High Intensity Effects on Fixed Target (non-LHC) beams in the CERN Injector Complex

Eirini Koukovini-Platia

Special thanks to: H. Bartosik, A. Huschauer, M. Migliorati, A. Oeftiger, G. Rumolo, M. Schenk

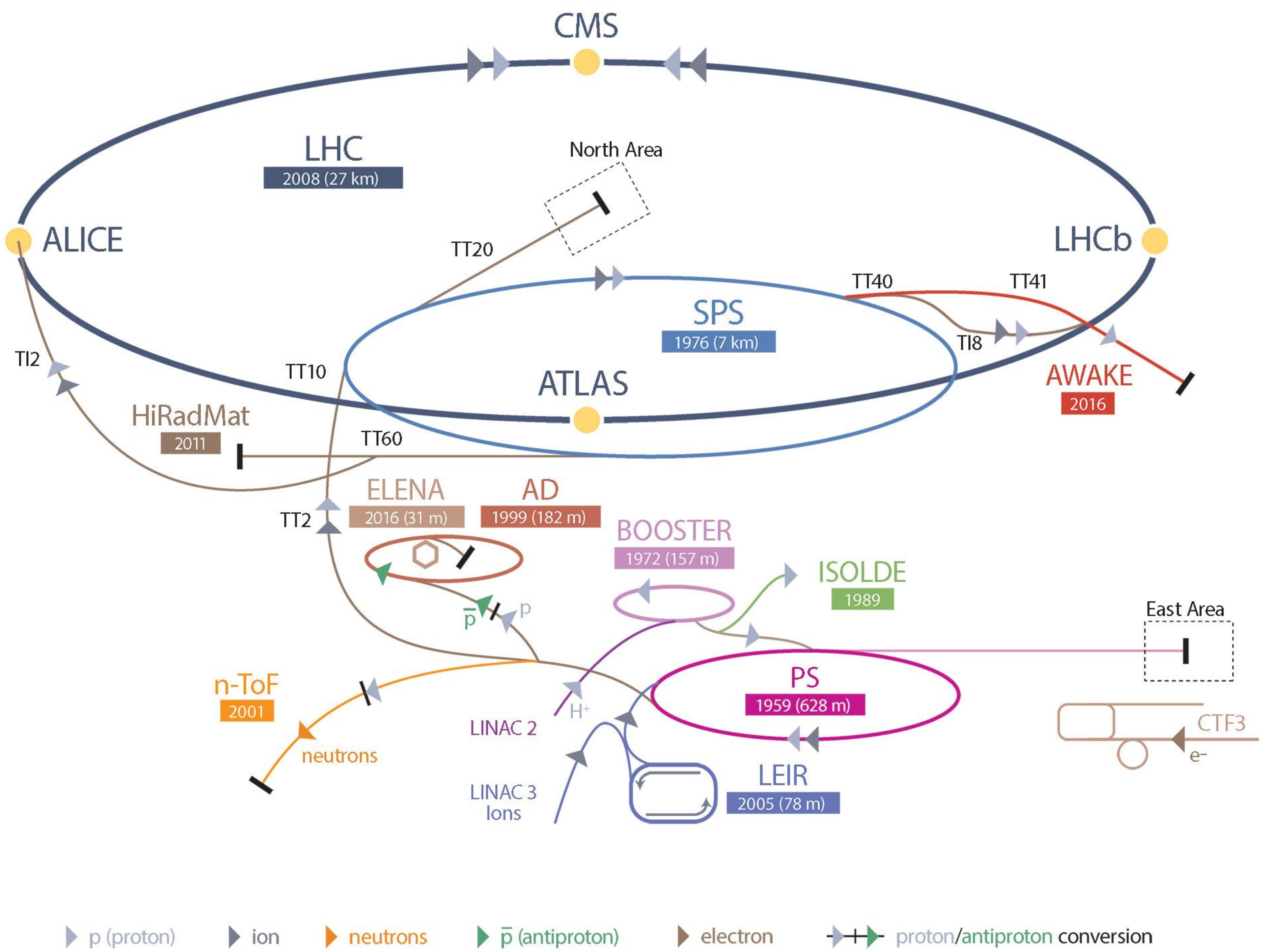
With the inputs of: C. Bracco, M. Calviani, C. Carli, R. Catherall, G. P. Di Giovanni, T. Eriksson, A. Fabich, L. Gatignon, S. Gilardoni, M. Giovannozzi, E. Gschwendtner, F. J. Harden, M. Lamont, A. Lasheen, A. Lombardi, E. Métral, B. Mikulec, R. Steerenberg

HB2018, 17-22 June 2018, Daejeon, Korea

Outline

- CERN's accelerator complex
- Main baseline items for upgrade in the complex
- Performance improvement after the LHC Injectors Upgrade (LIU) for fixed target (FT) users
- Ongoing activities to ensure the desired performance for the FT beams
- Final remarks

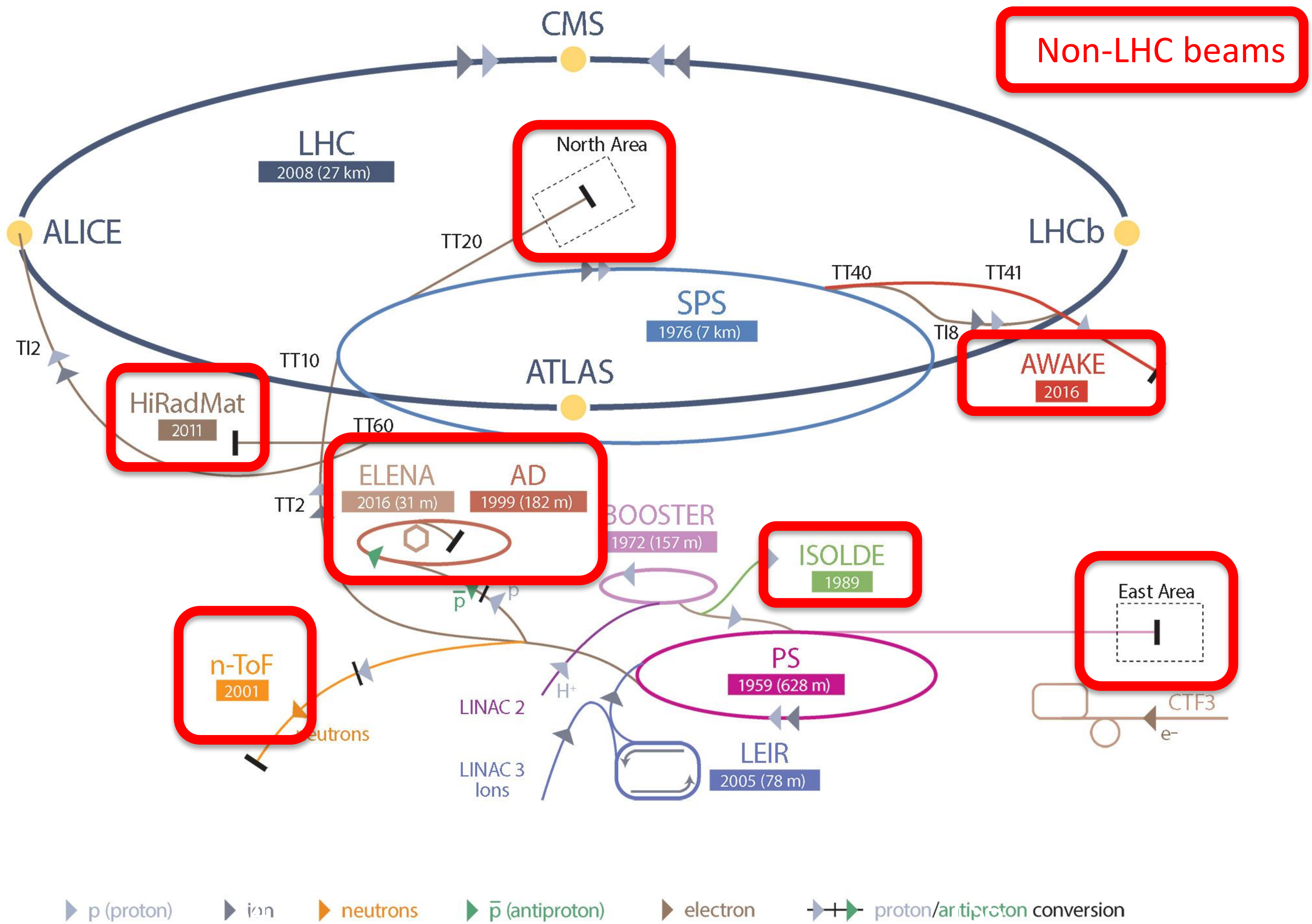
CERN's Accelerator Complex



Physics Beyond Colliders

- Complementary to high-energy colliders, a new exploratory group, named **Physics Beyond Colliders** [1], was officially formed by the CERN management in 2016
- Its goal is to explore the rich scientific potential of the CERN accelerator complex
- It involves projects, namely the FT users or **non-LHC beam** users, with different approach to LHC, High Luminosity LHC (HL-LHC) and future colliders
- These projects target fundamental physics questions (CP violation, dark matter etc.) similar to those addressed by high-energy colliders but require different types of beams and experiments (sub-eV, MeV-GeV range)

Non-LHC Beams



LIU Project

- Major upgrades [2] planned during the second Long Shutdown (LS2) to fulfill the High Luminosity LHC (HL-LHC) requirements (*see G. Rumolo talk, MOA1PL02*)
- The LIU targets to increase intensity / brightness for LHC beams by about a factor 2 and to increase injector reliability and lifetime to cover HL-LHC era (until 2035)

Main upgrades in PS Booster (PSB)

- H^- charge exchange injection at 160 MeV from Linac4 (double brightness out of the PSB) (*see G. Bellodi talk, MOA1PL03*)
- E_{beam} increase from 1.4 GeV to 2 GeV (new RF system and main power supply)

Main upgrades in Proton Synchrotron (PS)

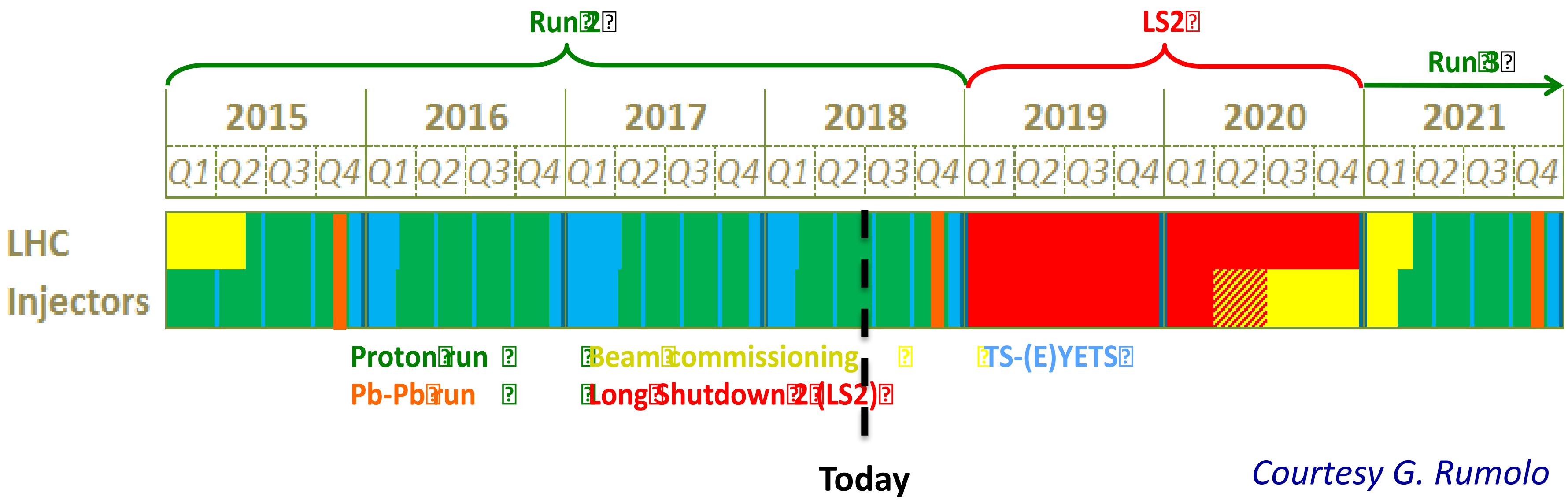
- Injection at 2 GeV for protons (higher brightness for same tune shift)
- Installed and upgraded longitudinal feedbacks (against coupled-bunch instabilities) and impedance reduction campaign [3]

Main upgrades in Super Proton Synchrotron (SPS)

- Upgrade of the main 200 MHz RF system (higher intensity)
- Electron cloud mitigation and longitudinal impedance reduction (higher intensity)

LIU Timeline

- Activities until LS2: performance tests and mitigation studies for high-intensity beam requests in the injectors complex
- Main LIU installations and hardware work during LS2
- Beam commissioning of LIU beams after LS2

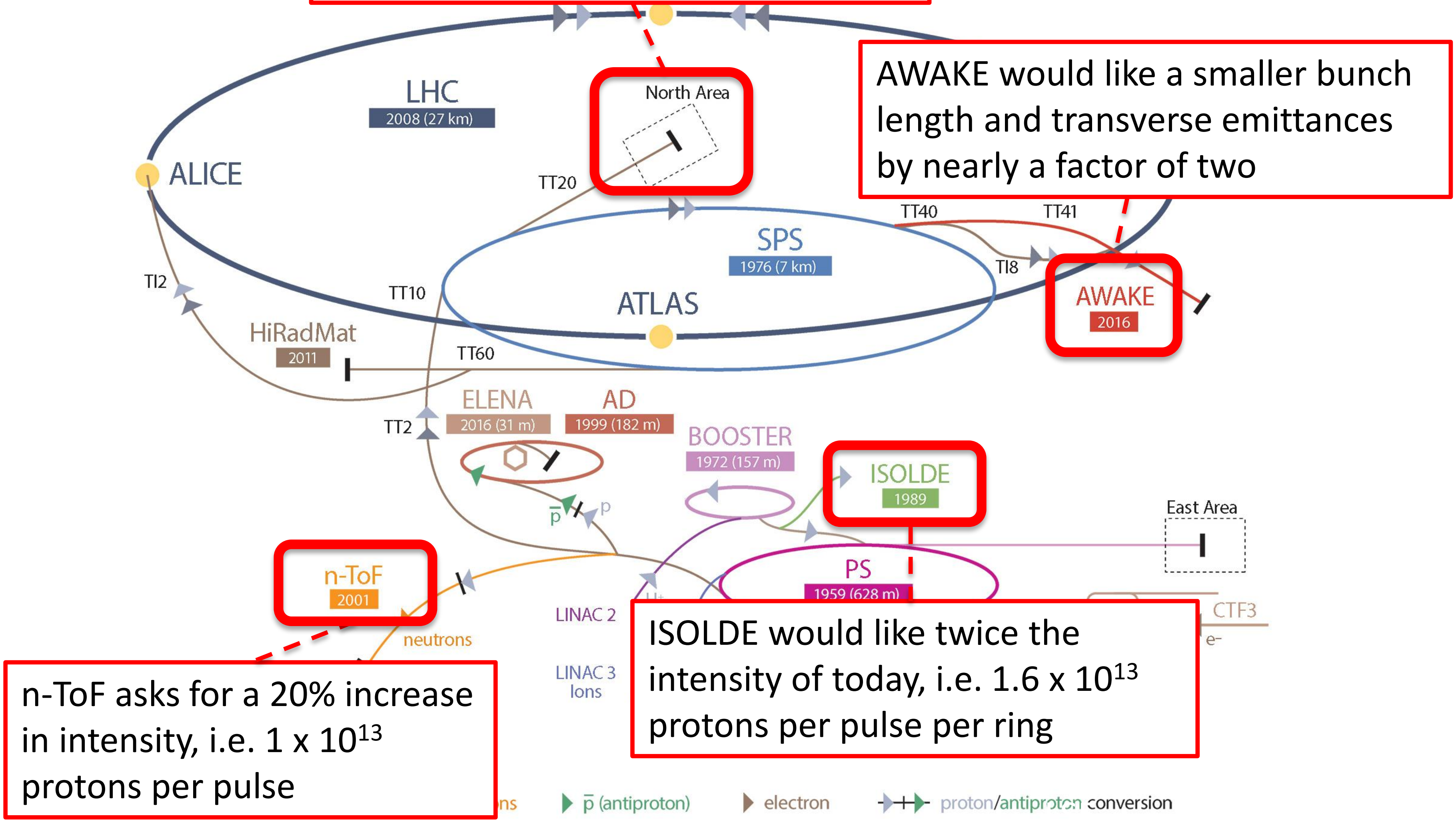


Courtesy G. Rumolo

Non-LHC Beams Post-LIU

- The policy is that after the LIU, the present complex performance, in terms of beam intensity and quality, must be preserved
- But will there be a positive impact for non-LHC beams and can it be quantified?
- Some users expect / wish for higher intensity after LIU
- Studies are focused on these users
- Need to address any intensity limitations and ensure successful proton delivery after LS2

Requests From Non-LHC Users



North Area requires a 14% increase in intensity, i.e. 4 x 10^{13} p/spill (*see A. Huschauer talk, WEA1WA02*)

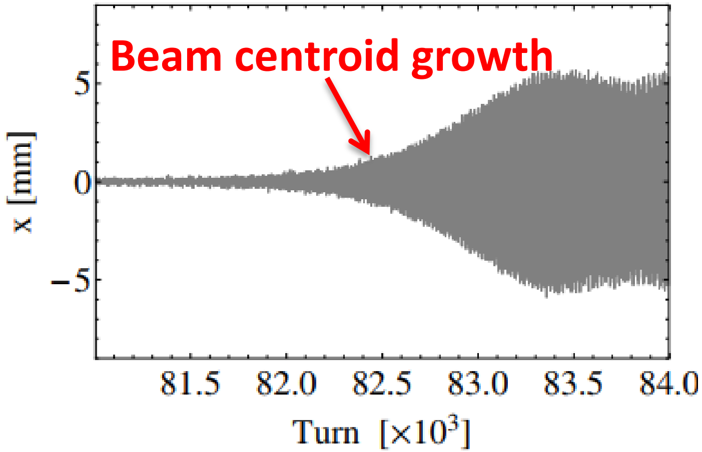
AWAKE would like a smaller bunch length and transverse emittances by nearly a factor of two

ISOLDE would like twice the intensity of today, i.e. 1.6 x 10^{13} protons per pulse per ring

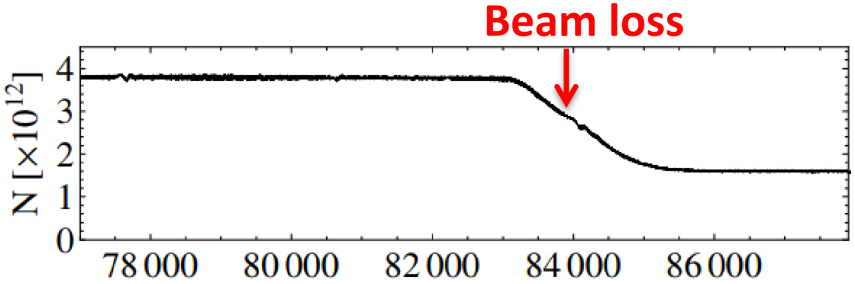
n-ToF asks for a 20% increase in intensity, i.e. 1 x 10^{13} protons per pulse

Studies Ongoing

- Intensity reach in the PSB as a function of the new linac beam parameters
- Space charge along the cycle of the PSB (another potential intensity-limiting factor)
- Horizontal instabilities along the cycle of the PSB for the higher intensity beams [4]



If transverse feedback is inactive:



M. McAteer *et al.*, THPRO082, IPAC14

- The source of the instability is still unknown (simulations are ongoing and MDs are planned over the next few months to study this)
- Crucial to understand as the new injection energy of 160 MeV is exactly the energy where the instability appears for some tune working points

Neutron Time-Of-Flight (n-ToF)

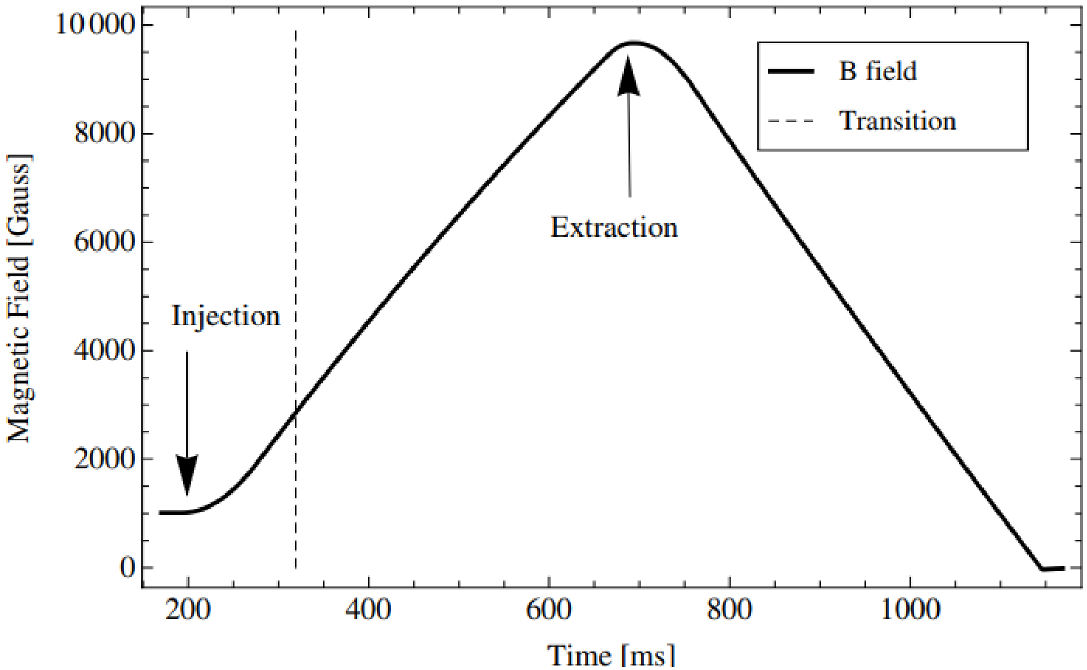
- Experiments are interested to increase the intensity by 20% after LS2
- The new lead target will be able to cope with 1 x 10^{13} p per pulse

Intensity limiting factors in the PS

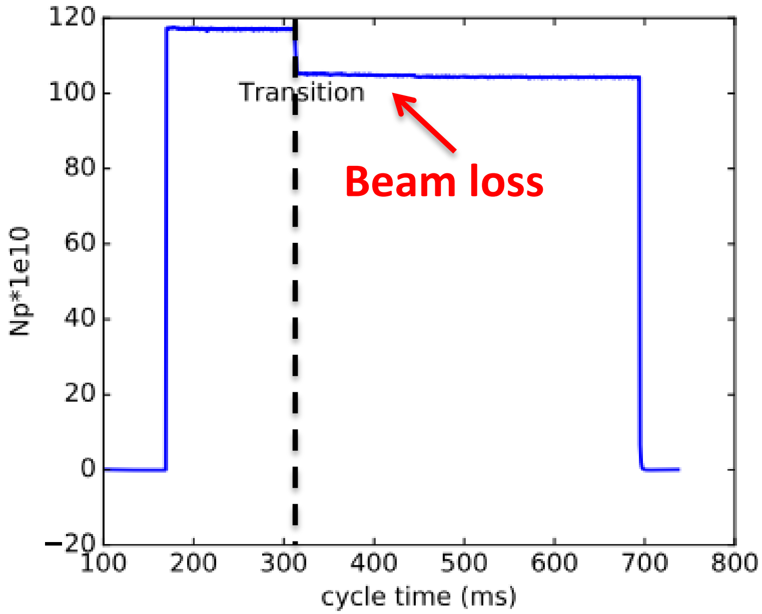
- Fast vertical instability at transition crossing
- For users that need short bunches on target:
    - RF power for bunch rotation before extraction
    - Losses at the extraction septum (due to the large momentum spread)

Instability at Transition Crossing

- In the PS, the beam routinely crosses transition energy
- With increasing beam intensity, a fast vertical instability is observed causing beam loss and limiting the beam intensity



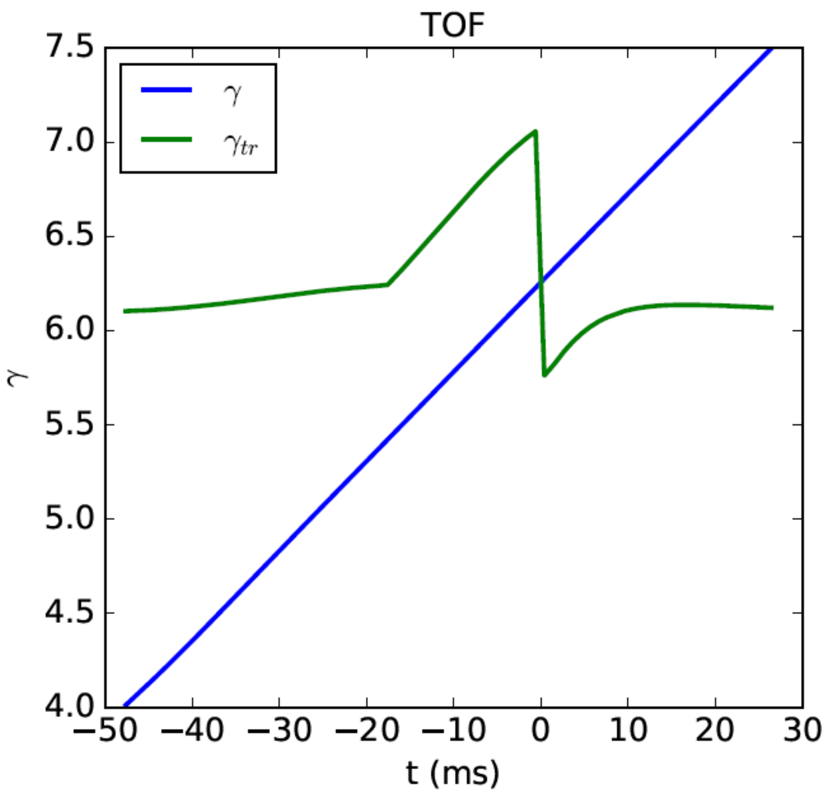
S. Aumon, CERN-THESIS-2012-261



Courtesy M. Migliorati

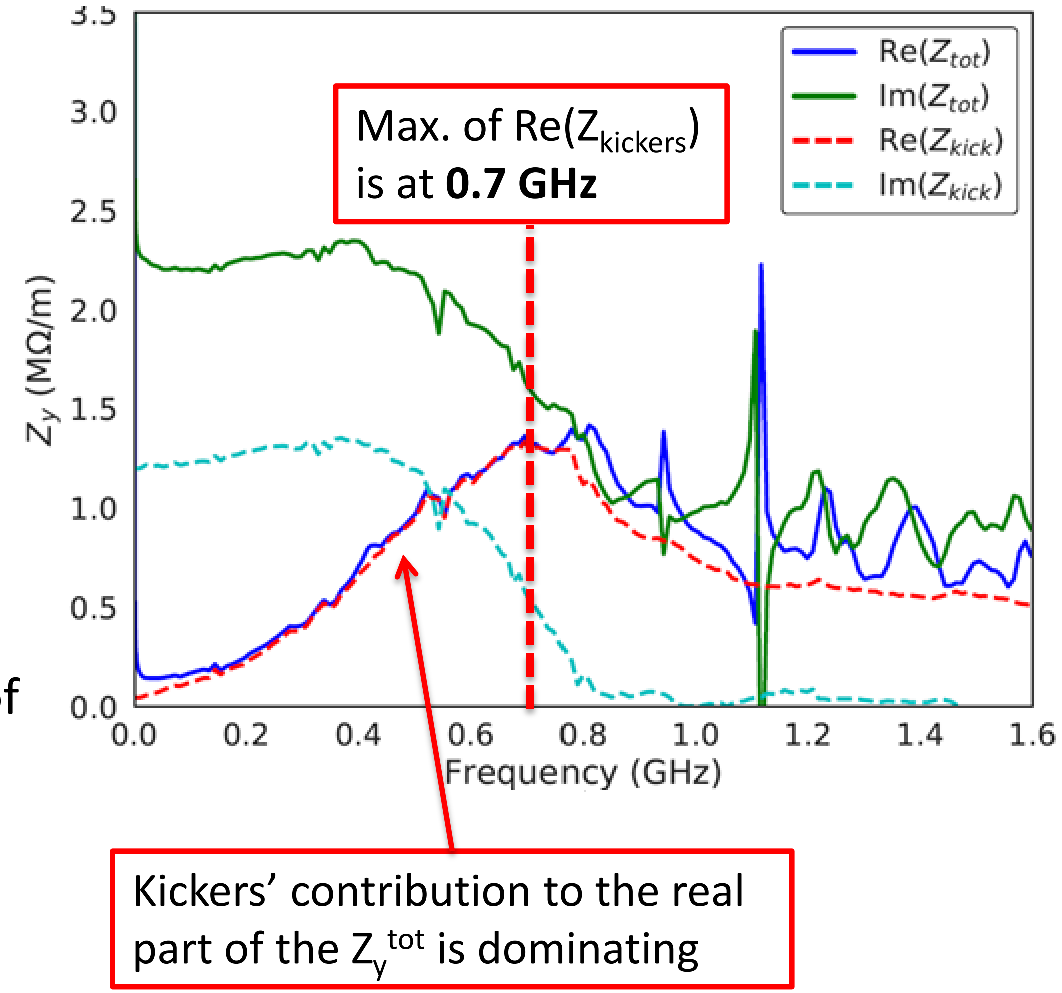
γ_t-jump scheme

- A γ_t-jump scheme is used in the PS, by means of fast pulsed quadrupoles, to artificially increase the transition crossing speed
- Thanks to this scheme, the beam intensity can be **increased from 180 x 10^{10} to about 800 x 10^{10} p per pulse**, i.e. more than a **factor 4**
- However, above a certain intensity, a **fast vertical instability** limits the intensity reach in the PS
- Understanding and mitigating this instability is crucial for the high-intensity run after LS2
- Previous studies in [5, 6] without the γ_t-jump



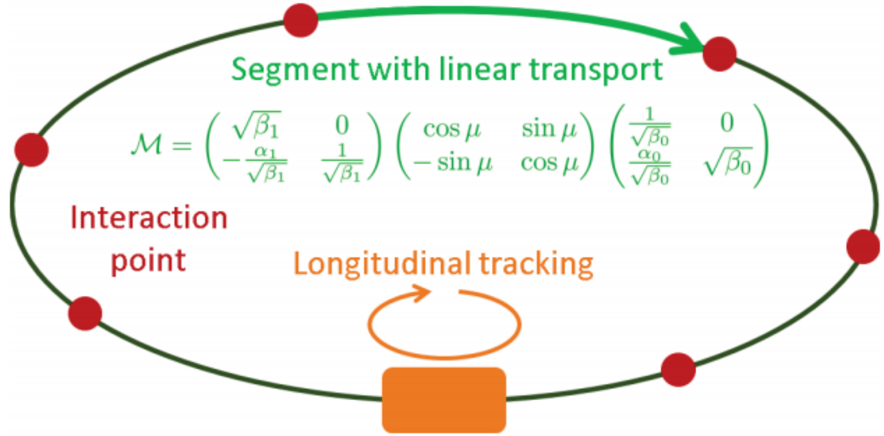
PS Impedance Model

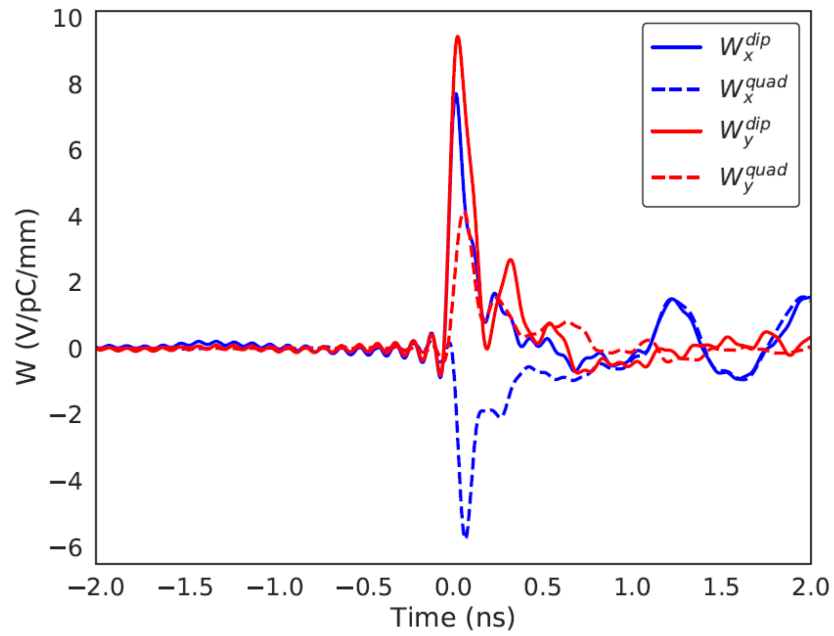
- Main components in the PS impedance model [7]
  - Resistive wall assuming a round chamber of 35 mm radius
  - RF cavities
  - Kickers
  - Septum
  - Transition steps
  - Vacuum ports
- The kickers have been identified as the main source of the instability [7]



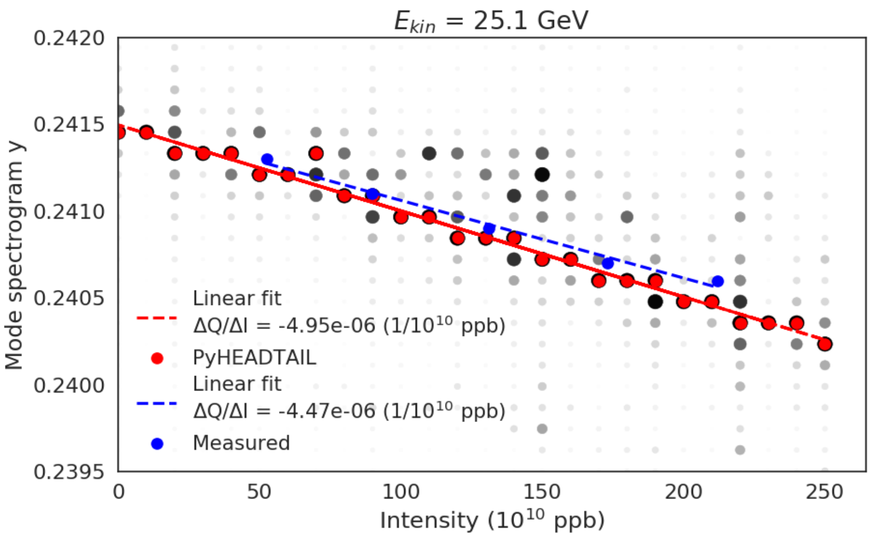
Courtesy K. Li

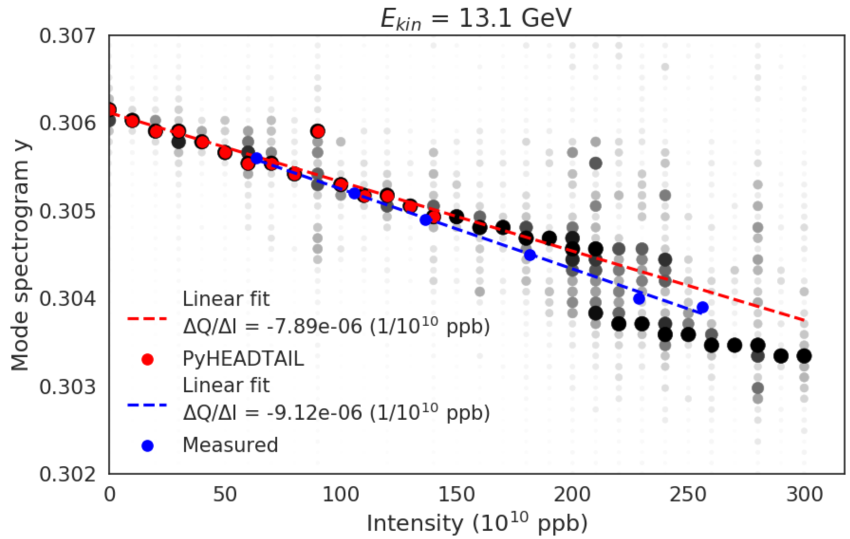
- The PyHEADTAIL 6D macroparticle tracking code is used to study the effect of wakefields [8]
- The PS ring is split into segments
- A particle beam is transported from one segment to another by means of linear transfer matrices
- Linear synchrotron motion for the longitudinal plane
- Zero chromaticity
- Simplified case without the γ_t-jump
- Input of the code are the beam parameters and the total wake function of the PS

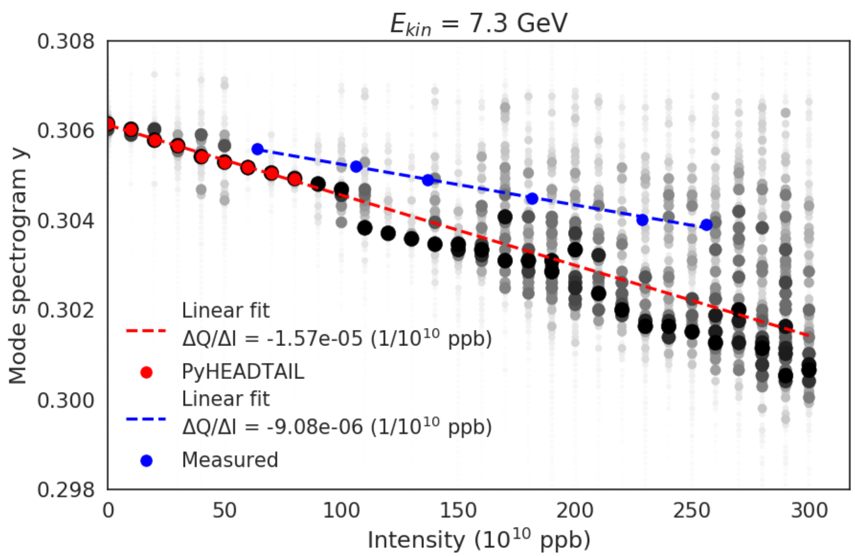


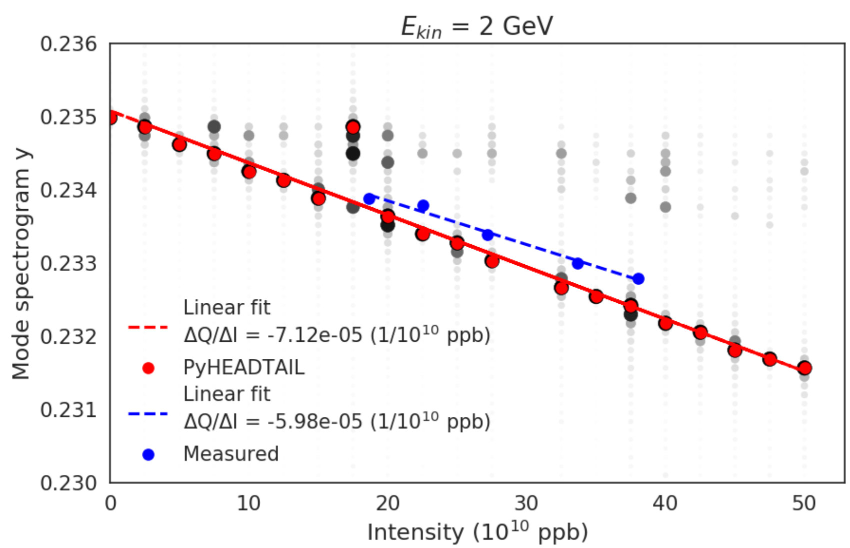


Tune Shift Measurements vs. PyHEADTAIL



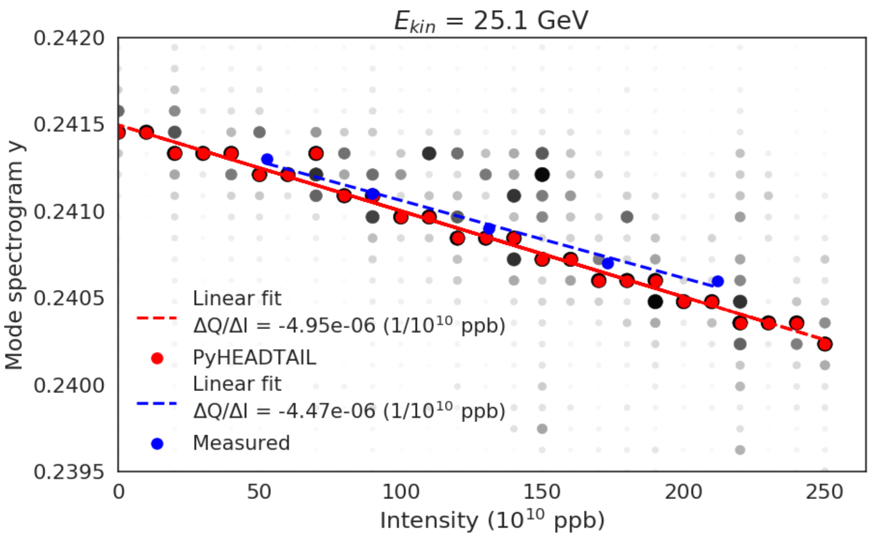


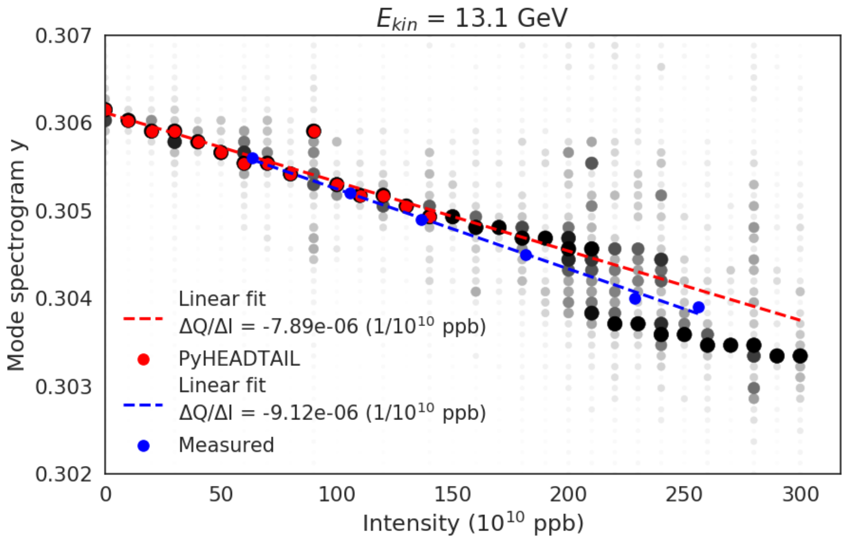




Measured data from [7]

Tune Shift Measurements vs. PyHEADTAIL





- Comparison of measured and simulated tune shifts
- At 2.0 GeV, 13.1 GeV and 25.1 GeV an **agreement between 85% to 90%** is found
- Overall, agreement is satisfactory and thus, the imaginary part of the PS impedance is well modeled

- At 7.3 GeV, **only 50% agreement is found**
- **Very critical energy**, near the transition crossing energy (6.1 GeV)
- PyHEADTAIL above 65 x 10^{10} p gives unstable results
- Measurements will be repeated before LS2

Measured data from [7]

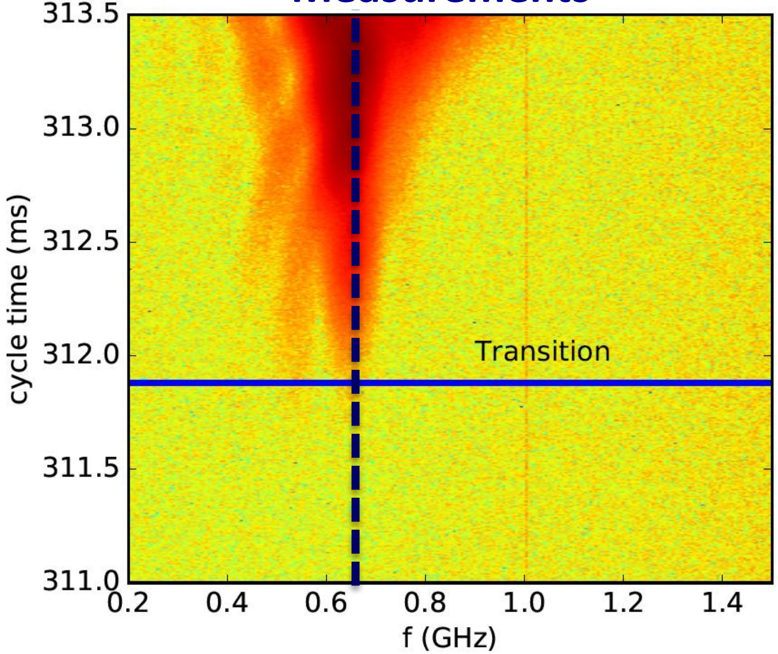
Characterization of the Instability

PyHEADTAIL Parameters

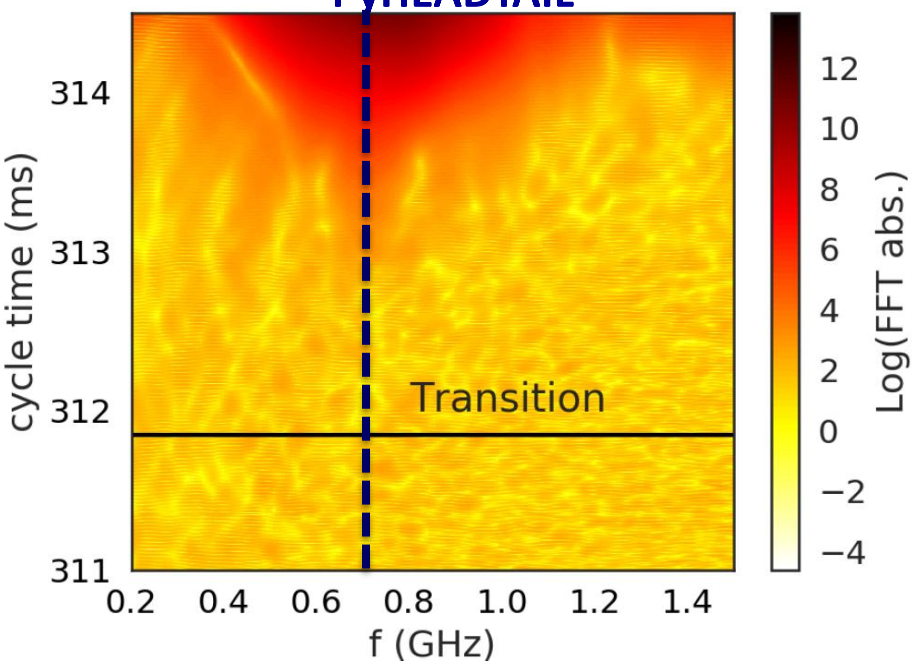
Turns	35000
γ	4.0 - 7.4
$4\varepsilon_z^{rms}$ (eVs)	1.8
$Q'_{x,y}$	(0, 0)
$Q_{x,y}$	(6.22, 6.22)

- FFT on centroid data to obtain the spectrogram
- Strongest part of the instability between **0.6 GHz** and **0.7 GHz**
- Good agreement with PyHEADTAIL
- Simulation also reproduces the onset of the instability in terms of cycle time (error < 0.5%)

Measurements

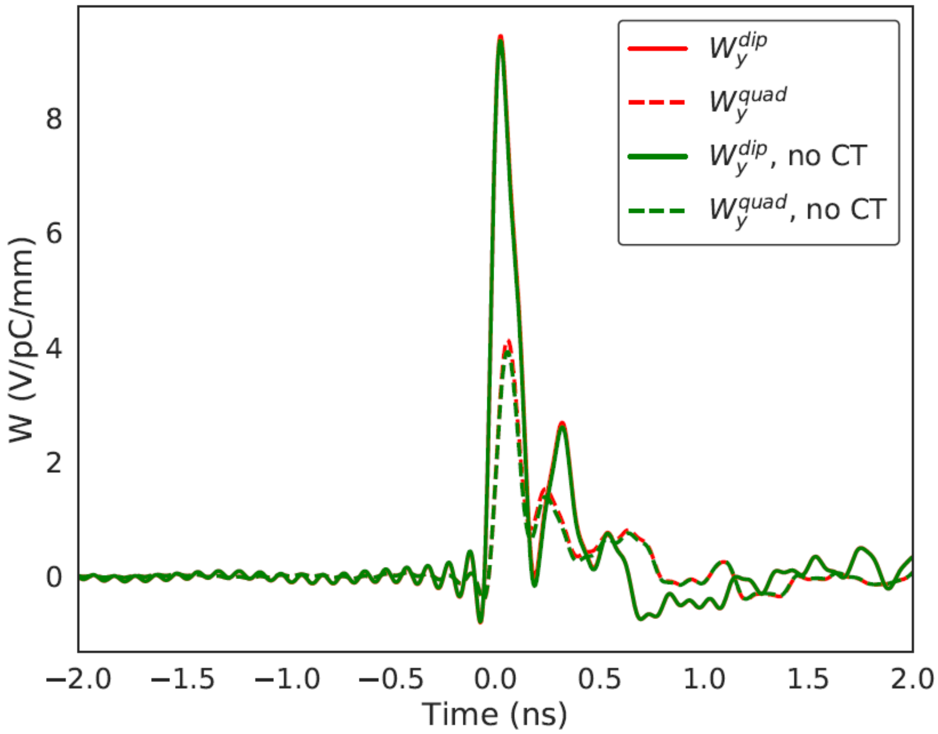


PyHEADTAIL



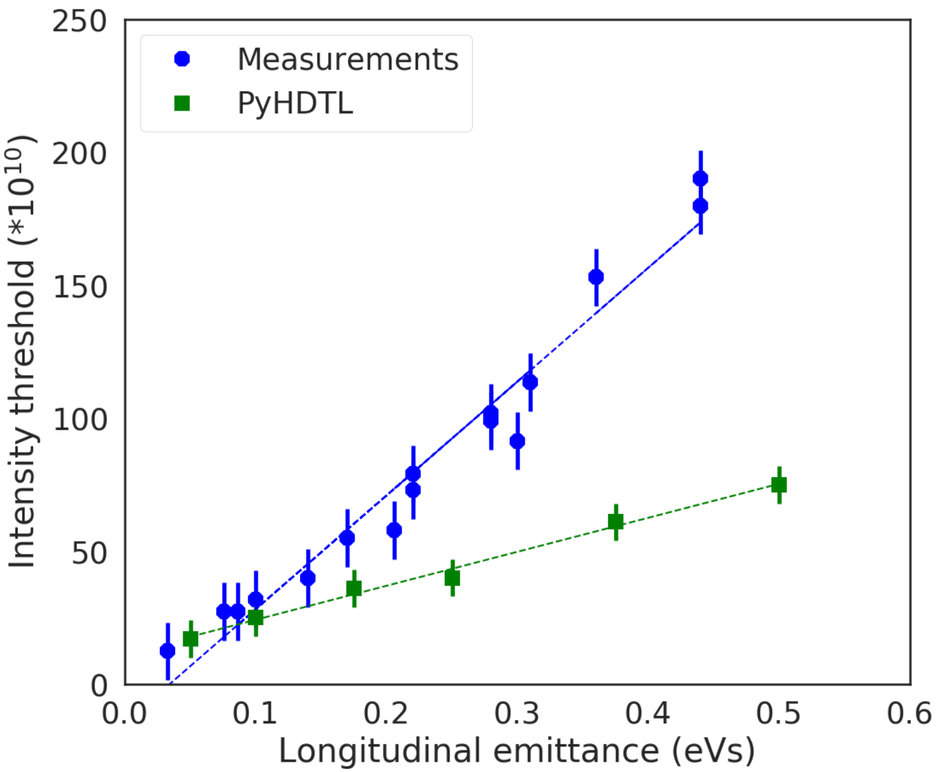
Impact of Envisaged Hardware Modifications

- **Obsolete equipment** previously used for the Continuous Transfer (CT) extraction in the PS **will be removed during the LS2**
- In principle, removal of equipment is beneficial for the machine impedance and might positively impact the instability thresholds
- However, **PyHEADTAIL does not predict any significant change** in the intensity threshold if the CT equipment is removed from the impedance model
- To be cross-checked with beam-based measurements post-LS2, but another mitigation mechanism is required



Threshold vs. Longitudinal Emittance

- The instability threshold has been measured as a function of the longitudinal emittance without the γ_t-jump scheme
- PyHEADTAIL (PyHDTL) simulations under the effect of wakefields can reproduce the linear dependence
- However, a **significant discrepancy** is noted, up to almost a factor 3, indicating that a stabilizing mechanism might be missing in the simulations
- A first hypothesis is that **space charge** could have an influence on the predicted thresholds



Space Charge in PyHEADTAIL

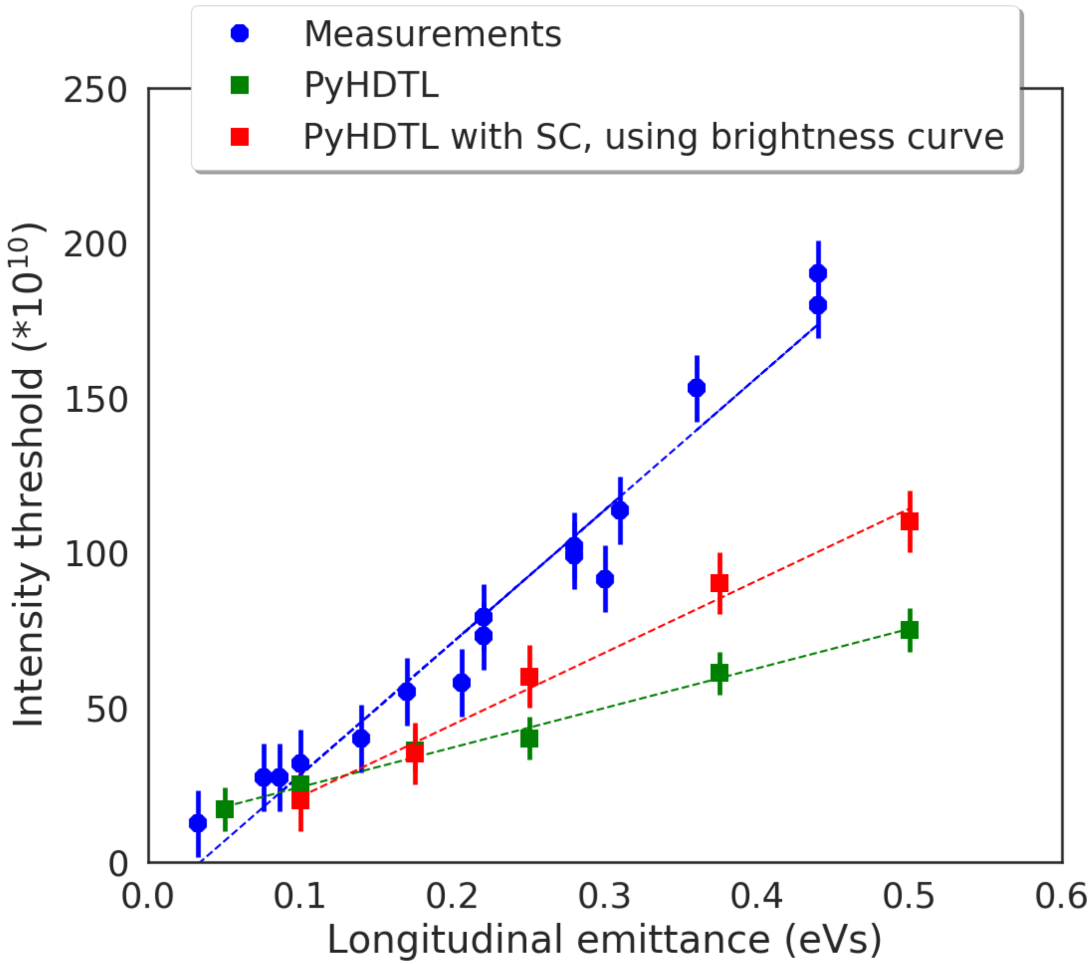
- Particle-in-cell (PIC) solver
- Simulations available also for graphics processing units (GPU)
- 2.5D (slice-by-slice) Poisson solver used
- 64 x 64 transverse grid and 64 longitudinal slices
- 60 space charge kicks along the PS ring
- Convergence studies done prior to the parameter choice

The rest of the simulation parameters are as before, i.e.

- Single-bunch
- Linear synchrotron motion
- Zero chromaticity
- No octupoles
- No transverse feedback
- No dispersion

Effect of Space Charge

- PyHEADTAIL results including the 2.5D PIC space charge module
- Including space charge is important
- It helps approach the measured results
- Further studies ongoing since some discrepancy is still present
- Some assumptions had to be made for the values of the transverse emittances
  a) that they follow the PSB brightness curve
  b) that $\varepsilon_x = \varepsilon_y$
- Measurements will be repeated before LS2



Final Remarks

- Some experiments will benefit from higher intensity / brightness beams that will be available thanks to the LIU
- Several facilities desire an increase of the delivered proton intensity, from 15% up to 100%
- Several intensity limitations identified. Ongoing studies include
  - intensity reach in the PSB as a function of the new linac beam parameters
  - space charge measurements and simulations for the PSB
  - investigation of the horizontal instability in the PSB
  - fast vertical instability in the PS and the effect of space charge
  - optimization of the PS operational cycle
- Few months left to collect all the necessary data before the LS2

References

[1] Physics Beyond Colliders, http://pbc.web.cern.ch/

[2] H. Damerau *et al.*, "Upgrade Plans for the LHC Injector Complex", CERN, Geneva, Switzerland, Rep. CERN-ATS-2012-111, May 2012.

[3] K. Hanke *et al.*, "The LHC Injectors Upgrade (LIU) Project at CERN: Proton Injector Chain", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, paper WEPVA036.

[4] M. McAteer *et al.*, "Observation of Coherent Instability in the CERN PS Booster", CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0127, June 2014.

[5] S. Aumon *et al.*, "Transverse Mode Coupling Instability Measurements at Transition Crossing in the CERN PS", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper TUPD049.

[6] S. Aumon, "High Intensity Beam Issues in the CERN PS", Ph.D. thesis, CERN, Geneva, Switzerland, CERN-THESIS-2012-261, 2012.

[7] S. Persichelli *et al.*, "Transverse beam coupling impedance of the CERN Proton Synchrotron", *Phys. Rev. Accel. Beams*, vol. 19, p. 041001, Apr. 2016

[8] E. Métral *et al.*, "Beam Instabilities in Hadron Synchrotrons", *IEEE Trans. Nucl. Sci.*, vol. 63, p. 1001, Apr. 2016.

CERN Physics Beyond Colliders

Thank you for your attention!