Muon Collider Feasibility Studies

D. Amorim, D. Schulte, E. Metral, M. Seidel, X. Buffat, T. Pieloni

Acknowledgements: Muon collider collaboration

CHART Meeting 11th October 2023, PSI

Why Muon Collider?

- Muons 200 heavier than electrons

  → SR losses negligibles respect to electrons

$$P_{synch} \propto \frac{1}{\rho^2}\frac{E^4}{m^4}$$

- First proposal in 1960 (Tikhonin et Budker)
- Between 2011-2016, le Muon Accelerator Program (MAP) in US has studied the feasibility of a series of colliders at 1.5 TeV, 3 TeV et 6 TeV
- In 2021, an international collaboration **(IMCC)** has been established to study a possible muon collider with a ECM of **3 TeV, followed by a collider with ECM 10 TeV**
- The accelerator community in US has shown strong interest in the study (Snowmass et P5)

Muon Collider Physics Pillars

The muon collider combines pp and ee advantages:

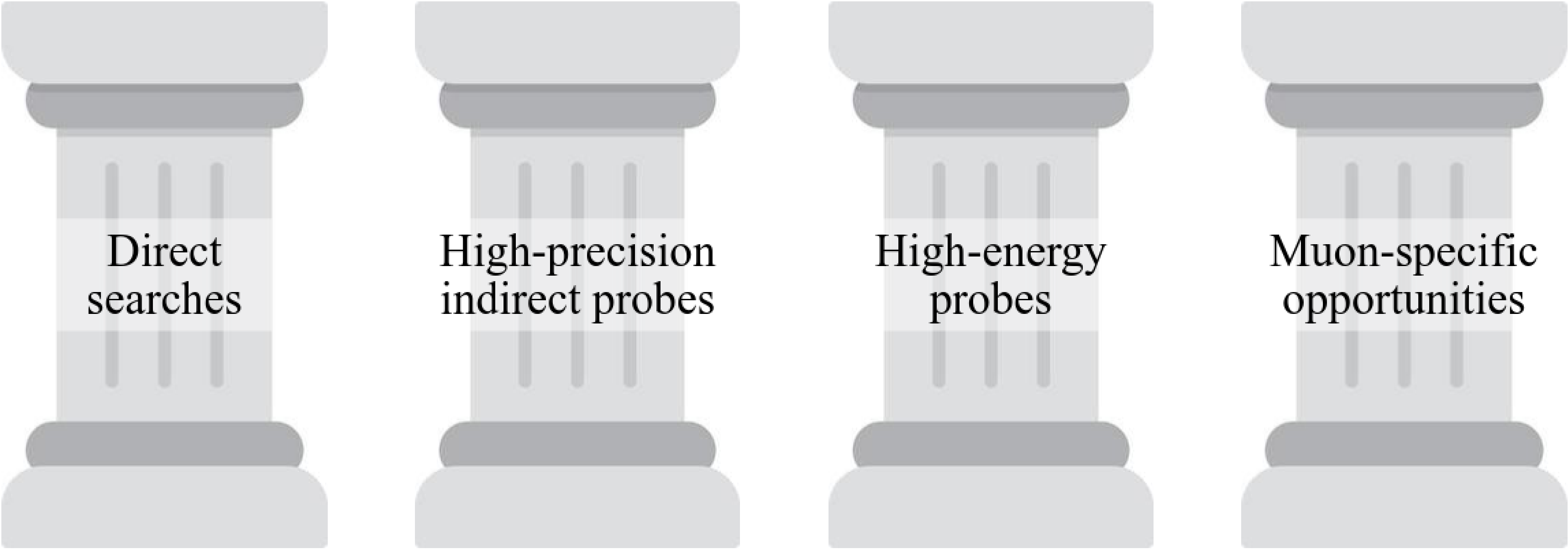
- High available energy for new heavy particles production
- High available statistics for precise measurements (and no QCD bck)

A. Wulzer, MuC Design Meeting (28/11/2022)

Furthermore:

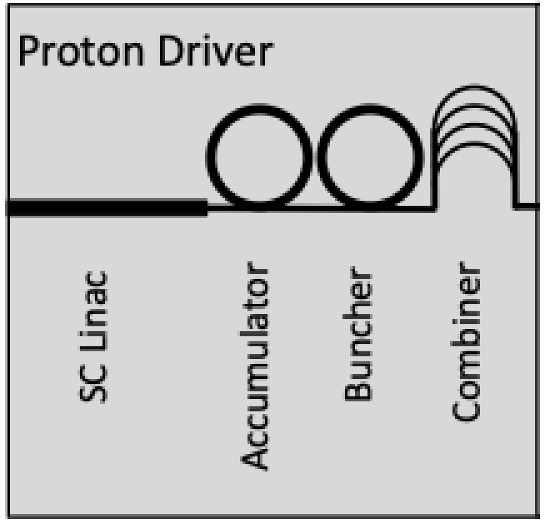
- Can measure processes of very high energy
- Collides muons, for the first time

+ Neutrino Physics



Muon Lifetime and accelerator design

- To maximise Luminosity one needs bunches wth high intensities (10^{13} muons/bunch) and small transverse beam sizes
- Muon lifetime at rest is $\boldsymbol{\tau_0 = 2.2\ \mu s}$ **: it is fundamental to accelerate the bunches of muons and anti-muons as fast as possible**, preserving their properties (i.e. transverse size).
- At 5 TeV, the lifetime $\boldsymbol{\tau = \gamma \cdot \tau_0} = 47323 \cdot 2.2\ \mu s = \boldsymbol{104\ ms}$



High power proton beam

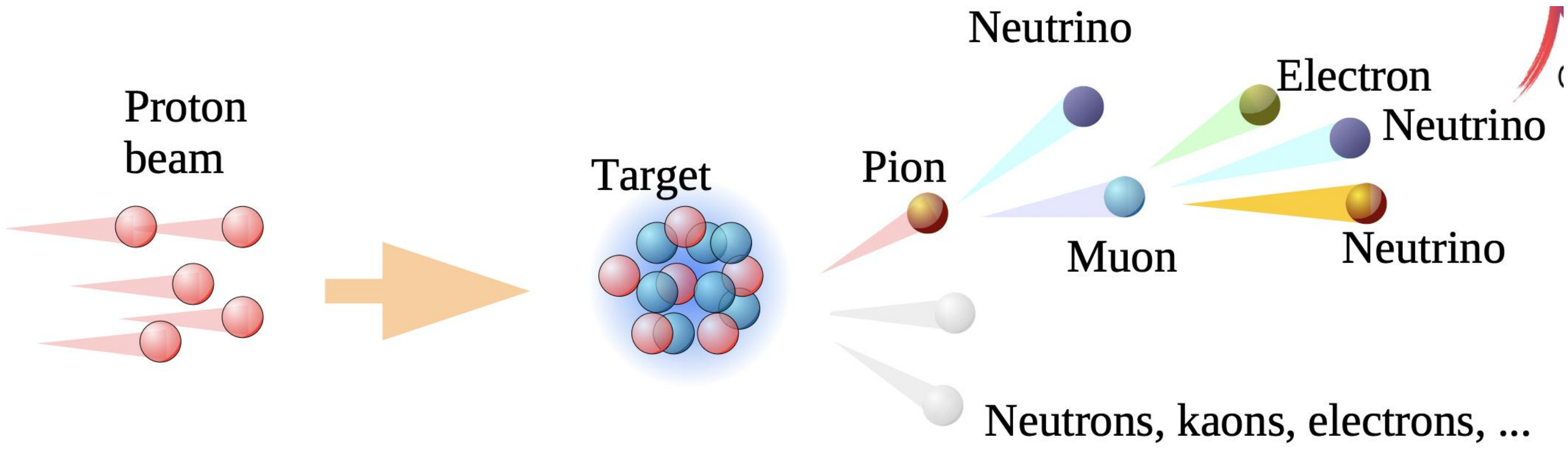
Production of muons and anti-muons and collection

Ionization Cooling

Acceleration

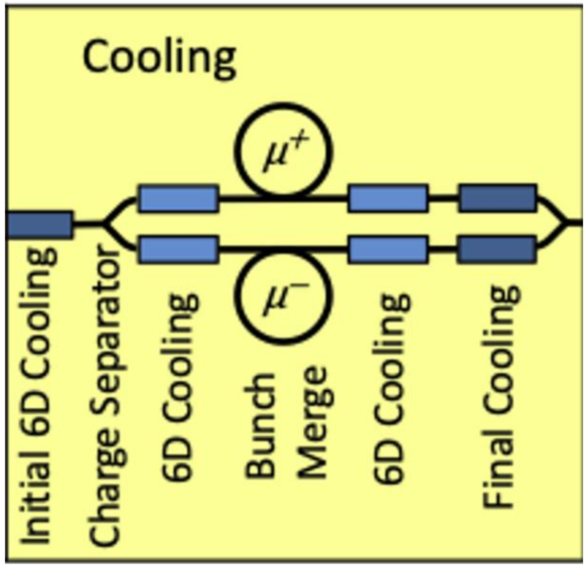
Collisions

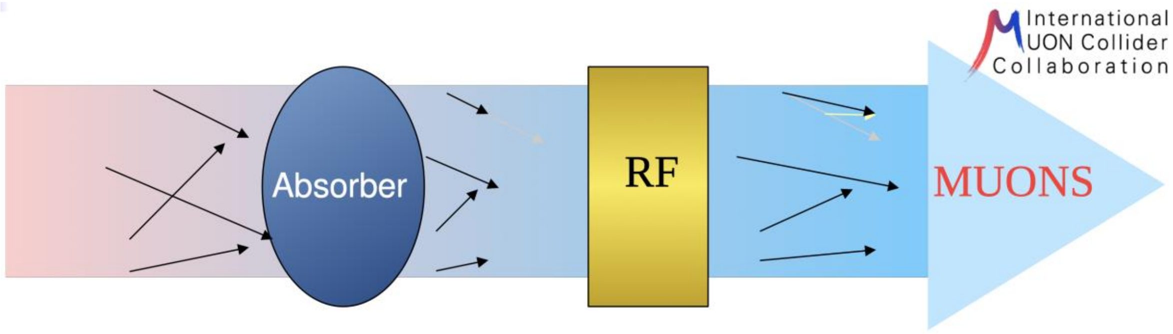
Muon production



- Muons produced by putting protons onto target
- Pions come out
- Pions decay radioactively to muons
- Enables an intense muon source

Muon Ionization Cooling

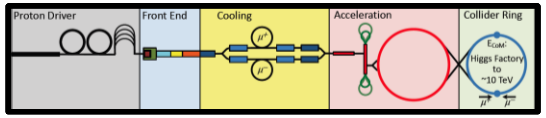




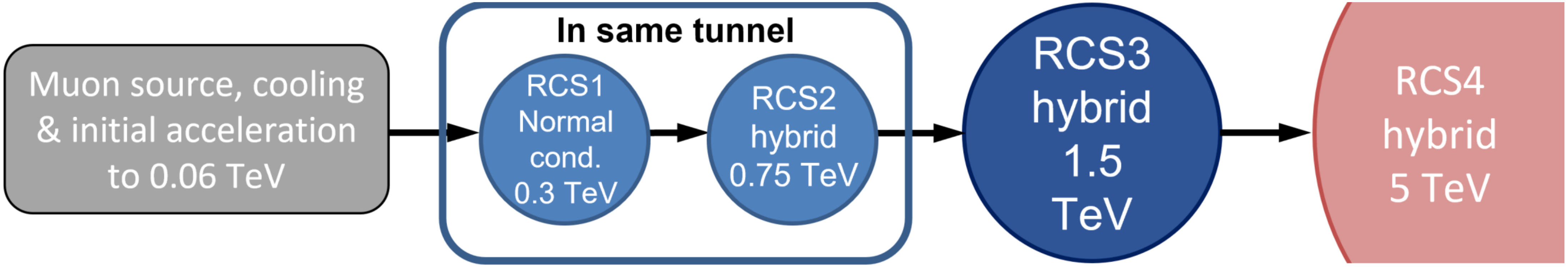
- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect

PhD Student @EPFL starting 1st November Josehine Potdevin

The high-energy complex



- Chain of rapid cycling synchrotrons, counter-rotating μ+/μ- beams
  → 60 GeV → 314 GeV → 750 GeV → 1.5 TeV → 5 TeV



- Hybrid RCSs have interleaved normal conducting (NC) and superconducting (SC) magnets.
- To go to 5 TeV, we have not one but four RCS:
  - Tradeoff between the ring size, survival rate, acceleration speed (at low energy, the ring can be smaller and thus we can accelerate faster).

Beam Collective effects Studies

- The muon bunches should have high intensity to provide the designed luminosity
  - **O(10^{13}) particles** per bunch **at the start of the acceleration chain**, **O(10^{12}) in the collider**
  - Intensities will decay in time due to the muon disintegration

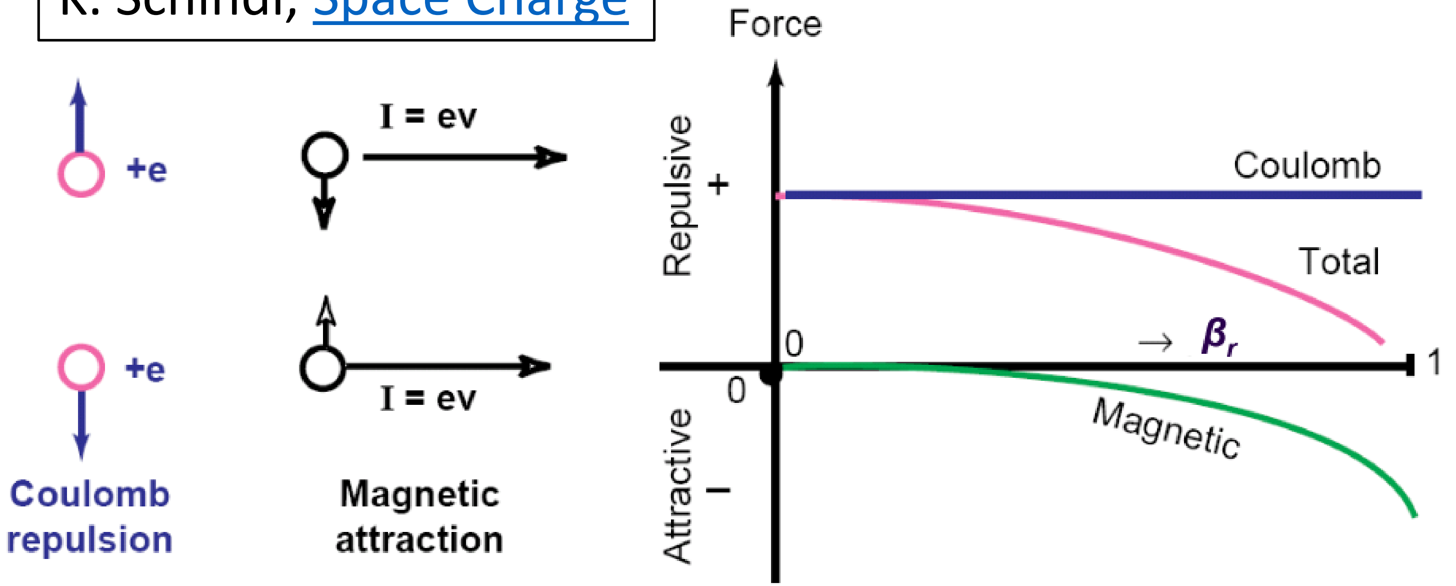
- Particles of each bunch will interact electromagnetically on close particles and with the enviroment.
- Such interactions can perturbe the particle and bunch motion→ intensity limitations have to be identified!
  - Increase in transverse beam size, muon losses, heat load of the equipment…
- Multiple effects can occur and need carefull considerations
  - Space charge effects
  - Impedance
  - Beam-beam interactions
  - Electron clouds

Space Charge

- When collected into packages the muons will experience the **repulsive Coulomb** force

- When in motion an **attractive magnetic** force will develop proportional to the relativistic β
  - For β=1 the attractive magnetic force compensates fully the coulomb repulsive one

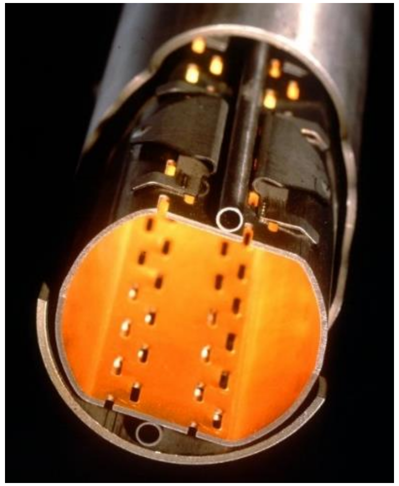
K. Schindl, Space Charge



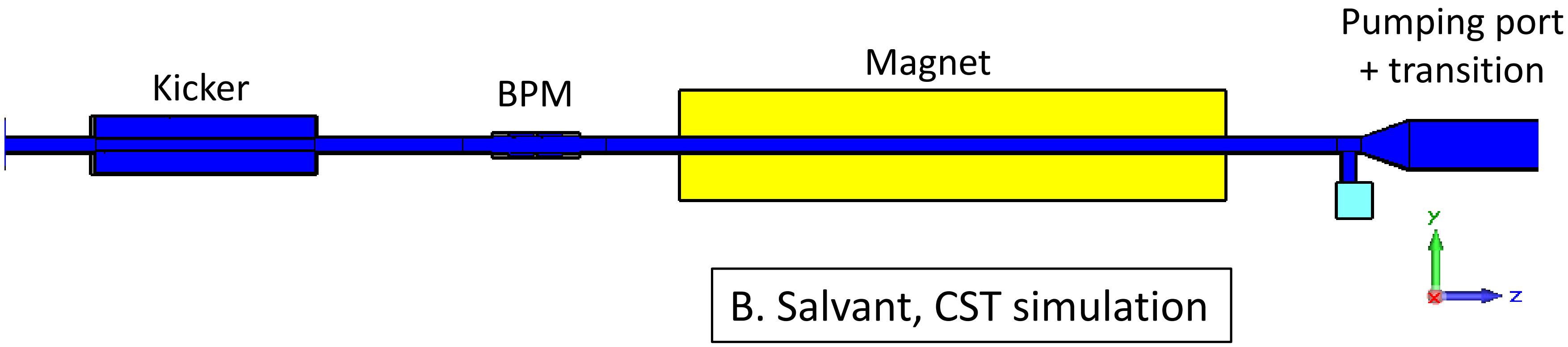
- For intermediate β the total force will be always repulsive and it's strenght depends on the bunch intensity and transverse distribution (very non-linear force)

Machine Impedance

- Muon bunches will interact electro-magnetically with the enviroment
- The machine impedance characterises such effects

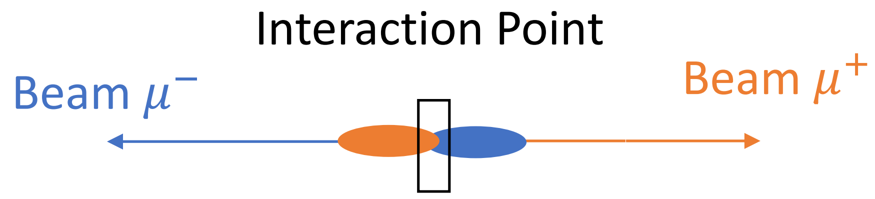


Chambre à vide LHC



- Such wake fields can perturb the particle motion in within the bunch and on the following ones
- These effects have to be reduced and optimized at the design stage of the equipments

Beam-beam interactions



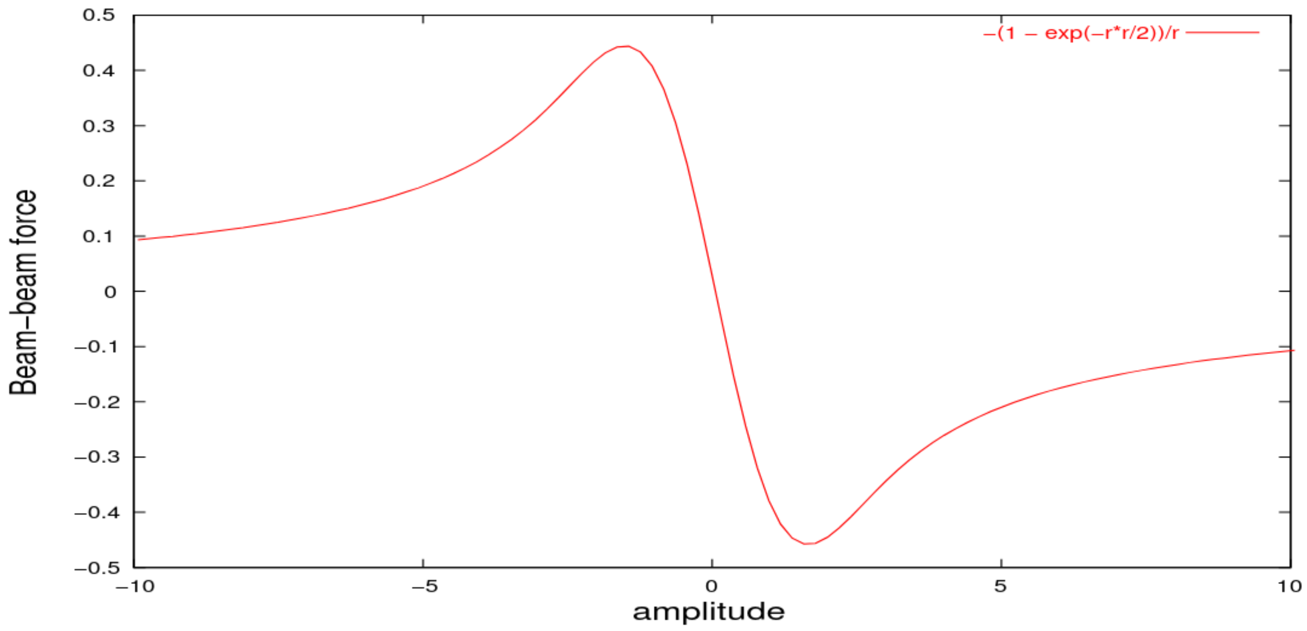


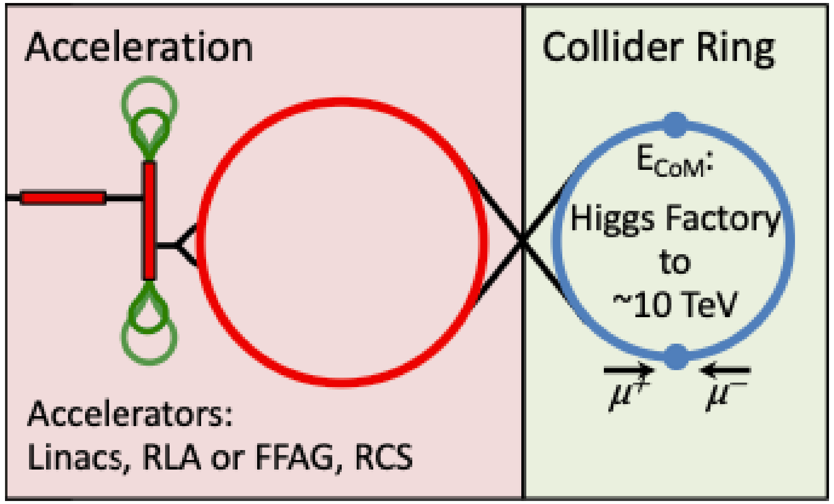
Fig. 1: Beam–beam force for round beams. Force in arbitrary units, amplitude in units of r.m.s. beam size

- Each bunch is a collection of charges →will generate an electromagnetic field
- When sharing a common beam pipe, as in IP the field of one beam will perturb the motion of the other and viceversa.
- It is a non-linear effect and it depends on the bunch intensity and transverse distributions

First studies for the Muon Collider

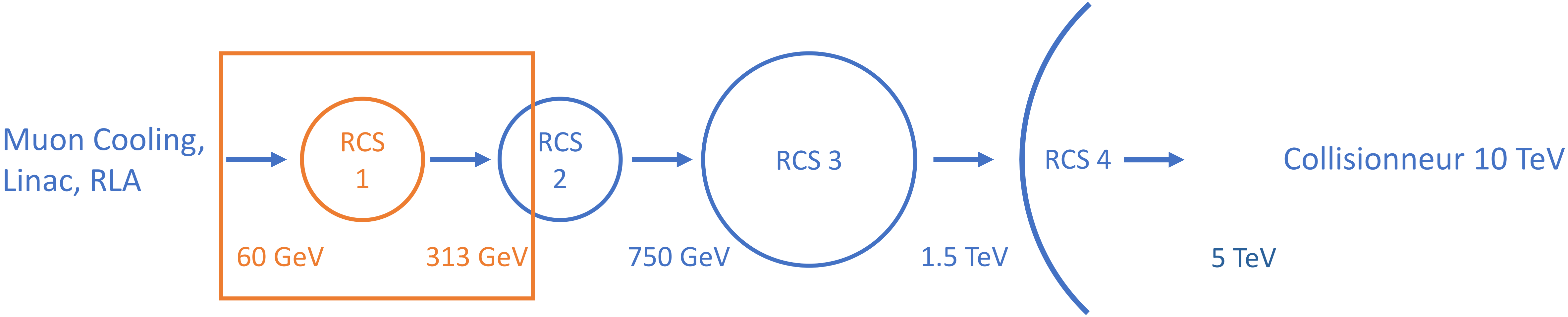
- Preliminary studies have focused on the **high energy collider of 10 TeV**

- Space Charge : in this part of the accelerator chain the particle energies are very high and the total force acting on the particles is negligible
  - This effect will be fundamental for the proton driver and the low energy chain
- Electron cloud : collisions will occur between single bunches in the collider→ no build-up occurs
- Beam Impedance
- **Beam-beam interactions**



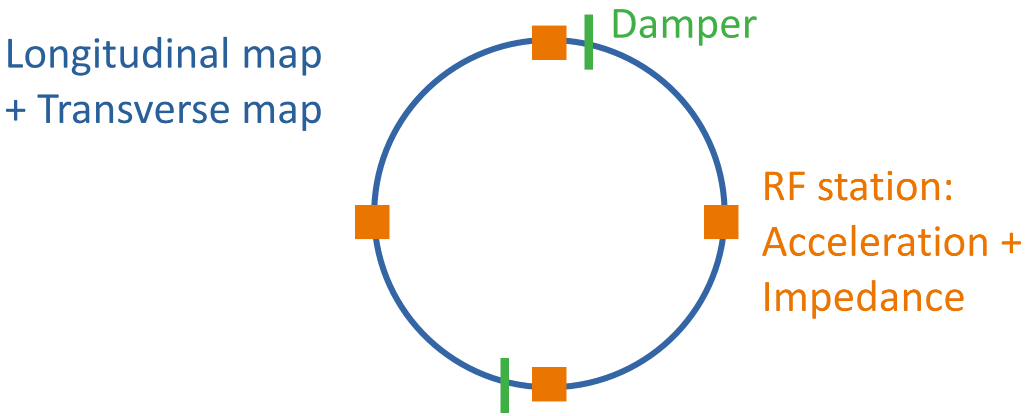
Impedance model and beam stability studies

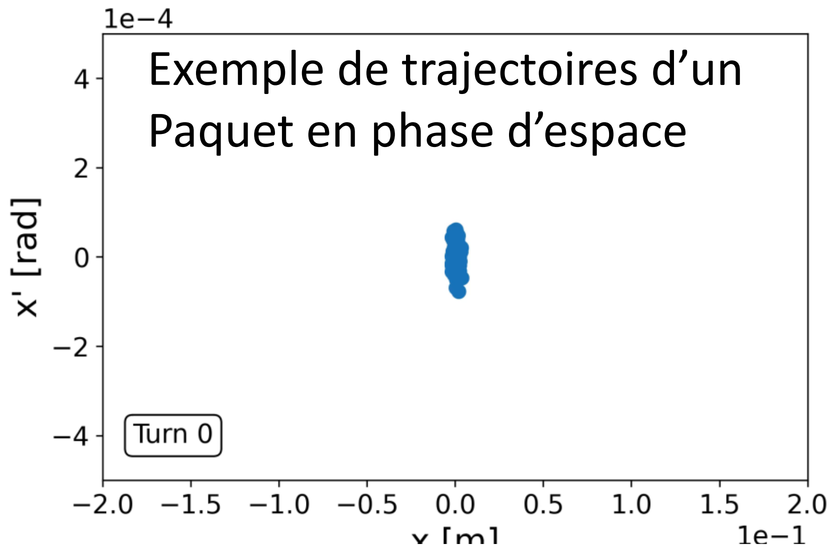
- RCS 1: $C = 5990\ m$, $E_{inj} = 63\ GeV$, $E_{ext} = 313\ GeV$, $N_b = 2.6 \cdot 10^{12}\ \mu^{+/-}$
  - To preserve 90 % of muons, the gain per turn in energy should be **of 14.7 GeV**. Beams are accelerated in 12 tours to reach extraction energy
  - O(700) superconducting accelerating cavities required (TESLA type with gradient of 30 MV/m
- The cavities impedance are one of the main contribution
- The High Order Modes from the cavities (studies from Tesla) are used for a first estimate of the impedance model

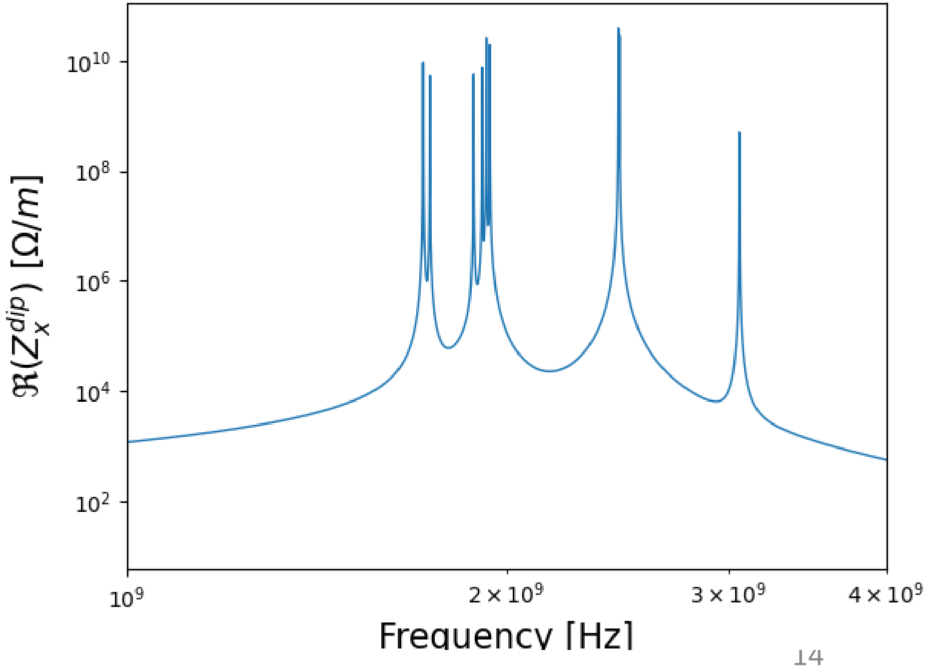


Impedance model and beam stability studies

- With the impedance model as it is → tracking simulations of particles done using PyHEADTAIL
  - Cavities are distributed over 32 RF stations
- The code can include multiple effects (Impedances, feedbacks, electron cloud…)





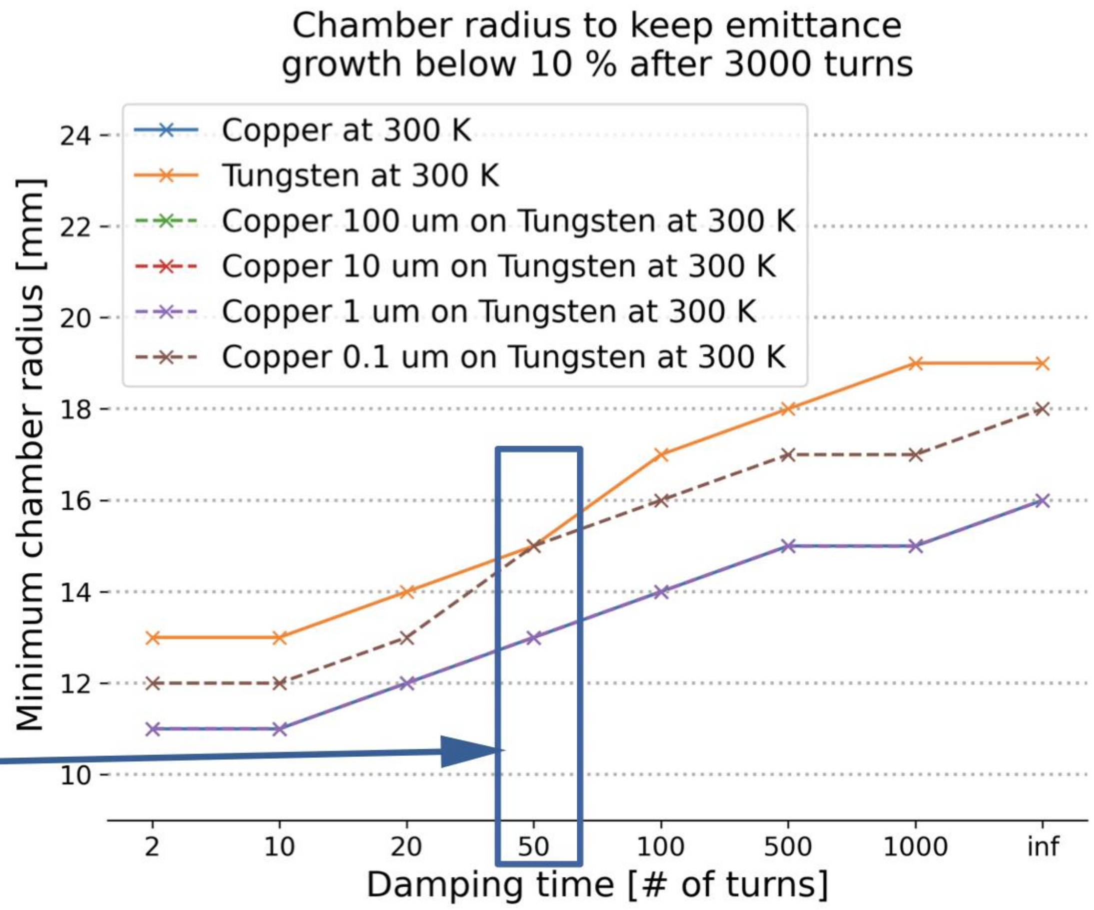


Vacuum Chamber Impedance and stability Studies

- Find Minimum chanber aperture which ensures transverse stability
- Investigate realistic cases for chamber materials:
  - Tungsten shield with copper coating layer (assume 300K)
  - Thicker copper coatings → find lower limit

- Lifetime at 5 TeV: 104 ms → 3100 turns in the 10 km ring
- **Copper coatings > 1μm perform as well as pure copper**
  - Minimum chamber radius below 20 mm for all damper settings

With copper coated tungsten and 50-turn damper: 13 mm radius



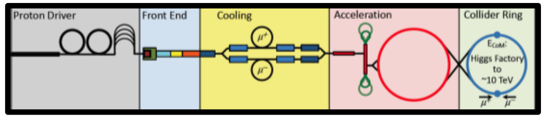
Conclusions

- The Project has started!
- A first model of the machine impedances for the RCSs exist and stability studies on-going:
  - Tools are in place
  - First Impedance Model for the 5TeV RCS → Collider
    - HOM from the Accelerating cavities (Tesla type)
    - Beam chamber material and transverse dimension studies
    - Beam-beam effects at collision
    - Extend the studies for the collider and for the other RCSs
- 1st Nov EPFL PhD Student Josephine will start the investigation of the beam dynamics and stability in the Muon cooling system
  - Space Charge (lower energies)
  - Wake fields in Matter (green field)

Publications and Presentations:

- - "Études d'instabilités transverses des faisceaux pour un projet de collisionneur muons anti-muons", contributed talk at the French Physical Society congress on July 5th 2023, giving a general overview of the Muon Collider study and its challenges in terms of beam instabilities, https://indico.ijclab.in2p3.fr/event/8021/sessions/4500/#20230705
- "Transverse impedance and beam stability studies for the muon collider ring" in Proceedings of IPAC 2023, https://doi.org/10.18429/JACoW-IPAC2023-WEPL185
- "Transverse impedance and beam stability studies for the muon collider Rapid Cycling Synchrotrons" in Proceedings of IPAC 2023, https://doi.org/10.18429/JACoW-IPAC2023-WEPL186
- "Status of the collective effects in the collider ring", presentation at the IMCC Annual Meeting 2023, June 2023 https://indico.cern.ch/event/1250075/contributions/5349692/attachments/2670071/4629350/2023-06-21_amorim_COLL10TeV_collective_effects.pdf
- "Status of the collective effects in the RCS", presentation at the IMCC Annual Meeting 2023, June 2023, https://indico.cern.ch/event/1250075/contributions/5350200/attachments/2670072/4629351/2023-06-21_amorim_RCS_collective_effects_v2.pdf
- "Collective effects", status report at Muon Collider Accelerator design meeting, 5th June 2023, https://indico.cern.ch/event/1283569/contributions/5419198/attachments/2659731/4607066/2023-05-22_MUC_collective_effects_coll10tev_v2.pdf
- "Transverse coherent instability studies for the high-energy part of the Muon Collider", proceeding and poster in HB 2023 (High Brightness Hadron Beams workshop), October 2023, to be published, https://indico.cern.ch/event/1138716/

The high-energy complex



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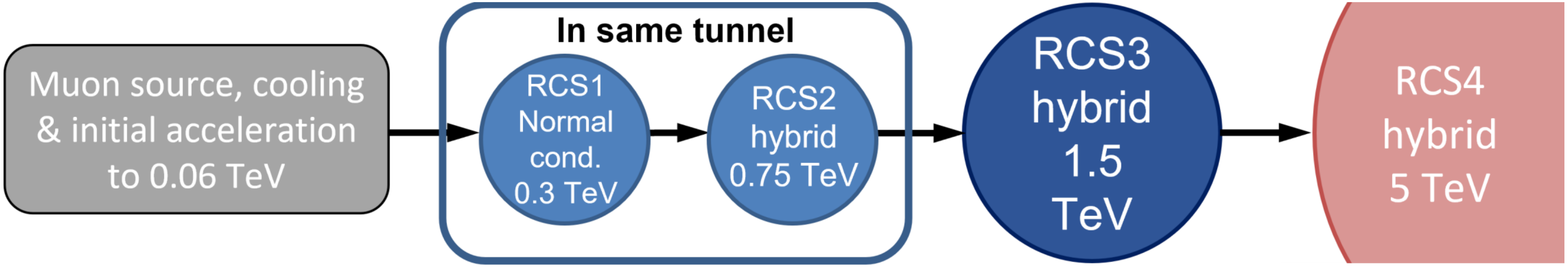

- Hybrid RCSs have interleaved normal conducting (NC) and superconducting (SC) magnets.
- To go to 5 TeV, we have not one but four RCS:
  - Tradeoff between the ring size, survival rate, acceleration speed (at low energy, the ring can be smaller and thus we can accelerate faster).
- This would be the first hybrid RCSs in the world!