Status of the International Muon Collider Complex Study at 10 TeV

Kyriacos Skoufaris

on behalf of the International Muon Collider Collaboration (IMCC)

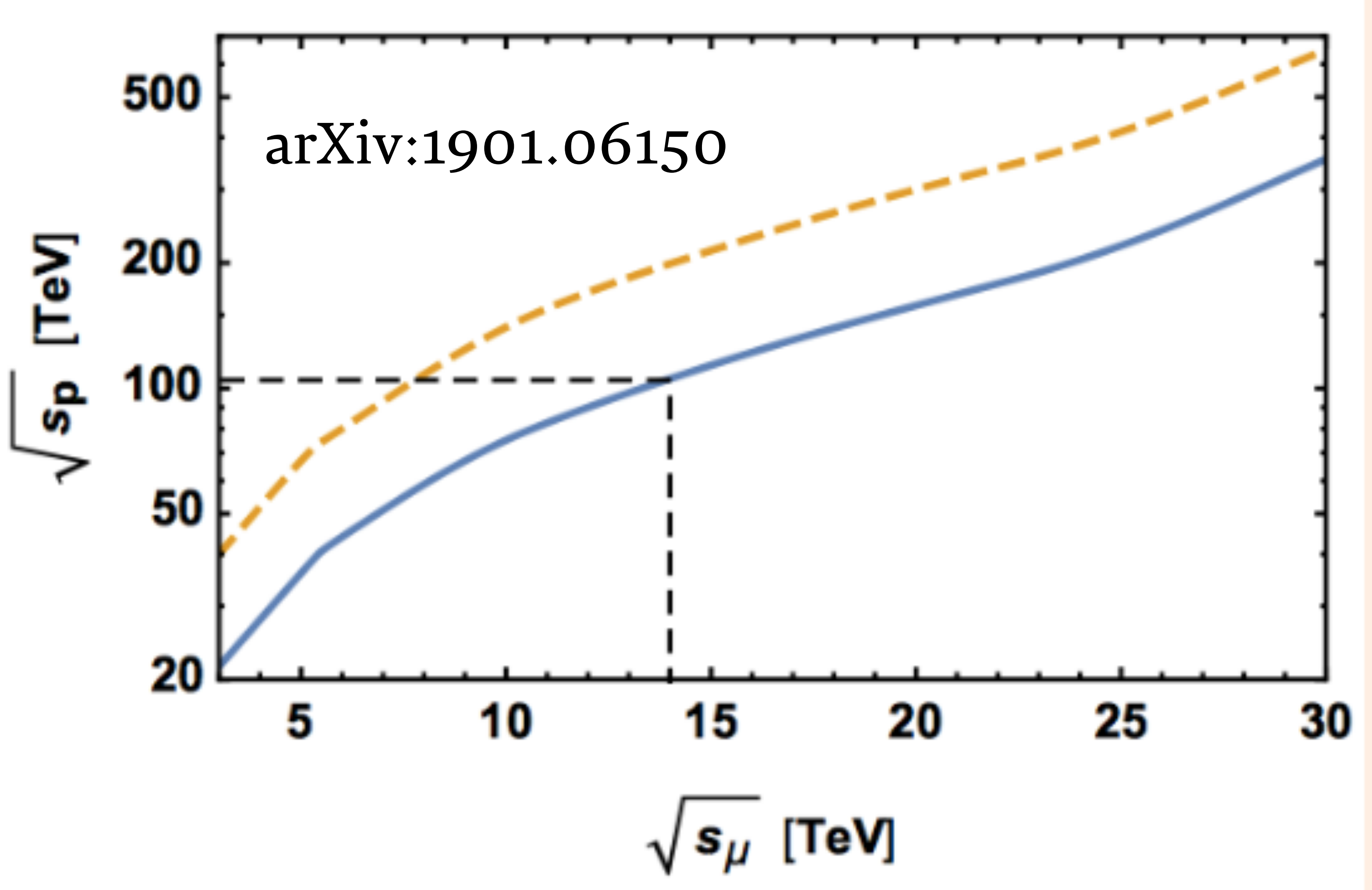
Funded by the European Union under Grant Agreement n. 101094300.

EPS - Accelerators for HEP, 21-25 August 2023

Motivation

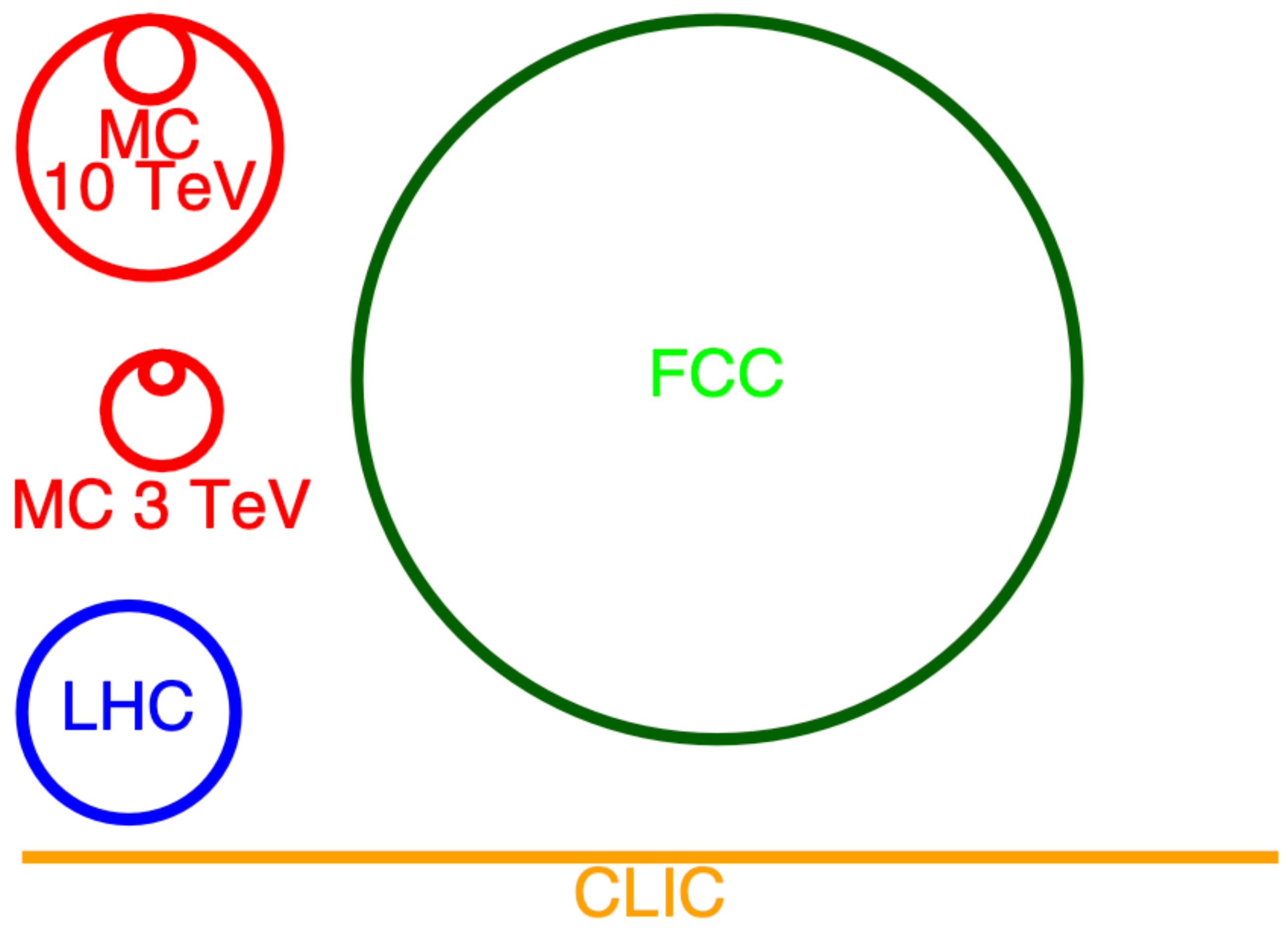
Muon collider promises unique opportunity for a **high-energy, precision and discovery machine in a compact form** (10TeV muon collider footprint comparable to 3TeV CLIC with physics potential comparable to FCC-hh).

Proton and muon collider energy for about equal cross section



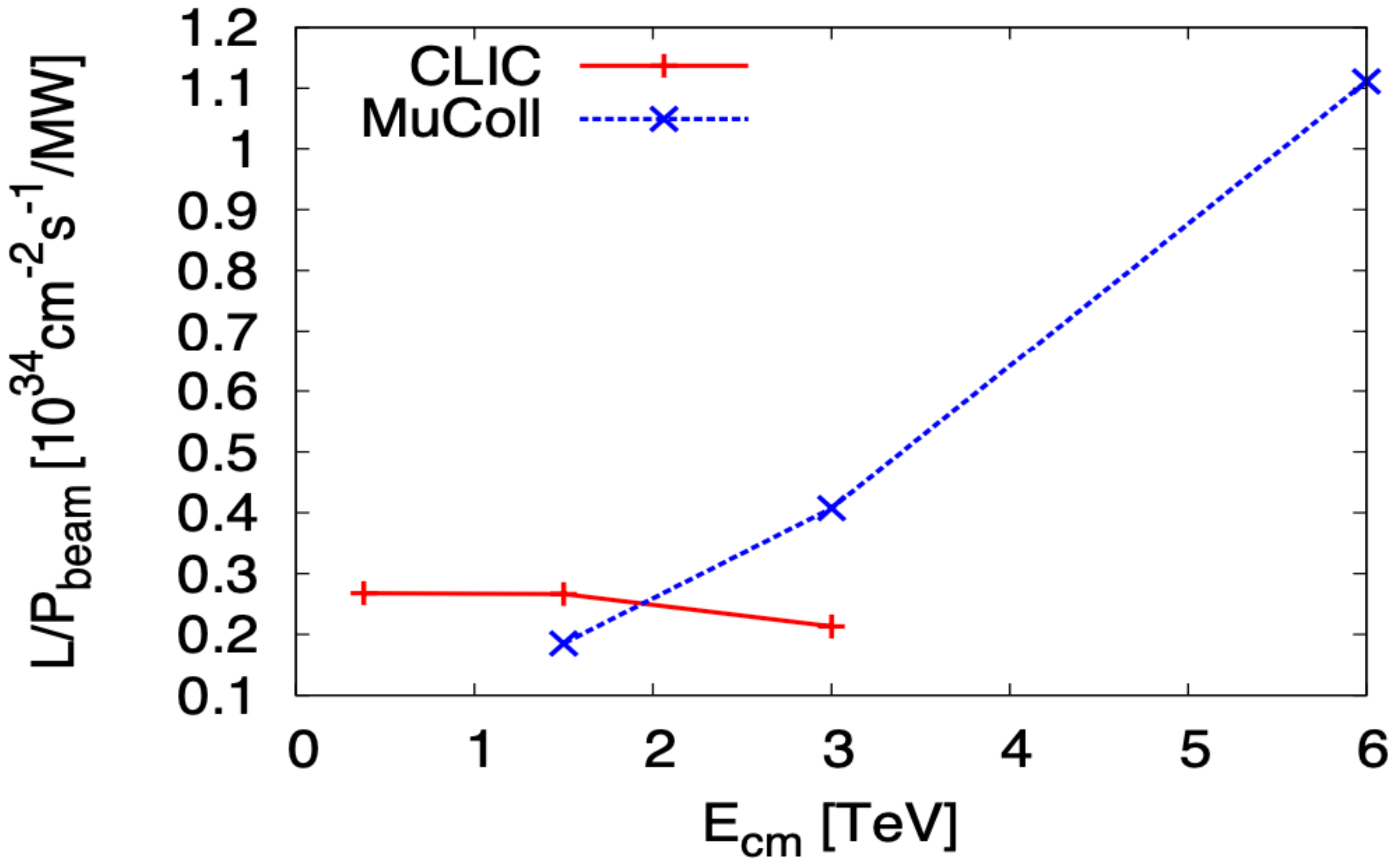
- **Discovery reach with lower energies** than for proton colliders.

Facility footprints for different high energy physics projects



- Compactness promises **cost effectiveness** and low CO_2 footprint for construction.

Luminosity per beam power as function of beam energy



- Increasing luminosity per beam power improve **power efficiency** and **precision potential**.

Muon lifetime at rest only 2.2μs (τ_{5TeV}=104ms).

Introduction

- High power proton beam (short intense bunches) and low repetition rate on target.
- Target and capture channel, protons produce pions which decay into muons.
- Large energy spread μ beam split to sequence of bunches.
- Stages of muon ionisation cooling in matter.
- Merging of μ bunches into one bunch.
- Low energy acceleration with recirculating linacs.
- Acceleration to collision energy in a sequence of pulsed synchrotrons.
- Collider packed with high field magnets to minimise circumference and maximise luminosity.

Short muon life-time —> Ionization cooling, fast acceleration, high RF gradients and high field magnets!

Introduction

Currently focus on 10 TeV, also explore 3 TeV.

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**40**
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
σ_δ	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β^*	mm	5	1.5	1.07
ε_L	MeV m	7.5	7.5	7.5
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

High average magnetic field.

High constant relative energy spread.

Small bunch length and β* that reduced with energy (proportional to 1/E).

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Yields constant number of events in the s-channel (cross section decries with energy).

- Tentative parameters based on MAP study, might add margins.
- Achieve goal in 5 years with two detectors.

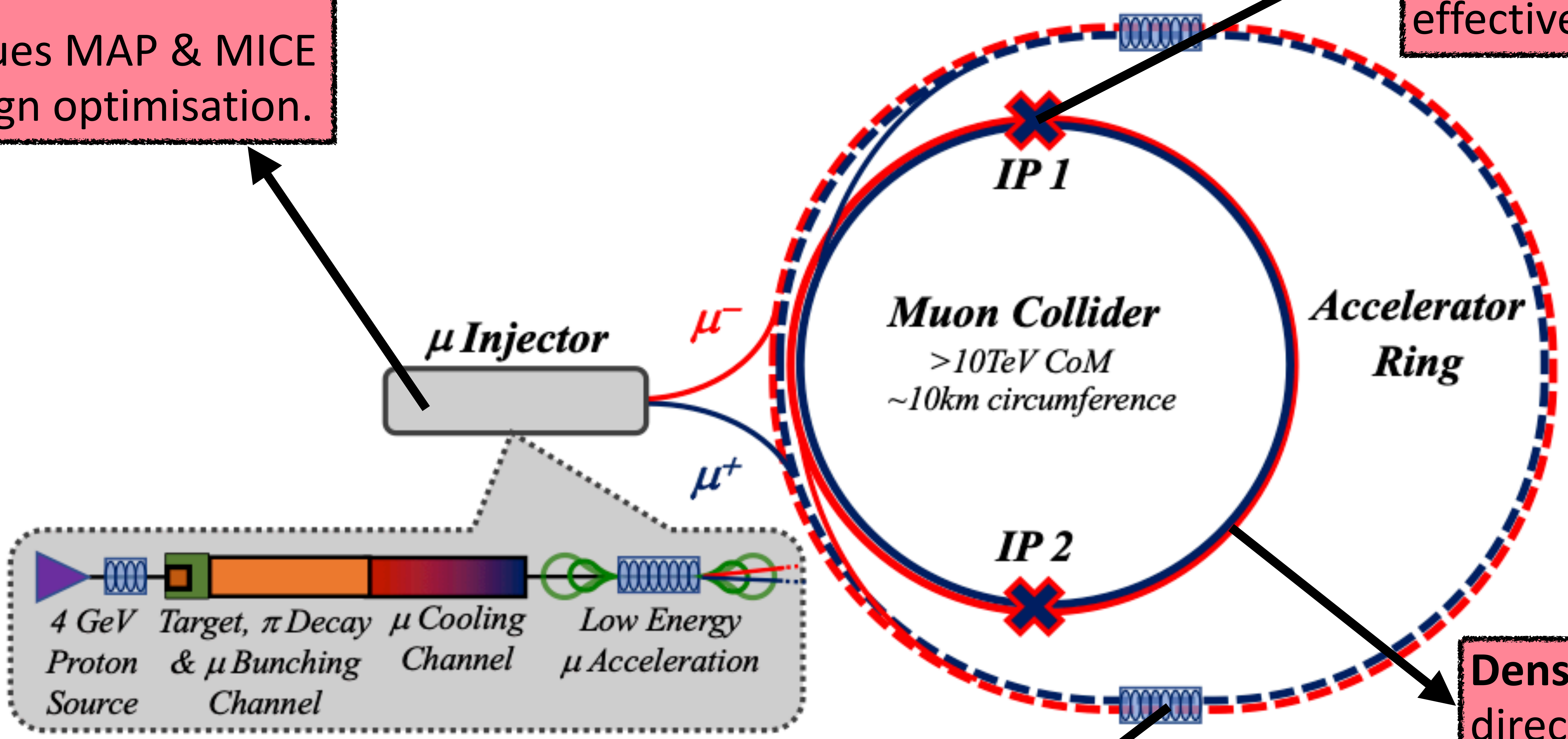
Design Baseline Overview - key challenges

Drives the **beam quality**.

IMCC continues MAP & MICE effort in design optimisation.

Beam-induced background.

Special design of absorbers for effective shielding.

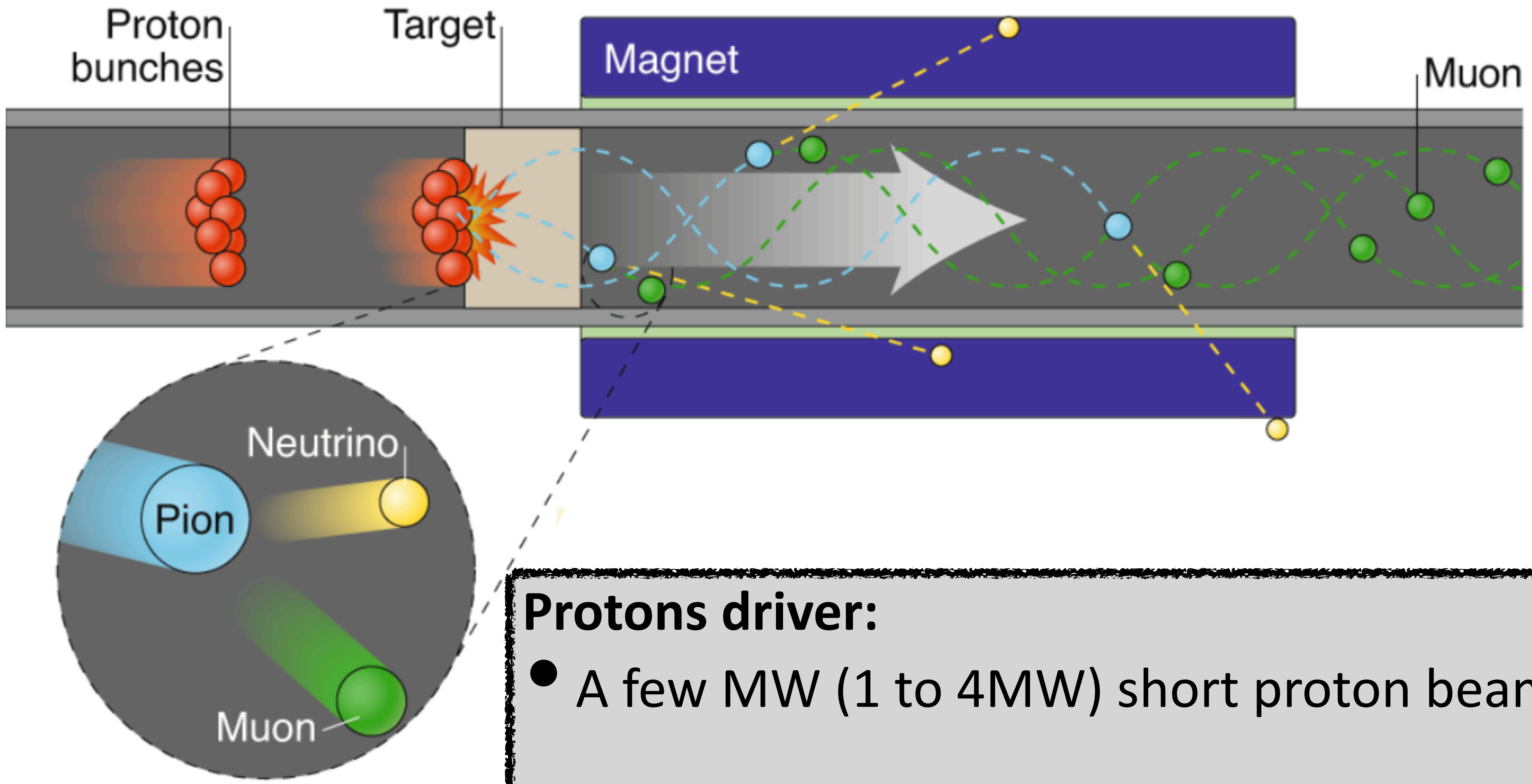


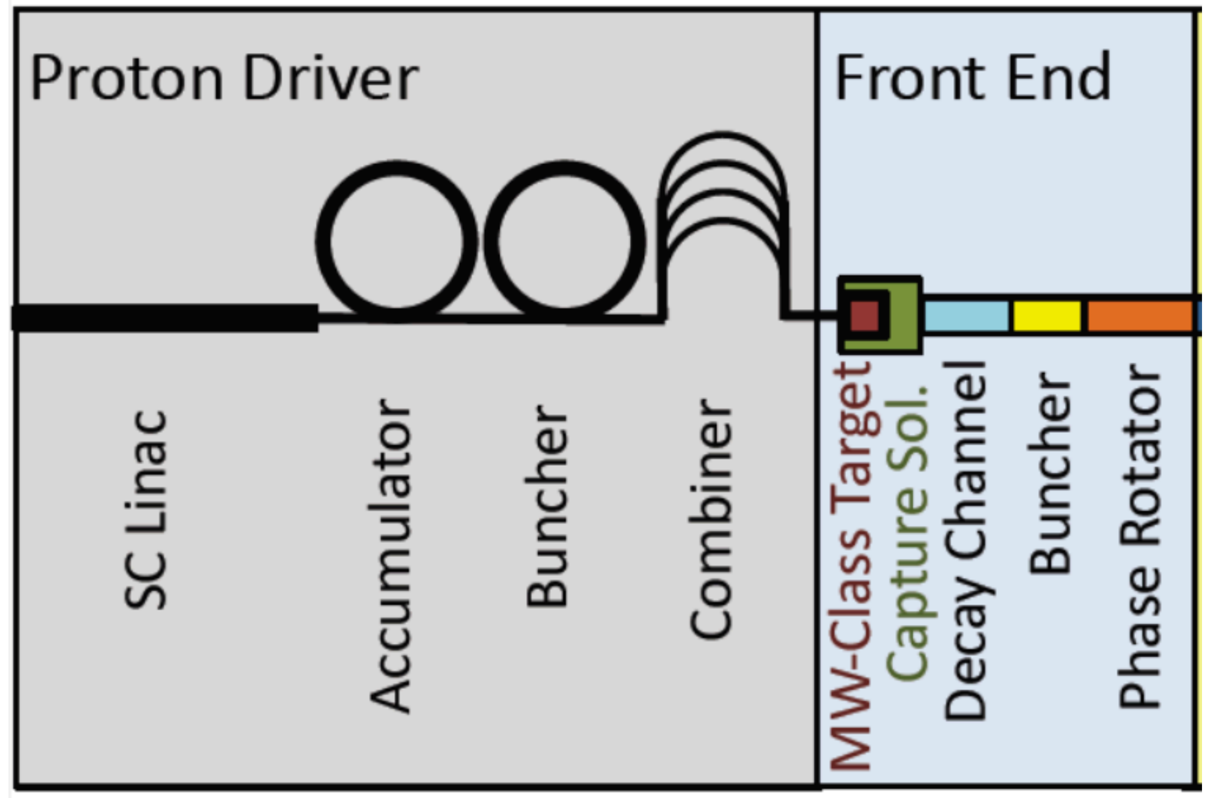
Dense neutrino flux in direction tangential to ring.

Mitigations planned to keep dose generated at Earth's surface at negligible levels.

Cost and **power** consumption limit energy reach e.g. 35km accelerator for 10TeV, **impacts beam quality**.

Muon Production and Capture





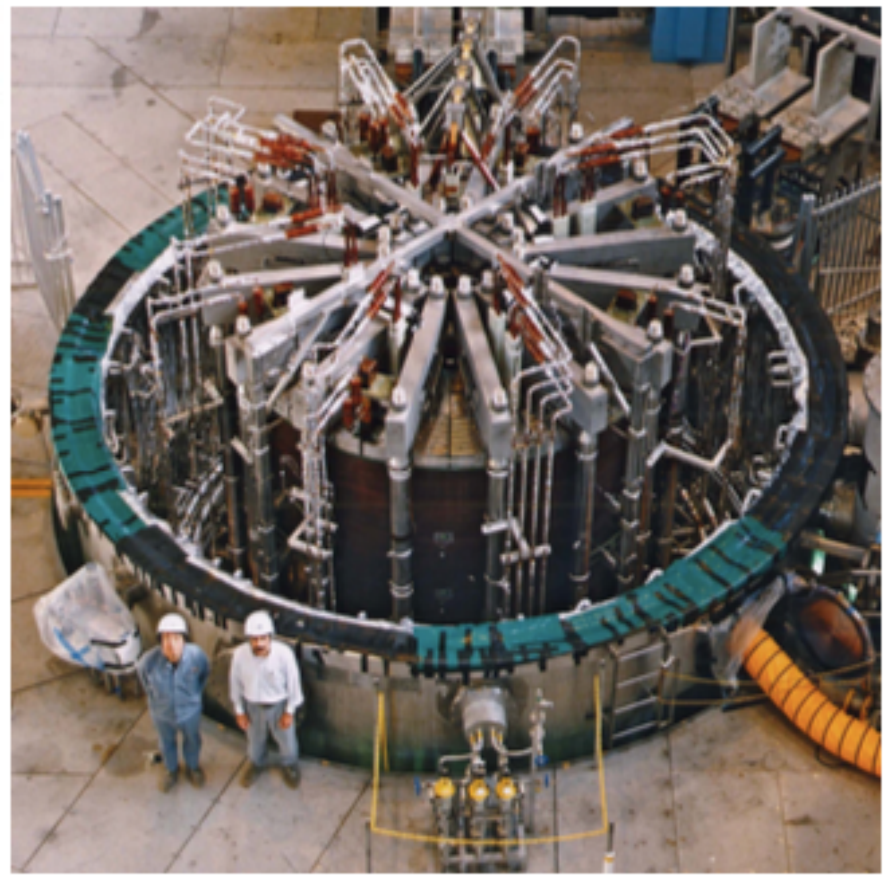
Protons driver:

- A few MW (1 to 4MW) short proton beam with lowish repetition rate.

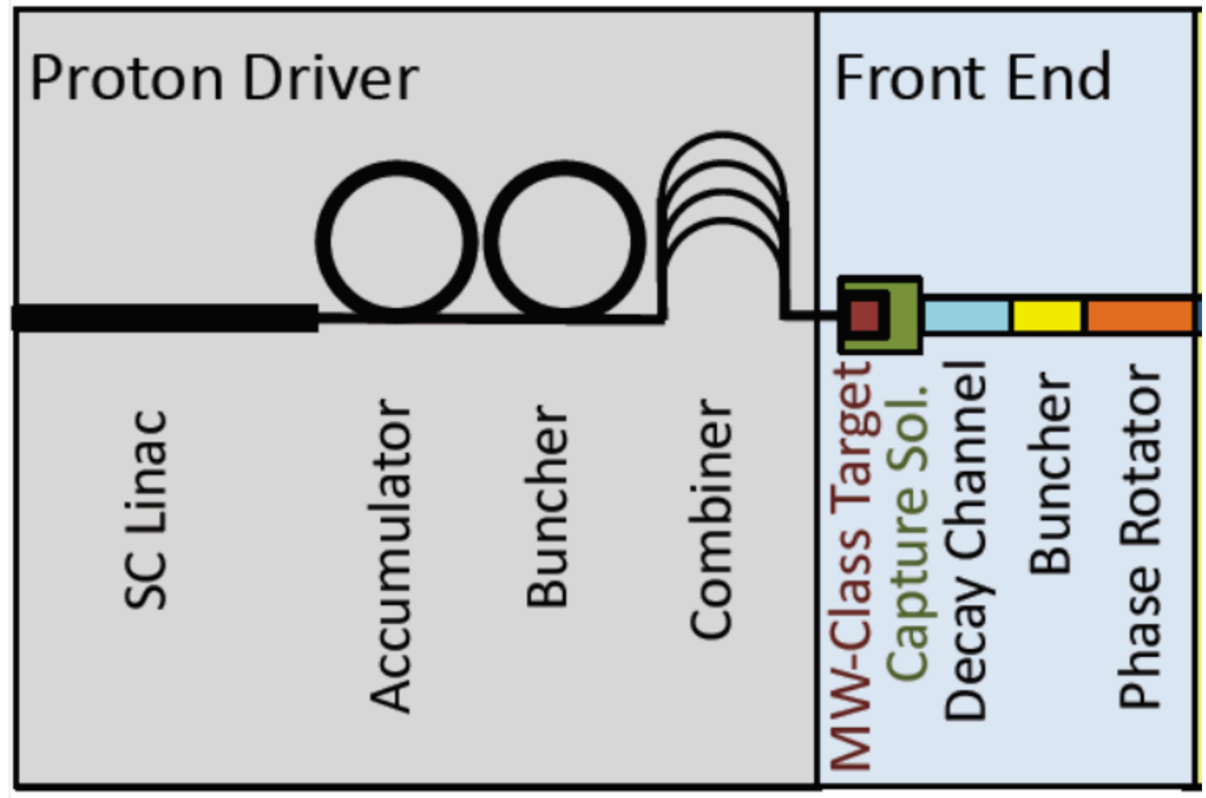
Front end:

- Proton beam hit the target (graphite, liquid metal jet or powder).
- **p** + N → **π** + X → **μ** + Y
- Collection of muons with large energy spread and generation of 21 bunches with equal energy.
- Large bore strong solenoidal fields for maximum intensity with minimum emittance.

ITER Central Solenoid Model Coil 13 T in 1.7 m (LTS)



Muon Production and Capture

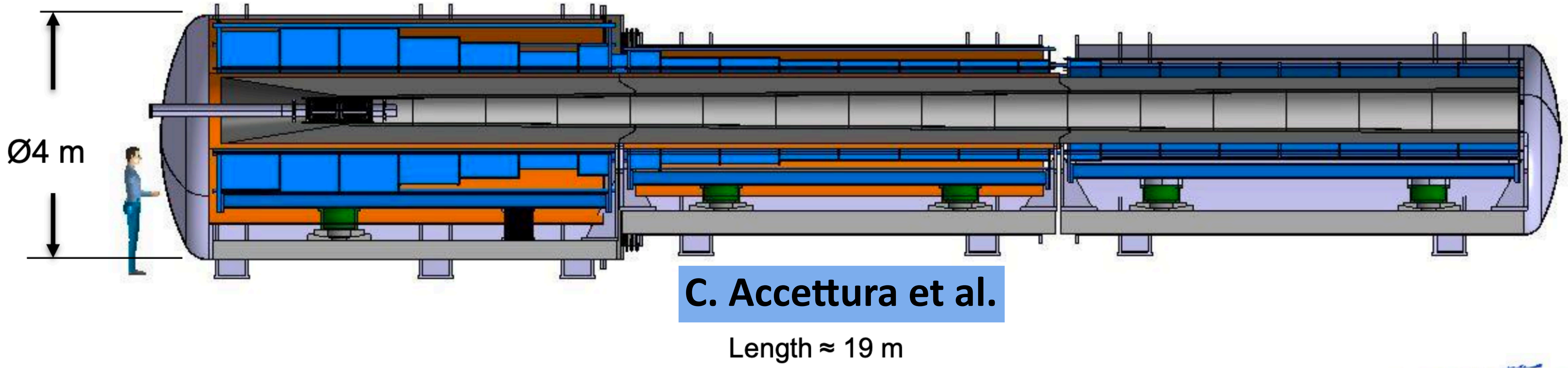


Proton complex:

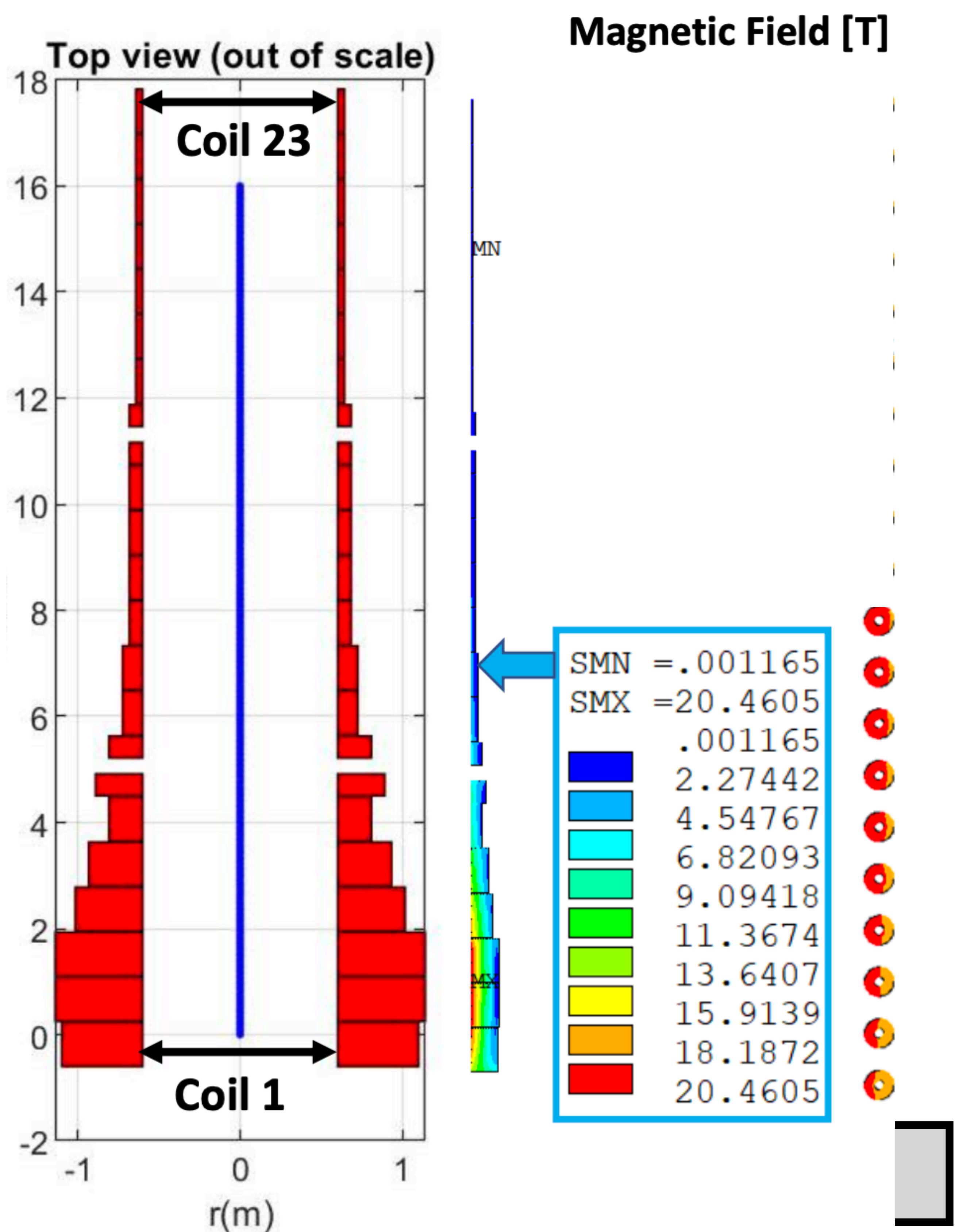
- Review of linac parameters is ongoing
  - high intensity machine development (CERN PS Booster, ESS).
- Baseline lattice for accumulator-compressor based on neutrino factory lattice.
- Work ongoing on limitations to accommodate the 2MW beam at 5Hz.

Studying 2 MW target:

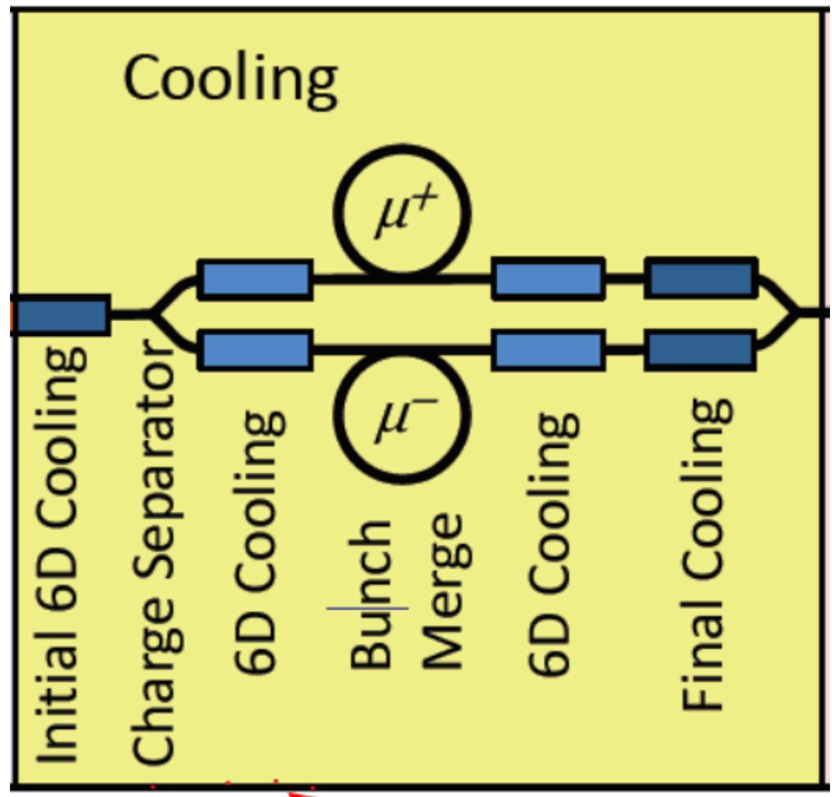
- Beam impact on target.
- Studies on parameter range for proton beam.
- Stress in target, shielding, vessel and window being studied.
- In general very promising.
- Studies using HTS solenoids ongoing.



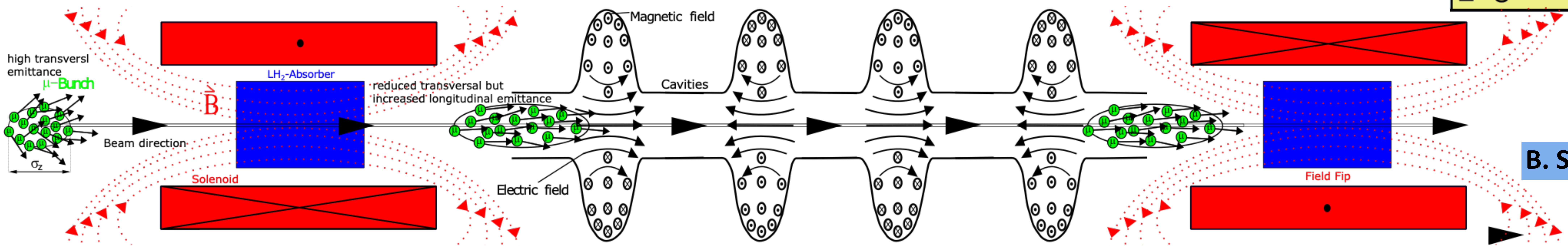
C. Accettura et al.



Muon Cooling



Short muon lifetime —> **Ionisation cooling only option**



B. Stechauner

Absorber: reduction of longitudinal and transverse momentum.

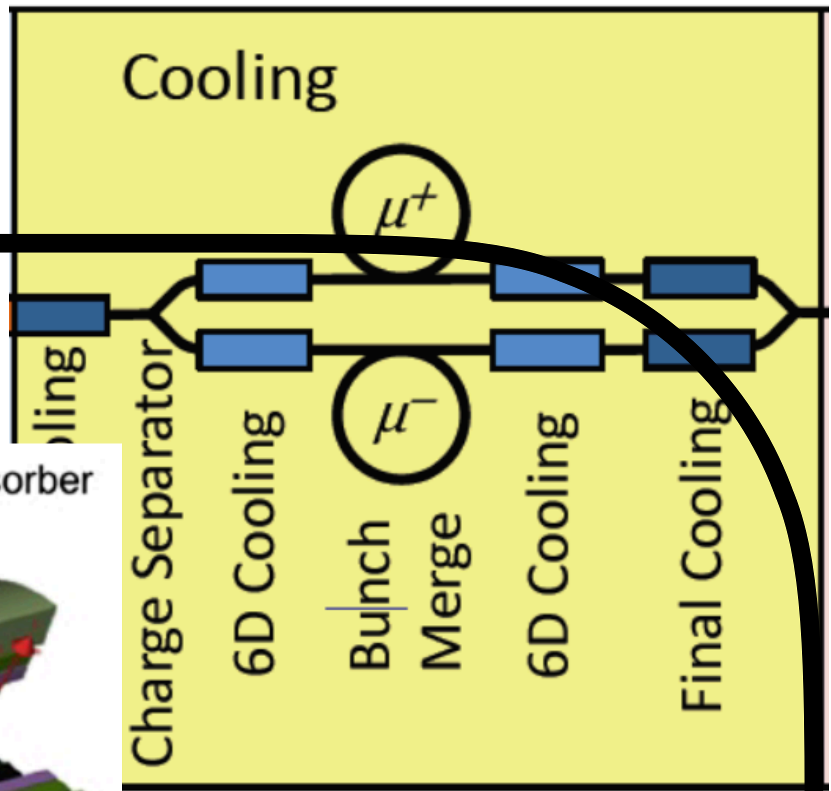
Scattering: beam blow-up —> need for strong solenoids and low Z absorbers.

Cavities: acceleration, i.e., increase of only longitudinal momentum.

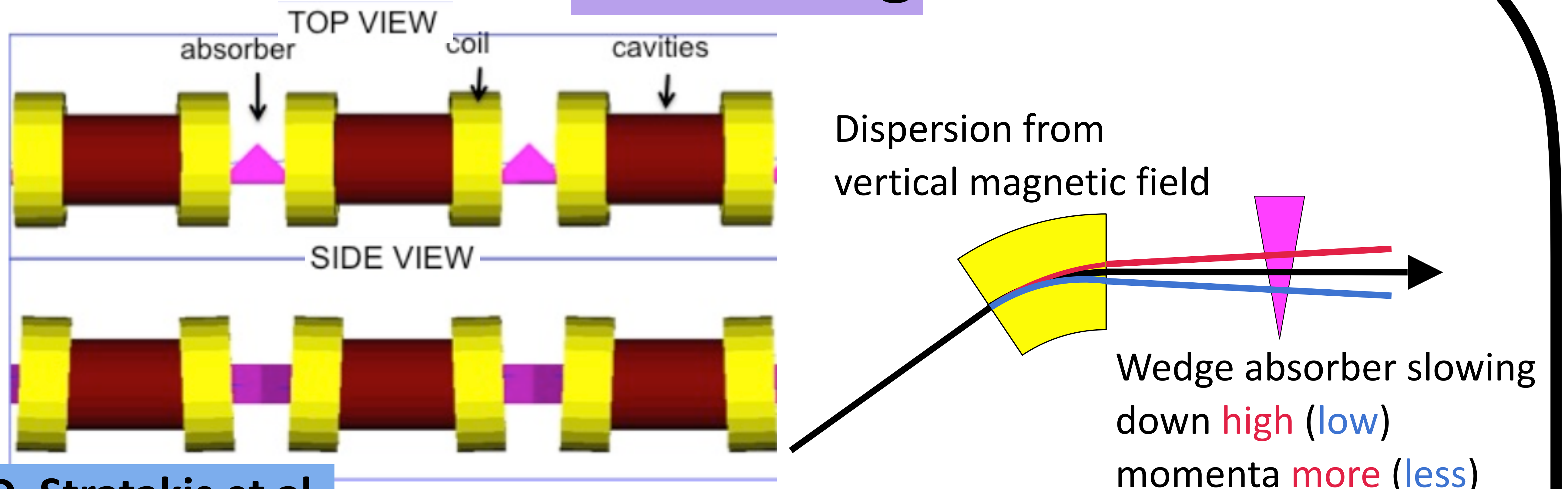
Net effect: reduction of transverse momentum and thus beam cooling.

Code development: RFTRACK integrating multiple scattering and collective effects, maintained at CERN.

Muon Cooling - 6D cooling



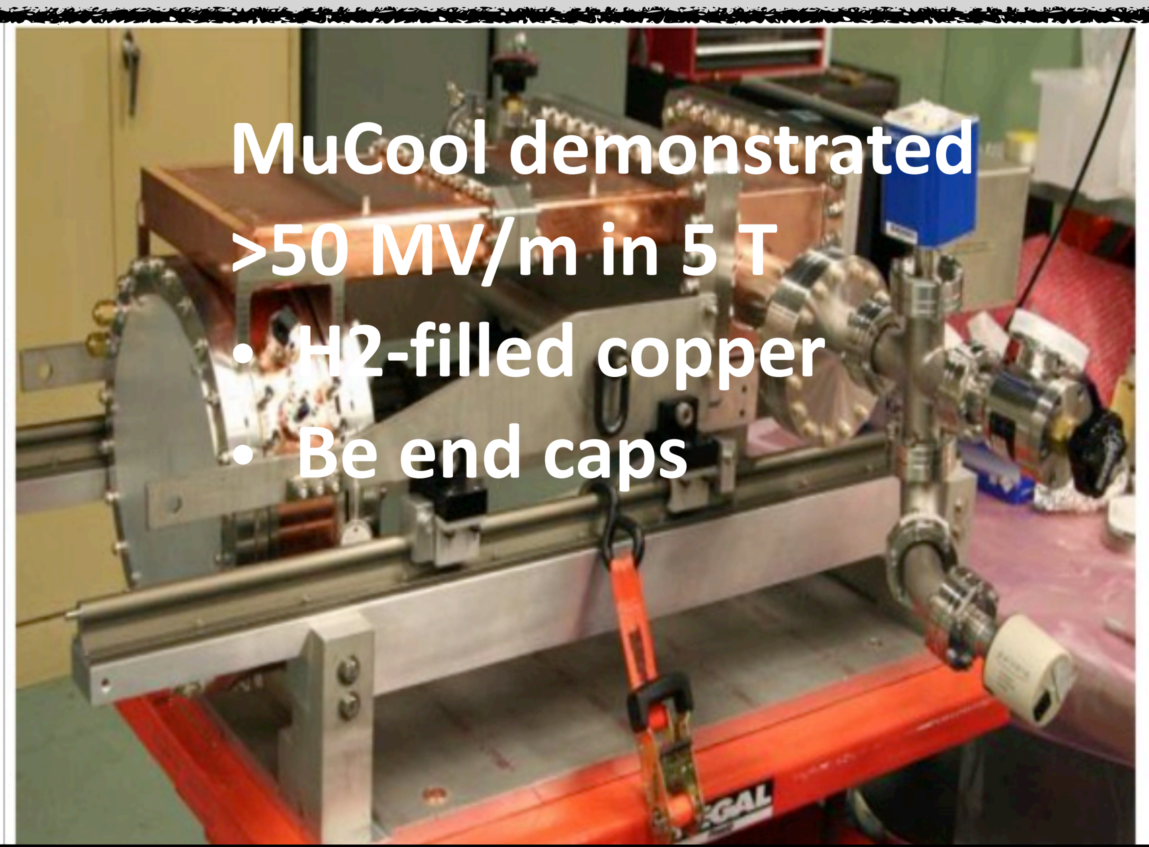
6D cooling



D. Stratakis et al.

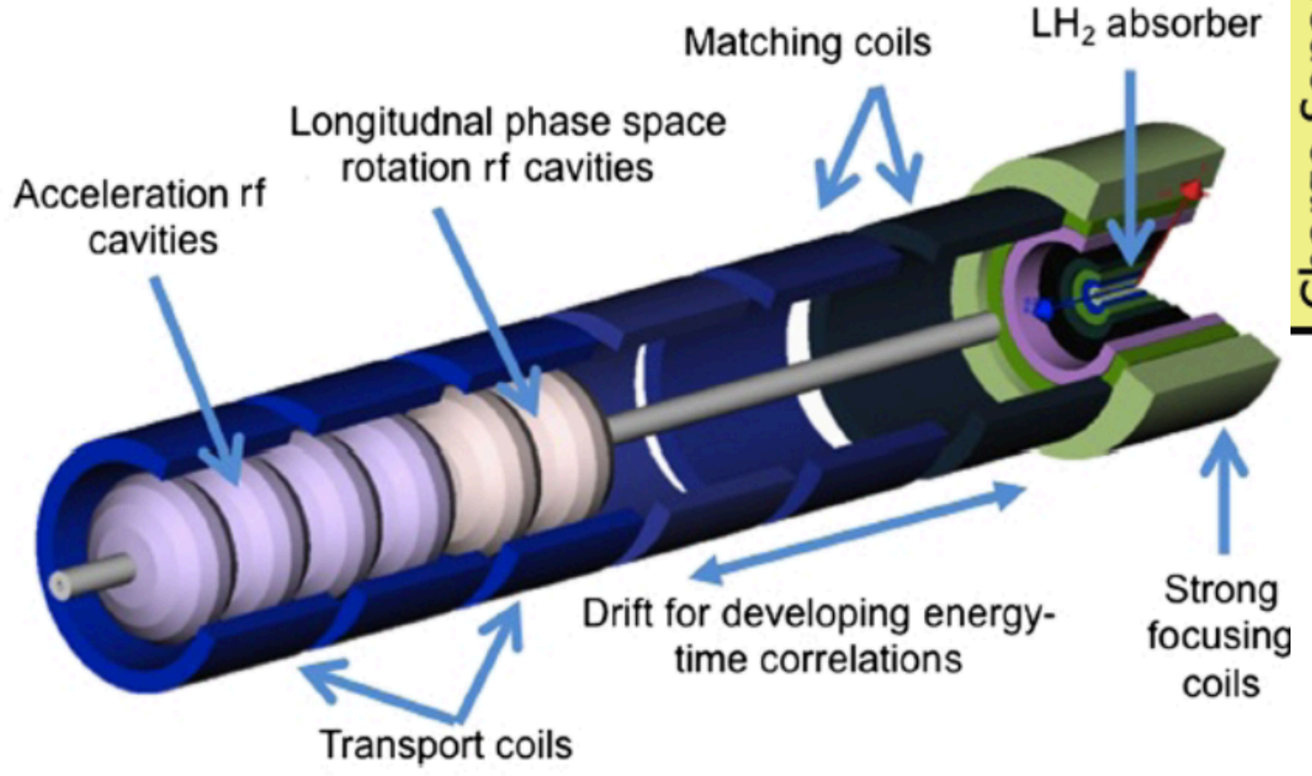
RF cavities in magnetic field:

- MAP demonstrated higher than goal gradient.
- Improve design based on theoretical understanding.
- Preparation of **new test stand**, but needs funding
  - test stand at CEA (700 MHz, need funding)
  - test at other frequencies in the UK considered.



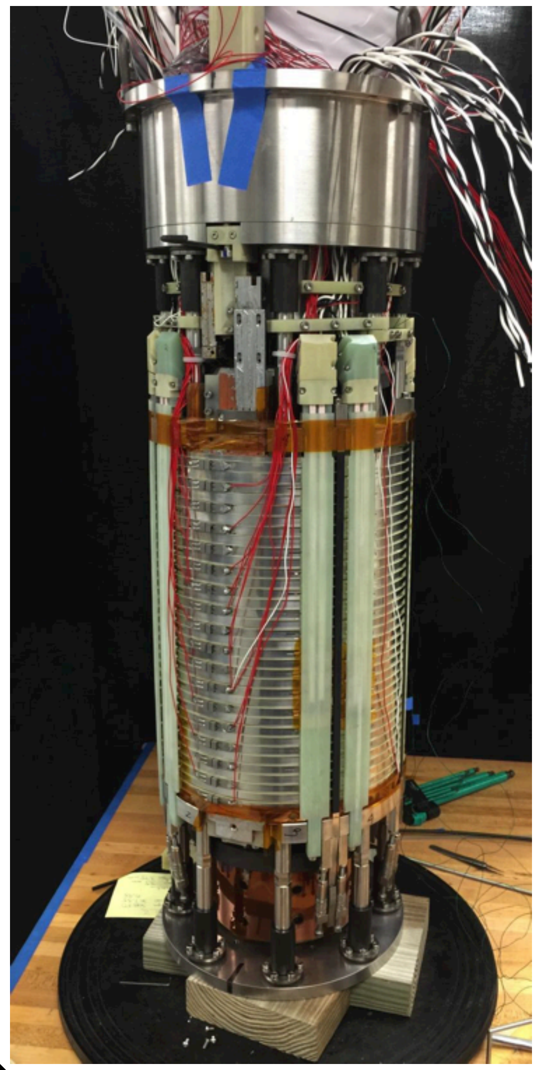
C. Marchand, A. Grudiev et al. (CEA, Milano, CERN, Tartu)

Final cooling



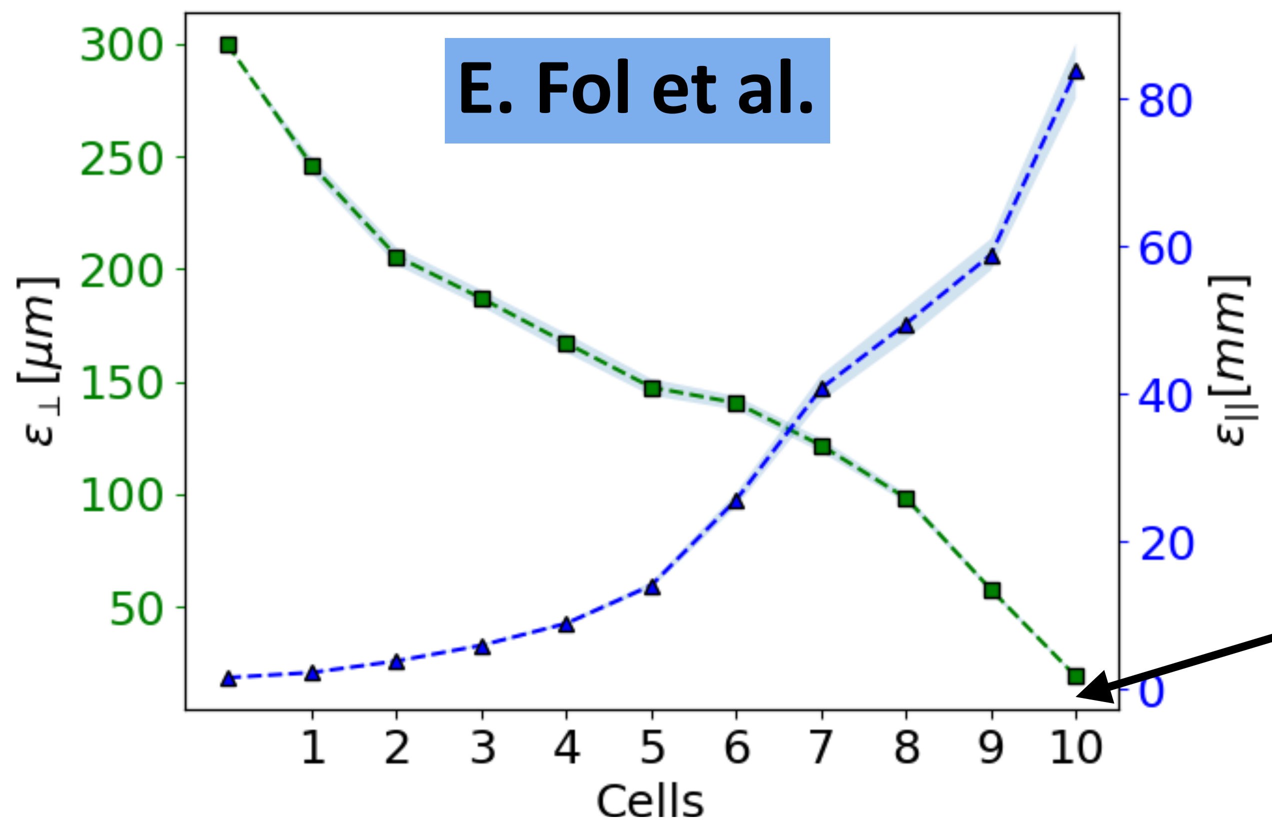
Assessment of realistic goal for highest field solenoids:

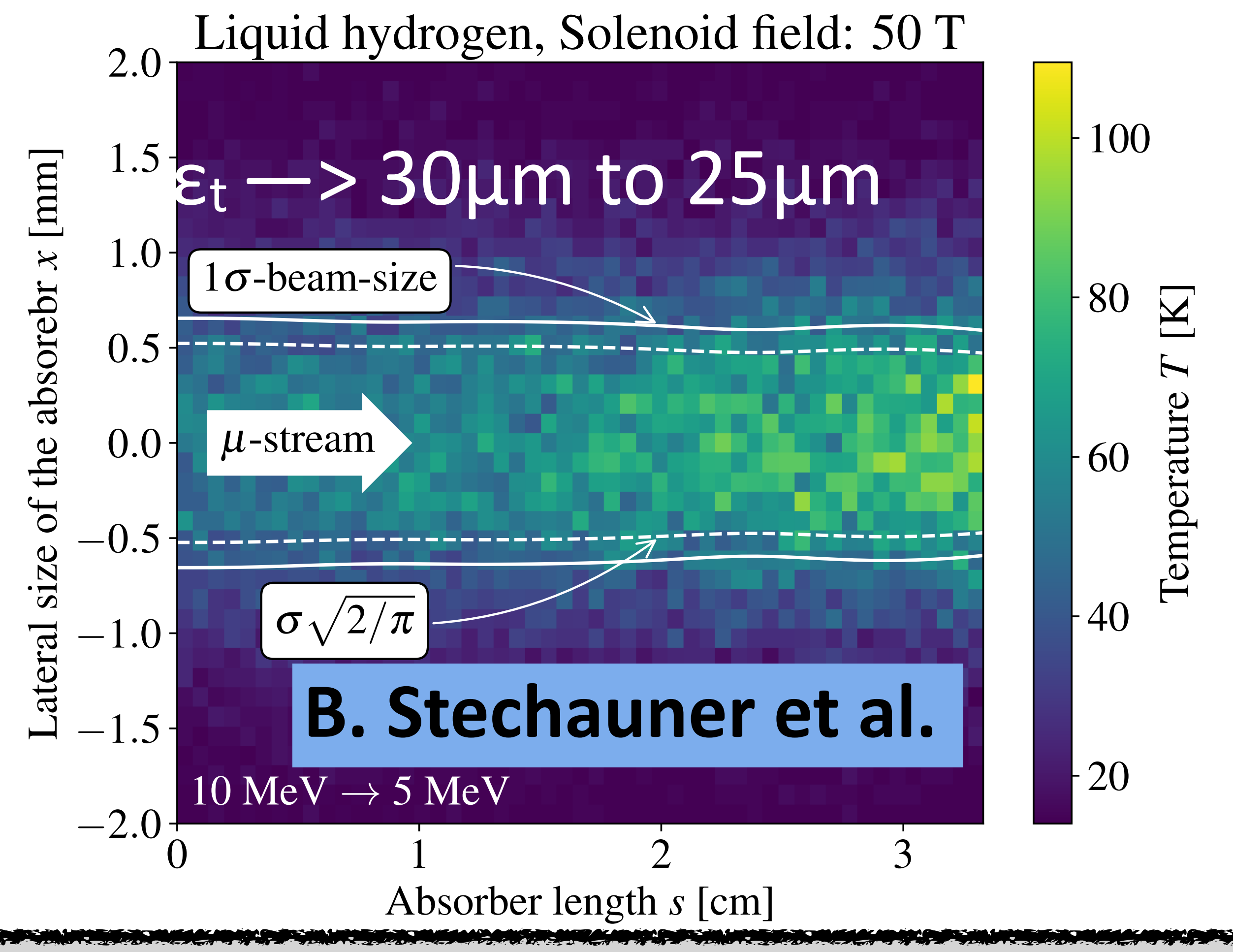
- MAP demonstrated 30 T
- now magnets aim for 40+ T
- even more can be possible
- synergy with high-field research.

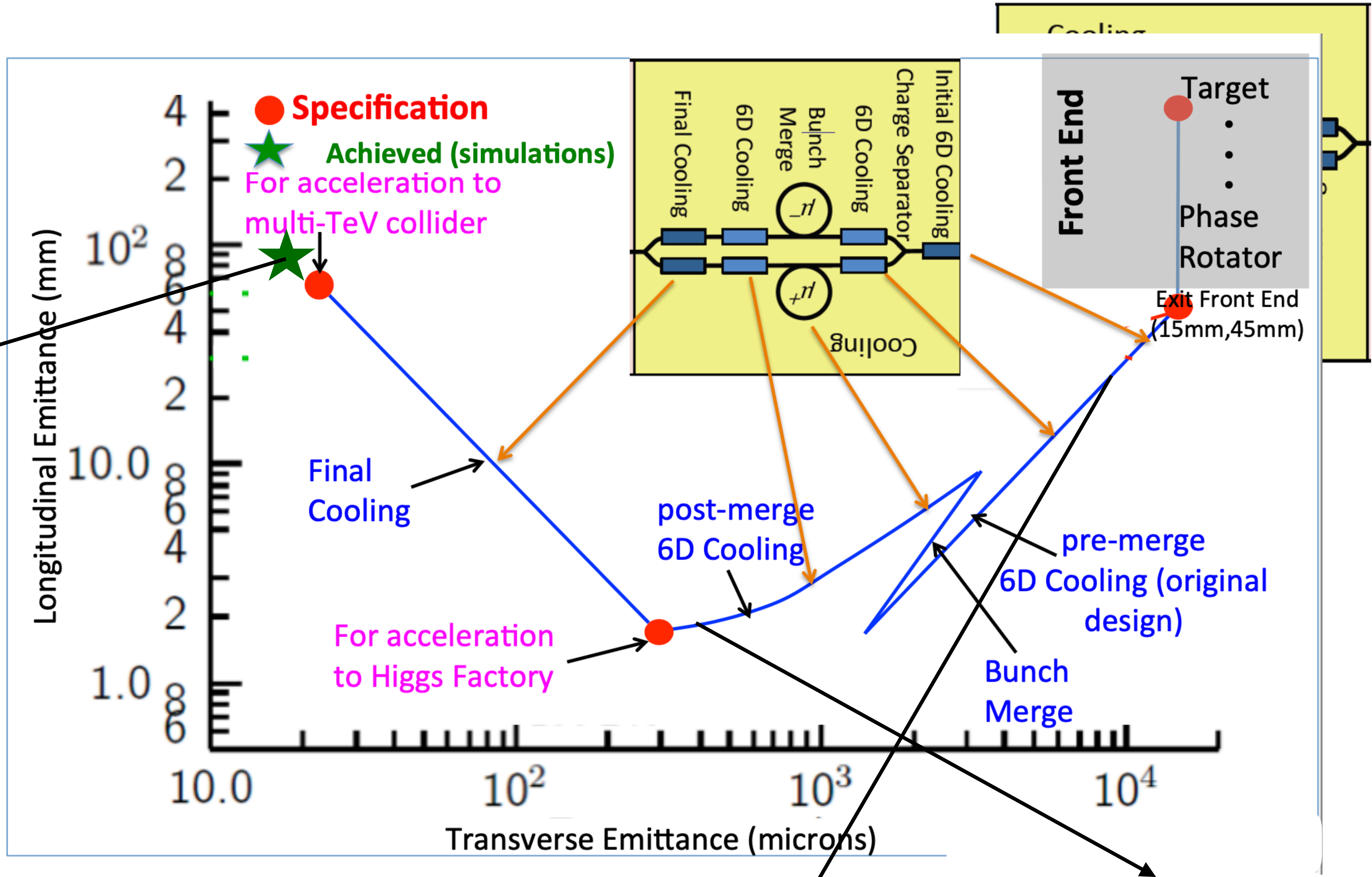


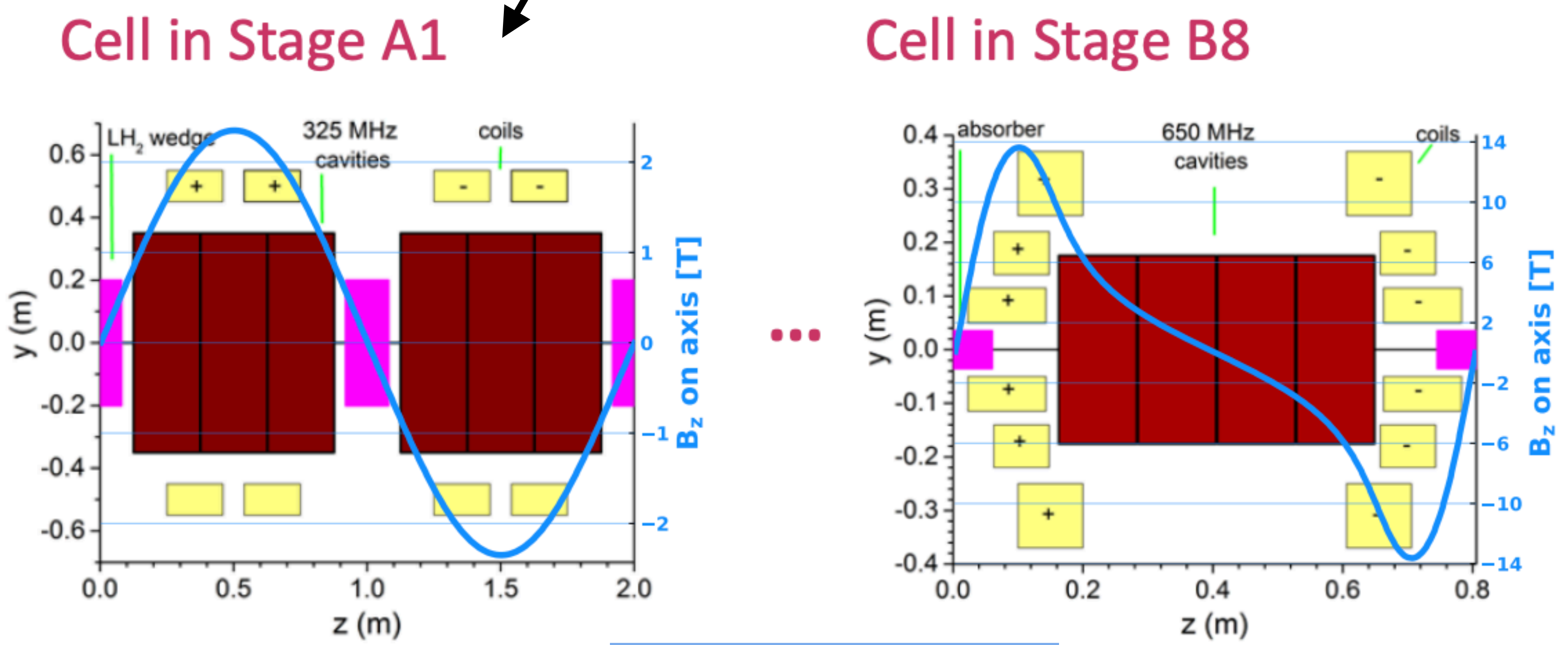
L. Bottura et al.
INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK and US-MDP

Muon Cooling







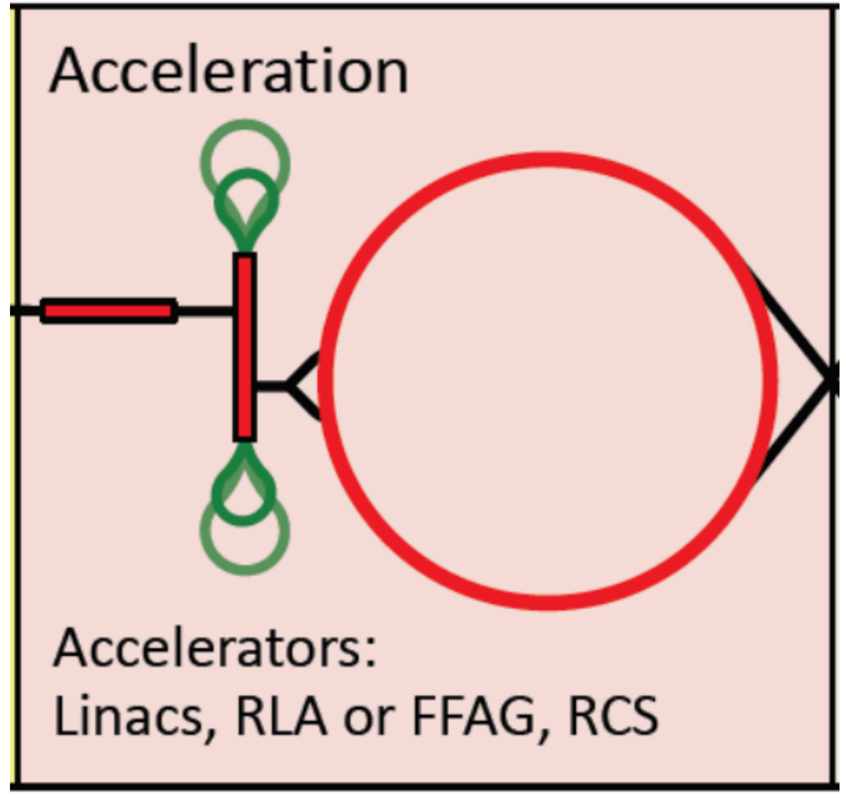


S. Fabbri et al.

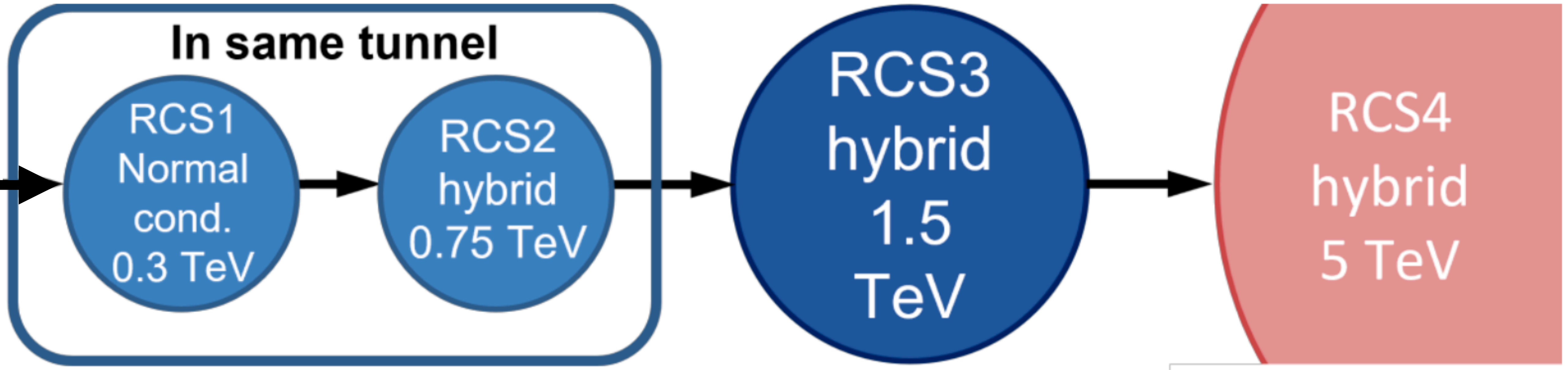
- Simulations using optimised parameters confirm the potential for lower emittance (compared to the baseline studies).
- Machine learning techniques are currently used for design optimisation.
- Liquid hydrogen is evaporated at the end of last cell thus an alternative like gaseous hydrogen with adjusted gas pressures might be used.

Acceleration

Fast acceleration to avoid significant muon losses due to decay



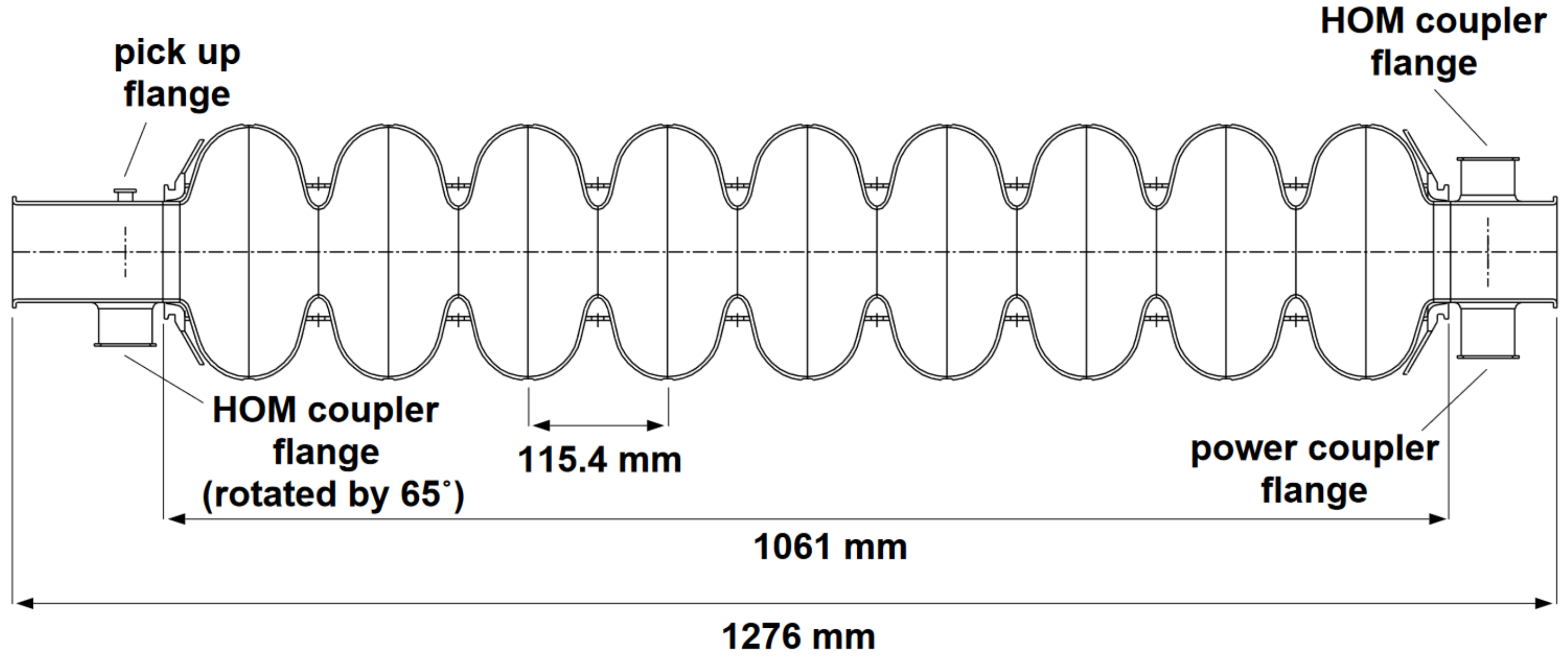
Initial acceleration to 0.06TeV

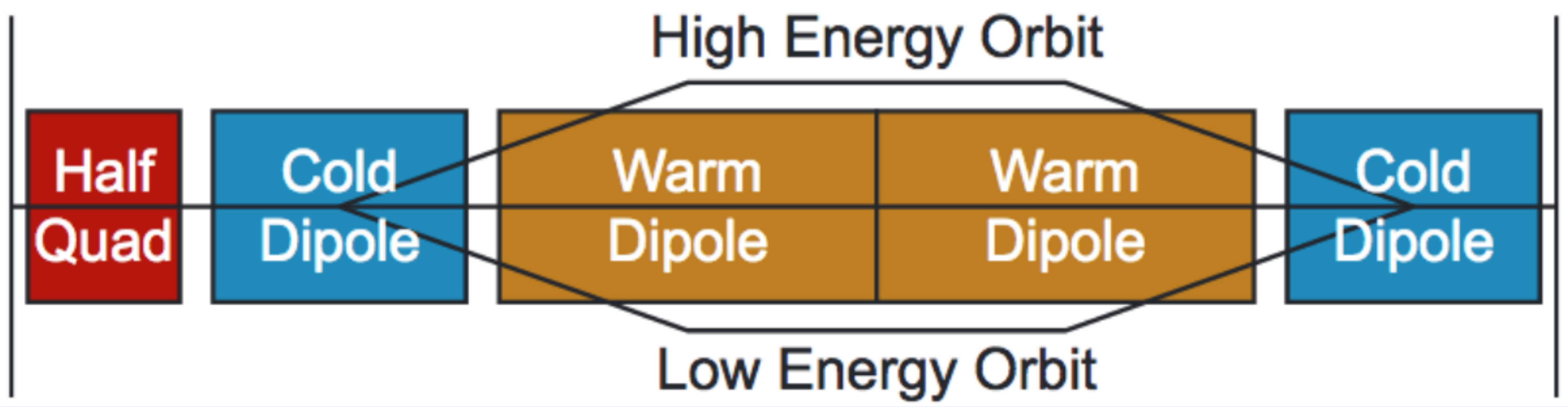


Re-Circulating Linacs

Rapid Cycling Sychrotron

- Use of high (average) RF gradients to accelerate single μ^+/μ^- bunch.
- Start with re-circulating linacs (RCL).
- Followed by rapid cycling synchrotrons (RCS)
  - acceleration within few tens of turns
  - studies based on Tesla cavities
  - hybrid RCSs have fast ramping normal conducting and constant superconducting dipoles
  - f_{RF} tuning for cavities
  - FFAs a possible alternative.





A. Chancé et al.

Acceleration

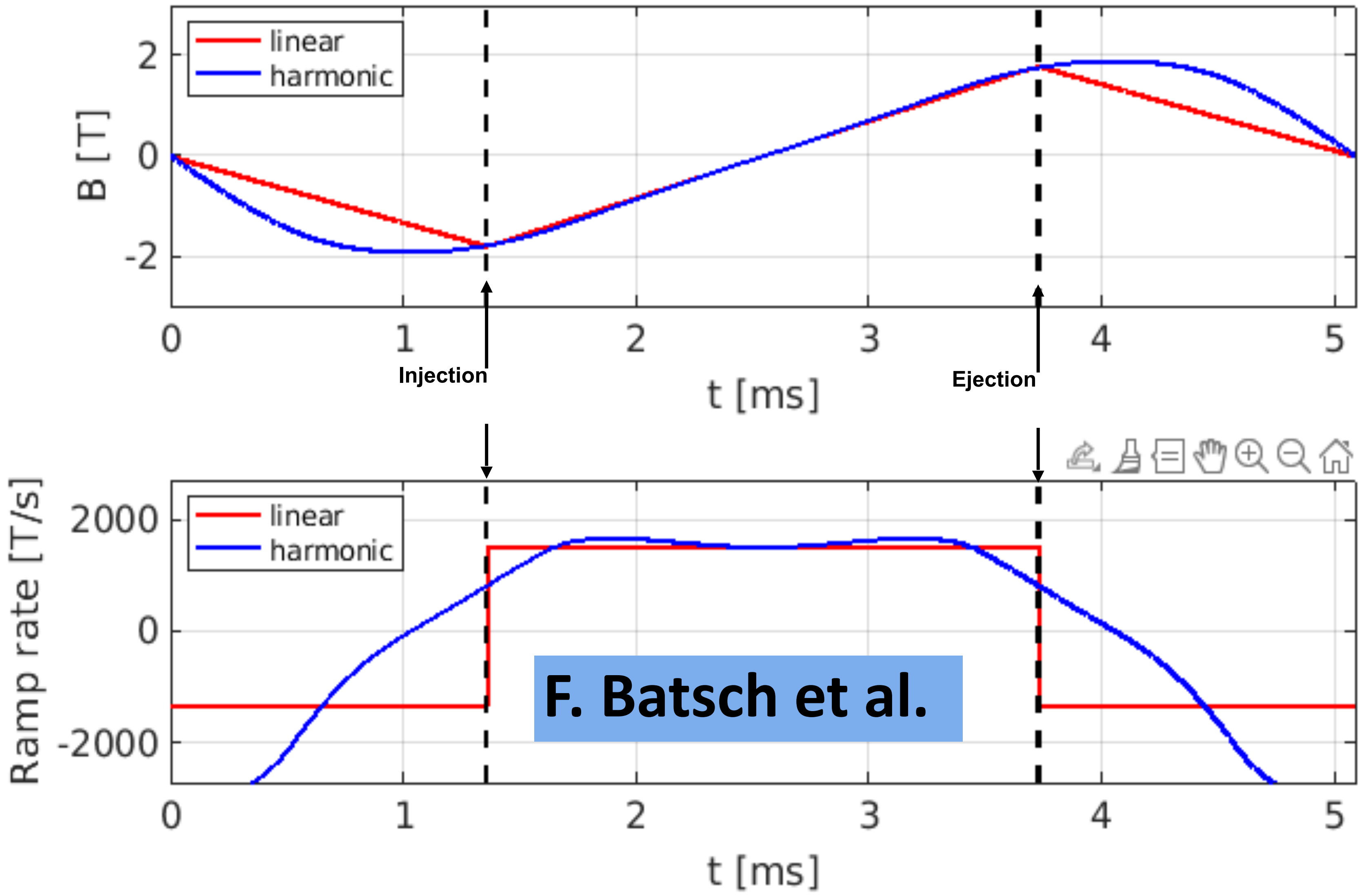
Fast-ramping magnet system:

- Expected to be **one of the most important cost and power drivers**.
- Magnet ramping and RF voltages require optimisation of acceleration parameters - RF voltages, synchronous phase, decay.
- Study quasi-linear ramping -> decrease peak power and magnet powering costs (natural resonant discharge of e.g. two harmonics).
- Management of the power in the resistive dipoles (tens of GW).

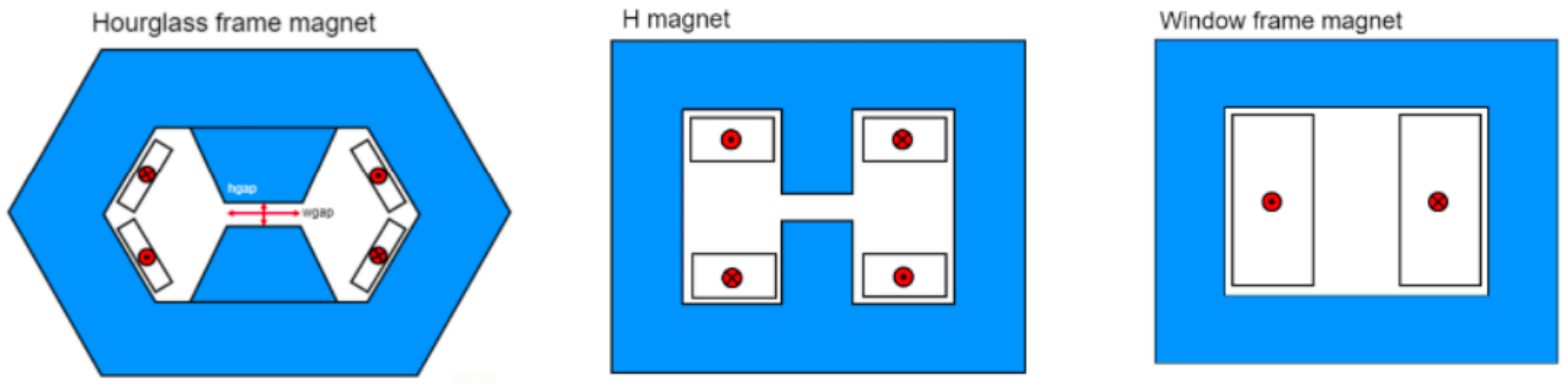
	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	No	Yes	Yes	Yes
Circumference [m]	5990	5990	10700	26659
Injection/extraction energy [TeV]	0.06/0.30	0.30/0.75	0.75/1.5	1.5/4.2
Survival rate [%]	90	90	90	90
Acceleration time [ms]	**0.34**	**1.10**	**2.37**	**5.75**
Number of turns	17	55	66	65
Energy gain/turn [GeV]	14.8	7.9	11.4	41.5
NC dipole field [T]	**0.36/1.8**	**-1.8/1.8**	**-1.8/1.8**	**-1.8/1.8**
SC dipole field [T]	**-**	**10**	**10**	**16**
NC/SC dipole length [m]	2.6/-	4.9/1.1	4.9/1.3	8.0/1.3
Number of arcs	34	26	26	26
Number of cells/arc	7	10	17	19
Cell length [m]	21.4	19.6	20.6	45.9
Path length diff. [mm]	**0**	**9.1**	**2.7**	**9.4**
Orbit difference [mm]	**0**	**12.2**	**5.9**	**13.2**
Min. dipole width [mm]	**17.4**	**19.6**	**10.7**	**18.8**
Min. dipole height [mm]	**14.8**	**6.4**	**4.2**	**4.4**
Bunch population	>2.5E12	>2.3E12	2.2E+12	
Survival rate per ring	90%	90%	90%	

A. Chancé et al.

Example for RCS3



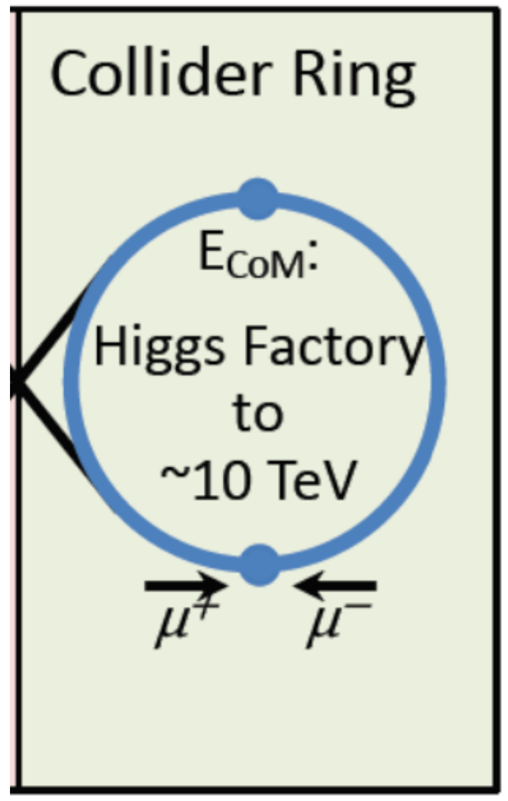
F. Batsch et al.



5.07 kJ/m | 5.65…7.14 kJ/m | 5.89 kJ/m

F. Boattini et al.

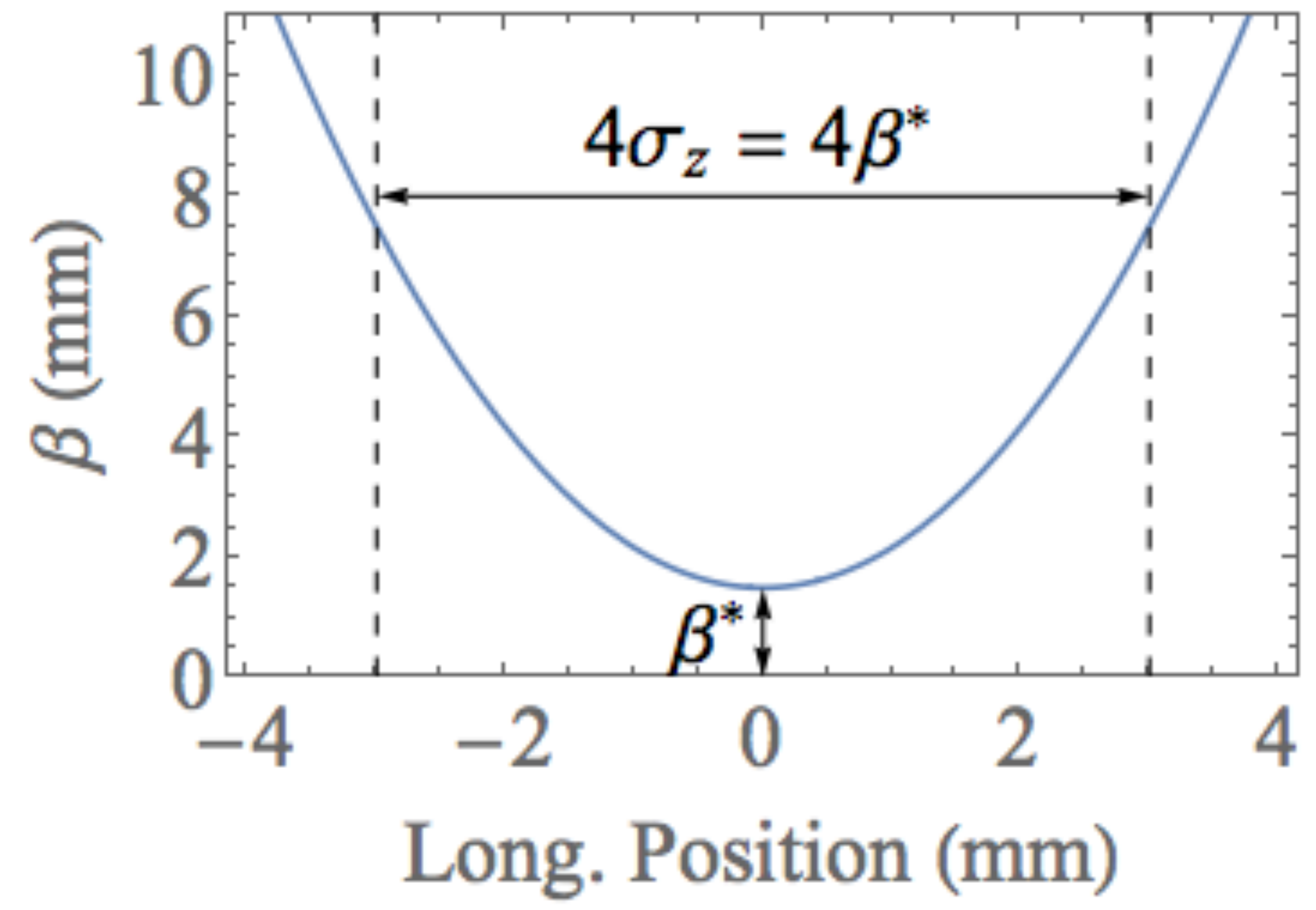
Muon Collider Ring



IMCC is currently focused on the development of a **10TeV** com energy collider ring with **~10km** circumference generating **$10ab^{-1}$** luminosity in 5 years.

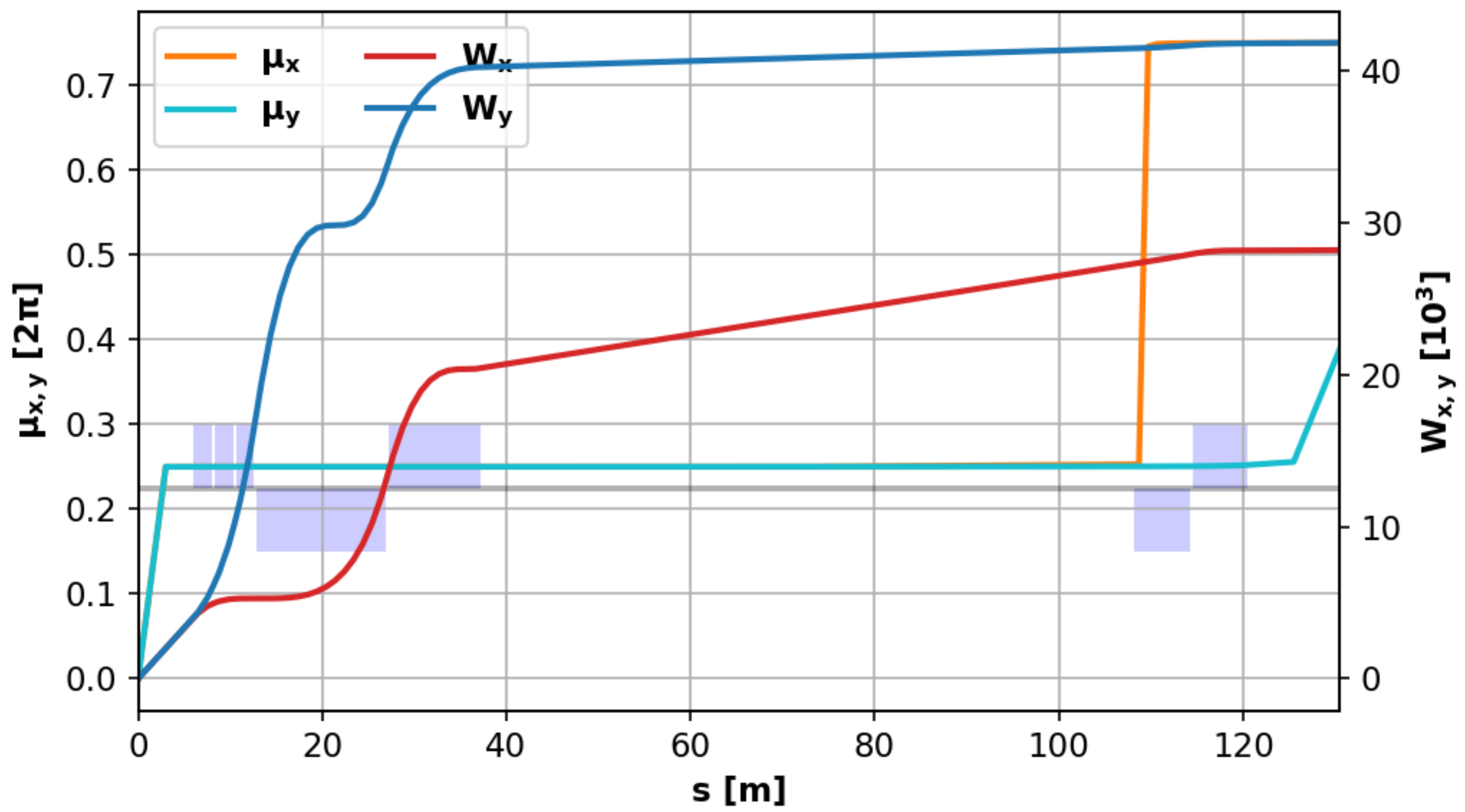
Beam characteristics:

- rms relative momentum spread σ_δ~10^{-3}.
- Twiss beta at IP and bunch length $\beta^*=\sigma_z=\varepsilon_l/(\sigma_\delta E)$=1.5mm (5ps).
- Hour glass effect becoming significant (lumi reduction f_{hg}~0.76).

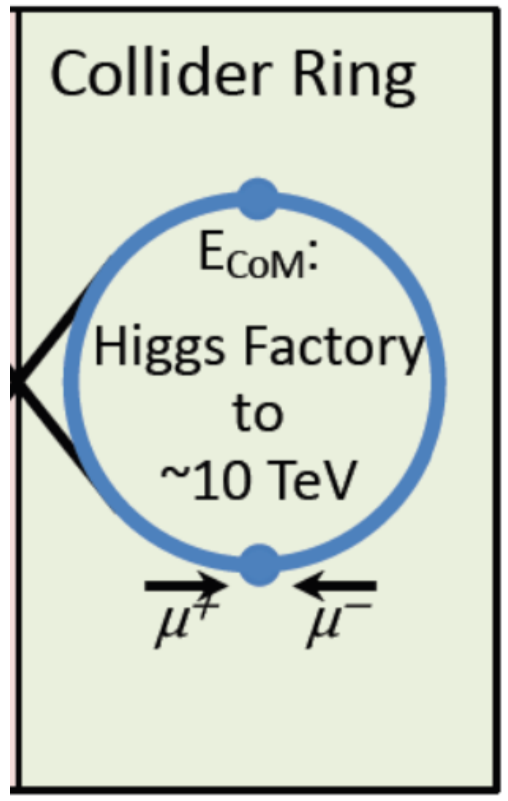


Challenging conditions for collider lattice design:

- Small β* at high beam rigidity enhancing chromatic effects.
- Large beta-functions at locations with superconducting magnets.
- Short bunch length to be kept for ~1000 turns.
- Radiation from muon decay products.

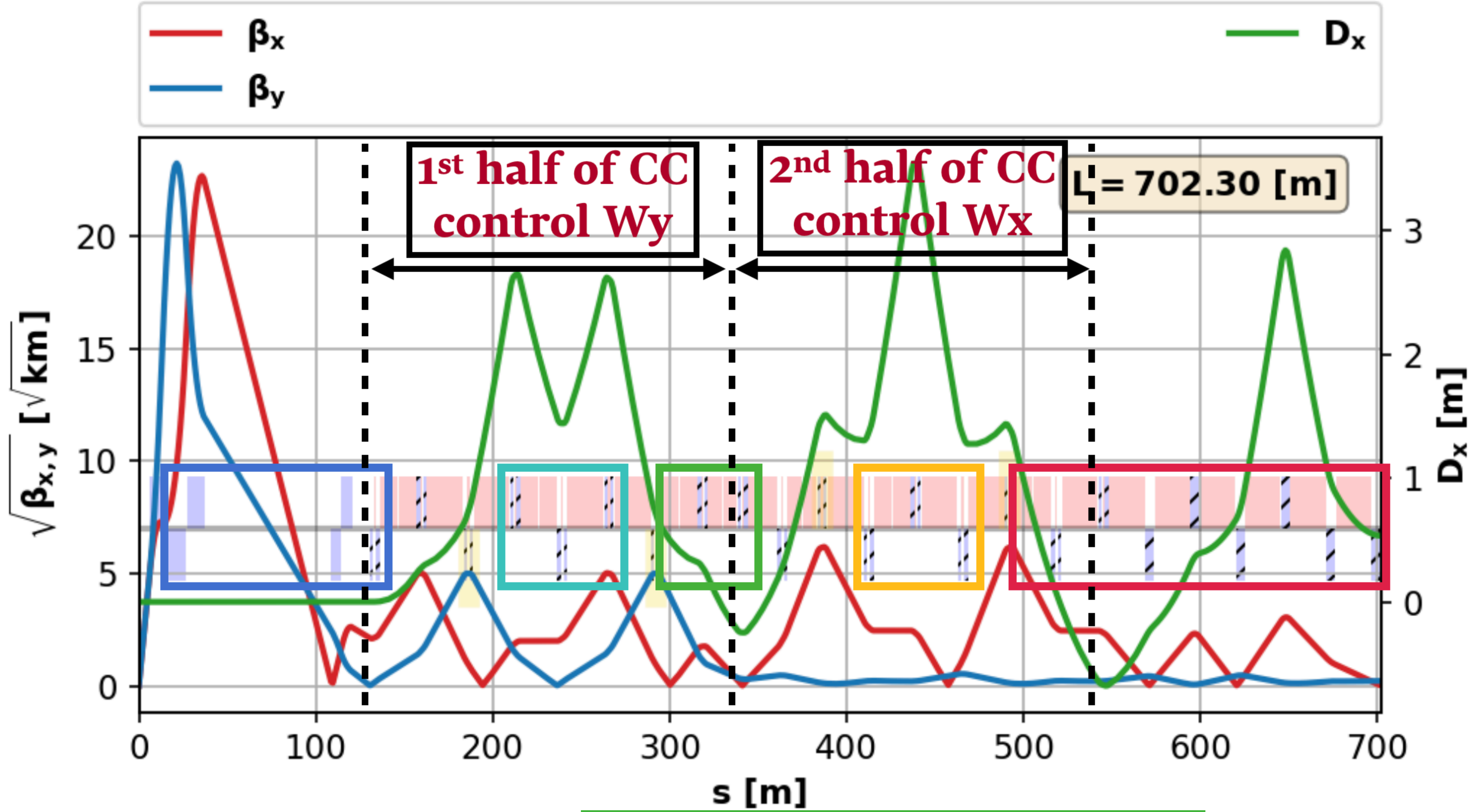


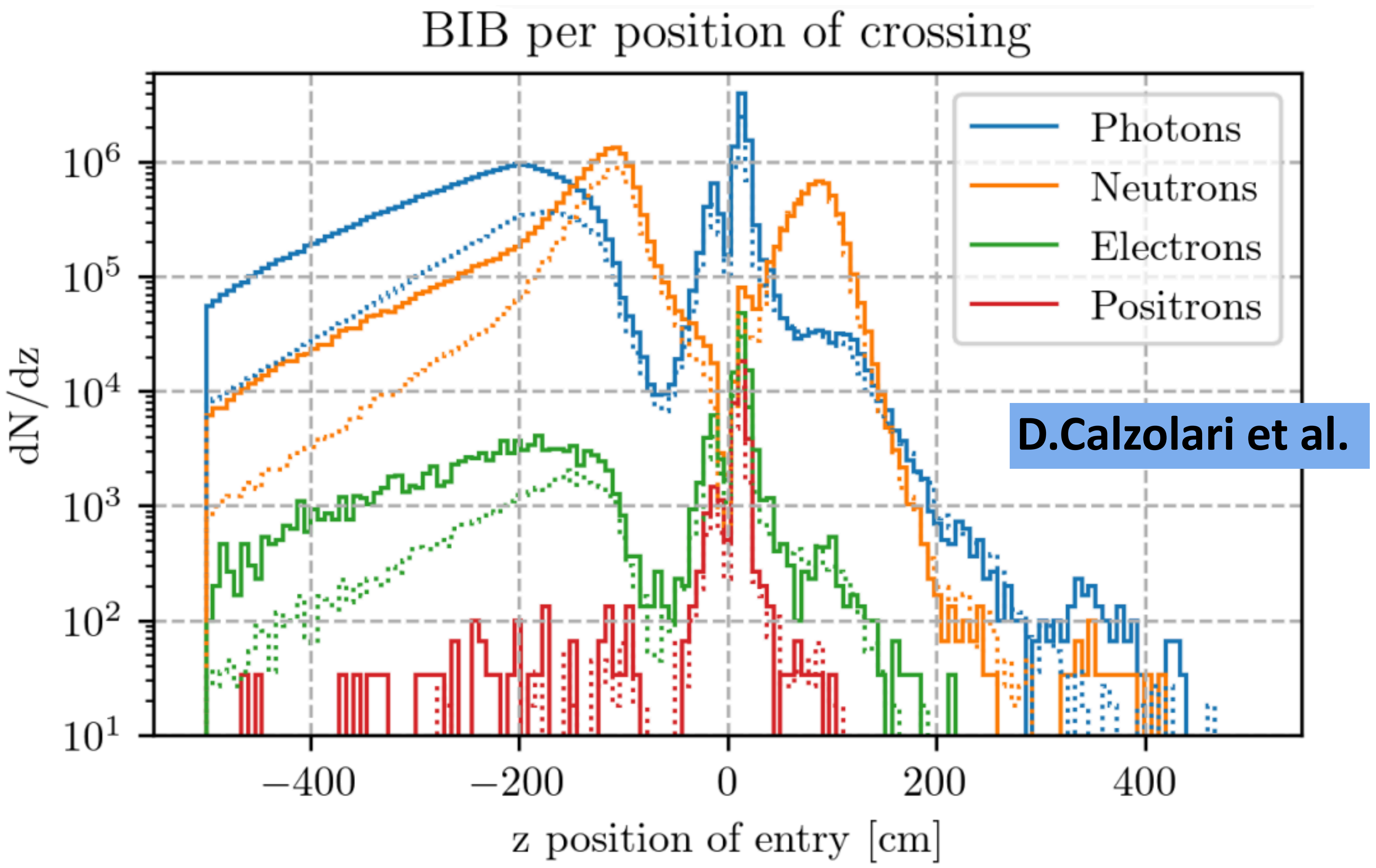
Muon Collider Ring - extended final focusing



Extended final focusing region:

- Final focusing quads (max βs~500km).
- Chromatic correction section for the control of the strong (non)linear chromatic aberrations.
- Matching section to connect with the arc and control of the working point.
- Muon decay products generate beam induced background at detectors and should be controlled as well as possible (nozzle see next presentation, addition of dipolar components in FF).

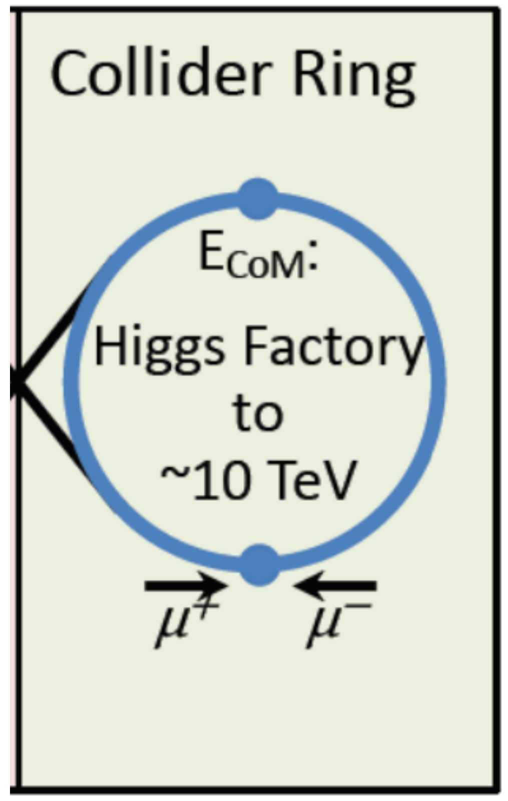




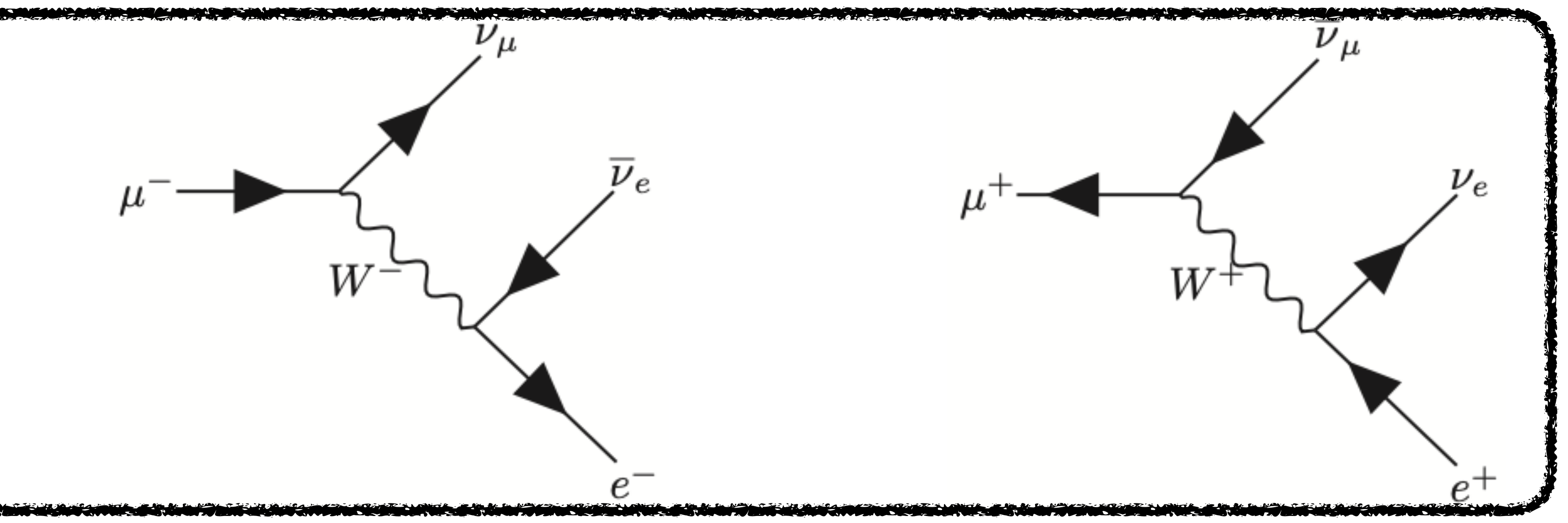
D.Calzolari et al.

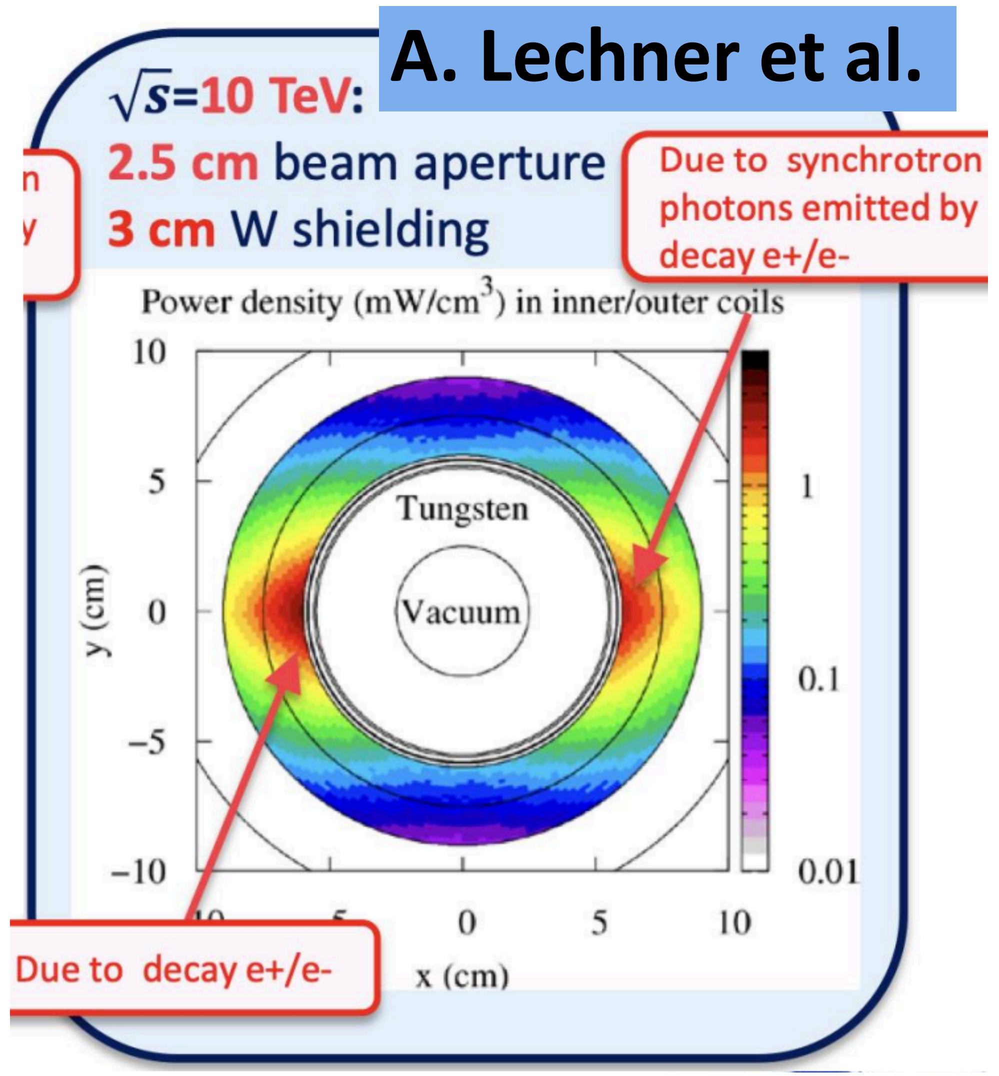
Control $\beta_{x,y}$, $\alpha_{x,y}$ and μ_y at the 1st half of CC	Control $\alpha_{x,y}$ and μ_x at the 2nd half of CC	
Generate -I transform at the 1st half of CC	Generate -I transform at the 2nd half of CC	Control of working point and matching with arc

Muon Collider Ring - radiation due to muon decay



Muon decay



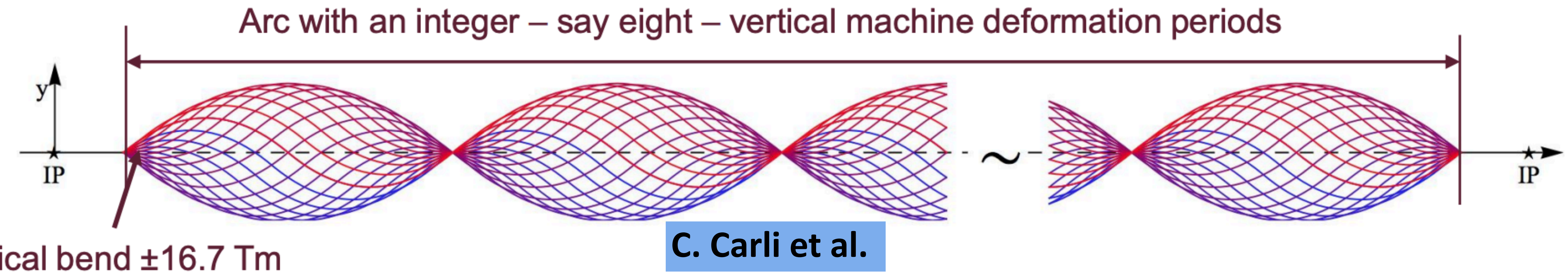


Due to photons and e^-/e^+:

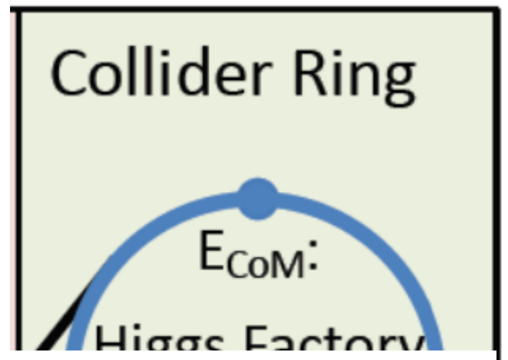
- W absorber to intercept most of shower (~500 W/m for 10km).
- Residual power "leaking" into cold mass.
- Cryo load, radiation damage etc. "under control" with 30-40mm absorber.

Due to neutrinos:

- Showers generated by neutrinos close the earth surface
  - extensive use of dipoles and combined function magnets for evenly distribute the neutrino radiation
  - wobbling of machine in vertical direction (modulation within ±1 mrad reduce peak dose by factor ~100)
  - positioning such that neutrinos from IR reach earth surface in uncritical areas.
- Cross sections and energy deposition per interaction about proportional to energy.
- Strong increase of maximum dose with muon energy.

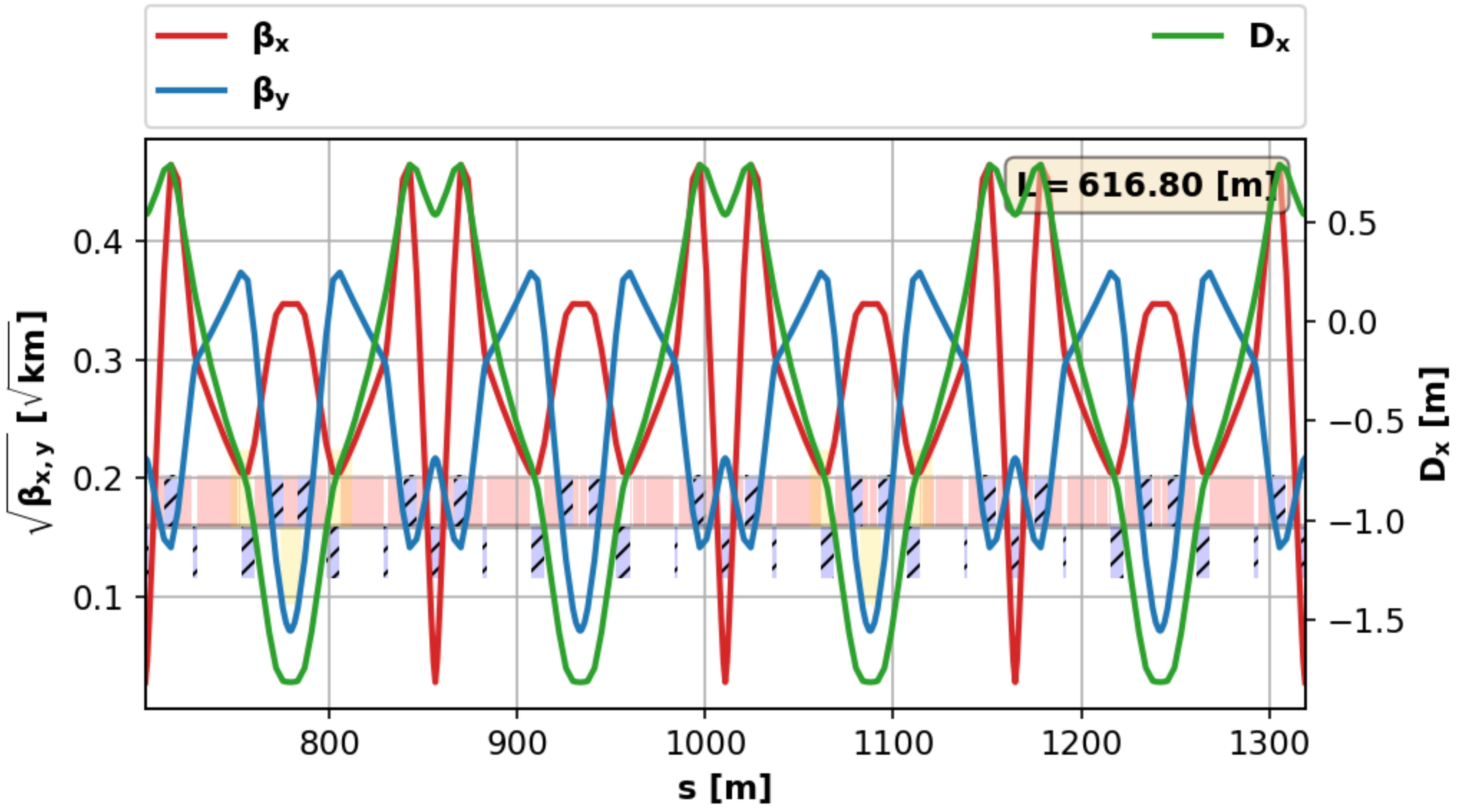


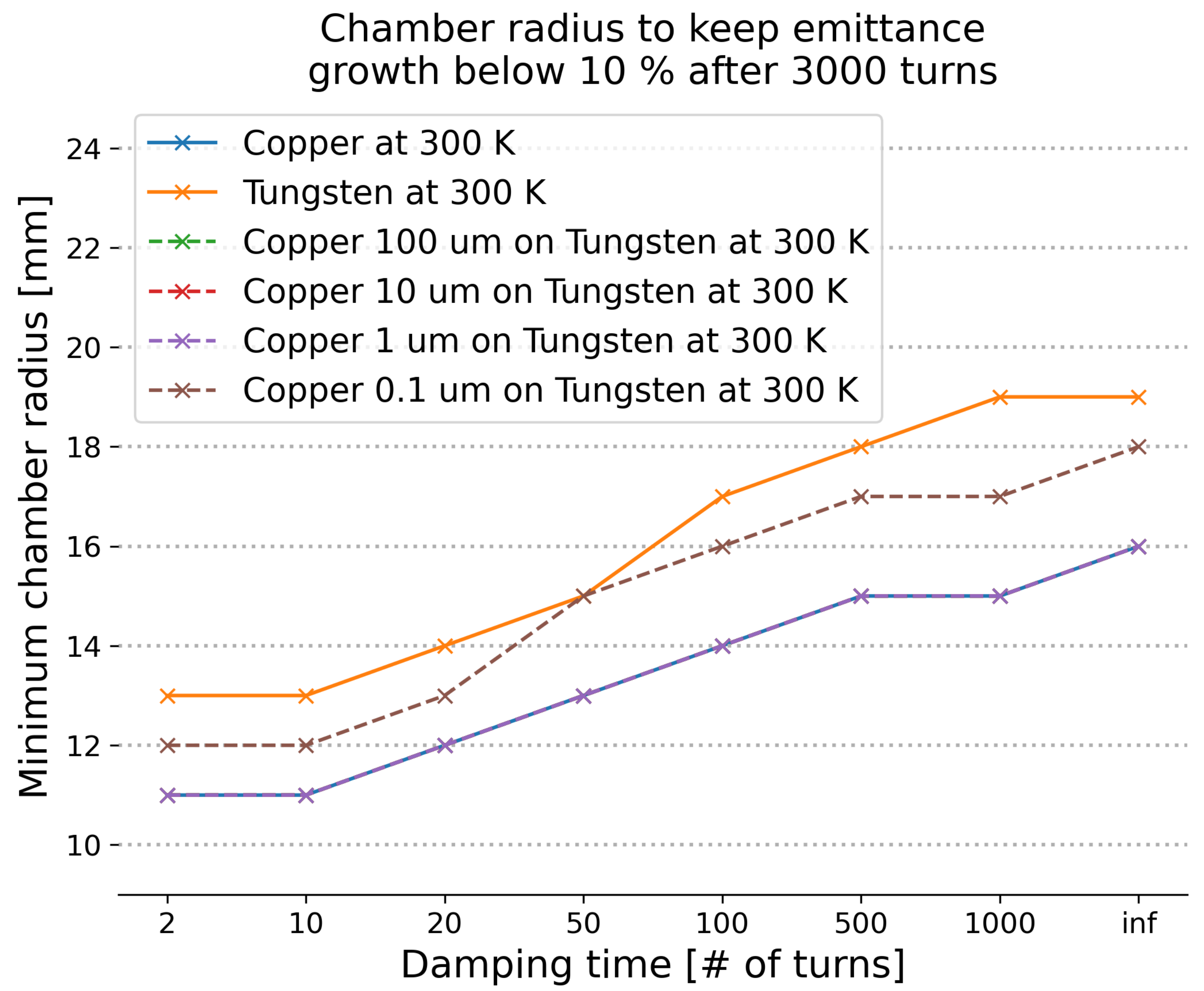
Muon Collider Ring - arc



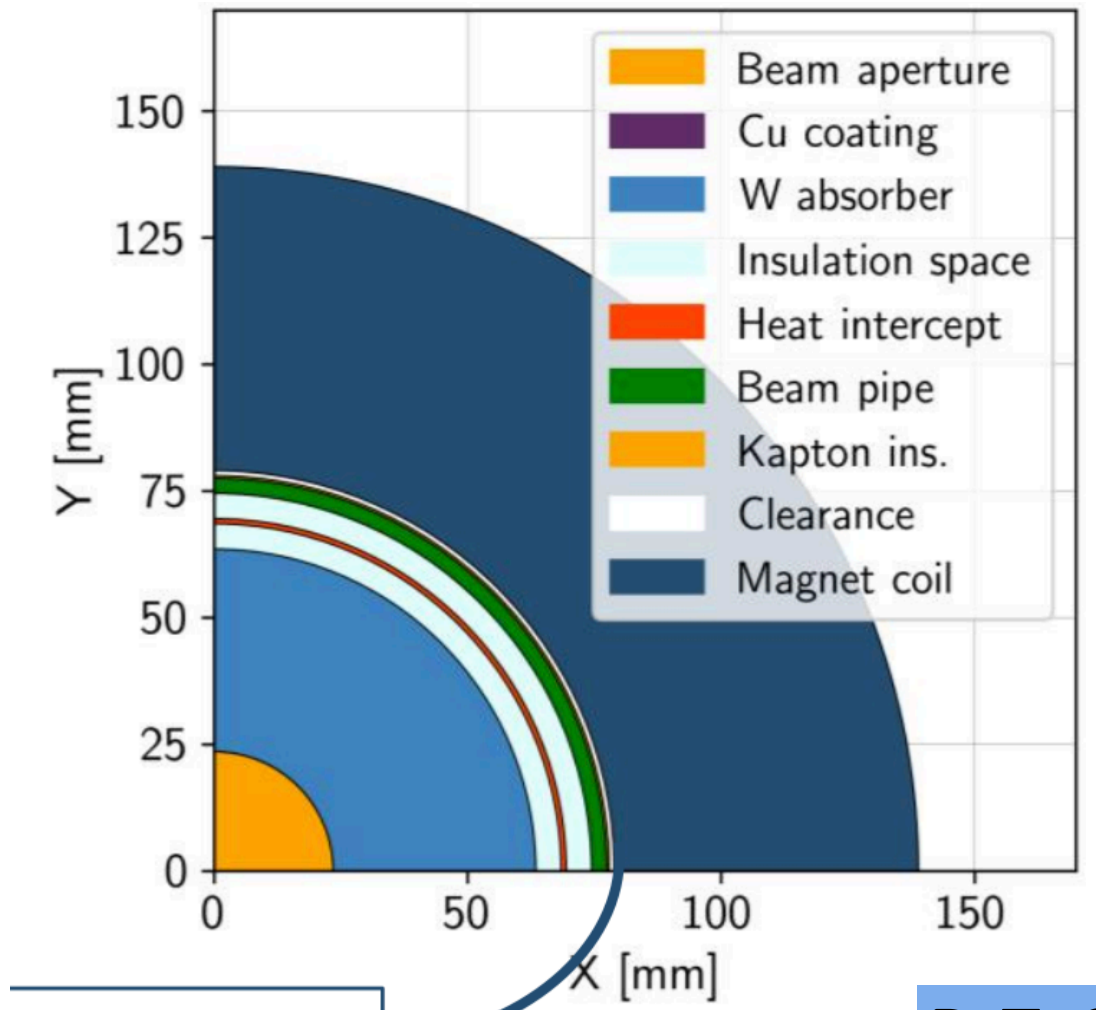
Arc:

- Flexible Momentum Compaction arc cells.
- Keep α_p to small values (restrict bunch lengthening).
- Controls linear chromaticity.
- Copper coated (>1µm) on tungsten and 50(>1000)-turn damper need for 13(<20)mm radius.
- Preliminary coil aperture 158mm.
- 25MW Cryo for a 10km ring
  - feasible only with "warm" W absorber
  - use of HTS appealing
  - cooling magnets under discussion, T_{abs}≥250K (CO_2 or water), T_{coil}≥10K (He or H_2).

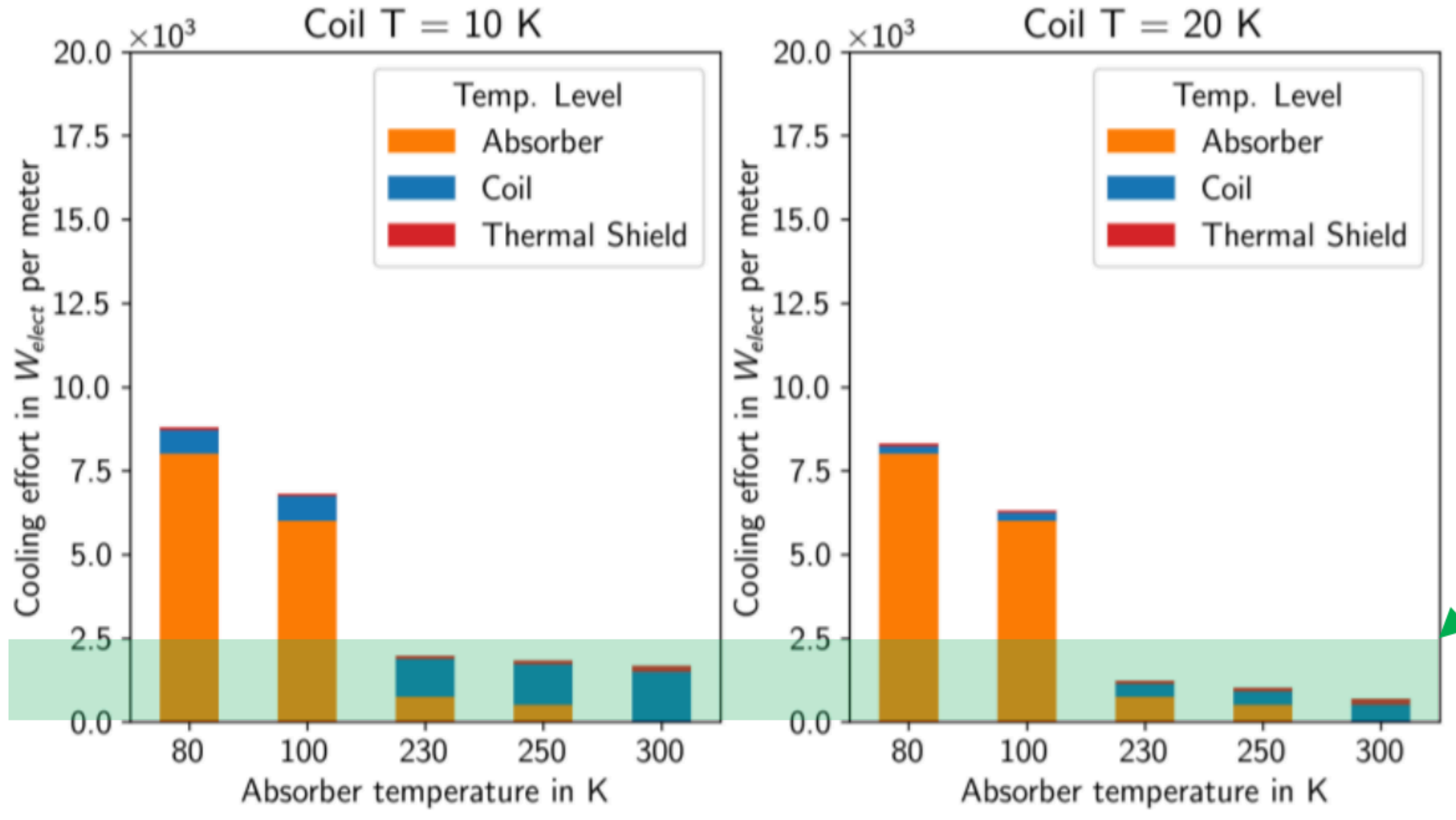




D. Amorim et al.



Coil aperture 158 mm



P. T. Coutinho et al.

Target:
25 MW for Cryo in collider
(2.5 kW_{el}/m)

Summary

Muon Collider is an attractive option for a future high-energy, high-luminosity lepton collider

- IMCC aims to design a 10+ TeV com energy muon complex.
- Might be more efficient in construction and operational cost than other future machines.

Collaboration exists and is growing

- Addressing key challenges.

A number of proof-of-principle experiments and component tests have been carried

- Practical demonstration of the underlying technologies.
- Underlying technologies will be exploited in order to ensure the best possible performance.

http://muoncollider.web.cern.ch

Thank you for your time!

Most of the presented studies are work in progress.

Many of the images shown are taken from MAP, MICE and IMCC publications.

Ideas on muon colliders

Present status of ideas on muon colliders are based on several studies in the past

Project	Place	Period
g-2 experiment (measuring the anomalous magnetic moment of the muon)	CERN	1959 - 1989
“On the effects at colliding μ meson beams” (F. Tikhonin, arXiv:0805.3961)	JINR Dubna	1968
“Accelerators and colliding beams” (G. Budker, μ^+/μ^- storage ring c.m.e. few 100’s GeV)	INP Novosibirsk	1969
European Muon Collaboration - EMC (interactions of muons up to 280GeV in NA2, NA9 and NA28 expiraments at SPS)	CERN	1973 - 1985
MC design considerations and ionization cooling of muons (A. Skrinsky and V. Parkhomchuk)	INP Novosibirsk	1981
Comprehensive theory of ionization cooling of muons (D. Neuffer)	Fermilab	1983
First US Studies on Muon Collider Complex (“Status of muon collider research and development and future plans” Phys. Rev. ST Accel. Beams 2, 081001 (1999))	USA	1990 - 1999
First European study on muon collider potential (“Prospective Study of Muon Storage Rings at CERN)	CERN	1999
Neutrino Factory and Muon Collider Collaboration - NFMCC	USA	2000 - 2010
Muon Accelerator Program - MAP	USA	2010 - 2017
Muon Ionization Cooling Experiment - MICE (demonstrate ionization cooling of muons, Nature volume 578, pages53–59 (2020))	UK	2015 - present
International Muon Collider Collaboration - IMCC (Muon collider complex with c.m.e. ~10TeV, Nature Physics volume 17, pages289–292 (2021))	Global	2021 - present
Muon collider physics case (physics case “explosion” last 3 years)	Global	1990 - present

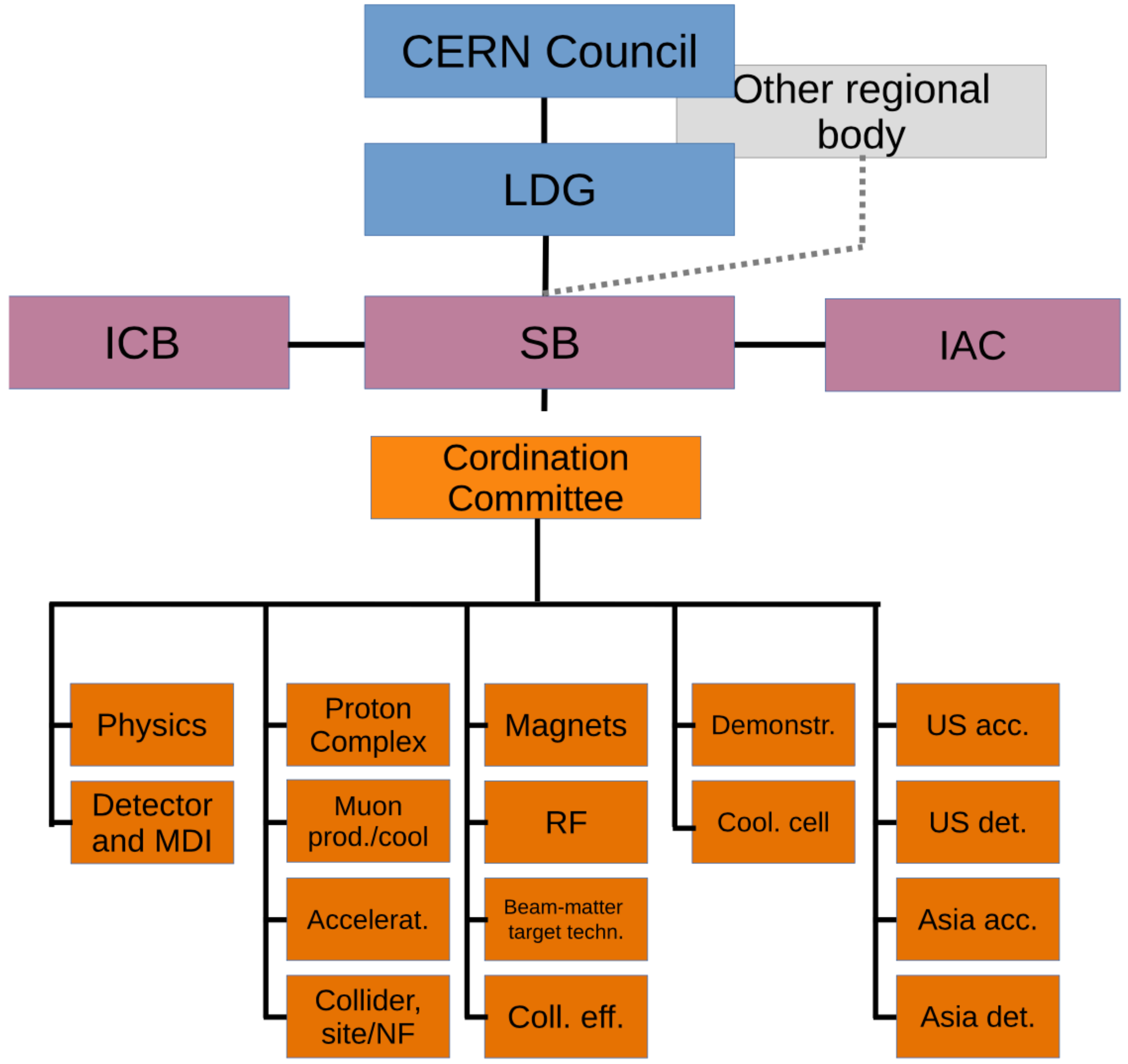
International Muon Collider Collaboration

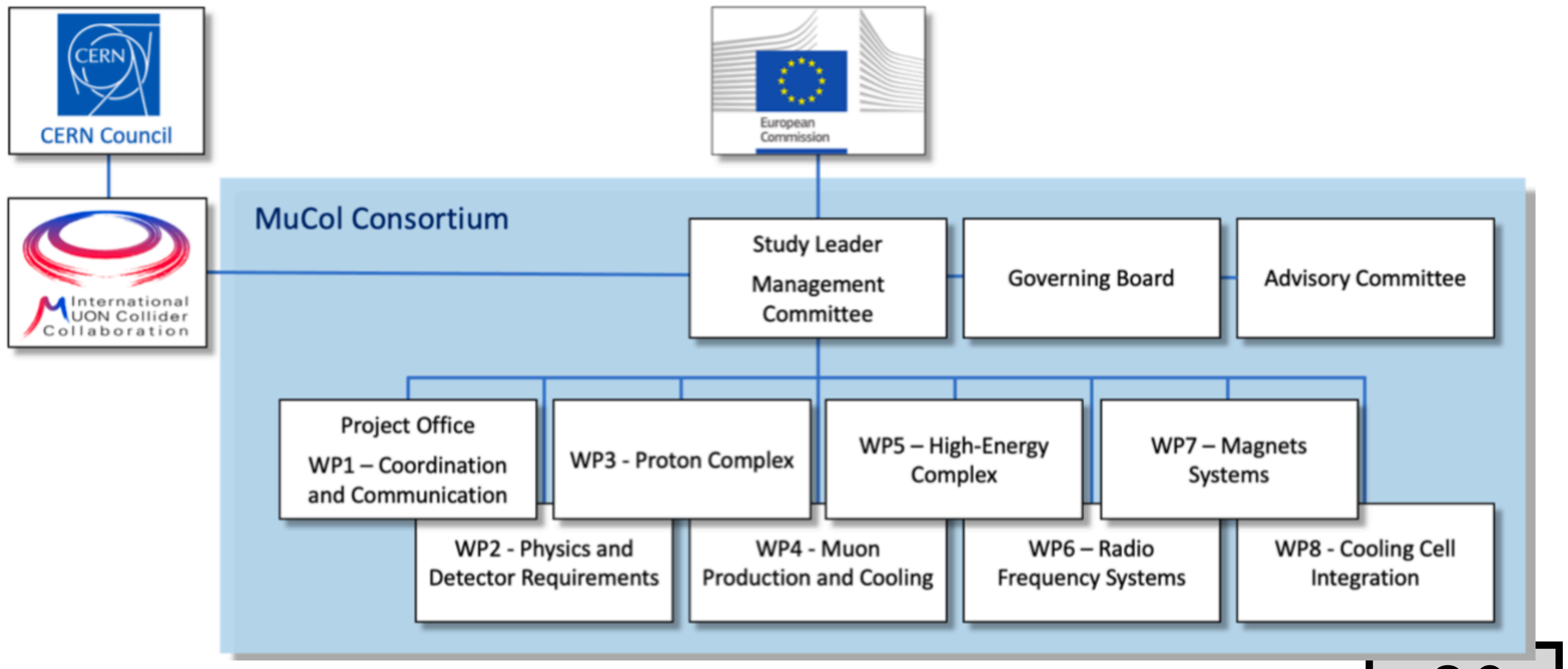
- The **collaboration is formed to implement an R&D Roadmap** for CERN Council:
  - **No insurmountable obstacle found for the muon collider**
    - but important need for R&D
    - develop funding scenarios.
  - Scenarios delivered by next ESPP update.
  - 50+ partner institutions (30+ already signed agreement).

- **US Snowmass strong interest**
  - To contribute to R&D and potentially collider in the US.
  - Now waiting for P5.

- **EU Design Study approved** this summer**,** 32 partners (EU+Switzerland+UK and partners), O(3+4 MEUR).

- Plan to apply in 2024 for **HORIZON-INFRA-2024-TECH** Goal: prepare experimental programme, e.g. **demonstrator, prototypes, …**





International Muon Collider Collaboration

IEIO	CERN
FR	CEA-IRFU
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	INFN
	INFN, Univ., Polit. Torino
	INFN, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
SE	ESS
	University of Uppsala
PT	LIP
NL	University of Twente
US	Iowa State University
	Wisconsin-Madison
	Pittsburg University
	BNL

UK	RAL
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
EST	Tartu University
LAT	Riga Technical Univers
AU	HEPHY
	TU Wien
ES	I3M
CH	PSI
	University of Geneva
	EPFL
BE	Louvain
FI	Tampere University
China	Sun Yat-sen University
	IHEP
	Peking University

IT	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
US	FNAL
	LBL
	JLAB
	Chicago
Japan	Akira Yamamoto
	Akira Sato
	Toru Ogitsu