MD analysis: Partially Stripped Ions in LHC

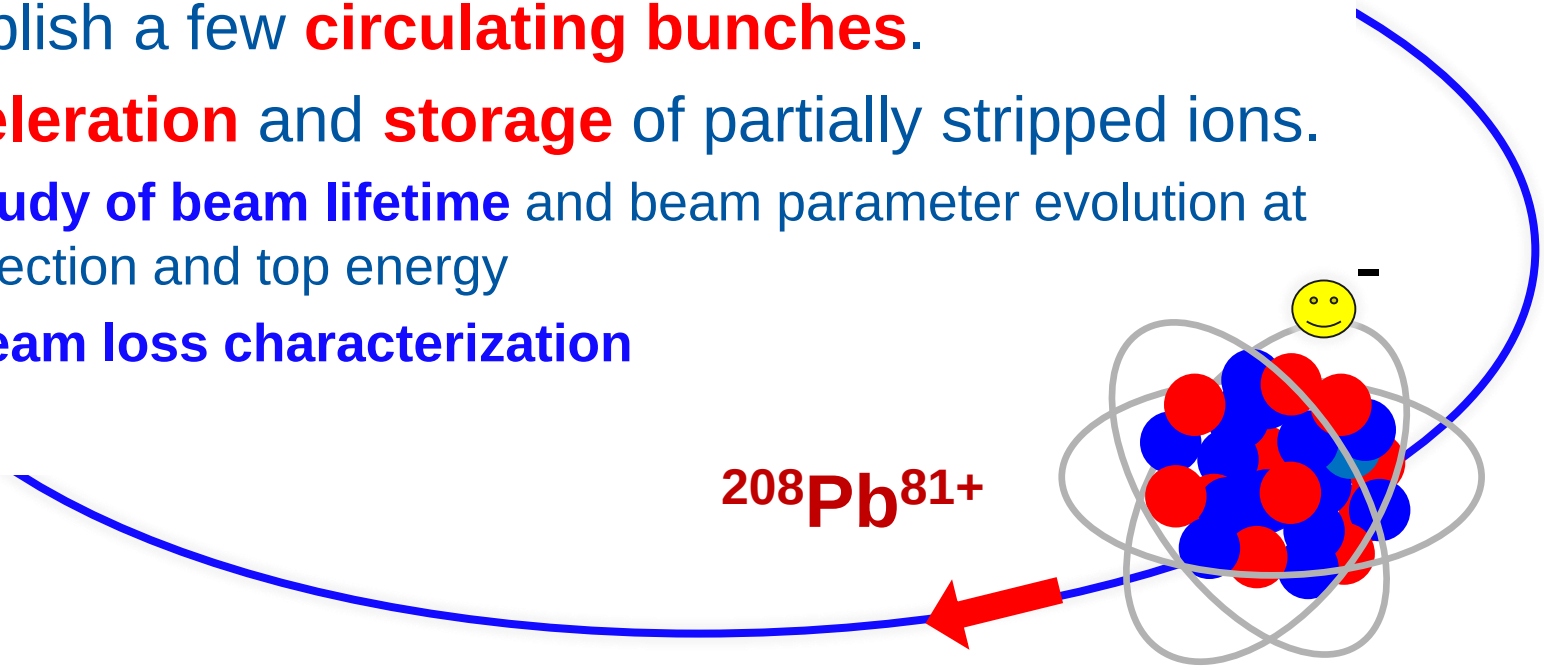
M. Schaumann

Thanks to S. Hirlander, R. Alemany and W. Krasny for discussions

Goals of this initial MD in the LHC

12 hours LHC-MD time on 25.07.2018

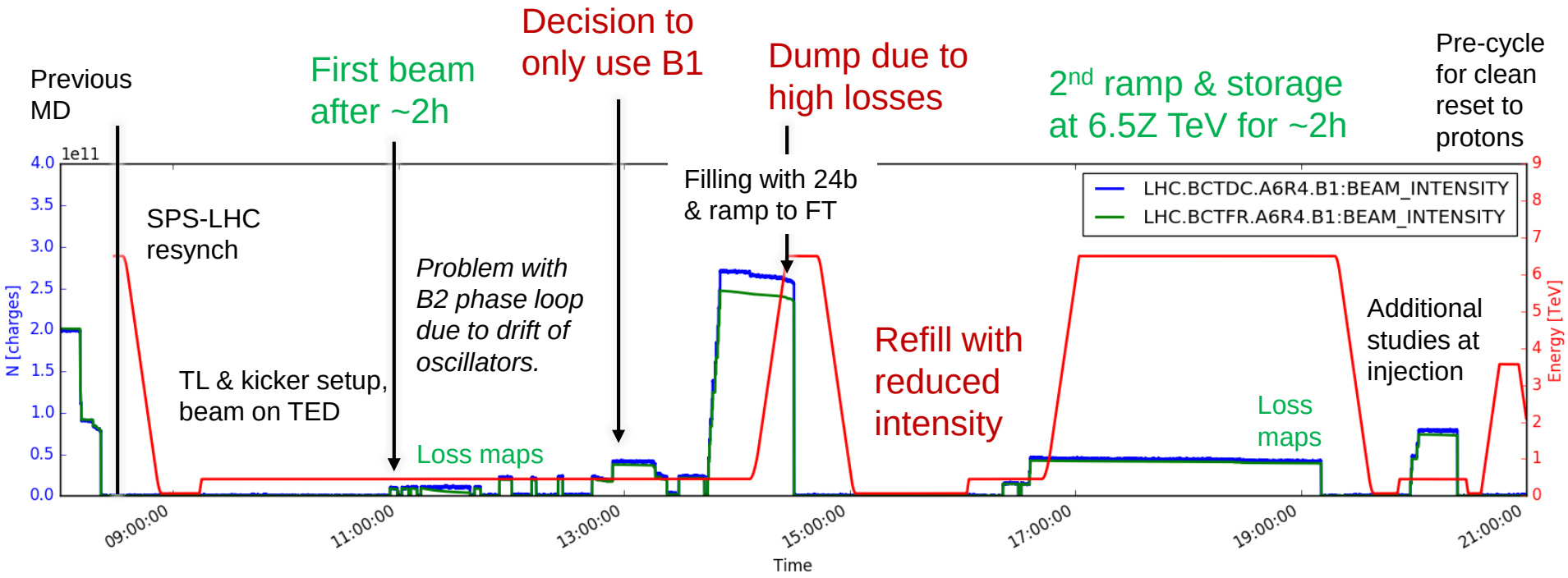
- **Inject** new particle “species” in the LHC
  - Well-known Pb-208, but with one remaining electron
- Establish a few **circulating bunches**.
- **Acceleration** and **storage** of partially stripped ions.
  - ➢ **Study of beam lifetime** and beam parameter evolution at injection and top energy
  - ➢ **Beam loss characterization**



MD Setup

- **LHC nominal cycle** until **flat top** (no squeeze, no collisions)
- **Usual injection setup for ions:**
  - particle type, transfer lines, kickers, SPS-LHC resynch & RF (lower RF-frequency than Pb^{82+})
- **Beam**:
  - Duplets with 2 bunches spaced by 200ns and total intensity of >2e10 charges (max.).
  - Pilot scraping in the SPS to get below 1e10 for initial injections.
- **Total circulating intensity**: **<3e11** (SETUP beam)

Evolution of the MD

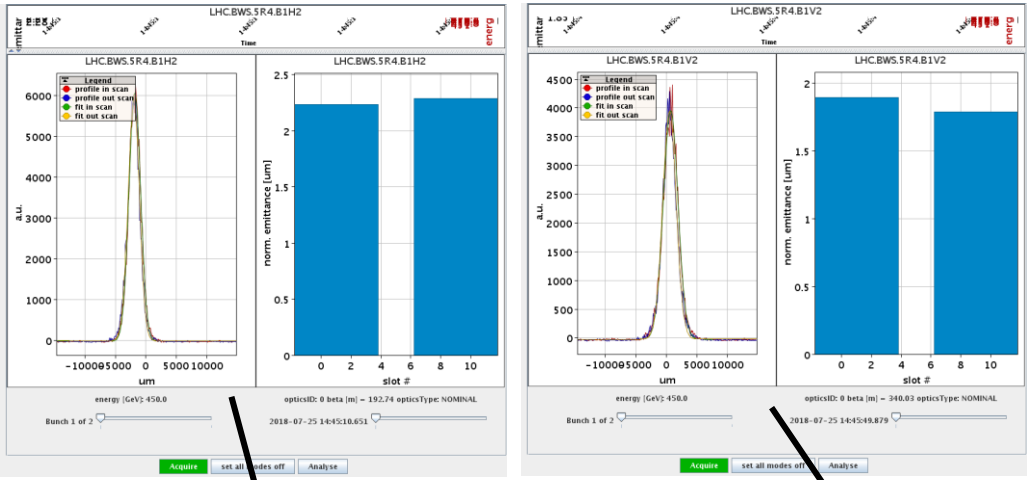


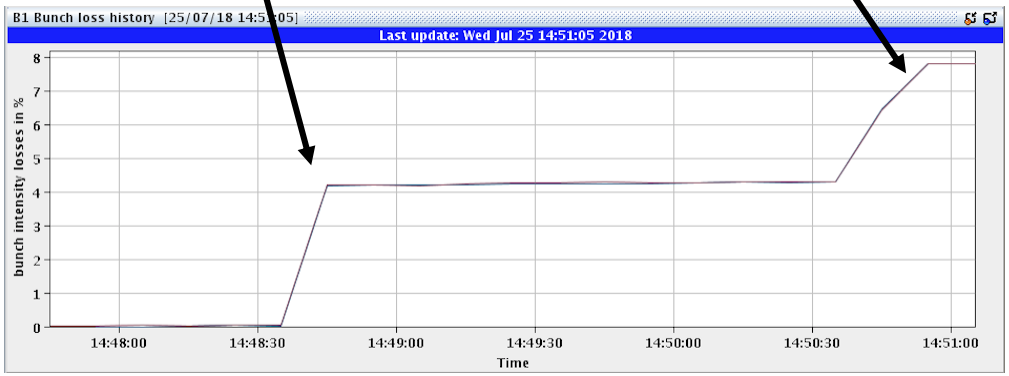
Decision to only use B1.
B2 not strictly necessary for the success of the MD, no collisions were foreseen.

Dump due to high losses 11R7.
Bad collimation efficiency and instability (zero octupoles and no damper).

Refill
Set octupoles during ramp, reduce number of bunches & bunch intensity.

Emittances Measurement

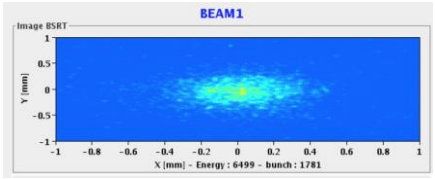




Emittances could not be measured well.

BSRT:

- No light at injection
- Not always acquiring at FT (2nd fill)

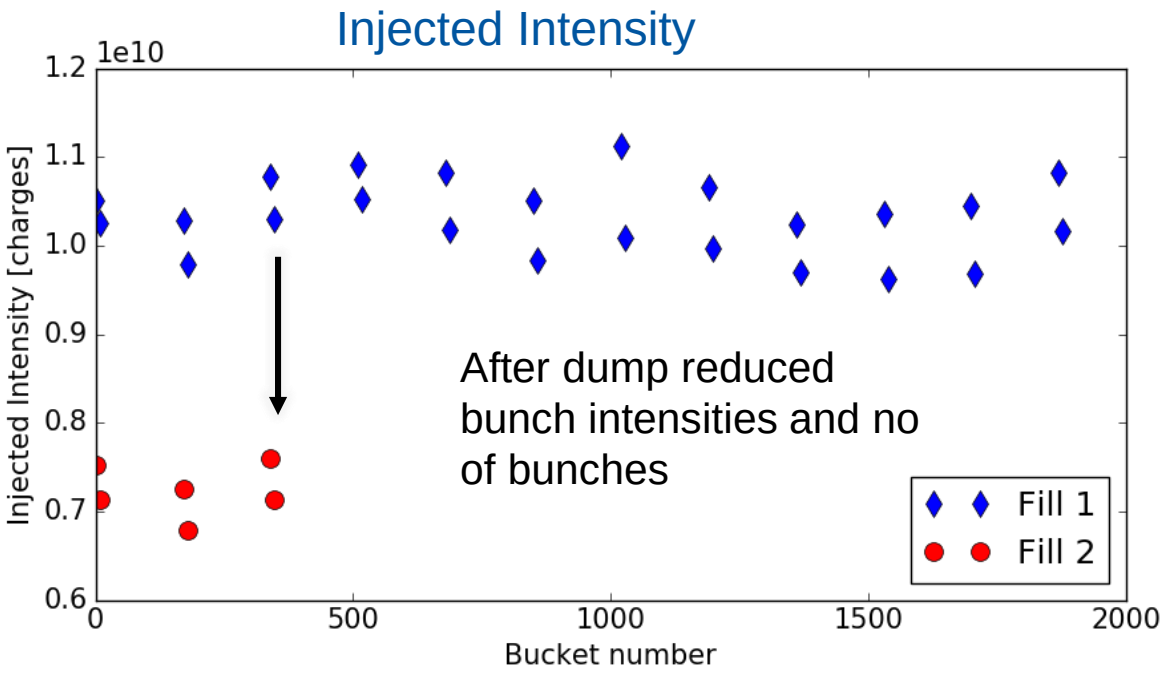


WS:

- ~4% intensity loss per scan by stripping of e-,
- Only two not optimized scans done
- not used at FT

No reliable information on emittance could be extracted

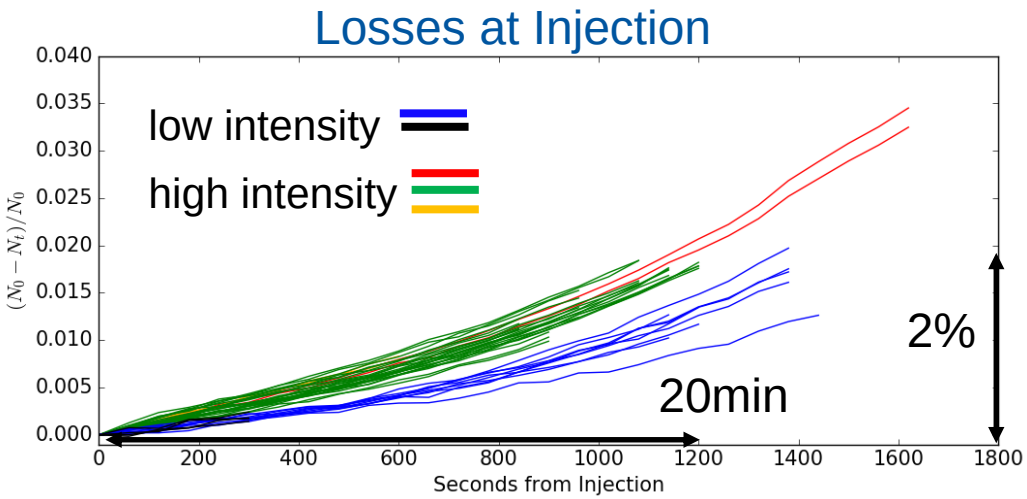
Injected Intensity



Fill 1:
- 1.1E10 charges/bunch
- 24 bunches

Fill 2 (reduced intensity):
- 0.75E10 charges/bunch (scraping in SPS)
- 6 bunches

Losses at Injection

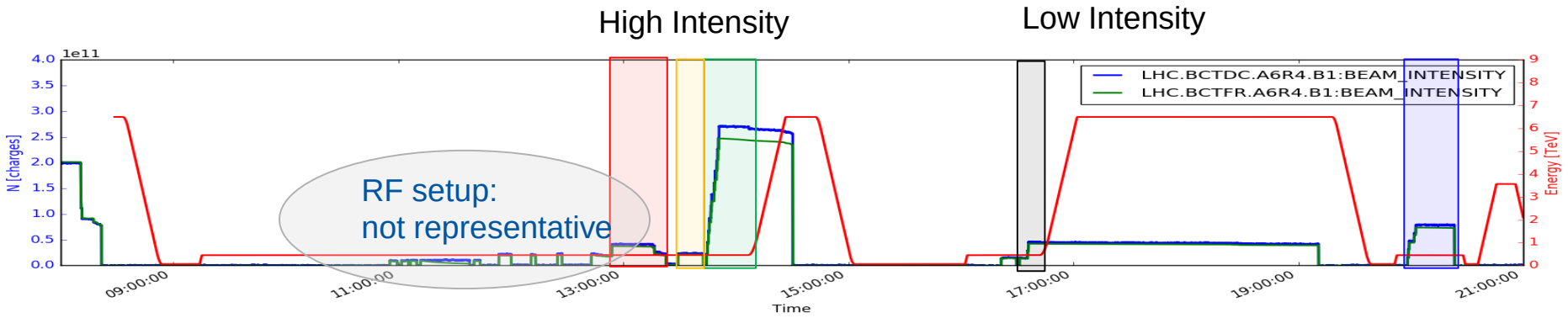


5 periods are analyzed:

- Bunches in different intensity regimes
- Dwell time: 20-30min

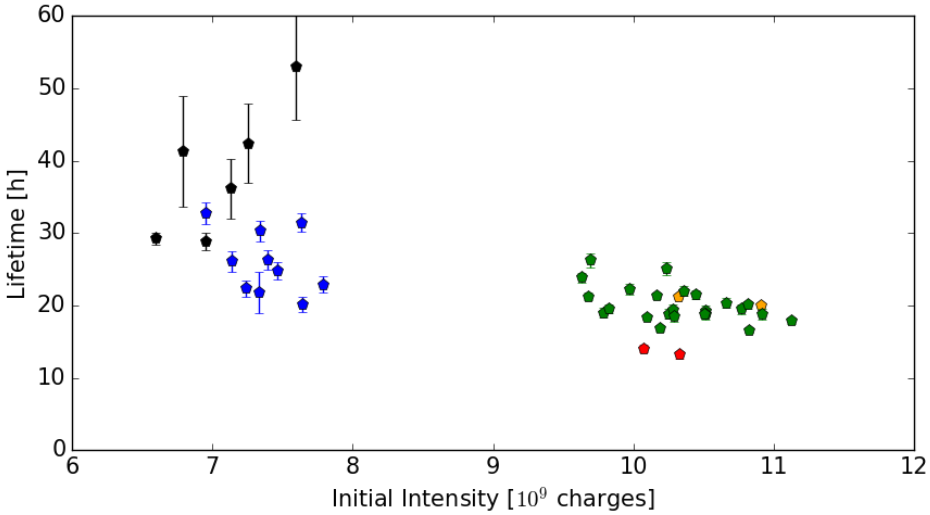
Observations:

1) **High intensity bunches lose faster.**
2) **Increasing loss rate over time**



Beam Lifetime at Injection (1)

Higher intensity bunches: lose faster = have smaller lifetime

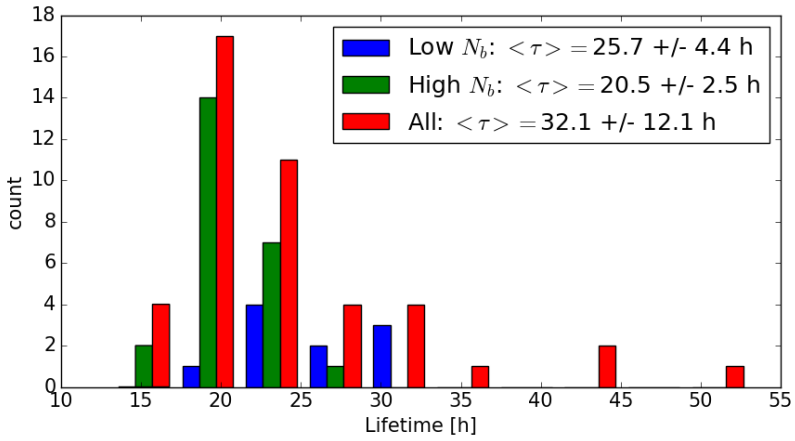


Lifetime fits of the form:

$$f(x; A, \tau) = Ae^{-x/\tau}$$

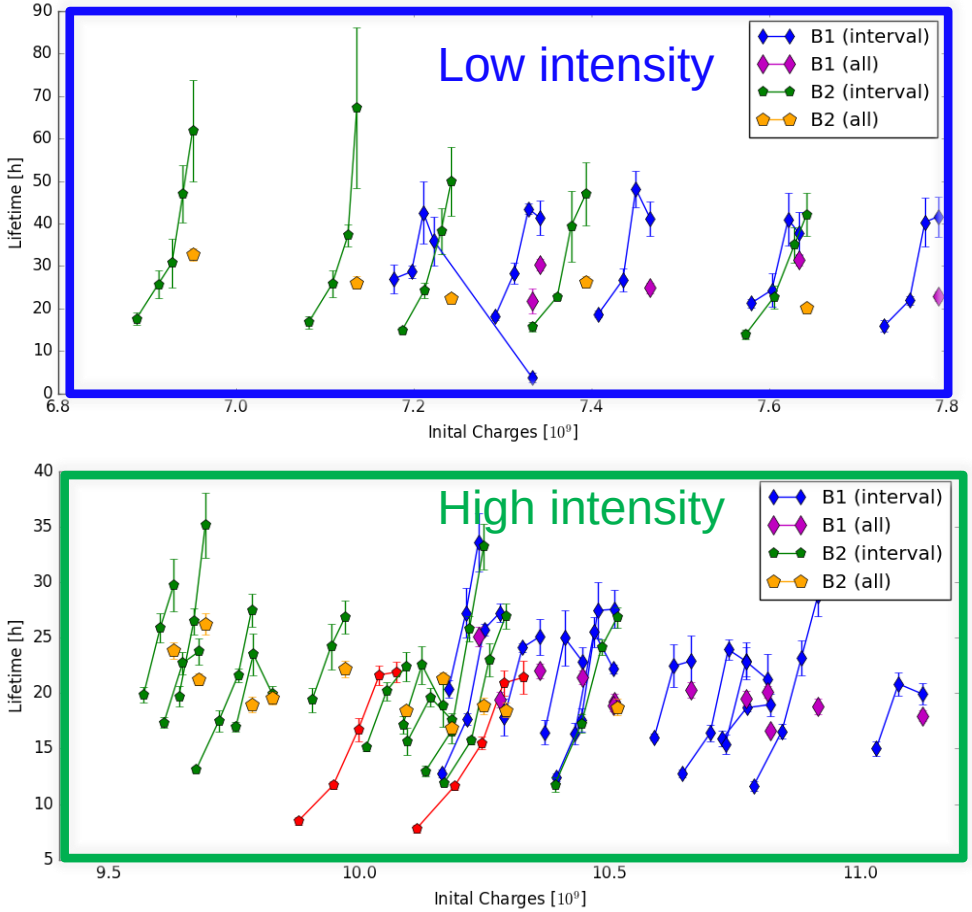
Average lifetime at 0.45 TeV proton equiv. energy: **~20h**

Beam Type	Nb [charges / ions]	Lifetime [h]
Low	7.4e9 / 0.9e8	25.7 +/- 4.4
High	10.3e9 / 1.3e8	20.5 +/- 2.5
All	9.2e9 / 1.1e8	32.1 +/- 12.1



Beam Lifetime at Injection (2)

With time: loss rate increases = lifetime decreasing

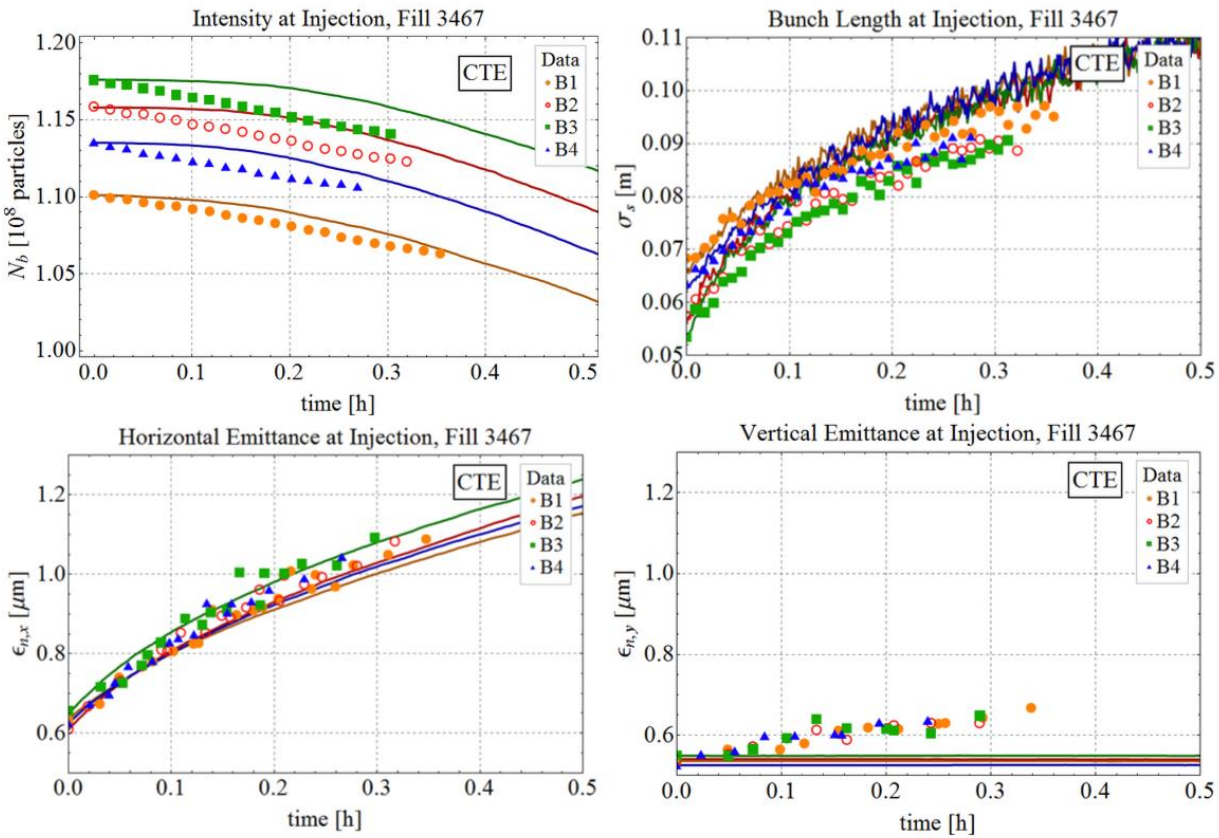


Lifetime fits over data intervals of 5 minutes.

Clear structure:
The longer the dwell time (smaller initial intensity at start of fit interval) **the smaller the lifetime.**

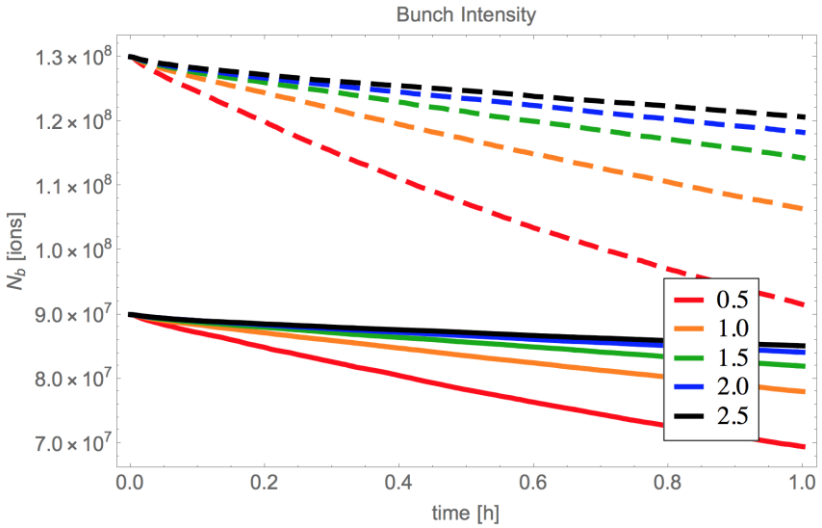
Pb82+ Injection Evolution of 2013

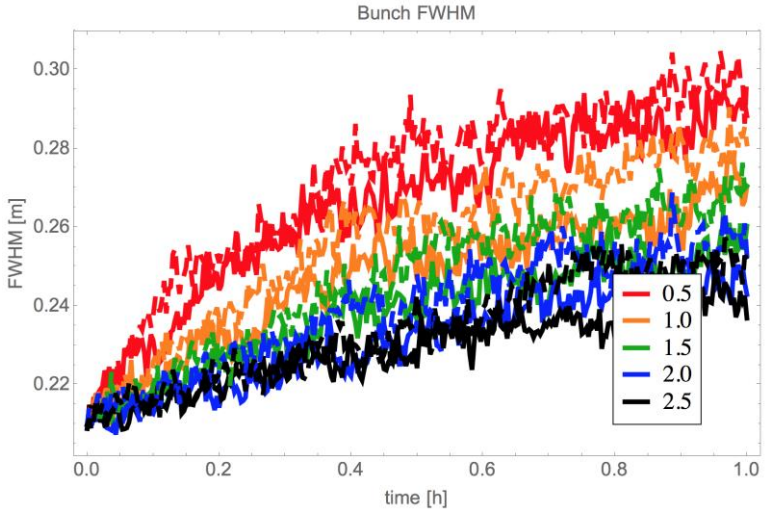
Similar bunch intensity as Pb81+

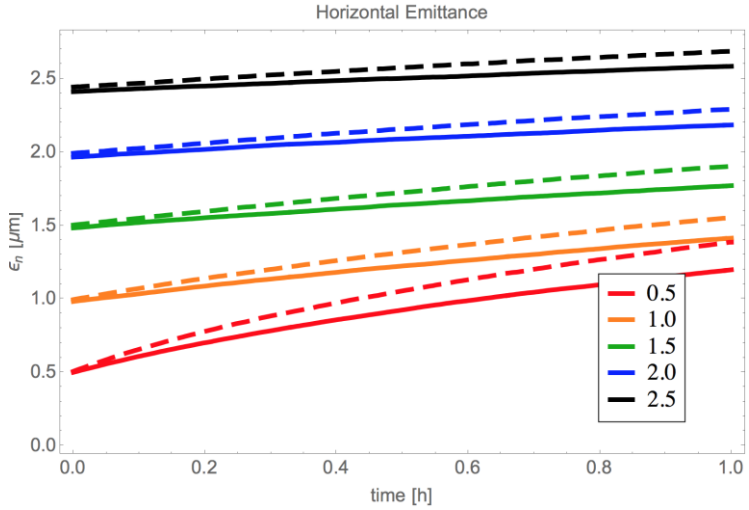


M. Schaumann, PhD Thesis, Fig. 4.7

CTE Simulations (Preliminary)



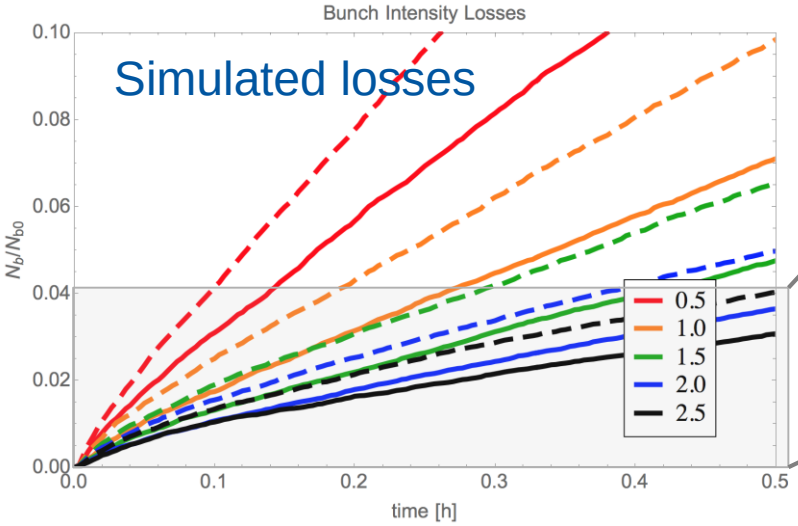




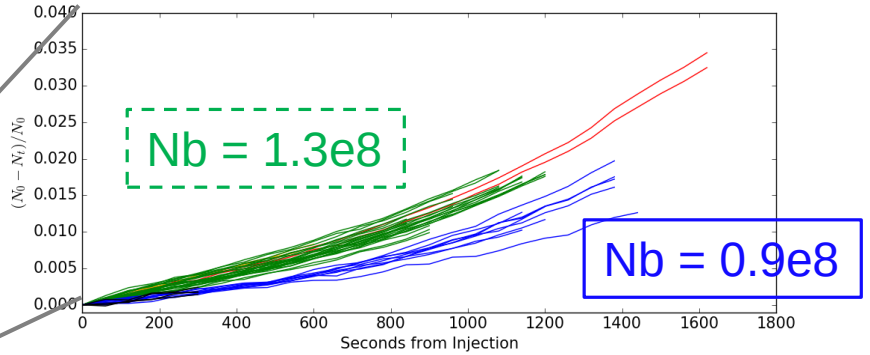
Simulation of
- Nb =**0.9e8** (solid) and **1.3e8** (dashed)
- Emittance = **0.5 → 2.5 um** (colors)
- Bunch length 10cm, but was 6cm

Including **IBS, radiation damping, debunching model**.

Losses: CTE vs Measurement (Preliminary)



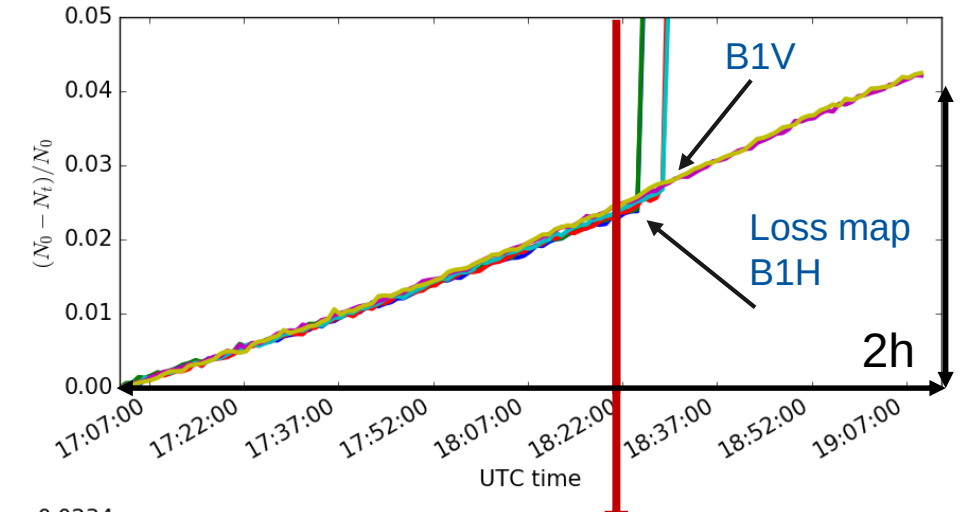
Measured losses

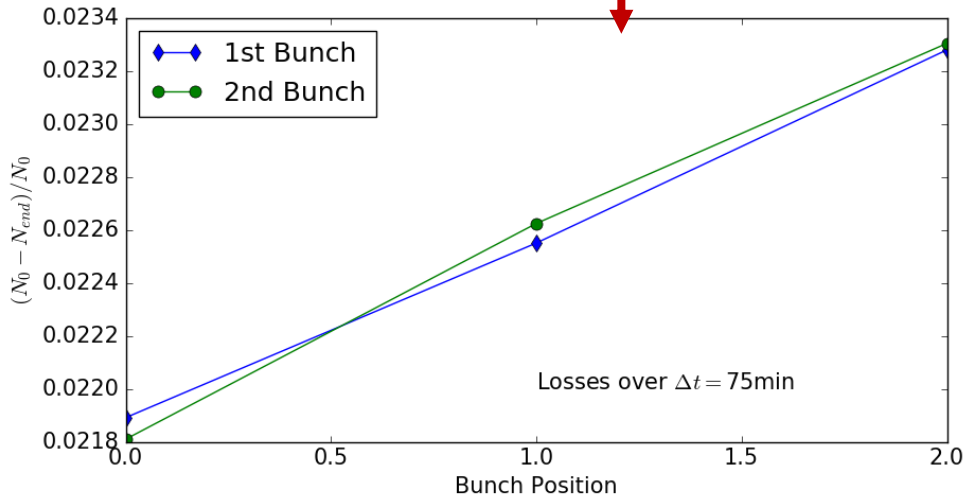


Comparison of the measured losses to simulations suggest that emittance was >2um.

→ But initial bunch length was assumed too large, reducing it can significantly impact the result.

Losses at FT: Fill 2



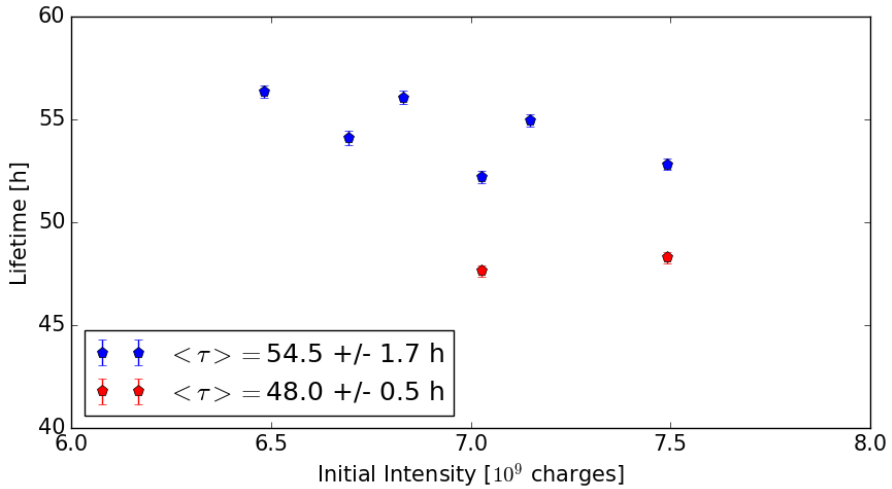


All bunches lose approx. with the same rate

Bunches injected last lose slightly more intensity

Difference 0.15%
Effect or measurement uncertainty?

Lifetime at Flat Top (1)



Lifetime fits of the form:

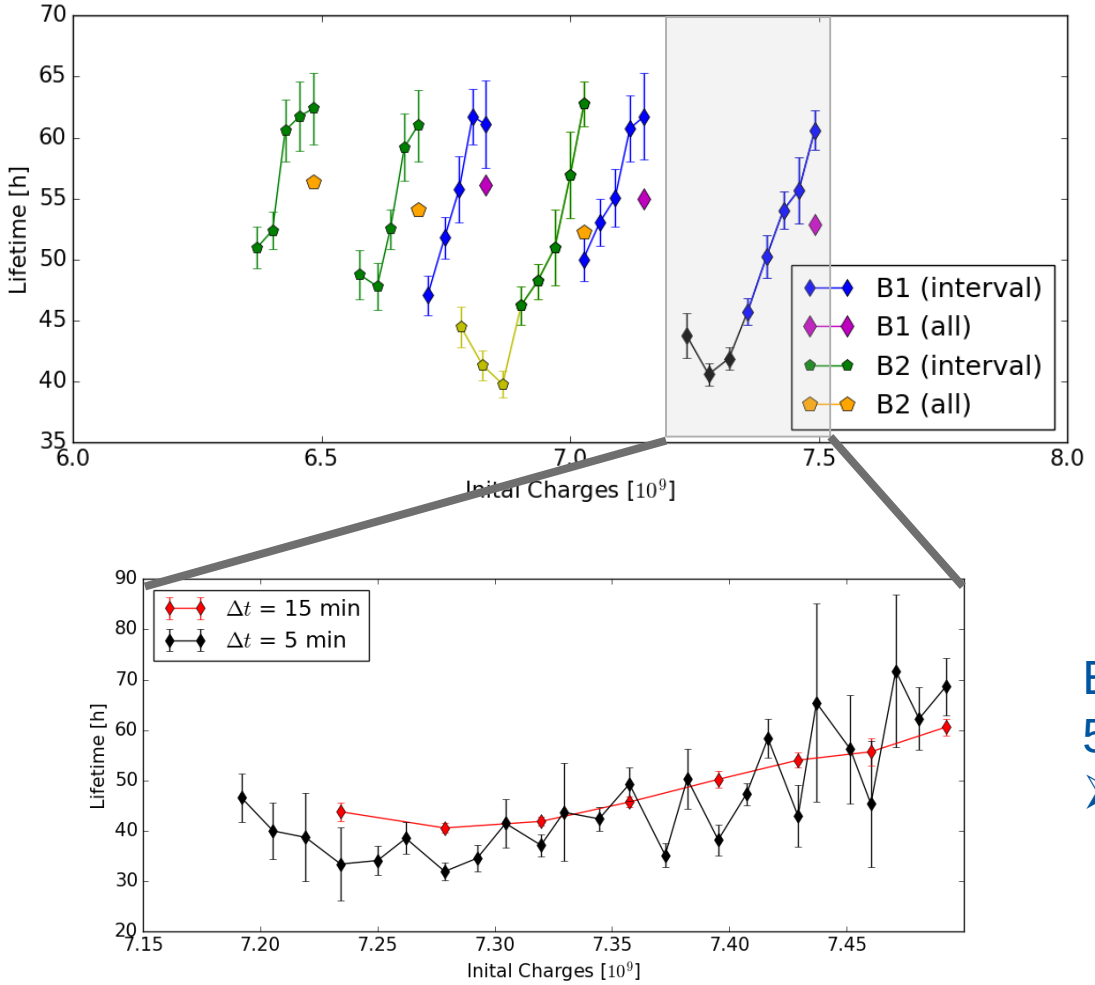
$$f(x; A, \tau) = Ae^{-x/\tau}$$

Fit over longer duration give smaller lifetime.

Beam Type	Nb [charges / ions]	Lifetime [h]
Low	7.0e9 / 0.86e8	54.5 +/- 1.7
Low	7.2e9 / 0.89e8	48.0 +/- 0.5

Average lifetime at 6.5 TeV proton equiv. energy: **~50h**

Lifetime at Flat Top (2)



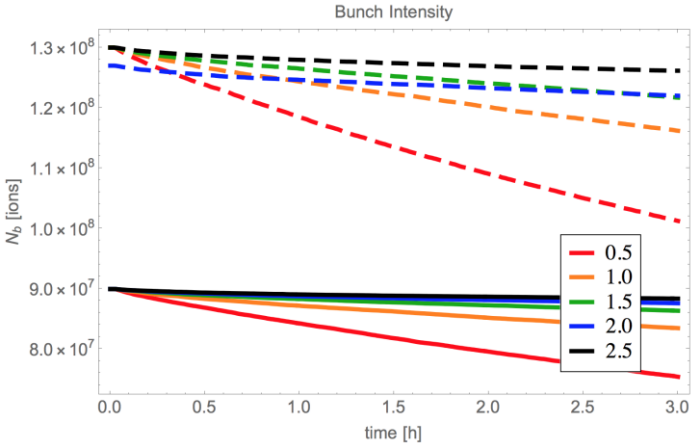
Lifetime fits over data intervals of 5 minutes.

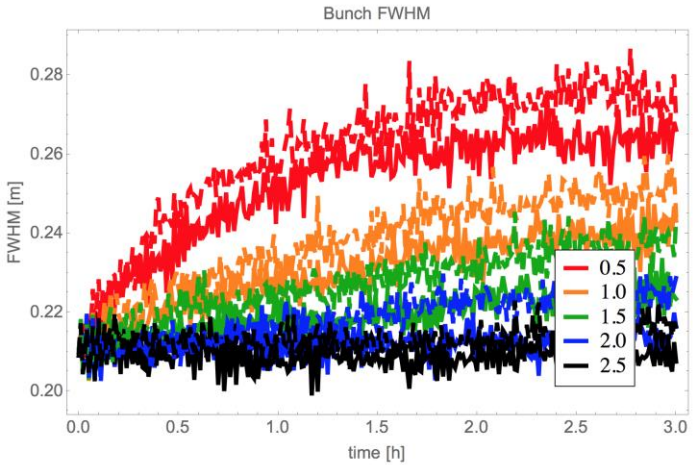
Similar behavior as at injection

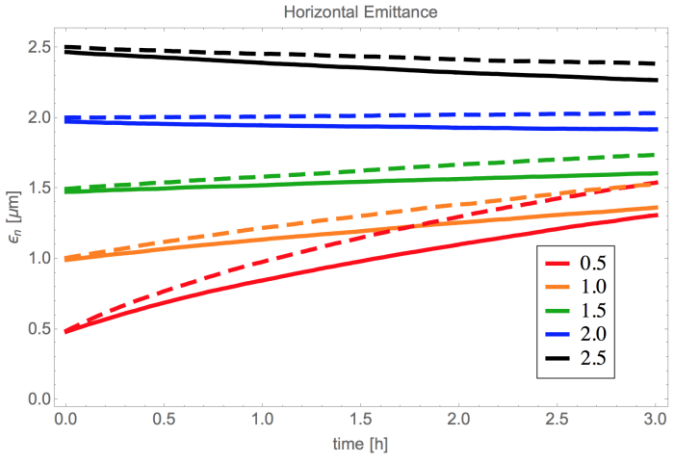
Effect of interval length: 5 min vs. 15 min

- *Similar effect to be expected for fits at injection!*

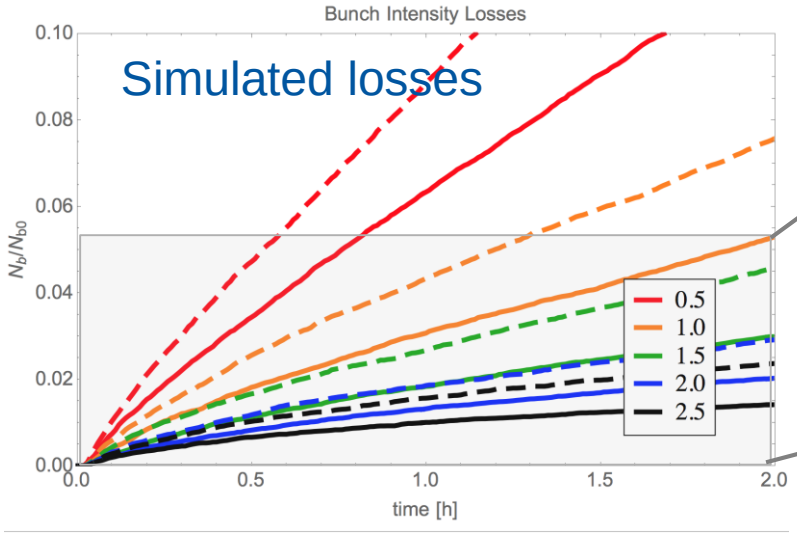
CTE Simulations

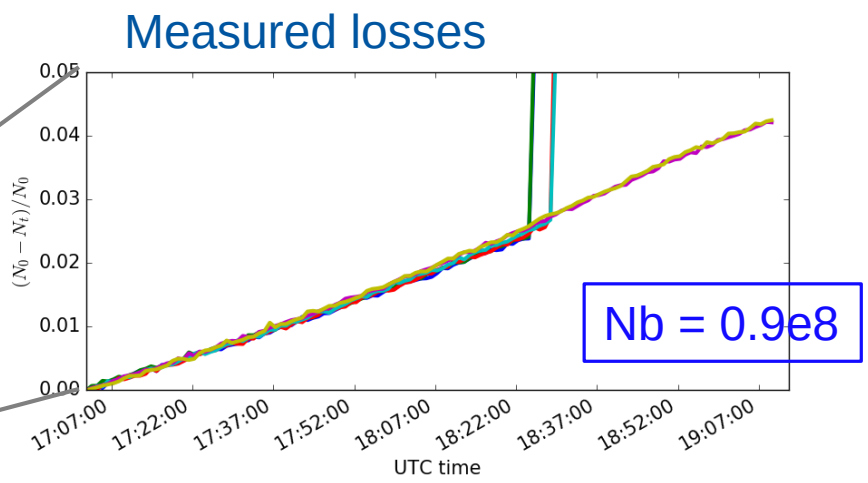






Losses: CTE vs Measurement





Debunching from IBS stronger at injection.
Assuming the emittances that can explain main losses at injection (>2um):
→ simulated loss rate at flat top is ½ of observed.
→ suggesting additional loss sources are stronger at flat top.

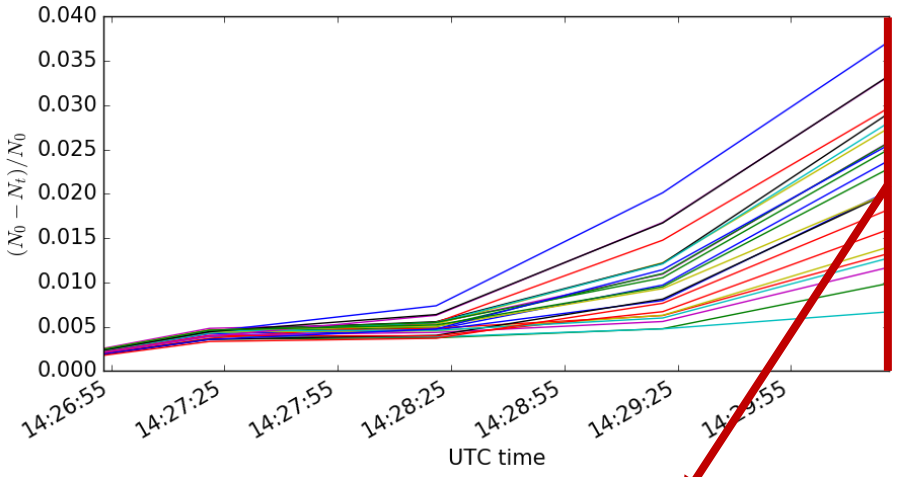
Summary and Outlook

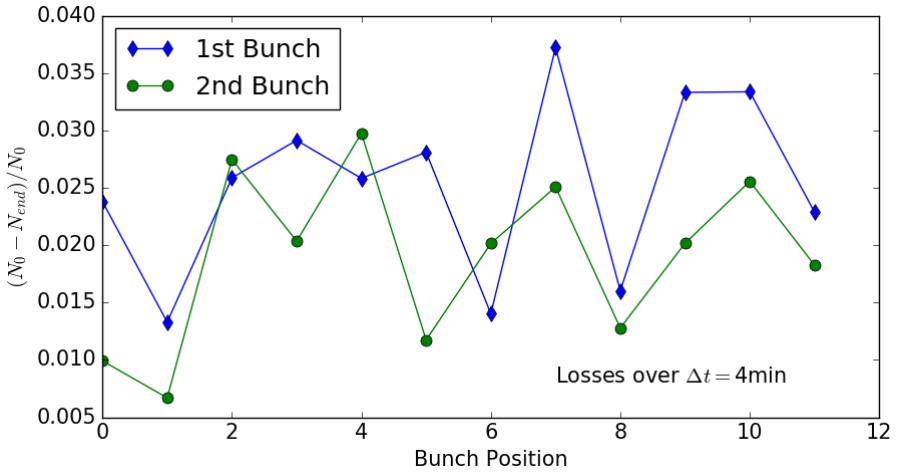
- Lifetime of Pb81+ beams have been studied in LHC at 450GeV and 6.5TeV proton equivalent energy.
- Main Observations:
  - **dominant limit** of the beam intensity is the **collimation efficiency** *(presented in previous meeting)*
  - As expected, e.g. from IBS, lifetime decreases with intensity
  - Lifetime decreases with storage time – *to be further investigated*
  - Average lifetime at Injection: **~20h**
  - Average lifetime at Flat top: **~50h**

- Preliminary beam dynamic simulations including IBS, radiation damping and debunching showed promising results but more studies needed.

Extra Slides

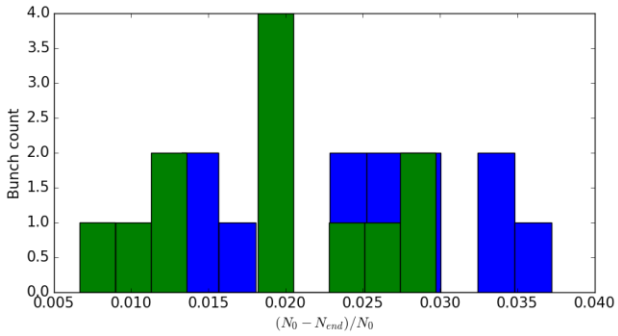
Losses at FT: Fill 1 (dumped)



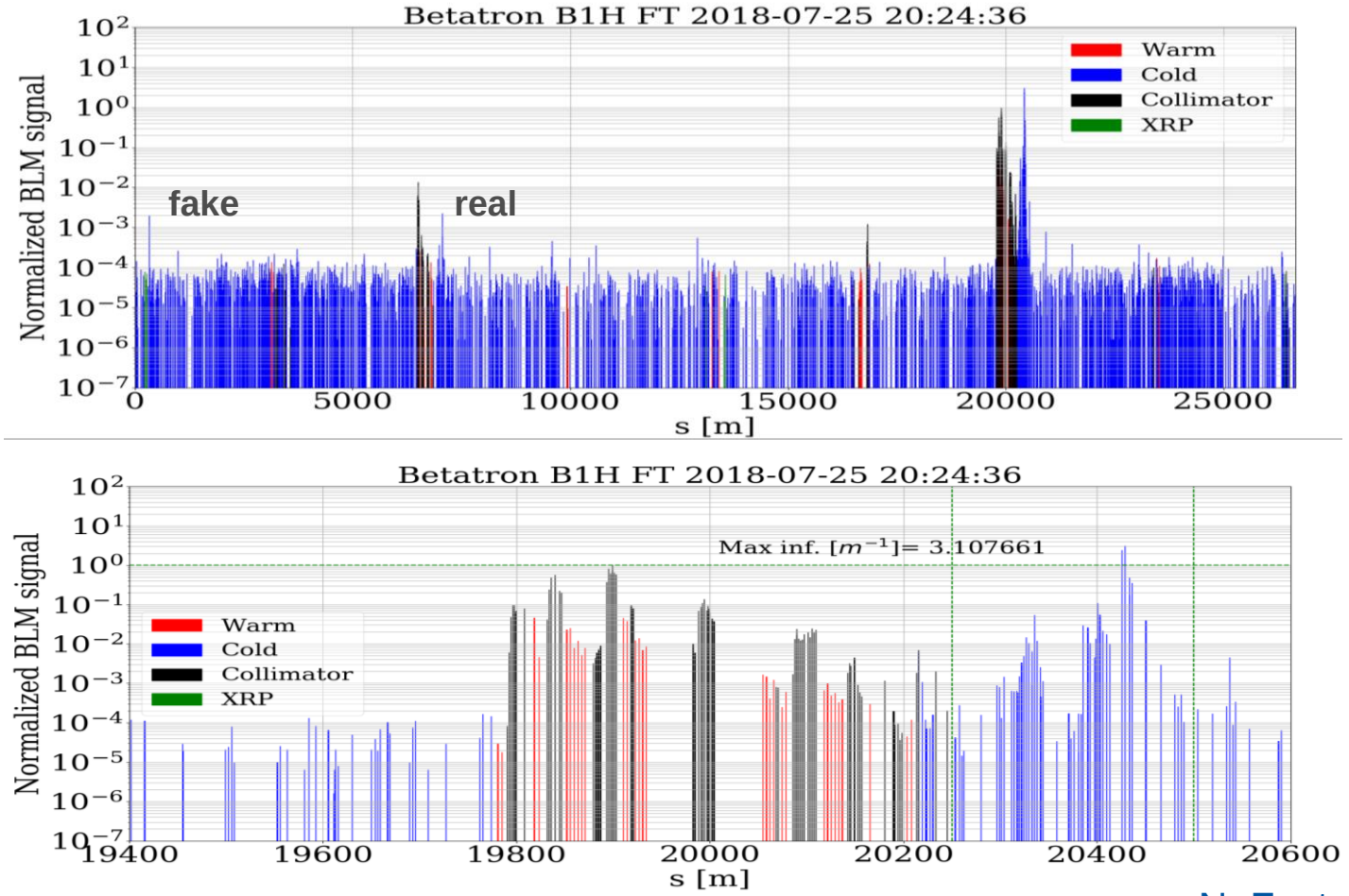


Bunches start losing with different rates, shortly after reaching FT

1st bunch of batch has tendency to lose more



Loss map – B1H at Flat top

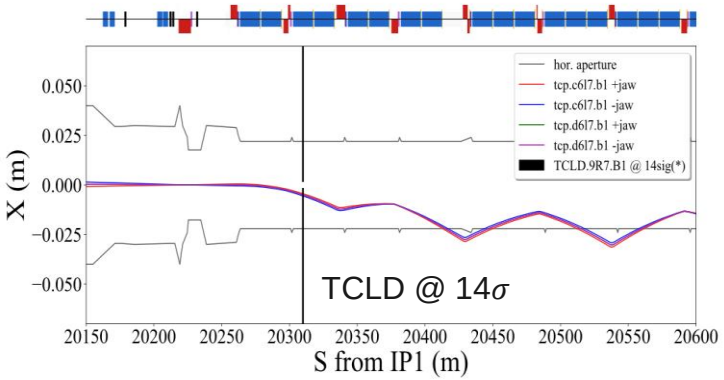


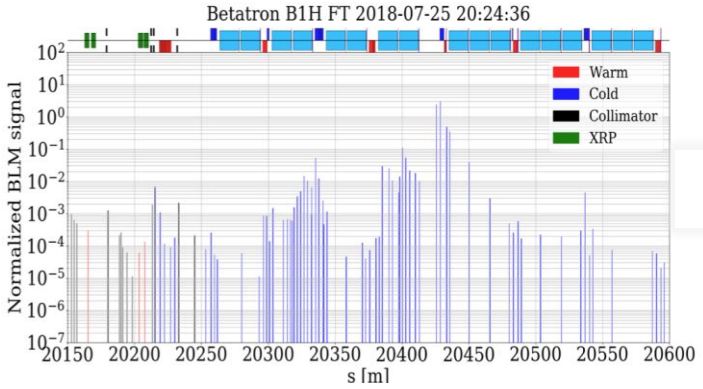
N. Fuster Martinez

A. Abramov, R. Bruce, N. Fuster Martinez

Collimation

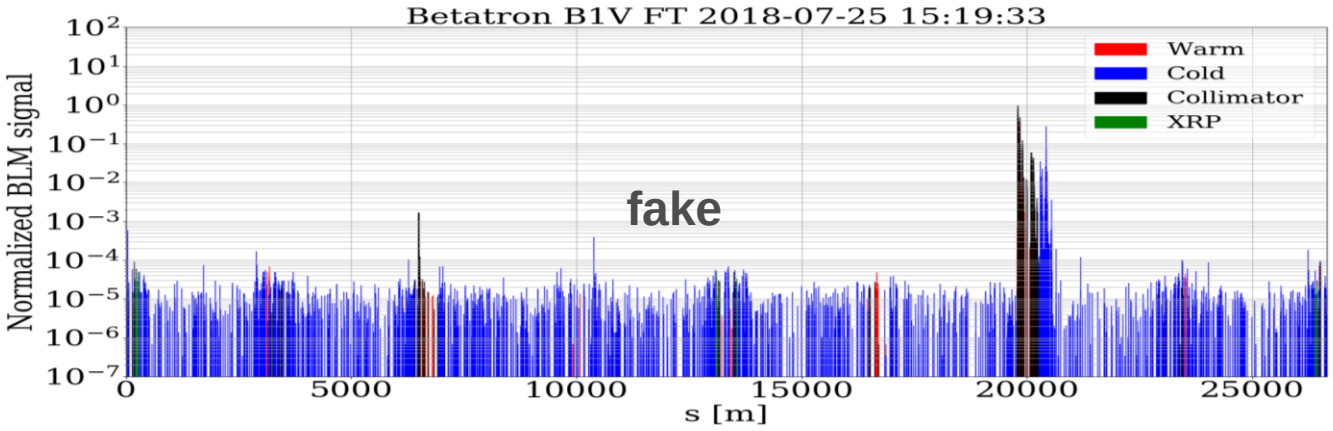
- **Worst collimation efficiency ever observed**.
  - → **limits intensity** that can be ramped reliably without spurious dumps.
  - → Lead to dump of fill 1 after small instability (no octupoles and no dampers).
- Very high **stripping probability of remaining electron** during passage through primary collimator.
  - → Fully stripped ions (Pb82+) scatter back in beam, but have **large magnetic rigidity offset** from main beam.
  - → Pb82+ follow locally generated dispersion and get **lost on aperture in cell 11**





- Foreseen momentum loss map was not done, because of the high losses in cell 11R7 we had a concerns that could induce a quench.
- Future alleviation under study: DS collimators, crystal collimation

Loss Map– B1V Flat top



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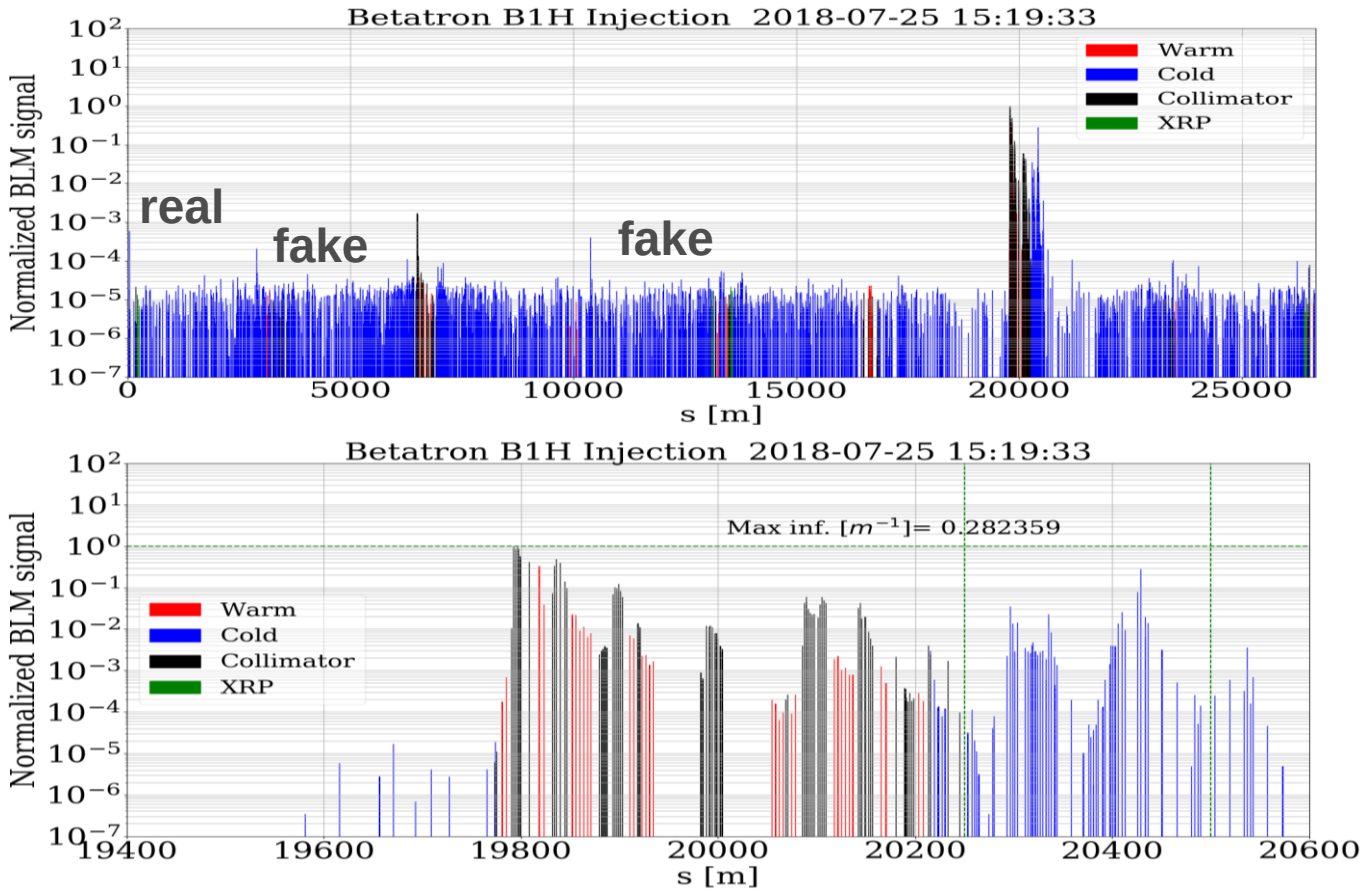
Loss Map – B1H Injection



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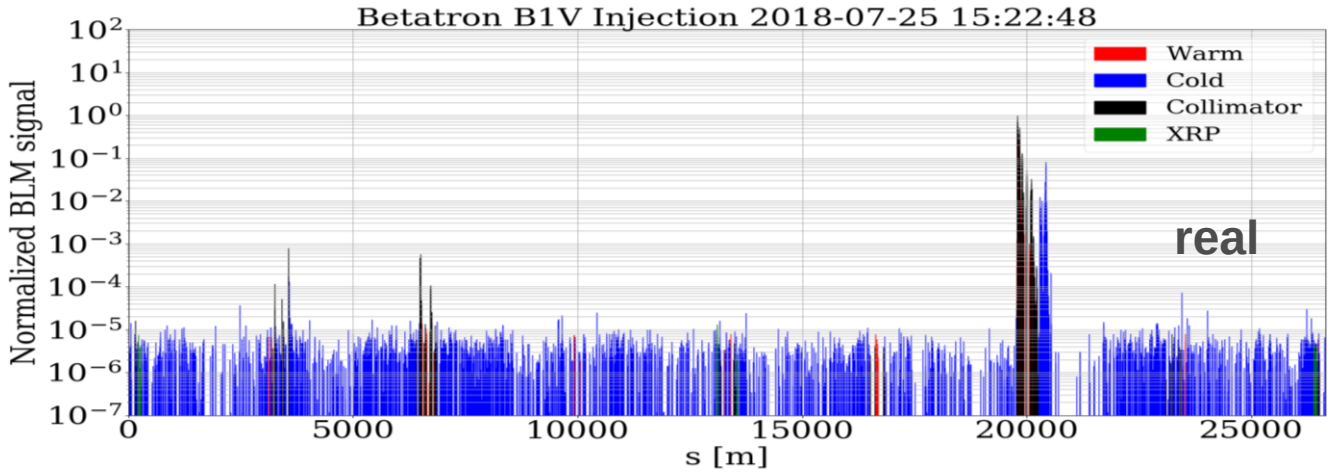
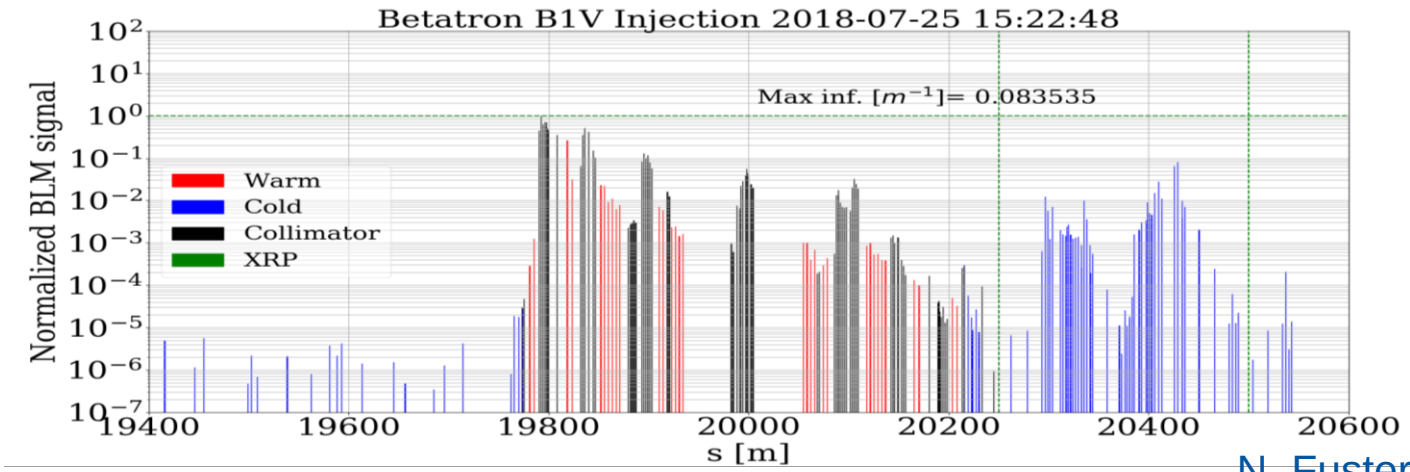
Loss Map – B1V Injection





N. Fuster Martinez

List of parameters

- RF voltage:
  - Injection 8MV
  - FT 12MV

Summary and Outlook

- On 25 July 2018 the **LHC injected, accelerated** and **stored** lead ions with one remaining electron (**208Pb81+**) for the first time.

  → Achieving the 1st milestone of the Gamma Factory

- A few Pb81+ bunches circulated at 6.5 TeV proton equivalent energy with **beam lifetimes of about 40-60 hours**.
- A **dominant limit** of the beam intensity is the **collimation efficiency**.

- **Crystal collimation** MD with PSI beams was requested to study its mitigation potential **to overcome the collimation limit**.
  - Scheduled for MD4, but was canceled just before the start due to unavailability of ion beams.