What after the LHC?

To a Higgs Factory and beyond

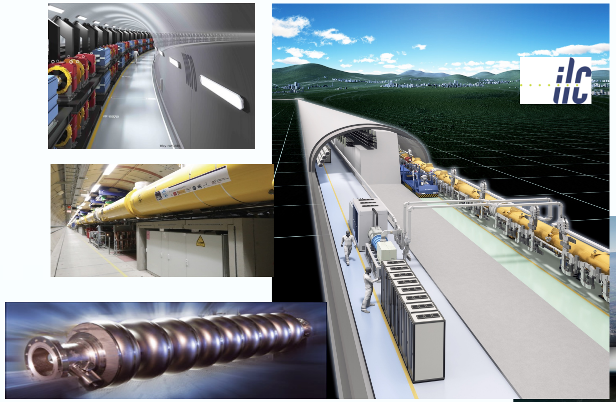
Institut national de physique nucléaire et de physique des particules

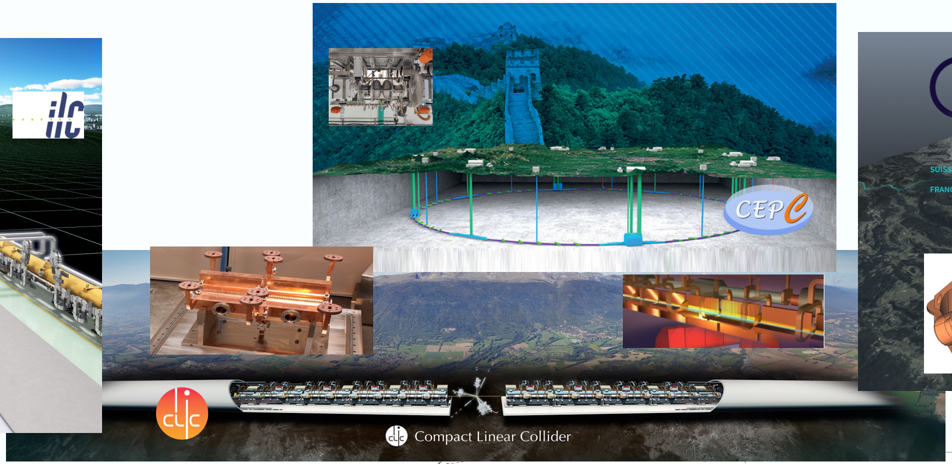
A. Faus-Golfe on behalf the IN2P3

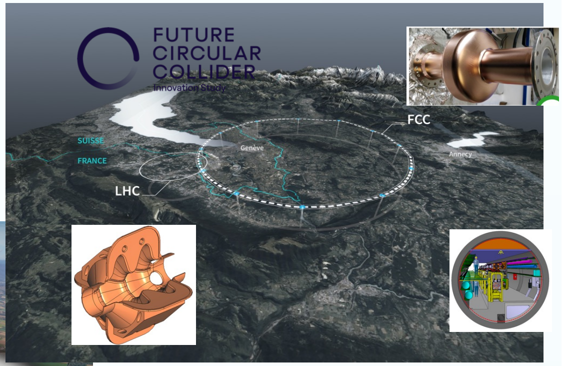
Present and Future Large Accelerator projects

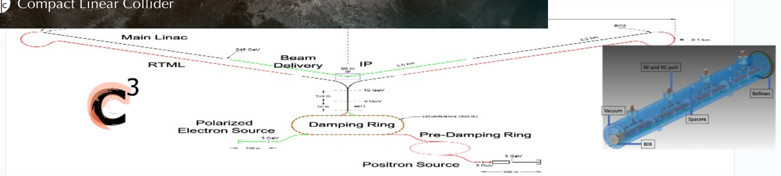
In operation
In construction
Under study

An uncompleted view …









International Large Scale Projects

Medium Term Plan

EPPSU ⟷ EPPSU

Long Term Plan

2020 2023 2026 2029 2032 2035 2038 2041 2044 2047 2050 2053 2056 2059 2062 2065 2068 2071 2074 2077

LHC
DAPHNE
Super KEKB
…

ESS
SC linac

HL-LHC
11T Nb_3Tn

FAIR

LBNF

EIC

CepC.
High current
Z-pole

CCC
Cool Copper

ILC
1.3GHz SC
nano-beam/stabilization

FCCee
High current
Z-pole

SppC

CLIC
12 GHz
nano-beam/stabilization

FCCeh
ERL

FCChh (FCCee)
16T Nb_3Tn/NbTn

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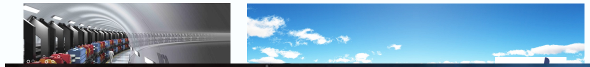
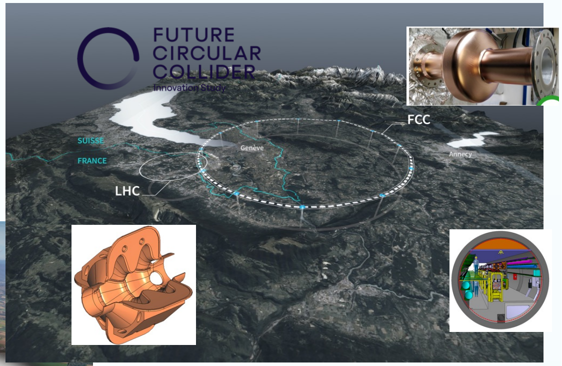
Year of start Physics

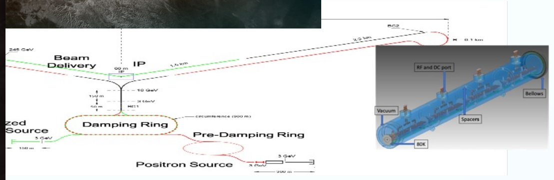
Present and Future Large Accelerator projects

An uncompleted view …

In operation
In construction
Under study







International Large Scale F

Medium Term Plan

EPPSU ⟷ EPPS

2020 2023 2026 2029 2032 2 … 2065 2068 2071 2074 2077

LHC
DAPHNE
Super KEKB
…

ESS
SC linac

HL-LHC
11T Nb_3Sn

F

FCChh (FCCee)
16T Nb_3Sn/NbTn

start Physics

A complex choice

$\mu^+\mu^-$

Medium Term Plan

Long Term Plan

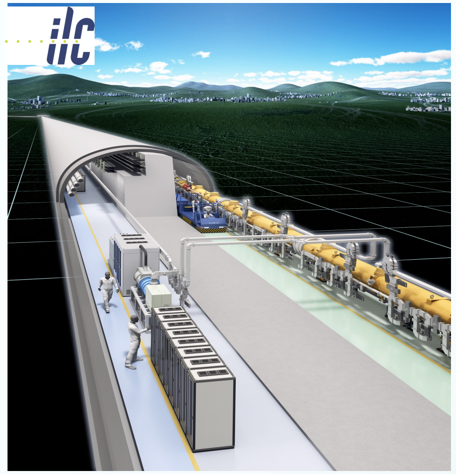
EPPSU 2020 — 2021 — 2022 — 2023 — 2024 — 2025 — 2026 — EPPSU 2027 — 2028 — 2029 — 2030 — 2031 — 2032 — 2033 — 2034 — 2035 — 2036 — 2037

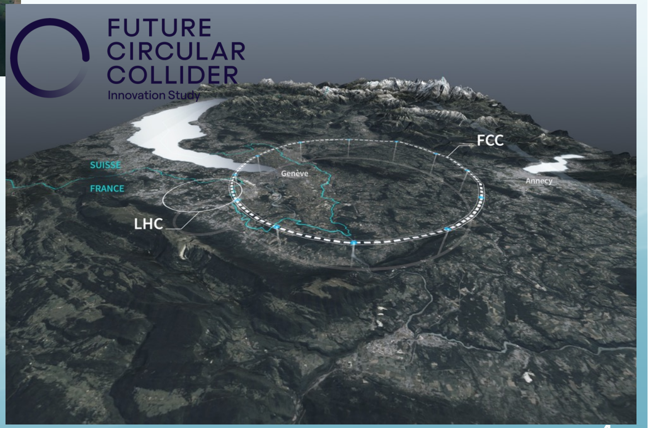
Outline

- **Future Collider Projects**
  - ESSP & Snowmass context
  - State of the Art and Scientific Issues
- **IN2P3 contribution**
  - R&D and Projects (2021-2025)
- **Future Perspectives**

Higgs Factories

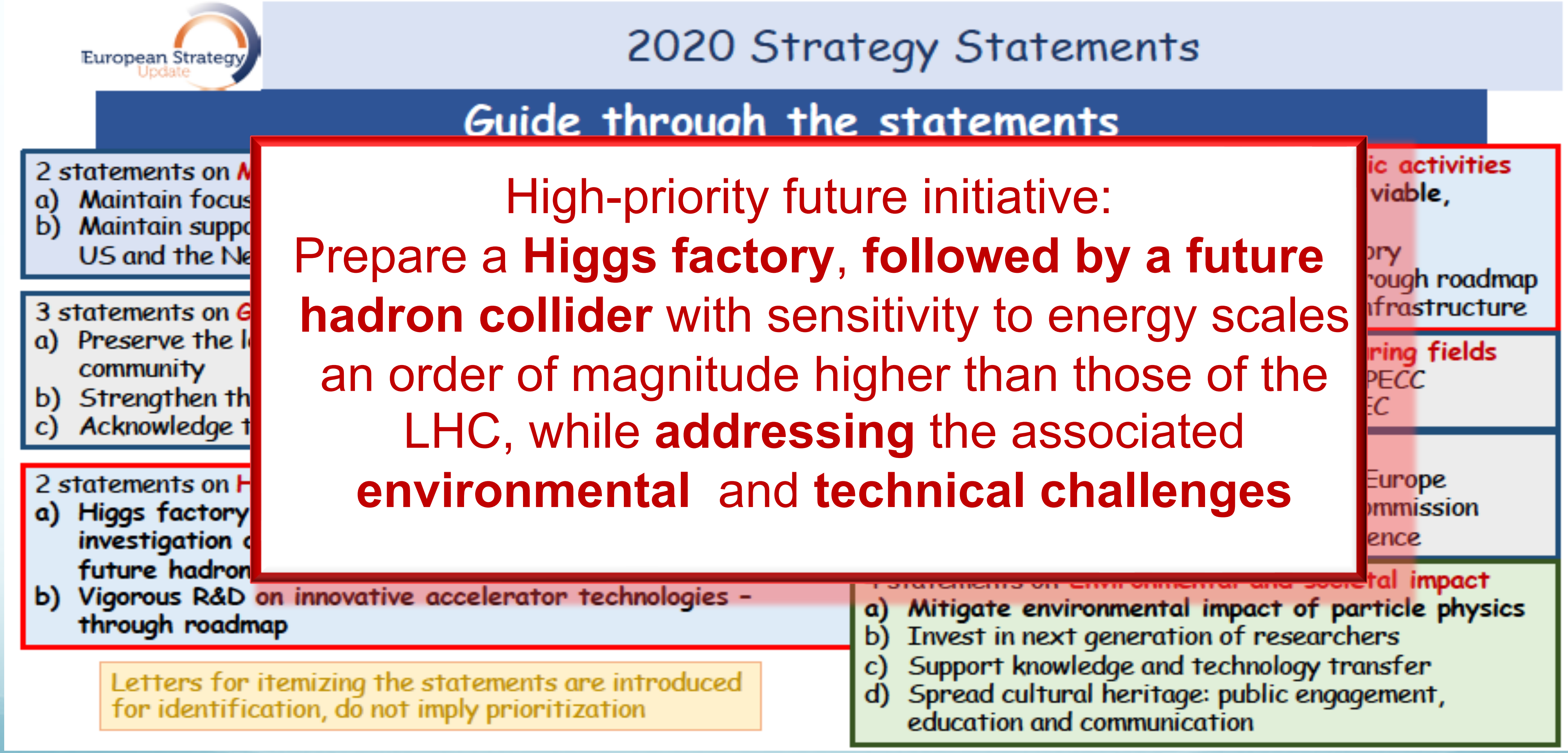
- Linear: ILC/CLIC
- Circular: FCC-ee





Context: EPPSU 2020 process update

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



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**

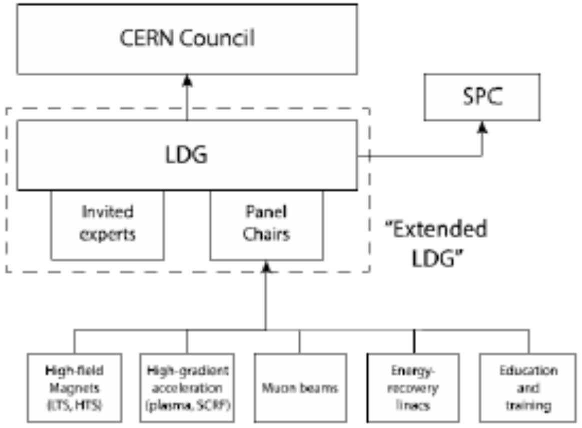
H. Abramowizc ESG January 2020.

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

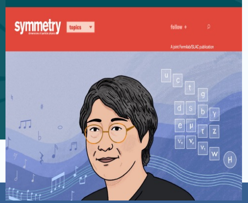
IN2P3 Panel Members: Kevin Cassou IJClab; Angeles Faus-Golfe IJClab; Walid Kaabi IJClab

➢ **LDG Report (2022)**

Context: Snowmass'21 process

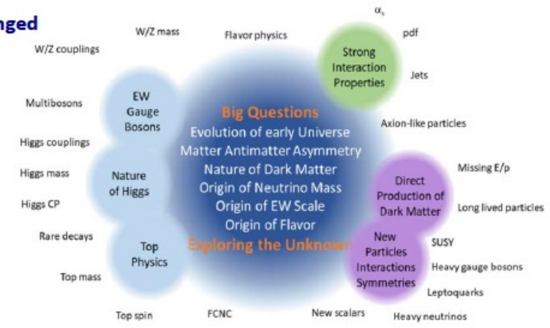
Moving Forward to P5

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

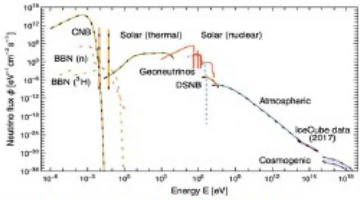
The most surprising thing that emerged from Snowmass was an overwhelming sentiment to engage in hosting a future collider in the US
...and the public praising of EF by Michael Peskin for enabling a vigorous discussion on future multi-TeV colliders

Highlights and Messages from the Snowmass Summer Study.
Prisca Cushman

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.
* A healthy program of projects of different sizes and time scales, with wide-ranging connections is highly desired and very much needed.

Impacts everywhere! But if we have to choose it's the Cosmic Frontier, due to deep connections and intertwined BSM searches in multiple areas.



Neutrinos are tools for astrophysics and cosmology. Astrophysics and cosmology provide insight into NF physics.

What surprised us? Great technical progress on the detectors!
Well, that was not totally a surprise– but it was even more impressive than expected!

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).

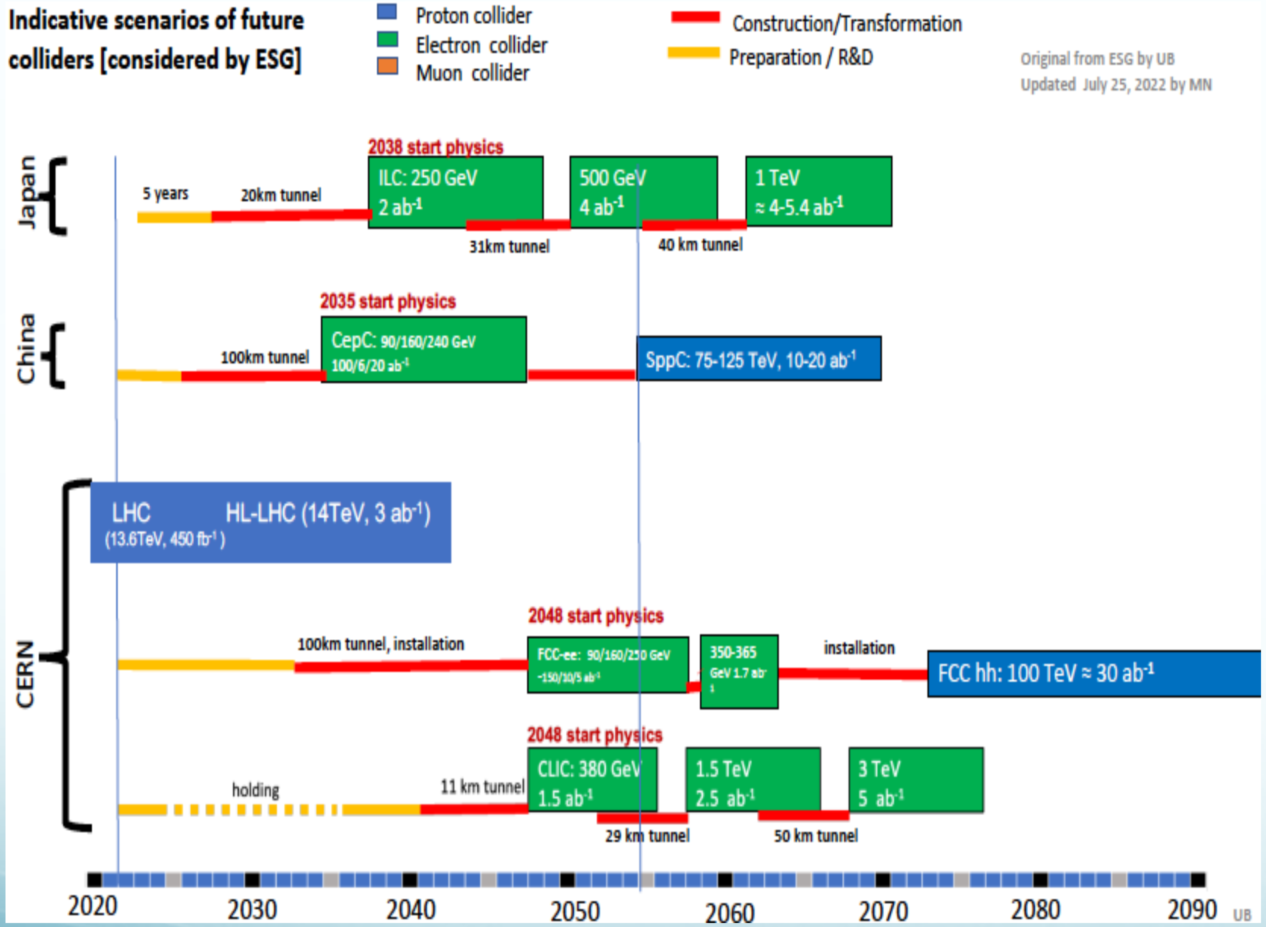
Surprising Thing this week at Snowmass:
We seem to be clever enough to be seriously taken by the Theory Frontier (they even did argue with us)...

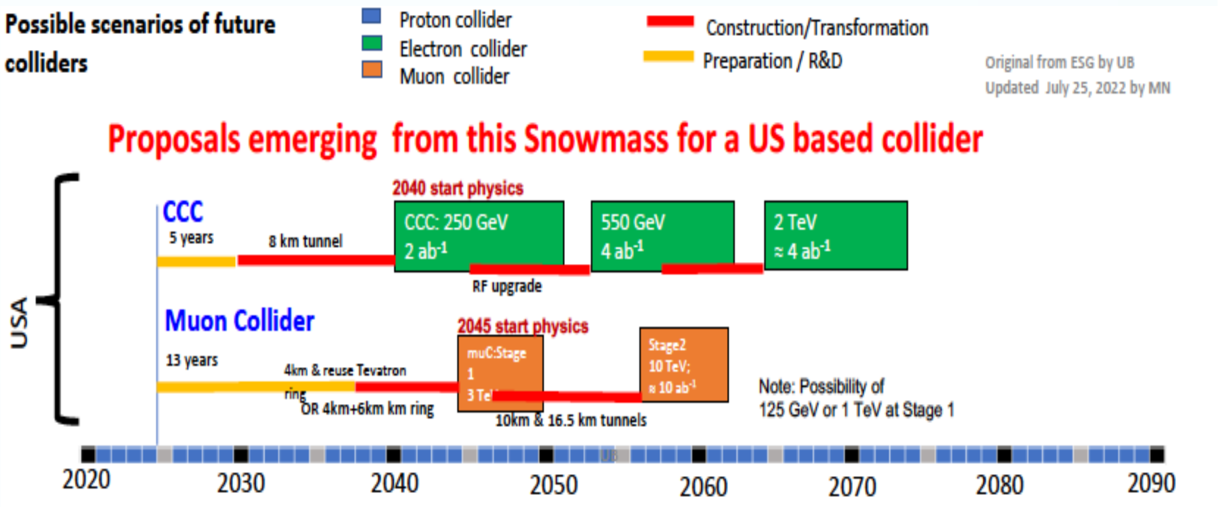
Angeles Faus-Golfe IJClab

Snowmass 2021

Community Summer Study
SNOWMASS
July 17-26 2022, Seattle

Context: HEP FC 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.

Future Colliders 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.

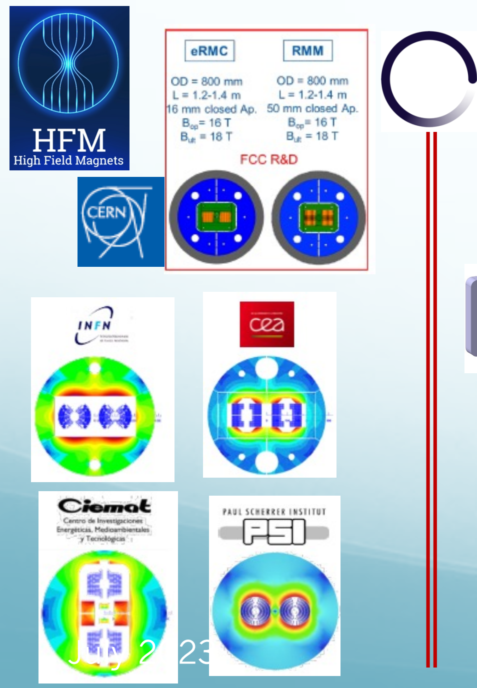
arXiv:2209.05827v1 [physics.acc-ph] 13 Sep 2022

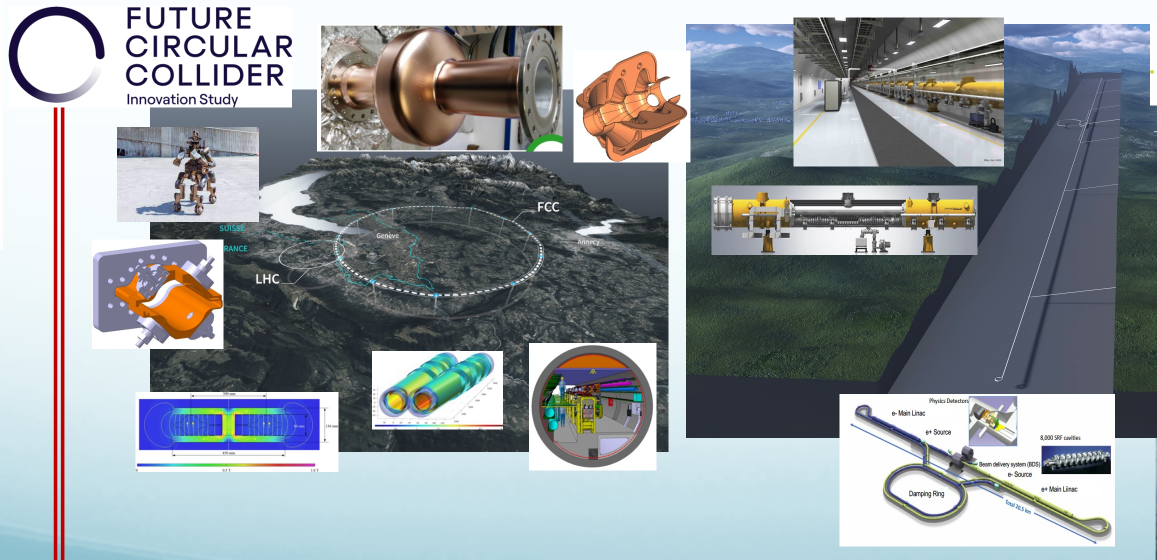
HEP FC Key Technologies

➤ HEP Large Accelerator Projects Key Technologies

IN2P3 ▭

			RF cavities						Magnets							
Components			**SCRF**				**NCRF**	**HLRF**	**SC Mag.**		**NC Mag.**	**Vac**	**IRs**	**Injec-e+**	**Sust – C footprint**	**Others**
Techniques			**Design**	**HG/HQ**	**CRYO**	**CRAB**		**HE-Klys**	**Nb_3Tn**	**CRYO**						
PROJECTS	**FCC**	**FCC-hh**				X			X	X		X			X	Integr.
		FCC-ee	X	X	X	X		X			X	X	X	X	X	Alig./Pos
	LC	**ILC**		X	X	X		X					X	X	X	
		CLIC				X	X	X			X		X		X	





e⁺e⁻ Higgs factory technology is ready

Context: FCC - Next Particle Colliders

A **rich R&D program** is driving the developing and building of these new facilities. A **strong cooperation** between national institutes, CERN and others global laboratories or collaborations is vital for the **progress of the field** and also for **preserving the expertise**.

In this context the **main goal** of **the FCC-NPC IN2P3 project** is to ensure an **appropriate contribution** to this vibrant and diverse R&D program focusing in where we have already demonstrated our **know-how** and **expertise**:

IN2P3

- Nanobeams handling
- Nanobeam stabilization and positioning techniques
- Luminosity and backgrounds
- High-intensity e+ sources
- e+e- polarimetry
- Dynamics vacuum and material studies
- SRF multipacting and materials

Scientific issues: Nanobeam size handling

$$L = f_{coll}\frac{N_b^2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

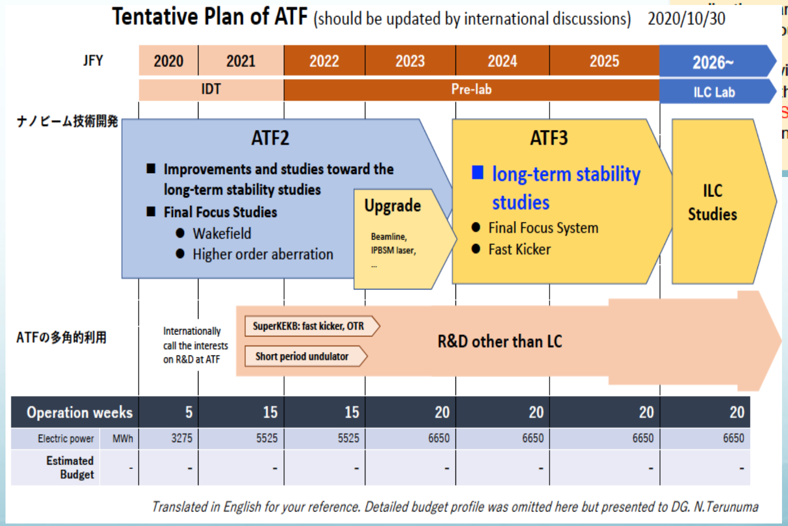
Very **high peak luminosity** needs **nanometre transverse IP beam sizes** (FCC-ee 30-70 nm, ILC 3-8 nm, CLIC 1-3 nm).
To **demagnify** the beams, complex **IR** and **FFS** are designed.

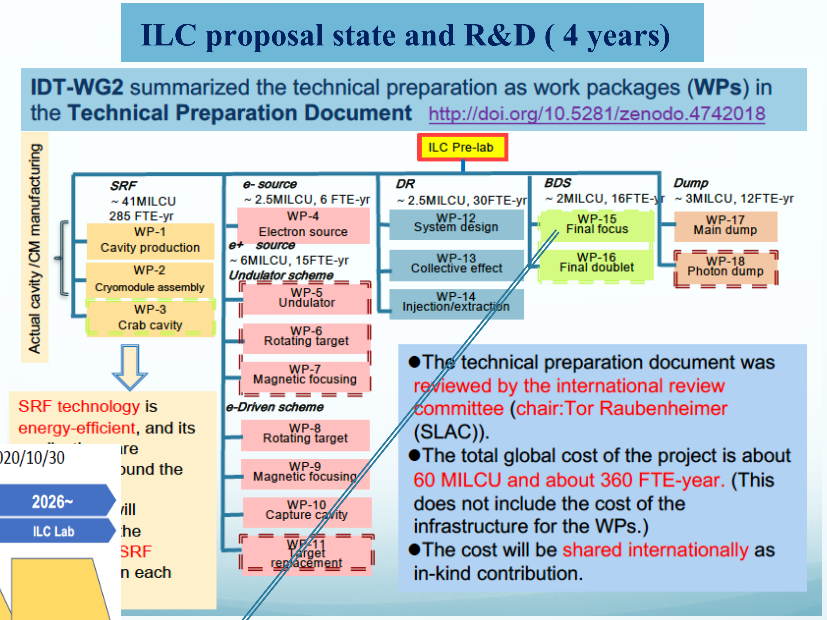
➢ ILC/CLIC scaled FFS: ATF2-3

ATF/ATF2 FFS has verified the **minimal technical feasibility** of ILC/CLIC-FFS, to **maximize** the **luminosity potential of ILC/CLIC** a further investigation and complementary experimental program on:

- Intensity dependence effects on the IP size
- Optical aberrations specially with smaller β_x^*, design optics (β_x^* x β_y^*)
- Smaller sizes ultra-low β^* (CLIC)

will be pursued in a follow-on upgraded facility **"ATF3"** (ILC-IDT framed).





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To **demagnify** the beams, complex **IR** and **FFS** are designed.

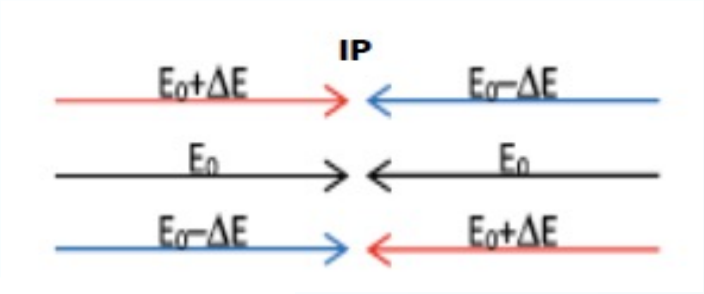
➢ FCC-ee IR studies:

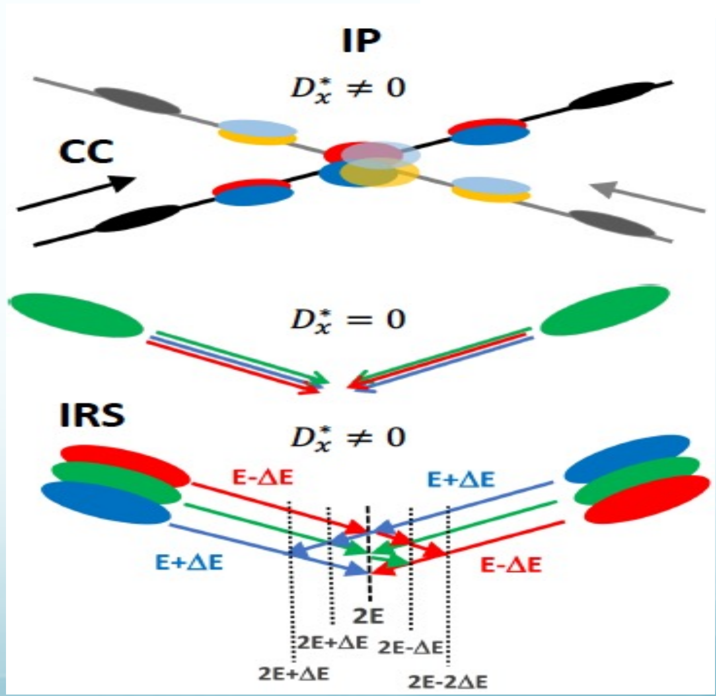
In some “special” IR configurations as **monochomatization** the **energy spread** could be **reduced** to **maximize** the **sensitivity** of certain **physics channels**. Further studies on:

- Parameters including Beamsstrahlung (BS) (increased ε_x σ_b) and crossing angle (Crab Cavities-CC)
- Optics design to generate antisymmetric D_x^* are needed to probe the feasibility of this kind of IR schemes.

Realistic IR simulations: Synchrotron Radiation (**SR**) and **Solenoidal detector** fields impacts in MADX code.

$$w = 2E_0 + 0(\varepsilon)^2$$





Crossing angle monochromatization scheme featuring IP dispersion of opposite signs for the colliding beams with (top) crab crossing (CC) and without (bottom) or integrated resonances scan (IRS). Different colors schematically indicate the bunch portions with slightly different energies.

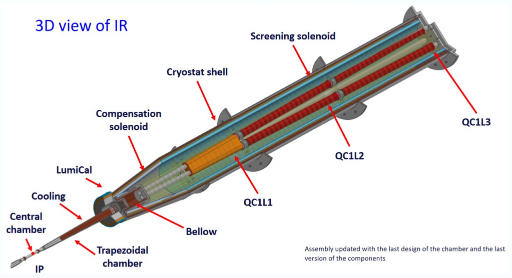
Scientific issues: Nanobeam stabilization and Positioning

Vibration mitigation and **misalignments control** are crucial to obtain **high luminosity** (CLIC FFS magnet specification displacements 0.2 nm at 4Hz).
With thousand of magnets**, dynamic positioning approach** by girder is the most effective approach.

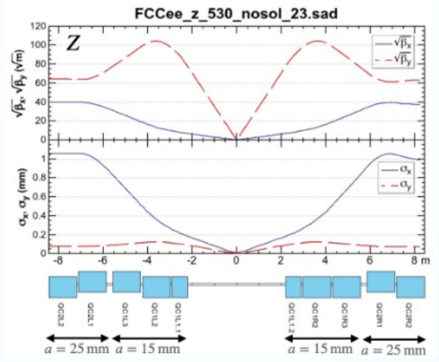
➢ Nanobeam stabilization

Ground Motion (GM), **structural vibrations effects** and **elements position inaccuracies** has an **impact on beam brightness** and **position stability** at the IP. R&D to mitigate this effect on:

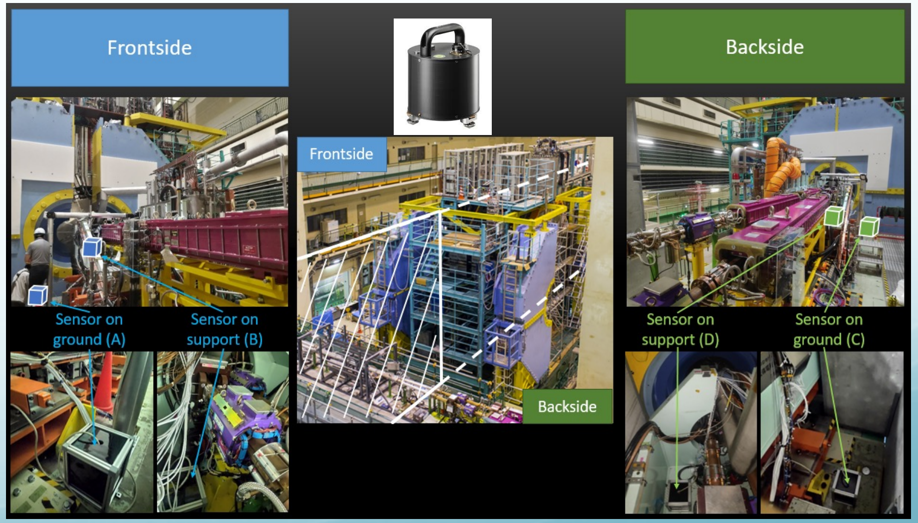
- Beam dynamics studies to evaluate **vibrations impacts**
- **Modelling** (finite elements simulation) of **mechanical dynamics behavior** and prototyping
- **Coherence motion**, reducing the relative motions between the elements (main experiments strategy-low cost)
- **Active control** to reduce the absolute motion (high-cost) and beam control trajectory
- **Vibration monitoring** to evaluate the seismic and cultural noise (luminosity correlation...)



FCCee : IR Design



FCCee : optics simulation at IP



4 seismic sensors (2 each side) BELLE II

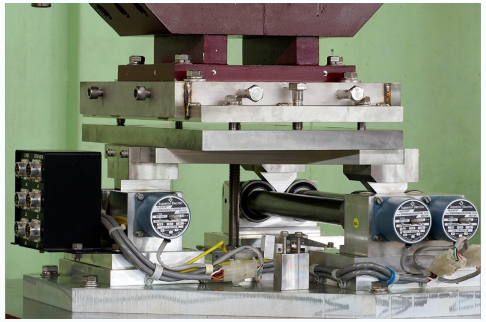
Scientific issues: Nanobeam stabilization and Positioning

Vibration mitigation and **misalignments control** are crucial to obtain **high luminosity** (CLIC FFS magnet specification displacements 0.2 nm at 4Hz).
With thousand of magnets, **dynamic positioning approach** by girder is the most effective approach.

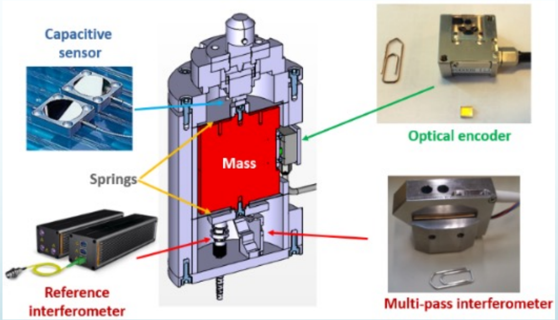
➢ Positioning systems and vibration sensors and actuators

FCC-ee positioning strategy based on the management of the **girder position**, with elements already aligned, is in the state of the art (ESRF, SLS, CepC). R&D to extend the application is needed:

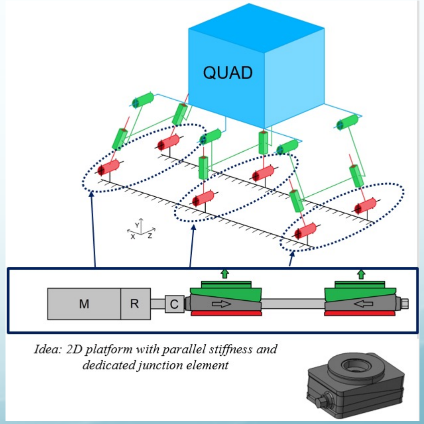
- **Actuators** (cam movers on components, control systems, nano-positioning systems)
- **Sensors**: Hydrostatic Leveling System (HLS), Wire Positioning Systems, differential sensors and vibrations sensors.




Camshaft driving motors at ATF2



R&D on vibrations sensors and differential measurements



R&D on dedicated movers

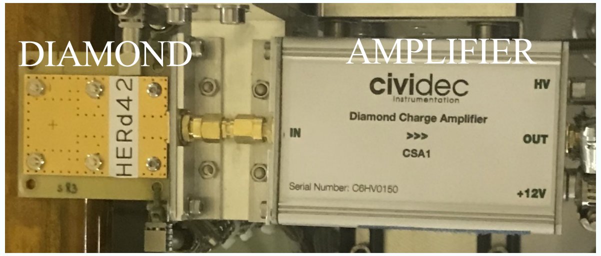
Scientific issues: Luminosity and Backgrounds

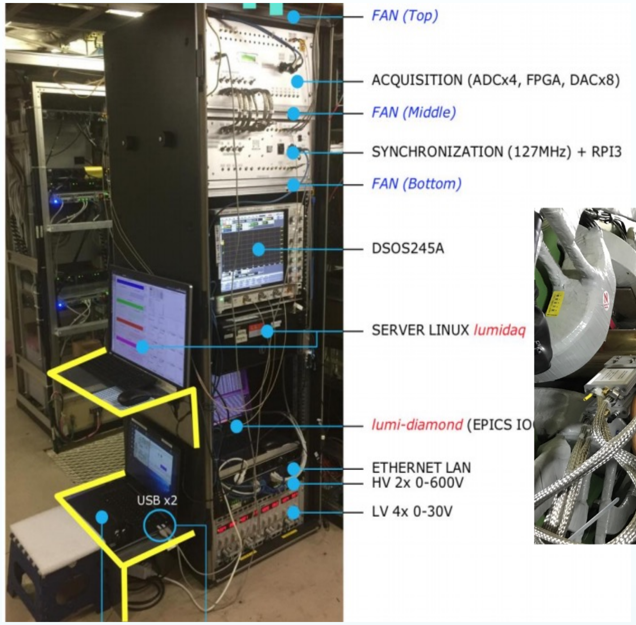
High luminosity implies the **continuous correction** of **residual beam offsets or aberrations**, **fast luminosity measurement** are an essential tool. **Backgrounds mitigation** are increasingly difficult with **ultra-low β*** and very **high currents**.

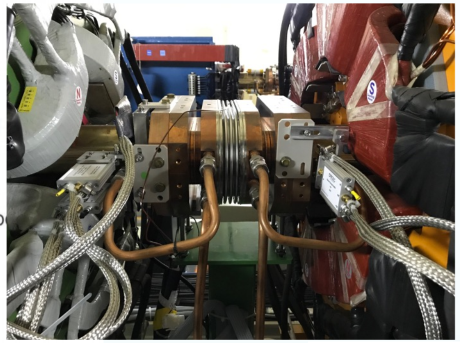
➢ Fast luminosity measurements

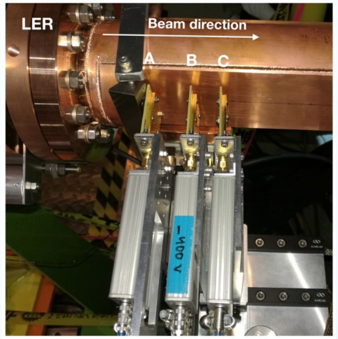
Fast Luminometers (1% precision at 1 kHz) designed by IJCLab are deployed at SuperKEKB with large dynamic range, bunch-by- bunch and serving also as beam loss monitors. Their measurements are the input for:

- **Feedback systems** which **stabilize** the **colliding beams** and **minimise** their **residual** horizontal and vertical **offsets.**
- **Aberration correction** tuning procedure
- **Luminosity optimization**, including mechanical vibration near the detector area





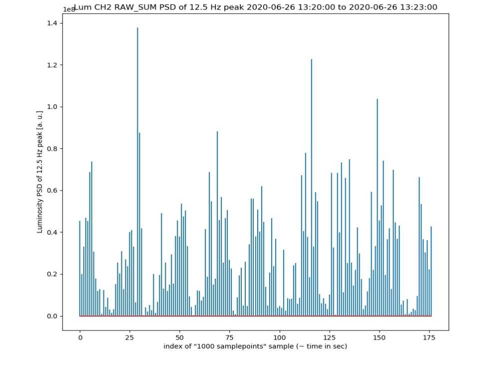




➢ Backgrounds

Simulation and **experimental** studies on beam loss backgrounds from continuous top-up injection system

Power Spectral Density component at 12.5 Hz reconstructed during 3 minute scan: injections are visible lasting 10 seconds every 20 seconds !



Scientific issues: High-Intensity e^+ sources

$$L = f_{coll} \frac{N_b^2}{4\pi\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

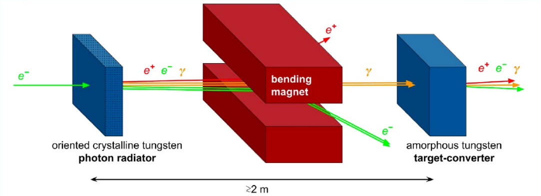
High-beam intensity and **low emittance e^+** are necessary to achieve high-luminosity
(ILC/CLIC 10^{16} e^+/s, 3.5×10^{10} e+/bunch or $\sim10^{13}$e+/s)

➢ Novel types of e^+ sources

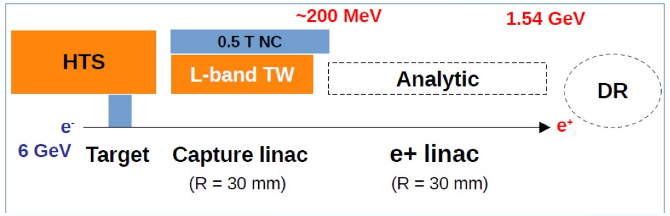
R&D beyond existing lepton injector technology :

- **Novel types of e^+ source** based on the hybrid scheme (channeling in crystals) with new granular targets.
- **e^+ capture system** based on **SC solenoid** as the matching device for the capture system
- Use of the **Artificial Intelligence** (AI) for global **optimisation** of the e^+ injector parameters
- PoP e+ experiment in PSI (P3).

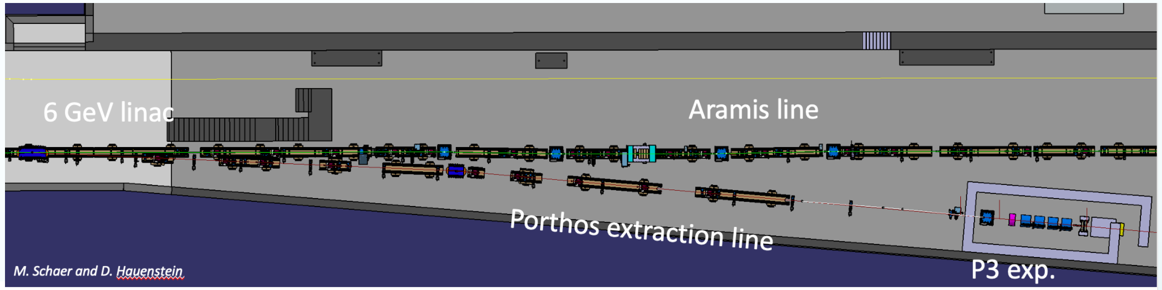
Crystal-based target Hybrid scheme

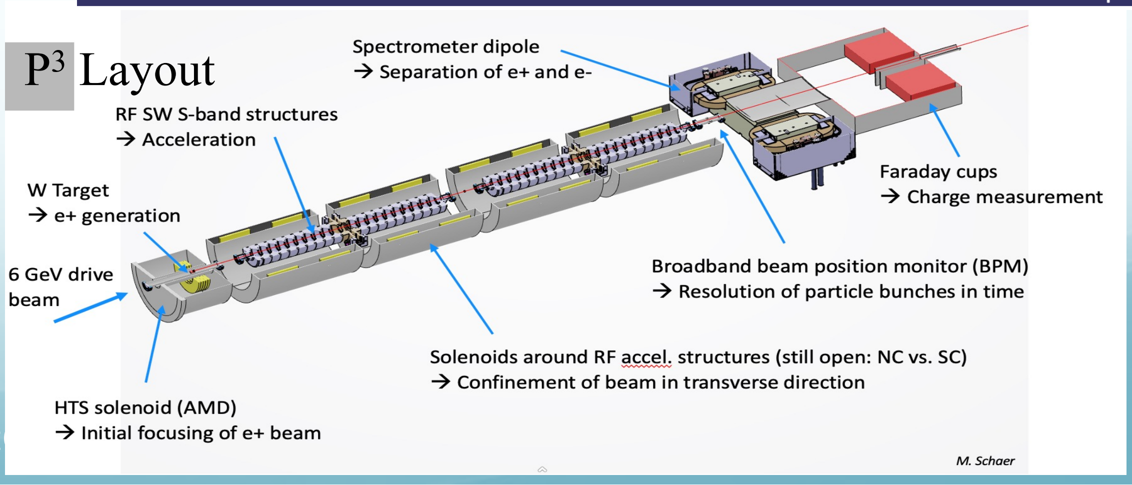


Capture system



PoP experiment for novel positron source (P3)





Scientific issues: e^+e^- Polarimetry

To **optimize** the **collision** of polarized beams, **rapid measurements of polarization** are a key ingredient. (ILC per-mil level precision)

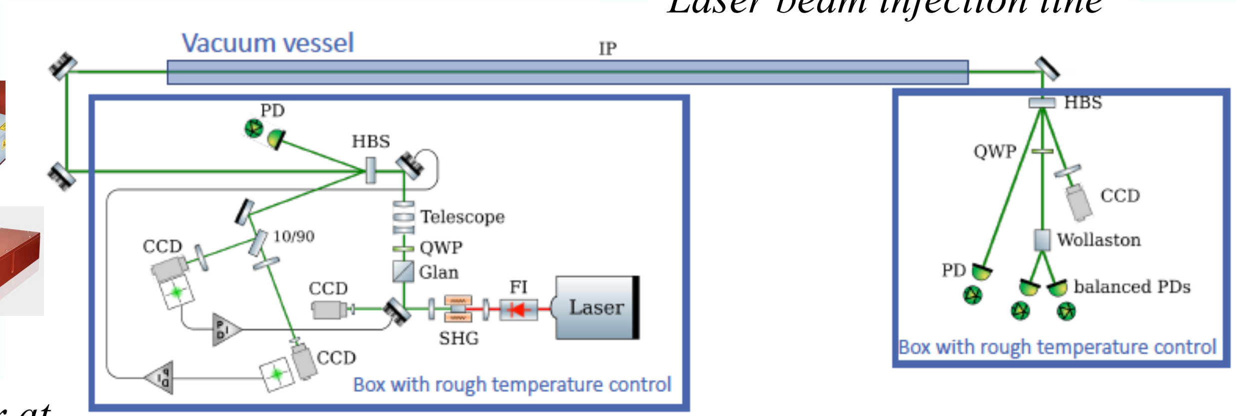
➢ Compton polarimetry

R&D on:

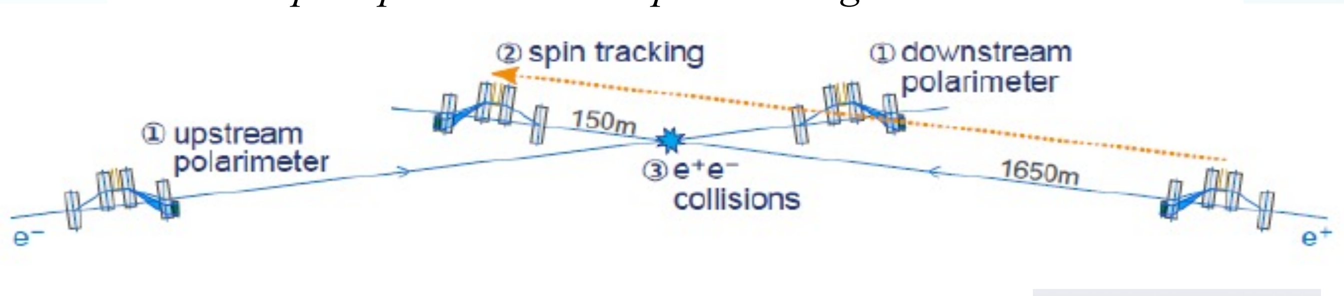
- Design of the **laser systems** in terms of the real time monitoring of the laser-beam polarization that enters as an unavoidable systematic uncertainty on longitudinal polarization
- Feasibility study of **per-mil level** precision
- **Beam energy measurement** by **resonant depolarization** at FCC-ee.

5W green laser at 250MHz

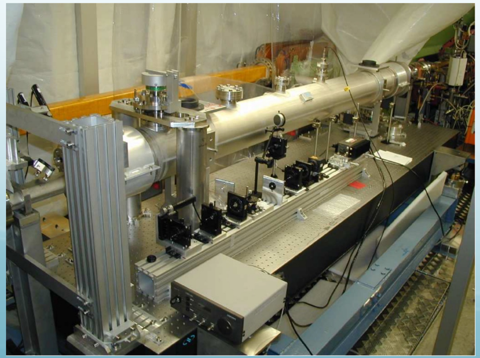
Laser beam injection line



ILC Compton polarimeter + Spin tracking + e^+e^- collision data



HERA polarization cavity



Upstream Laser design: 30µJ/pulse in red for continuous ellipsometry at 1.8 MHz, 100W in red 50W in green

Downstream Laser design: 100mJ at 2KHz

Scientific issues: Dynamics Vacuum and Material studies

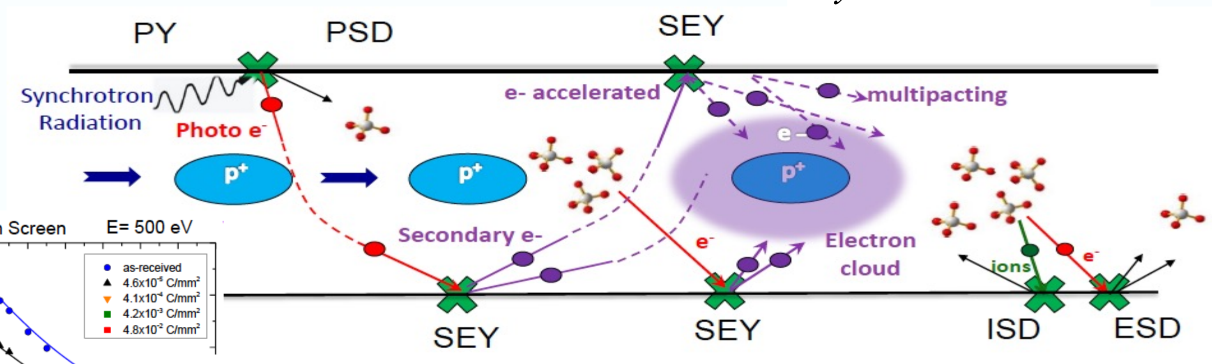
One of the main **potential limitation** in all future colliders is the **dynamic pressure**. Specifications of **vacuum systems** and vacuum studies, including **materials** are of paramount importance.

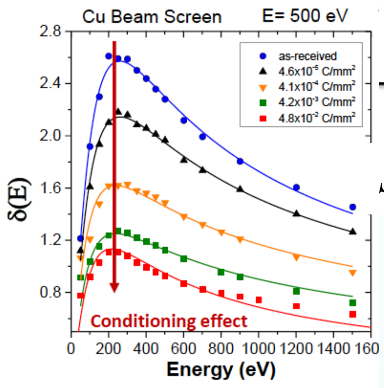
➢ Dynamics Vacuum and Materials studies

Experimental and **Simulation** studies on:

- Measurement of the **Secondary Emission Yield** (SEY) (multipacting)
- **Surface analysis** of materials
- In situ **measurements** of **pressure** and development of the **Dynamic pressure simulation** (DYVACS)
- **Ion Stimulated Desorption** (ISD) experimental studies at yields of production for the conditioning surfaces of FCC-ee

Dynamics Vacuum

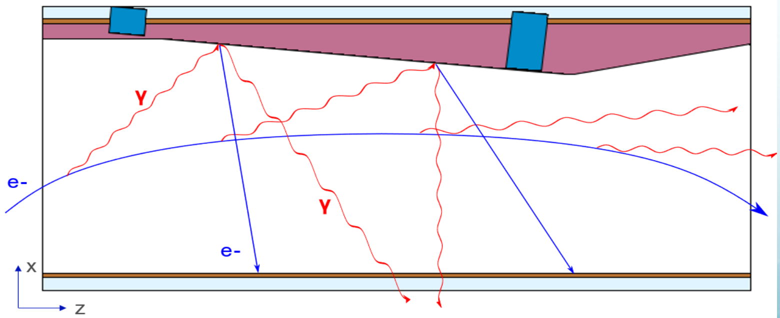




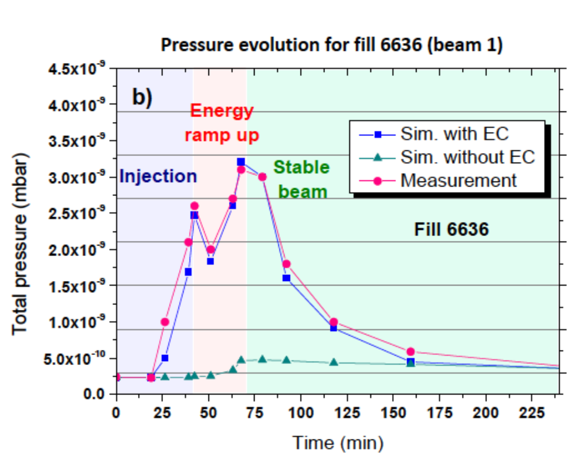
SEY measurements

LHC measurements versus DYVACs simulations

Compton scattering in a beam pipe

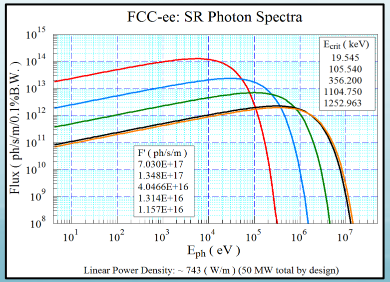


Compton scattering: photon collides with electron and is scattered into a different direction, dominant in the MeV range



E=182 Gev

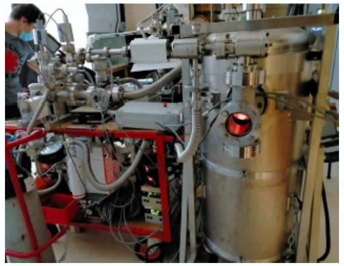
Energie critique ~ 1.2Mev !!!



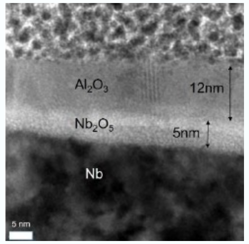
SRF Cryogenics and materials

Understanding the physics of SRF regime to **optimize** the **performance** of **Nb** or other **new materials** in terms of accelerating gradient and quality factor (cost) is crucial for the performance improvement of SCRF cavities.

➢ SRF materials



Plasma cleaning set-up

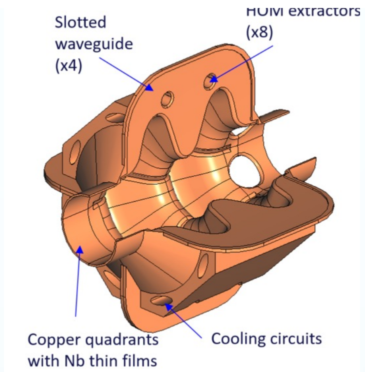


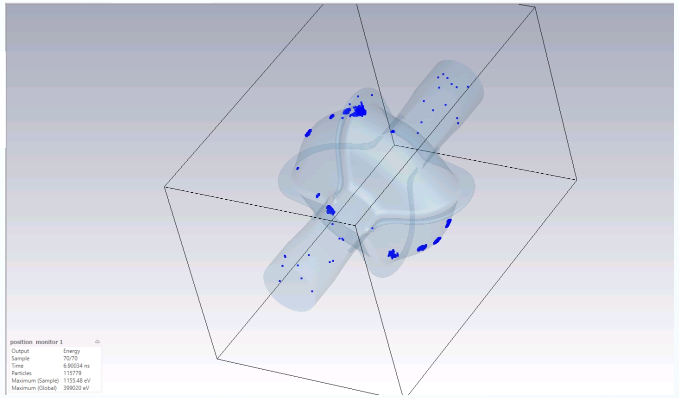
ALD deposition in Nb

Further studies on:

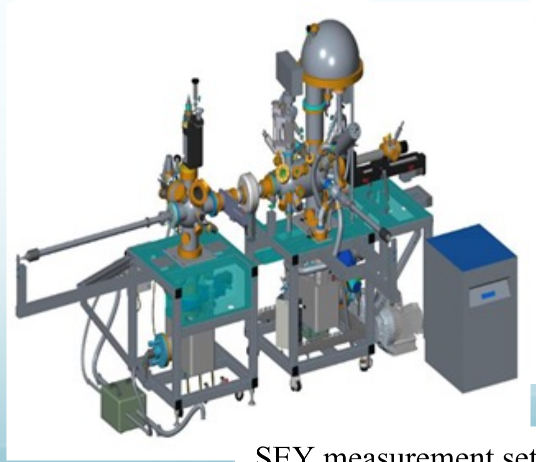
- Improvement of SCRF with **innovative surface treatments and processing** (plasma cleaning)
- **Heat Treatments**: N_2 infusion and doping of Nb surfaces (low-frequency and low-beta).
- **Thin films** SC materials (multipactor mitigation)
- **Multipacting modelling** (FCC-ee SRF SWELL) and benchmarking with experiments
- **SEY measurements** (FCC-ee SWELL cavity surface samples)

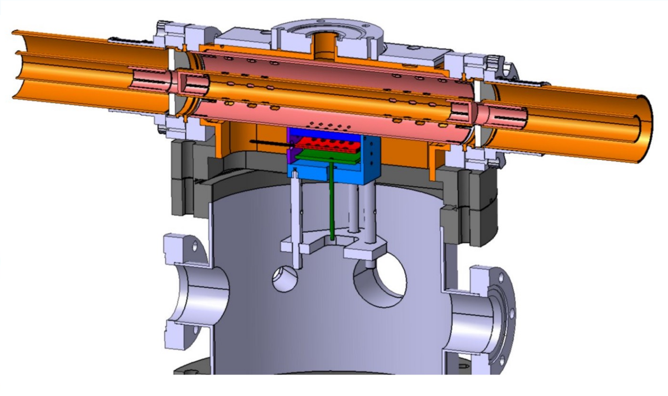
Slotted Waveguide Elliptical cavity (SWELL)





Preliminary studies of multipacting location





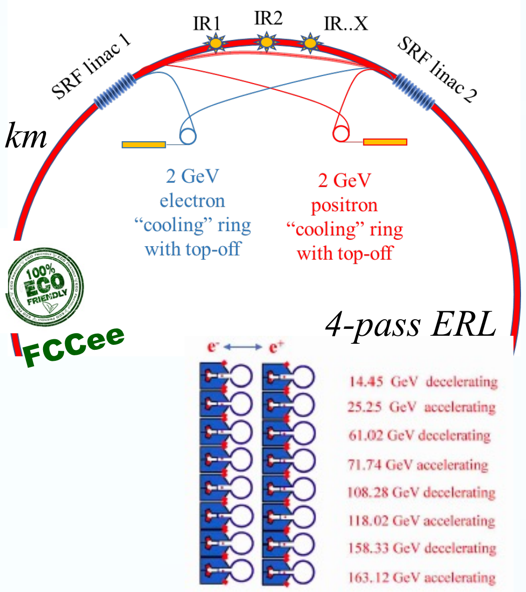
SEY measurement set-up at cryogenic temperature @ IJCLab (2024)

Beyond Higgs factories…

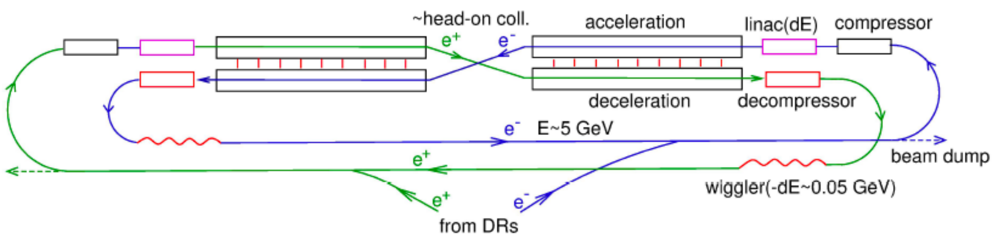
- **Boosting the performances** of Higgs factories
  - **ERLs** for FCCee and ILC
  - **Plasma Injectors**
- **Muon colliders**
- **Advance Linear Collider e+e-** : HEP Energies in PWA
- Dreamt colliders…

PERLE synergies

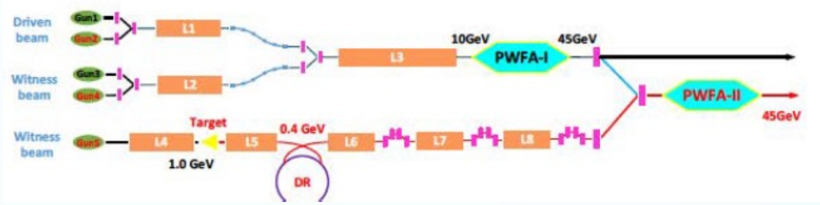
ERL based FCC-ee upgrade

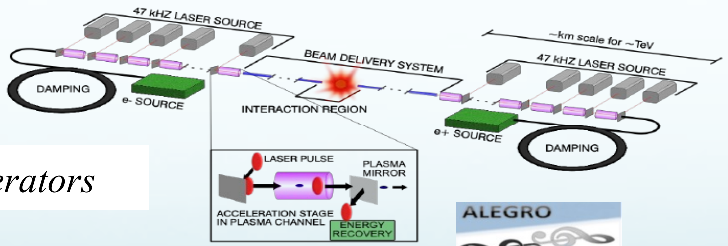


Twin SC LC with ERL



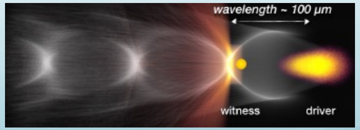
CEPC Injector Alternative: Plasma Accelerator up to 45GeV single stage)~120GeV (cascade)



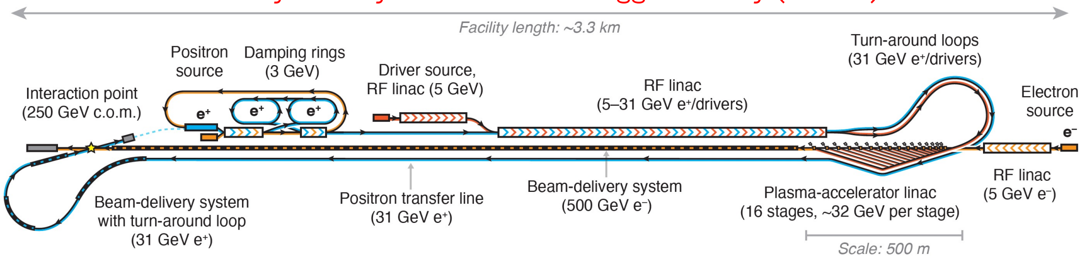


Linear colliders based on laser-plasma accelerators

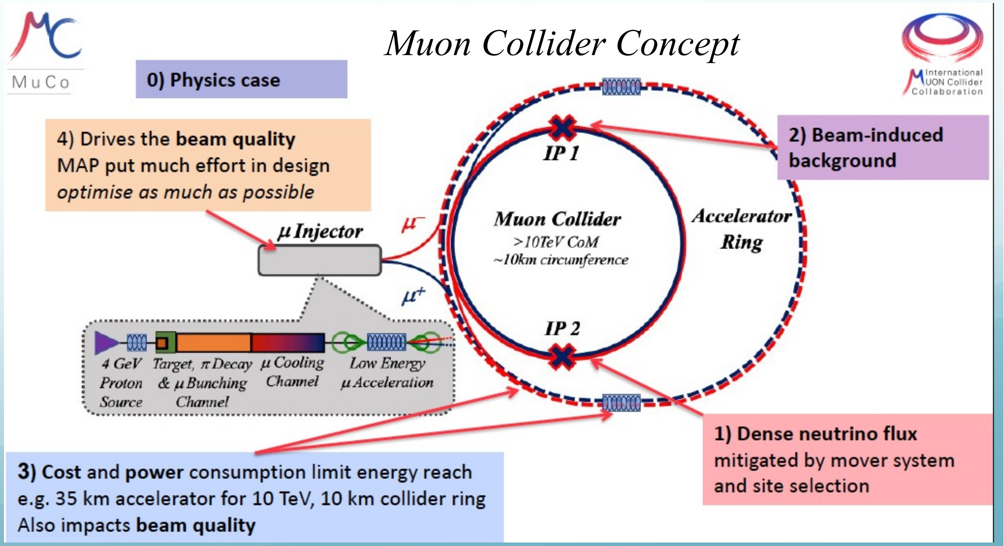
ALEGRO
Advanced LinEar collider study GROup



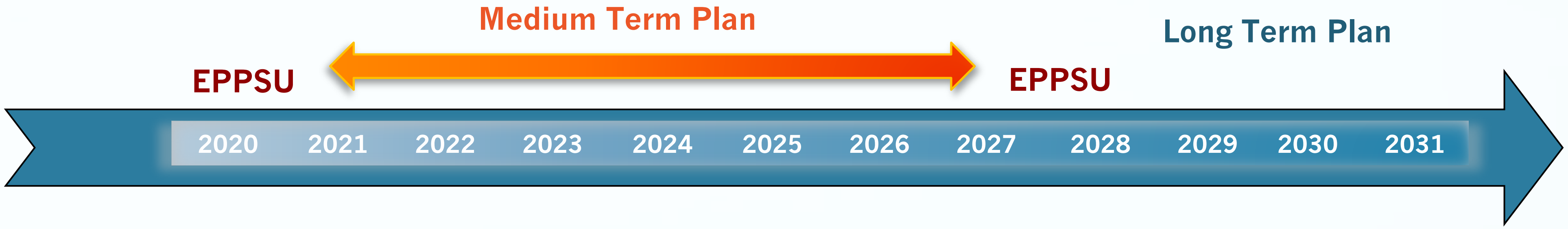
Hybrid Asymmetric Linear Higgs Factory (HALHF)



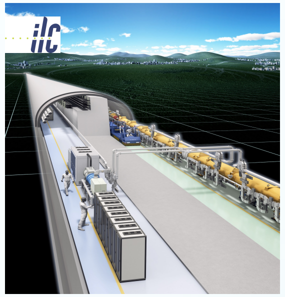
Muon Collider Concept

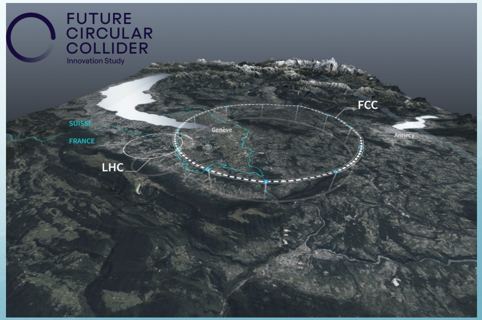


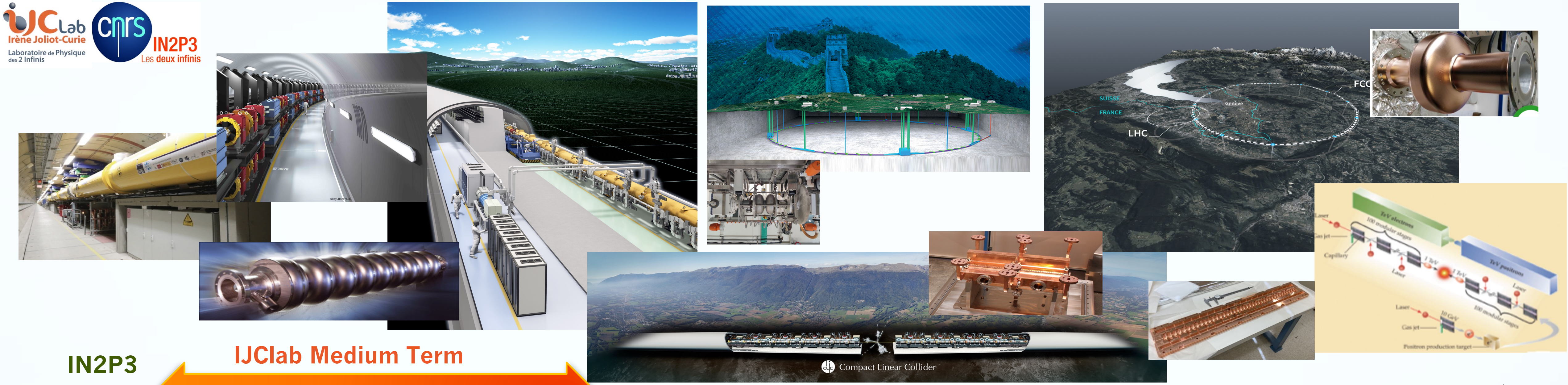
Projects and R&D Future Perspectives



PROJECTS R&D	Present	MT Future	
	B Factories	Higgs Factories	
	SuperKEKB	ILC/CLIC	FCC-ee
Nanobeams & IRs		X	X
Stabilisation & Positioning	X	X	X
e+ sources		X	X
Opt. systems for beam inter.	X	X	X
Vacuum & Materials			X
SRF Cryo & Materials			X







IJClab Medium Term

IN2P3 EPPSU — EPPSU

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037

- The **MT objective is to integrate, harmonize and synergize** the **IN2P3 R&D accelerator activities** related with **current and future colliders**
    - **Consolidate** the **R&D** areas
    - **Identify** the **approaches** with **greatest potential.**
- All of this in **alignment** with the **IN2P3 strategy** and having in view the next **EPPSU strategy update.**

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

HE&HL γγ

CERC

XCC γγ

EPCCF

HELEN

ReLiC

CEPC

FUTURE CIRCULAR COLLIDER
Innovation Study

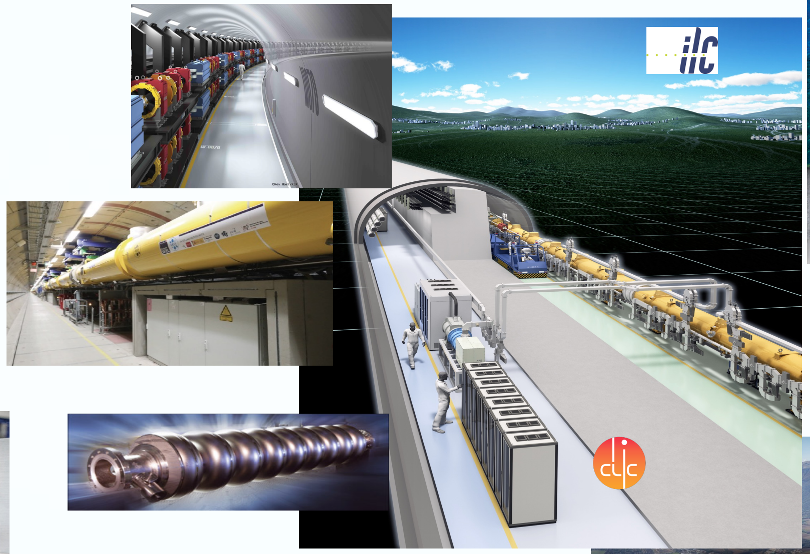
ilc

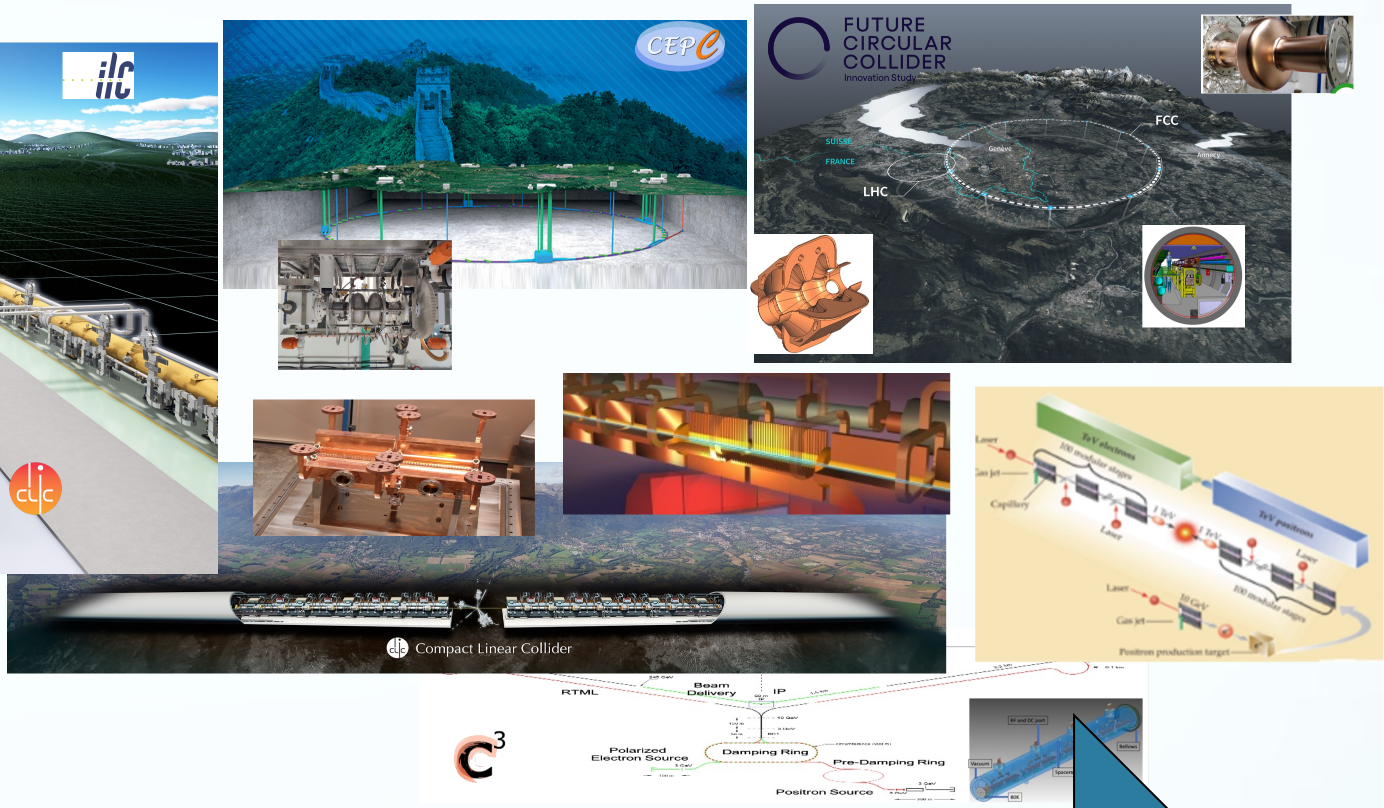
clic

C^3

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

cnrs IN2P3 Les deux infinis





Thanks for your attention