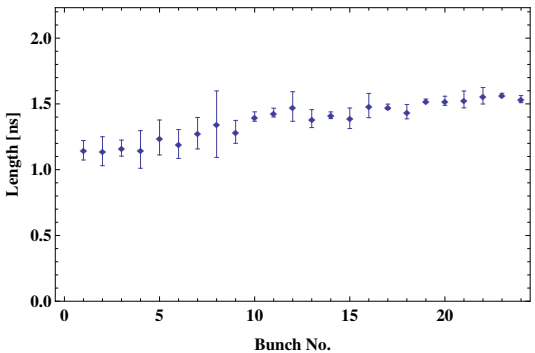


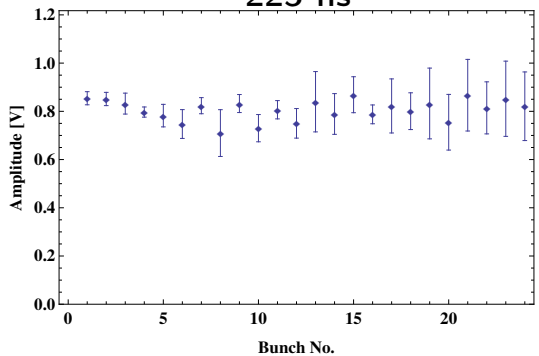
Cycle LHCION2

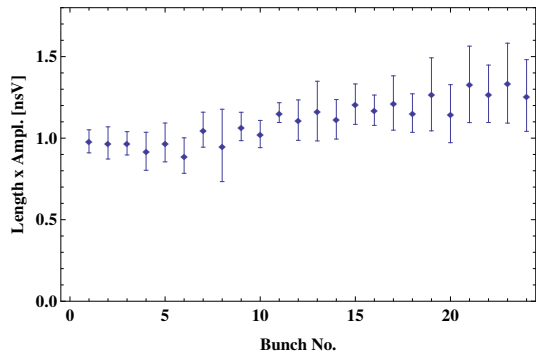
End Flat Top

Length | Amplitude | Length × Amplitude

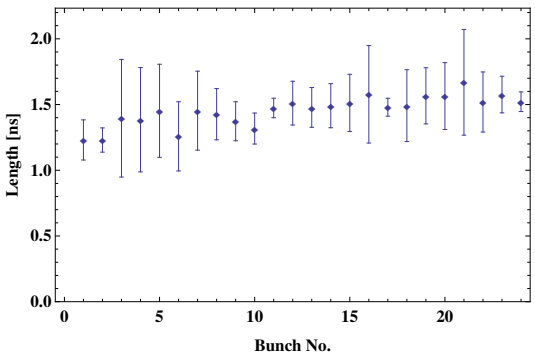
225 ns

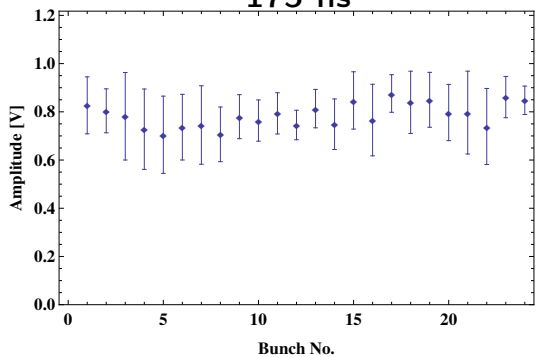


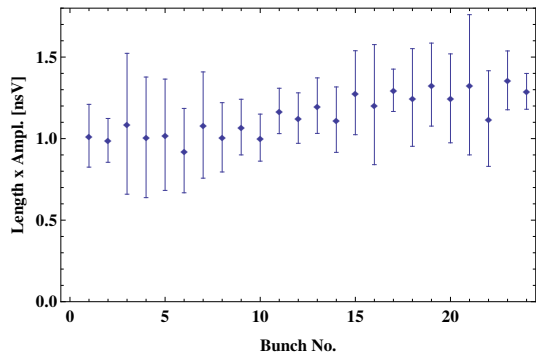




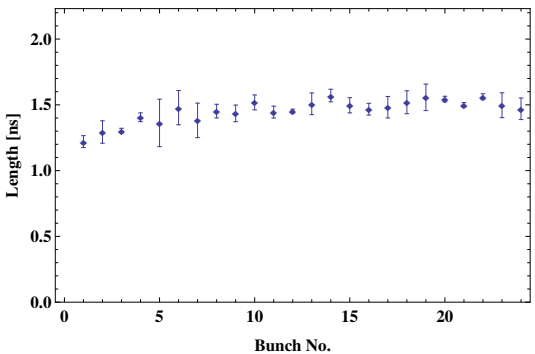
175 ns

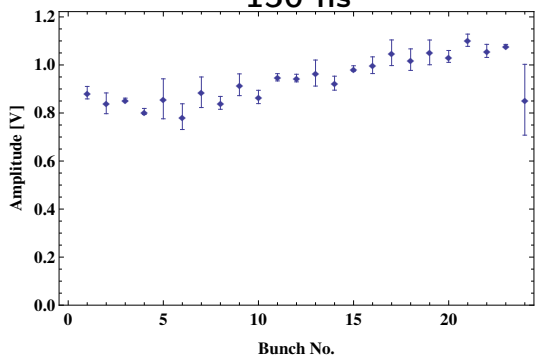


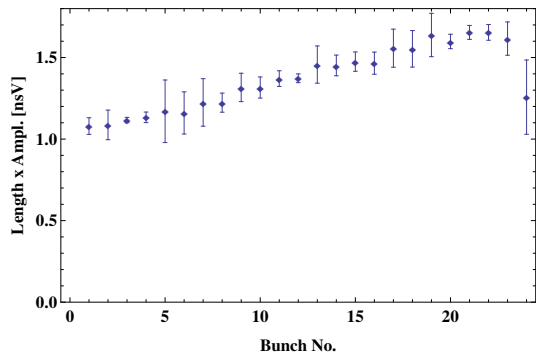




150 ns



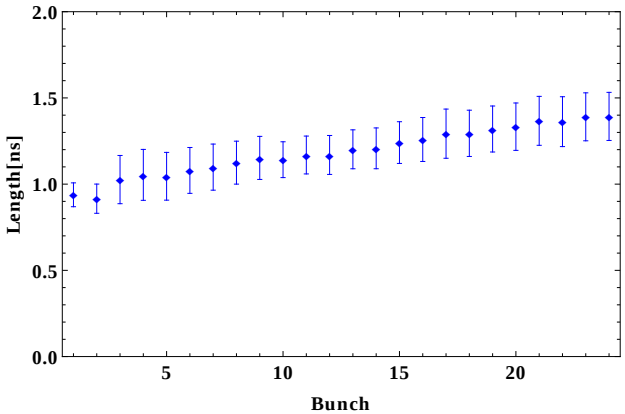


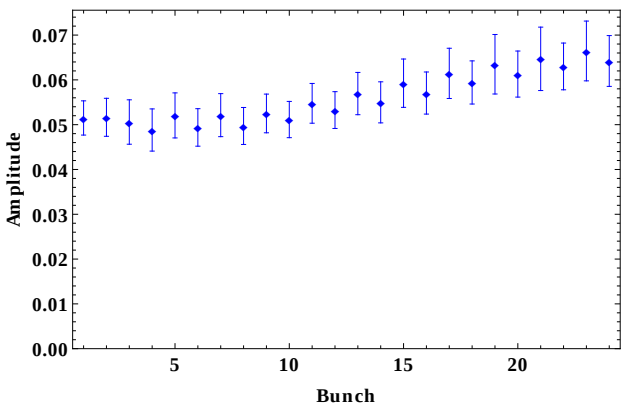


Cycle LHCION2

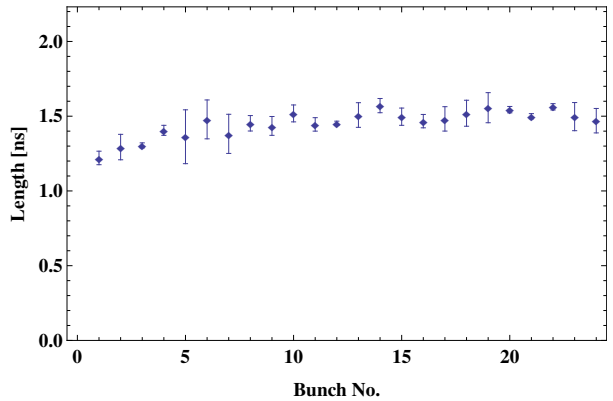
End Flat Top

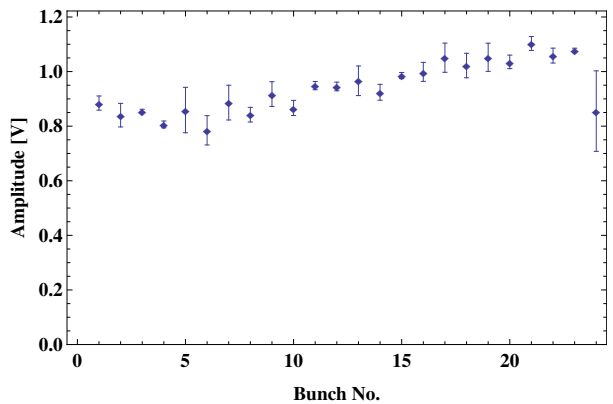
2013





2015 (150 ns)





Cycle LHCION2

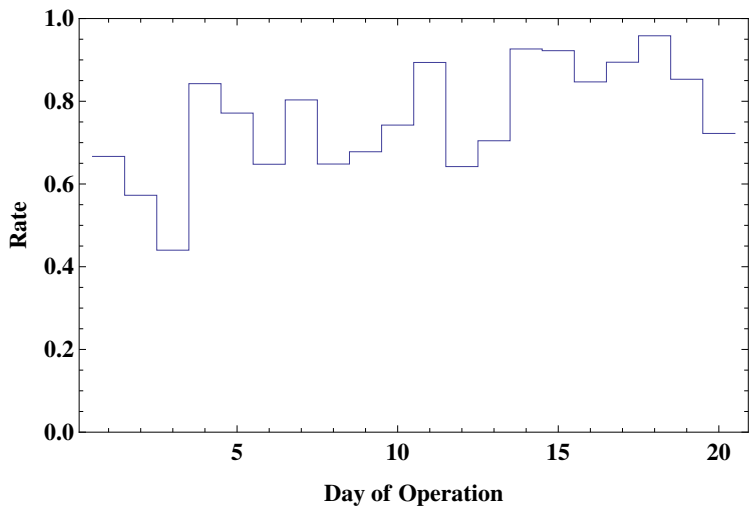
End Flat Top

BQM data for all cycles
SPS:LHC_ION_12INJ_Q20_2015_V1:LHCION2 with dynamic destination LHC: time span 2015-11-24 14:11 to 2015-12-13 19:35.

Average _OK

BQM Variable	Rate
SPS.BQM:1ST_BUNCH_POS_OK	0.87
SPS.BQM:BEAM_OK	0.75
SPS.BQM:BUNCH_INTENSITY_OK	0.83
SPS.BQM:BUNCH_LENGTH_OK	0.93
SPS.BQM:BUNCH_LENGTH_STDDEV_OK	0.93
SPS.BQM:BUNCH_PATTERN_OK	0.91
SPS.BQM:BUNCH_PEAK_OK	0.93
SPS.BQM:FIRST_BUNCH_POS_INJ_OK	0.99
SPS.BQM:SATELLITES_OK	0.94
SPS.BQM:STABILITY_OK	0.93

BEAM_OK

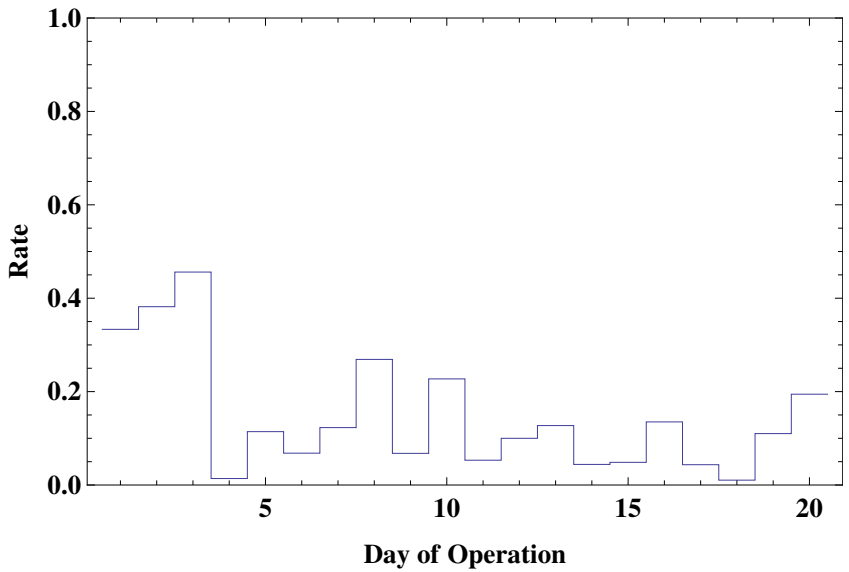


Cycle LHCION2

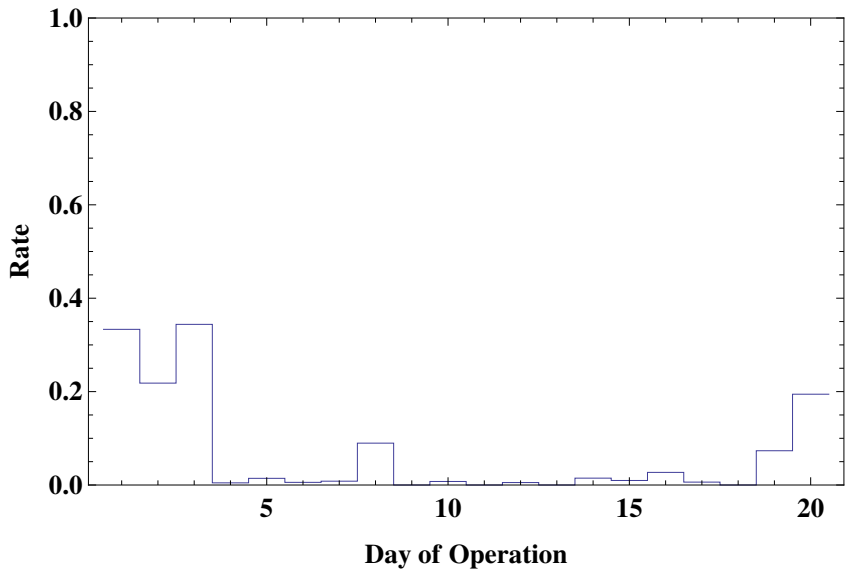
End Flat Top

Rephasing: 1ST_BUNCH_POS_OK = 0

POS_OK: 0



POS_OK = 0 ∧ others = 1



- better than expected
- physical limit length of Flat Top (2 s/1 s)

MD

End Flat Top

Slip stacking

- radial aperture at Flat Top
- phase loop off at Flat Top

MD

Radial Aperture

Radial steering limits

- relevant for rephasing
- relevant impedance (impedance model?)
- with extraction bumps on: -1 mm to +20 mm (mean CO)
- without extraction bumps on: -20 mm to +20 mm (mean CO)

MD

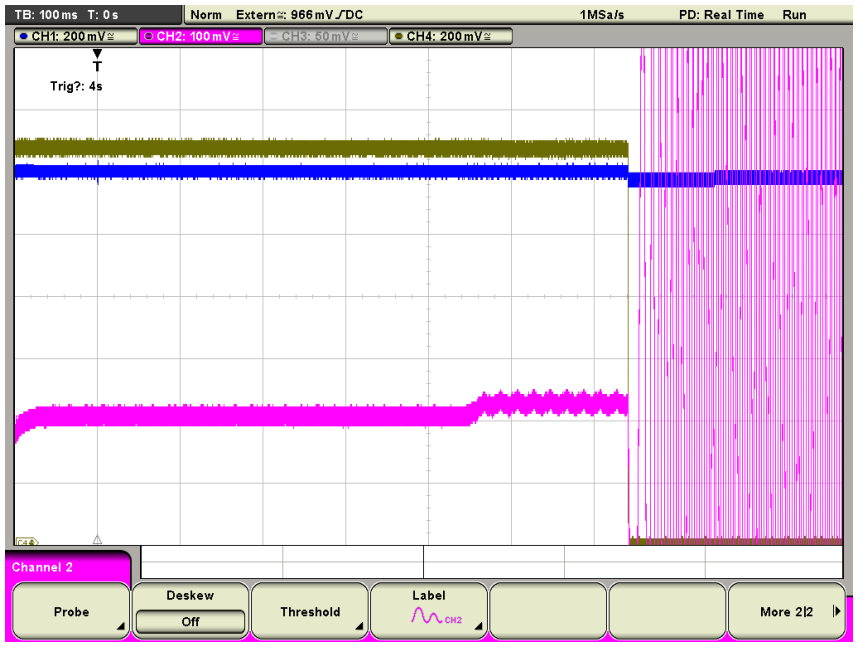
Phase Loop Off

- beam loss?
- bunch position shift?
- emittance increase?
- low level offsets, radial displacement?

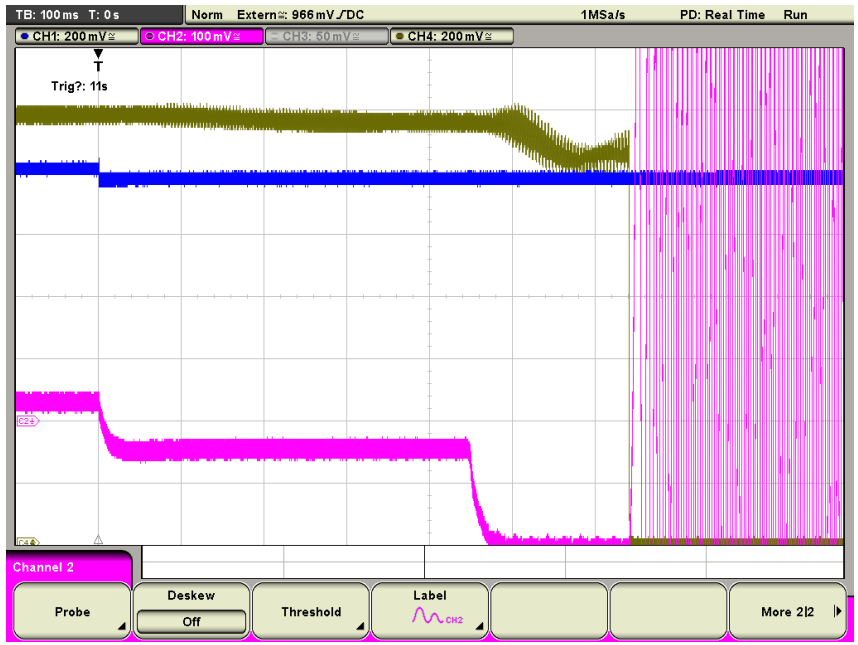
MD

Phase Loop Off

Phase Loop Not Off



Phase Loop Off



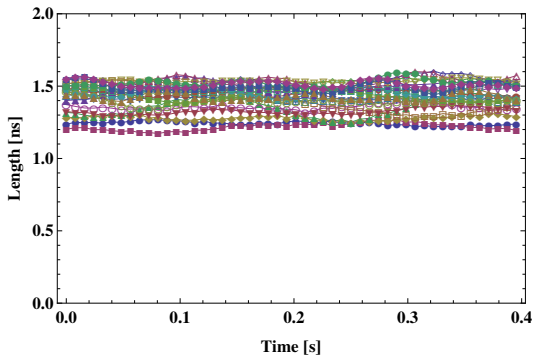
- CH1 (blue): $\Delta\Phi_{\mathrm{PL}}$, CH2 (pink): $\Delta\Phi_{\mathrm{SL}}$, CH4 (green): $\mathrm{AEW}_{\mathrm{pk}}$
- timebase 100 ms/div
- $t > 450$ ms: LSA

MD

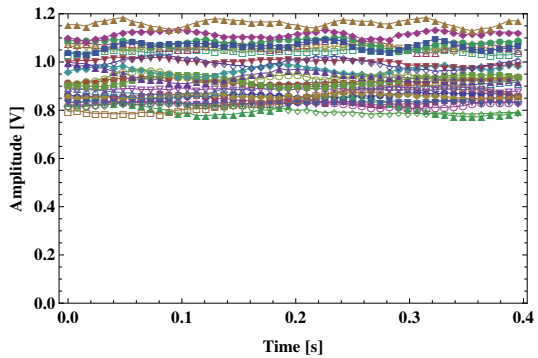
Phase Loop Off

Phase Loop Not Off

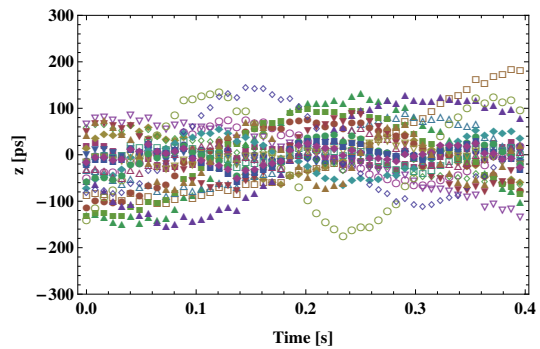
Length



Amplitude

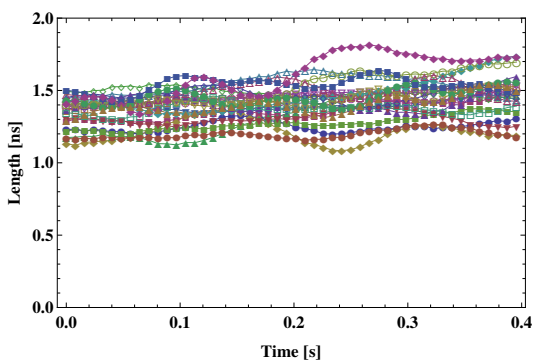


Position

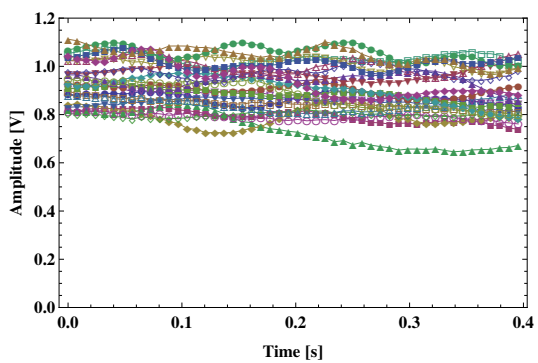


Phase Loop Off at $t_0 + 30$ ms

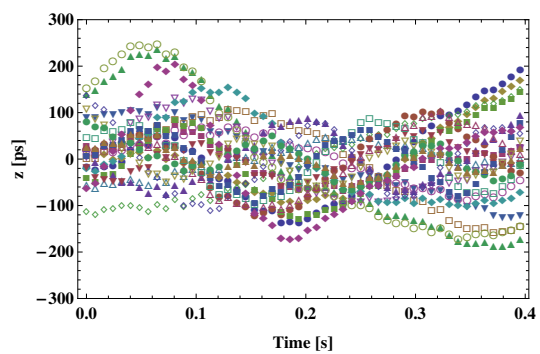
Length



Amplitude



Position



Summary and Outlook

Summary

- preliminary data for Run 2015
- beam related performance: no bad surprises
- transmission after transition now similar to Q26
- not much difference in performance for the batch spacings 225 ns, 175 ns, 150 ns
- record luminosities in LHC

Outlook

- new s/w FESA3
- new parallel cycle for h/w and s/w tests (no rephasing possible)

Acknowledgements

U. Wehrle

- commissioning and operation

BE-RF/CS, BE-RF/FB

- debugging of RF s/w and h/w

D. Manglunki, S. Cettour Cave and OP crews

- setting-up and operation