Summary of the Snowmass Agora on linear e^+e^- colliders

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Energy Frontier Workshop, March 28 – April 1, 2022

Event outline

- The event was held on December 15, 2021: https://indico.fnal.gov/event/52161/overview
- Organized by the Accelerator and Energy Frontiers, co-conveners: S. Belomestnykh and D. Denisov
- Four main talks: a Physics talk by Tao Han and three talks on the most advanced linear collider proposals: International Linear Collider (ILC, by Hasan Padamsee), Compact LInear Collider (CLIC, by Steinar Stapnes), and Cold Copper Collider (C^3, by Emilio Nanni)
- Speakers were asked to focus on Higgs Factory option (COM energy of $\gtrsim 250$ GeV) and briefly address challenges and possible energy and luminosity upgrades
- There was a Q&A session at the end

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Table of parameters (Higgs Factory)

Parameter	ILC	CLIC	C^3
COM energy (GeV)	250	380	250
Peak luminosity (10^{34} $cm^{-2}s^{-1}$)	1.35	1.5	1.3
Polarization e^- / e^+ (%)	80 / 30	80 / 0	80 / 0
Repetition rate (Hz)	5	50	120
Bunch spacing (ns)	554	0.5	5.26
Bunch train duration (μs)	727	0.176	0.7
Particles per bunch (10^{10})	2	0.52	0.63
IP beam size H / V, rms (μm)	0.52 / 0.0077	0.15 / 0.003	0.23 / 0.004
Full crossing angle (mrad)	14	20	14
Acceleration technology	SRF	Two-beam, NC RF	Cold NC RF
RF frequency (GHz)	1.300	11.994	5.712
Accelerating gradient (MV/m)	31.5	72	70
Site power (MW)	111	168	~150
Facility length (km)	20.5	11.4	8

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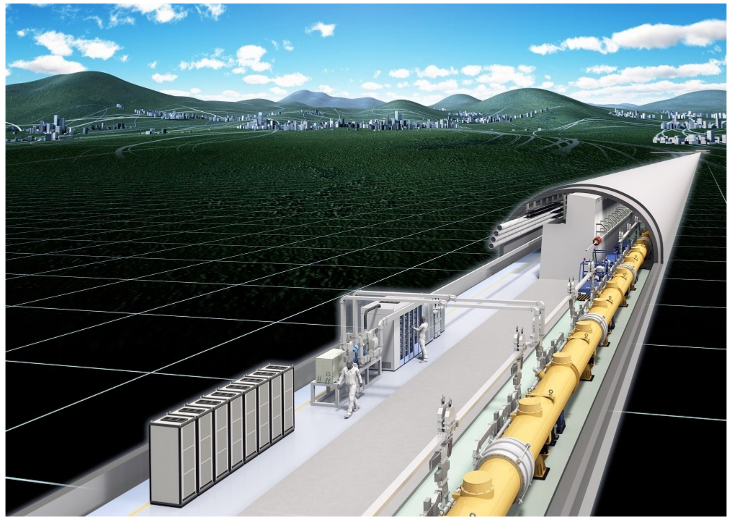
Advantages and challenges: ILC

ILC, http://arxiv.org/abs/2203.07622

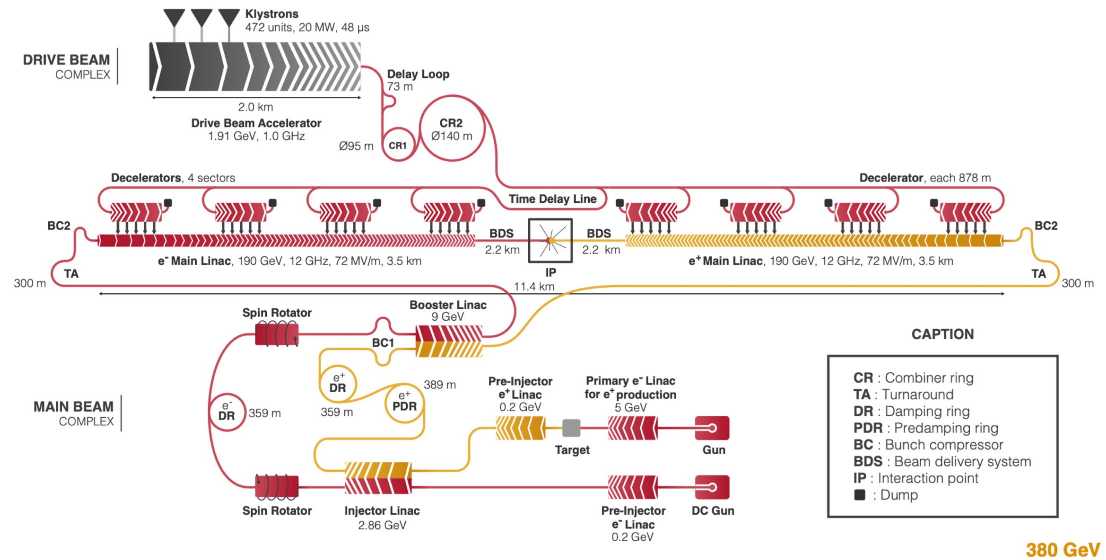
- Advantages
  - "Shovel ready" proposal, can be started as soon as decision to proceed is made. TDR was published in 2013, updated for ILC250 recently
  - Proven SRF technology (European XFEL is ~10% prototype demonstration of the core technology, unprecedented)
  - Power efficient (relative to other proposals)
  - Relaxed tolerances due to larger aperture of accelerating structures
  - Larger vertical beam size at IP
  - RF pulse length and bunch separation (727 μs and 554 ns) are large enough to allow corrections between pulses as well as within a bunch train (intra-train feedback)
  - Luminosity upgrades to 5.4×10^{34} $cm^{-2}s^{-1}$ by doubling the number of bunches and rep. rate
  - Energy upgrade to 500 GeV is part of the TDR, further upgrades possible with advances in SRF technology or with alternative technologies
  - Polarized e^+
- Challenges
  - Longer tunnel due to lower accelerating gradient
  - Need R&D to increase SRF gradient for energy upgrades beyond 500 GeV



Advantages and challenges : CLIC

CLIC, https://arxiv.org/abs/2203.09186

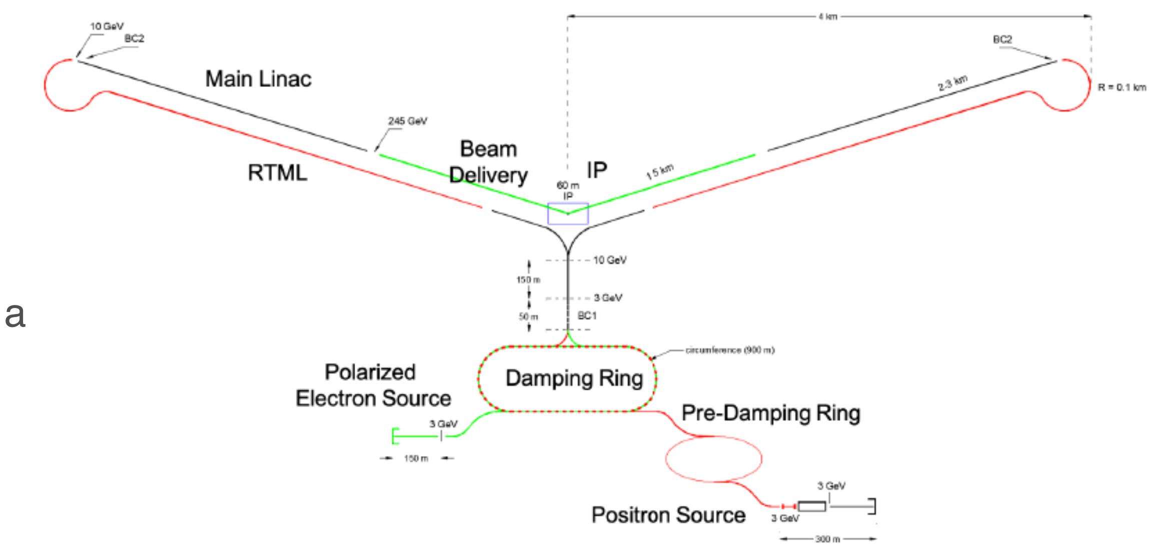
- Advantages
  - Shorter tunnel than ILC
  - Staged program with relatively straightforward energy upgrades up to 3 TeV (with an increase of gradient to 110 MV/m
  - Mature accelerator studies, existing test facility CTF3/CLEAR, two-beam acceleration technology was demonstrated at CTF3
  - Post-CDR (2012) level of readiness
  - Long-standing R&D efforts. Swiss FEL was built with similar structures (but C-band, not X-band), powered by klystrons
  - Potential luminosity upgrade from doubling the rep. rate
- Challenges
  - Less power efficient than ILC
  - An alternative klystron-driven option is more expensive and would require 10 time more klystrons
  - Alignment/stability might be a challenge
  - No polarized e^+



Advantages and challenges : C^3

C^3, https://arxiv.org/abs/2110.15800

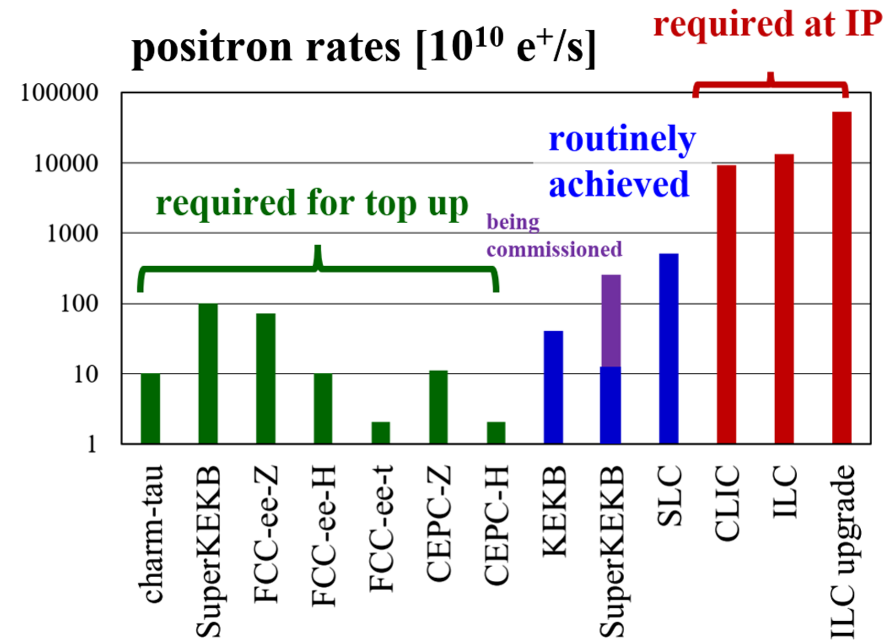
- Advantages
  - More compact than ILC
  - Straightforward energy upgrade to 550 GeV within the same footprint (with an increase of gradient to 120 MV/m)
  - Cold copper technology is promising and robust operation up to 120 MV/m is expected
  - Can fit on a national lab site
- Challenges
  - Pre-CDR
  - Less power efficient than ILC
  - Further R&D in several areas is necessary, should culminate with a demonstration facility
  - Need to develop a damped/detuned structure
  - Alignment/stability might be a challenge
  - No polarized e^+
  - Energy upgrade would require developing new RF sources and/or pulse compression scheme



Common challenges

Common challenges for the three collider proposals

- **Positron production**: All three linear colliders will need an unprecedented rate of positron production to reach their luminosities. While the solutions are proposed and being worked on, it is a big challenge.
- **Klystron efficiency**:
  - RF systems are key cost and efficiency drivers for linear colliders. Improving efficiency of klystrons (from L-band to X-band) will reduce the overall site power. While simpler designs followed up by industrialization would be beneficial to reduce the overall cost.
  - An example: Techniques for maximizing klystron efficiency, such as the Core Oscillation Method (COM), were explored in depth through the High Efficiency International Klystron Activity (HEIKA), yielding klystron efficiencies up to 80% at X-band.



from V. Shiltsev and F. Zimmermann, “Modern and future colliders,” *Rev. Mod. Phys.* **93** (2021)

Other proposals

Three more, early-stage, proposals were submitted to Snowmass. While they weren't presented at the Agora, I would like briefly mention them here for completeness.

- Higgs-Energy LEptoN (**HELEN**) Collider based on advanced SRF technology, https://arxiv.org/abs/2203.08211

Two ERL-based linear collider proposals:

- **ReLiC**: Recycling Linear e^+e^- Collider, https://arxiv.org/abs/2203.06476
- **ERLC**: A high-luminosity superconducting twin e^+e^- linear collider with energy recovery, https://arxiv.org/abs/2105.11015 (don't think it was submitted to Snowmass though)

Summary

- Three linear e^+e^- colliders were presented at the Snowmass Agora event on Dec. 15, 2021
- All machines propose similar luminosities at Higgs energy
- They are at different stages of development: from TDR ("shovel-ready") for ILC to post-CDR for CLIC to pre-CDR for C^3
- The machines have advantages and challenges, which we discussed briefly
- Two main common challenges are: positron production rate and klystron efficiency/cost
- R&D should continue to bring the proposals to the TDR level (CLIC and C^3) or address remaining challenges

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Thank you!