Accelerators for Lepton Collisions in the 500 GeV – 3 TeV Range

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SLAC NATIONAL ACCELERATOR LABORATORY

Introduction

This talk will review different options for achieving lepton collision energies in the 0.5 – 3 TeV center-of-mass range and cover the following projects:

> ILC, CLIC, Cold Copper Collider (C^3), Muon Collider (MC), Structure-Based/Argonne Flexible Linear Collider (AFLC), Laser-Plasma Linear Collider (LPLC), and Beam-Plasma Linear Collider (PLC).

This talk relies heavily on Snowmass presentations and Letters of Interest put forward by the groups championing these projects. There are references and contact information throughout the talk.

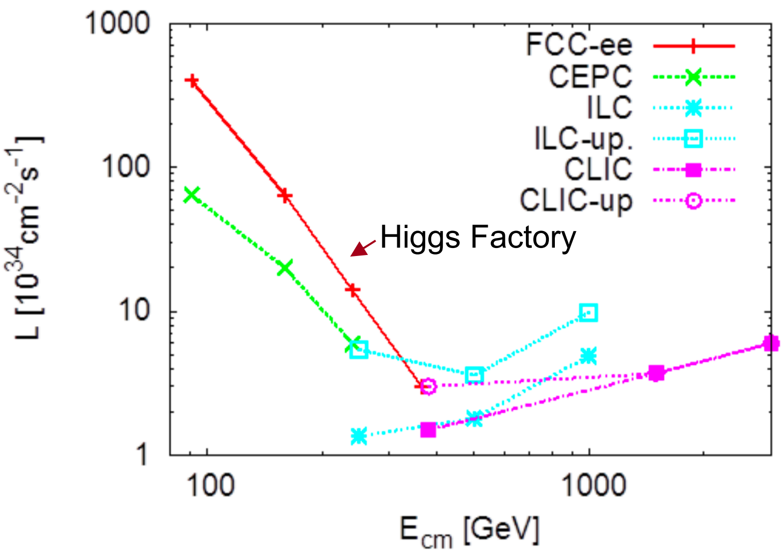
Circular vs. Linear Colliders

ESPP Physics Briefing Book arXiv:1910.11775

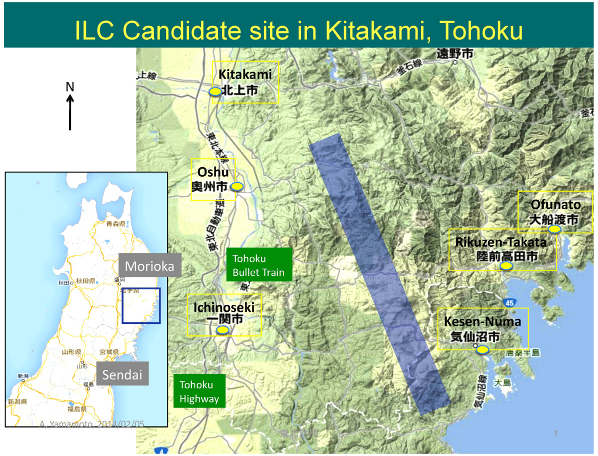
The FCC-ee and CEPC concepts produce higher luminosities than linear colliders at or below 250 GeV CM.

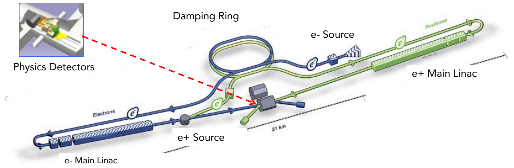
The luminosity of circular electron-positron colliders falls off rapidly with increasing energy.

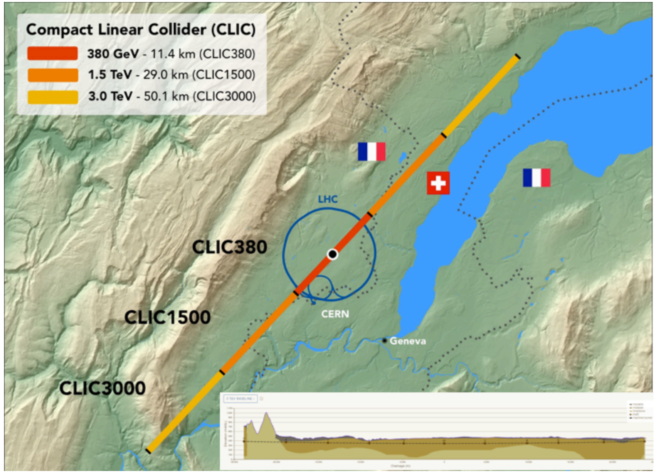
The large capital investment for circular machines is justified by the possibility of upgrading to a 100 TeV proton-proton collider.

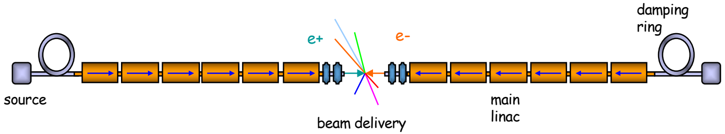


Linear Collider Concepts









Linear collider concepts also require large capital investment. They have a natural upgrade path from a Higgs Factory to a few TeV and possibly beyond.

They place no time or implementation constraints on future hadron or muon colliders.

Figures-of-Merit

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	Energy	Luminosity
Physics	• High collision energies are required to create high-mass particles	• High-energy collisions have small cross-sections. We need high luminosities to perform detailed studies. • The *luminosity in 1%* of the collision energy is a key parameter for precision studies. Beamstrahlung reduces the luminosity in 1% at high collision energies. • For multi-TeV discovery machines, *total luminosity* is the primary figure-of-merit.
Technology	• The length of the collider is determined by the *accelerating gradient* and the collision energy. • Higher accelerating gradients = smaller machines, meaning less civil infrastructure and lower costs. • High gradient technologies are not necessarily more expensive than their lower gradient counterparts.	• The *luminosity per wall plug power* (L/P) is the main figure of merit for collider efficiency. • L/P is maximized by reducing beam emittance and increasing acceleration efficiency. • Maximizing L/P = more bang for your buck.

Collider Concepts

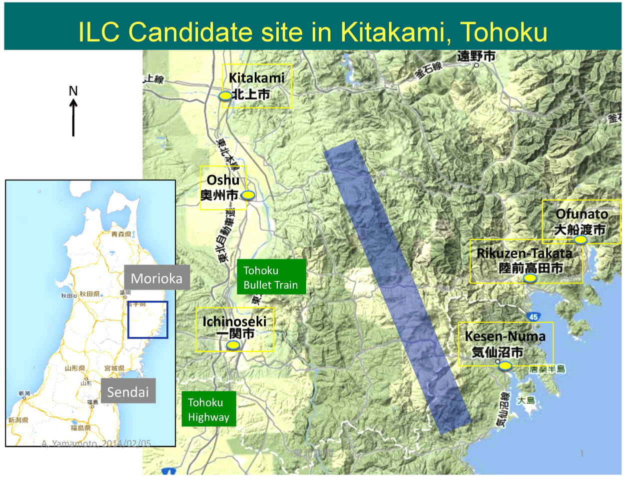
International Linear Collider (ILC)

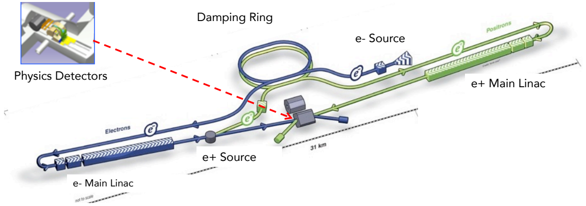
The ILC is a well-studied linear collider concept based on superconducting RF (SCRF) acceleration.

As of 2017, the baseline design is 250 GeV CM.

A TDR exists for CM energies up to 1 TeV.

There are two Snowmass LoIs detailing luminosity upgrade paths and energy upgrades up to 3 TeV based on improvements in SCRF technology.





[ILC summary covering 250 GeV – 1 TeV options](#)
[Snowmass LoI on luminosity upgrades](#)
[Snowmass LoI on energy upgrades](#)

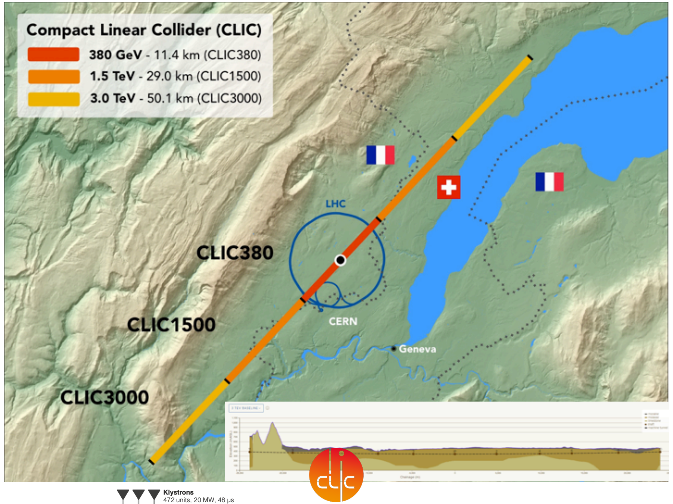
Contact: Mark Ross mcrec@slac.stanford.edu

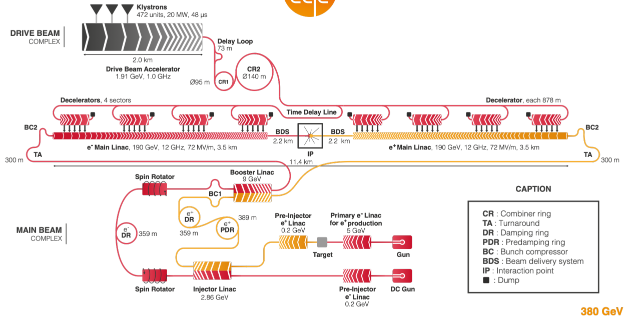
Compact Linear Collider (CLIC)

CLIC is a well-studied linear collider concept based on normal-conducting RF (NCRF) acceleration. CLIC uses a “two-beam” acceleration scheme.

A TDR exists for CM energies at 380 GeV, 1.5 TeV, and 3 TeV.

At 380 GeV, CLIC also considers a klystron-driven option.





[2018 update on CLIC design](#)
[Snowmass LoI on CLIC](#)

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Cold Copper Collider (C^3)

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C^3 is a novel collider concept that use NCRF cavities cooled to liquid nitrogen temperatures.

The cavities are optimized for efficiency using distributed RF coupling (maximize gradient per input power).

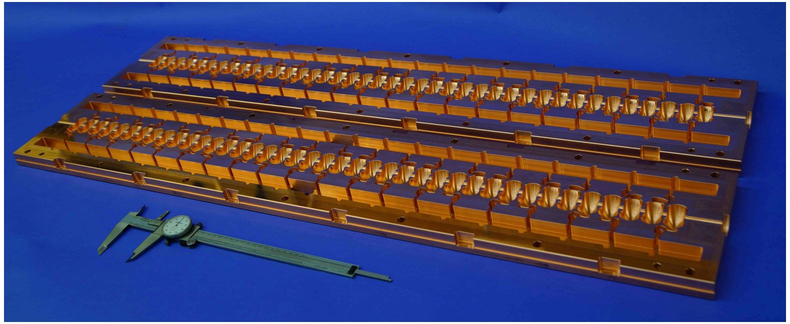
Cooled cavities have lower breakdown rates at higher gradients.

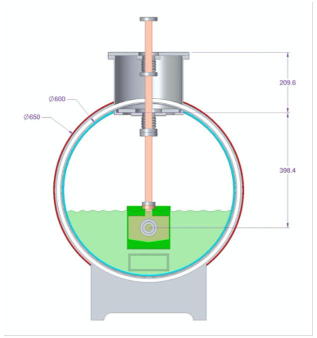
Project Goal: Develop 9m cryomodules as a scalable platform up to 3 TeV.

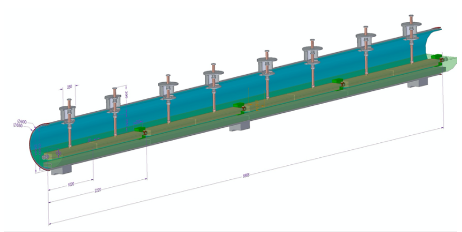
[C^3 Concept]()

[Snowmass LoI on C^3 Concept]()

Tantawi et al. "Distributed coupling and multi-frequency microwave accelerators," Jul. 5 2016, US Patent 9,386,682.







Contact: Emilio Nanni nanni@slac.stanford.edu
Sami Tantawi tantawi@slac.stanford.edu

Argonne Flexible Linear Collider (AFLC)

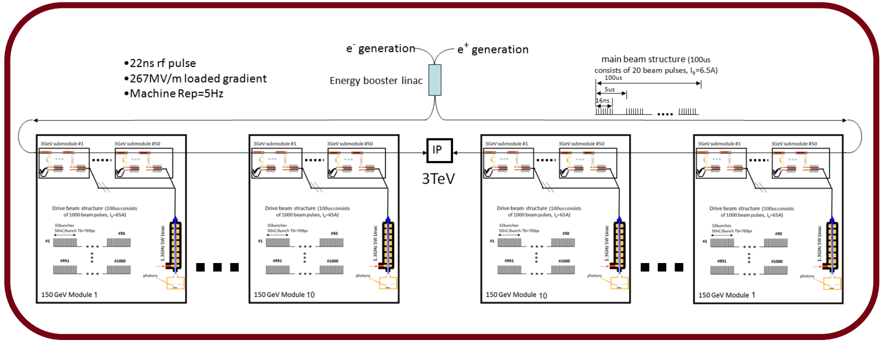
Structure-Based Wakefield Accelerator:

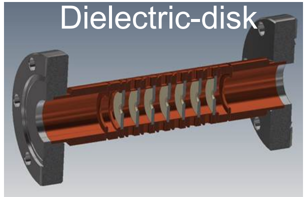
AFLC is a collider concept based on two-beam acceleration. The modular design provides flexibility to upgrade the energy from 250 GeV to 3 TeV.

High gradient: Short RF pulses (~20 ns) to reach high gradient. The baseline design uses K-band dielectric-loaded structure with high breakdown resistance, simple geometry, and low cost.

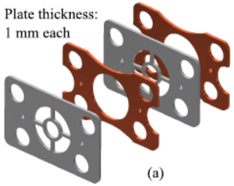
High efficiency: Novel structures and main beam shaping technologies are under investigation to improve the collider efficiency.

Dielectric TBA Concept
Snowmass LoI on AFLC

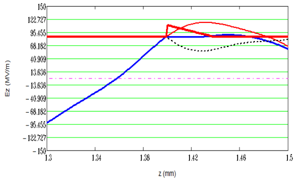




Metamaterial



Main beam shaping



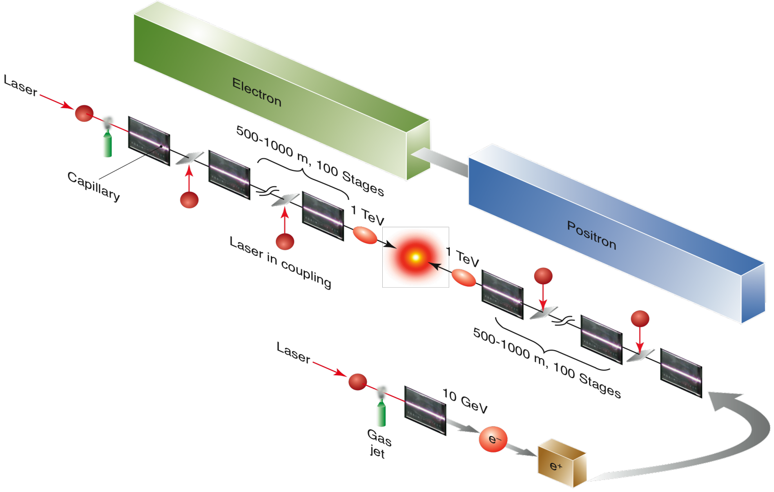
Contact: John Power JP@anl.gov

Laser-Plasma Linear Collider (Laser PLC)

The Laser PLC is a laser-driven plasma acceleration concept.

Laser plasma wakefield acceleration (LWFA) produces enormous accelerating gradients (~100 GV/m) and is the most compact approach to building a multi-TeV collider.

There is an international effort focused on engineering high-power, high-repetition rate lasers that could be used to drive the Laser PLC.



[Laser-Plasma Collider Concept]
[Snowmass LoI on LPLC]

Contact: Carl Schroeder cbschroeder@lbl.gov

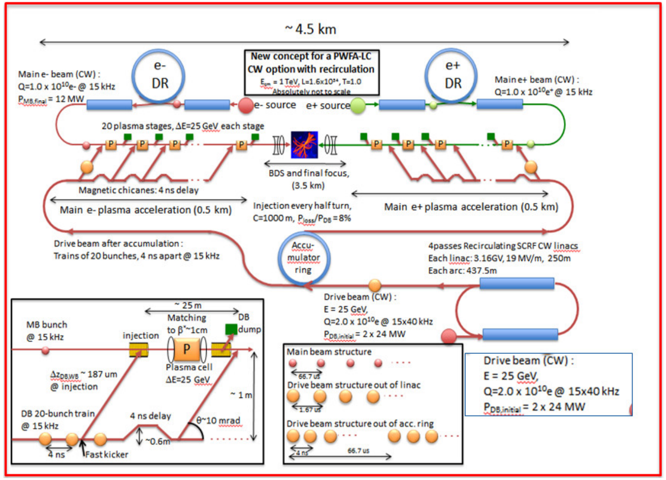
Beam-Plasma Linear Collider (Beam PLC)

The Beam PLC is a beam-driven plasma accelerator concept.

Beam-driven plasma wakefield acceleration (PWFA) also produces large accelerating gradients.

The plasma acts as a transformer, shifting energy from the drive beam to the main beam.

Possible applications include a plasma “afterburner” for the ILC and CLIC, or repurposing the ILC cavities for a drive-beam facility.



This design was submitted for Snowmass 2013, but significant progress has been made since then on addressing beam stability in plasma. See for example: [JBB Chen et al, J. Phys.: Conf. Ser. 1596 012057 (2020)]

[Plasma Linear Collider Concept]
[Snowmass LoI on PLC]

Contact: Spencer Gessner sgess@slac.stanford.edu
Erik Adli erik.adli@fys.uio.no

Strategy for Advanced Accelerators

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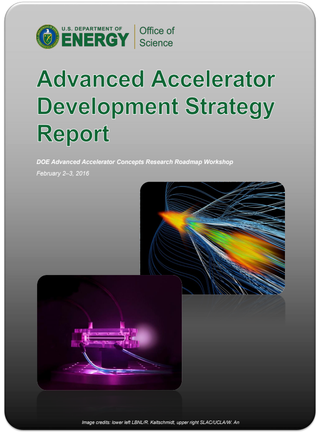
In 2016, the DOE held the Advanced Accelerator Concepts Research Roadmap Workshop which produced plans for the development of AAC technologies for linear collider applications.

Each of the three sub-fields (laser-driven plasma, beam-driven plasma, and structure-based) produced their own roadmap on research topics and goals, and each roadmap includes LC concept studies.

All three technologies are highlighting the need for *Integrated Design Studies* of linear colliders based on AAC technologies as part of Snowmass 2021.



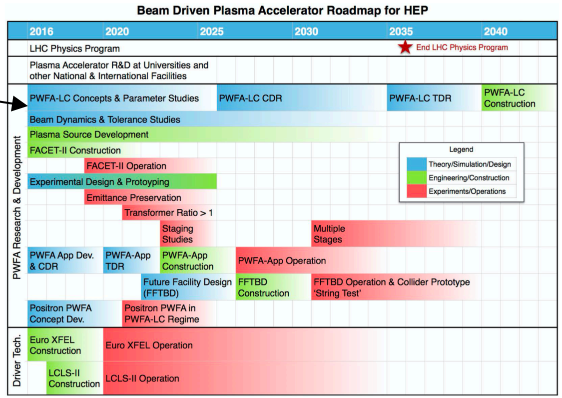


Figure 4: High level R&D roadmap for particle beam driven plasma accelerators.

Muon Collider (MC)

The muon collider is different than the other concepts discussed so far because:

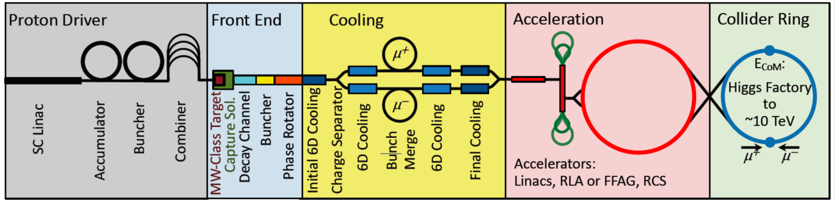
- It collides muons and anti-muons rather than electrons and positrons.
- It is a ring-shaped collider.

The luminosity of an MC increases with energy because of the increased muon lifetime.

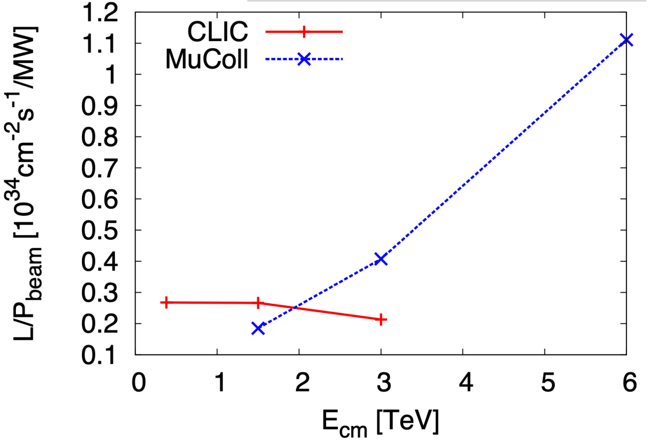
A new Muon Collider Collaboration is being formed at CERN with the goal of producing a CDR in the next 5 years!

ESPP Document on Muon Collider
Snowmass LoI on MC

From the MAP collaboration:
Proton source (M. Palmer et al.)



MuColl parameters from MAP collaboration



Contact: Daniel Schulte daniel.schulte@cern.ch

Comparison at 3 TeV

[1] CLIC is only project with a CDR at 3 TeV

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	Length (km)	Eff. Grad. (MV/m)	Luminosity (1E34)	Wall Plug Power (MW)	L/P (1E34/GW)
CLIC[1]	**50**	**60**	**5.9**	**589**	**10**
ILC	40	75	6.1	596	10
C^3	28.5	105	6.8	510	13
AFLC	18	166	5.9	222	27
LPLC	1.3	2300	10	315	32
BPLC	8	375	6.3	318	20
MC	4.5	N/A	4.4	230	19

For full parameter table at multiple energies, and list of references, see spreadsheet here:
https://docs.google.com/spreadsheets/d/13TT0b_dFaH5I7vnM9xgJxBSc_TFSR5nxHe1wa8RPdiI/edit?usp=sharing

Beyond 3 TeV

At CM collision energies in the 10 TeV-range, lepton colliders compete with hadron colliders as Energy Frontier discovery machines because leptons are fundamental particles (quarks and gluons carry ~1/7 the proton energy).

For linear colliders, advanced accelerator technologies operating with extremely high efficiencies are the only viable path to the 10 TeV scale.

Beamstrahlung becomes a limiting factor above 3 TeV for electron-positron colliders. Many novel ideas for mitigating beamstrahlung have been proposed, including the use of ultra-short bunches. Beamstrahlung can be avoided altogether by converting the lepton collider to a γ-γ collider.

Muon colliders have been proposed with 14 TeV CM energy. This option provides the highest L/P, but other issues like neutrino radiation become challenging.

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effi .

See for example: "Particle Colliders with Ultra-Short Bunches"
https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF0_EF0-CF7_CF0-TF6_TF0-AF6_AF0-CompF2_CompF0-037.pdf

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See C. Schroeder's Talk in Session 182 on "Energy and power limits of plasma accelerators"

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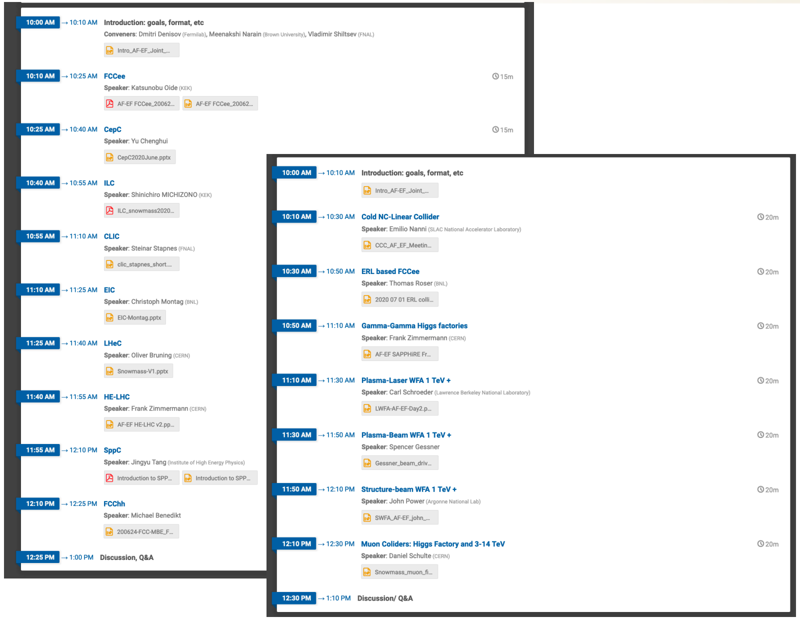
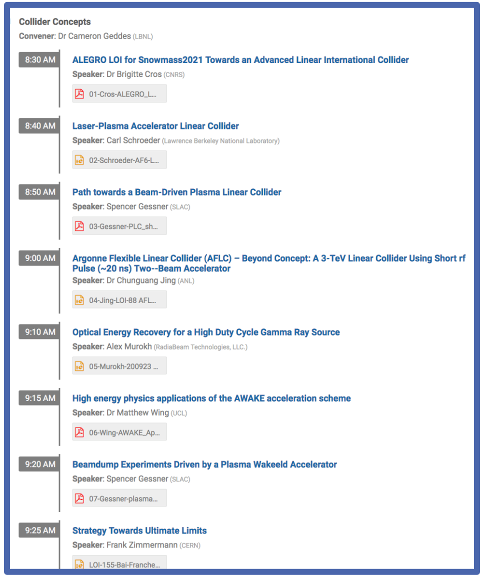
Snowmass Discussions on Future Colliders





There was a two-day joint AF-EF discussion on Future Colliders in June:

https://indico.fnal.gov/event/43871/

And a summary of collider concepts based on advanced acceleration as part of AF6

https://indico.fnal.gov/event/45651/

Conclusions

Existing technologies can be used to build linear colliders that can serve as Higgs factories and then be upgraded to the few-TeV scale.

CLIC has a mature design at 3 TeV. Novel concepts must “beat” CLIC in the luminosity per wall plug power figure-of-merit.

Advanced accelerator concepts are sometimes viewed as competing with ILC or CLIC. We should think of AACs as a method for extending the reach of ILC and CLIC.

Muon colliders have exciting potential at very high lepton collision energies.