Status of the electron cloud simulations for HL-LHC: build-up and instabilities

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Many thanks to:
G. Arduini, B. Bradu, E. Métral, V. Petit, A. Romano,
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INFN-CNAF HPC team
CERN HPC team

8th HL-LHC Collaboration Meeting, Fermilab, 14-16 October 2019

Outline

e-cloud buildup studies:

- Heat loads on the arc beam screens
  - Scaling with bunch intensity
- Hybrid schemes
- Studies for other devices

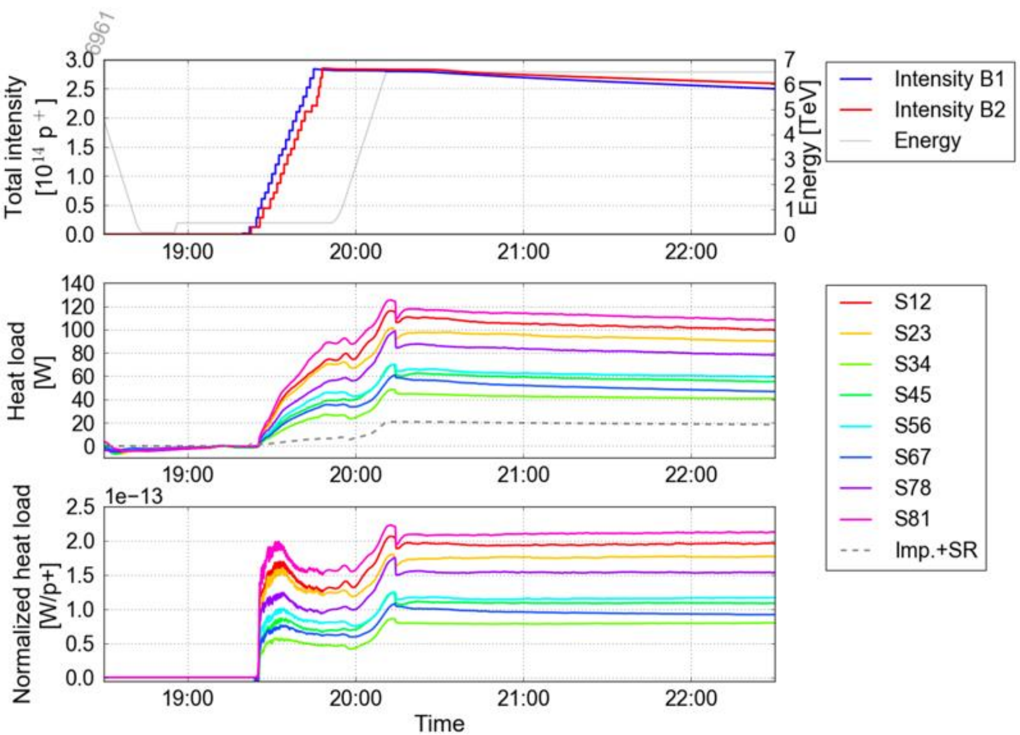
e-cloud instabilities:

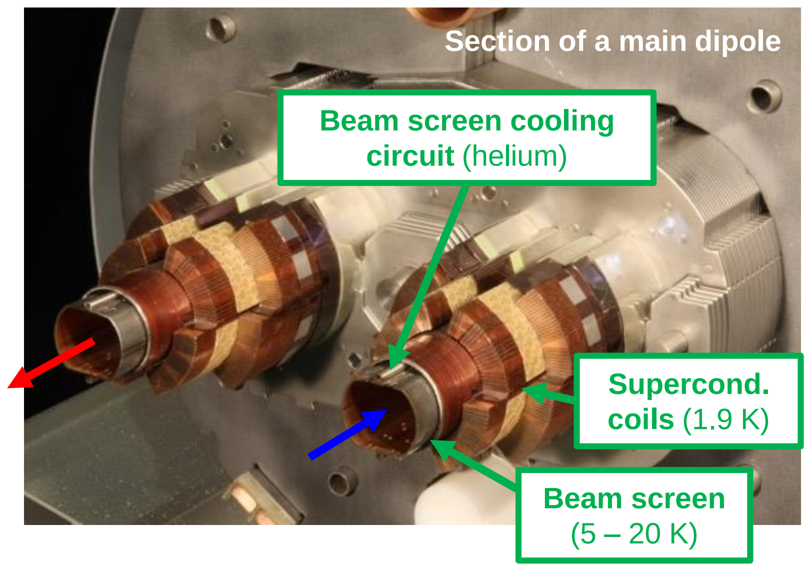
- Single-bunch instabilities
  - Dependence on RF settings
  - Dependence on bunch intensity
  - Effect of transverse feedback, chromaticity, octupoles
- Coupled-bunch instabilities
  - Effect of the bunch intensity
  - Effect of transverse feedback

Heat loads on the arc beam-screens

Beam induced heat loads on the arc beam screens have been a **challenge for LHC operation with 25 ns in Run 2**: dominating total load on the cryo-plants

- Much **larger** than expected from **impedance and synchrotron radiation**
- Large **differences observed between sectors** and between consecutive cells in the same sector
- A **degradation** is observed **between Run 1 and Run 2**
- Being followed-up by dedicated **Task Force**





Underlying mechanism

Beam observations during Run 2 indicated that:

- The additional heat load comes from **electron cloud effects**
- It is compatible with **alterations in the beam-screen surface** properties leading to a higher Secondary Electron Yield (SEY)

Observations

Total power associated to intensity loss is less than 10% of measured heat load

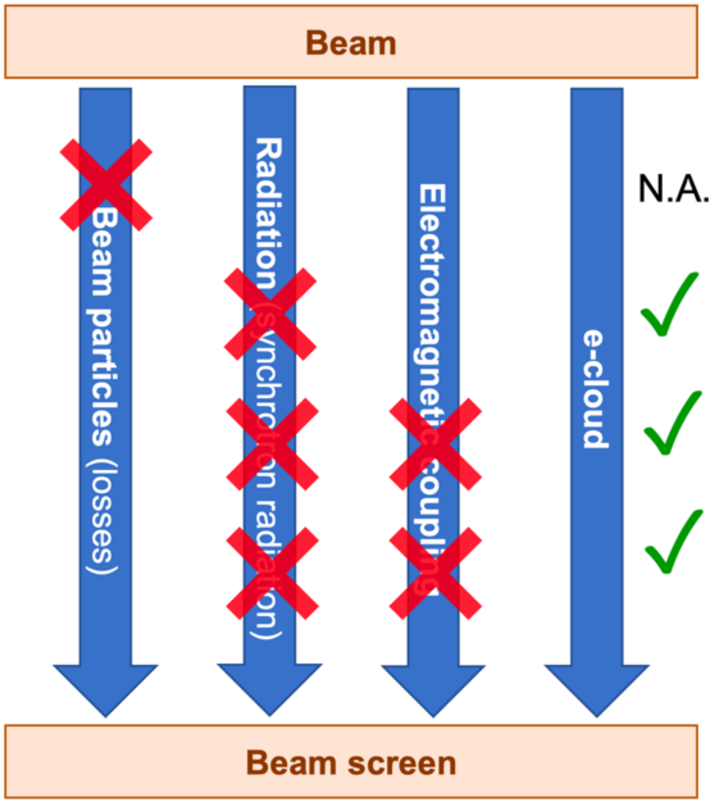
Heat load increases only moderately during the energy ramp

Heat loads with 50 ns are >10 times smaller than with 25 ns

Measured dependence on bunch intensity is not linear nor quadratic

✓ = **Good quantitative agreement** (assuming different SEY per sector)

✗ = **Excluded**



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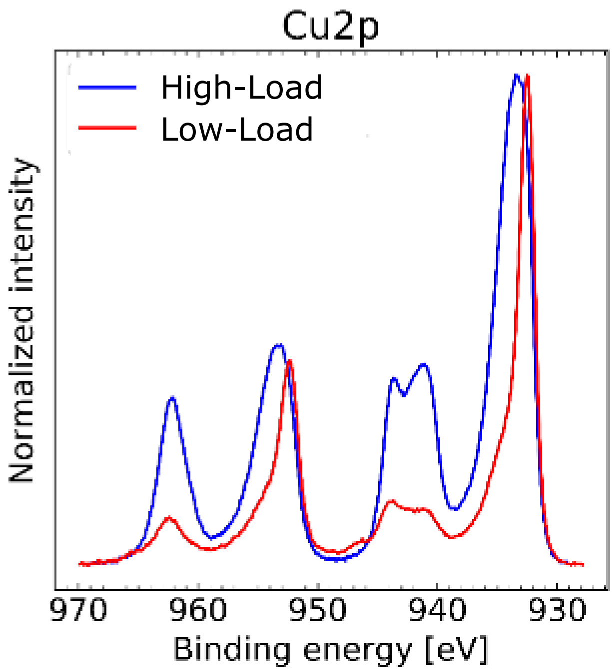
- It is compatible with **alterations in the beam-screen surface** properties leading to a higher Secondary Electron Yield (SEY)

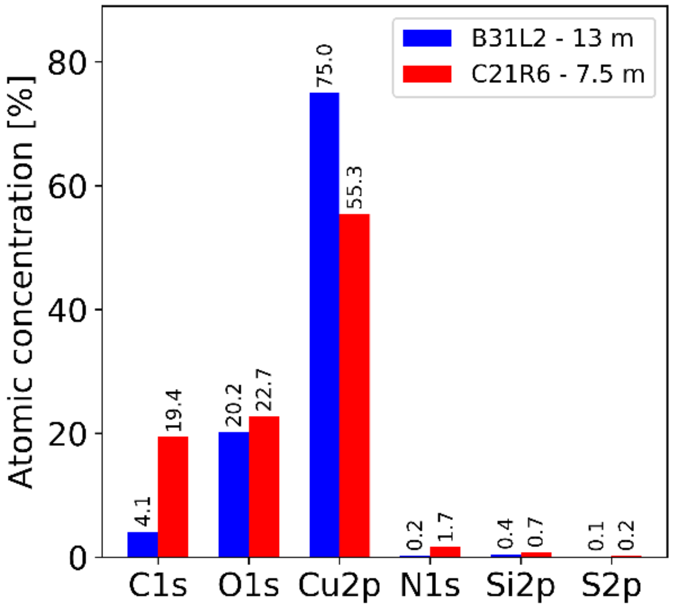
Laboratory analysis of beam screens extracted from high-load magnets identified:

- Presence of **cupric oxide (CuO)** instead of the native cuprous oxide (Cu_2O)
- Extremely **low concentration of Carbon**

Work ongoing to identify exact mechanisms leading to these alterations

XPS analysis:

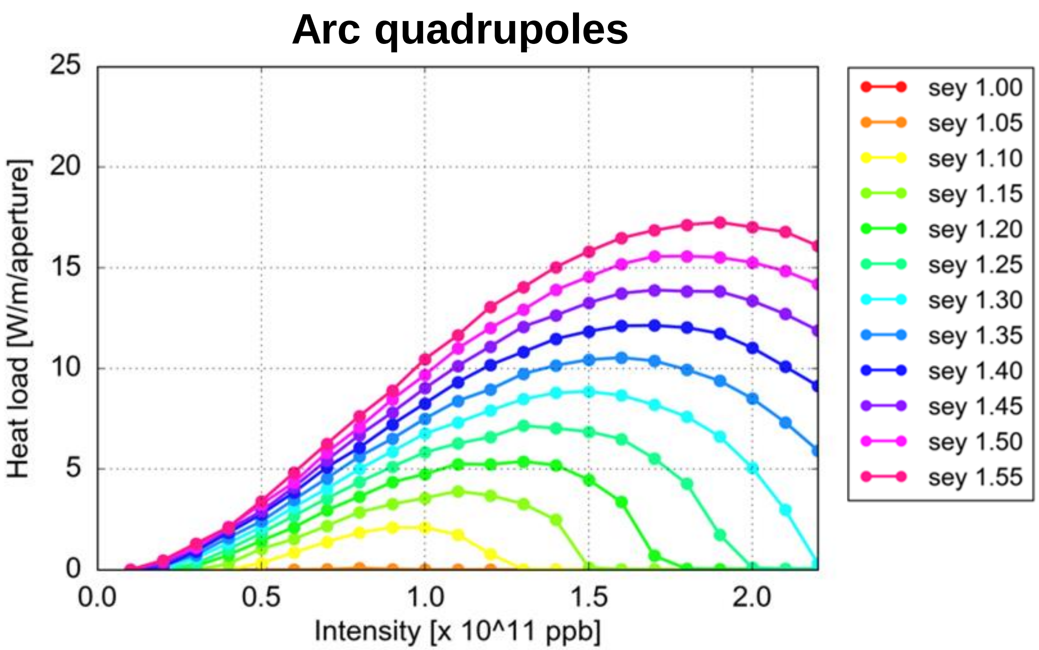


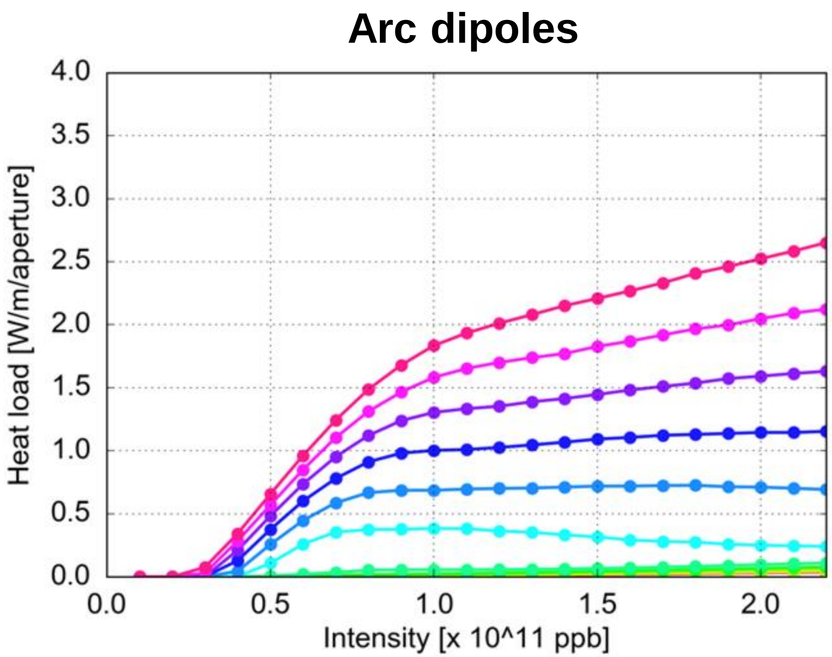


For more info: M. Taborelli, presentation at the LMC meeting, 2 Oct 2019

Arc heat loads - scaling with bunch intensity

- With the available model, **simulations foresee a relatively mild increase** of the heat load from e-cloud when increasing the bunch intensity to HL-LHC values

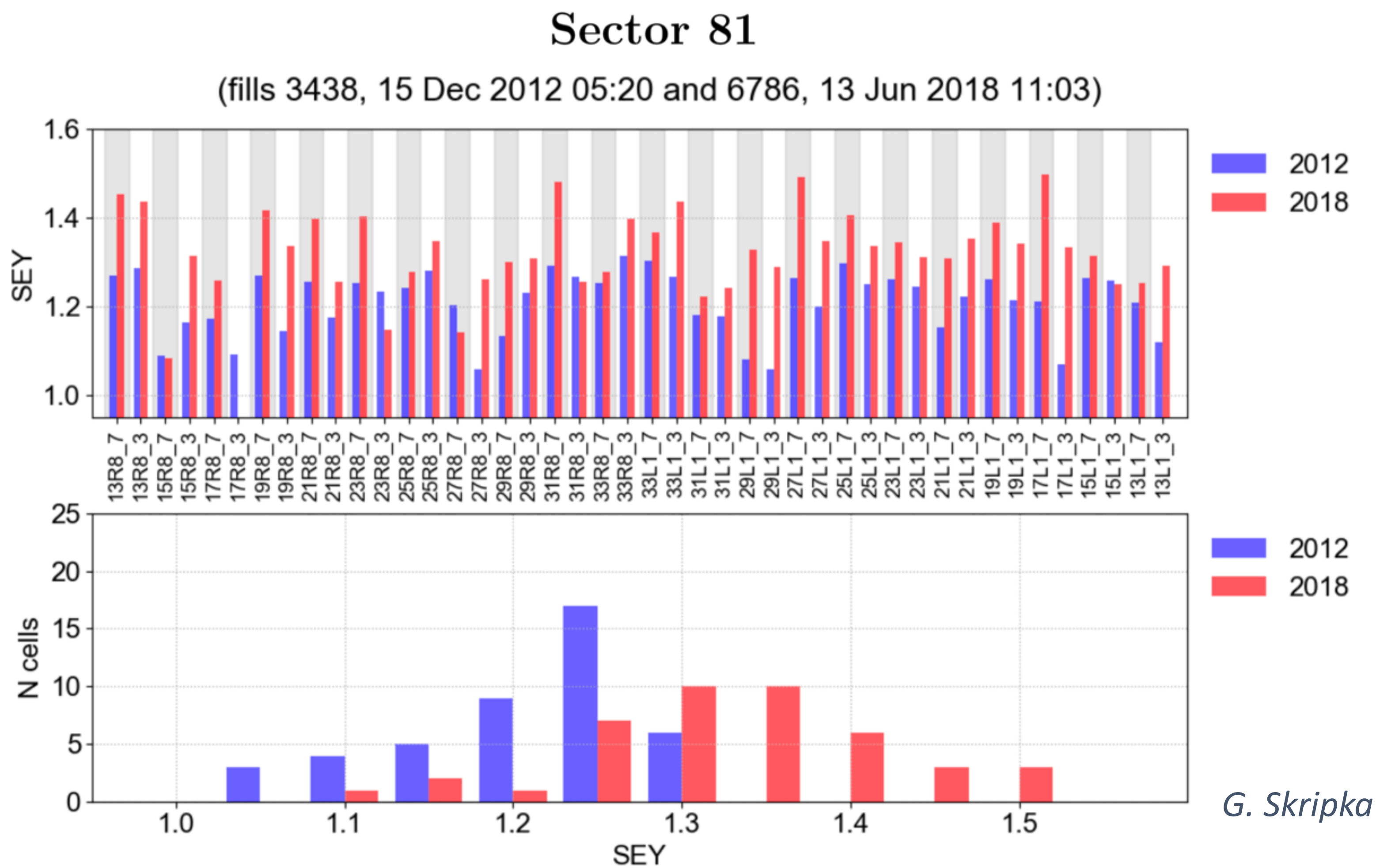




G. Skripka and G. Iadarola, Beam-induced heat loads on the beam screens of the HL-LHC arcs, CERN-ACC-NOTE-2019-0041

Arc heat loads - scaling with bunch intensity

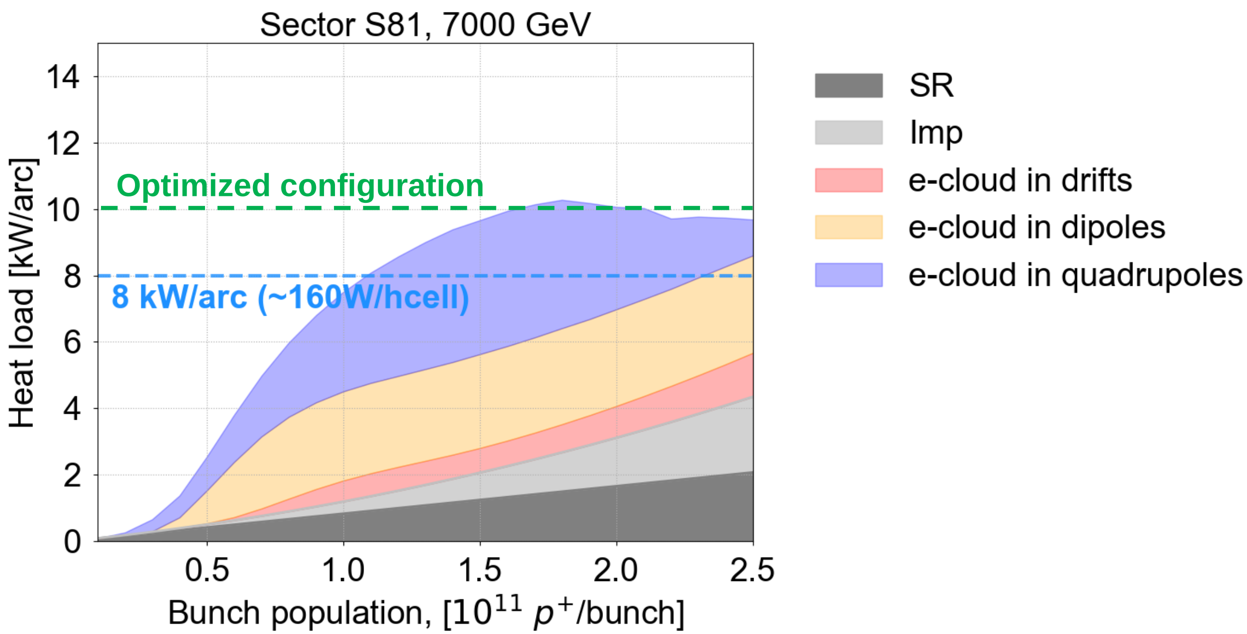
- To make predictions for HL-LHC, the **SEY for the different cells** has been **inferred from the measured heat loads**
    - The degradation between Run 1 and Run 2 is clearly visible



G. Skripka

Arc heat loads - scaling with bunch intensity

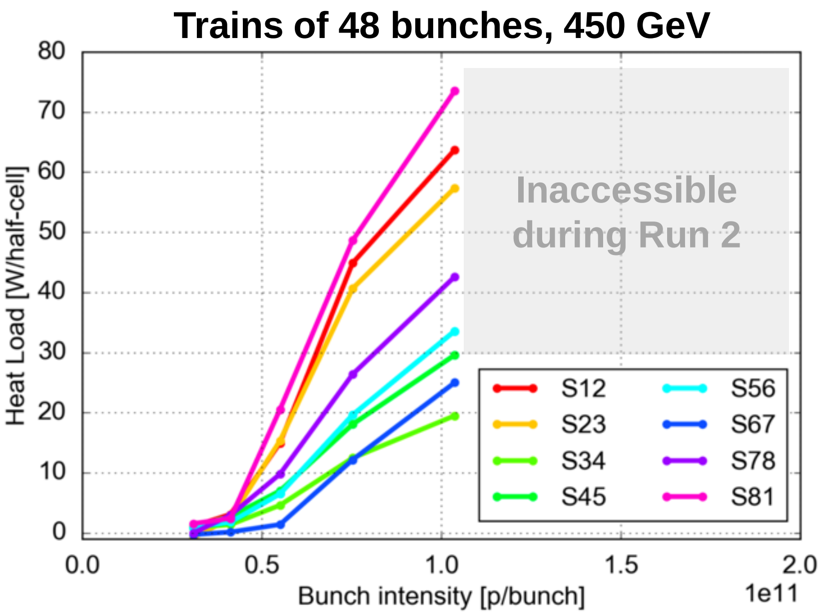
- For the **most critical sector** a heat load of **~10 kW/arc** is expected
  - This is **incompatible with the nominal cooling capacity** of 8 kW/arc
- An **optimized configuration** of the **cryogenic system** (using one cold-compressor unit for two arcs) has been devised and **routinely used in Run 2**
  - This increases the cooling capacity to **~10 kW/arc**, which is **compatible with the expected heat load** (assuming that we avoid further deterioration!)

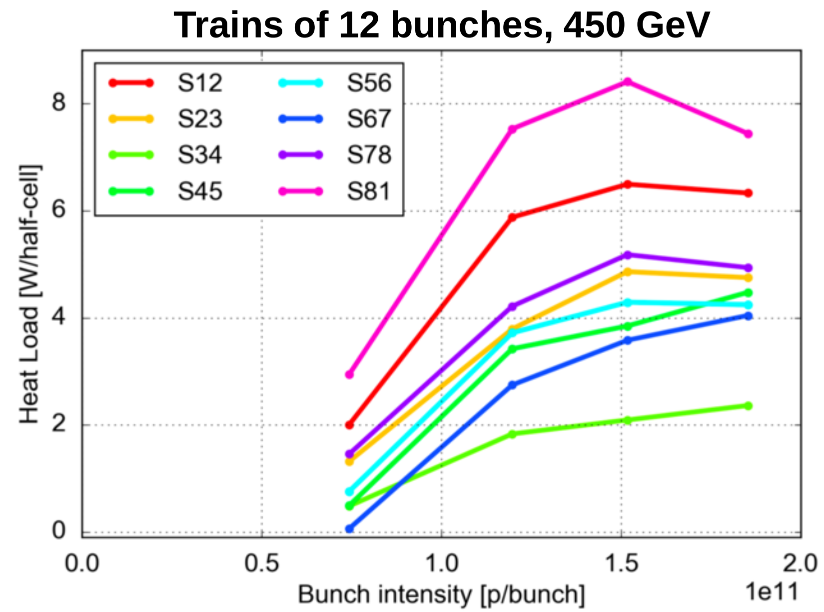


More info: G. Skripka, Scaling of e-cloud effects with bunch population, HL-LHC WP2 meeting 26 Feb 2019
K. Brodzinski, Maximum cooling capacity for cryogenics in Run 4, HL-LHC WP2 meeting 24 Sep 2019

Arc heat loads - scaling with bunch intensity

- A crucial element in the predictions presented so far is the expected **dependence of the e-cloud heat load on the bunch intensity**
- Significant **MD time in 2018** devoted to collect systematic measurements
- With long bunch trains it is **not possible to reach more than 1.2 p/bunch** (technical limitations in the injectors)
- Measurements with **higher bunch intensity** could be collected at the end of 2018 using trains of **12 bunches** and the 8b+4e scheme
    - Expected non-monotonic behaviour **observed experimentally for the first time**

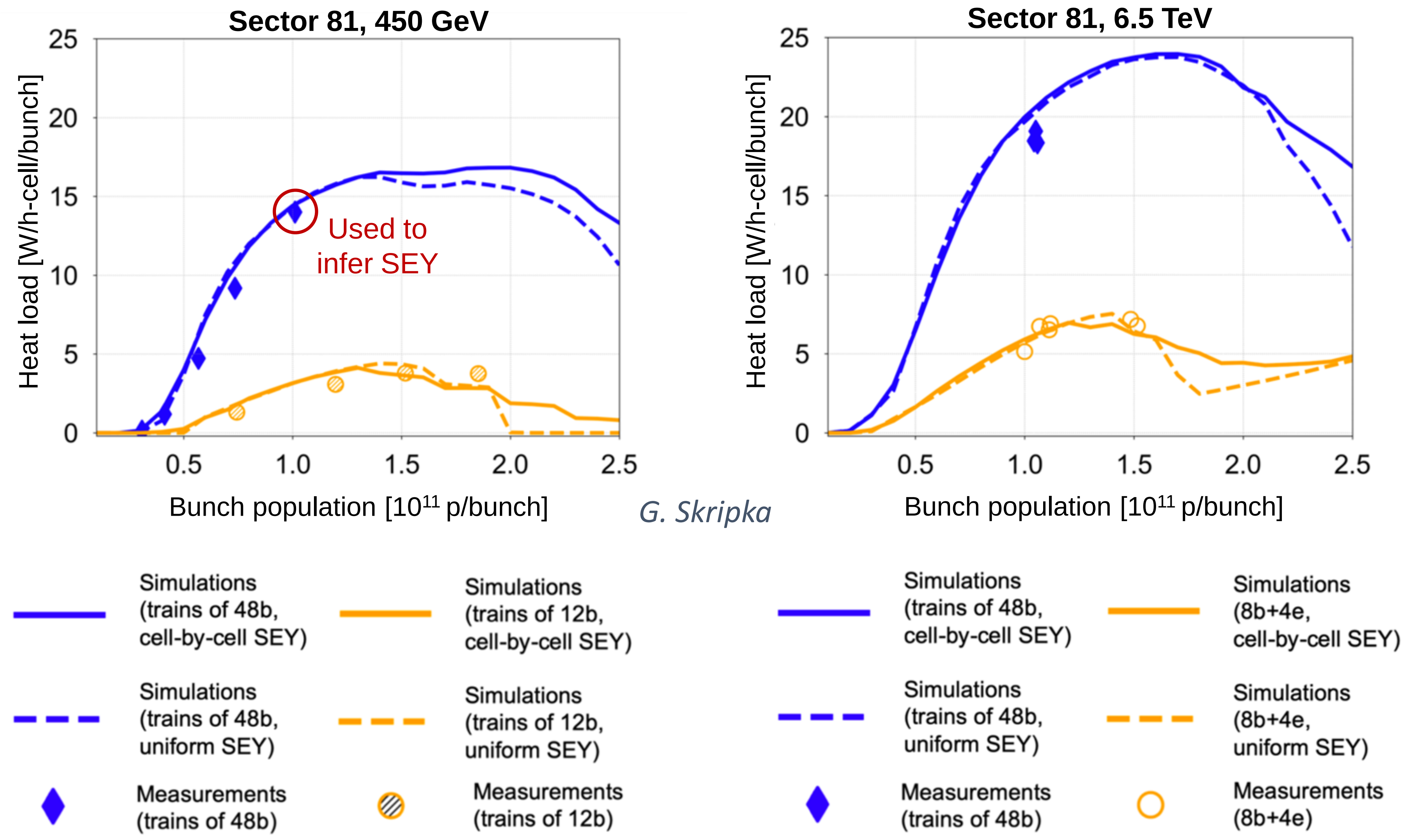




Arc heat loads - scaling with bunch intensity

- The collected measurements have been **compared against the simulation model**

  → The **agreement is very good**, in all tested beam configurations



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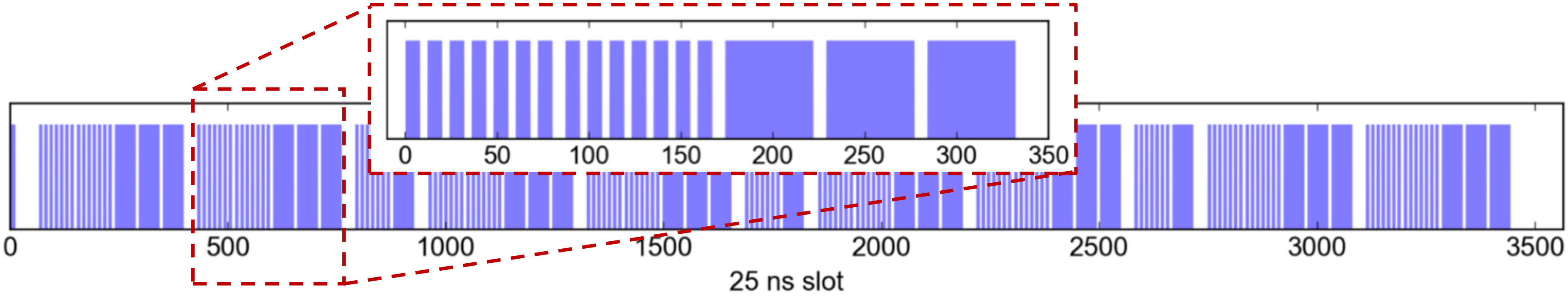
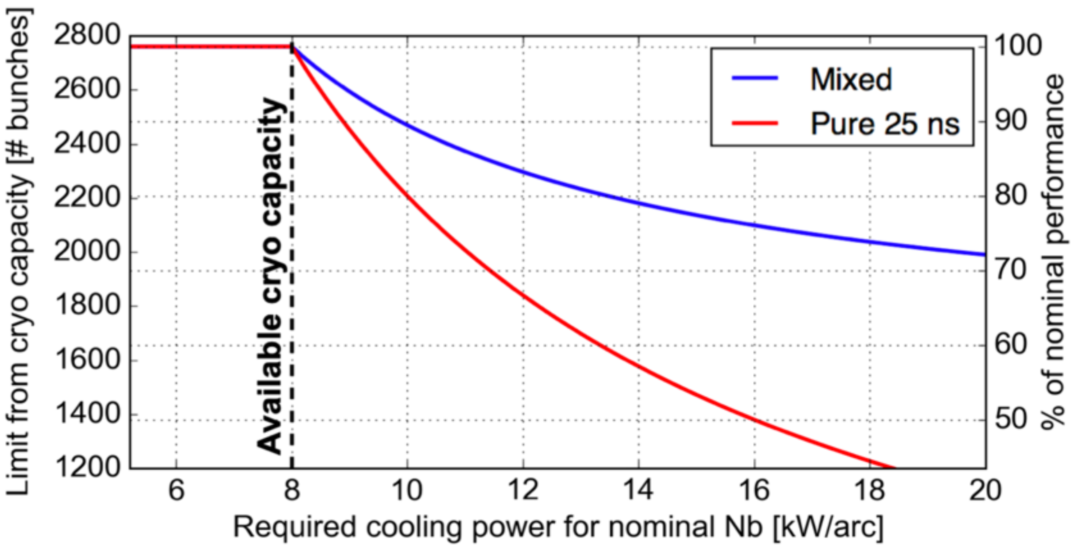
Arc heat loads – mixed scheme

- A **backup beam configuration** has been prepared in case limitations from e-cloud are stronger than expected:

  → **Hybrid schemes** combining 25 ns bunch trains and 8b+4e trains



The **fraction of 8b+4e** beam can be optimized to **match the available cooling capacity**



G. Skripka and G. Iadarola, Beam-induced heat loads on the beam screens of the HL-LHC arcs, CERN-ACC-NOTE-2019-0041

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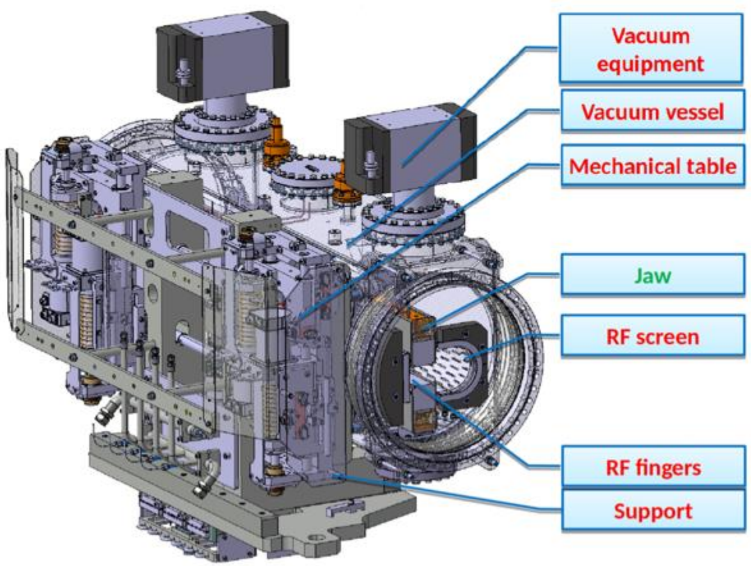
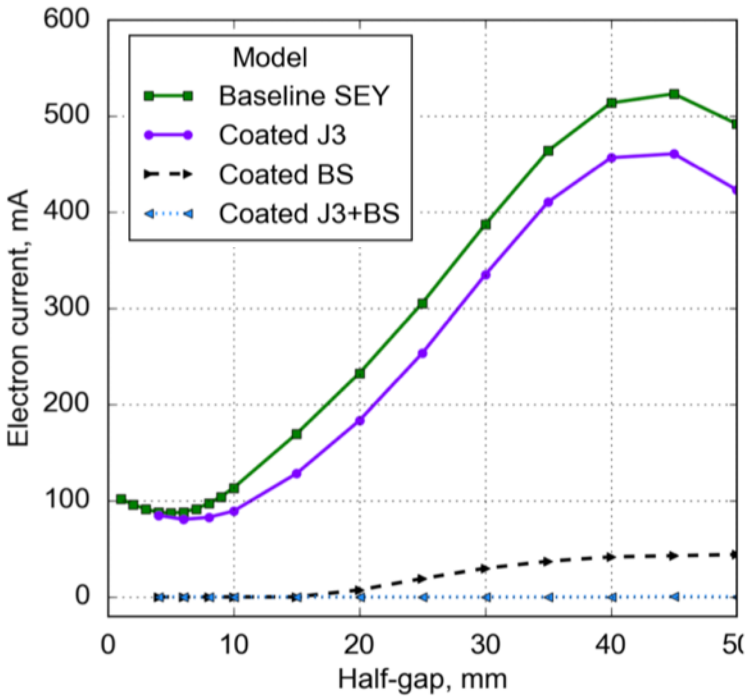
Buildup studies for other devices

- **TDIS injection absorber** (to be installed during LS2): simulation study performed to evaluated **different low-SEY coating options**
  - → **Coating of the RF screen** provides a strong suppression of the e-cloud
- Build-up study performed for **new collimators**:
  - → **e-cloud** formation is **not expected for operational values of the collimator gaps**





G. Skripka and G. Iadarola, Electron cloud studies for the LHC TDI and HL-LHC TDIS, [CERN-ACC-NOTE-2018-0060]
G. Iadarola and E. Wulff, Update on e-cloud validation of new materials, [ColUSM meeting 18 Jan 2019]

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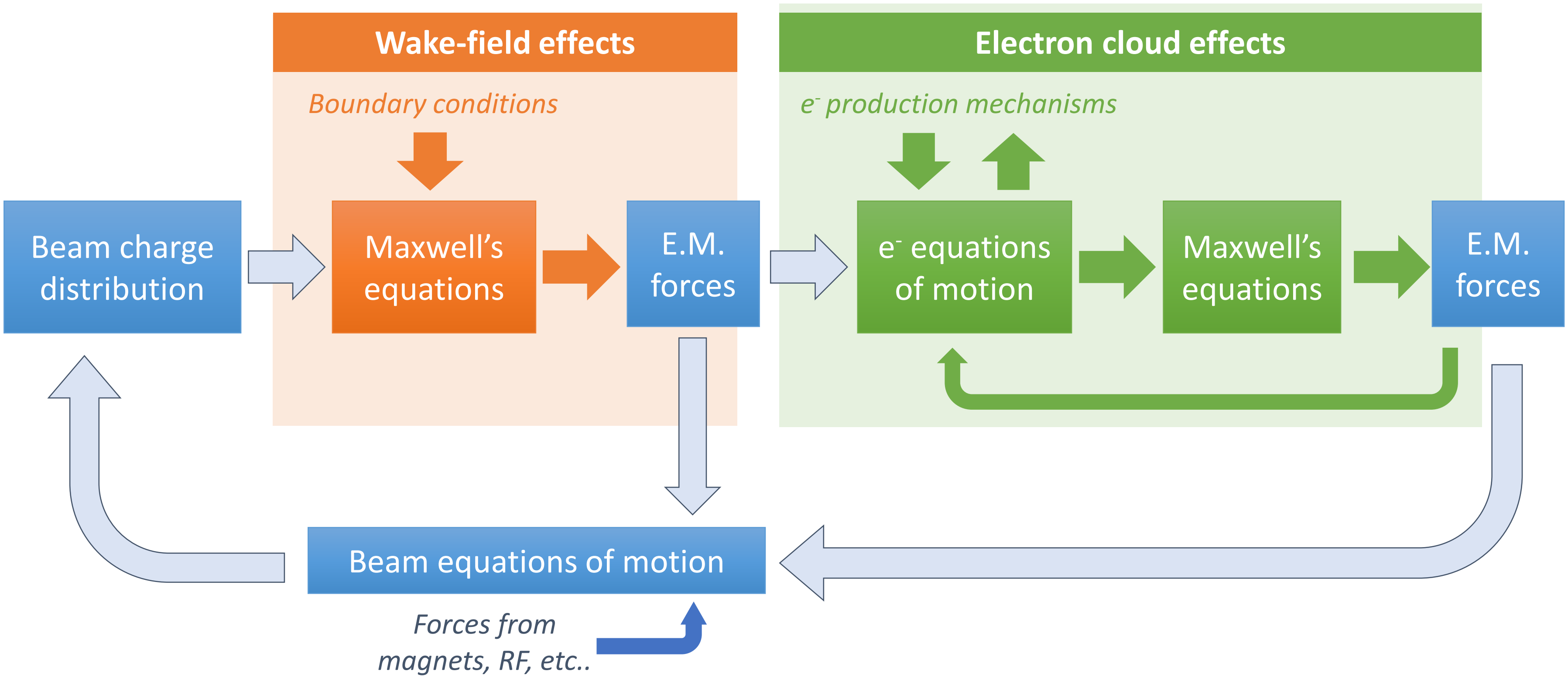
Instabilities driven by e-cloud

Instabilities driven by e-cloud arise from the **coupling via electromagnetic forces** between the **motion of the electrons** and the **dynamics of the proton beam**



- Due to the **non-linear nature of the electron dynamics** it is difficult to study these instabilities using analytical treatments
- Modeling and understanding strongly relies on **numerical simulations**

  → **PyECLOUD-PyHEADTAIL suite**, developed and maintained at CERN
- Simulations can be **very heavy** → relying on **HPC clusters** at CERN and at INFN-CNAF (Bologna)

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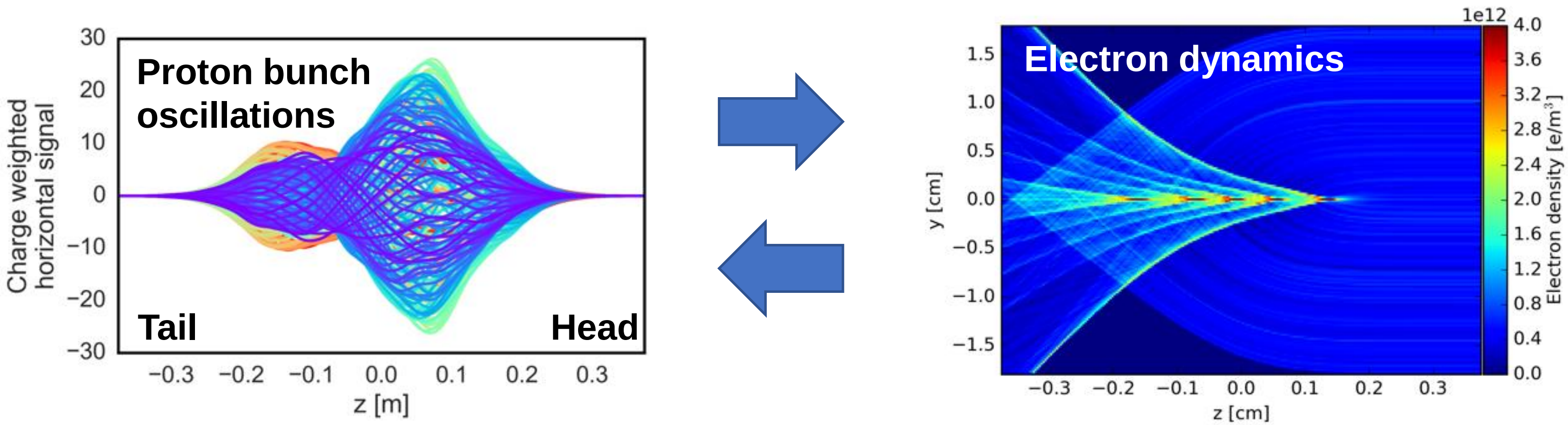
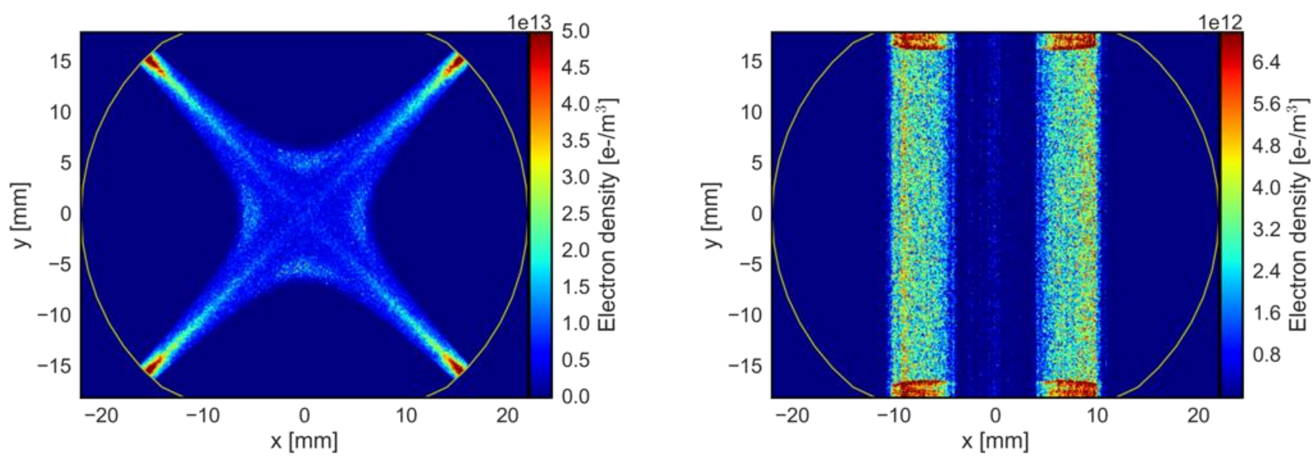
Intra-bunch instabilities at injection energy

- The **electron motion** is fast enough to act as a **coupling mechanism** between the **head** and the **tail** of the bunch (dominated by electrons at the beam location)
  - **Stronger at injection energy** due to lower beam rigidity

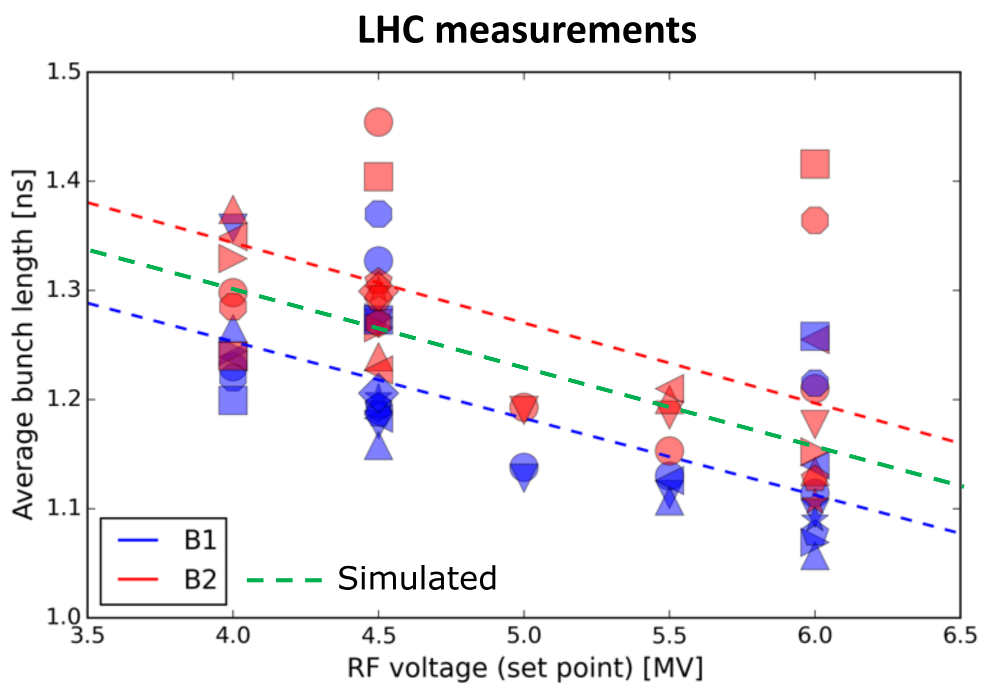


- Electrons in the **arc quadrupoles** are expected to be the **strongest contributor** (quadrupolar field concentrates a large electron density at the beam location)
  - Instabilities driven by **e-cloud in the quadrupoles** will be **considered in the following**



Dependence on RF settings

- The possibility of **lowering the RF voltage at injection** is being considered to cope with RF power limitations
  - → An **extensive simulation study** has been conducted to address the impact on e-cloud driven instabilities
- In the simulations the **bunch length has been adapted to the RF voltage** following the **dependence measured at the LHC**
  - In all simulations the longitudinal distribution is matched to the bucket



H. Timko, presentation at LMC meeting, 5 Sep 2018

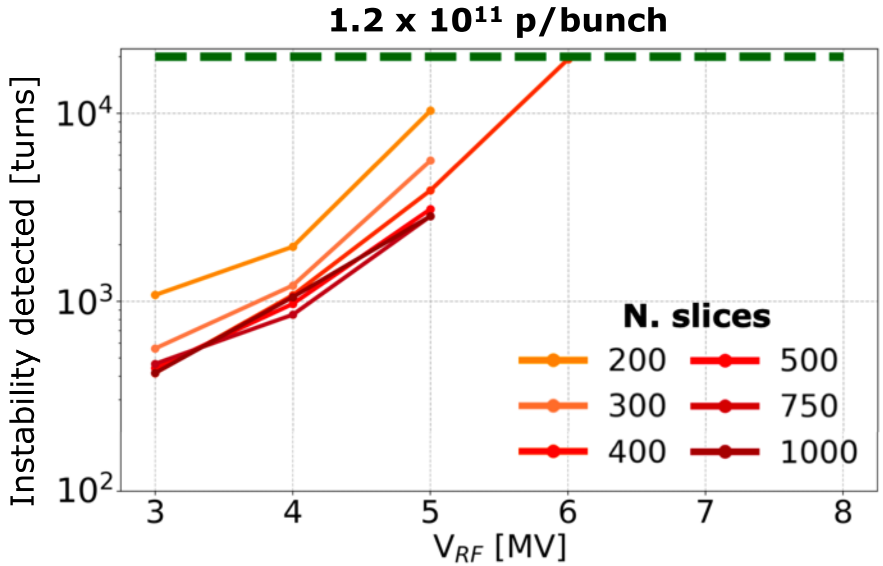
Intra-bunch instabilities at injection energy

- Thorough **parameter scans** were performed to identify **appropriate numerical settings**

Parameters defined as a result of the convergence study
(all parameters in the table have been scanned):

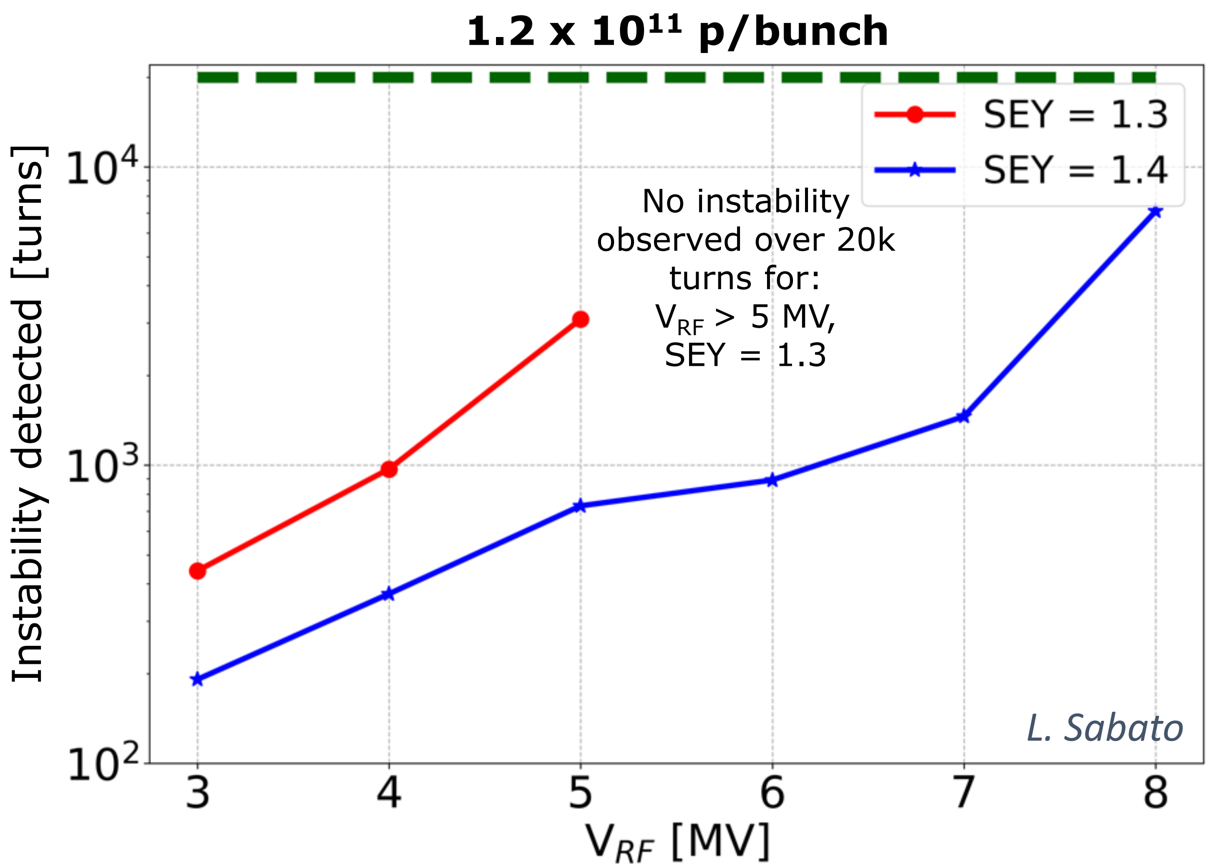
Numerical parameter	Chosen value
Slices/bucket	500
p^+ MPs	1.25×10^6
N_{kicks}	8
e^- MPs	5e5
Transverse grids (dual)	External: 0.8 mm Internal: 0.15 mm (0.2 σ_{beam})

Example of convergence test



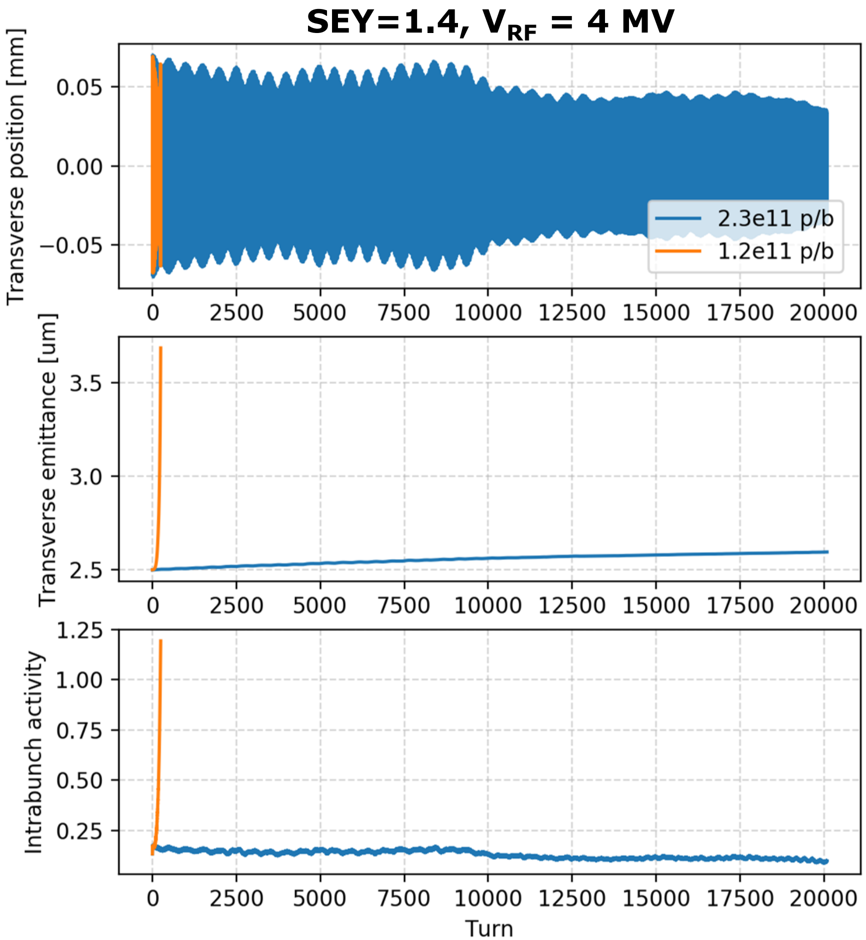
Effect of RF voltage

- Longitudinal settings were scanned together with the SEY parameter
- For **LHC bunch intensity** (1.2×10^{11} p/bunch):
    - The **instability develops faster for lower RF voltage**
    - Additional tests showed that this effect is **driven mainly by the lower synchrotron tune**

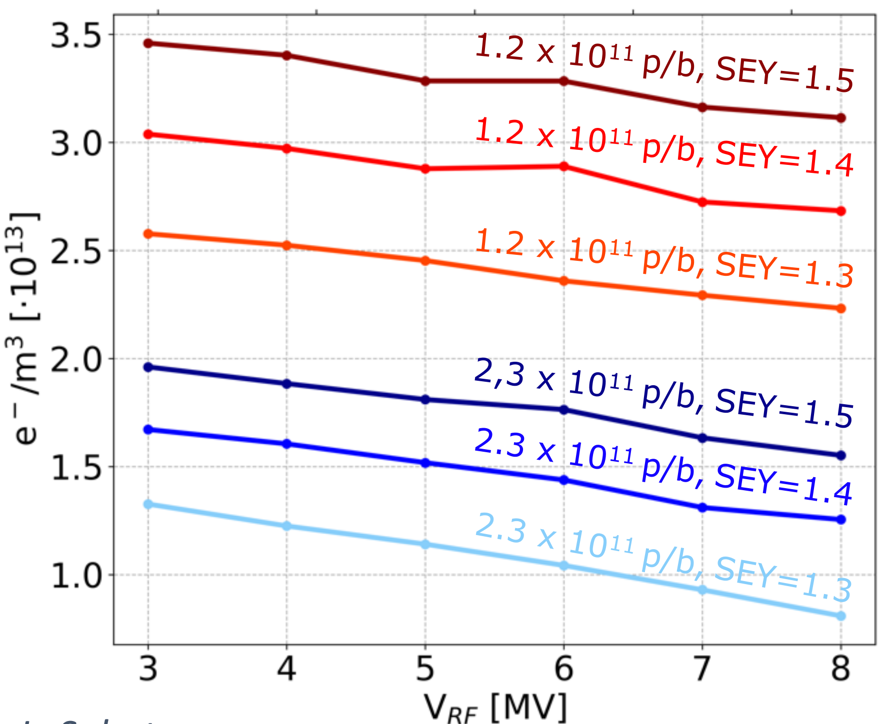


Effect of bunch intensity

- The same parameter range (SEY: 1.3 - 1.4, V_{RF}: 3 – 8 MV) has been explored for **HL-LHC intensity** (2.3 x 10^{11} p/bunch):
  - **No instability detected** even for the most unfavorable cases!
  - The reason is that for higher bunch intensity there are **less electrons in the chamber**



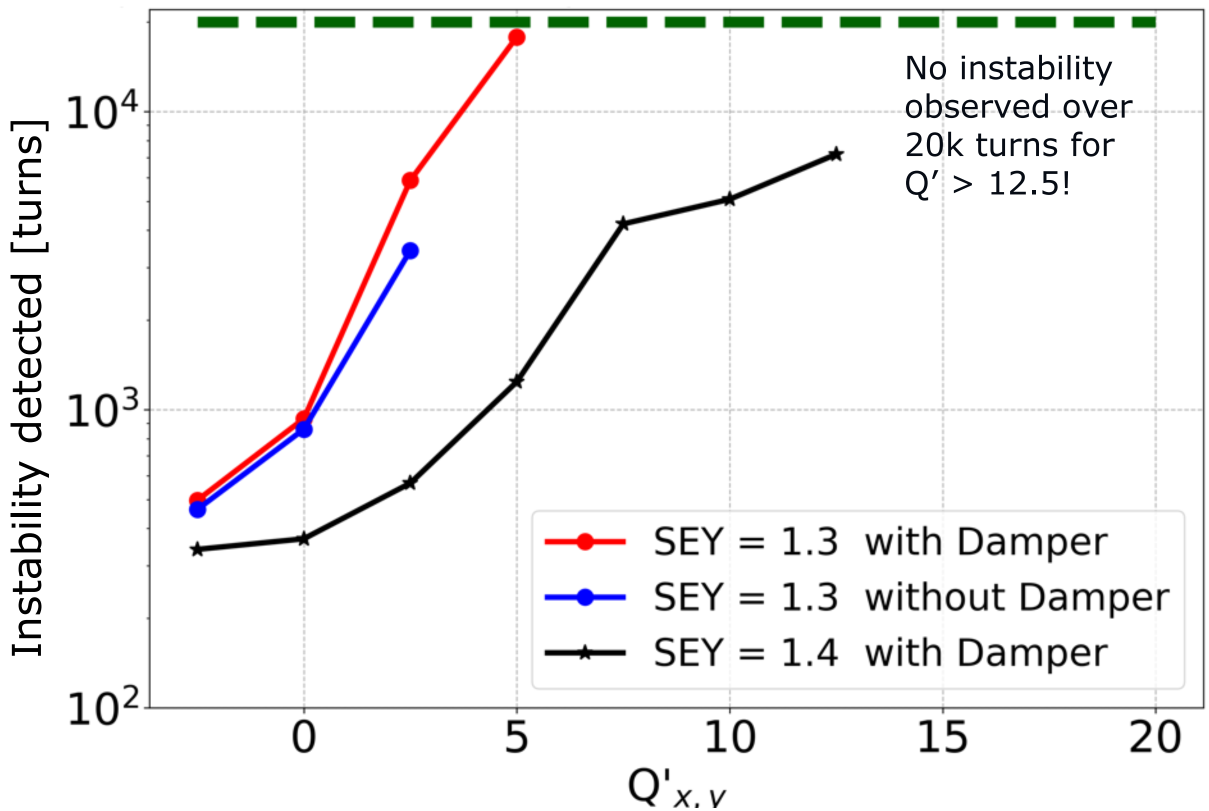
Average electron density at the beam location during the bunch passage



L. Sabato

Effect of transverse feedback and chromaticity

- For the case of LHC intensity (which an instability could be observed) the **effectiveness of different mitigation measures** has been investigated:
  - The instability is **strongly mitigated** by increasing the **chromaticity** settings
  - The **transverse feedback** (bunch-by-bunch, dumping time of 10 turns) is **mostly ineffective**



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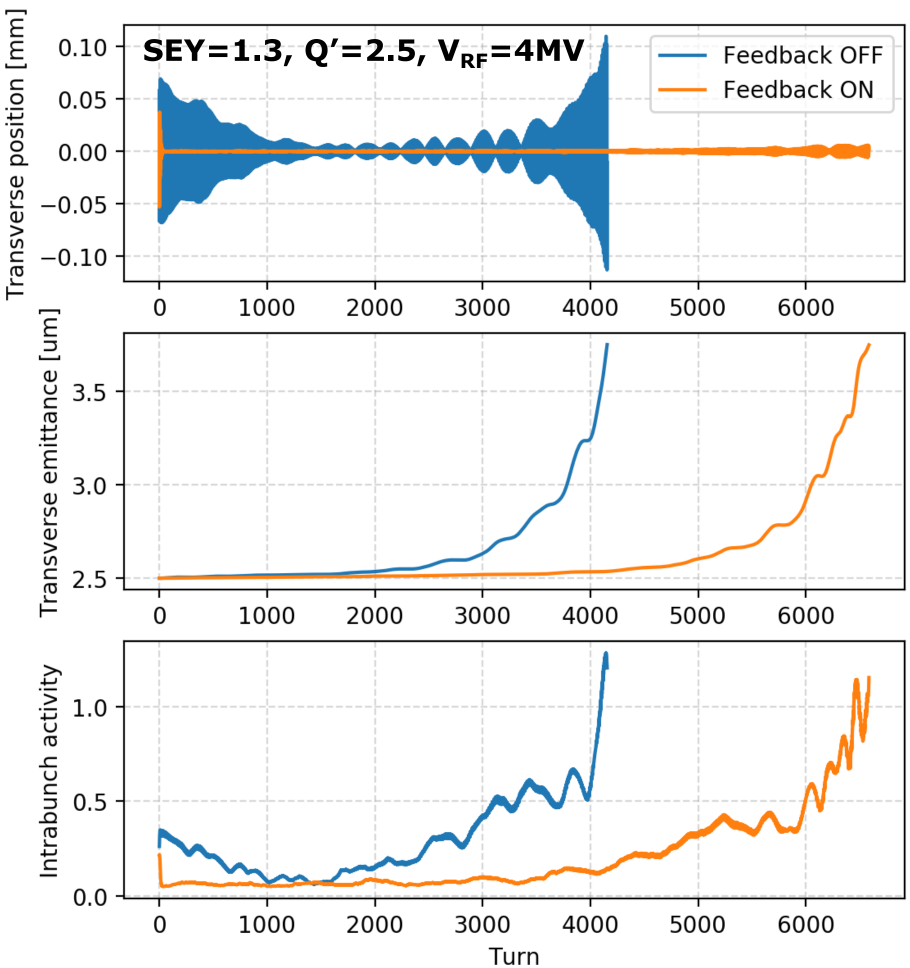
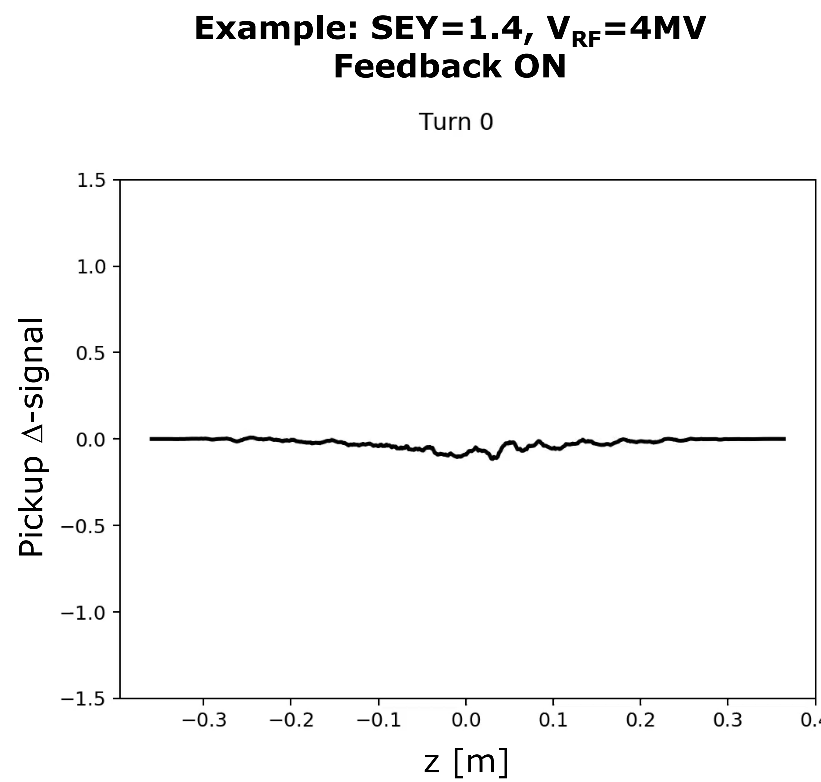
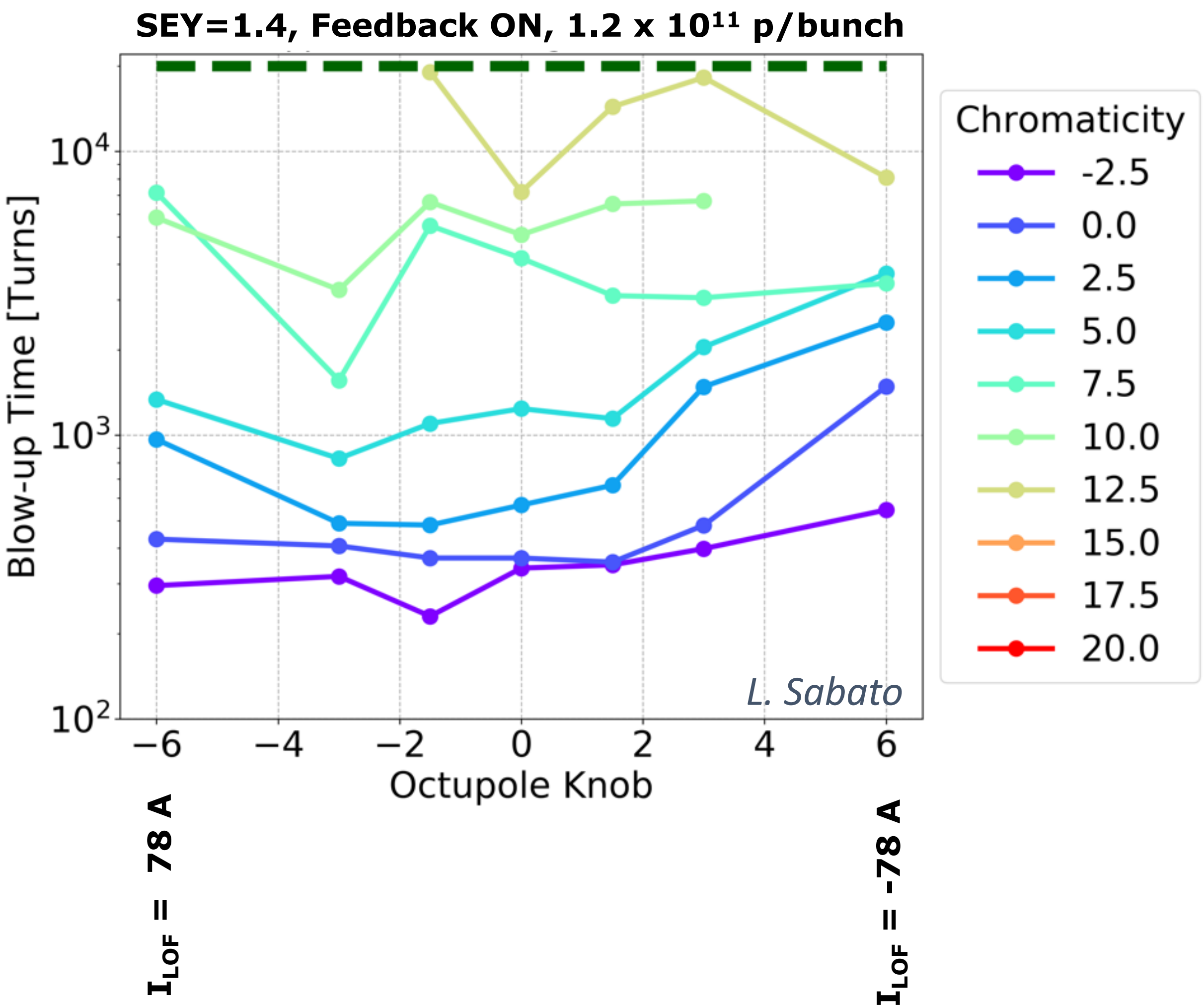
  - The **transverse feedback** (bunch-by-bunch, dumping time of 10 turns) is **mostly ineffective** → cannot damp **intra-bunch motion**





- For the case of LHC intensity the **octupole current** has also been scanned
  - → Much **less effective** compared to **chromaticity**



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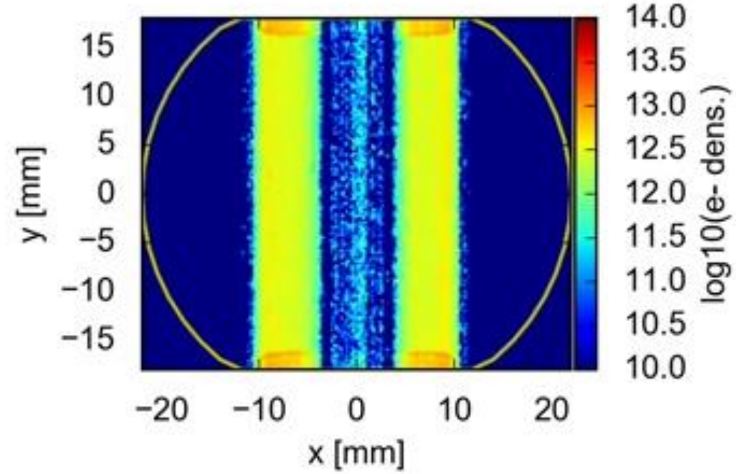
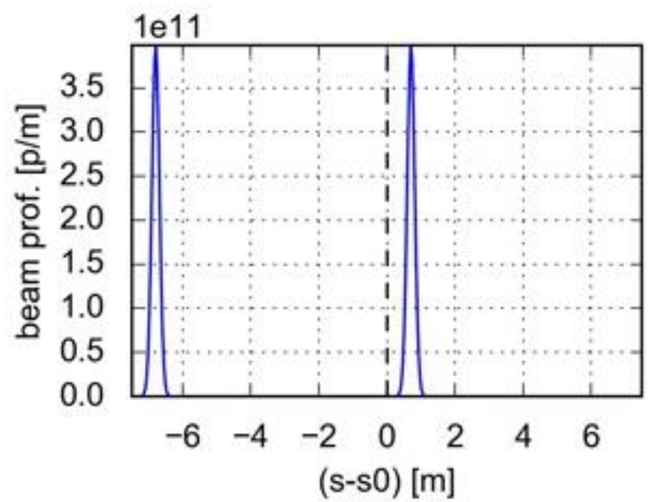
Coupled-bunch instabilities

- The **electrons in the two vertical stripes** typical of the e-cloud distribution in dipole magnets **contribute very little to single-bunch instabilities** but can **couple the motion of consecutive bunches**

- Simulation of these phenomena is **extremely heavy**
  - Requires the simulation of the full **e-cloud buildup** process **coupled with the beam dynamics** at each turn
  - The **PyECLOUD-PyHEADTAIL** suite and its **PyPARIS** parallelization layer have been recently been extended to **exploit HPC clusters** to perform these simulations





For more info: G. Iadarola, New tools for the simulation of coupled bunch instabilities driven by electron cloud, [e-cloud meeting 14 Feb 2018]()

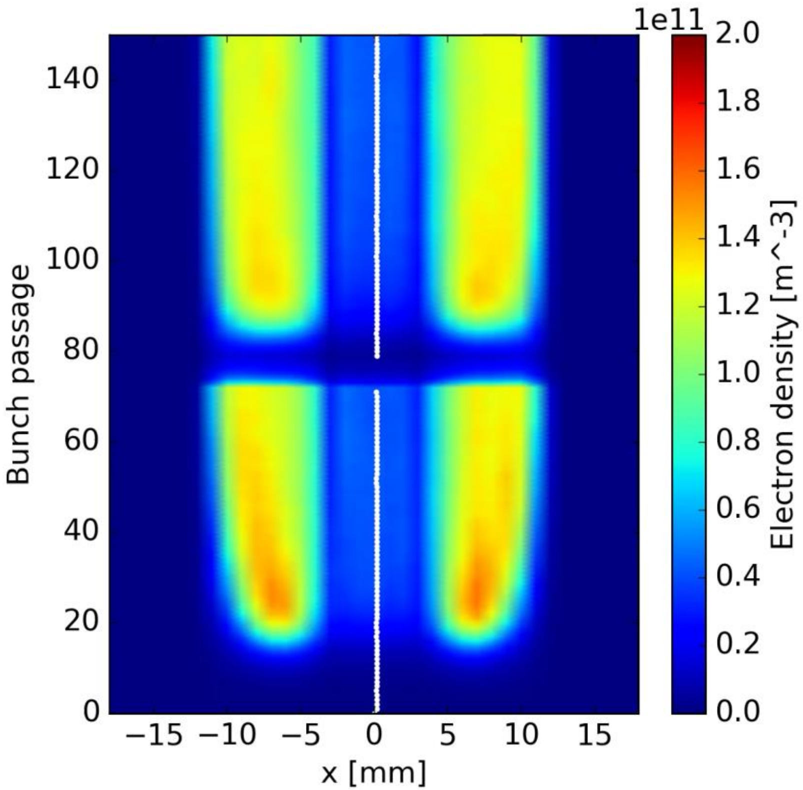
Coupled-bunch instabilities

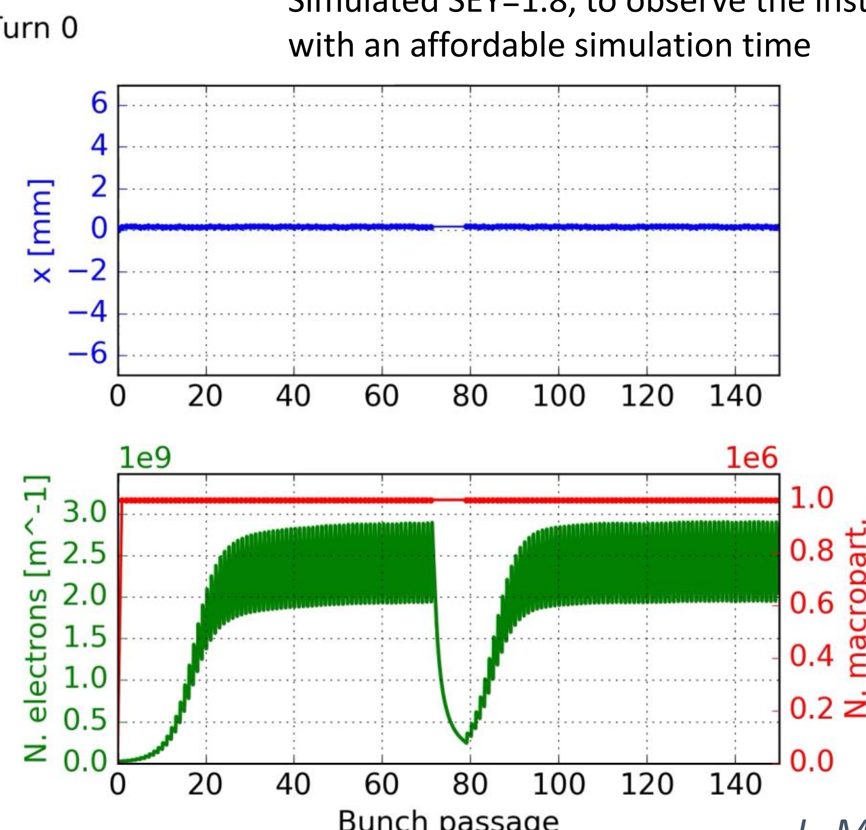
Example of simulation for **LHC bunch intensity** (1.2 x 10^{11} p/bunch)

- A train of 144 bunches is simulated
- The simulation requires a total **144 x 10^6 proton MPs** for the bunches and **160 x 10^6 electron MPs**
- It is performed on **800 CPU-cores** on the CERN HPC cluster

Coupling between the motion of the bunches and the electron distribution is visible

Simulated SEY=1.8, to observe the instability with an affordable simulation time





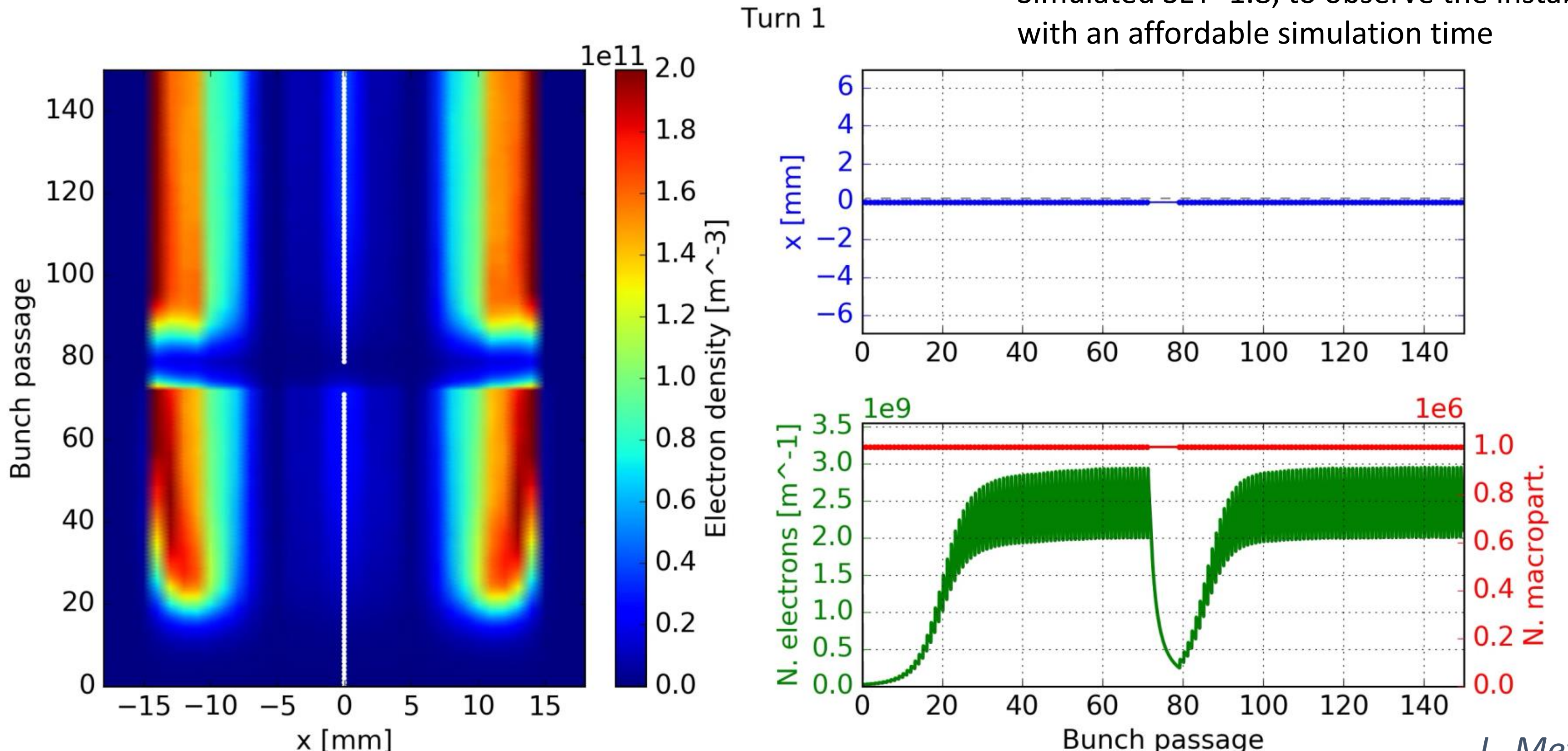
L. Mether

Coupled-bunch instabilities

The same simulation is performed for **HL-LHC bunch intensity** (2.3 x 10^{11} p/bunch)

- As a result of the larger bunch intensity, the **electron stripes are further away from the beam**
- The instability **pattern along the bunch train is different**
    - Most unstable bunches are in the **middle of the first train**

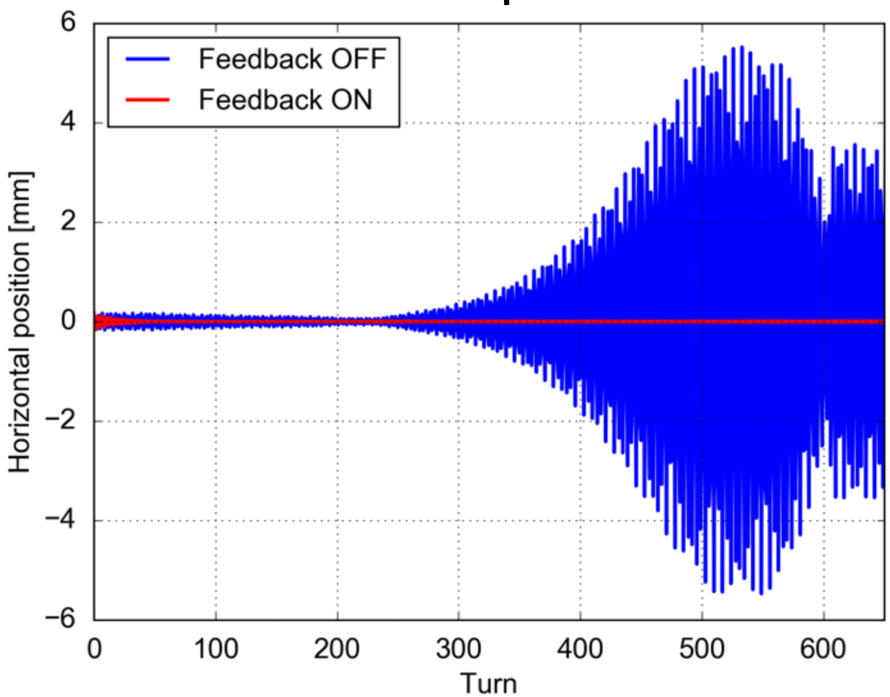
Simulated SEY=1.8, to observe the instability with an affordable simulation time



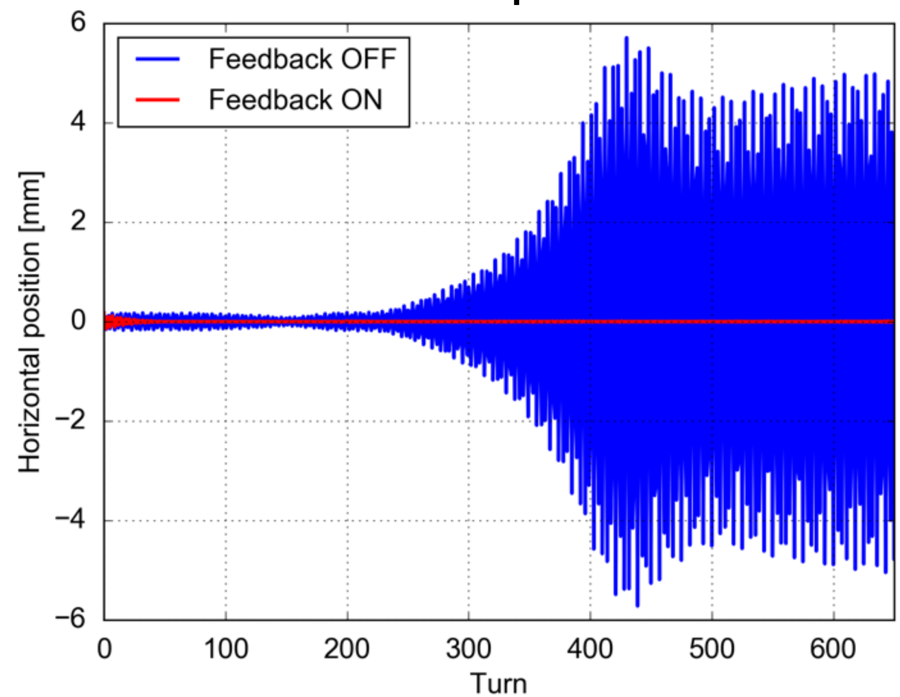
L. Mether

- For the two values of the bunch intensity the **rise-time of the instability is similar**
- The simulations have been **repeated with the transverse feedback active** (20 turns dumping time)
  - In both cases the **feedback fully suppresses the instability** (over the simulated timespan)

1.0 x 10^{11} p/bunch



2.3 x 10^{11} p/bunch



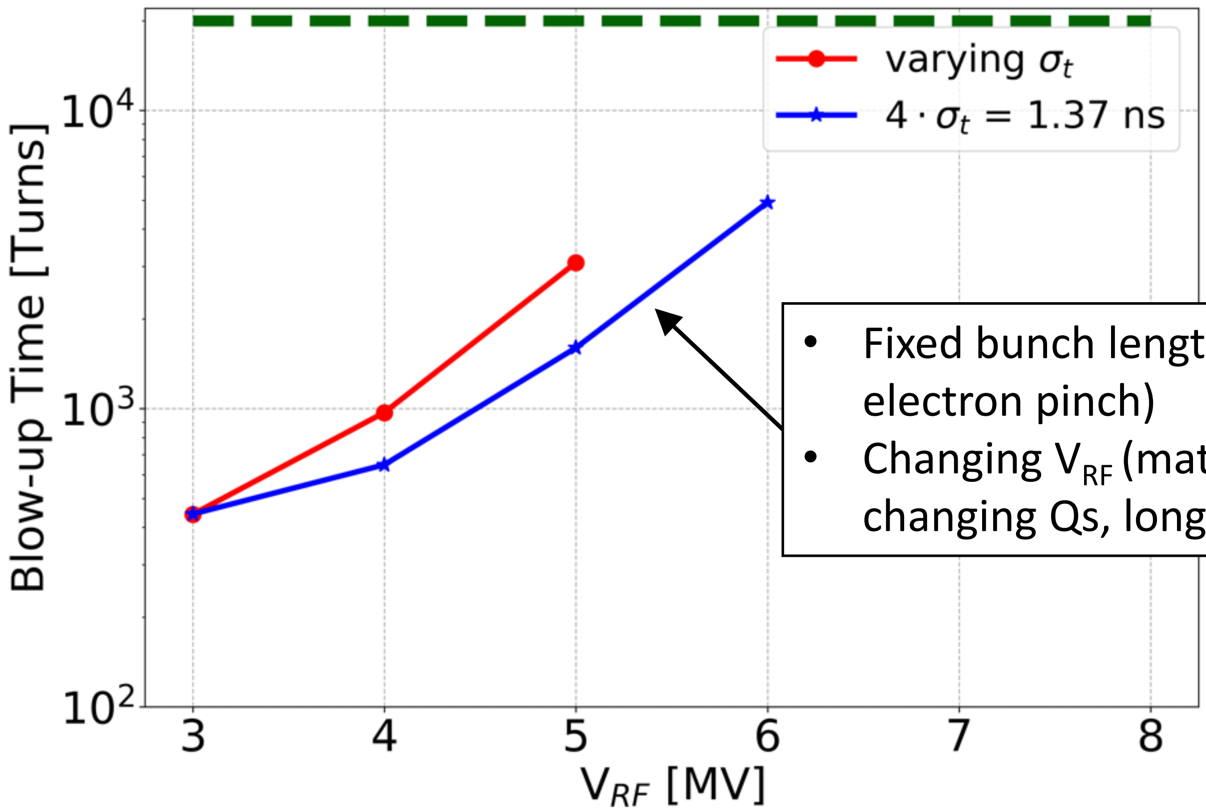
L. Mether

Summary and conclusions

- The **heat loads** expected in the **arc-beam screens** have been **simulated using SEY estimated from heat load measurements** (at a cell-by-cell level)
    - For the most critical sectors a heat load of **~10 kW/arc** is expected
    - **Optimized cryogenics configuration** deployed in Run 2 allows for ~sufficient cooling capacity (with no margin)
    - Important to **avoid further degradation** of the SEY
- **Dependence** of heat loads on **bunch intensity probed experimentally** at the LHC during 2018 using short bunch trains→ found to be **consistent with simulation model**
- Transverse **instabilities** due to electron cloud are being studied using **HPC computing resources**:
    - **Single bunch instabilities** driven by e-cloud in the main quadrupoles at **450 GeV**:
        - Found a **significant dependence** of the instability risetime on **RF settings**
        - High **chromaticity** is found to be the most effective mitigation
        - The beam is **more stable for HL-LHC bunch intensity** (e-cloud density is lower)
        - Effect of **dipoles and drifts** will be investigated in the near future
    - First studies on **coupled-bunch instabilities** conducted on CERN HPC cluster
        - **Bunch-by-bunch feedback** fully **suppresses the instability** in simulation
        - Next step is to move to **more realistic scenarios**: octupoles, Q' etc.

Thanks for your attention

Bunch Length and RF Voltage Amplitude



- **SEY = 1.3**

- Fixed bunch length (same electron pinch)
- Changing V_{RF} (matched bunch, changing Qs, long. emittance)

1. The dominant element is the change of V_{RF} and not the change in bunch length