Swiss Accelerator Research and Technology

CHART PROGRAM
Beam dynamics and Stability Studies

J. Barranco, L. Coyle, P. Goncalves, T. Pieloni, L. Rivkin, M. Schenk, C. Tambasco, X. Buffat, S. Furuseth
Laboratory of Particle Accelerator Physics

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CHIPP Meeting 1st July 2019 Kandersteg

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Future Circular Collider hh (FCC-hh) and the High Energy LHC (HE-LHC) beam stability studies:

Conceptual Design Studies

CHART II (2019-2024):

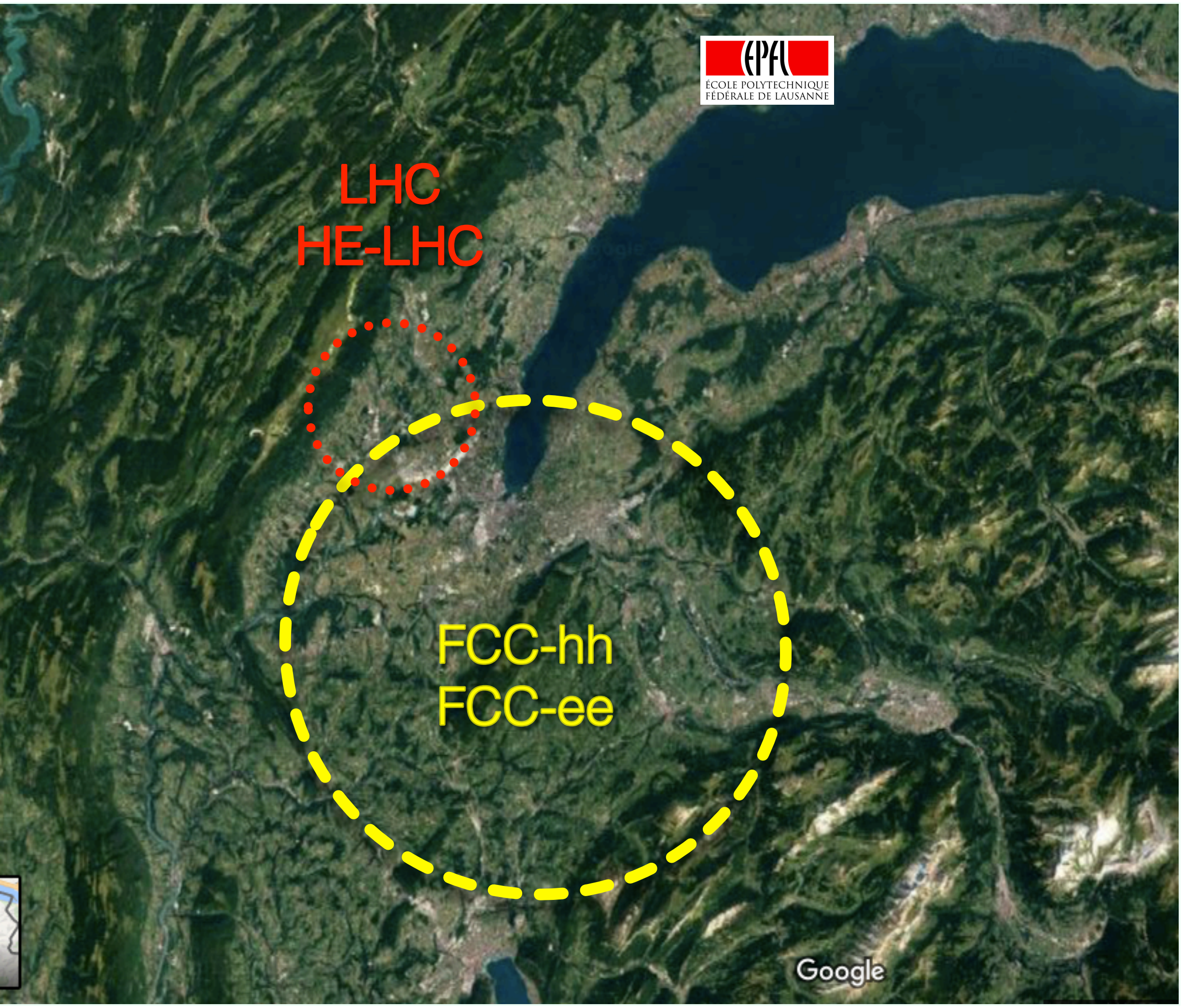
Continue Hadron Colliders beam dynamics studies:

1. IR design and beam-beam effects with important synchrotron radiation
1. Alternative solutions (flat optics, crossing schemes)
2. Landau damping schemes and alternatives
3. Machine Learning techniques applied to accelerators
4. Improve understanding of Luminosity measurements at hadron colliders

Engage on the FCC-ee collider studies

- Stability in strong radiation damping regimes
- Multi-turn and multiple experiments beams dynamics and stability
- Develop tools and models for lepton collider design → retain experience and knowledge

Colliders beam dynamics



....“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

CERN should undertake design studies for accelerator projects in a global context,

- *with emphasis on **proton-proton and electron-positron high-energy frontier machines**.*
- *These design studies should be coupled to a vigorous accelerator **R&D programme, including high-field magnets and high-gradient accelerating structures**,*

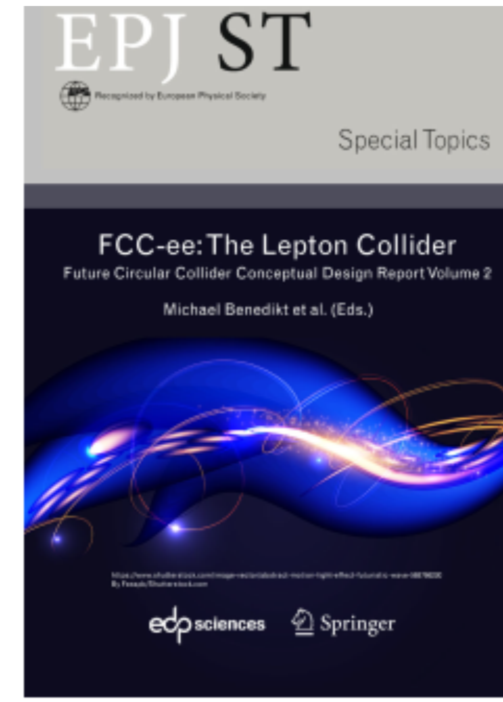
Hadron Colliders
FCC-HH (100 Km for energy 100 TeV)
HE-LHC (27 TeV at LHC tunnel)

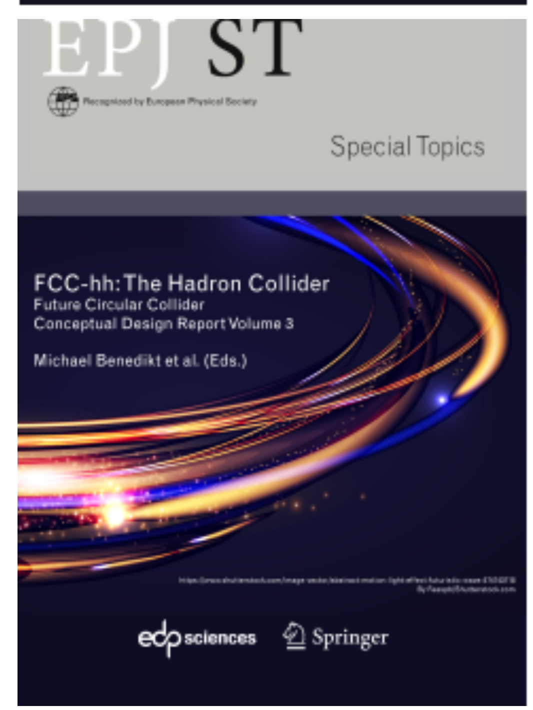
Conceptual Design Report

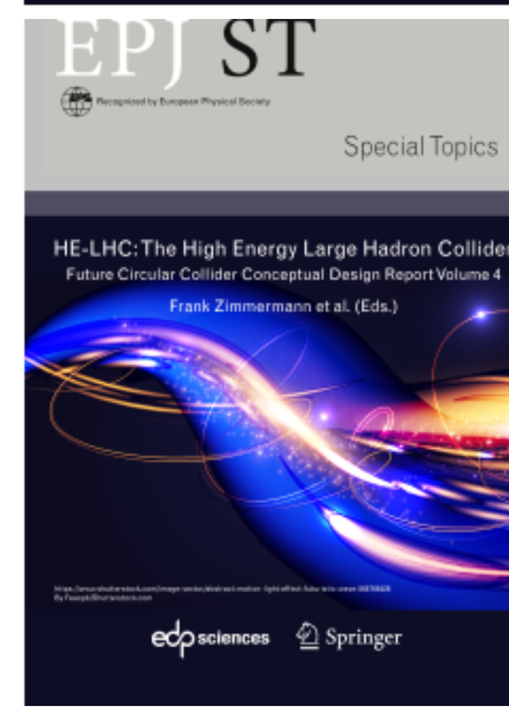
FCC Week 24-28 June 2019
https://indico.cern.ch/event/727555/

FCC-hh Studies: Collider Design and Performance

- Interaction Regions design beam-beam effects
- Collision schemes and operational scenario for baseline and ultimate configurations
- Alternative solutions (flat optics, crossing schemes, global compensations)
- Beam stability and Landau damping studies
- Alternative devices for Landau damping
- Development of new techniques for operational optimization of accelerators (i.e. machine learning methods)







FCC-hh HE-LHC

HE-LHC Studies: Collider Design and Performance

- Interaction Regions design beam-beam effects
- Beam stability and Landau damping

Conceptual Design Report Studies

FCC-hh Studies: Collider Design and Performance

- Interaction Regions design beam-beam effects
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Interaction Region and ARC design

- Beam stability and Landau damping studies
- Alternative devices for Landau damping

Beam Stability

- Development of new techniques for operational optimization of accelerators (i.e. machine learning methods)

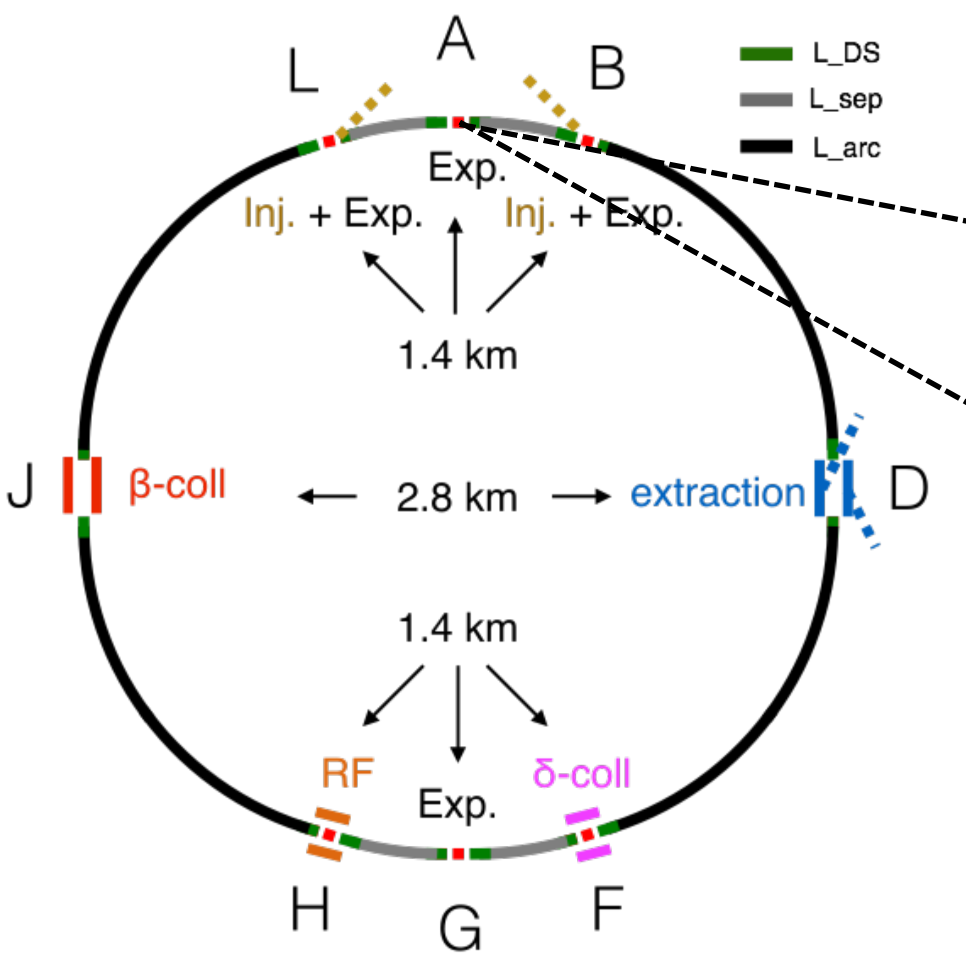
EPFL, PSI and
Swiss Data Science Centre
“PACMAN” Project ML to Accelerators optimization and design

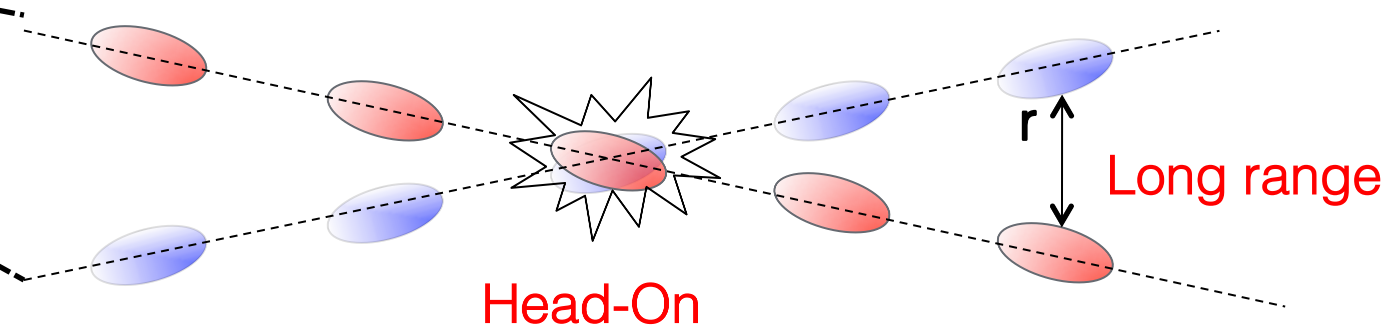
HE-LHC Studies: Collider Design and Performance

- Interaction Regions design beam-beam effects
- Beam stability and Landau damping

Interaction regions design
and
Beam Stability

Colliders beam dynamics





352 Long-range Beam-beam interactions
4 Experimental areas
Lattice

Design:

1. Expand existing models for FCC design and continue benchmarking to data (LHC, RHIC)
2. Design 2 High luminosity experiments → maximum luminosity together with good lifetimes
3. Design 2 Low luminosity experiments → they should be in the shadow of the high luminosity ones
4. Contribute in the arcs design and define tolerances on magnets field quality → operational scenario
5. Identify limitations → explore mitigations

High Energy Colliders parameters: Present/Future

PARAMETERS	LHC HL-LHC	High Energy LHC	FCC-hh Baseline - Ultimate	
Center of Mass Energy [TeV]	14	27	100	
Dipole Fields [T]	8.33	16	16	
Circumference [Km]	27	27	100	
Beam-Beam Interactions	120 LR + 4 HO	120(600)LR + 4 HO	352 LR + 4 HO (1764)	
Lattice Elements	23000	30000	100000	
Beam Current [A]	0.58 - 1.12	1.12	0.5	
Bunch Intensity [10^{11}]	1.15 - 2.2	2.2 (0.44)	1	1 (0.2)
Bunch spacing [ns]	25	25 (5)	25	25 (5)
RMS bunch length [cm]	7.55 – 8.1	7.55	7.55	
Luminosity [10^{34} cm^{-2}s^{-1}]	1 - 5	25	5	30
Events/bunch crossing	27 - 135	800 (160)	170	1k (200)
Stored Energy [GJ]	0.36 – 0.7	1.3	8.4	
β* [m]	0.55 – 0.2	0.25	1.1- 0.3	
Transverse beam size [μm]	3.75-2.5	2.5 (0.5)	2.2 (0.4)	

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8.4 GJ beams

Can we control such beams? Which losses can we allow? How can we make predictions? How can we design for the future? Which are the limits?

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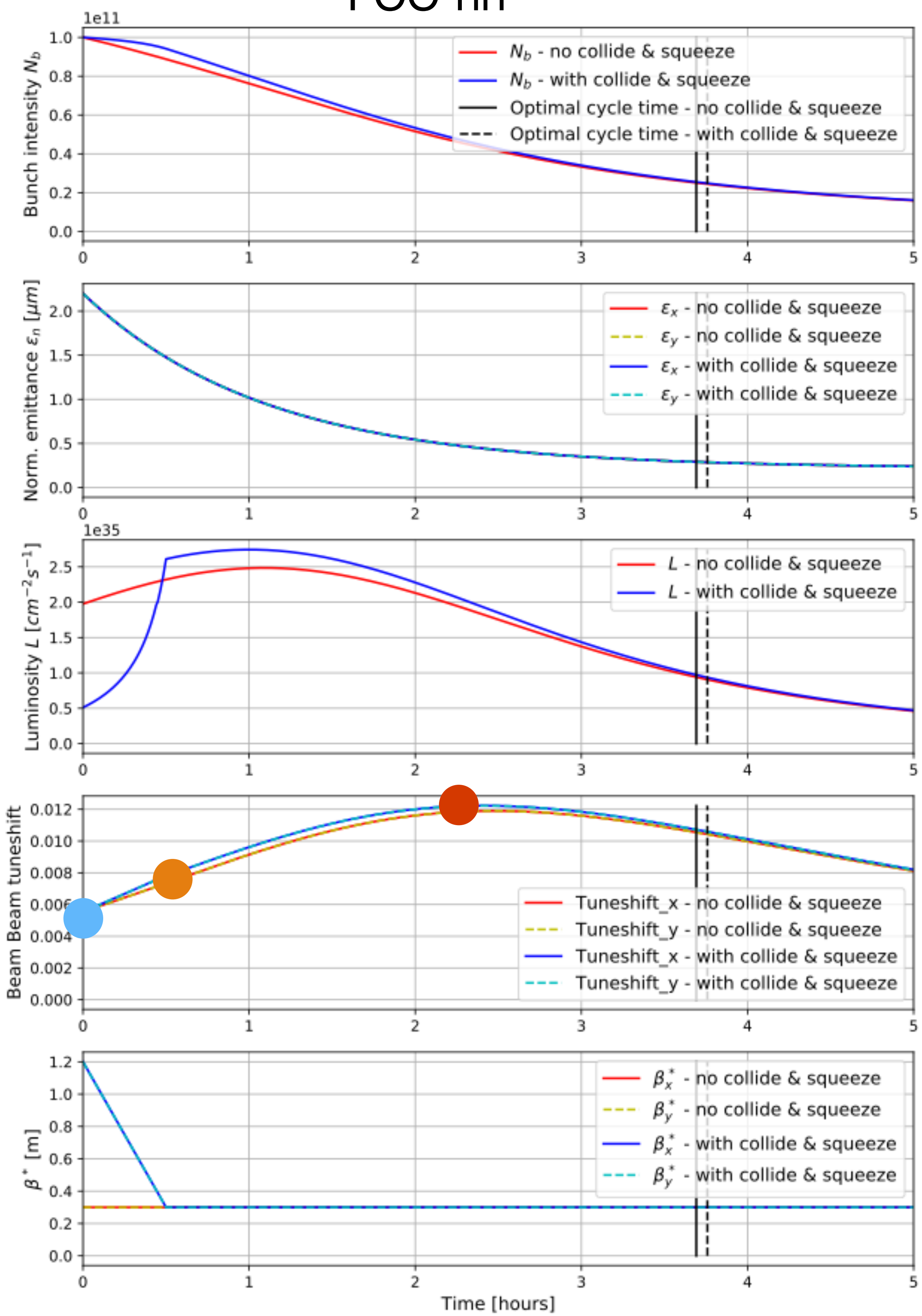
Evolution of beam parameters: beam-beam effects

FCC-hh



Due to strong radiation damping (emittance reduction) the **beam-beam tune changes over the fill:**

- $\Delta Q_{TOT} = 0.011$ at the beginning of the fill
- $\Delta Q_{TOT} = 0.016$ at the END of the Collide&Squeeze
- $\Delta Q_{TOT} = 0.03$ after two hours (maximum value)

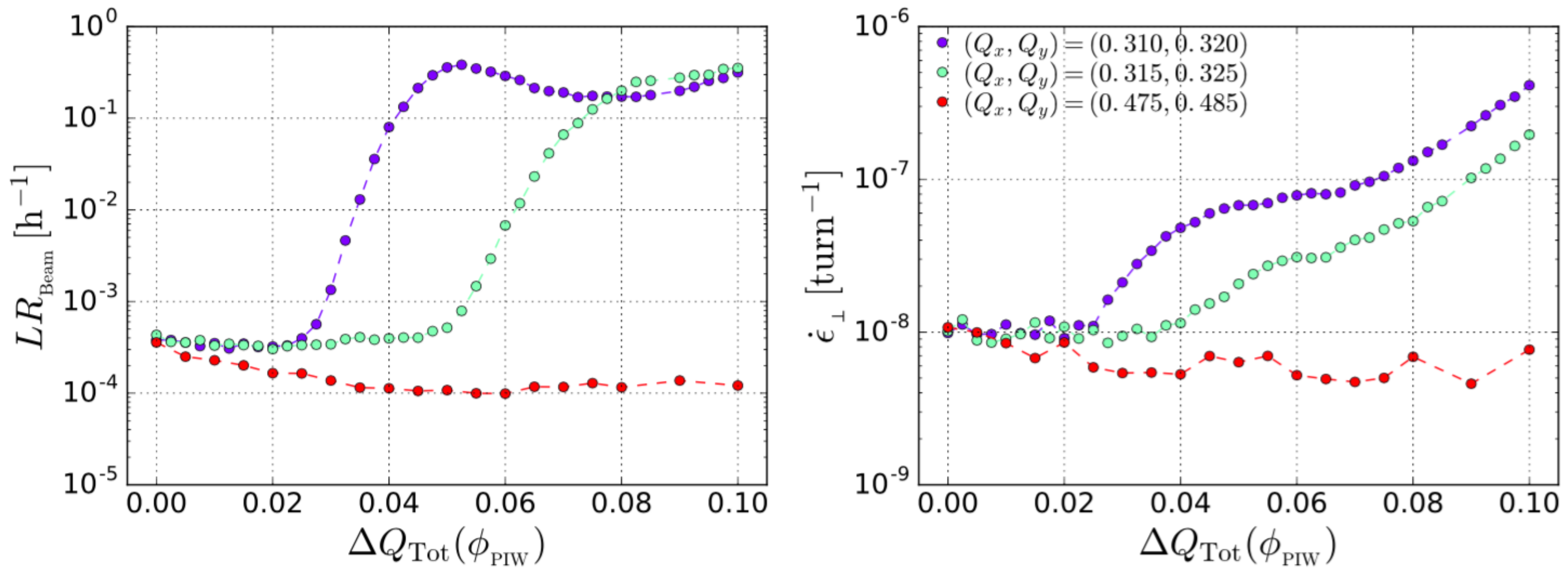
Explore limitations for the different beam-beam cases
Propose a robust baseline and explore limits of ultimate

- Strong non-linear electromagnetic forces
- First time that hadron colliders experience Important radiation damping

Equilibrium state not easy to predict and consequently the luminosity reach!

Head-on limit: losses and emittance growth

Full crab crossing



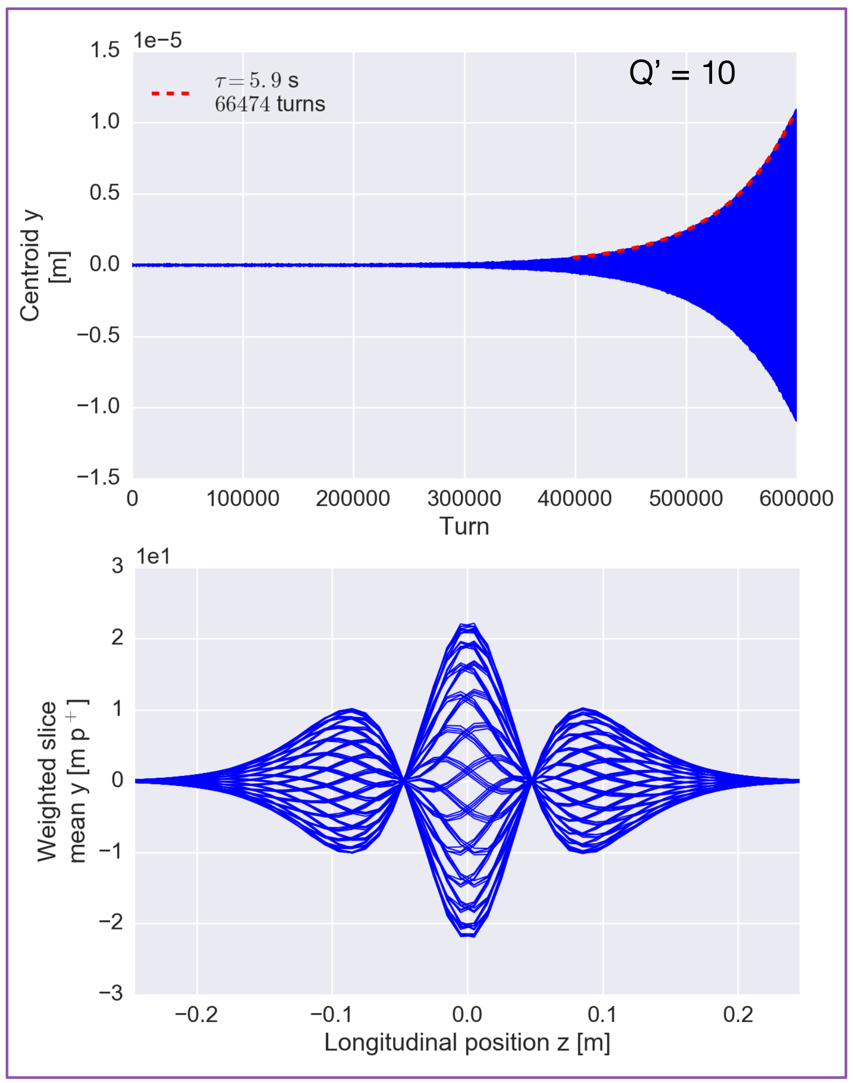
PHD Student EPFL S. Furuseth

- **Baseline scenario (total beam-beam tune shift 0.02) shows no limitations** (confirmed also by LHC measurements and experimental investigations to benchmark models)
- The ultimate beam-beam tune shift of **0.03 considered for the FCC-hh baseline with crab cavities seems within reach but challenging!**
- **Further studies needed to explore possible limitations linked to a larger head-on beam-beam tune shift**

LHC and or SuperKEKB data benchmark fundamental to understand real predictive power of models!

Two beam stability

Higher energy → might result in more violent coherent instabilities
In order to ensure maximum stability at top energy an operational scenario to enhance Landau damping has been integrated in the FCC-hh and HE-LHC designes + benchmark to LHC cases



Landau damping is ensured with a system of approximately 500 octupole magnets at G_{max}=220000 T/m^3

Detuning w. transverse amplitude

$$\Delta Q^i_{x,y} = \Delta Q^i_{x,y}\left(J^i_x, J^i_y\right)$$

Example: *Landau octupoles (LO)*

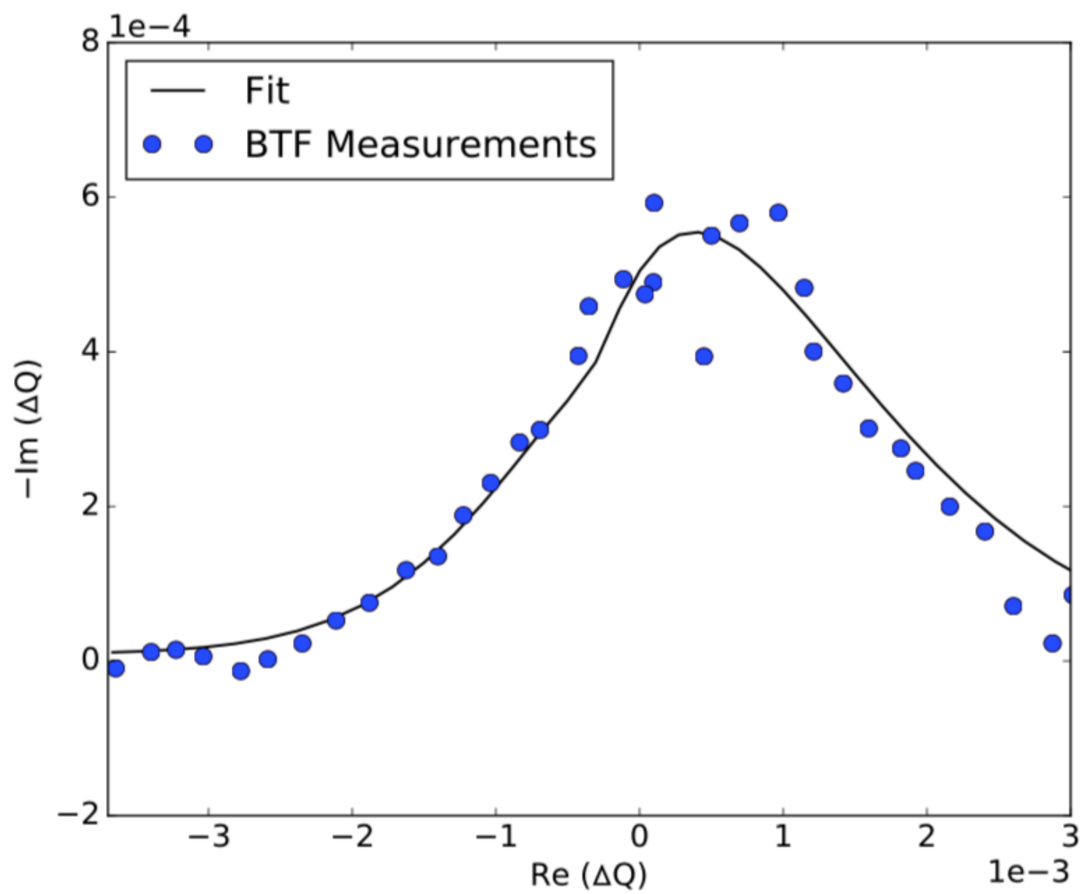
$$\Delta Q^i_x = a_{xx} J^i_x + a_{xy} J^i_y$$
$$\Delta Q^i_y = a_{yy} J^i_y + a_{xy} J^i_x$$

M. Schenk EPFL PHD

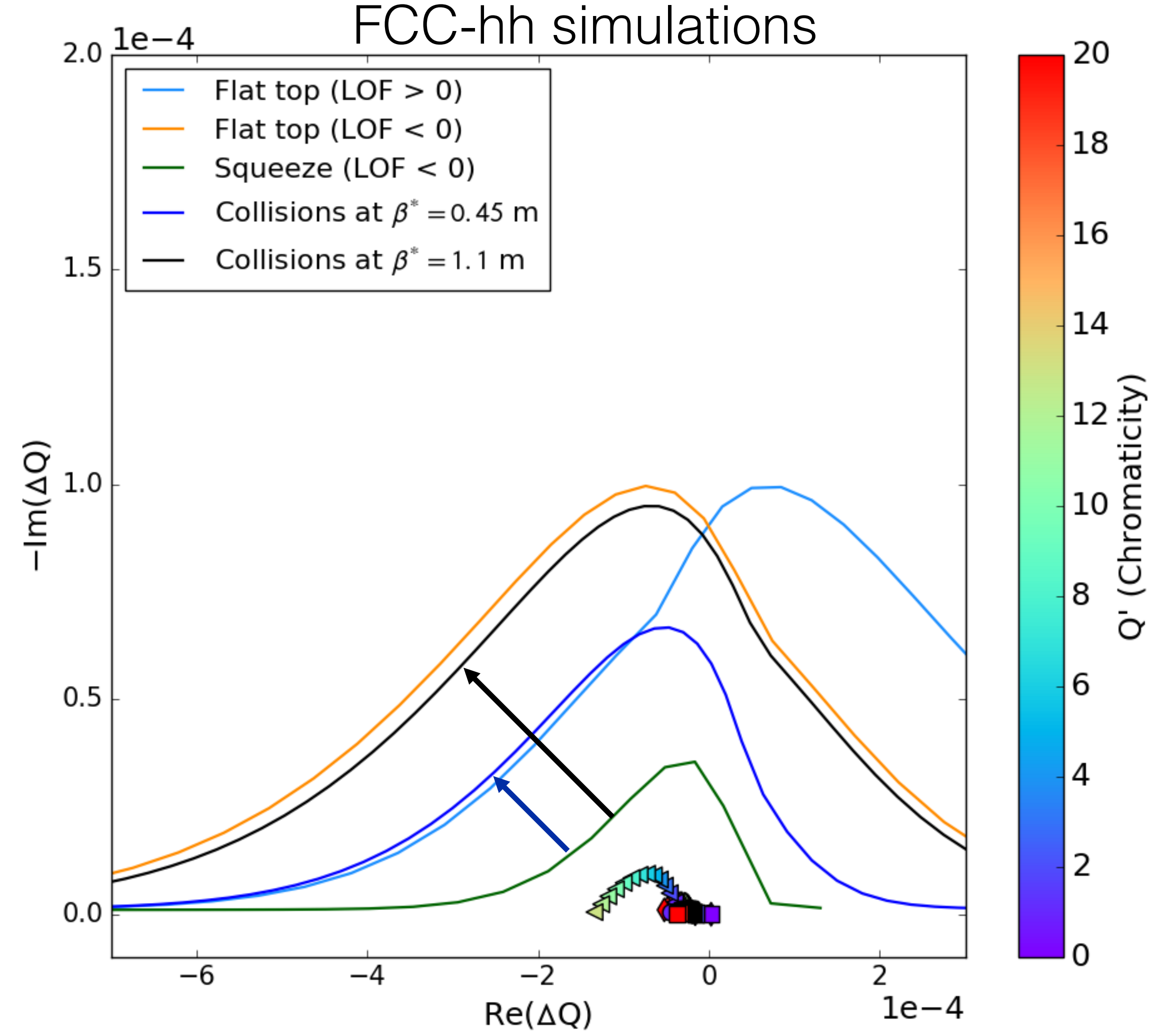
Two beam stability

Continue understanding of models and benchmark to observations from LHC during dedicated machine development experiments

Stable Area of Landau damping
Measurements LHC



Stable Area of Landau damping
FCC-hh simulations



C. Tambasco EPFL PhD

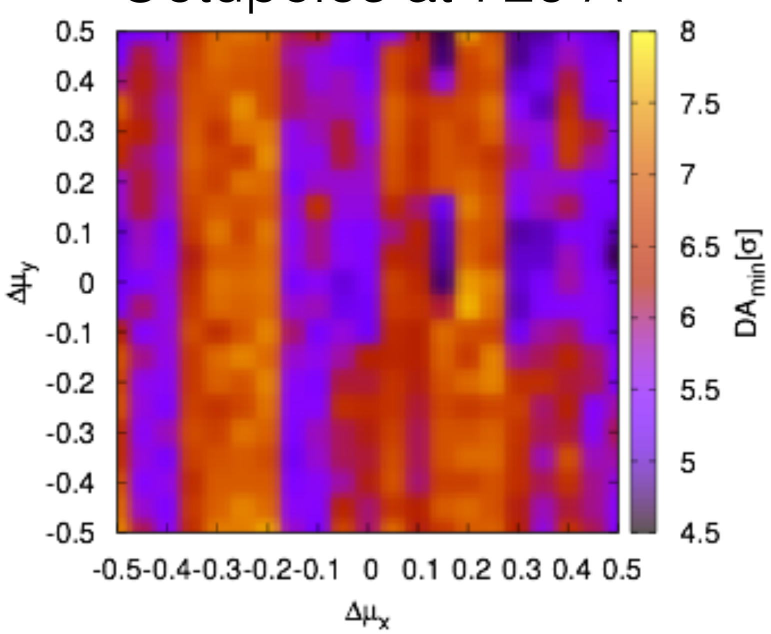
- At higher energies Octupoles are less effective: $\Delta Q^i_{x,y} \propto 1/\gamma^2$
- Coherent instabilities are a major concern for high energy colliders → LHC shows models have factors differences respect to observations
- Continuous investigations are fundamental to improve the understanding

Global compensation of beam-beam effects

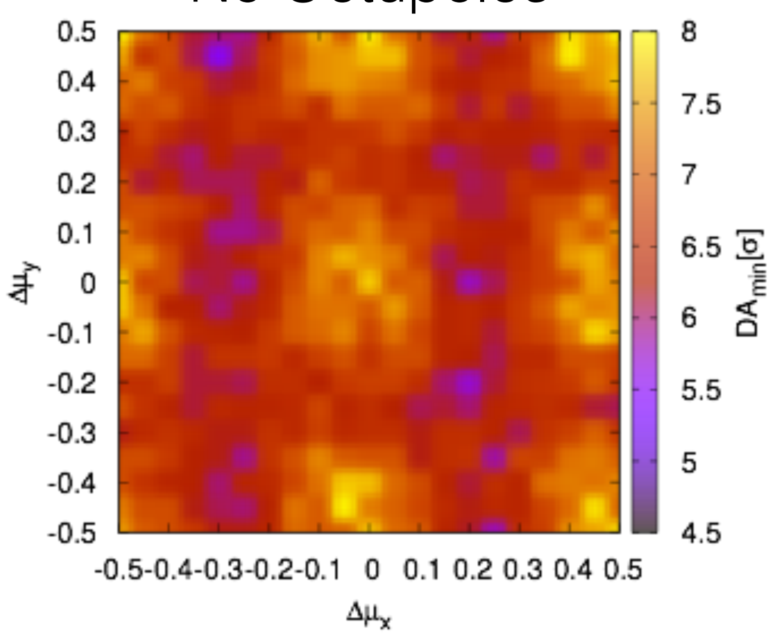
Dynamic aperture is used to design and optimize the long-term stability of particles trajectories
DA = area in real transverse particle space where all particles perform stable trajectories over long time tracking through the machine elements

Arc design and optimization

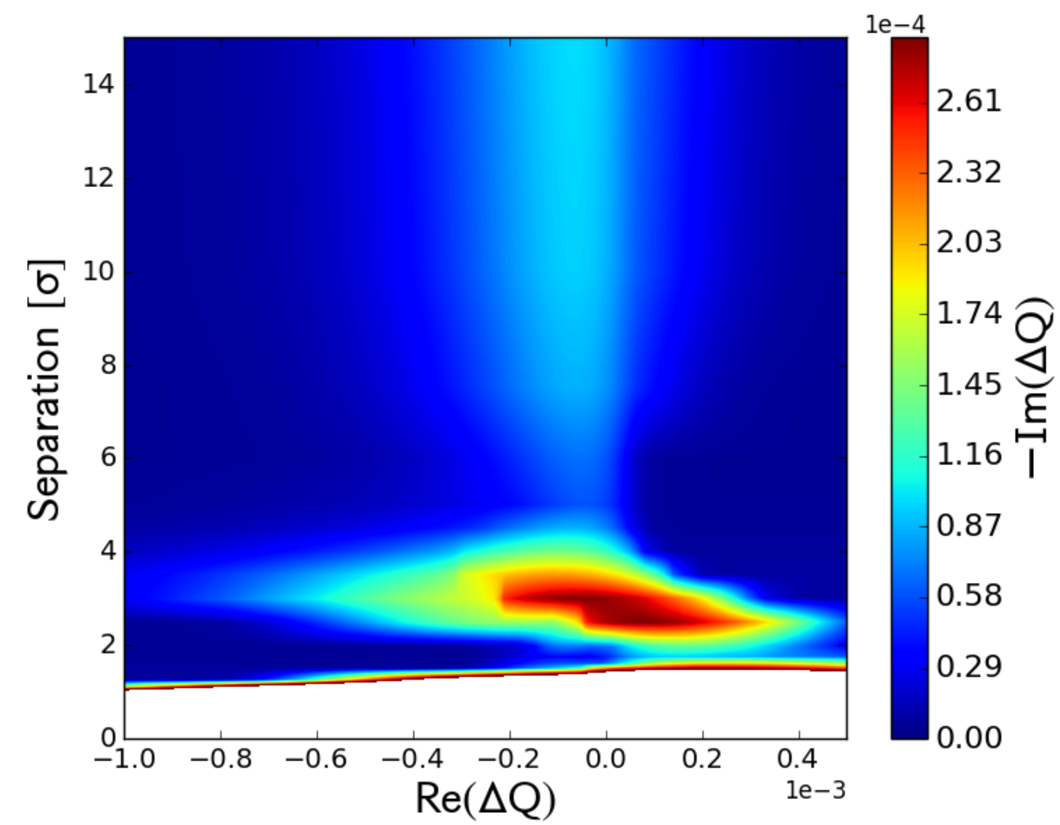
Octupoles at 720 A



No Octupoles



Stability area evolution while colliding

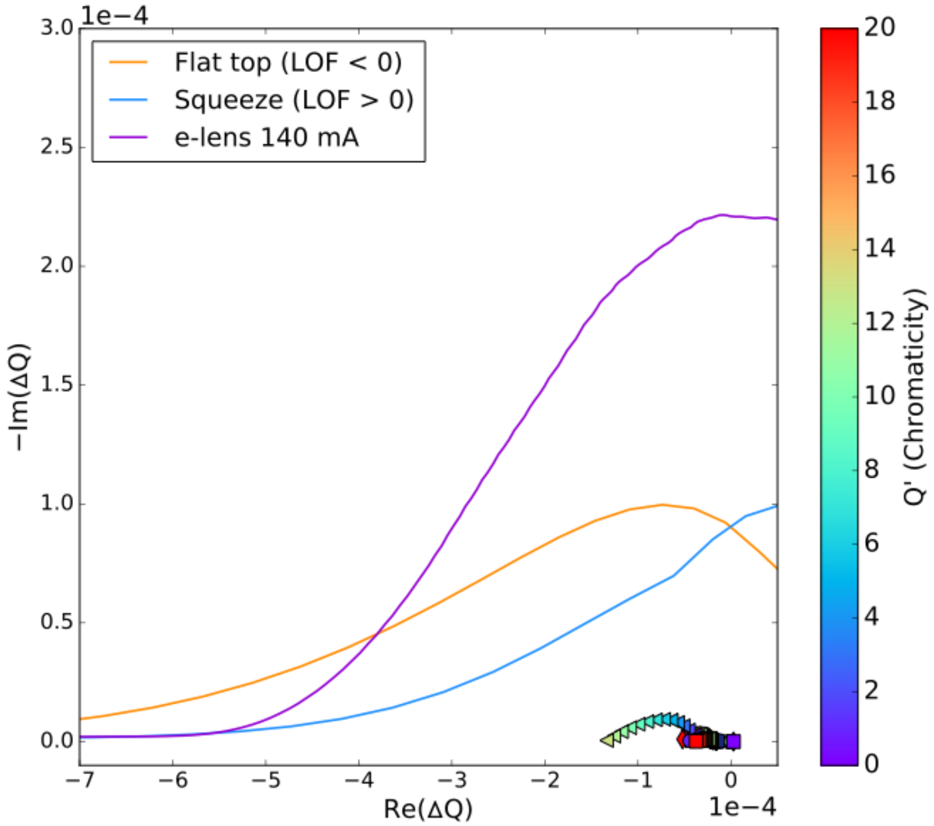


Fully integrate Landau damping devices in the machine design to profit of compensations of effects
J. Shi et al., CERN-ACC-NOTE-2017-036, J. Barranco et al. CERN-ACC-NOTE-2017-0036

Lattice and Beam-Beam optimized together to enhance at a design stage the natural compensation between effects and allow flexibility for boosting performances

Alternative methods are under investigation for Landau damping: Electron Lens

Electron lens [V. Shiltsev et al., 10.1103/PhysRevLett.119.134802]

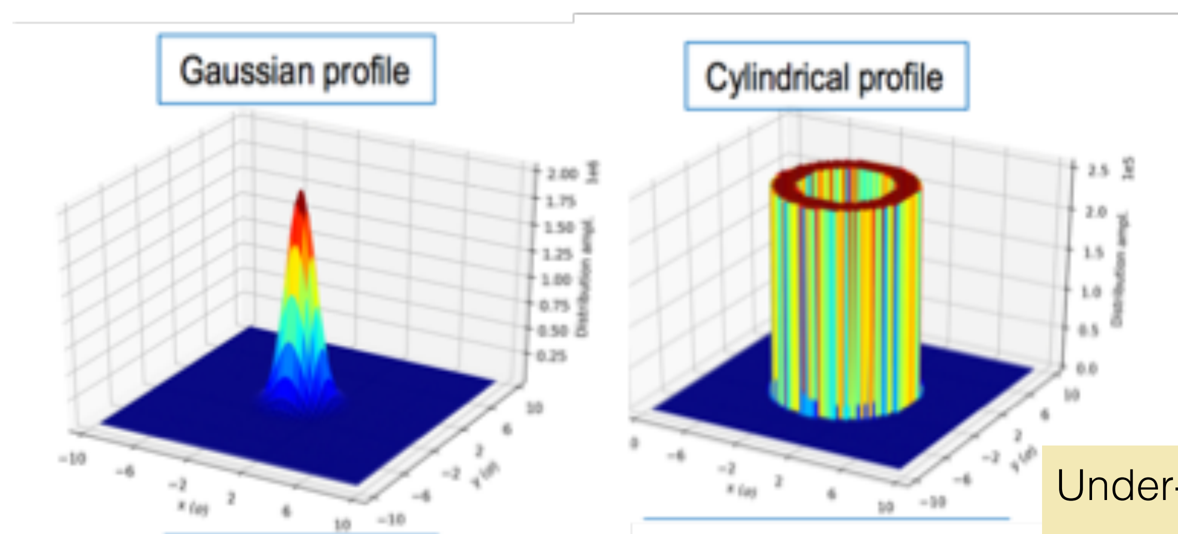


Colliders with higher energies 50 TeV Beams

- Potentially leads to more violent instabilities
- Landau Octupoles less effective due to lower transverse beam size and beams rigidity

$$\Delta Q^{i}_{x,y} \propto 1/\gamma^2$$

An electron beam acting on the protons can provide a very large detuning with amplitude → Landau damping



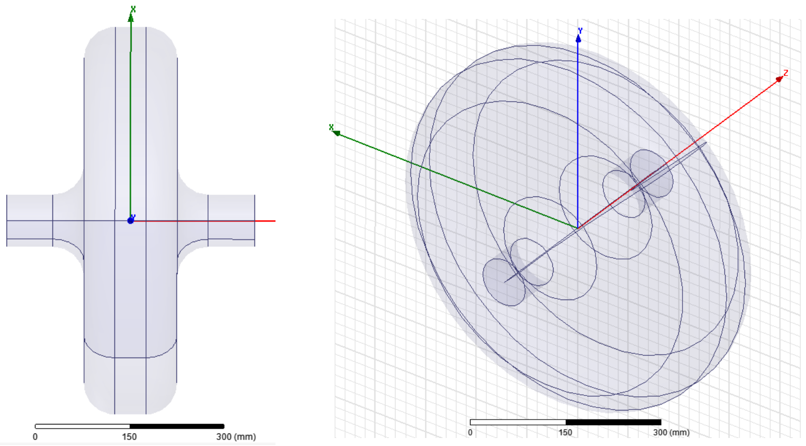
Under-graduated students EPFL
F. Barantani
D. Machain Riviera

Core particles affected (more particles) → more effective
Independent of the beam energy
Interesting device:

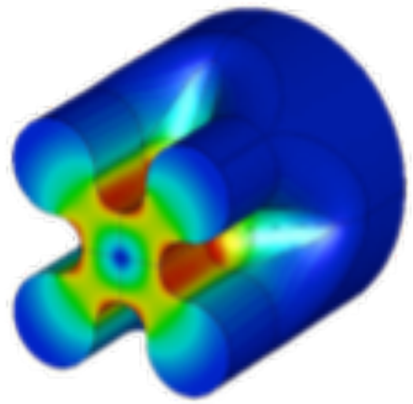
1. Possible use in collimation of tail particles → reduced background and losses
2. Can compensate beam-beam head-on effects → higher limit → higher luminosity

Alternatives for Landau damping: RF quadrupoles

Proposal by Alexej Grudiev, Phys. Rev. ST Accelerators and Beams **17**, 011001, 2014.

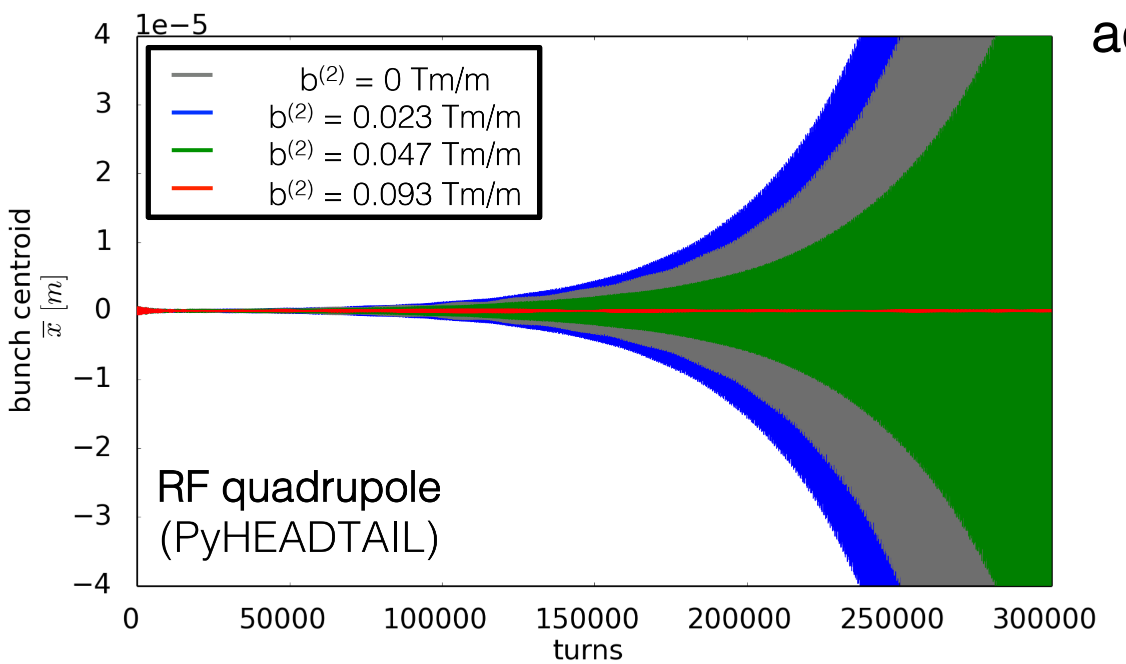


Example: *Pillbox cavity*



An RF quadrupole introduces a betatron tune spread to 'damp' transverse collective instabilities via Landau damping

Landau Octupole Detuning w. transverse amplitude	RF-Quadrupole Detuning w. longitudinal amplitude
$\Delta Q^i_{x,y} = \Delta Q^i_{x,y}\left(J^i_x, J^i_y\right)$	$\Delta Q^i_{x,y} = \Delta Q^i_{x,y}\left(J^i_z\right)$



An RF quadrupole is equally able to cure the instability by introducing a large enough betatron tune spread. And it provides additional advantage for potential future high energy accelerators

- On the energy ramp, the detuning from LO is affected by both adiabatic damping and increased beam rigidity, i.e.

$$\Delta Q^i_{x,y} \propto 1/\gamma^2$$

- An RF quadrupole is only affected by the increased beam rigidity, i.e.

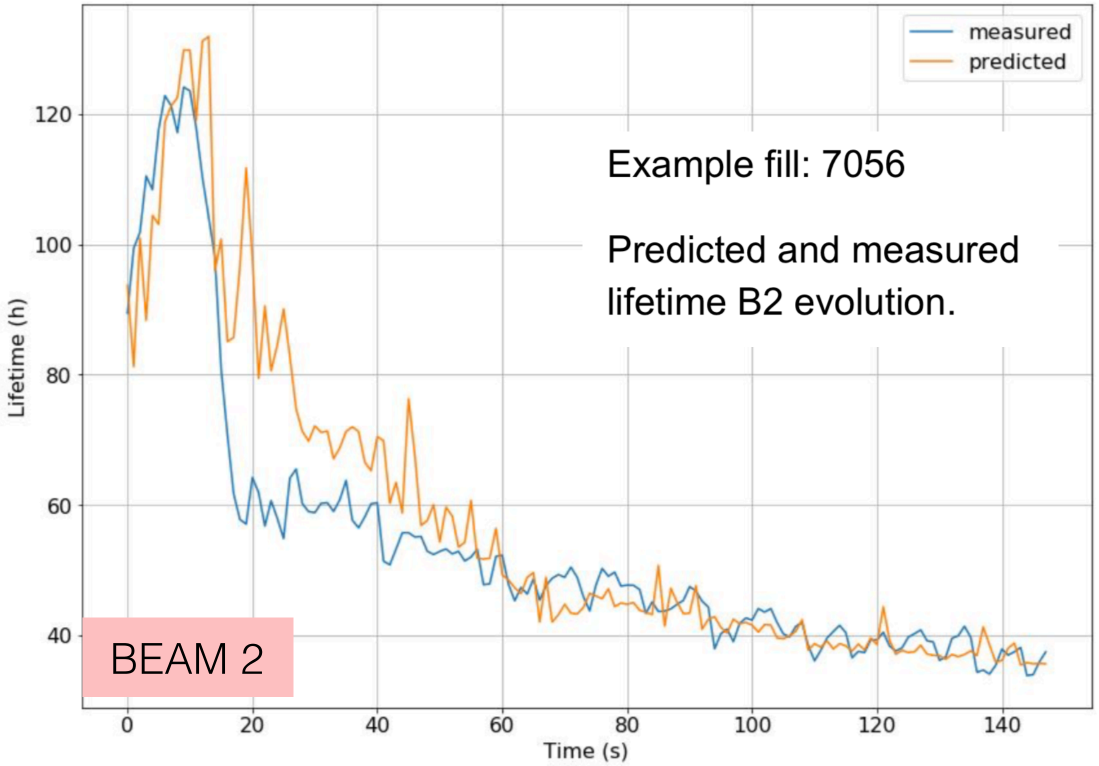
$$\Delta Q^i_{x,y} \propto 1/\gamma$$

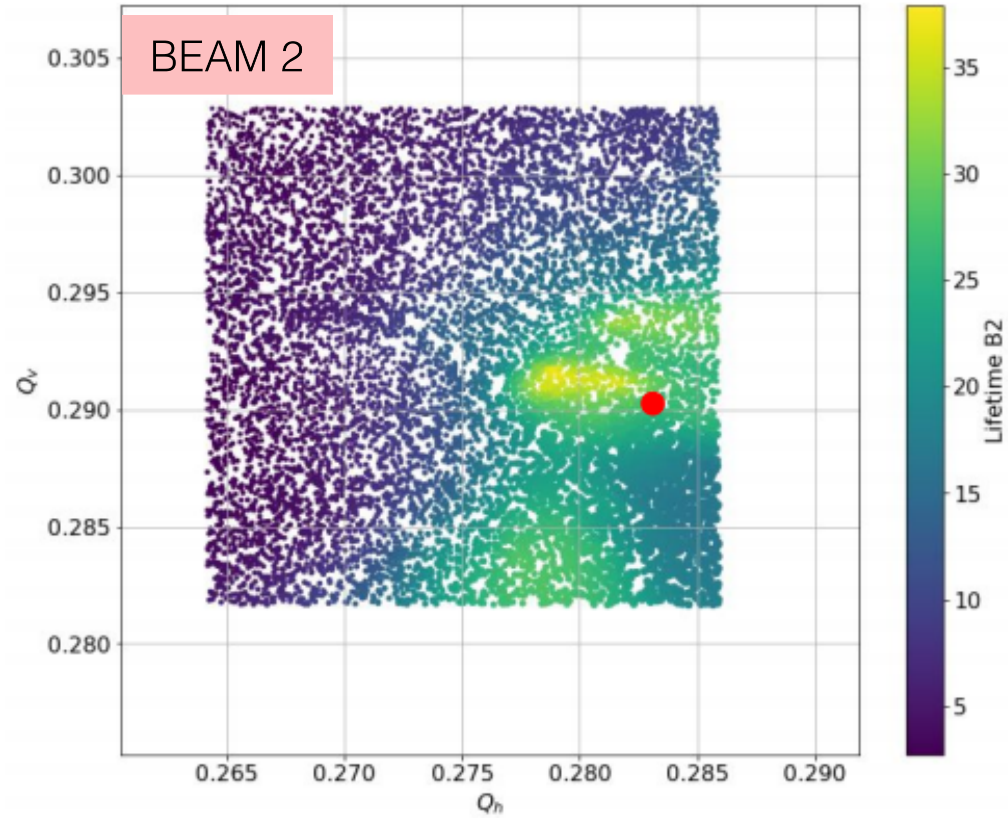
EPFL PHD Thesis 2019 M. Schenk

Machine Learning applied to the accelerators

Preliminary results

- Evaluated various machine learning models
  best performance with Gradient Boosted Decision Trees
- Promising study
  - Model predicts optimum working point *(red)* in agreement with MD data
  - Trends in beam lifetime vs. time predicted correctly





L. Coyle EPFL master project 2018

Machine Learning applied to the accelerators

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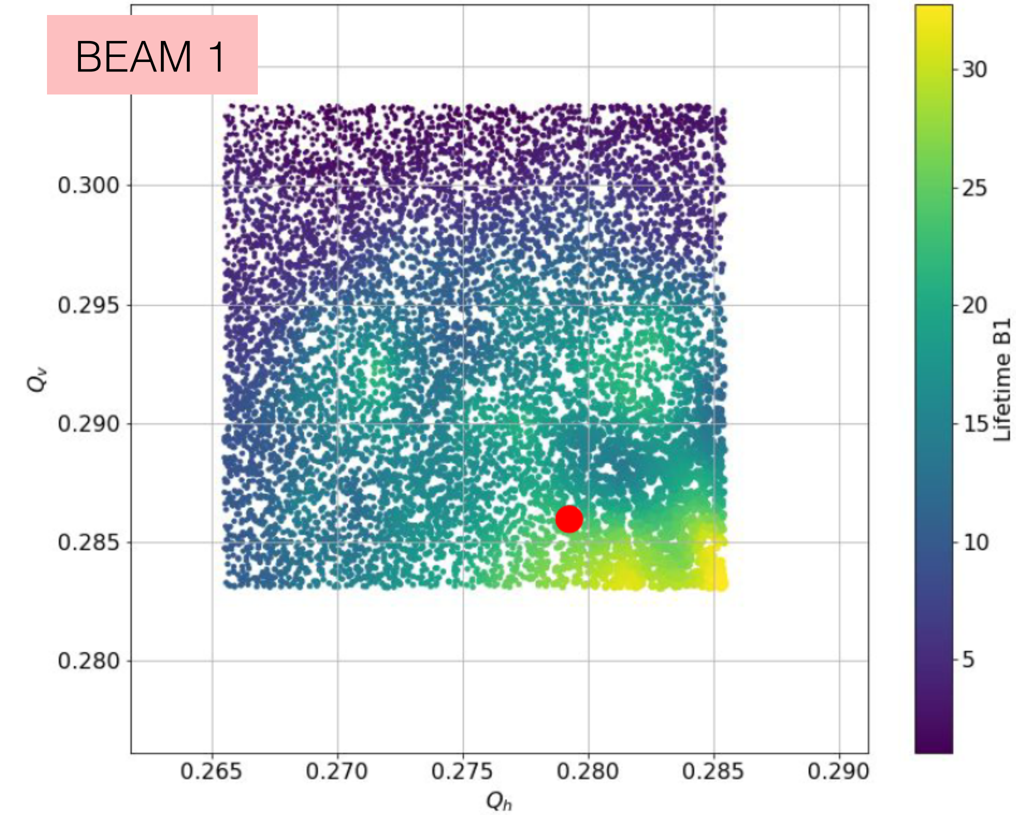
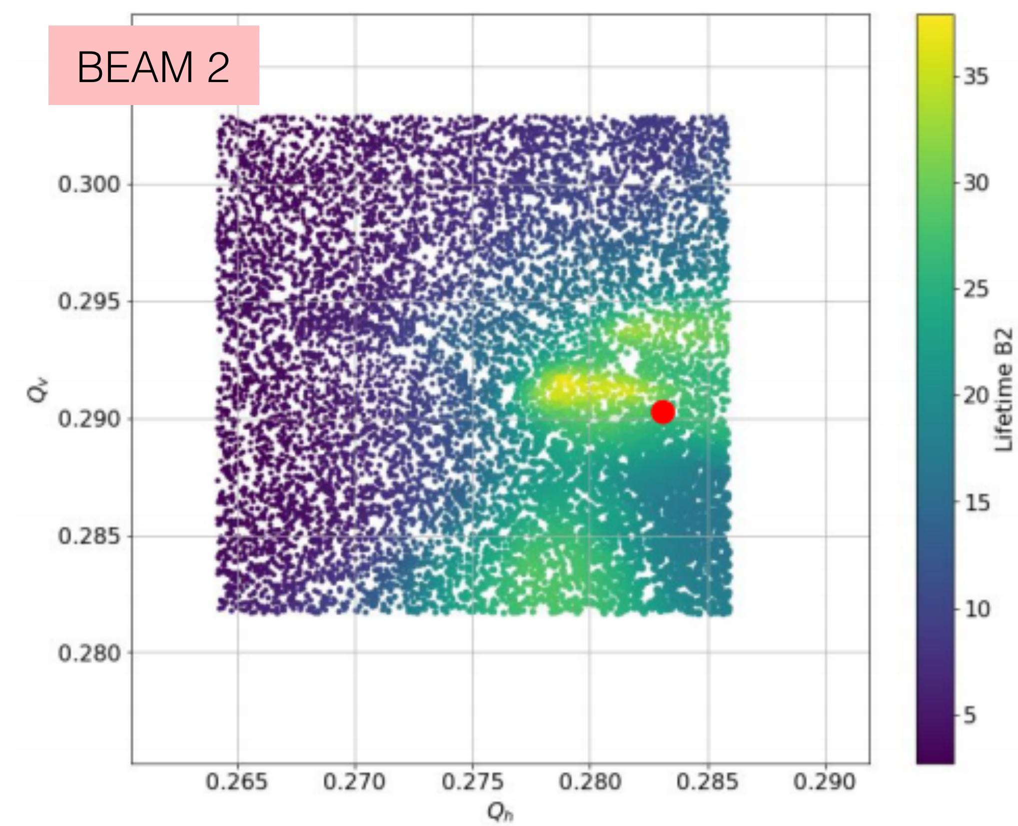
  Boosted Decision Trees
- Promising study
  - Model predicts optimum working point *(red)* in agreement with MD data
  - Trends in beam lifetime vs. time predicted correctly
- Beams 1 and 2 behave differently
- Clean, high-quality data is important
  - Fake correlations between the two beams
  - Differences between available measurement devices
  - Acquired clean data set during dedicated MD
- Collective effects can be relevant:
  impedance, electron-cloud, etc.

Feedback to physics models the informations acquired
Explore the use of ML in designing accelerators





PACMAN PROJECT with SDSC-PSI-EPFL

Next

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FCC-ee collider studies

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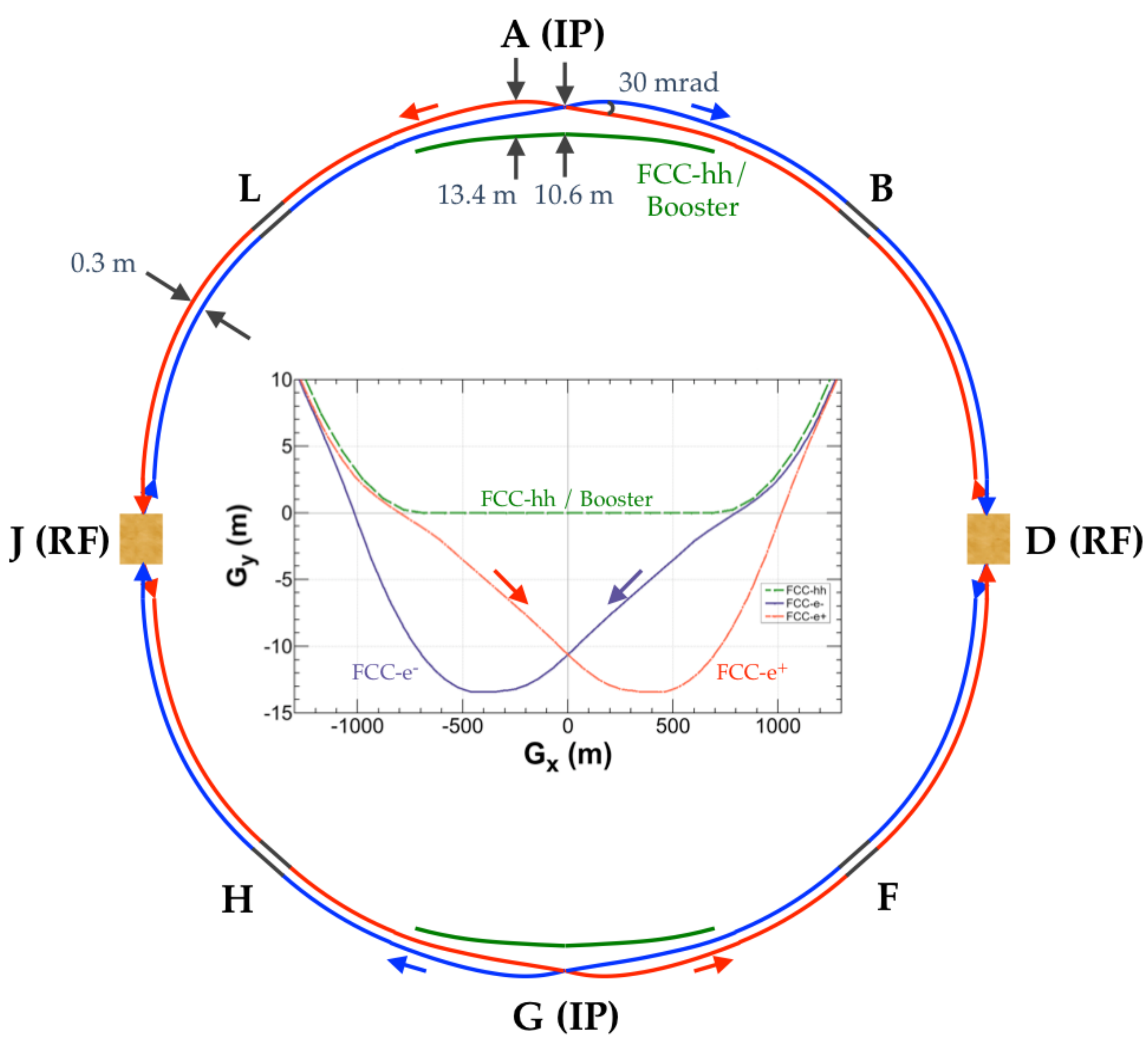
Future Studies

FCC-ee



- Extend physics models of the accelerator to account for multiple IPs with strong beam-beam effects

→ Far more challenging than FCC-hh

- Model the loss of synchrotron radiation and IP beam-beam interactions

→ Optics and interaction regions are coupled

- Propose a robust design and tools for beam dynamics studies

- Benchmark models to existing machines SUPERKEKB and DAFNE as a test-facility

- Define the limits and predictive power of models

- Gain knowledge in the design of lepton colliders

Summary

- In the CHART I funding period a big effort has been made to define a robust baseline scenario for both FCC hadron colliders options based on beam-beam effects and Landau damping studies → all results are summarized in the CDR and studies documented in a longer version of the CDR in preparation.
- **Alternative scenarios** have been explored to allow for flexibility, higher performances making use of newer tools for the design
- **Alternative solutions for Landau damping: RF quads and electron lenses** have shown some potential of use and will be explored further
- **Machine learning technique** are under study to be used for collider operation and design, hoping for bringing back input to present models
- **The continuous benchmark to LHC data** has shown to useful to the LHC (with direct improvement of the understanding of the collider) and fundamental to test the predictive power of our present models
- **In the future: more challenging studies are foreseen with the goal to have a complete study of a circular lepton collider option beyond the present CDR: develop the models and tools needed for the design of multiple Ips, Multi turns effects dynamics**

Summary

Gain experience and knowledge in circular lepton colliders design,

training the next generation of accelerator physicists

Thank you for your attention!