AITANA

MATTER AND TECHNOLOGY

Hardware & Accelerator R&D

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CPAN Ingenio 2010 Days – Future Collider for Early-Career Researchers Session

VNIVERSITAT DE VALÈNCIA

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Outline

- Prior comments
- Current status
- Next steps
- HEP options and comparisons
- Circular colliders
- Linear colliders
- Spanish accelerators community
- Detectors
- CNID
- Recap and roadmap to higher energy
- Summary

Prior comments

- Most of the information presented in these slides has been obtained from LCWS, FCC Week, and other 2024 meetings, and will be reproduced as precisely as possible
- This presentation is too short to cover specific details about the different topics, so please check the links provided on each slide for further information.

Consensus...

- European Strategy for Particle Physics (ESPP): electron-positron Higgs factory is the highest priority next collider.

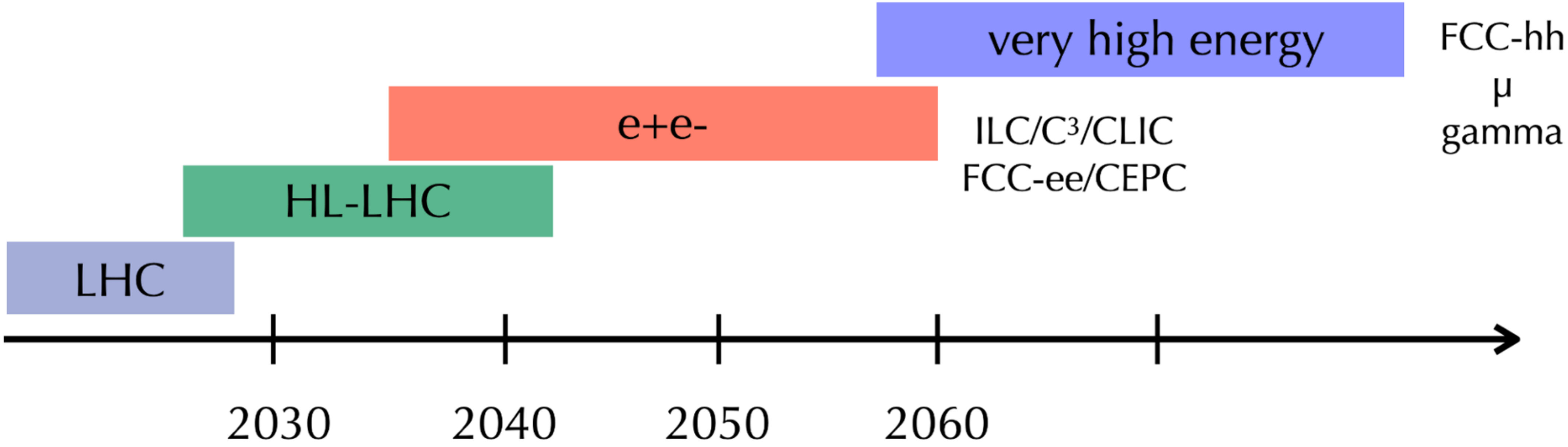
Consensus... or not

- European Strategy for Particle Physics (ESPP): electron-positron Higgs factory is the highest priority next collider.

  - Circular?

  - Linear?

Possible roadmap



Wish list beyond HL-LHC:

1. Establish Yukawa couplings to light flavor $\Longrightarrow$ needs precision
2. Establish self-coupling $\Longrightarrow$ needs high energy

Options for next HEP machine

- Circular collider covering a region of 90-350 GeV cme
  - A circular collider (CC): e,g, FCC(CERN) and CECP(IHEP)
    - Double storage rings of 90-100 km circumference
    - Well established technology. Many CC's have been built, the largest one LEP with 27 km circumference at 207 GeV cme
- A linear collider (LC): e.g. CLIC, C3, HALHF and ILC
  - Colliding e+ e- accelerated by linacs, with a total length of ~3 km to 20 km depending on the acceleration gradient of the technology used
    - ILC: super conducting L-band RF cavities (series production experience @European XFEL), 32 MeV/m
    - CLIC: normal conducting room temperature X-band Cu RF cavities, 72 MeV/m
    - CCC: normal conductive liquid N2 temperature X-band Cu RF cavities, 70 MeV/m
    - HALHF: Plasma wake-field accelerated 500 GeV e- (1.2 GeV/m) against 31 GeV e+ conventional linac

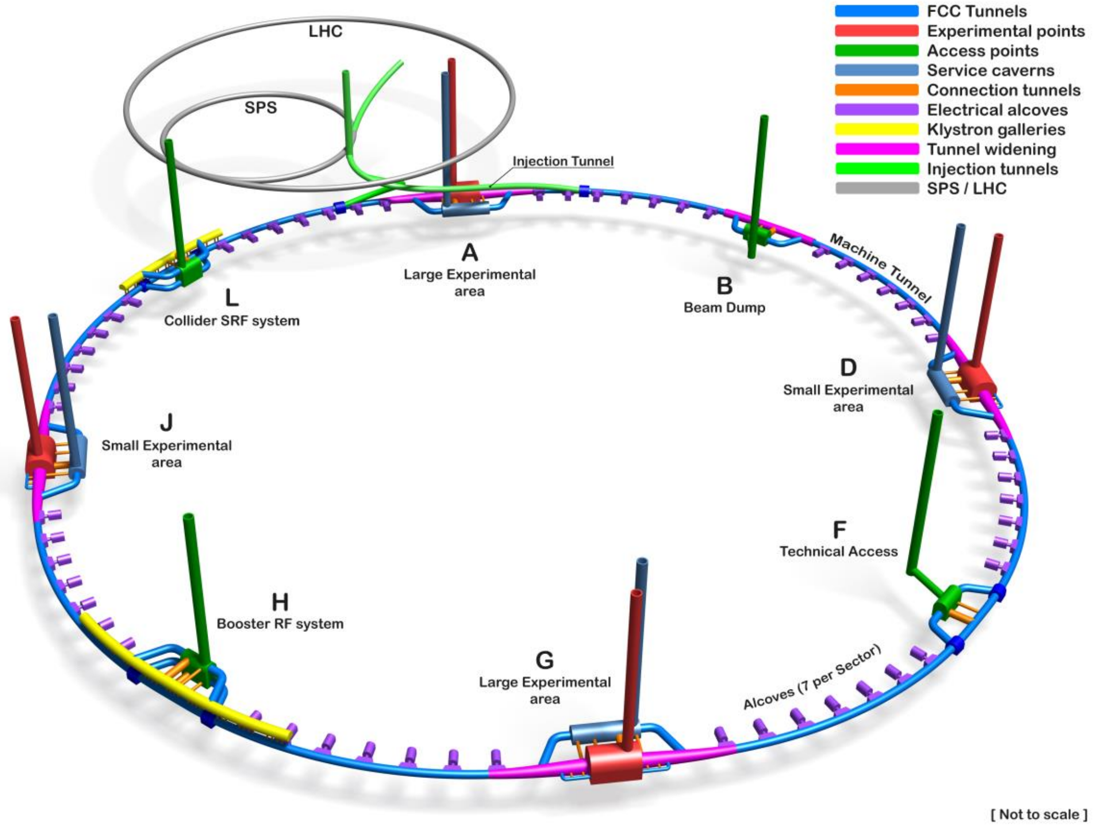
Comparison

Machine	Circular collider	Linear Collider
Some advantages	Higher luminosity at 250 GeV and below • Excellent electroweak physics • Good sensitivities in rare phenomena in the Higgs decays	Longitudinal polarization and constant luminosities for above 250 GeV • Comparable sensitivities in the Higgs coupling measurements • Excellent top physics
Number of interaction points	Can have several interaction points	Only one interaction point
Footprint	90 to 100 km tunnel will result in larger environmental impact and cost for the civil engineering	Shorter tunnel of 3 to 20 km will have additional advantages such as simplified logistics in the installation and maintenance.

Circular colliders

FCC-ee

- Future Circular Collider: FCC-ee before FCC-hh – cost of FCC-hh to be spread over the years
- CDR in 2019
- 4 interaction points à robustness, statistics, possibility of specialized detectors to maximize physics output
- Civil Engineering:
  - Tunnel Circumference: 90.7 km
  - Large experiment sites: 2
  - Small experiment sites: 2
  - Deepest shaft: 400m
  - Average shaft depth: 243m
- FCC-ee construction cost up to operation at ZH : ~ 15 BCHF
  - Civil engineering (tunnel, experimental caverns, surface sites, etc.), FCC-ee collider and injectors, Technical infrastructure, Other infrastructure (roads, power lines, land, etc.), 4 detectors
  - Does not include upgrade to ttbar operation (~ 1.5 BCHF)



FCC-ee

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
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	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

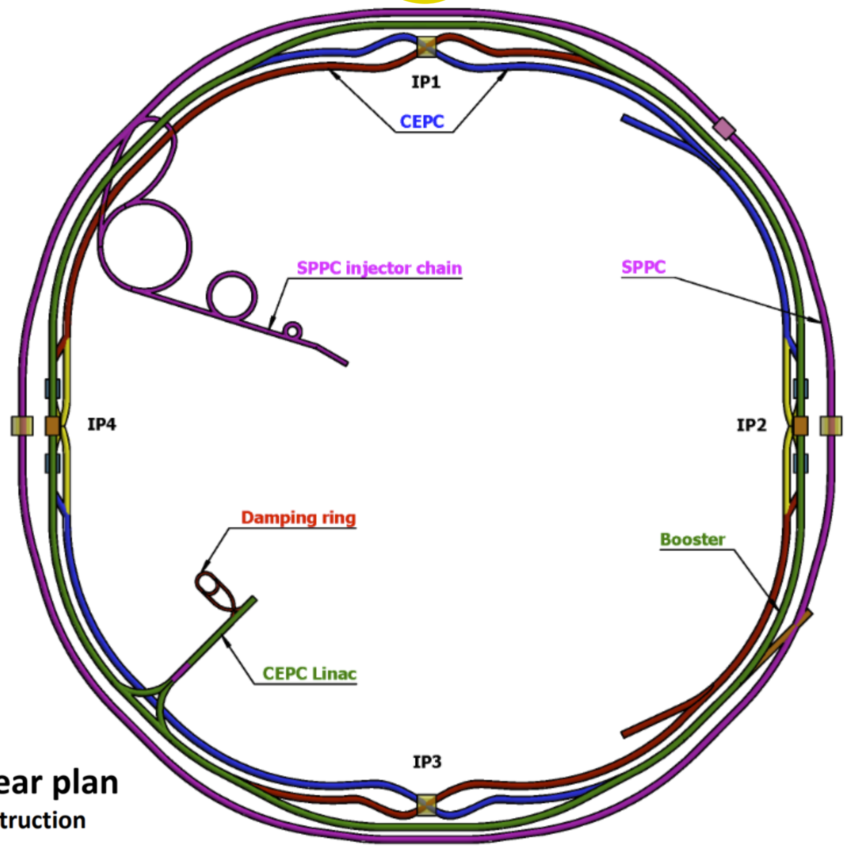
➢ Some technical challenges:

- High-field superconducting magnets with emphasis on HTS (for both FCC-hh and FCC-ee)
- SRF cavities with increased gradient performance and energy efficiency
- High-power RF sources (klystrons, solid state amplifiers) aiming at improving efficiency by up to 40% compared to current technology
- New cryogenic fluids and thermodynamic processes to improve energy efficiency of cooling plants
- Detector technologies coping with machine luminosities and radiation levels, and with performance matching expected stat. uncertainties
- Synchrotron Radiation load: cumulative dose and heat dissipation.

2021- 25: Feasibility Study → **2027/2028:** project approval by CERN Council → **2032:** construction starts → **2041:** HL-LHC ends → **2045:** Operation of FCC-ee → **2070:** Operation of FCC-hh

CEPC

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Energy (GeV)	**120**	**45.5**	**80**	**180**
Bunch number	268	11934	1297	35
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF frequency (MHz)	650			
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**5.0**	**115**	**16**	**0.5**



2012.9 CEPC proposed

2015.3 Pre-CDR

2018.11 CDR

2023.12 TDR

2025 CEPC Proposal
CEPC Detector reference design

2027 EDR

15th five year plan Start of construction

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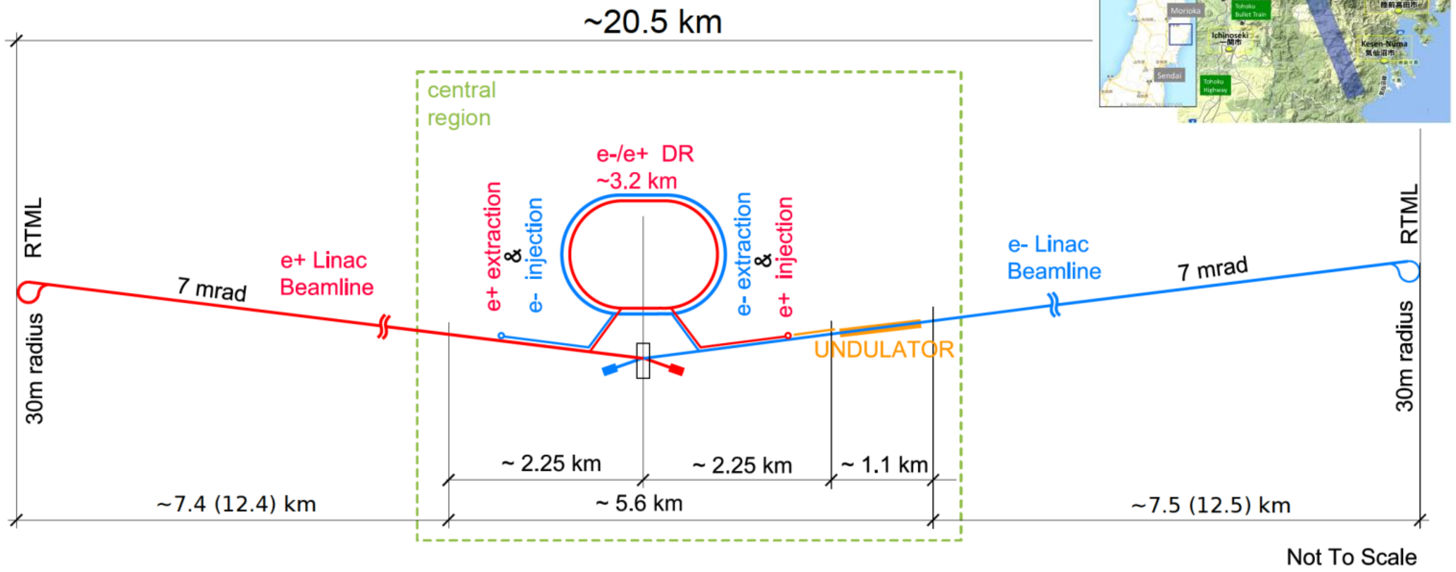
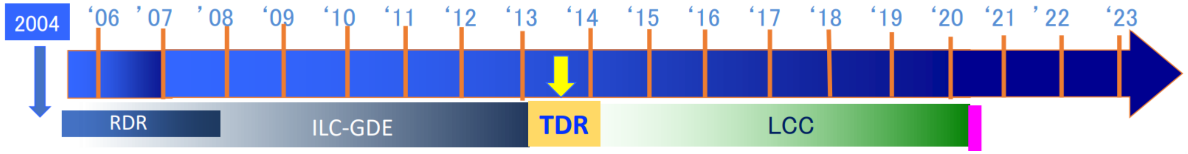
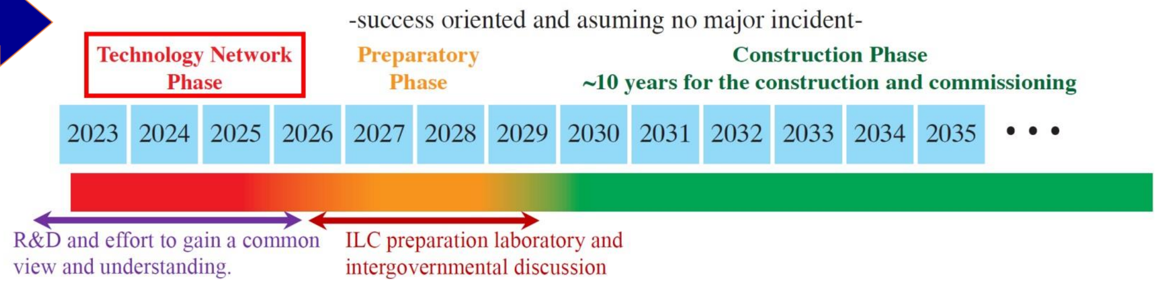
Linear colliders

ILC

- International Linear Collider baseline: 250 GeV Center of Mass Superconducting RF Linear Accelerator (31.5 MV/m)
- Technology mature to be ready for an e+/e- Higgs Factory based on the Linear Collider technology
- SRF technology in operation on the European XFEL
- The ILC is configured to have two detectors that share one interaction point, with one detector in data taking position at any time, in a so–called “push– pull”







- Construction cost: ~ 5BCHF

ILC

➢ Technical challenges (ITN):

SRF

e-, e+ Sources

Nano-Beam

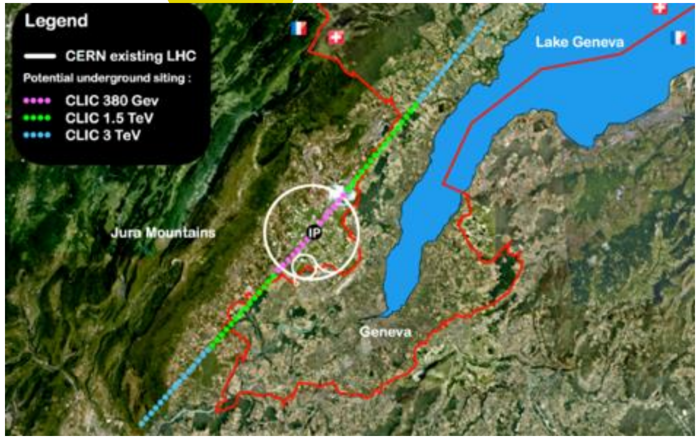
WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	DR System design
WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

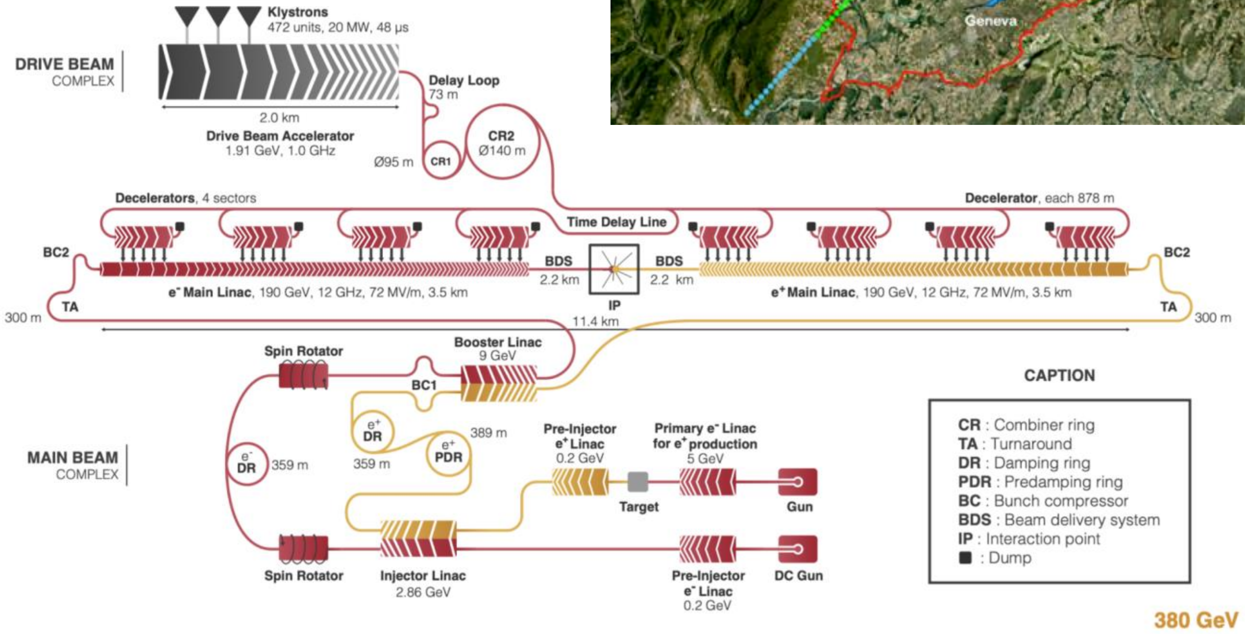
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade
Centre of mass energy	$\sqrt{s}$	GeV	250	250
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)
Repetition frequency	f_{rep}	Hz	5	5
Bunches per pulse	n_{bunch}	1	1312	2625
Bunch population	N_{e}	10^{10}	2	2
Linac bunch interval	Δt_{b}	ns	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8
Beam pulse duration	t_{pulse}	μs	727	961
Average beam power	P_{ave}	MW	5.3	10.5
RMS bunch length	σ^*_{z}	mm	0.3	0.3
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35
RMS hor. beam size at IP	σ^*_{x}	nm	516	516
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %
Site AC power	P_{site}	MW	111	128
Site length	L_{site}	km	20.5	20.5

DESY-22-045, "The international linear collider: Report to snowmass 2021"
ILC Technology Network (ITN), Shin Michizono, LCWS2024

CLIC

- Compact Linear Collider: Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- High-gradient Accelerating structures at 12 GHz (L~25 cm), 100 MV/m
- Expandable: Staged program with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.
- Construction cost:
  - CLIC 380 GeV Drive-Beam based: ~ 6 BCHF – 11km
  - From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML) - 29 km
  - From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML) -50 km





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CLIC

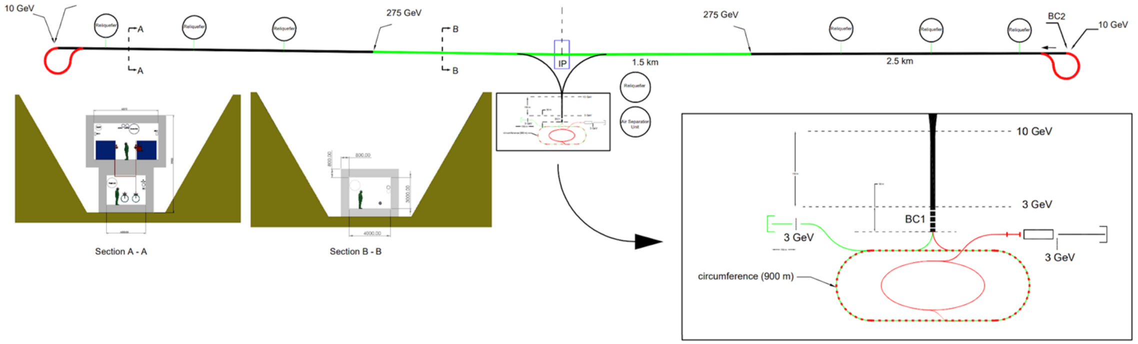
- Technical Challenges:
  - The X-band technology readiness for the 380 GeV CLIC initial phase - manufacturability and developments
  - Optimizing the luminosity at 380 GeV
  - Improving the power efficiency for both the initial phase (already in Snowmass report) and at high energies, including more general sustainability studies
- Preparing "Project Readiness Report" as a step toward a TDR
- Assuming ESPP in ~ 2025-6, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.
- Considering also 100 Hz running at 250 GeV (i.e. two parallel experiments)

Table 1.1: Key parameters of the CLIC energy stages.

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

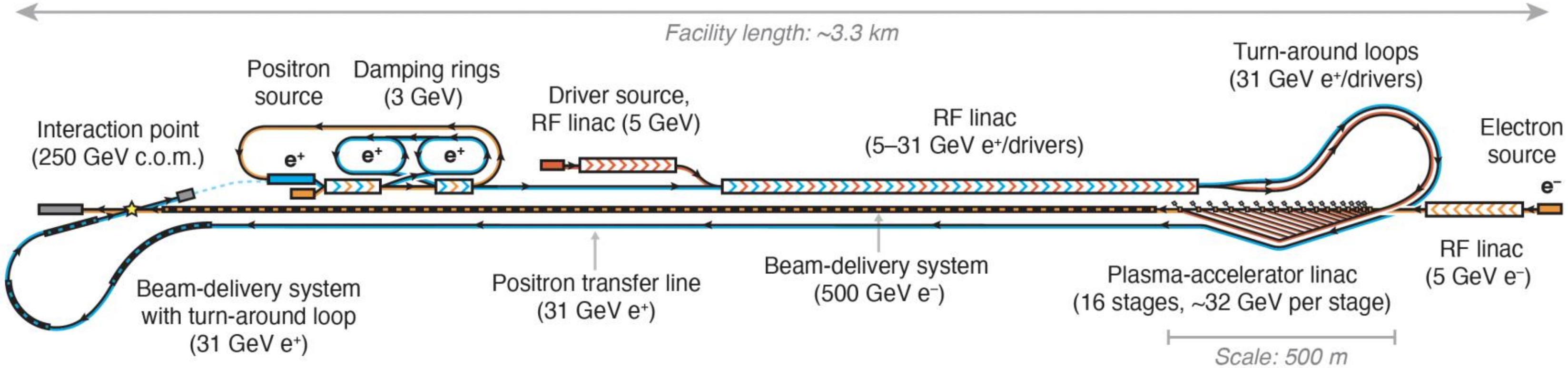
C3

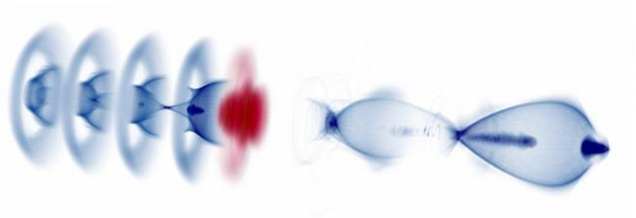
- Cool Copper Collider: cryogenic cool copper in the normal conducting RF program
- 8 km footprint for 250/550 GeV CoM $\Longrightarrow$ 70/120 MeV/m
- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site
- Large portions of accelerator complex are compatible between LC technologies
  - Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM)
  - Damping rings and injectors to be optimized with CLIC as baseline
- Demonstrate fully engineered cryomodule
  - ~50 m scale facility
  - 3 GeV energy reach



Scenario	C^3 -250	C^3 -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
Single Beam Power [MW]	2	2.45
Site Power [MW]	~150	~175

HALHF



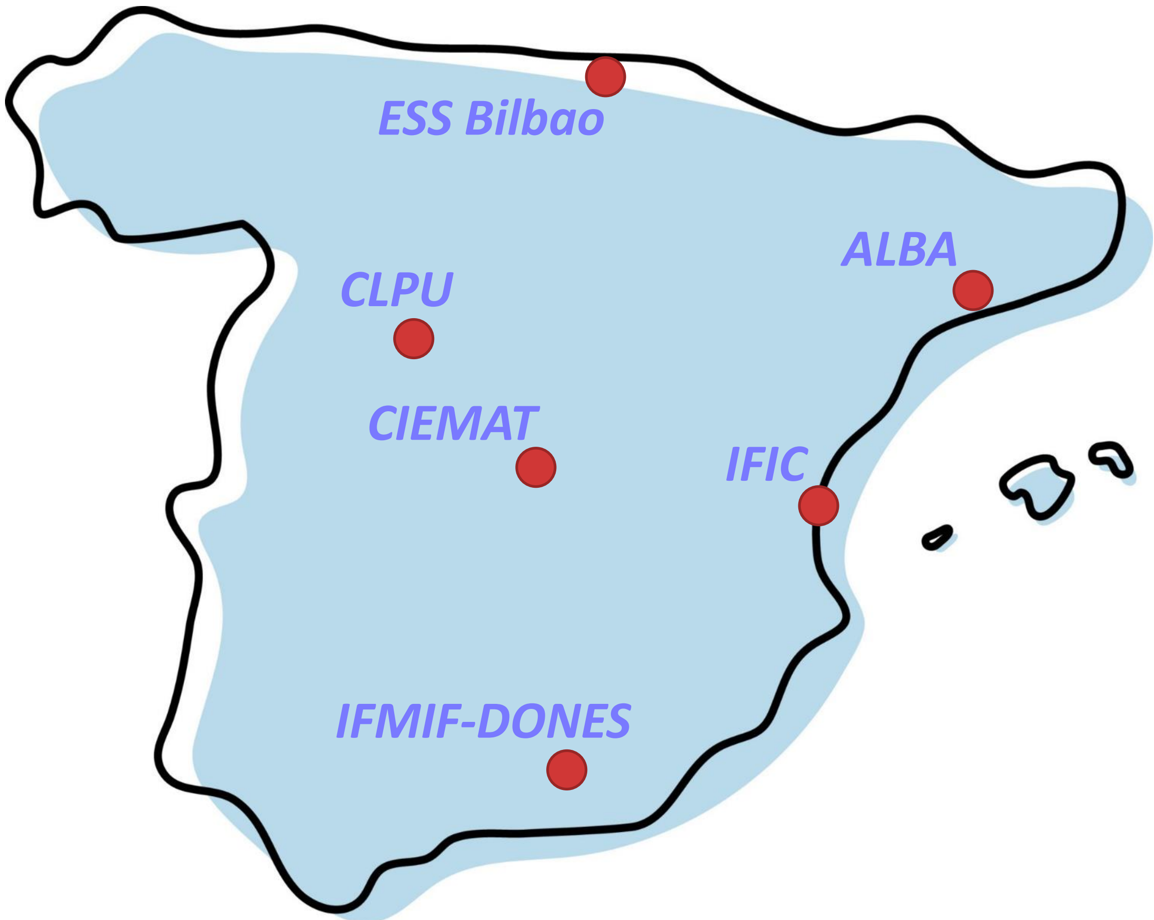


- **New concept**, aiming for pre-CDR
- 500 GeV for electrons with plasma acceleration
- 31 GeV positrons with RF based linac, used also to provide electron drivebeam for the plasma acceleration
- Reach 250 GeV collision The basic idea is – there are enough problems with a PWFA e^- accelerator; e^+ is even more difficult. Bypass this for e^+e^- collider by using conventional linac for e^+
- Plasma key-challenges: Multi-staging, emittances, energy spread, stabilities, spin polarisation preservation, efficiencies, rep rate, plasma cell cooling and more

Parameter	*Unit*	*HALHF*		*ILC*	*CLIC*
		e^-	e^+	e^-/e^+	e^-/e^+
Center-of-mass energy	GeV	250		250	380
Center-of-mass boost		2.13		-	-
Bunches per train		100		1312	352
Train repetition rate	Hz	100		5	50
Average collision rate	kHz	10		6.6	17.6
Average linac gradient	MV/m	1200	25	16.9	51.7
Main linac length	km	0.41	1.25	7.4	3.5
Beam energy	GeV	500	31.25	125	190
Bunch population	10^{10}	1	4	2	0.52
Average beam current	µA	16	64	21	15
Horizontal emittance (norm.)	µm	160	10	5	0.9
Vertical emittance (norm.)	µm	0.56	0.035	0.035	0.02
IP horizontal beta function	mm	3.3		13	9.2
IP vertical beta function	mm	0.1		0.41	0.16
Bunch length	µm	75		300	70
Luminosity	$cm^{-2}\ s^{-1}$	0.81×10^{34}		1.35×10^{34}	2.3×10^{34}
Luminosity fraction in top 1%		57%		73%	57%
Estimated total power usage	MW	100		111	168
Site length	km	3.3		20.5	11.4

Spanish Accelerator Community

- Technical areas:
  - Further development of high-field superconducting magnet technology
  - Advanced technologies for superconducting and normal-conducting radio frequency (RF) accelerating structures
  - Development and exploitation of laser/plasma acceleration techniques
  - Studies and development towards future bright muon beams and muon colliders
  - Advancement and exploitation of energy-recovery linear accelerator technology

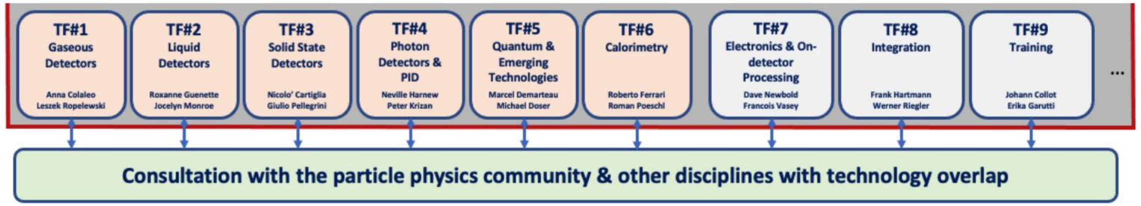


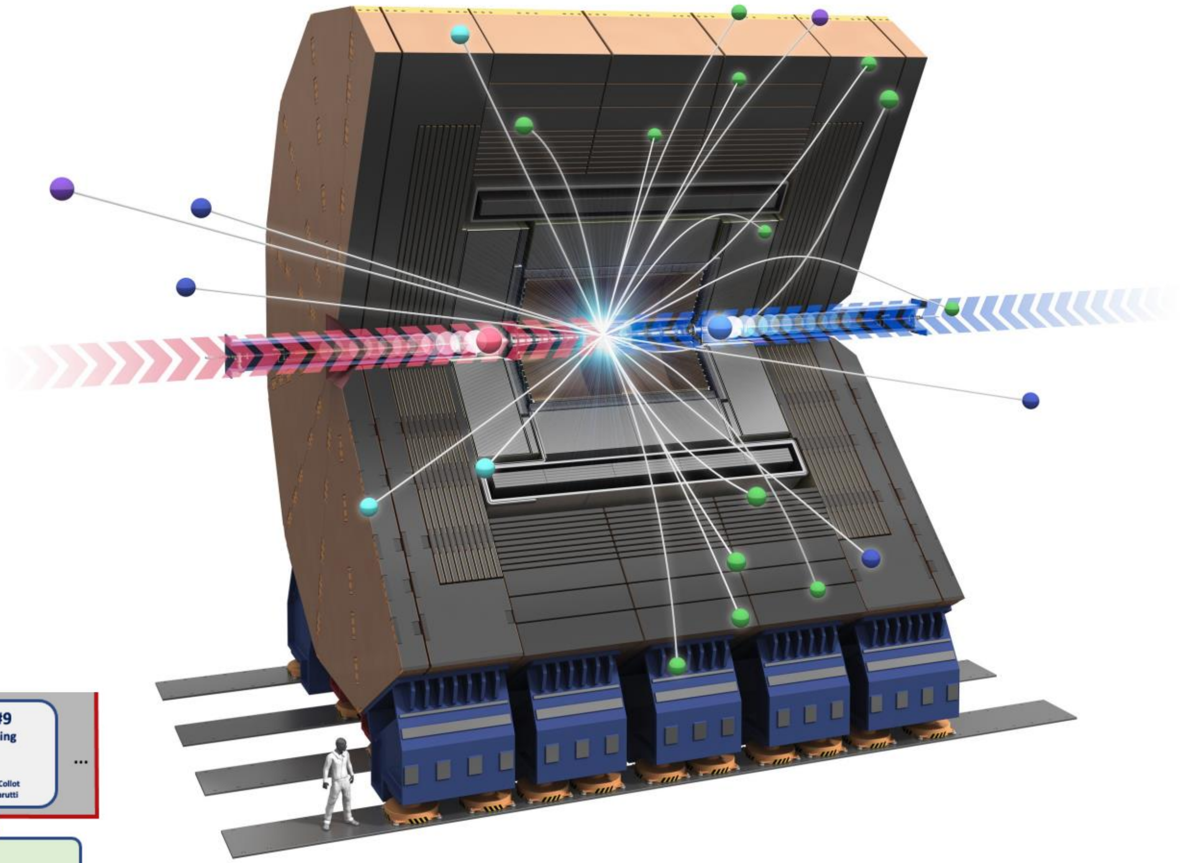
Spanish Accelerator Community

- CIEMAT:
  - CLIC-CTF3: septum magnet, horizontal/vertical window frame steerers, kickers, quadrupole precision movers …
  - ILC: with KEK to develop a conduction cooled superconducting magnet package with large temperature margin …
  - FCC-hh: high field magnets, such Nb3Sn coils, design and fabrication of a demonstrator aimed to 14 T field, HTS sextupole with a peak field of 15 T for FCC is under consideration…
- IFIC:
  - CLIC: Testing and conditioning of High-Gradient S-band structures for future linear colliders and potential applications in medicine …
  - ILC: Development of a new beam line facility, ELBEX (Extracted Lepton Beam at the European XFEL), at the European X-ray Free Electron Laser (EuXFEL), high resolution resonant cavity BPMs developments…
- ALBA:
  - CLIC: CLIC Damping Ring (DR) Technologies, Kicker, beam impedances and collective effects studies …
  - FCC: beam vacuum chamber with a beam screen to cope with the synchrotron radiation power of FCC-hh at cryogenic temperatures, High Temperature Coated Superconductors tapes as elements for the FCC-hh beam screen…
- ESS-Bilbao:
  - Recovery linacs. PERLE is a compact three-turn ERL (Energy Recovery Linac) project based on SRF technology
- CLPU:
  - laser-driven plasma wakefield acceleration
- IFMIF-DONES:
  - very high-intensity hadron machine for neutron irradiation

Detectors

- Many similar detector requirements between ILC, CLIC, FCC -ee, CEPC.
  - Ultra -lightweight tracker to minimize multiple scattering.
  - Low power consumption.
  - Precision momentum resolution
  - Excellent EM resolution
  - Unprecedented low jet energy resolution to distinguish W/Z/H to dijets
  - Micron -precision b - and c - tagging capability
  - Particle ID in a broad momentum range, incl. Pico -second timing capability allows for quark flavor physics at Z pole
  - Detector Benchmarks for ILC-CLIC/FCC-ee: ILD, IDEA, CLD, SiD, ALLEGRO
- ECFA: The most urgent R&D topics in each domain identified as Detector R&D Themes (DRDTs)

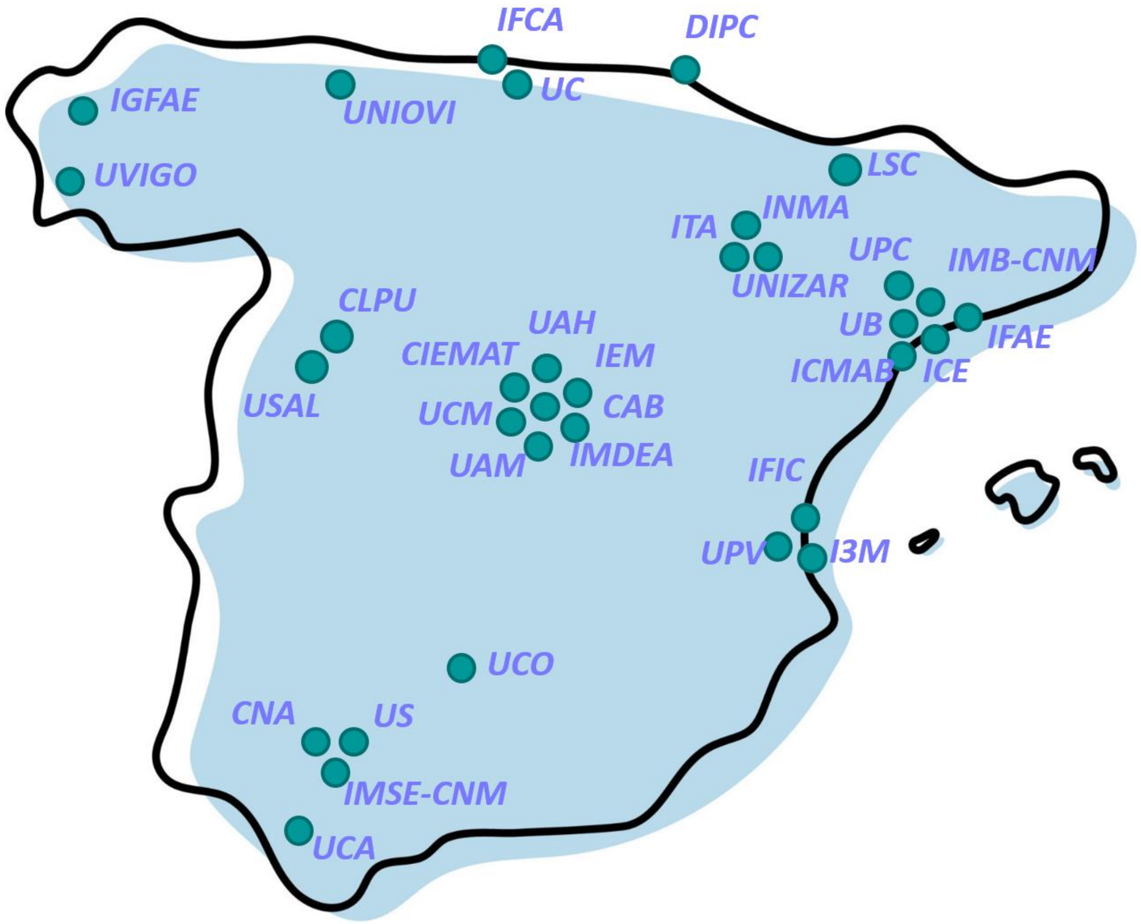




CPAN network on Instrumentation and Detectors

CPAN NETWORK ON INSTRUMENTATION AND DETECTORS

- Proposal for a network on Instrumentation and Detectors, XV CPAN Days, October 2023, Santander and Kick-off meeting in Valencia, May 2024
- Building a Community of Experts in Instrumentation and Detectors, Platform for sharing and exchanging knowledge, technologies, practices, and research findings in instrumentation across different fields and disciplines, Promoting collaboration among groups that may lead to joint research projects, Annual Workshop, Schools and courses
  - WG1 Gaseous detectors: IGFAE, CIEMAT
  - WG2 Liquid detectors: CIEMAT, IFIC
  - WG3 Solid state: IFAE, IFIC, IEM
  - WG4 Calorimetry: CIEMAT, IGFAE
  - WG5 Quantum/Superconductor sensors: IMB-CNM, IUNIZAR
  - WG6 Electronics: UNIOVI, ITA, IFIC
  - WG7 Mechanics & Integration: IFAE, UV
  - WG8 Applications: US, IFIC
  - WG9 Scintillators and photodetectors: UCM, UB
  - WG10 Characterization Techniques: CNA, IFCA
  - WG11 Training: to de appointed (dependent of the institution leading the school organization)
  - WG12 Low-Background experiments: UNIZAR, DIPC, CIEMAT
  - Coordinator: Iván Vila (IFCA); Deputy Coordinators: Cesar Domingo (IFIC) + Inés Gil (Ciemat)



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Condensed version

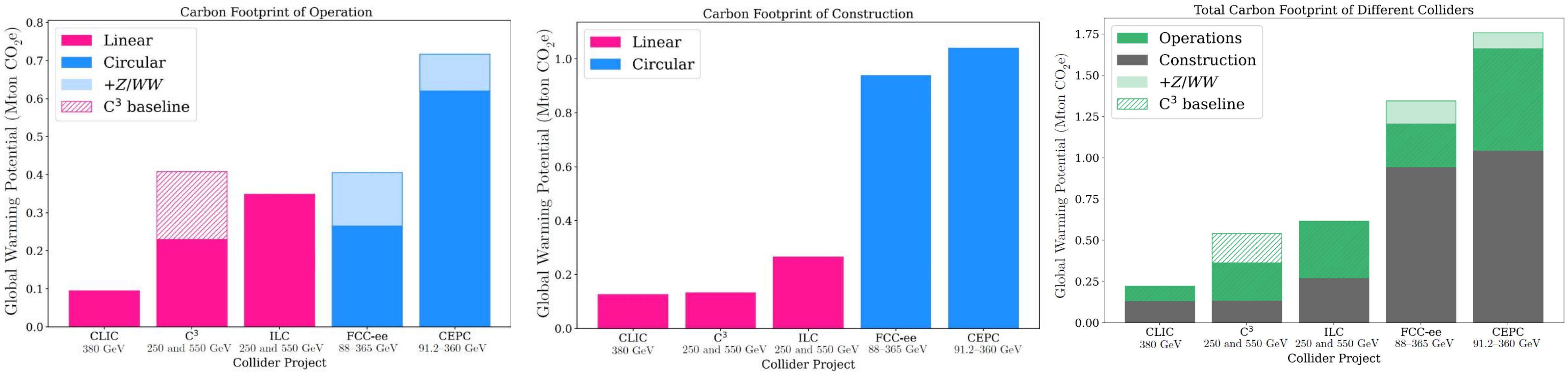
- A circular collider (CC):
  - FCC-ee (CERN) – 90 km circular machine - 15 BCHF (240 GeV) + 1.5BCHF (365 GeV) – CDR 2019
  - CECP (IHEP)
- A linear collider (LC):
  - ILC (Tohoku): super conducting L-band RF cavities, 32 MeV/m – 20 km long - 5 BCHF (250 GeV) – TDR in 2013
  - CLIC (CERN): normal conducting room temperature X-band Cu RF cavities, 72 MeV/m – (Max: 100 MeV/m) – 11.5 km long - 6 BCHF (380 GeV) – CDR 2012 – Towards a TDR
- Other proposals:
  - C3: normal conductive liquid N2 temperature X-band Cu RF cavities, 75 MeV/m – (Max: 150 MeV/m)
  - HALHF: Plasma wake-field accelerated 500 GeV e- (1.2 GeV/m) against 31 GeV e+ conventional linac

Pathways to Higher Energy

- FCC-ee (~360 GeV) upgrade path: Reuse 90 km tunnel to install a pp collider 100 TeV (FCC-hh)
- CLIC (380 GeV) upgrade path:
  - First upgrade: Extend the tunnel (11 km to 29 km) to increase the energy up to 1.5 TeV.
  - Second upgrade: Extend the tunnel (29 km to 50 km) to increase the energy up to 3 TeV.
- ILC (250 GeV) upgrade path:
  - Extend the tunnel (20 km to 31 km) to increase the energy up to 500 GeV
  - Reuse the 20 km tunnel and replace the SRF accelerators by high gradient accelerators, such C3 technology, reaching up to 2 TeV.
- O(10) TeV upgrade path for linear colliders:
  - Year 2060 and onward: reuse the tunnels to install wakefields accelerator technology

Sustainability

- Global warming potential including construction and operation, (left) unweighted and (b) weighted with respect to the average coupling precision.



Which one?

- Which machine should be constructed?

Which one?

- Which machine should be constructed?

IT'S NOT PARTICULARY IMPORTANT!!

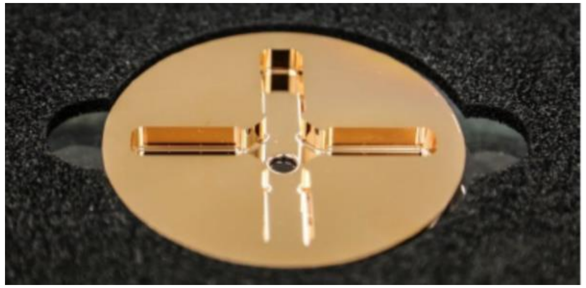
In the medium term, even if the framework project is not ultimately constructed, all groundbreaking technology developed will find applications in other scientific projects or societal uses. This happen for research on detectors and accelerators.

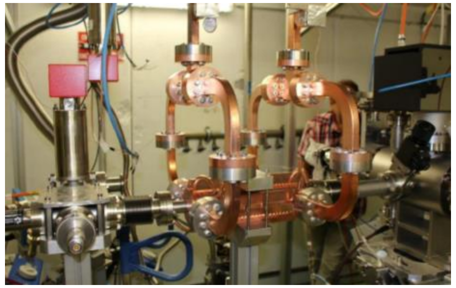
Technology transfer

- Projects with a long trajectory, such as ILC (TDR 2013) or CLIC (CDR 2012), have already produced significant technological advancements that have been applied in other scientific projects or societal uses:

Technology transfer

- Projects with a long trajectory, such as ILC (TDR 2013) or CLIC (CDR 2012), have already produced significant technological advancements that have been applied in other scientific projects or societal uses:
- For example – high gradient warm copper technology.





- Trieste FERMI: Linearizer
- SwissFEL: Linearizer and PolariX deflector
- SARI: Linearizer, deflector
- CERN: Xbox-1 with CLEAR accelerator
- DESY: FLASHForward and FLASH2, PolariX deflectors
- SLAC: NLCTA, XTA
- Argonne: AWAC

- KEK: NEXTEF
- CERN: Xbox-2,3 and Sbox
- Tsinghua: TPot
- Valencia: IFIC Vbox
- Trieste: FRMI S-Band
- SLAC: Cryo-systems
- LANL: CERF-NM
- INFN Frascati: TEX
- Melbourne: AusBox

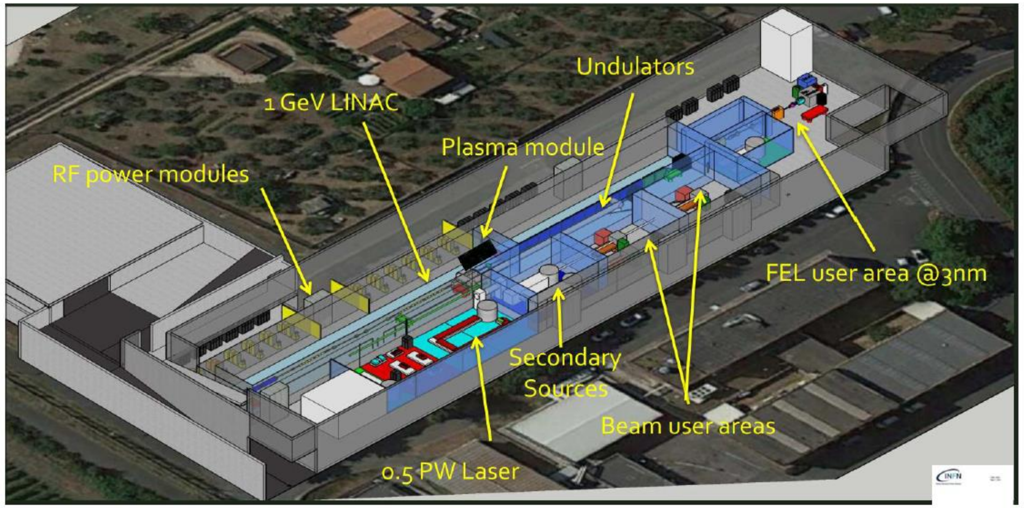
- TU Eindhoven: SMART*LIGHT, ICS
- Tsinghua: VIGAS, ICS
- CERN: AWAKE electron injector
- INFN Frascati: EuPRAXIA@SPARC_LAB
- DESY: SINBAD/ARES, deflector
- CHUV/CERN: DEFT medical accelerator
- Daresbury: CLARA, linearizer
- Trieste: FERMI energy upgrade

CLIC – HG technology

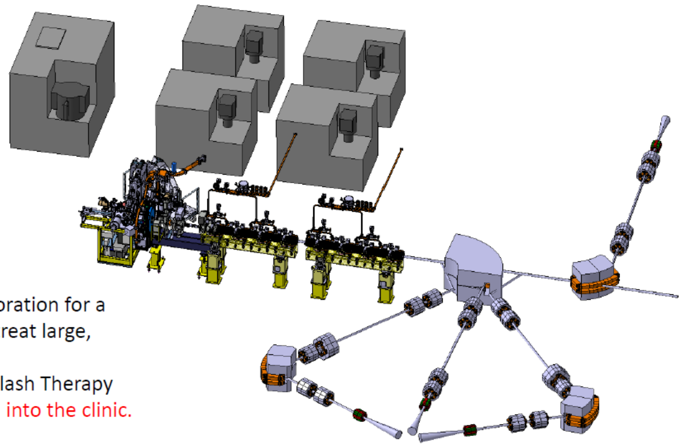
- Scientific application
  - 5 GeV Plasma based accelerator
- Medical application
  - VHEE Flash Therapy machine

EuPraxia@SPARC_LAB

Combining 1 GeV x-band linac with beam driven plasma wake field acceleration



The DEFT concept



CHUV and CERN collaboration for a VHEE FLASH facility to treat large, deep-seated tumors.
DEFT – Deep Electron Flash Therapy
Taking VHEE *and* FLASH into the clinic.

Technology transfer to industry

XVI CPAN Days – ERC

Last comments

- TECH. CHALLENGES + RESOURCES + TIME = BENEFITS TO SOCIETY

- The future of our field is being decided, therefore personal interests must be set aside to make a realistic and responsible decision—one that is fair to ourselves, the taxpayers, and the environment.

Thanks

… N. Fuster, D. Esperante, J. Fuster, B. Gimeno A. Menendez, D. Gonzalez, C. Blanch, L. K. Pedraza, P. Martin, E. Martinez, J. C. Fernandez, J. Reina …

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AITANA MATTER AND TECHNOLOGY

Where are we?

- LHC major Milestone: Observation of the Higgs boson in 2012.
- Since then, LHC did not yet deliver clear indications of a new energy frontier where NP may appear.
- HOWEVER: There are clear sign and indications that NP must exist.
  - Neutrino oscillation
  - Gravitational effects of dark matter
  - Matter-Antimatter asymmetry
  - …
- ¿Which is the specific energy range to search?

What next?

- **Which particles could be collided?**
  - **Hadrons** (like heavy machinery at an archaeological excavation), Faster, but some details could go unnoticed.
  - **Leptons** (like brush excavation), limited, but precise.

- **Machine type (linear or circular)**
  - **Hadrons:** Heavy particles: difficult to accelerate and bend – linear machines not an option, circular limited by magnetic field strength
  - **Leptons:** Accelerated quickly to high momenta, feasible with linear – no recirculating, energy limited by the machine length. Circular machine are limited by synchrotron radiation