CLEAR: a Long-Term Outlook

R. Corsini, D. Gamba for the CLEAR Team

CLEAR Review 2024 – 29th May 2024 - CERN

Outline

- Back to the Basics:
  - Overview of CLEAR Infrastructure and Goals
- Expected Use of CLEAR in the Coming Years:
  - Contributions to a Higgs Factory at CERN: with an emphasis on FCC-ee
  - Contributions to the Irradiation Facility Ecosystem for Detectors R&D
  - Contributions to Accelerator Technology, including Training and Controls
- Looking Ahead:
  - CLEAR as an Incubator for FCC-ee Injector as CLEAR++
- Conclusions

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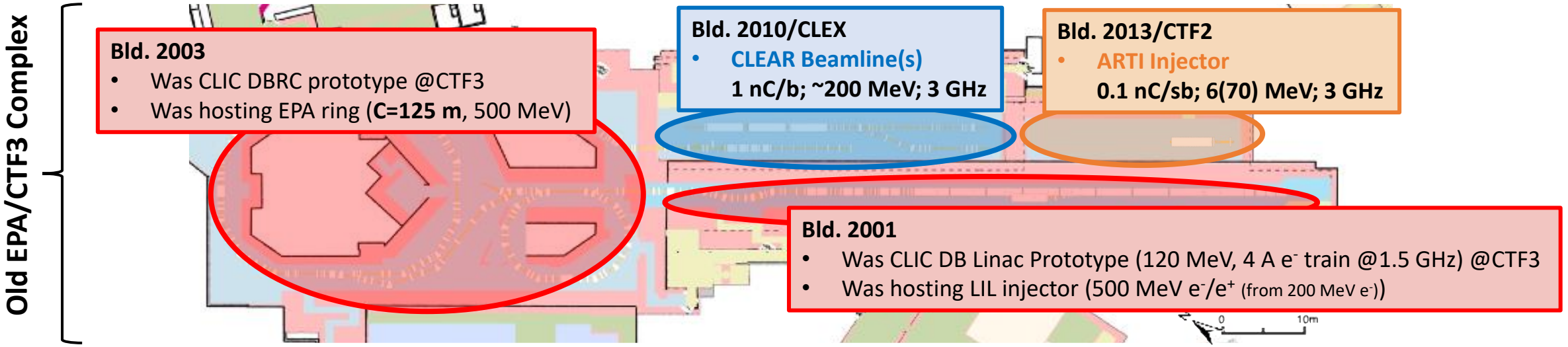
Back to the Basics: CLEAR and its Scientific and Strategic Goals



- Providing a **test facility at CERN** with high availability, easy access and high-quality e^- beams.
  - Performing **R&D on accelerator components**, including beam instrumentation prototyping and high gradient RF technology
  - Providing an **irradiation facility** with high-energy electrons, e.g. for testing electronic components (e.g. in collaboration with ESA) or for medical purposes (e.g. VHEE/FLASH)
  - Performing **R&D on novel accelerating techniques** – electron driven plasma and THz acceleration

- Maintaining CERN and European **expertise for electron LINACs** linked to future collider studies
- Using it as a **training infrastructure** for the next generation of accelerator scientists and engineers

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Expectations and Outlook on Activities 2025+

Demand for experiments on CLEAR **steadily increased** (bar the pandemic period)

- We expect **requests will not decrease** for the next few years (see CSB-2024):
  - **Beam diagnostics R&D** is an **important area**, with about 30% of total tests, and now shared equally between CERN and external users.
  - **Novel acceleration techniques** (plasma, THz, X-band, high gradient) are not growing, but there are a few long-term programs (including Plasma Lens, continued support to AWAKE, and potentially a full-fledged ICS experiment) which **must be maintained** with priority as **part of the LDG roadmap.**
  - **Medical activities** are a highlight – the next 4-5 years will be critical to fully establish VHEE/FLASH. CLEAR will have a **pivotal role in the field** for several years a unique facility for VHEE/FLASH, including knowledge transfer to other labs with capability for animal testing.
  - Activity in other areas (e.g. **irradiation**, **neutron production**, beam test of **particle detectors/components**) is also **increasing overall**, and it will provide further opportunities.
  - The role of **training** and EU projects, with CLEAR being **recognized as a valuable infrastructure** in projects such as EURO-LABS.
- We are **saturating our capacity** to provide beam time to all users. Planned improvement and consolidation will enable us to cope with a slightly higher load.

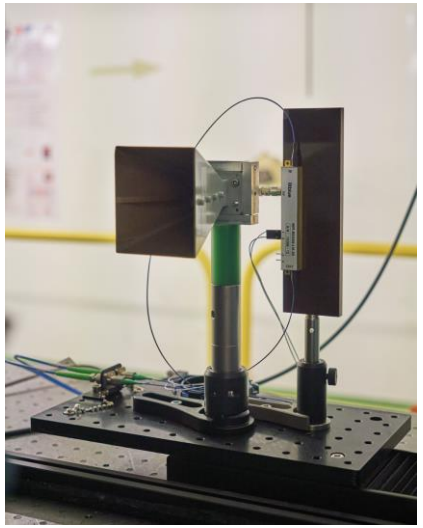
From a **strategic viewpoint**, the CSB-2024 finds that CLEAR could serve as a **bridge towards an electron-beam test facility** based around **developing key components required for a Higgs factory** and recommends **CLEAR team be centrally involved in discussions** for such a facility at CERN.

Present CLEAR Contributions to FCC-ee

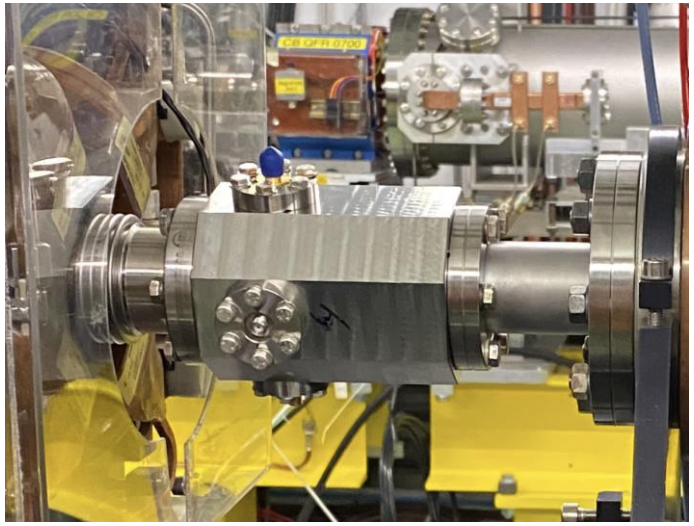
Performed Beam Diagnostics

Experiments in 2023

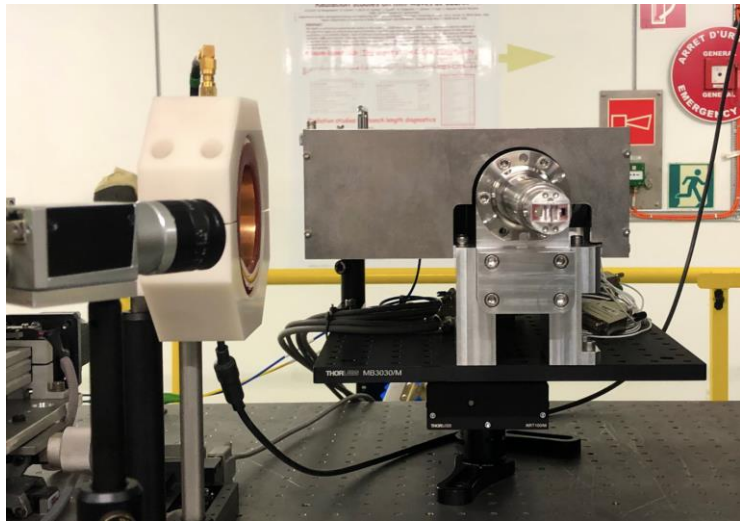
- Performed by CERN & external institutes, usually in collaboration



Coherent Cherenkov diffraction radiation dielectric buttons (FCC-ee bunch length monitors)



Broadband Pick-up for the PSI Positron Production Project (P^3 - FCC-ee collaboration)



Bunch Profile Monitor for FCC-ee (KIT - Karlsruhe)

Planned Experiments in 2024

Continuation of previous experiments:

- Electro-Optical Longitudinal **Bunch Profile Monitor** for FCC-ee (KIT)
- Coherent Cherenkov diffraction radiation **dielectric buttons** (CERN, BI)

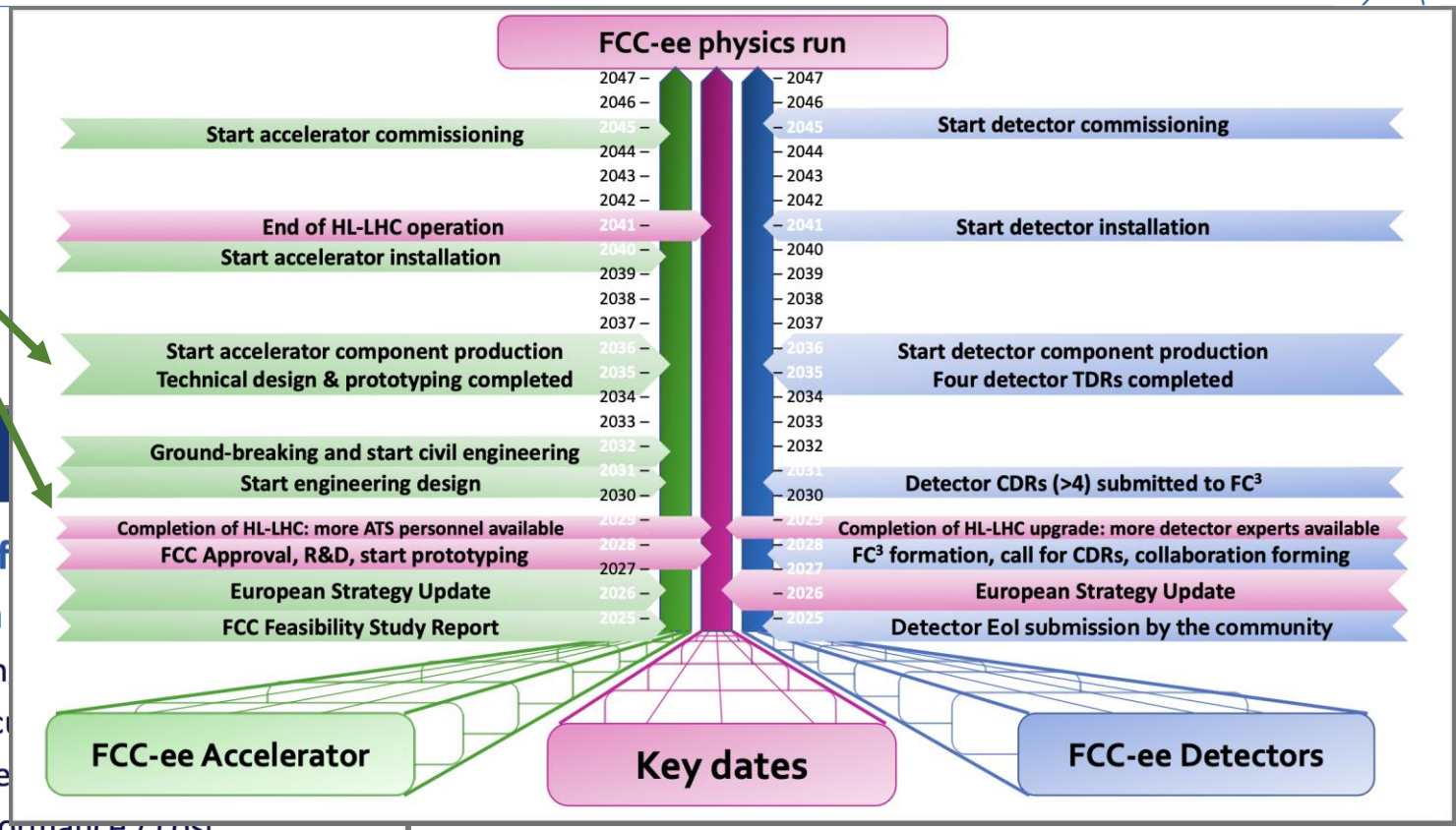
NEW: Damage **test of positron target** materials (CERN/STI – M. Calviani, A. P. Marcone)

⇨ discussion ongoing on the program, including positron detection, etc…

An Overview of FCC-ee: What to Expect

M. Benedikt, F. Zimmermann @FCC-Week-2023

- **CERN interest (and resources) in FCC-ee R&D expected to boost late 2020s**
- **It is wise to bridge e^- LINAC know-how at least till start of first stages of "final" facility, i.e. early 2030s**



FUTURE CIRCULAR COLLIDER

Summary

- **FCC-ee has highest luminosity at Z, W and H@240 GeV of**
- **Feasibility Study is preparing for Mid-Term review with a**
  - Beam optics and beam physics, inc. collective effects, addressin
  - Describe high-cost technical systems, e.g. SRF, arc magnets, vacu
  - Layout identified to ensure complete civil / infrastructure cost e
  - Alternative options and R&D identified to further improve performance / cost
- **Based on 60 years of experience with circular e^+e^- colliders, some of which currently in operation, hence no need for a large demonstrator facility**
  - Super KEKB and EIC will provide important information
  - R&D on components focused on improved performance, increased efficiency, industrialization, cost aspects, sustainability and minimizing environmental impact
  - R&D timelines are consistent with construction in 2030's
- **Very significant progress over the last two years!**

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A demonstrator facility is not to be expected!

- If approved, **CERN will likely build directly the final FCC-ee (injector) complex**

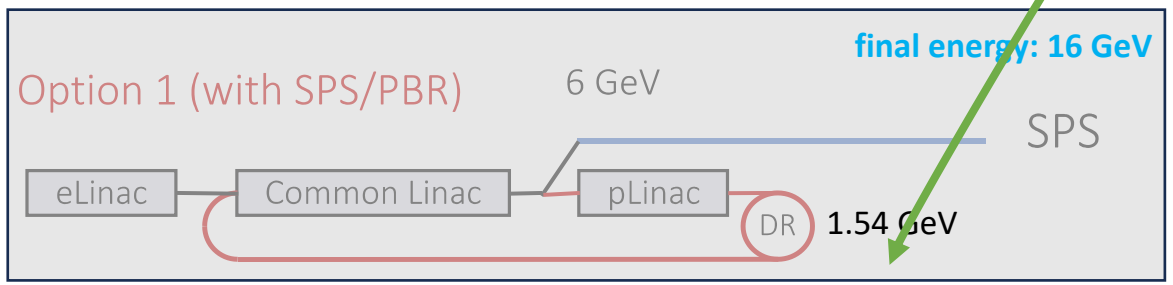
Tor Raubenheimer @FCC-Week-2023

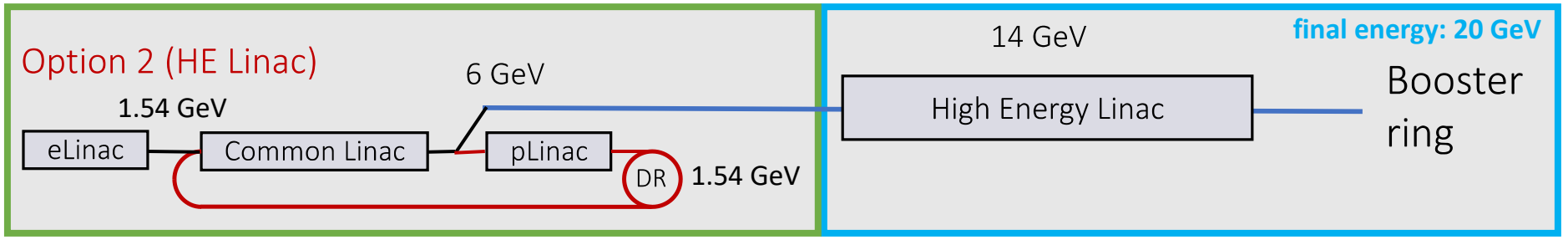
FCC-ee Complex and its Injector

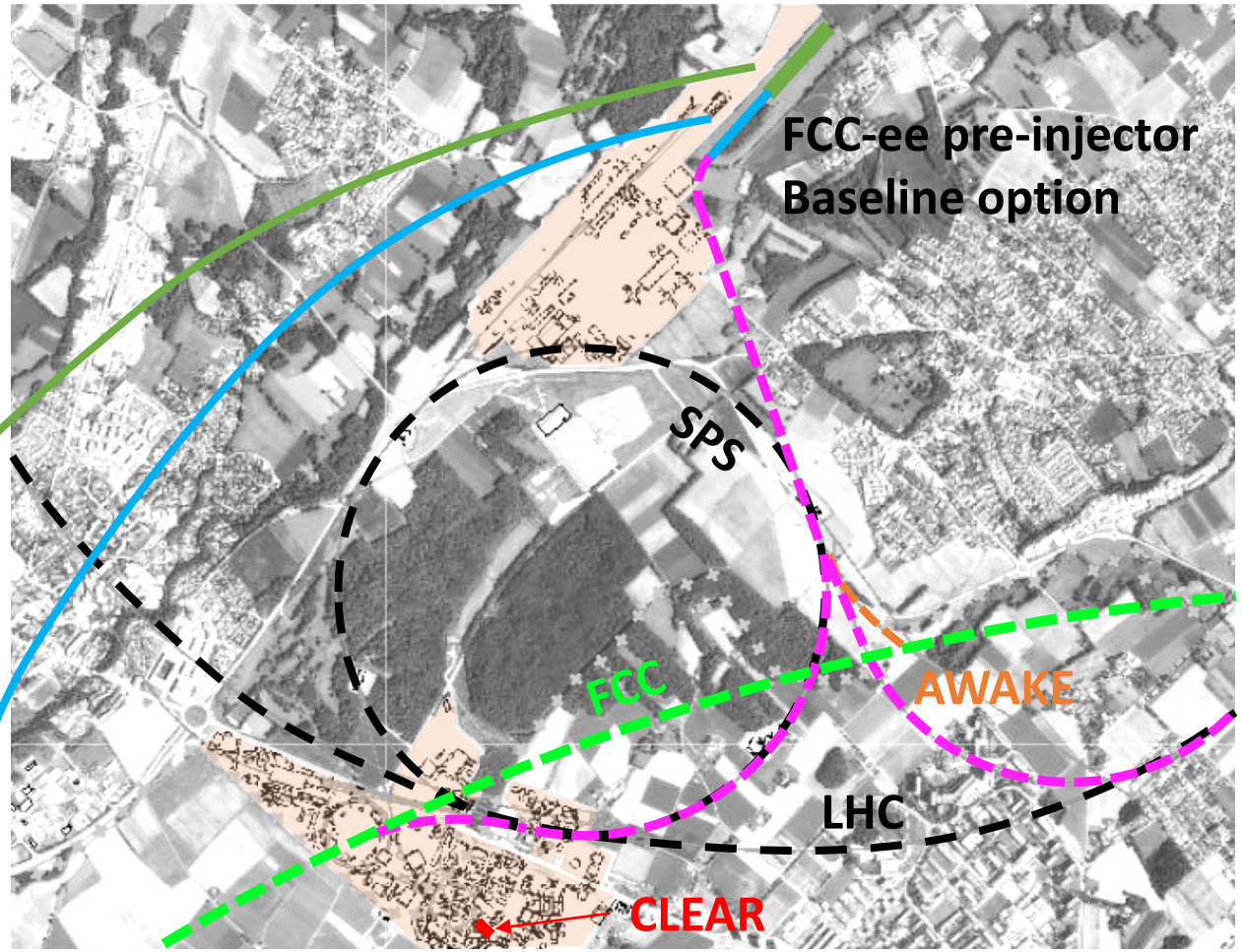
Most likely injector option:

- **LINACs** & **damping ring** on Prevessin site
- Transfer to SPS BA4
- 1 beam through SPS tunnel
- 1 beam through TT40/TI8
  - (can also send beam toward AWAKE)

In general, size/challenges of such a complex are not comparable to CLEAR







Option 2 is the present baseline

Parts of this slides from H. Bartosik @ PBCWS2024

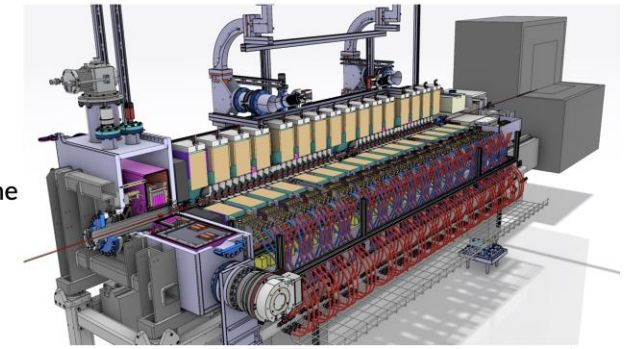
Selected FCC-ee challenges/considerations

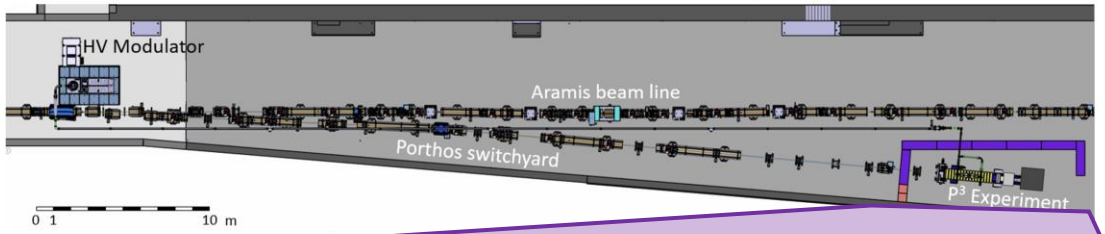
- **Prototyping the positron production at high energy (but not intensity), covered by P³**

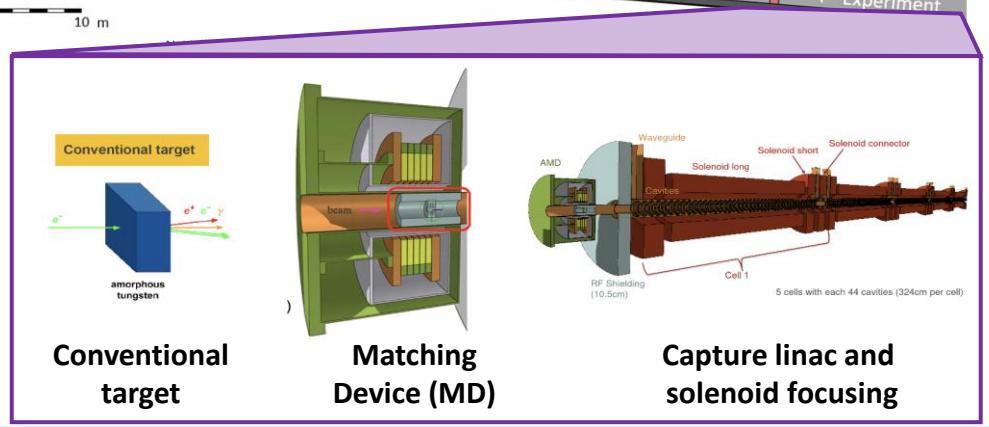
From P. Craievich @CERN-RF-Seminar

PSI Positron Production (p-cubed) experiment (Page 22)

- Design phase well advanced, several components are ordered
- Installation on the Porthos extraction line ongoing
- Ongoing collaboration with CERN STI for the target
- Experiments in 2025/2026

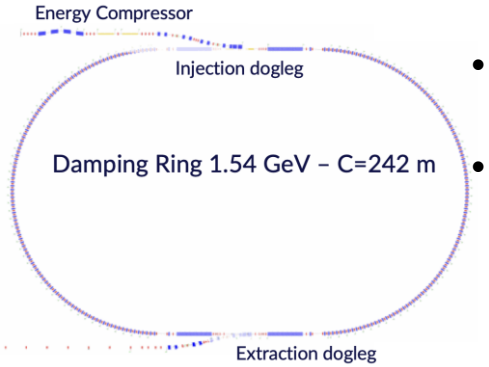






Conventional target | **Matching Device (MD)** | **Capture linac and solenoid focusing**

- **Damping Ring challenges maybe worth investigating… but no space at CLEAR**



- **EPA ring** was only **120 m** in circumference
- Possibly, some aspects already covered by tests in **light sources**?!

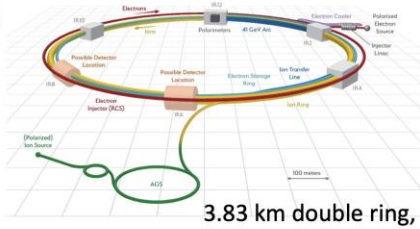
- **EIC in the US used as proof-of-principle?**

US Electron Ion Collider (EIC) — Future Circular Collider — Brookhaven National Laboratory / Jefferson Lab

US EIC Electron Storage Ring similar to, but more challenging than, FCC-ee
beam parameters almost identical, but twice the maximum electron beam current, or half the bunch spacing, and lower beam energy

>10 areas of common interest identified by the FCC and EIC design teams, addressed through **joint EIC-FCC working groups**, still evolving

EIC will start beam operation about a decade prior to FCC-ee
The EIC will provide an invaluable opportunity to train next generation of accelerator physicists on an operating collider as well as testing hardware prototypes, beam control schemes, etc.



3.83 km double ring,
full-energy e^- injection,
injection rate 1 Hz,
every 2 min into same bucket

	EIC	FCC-ee-Z
Beam energy [GeV]	10 (18)	45.6 (80)
Bunch population [10^{11}]	1.7	1.7
Bunch spacing [ns]	10	15, 17.5 or 20
Beam current [A]	2.5 (0.27)	1.39
SR power / beam /meter [W/m]	7000	600
Critical photon energy [keV]	9 (54)	19 (100)

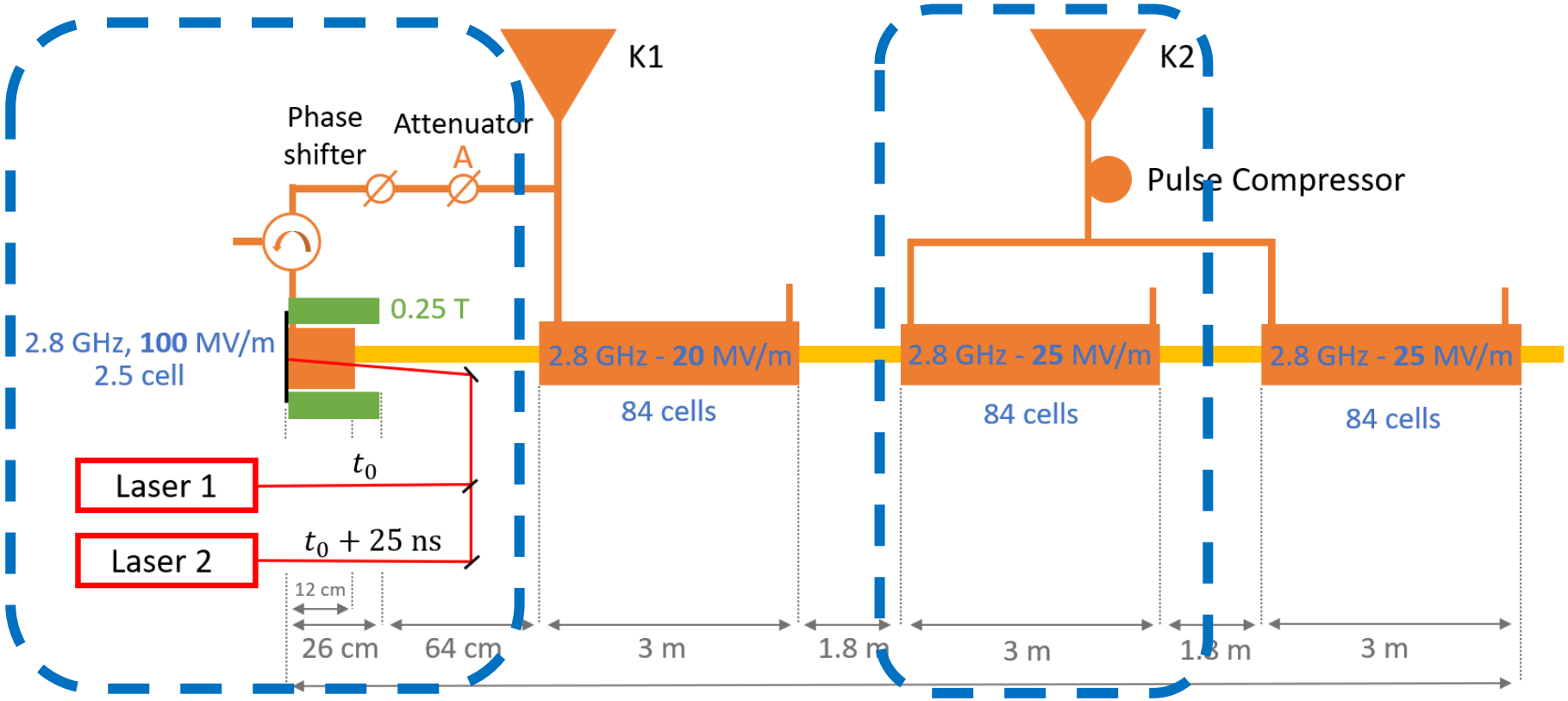
T. Raubenheimer @FCC-Week-2023

FCC-ee Electron Source Frontend

- Not surprisingly, **not very different than CLEAR Frontend**, but slightly different parameters
- **CLEAR/CTF2 have expertise** and space adapted to **test prototypes** and **key concepts**, e.g.:

2-bunches production as FCC-ee probably possible/testable at CLEAR

A **prototype 2.8 GHz module** from source to structure, with beam, could be tested in CLEAR/CTF2



Courtesy of Zdenek Vostrel and Steffen Doebert

CLEAR can be a test bed for **tools/techniques for beam properties characterisation**

	CLEAR:
200 MeV	200 MeV
5 nC/bunch	1 nC/bunch
σ_z = 1 mm	σ_z = 1 mm
σ_δ = 0.2 %	σ_δ = 0.2 %
ε_N < 5 µm	ε_N < 20 µm

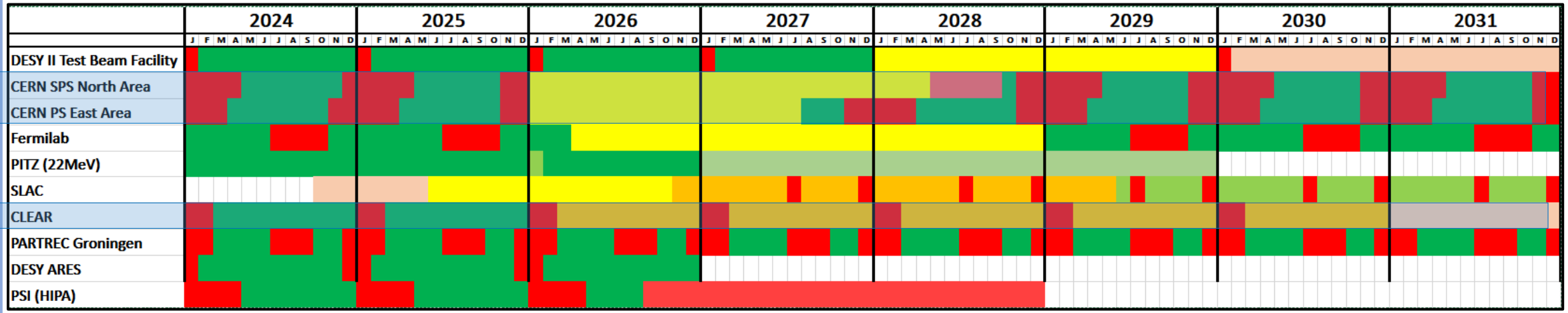
From P. Craievich @ FCC-Week-2023

Plus: Shortage of Detectors R&D Test Facilities on the Horizon

- Till today, **CLEAR** has been **marginally used for Detectors R&D**
  - **Might become relevant to bridge over LS3+,** when most facilities will be in shutdown?
  - CLEAR might be **missing "low intensity" capabilities**
    - Independent **testing of low intensity beams (down to single electron) ongoing in 2024**
  - **e^- irradiation** possibly more adapted to **FCC-ee components** testing?

International Test Beam Schedule *(from B. Holzer@Chamonix2024 and P. Pelissou@BTTB-SW24)*

- Compilation by the respective test beam coordinators
  - See https://cern.ch/international-facilities
- Aim: Rough estimate on available beam time to help the users with the planning of their test beams
- HEP detector R&D mostly performed at CERN, DESY and Fermilab



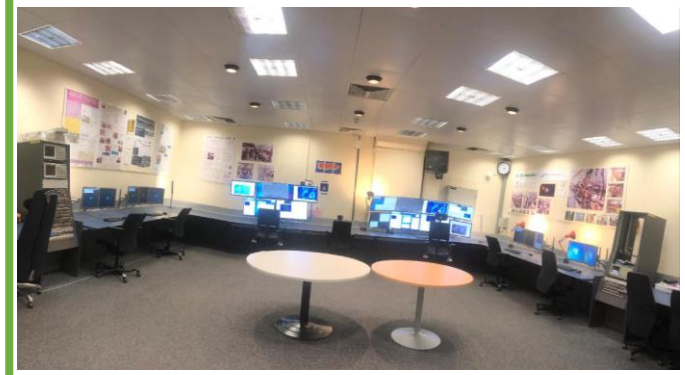
High Demand for Training Opportunities

juas
Joint Universities Accelerator School



- **Hands-on training (JUAS, EURO-LABS)**
- **Hosting Trainees, Summer/Technical and PhD students, Fellows, Associates…**
- **Possible to develop specific trainings for people involved in future e⁻ machine design/operation !**

Contributed to more than 10 PhD thesis in the last 5 years!



PhD Thesis:

- **University of Manchester (2023)**: Design and Experimental Verification Study of Non-invasive Short Electron Bunch Length Monitor for AWAKE Run 2 (link).
- **University of Jagiellonian (2022):** Non-Invasive Beam Diagnostics With Schottky Signals and Cherenkov Diffraction Radiation (link).
- **University of Huddersfield (2022)**: Design and Development of an Optical Beam Loss Monitor Based on Cherenkov Light Detection for the CERN Super Proton Synchrotron Accelerator (link).
- **University of Oxford (2022):** Studies for upgrading and optimising the CLEAR beamline, and generating uniform electron-beam profiles for irradiation experiments (link).
- **University of Cambridge (2021)**: Convolutional neural networks and photonic crystals for particle identification at high energy collider experiments (link).
- **University of Naples (2021)** : Measurements of wakefields and bunch length with beam in linear electron accelerators: a case study at CLEAR (link).
- **University of Oxford (2020):** Development of a beam position monitor for co-propagating electron and proton beams (link).
- **University of Strathclyde (2020):** Investigation of focused Very High Energy Electrons (VHEEs) as a new radiotherapy method (link).
- **University of Manchester (2019):** VHEE Radiotherapy Studies at CLARA and CLEAR facilities (link).
- **University of Jyväskylä (2019):** Single-Event Radiation Effects in Hardened and State-of-the-art Components for Space and High- Energy Accelerator Applications (link).
- **University of Oslo (2019):** Emittance growth and preservation in a plasma-based linear collider (link).

Prototyping of LINACs Control Technology

- Most of CERN injector complex is based on **"low" frequency RF**, **low-rep-rate machines** and has **developed associated technology** to ensure their **reliable operation**
- CTF3 before, and now **CLEAR** (and AWAKE) are **custodian of high-frequency** (up to X-band), and high-rep rate (up to 50/100 Hz) **accelerator/beam control technology**
- CLEAR is the **ideal test bed to deploy future technologies** relevant to any Higgs Factory:
  - **White rabbit timing** distribution
  - Test of new generation **ADCs cards** for fast digitisers (see AOS-3601)
  - New generation of **Digital Cameras for BTVs** (and associated controls)
  - Possibly many other systems, e.g. new **LLRF components/controls**, new **transfer lines BPMs**, …
  - **BONUS:**
    - **Consolidation of CLEAR infrastructure** with benefit to maintainability and reliability
    - **Low impact/risk of downtime/damages** in case of failure of technology under test
- CLEAR is the **ideal test bed for new operation paradigm for LINACs**, e.g. using **Machine Learning models**:
  - Some **AI-based experiment done in the past**, e.g. Imaging experiment by G. Trad
  - Presently **working on an AI-based "energy-jitter predictor"** by A. Gilardi
  - **Discussions ongoing** with the Data Science for Beam Operation **(BE-CCS-DSB) section**

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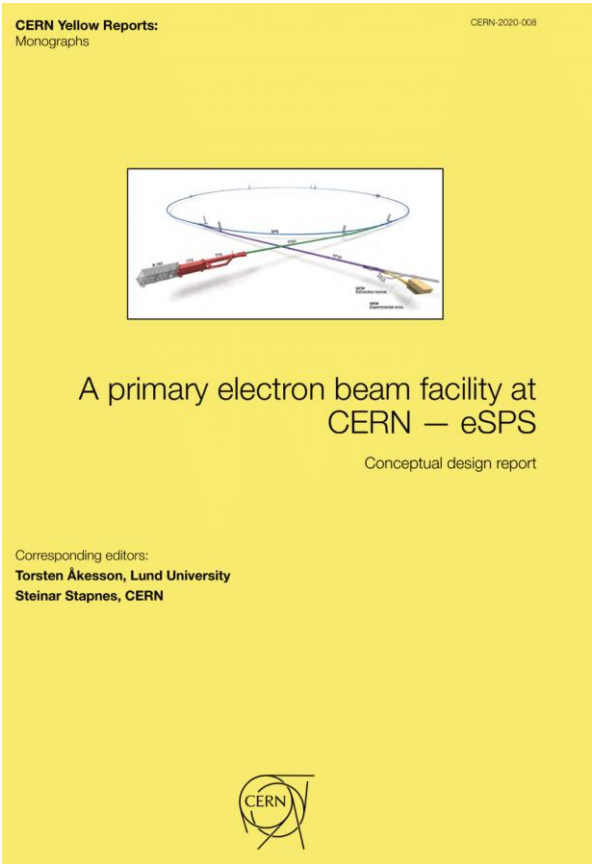
CLEAR++ during FCC-ee Construction!

Slide mostly from H. Bartosik @ PBCWS2024

- **Proposal** for **primary electron facility** was already made in context of **eSPS** (original proposal for Light Dark Matter eXperiment – LDMX)
- Inspired by this proposal, **FCC-ee injector beams** could be used for a **CLEAR-like facility** (including also damping ring):
  - **R&D for accelerator components and beam diagnostics for FCC-ee** or the injector itself (in particular if injector goes online ahead of FCC-ee and/or is built in stages)
  - **Irradiation facility** (e.g. for testing electronics components)
  - **Medical research**
  - **Use synchrotron light from damping ring** to test coatings, photon desorption
  - **Plasma wakefield acceleration test facilities** (electron driven, but maybe even in combination with proton driven plasma, see next slide)
  - ➢ **The present CLEAR User Community could be the seed of a wider user community of such a facility!**
- **BONUS:** FCC-ee injector layout **could still work for eSPS proposal** (especially if SPS is part of the FCC-ee injector)

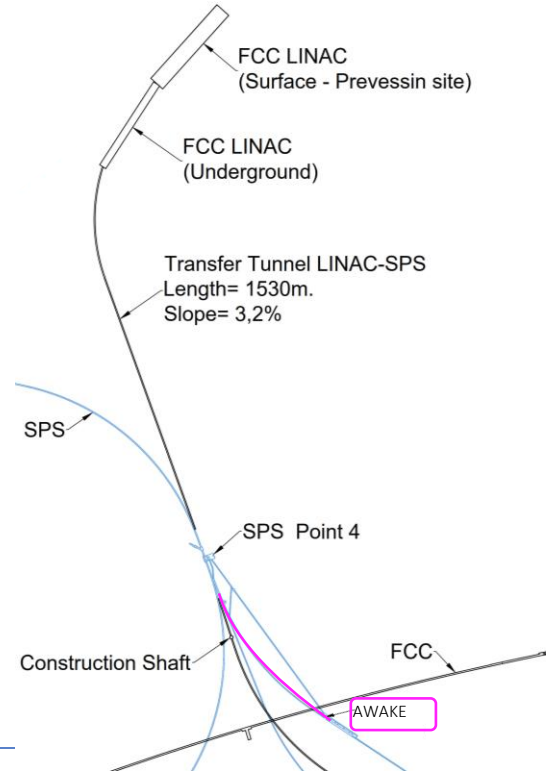


Plus: e+/e- beams interesting for AWAKE++!

Slide mostly from H. Bartosik @ PBCWS2024

- The layout of the **FCC-ee injector complex passes through SPS BA4**, i.e. the **SPS extraction** point of protons for the plasma wakefield acceleration experiment **AWAKE**
- Keeping SPS operation with protons, there would be a unique opportunity to perform **proton driven plasma wakefield acceleration of 20 GeV electrons and *positrons***
  - Lepton beam parameters fit extremely well for **wakefield experiments**
  - **Unique possibility of positron acceleration** (currently no experiments worldwide)
- With the two-bunches setup, also **electron driven plasma wakefield acceleration** experiments can be performed
  - 1st electron beam is the drive beam, 2nd one is the witness beam
  - In addition, another unique possibility to test positron acceleration
- Proton beam line, experimental facility as well as lepton injection area and tunnel to the experiment exists
  - Would **"only" require ~800 m transfer line for e+/e- in TT40/41 tunnel**

➢ **CLEAR++ and AWAKE++: Perfectly Aligning with the LDG Roadmap to Strengthen CERN's Ambitions in Novel Acceleration Techniques!**



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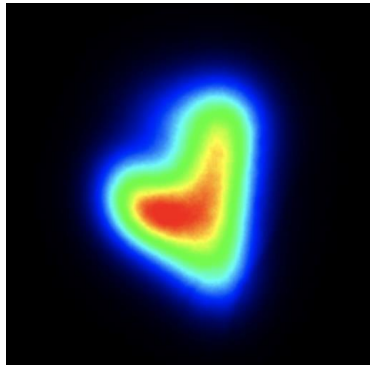
Conclusions

- **Beam requests are growing**, and the **facility is very close to saturation**
  - The present and **expected requests** will amply **keep the facility** and **its team fully busy** for the next few years (at least until the early 2030s) **with high-impact R&D** and **experiments** [see previous talks]
- The **facility is already "expanding"** where possible, **with modest investments**
  - More "local space" is available, but a **local major expansion is probably not justified, today**
- **CLEAR** is a **potential steppingstone towards** the next flagship accelerator at CERN, **FCC-ee** (or its potential alternatives)
  - Several **FCC-ee related experiments** have already been **performed or are planned**
  - **Additional synergies** with design and prototyping **exist**, though **mostly unexplored** due to **scarce resources** and **planning uncertainties**
    - **This includes detectors R&D**, especially during LS3 as the only running irradiation facility at CERN
- The **CLEAR** facility is **fundamental** for **maintaining** and **training e-beam know-how at CERN**
  - This applies **not only to young physicist**, but **also to e-LINAC-specific system designers/engineers**
- Assuming FCC-ee will be approved, the present **FCC-ee injector baseline design** is compatible with being a **CLEAR-like facility**, with **multi-purpose user-dedicated areas**
  - Such a use case could **boost commissioning efficiency** and **maximize facility investment returns**
  - **eSPS proposal exercise** could be a **starting point for a dedicated study** in this direction
  - **CLEAR (and AWAKE) can bridge the present user community toward such a unique facility !**

Thanks for your attention!

Acknowledgements to the CLEAR dream team:

R. Corsini, S. Doebert, W. Farabolini, D. Gamba, A. Ghilardi, P. Korysko, A. Malyzhenkov, A. Aksoy, K. Sjobaek, L. Dyks, V. Rieker, J. Bateman, C. Robertson, L. Wroe, E. Granados, M. Martinez, S. Curt, …



APPENDIX

CLEAR has a Strategic Role for Future Higgs Factories

Main relevant areas already being exploited:

1. Beam diagnostics R&D for FCC-ee

2. Other FCC-ee dedicated experiments in CLEAR

3. Both the CLEAR machine and its experimental team might be the seed for a future larger facility paving the way to FCC-ee

4. Keeping at CERN hands-on experience (both on hardware and beam operation) on electron accelerators – a role partly shared with AWAKE

5. Training of young scientists

Relevant Findings and Recommendations from CSB Meeting 2024

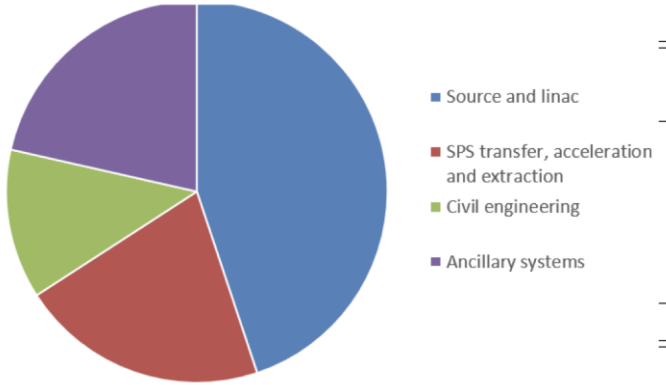
From CLEAR Scientific Board Meeting 2024:

- **Recommendation 1:** More visibility should be given to the CLEAR capabilities for tests of **advanced acceleration concepts** in order to attract more users from other broad international collaborations such as **EuPRAXIA**.
- **Finding 7:** A detailed run schedule will be prepared but it already seems clear that the in-hand requests can be expected largely to fill the available beamtime in 2024. If user demand continues to increase, a tighter selection of experiments may be required in the future.
- **Recommendation 3:** CSB recommends that CERN support this approach towards upgrades, including CTF2. The committee encourages the CLEAR team to investigate the possibilities for utilisation of CTF2, define the necessary resources, and evaluate the user interest in CTF2 beyond the planned Inverse Compton Scattering (ICS) studies.
- **Finding 12:** A CLEAR programme beyond 2025 could serve as a crucial step and bridge towards an electron-beam test facility based around **developing key components required for a Higgs factory**.
- **Recommendation 4:** CSB recommends that the CLEAR team be **centrally involved in discussion of electron test facilities for a future Higgs factory at CERN**.

Relevance of e-SPS for CLIC, cost

Table 6.1: Main CLIC related activities and their relation to the 3.5 GeV linac for eSPS.

Details	Purpose	eSPS Equivalent	Comment
Main linac modules			
Build ten prototype modules in qualified industries, two beam and klystron versions	Final technical design, qualify industry partners, verify performance	12 X-band klystron modules	Covered by eSPS but adaptations to two beam modules need to be considered
Accelerating structures			
Around 50 structures incl. for modules above	Industrialisation, manufacturing and cost optimisation	Same number needed	Programmes overlapping
Operating X-band test-stands, high efficiency RF			
X-band test-stands at CERN and collaborating institutes, cost optimised X-band RF	X-band component test, validation and optimisation, cost reduction and industrially available RF units	Similar test capacity needed for eSPS, 24 X-band RF units needed for eSPS	Programmes overlapping
Technical components			
Magnets, instrumentation, alignment, stability, vacuum	Luminosity performance, costs and power, industrialisation	These components are also needed for eSPS	eSPS specifications less stringent, however significant advantage to implement in smaller complete system
Design & Parameters			
Beam dynamics studies, parameter optimisation, costs, power	Luminosity performance, risk, costs and power reduction	Needed for eSPS linac	Specific studies for CLIC needed but good reality check



Item	cost [MCHF]
Source and linac	49.8
SPS transfer, acceleration and extraction	23.4
Civil engineering	14.0
Ancillary systems	23.8
Sum	111.0

- May a similar project be developed based on requirements for FCC-ee ?
- Is it the size/cost/time scale relevant/affordable?
- Possibly, such facility should aim at being compatible with (parts of) the final FCC-ee injector complex