Institut national de
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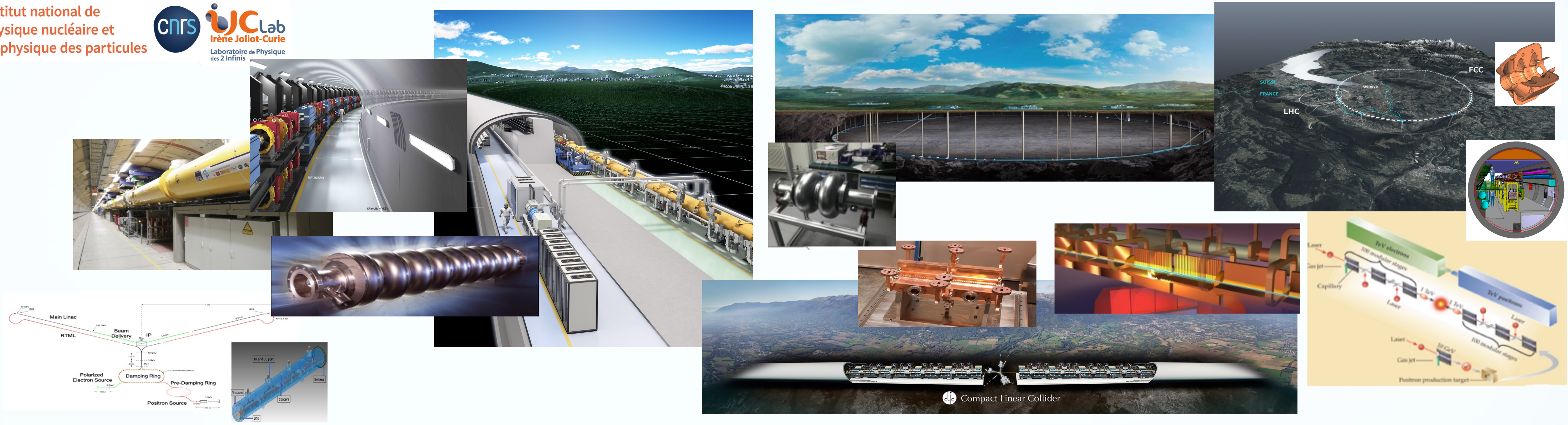
de physique des particules
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis



Future e⁺e⁻ Higgs Facilities

To a Higgs Factory and beyond

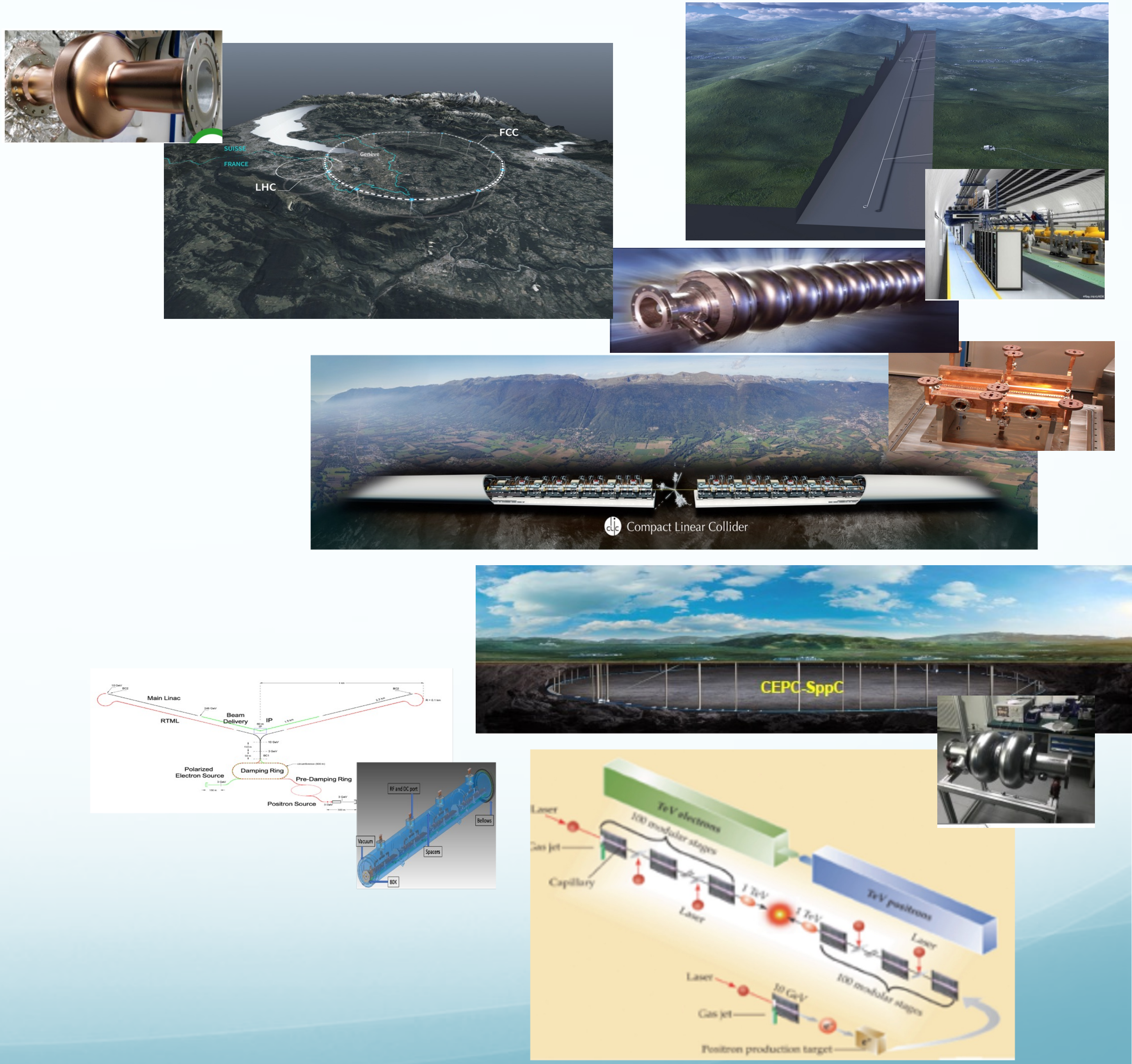
A. Faus-Golfe

IAS PROGRAM
High Energy Physics
February 12 – 16, 2023
Conference: February 14 – 16, 2023

February 2023

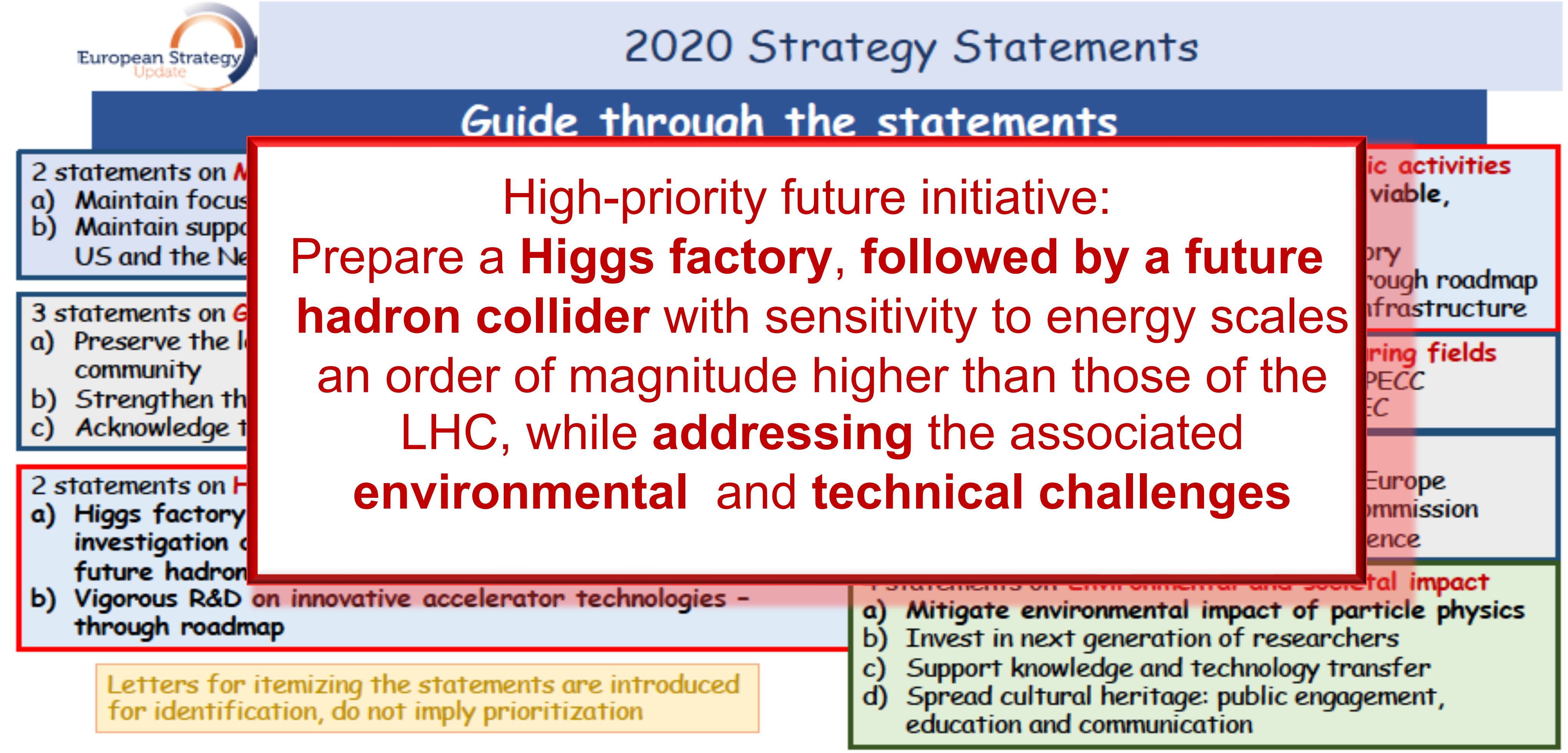
Outline

- **Introduction: Setting the scope**
    - EPPSU-2020 - LDG roadmap
    - Snowmass’21
- **EW / Higgs factories**
    - Linear
    - Circular
    - $\gamma\gamma$
- **Summary and Perspectives**



Context: EPPSU 2020 process update

20 strategy statements have been unanimously adopted by the European Strategy Group (ESG) in January 2020:



2020 Strategy Statements

Guide through the statements

2 statements on M
a) Maintain focus
b) Maintain suppo
US and the Ne

3 statements on G
a) Preserve the l
community
b) Strengthen th
c) Acknowledge t

2 statements on H
a) Higgs factory
investigation o
future hadron
b) Vigorous R&D on innovative accelerator technologies – through roadmap

Letters for itemizing the statements are introduced for identification, do not imply prioritization

ic activities
viable,
ory
rough roadmap
nfrastructure

ring fields
PECC
EC

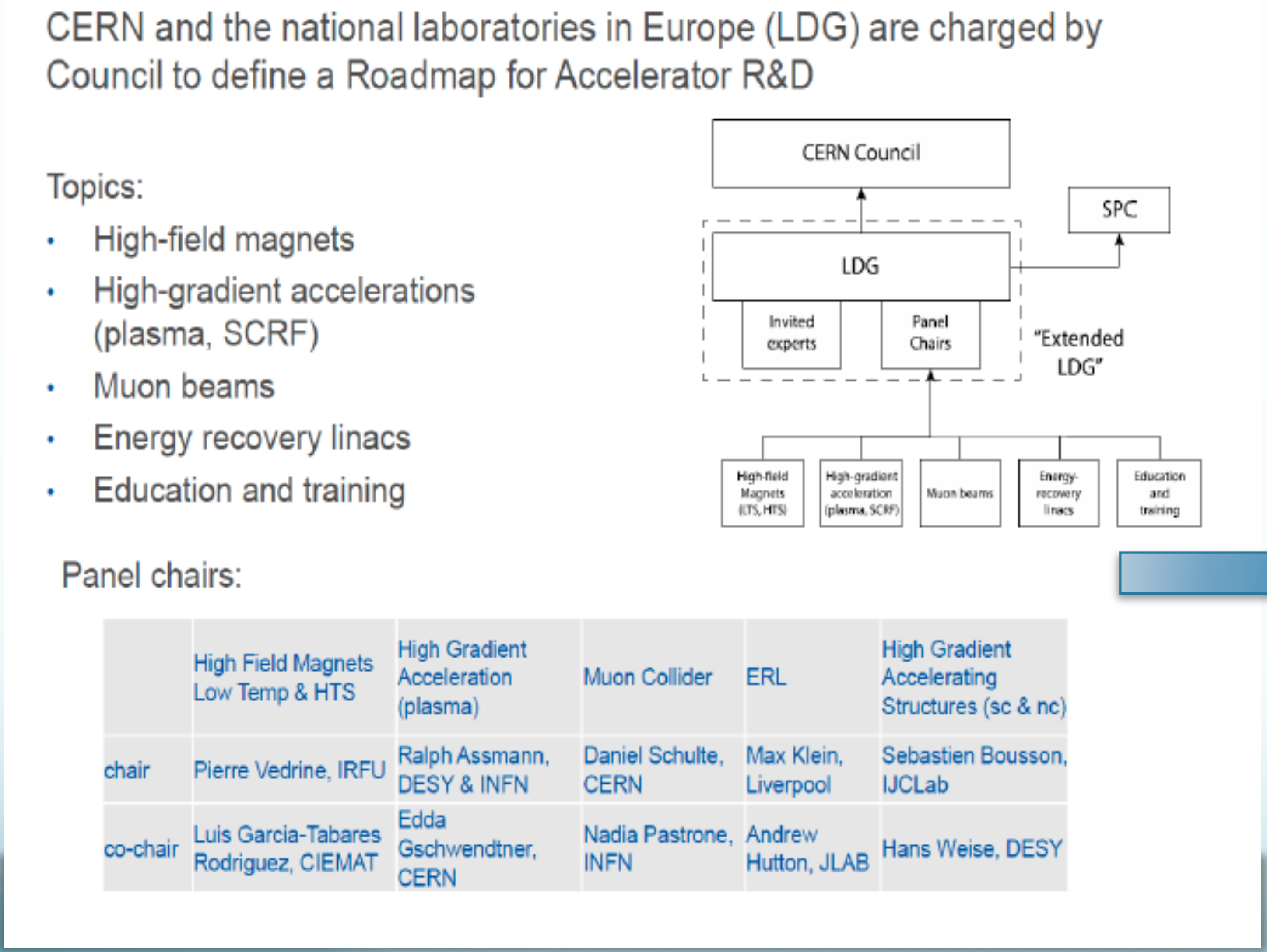
Europe
ommission
ence

tal impact
a) Mitigate environmental impact of particle physics
b) Invest in next generation of researchers
c) Support knowledge and technology transfer
d) Spread cultural heritage: public engagement, education and communication

High-priority future initiative:
Prepare a **Higgs factory**, **followed by a future hadron collider** with sensitivity to energy scales an order of magnitude higher than those of the LHC, while **addressing** the associated **environmental** and **technical challenges**

H. Abramowizc ESG January 2020.

Context: The LDG process



CERN and the national laboratories in Europe (LDG) are charged by Council to define a Roadmap for Accelerator R&D

Topics:

- High-field magnets
- High-gradient accelerations (plasma, SCRF)
- Muon beams
- Energy recovery linacs
- Education and training

Panel chairs:

	High Field Magnets Low Temp & HTS	High Gradient Acceleration (plasma)	Muon Collider	ERL	High Gradient Accelerating Structures (sc & nc)
chair	Pierre Vedrine, IRFU	Ralph Assmann, DESY & INFN	Daniel Schulte, CERN	Max Klein, Liverpool	Sebastien Bousson, IJCLab
co-chair	Luis Garcia-Tabares Rodriguez, CIEMAT	Edda Gschwendtner, CERN	Nadia Pastrone, INFN	Andrew Hutton, JLAB	Hans Weise, DESY

➢ **LDG Report (2022)**

Institut national de physique nucléaire et de physique des particules

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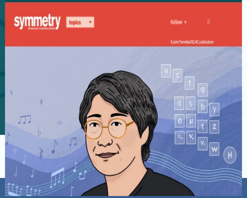
Context: Snowmass'21 process

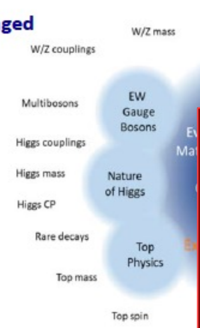
Moving Forward to P5

Hitoshi Murayama



Energy Frontier (Message)

- **Compared to Snowmass 2013 the physics landscape has significantly changed**
  - The program of measuring the Higgs boson properties is well underway at the LHC with growing precision
  - A broad range of searches have explored multiple BSM scenarios without convincing evidence of new physics
  - The HL-LHC is an approved project
- **Without a robust support for the HL-LHC and a clearly defined path towards a Higgs factory we leave critically important physics unchecked and crucial questions unanswered**
- **The EF community should be prepared to explore a broad range of BSM phenomena at the 10 TeV mass scale**



The Energy Frontier community voices a strong support for

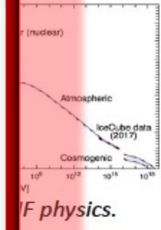
1. **HL-LHC operations and 3 ab^{-1} physics program, including auxiliary experiments**
2. **The fastest path towards an e^+e^- Higgs factory (linear or circular) in a global partnership**
3. **A vigorous R&D program for a multi-TeV collider (hadron or muon collider)**

The Energy Frontier is >50% of the US HEP community, therefore the potential impact on CEF (governmental advocacy, workforce training, diversity and inclusion) are critical to the progress of HEP

The most surprising thing that emerged from Snowmass was an overwhelming sentiment to engage in hosting a future collider in the US
...and the public praising of EF by Michael Peskin for enabling a vigorous discussion on future multi-TeV colliders

Neutrino Frontier

* We need to **finish DUNE**, and its broad physics program.
Both Phase I and Phase II are required to complete the original DUNE design.
* We are excited about long-term, broader possibilities that make use of our investment in the facility and could expand the DUNE scope beyond that originally envisioned.



F physics.

EW-Higgs factories:
The **fastest** path towards an **e^+e^- Higgs** factory
(linear or circular) in a global partnership

Accelerator Frontier

Message

- The accelerator community has technology and expertise to address the next generation accelerator.
- By the time of next Snowmass/P5 a National Future Colliders R&D program (new initiative!) should consider international and US based options and carry out technical and design studies sufficient to make informed decision on future directions toward
  - Higgs/EW factories
  - 10 TeV/parton colliders.

Intersections: Progress in accelerators will critically impact all future particle physics endeavors (neutrinos, colliders, DM) and therefore R&D should be prioritized by P5 inclusively
accelerators need to be part of the P5 charge.
Full utilization of the unique proton power capability of the upcoming PIP-II accelerator should be developed by the HEP community (use remaining 98% of full beam power).

Surprising Thing this week at Snowmass:
We seem to be clever enough to be seriously taken by the Theory Frontier (they even did argue with us)...

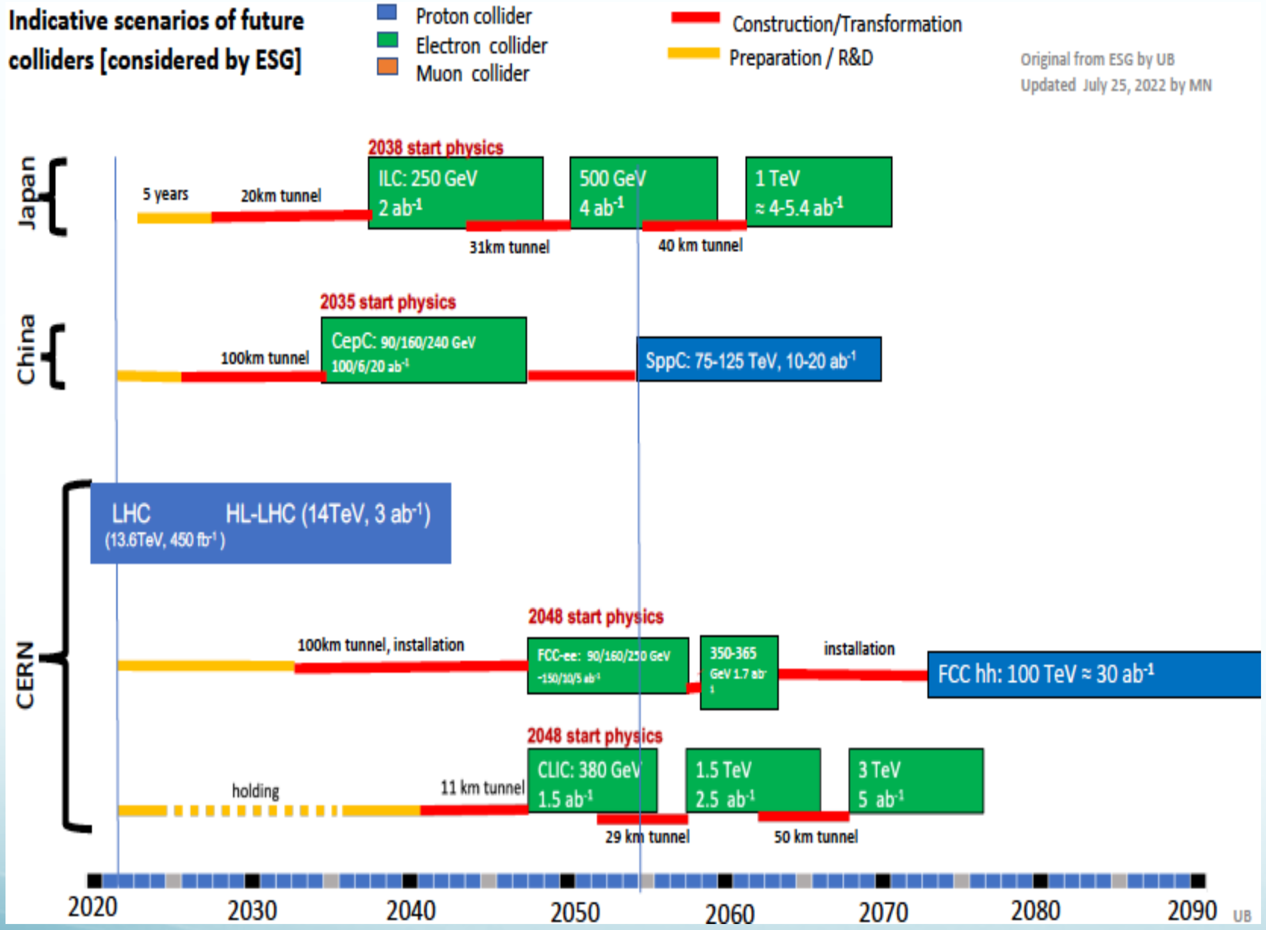
Highlights and Messages from the Snowmass Summer Study.
Prisca Cushman

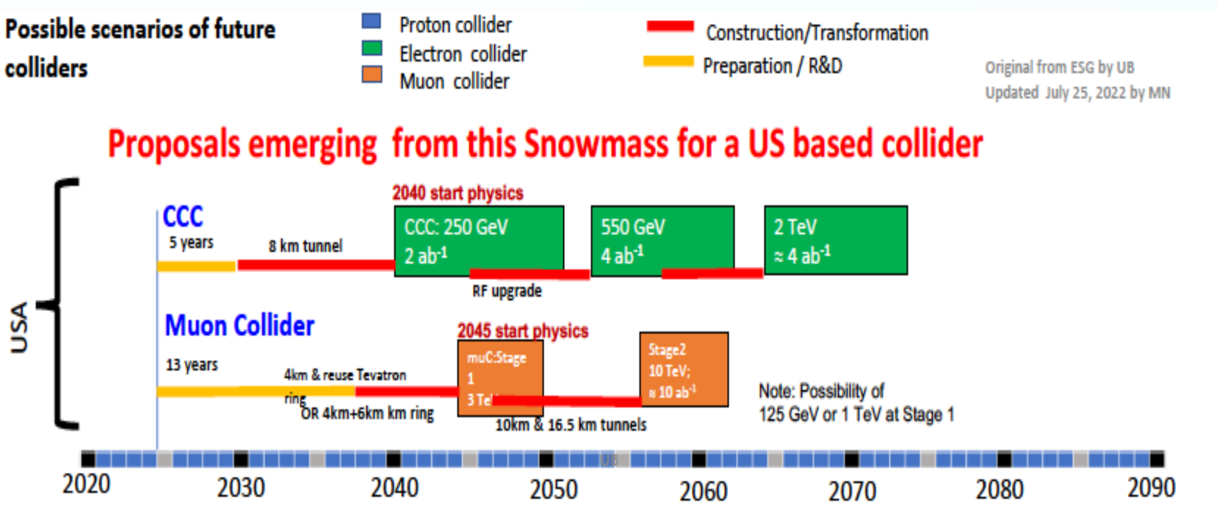
Snowmass 2021

Community Summer Study
SNOWMASS
July 17-26 2022, Seattle

2023

Context: HEP Future Coliiders new Timelines

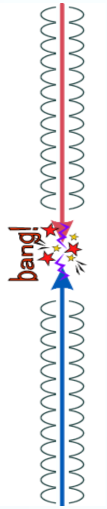




- Timelines technologically limited
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

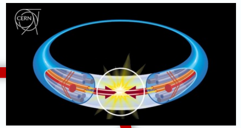
- Consider proposing hosting ILC in the US.

EW Higgs colliders projects



Linear

- ILC
- CLIC
- C3
- HELEN
- ReLiC
- ERLC *



Circular

- FCC-ee
- CEPC
- CERC
- EPCCF
- LEP3 *
- MCS*

γγ

- XCC
- HE&HL γγ

* not white paper but considered for completeness

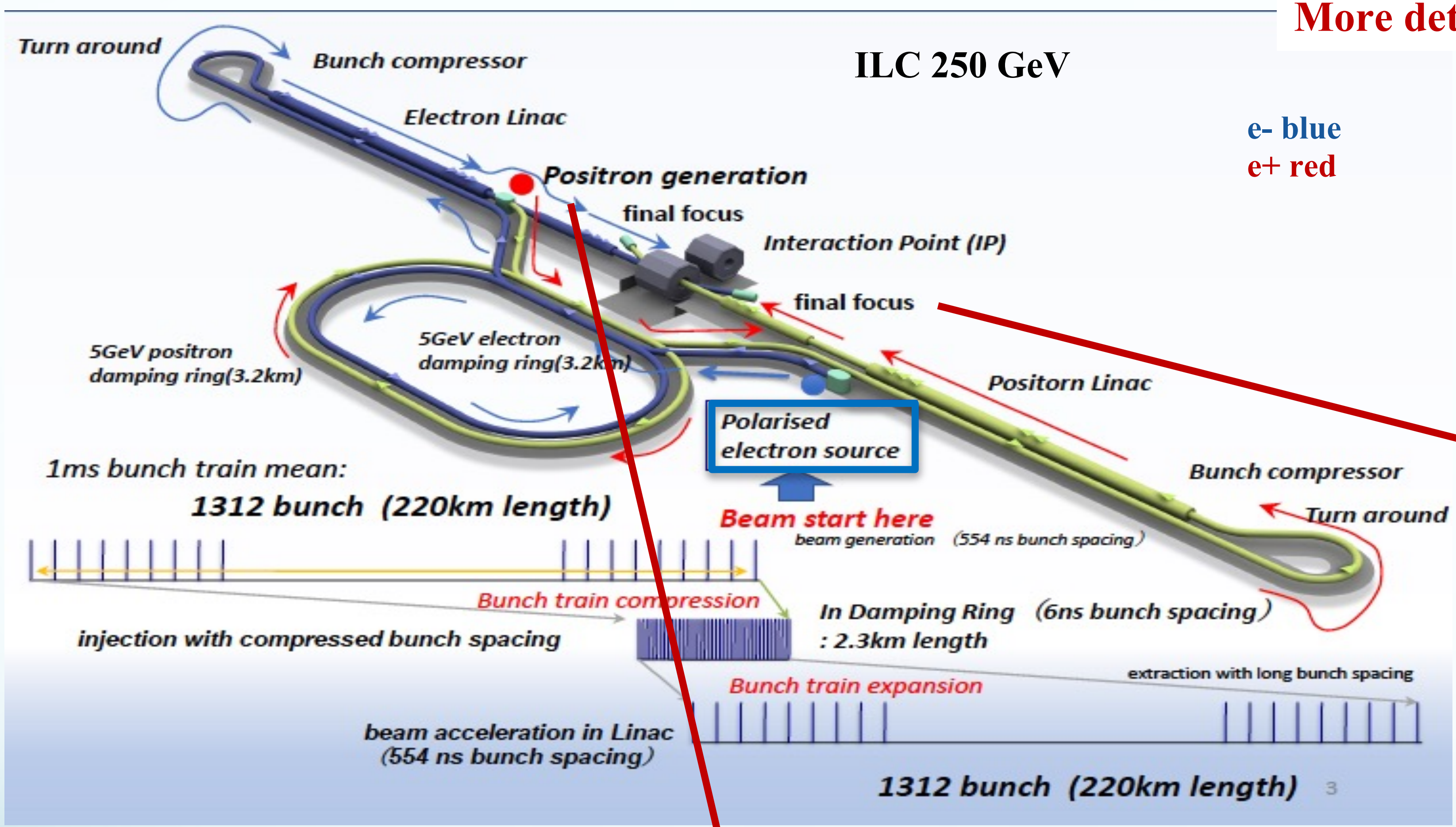
AF03 : EW/Higgs Factories

A small number of the proposals are ready or close to a construction phase, most of the proposals are very high-level in the conceptional design stage. These proposals should focus on main R&D tasks to move forward to a TDR

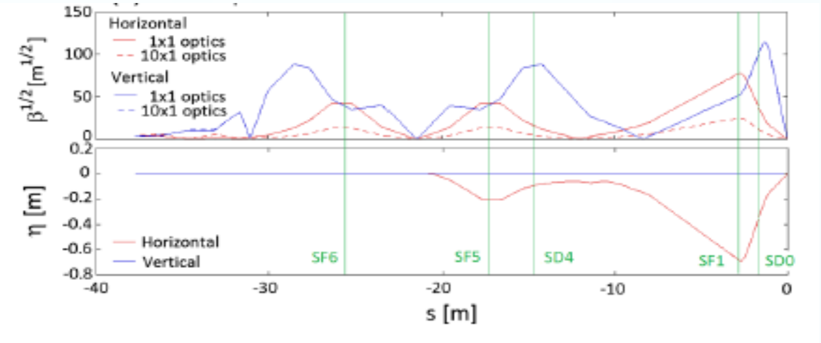
Some dedicated and fruitful discussions have been made during Snowmass21 AF03

ILC Accelerator Design and Challenges

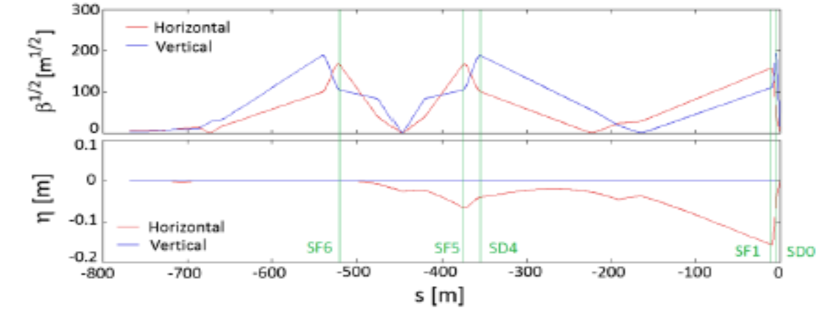
More details in A. Yamamoto’s talk



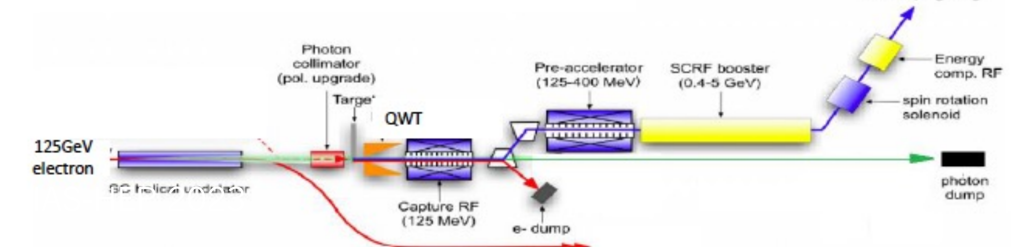
ATF2



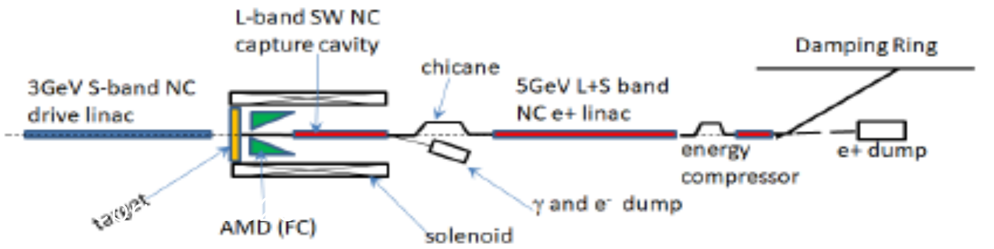
ILC



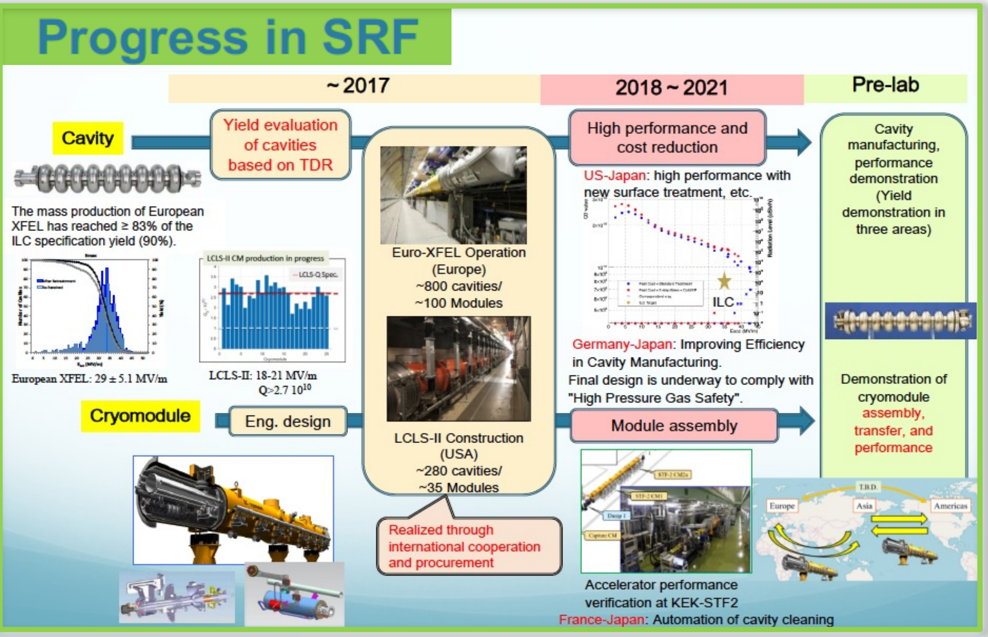
- **SC helical undulators** (baseline): rotating target, polarized (e^- at 125 GeV)



- **Electron driven source**: dedicated 3 GeV NC S-band TW e^- (pair production).



ILC Key technologies



Progress in SRF

~2017 | 2018~2021 | Pre-lab

Cavity

Yield evaluation of cavities based on TDR

The mass production of European XFEL has reached ≥ 83% of the ILC specification yield (90%).

European XFEL: 29 ± 5.1 MV/m

LCLS-II CM production in progress

LCLS-II: 18-21 MV/m
$Q > 2.7\ 10^{10}$

Euro-XFEL Operation (Europe)
~800 cavities/
~100 Modules

LCLS-II Construction (USA)
~280 cavities/
~35 Modules

Realized through international cooperation and procurement

High performance and cost reduction

US-Japan: high performance with new surface treatment, etc.

Germany-Japan: Improving Efficiency in Cavity Manufacturing.
Final design is underway to comply with "High Pressure Gas Safety".

Cavity manufacturing, performance demonstration (Yield demonstration in three areas)

Cryomodule

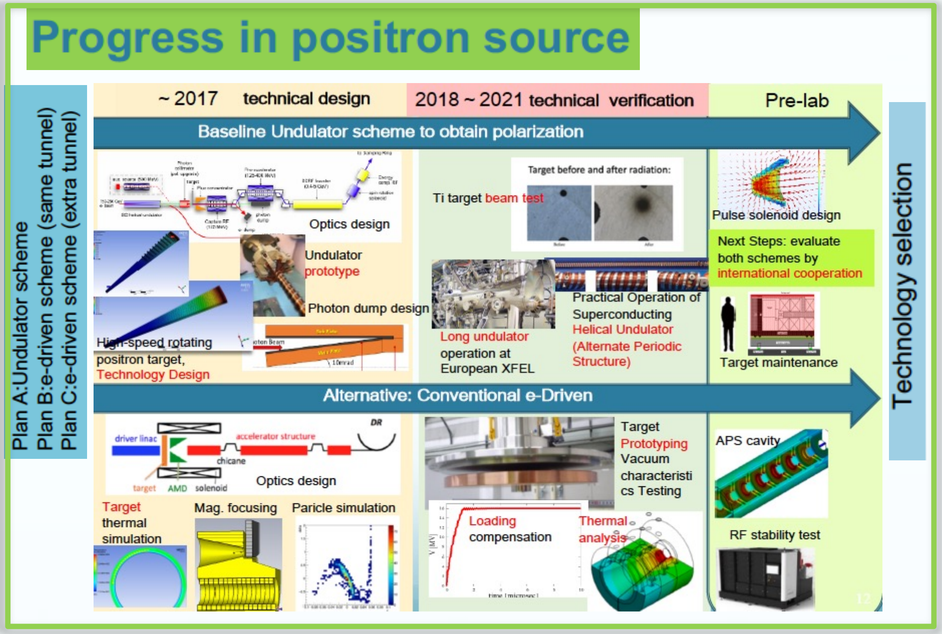
Eng. design

Module assembly

Accelerator performance verification at KEK-STF2

France-Japan: Automation of cavity cleaning

Demonstration of cryomodule assembly, transfer, and performance



Progress in positron source

Plan A:Undulator scheme
Plan B:e-driven scheme (same tunnel)
Plan C:e-driven scheme (extra tunnel)

~2017 technical design | 2018~2021 technical verification | Pre-lab

Baseline Undulator scheme to obtain polarization

Optics design

Undulator prototype

Photon dump design

High-speed rotating positron target, Technology Design

Ti target beam test

Target before and after radiation:

Long undulator operation at European XFEL

Practical Operation of Superconducting Helical Undulator (Alternate Periodic Structure)

Pulse solenoid design

Next Steps: evaluate both schemes by international cooperation

Target maintenance

Alternative: Conventional e-Driven

Optics design

Target thermal simulation

Mag. focusing

Paricle simulation

Target Prototyping Vacuum characteristics Testing

Loading compensation

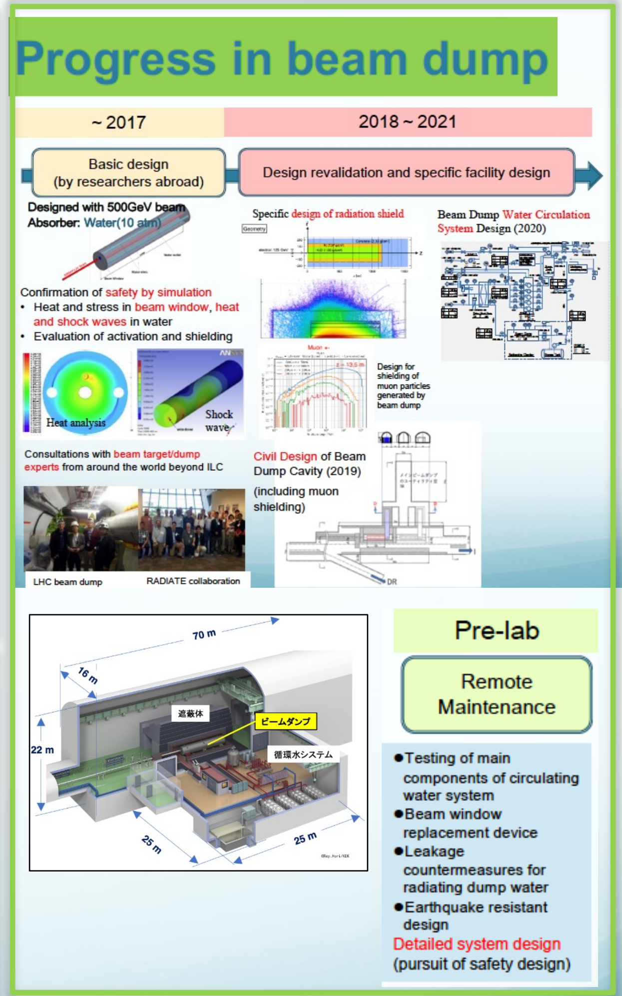
Thermal analysis

APS cavity

RF stability test

Technology selection

12



Progress in beam dump

~2017 | 2018~2021

Basic design (by researchers abroad)

Design revalidation and specific facility design

Designed with 500GeV beam
Absorber: Water(10 atm)

Confirmation of safety by simulation
- Heat and stress in beam window, heat and shock waves in water
- Evaluation of activation and shielding

Consultations with beam target/dump experts from around the world beyond ILC

LHC beam dump

RADIATE collaboration

Specific design of radiation shield

Design for shielding of muon particles generated by beam dump

Civil Design of Beam Dump Cavity (2019)

(including muon shielding)

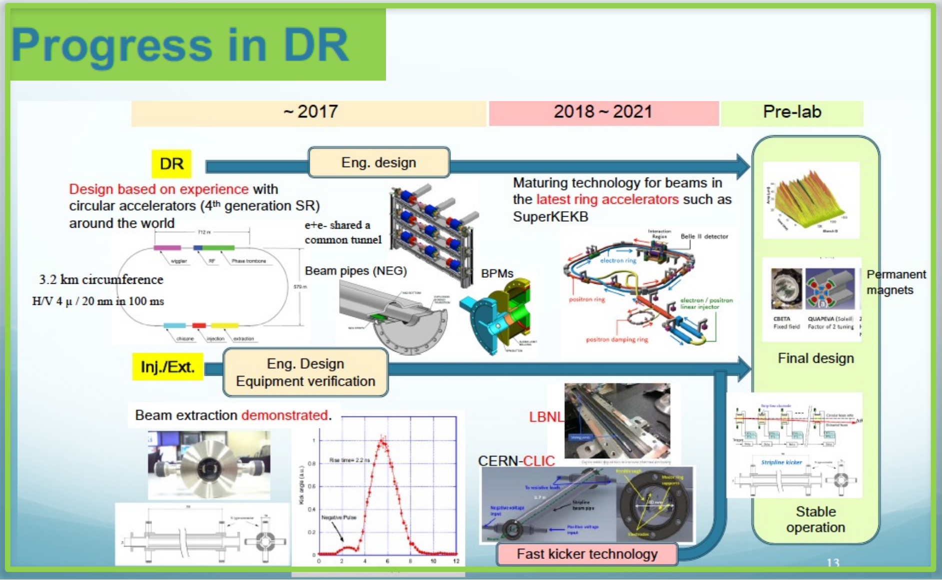
Beam Dump Water Circulation System Design (2020)

Pre-lab

Remote Maintenance

- Testing of main components of circulating water system
- Beam window replacement device
- Leakage countermeasures for radiating dump water
- Earthquake resistant design

Detailed system design
(pursuit of safety design)



Progress in DR

~2017 | 2018~2021 | Pre-lab

DR

Eng. design

Design based on experience with circular accelerators (4th generation SR) around the world

3.2 km circumference
H/V 4 μ / 20 nm in 100 ms

e+e- shared a common tunnel

Beam pipes (NEG)

BPMs

Maturing technology for beams in the latest ring accelerators such as SuperKEKB

Permanent magnets

Final design

Inj./Ext.

Eng. Design
Equipment verification

Beam extraction demonstrated.

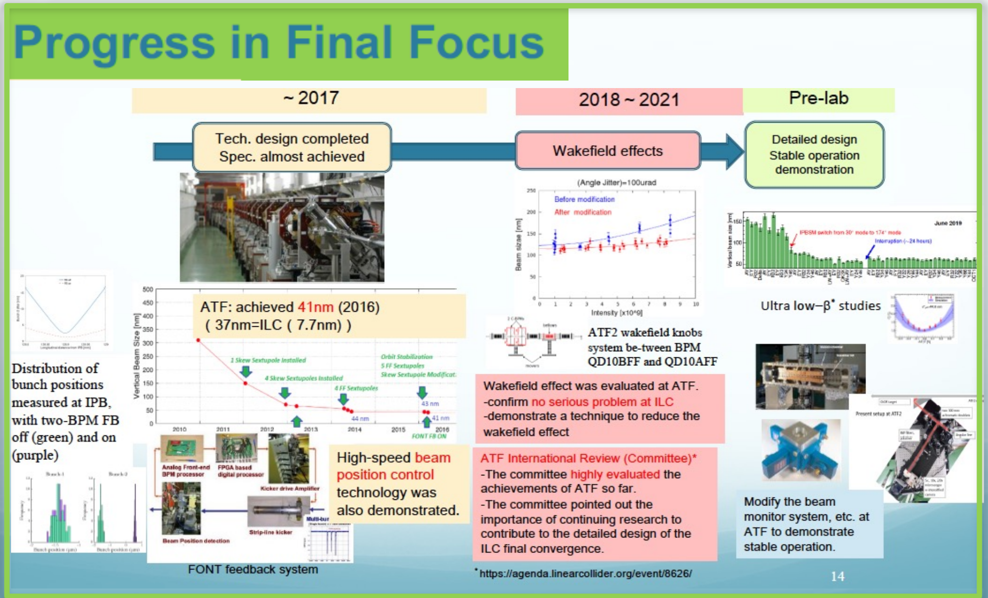
LBNL

CERN-CLIC

Fast kicker technology

Stable operation

13



Progress in Final Focus

~2017 | 2018~2021 | Pre-lab

Tech. design completed
Spec. almost achieved

ATF: achieved 41nm (2016)
(37nm=ILC (7.7nm))

Distribution of bunch positions measured at IPB, with two-BPM FB off (green) and on (purple)

High-speed beam position control technology was also demonstrated.

FONT feedback system

Wakefield effects

ATF2 wakefield knobs system be-tween BPM QD10BFF and QD10AFF

Wakefield effect was evaluated at ATF.
-confirm no serious problem at ILC
-demonstrate a technique to reduce the wakefield effect

ATF International Review (Committee)*
-The committee highly evaluated the achievements of ATF so far.
-The committee pointed out the importance of continuing research to contribute to the detailed design of the ILC final convergence.

*https://agenda.linearcollider.org/event/8626/

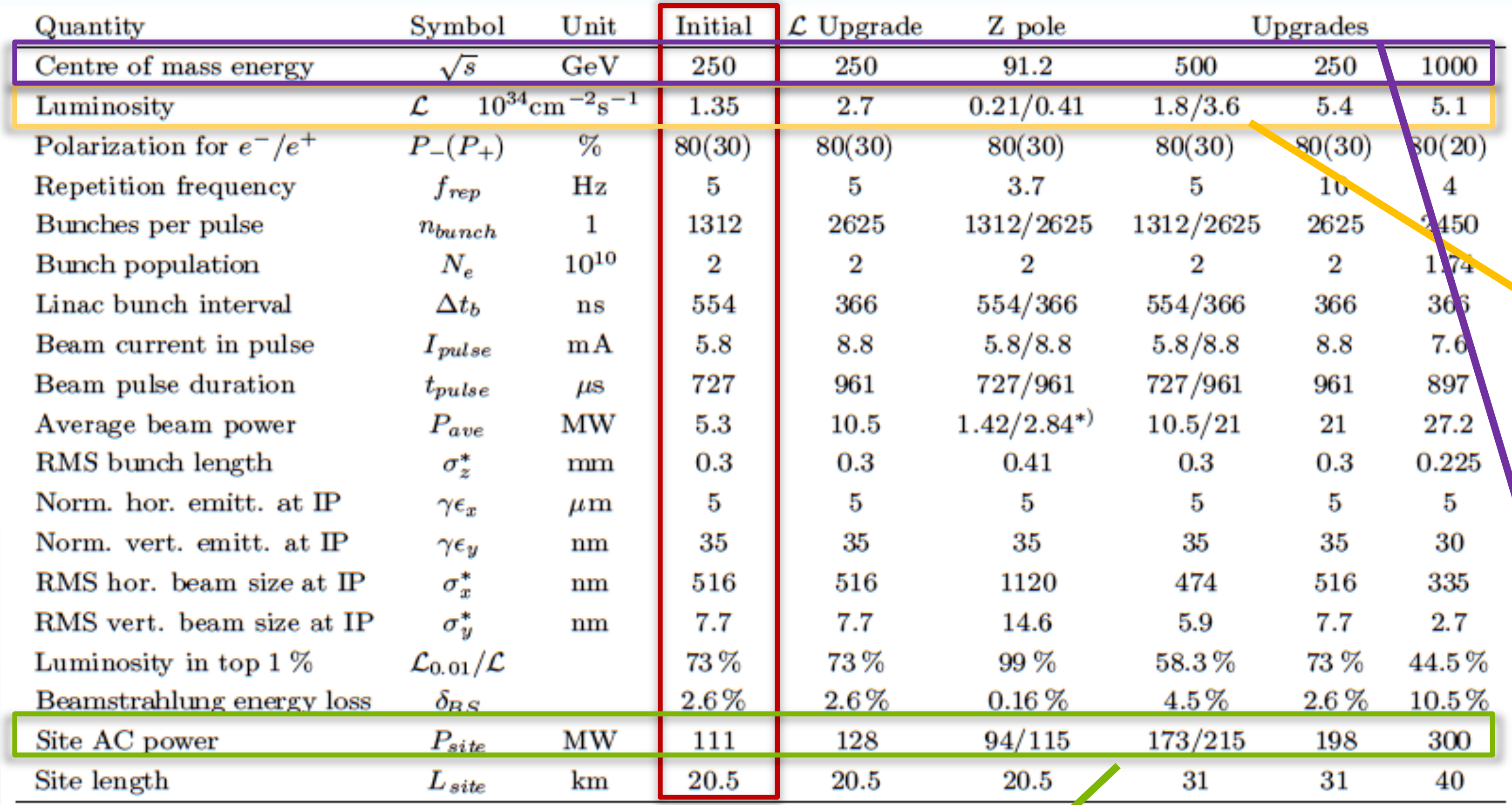
Detailed design
Stable operation
demonstration

Ultra low−β* studies

Modify the beam monitor system, etc. at ATF to demonstrate stable operation.

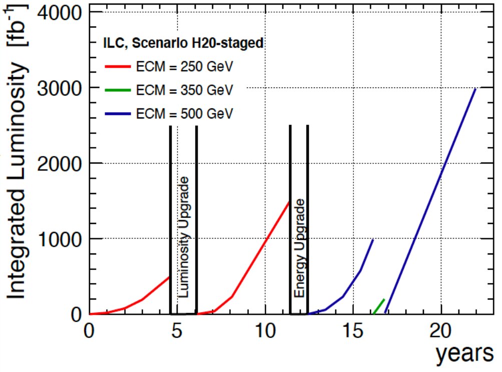
14

ILC Baseline, extension and upgrades

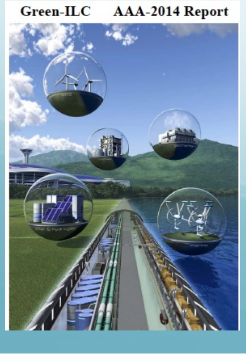


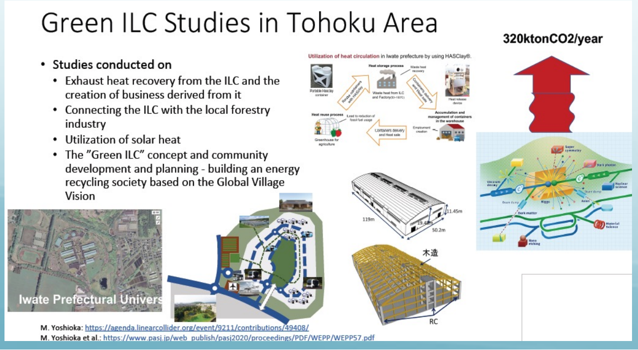
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ^*_z	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ^*_x	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ^*_y	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	128	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

- **Luminosity upgrades**:
  - 2 x bunches, 2 x RF (1.35 -> 2.7x10^{34})
  - Run = 500GeV machine at 250GeV, 10Hz: factor 2 (2.7x10^{34} -> 5.4x10^{34})
  - Improve power efficiency



- **Energy upgrades**: 500GeV (31.5 MV/m Q_0=1 x 10^{10}) , 1TeV (45 MV/m Q_0=2 x 10^{10}, 300 MW) more SCRF, tunnel extension
  - Kitakami site: 50km long, sufficient for 1TeV

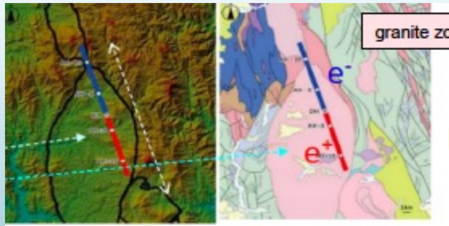


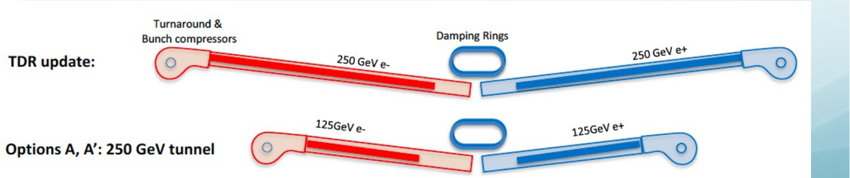


Green ILC Studies in Tohoku Area

- Studies conducted on
  - Exhaust heat recovery from the ILC and the creation of business derived from it
  - Connecting the ILC with the local forestry industry
  - Utilization of solar heat
  - The "Green ILC" concept and community development and planning - building an energy recycling society based on the Global Village Vision

M. Yoshioka: https://agenda.linearcollider.org/event/9211/contributions/49408/
M. Yoshioka et al.: https://www.pasj.jp/web_publish/pasj2020/proceedings/PDF/WEPP/WEPP57.pdf

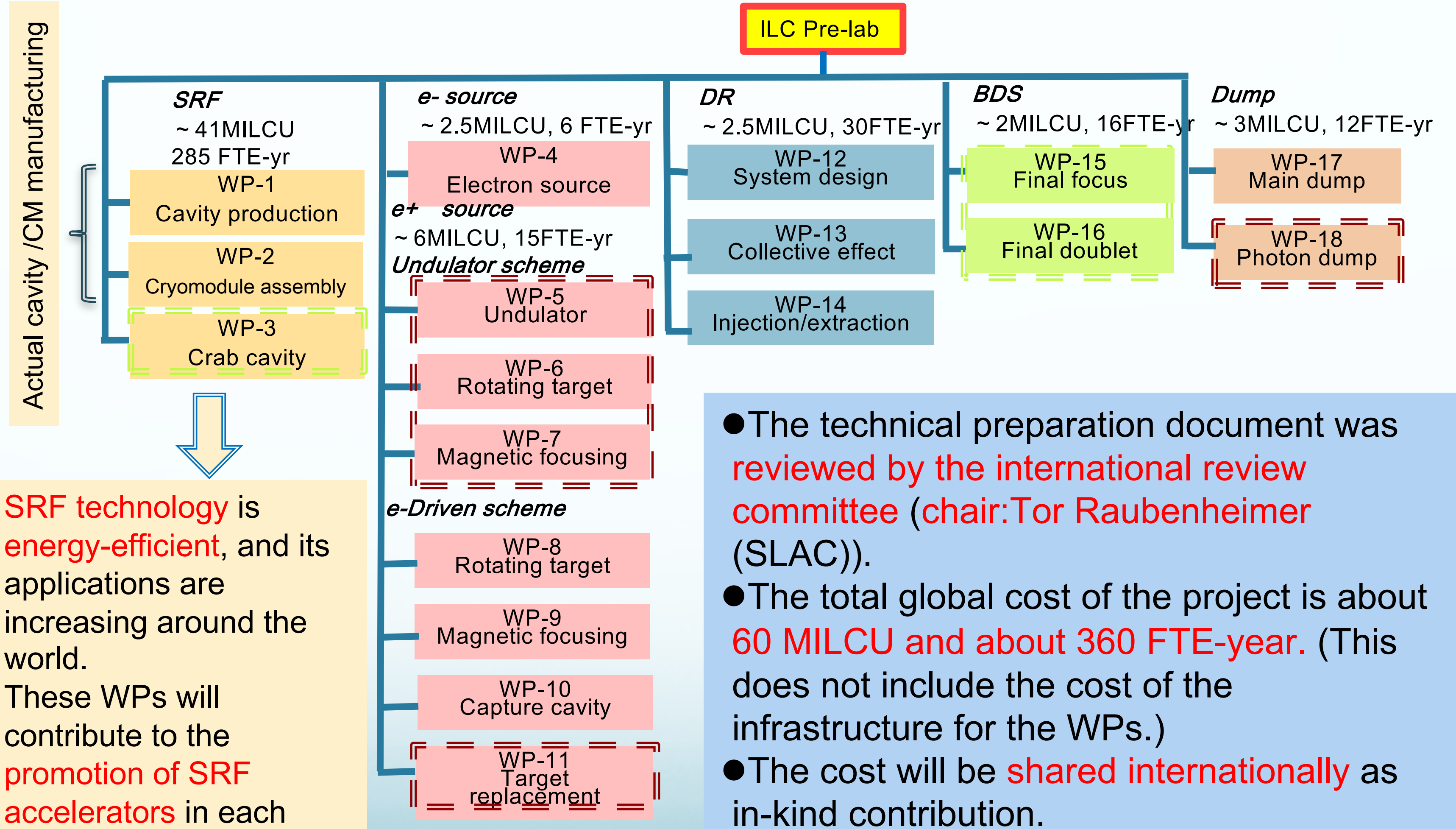




More details in F. Zimmermann's talk

ILC proposal state and R&D (4 years)

IDT-WG2 summarized the technical preparation as work packages (**WPs**) in the **Technical Preparation Document** http://doi.org/10.5281/zenodo.4742018



ILC Pre-lab

Actual cavity /CM manufacturing

SRF
~41MILCU
285 FTE-yr
- WP-1 Cavity production
- WP-2 Cryomodule assembly
- WP-3 Crab cavity

e- source
~2.5MILCU, 6 FTE-yr
- WP-4 Electron source

e+ source
~6MILCU, 15FTE-yr

Undulator scheme
- WP-5 Undulator
- WP-6 Rotating target
- WP-7 Magnetic focusing

e-Driven scheme
- WP-8 Rotating target
- WP-9 Magnetic focusing
- WP-10 Capture cavity
- WP-11 Target replacement

DR
~2.5MILCU, 30FTE-yr
- WP-12 System design
- WP-13 Collective effect
- WP-14 Injection/extraction

BDS
~2MILCU, 16FTE-yr
- WP-15 Final focus
- WP-16 Final doublet

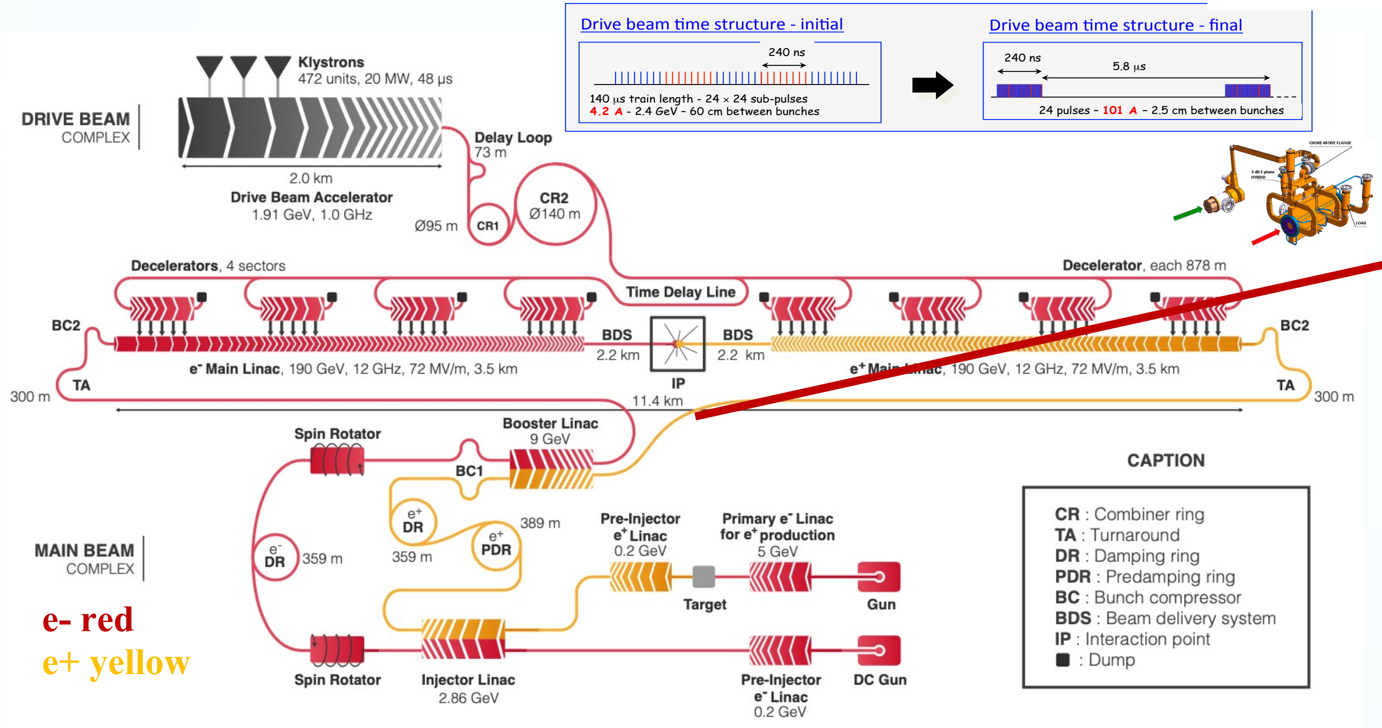
Dump
~3MILCU, 12FTE-yr
- WP-17 Main dump
- WP-18 Photon dump

SRF technology is energy-efficient, and its applications are increasing around the world.
These WPs will contribute to the promotion of SRF accelerators in each region.

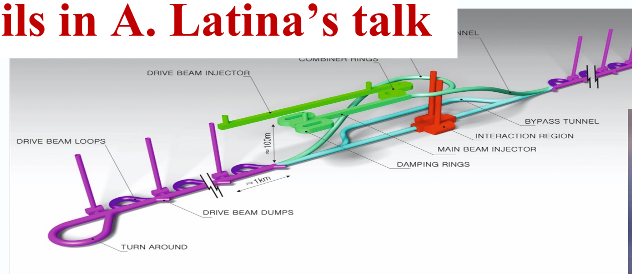
- ●The technical preparation document was reviewed by the international review committee (chair:Tor Raubenheimer (SLAC)).
- ●The total global cost of the project is about 60 MILCU and about 360 FTE-year. (This does not include the cost of the infrastructure for the WPs.)
- ●The cost will be shared internationally as in-kind contribution.

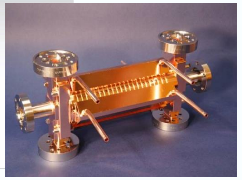
CLIC Accelerator Design and Challenges

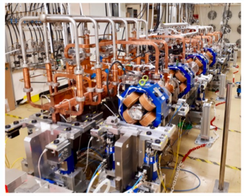
More details in A. Latina's talk



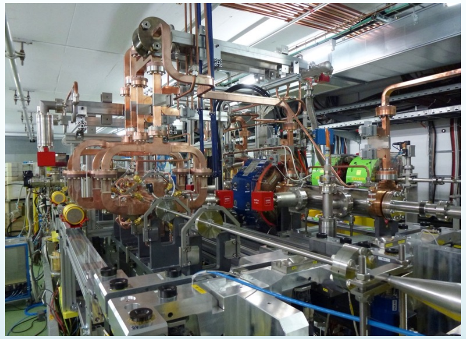
e- red
e+ yellow

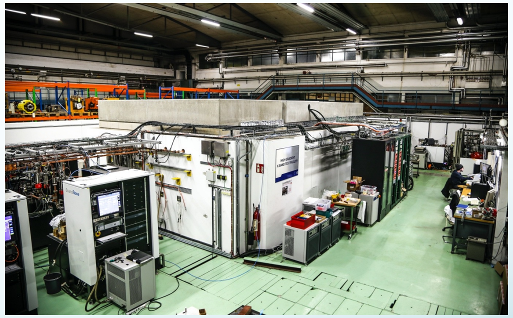






1. **Drive beam** accelerated to ~2 GeV using conventional klystrons
2. **Intensity increased** using a series of delay loops and combiner rings
3. Drive beam **decelerated** and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides

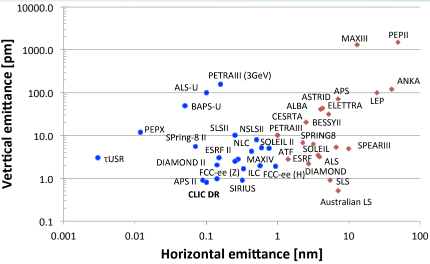




Four **main challenges**

1. **High-current drive beam** bunched at 12 GHz (CTF3 addressed all drive-beam production issues)
2. Power transfer and main-beam acceleration, **efficient RF power**
3. Towards 100 MV/m gradient in main-beam **X-band cavities**
4. **Alignment and stability** ("nano-beams")

Target and achieved emittance in existing and planned machines



CLIC Key technologies

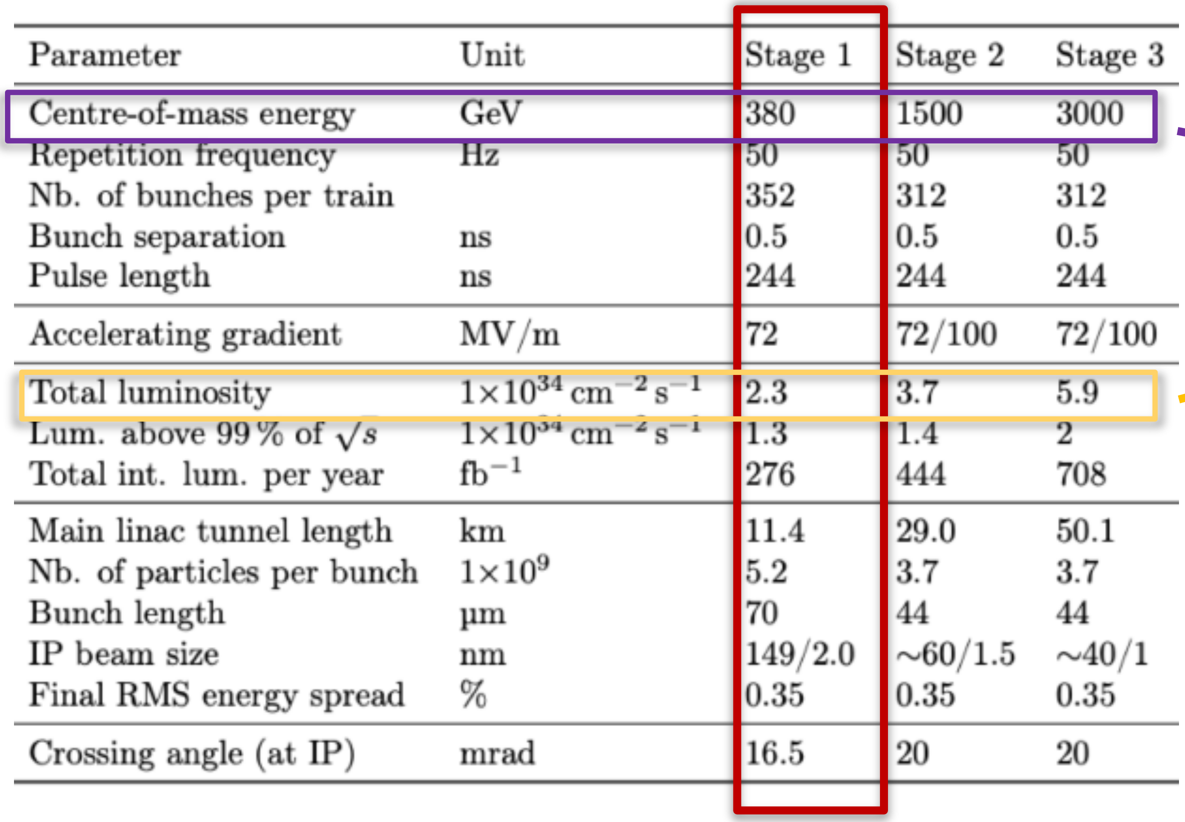
The **CLIC accelerator** studies are mature:

- Optimised design for cost and power

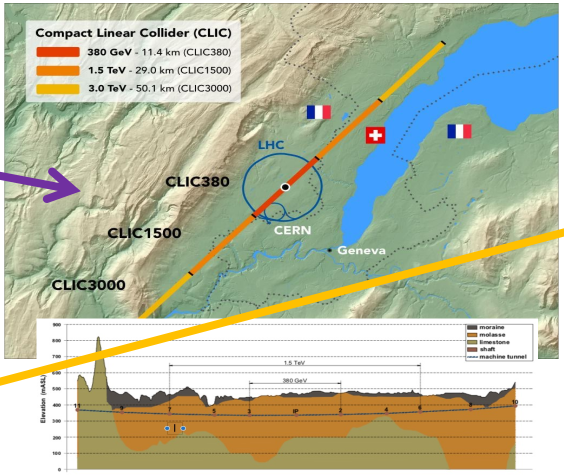
- Many tests in CTF3, FELs, light sources and test-stands

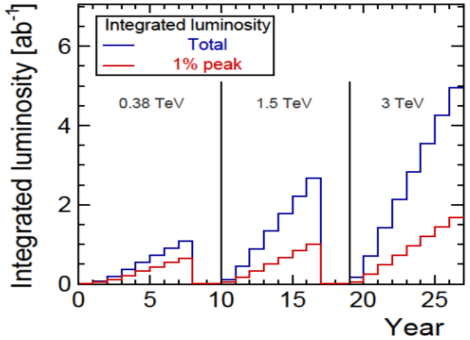
- Technical developments of “all” key elements

CLIC Baseline, extension and upgrades

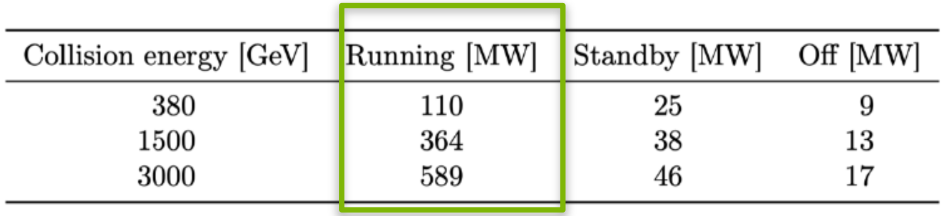


Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20





Further work on **luminosity performance**, possible improvements and margins, operation at the Z-pole and gamma-gamma are ongoing



Collision energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	110	25	9
1500	364	38	13
3000	589	46	17

- **Energy studies:**
- Running when energy is cheap
- Renewable energy (carbon footprint)
- Recovering energy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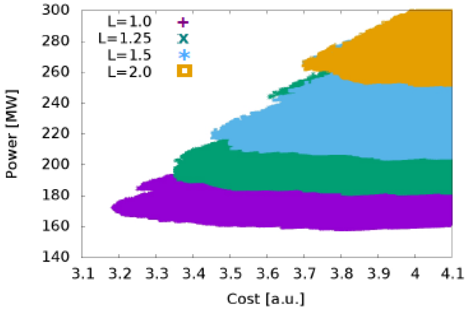
- Very **large reductions** since **CDR (2018)**, better estimates of nominal settings, much more optimised drive-beam complex and more efficient klystrons, injectors more optimisation, etc
- Further savings possible, main target damping ring RF and improved L-band klystrons for drive-beam

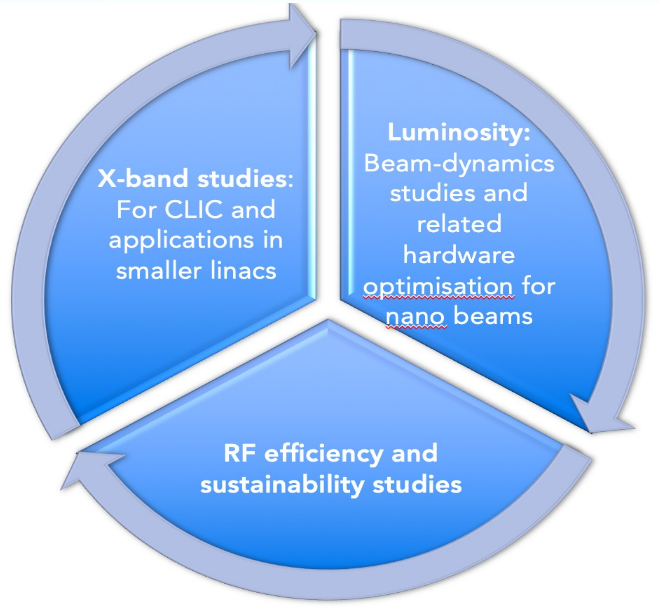


Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum*

More details in F. Zimmermann's talk

CLIC proposal state and R&D

Project Readiness Report as a step toward a TDR – for next ESPP. Assuming ESPP in 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.



X-band studies: For CLIC and applications in smaller linacs

Luminosity: Beam-dynamics studies and related hardware optimisation for nano beams

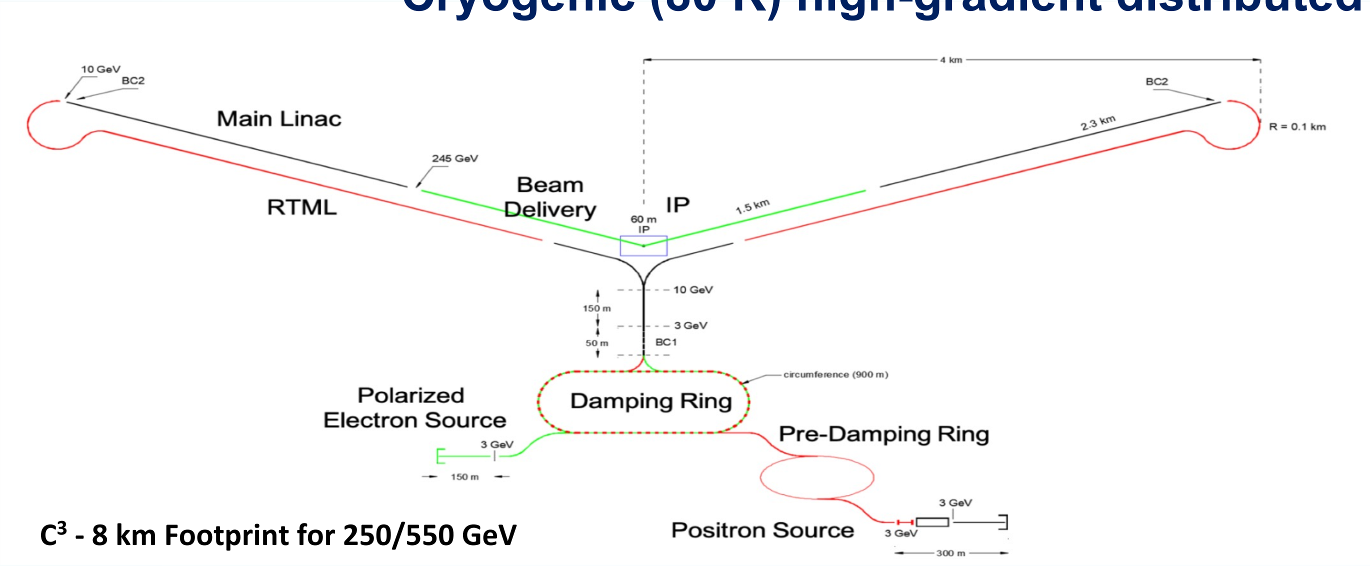
RF efficiency and sustainability studies

Goals for **R&D** studies by ~2025, key improvements:

- **Luminosity** numbers, covering beam-dynamics, nanobeam, and positrons - at all energies. Performance risk reduction, system level studies
- **Energy/power**: 380 GeV well underway, 3 TeV to be done, L-band klystron efficiency
- **Sustainability issues**, more work on running/energy models and carbon footprint
- **X-band progress** – for CLIC, smaller machines, industry availability, including RF network
- R&D for **higher energies**, gradient, power, prospects beyond 3 TeV
- **Cost update**, only discuss changes wrt Project Implementation Plan in 2018
- **Low cost klystron version** – reoptimize for power, cost and fewer klystrons

C3 Accelerator Design and Challenges

Cryogenic (80 K) high-gradient distributed coupling accelerator concept



C^3 - 8 km Footprint for 250/550 GeV

- **8 km footprint** for **250/550 GeV** $\Longrightarrow$ **70/120 MV/m** (7 km footprint at 155 MeV/m for 550 GeV present Fermilab site)
- Large portions of **accelerator complex** are **compatible** between **LC technologies**:
  - BDS and IP modified from ILC (1.5 km for 550 GeV)
  - DR and injectors to be optimized with CLIC as baseline

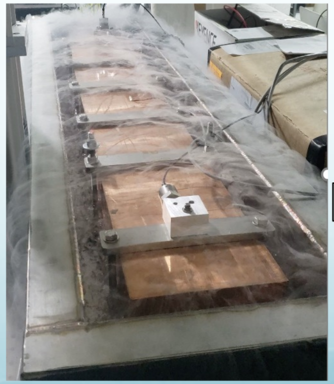
Accelerator Design

- Engineering and design of prototype cryomodule underway

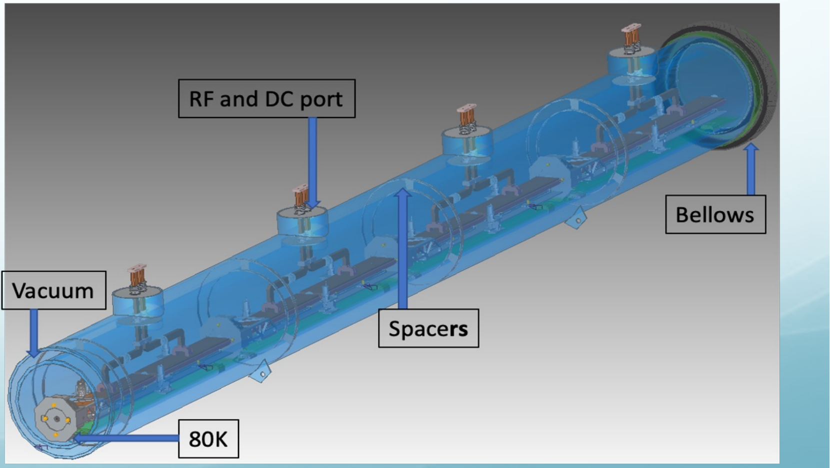
Focused on challenges:

- Gradient – Scaling up to meter scale cryogenic tests
- Vibrations – Measurements with full thermal load
- Alignment – Working towards raft prototype
- Cryogenics – Two-phase flow simulations to full flow tests
- Damping – Materials, design and simulation
- Beam Loading and Stability - Thermionic beam test
- Scalability – Cryomodules and integration

Vibration Studies



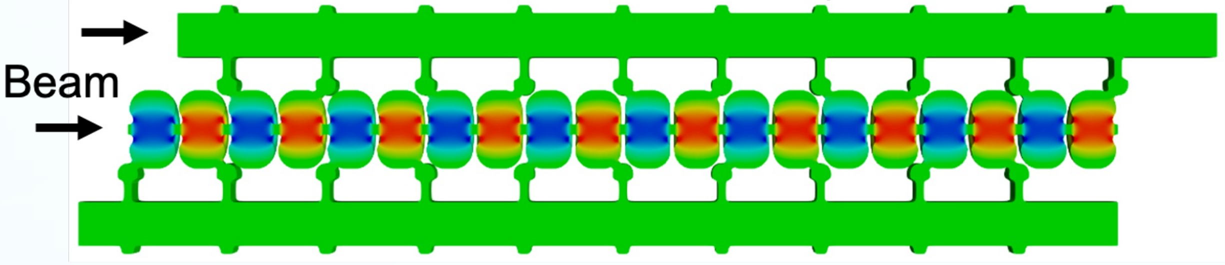
Cryomodule Concept



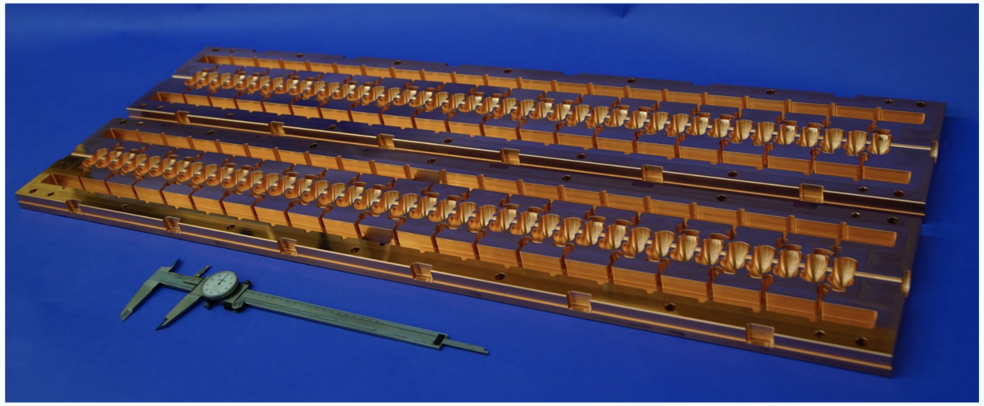
C3 Key technologies

Present Focus is the Main Linac, in Future Expand to Rest of Complex

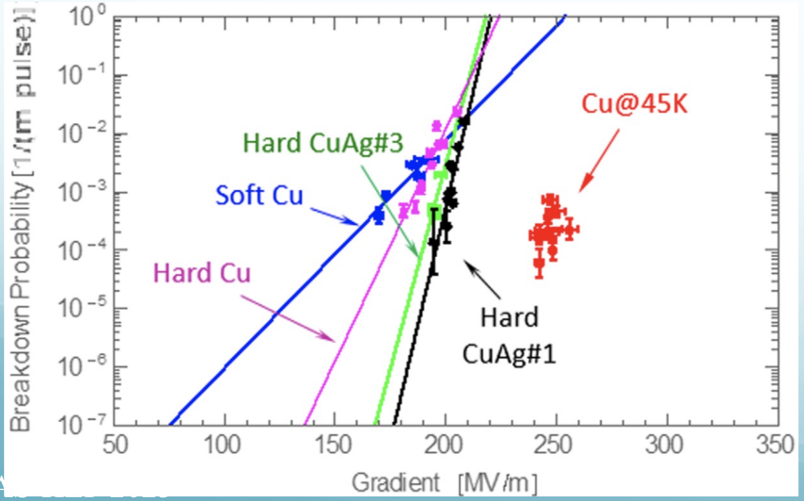
Maximize Structure Efficiency and Performance
Distributed Coupling

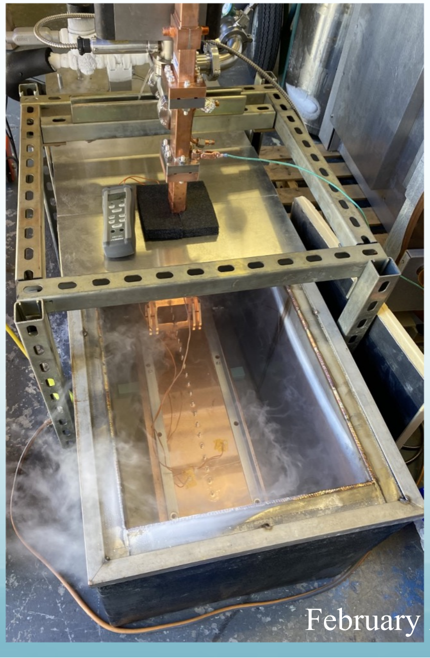


Modern Manufacturing
Prototype One Meter Structure

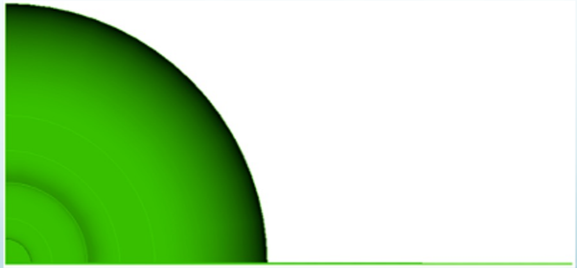


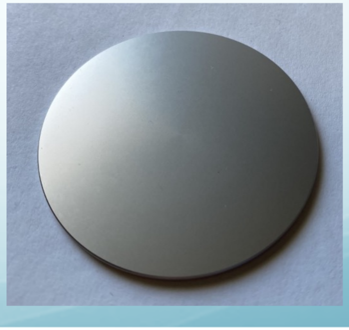
High Accelerating Gradients
Cryogenic Operation



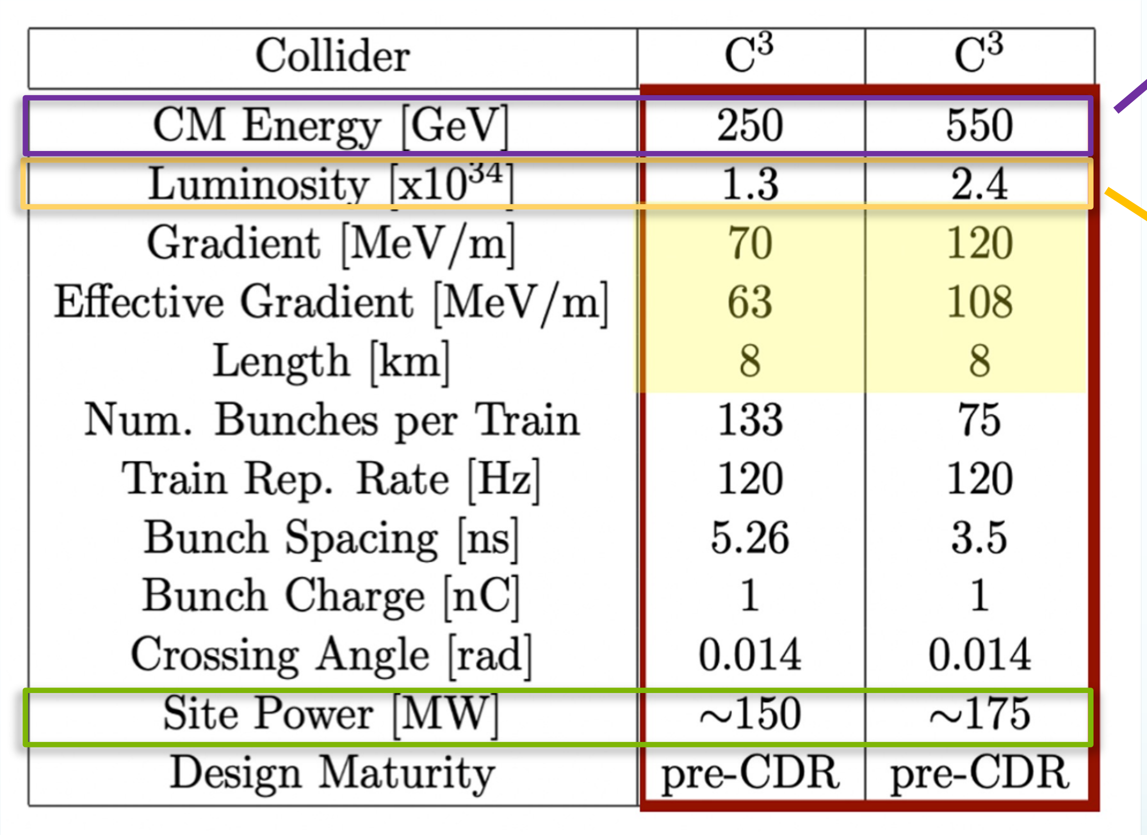


Integrated Damping
Slot Damping with NiChrome Coating





C3 Baseline, extension and upgrades



Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

More details in F. Zimmermann's talk

Energy

- Scalability studied to 3 TeV
- Requires RF pulse compression for reasonable site power
- Higher gradient option (155 MeV/m) in consideration

Luminosity

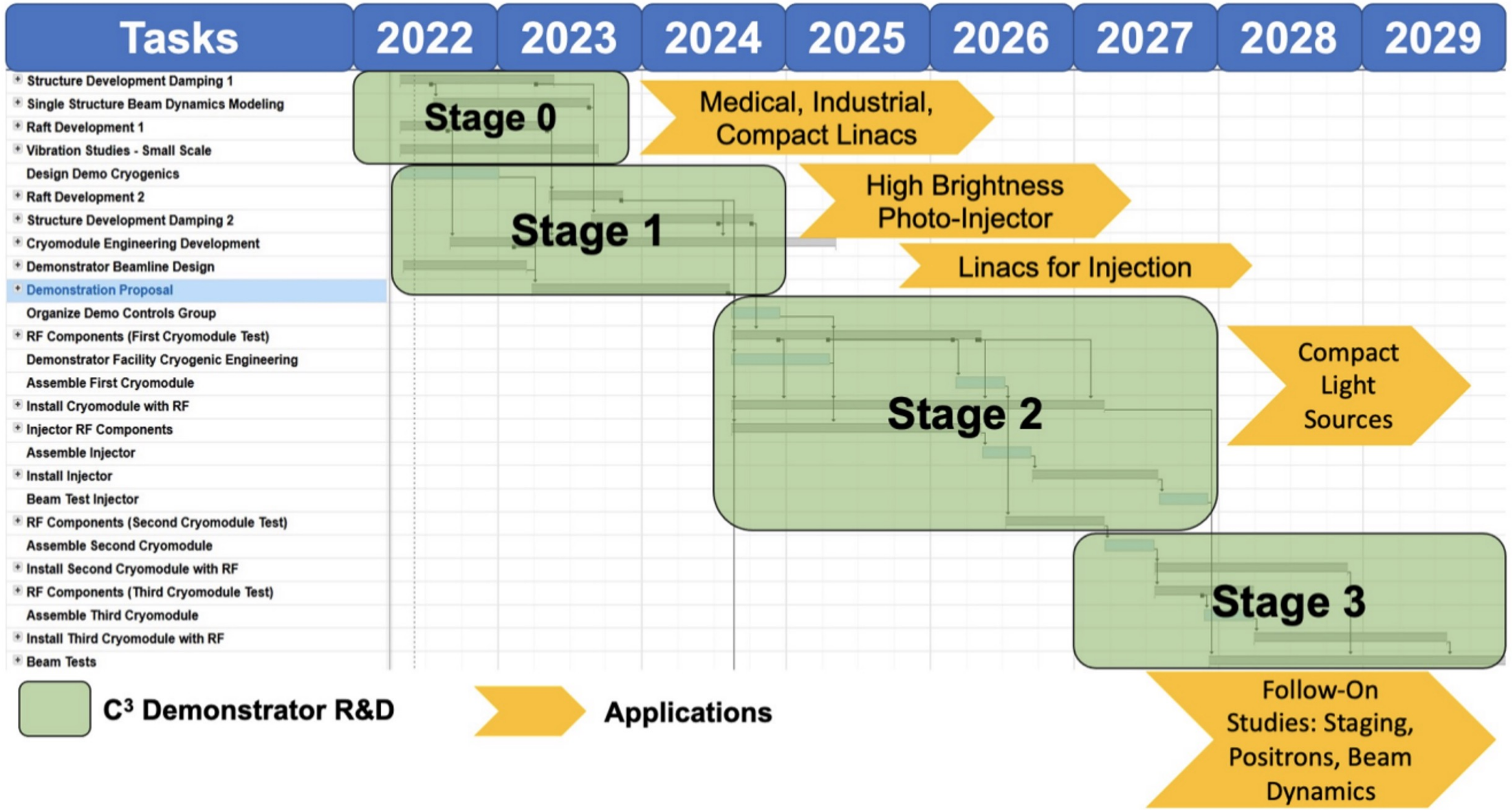
- Beam power can be increased for additional luminosity
- C^3 has a relatively low current for 250 GeV CoM (0.19 A) - Could we push to match CLIC at 1.66 A? (8.5X increase?)
- Pulse length and rep. rate are also options

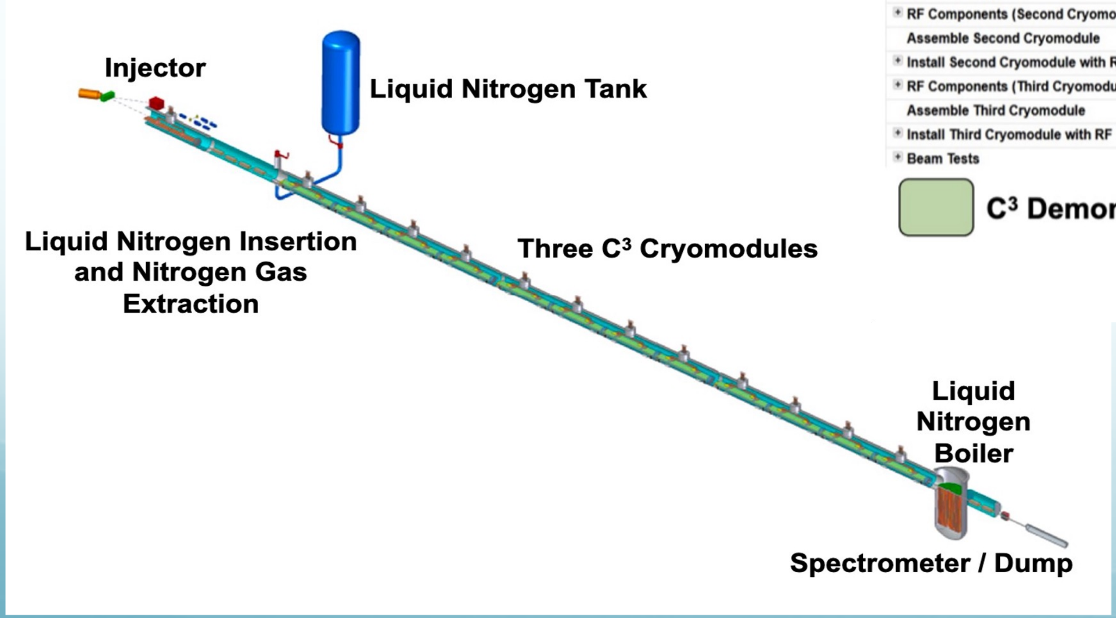
Parameter	Units	Baseline	High-Lumi
Energy CoM	GeV	250	250
Gradient	MeV/m	70	70
Beam Current	A	0.2	1.6
Beam Power	MW	2	16
Luminosity	x10^{34}	1.3	10.4
Beam Loading		45%	87%
RF Power	MW/m	30	125
Site Power	MW	~150	~180

C3 proposal state and R&D (5 years)

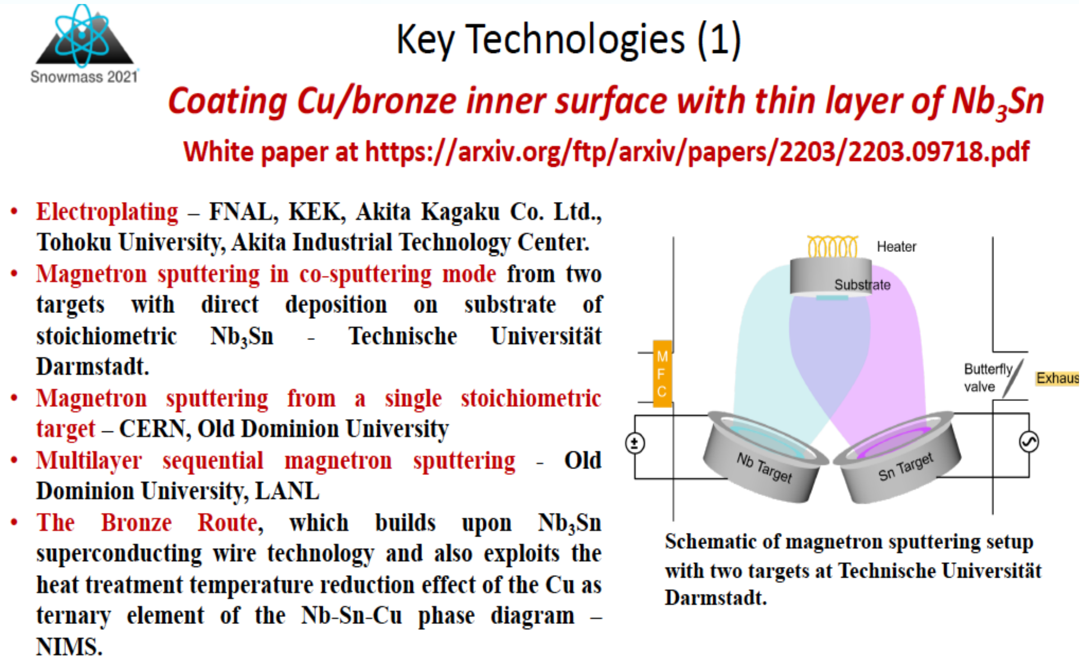
Next Steps:
C^3 Demonstration R&D Plan

- Demonstrate fully engineered cryomodule. ~50 m scale facility
- 3 GeV energy reach
- Answer technical questions needed for CDR





C3 based on SC Nb_3Sn



Snowmass 2021

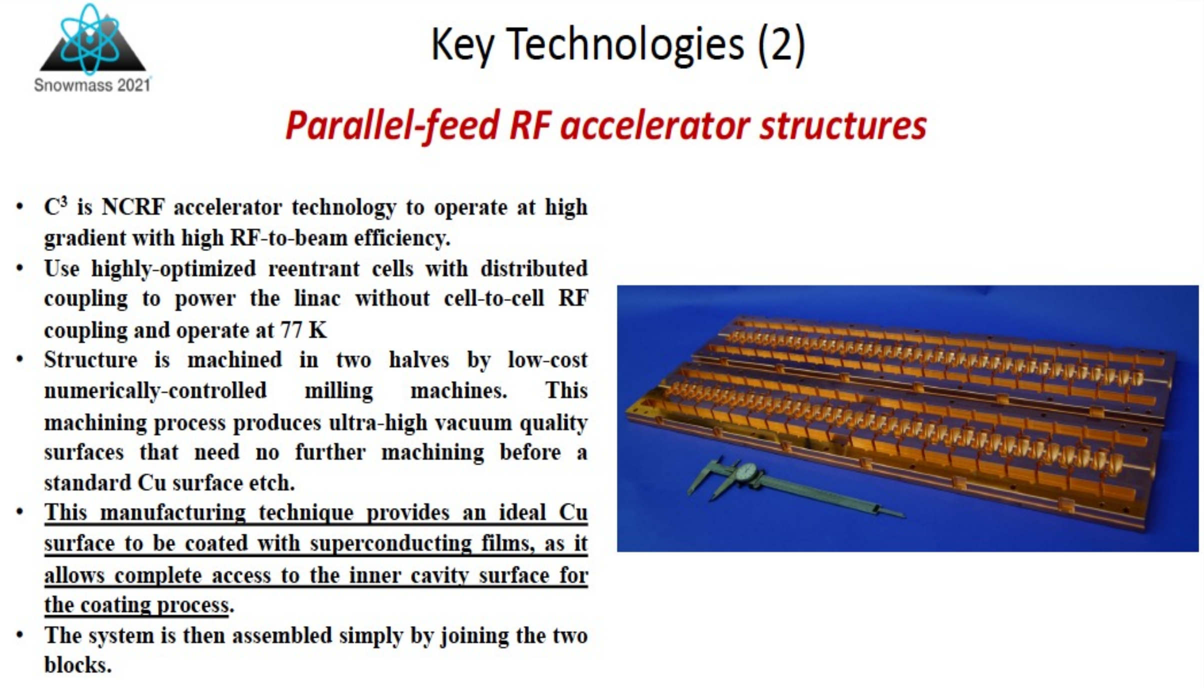
Key Technologies (1)

Coating Cu/bronze inner surface with thin layer of Nb_3Sn

White paper at https://arxiv.org/ftp/arxiv/papers/2203/2203.09718.pdf

- **Electroplating** – FNAL, KEK, Akita Kagaku Co. Ltd., Tohoku University, Akita Industrial Technology Center.
- **Magnetron sputtering in co-sputtering mode** from two targets with direct deposition on substrate of stoichiometric Nb_3Sn - Technische Universität Darmstadt.
- **Magnetron sputtering from a single stoichiometric target** – CERN, Old Dominion University
- **Multilayer sequential magnetron sputtering** - Old Dominion University, LANL
- **The Bronze Route**, which builds upon Nb_3Sn superconducting wire technology and also exploits the heat treatment temperature reduction effect of the Cu as ternary element of the Nb-Sn-Cu phase diagram – NIMS.

Schematic of magnetron sputtering setup with two targets at Technische Universität Darmstadt.



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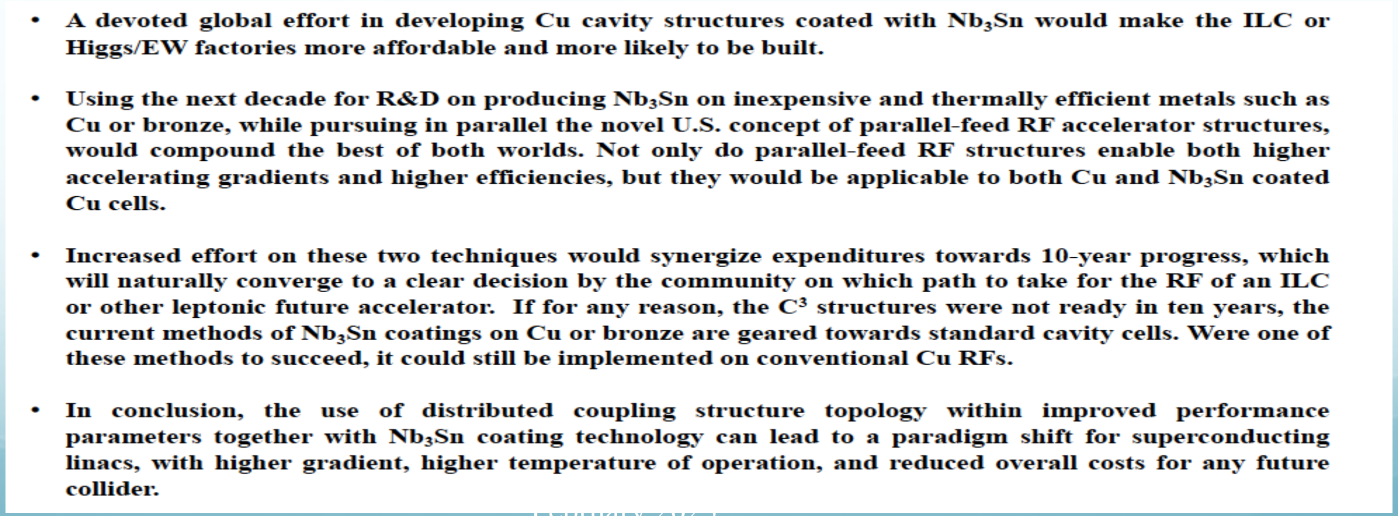
Key Technologies (2)

Parallel-feed RF accelerator structures

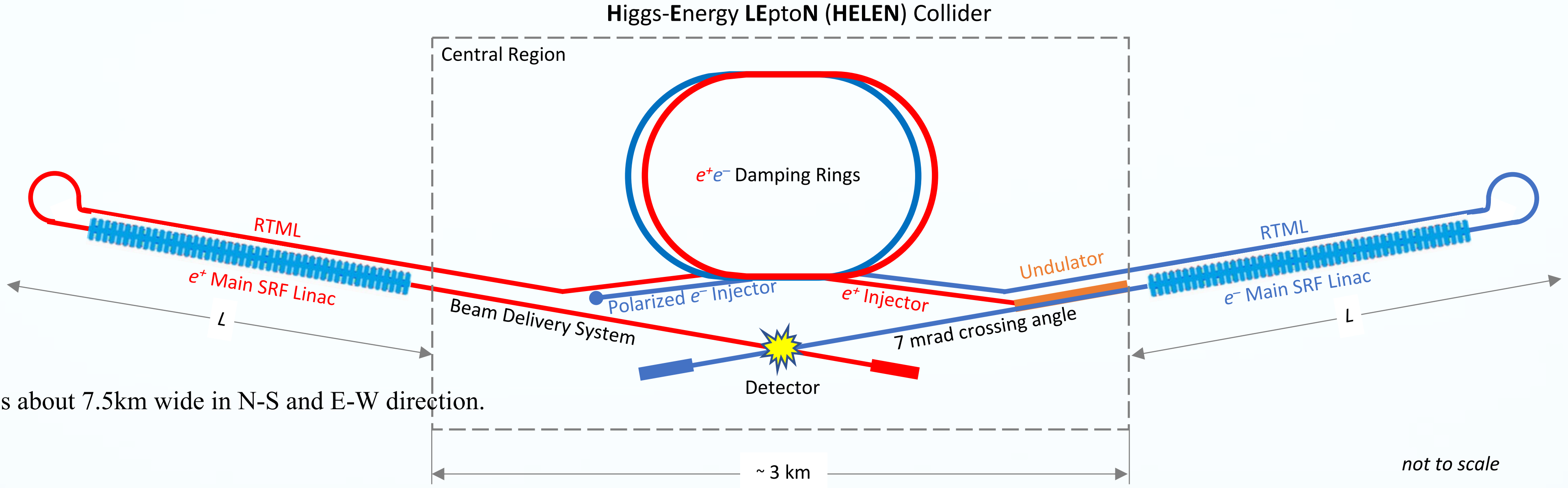
- C^3 is NCRF accelerator technology to operate at high gradient with high RF-to-beam efficiency.
- Use highly-optimized reentrant cells with distributed coupling to power the linac without cell-to-cell RF coupling and operate at 77 K
- Structure is machined in two halves by low-cost numerically-controlled milling machines. This machining process produces ultra-high vacuum quality surfaces that need no further machining before a standard Cu surface etch.
- This manufacturing technique provides an ideal Cu surface to be coated with superconducting films, as it allows complete access to the inner cavity surface for the coating process.
- The system is then assembled simply by joining the two blocks.



- **A devoted global effort in developing Cu cavity structures coated with Nb_3Sn would make the ILC or Higgs/EW factories more affordable and more likely to be built.**
- **Using the next decade for R&D on producing Nb_3Sn on inexpensive and thermally efficient metals such as Cu or bronze, while pursuing in parallel the novel U.S. concept of parallel-feed RF accelerator structures, would compound the best of both worlds. Not only do parallel-feed RF structures enable both higher accelerating gradients and higher efficiencies, but they would be applicable to both Cu and Nb_3Sn coated Cu cells.**
- **Increased effort on these two techniques would synergize expenditures towards 10-year progress, which will naturally converge to a clear decision by the community on which path to take for the RF of an ILC or other leptonic future accelerator. If for any reason, the C^3 structures were not ready in ten years, the current methods of Nb_3Sn coatings on Cu or bronze are geared towards standard cavity cells. Were one of these methods to succeed, it could still be implemented on conventional Cu RFs.**
- **In conclusion, the use of distributed coupling structure topology within improved performance parameters together with Nb_3Sn coating technology can lead to a paradigm shift for superconducting linacs, with higher gradient, higher temperature of operation, and reduced overall costs for any future collider.**

Higgs-Energy LEptoN collider (HELEN)

An ILC with advanced SRF and reduced length, suitable for the Fermilab campus.

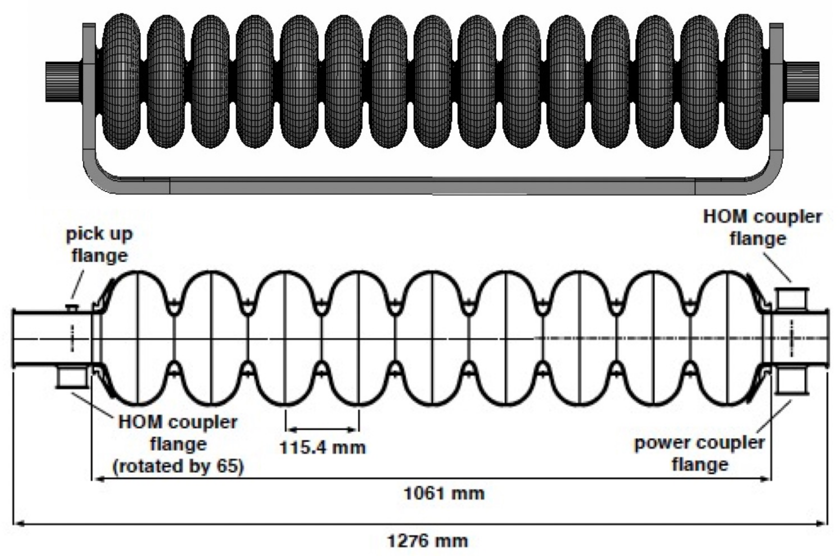


Fermilab campus is about 7.5km wide in N-S and E-W direction.

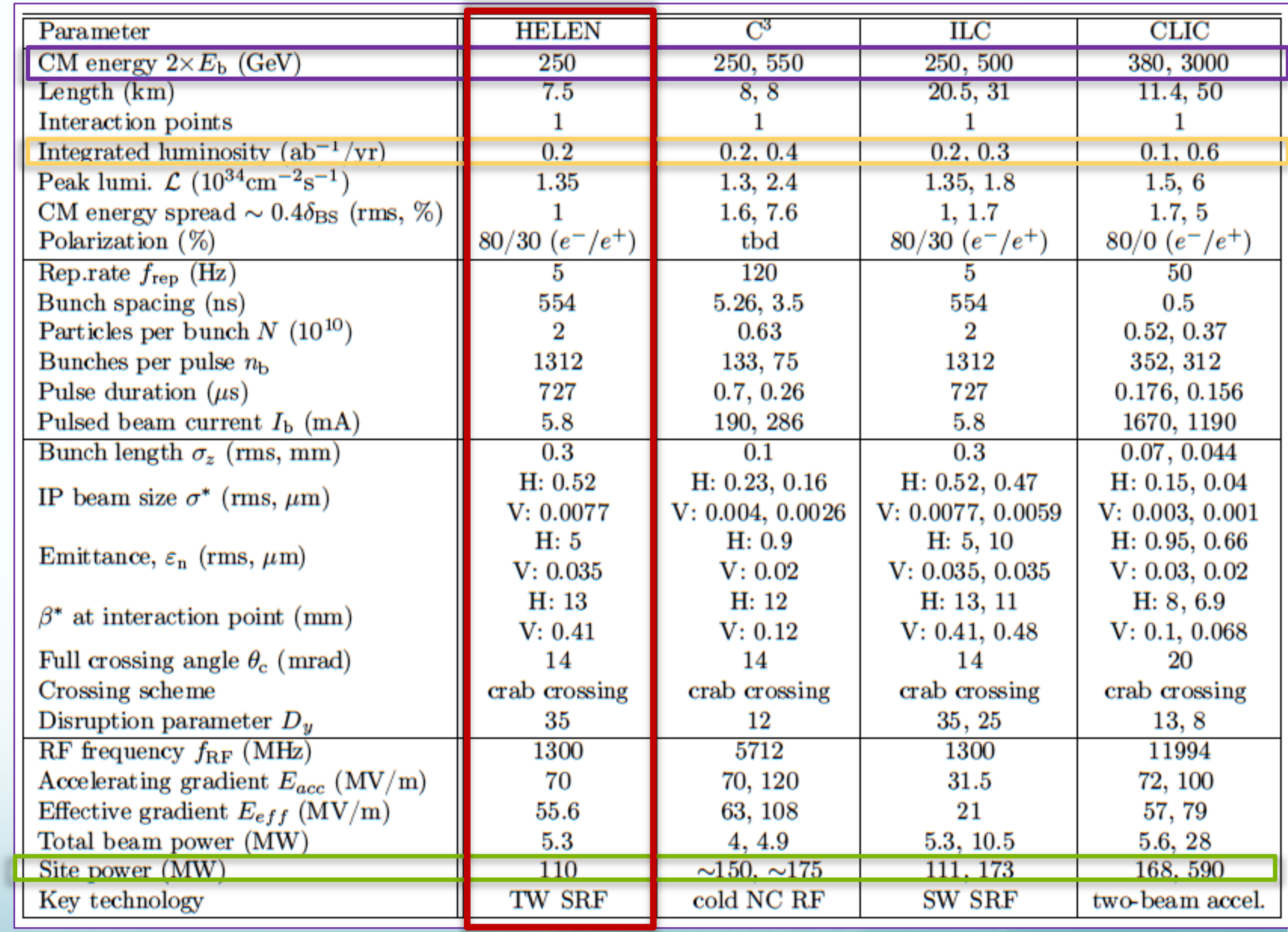
- Accelerating gradients of **50 MV/m** have been **shown**, much beyond the ILC design with 31.5 MV/m.
- **Traveling wave SRF structures** with innovations in cavity surface treatments and processing should allow **70 MV/m**.
- **Nb_3Sn** may enable **90 MV/m** standing wave cavities, and even more with traveling waves.
- A conceptual LC design with advanced cavities leads to reduced length for a **250 GeV e^+e^- collider.**
  - **55MV/m, 71% fill factor ➔ 9.4km**
  - **70MV/m, 84% fill factor ➔ 7.5km**
  - **90MV/m, 71% fill factor ➔ 6.9km**

Baseline Design and LC comparisons

- The HELEN baseline uses **traveling waves (TW) SRF operating at 70 MV/m is selected as the baseline option**.



- Circularly TW cavities don’t waste energy on non-accelerating backward waves!
- Most of the HELEN parameters (except for SRF) are identical to those of the ILC.

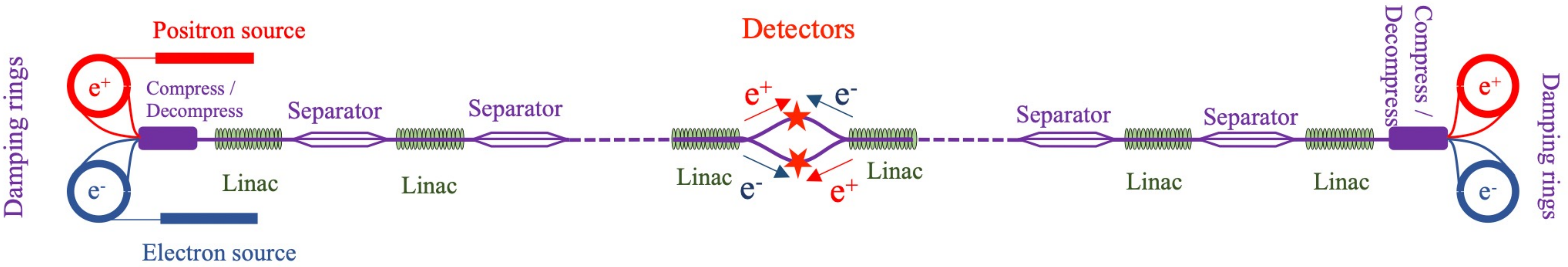


Parameter	HELEN	C^3	ILC	CLIC
CM energy $2\times E_b$ (GeV)	250	250, 550	250, 500	380, 3000
Length (km)	7.5	8, 8	20.5, 31	11.4, 50
Interaction points	1	1	1	1
Integrated luminosity (ab^{-1}/yr)	0.2	0.2, 0.4	0.2, 0.3	0.1, 0.6
Peak lumi. $\mathcal{L}$ (10^{34}cm^{-2}s^{-1})	1.35	1.3, 2.4	1.35, 1.8	1.5, 6
CM energy spread $\sim 0.4\delta_{BS}$ (rms, %)	1	1.6, 7.6	1, 1.7	1.7, 5
Polarization (%)	80/30 (e^-/e^+)	tbd	80/30 (e^-/e^+)	80/0 (e^-/e^+)
Rep.rate f_{rep} (Hz)	5	120	5	50
Bunch spacing (ns)	554	5.26, 3.5	554	0.5
Particles per bunch N (10^{10})	2	0.63	2	0.52, 0.37
Bunches per pulse n_b	1312	133, 75	1312	352, 312
Pulse duration (μs)	727	0.7, 0.26	727	0.176, 0.156
Pulsed beam current I_b (mA)	5.8	190, 286	5.8	1670, 1190
Bunch length σ_z (rms, mm)	0.3	0.1	0.3	0.07, 0.044
IP beam size σ^* (rms, μm)	H: 0.52 V: 0.0077	H: 0.23, 0.16 V: 0.004, 0.0026	H: 0.52, 0.47 V: 0.0077, 0.0059	H: 0.15, 0.04 V: 0.003, 0.001
Emittance, ε_n (rms, μm)	H: 5 V: 0.035	H: 0.9 V: 0.02	H: 5, 10 V: 0.035, 0.035	H: 0.95, 0.66 V: 0.03, 0.02
β^* at interaction point (mm)	H: 13 V: 0.41	H: 12 V: 0.12	H: 13, 11 V: 0.41, 0.48	H: 8, 6.9 V: 0.1, 0.068
Full crossing angle θ_c (mrad)	14	14	14	20
Crossing scheme	crab crossing	crab crossing	crab crossing	crab crossing
Disruption parameter D_y	35	12	35, 25	13, 8
RF frequency f_{RF} (MHz)	1300	5712	1300	11994
Accelerating gradient E_{acc} (MV/m)	70	70, 120	31.5	72, 100
Effective gradient E_{eff} (MV/m)	55.6	63, 108	21	57, 79
Total beam power (MW)	5.3	4, 4.9	5.3, 10.5	5.6, 28
Site power (MW)	110	~150, ~175	111, 173	168, 590
Key technology	TW SRF	cold NC RF	SW SRF	two-beam accel.

More details in F. Zimmermann’s talk

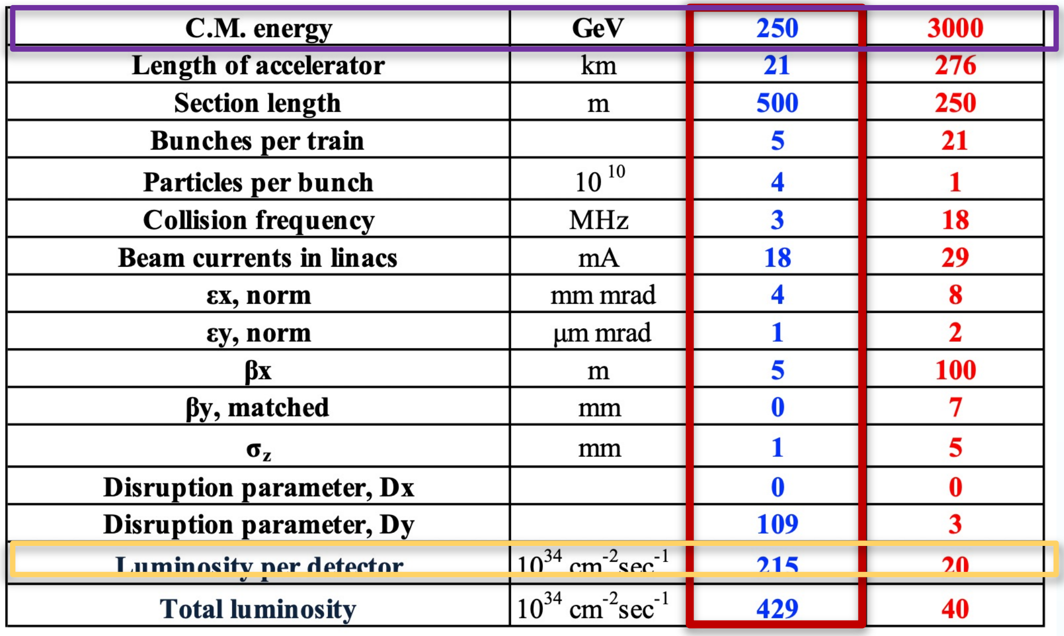
ReLiC – Recycling Linear Collider

ReLiC collider recycles polarized electrons and positrons, and their energy



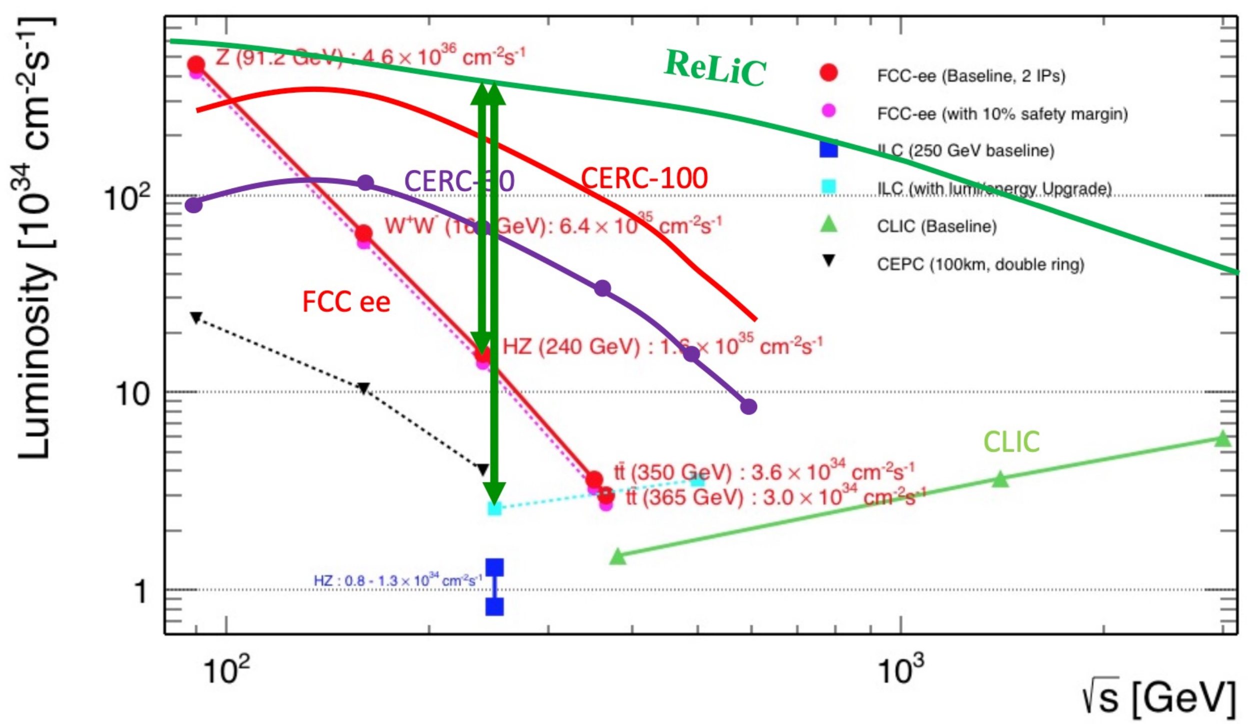
- Flat beams are emittance-cooled and polarized in damping rings with “top off” to replace burned-off particles (only nAs)
- Beams are accelerated **on-axis** in SRF linacs to avoid emittance growth and collide in one of the detectors
- After collision at the top energy, they are decelerated in the opposite linacs
- Decelerating bunch trains are separated from the axis to avoid collision with the accelerating one.
- After few damping times the trip repeats in the opposite direction and beams collide in a second detector

ReLiC would be capable of very high luminosity



C.M. energy	GeV	250	3000
Length of accelerator	km	21	276
Section length	m	500	250
Bunches per train		5	21
Particles per bunch	10^{10}	4	1
Collision frequency	MHz	3	18
Beam currents in linacs	mA	18	29
εx, norm	mm mrad	4	8
εy, norm	μm mrad	1	2
βx	m	5	100
βy, matched	mm	0	7
σ_z	mm	1	5
Disruption parameter, Dx		0	0
Disruption parameter, Dy		109	3
Luminosity per detector	10^{34} cm^{-2}sec^{-1}	215	20
Total luminosity	10^{34} cm^{-2}sec^{-1}	429	40

Gain of 40 to 200 at HIGS energy



- Except for the energy recovery, most design aspects correspond to the ILC.

More details in F. Zimmermann's talk

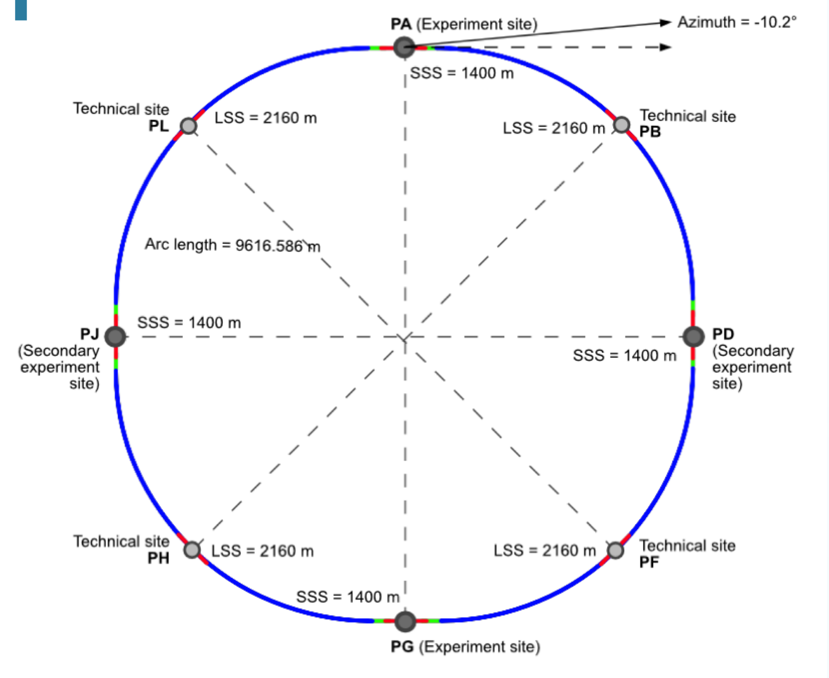
- The luminosity can be vastly larger, by two orders of magnitude.
- The power needs can be similar to the ILC numbers when progress in high-Q SRF and in cryogenic technology are made.
- A related ERL linear collider proposal (**ERLC**) uses two-axes SRF cavities and comes to similar vast luminosity increases.
- These ERL-based designs provide the most energy efficient luminosity values!

FCC-ee Accelerator Design

More details in M. Hofer's talk

High luminosity precision study of Z, W, H, and $t\bar{t}$; unprecedented energy resolution at Z (<100 keV) and W ; **Low-risk technical solution** based on 60 years of e^+e^- circular colliders and particle detectors; R&D on components for improved performance but no need for "demonstration"; Infrastructure could support a **century of physics** : FCC-ee → FCC-hh → FCC-eh and several other options ; **Strong support** from CERN, partners, and ESPP ; **Ongoing study focused on siting & "feasibility" for 2026 ESPP**

Parameter [4 IPs, *C*=91.1 km]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1400	135	26.7	5.0
number bunches/beam	8800	1120	336	42
bunch intensity [10^{11}]	2.76	2.29	1.51	2.26
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.48/0	4.0/7.67
long. damping time [turns]	1170	216	64.5	18.5
vertical beta* [mm]	0.8	1	1	1.6
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	10	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.32 / 15.2	3.55 / 7.02	2.5 / 4.45	1.67 / 2.54
luminosity per IP [10^{34} cm^{-2}s^{-1}]	181	17.3	7.2	1.25
tot. integr. luminosity / yr [ab^{-1}/yr]	86	8	3.4	0.6



Double ring e^+e^-; **common footprint w/ future 100 TeV hadron collider** (FCC-hh)

Asymmetric IR layout & optics; Θ_c=30 mrad, **"virtual" crab-waist collision**, 2 or 4 IPs – dynamic aperture;

SR power 50 MW/beam ; Top-up injection

key concepts (top-up, crab waist, …) demonstrated in routine operation at previous machines ; **technology available**

K. Oide

strong synergies with SuperKEKB & US EIC

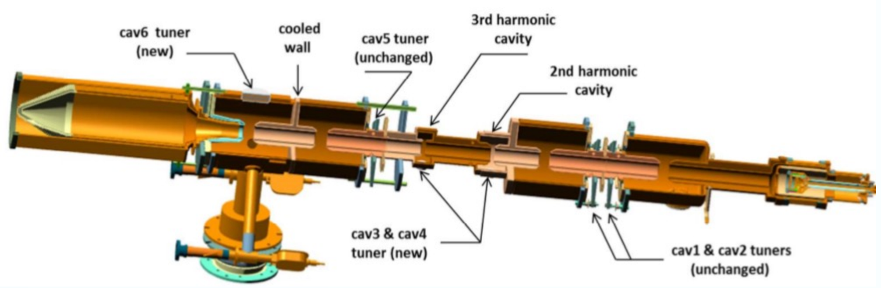
Institut national de physique nucléaire et de physique des particules

FCC-ee Key Accelerator Technologies

Jefferson Lab

efficient RF power sources (400 & 800 MHz)

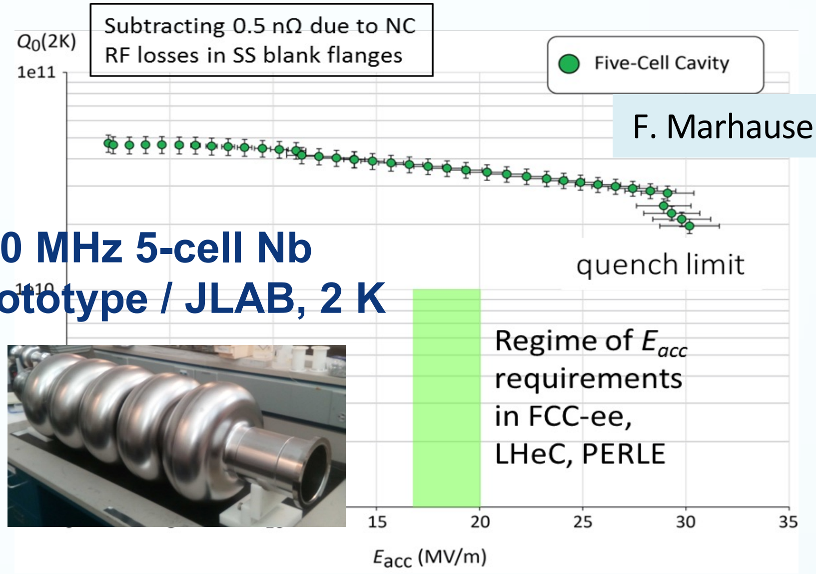
I. Syratchev



FPC & HOM coupler, cryomodule, thin-film coatings…

efficient SC cavities

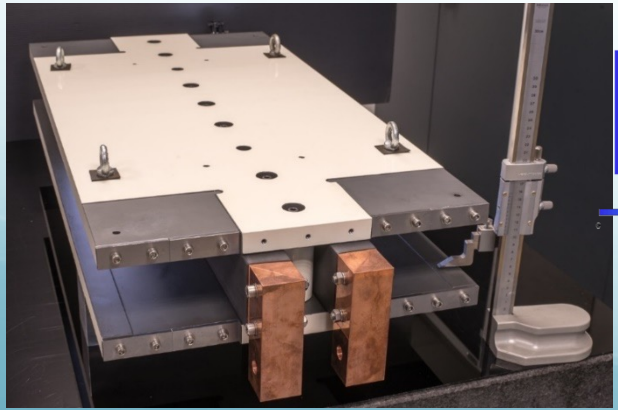
400 MHz 1-,2- & 4-cell Nb/Cu , 4.5 K

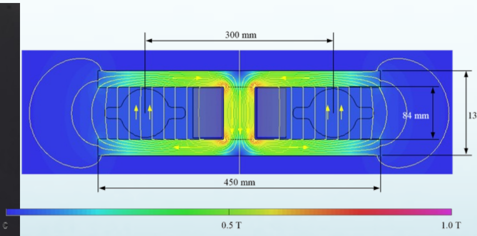


F. Marhauser

800 MHz 5-cell Nb prototype / JLAB, 2 K

twin aperture arc dipoles

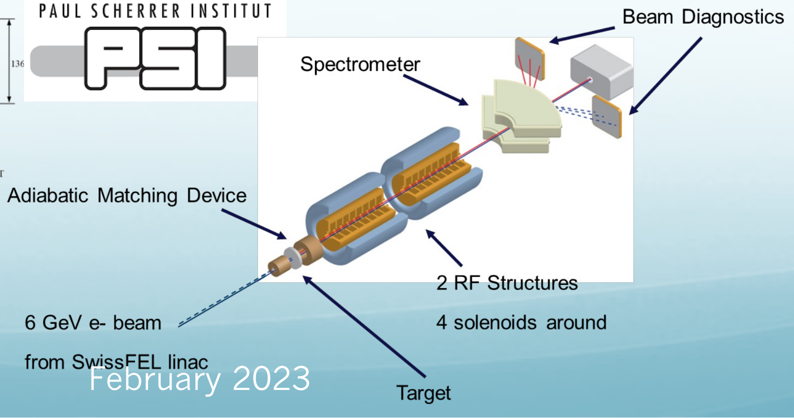




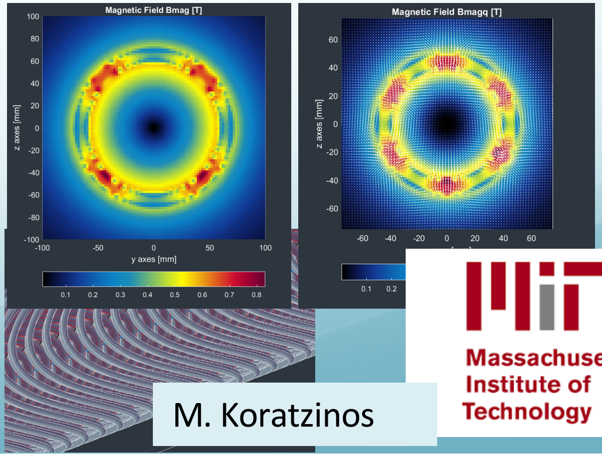
A. Milanese

prototype high-yield e⁺ source w HTS solenoid at SwissFEL

PAUL SCHERRER INSTITUT PSI



under study: CCT HTS quad's & sext's for arcs



Massachusetts Institute of Technology

M. Koratzinos

FCC Civil Engineering & Site

Optimized placement and layout (2021)

8 surface sites – less land, <40 ha

Possibility of 4 FCC-ee experiments

All sites close to road infrastructures <
 5 km of new road constructions in total for all sites combined

Several sites close to **400 kV grid lines**

Good road connections of PD, PF, PG, PH suggest **operation pole around Annecy / LAPP**

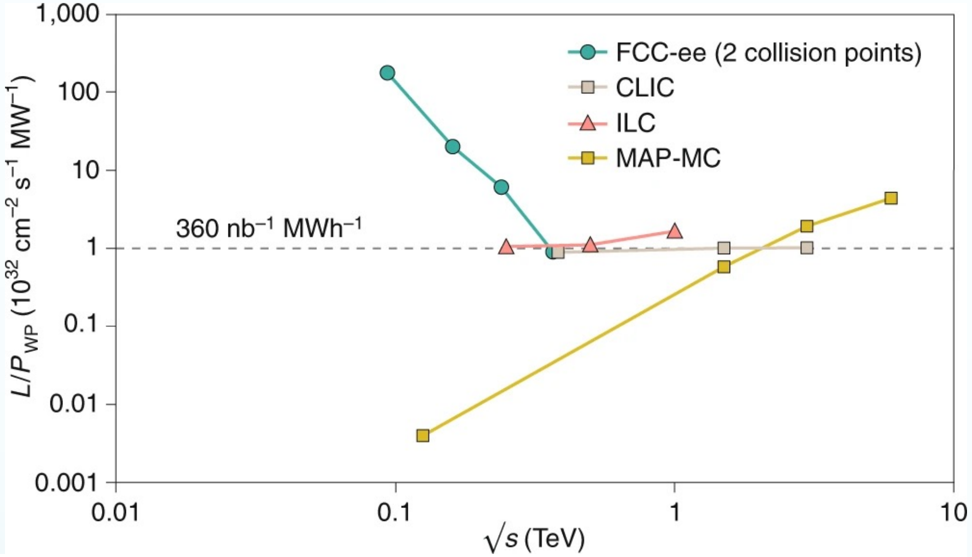
J. Gutleber

Site investigations planned for 2024 – 2025: ~40-50 drillings, 100 km of seismic lines

FCC-ee Sustainability Studies

highly sustainable Higgs factory

luminosity vs. electricity consumption



Thanks to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

FCC-ee annual energy consumption ~ LHC/HL-LHC

120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880					69	199872	MWh
Energy consumption / year	365	8760						1.52	TWh
Average power								174	MW

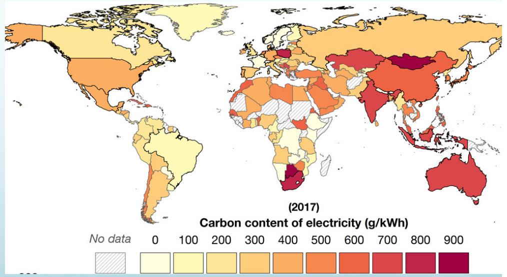
J.-P. Burnet, FCC Week 2022

CERN Meyrin, SPS, FCC	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Energy consumption (TWh/y)	1.82	1.92	2.09	2.54

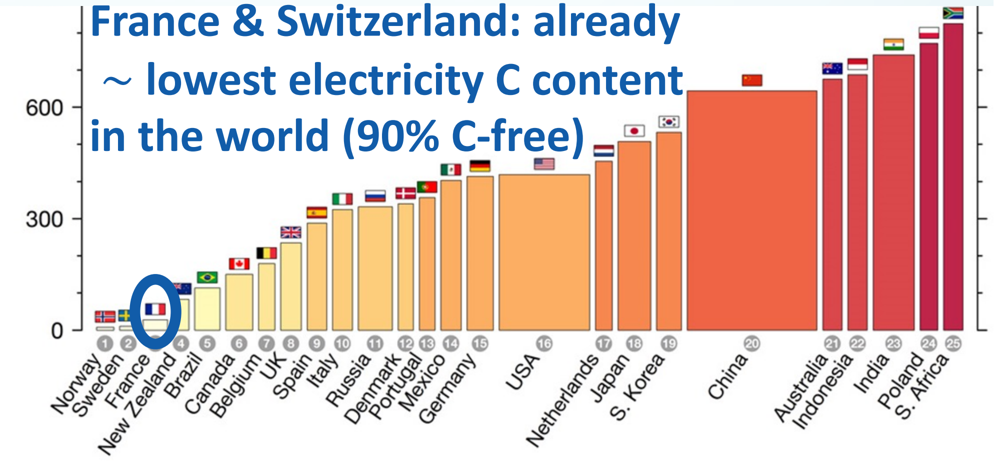
incl. CERN site & SPS

More details in F. Zimmermann's talk

powered by mix of renewable & other C-free sources



https://www.carbonbrief.org/



France & Switzerland: already ~ lowest electricity C content in the world (90% C-free)

optimum usage of excavation material

int'l competition "mining the future®"

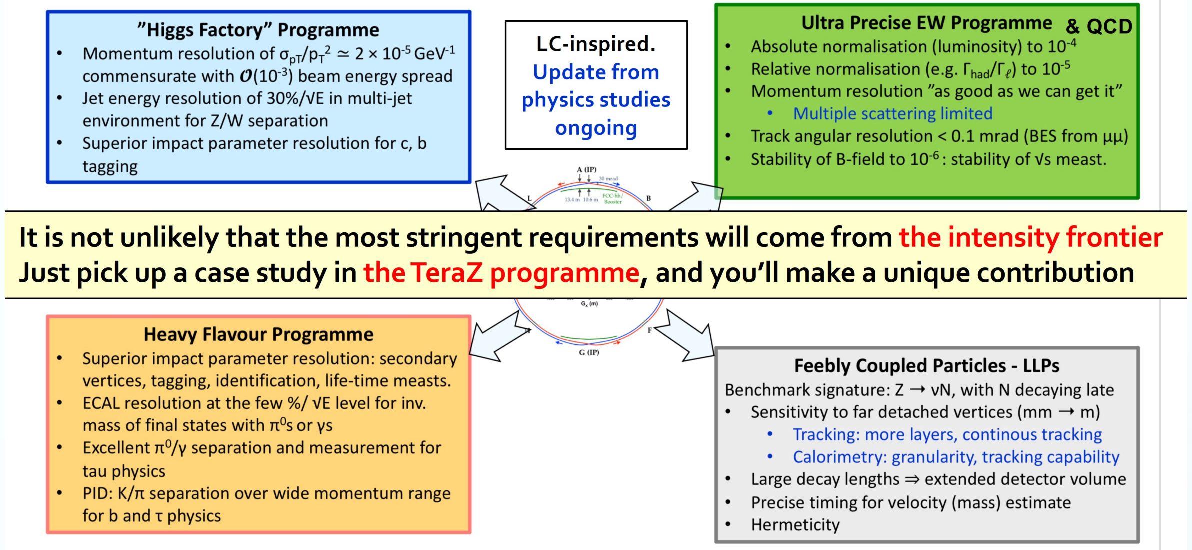
https://indico.cern.ch/event/1001465/

FCC-ee upgrades, extensions, possible staging

- **≥4 differently optimized experiments**
- FCC-ee: not only Higgs, but **Z and W factory** (TeraZ); **$t\bar{t}$ upgrade** (~1 BCHF); optional **direct *s*-channel Higgs production** at 125 GeV
- **civil construction & technical infrastructures shared with** [and prepare] 100 TeV **hadron collider FCC-hh – stage 2 of FCC integrated program**
- numerous other possible extensions (ep/eA/AA, Gamma Factory, ERL upgrade, LEMMA-type μ collider FCC-μμ ? …)

Calls for at least 4 detector concepts; 3 under development (CLD, IDEA, NL ECAL, with room for more)

P. Janot, M. Dam, et al.



"Higgs Factory" Programme
- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

LC-inspired.
Update from physics studies ongoing

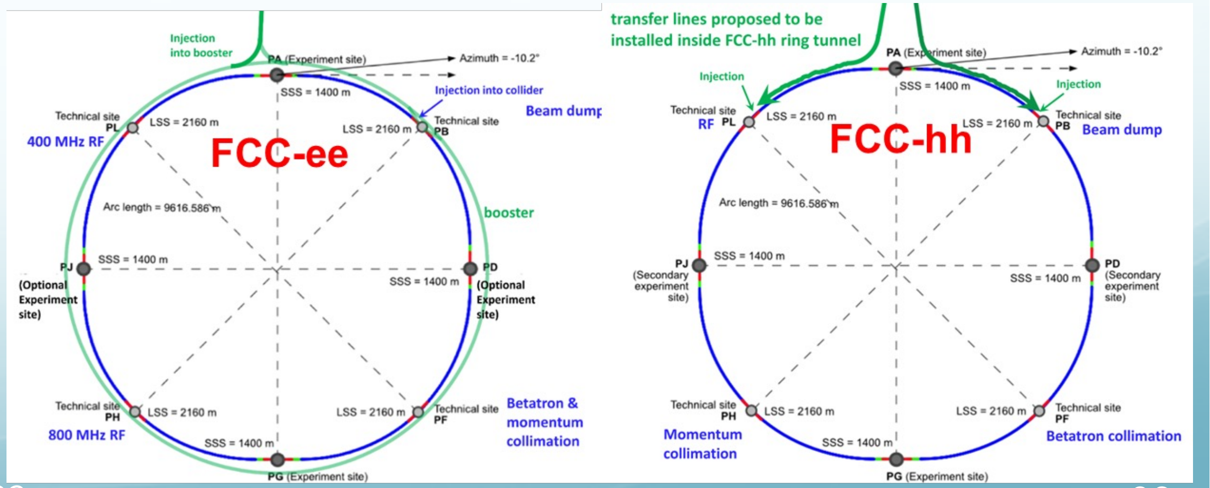
Ultra Precise EW Programme & QCD
- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6}: stability of √s meast.

It is not unlikely that the most stringent requirements will come from the intensity frontier
Just pick up a case study in the TeraZ programme, and you'll make a unique contribution

Heavy Flavour Programme
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs
Benchmark signature: Z → νN, with N decaying late
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

Common FCC detector software framework in a joint effort



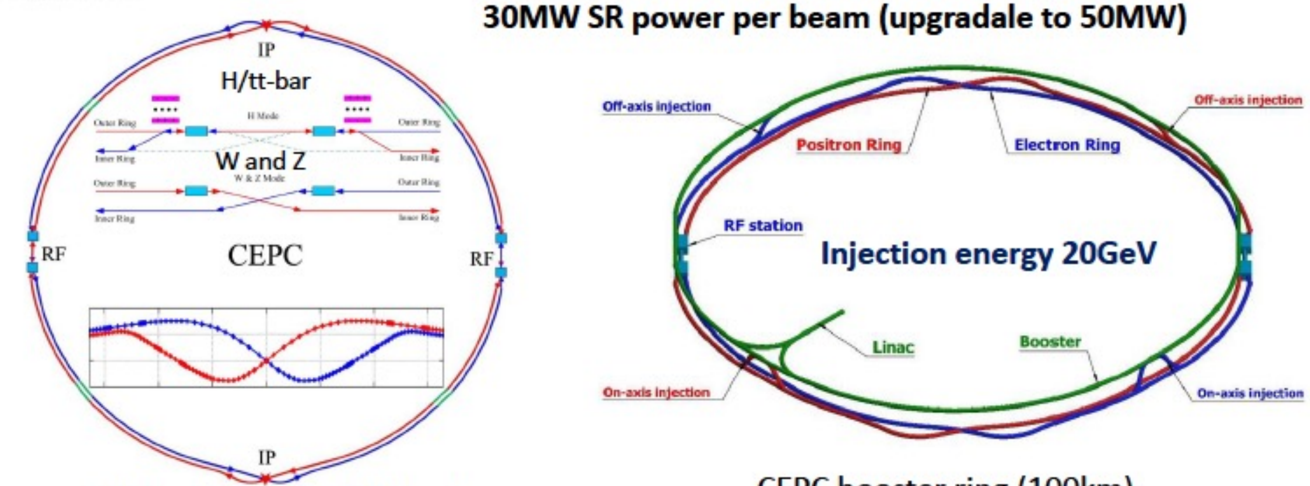
2045 - 2060

2070 - 2090++

CEPC Accelerator Design and Challenges

CEPC as a Higgs Factory： H, W, Z, upgradable to tt-bar, followed by a SppC ~125TeV

30MW SR power per beam (upgradale to 50MW)



CEPC collider ring (100km)

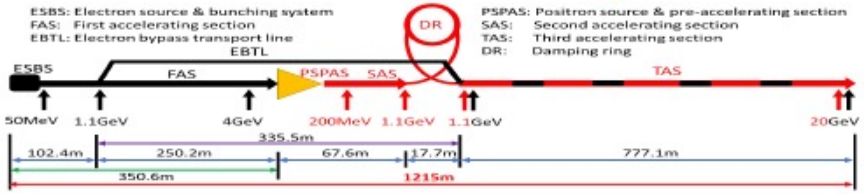
CEPC booster ring (100km)

More details in CEPC's talks

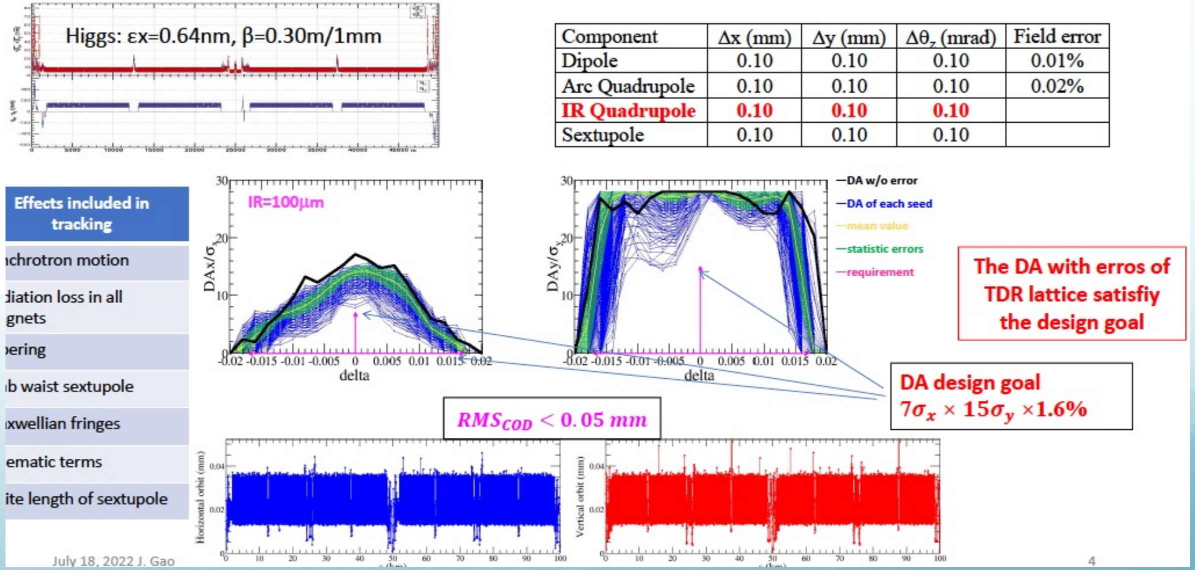
CEPC TDR S+C-band 20GeV linac injector

ESBS: Electron source & bunching system
FAS: First accelerating section
EBTL: Electron bypass transport line

PSPAS: Positron source & pre-accelerating section
SAS: Second accelerating section
TAS: Third accelerating section
DR: Damping ring



-dynamic apertures with errors



Component	Δx (mm)	Δy (mm)	Δθz (mrad)	Field error
Dipole	0.10	0.10	0.10	0.01%
Arc Quadrupole	0.10	0.10	0.10	0.02%
IR Quadrupole	**0.10**	**0.10**	**0.10**	
Sextupole	0.10	0.10	0.10	

Effects included in tracking

- ıchrotron motion
- diation loss in all gnets
- ɔering
- ıb waist sextupole
- ıxwellian fringes
- ematic terms
- ite length of sextupole

The DA with erros of TDR lattice satisfiy the design goal

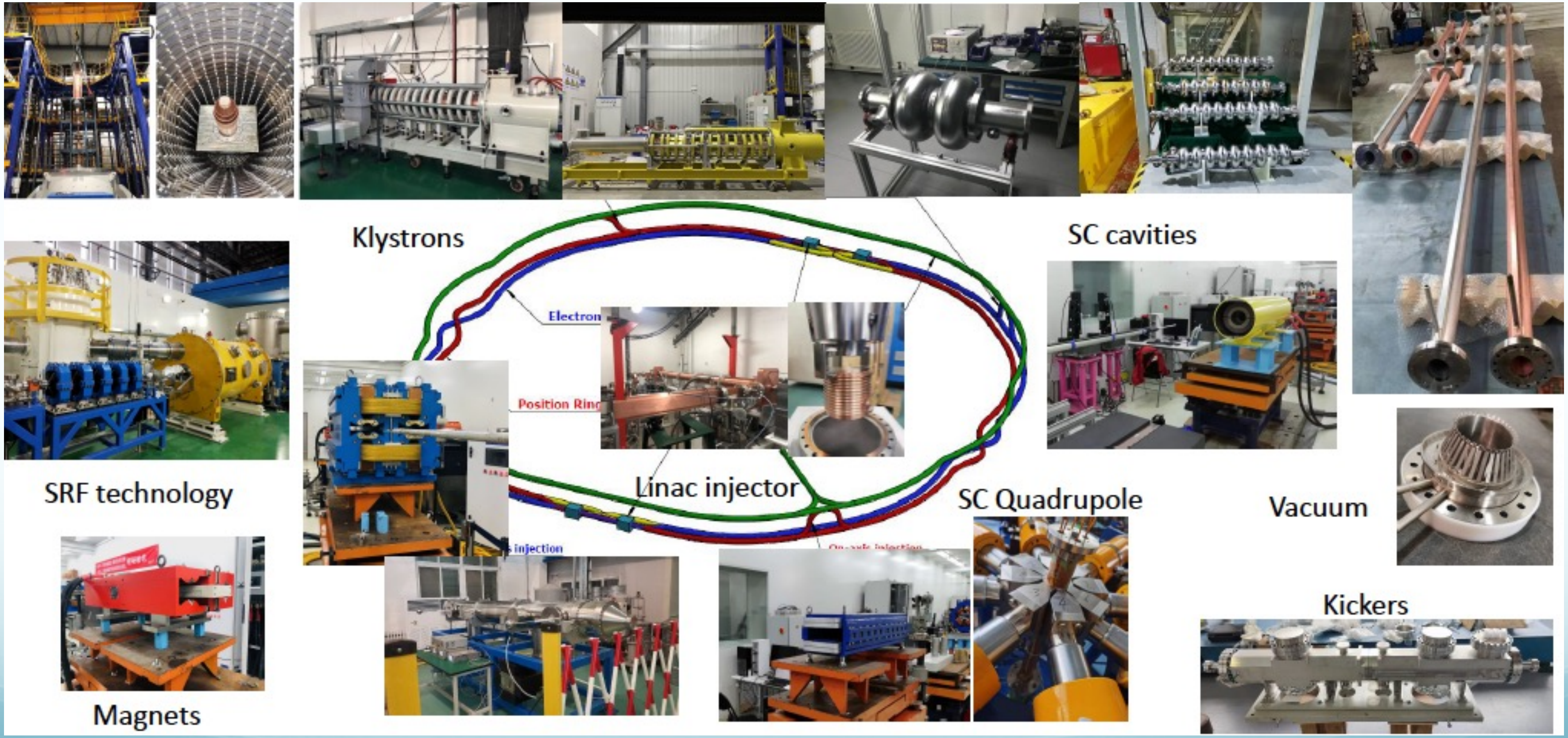
DA design goal
$7\sigma_x \times 15\sigma_y \times 1.6\%$

$RMS_{COD} < 0.05\ mm$

July 18, 2022 J. Gao

4

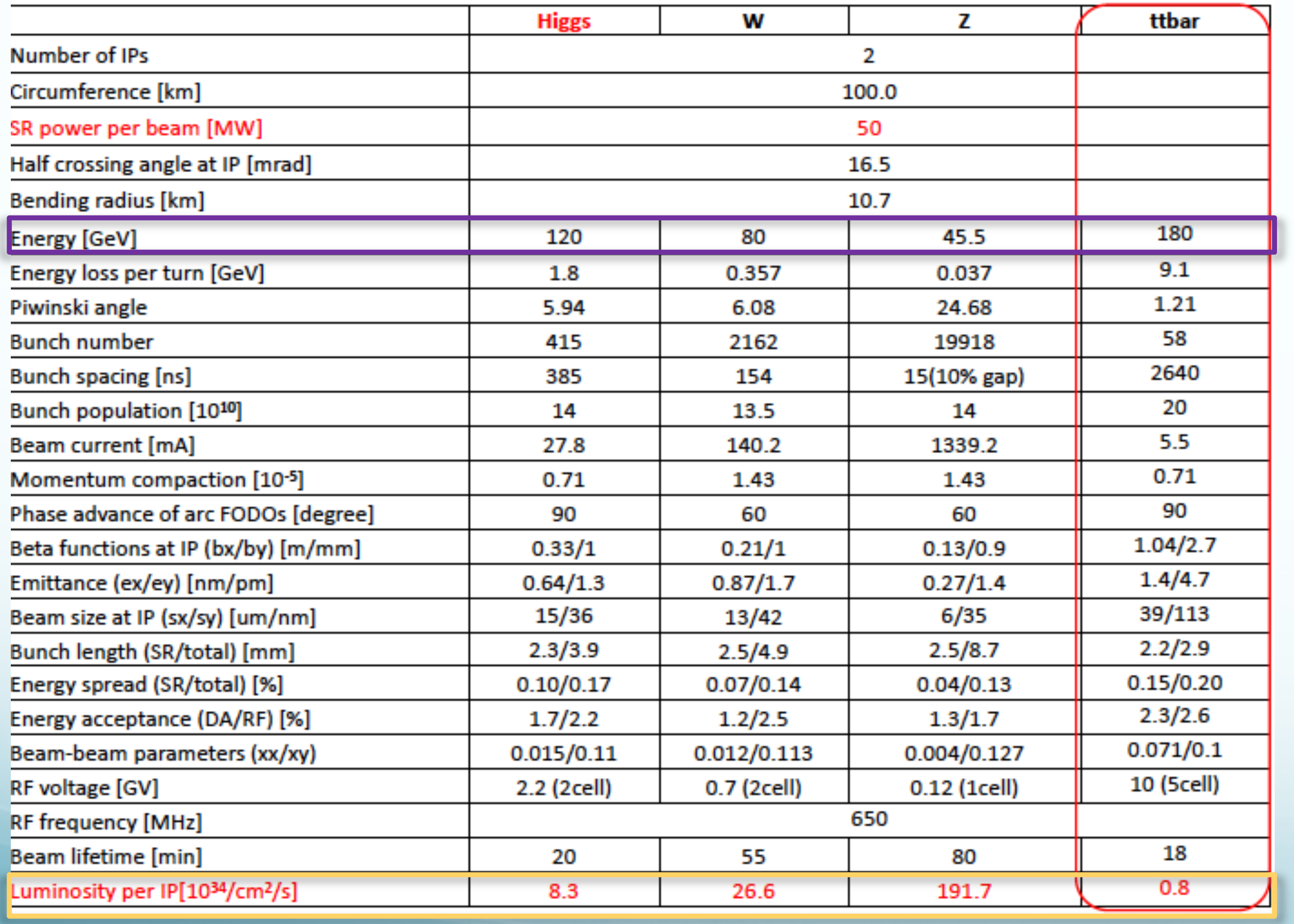
CEPC Key technologies



CEPC Baseline, extension and upgrades

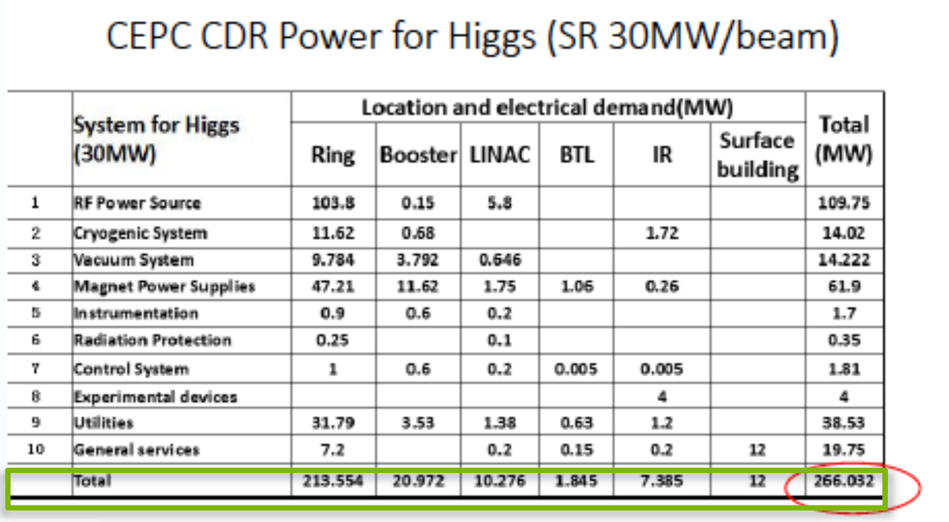
More details in F. Zimmermann's talk

CEPC TDR Parameters (upgrade)



	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	50			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	120	80	45.5	180
Energy loss per turn [GeV]	1.8	0.357	0.037	9.1
Piwinski angle	5.94	6.08	24.68	1.21
Bunch number	415	2162	19918	58
Bunch spacing [ns]	385	154	15(10% gap)	2640
Bunch population [10^{10}]	14	13.5	14	20
Beam current [mA]	27.8	140.2	1339.2	5.5
Momentum compaction [10^{-5}]	0.71	1.43	1.43	0.71
Phase advance of arc FODOs [degree]	90	60	60	90
Beta functions at IP (bx/by) [m/mm]	0.33/1	0.21/1	0.13/0.9	1.04/2.7
Emittance (ex/ey) [nm/pm]	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Beam size at IP (sx/sy) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Energy spread (SR/total) [%]	0.10/0.17	0.07/0.14	0.04/0.13	0.15/0.20
Energy acceptance (DA/RF) [%]	1.7/2.2	1.2/2.5	1.3/1.7	2.3/2.6
Beam-beam parameters (xx/xy)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF voltage [GV]	2.2 (2cell)	0.7 (2cell)	0.12 (1cell)	10 (5cell)
RF frequency [MHz]	650			
Beam lifetime [min]	20	55	80	18
Luminosity per IP[10^{34}/cm^2/s]	8.3	26.6	191.7	0.8

CEPC TDR Power and Green CEPC

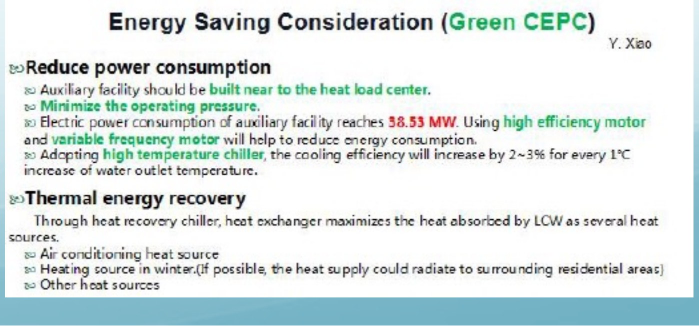


CEPC CDR Power for Higgs (SR 30MW/beam)

	System for Higgs (30MW)	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	103.8	0.15	5.8				109.75
2	Cryogenic System	11.62	0.68			1.72		14.02
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	47.21	11.62	1.75	1.06	0.26		61.9
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	31.79	3.53	1.38	0.63	1.2		38.53
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	213.554	20.972	10.276	1.845	7.385	12	266.032

Total TDR power at Higgs (SR 30MW/beam): 272MW
where
Linac:**15.5MW**
Booster ring: **19.8MW**
Coolider ring: **214.664MW**

Total TDR power at upgrade Higgs (SR 50MW/beam): 344MW



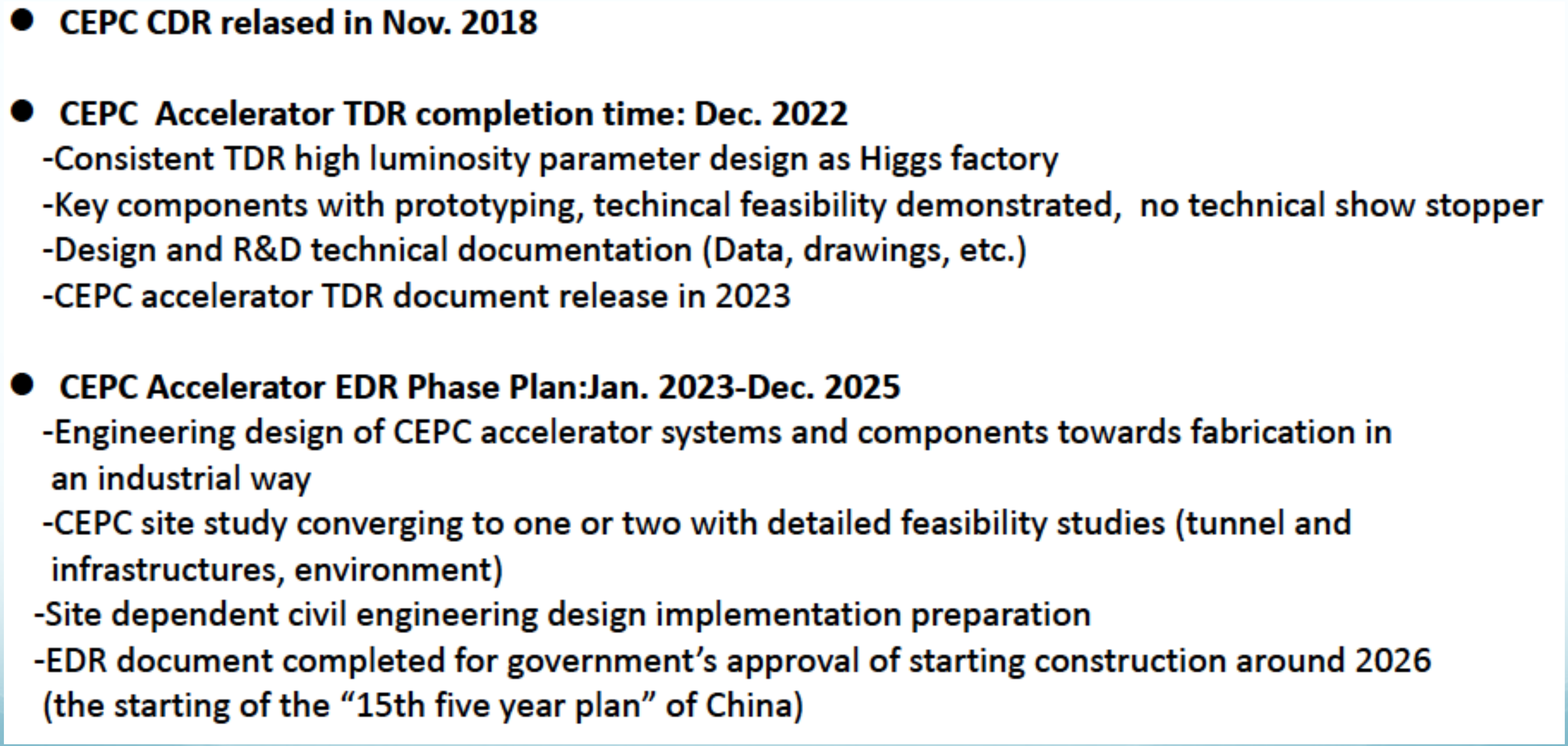
Energy Saving Consideration (Green CEPC)

Y. Xiao

- **Reduce power consumption**
  - Auxiliary facility should be **built near to the heat load center.**
  - **Minimize the operating pressure.**
  - Electric power consumption of auxiliary facility reaches **38.53 MW**. Using **high efficiency motor** and **variable frequency motor** will help to reduce energy consumption.
  - Adopting **high temperature chiller**, the cooling efficiency will increase by 2~3% for every 1°C increase of water outlet temperature.
- **Thermal energy recovery**

Through heat recovery chiller, heat exchanger maximizes the heat absorbed by LCW as several heat sources.
  - Air conditioning heat source
  - Heating source in winter.(If possible, the heat supply could radiate to surrounding residential areas)
  - Other heat sources

CEPC proposal state and R&D



- **CEPC CDR relased in Nov. 2018**

- **CEPC Accelerator TDR completion time: Dec. 2022**

  -Consistent TDR high luminosity parameter design as Higgs factory

  -Key components with prototyping, techincal feasibility demonstrated, no technical show stopper

  -Design and R&D technical documentation (Data, drawings, etc.)

  -CEPC accelerator TDR document release in 2023

- **CEPC Accelerator EDR Phase Plan:Jan. 2023-Dec. 2025**

  -Engineering design of CEPC accelerator systems and components towards fabrication in an industrial way

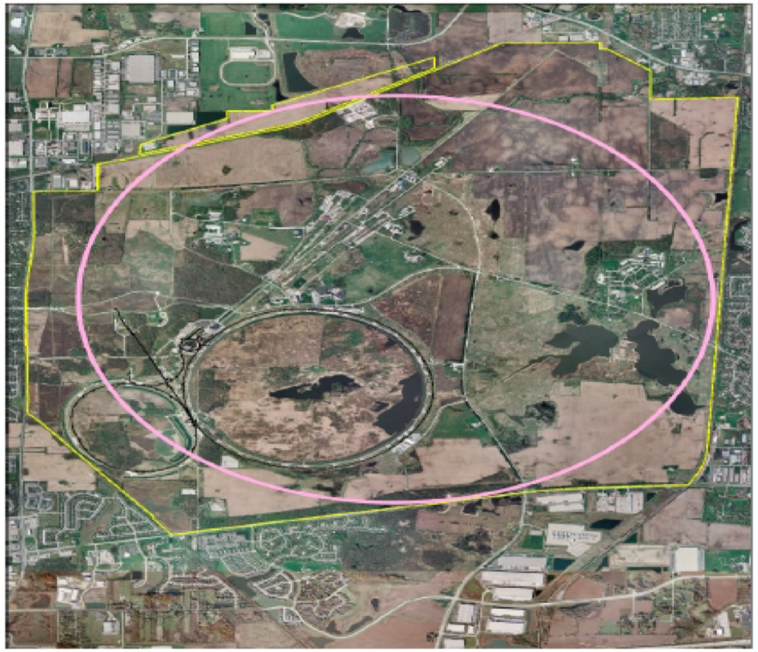
  -CEPC site study converging to one or two with detailed feasibility studies (tunnel and infrastructures, environment)

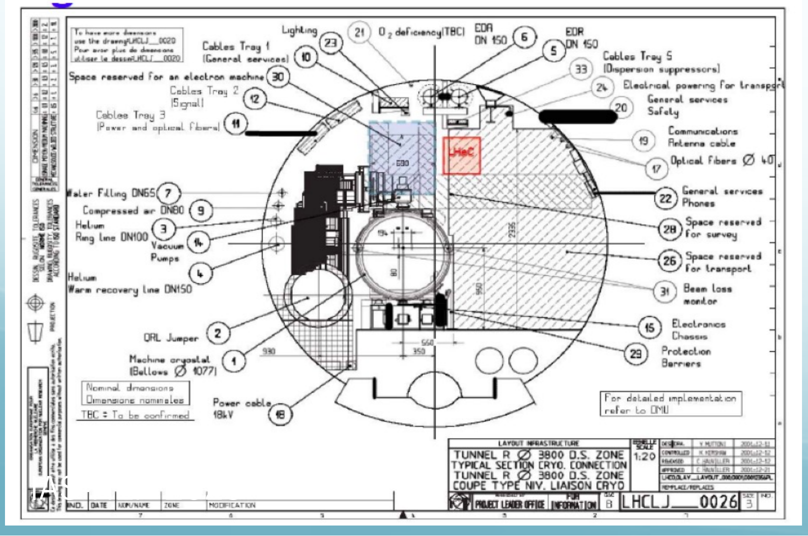
  -Site dependent civil engineering design implementation preparation

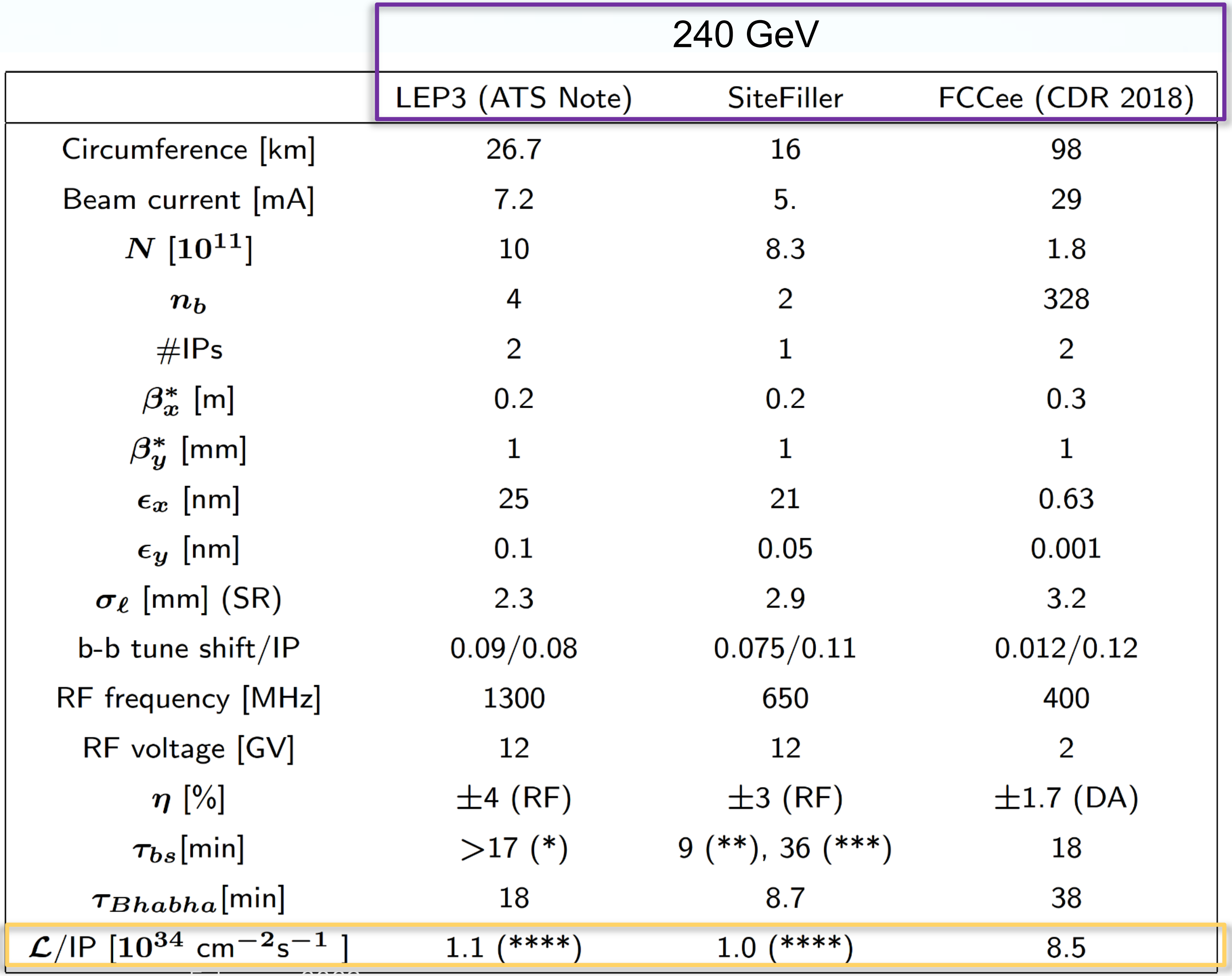
  -EDR document completed for government's approval of starting construction around 2026 (the starting of the "15th five year plan" of China)

FNAL “Site Filler” EPCCF and LEP3*

* not proposed white paper







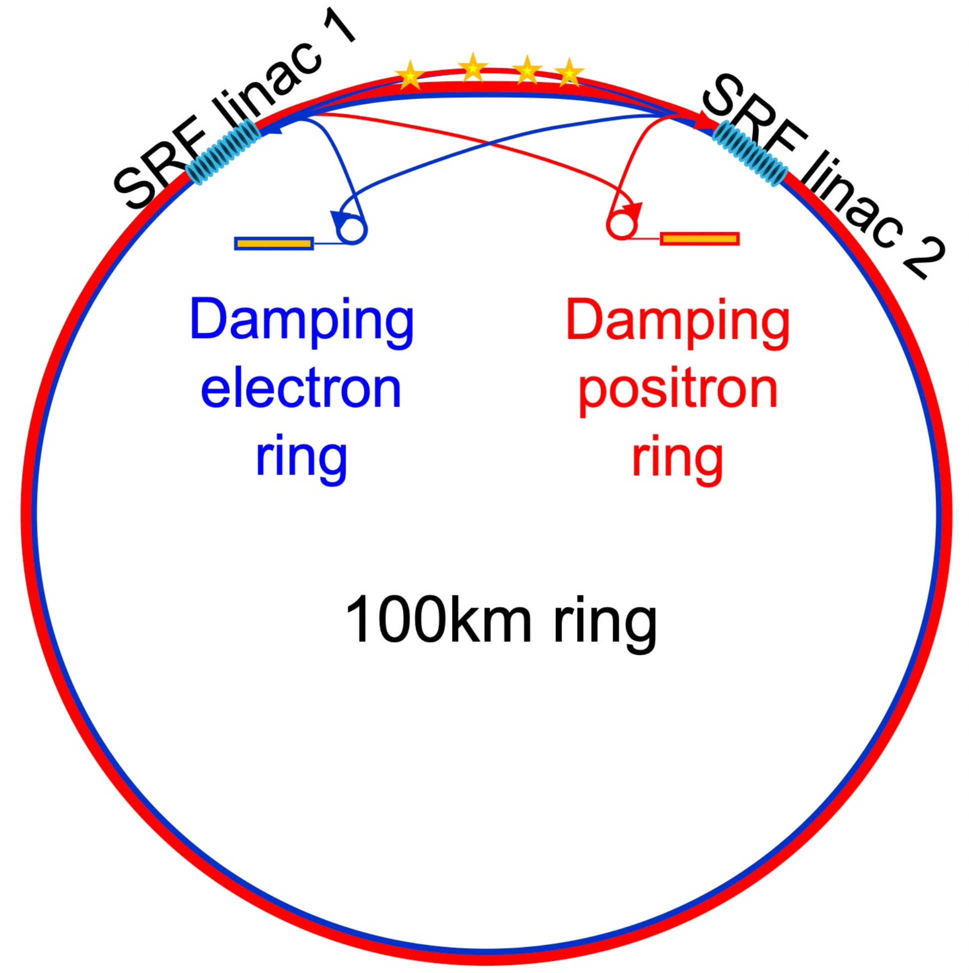
	240 GeV		
	LEP3 (ATS Note)	SiteFiller	FCCee (CDR 2018)
Circumference [km]	26.7	16	98
Beam current [mA]	7.2	5.	29
N $[10^{11}]$	10	8.3	1.8
n_b	4	2	328
#IPs	2	1	2
β_x^* [m]	0.2	0.2	0.3
β_y^* [mm]	1	1	1
ϵ_x [nm]	25	21	0.63
ϵ_y [nm]	0.1	0.05	0.001
σ_ℓ [mm] (SR)	2.3	2.9	3.2
b-b tune shift/IP	0.09/0.08	0.075/0.11	0.012/0.12
RF frequency [MHz]	1300	650	400
RF voltage [GV]	12	12	2
η [%]	±4 (RF)	±3 (RF)	±1.7 (DA)
τ_{bs}[min]	>17 (*)	9 (**), 36 (***)	18
τ_{Bhabha}[min]	18	8.7	38
$\mathcal{L}$/IP $[10^{34}$ cm^{-2}s^{-1}]	1.1 (****)	1.0 (****)	8.5

CERC Baseline design

- Flat beams are cooled in damping rings with top off
- Bunches are ejected with collision frequency
- Beams are accelerated with SRF linacs in two four-path ERLs
- After collision at top energy RF phases are changed to deceleration returning most energy to SRF linacs
- Decelerated beams are reinjected into cooling rings
- After a few damping times the trip repeats

CERC combines the advantages of existing colliders:

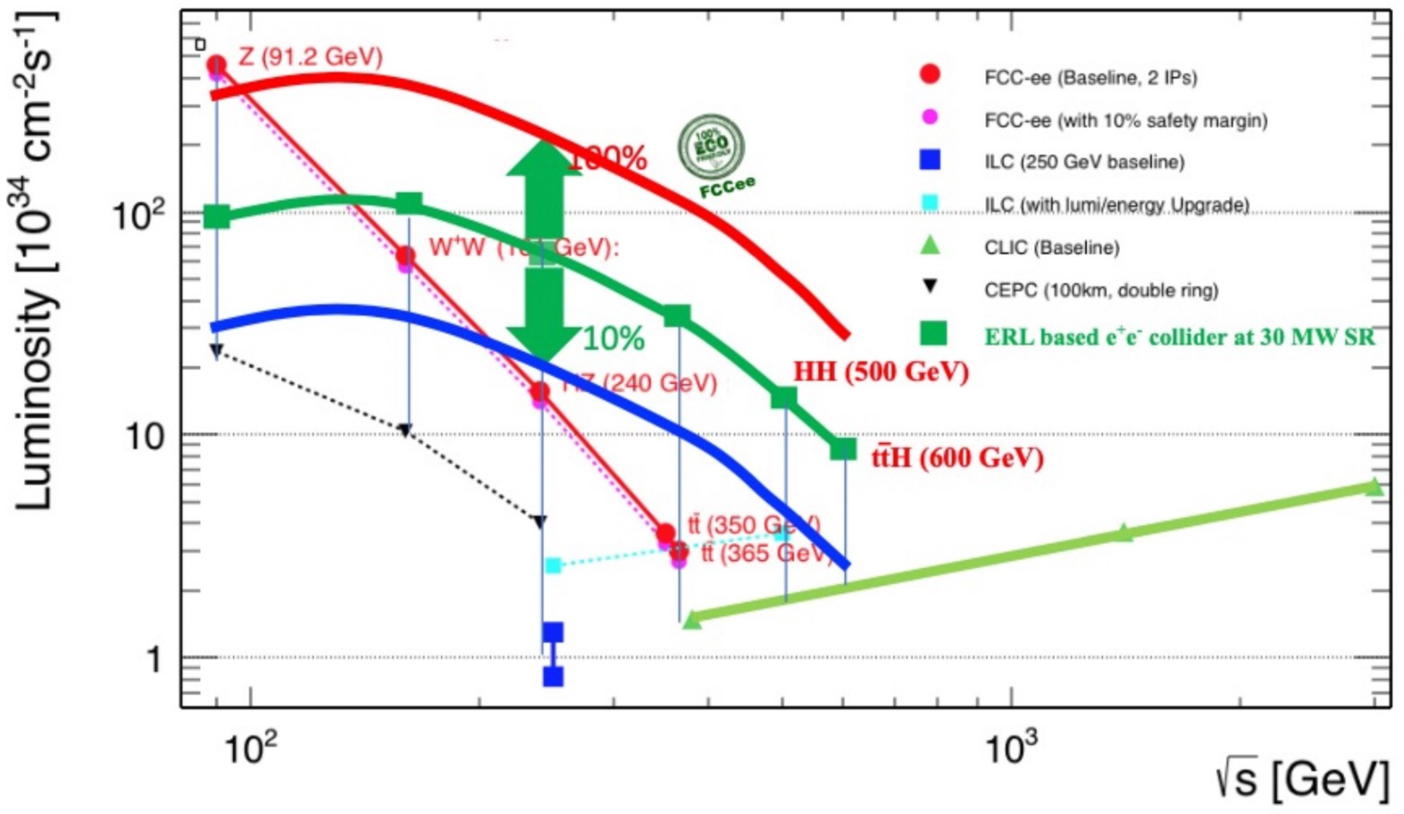
- Storage ring colliders: the energy and the particles of used beams are reused
- Linear colliders: efficient collisions can use a larger disruption parameter than a ring collider, because beams only collide once at high energy before recapture.
- This allows for significantly larger luminosity than in a ring, by an order of magnitude.



CERC Upgrades, extension and stageability

CERC can be built in stages, increasing the energy by adding SRF cavities

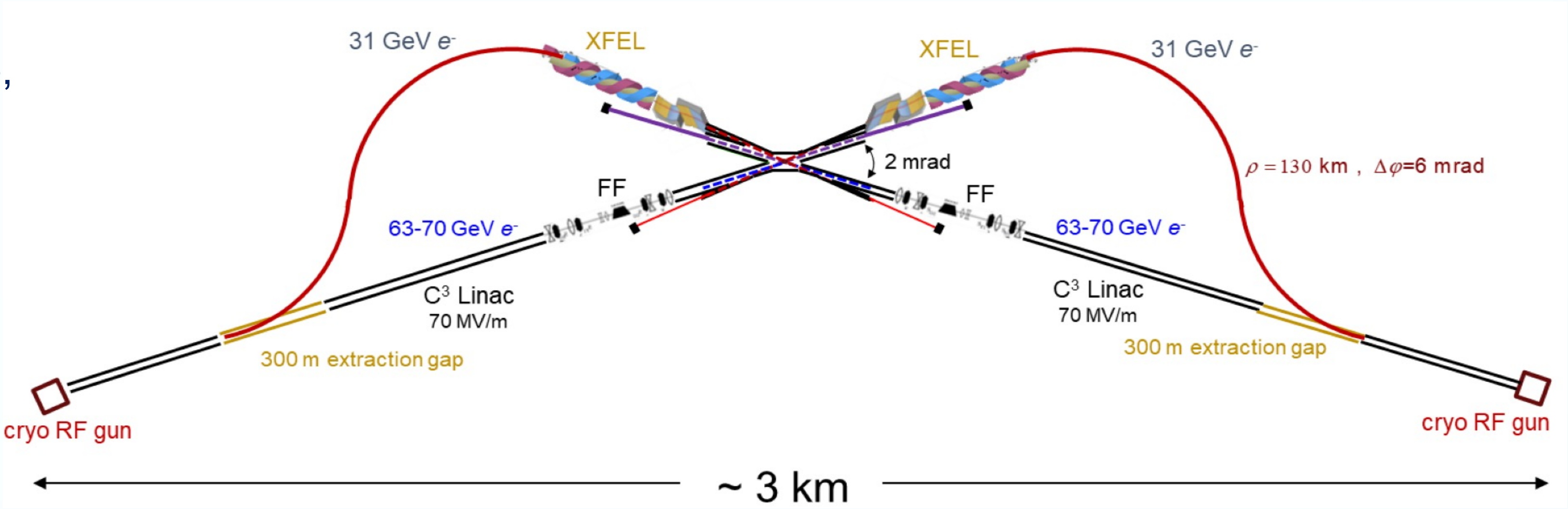
- CERC in luminosity is correlated to the SR power
  - 30 MW total SR power ➔ green
  - 100 MW ➔ 3 times more (solid red)
- CERC energy upgrade to cover √s ~500-600 GeV with increasing luminosity advantage over FCC-ee.
- CERC can be used for hadron-electron and hadron-positron collider in conjunction with FCC-hh

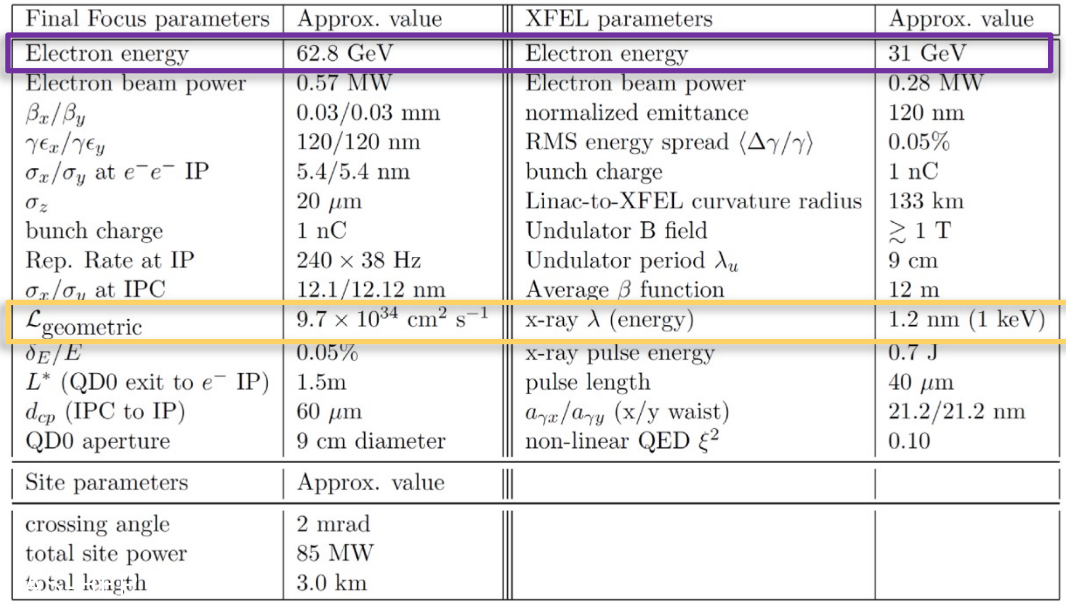


More details in F. Zimmermann's talk

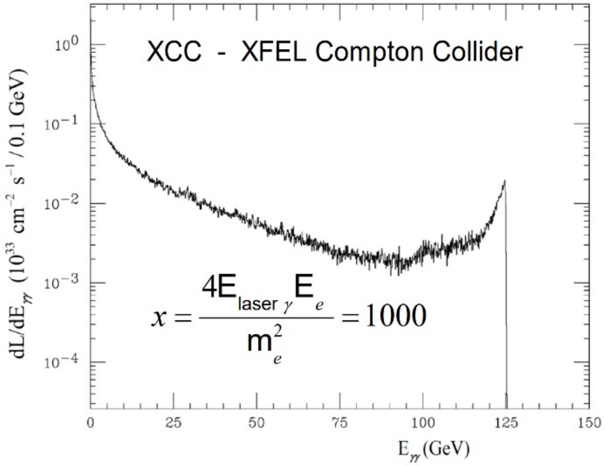
$\gamma\gamma$ colliders with FELs: XCC

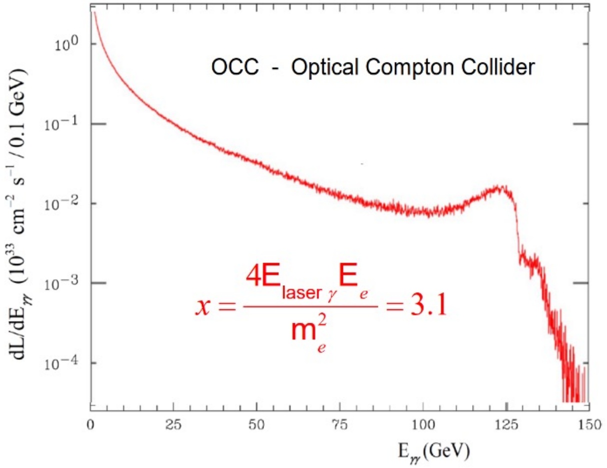
- Cryo Cu RF Gun, 120 nm-rad emittance, 76 1nC bunches, 240 Hz, 90% pol.
- Cryo Cu Linac, 70 MV/m, 76 1nC bunches, 240 Hz
- 700 mJ/pulse 1 keV γ XFEL
- X-ray focusing to 70 nm FWHM for 700 mJ/pulse 1 keV γ

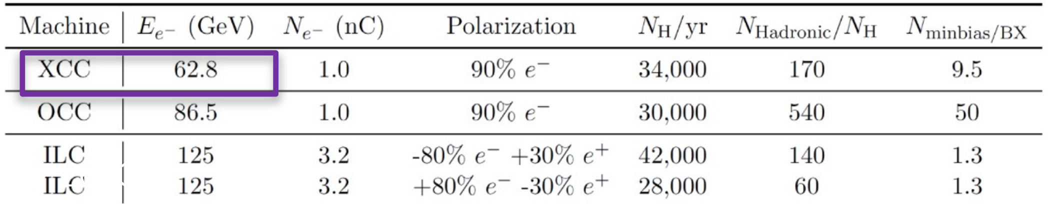




Final Focus parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	62.8 GeV	Electron energy	31 GeV
Electron beam power	0.57 MW	Electron beam power	0.28 MW
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	120/120 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	0.05%
σ_x/σ_y at e^-e^- IP	5.4/5.4 nm	bunch charge	1 nC
σ_z	20 μm	Linac-to-XFEL curvature radius	133 km
bunch charge	1 nC	Undulator B field	$\gtrsim 1$ T
Rep. Rate at IP	240 × 38 Hz	Undulator period λ_u	9 cm
σ_x/σ_y at IPC	12.1/12.12 nm	Average β function	12 m
$\mathcal{L}_{\text{geometric}}$	9.7×10^{34} cm^2 s^{-1}	x-ray λ (energy)	1.2 nm (1 keV)
δ_E/E	0.05%	x-ray pulse energy	0.7 J
L^* (QD0 exit to e^- IP)	1.5m	pulse length	40 μm
d_{cp} (IPC to IP)	60 μm	$a_{\gamma x}/a_{\gamma y}$ (x/y waist)	21.2/21.2 nm
QD0 aperture	9 cm diameter	non-linear QED ξ^2	0.10
Site parameters	Approx. value		
crossing angle	2 mrad		
total site power	85 MW		
total length	3.0 km		







Machine	E_{e^-} (GeV)	N_{e^-} (nC)	Polarization	N_{H}/yr	$N_{\text{Hadronic}}/N_{\text{H}}$	$N_{\text{minbias/BX}}$
XCC	62.8	1.0	90% e^-	34,000	170	9.5
OCC	86.5	1.0	90% e^-	30,000	540	50
ILC	125	3.2	-80% e^- +30% e^+	42,000	140	1.3
ILC	125	3.2	+80% e^- -30% e^+	28,000	60	1.3

XCC Sustainability

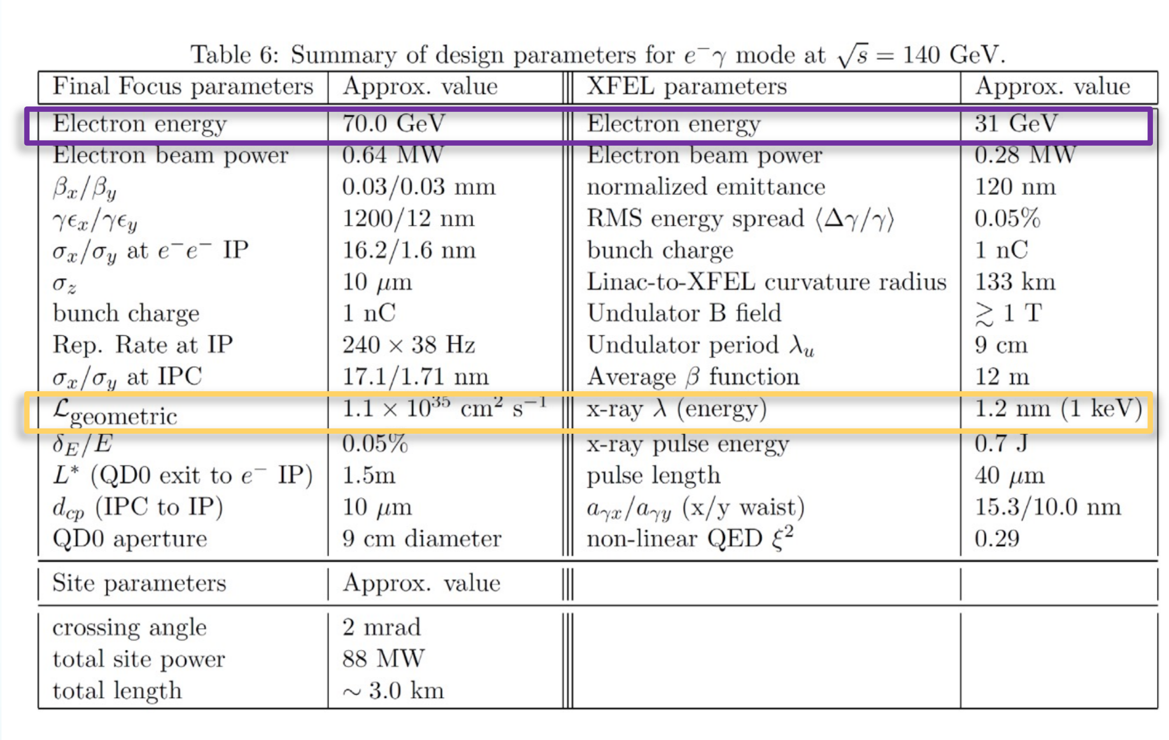


Table 6: Summary of design parameters for $e^-\gamma$ mode at $\sqrt{s} = 140$ GeV.

Final Focus parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	70.0 GeV	Electron energy	31 GeV
Electron beam power	0.64 MW	Electron beam power	0.28 MW
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	1200/12 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	0.05%
σ_x/σ_y at e^-e^- IP	16.2/1.6 nm	bunch charge	1 nC
σ_z	10 μm	Linac-to-XFEL curvature radius	133 km
bunch charge	1 nC	Undulator B field	$\gtrsim 1$ T
Rep. Rate at IP	240 × 38 Hz	Undulator period λ_u	9 cm
σ_x/σ_y at IPC	17.1/1.71 nm	Average β function	12 m
$\mathcal{L}_{\text{geometric}}$	1.1×10^{35} cm^2 s^{-1}	x-ray λ (energy)	1.2 nm (1 keV)
δ_E/E	0.05%	x-ray pulse energy	0.7 J
L^* (QD0 exit to e^- IP)	1.5m	pulse length	40 μm
d_{cp} (IPC to IP)	10 μm	$a_{\gamma x}/a_{\gamma y}$ (x/y waist)	15.3/10.0 nm
QD0 aperture	9 cm diameter	non-linear QED ξ^2	0.29
Site parameters	Approx. value		
crossing angle	2 mrad		
total site power	88 MW		
total length	$\sim$ 3.0 km		

Parameter	Units	Value
Single Beam Power (70 GeV e^-)	MW	0.64
Single Beam Power (31 GeV e^-)	MW	0.28
Total Beam Power	MW	1.84
Electrical Power for RF	MW	23
Electrical Power for Cryo-Cooler	MW	34
Accelerator Complex Power	MW	31
Site Power	MW	88

More details in F. Zimmermann's talk

- The XCC is presented as a lower cost alternative to e+e- Higgs factories
  - --- 140 GeV vs 250 GeV Linac
  - --- No damping rings
  - --- No positron source

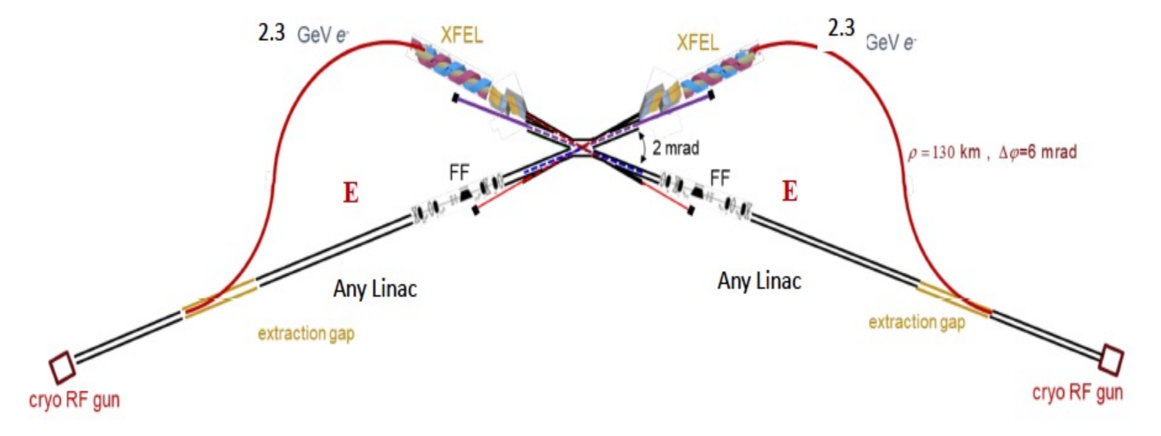
- The XCC at E_{cm}=125-140 GeV can measure absolute Higgs couplings in a model independent manner with an accuracy of order 1% , which is close to the ILC precision. To fully match or exceed the ILC Higgs coupling accuracy, a way must be found to increase the top 1% e-γ luminosity at E_{cm}=140 GeV.

- There are strong synergies between XCC and the XFEL programs. Solutions to high energy/pulse XFEL production and focusing issues at XCC will lead to new opportunities in XFEL photon science.

HE - HL $\gamma\gamma$ Colliders

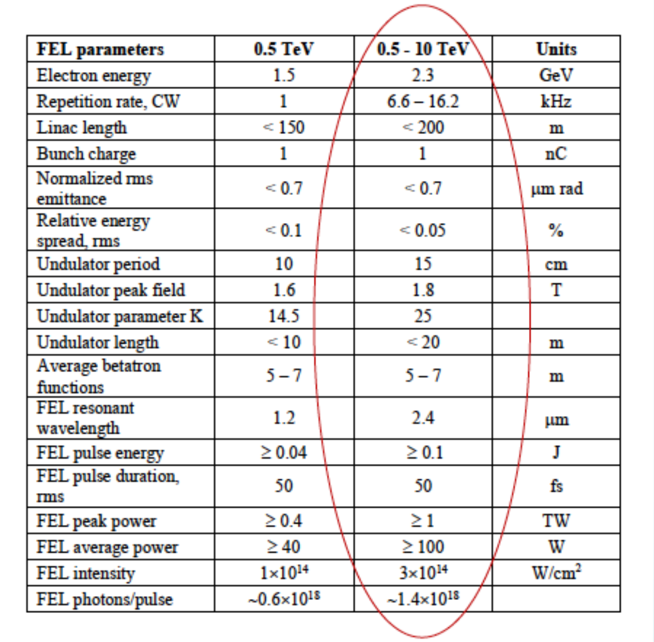
With the best of modern standard lasers, high-energy $\gamma\gamma$ colliders from electron beams of E ≥ 250 GeV are possible at the expense of photon luminosity, or 1% of the geometric e+e- luminosity, i.e. 10 times lower than for photon colliders at c.m. energies below 0.5 TeV.

<u>We show how a single Free Electron Laser (FEL) design meets the specs to produce $\gamma\gamma$ colliders as second interaction regions of e+e- colliders over the energy range of 0.5 TeV to 10 TeV c.m. without sacrificing $\gamma\gamma$ luminosity.</u>



$\gamma\gamma$ collider parameters	0.5 TeV	1.0 TeV	3.0 TeV	10 TeV	Units
x-factor	2 (4)	4	12	40	
Max. photon energy	0.17 (0.20)	0.40	1.38	4.88	TeV
$L_{\gamma\gamma} / L_{ee}$	≤ 10	≤ 10	≤ 6	≤ 3	%

This FEL increases the expected γ intensity by a factor of 10 in the luminosity of $\gamma\gamma$ colliders as second interaction regions of 0.5 TeV to 1 TeV c.m. e+e- colliders, a factor of 6 for a 3 TeV c.m. e+e- collider, and a factor of 3 for a 10 TeV c.m. e+e- collider. This FEL concept therefore paves the way for High Energy & High Luminosity $\gamma\gamma$ colliders.

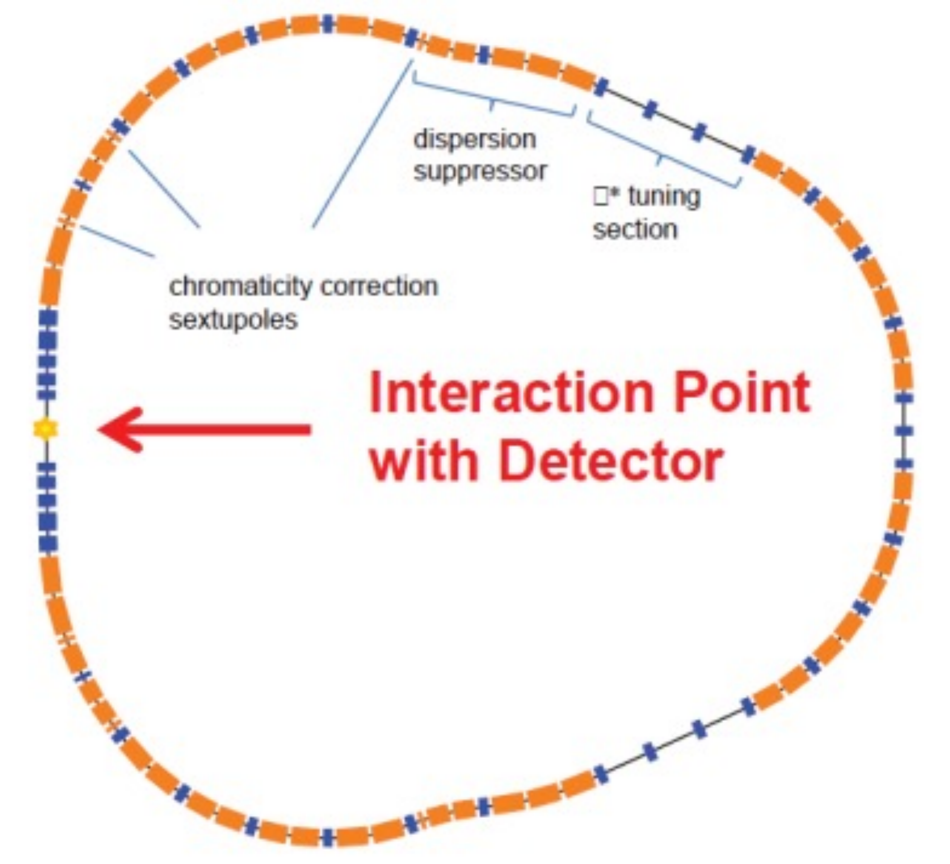


FEL parameters	**0.5 TeV**	**0.5 - 10 TeV**	**Units**
Electron energy	1.5	2.3	GeV
Repetition rate, CW	1	6.6 – 16.2	kHz
Linac length	< 150	< 200	m
Bunch charge	1	1	nC
Normalized rms emittance	< 0.7	< 0.7	µm rad
Relative energy spread, rms	< 0.1	< 0.05	%
Undulator period	10	15	cm
Undulator peak field	1.6	1.8	T
Undulator parameter K	14.5	25	
Undulator length	< 10	< 20	m
Average betatron functions	5 – 7	5 – 7	m
FEL resonant wavelength	1.2	2.4	µm
FEL pulse energy	≥ 0.04	≥ 0.1	J
FEL pulse duration, rms	50	50	fs
FEL peak power	≥ 0.4	≥ 1	TW
FEL average power	≥ 40	≥ 100	W
FEL intensity	1×10^{14}	3×10^{14}	W/cm^2
FEL photons/pulse	~0.6×10^{18}	~1.4×10^{18}	

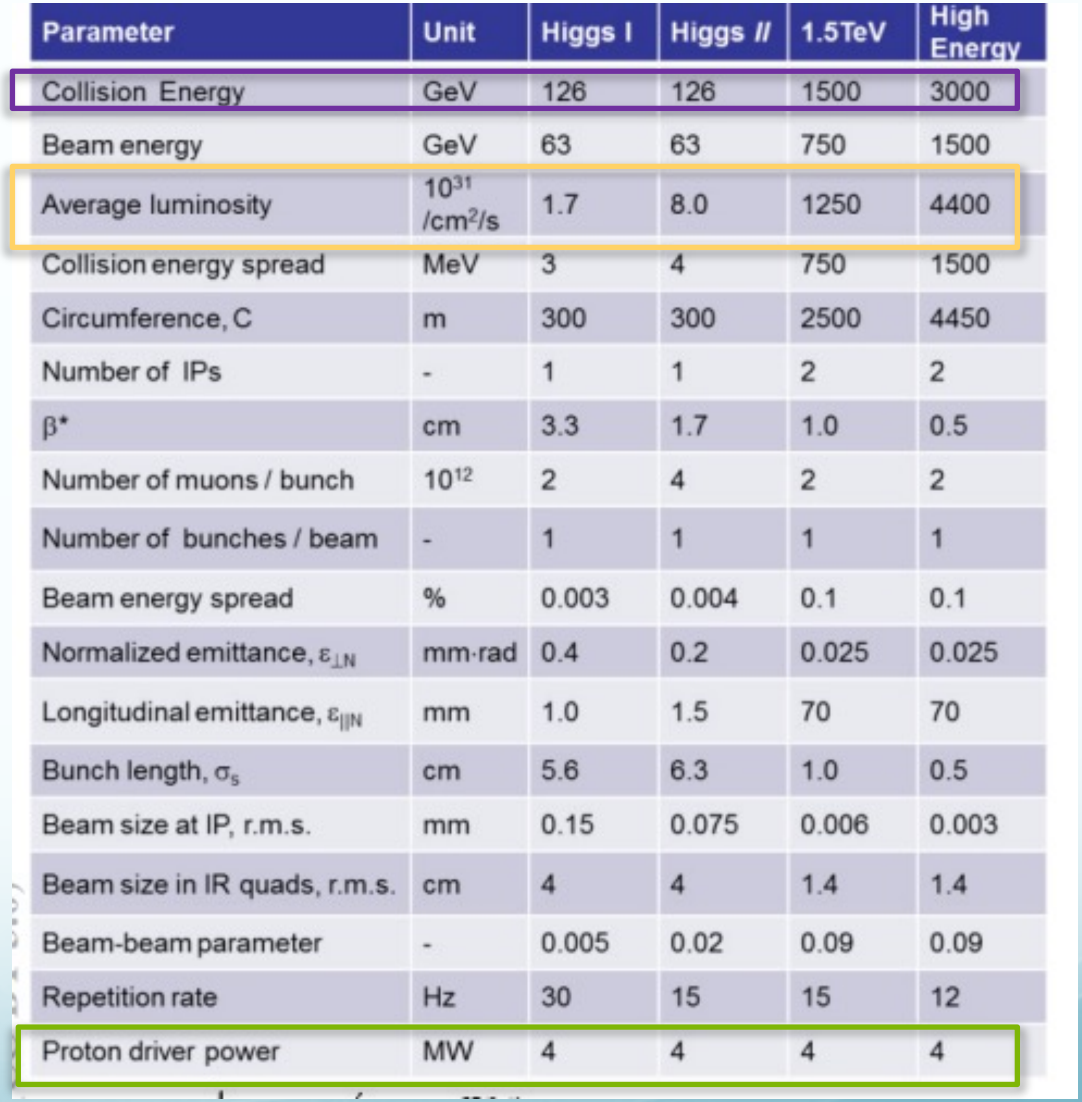
To produce $\gamma\gamma$ colliders as second interaction regions of e+e- colliders over the energy range of 0.5 TeV to 10 TeV c.m., at 2.3 GeV every other bunch from each electron/positron beam is diverted to two identical high gain SASE FEL lines, where a helical undulator produces circular polarized 0.5 eV light with 0.1-1 Joules per pulse in a footprint of approximately 5 x 20 m2 each. The central FEL wavelength of 2.4 µm, obtained with either standard warm magnet or superconducting technology for the undulator, maximizes the luminosity of the $\gamma\gamma$. At least up to 1 TeV c.m., the $\gamma\gamma$ luminosity reaches approximately 10% of the electron-positron luminosity by virtue of the optimized FEL design, which is a factor of 10 higher than the 1% otherwise expected to date.

Muon Collider Higgs Factory

* not proposed white paper



US MAP, D. Neuffer et al., 2013



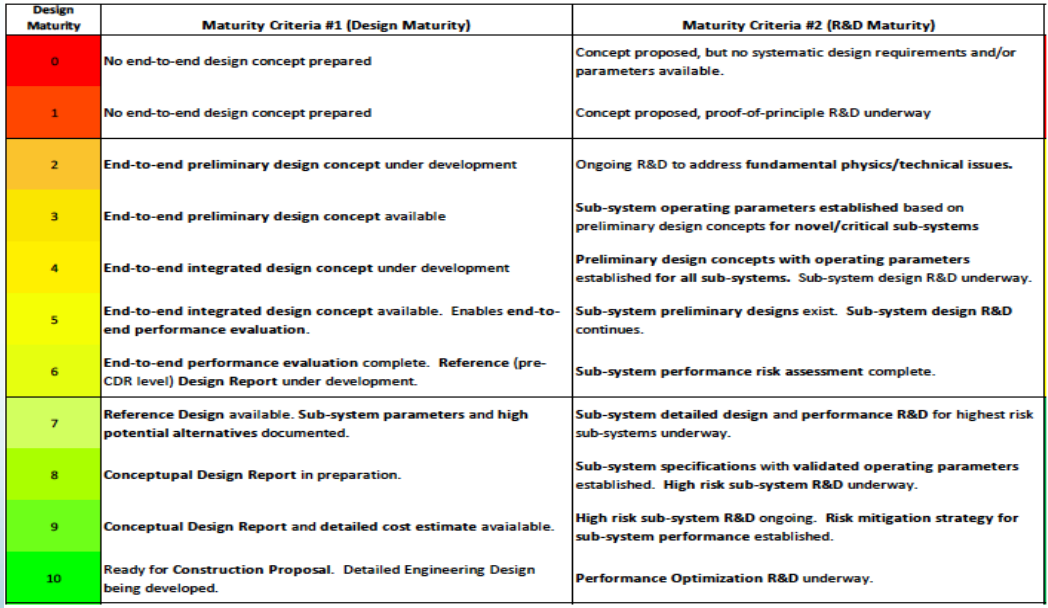
Parameter	Unit	Higgs I	Higgs II	1.5TeV	High Energy
Collision Energy	GeV	126	126	1500	3000
Beam energy	GeV	63	63	750	1500
Average luminosity	10^{31} /cm^2/s	1.7	8.0	1250	4400
Collision energy spread	MeV	3	4	750	1500
Circumference, C	m	300	300	2500	4450
Number of IPs	-	1	1	2	2
β^*	cm	3.3	1.7	1.0	0.5
Number of muons / bunch	10^{12}	2	4	2	2
Number of bunches / beam	-	1	1	1	1
Beam energy spread	%	0.003	0.004	0.1	0.1
Normalized emittance, $\varepsilon_{\perp N}$	mm·rad	0.4	0.2	0.025	0.025
Longitudinal emittance, $\varepsilon_{\|\|N}$	mm	1.0	1.5	70	70
Bunch length, σ_s	cm	5.6	6.3	1.0	0.5
Beam size at IP, r.m.s.	mm	0.15	0.075	0.006	0.003
Beam size in IR quads, r.m.s.	cm	4	4	1.4	1.4
Beam-beam parameter	-	0.005	0.02	0.09	0.09
Repetition rate	Hz	30	15	15	12
Proton driver power	MW	4	4	4	4

More details in F. Zimmermann's talk

Collider Maturity

Collider	Design Maturity	R&D Maturity
ILC-250	10	9-10
ILC-500	10	9-10
ILC-1000	6-7	6-7
CLIC-380	9	10
CLIC-1500	8	9-10
CLIC-3000	8	8-9
C3-250	3	3
C3-550	3	2
C3-Nb_3Sn	1	0
HELEN	3 (ML)	2 (SRF)
ReLiC	3	4
ERLC	3	4
XCC $\gamma\gamma$	2	2
HE&HL $\gamma\gamma$	0	0

Collider	Design Maturity	R&D Maturity
FCC-ee	9	9
CEPC	9	9
CERC	3	4
LEP3	3	8
EPCCF	3	8
MC-HF	3	2



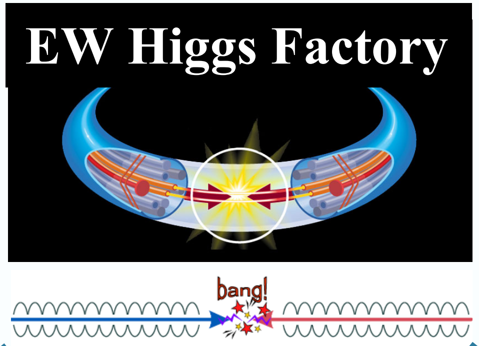
Design Maturity	Maturity Criteria #1 (Design Maturity)	Maturity Criteria #2 (R&D Maturity)
0	No end-to-end design concept prepared	Concept proposed, but no systematic design requirements and/or parameters available.
1	No end-to-end design concept prepared	Concept proposed, proof-of-principle R&D underway
2	End-to-end preliminary design concept under development	Ongoing R&D to address fundamental physics/technical issues.
3	End-to-end preliminary design concept available	Sub-system operating parameters established based on preliminary design concepts for novel/critical sub-systems
4	End-to-end integrated design concept under development	Preliminary design concepts with operating parameters established for all sub-systems. Sub-system design R&D underway.
5	End-to-end integrated design concept available. Enables end-to-end performance evaluation.	Sub-system preliminary designs exist. Sub-system design R&D continues.
6	End-to-end performance evaluation complete. Reference (pre-CDR level) Design Report under development.	Sub-system performance risk assessment complete.
7	Reference Design available. Sub-system parameters and high potential alternatives documented.	Sub-system detailed design and performance R&D for highest risk sub-systems underway.
8	Conceptupal Design Report in preparation.	Sub-system specifications with validated operating parameters established. High risk sub-system R&D underway.
9	Conceptual Design Report and detailed cost estimate avaialable.	High risk sub-system R&D ongoing. Risk mitigation strategy for sub-system performance established.
10	Ready for Construction Proposal. Detailed Engineering Design being developed.	Performance Optimization R&D underway.

arXiv:2209.05827v1 [physics.acc-ph] 13 Sep 2022

Joint technology R&D topics beyond CDR

Energy not challenging

- **SCRF:** Nb3Sn coated Copper cavities and TW structures (70 MV/m)
- **NCRF:** Cryo-cooled Copper structures (120 MV/m), HTS coatings
- **Cryogenics:** massive production, plugged compatibility, transport issues, gas-pressure regulations, more efficient gas coolers



Sustainability

- **Energy consumption, efficiency, sustainability, carbon footprint**
- **High-Efficiency RF power sources:** Klystrons, Solid State Amplifiers, IOTs ..

Luminosity precision !!!!

- **Positioning, Monitoring, Alignment and Stabilisation**: global strategies, instrumented girders, radiation-hard ground motion sensors.
- **e+ production optimization**: flux concentrators, pulsed solenoid, capture linacs, targetry issues....
- **Nanobeams** colliding techniques: concepts and feedback
- **Damping Rings and Booster**: low emittances and 4th generation lattices for colliders
- **Magnets**: Interaction Region, Permanents, Injection/Extraction devices

- **Manufacturing** techniques including additive, cost reduction and massive production
- **High power Beam Dumps** (multi-MW)
- Machine protection and collimation
- Polarized beams and polarimetry
- Beam instrumentation
- Robotics and automatization

There is no favorable wind if we don't know where we are going...

HE&HL γγ

CERC

HELEN

XCC γγ

EPCCF

ReLiC

CEPC

FUTURE CIRCULAR COLLIDER
Innovation Study

ilc

clic

C^3

Thanks to:
Georg Hoffstaetter, Qing Qin and Frank Zimmermann

HE&HL γγ

CERC

XCC γγ

EPCCF

HELEN

ReLiC

CEPC

FUTURE CIRCULAR COLLIDER
Innovation Study

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clic

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General comments

- Transfer of know-how, experience and expertise to the **young generation** is crucial. These colliders will be the colliders for the next generation of accelerator physicists. Our projects need to be attractive/motivation to them (co-ownership responsibilities, better career perspectives).

- The next Higgs collider will be certainly unique and is a **global enterprise**

- **Coordination** and **harmonization** between the EPPSU 2020-LDG and USA Snowmass'21 process will be necessary in some common topics. We have some tools on hand as the recently approved EAJADE (Europe–America–Japan Accelerator Development and Exchange programme) focused in Higgs Factories, with participation of major EU (CERN, INFN, CEA, DESY, CNRS, CSIC, UOXF), Japan (KEK, Tokyo Univ., Tohoku Univ.) USA (BNL, FNAL, SLAC, JLAB, LBNL, Cornell Univ.) and Canada (VISPA) labs.

- **Societal impact** (medical, industrial, security,...) of colliders projects has to be better explained, communicated and exploited. All colliders are expensive projects, we have to convince about the need of having these kind of facilities. The transition of accelerator technology, from its use in basic science to applications more directly benefiting society, has been a very visible trend in recent decades; and that represents only the first step in a major evolution for particle accelerators.