Accelerator Physics and Challenges for Future Colliders III

D. Schulte, CERN

Muon Collider

Motivation and Goal

Previous studies in US (now very strong interest again), experimental programme in UK and alternatives studies by INFN

New strong interest in **high-energy, high-luminosity lepton collider**

- Combines **precision physics** and **discovery reach**
- Application of hadron collider technology to a lepton collider

Muon collider promises **sustainable** approach to the **energy frontier**

- limited power consumption, cost and land use

Technology and **design advances** in past years

- review did not find any showstoppers

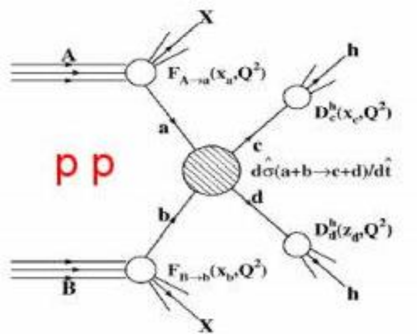
Goal is

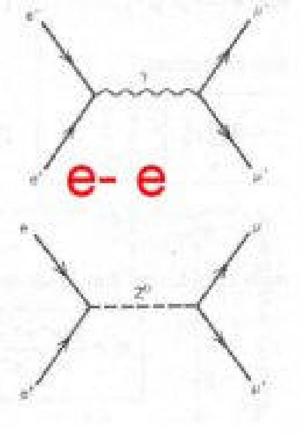
- 10+ TeV collider
- potential initial energy stage (e.g. 3 TeV)
- higher energies to be explored later

Physics Goals

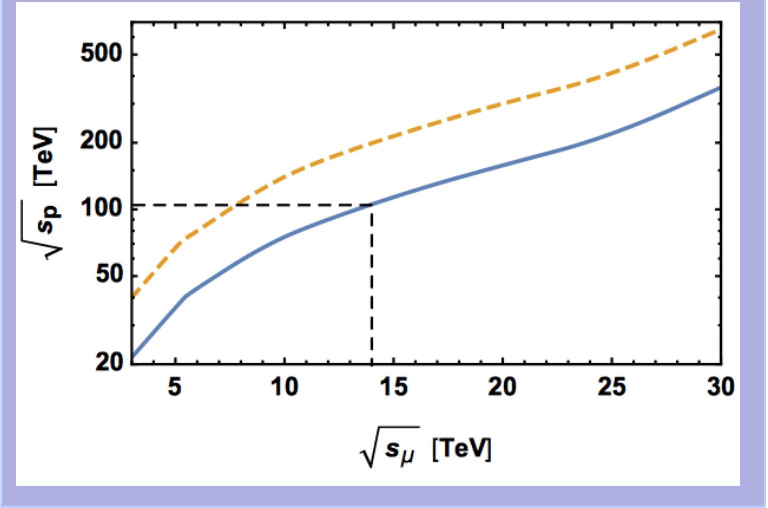
Energy for discovery reach

10-14 TeV lepton collisions comparable to 100-200 TeV proton collisions



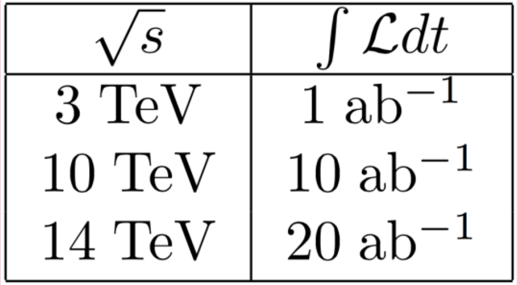


Leptons make the full energy available for particle production, protons only a fraction



Luminosity must increase as E_{cm}^2 as production cross sections decrease

Theorists defined goals:
Yields constant number of events in the s-channel

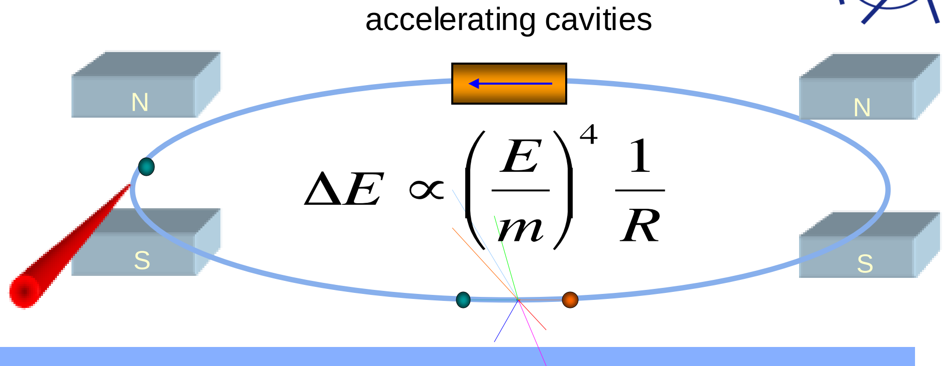


$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

High-energy Colliders

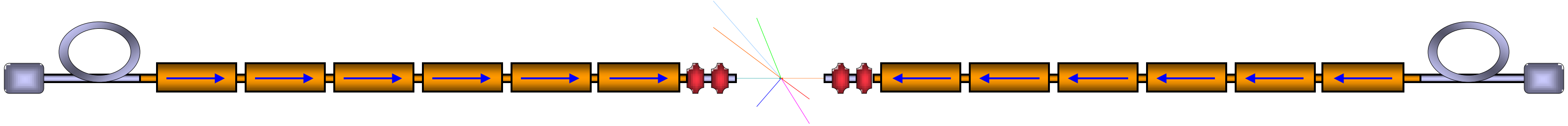
Electron-positron rings are **multi-pass** colliders limited by synchrotron radiation: **LEP, FCC-ee, CEPC**

Hence **proton rings** are energy frontier: **LHC, FCC-hh, SppC**



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

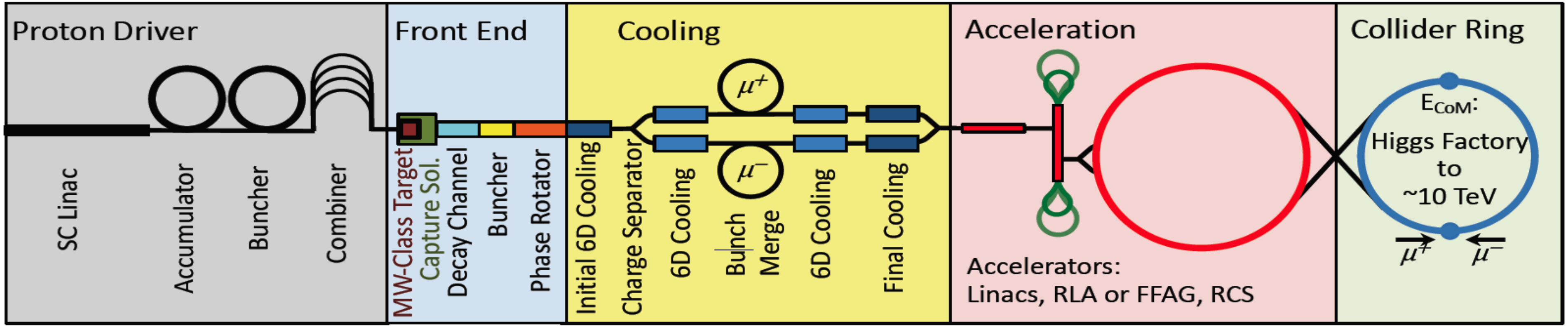
Electron-positron linear colliders avoid synchrotron radiation, but **single pass: SLC, ILC, CLIC**
Typically cost proportional to energy and power proportional to luminosity,



Novel approach: **muon collider** (the first of its kind)
Large mass suppresses synchrotron radiation => **multi-pass**
Fundamental particle requires less energy than protons
But lifetime at rest only 2.2 μs
Proportional to energy

Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is τ = γ x 2.2 μs



Short, intense proton bunch

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

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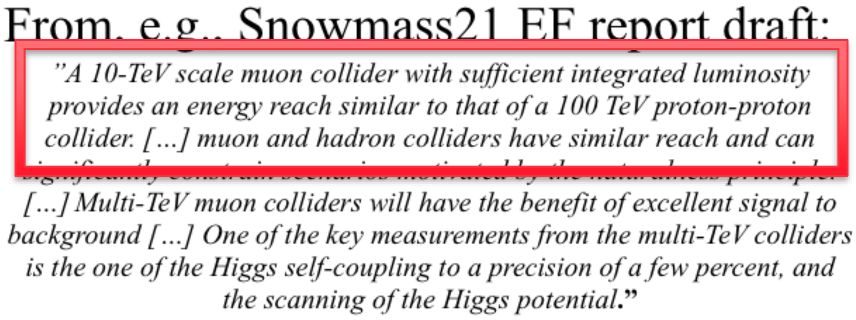
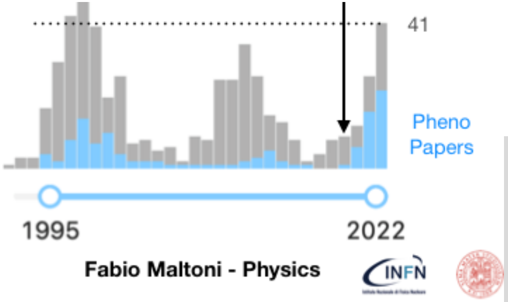
A New Interest in Muon Colliders



From, e.g., Snowmass21 EF report draft:

> *"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. […] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. […] Multi-TeV muon colliders will have the benefit of excellent signal to background […] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential."*



from F. Maltoni at IMCC Annual Meeting

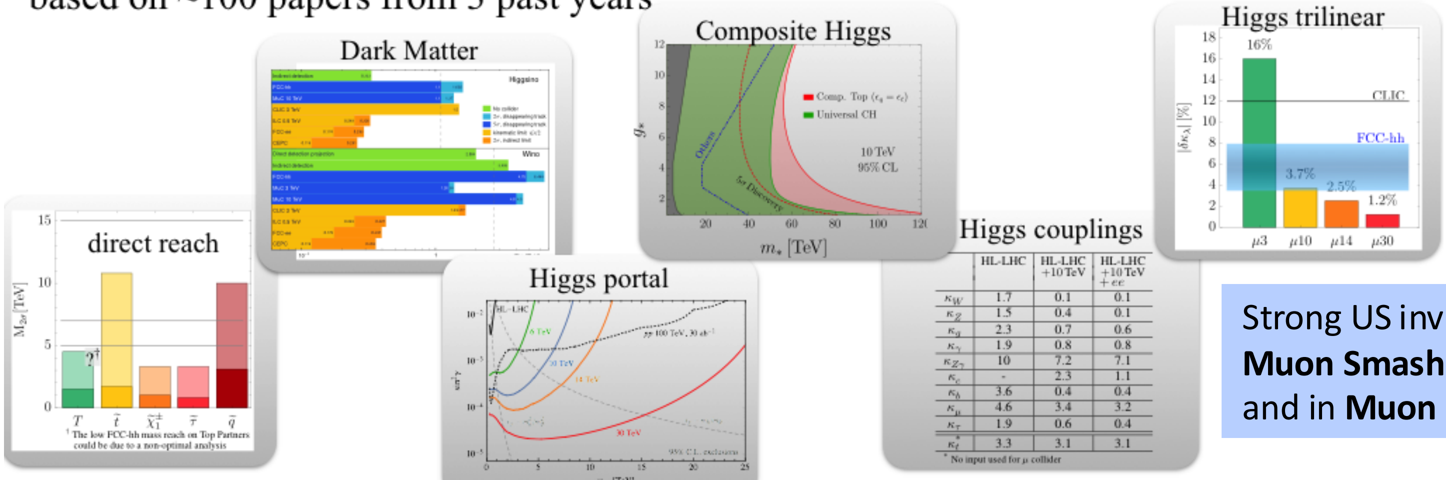
A. Wulzer, F. Maltoni, P. Meade et al.

O(150) authors, 15 editors, 100 papers

DELPHES card available

Selected summary plots, from Snowmass21 reports:

2 IMCC reports, plus Muon Collider Forum report. Total of 15 editors, ~150 authors, based on ~100 papers from 3 past years



† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

Higgs couplings

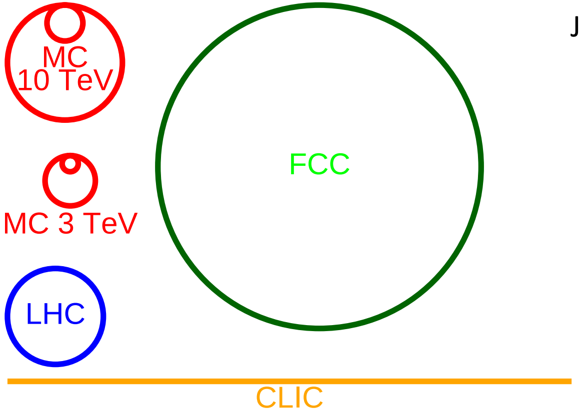
	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV $+ee$
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

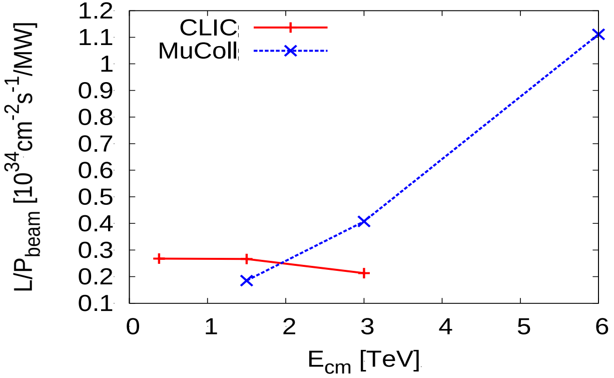
* No input used for μ collider

Strong US involvement starting with **Muon Smasher's Guide** and in **Muon Collider Forum**

Muon Collider Promises

US Snowmass Implementation Task Force: Th. Roser, R. Brinkmann, S. Cousineau, D. Denisov, S. Gessner, S. Gourlay, Ph. Lebrun, M. Narain, K. Oide, T. Raubenheimer, J. Seeman, V. Shiltsev, J. Straight, M. Turner, L. Wang et al.





	CME [TeV]	Lumi per IP [10^{34}cm^{-2}s^{-1}]	Years to physics	Cost range [B$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
ILC	0.25	2.7	<12	7-12	140
CLIC	0.38	2.3	13-18	7-12	110
ILC	3	6.1	19-24	18-30	400
CLIC	3	5.9	19-24	18-30	550
MC	3	1.8	19-24	7-12	230
MC	10	20	>25	12-18	300
FCC-hh	100	30	>25	30-50	560

Judgement by ITF, take it *cum grano salis*

Goal and Accelerator R&D Roadmap

Muon collider is on European **Accelerator R&D Roadmap**

- Reviews in Europe and US found **no insurmountable obstacle**

Implementing workplan

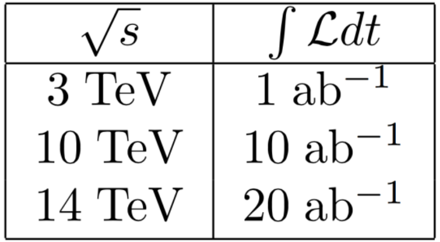
- Goal: **Project Evaluation Report** and **R&D Plan** to next ESPPU/other processes
- 10+ TeV collider, potential 3 TeV initial stage
- CERN has budget in MTP, hosting a collaboration
- Design Study supported by EC, Switzerland, UK and partners contribute
- Strong interest in US community to join and contribute at same level as Europe

We still need more resources

- But **doubled last year** with EU Design Study
- **Might double** with US joining
- Preparing other requests
- Exploitation of synergies

Label	Begin	End	Description	Aspirational		Minimal	
				[FTEy]	[kCHF]	[FTEy]	[kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment and similar costs. Colours are included for comparison with the resource profile Fig. 5.7.



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

http://arxiv.org/abs/2201.07895

Muon Collider Timeline (Roadmap)

Muon collider important in the long term

- Even after potential FCC-hh

But also **plan B as next project in Europe** and maybe **plan A in US** and elsewhere

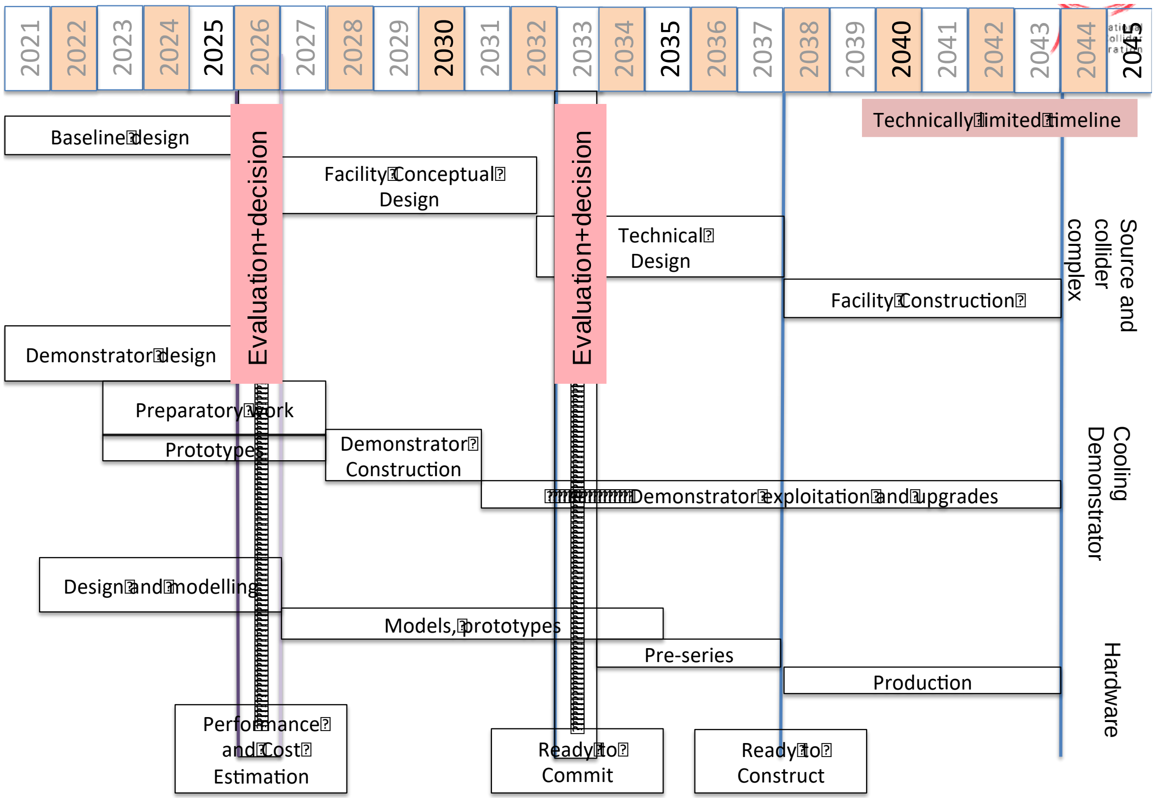
Fast track option if require next as project after HL-LHC:

- Lower energy initial option, e.g. 3 TeV
- Upgrade to 10 TeV later
    - Little extra cost

Subject to funding

Technically limited timeline

To be reviewed considering progress, funding and decisions



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Evaluation+decision

Evaluation+decision

Source and collider complex

Baseline design

Facility Conceptual Design

Technical Design

Facility Construction

Cooling Demonstrator

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Hardware

Design and modelling

Models, prototypes

Pre-series

Production

Performance and Cost Estimation

Ready to Commit

Ready to Construct

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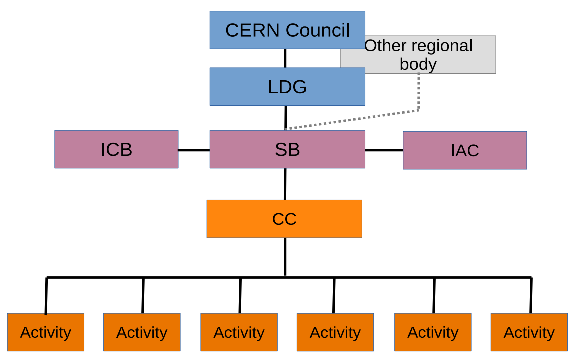
Muon Collider Community

CERN-hosted **collaboration**

O(70) partners, 60+ already signed MoC


CERN Council
Other regional body
LDG
ICB
SB
IAC
CC
Activity
Activity
Activity
Activity
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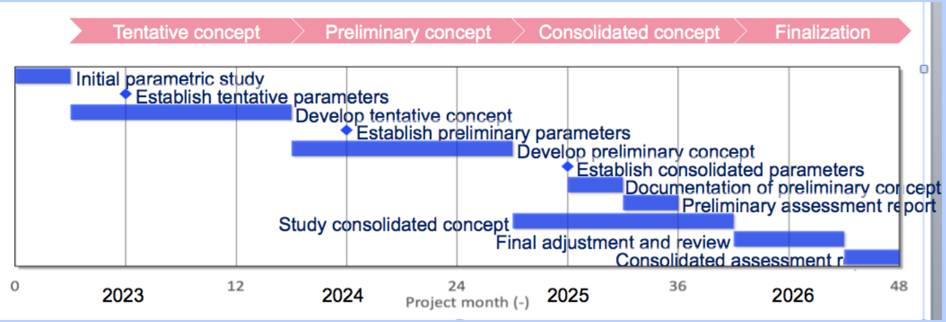
Activity

EU Design Study helped to kick-start collaboration (since March 2023, EU+Switzerland+UK and partners)

EU support also helps with funding in institutes



Looking for **new partners**

- In particular US
- But also other regions

Increase resources of partners with other **funding requests**:

- Submit to **HORIZON-INFRA-2024-TECH**
  - Focus on magnet technologies
- **National funding agencies**

IMCC Partners

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham

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
	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
Mal	**Univ. of Malta**
EST	***Tartu University***

SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical University**
CH	**PSI**
	University of Geneva
	EPFL
BE	**Univ. Louvain**
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
China	***Sun Yat-sen University***
	IHEP
	Peking University
KO	**KEU**
	Yonsei University

US	**Iowa State University**
	University of Iowa
	Wisconsin-Madison
	University of Pittsburgh
	Old Dominion
	Chicago University
	Florida State University
	RICE University
	Tennessee University
	MIT Plasma science center
	Pittsburgh PAC
India	***CHEP***

US	FNAL
	LBL
	JLAB
	BNL

US P5: The Muon Shot

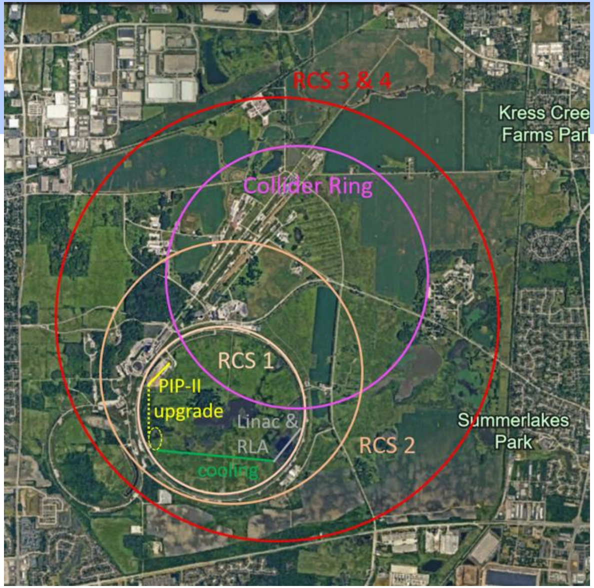
US has been instrumental in advancing the muon collider during Snowmass process

- See the contributions even increase after the process

Particle Physics Project Prioritisation Panel (P5) supports US ambition to host a 10 TeV parton-parton collider

- Endorses muon collider R&D: ”This is our muon shot”
- Recommend joining the IMCC and consider FNAL as a host candidate

Warmly welcome the US



Informal discussion with DoE (Regina Rameika, Abid Patwa):

- DoE wants to maintain IMCC as a **international collaboration**
- **Addendum to CERN-DoE-NSF agreement** is being preparation
  - Will allow labs to join
- Universities are joining already now

IMCC prepares options for Europe and for the US in parallel

Tentative Staged Target Parameters

Target integrated luminosities

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

Need to spell out scenarios

Need to integrate potential performance limitations for technical risk, cost, power, …

Parameter	Unit	3 TeV	10 TeV	10 TeV	10 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**tbd**	**13**
N	10^{12}	2.2	1.8	1.8	1.8
f_r	Hz	5	5	5	5
P_{beam}	**MW**	**5.3**	**14.4**	**14.4**	**14.4**
C	km	4.5	10	15	15
<B>	T	7	10.5	7	7
ε_L	MeV m	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	tbd	0.1
σ_z	mm	5	1.5	tbd	1.5
β	mm	5	1.5	tbd	1.5
ε	µm	25	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	1.3	0.9

Examples as discussion basis

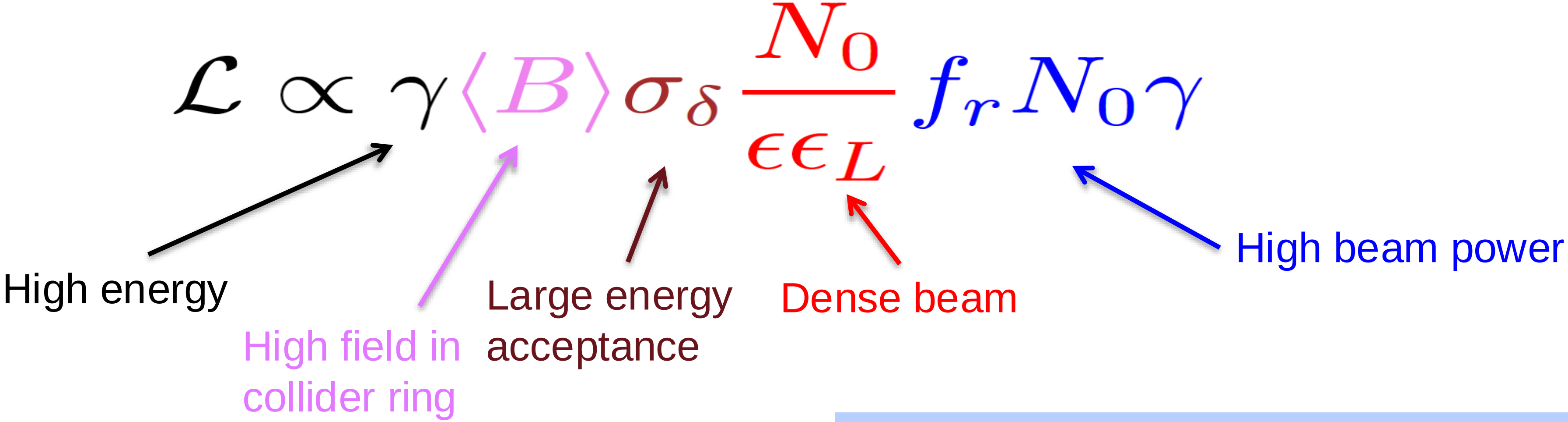
numbers will change

Muon Collider Luminosity Scaling

Fundamental limitation

Requires emittance preservation and advanced lattice design

Applies to MAP scheme



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

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

Luminosity per power increases with energy
Provided technologies can be made available

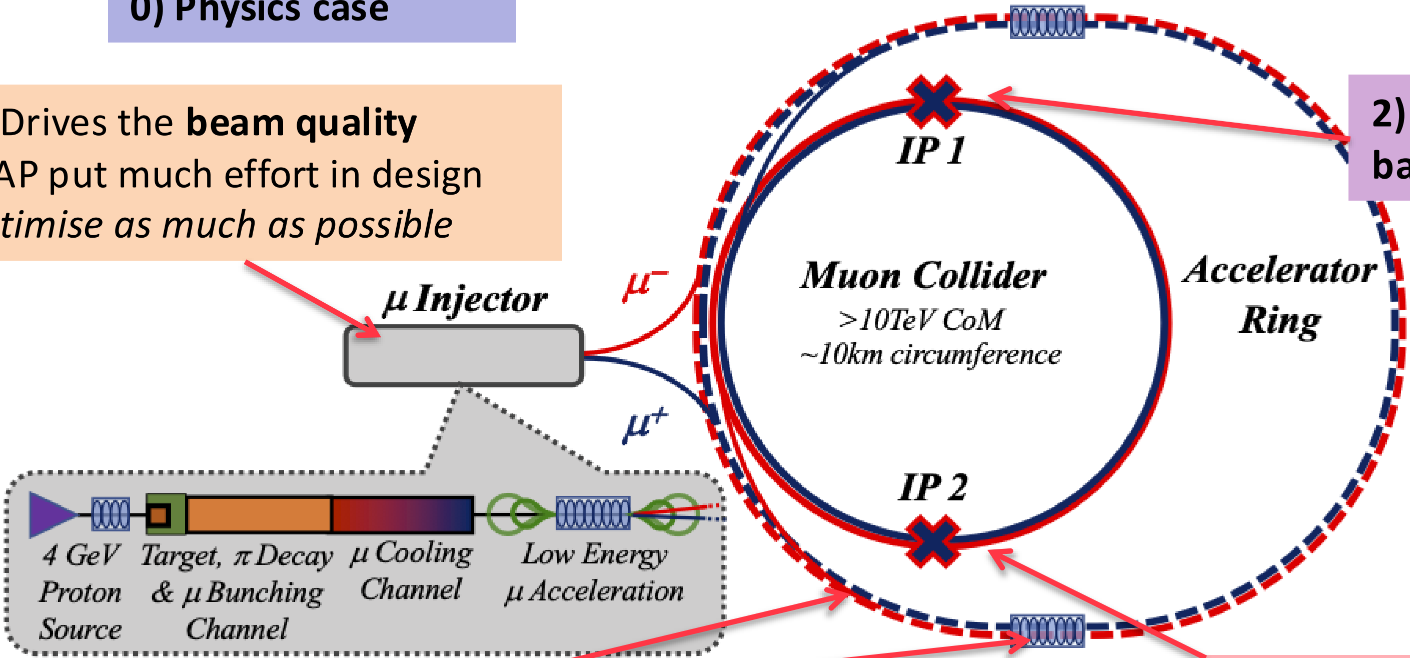
Constant current for required luminosity scaling

Key Challenges

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible

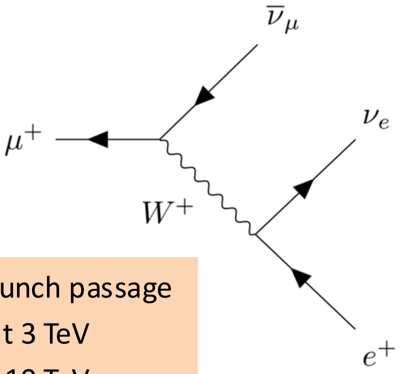
2) Beam-induced background

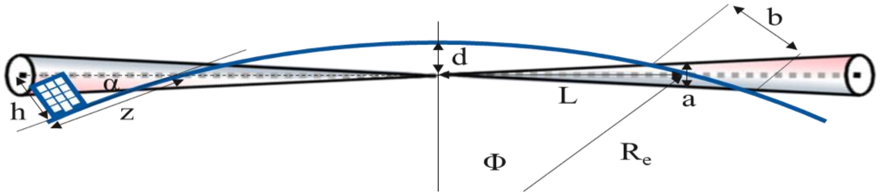


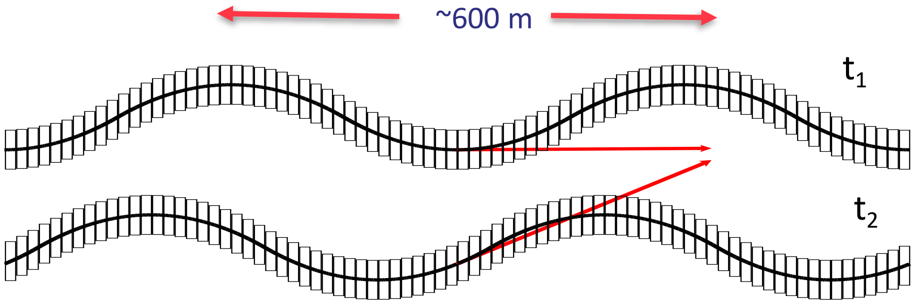
1) Dense neutrino flux
mitigated by mover system
and site selection

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

Muon Decay and Neutrino Flux





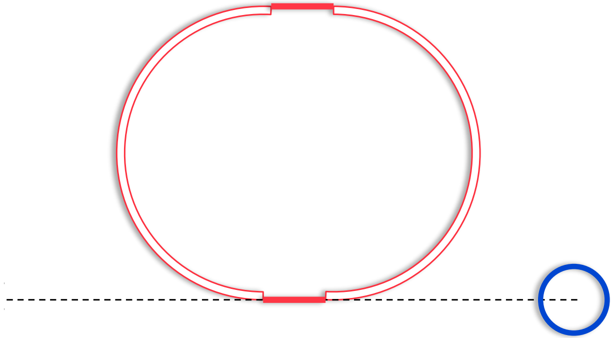


Muon decays per bunch passage

- 235,000 m^{-1} at 3 TeV
- 58,000 m^{-1} at 10 TeV

But want to have **negligible impact from arcs**

- Similar impact as LHC
- At 3 TeV this is the case for 200 m depth
- At 10 TeV use angle change of +/- 1 mradian to go from acceptable to negligible level
  - Mockup of mover system planned
  - Impact on beam to be checked



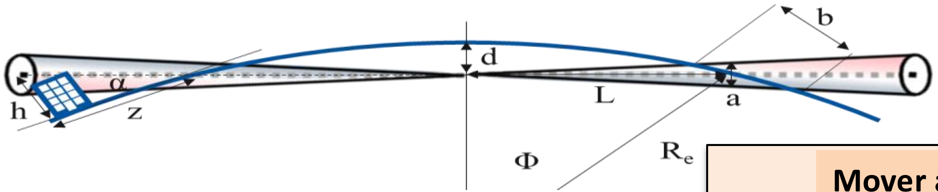
Impact of experimental insertions

- 3 TeV design acceptable with no further work
- Maybe acquire land in direction of experiment, also for 10 TeV

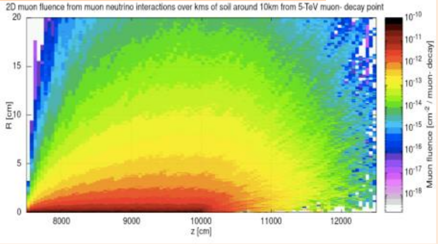
Neutrino Flux

Goal: **similar to LHC**: limit neutrino flux to have **negligible impact**, "fully optimised" (10% of MAP goal)

Verify performance of concept to be good for 14 TeV

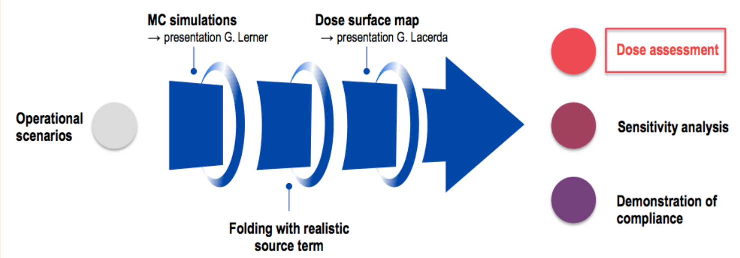


FLUKA dose studies



G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme



MC simulations
→ presentation G. Lerner

Dose surface map
→ presentation G. Lacerda

Operational scenarios

Folding with realistic source term

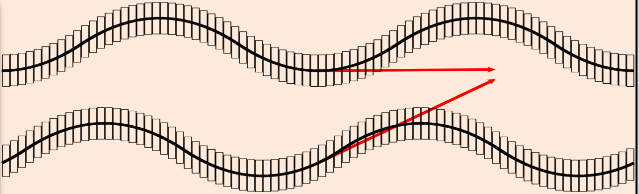
Dose assessment

Sensitivity analysis

Demonstration of compliance

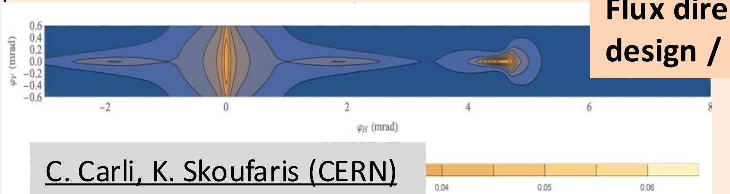
C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

Mover and support system



F. Bertinelli et al. (CERN, Riga)

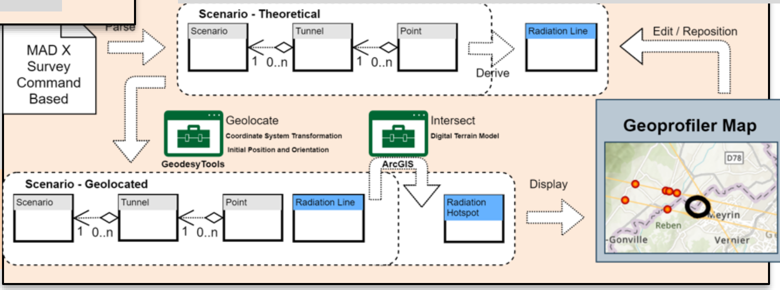
Flux direction map / lattice design / mover impact on beam



C. Carli, K. Skoufaris (CERN)

G. Lacerda, Y. Robert, N. Guilhaudin (CERN)

Mitigation: Site choice tool



MAD X Survey Command Based

Parse

Scenario - Theoretical

Scenario

Tunnel

Point

Radiation Line

Derive

Edit / Reposition

Geolocate

Coordinate System Transformation

Initial Position and Orientation

GeodesyTools

Intersect

Digital Terrain Model

ArcGIS

Scenario - Geolocated

Scenario

Tunnel

Point

Radiation Line

Radiation Hotspot

Display

Geoprofiler Map

Muon Decay and Detector Background

Muon decays produce electrons and positrons

- Loss per unit length almost independent of energy
- First results indicate that background does not increase much with energy

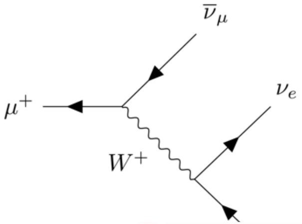
1.5 and 3 TeV studies, concept based on CLIC detector

- **Masks** to mitigate background
- Detailed **FLUKA studies** of masks/beamline
- **Tracking detector radiation level similar to HL-LHC**

Studies with **beam-induced background** in progress

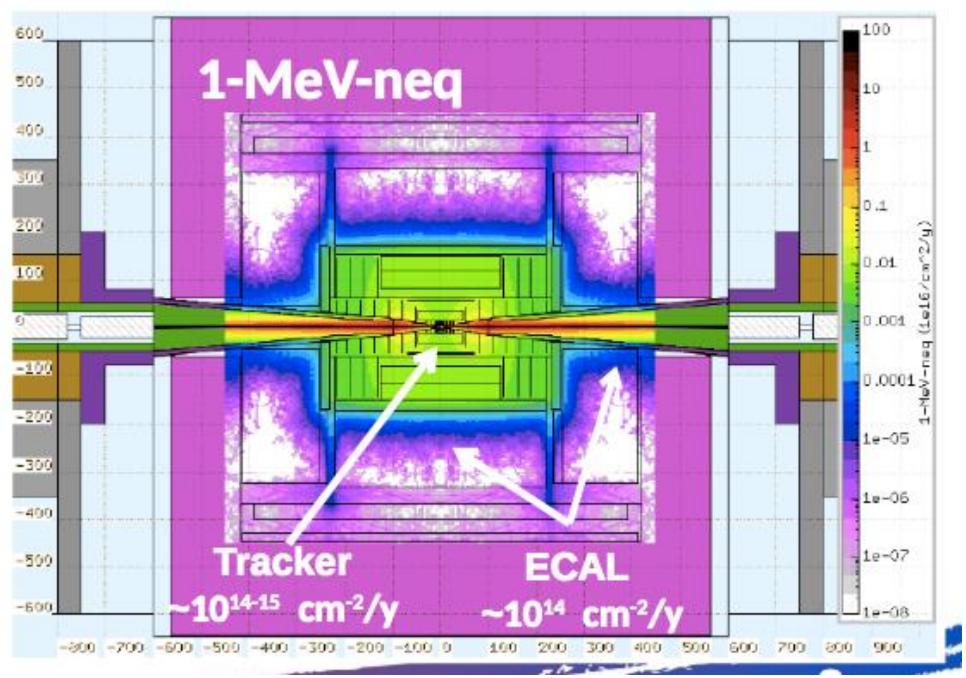
- some channels are not affected by background
- some improvement required for other channels

Concept for **10 TeV** in progress

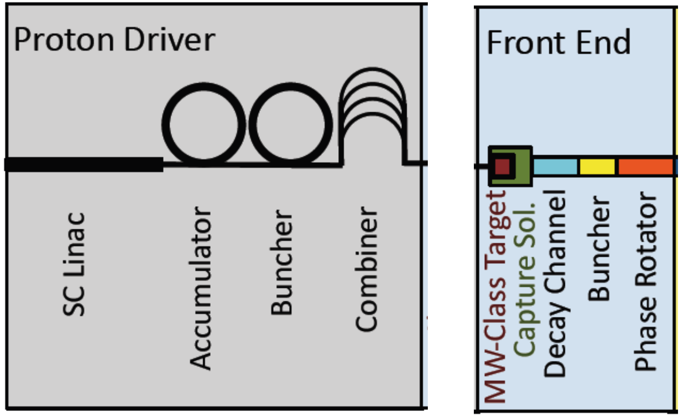


Detector team
O(69) authors, O(150 signatories)

D. Lucchesi, F. Meloni et al.

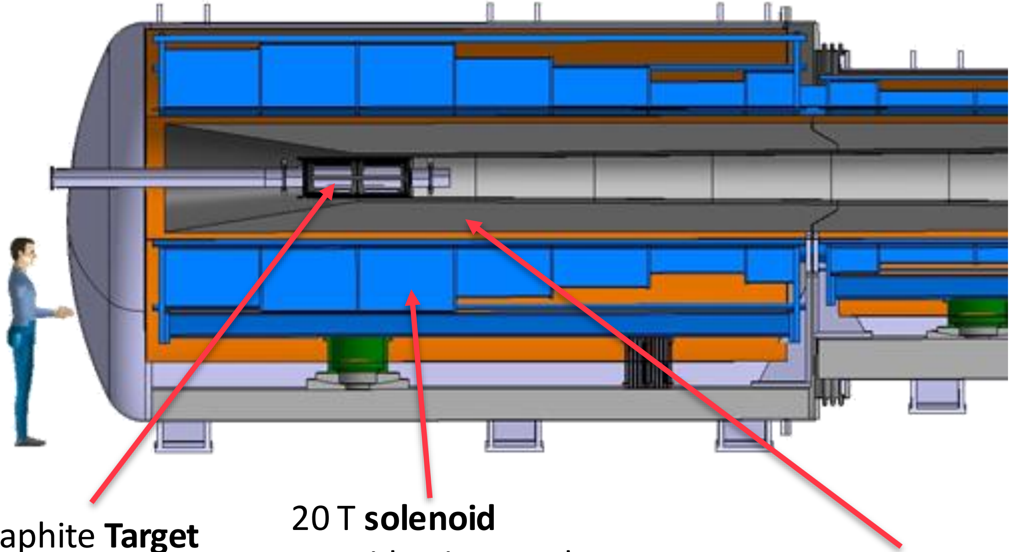


Proton Complex and Target



protons $\xrightarrow{\text{in target}}$ pions $\xrightarrow{\text{decay}}$ muons

400 kJ protons to produce 5 x 10^{13} captured muon pairs



Graphite **Target**

20 T **solenoid**
to guide pions and muons

Tungsten shielding
To protect magnet

5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand

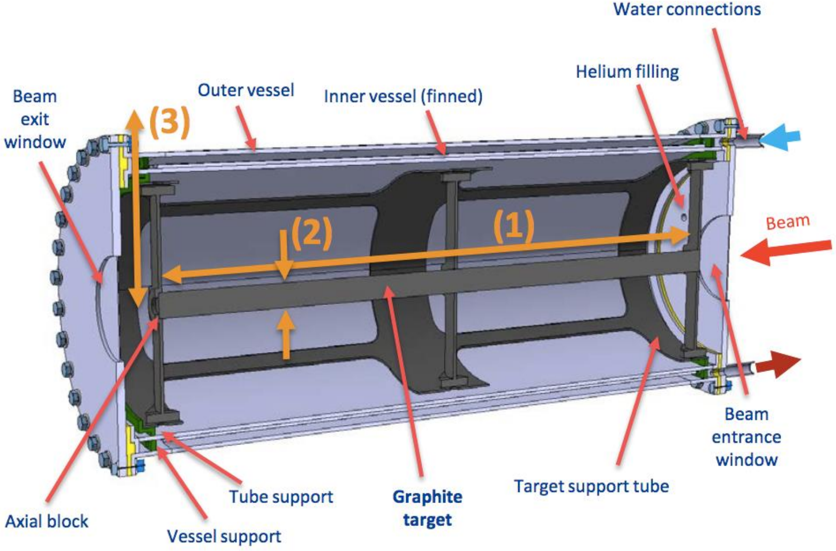
ESS and Uppsala will focus on merging beam into high-charge pulses

Optimisation of parameters planned

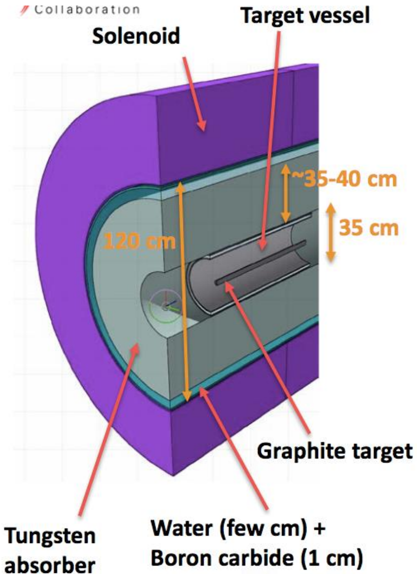
Target Design

5 x 10^{14} protons/pulse, 5 GeV (0.4 MJ), 5 Hz

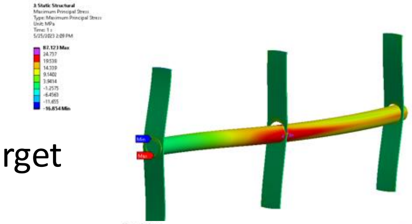
- graphite rod with 15 mm radius
- or liquid lead
- or fluidised tungsten



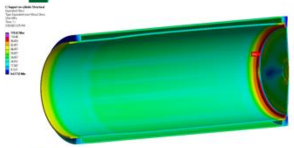
CNGS target
3.5 x 10^{13} protons/pulse, 400 GeV (2.2 MJ), 1/6 Hz

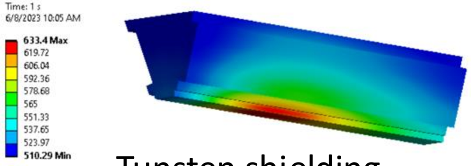


Target



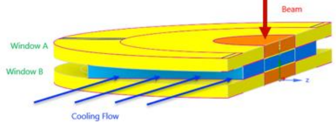
Vessel





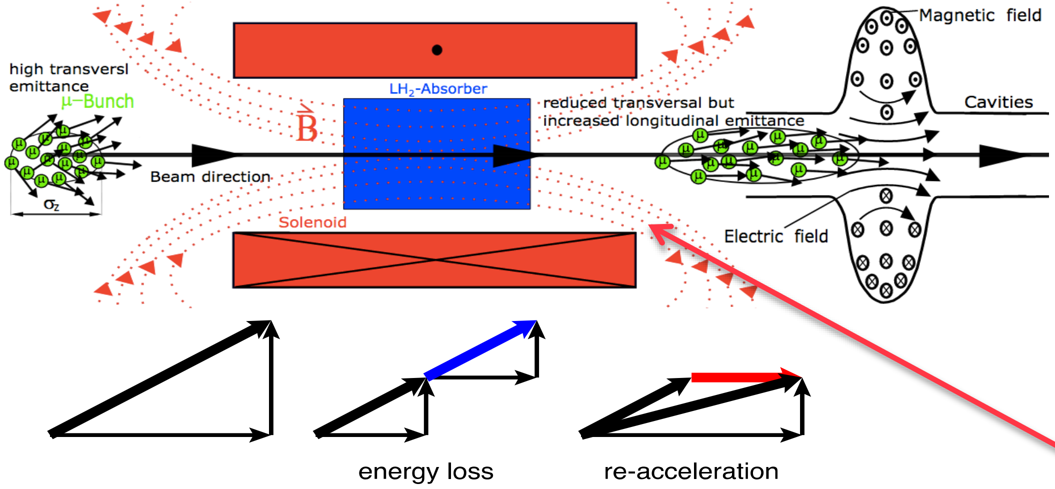
Tunsten shielding

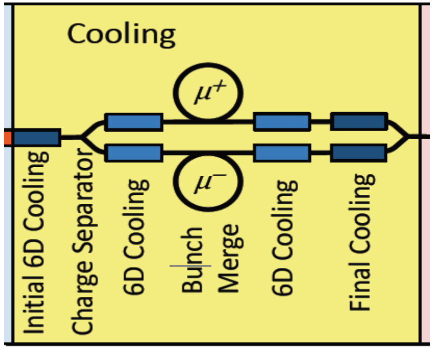
Window



A. Lechner, D. et al.

Final Cooling Principle





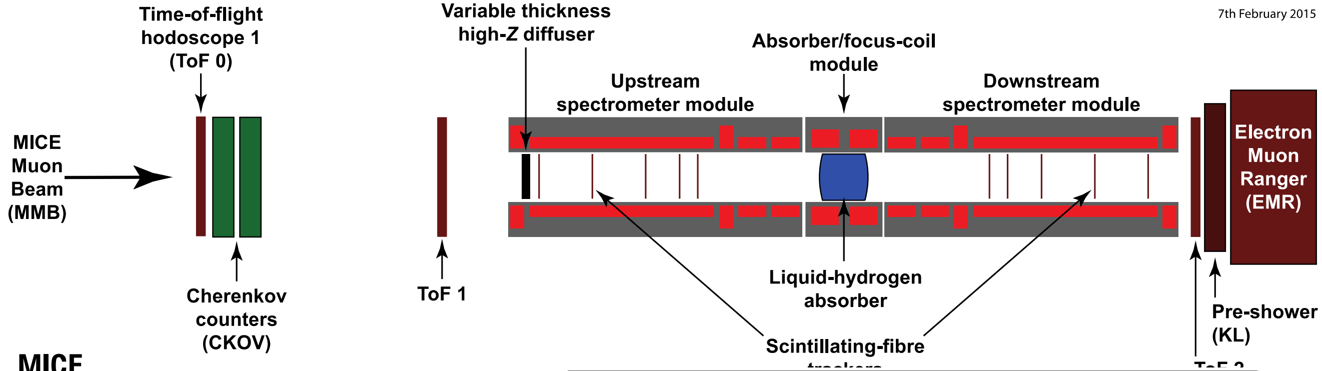
High field solenoids minimise beta-function and impact of multiple scattering

Energy loss = cooling

Multiple scattering = heating

$$\frac{d\epsilon_\perp}{ds} = -\boxed{\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E}} + \boxed{\frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}}$$

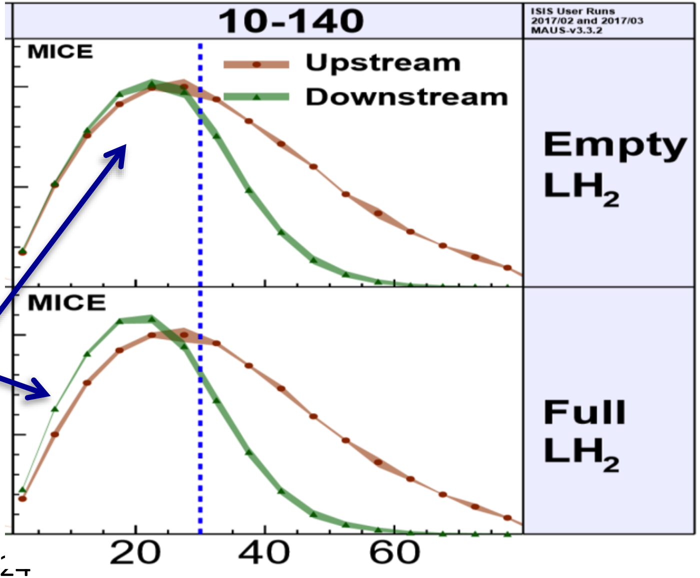
MICE: Cooling Demonstration



Nature vol. 578, p. 53-59 (2020)

Principle of ionisation cooling has been demonstrated

Use of data for benchmarking is still ongoing

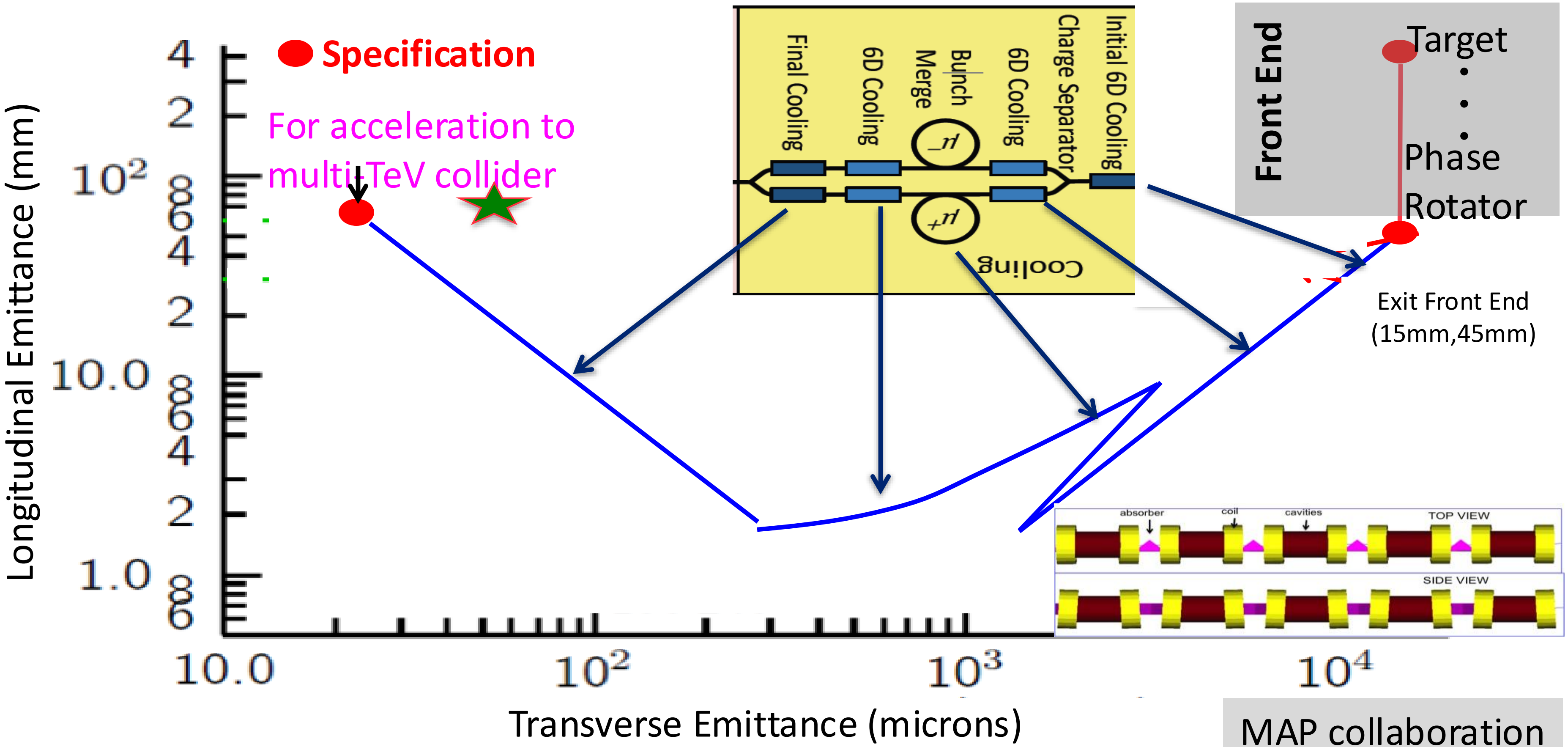


More particles at smaller amplitude after absorber is put in place

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering challenge

Cooling: The System Chain



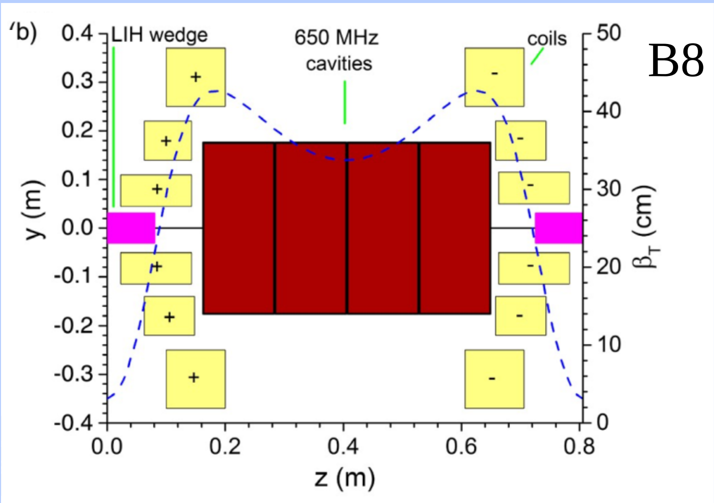
MAP collaboration

Cooling Cell Technology

Will develop example **cooling cell with integration**

- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**

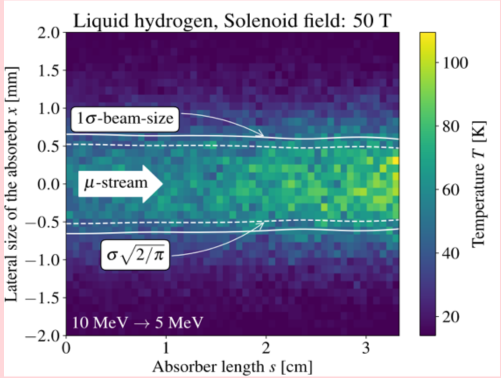
L. Rossi et al. (INFN, Milano, STFC, CERN),
J. Ferreira Somoza et al.



Most complex example 12 T

Windows and absorbers for high-density muon beam

- Pressure rise mitigated by vacuum density
- Plan window test in HiRadMat



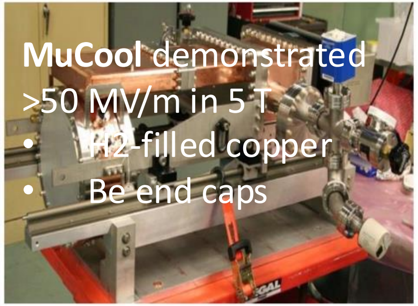
RF cavities in magnetic field

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
- Use of CLIC breakdown experiment considered



MuCool demonstrated >50 MV/m in 5 T

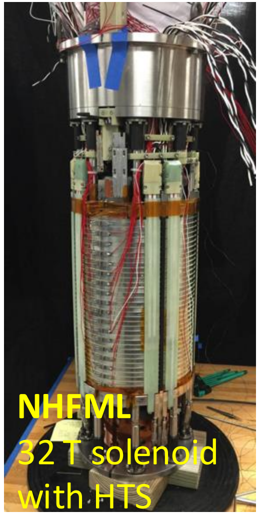
- H_2-filled copper
- Be end caps

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

Solenoid R&D

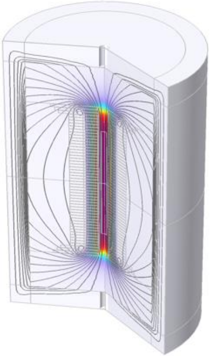
Started **HTS solenoid** development for high fields
Synergies with fusion reactors, NRI, power generators for windmills, …

A Portone, P. Testoni,
J. Lorenzo Gomez, F4E



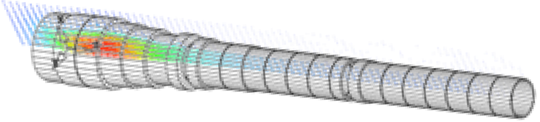
Final Cooling solenoid
Goal 40 T
Estimation of limit

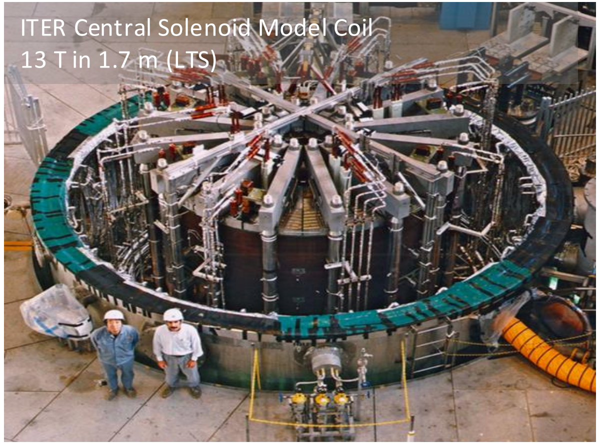
$B_{max} \approx 55$ T



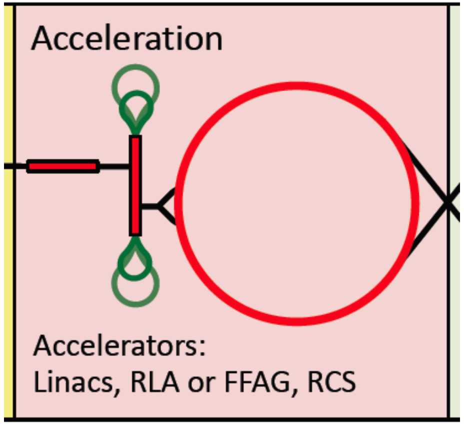
Target solenoid, 20 T, 20 K

15 T Nb_3Sn with 5 T resistive insert
Or 20 T HTS seems possible
Relevant for advanced fusion reactors

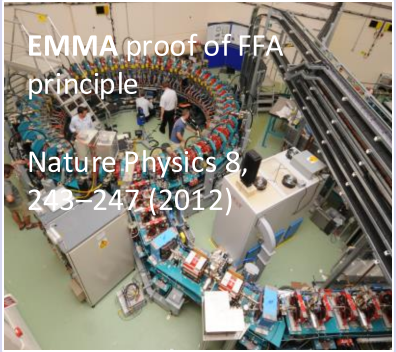




Acceleration Complex



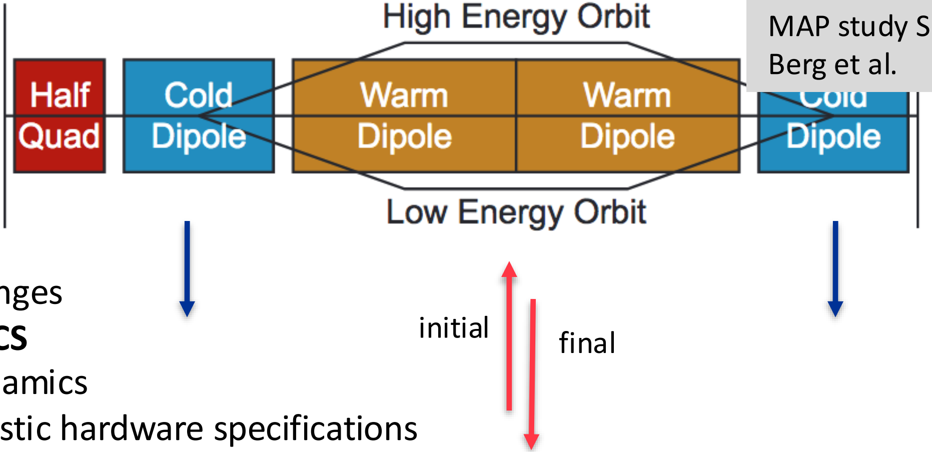
Accelerators:
Linacs, RLA or FFAG, RCS


EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)

Core is sequence of hybrid pulsed synchrotron (0.4-11

- Alternative FFA



MAP study S. Berg et al.

Started work on key challenges

- **Integrated design of RCS**
    - Longitudinal dynamics
    - Lattice with realistic hardware specifications
    - Collective effects
- **Concept of key components**
    - Fast-ramping normal magnets
    - HTS alternative
    - Efficient power converters
    - RF with transient beam loading

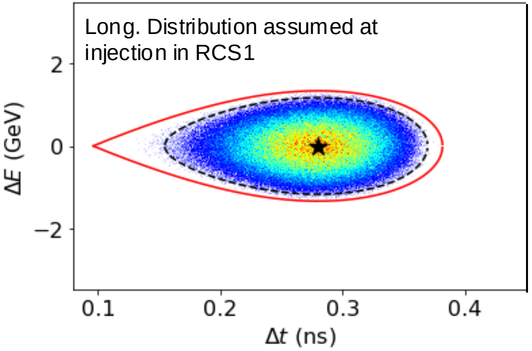
Lattice and integration: A. Chance et al. (CEA)
Long. dynamics and RF systems: H. Damerell, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)
Power converter: F. Boattini et al.
Magnets: L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
FFA: S. Machida et al. (RAL)

Collective Effects and RF Design

Longitudinal dynamics and RF important due to high bunch charge

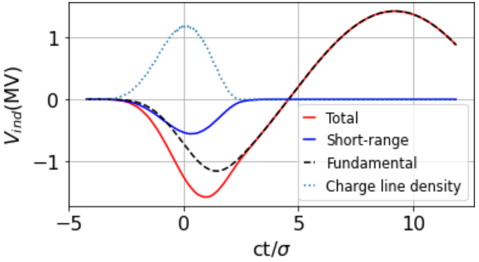
- > 30 RF stations needed
- Orbit length changes require frequency tuning required
- Single-bunch HOM power loss up to 10 kW during pulse
- CW average is lower, development of high-capacity couplers needed

A. Chance, H. Damerell, F. Batsch, U. van Rienen, A. Grudiev et al. (CEA, Rostock, Milano, CERN)
E. Metral, D Amorim et al. (CERN)



1.3 GHz appears possible for longitudinal effects and stability

Induced voltages in RCS1 for a single bunch →

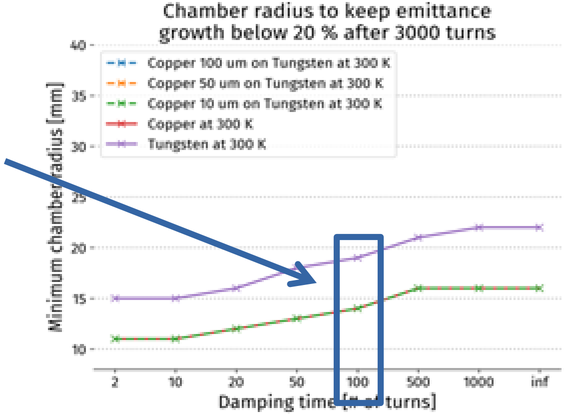


Collider ring single beam instability limits

Conservative feedback

Copper coating beneficial (few microns)

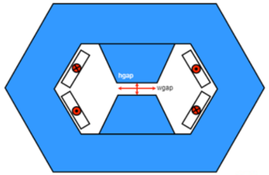
Beam-beam studies started



Fast-ramping Magnet System

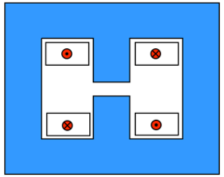
F. Boattini et al.

Hourglass frame magnet



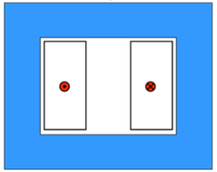
5.07 kJ/m

H magnet



5.65…7.14 kJ/m

Window frame magnet



5.89 kJ/m

Management of the **power in the resistive dipoles** (several tens of GW):

- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

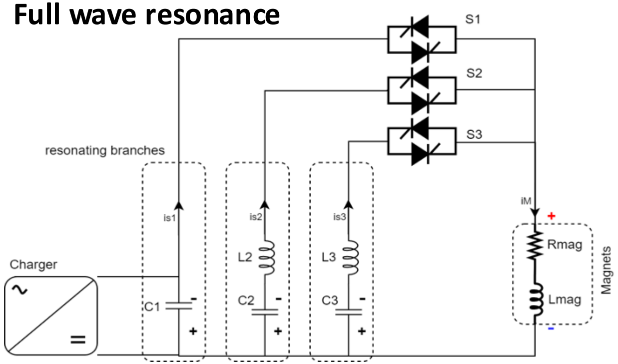
FNAL 300 T/s HTS magnet

Could also use HTS driven dipoles

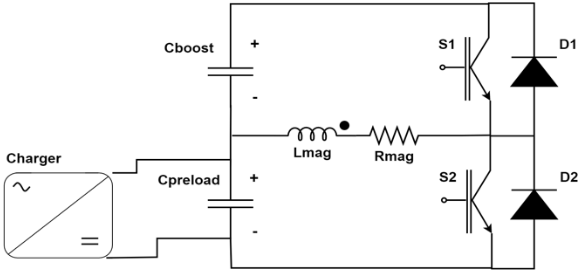
Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

Full wave resonance



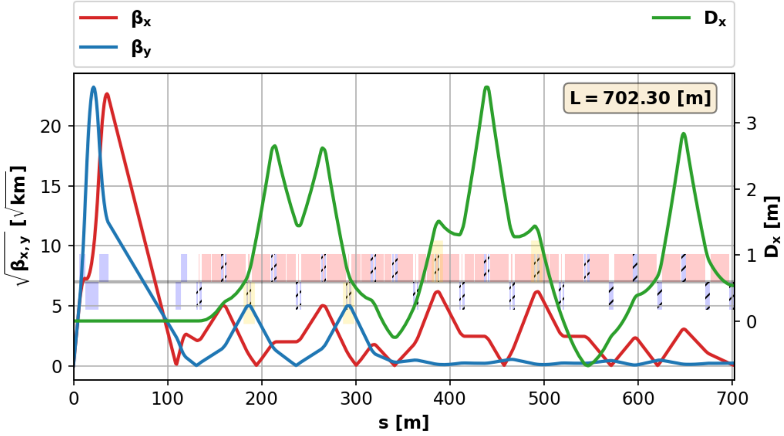
Commutated resonance (new)



Collider Ring

Challenges:

- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches



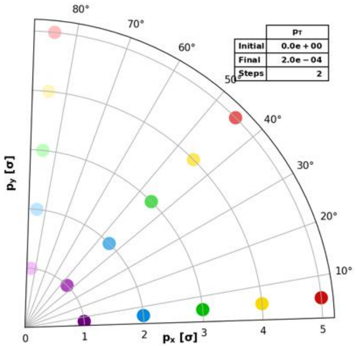
K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas

MAP developed 4.5 km ring for 3 TeV with Nb_3Sn

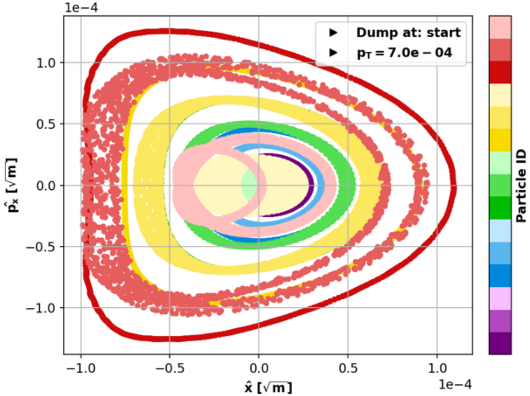
- magnet specifications in the HL-LHC range

Work progressing on **10 TeV collider ring**

- around 16 T HTS dipoles or lower Nb_3Sn
- final focus based on HTS



pT [%]	DAmin [σ]
0.07	5
0.08	4
0.09	3
0.1	<1

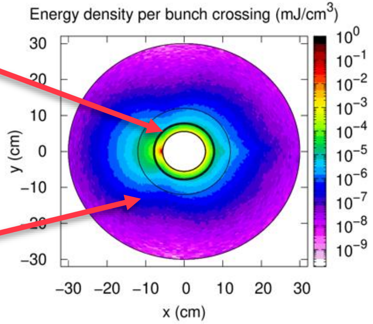


Important progress: V0.6 good dynamic aperture at almost 0.1% off-energy, approaching the target

Collider Ring Technology

Power loss due to muon decay 500 W/m
FLUKA simulation of **shielding:**
Require 30-40 mm tungsten

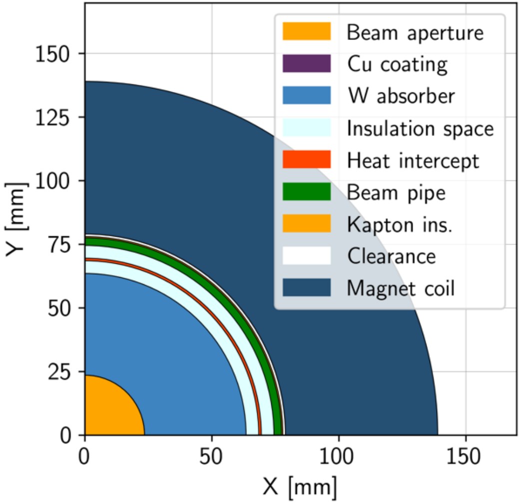
- Few W/m in magnets
- No problem with radiation dose



Shielding

A. Lechner
D. Calzolari
(CERN)

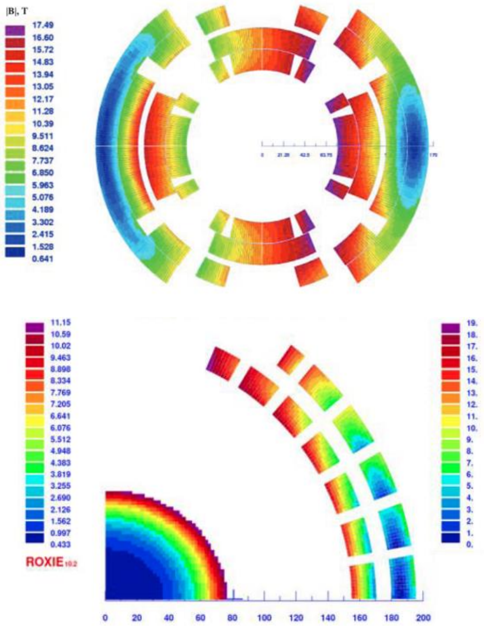
Coil



K. Skoufaris, Ch. Carli, D. Amorim, A. Lechner, R. Van Weelderen, P. De Sousa, L. Bottura et al.

L. Bottura et al.

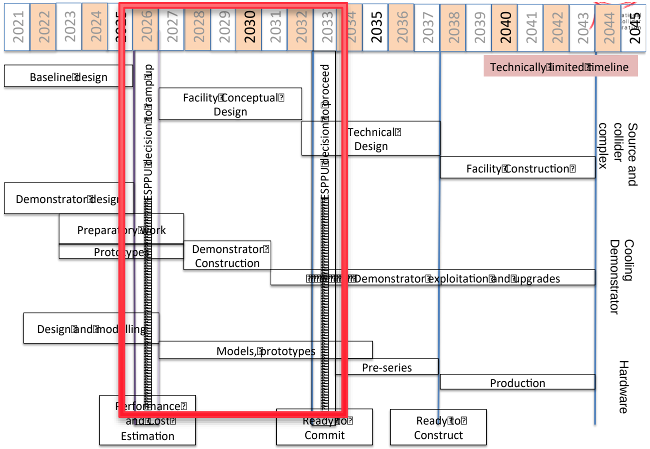
Initial **estimate of magnet field limits**:
11 T for Nb_3Sn, more for HTS/hybrid
Need **stress management**



Different **cooling scenarios** studied
< 25 MW power for cooling possible
Shield with CO_2 at 250 K (preferred) or water
Support of shield is important for heat transfer
Discussion on options for magnet cooling

R. Van Weelderen, P. De Sousa

CDR Phase, R&D and Demonstrator Facility


2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Baseline design

ESPPU decision to ramp up

Facility Conceptual Design

ESPPU decision to proceed

Technical Design

Facility Construction

Source and collider complex

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Cooling Demonstrator

Design and modelling

Models, prototypes

Pre-series

Production

Hardware

Performance and Cost Estimation

Ready to Commit

Ready to Construct

Broad R&D programme can be distributed world-wide

- **Models** and **prototypes**
    - Magnets, Target, RF systems, Absorbers, …
- **CDR** development
- **Integrated tests**, also with beam

Cooling demonstrator is a key facility

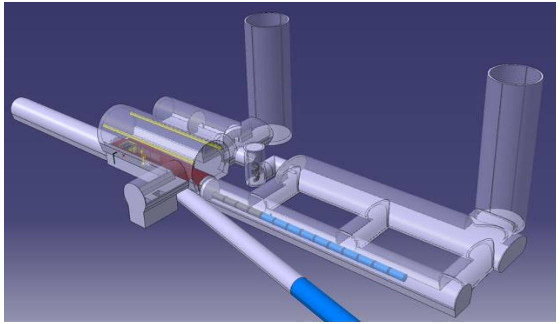
- look for an existing proton beam with significant power

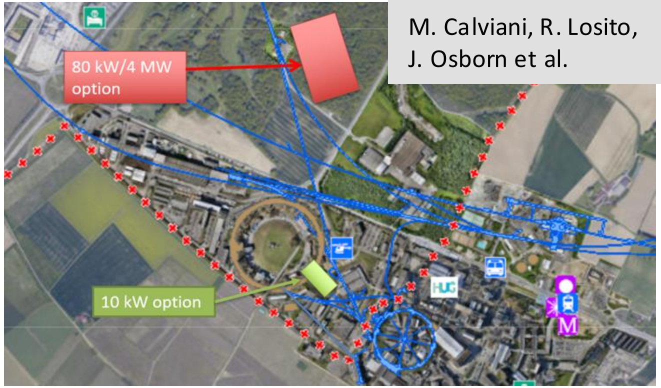
Different sites are being considered

- CERN, FNAL, ESS …
- **Discussed at ACE at FNAL**
- **Site at CERN possible**
- J-PARC also interesting as option

Could be used to house physics facility

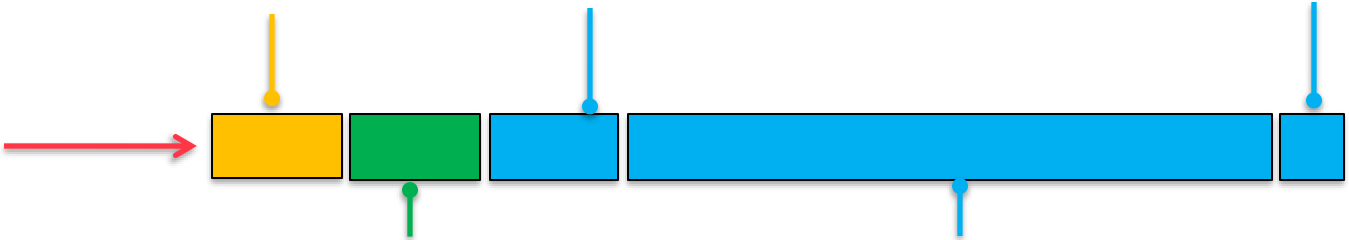
- **Synergies workshop** to explore good options





M. Calviani, R. Losito, J. Osborn et al.

Test Facility Dimensions



Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

Collimation and **upstream diagnostics** area, 10 m

Downstream diagnostics area, 5 m

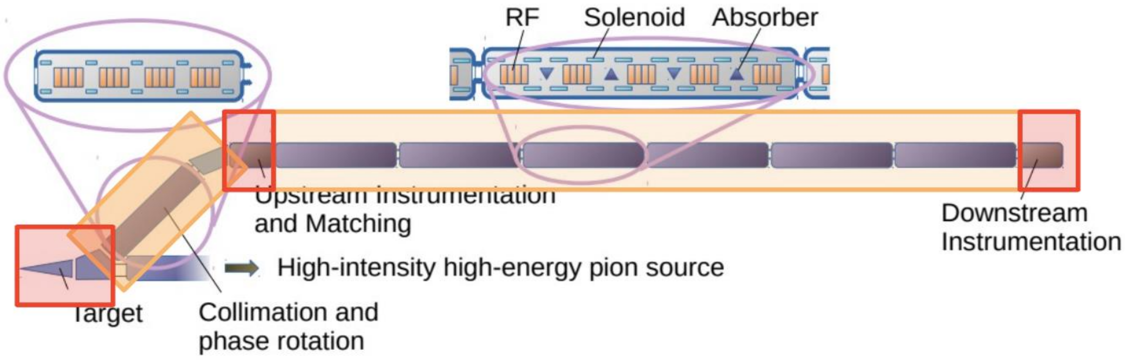
Momentum selection chicane, 10 m

Cooling area, 50 m

Look for an existing proton beam with significant power

Different sites are being considered

- CERN, FNAL, ESS are being discussed
- J-PARC also interesting as option



Implementation Considerations

Reviewing timeline (still evolving)

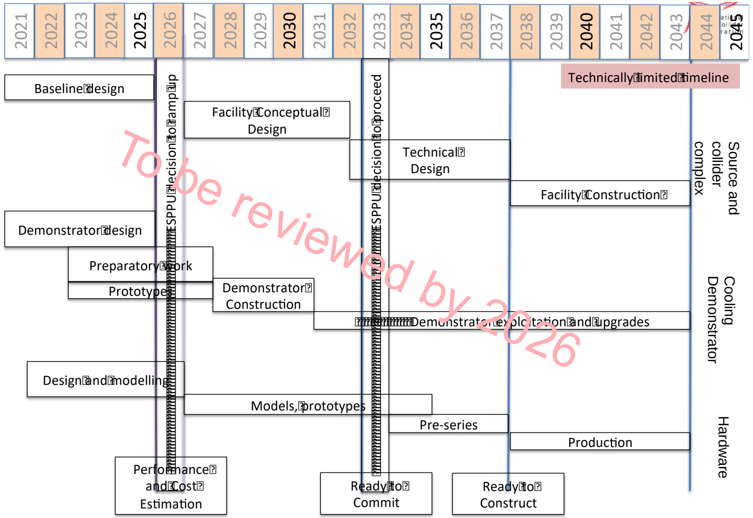
- Uncertainties from physics case (e.g. HL-LHC), society development, budget profile etc.

Goal:

- Identifying shortest possible timeline
    - Technically limited, success-oriented schedule

- On the critical path
    - Muon cooling technologies and integration
    - Magnet technology
    - Detector technologies

- Technology appears to be ready before 2040
    - Provided funding is being made available
    - Initial stage to start physics before 2050 appears possible
    - To be confirmed before next ESPPU



Magnet Roadmap

Consensus of experts (review panel):

- Anticipate technology to be **mature in O(15 years):**
  - **HTS solenoids** in muon production target, 6D cooling and final cooling
    - HTS tape can be applied more easily in solenoids
    - Strong synergy with society, e.g. fusion reactors
  - **Nb_3Sn 11 T magnets** for collider ring (or HTS if available): 150mm aperture, 4K
- This corresponds to 3 TeV design
- Could build 10 TeV with reduced luminosity performance
  - Can recover some but not all luminosity later

Still under discussion:

- Timescale for HTS/hybrid collider ring magnets
- For second stage can use **HTS or hybrid collider ring magnets**

Strategy:

- HTS solenoids
- Nb_3Sn accelerator magnets
- HTS accelerator magnets

Seems technically good for any future project

Staging Approaches

Assumptions:

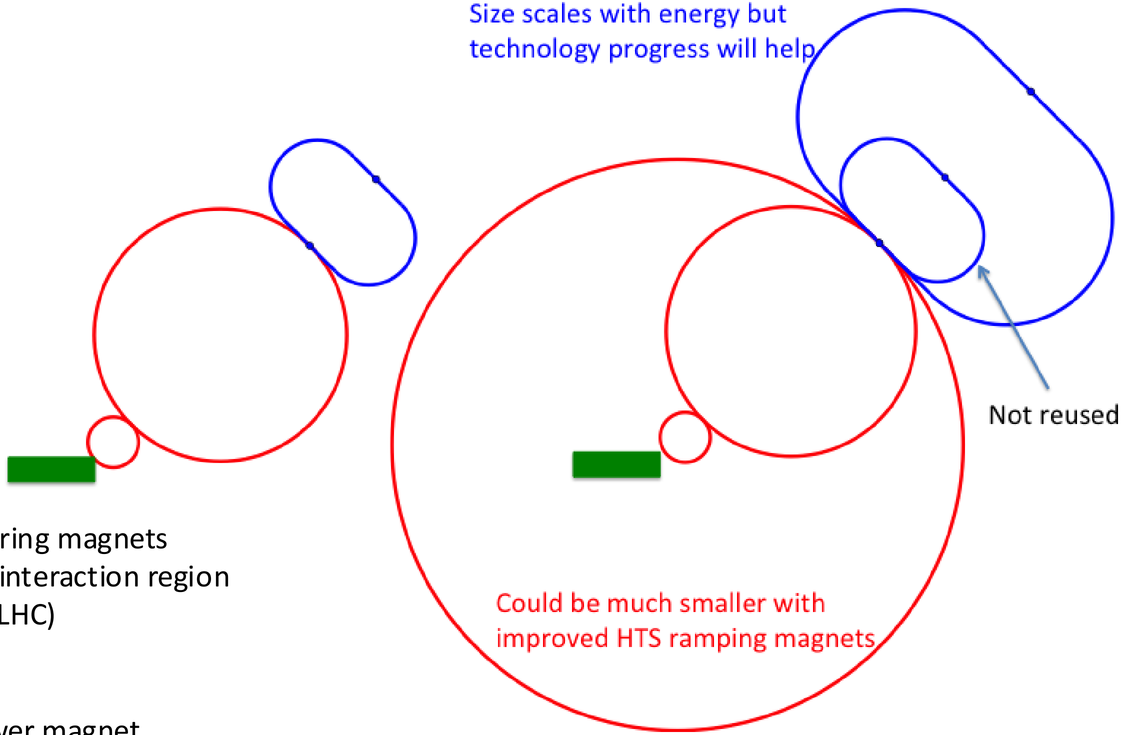
- In O(15 years):
  - HTS technology available for solenoids
  - Nb_3Sn available for collider ring
- In O(25 years):
  - HTS available for collider ring

Scenario 1: Energy staging

- Start at lower energy (e.g. 3 TeV)
- Build additional accelerator and collider ring later
- Requires less budget for first stage
- 3 TeV design takes lower performance into account

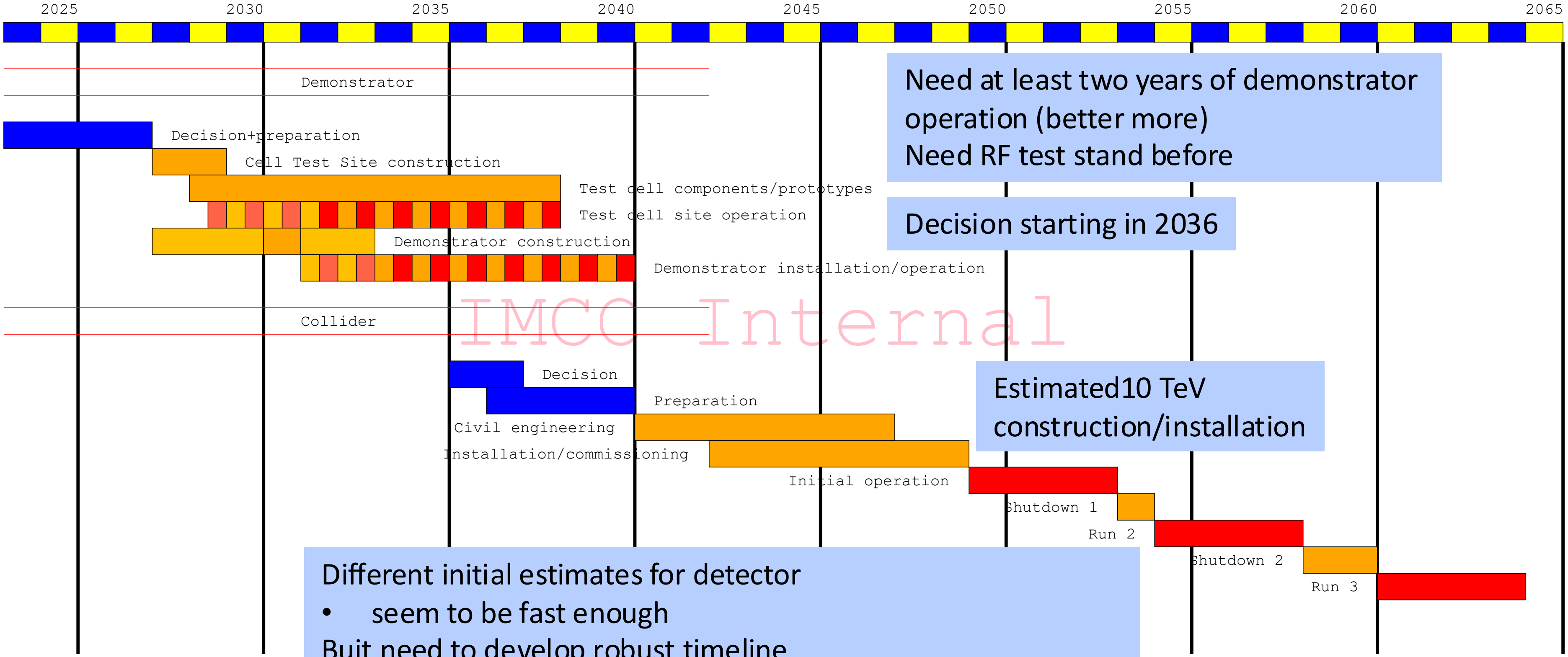
Scenario 2: Luminosity staging

- Start at with full energy, but less performant collider ring magnets
- Main sources of luminosity loss are collider arcs and interaction region
  - Can recover interaction region later (as in HL-LHC)
  - But need full budget right away
  - Some luminosity loss remains (O(1.5))
  - More power for the collider ring required (lower magnet temperature)



Tentative Timeline (Fast-track 10 TeV)

Only a basis to start the discussion, will review this year



Need at least two years of demonstrator operation (better more)
Need RF test stand before

Decision starting in 2036

Estimated10 TeV construction/installation

Different initial estimates for detector
- seem to be fast enough

Buit need to develop robust timeline

Plan for ESPPU

Study **green field** designs and continue to work on them

- International collaboration
- Parameters, lattice designs, component designs, beam dynamics, cost, …

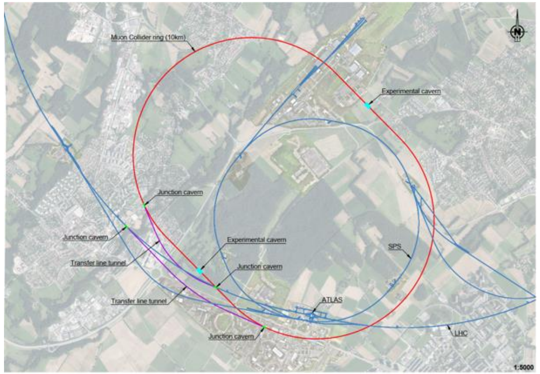
Perform example **civil engineering studies**

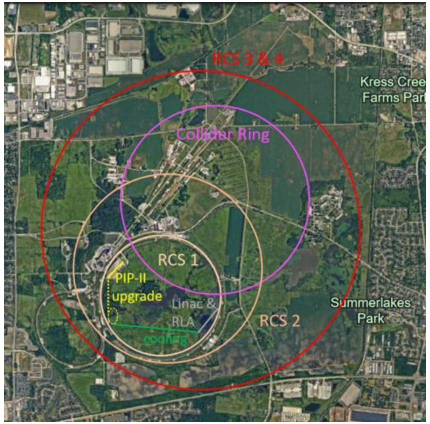
- CERN (collider and demonstrator)
- FNAL, the US started doing similar studies

Provide parameters tables for the implementation at existing sites (FNAL, CERN, …)

- Scaled from green field design using existing infrastructure
- Do not have the resources and time to make detailed designs for CERN and FNAL for ESPPU

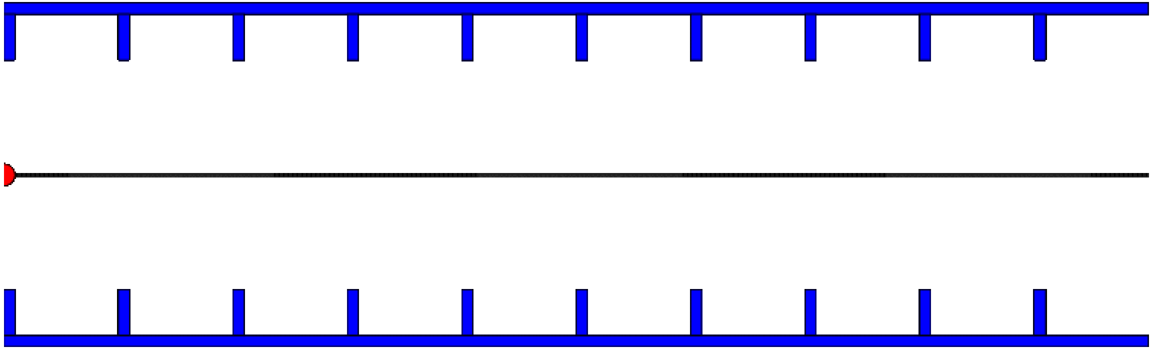
Reuse of SPS and LHC tunnels and implementation at CERN looks not too bad right now





Electron-proton Collider

A particle that is 180° out of phase leaves energy in a cavity



Energy Recovery Principle

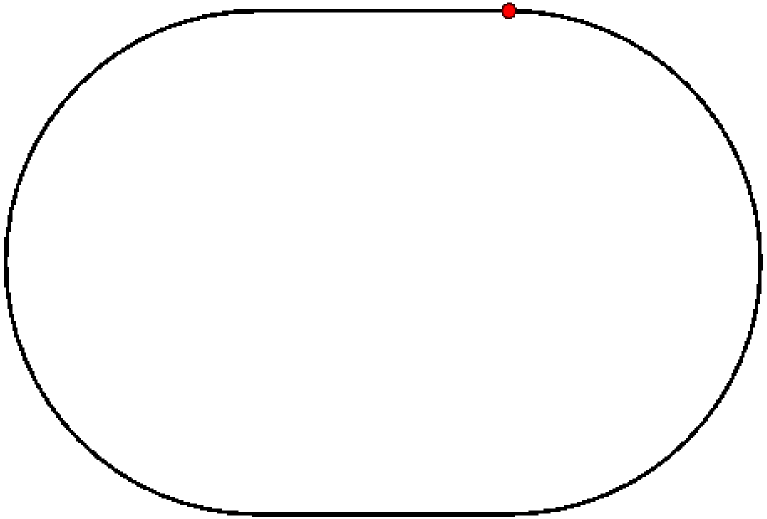
Decelerate beam almost to 0 GeV

Need dedicated arc for each turn

But can share on the way up dand down

Interesting optics design in the linacs to accommodate very different energies

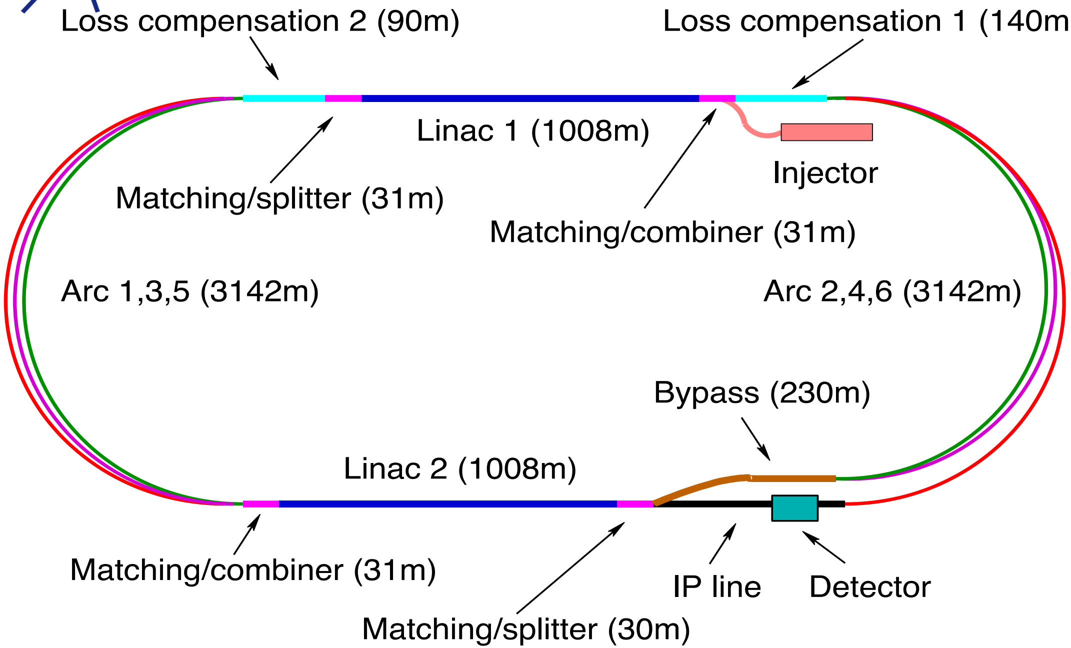
- Rule of thumb: design for the lowest energies



Power needed to

- Control the linac RF
- To keep the linac cavities superconducting
- To compensate the synchrotron radiation from the arcs

LHeC / FCC-eh



Loss compensation 2 (90m)

Loss compensation 1 (140m)

Linac 1 (1008m)

Injector

Matching/splitter (31m)

Matching/combiner (31m)

Arc 1,3,5 (3142m)

Arc 2,4,6 (3142m)

Bypass (230m)

Linac 2 (1008m)

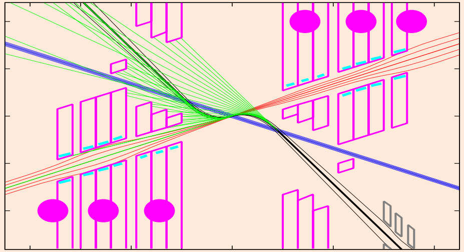
Matching/combiner (31m)

IP line

Detector

Matching/splitter (30m)

Interaction region



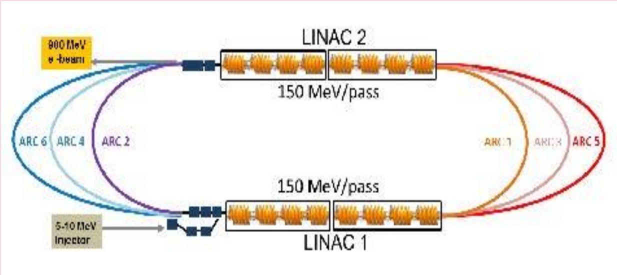
M. Klein et al

	LHeC CDR	HL-LHeC	HE-LHeC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
L [10^{33}cm^{-2}s^{-1}]	1	8	12	15

Development of accelerator technology

E.g. RF power required to control cavities

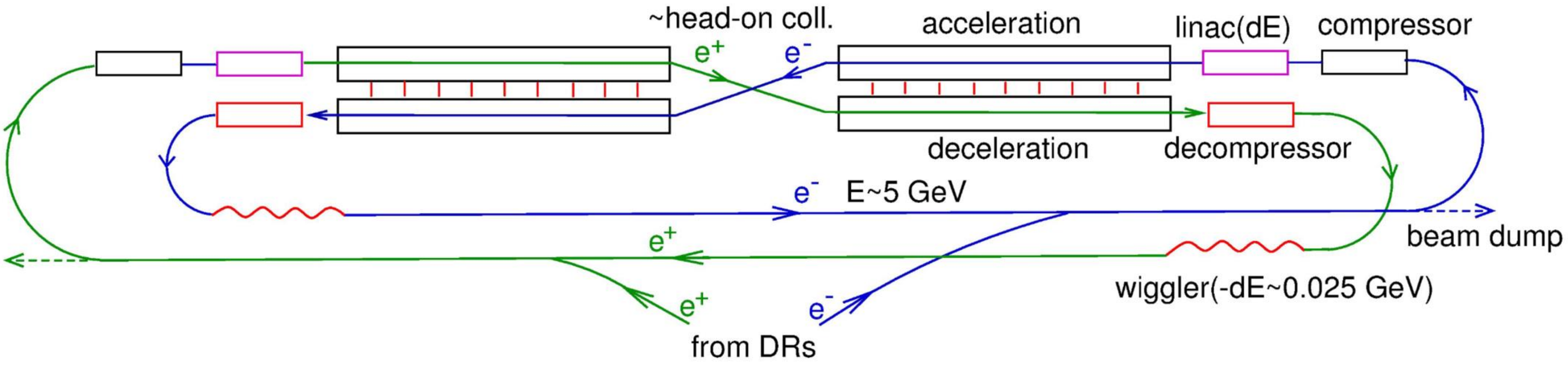
Test facility (PERLE) planned in Orsay



Energy-recovery Linear Collider

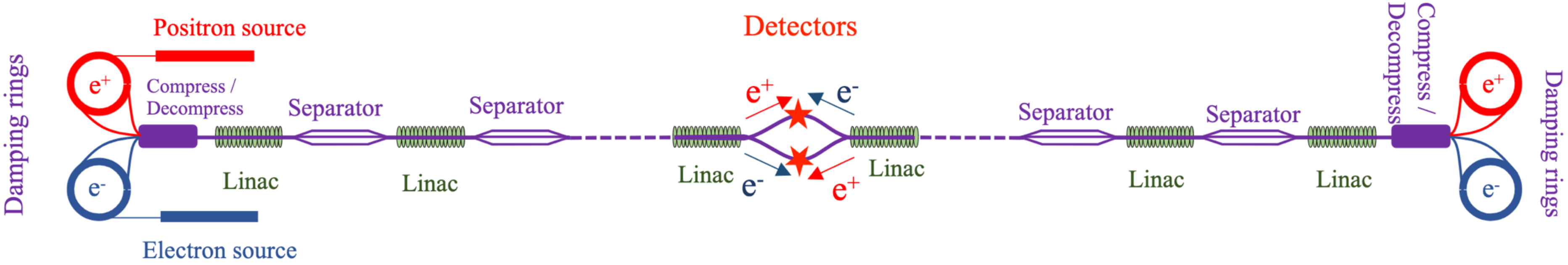
And the Cool Copper Collider (CCC)

ERLC



Basic idea is to extract the beam energy in a second beamline to reduce RF power consumption

RLHIC



Basic idea is to extract the beam energy in the same beamline to reduce RF power consumption

Requires to separate the bunches going in the different direction

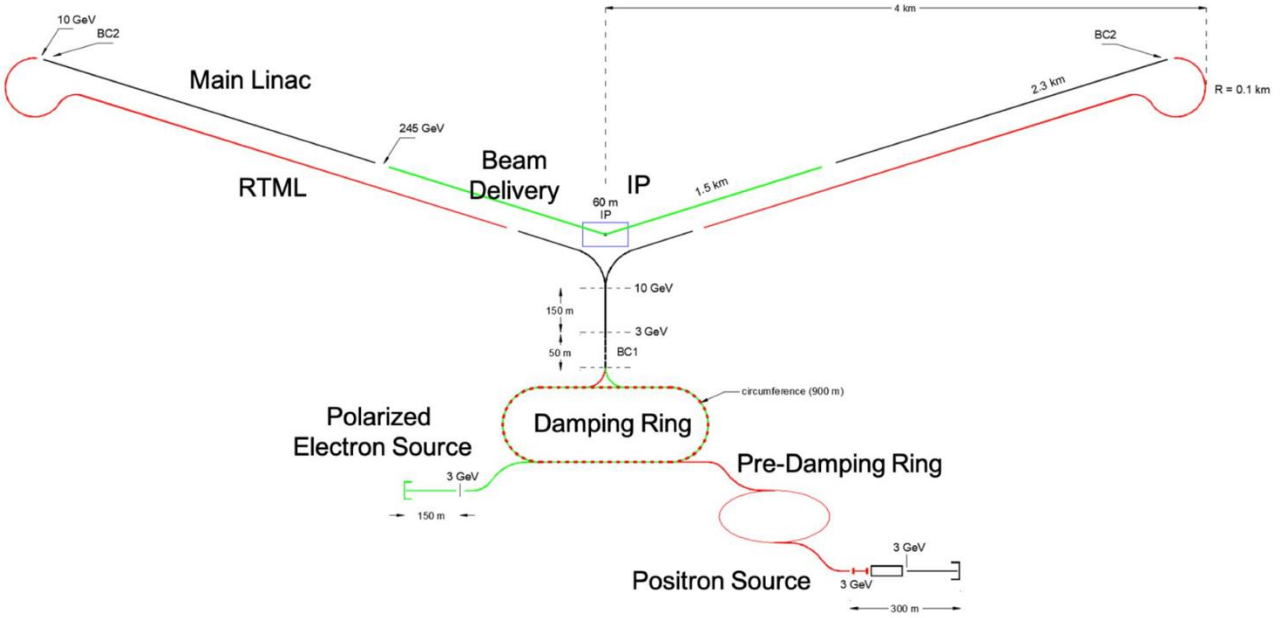
CCC

Cool copper structure to nitrogen temperatures

- Or a bit below

Increases conductivity by. Factor of a few

- Less losses in the RF structures allows to fill them more slowly, reducing the cost of the RF system
- Can somewhat increase the gradient before breakdown
- But have to pay for cryogenics

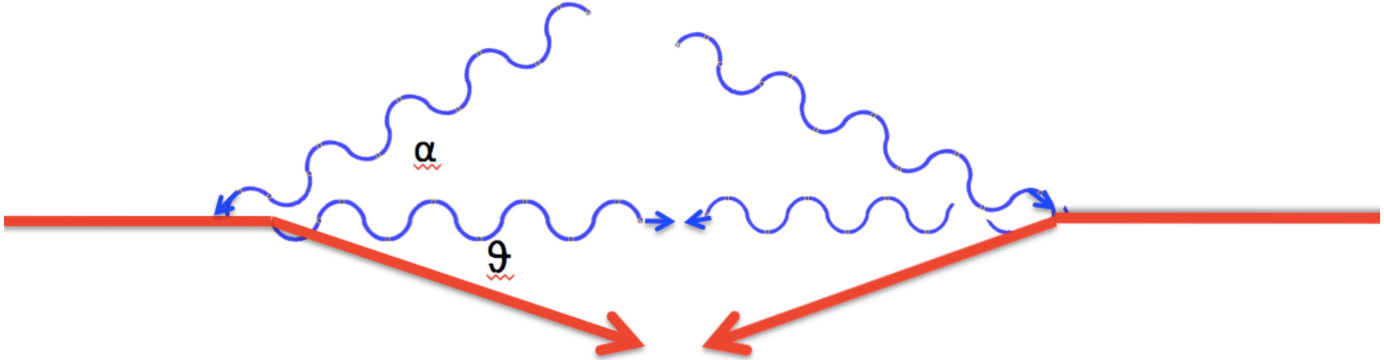


Gamma-gamma Collider

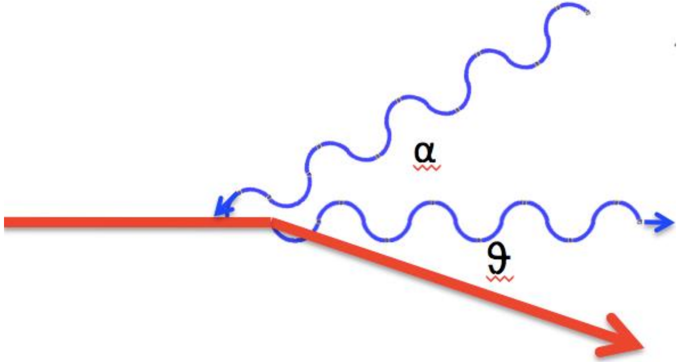
Note: Gamma-gamma Collider Concept

Based on e^-e^- collider

Collide electron beam with laser beam before the IP



Note: Gamma-gamma Collider Concept

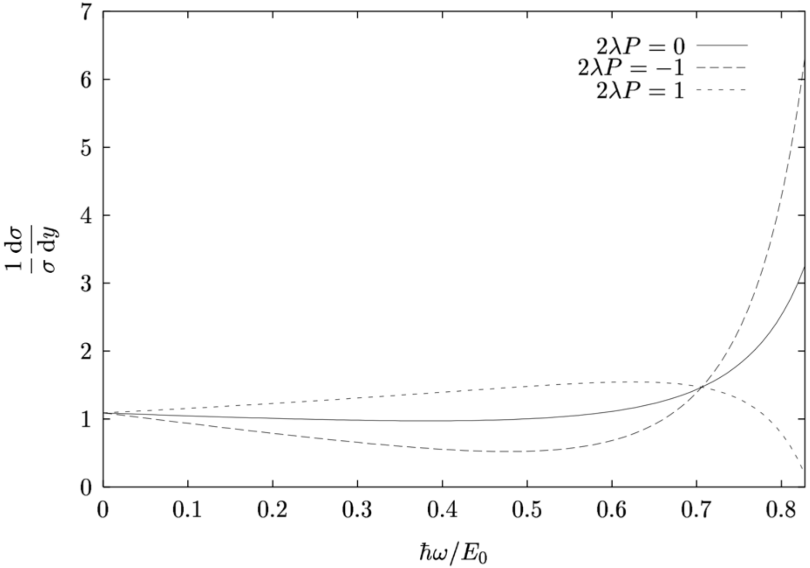


Backscattered photons can have a range of energies

- Depending on the photon energy

Maximum energy of backscattered photon

$$\hbar\omega_m = \frac{x}{x+1}E_0 \quad x = \frac{4E_0\hbar\omega_0}{m^2c^4}$$



Maximum practical energy is 83% of the beam energy

Otherwise backscattered photons can produce electron-positron poairs with further photons of the laser

Requires laser in the eV region, O(J) per pulse

Note: Gamma-gamma Collider Concept

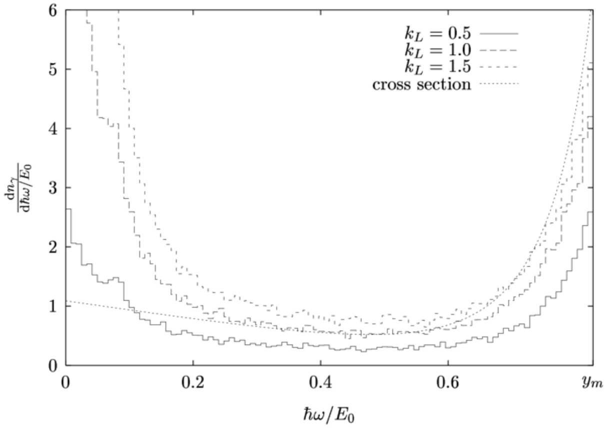
Photon-photon luminosity has a wide spectrum

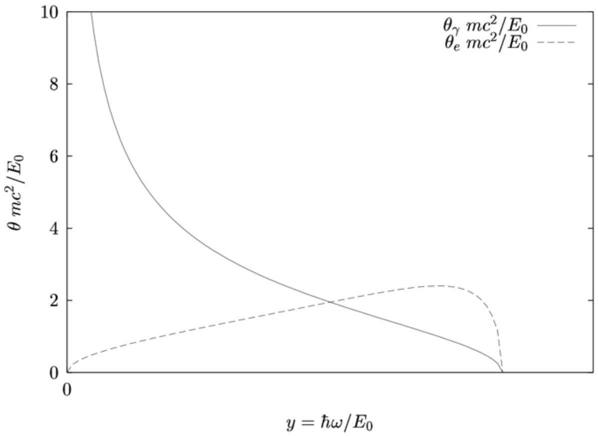
- Electrons can scatter more than once

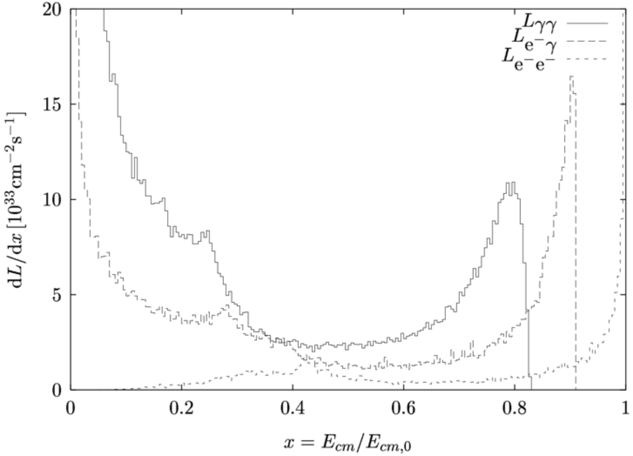
Spacing laser-electron and photon-photon collision further apart helps

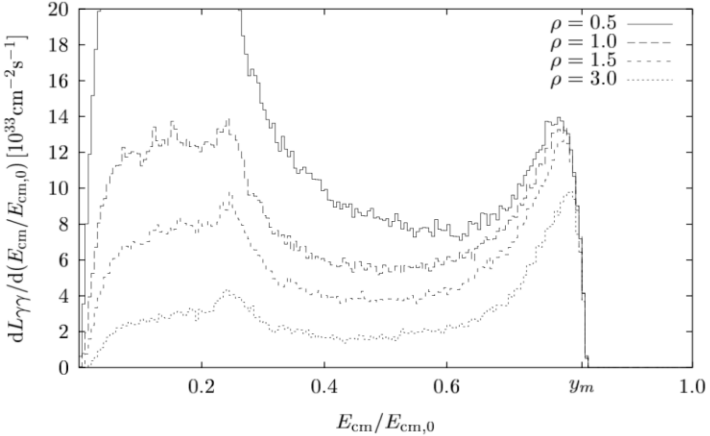
- But reduces luminosity

Can expect about 10% of the e-e- luminosity for gamma-gamma







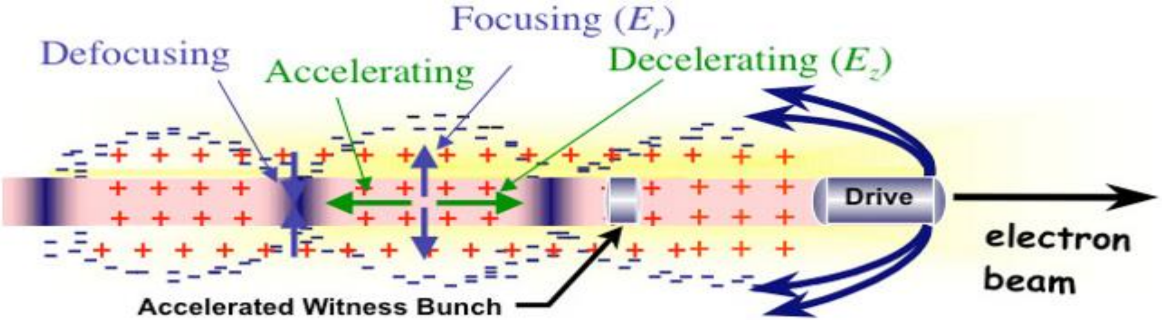


Plasma-based Collider

Note: Plasma Acceleration

Plasma can be generated by electron beam, proton beam or laser beam

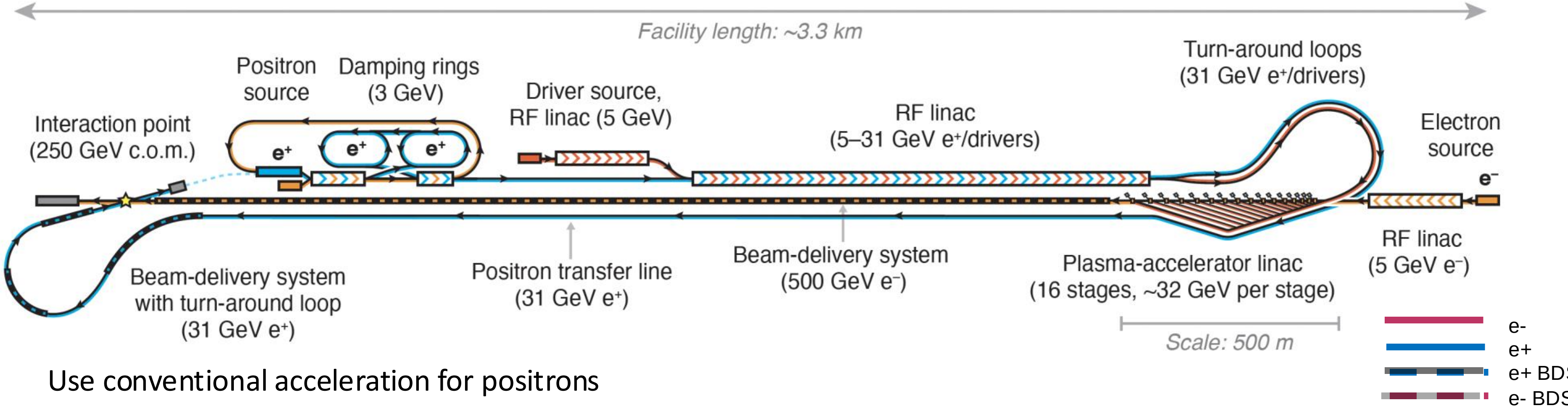
50 GV/m demonstrated with 42 GeV energy gain



I. Blumenfeld et al, Nature 445, p. 741 (2007)

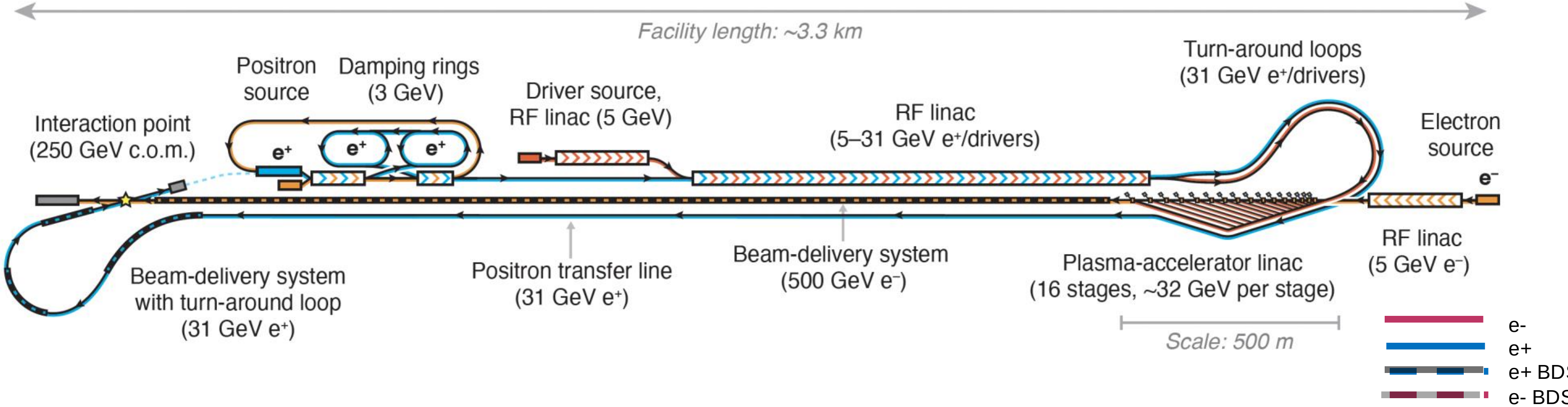
- Practical solution for efficient acceleration of positrons has to be developed
- Efficiency and beam quality have severe challenges
- Strong plasma focusing is good for beam stability but generates synchrotron radiation
- Application in other fields seem promising, e.g. free electron laser

HALHF Concept



- Use conventional acceleration for positrons
  - Avoids difficulties of accelerating positrons in plasma
  - Accelerate to low energy (31 GeV, 4 times less than 125 GeV)
- Accelerate electron in plasma
  - Profit from high gradient
  - Accelerate to high energy (500 GeV, 4 times more than 125 GeV)
- Results in
  - Centre-of-mass energy remains at 250 GeV
  - Physics is boosted in the detector

HALHF Concept

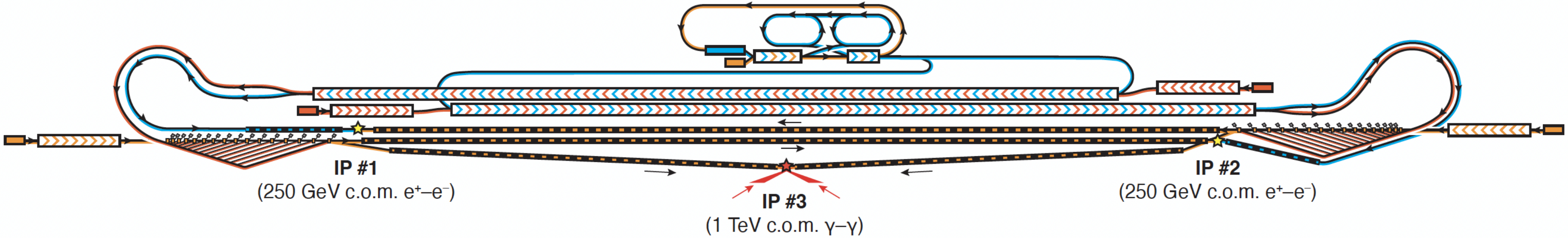


Optimum luminosity per total beam power is reached in both beam powers are equal

- Reduce electron current, also good for plasma
- Increase positron current, not too bad for conventional acceleration

Luminosity proportional to N_pN_e proportional to P_pP_e proportional to $P_p(P_T\text{-}P_p)$, maximum for $2Pp=P_T$

Further Development



Separation of positrons and drive beam

- More linacs but can enable two IPs

Energy upgrade to ttbar (380 GeV) or Higgs self coupling (550 GeV)

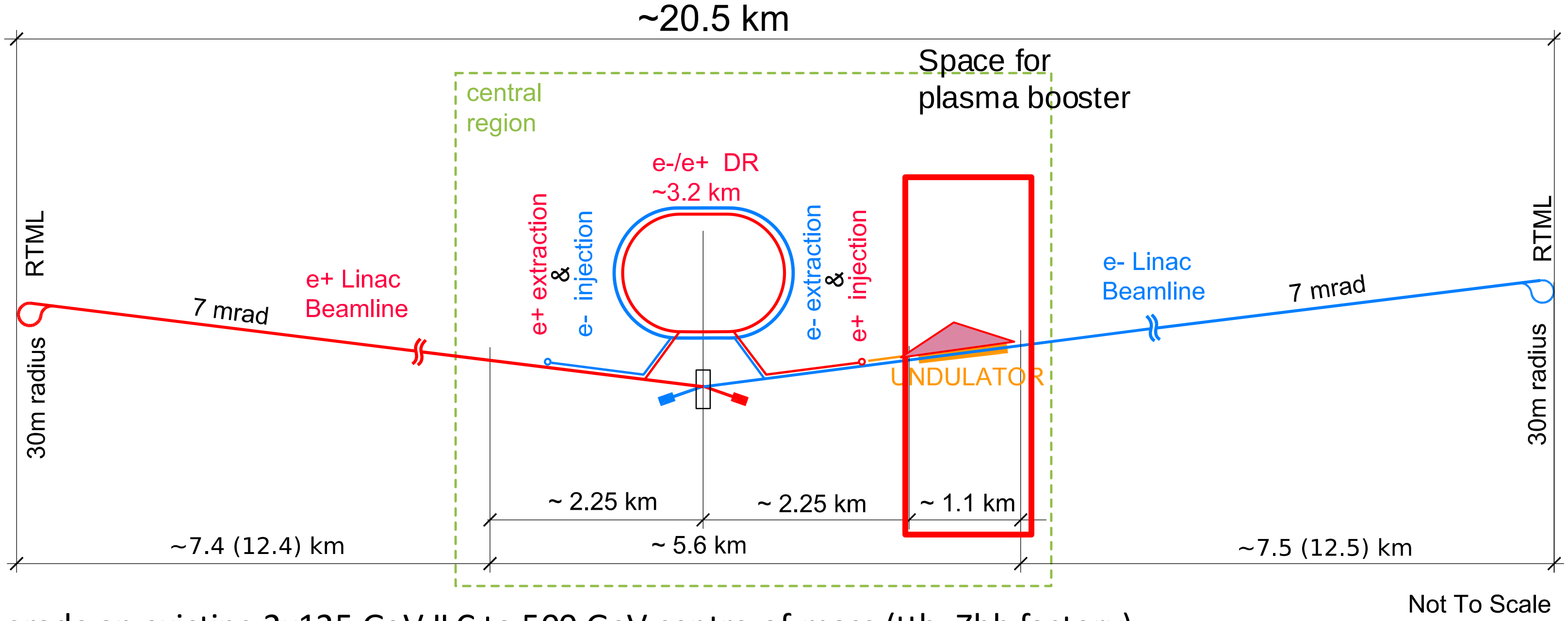
- Upgrade both beam energies in proportion

Many things need to be studied and developed but interesting concept

- However not as mature than “conventional” linear colliders, ILC and CLIC

D. Schulte, Future Colliders 3, BND, 2024

ILC Energy Upgrade a la HALHF

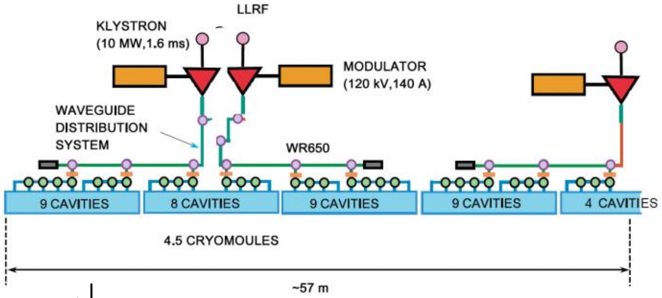


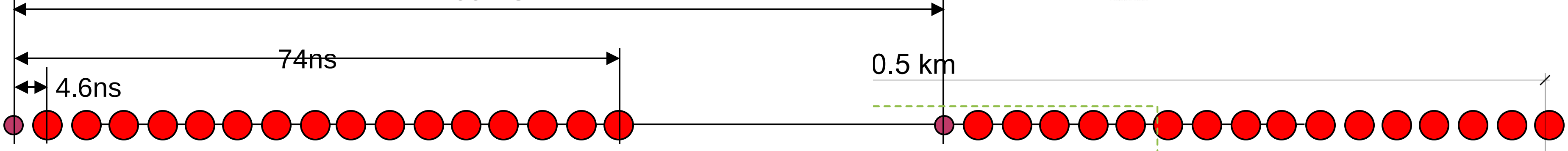
Upgrade an existing 2x125 GeV ILC to 500 GeV centre-of-mass (tth, Zhh factory)
Positrons at 125 GeV, electrons at 500GeV -> 500GeV COM

- Use electron linac for drive and witness beam:
  run a lower gradient but higher current, upgrade RF on electron arm
- Use space for undulator source between electron ML and BDS to install plasma booster
- BDS already laid out for 500 GeV

ILC Energy Upgrade a la HALHF

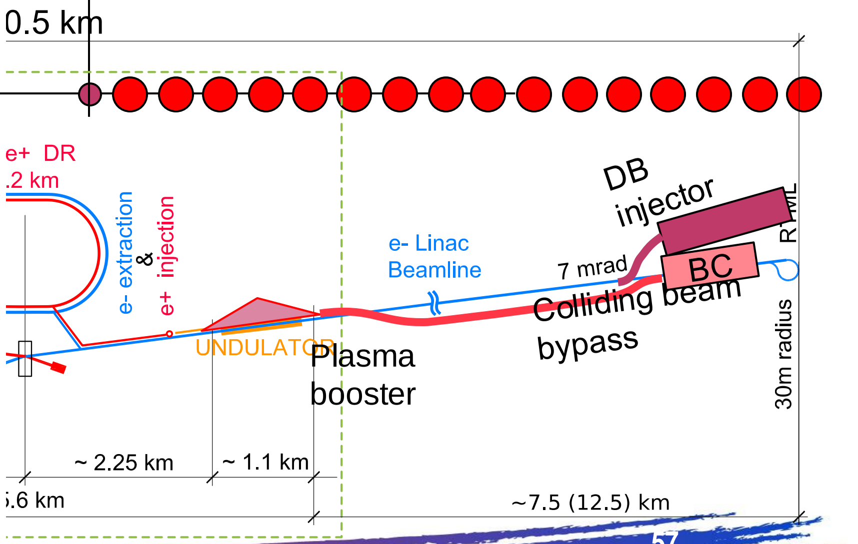
- Requires 3x more klystrons than in baseline configuration (baseline: 2 klystrons for 9 cryomodules) -> fits RF cell structure





Overall: 656 mini trains in pulse -> pulse length 1090us

- Can’t inject DB @ 15 GeV - $$$ - so separate DB &CB
- - but problems with this too. Watch this space....



To infinity & beyond…

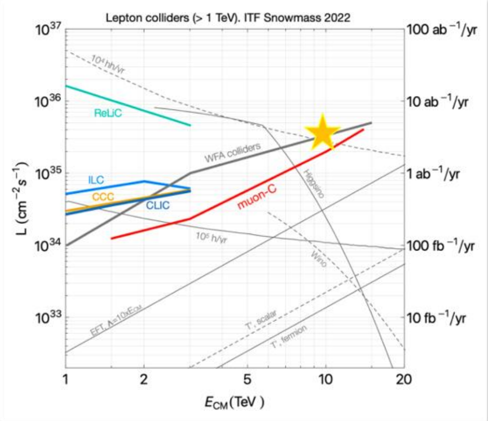
Design Study for a 10 TeV Wakefield Accelerator Collider

The P5 Report recommends:

Vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies. . .

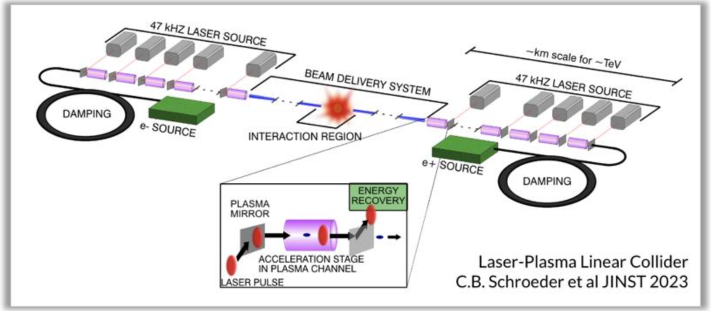
And requests a design study on wakefield colliders:

A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout.



The US Advanced Accelerator Community will pursue an end-to-end design of a 10 TeV Wakefield Collider. We aim to engage with our colleagues worldwide in this process.

Working groups, timelines, and deliverables will be announced at the AAC24 Workshop in July.



Laser-Plasma Linear Collider
C.B. Schroeder et al JINST 2023

D. Schulte, Future Colliders 3, BND, 2024

Conclusion and Thanks

- Touched only a small part of the exciting accelerator technologies
- Quite some work ahead to develop the future colliders
- ILC and CLIC are mature
- FCC-ee feasibility is being studied
    - Implementation next to CERN, cost, etc
    - In the long run FCC-hh can follow
- CEPC and SPPC are being considered in China (implementation in the next five-year plan?)
- Muon collider is less mature but would offers a long-term lepton path
- Plasma-based colliders are more speculative at this moment
- LHeC would offer electron-proton collisions

Many thanks to Reende Steerenberg, Steinar Stapnes, Lucio Rossi, Mark Palmer, Ralph Assmann, Jean-Pierre Delahaye, Lucie Linssen, Steffen Doebert, Alexej Grudiev, Frank Tecker, Walter Wuensch, Stephane Poss, Jan Strube, Joerg Wenninger, M. Benedikt, Frank Zimmermann, Bernhard Holzer, Roberto Kersevan, Ph. Lebrun, …

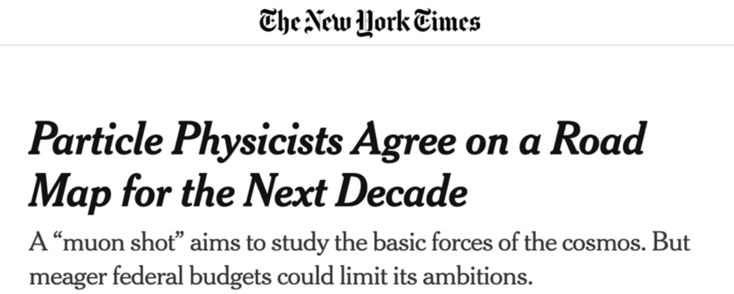
If you can look into the seeds of time,
and say which grain will grow and which will not;
speak then to me. (Shakespeare)

Reserve

US P5: The Muon Shot

Particle Physics Project Prioritisation Panel (P5) endorses muon collider R&D: ”This is our muon shot”

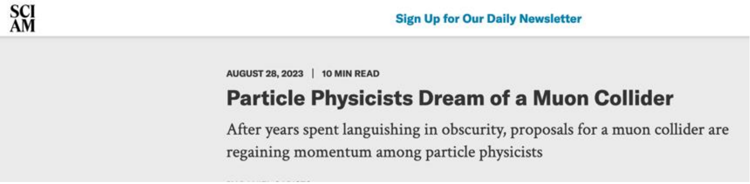
Recommend joining the IMCC
Consider FNAL as a host candidate



The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.



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AUGUST 28, 2023 | 10 MIN READ

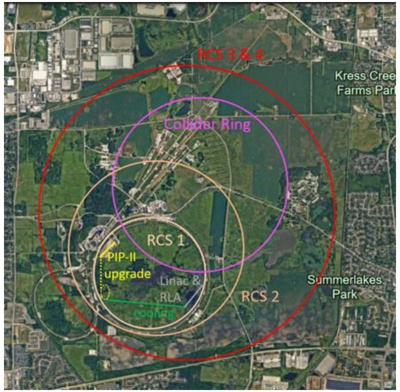
Particle Physicists Dream of a Muon Collider

After years spent languishing in obscurity, proposals for a muon collider are regaining momentum among particle physicists

EDITORIAL | 17 January 2024

US particle physicists want to build a muon collider – Europe should pitch in

A feasibility study for a muon smasher in the United States could be an affordable way to maintain particle physics unity.



We welcome the US community

Already participation, also in leadership
- Will increase and reorganise in 2024

Ambition of US to host collider is excellent news