Introduction

Lepton collider physics opportunities and energy scales

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BERKELEY LAB
Lawrence Berkeley National Laboratory

The context: The Energy Frontier

More info
EF Workshop
Aug 30 - Sep 3rd

The Energy Frontier (EF) group at Snowmass will explore the TeV energy scale and beyond, under different future accelerator scenarios, including lepton-lepton, hadron-hadron, and lepton-hadron colliders

- Obvious strong synergy with Accelerator, Theory, Instrumentation Frontiers

Sharp physics questions will bring focus to issues pertaining to EF future directions

- Re-evaluate existing ideas and emphasize how existing work can lead to new ideas
    - for example HL-LHC
- results may shape future colliders
- Identify new ideas
- Highlight scientific merit of collider options and connections with other Frontiers to address those questions

Snowmass is our time to innovate and set new directions

A sample of the key Physics questions for EF

- What is the origin of the electroweak scale?
- How to build a complete program of BSM searches via both model-specific and model independent explorations?
- What can we learn of the nature of strong interactions in different regimes?

Finding answers generates more specific questions, among which

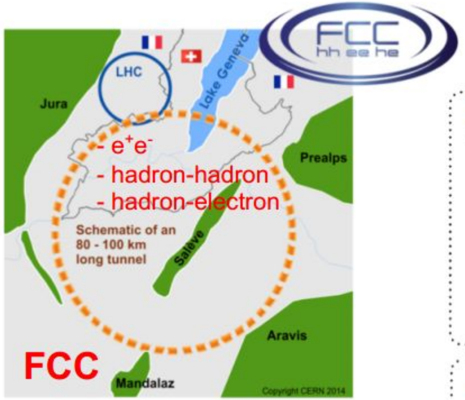
- What collider/detector properties are necessary to probe e.g. the Higgs self interactions?
- Explore a comprehensive range of future collider options to understand what is needed from the collider and experimental communities.
- Identify technologies which will lead to discoveries.

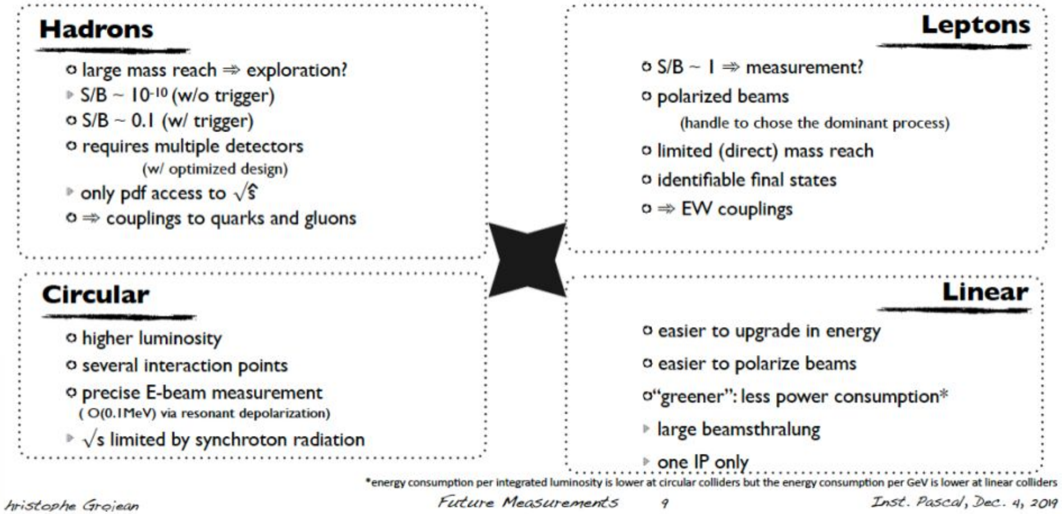
And also

- What Theory calculations do we need to capitalize on?
- Where does theoretical accuracy matter most? How to reduce theory systematics where needed?
- Where do new approaches in searches or data analysis matter most?

Which machines?

A. Tricoli, EF Workshop





Hadrons

- large mass reach ⇒ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇒ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇒ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇒ EW couplings

Circular

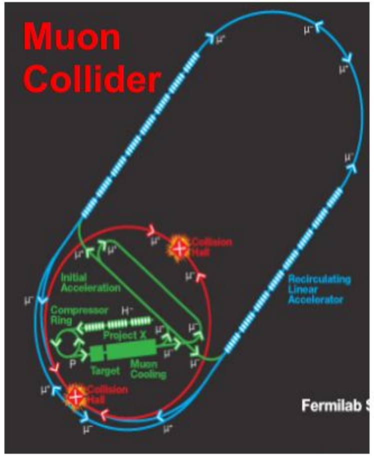
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

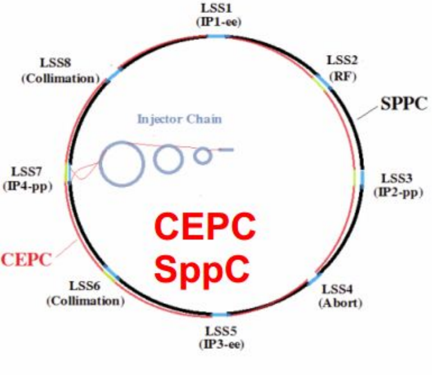
Linear

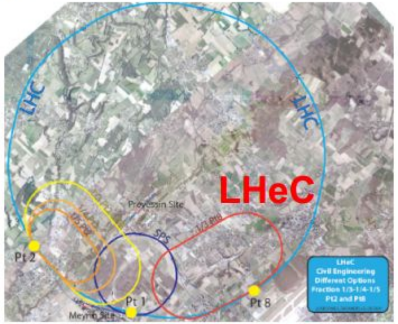
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

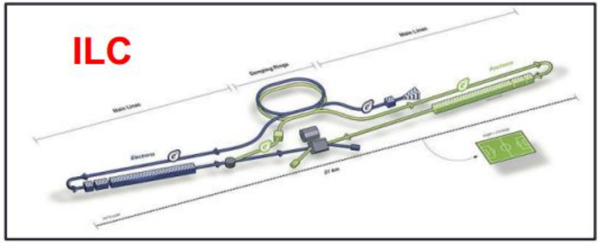
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

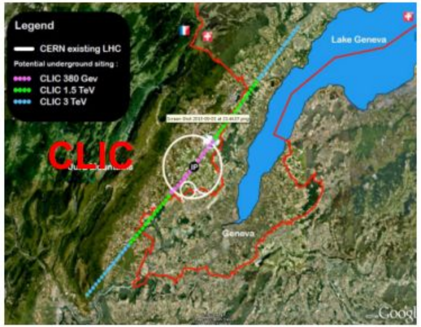
hristophe Grojean Future Measurements 9 Inst. Pascal, Dec. 4, 2019









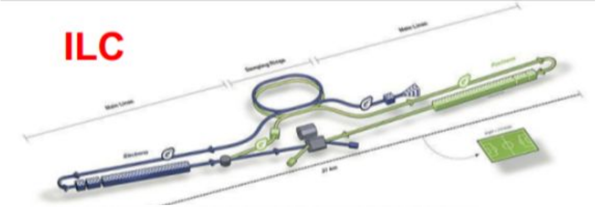


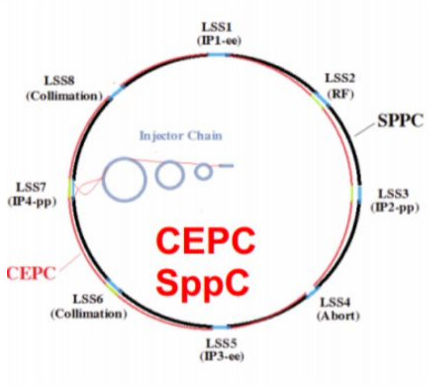
- gamma-gamma colliders?

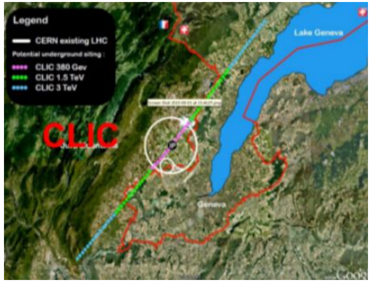
What’s beyond High-Luminosity LHC?

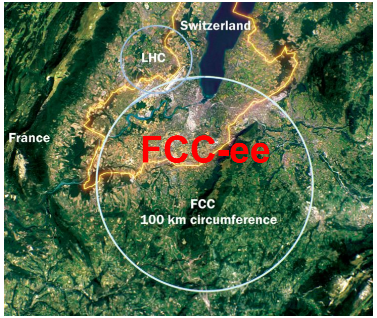
Not all options are “equal”

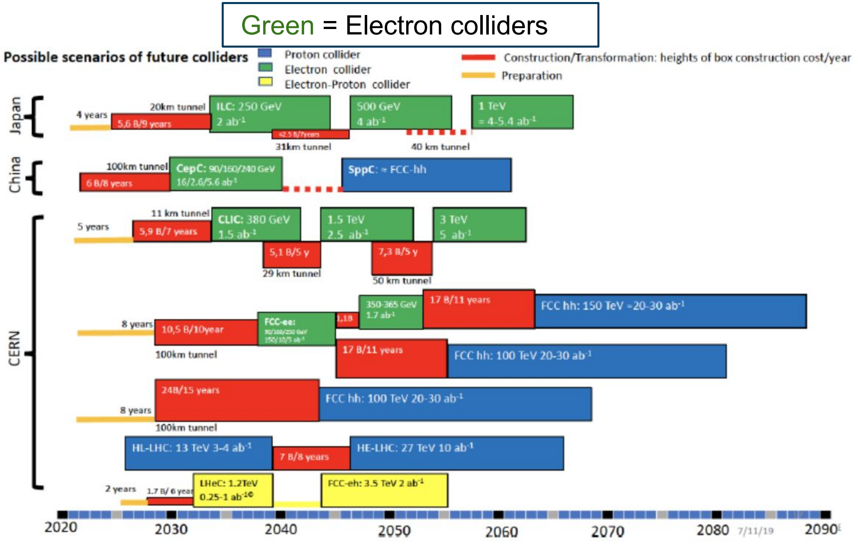
- Different level of maturity, ranging from conceptual designs to “ready-to-go”
- The European Strategy process converged to encouraging a “short-term” e^+e^- Higgs-factory
    - Short-term = after taking advantage of the already-approved HL-LHC project
    - Depending on the choice, with upgrades can lead to energies up to ~1 TeV
- At the same time, there’s a clear <u>need to plan further ahead for an energy-frontier collider</u>











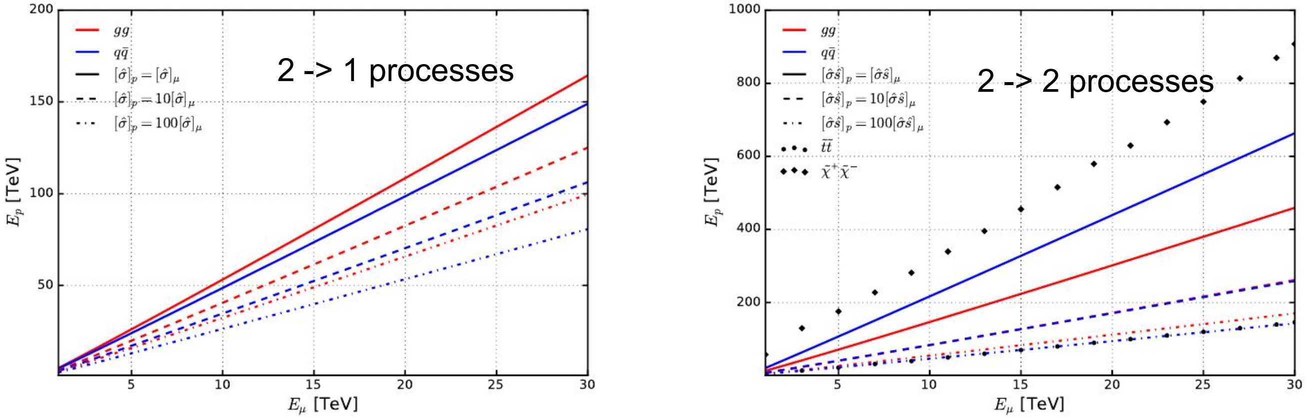
Ursula Bassler @ Granada meeting

The Future of Energy Frontier

Long-term there's the desire to push the energy frontier at new heights!

- ~100 TeV proton-proton colliders (FCC-hh, CppC in China)
  - FCC-hh in particular is among the options that have been studied and discussed for longer
- Renewed interest in high-energy lepton colliders, e.g. Muon Collider
- Advances in technology make also possible to foresee multi-TeV e^+e^- and γγ colliders

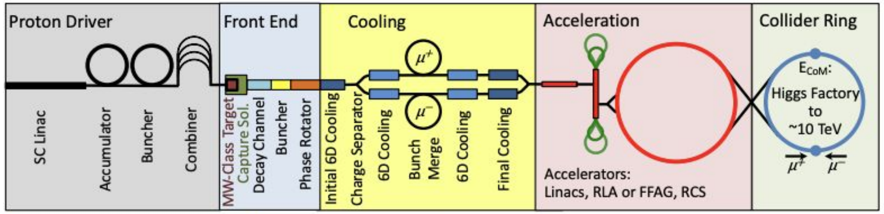
Multi-TeV lepton (and photon) colliders have been scarcely studied in the context of the European Strategy and are much more prominent - yet understudied - concepts in the Snowmass context



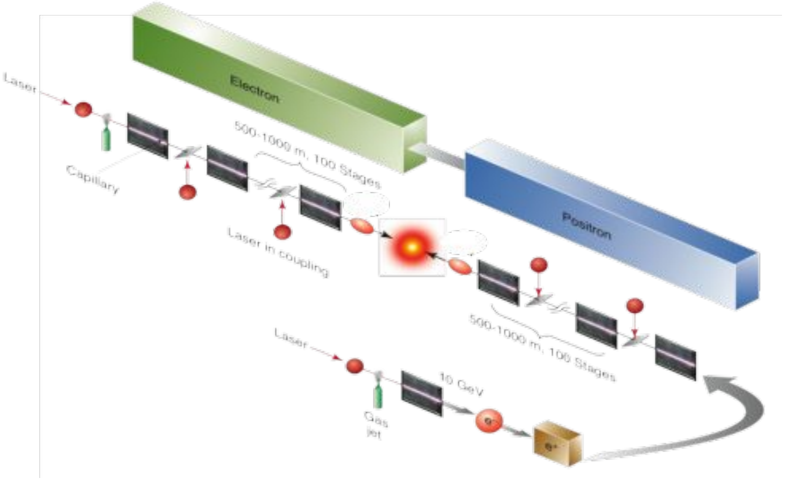
JHEP 2020, 80 (2020)

Options for future lepton and gamma-gamma collider at 1-15 TeV are being opened by new accelerator technology

Muon accelerators enable many-TeV ring colliders



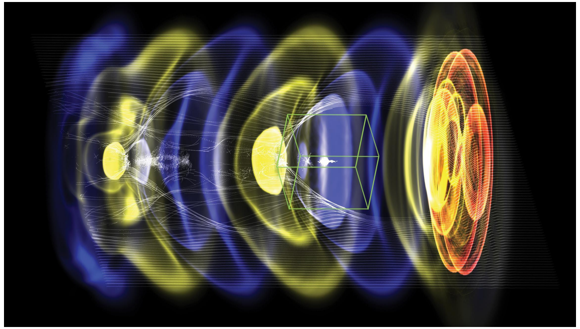
Laser-plasma accelerators enable many-TeV linear colliders



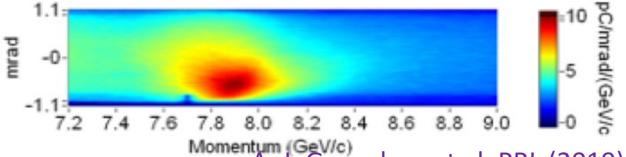
- Muon colliders, unpolarized
  - High-mass muons allow for ring-based colliders;
  - Muons decay and created with large emittance → must be confined by magnetic channels (SC magnets), cooled and accelerated (NC and SC RF) quickly.
- Polarized electron-positron and gamma-gamma colliders:
  - Linear, single interaction point
  - Laser-plasma acceleration at high gradient
  - Low emittance injection, rapid cooling & focusing
- Both concepts are in accelerator R&D phase
- TeV to 15 TeV energy reach
- Strong progress since last Snowmass
- Consideration of physics signatures and sequence with energy important to motivate accelerator R&D

Laser driven plasma accelerators offer high gradients for future lepton colliders

Laser (red) drives plasma density wave (blue-yellow), accelerating electrons (white)

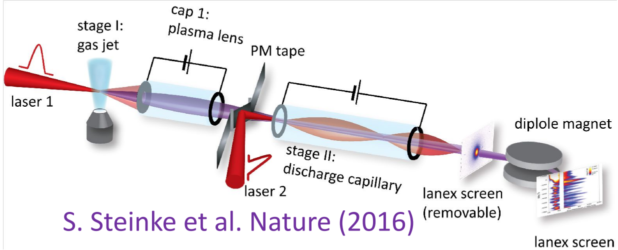


8 GeV beams



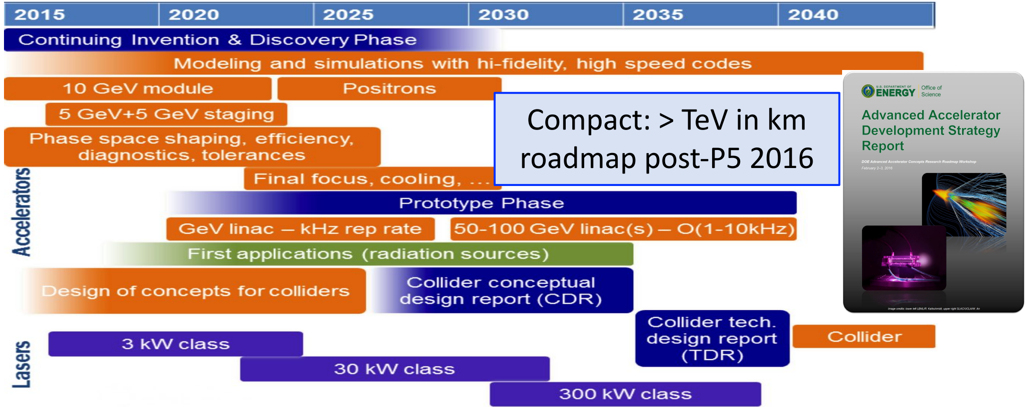
A. J. Gonsalves et al. PRL (2019)

Staging of two modules



S. Steinke et al. Nature (2016)

- Gradients 10 GeV/m & beyond
  - Also: ultra-bright beams, fast cooling & focusing
  - Micron-scale beams, quantum Beamstrahlung scaling
- Polarized electron-positron and gamma-gamma colliders
- LBNL a leader in rapid development. Since last Snowmass:
  - Staging of two modules + beamline for multi-GeV
  - 8 GeV record – in range of collider stage
  - Simulations show collider performance accessible
  - Fiber laser combination for efficient drivers at rate
- Internationally competitive: efficient stages, positrons & hollow channels, 0.1 μm emittance & path to nm-class, FEL at 27nm…



2015
2020
2025
2030
2035
2040

Continuing Invention & Discovery Phase

Modeling and simulations with hi-fidelity, high speed codes

10 GeV module

Positrons

5 GeV+5 GeV staging

Phase space shaping, efficiency, diagnostics, tolerances

Final focus, cooling, …

Prototype Phase

GeV linac – kHz rep rate

50-100 GeV linac(s) – O(1-10kHz)

First applications (radiation sources)

Design of concepts for colliders

Collider conceptual design report (CDR)

Collider tech. design report (TDR)

Collider

3 kW class

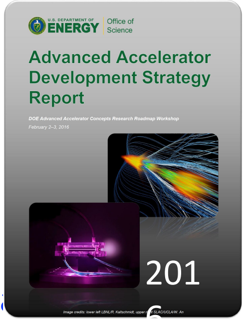
30 kW class

300 kW class

Compact: > TeV in km roadmap post-P5 2016

AF6 in Snowmass, and European planning

Plasma collider roadmap can enable 1-15 TeV polarized e+e- and gamma-gamma



U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An

- Collider roadmap post-P5: DOE Advanced Accelerator Development Strategy
  - Short beams, low emittance reduce power needs – lower beamstrahlung
  - High gradients could enable practical energy recovery
  - Plasma focusing may improve beam delivery
  - Energy spread and emittance growth tractable – power is the key limit
- Sequence of collider concepts available to the 15 TeV class: polarized e+e- or gamma-ga
  - Potential (and need) to sequence up in energy, from Higgs factory to multi-TeV
  - Re-use near-term LC infrastructure (e.g. ILC)
  - Next step for AF: integrated design study, self consistent and including tradeoffs
  - R&D in progress, TRL~3: beam quality, multi-stage efficiency, alignment, kHz drivers…
- Snowmass analysis of high level physics signatures currently missing, important to continue R&D

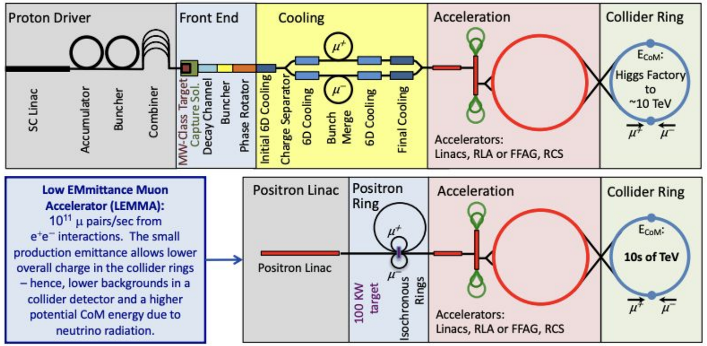
Concept		Components			Performance Parameters			
Accelerator Technology	**Energy**	**Beam source**	**Interstage Coupling**	**Beam Delivery**	**Effective Gradient**	**Luminosity**	**Efficiency**	**Power (no recovery)**
ILC, SC RF	0.5 TeV	Damp. Ring	N/A	ILC BDS	31.5 MV/m	2.7E34		240 MW
Plasma	3 TeV	Damping	Mag. or Plasma	Trad. BDS	1 or 10 GeV/m	3E34	15%	185-315 MW
Plasma	15 TeV	Plas. cath.@nm	Plas. lens	Plas. lens	10 GeV/m	5E35	15%	900-1100 MW

km-scale length

Added detail: EF restart talk, CPM: Plasma collider limits and options. AF6 page, and workshop

Muon capture and cooling offer ring-based future lepton colliders

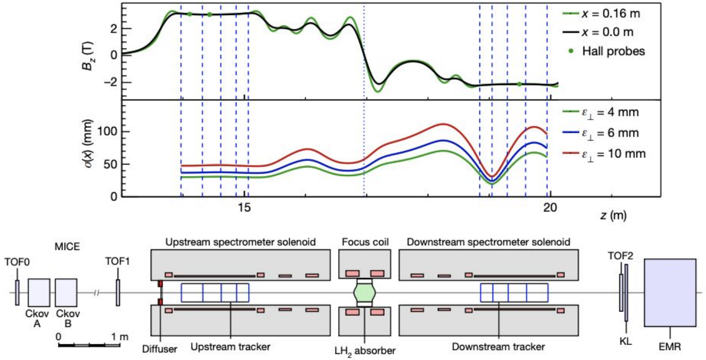
Production via protons (US MAP) or electrons



Low EMmittance Muon Accelerator (LEMMA): 10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Potential plasma role

MICE experiment demonstrated ionization cooling (major contribution from LBNL)



Nature, Vol 578, P53

- High muon mass allows (unpolarized) rings at high energy
  - Muons produced by high power beam on target
  - Captured and cooled in strong magnetic channel
- LBNL a leader in development of muon accelerator:
  - Beam physics with muon beams;
  - High gradient normal conducting RF for muon cooling;
  - High field superconducting magnets.
- Since last Snowmass:
  - Muon cooling demonstration (without RF): key technology;
  - High gradient NCRF demonstration in a 3-Tesla magnetic field;
  - Lead the U.S. Magnet Development Program: high field SC dipoles and higher field high-temperature superconducting magnets
  - Concepts for colliders at multiple energies;
- Strong community and international engagement, muon forum as part of Snowmass and European activities

Muon collider roadmap can enable 1-15 TeV machines

- After last Snowmass, initially US effort cut back. Resurgent interest with new results
    - Muon cooling demonstrated without RF
    - Demonstration of high gradient in a strong magnetic field
    - Accelerator issues appear tractable – power, size, neutrino radiation key limits
- Sequence of collider concepts available to the 15 TeV class
    - Potential (and need) to sequence up in energy, from Higgs factory to multi-TeV
    - Next step for AF: continue developing collider concept and options
    - R&D in progress, TRL~3: cooling, beam induced background, NCRF structures in magnetic field, SRF cavities, large bore 10-15T SC dipoles & 30T solenoids…
- Snowmass analysis of high level physics signatures in progress, important to continue R&D

Concept		Performance Parameters		
Accelerator Technology	**Energy**	**Total length all accelerators**	**Luminosity**	**Power (no recovery)**
RF, cooled μ	0.35	3 km	0.6E34	200 MW
RF, cooled μ	3 TeV	>10 km	2.25E34	230 MW
RF, cooled μ	14 TeV	TBD	4E35	TBD

Muon Collider Parameters developed under MAP: further information from Muon Collider Forum

Lepton collider physics opportunities and energy scales

Moderators: GianLuca Sabbi, Zoltan Ligeti

Panelists: Carl Schroeder, Derun Li, Hitoshi Murayama, Jeroen van Tilborg, Kevin Einsweiler, Marlene Turner, Nathaniel Craig, Tengming Shen

Reminder:
Everyone is encouraged to participate in the discussion and express their views!

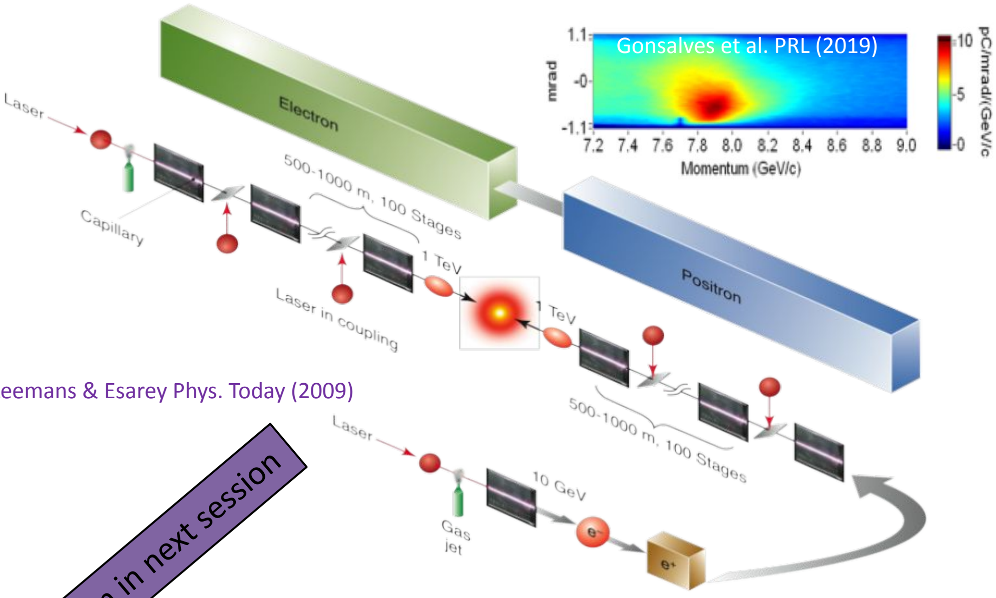
Lepton collider physics starting questions

Physics opportunities and accelerator technologies for leptons and gammas at few TeV to 15 TeV scales, focusing on advanced concepts such as the muon collider and laser plasma accelerators in which LBNL is a leader and where new concepts for colliders are emerging

- What are the key differences in the physics reach of very high-energy e+e-, gamma-gamma and muon colliders at the TeV to 14-TeV energy? Is the ability to produce polarized initial states (available for e+e- and gamma-gamma) a significant advantage in key physics observables?
- These options might pose different challenges in technological R&D to build a detector capable of extracting the physics output with the needed accuracy. What are, in your opinion, outstanding items that still need to be proven?
- How can LBNL-led technologies in plasma based accelerators for e+e- and gamma-gamma, or in muon systems, access each of these regimes? What are the R&D needs for each, distinct characteristics and potential showstoppers?
- Can we define a path that returns physics from near term machines? For example, what physics could we learn from near-term accelerators(and what are the differences) in the 30-60 GeV range?
- What would a near-term 40GeV-class machine look like (e.g. achievable luminosity, etc..) at LBNL that would be a technological stepping stone and demonstrator toward an energy frontier machine? How would that differ from already-built accelerators ~40 years ago in a similar energy range (e.g. PETRA, TRISTAN)
- What special expertise is available at LBNL that could help address the critical issues? Are there opportunities for new collaborations across groups and divisions that could be applied to these areas?

Backup material

Next session: LBNL experiment, laser-plasma collider demonstrator at 30-60 GeV



Leemans & Esarey Phys. Today (2009)

Discussion in next session

- Laser-plasma accelerators: > 10 GeV/m
- LBNL's BELLA Center leads development: 8 GeV record, staging, injection control
- Next initiative: kBELLA facility will demonstrate scaling to/beyond kHz rates for luminosity
- Compact colliders: polarized e+e-, gamma-gamma at TeV to 15 TeV accessible
    - Potential collider issues have been analyzed
    - Related: photon sources for applications in medicine, industry, security

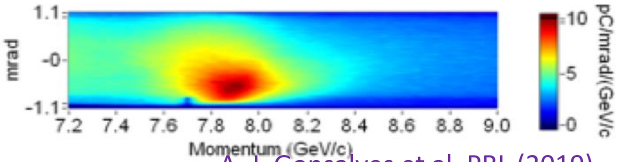
Beyond kBELLA, before collider: LBNL could host demonstration accelerator to the 30-60 GeV level

- Prove injector and few stages, potentially with focusing and positrons

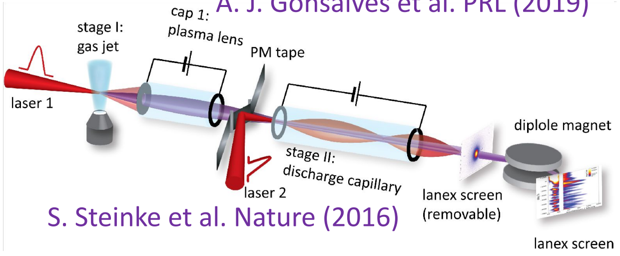
Are there physics signatures of interest at the 30-60 GeV level from polarized electron-positron or gamma-gamma?
What luminosity or other parameters would be required to exceed past machines?
Are there strong-field QED or other additional experiments accessible with this beam and a PW-class laser?

Rapid experimental progress since last Snowmass

- LWFA 8 GeV energy gain in single 20 cm stage using PW laser (also: multi- GeV PWFA).
- Proof-of-principle staging of LWFAs (~100 MeV energy gain) using plasma-based stage coupling
- Optimized beam loading in PWFA enables uniform, high-efficiency acceleration.
- Demonstration >1GeV/m gradients SWFA dielectric structures.
- FEL at 27nm (LWFA) and in (PWFA) demonstrate beam quality

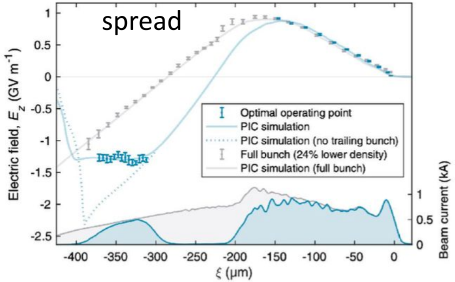


A. J. Gonsalves et al. PRL (2019)



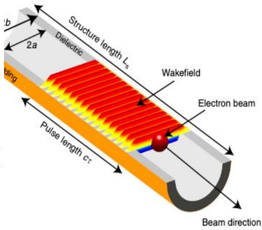
S. Steinke et al. Nature (2016)

42% transfer efficiency with 0.2% energy spread



C. A. Lindstrom et al. PRL (2021)

GeV/m structure



B. O'Shea et al. Nature Comm. (2016)

LWFA: W. Wang et. al, Nature Vol 595 (2021)

Also: positron PWFA, hollow channels for low emittance growth, 0.1 micron emittance with path to nm-class…

Assessment of limits indicates potential for 15 TeV-class

- AAC community has accessed potential limits of high-gradient linac technology
  - Shaped bunches can be used to efficiently accelerate beams without energy spread growth
  - Ion motion induced by dense beams can mitigate transverse hosing instability
  - Scattering in plasma mitigated by strong plasma focusing
  - Energy spread from synchrotron radiation in plasma limited by small beam emittances
  - Laser and beam energy recovery may be used for improved efficiency

- Additional technical challenges require R&D
  - 100's of stages: Beam matching / coupling between including efficiency ≥ 99%
  - Small accelerating structures place challenging alignment and jitter tolerances
  - Plasma-based beam delivery system and final focus

- Wall-plug power (operating costs) will limit energy reach of e+/e- linear colliders based on AAC
  - Beamstrahlung limits bunch charge and luminosity requirements increase required power:
  - Short beams and low emittance reduce power requirements (LOIs inc. 37, 190)
  - High gradients could enable practical energy recovery

$$P_{\text{beam}} \propto \gamma^{5/2}\sigma_z^{1/2}\sigma_x$$

AAC technology are capable of 15-TeV-class e+e- linear collider parameters

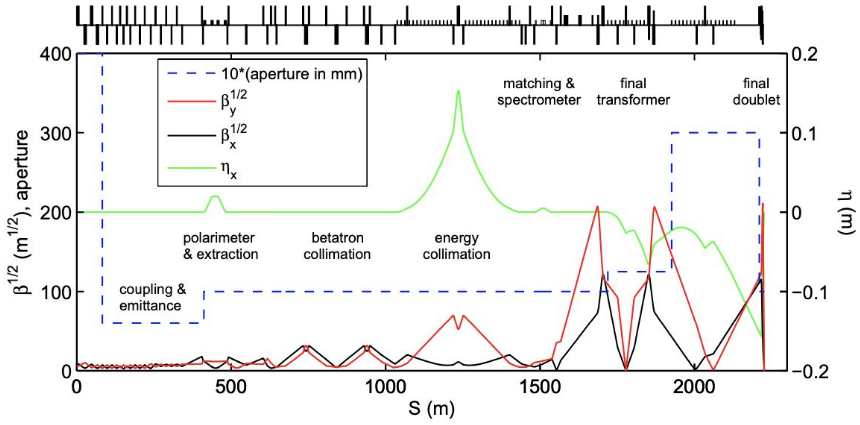
Interaction point beam delivery and machine-detector interface

- A traditional BDS system contains diagnostic sections and collimation sections in addition to the Final Focus and Machine-Detector Interface.
  - Can we develop novel diagnostics (e.g. betatron radiation) to characterize the beam emittance?
  - Can we develop novel collimation schemes?

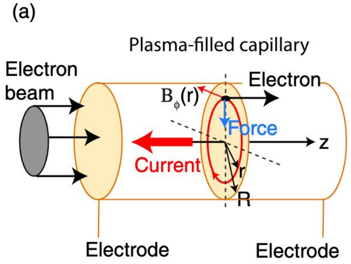
- The Final Focus uses the local chromatic correction in the final doublet.
  - Can we employ novel chromatic correction techniques with shaped plasma lenses?
  - Can we reduce the beam spot using strong focusing from plasma lenses?

- Bunch format: default evenly spaced 10-100kHz class (10-100μs), other formats possible

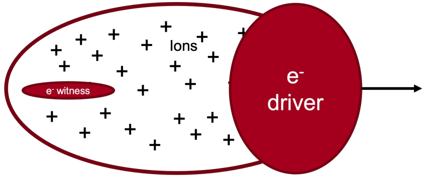
ILC BDS



Active Plasma Lens

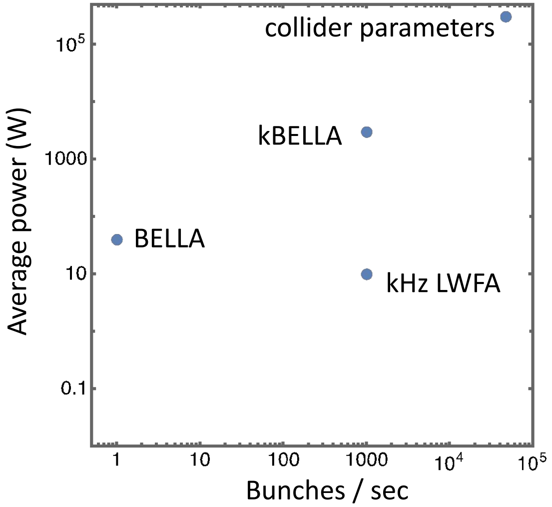


Passive Plasma Lens

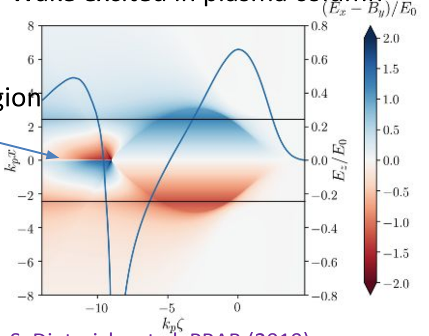


AAC facility next steps will advance technology and test key remaining parameters

- Rapid investment in Europe, Asia, incl. EuPRAXIA ($600M-class)
  - US R&D, facility base creates leadership opportunities
- High-average power and high repetition rate plasma accelerators:
  - *Technical challenges*: targetry at repetition rate, heat deposition and management (~kW/cm), structure durability
  - *kBELLA project*: kHz, J-class laser. Technology available; precision via active feedback, applications on collider roadmap
- Positron acceleration R&D
  - *Technical challenges:* plasma acceleration of stable, high-quality e+ beams, with high efficiency (comparable to e-)
  - *FACET-II upgrade*: plasma-based positron acceleration experiments/tests (e.g., plasma columns or hollow channels)
- Near term applications will establish technology, benefit colliders
  - Compton MeV photon sources, FELs, nQED, injectors… societal benefit and increased return on investment for HEP



Wake excited in plasma column



e+ focusing and accelerating region

S. Dieterichs et al. PRAB (2019)

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  - Demonstration of high gradient in a strong magnetic field
  - Accelerator issues appear tractable – target, cooling, power, size, neutrino radiation
- Sequence of collider concepts available to the 10 TeV class
  - Potential to sequence up in energy
  - Next step for AF: continue developing collider concept and options, including phased approach from Neutrino or Higgs factory
  - R&D in progress, TRL~3: cooling, beam induced background, NCRF structures in magnetic field, SRF cavities, large bore 10-15 T Nb3Sn superconducting dipole magnets to keep collider ring small, large aperture IR magnets, >30 T HTS solenoid.
- Snowmass analysis of high level physics signatures in progress, important to continue R&D

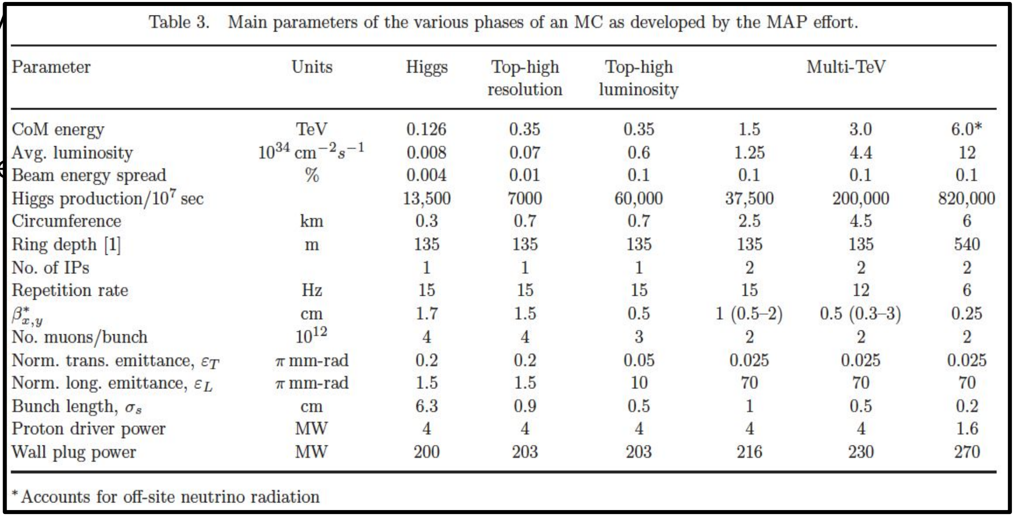

Table 3. Main parameters of the various phases of an MC as developed by the MAP effort.

Parameter	Units	Higgs	Top-high resolution	Top-high luminosity	Multi-TeV		
CoM energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. luminosity	10^{34} cm$^{-2}s^{-1}$	0.008	0.07	0.6	1.25	4.4	12
Beam energy spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs production/10^7 sec		13,500	7000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5–2)	0.5 (0.3–3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. trans. emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. long. emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton driver power	MW	4	4	4	4	4	1.6
Wall plug power	MW	200	203	203	216	230	270

*Accounts for off-site neutrino radiation

Muon Collider Parameters developed under MAP