C^3: An Advanced Concept for a High Energy e^+e^- Linear Collider

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Introduction

Electron-positron linear colliders could provide a path to 'clean' physics at the TeV-scale. The world-wide community has made significant investments in developing designs, demonstrating the acceleration systems, and the ancillary systems such as particle sources, damping rings, and final foci. However, the cost of these facilities is large, which has prevented the construction of a next generation facility. We have begun an study of an alternative accelerator structure with beam characteristics suitable for a TeV collider, the Cool Copper Collider (C^3),[1] with the goal of significantly reducing capital and operating costs. This study focuses on a new normal conducting radio frequency (NCRF) structure with internal manifolds distributing the RF to each cell, eliminating the need to transmit RF power through the cavity irises permitting the entire structure to be designed for high shunt impedance and low breakdown.[2] In addition, the structure will be cooled to ~80 K in liquid nitrogen (LN), increasing the shunt impedance by ~2.5-3X and reducing the breakdown rate.[3,4] The optimal gradient and length for a NCRF linac depends directly on the cost of RF power, usually characterized by cost per peak RF kilowatt, which includes the modulator, RF source and RF distribution. DOE-HEP funds a General Accelerator R&D (GARD) program, which has produced a decadal roadmap that includes a cost goal of $2/peak kW[5] and this cost was *assumed* in this concept.

To guide the design, we scale the accelerator requirements for luminosity and beam power from the existing established CLIC CDR[6] and ILC TDR.[7] Table 1 shows the main parameters for a 2 TeV center of mass linac. For lower energy designs, the beam power would scale roughly linearly, with modifications below 300 GeV to maintain a linear luminosity scaling with energy. As part of the Snowmass process we intend to further explore this accelerator concept and understand the requirements for e^+e^- sources, damping rings, and beam delivery systems. We will also explore power consumption and system efficiency targeting an overall *main linac's* power consumption of <200 MW. This study will include the latest advances in RF sources and the performance of prototype accelerating structures.

Optimization

The primary obstacle to building any next-generation e^+e^- collider appears to be the cost. The approach of this proposal is therefore to seek the minimum for both capital and operating costs.

Table 1: Parameters for the main linac.

Parameter	Units	Value
Center of Mass Energy	TeV	2
Single Beam Power	MW	9
Train Repetition Rate	Hz	120
Bunch Charge	nC	1
RF Pulse Length	ns	250
Bunch Spacing	Periods (ns)	19 (3.3)
Average Current	μA	9
Peak Current	A	0.3
Luminosity	$\times 10^{34}$ cm^{-2}s^{-1}	4.5
Operating Temp	K	80
Loaded Accelerating Gradient	MV/m	117
Filling Factor per Module	%	90
Single Linac Length	km	9.5
Cavity Fundamental	GHz	5.712
Shunt Impedance	MΩ/m	298
a/λ		0.05

RF to Beam Efficiency	%	42
RF Source Cost	$/peak kW	2
Structure Cost	k$/m	100
RF Compressors	k$/m	15
Tunnel Cost	k$/m	50

For an NCRF machine, the dominant capital cost is the RF sources. In practice, an NCRF collider operates with a low duty cycle where the cost of RF sources is driven by the peak power that the RF system must deliver to the linac. RF sources optimized for short pulse and low duty cycle operation can have significantly simplified cooling systems. Other potential simplifications in the design can, for example, reduce susceptibility to oscillations in the RF source. The GARD RF decadal roadmap specifically lays out these requirements. In particular, it calls for a dramatic improvement in the cost of low duty cycle RF sources (in $/peak kW). The GARD RF power goal is a cost of $2/peak kW encompassing the full system including the modulator and high-power amplifier. Achieving reduced RF source cost and increasing the efficiency of RF power consumption by accelerators must be a central research theme for the practical implementation of this technology.

The impact of the pulse format on the capital and operating costs is also considered. The repetition rate is kept low at 120 Hz to simplify the cooling of detector instrumentation and to simplify the damping ring. Beam loading has also been optimized to reduce the operational cost of the accelerator, trading increased peak power requirements for higher electrical efficiency and reduced cooling capacity.

Summary

We are exploring a new concept for high gradient, high power linacs designed for an e^+e^- linear collider in the TeV class. The linac design is based on two features: an accelerator structure with a separate feed to each cavity permitting the iris to be optimized for gradient and breakdown; and a structure that operates in LN, causing the Cu (or Cu alloy) conductivity to increase and reduce the RF power requirements by ~2.5-3X. An initial analysis of both short-range and long-range wakefields has been used in the optimization. The detailed solution requires further design of the structure and the RF distribution for damping and detuning. The optimal gradient for a cost-optimized collider depends strongly on the cost of RF power, and we assume the value from the DOE GARD decadal roadmap of $2/peak kW. This RF cost has not yet been demonstrated, but progress is being made on both klystrons and modulators, as will be reported elsewhere. If the DOE-HEP GARD goal for RF power of $2/peak kW could be achieved, the linac cost, including tunnels and utilities but not ancillary systems (e^+e^- sources, damping rings, beam delivery, IP, etc.) would be about $3.2M/GeV, which is significantly less per GeV than other designs. This concept for the Cool Copper Collider is a potential breakthrough for the High Energy Physics community in exploring e^+e^- physics, that could mature rapidly with demonstration of modular units and leverage the significant investment and effort for other systems in the accelerator complex (e.g. final focus, injector, and damping rings).

Acknowledgements

This work was supported by the Department of Energy under contract DE-AC02-76SF00515 and the U.S.-Japan Science and Technology Cooperation Program under contract DE-AC02-76SF00515.

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[6] CLIC values are from Updated Baseline for a Staged Compact Linear Collider https://arxiv.org/abs/1608.07537 Table 9.

[7] ILC values are from The International Linear Collider Machine Staging Report 2017, https://arxiv.org/abs/1711.00568 Table 5.1;