Future Collider Projects

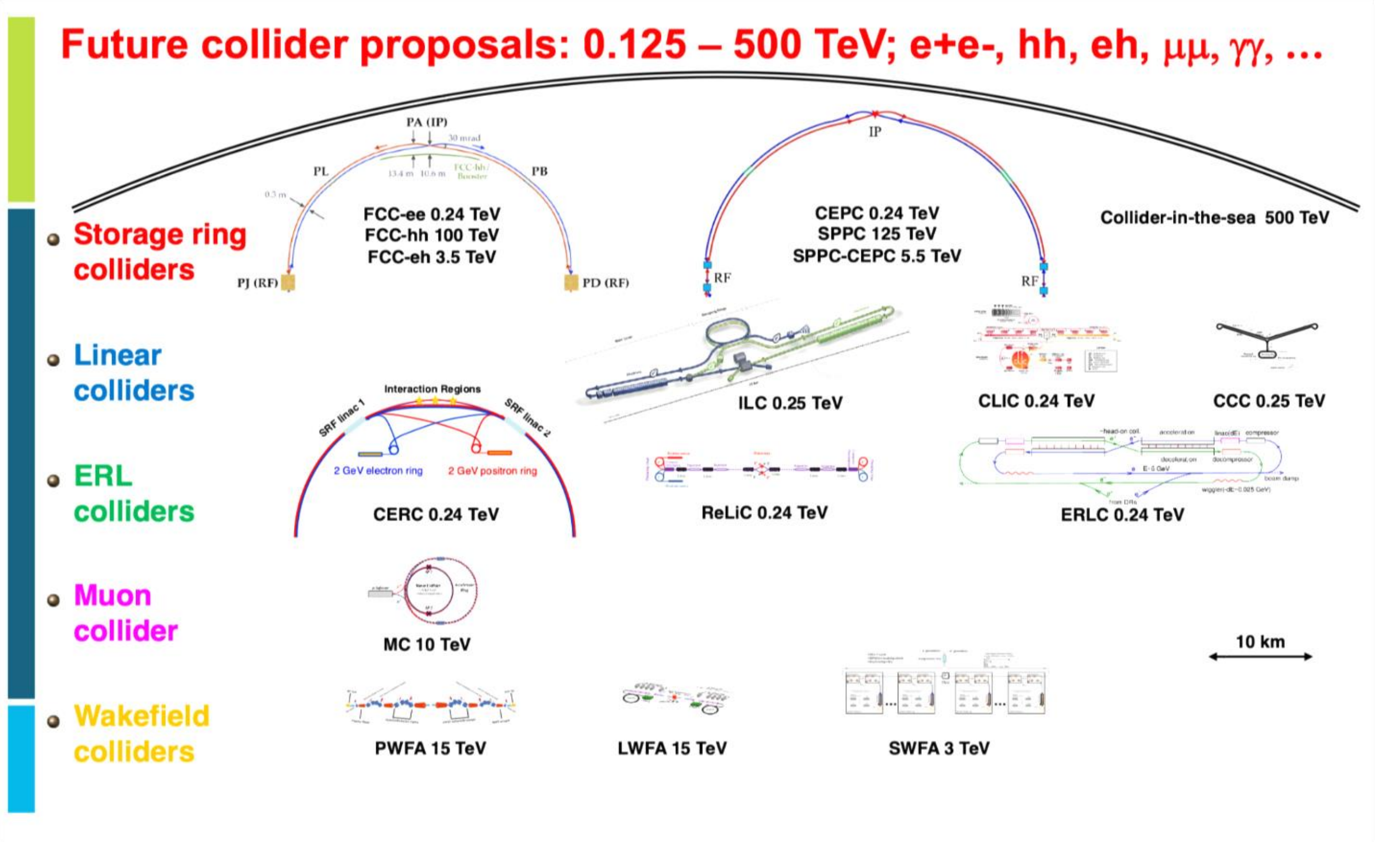
D. Schulte
CHIP/CHART Workshop, June 2023

Collider Proposals at Snowmass

Implementation Task Force (ITF) looked at many different proposals

Cannot cover them all

Select according to European view



Key Collider Options

Europe:
ESPPU concluded
- Long term ambition is high-energy hadron collider
- Higgs factory is most urgent project after HL-LHC

Plan A is **FCC**
- **FCC-ee**, e^+e^- circular collider, 91.2-365 GeV
- **FCC-hh**, hadron collider, O(100 TeV), same tunnel

Prudently prepare plan B
- **CLIC**, an e^+e^- linear collider 380 GeV-3 TeV
- **Muon collider**, as initiated by ESPPU, 3-10+ TeV

Also in the R&D Roadmap
- Energy recovery linacs (**LHeC, FCC-eh,** electron-proton)
- Plasma technology

US:
Waiting for the P5 process to finish
But interest in community for
- Linear collider (mainly **CCC**), 0.24-3 TeV
- **Muon collider, 3-**10+ TeV

Japan:
ILC, 0.25-1 TeV, 3 TeV

China:
Interest in **CepC/SppS**, comparable to FCC-ee/FCC-hh

Many more less mature proposals

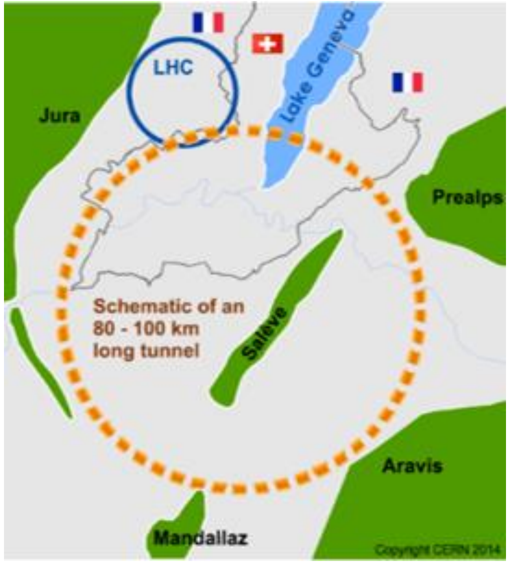
Will not give all details but shorter reminder of key projects and a bit on the novel ones

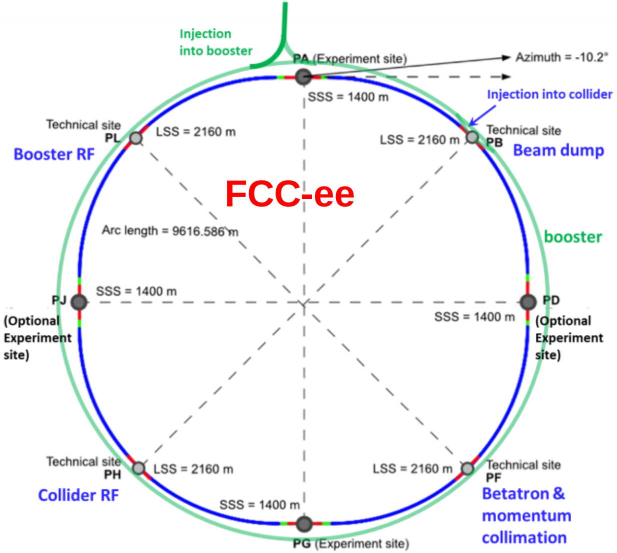
FCC Overview

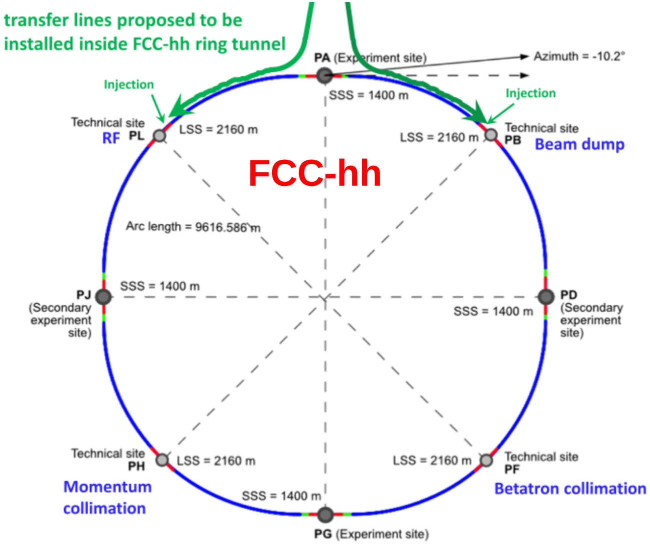
Similar to LEP/LHC staging
Focus on site studies

FCC-ee at Z, WW, ZH and tt

FCC-hh at 80-116 TeV, depending on magnet technology (Nb_3SN vs HTS)





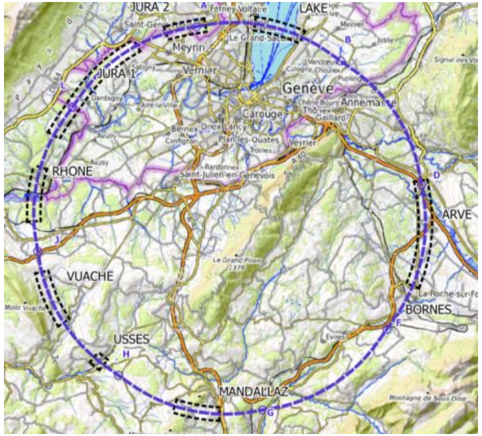


CepC and SppC is a similar approach in China

FCC Goals for 2021-2025

- demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- optimising design of colliders and their injector chains, supported by R&D to develop the needed key technologies;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- consolidation of the physics case and detector concepts for both colliders.

Site development ongoing



FCC Design

Parameter	unit	Z	WW	ZH	tt
Sqrt(s)	GeV	91.2	160	240	365
Max power	MW	222	247	273	357
Energy/year	TWh	1.07	1.21	1.33	1.77
Luminosity / IP	$10^{34}cm^{-2}s^{-1}$	182	19.4	7.3	1.33
Beam current	A	1280	135	26.7	5

Work on FCC-ee design, e.g. collider ring lattice

- Aim at 4 detectors
- High current at Z poses important challenges
- Beamstrahlung gives important bunch lengthing
- Very fast bunch-to-bunch feedback (6-7 turns)

Hadron collider lattice follows FCC-ee

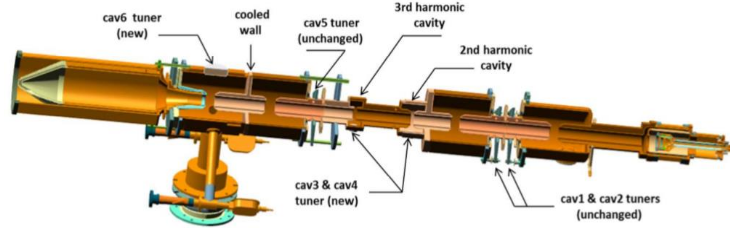
Energy 80-116, depending on magnet technology choice

About 560 MW power consumption

Luminosity up to 30 x 10^{34} $cm^{-2}s^{-1}$

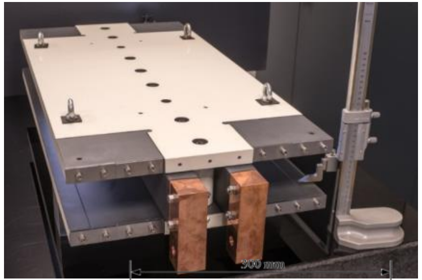
FCC Technology Development Examples

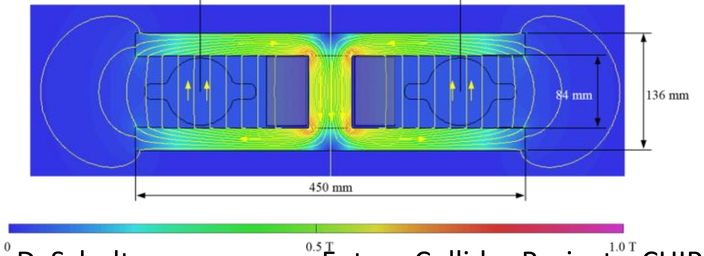
Efficient RF power sources (400 & 800 MHz)



800 MHz 5-cell Nb
prototype / JLAB, 2 K

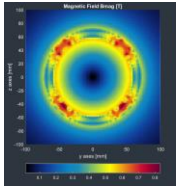
Efficient twin aperture arc dipoles

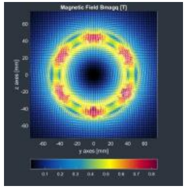




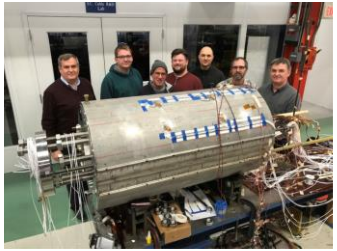
400 MHz 1-,2- & 4-cell
Nb/Cu , 4.5 K

Under study: CCT HTS
quad's & sext's for arcs



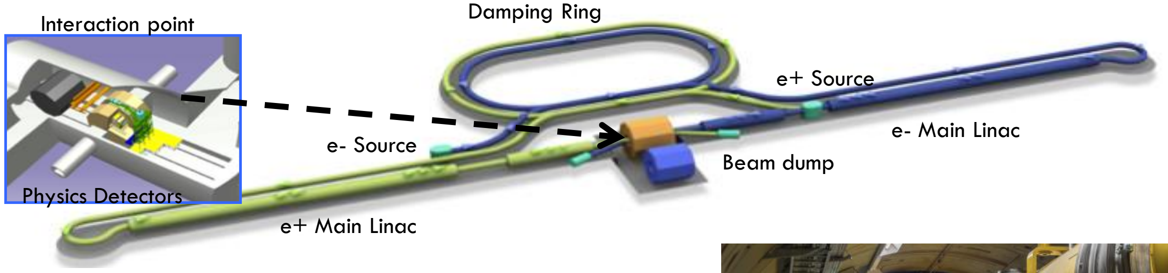


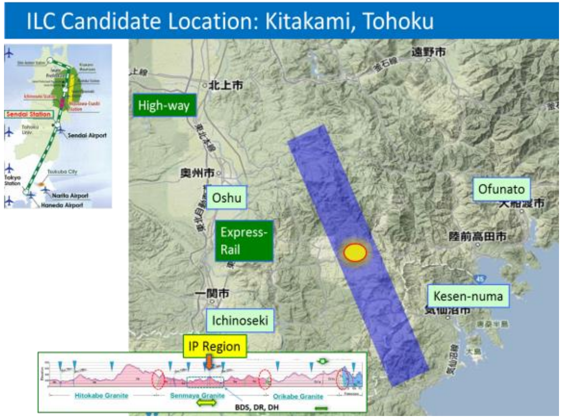
HL-LHC
12 T Nb_3Sn
quadrupole



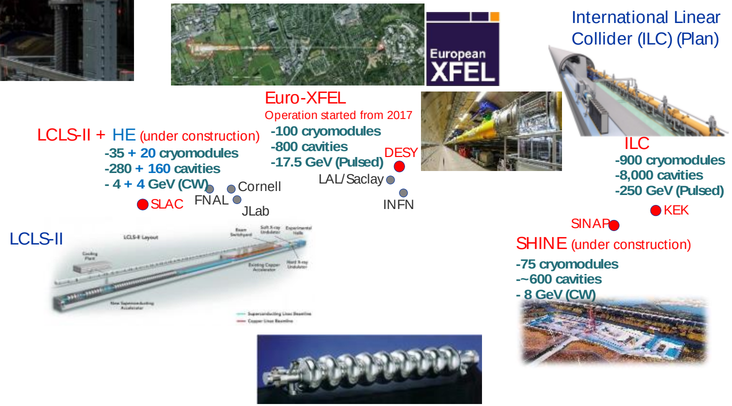
FNAL dipole
demonstrator
4-layer cos theta
14.5 T Nb_3Sn in 2019

ILC





Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Repetition rate	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10 ^{10}



ILC Progress

Recent progress:
A subset of the technical activities of the full ILC preparation phase programme have been identified as critical. Moving forward with these is being supported by the MEXT (ministry) providing increased funding.
European ILC studies, distributed on five main activity areas, is foreseen to concentrate (for the accelerator part) on these technical activities :

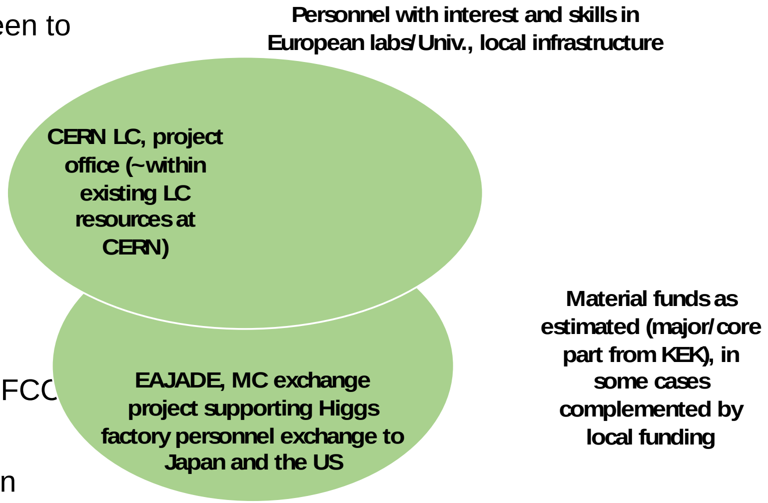
A1 with three SC RF related tasks
- SRF: Cavities, Module, Crab-cavities

A2 Sources
- Concentrate on undulator positron scheme – fast pulses magnet, consult on conventual one (used by CLIC and FCC-ee)

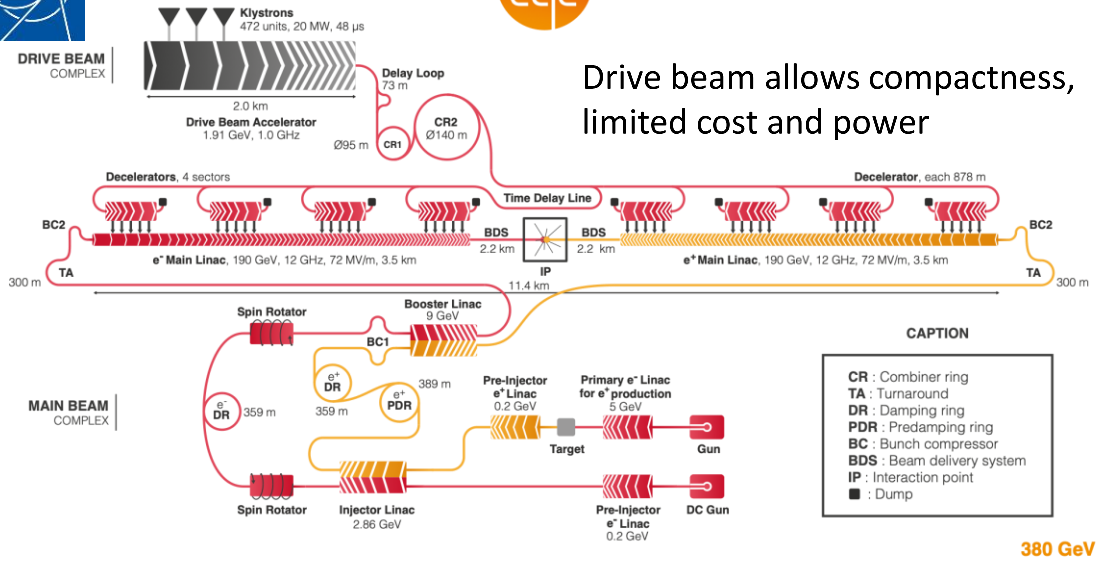
A3 Damping Ring including kickers
- Low Emittance Ring community, and also kicker work in CLIC and FCC

A4 ATF activities for final focus and nanobeams
- Many European groups active in ATF, more support for its operation expected using the fresh funding

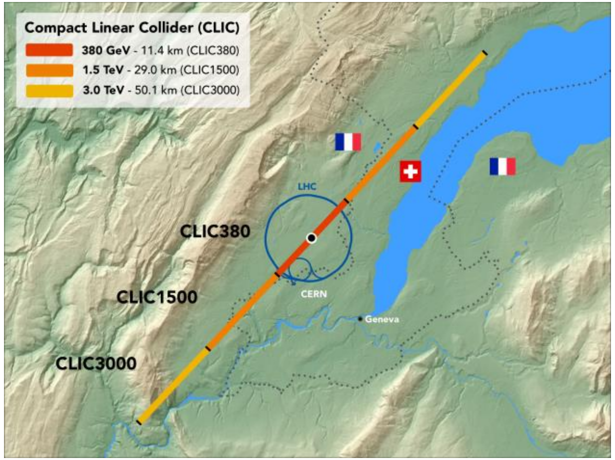
A5 Implementation including Project Office
- Dump, CE, Cryo, Sustainability, MDI, others (many of these are continuations of on-going collaborative activities)



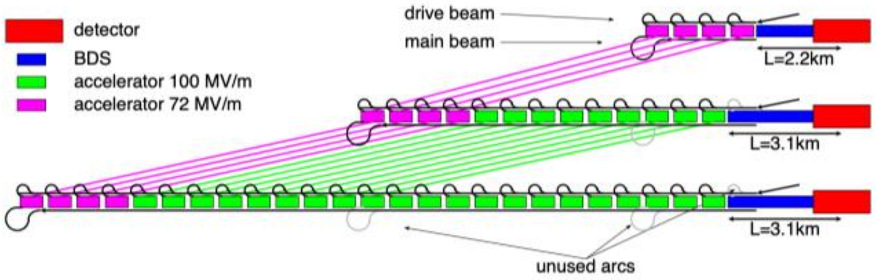
CLIC



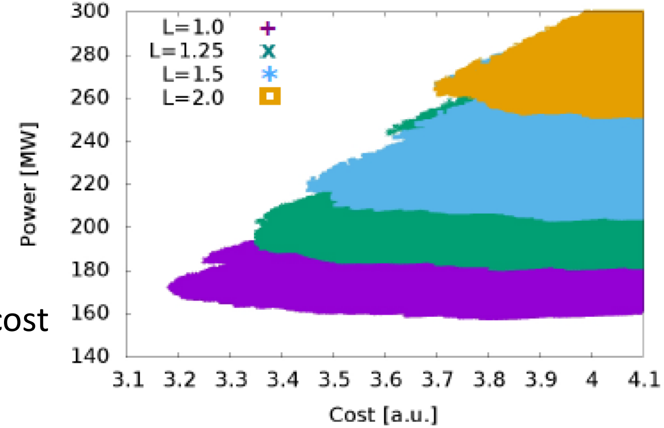
Drive beam allows compactness, limited cost and power



Stages possible: 0.38, 1.5 and 3 TeV



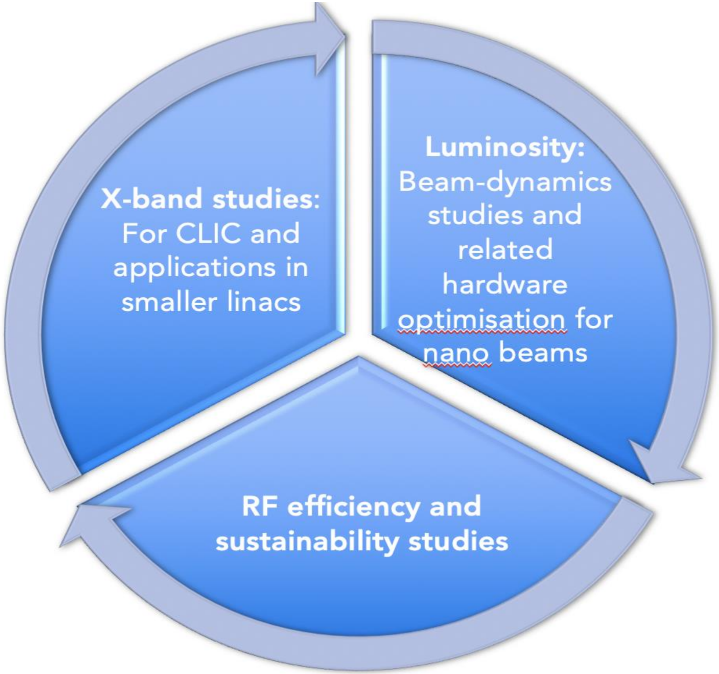
Optimised for cost and power



CLIC Work

Project Readiness Report as a step toward a TDR

Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

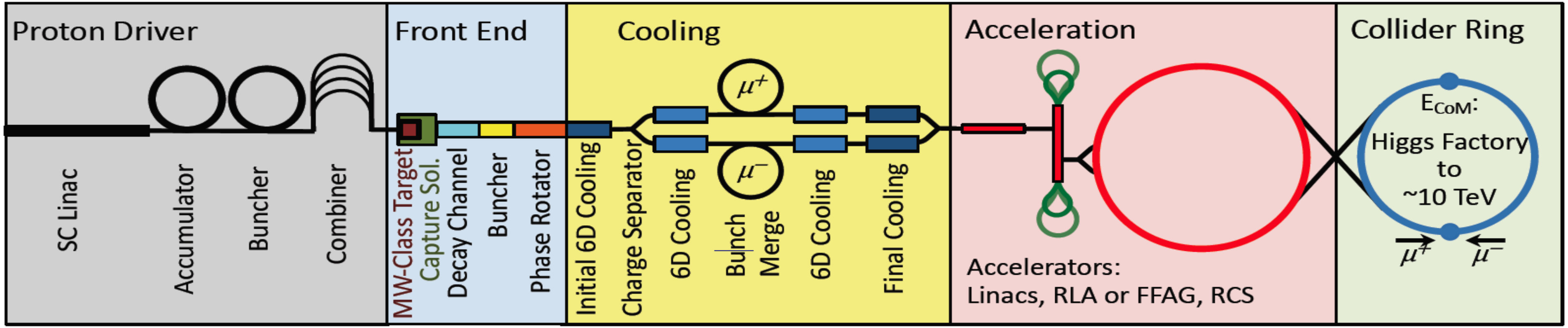


Muon Collider Overview

Muon collider has been studied in the US (“MAP”), experiments have been performed in the UK (“MICE”) and some alternatives have been considered at INFN (“LEMMA”)

Renewed interest thanks to **technology and design advances** and new goal of **very high-energy, high-luminosity lepton collisions**

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

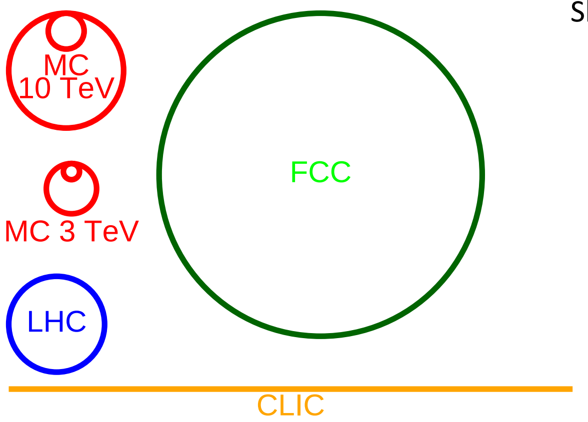
Ionisation cooling of muon in matter

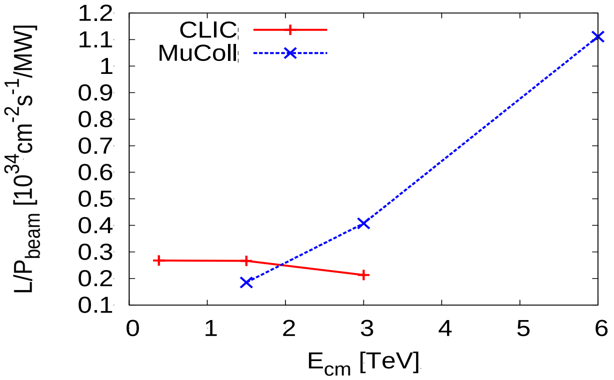
Acceleration to collision energy

Collision

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

http://arxiv.org/abs/2201.07895

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

Key work

- Design of critical beam complex
- Address technologies
- Prepare demonstrator

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [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.

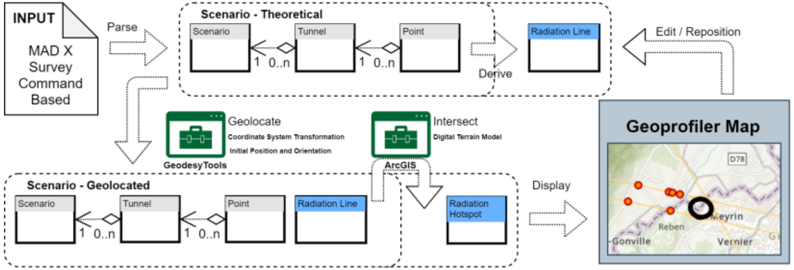
$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Muon Collider R&D Examples

Detector studies
- 10 TeV design
- Beam-induced background

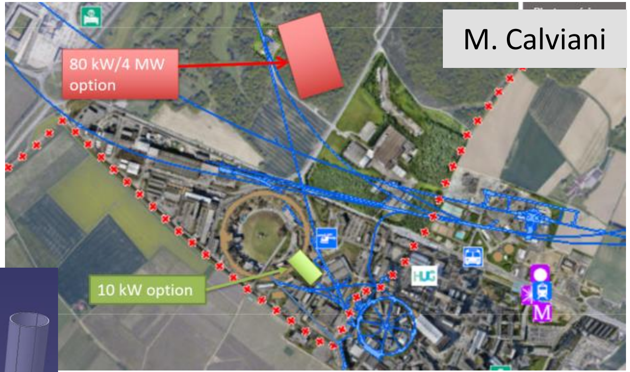
Promising but more work required

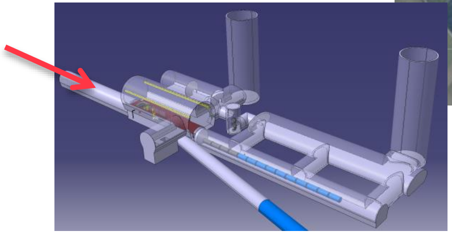
Siting/environemental impact
- Want negligible impact on environnement

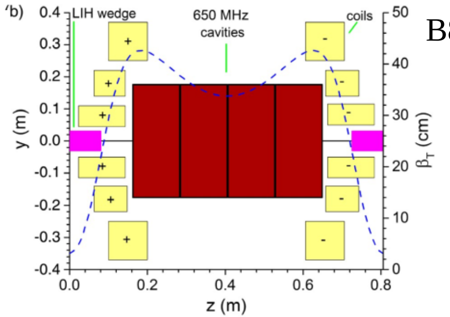


Muon production/cooling demonstrator

CERN example: PS beam
- 10^{13} p at 20 GeV every 1.2 s
- Could use SPL beam







B8

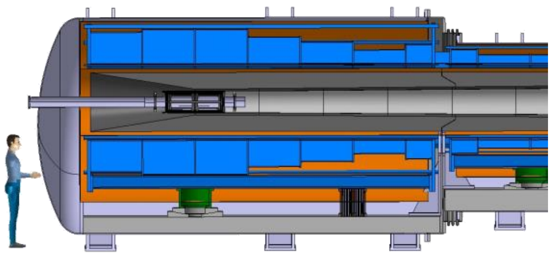
Cooling Cell Design

RF in magnetic field

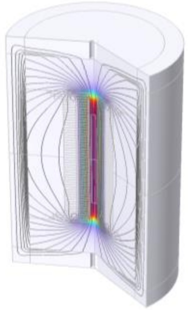
HTS solenoids

20 T target solenoid in HTS

ITER 13 T LTS solenoid could already work



40 T HTS solenoid



Other Ideas: CCC and LHeC/FCC-eh

CCC:
Linear collider with copper structures cooled to 50-70 K

- Less loss in copper
    - Less peak RF power required
- But need cryogenic power
    - Cheaper

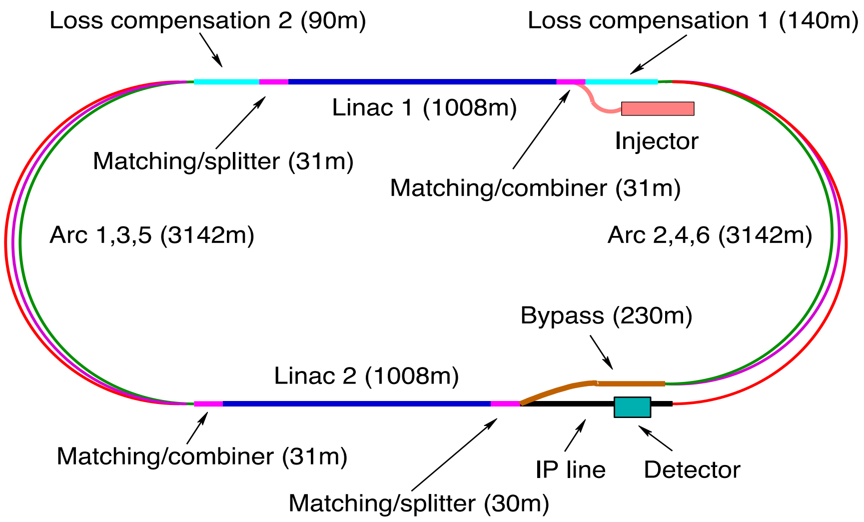
In conclusion:

- Somewhat cheaper
- But need to address challenges
    - Need to identify more of them
- Not more power efficient

	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

LHeC, FCC-eh
Collider electron from linac with LHC/FCC hadron beam
Recirculating linac allows to recover beam energy

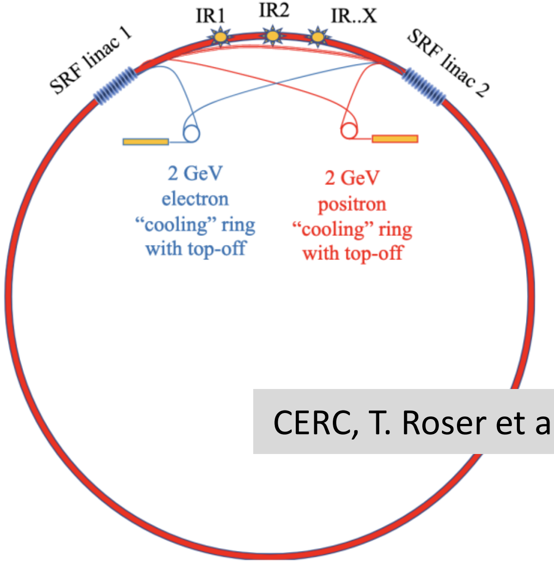
800 MW beam power for 100 MW power consumption



Other Energy Recovery: ERLC, ReLiC, CERC

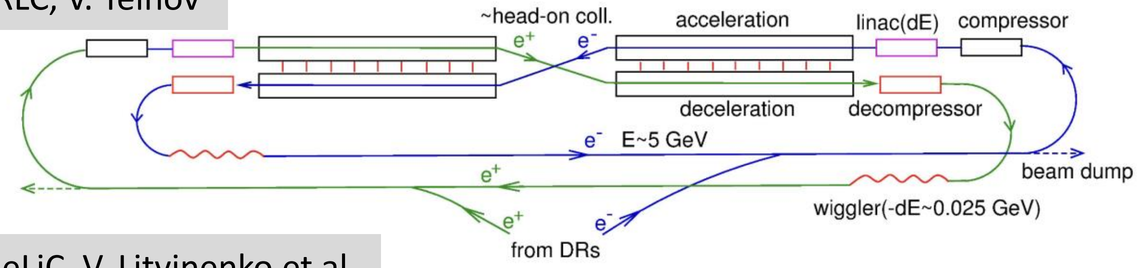
Several proposals based on recirculation and energy recovery

- Actually not a new idea, many discussions in the past
  - E.g. H. Gerke, K. Steffen in 1979, DESY PET-79/04
- **take current proposals cum grano salis**

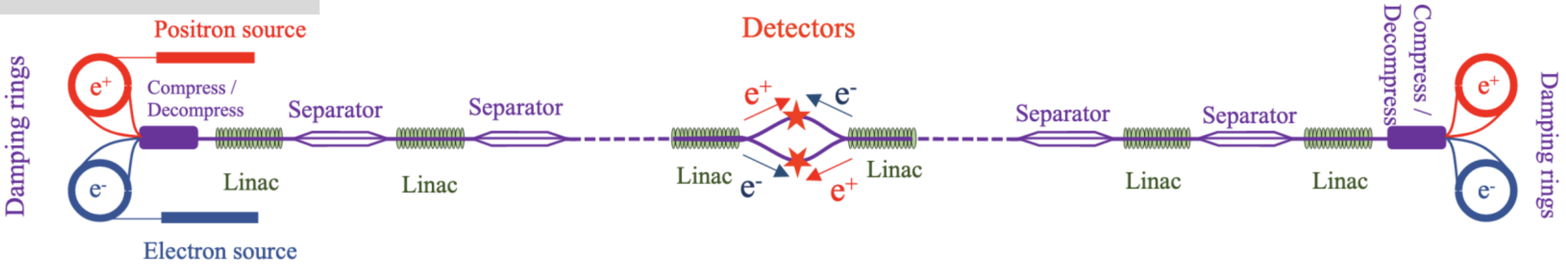


CERC, T. Roser et al.

ERLC, V. Telnov



ReLiC, V. Litvinenko et al.



Conclusion

Several interesting projects are being developed

- Range of promises and risks

Europe focuses on

- FCC
- CLIC
- Muon collider

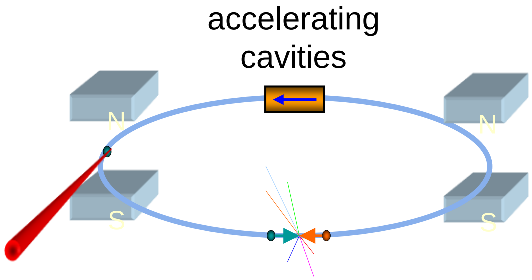
Other options

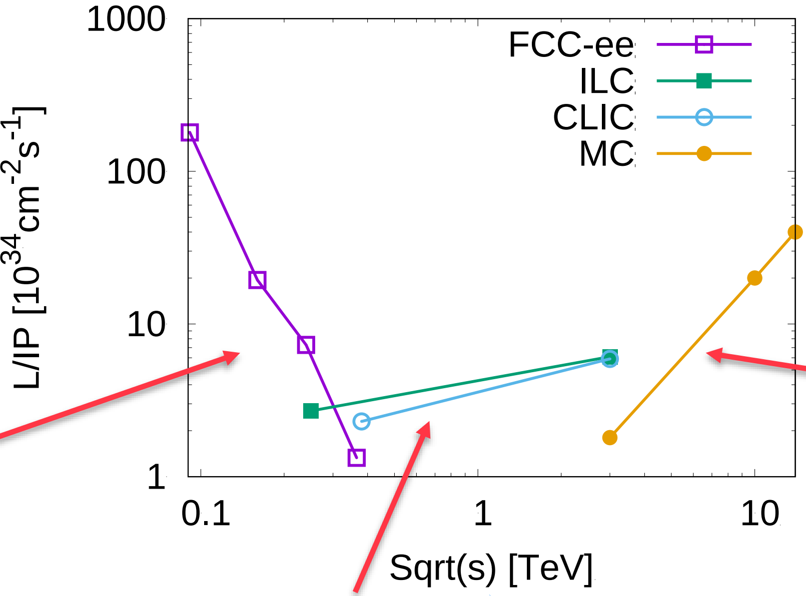
- ILC
- CepC/SppC
- CCC?

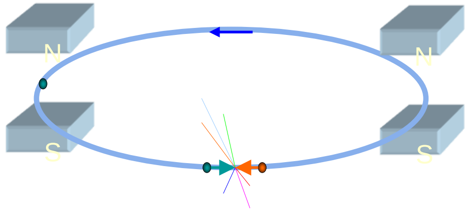
Sustainability is of importance to the projects

Reserve

Lepton Collider Energies and Luminosities







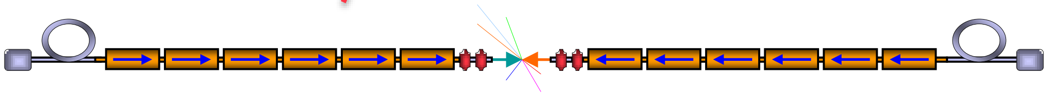
Muons do not radiate much

- Did not yet explore 30 TeV

Circular e^+e^-

- FCC-ee, CEPC similar
- Strong energy dependence due to synchrotron radiation

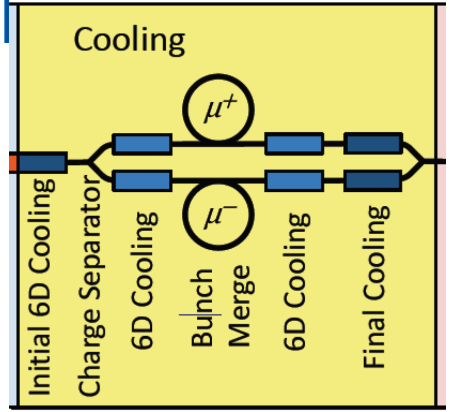
Comparable reach to 100 TeV hadrons, ask your favorite theorist

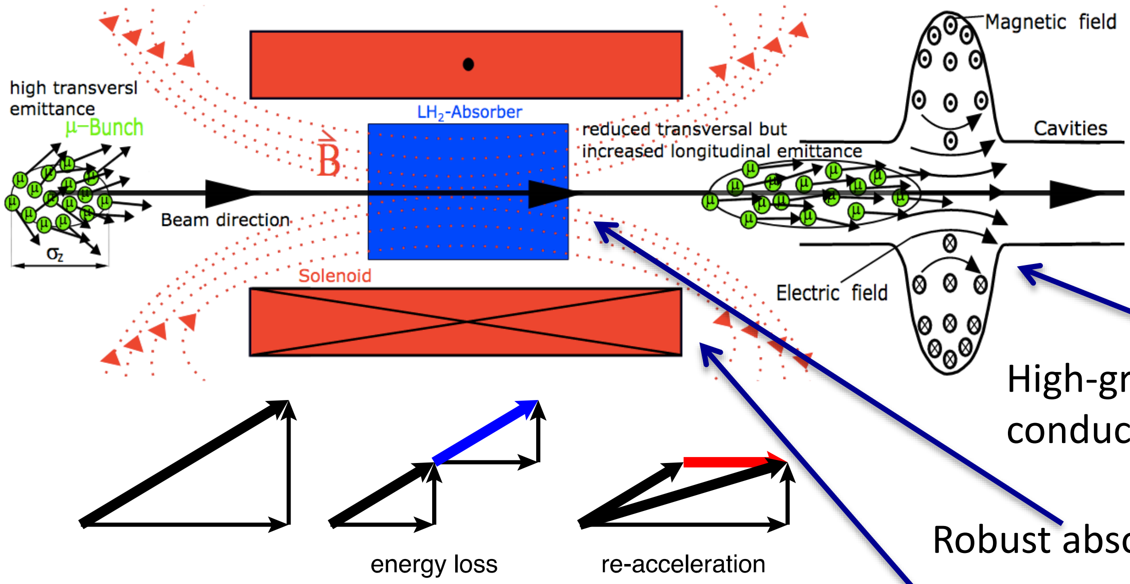


Linear e^+e^-

- ILC, CLIC
- ILC at 3 TeV is not well studied

Muon Cooling Principle



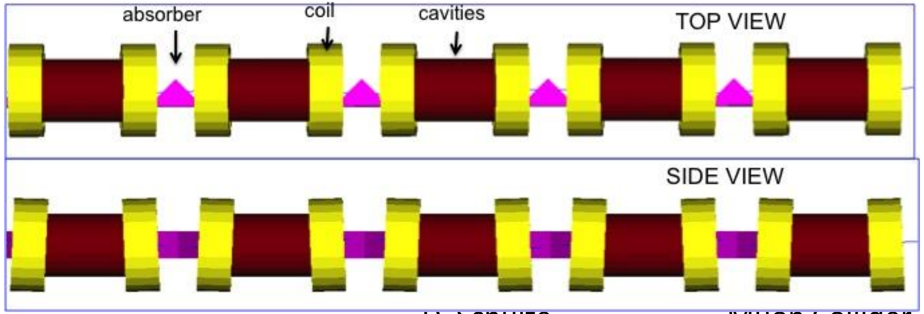


High-gradient normal-conducting cavities

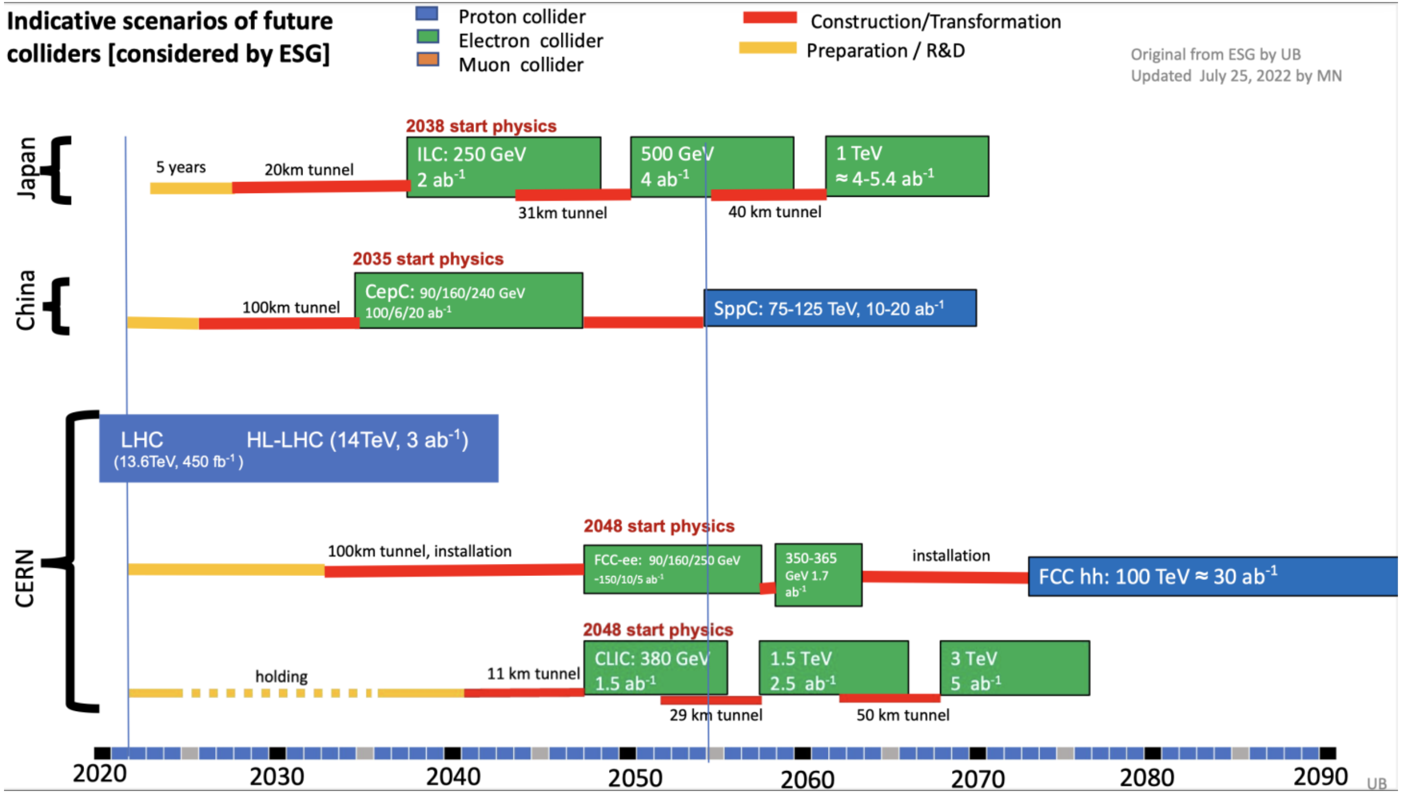
Robust absorbers

High-field, superconducting solenoid

C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



Main High-energy Colliders by Snowmass



ILC

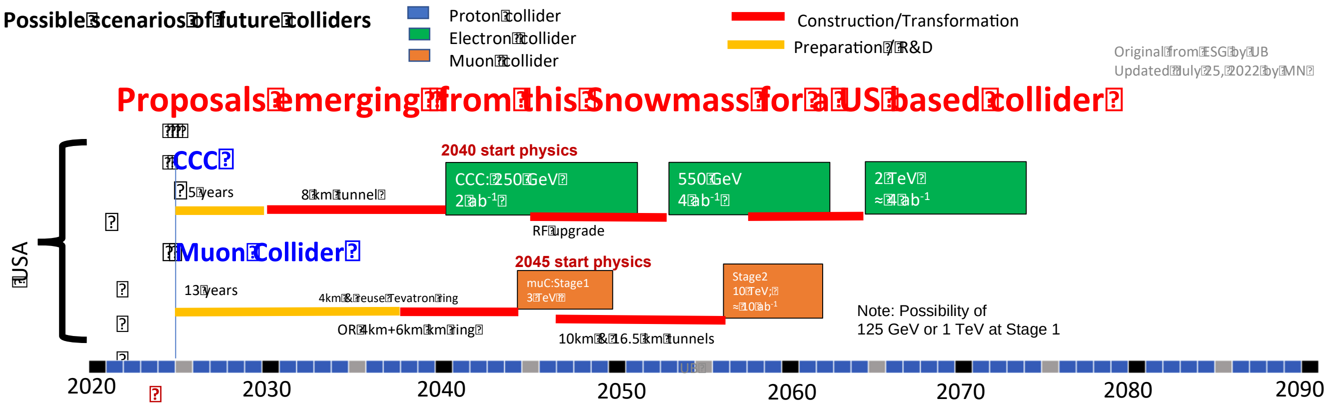
CepC / SppC

FCC

CLIC

Timeline in Europe driven by HL-LHC

Main High-energy Colliders by Snowmass



CCC

Muon Collider

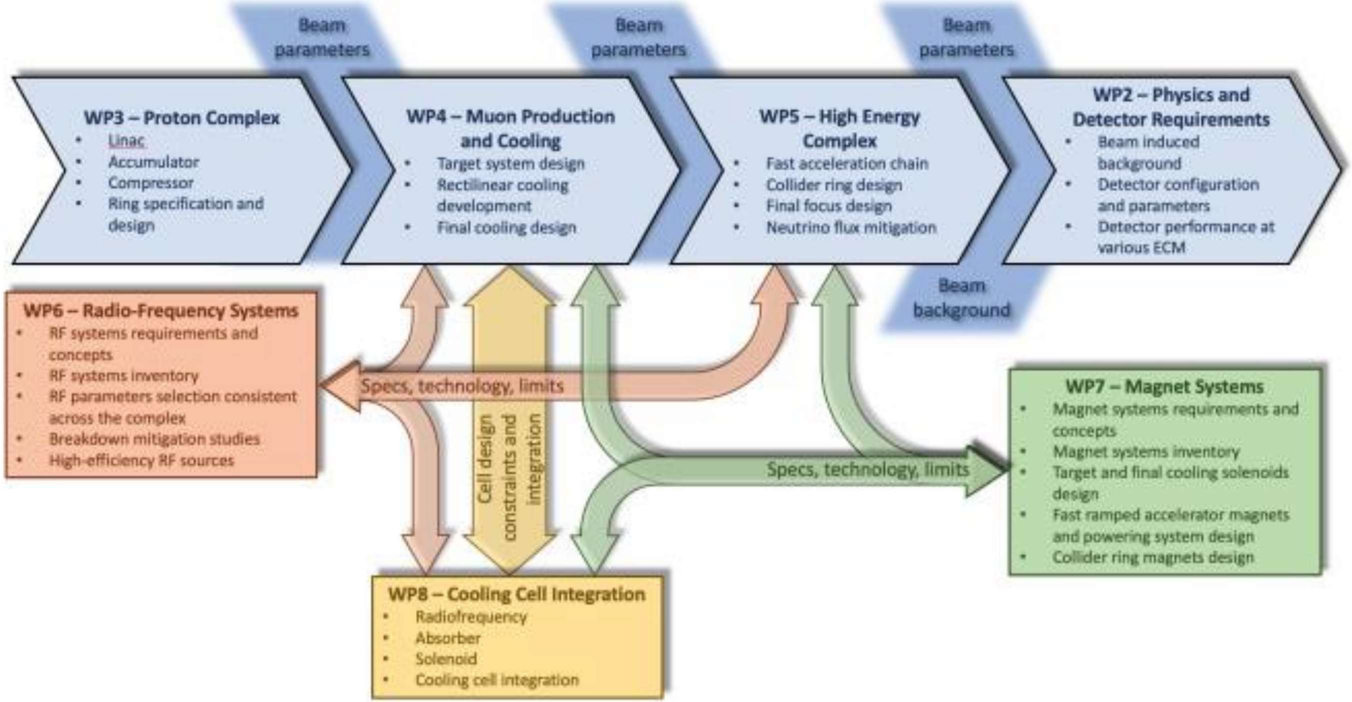
- Also plan B for CERN

Interest in the US to host a high-energy frontier project

Muon collider considered a plan B for CERN

- Timeline will depend on

Current Work



CDR Phase, R&D and Demonstrator Facility

Broad R&D programme required and can be distributed world-wide

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

Integrated cooling demonstrator is a key facility

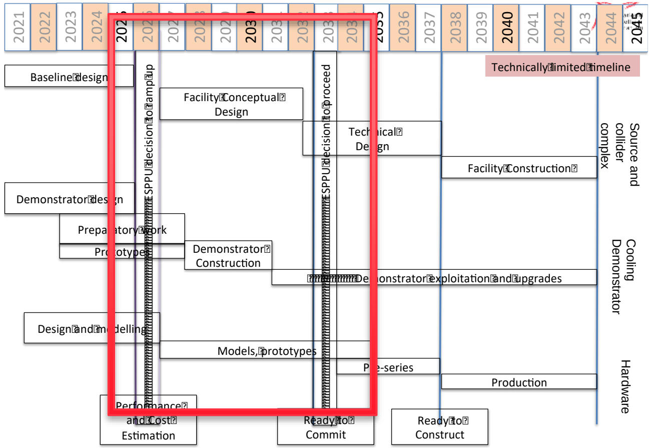
- look for an existing proton beam with significant power

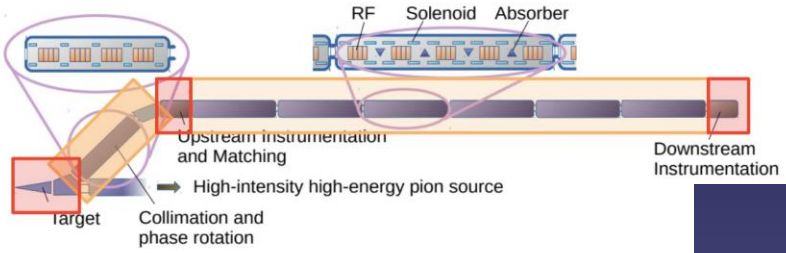
Different sites are being considered

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

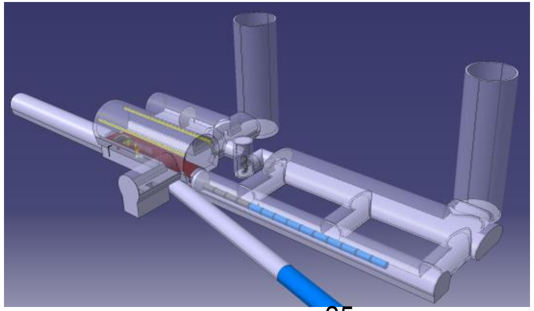
Could be used to house physics facility

- Are trying to explore what are good options





C. Rogers, R. Losito, et al.



Reserve

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

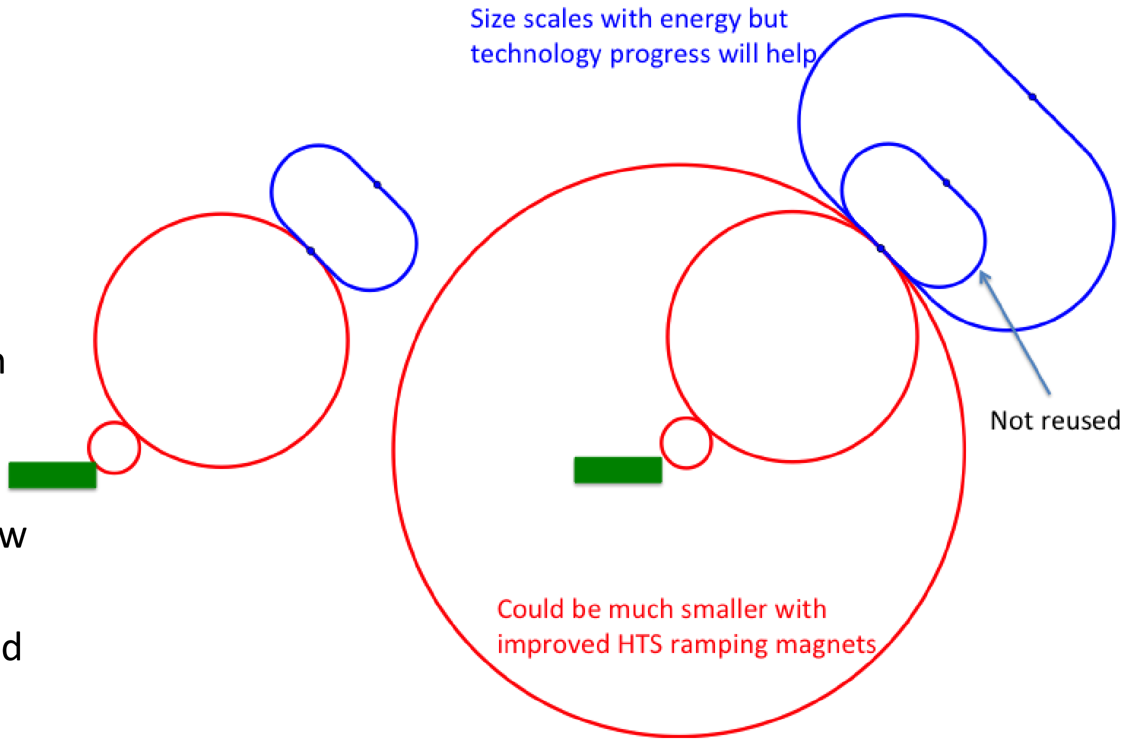
Staging

Ideally would like full energy right away, but staging could lead to faster implementation

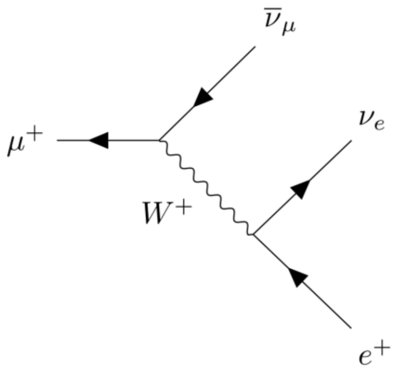
- Substantially less cost for a first stage
- Can make technical compromises
    - e.g. 8 T NbTi magnets would increase collider ring from 4.5 to 6 km and reduce luminosity by 25%
- Timeline might be more consistent with human lifespan

Upgrade adds one more accelerator and new collider ring

- only first collider ring is not being reused



Muon Decay



About 1/3 of energy in electrons and positrons:

Experiments needs to be protected from **background** by masks

- simulations of 1.5, 3 and 10 TeV
- optimisation of masks and lattice design started
- first results look encouraging
- will be discussed at ICHEP

Collider ring magnets need to be shielded from losses

Losses elsewhere will also need to be considered but are less severe

D. Lucchesi, A. Lechner, C Carli et al.

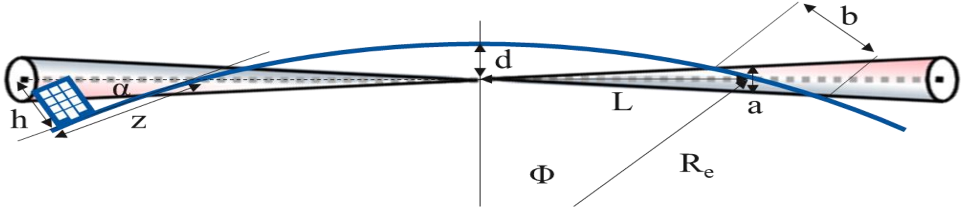
Neutrino flux to have negligible impact on environment

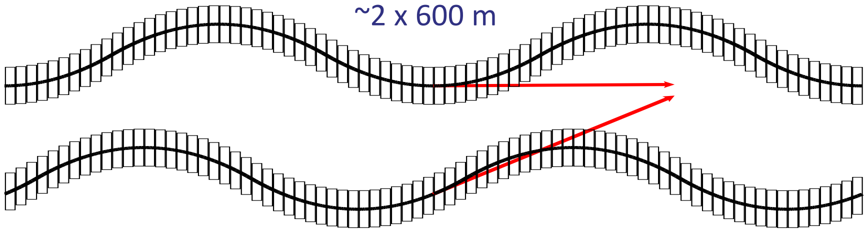
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

Above about 3 TeV need to make beam point in different vertical directions

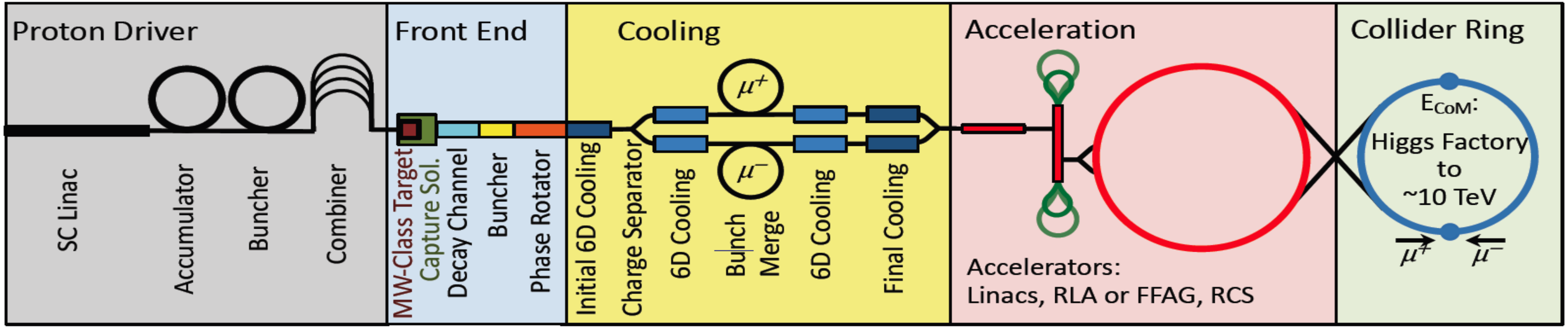
Mechanical system with 15cm stroke, 1% vertical bending

Length of pattern to be optimised for minimal impact on beam





Key Challenges



Proton complex
- Compressing protons to few bunches

Target
- Target
- Solenoid

Cooling channel
- Channel design
- Solenoids
- RF in magnetic field
- Absorbers
- Integration

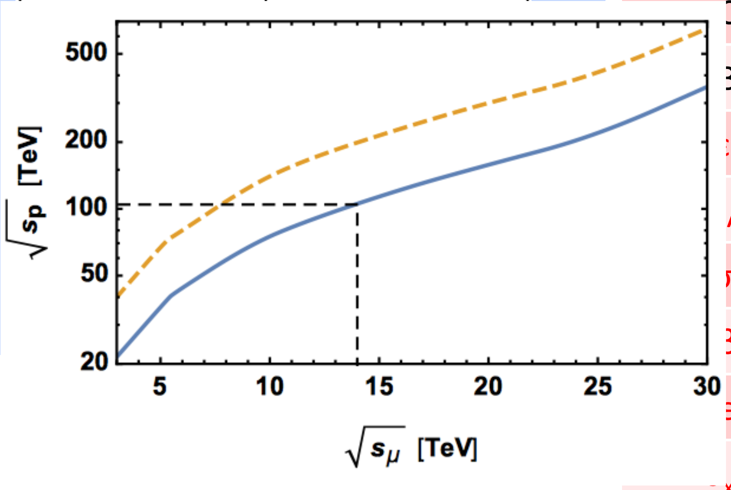
RCS
- Beam dynamics
- Ramping magnets
- Power converter
- RF system

Collider ring
- Optics
- Magnets
- Neutrino flux
- Detector background

Initial Target Parameters

Target integrated luminosities

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



Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
C	km	4.5	10	14	
B>	T	7	10.5	10.5	
$_L$	MeV m	7.5	7.5	7.5	
/ E	%	0.1	0.1	0.1	
$_z$	mm	5	1.5	1.07	
3	mm	5	1.5	1.07	
ε	µm	25	25	25	
$_{x,y}$	µm	3.0	0.9	0.63	

US Snowmass

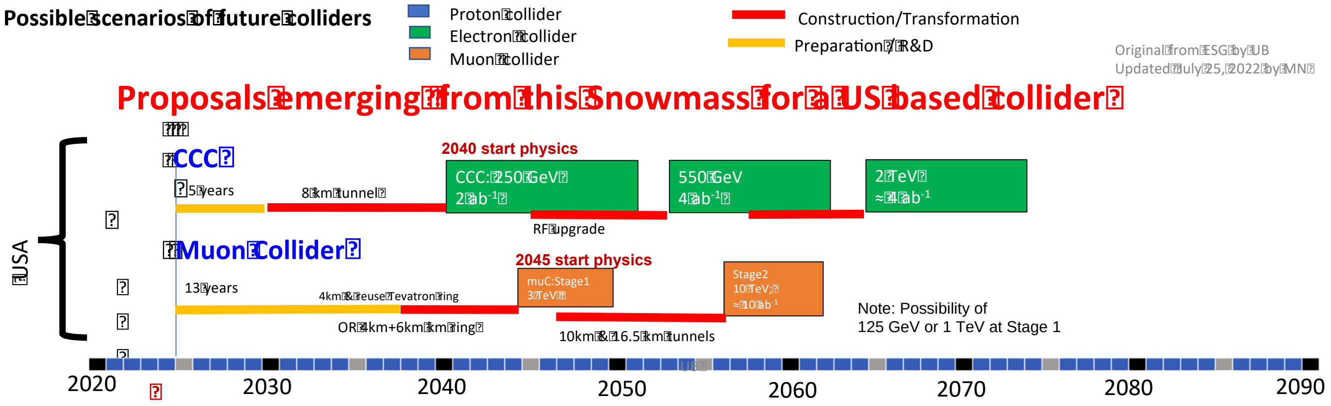
Strong interest in the US community in muon collider

- seen as an energy frontier machine
- decoupled from LC

US community wants funding for **R&D**

- **Goal: match European effort**

Community interested in the US to **host a muon collider**



- Timelines technologically limited
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

Consider proposing hosting ILC in the US.

Meenakshi Narain: Energy Frontier / Large Experiments, Snowmass Community Summer Study July 17-26, 2022

US Snowmass, cont.

Implementation Task Force

Muon Collider is a viable option for the HEP future

They made cost and power estimate for muon collider take it *cum grano salis*

Place MC in same risk tier as FCC-hh

ITF's Look Beyond Higgs Factories

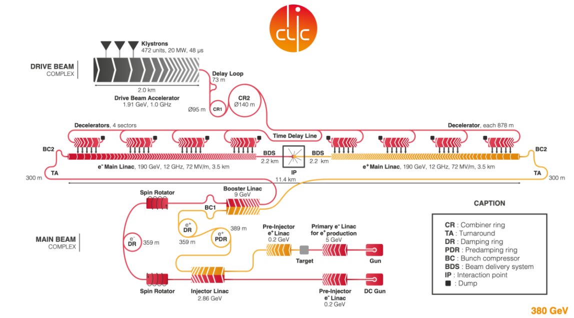
ITF Report – T.Roser, et al, arXiv:2208.06030

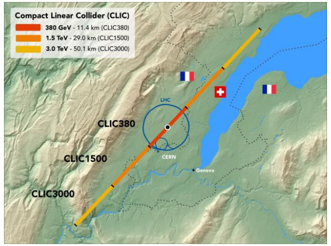
	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	*O*(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

Thomas Roser et al

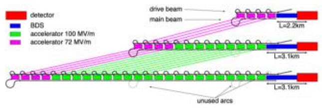
CLIC Energy upgrades

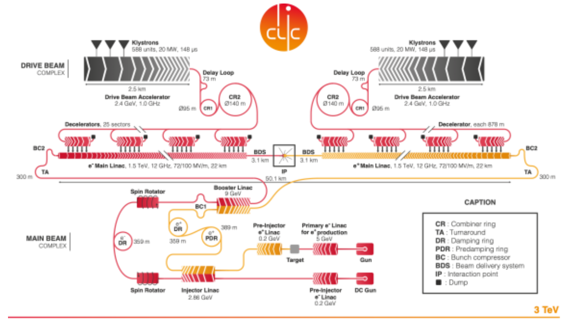
CLIC can easily be extended into the multi-TeV region (3 TeV studied in detail)





Extend by extending main linacs, increase drivebeam pulse-length and power, and a second drivebeam to get to 3 TeV





CLIC - Scheme of the Compact Linear Collider (CLIC)

ILC has foreseen extensions to ~ 1TeV with existing or modestly improved SCRF technology:

- However, improvements in gradients with for example travelling wave structures or Nb_3Sn coating have motivated ideas of reaching ~3 TeV in 50km (gradients well above 50 MeV/m needed)
- https://arxiv.org/abs/2204.01178
  and
  https://www.frontiersin.org/articles/10 … 33
  479/full

Will describe briefly later:
C3 (cool copper) is similar to CLIC in gradient and a 2 TeV C3 concept have been formulated. C3 would also fit into an ILC tunnel with its suitable klystron gallery, as a potential upgrade.

CLIC

Normal-conducting accelerating structures allow high gradients
But high losses -> use very short pulses -> requires very high input power -> expensive

Solution is drive beam that compresses 150 microsecond pulse to 250 ns

Accelerator R&D Roadmap

No insurmountable obstacle found for the muon collider

- but important need for R&D

Aim at **10+ TeV** and potential initial stage at **3 TeV**

Full scenario deliverables by next ESPPU/other processes

- **Project Evaluation Report**
- **R&D Plan** that describes a path towards the collider;

Allows to make **informed decisions**

Interim report by end of 2023

Do not yet have the resources of the reduced scenario

- Will do as much as possible, following priorities and available expertise and resources
- Are approaching O(40 FTE)
- Efforts to increase resources

Scenario	FTEy	M MCHF
Full scenario	445.9	11.9
Reduced scenario	193	2.45

http://arxiv.org/abs/2201.07895

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.

Technically Limited Timeline (From Roadmap)

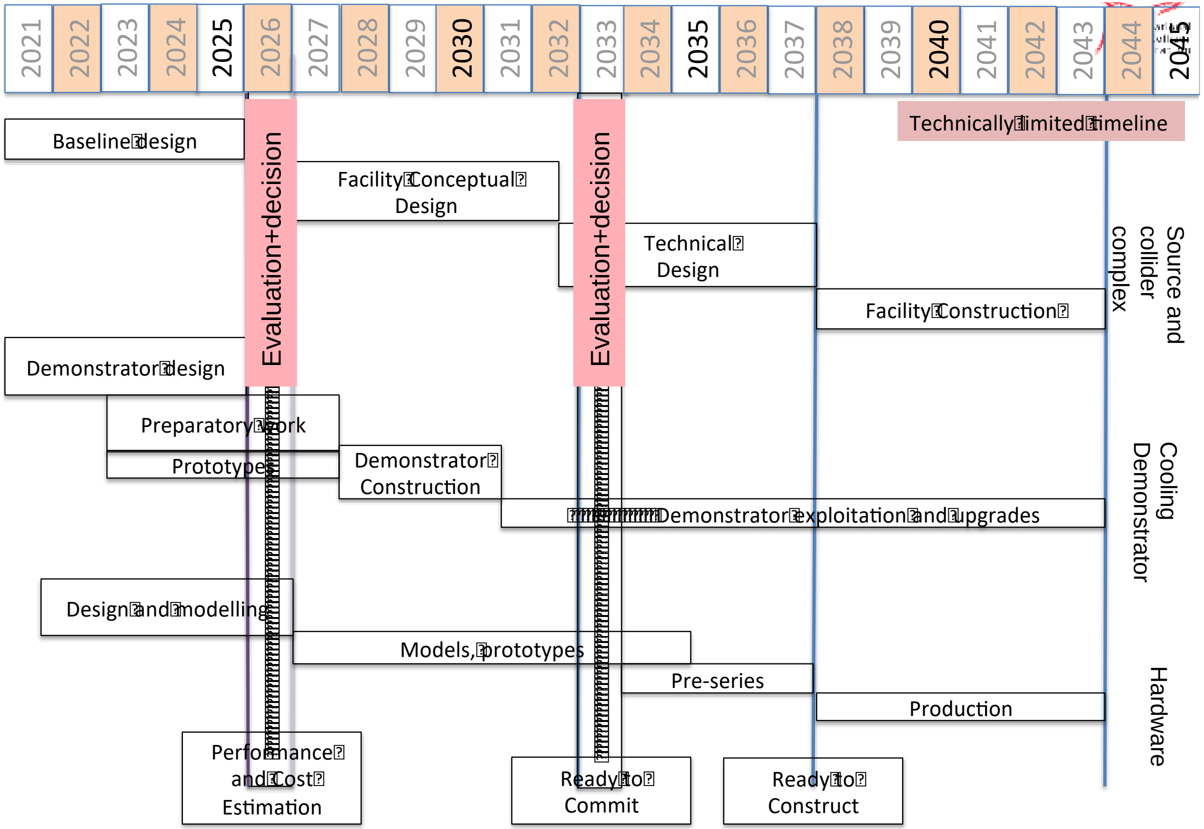
Muon collider important in the long term

Fastest track option with important ramp-up of resources to see if muon collider could come directly after HL-LHC

- Compromises in performance, e.g. 3 TeV

Needs to be revised but do not have enough information at this point for final plan

To be reviewed considering progress, funding and decisions



Roadmap Schedule

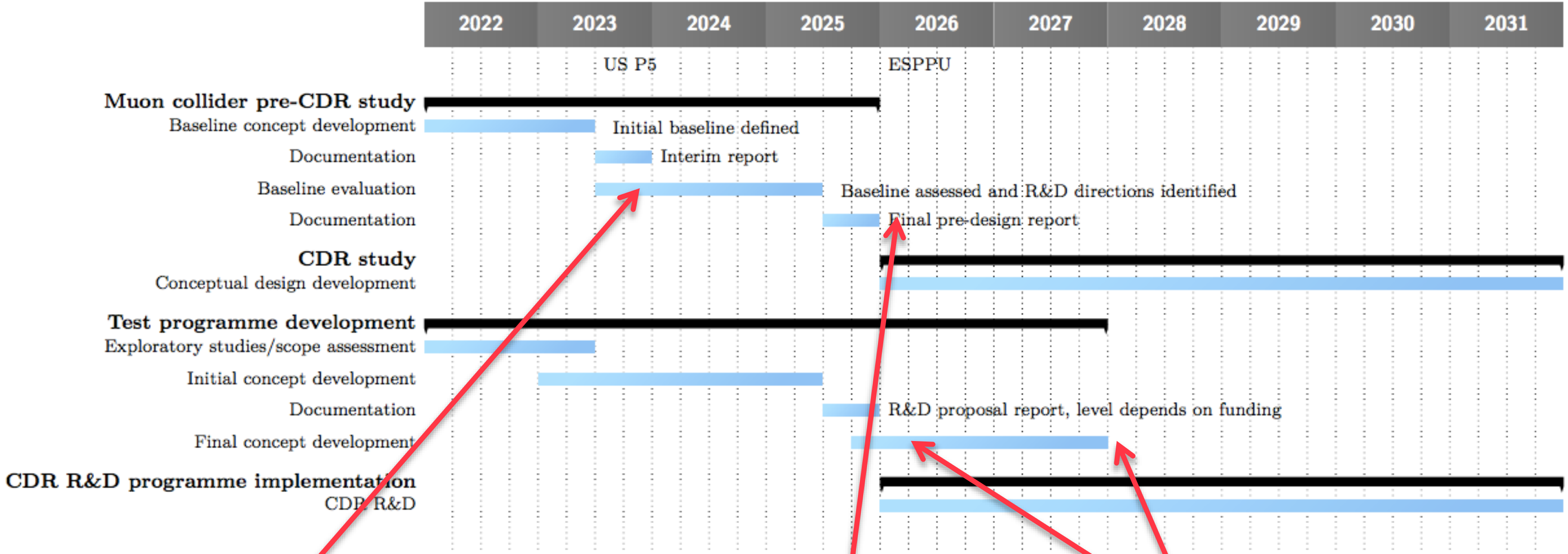


Fig. 5.4: Overall timeline for the R&D programme.

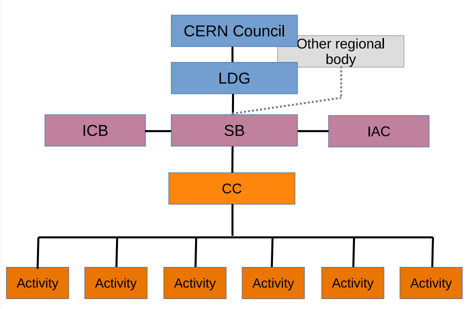
2023
Interim Report to gauge progress
Initial baseline defined

2025
Assessment Report

2025-2027
R&D plan will be refined

Muon Collider Community

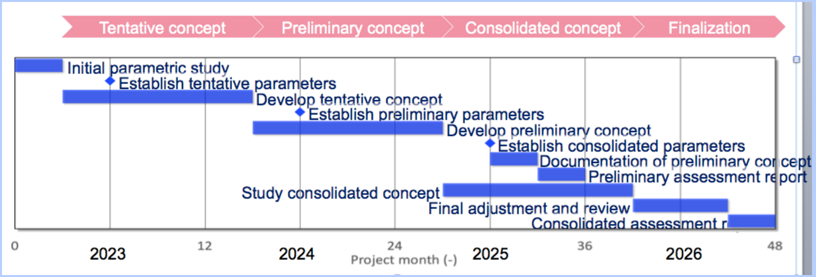
Formed **collaboration** to implement and R&D Roadmap for CERN Council



50+ partner institutions
30+ already signed formal agreement

EU Design Study approved

(EU+Switzerland+UK and partners)



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

TIARA wants magnet proposal

US Snowmass has **strong support**

- to contribute to R&D
- as a collider in the US

Lia appointed team to prepare P5 ask

Some first contacts with others

MoC and Design Study Partners

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
Mal	**Univ. of Malta**
BE	***Louvain***

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
SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**

US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
CH	**PSI**
	University of Geneva
	EPFL

KO	**KEU**
	Yonsei University
India	***CHEP***
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
	Tenessee

US P5 Ask

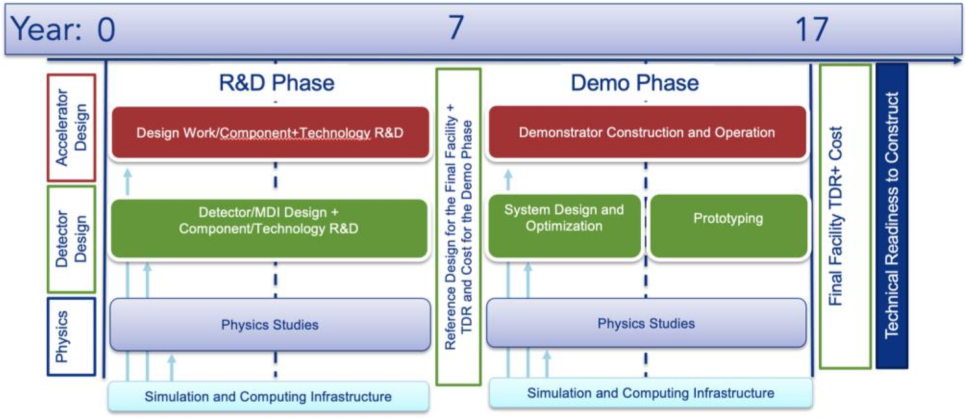
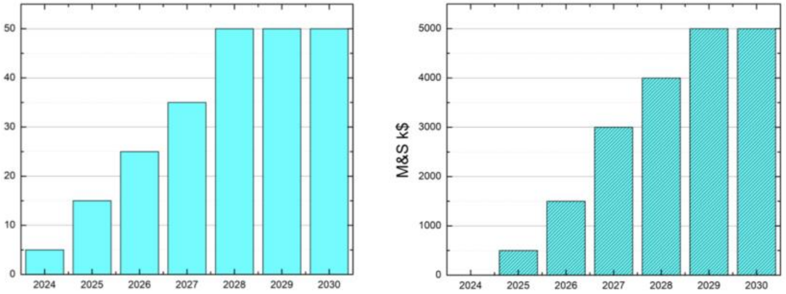


Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.



: FTE and M&S profiles for accelerator R&D corresponding to the first phase of the
. We assume here that funding can start in 2024. The M&S is in FY23 dollars and
n is not included in these estimates.

S. Jindariani, D. Stratakis, Sridhara Dasu et al.
Goal is to contribute as much as Europe
Start of construction a bit later than in Roadmap
Will try to harmonise/define scenarios once US joins

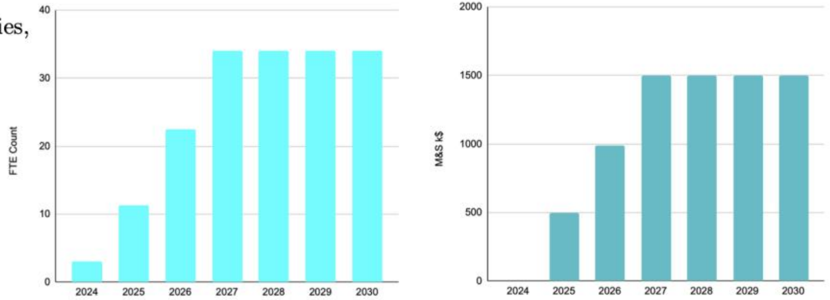
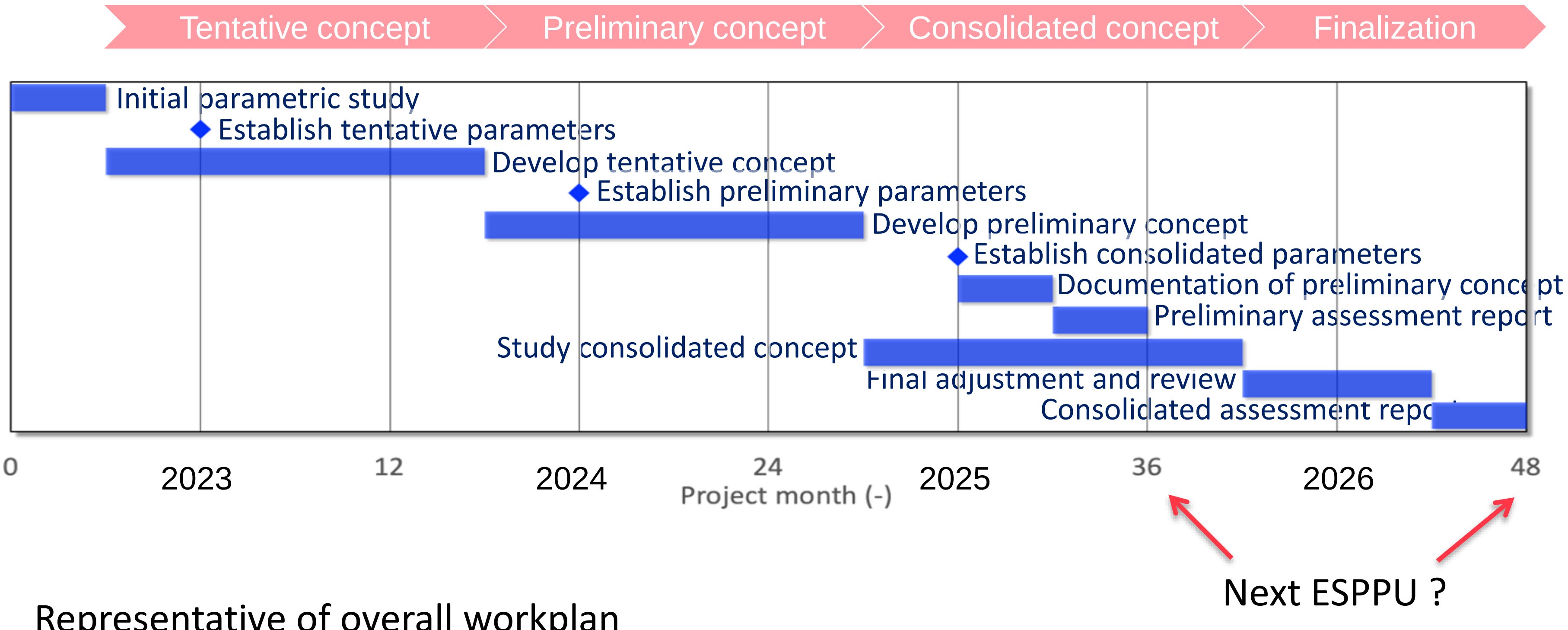


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

Total resources would approach Roadmap

- Some increase in Europe and Asia assumed
- 1-2 years delay
- But profile is different

EU Design Study Timeline

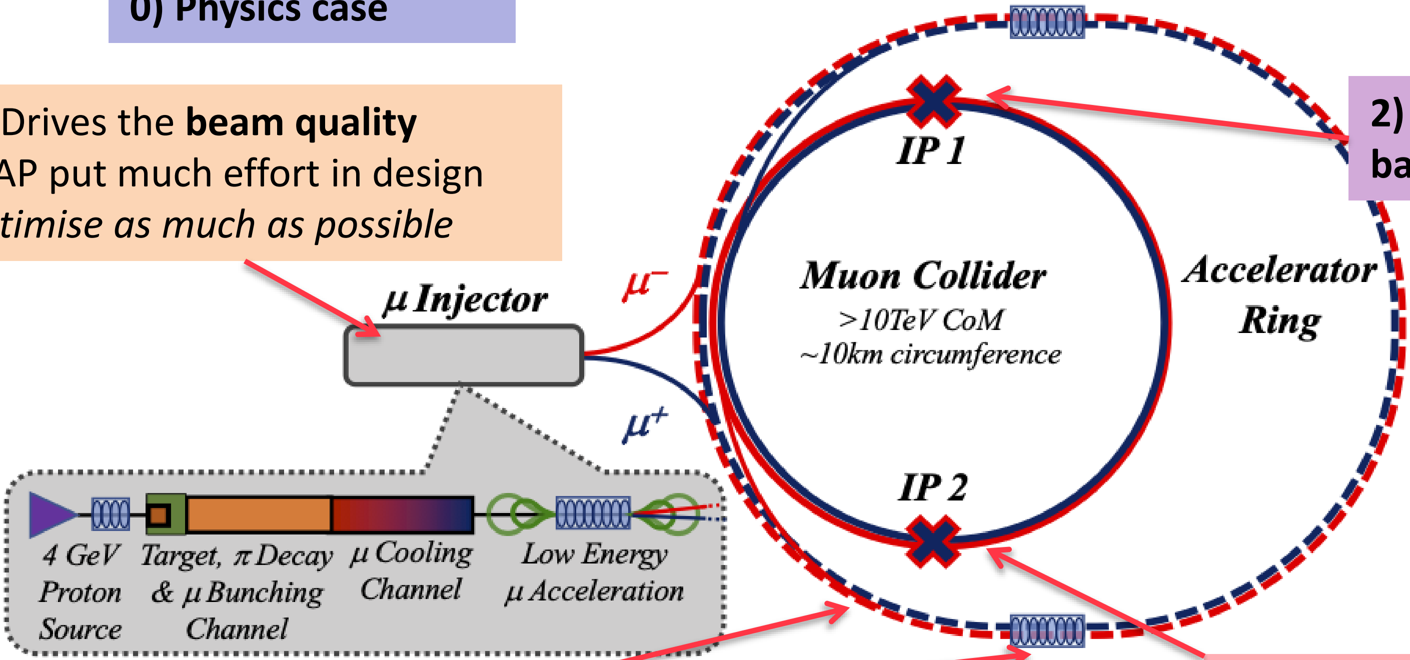


Representative of overall workplan

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

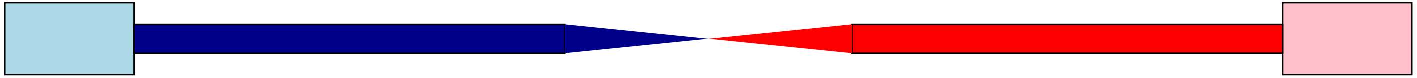
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Linear Colliders

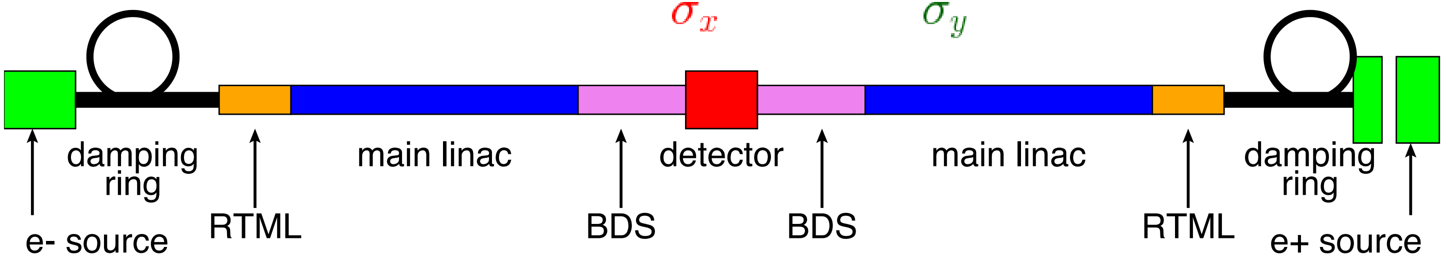
Key challenges:

Accelerate the beam in single pass -> high gradient -> high stored RF energy -> high losses

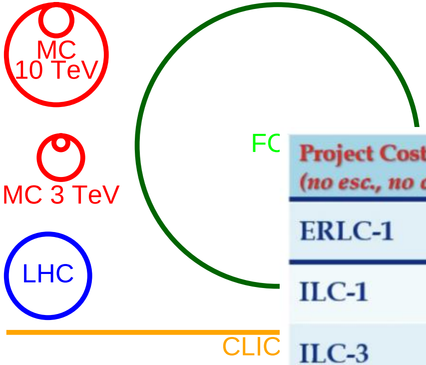
Collider in single pass -> high beam density -> limits from focusing, beam emittance, beamstrahlung, …

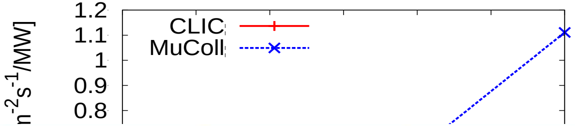


$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



Muon Collider Promise





Project Cost (no esc., no cont.)	4	7	12	18	30	50
ERLC-1						
ILC-1						
ILC-3						
CCC-2						
CLIC-3						
ReLiC-3						
MC-3						
MC-10						
SPPC-125						
FCChh-100						
pp-inSea-500						

Compactness should lead to

Luminosity to beam power i

- 14 TeV MC would need l

The Cool Copper Collider (CCC)

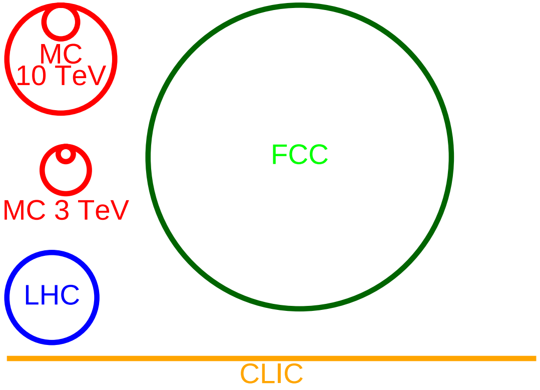
Rational:

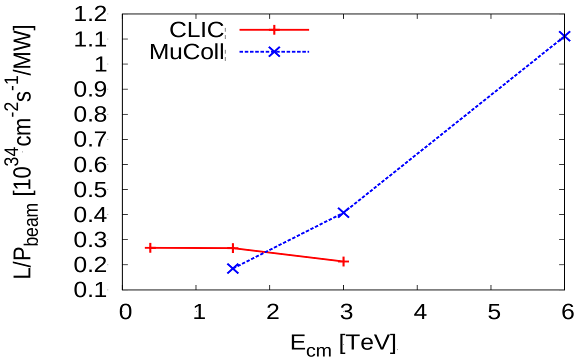
Operate normal conducting structures around 50-70 K

- Reduces loss in accelerating cavities => longer RF pulses => less RF peak power
- But requires cooling

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*

Sustainability

Sustainability has since long been an implicit consideration by reducing power use and cost

- CLIC did null cost and power optimization by varying all parameters

Will certainly try to improve in the future

- Started proper estimation of CO_2 footprint for some projects
- Challenging since it need to anticipate future changes, e.g. CO_2 for electrical power
- This applies also to CO_2 footprint of materials
  - Some results from power use to produce material and components
  - For concrete also chemical contribution to CO_2 is very important

Also started considering impact of collider R&D on energy applications for society

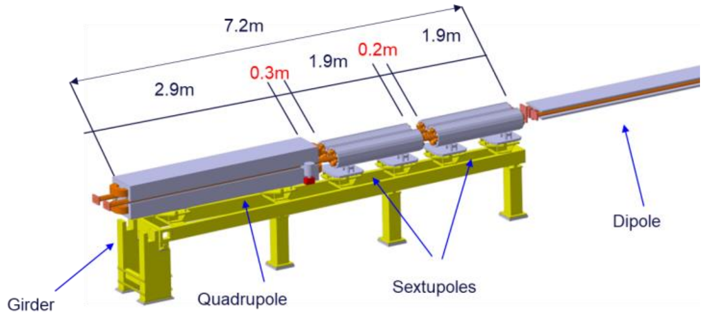
- E.g. solenoid around muon collider target is very similar to central solenoid for ITER
- Potential important application of HTS in wind-based power generators

FCC

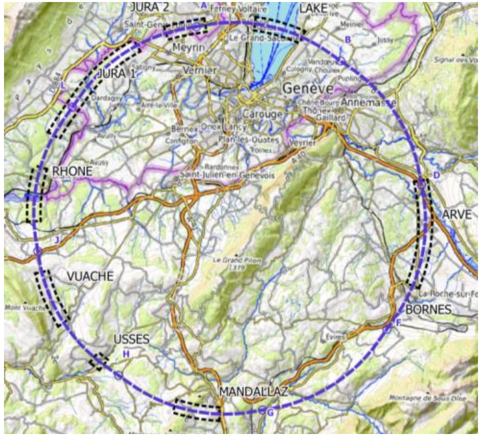
Work on FCC-ee design, e.g. collider ring lattice
- High current at Z poses important challenges
- Beamstrahlung gives important bunch lengthing
- Very fast bunch-to-bunch feedback (6-7 turns)

Parameter	unit	Z	WW	ZH	tt
Sqrt(s)	GeV	91.2	160	240	365
Max power	MW	222	247	273	357
Energy/year	TWh	1.07	1.21	1.33	1.77
Luminosity / IP	$10^{34}cm^{-2}s^{-1}$	182	19.4	7.3	1.33
Beam current	A	1280	135	26.7	5

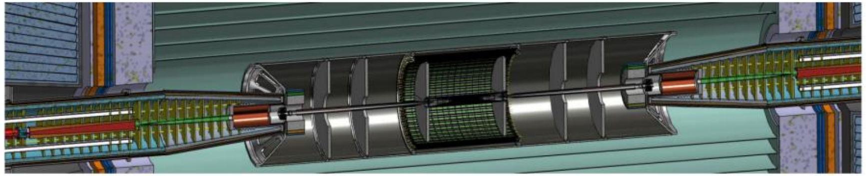
Arc Mockup



Site development ongoing



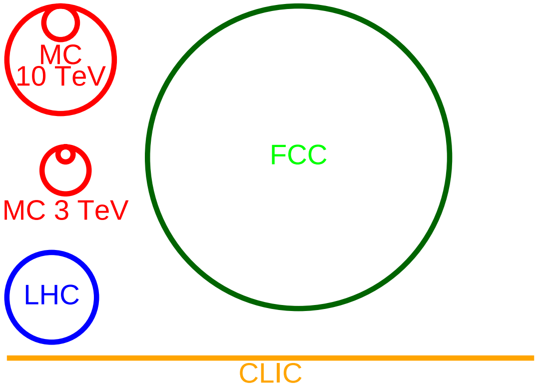
Machine detector interface



Muon Collider Promises

Cost:
- Muon collider compactness expected to reduce cost

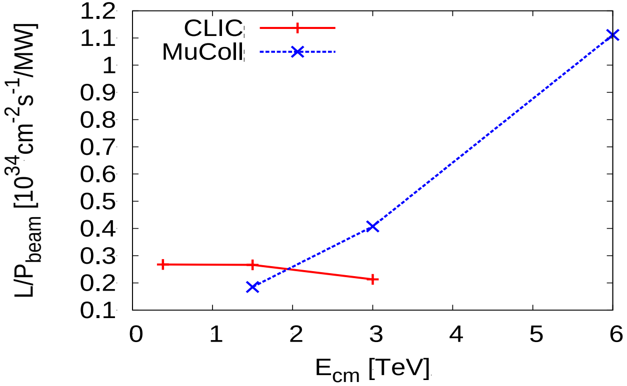
Luminosity:
- Should increase with square of energy
- Lumionosity to power constant in LC
- Plasma-based LC face the very same problem
  - Even more severe than in CLIC/ILC
- Muon collider can improve efficiency at higher energy



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

Goal from physics, current tentative parameters achieve this in 5 years in one detector

Aim 10 TeV collider
O(3 TeV) initial stage



US 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.

ITP assessed many colliders and estimated:

- Time to first physics (technical)
- Cost scale
- Power consumption
- Take it *cum grano salis*

	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

FCC Goals for 2021-2025

- demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;

- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;

- optimising design of colliders and their injector chains, supported by R&D to develop the needed key technologies;

- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;

- development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;

- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);

- consolidation of the physics case and detector concepts for both colliders.