



# Future Collider Projects

D. Schulte

CHIP/CHART Workshop, June 2023



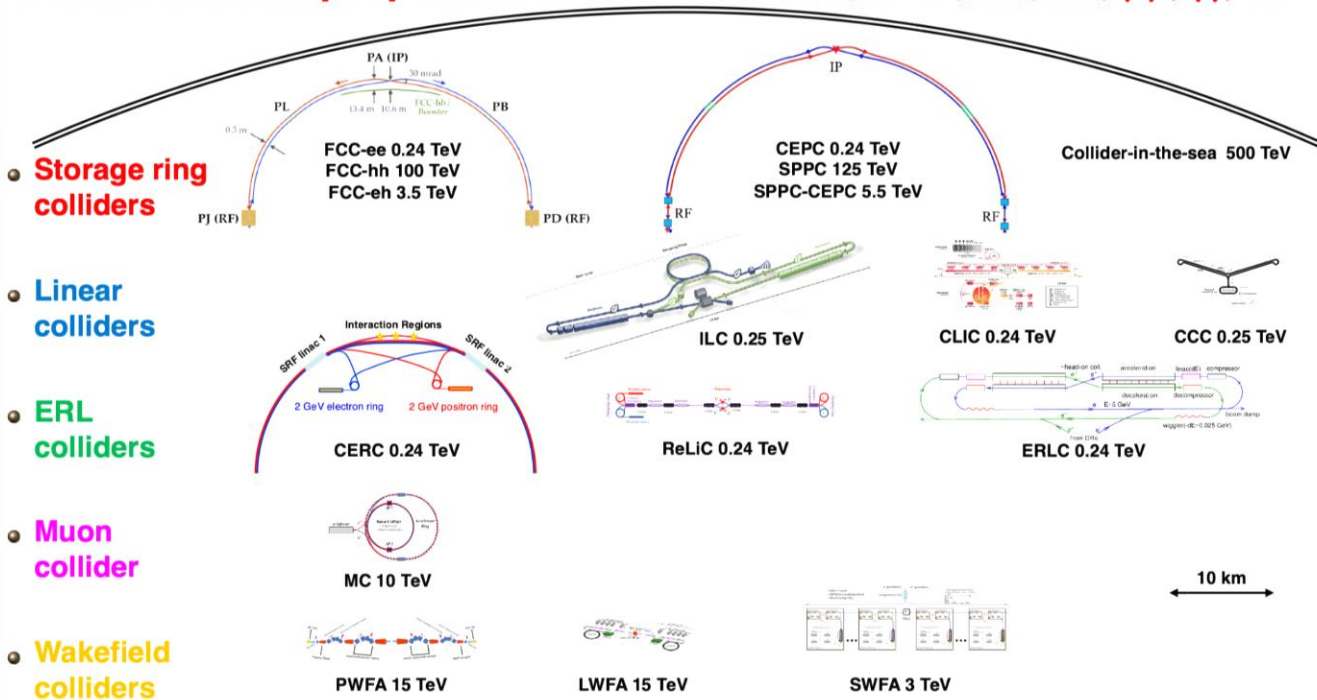
# Collider Proposals at Snowmass

Implementation Task Force (ITF) looked at many different proposals

Cannot cover them all

Select according to European view

**Future collider proposals: 0.125 – 500 TeV; e+e-, hh, eh, μμ, γγ, ...**





# 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, 10 TeV

Also in the R&D Roadmap

- Energy recovery linacs (**LHeC**, **FCC-eh**)
- 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**, 10 TeV

## Japan:

**ILC**, 0.25-1 TeV, 3 TeV

## China:

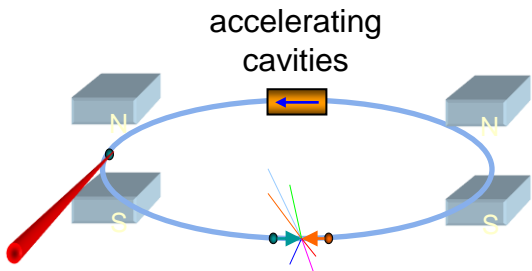
Interest in **CepC/SppS**, comparable to FCC-ee/FCC-hh

Many more less mature proposals

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

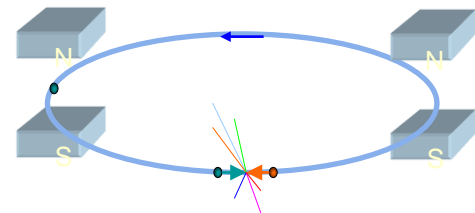
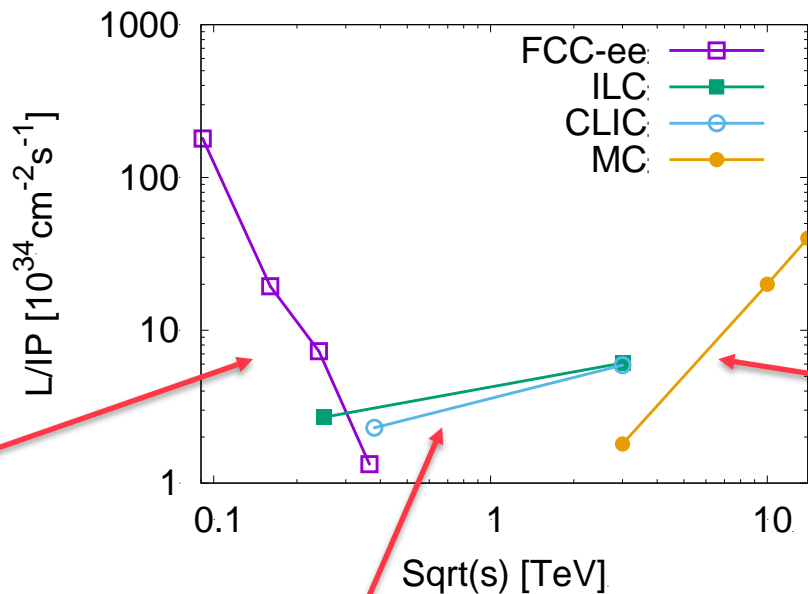


# Lepton Collider Energies and Luminosities



Circular  $e^+e^-$

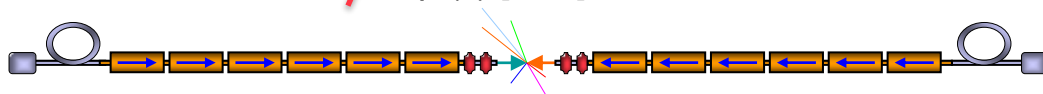
- FCC-ee, CEPC similar
- Strong energy dependence due to synchrotron radiation



Muons do not radiate much

- Did not yet explore 30 TeV

Comparable reach to 100 TeV hadrons, ask your favorite theorist



Linear  $e^+e^-$

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

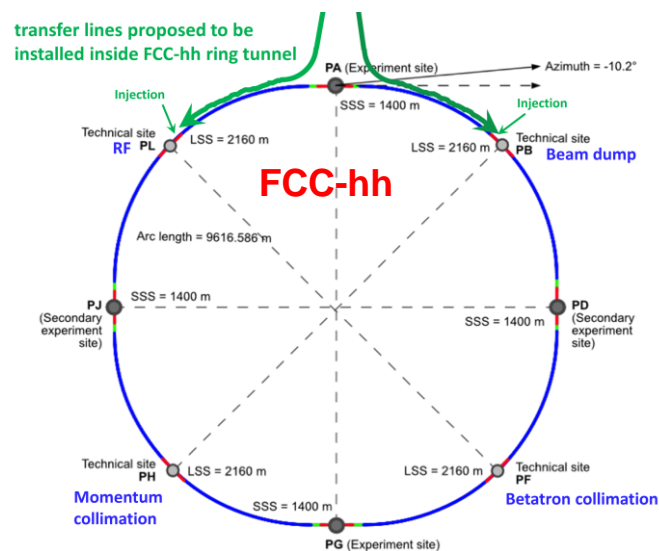
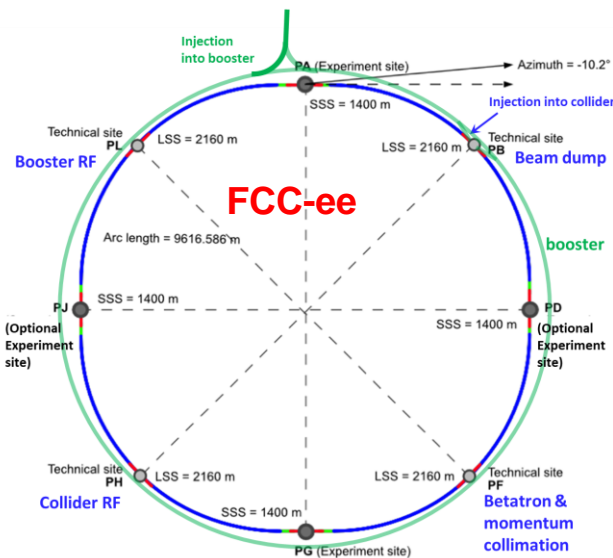
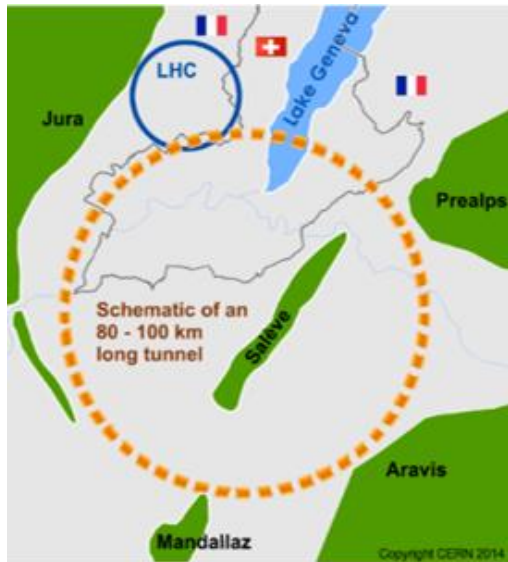


# FCC Overview

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<sub>3</sub>SN vs HTS)

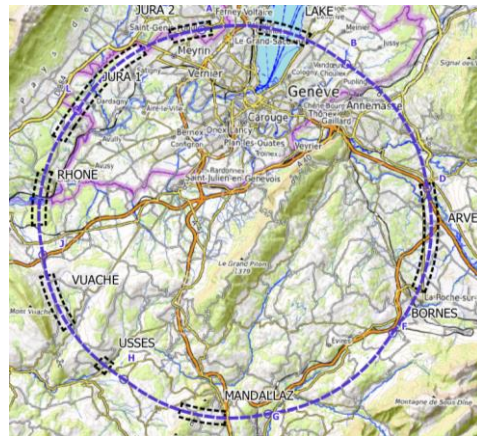


CepC and SppC is a similar approach in China

# 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	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	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 lengthening
- Very fast bunch-to-bunch feedback (6-7 turns)

Hadron collider lattice follows FCC-ee

Energy 80-116, depending on magnet technology choice

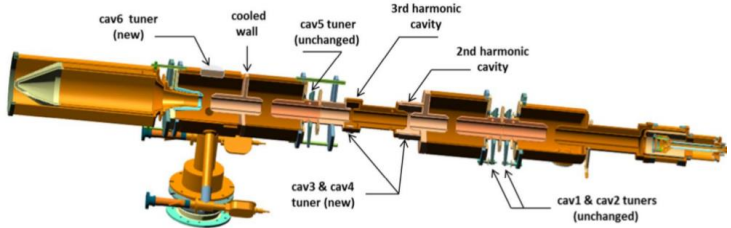
About 560 MW power consumption

Luminosity up to  $30 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$



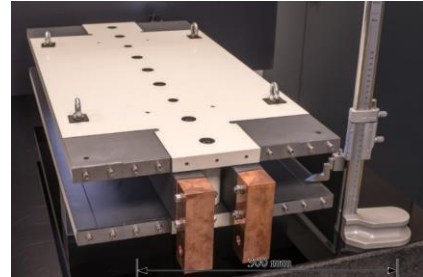
# FCC Technology Development Examples

## Efficient RF power sources (400 & 800 MHz)



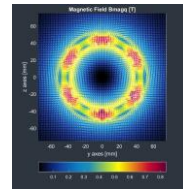
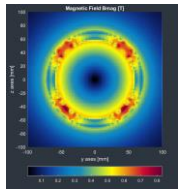
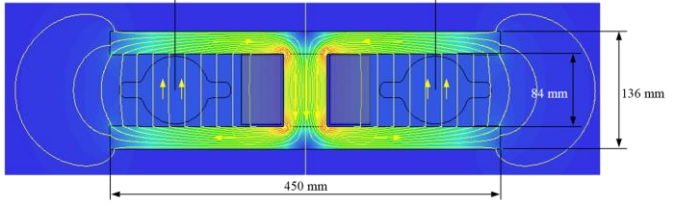
800 MHz 5-cell Nb prototype / JLAB, 2 K

## Efficient twin aperture arc dipoles

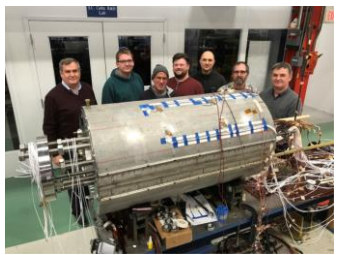


400 MHz 1-,2- & 4-cell Nb/Cu , 4.5 K

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



HL-LHC 12 T Nb<sub>3</sub>Sn quadrupole

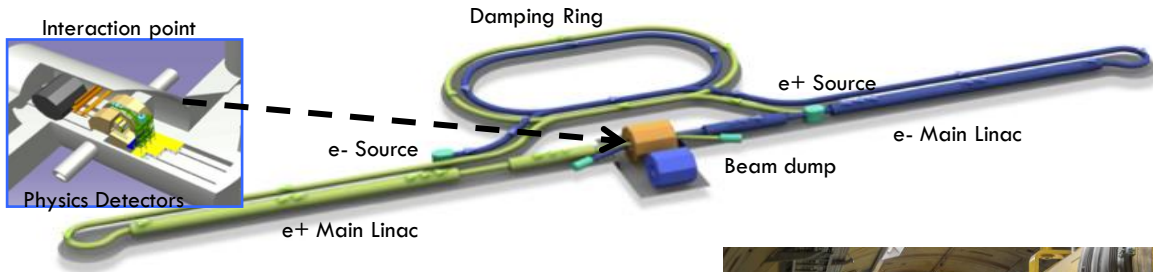


FNAL dipole demonstrator 4-layer cos theta 14.5 T Nb<sub>3</sub>Sn in 2019





# ILC



ILC Candidate Location: Kitakami, Tohoku



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	$1.35 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
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) $Q_0 = 1 \times 10^{10}$





# 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

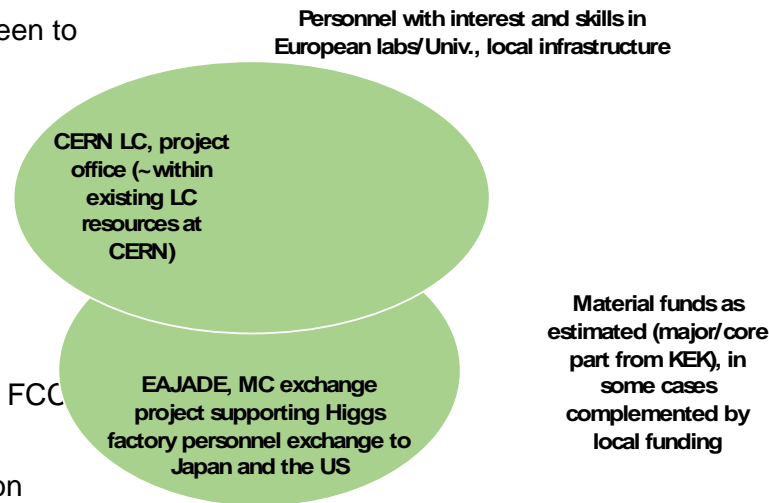
- Low Emittance Ring community, and also kicker work in CLIC and FCC

### A4 ATF activities for final focus and nanobeams

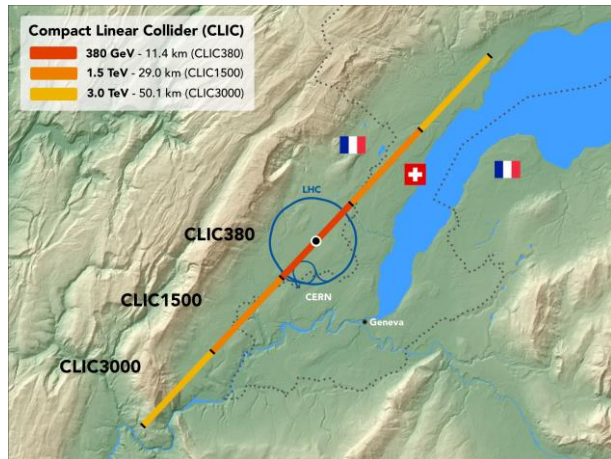
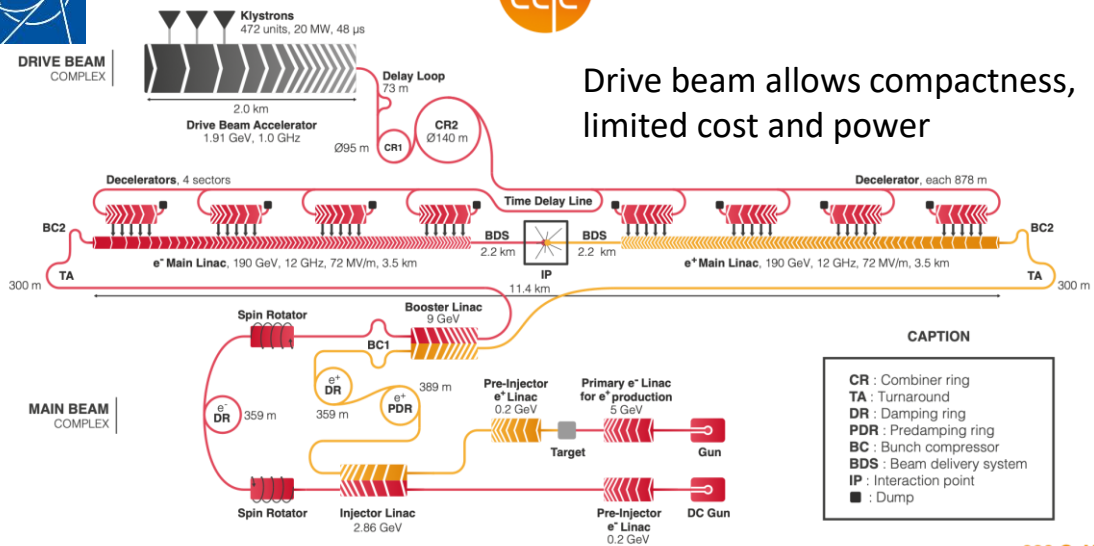
- Many European groups active in ATF, more support for its operation expected using the fresh funding

### A5 Implementation including Project Office

- Dump, CE, Cryo, Sustainability, MDI, others (many of these are continuations of on-going collaborative activities)

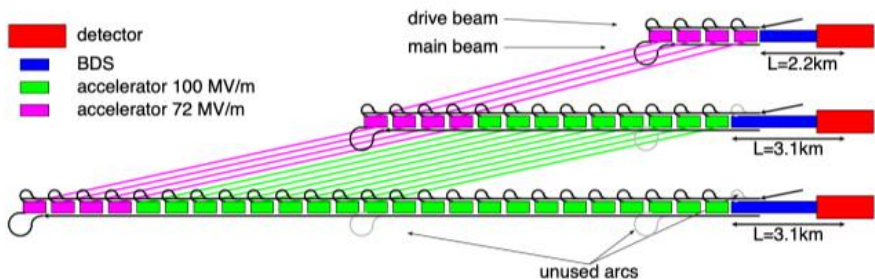


Drive beam allows compactness, limited cost and power



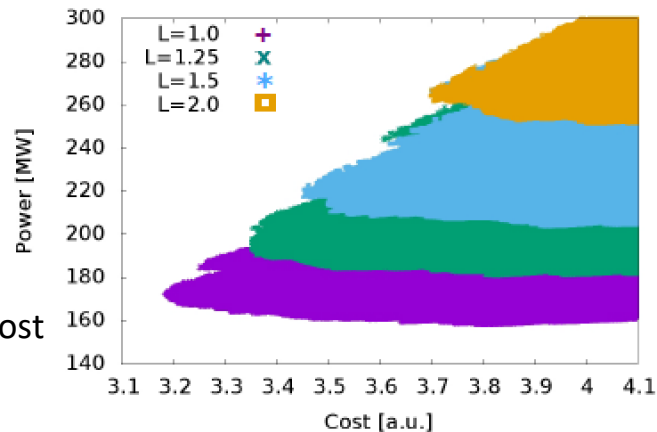
**CAPTION**  
 CR : Combiner ring  
 TA : Turnaround  
 DR : Damping ring  
 PDR : Predamping ring  
 BC : Bunch compressor  
 BDS : Beam delivery system  
 IP : Interaction point  
 ■ : Dump

Stages possible: 0.38, 1.5 and 3 TeV



380 GeV

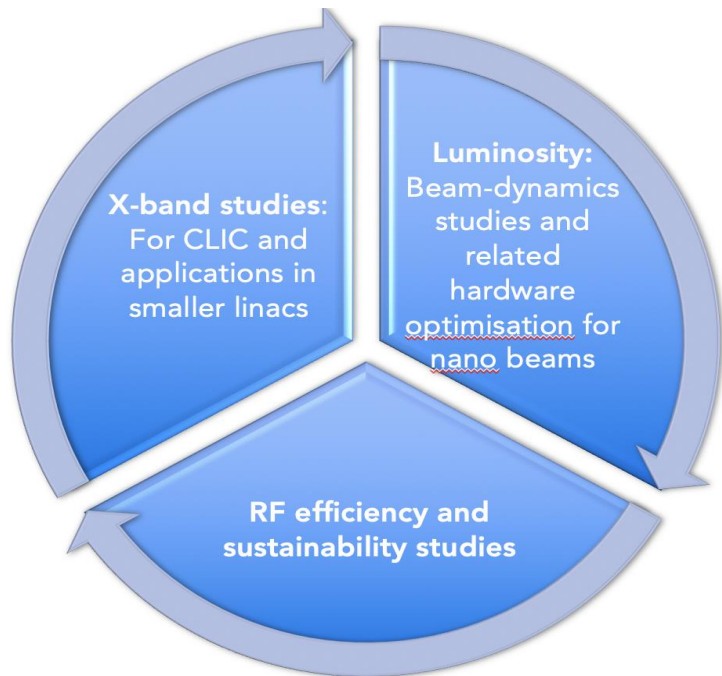
Optimised for cost and power



# 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.



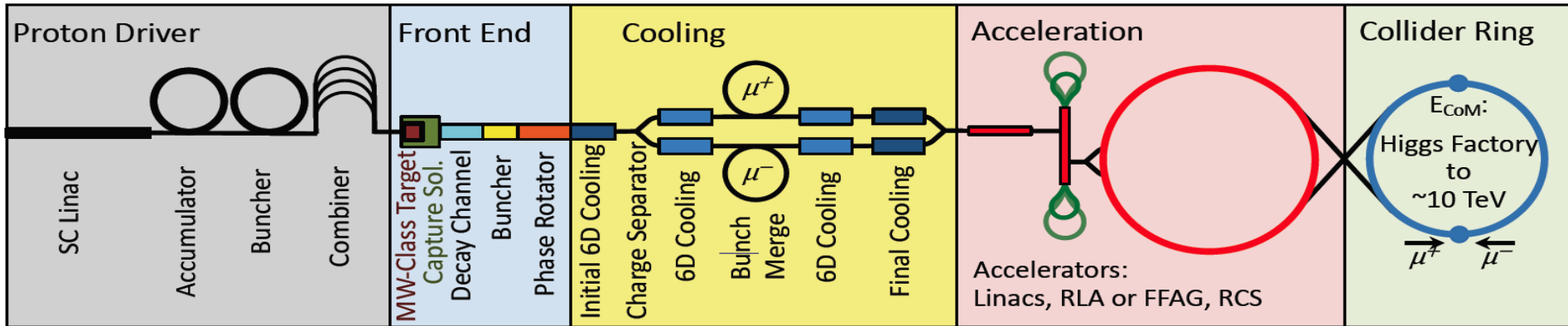


# Muon Collider Overview

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  $\tau = \gamma \times 2.2 \mu\text{s}$



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



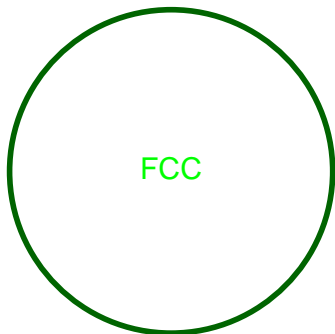
# Muon Collider Promises

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.

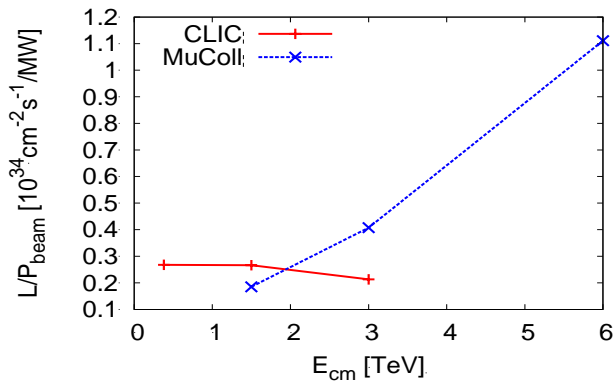
MC  
10 TeV

MC  
3 TeV

LHC



CLIC



	CME [TeV]	Lumi per IP [10 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup> ]	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**

<http://arxiv.org/abs/2201.07895>

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

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

Key work

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

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab <sup>-1</sup>
10 TeV	10 ab <sup>-1</sup>
14 TeV	20 ab <sup>-1</sup>



# Muon Collider R&D Examples

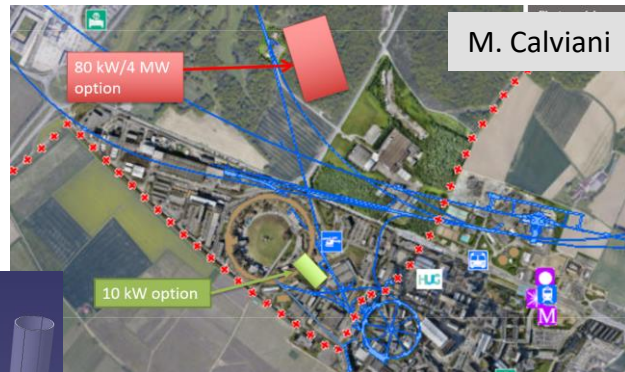
## Detector studies

- 10 TeV design
  - Beam-induced background
- Promising but more work required

## Muon production/cooling demonstrator

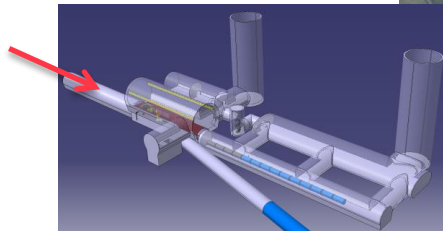
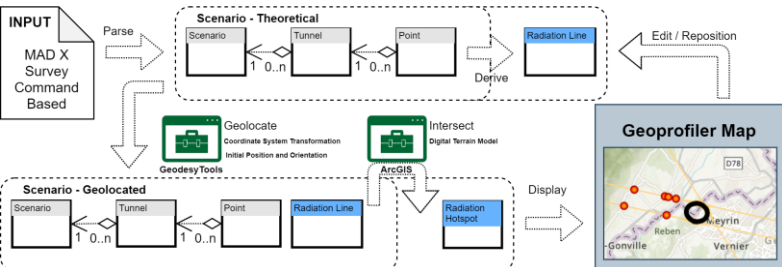
CERN example: PS beam

- $10^{13}$  p at 20 GeV every 1.2 s
- Could use SPL beam



## Siting/environmental impact

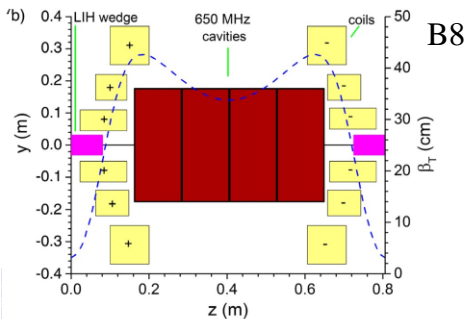
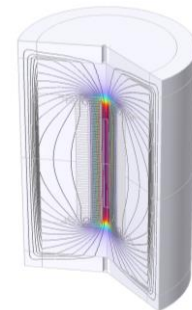
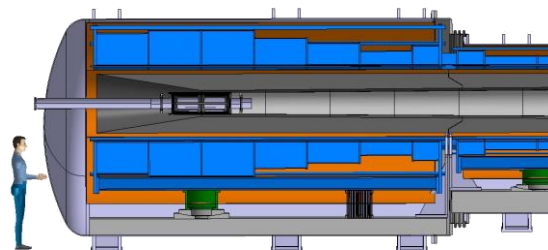
- Want negligible impact on environment



## HTS solenoids

20 T target solenoid in HTS  
ITER 13 T LTS solenoid could already work

40 T HTS solenoid



**Cooling Cell Design**  
RF in magnetic field

D. Scruete

Muon Collider, Heidelberg, January 2023





# Conclusion

Several interesting projects are being developed

- Range of promises and risks

Europe focuses on

- FCC
- CLIC
- Muon collider

Other options

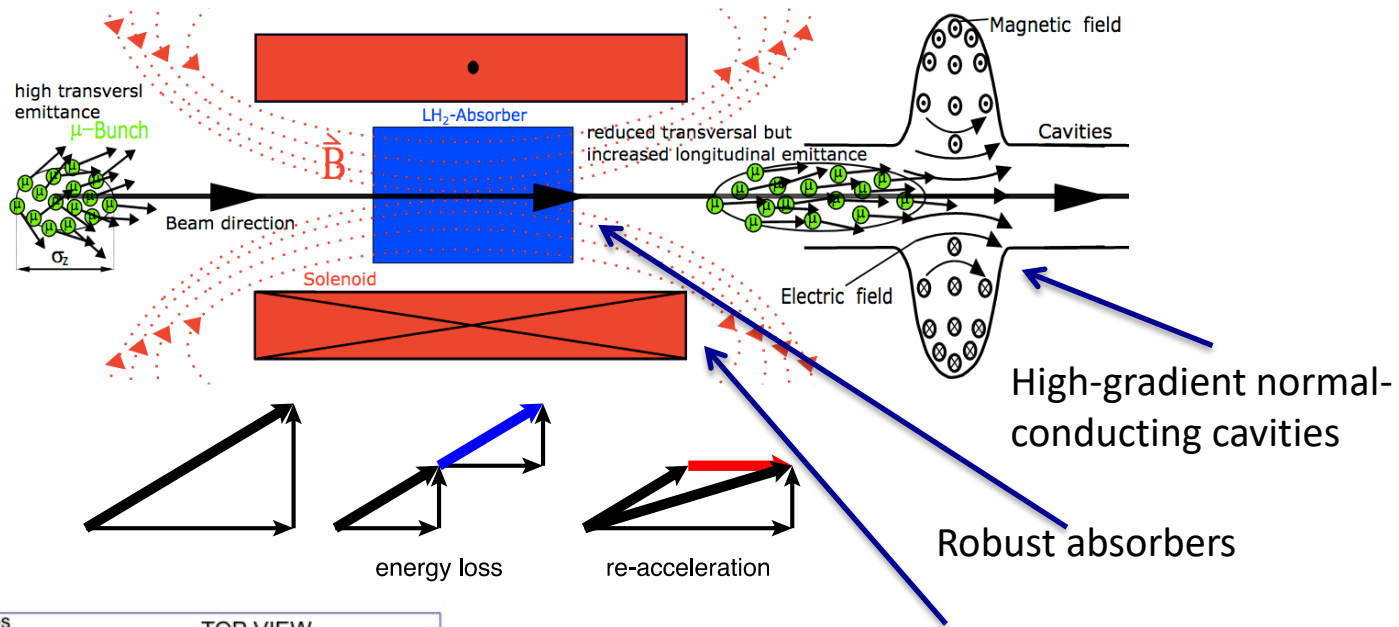
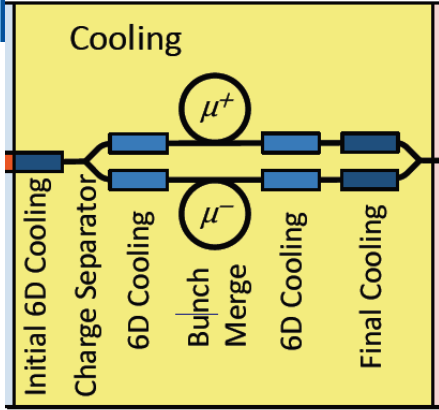
- ILC
- CepC/SppC
- CCC?

Sustainability is of importance to the projects

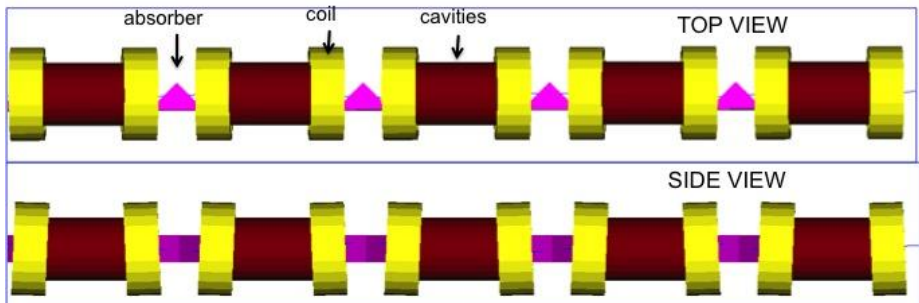


# Reserve

# Muon Cooling Principle



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

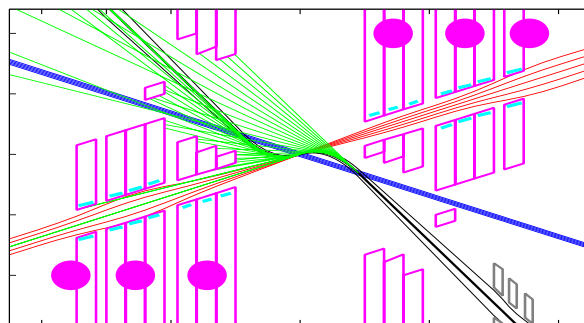
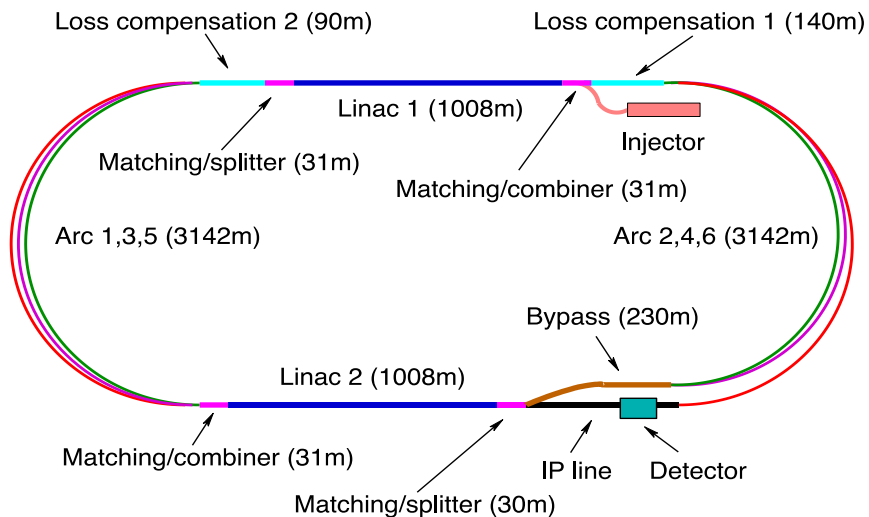




# Energy Recovery: LHeC/FCC-eh

Recirculating linac allows to recover beam energy

800 MW beam power for  
100 MW power  
consumption



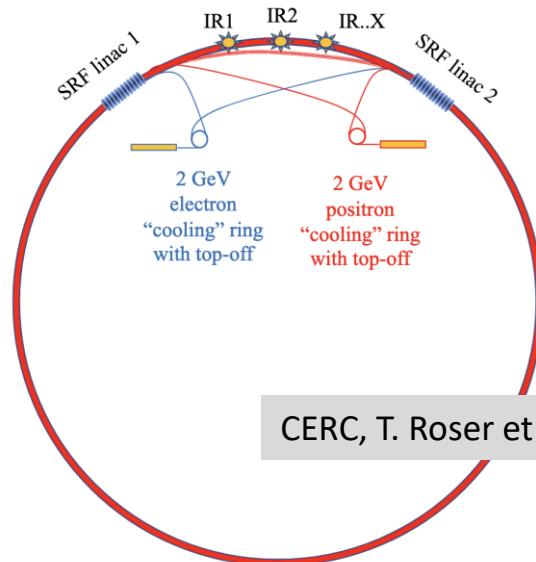
	LHeC CDR	HL- LHeC	HE- LHeC	FCC -he
$E_p$ [TeV]	7	7	12.5	50
$E_e$ [GeV]	60	60	60	60
$L$ [ $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ ]	1	8	12	15



# Energy Recovery: ERLC, ReLiC, CERC

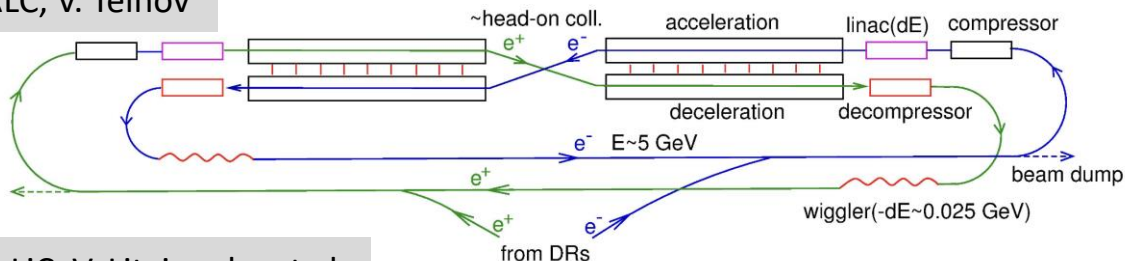
Several proposals based on recirculation and energy recovery

- 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

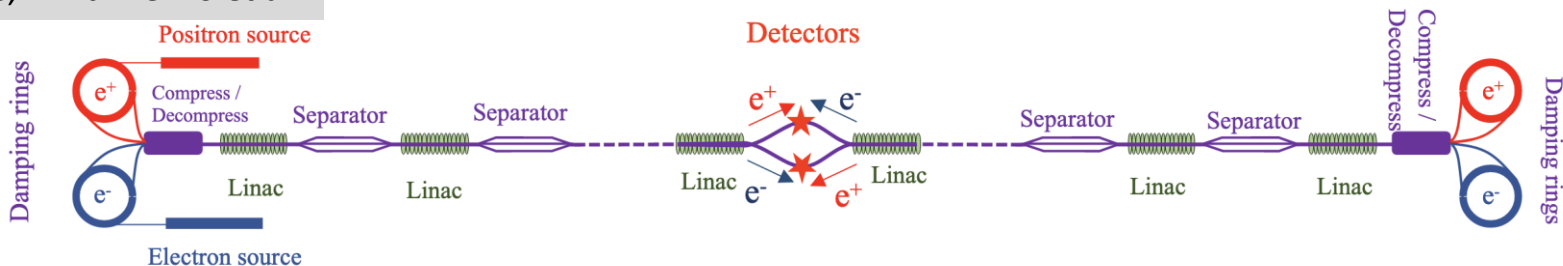


CERC, T. Roser et al.

ERLC, V. Telnov



ReLiC, V. Litvinenko et al.



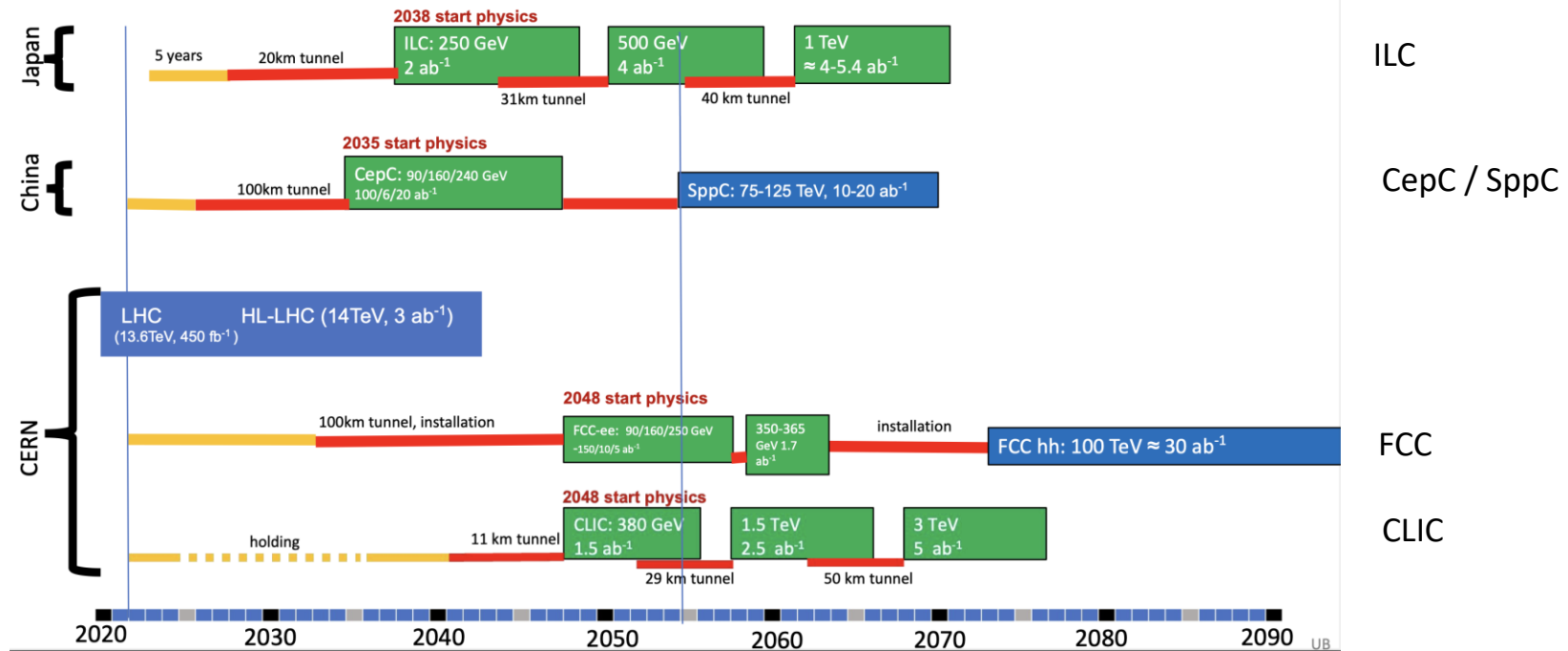


# Main High-energy Colliders by Snowmass

Indicative scenarios of future colliders [considered by ESG]

- Proton collider
- Electron collider
- Muon collider
- Construction/Transformation
- Preparation / R&D

Original from ESG by UB  
Updated July 25, 2022 by MN



Timeline in Europe driven by HL-LHC



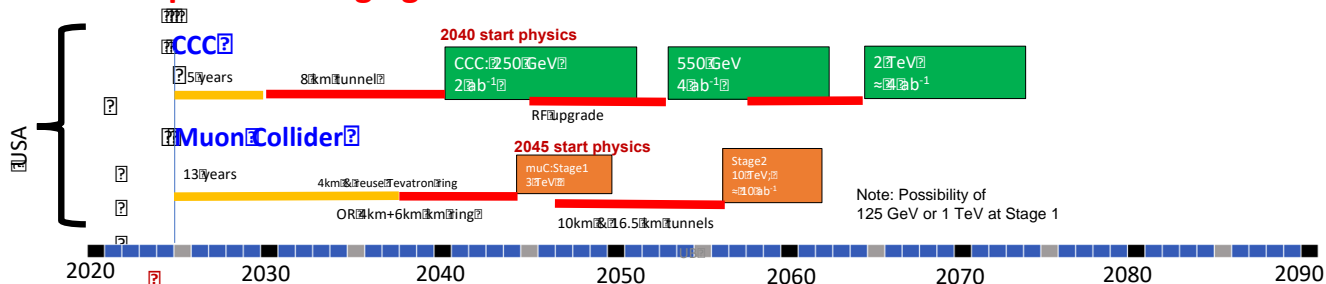
# Main High-energy Colliders by Snowmass

Possible scenarios of future colliders

- Proton Collider
- Electron Collider
- Muon Collider
- Construction/Transformation
- Preparation/R&D

Original from ESG by UB  
Updated July 25, 2022 by MN

## Proposals emerging from this Snowmass for a US based collider



CCC

Muon Collider

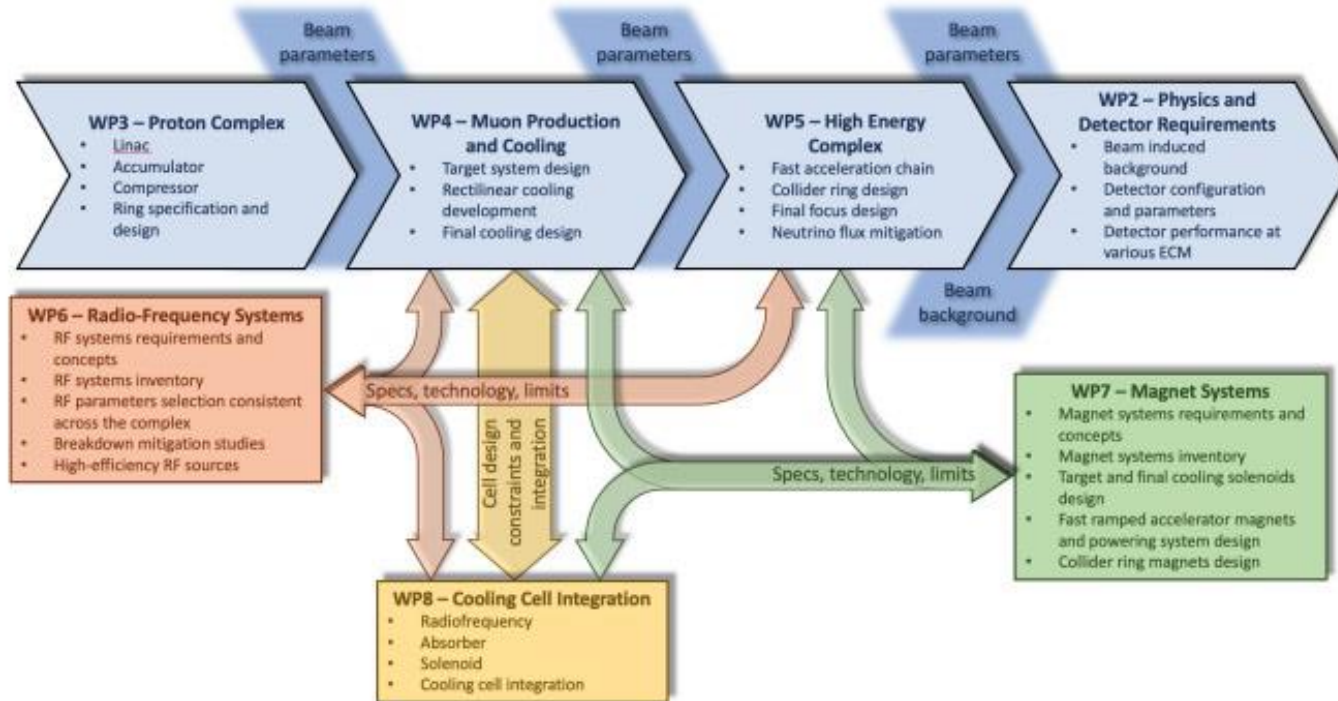
- Also plan B for CERN

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

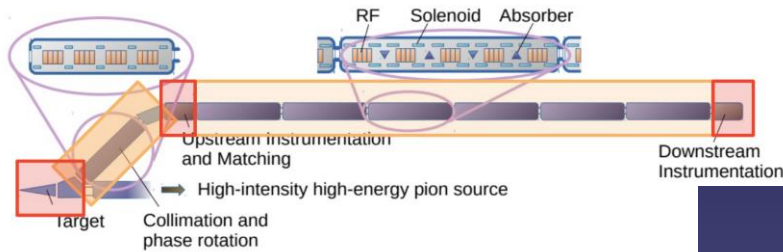
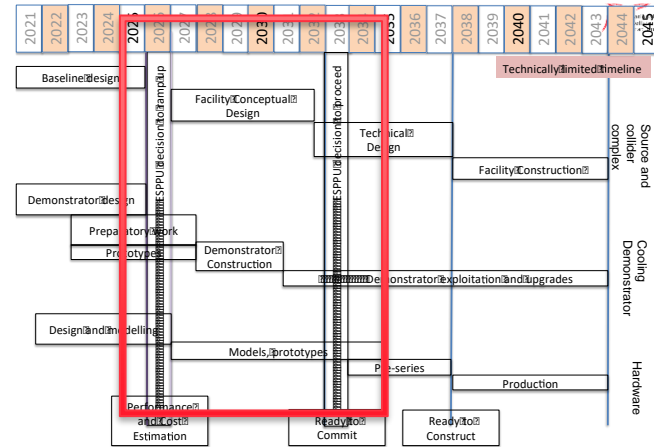
- look for an existing proton beam with significant power

Different sites are being considered

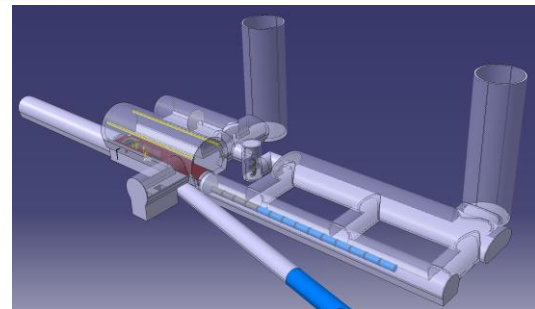
- CERN, FNAL, ESS are being discussed
- J-PARC also interesting as option

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  $\rightarrow$   $\gamma$   
 High field in collider ring  $\rightarrow$   $\langle B \rangle$   
 Large energy acceptance  $\rightarrow$   $\sigma_{\delta}$   
 Dense beam  $\rightarrow$   $\frac{N_0}{\epsilon \epsilon_L}$   
 High beam power  $\rightarrow$   $f_r N_0 \gamma$

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

Constant current for required luminosity scaling



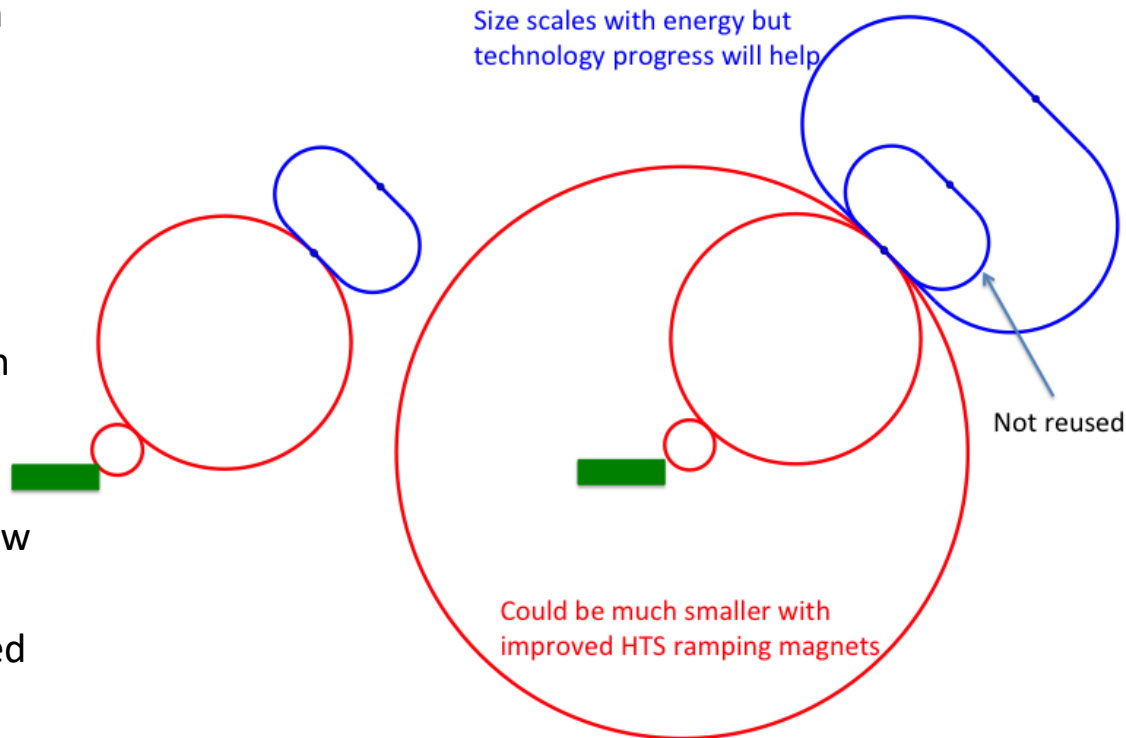
# Staging

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

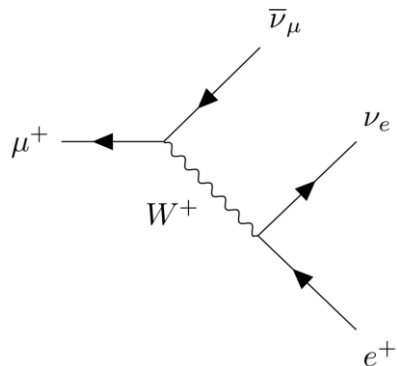
Upgrade adds one more accelerator and new collider ring

- 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

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

**Collider ring magnets** need to be shielded from losses

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

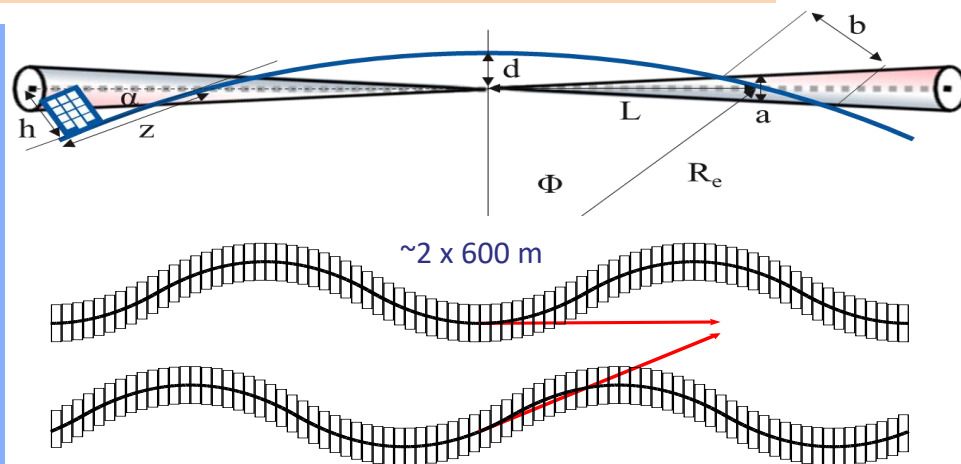
**Neutrino flux** to have negligible impact on environment

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

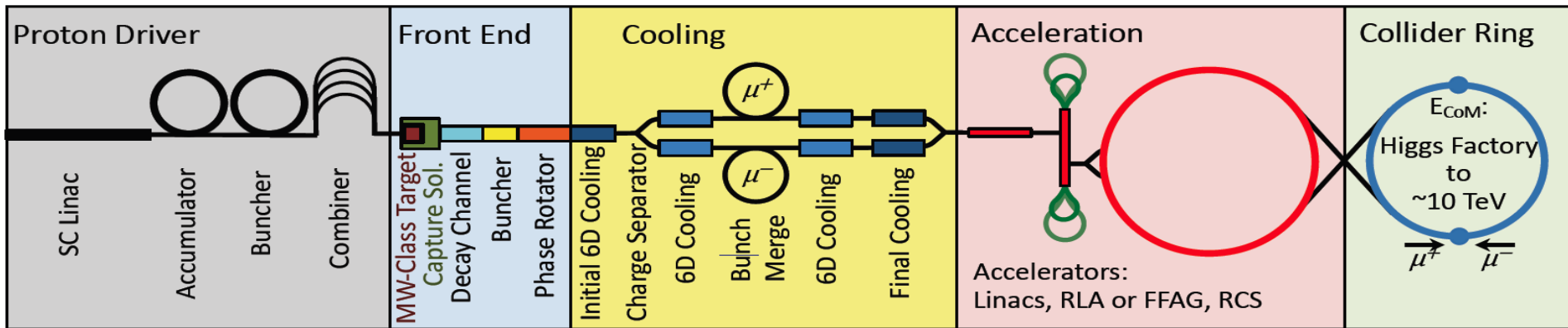
Above about 3 TeV need to make beam point in different vertical directions

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

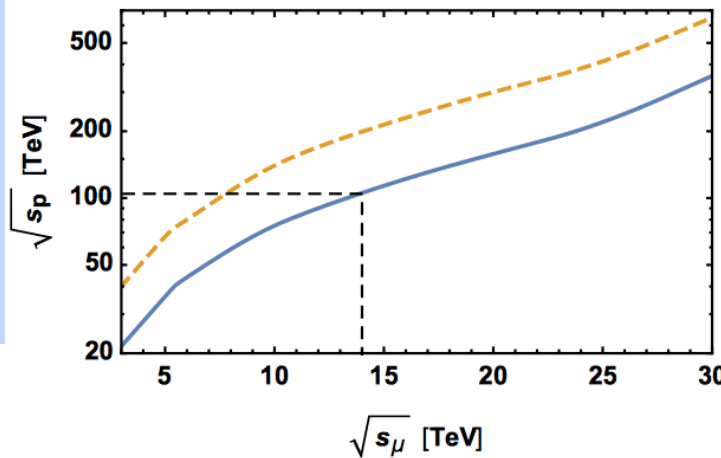
- Optics
- Magnets
- Neutrino flux
- Detector background



# Initial Target Parameters

## Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab <sup>-1</sup>
10 TeV	10 ab <sup>-1</sup>
14 TeV	20 ab <sup>-1</sup>



Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup>	1.8	20	40	2 (6)
N	10 <sup>12</sup>	2.2	1.8	1.8	
f <sub>r</sub>	Hz	5	5	5	
P <sub>beam</sub>	MW	5.3	14.4	20	28
C	km	4.5	10	14	
3>	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	
e	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**

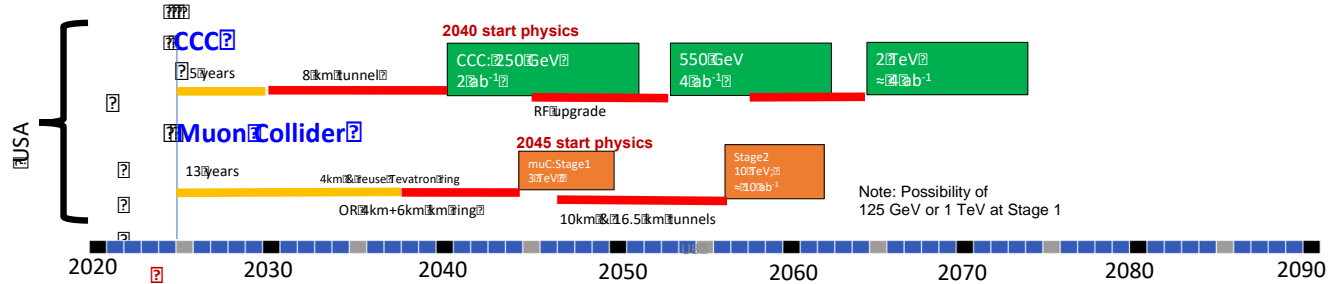
Community interested in the US to host a muon collider

Possible scenarios of future colliders



Original from ESG by IJB  
Updated July 25, 2022 by MN

## Proposals emerging from this Snowmass for a US based collider



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

Consider proposing hosting IL/CLIC in the US.



D. Schulte

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 1 <sup>st</sup> Physics	Cost Range (2021 B\$)	Electric Power (MW)
<b>FCCee</b> :0.24	0.24	8.5	0-2	13-18	12-18	290
<b>ILC</b> :0.25	0.25	2.7	0-2	<12	7-12	140
<b>CLIC</b> :0.38	0.38	2.3	0-2	13-18	7-12	110
<b>HELEN</b> :0.25	0.25	1.4	5-10	13-18	7-12	110
<b>CCC</b> :0.25	0.25	1.3	3-5	13-18	7-12	150
<b>CERC(ERL)</b>	0.24	78	5-10	19-24	12-30	90
<b>CLIC</b> 3	3	5.9	3-5	19-24	18-30	~550
<b>ILC</b> 3	3	6.1	5-10	19-24	18-30	~400
<b>MC</b> 3	3	2.3	>10	19-24	7-12	~230
<b>MC</b> 10-IMCC	10-14	20	>10	>25	12-18	O(300)
<b>FCChh</b> 100	100	30	>10	>25	30-50	~560
<b>Collider</b> in-Sea	500	50	>10	>25	>80	>>1000

Thomas Roser et al





# 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.RFHE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RFMC	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)

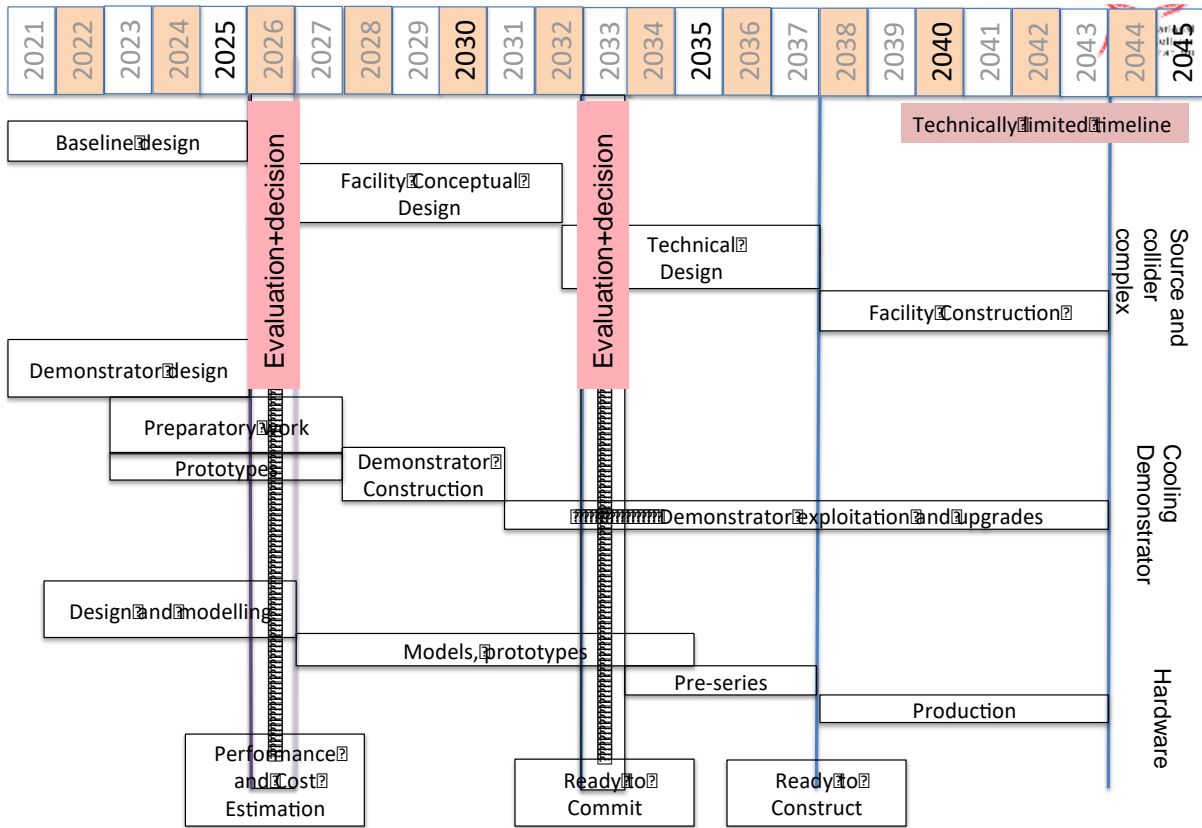
Muon collider important in the long term

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

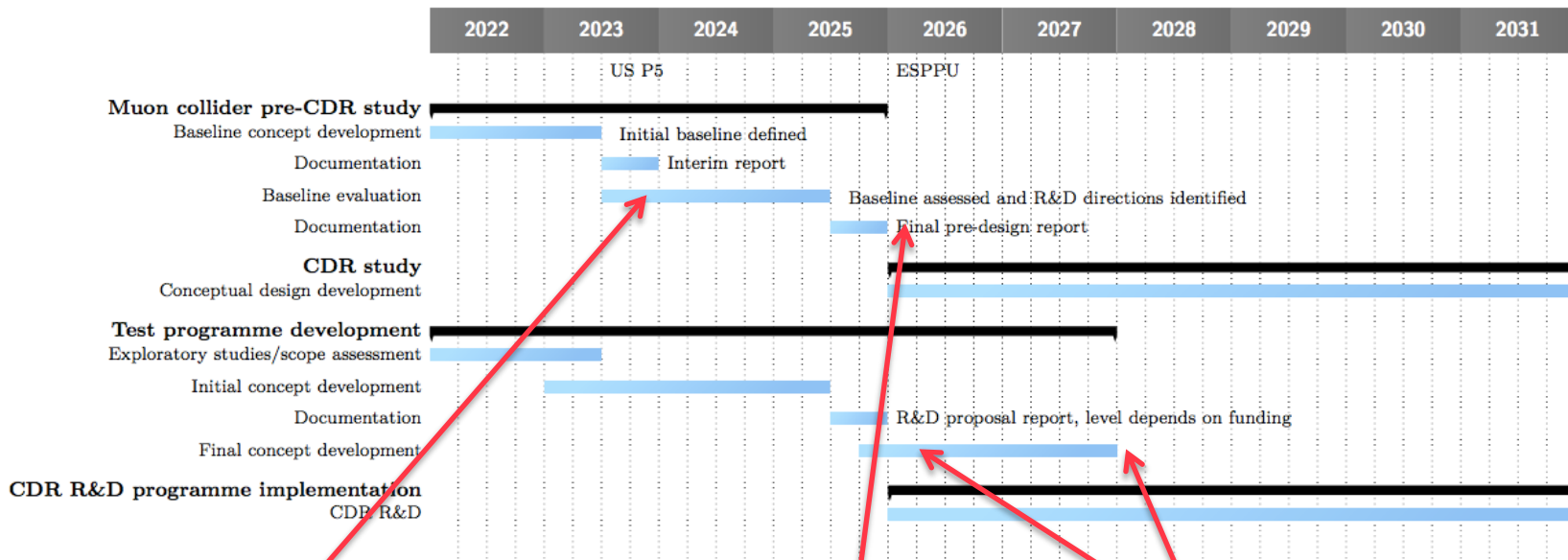
Needs to be revised but do not have enough information at this point for final plan

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

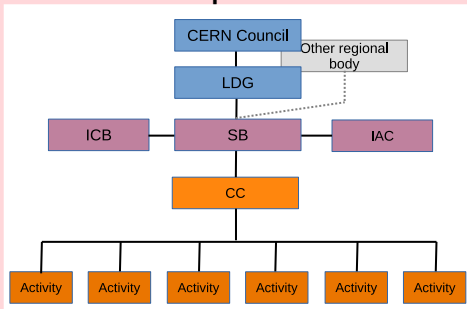
R&D plan will be refined



# Muon Collider Community



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

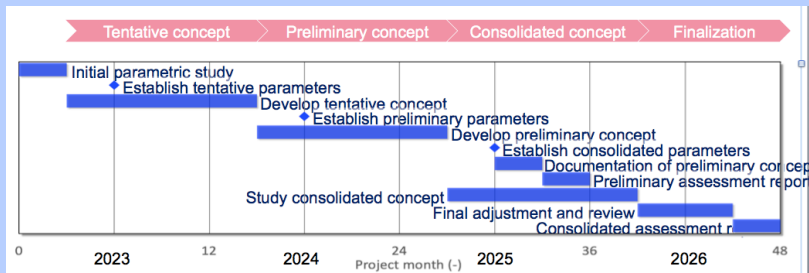


50+ partner institutions  
30+ already signed formal agreement

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

**TIARA** wants magnet proposal

**EU Design Study approved**  
(EU+Switzerland+UK and partners)



**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	<b>CERN</b>
FR	<b>CEA-IRFU</b>
	CNRS-LNCMI
DE	DESY
	<b>Technical University of Darmstadt</b>
	<b>University of Rostock</b>
	KIT
IT	<b>INFN</b>
	<b>INFN, Univ., Polit. Torino</b>
	<b>INFN, Univ. Milano</b>
	<b>INFN, Univ. Padova</b>
	<b>INFN, Univ. Pavia</b>
	<b>INFN, Univ. Bologna</b>
	<b>INFN Trieste</b>
	<b>INFN, Univ. Bari</b>
	<b>INFN, Univ. Roma 1</b>
	ENEA
Mal	<b>Univ. of Malta</b>
BE	<b>Louvain</b>

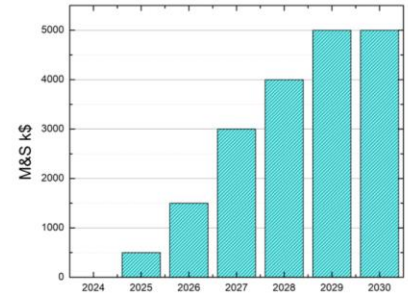
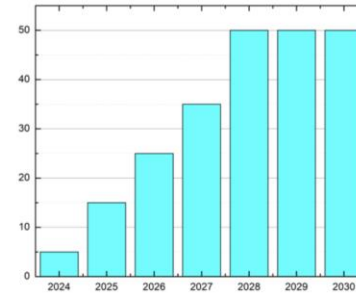
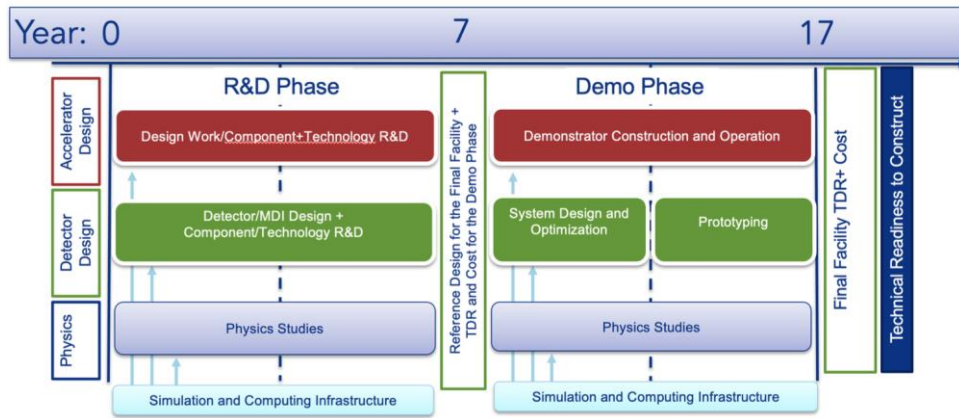
UK	<b>RAL</b>
	UK Research and Innovation
	<b>University of Lancaster</b>
	<b>University of Southampton</b>
	<b>University of Strathclyde</b>
	<b>University of Sussex</b>
	<b>Imperial College London</b>
	Royal Holloway
	<b>University of Huddersfield</b>
	<b>University of Oxford</b>
	<b>University of Warwick</b>
	<b>University of Durham</b>
SE	<b>ESS</b>
	<b>University of Uppsala</b>
PT	<b>LIP</b>
NL	<b>University of Twente</b>
FI	<b>Tampere University</b>
LAT	<b>Riga Technical Univers.</b>

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

KO	<b>KEU</b>
	<b>Yonsei University</b>
India	<b>CHEP</b>
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
	Tennessee



# US P5 Ask



: 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 is not included in these estimates.

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

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

Total resources would approach Roadmap

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

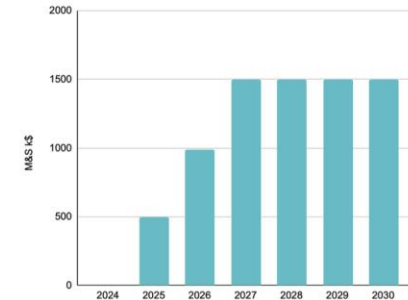
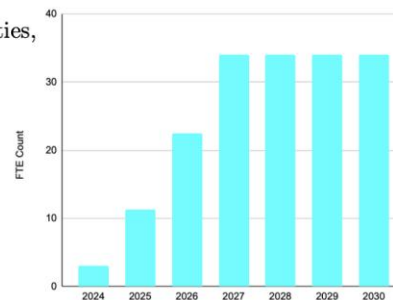
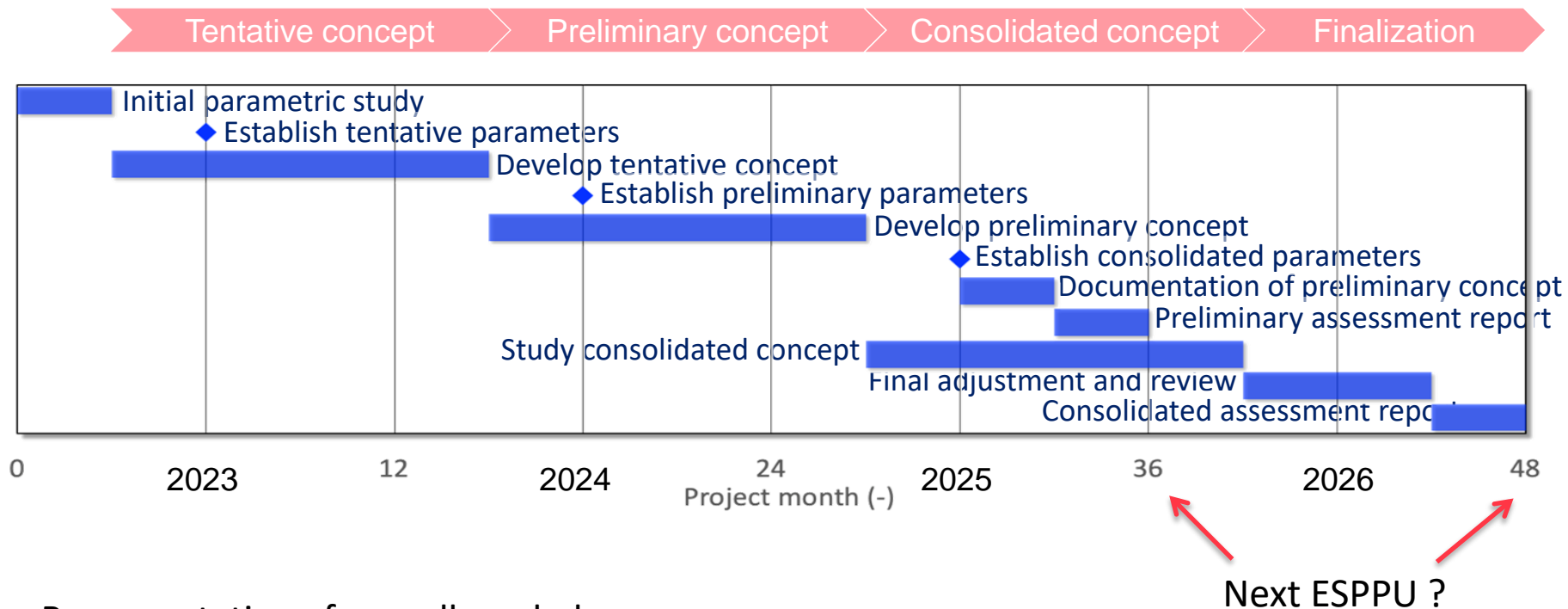


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.



# EU Design Study Timeline



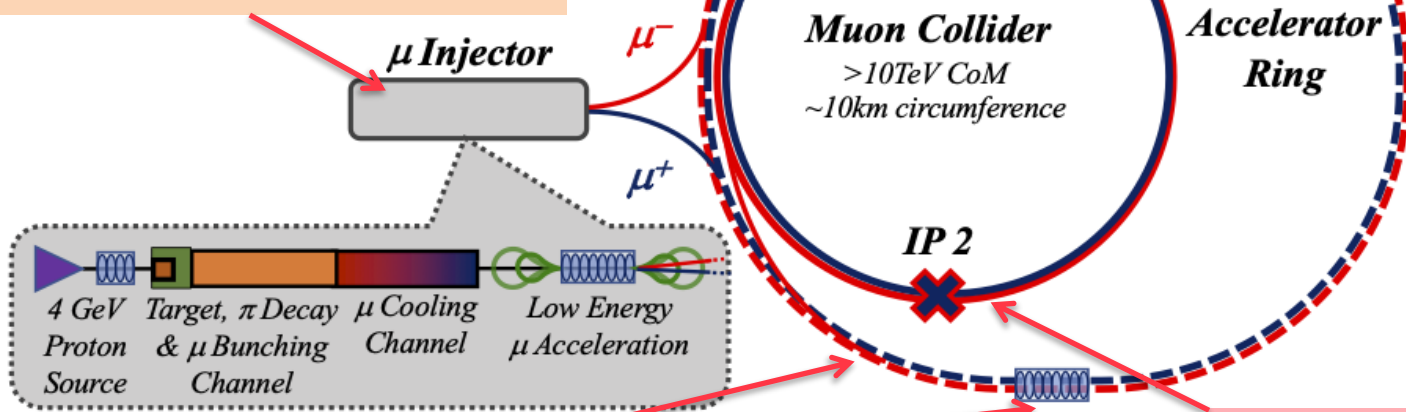
Representative of overall workplan

# 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**



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

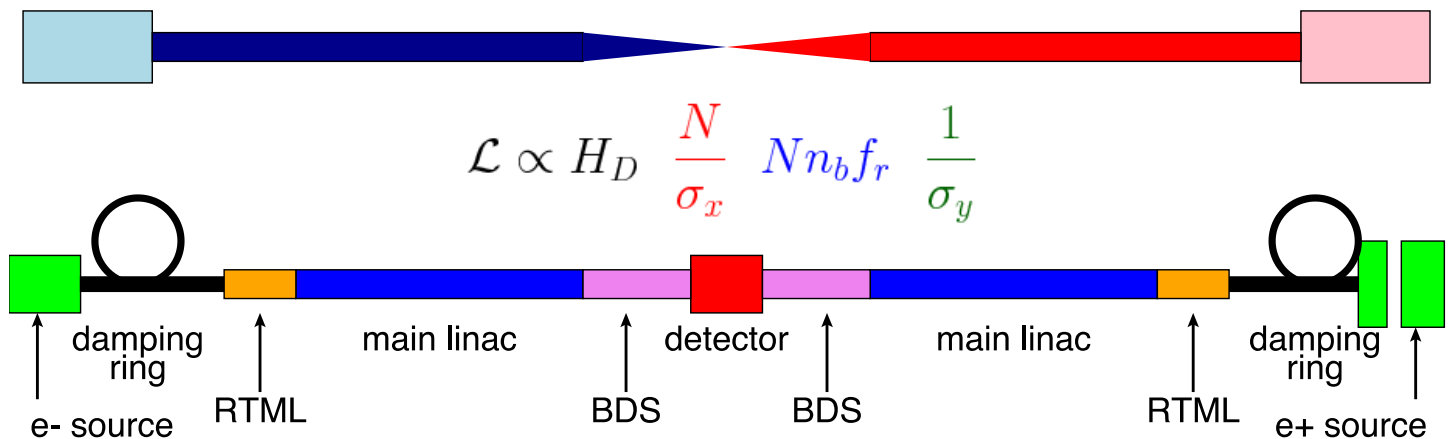
1) **Dense neutrino flux**  
mitigated by mover system  
and site selection

# 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, ...



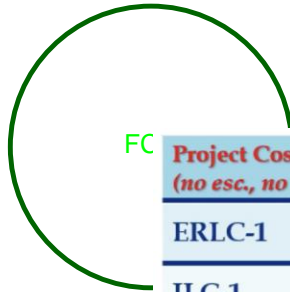


# Muon Collider Promise

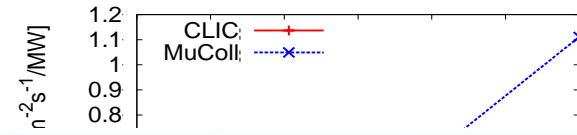
MC  
10 TeV

MC  
3 TeV

LHC



CLIC



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:

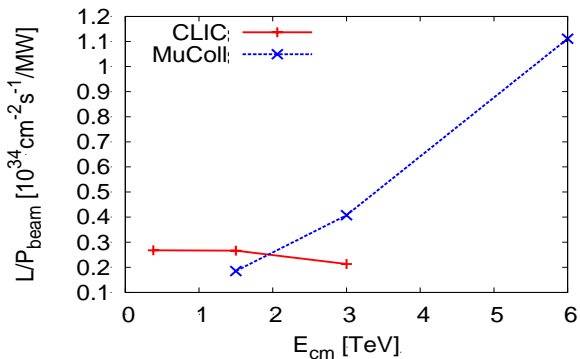
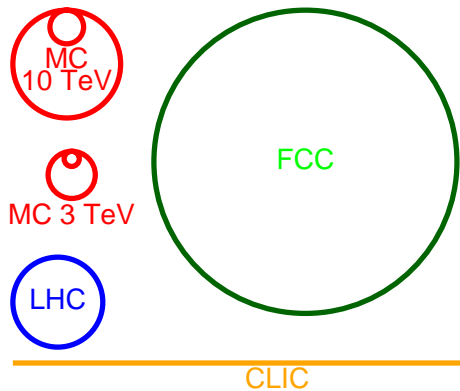
Operate normal conducting structures around 50-70 K

- 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 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup> ]	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<sub>2</sub> footprint for some projects
- Challenging since it need to anticipate future changes, e.g. CO<sub>2</sub> for electrical power
- This applies also to CO<sub>2</sub> footprint of materials
  - Some results from power use to produce material and components
  - For concrete also chemical contribution to CO<sub>2</sub> 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

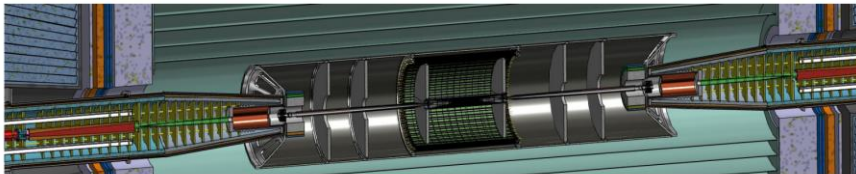


Work on FCC-ee design, e.g. collider ring lattice

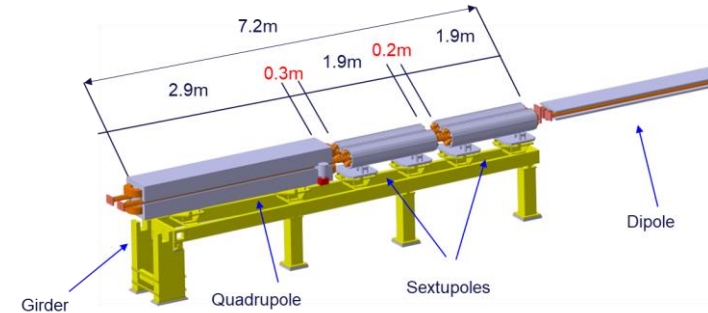
- High current at Z poses important challenges
- Beamstrahlung gives important bunch lengthening
- Very fast bunch-to-bunch feedback (6-7 turns)

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	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	182	19.4	7.3	1.33
Beam current	A	1280	135	26.7	5

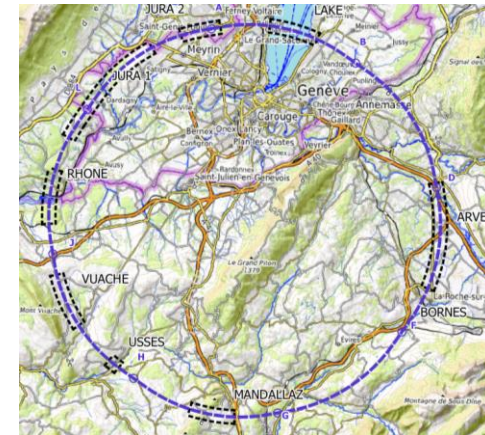
## Machine detector interface



## Arc Mockup



## Site development ongoing





# Muon Collider Promises

## Cost:

- Muon collider compactness expected to reduce cost

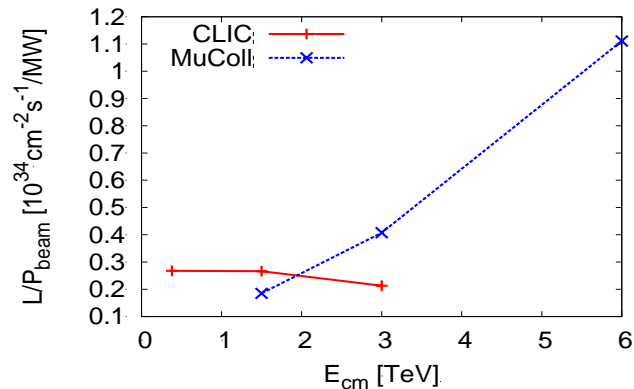
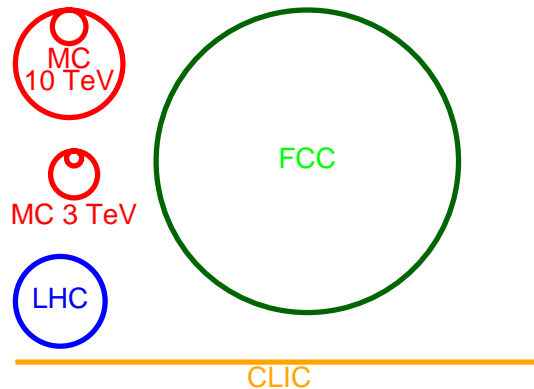
## Luminosity:

- Should increase with square of energy
- Luminosity 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 ab <sup>-1</sup>
10 TeV	10 ab <sup>-1</sup>
14 TeV	20 ab <sup>-1</sup>

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 [ $10^{34}\text{cm}^{-2}\text{s}^{-1}$ ]	Years to physics	Cost range [B\$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
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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.