ILC Upgrades based on Advanced Accelerator Technology

Spencer Gessner

Americas Workshop on Linear Colliders

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U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

Introduction

- The ILC project is the fastest route to a Higgs Factory. It can be upgraded to 1 TeV CM energy with existing SRF technology.
- New ideas for upgrades to 3 TeV CM energy have been proposed based on SRF technology. See for example Snowmass LOI 75.
- There is global interest in lepton collisions at even higher energies.
- This talk: **A path to upgrade the ILC to 3-14 TeV CM energy.**

ILC Facility

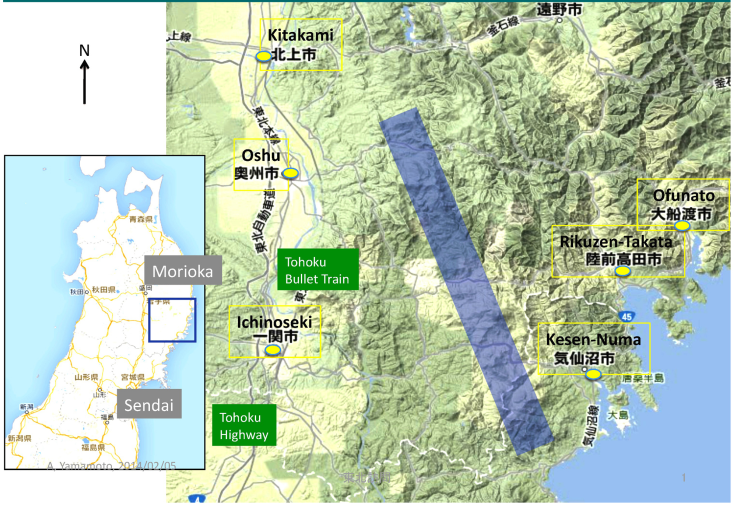
The ILC represents a huge opportunity for particle physics.

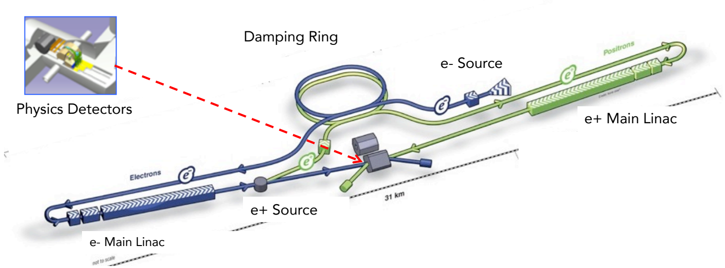
In the near-term: a Higgs Factory followed by operation at 500 GeV and 1 TeV.

In the long-term:

- How can we achieve 14 TeV CM energy with a 40-50 km long tunnel?
- How can we achieve ultra-high luminosities with 300-600 MW site power?

ILC Candidate site in Kitakami, Tohoku





Advanced Accelerator Technologies

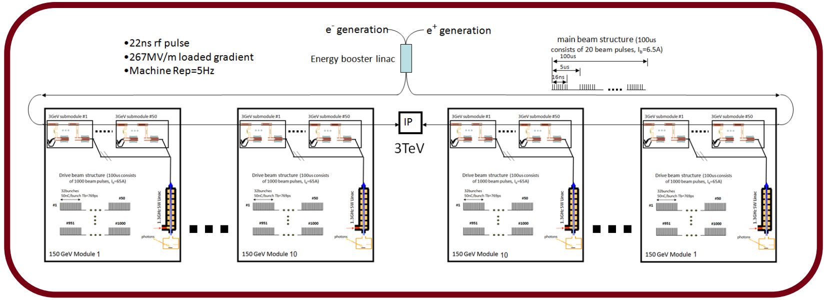
Advanced Accelerator research explores *high-gradient* acceleration (>1 GV/m). Several technologies are being studied:

- Beam-driven wakefield structures.
- Laser-driven dielectric accelerators.
- Laser-driven plasma accelerators.
- Beam-driven plasma accelerators.

For a high-level overview, see the DOE Advanced Accelerator Roadmap and the ICFA ALEGRO summary document.

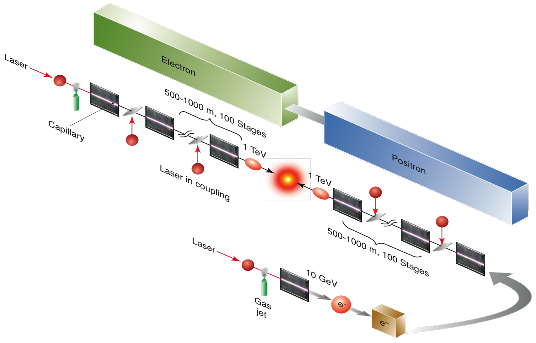
This talk focuses on beam-driven plasma acceleration with drive beams from an SRF linac.

Snowmass LoI on Structure-Based Wakefield Linear Collider



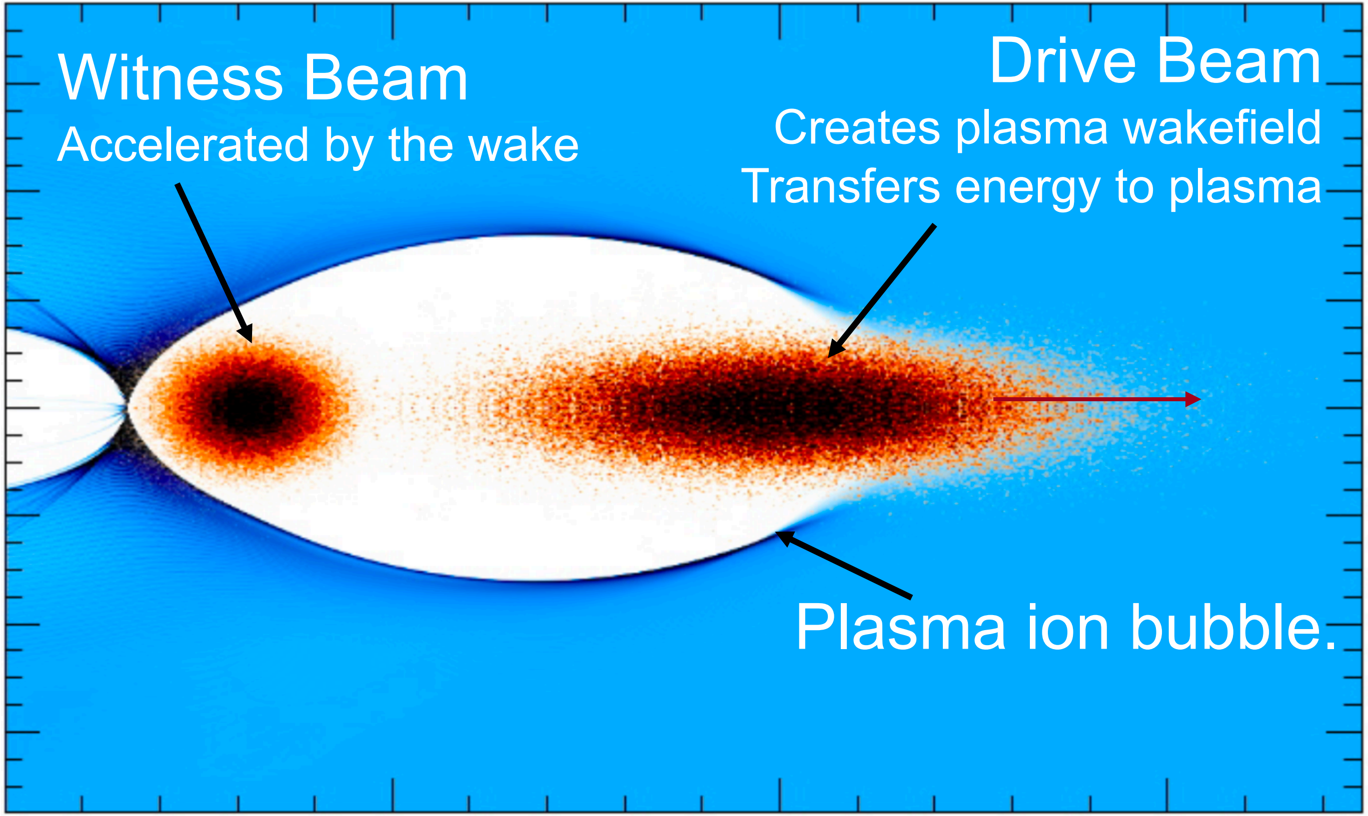
Contact: John Power JP@anl.gov

Snowmass LoI on Laser-Driven Plasma Collider



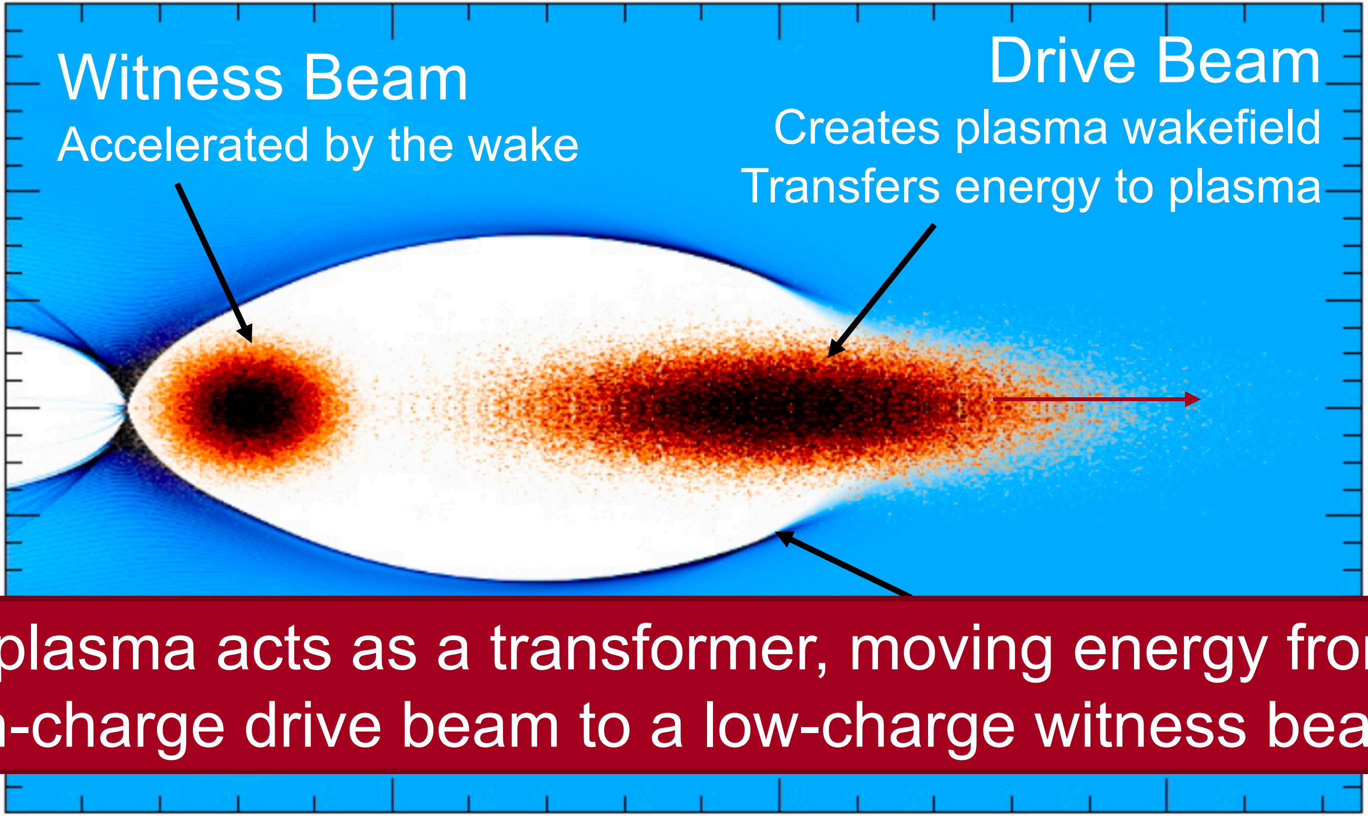
Contact: Carl Schroeder cbschroeder@lbl.gov

Plasma Wakefield Acceleration



QuickPIC Simulation W. An. UCLA

Plasma Wakefield Acceleration



The plasma acts as a transformer, moving energy from a high-charge drive beam to a low-charge witness beam.

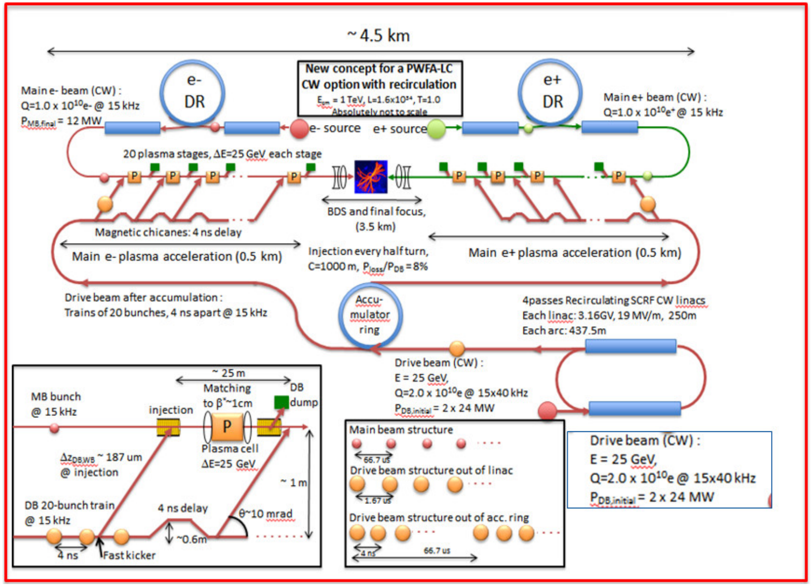
QuickPIC Simulation W. An. UCLA

A Plasma-Based Linear Collider

For Snowmass 2013, we put together a white paper on a beam-driven plasma linear collider (PLC).

The drive beams are generated by a CW SRF linac to maximize efficiency.

Many assumptions went into this design. We've learned a lot since then!



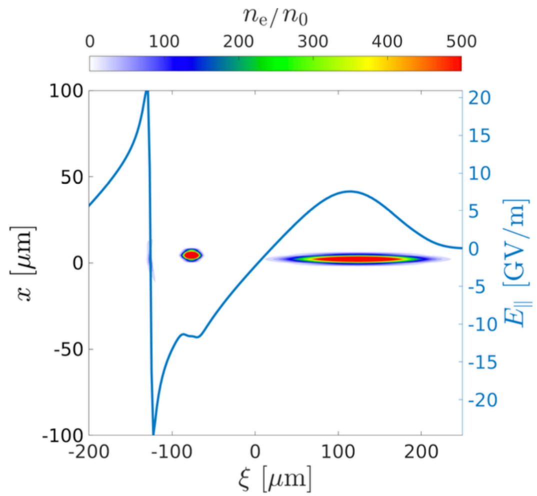
E. Adli, J.P. Delahaye, S.J. Gessner, M.J. Hogan, T. Raubenheimer, W. An, C. Joshi, W. Mori
[arXiv:1308.1145 [physics.acc-ph]]

Beam Stability in Plasma

In order to deliver high-quality beams for collisions, the beam emittance must be preserved throughout the linac.

In 2017, a group from Fermilab noted that there is a trade off between efficiency and stability in the plasma (Lebedev et al. PRAB 2017).

Plasma acceleration must be stable *and* efficient in order to achieve high luminosities with reasonable power consumption.



Stable configuration with a 5 micron-long witness bunch

J.B.B. Chen, D. Schulte, E. Adli, J. Phys.: Conf. Ser. (2020)

These considerations have been included in new theoretical and computational work on PLCs. The results are promising (Chen, Schulte, Adli arXiv:2009.13672)!

Design Concepts Based on the ILC

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How can we utilize the ILC infrastructure and accelerator in the design of a PLC?

Some ideas:

1. Energy doubling with plasma “afterburner”.
2. Multi-linac high transformer ratio acceleration.
3. A separate drive beam complex.

Plasma Afterburner

"Just" add plasma to the end of the accelerator!

Pros:
- Conceptually simple.
- Uses existing SRF linac as is.

Cons:
- Accelerating a high-charge drive bunch and low-charge witness bunch will produce large wakefields in the SRF linac.
- The inter-pulse bunch spacing is tight (500 ns).
- Limited to energy doubling?

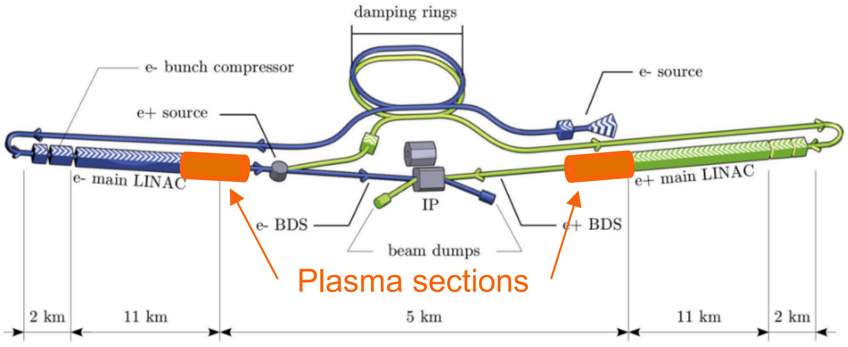


Figure: ILC 500 GeV layout with dimensions (not to scale)

For some considerations on the plasma afterburner, see for example T. Raubenheimer, AIP Conf. Proc. 2004.

Multi-Linac Driver

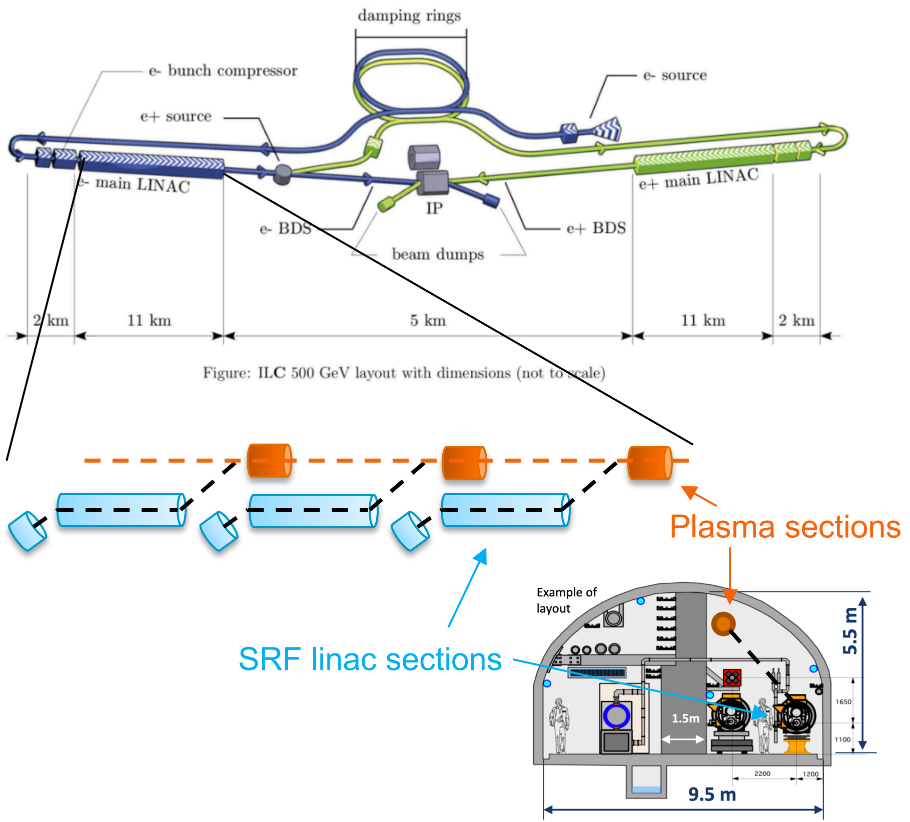
Use the existing linac but split it in pieces.

Pros:

- Uses existing linac "in-situ".
- Achieves energy multiplication through use of high-transformer ratio acceleration (linac sections are optimized for high-charge, shaped drive beams).

Cons:

- Space is at a premium!
- Need to convert SRF cavities to CW.



Separate Drive Beam Complex

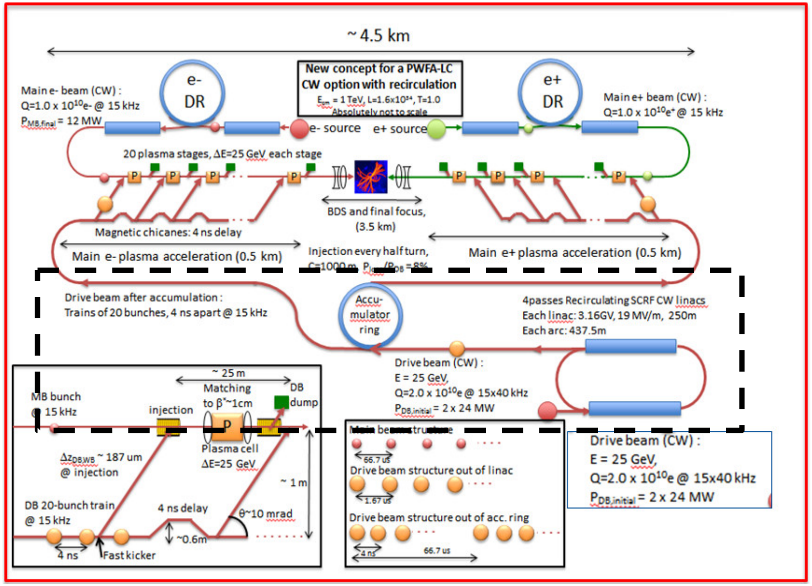
Use existing ILC tunnel for main beam, but SRF is used in separate drive beam complex.

Pros:

- Achieves highest possible energies through bunch multiplication (each main bunch accelerated by N drive bunches).

Cons:

- Requires significant civil engineering.



Maximizing Luminosity

The key figure-of-merit is luminosity per input power.

For reference:

- ILC at 1 TeV and 5×10^{34} cm^{-2} s^{-1} uses 300 MW.
- CLIC at 3 TeV and 6×10^{34} cm^{-2} s^{-1} uses 590 MW.
- San Francisco uses 640 MW.
- Goal: 14 TeV and 40×10^{34} cm^{-2} s^{-1}

Advanced Accelerators have a secret weapon: short bunches!

$$\mathcal{L} = \frac{0.30 H_D}{4\pi\alpha^2} \sqrt{\frac{\gamma}{r_e \sigma_z}} \frac{n_\gamma^{3/2}}{\sigma_y} \frac{\eta P_{AC}}{\mathcal{E}_b}$$

Reduce σ_z from 300 μm to 3 μm.

Caveat: Requires significant re-thinking of BDS. See for example AWLC talk by G. White.

Challenges to be solved

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Among the many challenges we need to tackle are:

- High-efficiency, high-quality acceleration in a single stage.
- Coupling between plasma stages.
- Positron acceleration in plasma.
- High repetition-rate plasma acceleration.
- Beam Delivery and Machine Interface considerations.

FACET

FLASHForward

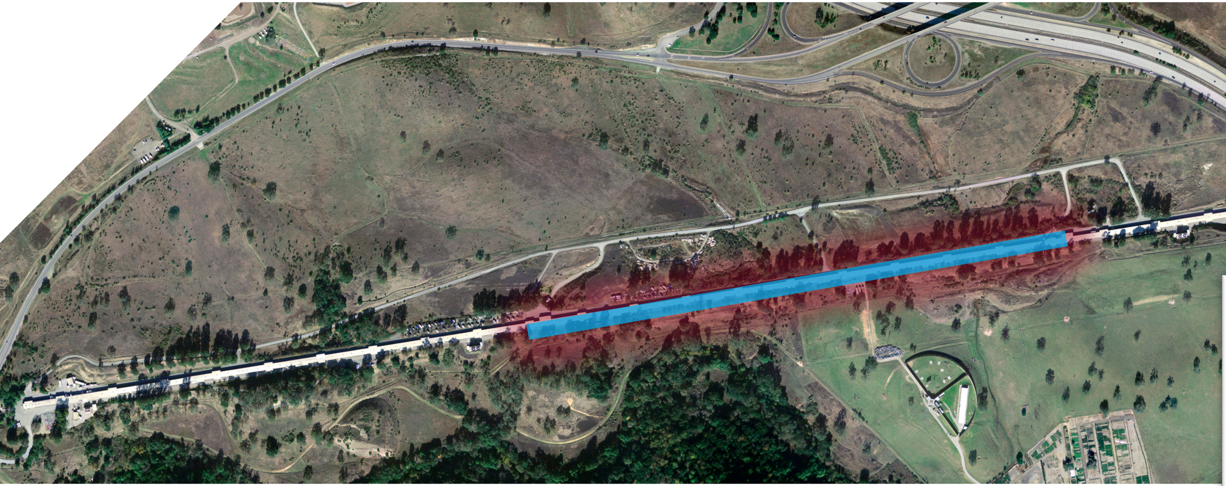
We are poised to begin a new series of experiments at FACET-II at SLAC where we will address many of these issues.

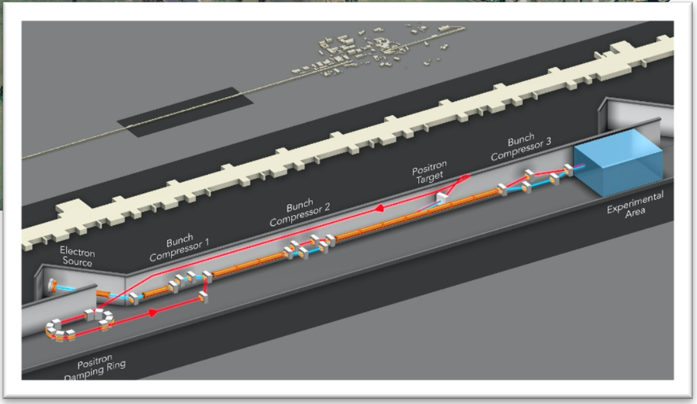
FACET-II

SLAC

FACET·II

Facility for Advanced Accelerator Experimental Tests





For information on upcoming experiments at FACET-II, check out our workshop next week.

The Next Steps

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As part of the Snowmass process, we submitted a proposal that calls for an *Integrated Design Study* of a PLC.

The IDS will dive into the details of what a PLC could look like.

- We will consider the ILC layout and infrastructure as a framework for the IDS.
- We need input from the SRF community on how to optimize drive beam acceleration in SRF cavities to achieve maximum efficiency.

We must also pursue the next generation of test facilities that will allow us to study issues relevant to PLC collider design such as inter-stage coupling and high-repetition rate operation.

Conclusions

The ILC is a tremendous opportunity for particle physics.

The Advanced Accelerator community is committed to finding solutions for ultra-high energy linear colliders. There is significant engagement on this topic in the Snowmass AF6 Working Group.

We are addressing many of the known challenges in upcoming and ongoing experiments at facilities including FACET-II at SLAC and FlashForward at DESY, but we also need to pursue next-gen facilities.

If you build it. . .

. . . we will find a way to the highest possible energies!

Backup

Figures-of-Merit

	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.

Strategy for Advanced Accelerators

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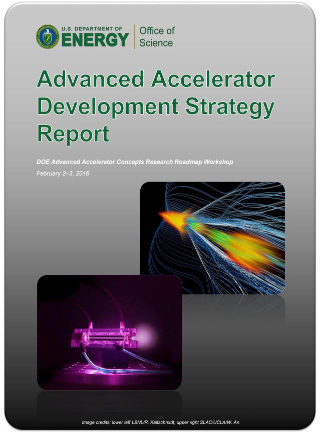
In 2016, the DOE held the Advanced Accelerator Concepts Research Roadmap Workshop which produced plans for the development of AAC technologies for linear collider applications.

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.



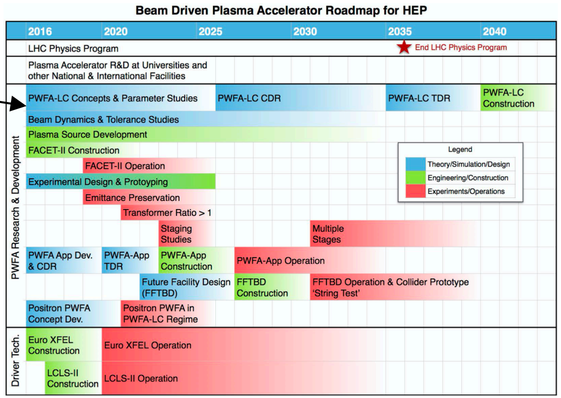


Figure 4: High level R&D roadmap for particle beam driven plasma accelerators.

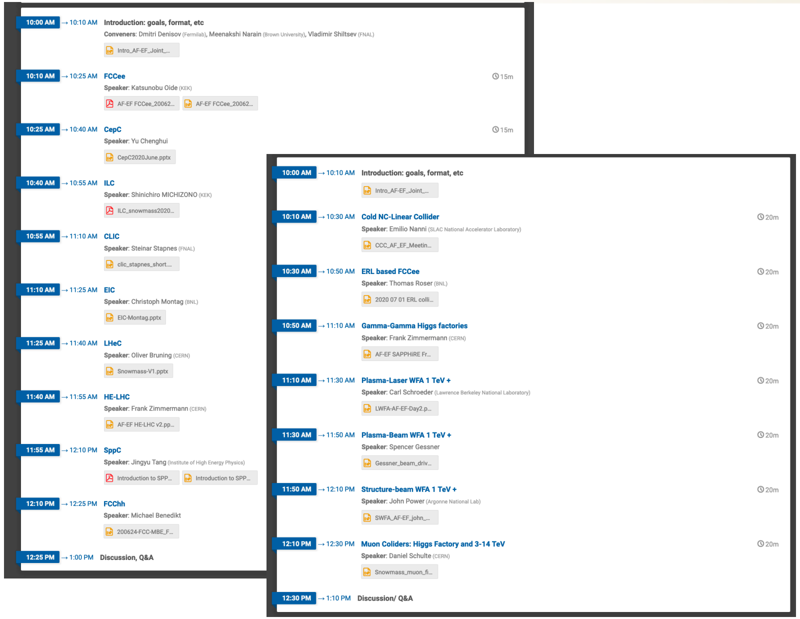
Comparison at 3 TeV

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

	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

Snowmass Discussions on Future Colliders



10:00 AM → 10:10 AM Introduction: goals, format, etc
Conveners: Dmitri Denisov (Fermilab), Meenakshi Narain (Brown University), Vladimir Shiltsev (FNAL)
Intro_AF-EF_Joint_...

10:10 AM → 10:25 AM FCCee 15m
Speaker: Katsunobu Oide (KEK)
AF-EF FCCee_20062... AF-EF FCCee_20062...

10:25 AM → 10:40 AM CepC 15m
Speaker: Yu Chenghui
CepC2020June.pptx

10:40 AM → 10:55 AM ILC
Speaker: Shinichiro MICHIZONO (KEK)
ILC_snowmass2020...

10:55 AM → 11:10 AM CLIC
Speaker: Steinar Stapnes (FNAL)
clic_stapnes_short...

11:10 AM → 11:25 AM EIC
Speaker: Christoph Montag (BNL)
EIC-Montag.pptx

11:25 AM → 11:40 AM LHeC
Speaker: Oliver Bruning (CERN)
Snowmass-V1.pptx

11:40 AM → 11:55 AM HE-LHC
Speaker: Frank Zimmermann (CERN)
AF-EF HE-LHC v2.pp...

11:55 AM → 12:10 PM SppC
Speaker: Jingyu Tang (Institute of High Energy Physics)
Introduction to SPP... Introduction to SPP...

12:10 PM → 12:25 PM FCChh
Speaker: Michael Benedikt
200624-FCC-MBE_F...

12:25 PM → 1:00 PM Discussion, Q&A

10:00 AM → 10:10 AM Introduction: goals, format, etc
Intro_AF-EF_Joint_...

10:10 AM → 10:30 AM Cold NC-Linear Collider 20m
Speaker: Emilio Nanni (SLAC National Accelerator Laboratory)
CCC_AF_EF_Meetin...

10:30 AM → 10:50 AM ERL based FCCee 20m
Speaker: Thomas Roser (BNL)
2020 07 01 ERL colli...

10:50 AM → 11:10 AM Gamma-Gamma Higgs factories 20m
Speaker: Frank Zimmermann (CERN)
AF-EF SAPPHIRE Fr...

11:10 AM → 11:30 AM Plasma-Laser WFA 1 TeV + 20m
Speaker: Carl Schroeder (Lawrence Berkeley National Laboratory)
LWFA-AF-EF-Day2.p...

11:30 AM → 11:50 AM Plasma-Beam WFA 1 TeV + 20m
Speaker: Spencer Gessner
Gessner_beam_driv...

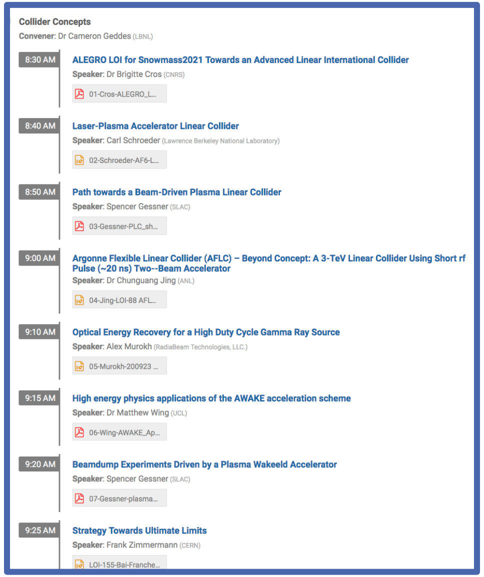
11:50 AM → 12:10 PM Structure-beam WFA 1 TeV + 20m
Speaker: John Power (Argonne National Lab)
SWFA_AF-EF_john_...

12:10 PM → 12:30 PM Muon Colliders: Higgs Factory and 3-14 TeV 20m
Speaker: Daniel Schulte (CERN)
Snowmass_muon_fi...

12:30 PM → 1:10 PM Discussion/ Q&A

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

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



Collider Concepts
Convener: Dr Cameron Geddes (LBNL)

8:30 AM ALEGRO LOI for Snowmass2021 Towards an Advanced Linear International Collider
Speaker: Dr Brigitte Cros (CNRS)
01-Cros-ALEGRO_L...

8:40 AM Laser-Plasma Accelerator Linear Collider
Speaker: Carl Schroeder (Lawrence Berkeley National Laboratory)
02-Schroeder-AF6-L...

8:50 AM Path towards a Beam-Driven Plasma Linear Collider
Speaker: Spencer Gessner (SLAC)
03-Gessner-PLC_sh...

9:00 AM Argonne Flexible Linear Collider (AFLC) – Beyond Concept: A 3-TeV Linear Collider Using Short rf Pulse (~20 ns) Two--Beam Accelerator
Speaker: Dr Chunguang Jing (ANL)
04-Jing-LOI-88 AFL...

9:10 AM Optical Energy Recovery for a High Duty Cycle Gamma Ray Source
Speaker: Alex Murokh (RadiaBeam Technologies, LLC.)
05-Murokh-200923 ...

9:15 AM High energy physics applications of the AWAKE acceleration scheme
Speaker: Dr Matthew Wing (UCL)
06-Wing-AWAKE_Ap...

9:20 AM Beamdump Experiments Driven by a Plasma Wakeeld Accelerator
Speaker: Spencer Gessner (SLAC)
07-Gessner-plasma...

9:25 AM Strategy Towards Ultimate Limits
Speaker: Frank Zimmermann (CERN)
LOI-155-Bai-Franche...

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

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