Fermilab



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The path to 10 TeV parton c.m. colliders

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U.S. DEPARTMENT of ENERGY

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Talk overview

- This talk will discuss accelerator R&D challenges for future ~10 TeV parton center-of-mass energy colliders

Roads don't necessarily have to go anywhere,
they just have to have somewhere to start.
- from Wyrd Sisters by Terry Pratchett

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  - Circular *pp* colliders – most advanced designs based on traditional accelerator approaches
  - Muon collider – requires extensive R&D and a demonstrator facility
  - High-energy wakefield colliders – well beyond state-of-the-art, require a lot of innovations

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Image generated by Gemini AI

Talk overview

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  - Circular *pp* colliders – most mature designs based on traditional accelerator approaches
  - Muon collider – requires extensive R&D and a demonstrator facility
  - High-energy wakefield colliders – well beyond state-of-the-art, require a lot of innovations
- And no Sci-Fi collider proposals will be discussed at all.

Roads don't necessarily have to go anywhere,
they just have to have somewhere to start.
- from Wyrd Sisters by Terry Pratchett



Image generated by Gemini AI

A very high energy hadron collider on the Moon

J. Beacham and F. Zimmermann, *New J. Phys.* **24**, 023029 (2022)

Not in this talk ☺

Collider in the sea: Vision for a 500 TeV world laboratory

P.M. McIntyre et al, *NAPAC'2016*



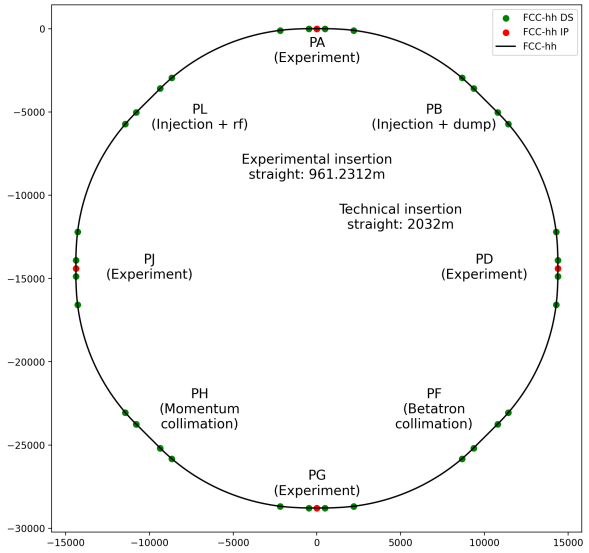


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~100 TeV circular *pp* colliders

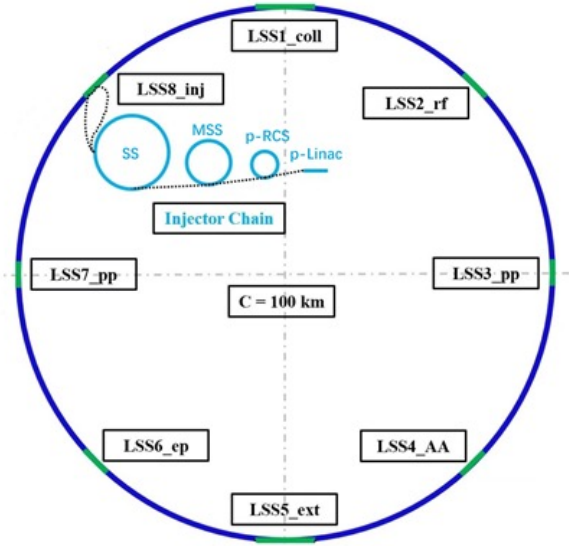
Circular *pp* colliders

~100 TeV, a natural continuation at the energy frontier with *pp* collisions



parameter	FCC-hh	SPPC
Peak luminosity [10^{34} cm^{-2}s^{-1}]	5 / 30	4.3 / 10
collision energy cm [TeV]	85* - 121	75 - 125
dipole field [T]	14 - 20	12 - 20
circumference [km]	90.7	100

*) 88 TeV with a new optics: F. Capoani et al, FCC Week 2026



$$E = ecB\varrho$$

FCC-hh

- Stage 2 of the Future Circular Collider, to be installed in the tunnel after FCC-ee
- 4 interaction regions
- Start operation in ~2070
- There will be significantly more time for high-field magnet R&D aiming at highest possible energies

G. Perez Segurana et al, FCC Week 2025

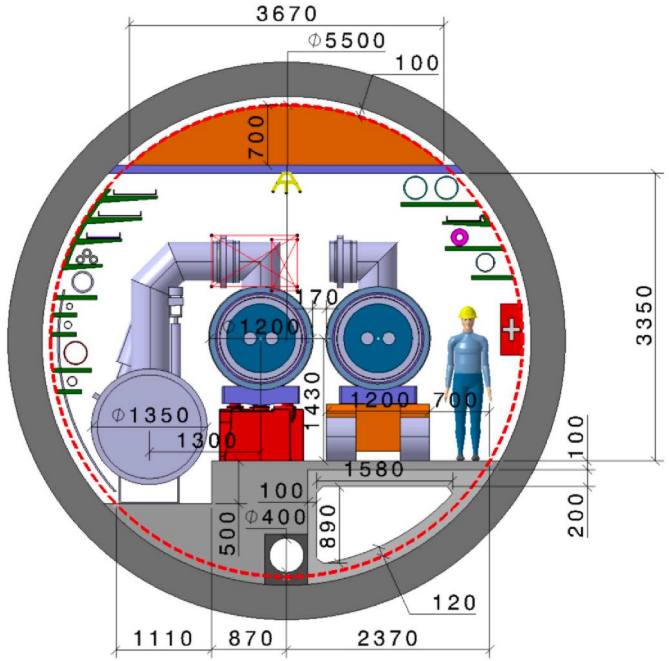
SPPC

- To be installed in the same tunnel with the previously built CEPC
- 2 interaction regions for CEPC + 2 interaction regions for SPPC
- Space reserved for *ep* collisions

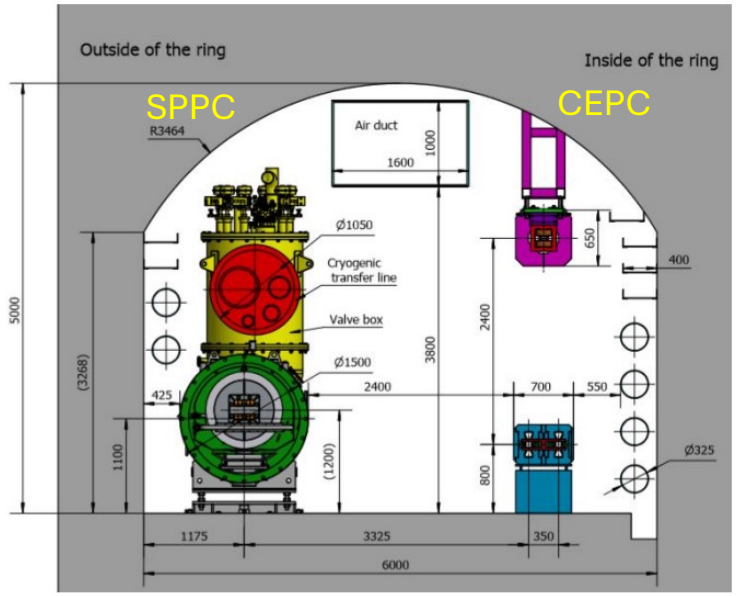
Y. Wang, CEPC Workshop 2026

Key challenges for *pp* colliders

- High-field superconducting magnets: 14 - 20 T. The **superconducting magnet technology** will determine the energy reach of the machine.
- Beam optics design: maximize dipole filling factor to maximize collision energy
- Power load on cold vacuum chamber in arcs from synchrotron radiation: 4 MW for FCC-hh (~10^3 times higher than LHC) → cryogenics, vacuum
- Stored beam energy: ~ 9 GJ (~10 times of HL-LHC) → machine protection
- Pile-up in the detectors: ~1,000 events/xing
- R&D to reduce energy consumption (4 TWh/year) → cryogenics, HTS, beam current, …



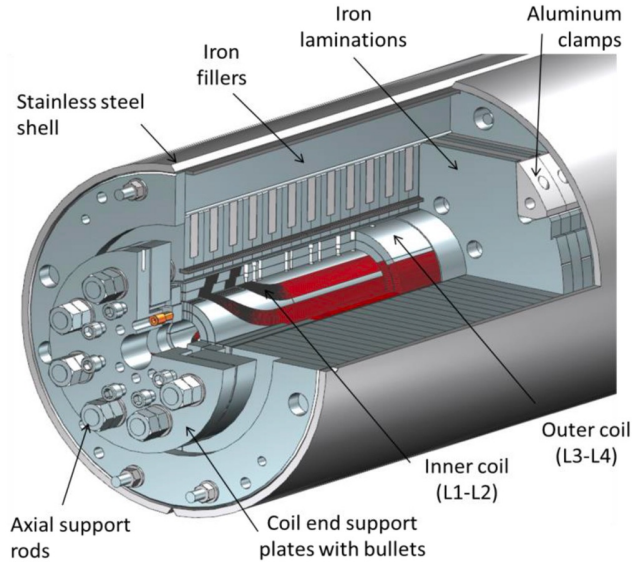
Cross section of the FCC-hh tunnel with a 16 T SC magnet



Cross section of the CEPC / SPPC tunnel

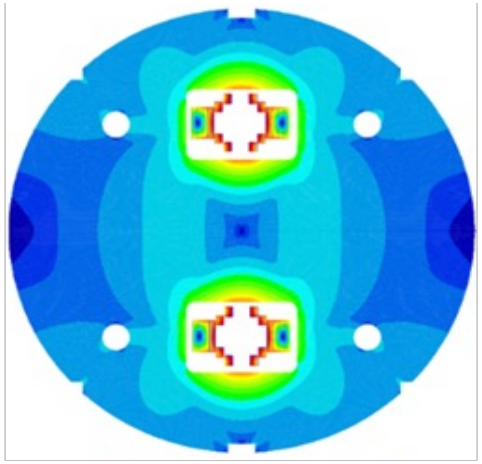
SC magnets for *pp* colliders

- Superconducting magnets with dipole fields in the 14 - 20 T range are beyond state-of-the-art.
- Three active R&D programs: HFM in Europe + KEK (Japan), MDP in the USA, and High Field Magnet R&D at IHEP (China)
- **Nb_3Sn**, a low-temperature superconductor,
  - Used for HiLumi LHC accelerator magnets.
  - To date, a field of ~14.5 T at 1.9 K has been demonstrated in Nb_3Sn R&D magnets FRESCA2 (100-mm aperture, block-type, CERN/CEA) and MDPCT1 (60-mm aperture, cos-theta, USMDP).
  - Maximum practical fields ~ 14-15 T at 4.2 / 1.9 K. Although there is still some room for improvement.
- For ~ 20 T magnets, several hybrid designs (HTS + LTS) are under development

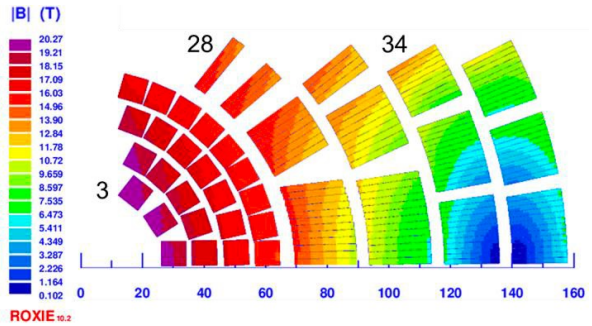


3D model of MDPCT1 magnet

Qingjin Xu, FCC Week 2025



20 T Nb_3Sn + HTS design for SPPC

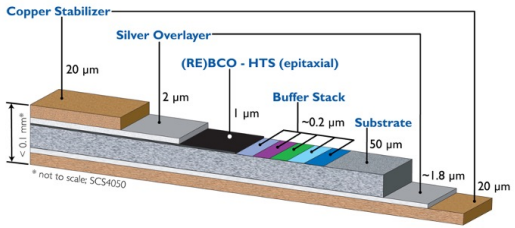


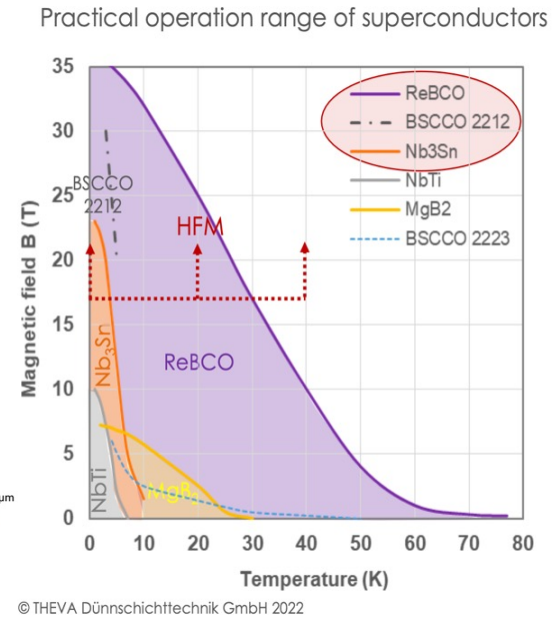
Calculated distribution of magnetic field in the coil of a 20 T cos-theta hybrid ReBCO/Nb_3Sn magnet

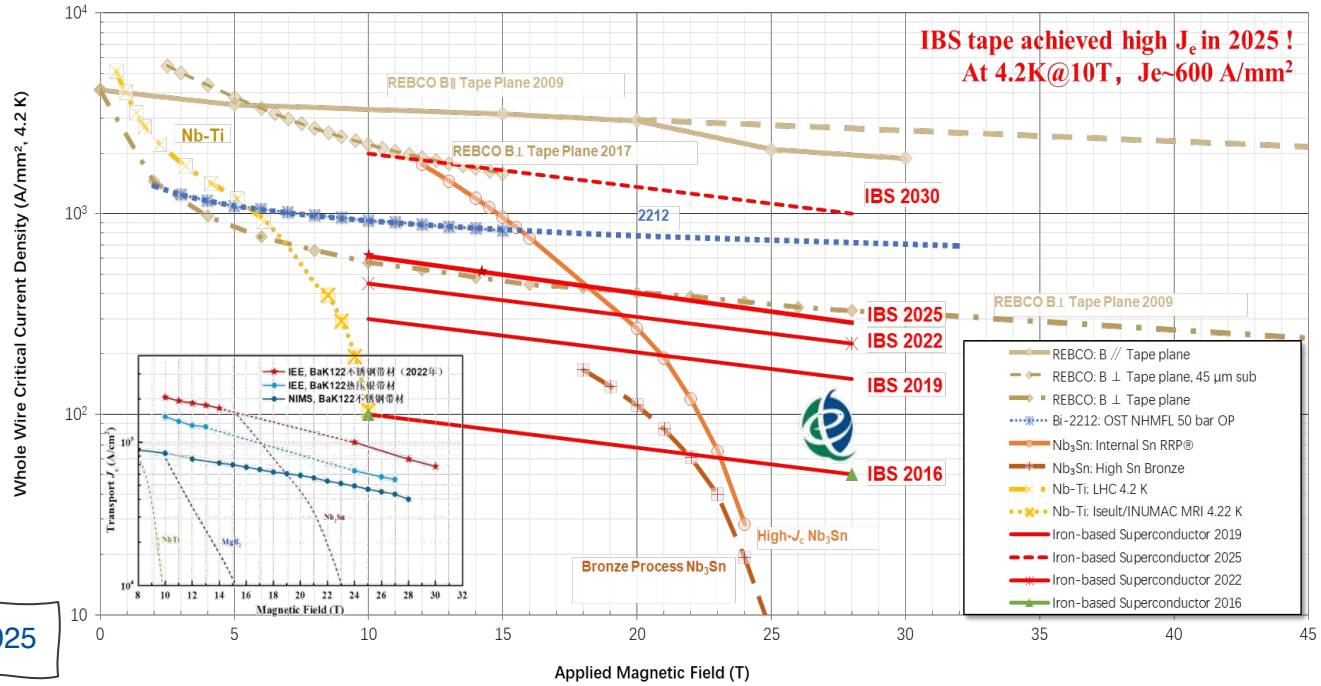
A. Zlobin, arXiv:2408.11023

HTS conductors for *pp* colliders

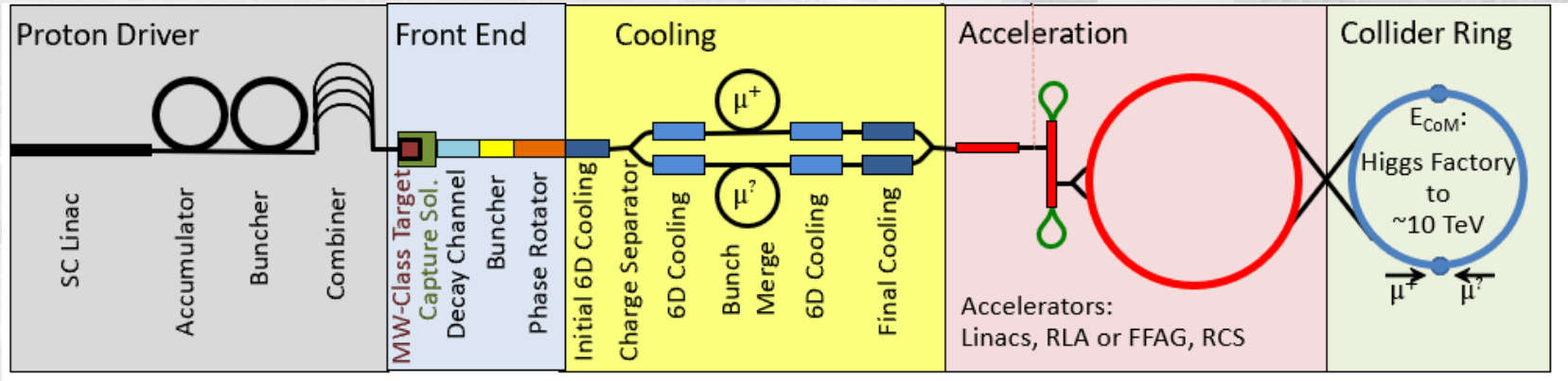
- Conductor ultimately determines the magnet performance. Potential HTS conductor choices: **ReBCO** and **iron-based superconductors** (IBS).
- **ReBCO**
  - Excellent performance at elevated temperatures – can operate at 20 K.
  - Available as flexible tape, anisotropic – not good for field quality?
  - R&D to improve performance and make into a magnet conductor
  - Very expensive, but Fusion can drive capacity and substantially lower cost.
  - In 2025 test at IHEP, a stand-alone test (ReBCO coil) reached 7.8 T in the aperture at 4.2 K.
- **IBS**
  - Active R&D in China.
  - Steady performance improvement
  - Potentially lower cost than other HTS
  - Could be a game changer
- Common problems:
  - Stress management
  - Quench protection







Qingjin Xu, FCC Week 2025



2

10 TeV muon collider

Muon collider

- Muon collider (MC) combines precision and energy reach needed to test the deepest questions of particle physics
- Smaller footprint than proton-proton collider for the same pCM energy
- Muons are 207 times heavier than electrons and are not limited by synchrotron radiation
- BUT muons decay (2.2 μs lifetime at rest), hence must be accelerated rapidly
- 5-7 years of R&D to prepare a concept of demonstration facility

$$\mathcal{L} = \frac{N_+ N_- n_{eff} f_{rep}}{4\pi\sigma_x^*\sigma_y^*}$$

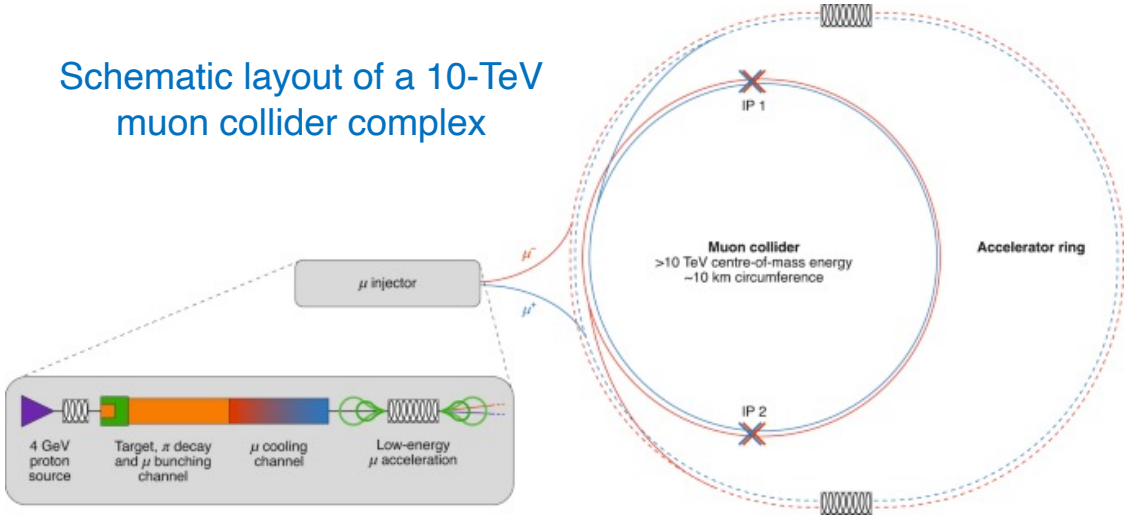
$n_{eff} \approx 150\bar{B}$ is the *effective* number of turns

- The muon collider concept was developed by U.S. Muon Accelerator Program (2011-2016)
- In 2022, the International Muon Collider Collaboration (IMCC) was formed, hosted by CERN
- Potentially energy-efficient path toward 10 TeV pCM collider

Tentative parameters for a muon collider at different energy and luminosity stagings

Parameter	Symbol	Unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10	10	10
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34}cm^{-2}s^{-1}$	2.1	21	5 (tbc)	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_r	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_\parallel$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_\perp$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9
Protons on target/bunch	N_p	10^{14}	5	5	5	5
Proton energy on target	E_p	GeV	5	5	5	5

Schematic layout of a 10-TeV muon collider complex



Nature Physics | *VOL 17* | *March 2021* | *289–292* | *www.nature.com/naturephysics*

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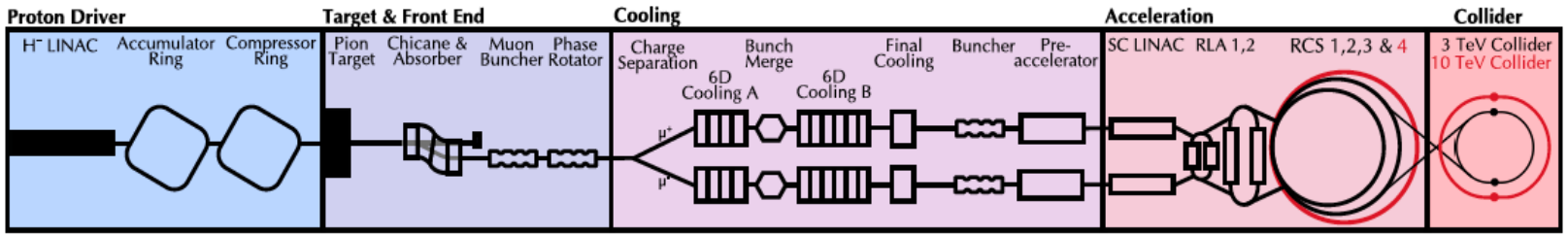
Key challenges for muon collider

Challenges at each step of the muon collider accelerator chain

- Proton driver: 1-4 MW beam power at 5-20 GeV; accumulate bunches with up to 10^14 particle, compress to ns duration; deliver at 5-10 Hz rate
- Target must withstand beam power, will be immersed in a ~15 T SC solenoid with ~2 m aperture; muons to be captured for cooling
- **6D ionization cooling of muon beams**: challenging high-filed solenoids, NC RF in high magnetic field
- Muon acceleration: need to accelerate muon as fast as possible to reduce the loss of muons due to decay (SRF)
- High-field accelerator magnets, including very fast ramping magnets
- Collider ring: challenging MDI to suppress breakdown originating from muon decays

After the ESPPU-2026, the Accelerator R&D Roadmap is being updated, to be presented at the LDG meeting.

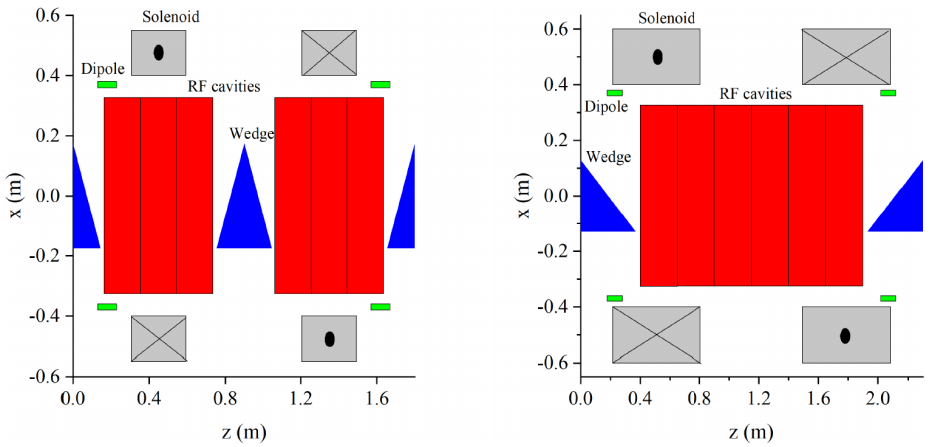
- The scale of the MC R&D would be a significant fraction of the final facility cost.
- The primary R&D goal – **6D ionization cooling demonstrator**.
- With sufficient funding and successful development of key technologies – colliding beams in 2050s?



Muon collider conceptual layout

RF and solenoids for ionization cooling

- Ionization cooling channel consists of ~850 muon cooling cells
- The cooling of muons requires very compact assembly of normal conducting RF cavities, superconducting solenoids, and liquid hydrogen wedge absorbers
- Large bore solenoids: from 2.5 T to 17.2 T
- RF cavities (325 and 704 MHz) must operate in multi-tesla fields
- The total number of RF cavities is 7686 with peak power of ~20 GW
- Absorbers (wedge-shaped) must tolerate large muon beam intensities



Schematic of the (left) A-type and (right) B-type cooling cell layout

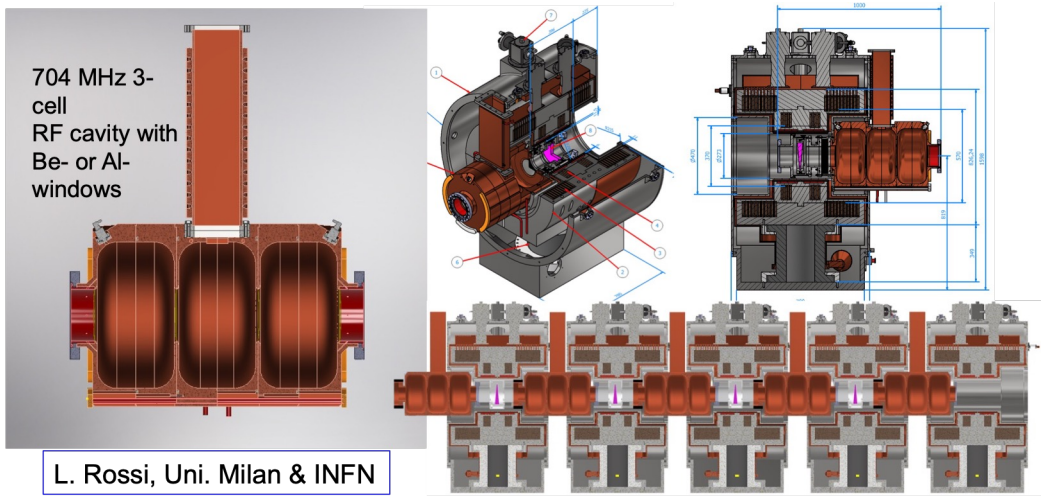
Main parameters for the rectilinear cooling cell components

	Cell Length (m)	Stage Length (m)	Pipe Radius (cm)	Max. B_z On-Axis (T)	Int. B_y (Tm)	$\beta_\perp$ (cm)	D_x (mm)	On-Axis Wedge Len. (cm)	Wedge Angle (deg)
A-Stage 1	1.8	104.4	28	2.5	0.102	70	-60	14.5	45
A-Stage 2	1.2	106.8	16	3.7	0.147	45	-57	10.5	60
A-Stage 3	0.8	64.8	10	5.7	0.154	30	-40	15	100
A-Stage 4	0.7	86.8	8	7.2	0.186	23	-30	6.5	70
B-Stage 1	2.3	50.6	23	3.1	0.106	35	-51.8	37	110
B-Stage 2	1.8	66.6	19	3.9	0.138	30	-52.4	28	120
B-Stage 3	1.4	84.0	12.5	5.1	0.144	20	-40.6	24	115
B-Stage 4	1.2	66.0	9.5	6.6	0.163	15	-35.1	20	110
B-Stage 5	0.8	44.0	6	9.1	0.116	10	-17.7	12.5	120
B-Stage 6	0.7	38.5	4.5	11.5	0.087	6	-10.6	11	130
B-Stage 7	0.7	28.0	3.75	13	0.088	5	-9.8	10	130
B-Stage 8	0.65	46.15	2.85	15.8	0.073	3.8	-7	7	140
B-Stage 9	0.65	33.8	2.3	16.6	0.069	3	-6.1	7.5	140
B-Stage 10	0.63	29.61	2.0	17.2	0.069	2.7	-5.7	6.8	140

	RF Frequency (MHz)	Num. RF	RF Length (cm)	Max. RF Gradient (MV/m)	RF phase (deg)
A-Stage 1	352	6	19	27.4	18.5
A-Stage 2	352	4	19	26.4	23.2
A-Stage 3	704	5	9.5	31.5	23.7
A-Stage 4	704	4	9.5	31.7	25.7
B-Stage 1	352	6	25	21.2	29.9
B-Stage 2	352	5	22	21.7	27.2
B-Stage 3	352	4	19	24.9	29.8
B-Stage 4	352	3	22	24.3	31.3
B-Stage 5	704	5	9.5	22.5	24.3
B-Stage 6	704	4	9.5	28.2	22.1
B-Stage 7	704	4	9.5	28.5	18.4
B-Stage 8	704	4	9.5	27.1	14.5
B-Stage 9	704	4	9.5	29.7	11.9
B-Stage 10	704	4	9.5	24.9	12.2

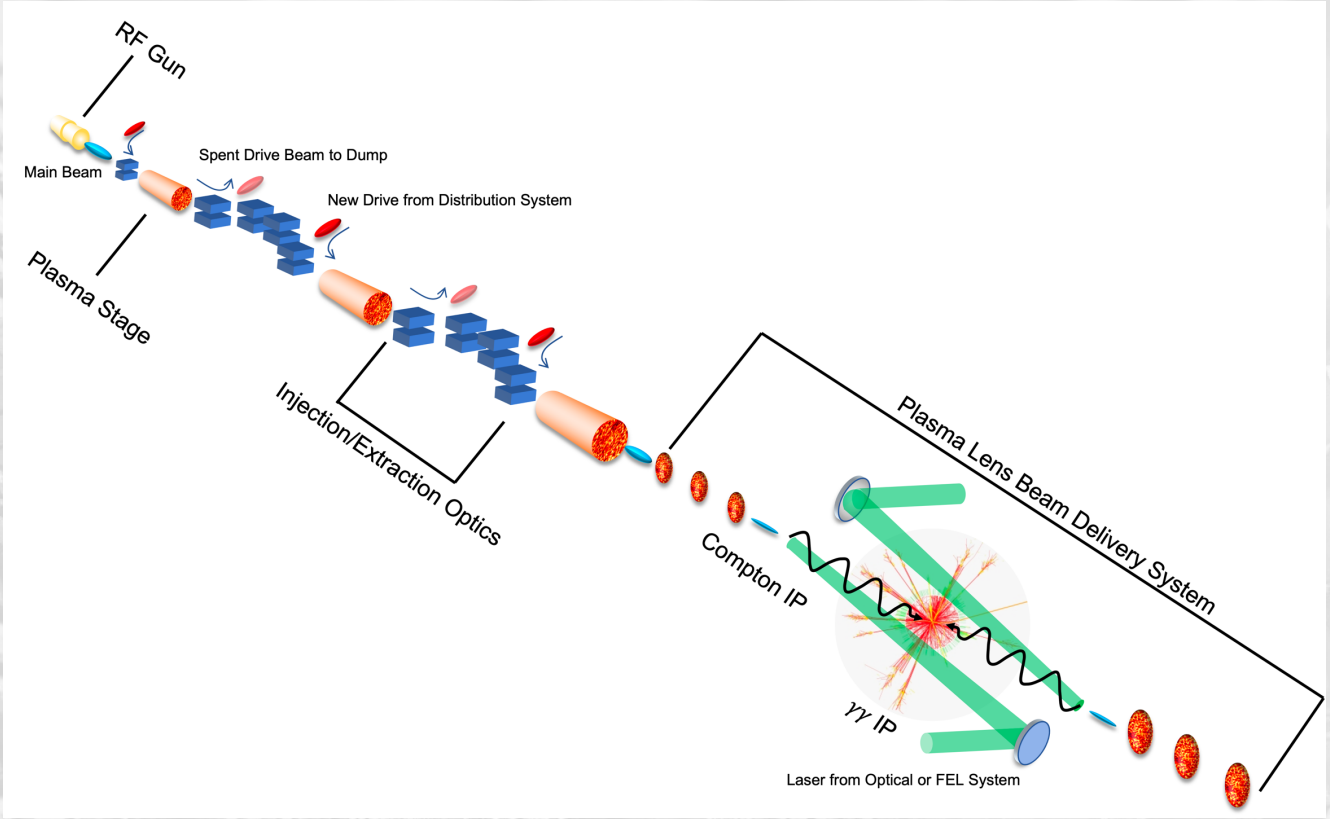
RF in magnetic field

- Challenges: high gradients in high magnetic field, high radiation, no synergies with other projects
- Previously demonstrated (MAP):
  - 50 MV/m in 3 T magnetic field, 800 MHz beryllium cavity, 30 us @ 10 Hz
  - 10 MV/m in 4 T, 200 MHz RF cavity prototype for MICE, 1 ms @ 1 Hz
  - Strong magnetic field focusing field emission electrons, thus facilitating RF breakdown
- Extremely important high gradient RF test stands with high magnetic field
  - No test stands in the 300 to 700 MHz range, but tests at higher frequencies – e.g., at S-band – are very useful to advance our understanding of the RF breakdown in strong magnetic fields.
  - Two S-band test stands being built: at INFN/LASA (7 to 10 T, homogeneous or gradient axial field) and at SLAC (5 T solenoid, upgradable to 1.3 GHz later)
- Integration study for 6D cooling demonstrator



L. Rossi, Uni. Milan & INFN

A. Grudiev, AAC Workshop 2026



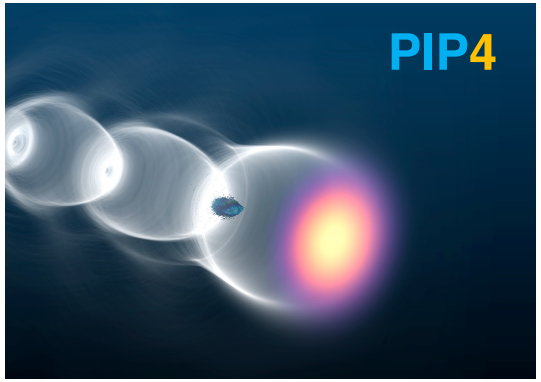
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10 TeV wakefield colliders

Wakefield colliders

Don't believe in miracles – depend on them
- Laurence J. Peter

- Three technologies are under development:
  - Laser-driven plasma (LWFA), 10-100 GV/m
  - Beam-driven plasma (PWFA), ~0.3 GV/m
  - Structure-based (SWFA), 1-100 GV/m



- It is very important to have a routinely operating wakefield accelerator with a reasonable bunch charge and repetition rate.
- Perhaps Plasma Injector for PETRA IV would be such a proof of principle machine.

The Plasma Injector for PETRA IV: CDR, 2025

- Many critical issues must be addressed:
  - Acceleration of positrons
  - Beamstrahlung
  - Staging of multiple plasma acceleration cells
  - Emittance control
  - Jitter and scattering in plasma
  - Power efficiency
  - …
- Different collision options are under consideration: e^+e^-, e^-e^- and $\gamma\gamma$

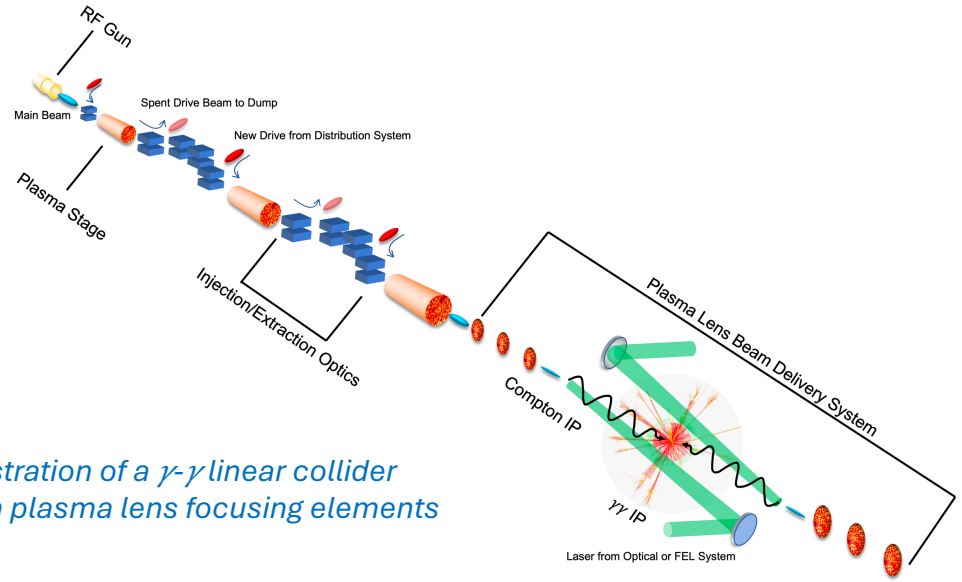


Illustration of a γ-γ linear collider with plasma lens focusing elements

T. Barklow et al., *JINST* **18**, P09022 (2023)

The 10 TeV Wakefield Collider Design Study

The Design Study aims to produce a unified, self-consistent concept for a 10 TeV parton-center-of-mass (pCM) collider based on wakefield accelerator (WFA) technology.

The Study is Initiated by the 2023 P5 Report, but it is a **global** undertaking.

This is an HEP-wide **community** effort. The study requires input from:

- HEP Theorists
- Detector Physicists
- Accelerator Physicists

The 10 TeV Design Study is primarily a volunteer effort.

ALEGRO 2025 WORKSHOP
ADVANCED LINEAR COLLIDER STUDY GROUP

ALEGRO 2025 @ SLAC

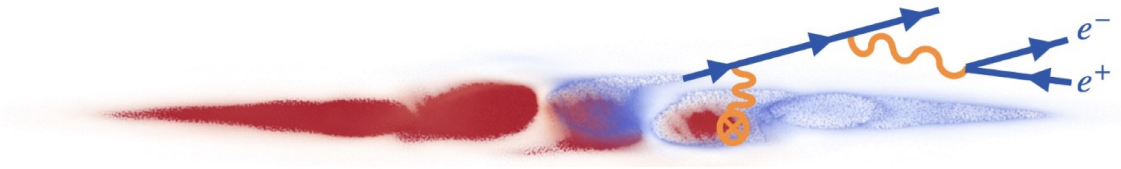




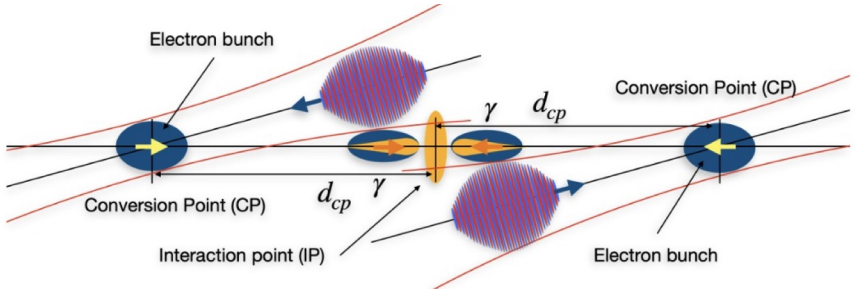
ALEGRO 2026 @ INFN

Slide provided by S. Gessner

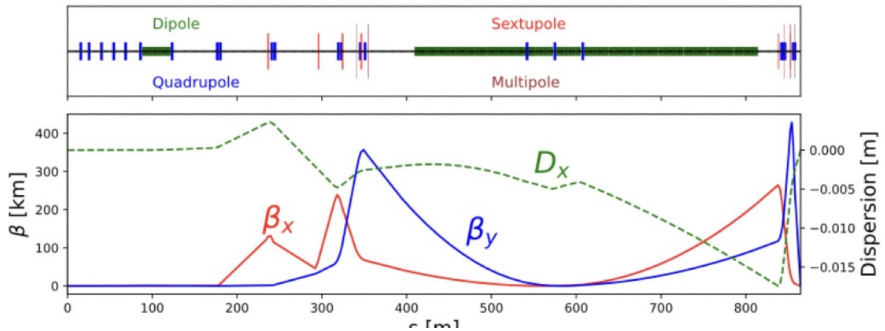
Recent Progress



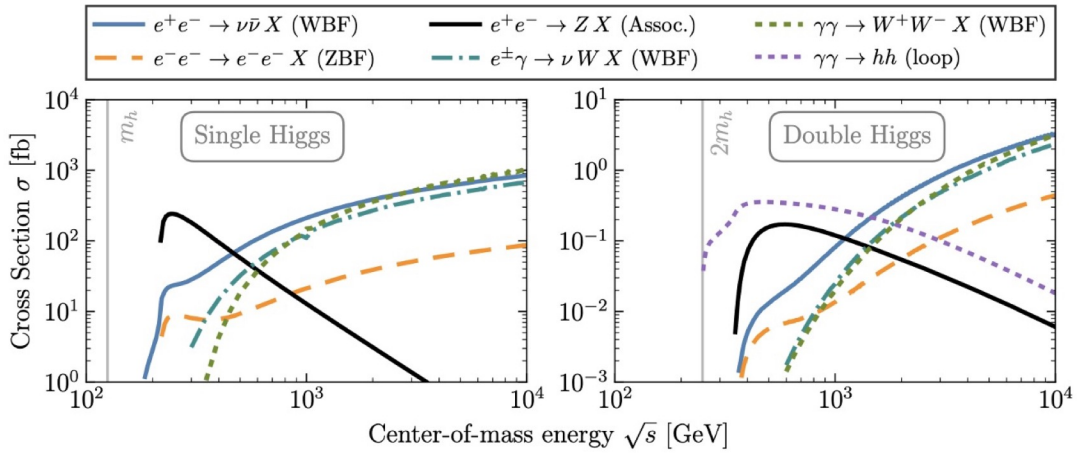
Benchmarked beam-beam models [arXiv:2610.17557]



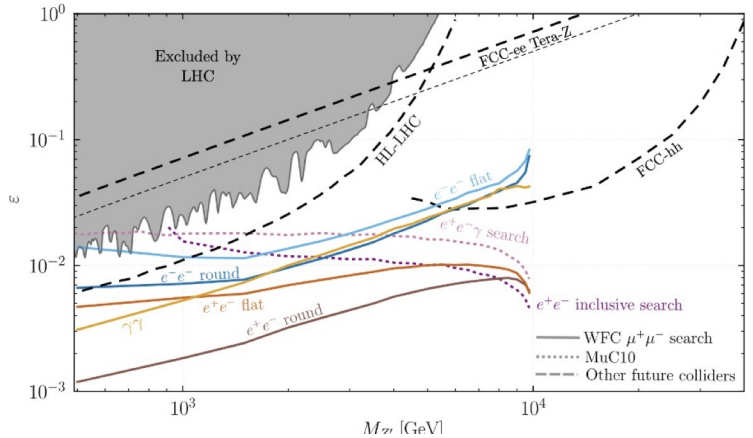
Gamma-gamma collider design [arXiv:2608.25137]



Final Focus system for 10 TeV [arXiv:2602.15777]



Higgs couplings with beamstrahlung [arXiv:2607.19463]



Vector resonances with beamstrahlung [arXiv:2603.18146]

Recent publications can be found here: https://10tev-wakefield-collider.github.io/publications/

Slide provided by S. Gessner

4

Summary

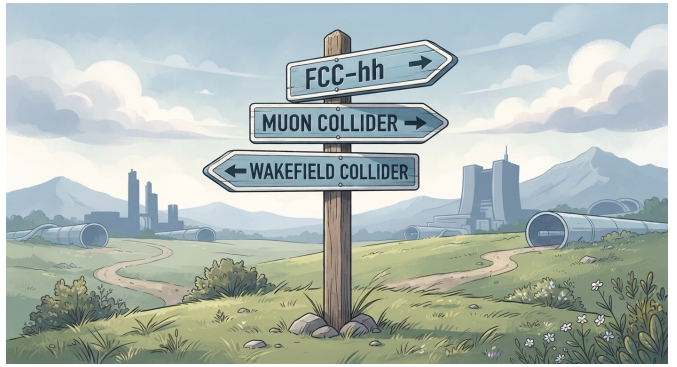


Summary

- The 10 TeV pCM collider designs are at different stages of maturity, but all require quite extensive R&D efforts covering a wide range of challenging topics: beam optics, MDI, positron acceleration, muons ionization cooling, high-field SC magnet and RF technologies…
- If FCC-ee or CEPC to go ahead, then a logical follow-up would be a ~100 TeV circular *pp* collider.
- A muon collider could provide precision and energy reach in a more compact and energy-efficient configuration.
- A self-consistent concept of a wakefiled collider still need to be developed.



Images generated by Gemini AI



If you don't know where you are going, you will probably end up somewhere else.

- Laurence J. Peter

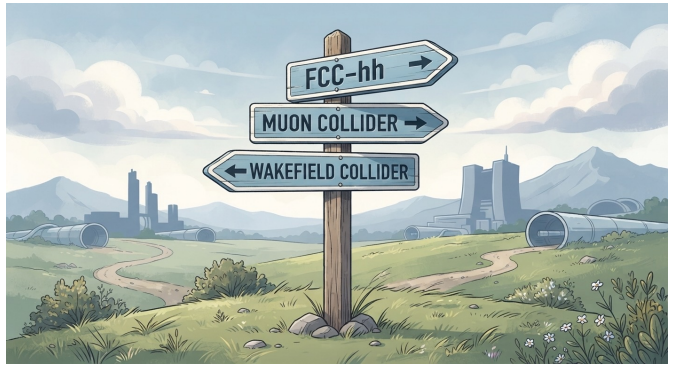
Summary

"I always tend to assume there's an infinite amount of money out there."
"There might as well be, "Arsibalt said, "but most of it gets spent on pornography, sugar water and bombs. ***There is only so much that can be scraped together for particle accelerators.****"*
– from Anathem by Neal Stephenson

- The 10 TeV pCM collider designs are at different stages of maturity, but all require quite extensive R&D efforts covering a wide range of challenging topics: beam optics, MDI, positron acceleration, muons ionization cooling, high-field SC magnet and RF technologies…
- If FCC-ee or CEPC to go ahead, then a logical follow-up would be a ~100 TeV circular *pp* collider.
- A muon collider could provide precision and energy reach in a more compact and energy-efficient configuration.
- A self-consistent concept of a wakefiled collider still need to be developed.
- I gave you just a snapshot of accelerator R&D topics for 10 TeV pCM colliders. There is a lot more to study and develop.
- Synergies exist not only between the colliders but also with other accelerators. These opportunities should be leveraged as much as possible.
- Any future collider will need very high AC power* to operate; special attention should be given to R&D topics that would improve efficiency of various systems.



Images generated by Gemini AI



If you don't know where you are going, you will probably end up somewhere else.
- Laurence J. Peter

**) Perhaps it is not that high anymore if we compare with the power-hungry AI data centers?*


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