Status of C³ R&D

The Higgs Boson at Future Colliders

web.slac.stanford.edu/c3/

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LCWS2024 International Workshop on Future Linear Colliders

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT OF ENERGY

Lots of updates!

Over the last year, significant progress in various areas and many talks at LCWS24!

- **Gradient** – Scaling up to meter scale cryogenic tests (Emilio, Dennis)
- **Vibrations** – Measurements with full thermal load (Ankur)
- **Alignment** – Working towards raft prototype (Harry)
- **Damping** – Materials, design and simulation (Wei-Hou, Shumail, Zhengai)
- **Scalability** – Cryomodules and integration (Andy)
- **LLRF Control** with RF System on Chip (Ankur)

Parameter	Symbol [unit]	C^3-250 (PS1)	C^3-250 (PS
Center-of-mass Energy	$\sqrt{s_0}$ [GeV]	250	
RMS bunch length	σ_z^* [µm]	100	
Horizontal beta function at IP	β_x^* [mm]	12	
Vertical beta function at IP	β_y^* [mm]	0.12	
Normalized horizontal emittance at IP	ϵ_x^* [nm]	900	1000
Normalized vertical emittance at IP	ϵ_y^* [nm]	20	12
RMS horizontal beam size at IP	σ_x^* [nm]	210	221
RMS vertical beam size at IP	σ_y^* [nm]	3.1	2.4
Vertical waist shift	w_y [µm]	0	80
Geometric Luminosity	$\mathscr{L}_{\text{geom}}$ [10^{34} cm^{-2} s^{-1}]	0.75	0.92
Horizontal Disruption	D_x	0.32	0.29
Vertical Disruption	D_y	21.5	26.5
Average Beamstrahlung Parameter	$\langle\Upsilon\rangle$	0.065	0.062
Total Luminosity	$\mathscr{L}$ [10^{34} cm^{-2} s^{-1}]	1.35	1.90
Peak luminosity fraction	$\mathscr{L}_{0.01}/\mathscr{L}$ [%]	73	74
Enhancement Factor	H_D	1.8	2.1
Average Energy loss	δ_E [%]	3.3	3.1
Photons per beam particle	n_γ	1.4	1.3
Average Photon Energy fraction	$\langle E_\gamma/E_0\rangle$ [%]	2.5	2.4
Number of incoherent particles/BX	N_{incoh} [10^4]	4.7	5.9
Total energy of incoh. particles/BX	E_{incoh} [TeV]	58	71

Dimitri's talk

B. Bullard's talk on sustainability

BIB in 2nd Dimitris' talk

Lots of updates!

C³ Main Linac
(Wei-Hou Tan, SLAC)

250 GeV beam dynamics studies

Studying the impact of long-range wakefields on the beam emittance due to bunch-to-bunch random jitter

- Mitigation: damping
- Mitigation: detuning

Parameter	Value
Cryocooled temperature	77 K
Length	8 km
Center of mass energy	250 GeV
Number of bunches	133
Charge per bunch	1 nC
Bunch spacing	5.25 ns (30 RF cycles)
Field gradient	70 MV/m

- Valery Dolgashev (SLAC)
"Compact Traveling Wave X-band Linac with RF Power Flow Outside Accelerating Cavities"

Implementation Concept

- Harry Van Der Graaf (Nikhef National institute for subatomic physics)
"The alignment of the modules of the Cool Copper Collider (C^3) with the Rasnik 3-point alignment"
(remote)

Alignment over long distance (> 100 m): RasClic, later RasDif:

- replace lens by zone plate
- replace coded mask by monochromatic spherical-wave light source (1 $ laser diode)

Ongoing C3 R&D project:

the Quarter Cryo Module QCM

Phase 1: dummy AccStructures: testing cooling, mechanics, vibrations

Update on CARIE high gradient photocathode test stand at LANL — Evgenya Simakov — 1320, Science building n.4 (CHANGED) — 11:40 - 12:00

LANL C-band Engineering Research Facility (CERF-NM)

CERF-NM was built with $3M of LANL's internal infrastructure investment.

- Powered with a C-band Canon klystron
- Conditioned to 50 MW
- Frequency 5.712 GHz
- 300 ns – 1 µs pulse length
- Rep rate up to 200 Hz (typical 100 Hz)
- Nominal bandwidth 5.707-5.717 GHz

Various developments for C³ (hardware)

- ✓ Has been developing an C-band test facility
- ✓ To build a HG RF breakdown study facility
- ✓ To build a cryo-cooled photoinjector study facility
- ✓ To conduct material studies
- ✓ To demonstrate high-quantum-efficiency cathodes in a HG RF injector

Hard work and great results - congratulations!

Applications

Distributed Coupling Linac for Efficient Acceleration of High Charge Electron Bunches — Ankur Dhar — 1320, Science building n.4 (CHANGED) — 16:00 - 16:20

Distributed Coupling as applied to Injector Linac Design

Design balances shunt impedance with aperture size

- S-band cavities designed with aperture ratio a/λ=0.135

Better output emittance compared to baseline traveling wave structures with 14 nC bunches

- Emittance calculated for a/λ=0.125 cavities
- Baseline design informed by EIC specs

Linac Properties			
Freq (GHz)	2.856	E_{max}/E_{acc}	2.63
a (mm)	14.12	E_{acc}/Z_0H_{max}	0.995
a/λ	0.135	R_s (MΩ/m)	58
P_{diss} (MW)	5	E_{acc} (MV/m)	18

- ✓ Based on the C3 technology applied to Injector Linac
- ✓ Large Aperture distributed coupled Linac in S-band.
- ✓ The assembly and brazing performed in SLAC.
- ✓ Proposals for testing the structure

Assembly of Injector Linac

Linac formed from two slabs, which are brazed

Y-Coupler is brazed on afterwards to provide even power splitting between each side

Assembly and brazing was done in house at SLAC

Future Test Plans

Summary of RF Breakdown Studies using Single Cell Standing Wave Accelerating Structures — Valery Dolgashev

- ✓ At SLAC, many single cell cavities were tested, more than 50.
- ✓ A lot of data has been accumulated, that is very useful to understand new HGT results.
- ✓ Recently we found hard copper and copper alloy have good HG performance.
- ✓ We will investigate such materials in the near future.

Various developments for C³ (designing)

HOM Detuning and Damping of C-Band Distributed Coupling Structure — Zenghai Li — 1320, Science building n.4 (CHANGED) — 11:00 - 11:20

180 deg/cell Structure HOM Damping with Tapered Lossy Slot – Dongsung Kim

135/cell Structure – Possible Damping Scheme (power feed V1)

A Wakefield Resilient, High Shunt Impedance Accelerating Structure for the Cold Copper Collider — Muhammad Shumail — 1320, Science building n.4 (CHANGED) — 11:20 - 11:40

Cavity (with two different coupler implementations) Parameters Determined Through HFSS® Simulations

Parameters @ 77 K	Cavity Left	Cavity Right
Resonant Frequency, f_0 (GHz)	5.712	5.712
Coupling Coefficient, β	1.8625	1.8634
Reflection Coefficient, Γ	0.3013	0.3015
Shunt Impedance, r_s (MΩ/m)	317.22	317.22
$\eta H_{surf,peak}$ / Gradient	1.14	1.14
Quality Factor, Q_0	30124	30122

Cavity Phases in an Accelerator Made of 135° Phase Advance Cavities

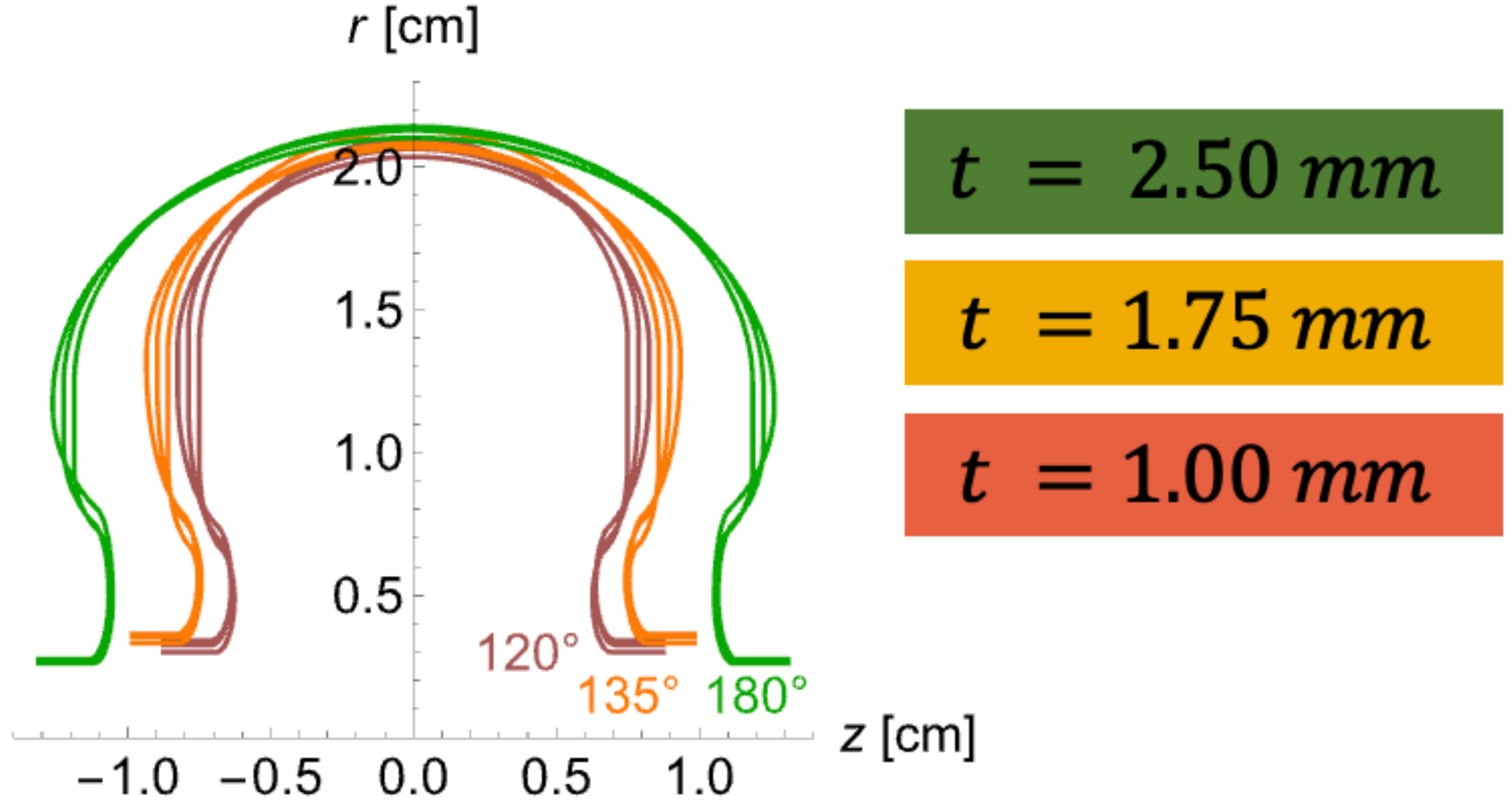
- ✓ New LLRF system is presented based on RFSoC.
- ✓ RFSoC is an Rf system-on-chip technology which integrates all the essential components including programmable logic, and processors
- ✓ RFSoC based LLRF significantly reduces hardware complexity and enables more flexibility in operation
- ✓ They fabricated the LLRF based on RFSoC, and test it on pulse-to-pulse fluctuation, etc.

Pulse-to-pulse Fluctuation with SSA

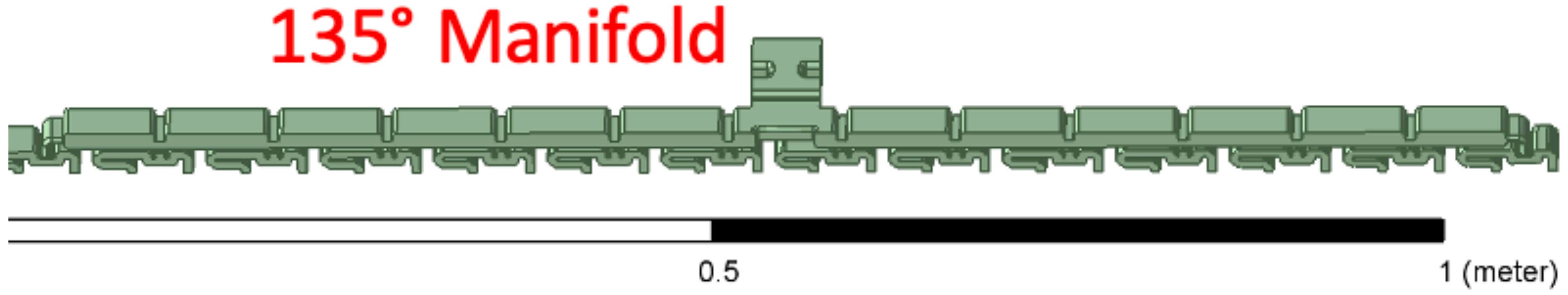
Some changes to review

Cavity Geometry Optimized for Constant Aperture

Structure optimization at 5.712 GHz for phase advance of interest:
180°, 135°, and 120°.



135° Manifold



Disk T=2.5mm	180° (Original)	135°	120°
Aperture radius (a)	$2.624\ mm$	$3.33\ mm$	$3.00\ mm$
Gap width (g)	$21.06\ mm$	$15.00\ mm$	$12.54\ mm$
Quality factor (Q_0)	13,846	11,625	10,624
Shunt impedance (R_s)	$114.2\ M\Omega/m$	$114.1\ M\Omega/m$	$114.1\ M\Omega/m$
max$(E_s/Gradient)$	2.00	2.00	1.98

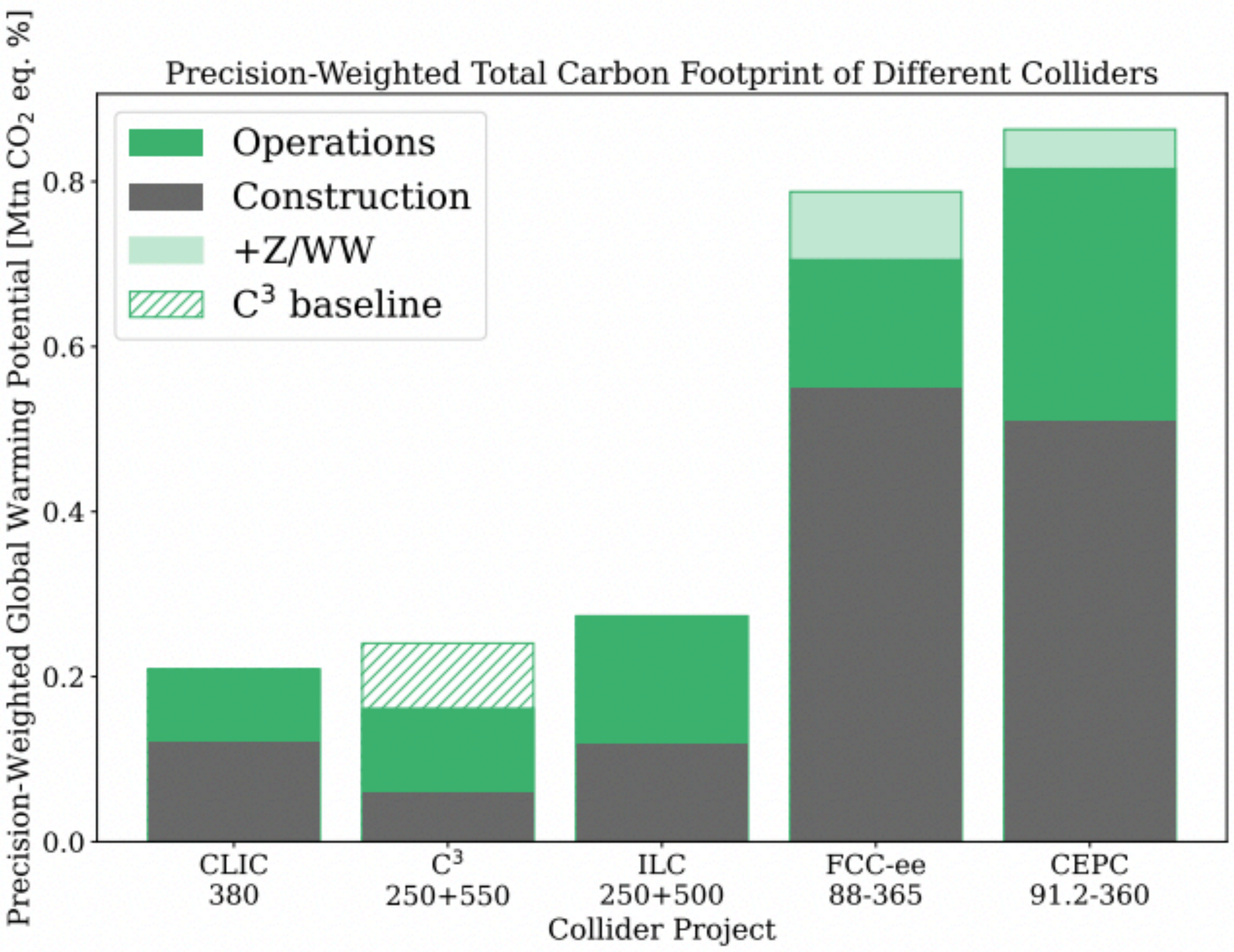
Disk T=1.75	180°	135° (Update)	120°
Aperture radius (a)	$\mathbf{2.74\ mm}$	$\mathbf{3.55\ mm}$	$\mathbf{3.26\ mm}$
Gap width (g)	$21.32\ mm$	$\mathbf{14.84\ mm}$	$12.76\ mm$
Quality factor (Q_0)	13,883	**11,614**	10,773
Shunt impedance (R_s)	$114.3\ M\Omega/m$	$\mathbf{114.1\ M\Omega/m}$	$114.0\ M\Omega/m$
max$(E_s/Gradient)$	2.00	**2.01**	2.00

Disk T=1.0 mm	180°	135°	120°
Aperture radius (a)	$2.75\ mm$	$3.63\ mm$	$3.41\ mm$
Gap width (g)	$21.06\ mm$	$15.10\ mm$	$12.74\ mm$
Quality factor (Q_0)	13,621	11,674	10,795

Trans. Wakefield Dramatically Reduced Scales as a^{-4}

About Sustainability

PRX Energy 2 047001



Main Linac Power

About Sustainability

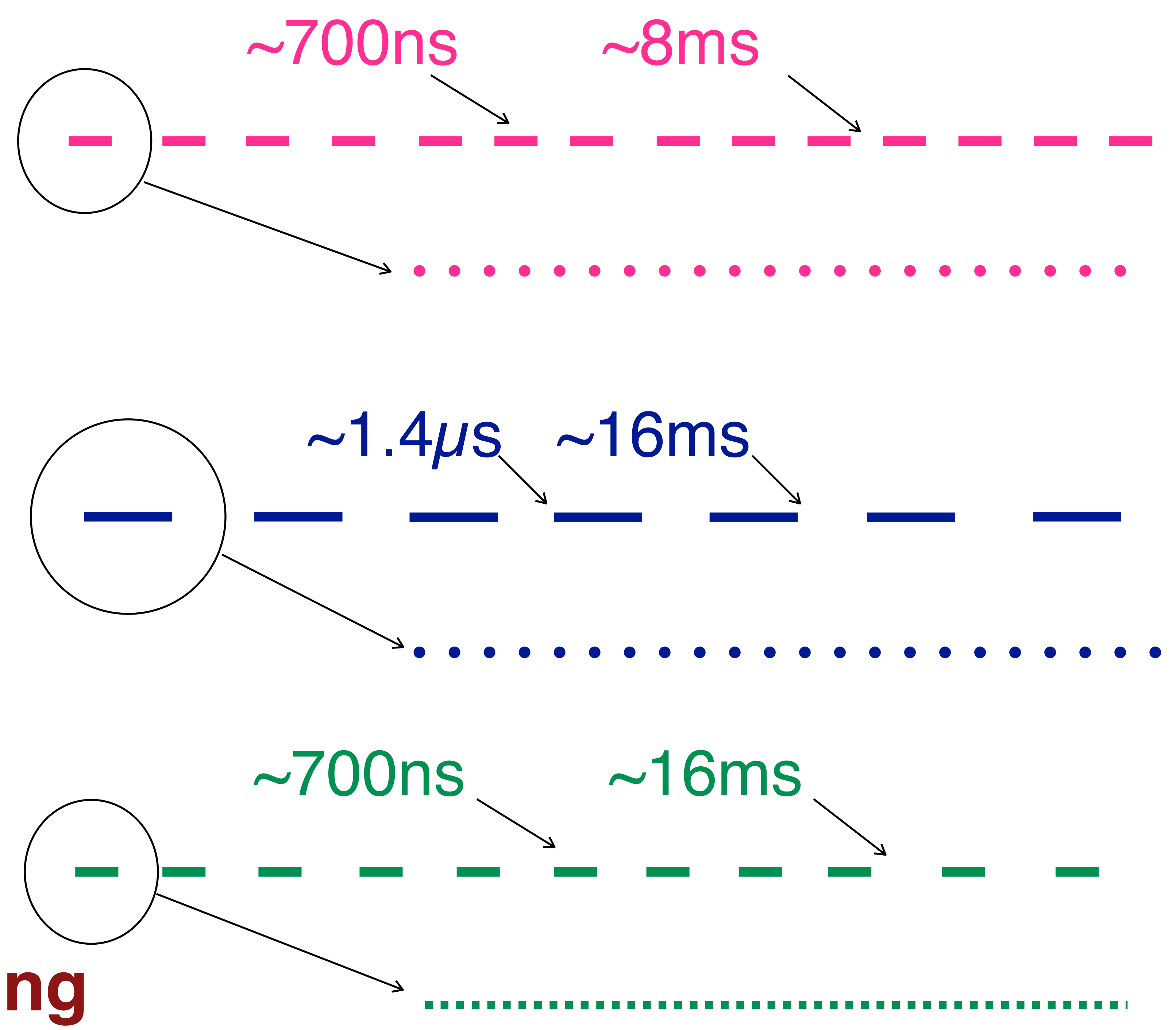
PRX Energy 2 047001

Main Linac Power

Scenario	RF System (MW)	Cryogenics (MW)	Total (MW)	Reduction (MW)
Baseline 250 GeV	40	60	100	-
RF Source Efficiency Increased 15%	31	60	91	9
RF Pulse Compression	28	42	70	30
Double Flat Top	30	45	75	25
Halve Bunch Spacing	34	45	79	21
All Scenarios Combined	13	24	37	63

New “sustainable” parameter set ?

C^3 250 Bunch Format



Baseline

C^3 Trains at 120Hz, 1 train 133 bunches
Bunches are 5 ns apart

Double-flat top

C^3 Trains at 60Hz, 1 train 266 bunches
Bunches are 5 ns apart

Double-flat top
+
Halved bunch spacing

C^3 Trains at 60Hz, 1 train 266 bunches
Bunches are 2.65 ns apart

Constant luminosity

New “sustainable” parameter set ?

scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125