UNIVERSITÉ
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Future collider options and accelerator challenges

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The Future of Particle Physics

- **Why Do We Need a New Collider?**

✅ **Past Successes:** LHC discoveries (Higgs boson, precision SM tests)

❌ **LHC Limitations:** Reaching energy and precision limits → **Need for a next-generation collider**

- **Future Goals:**
    - **Explore the energy frontier** (search for new physics, dark matter)
    - **Precision Higgs and electroweak studies** (beyond current capabilities)
    - **Investigate the nature of fundamental forces** with higher luminosity and energy

Disclaimer: Due to the broad range of proposed future accelerators and their evolving technical details, only a selection of the latest concepts will be highlighted in this presentation.

Primary Concepts for Future Colliders

- **Europe**
  - **From ESPPU**
    - Long-term goal is high energy hadron collider
    - Higgs factory most urgent project after HL-LHC
  - **Plan A:**
    - FCC-ee | FCC-hh
  - **Plan B:**
    - CLIC | Muon Collider
  - **Further In R&D Roadmap**
    - Energy recovery linacs (LHeC, FCC-eh)
    - Plasma technology

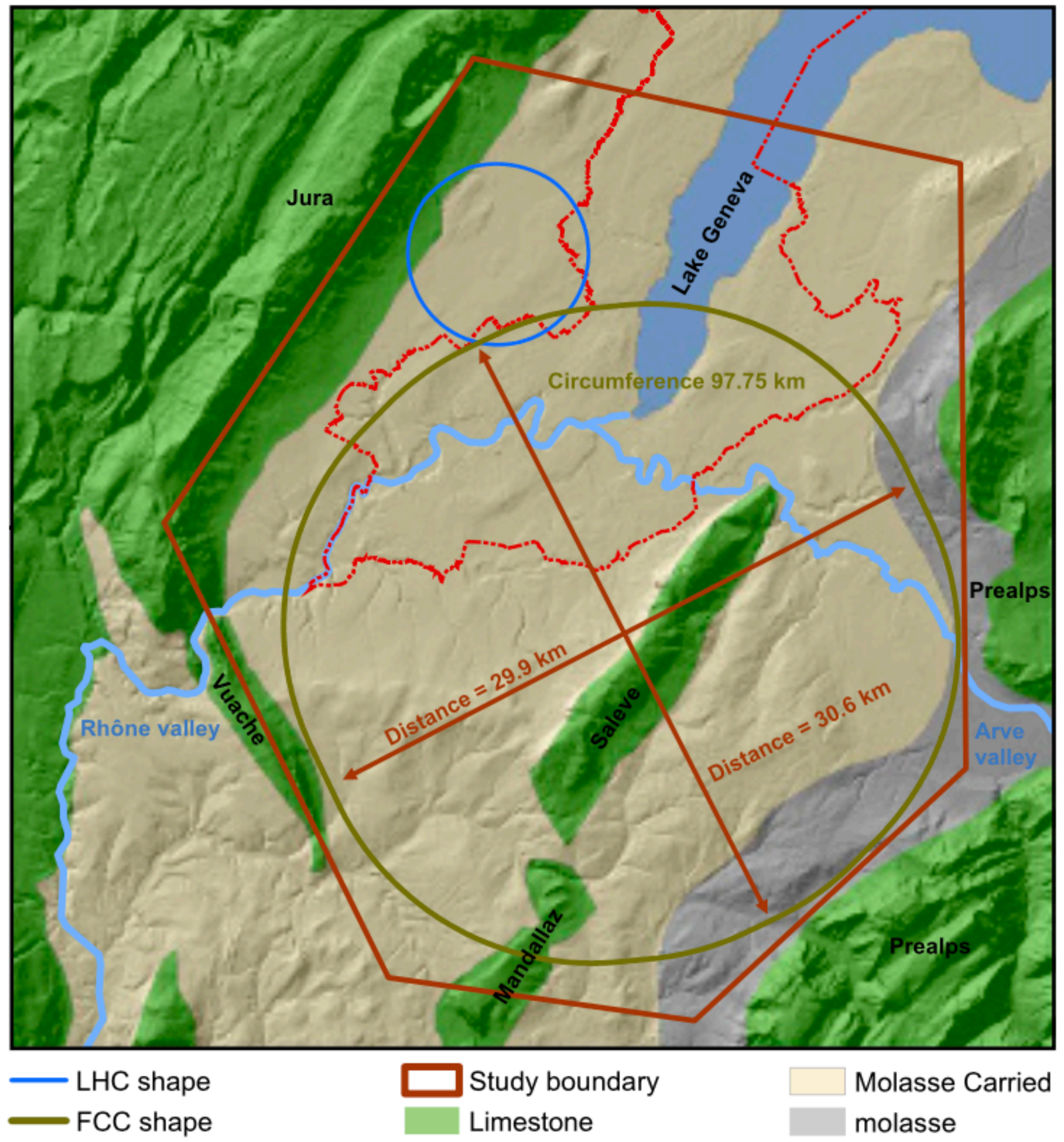
- **US**
  - **Interest in:**
    - Linear collider (mainly C^3)
    - Muon collider
- **Japan**
  - **Interest in:**
    - ILC
- **China**
  - **Interest in:**
    - CepC/SppS (comparable to FCC-ee/FCC-hh)

- **Many other concepts still at less advanced stages**

Future Circular Collider

Future Circular Collider (FCC):

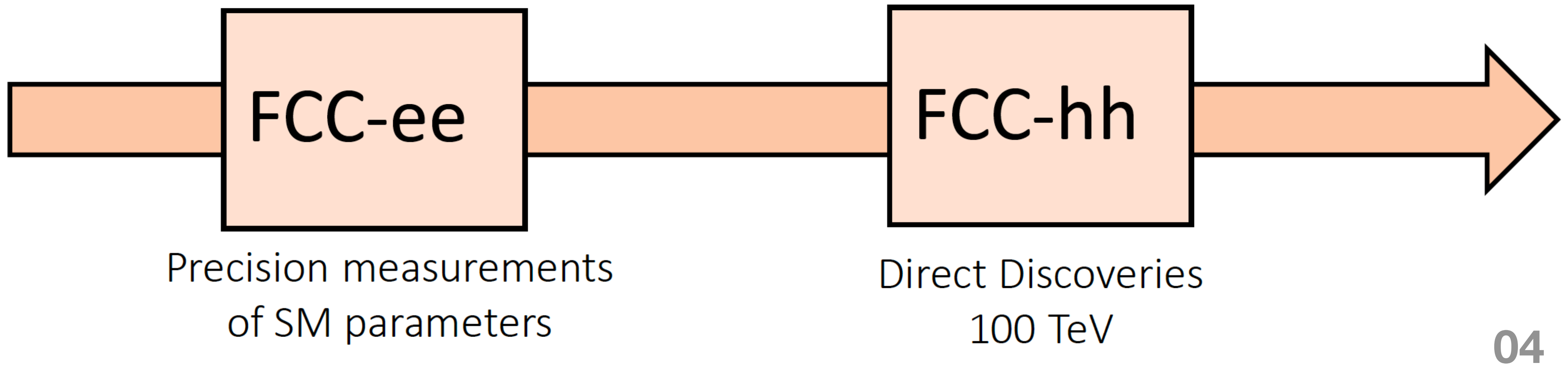
- **91km circumference**
- **Two stages:**
  - **Stage 1**: FCC-ee (Z, W, H, tt) as a high luminosity factory for Higgs, EW and top
  - **Stage 2**: FCC-hh (~100 TeV) logical progression at energy frontier, with ion and e-h options



- **Event Statistics (FCC-ee):**
  - Enormous performance increase compared to LEP
  - Great energy range for the heavy particles of the SM

The FCC is one of the leading-edge facility for direct discovery of new physics!

Z peak	**E_{cm} : 91 GeV**	**$6\ 10^{12}$ e+e- → Z**	**LEP x 3 10^5**
WW threshold	**E_{cm} : 161 GeV**	**$2.5\ 10^8$ e+e- → WW**	**LEP x 2.10^3**
ZH threshold	**E_{cm} : 240 GeV**	**$2.4\ 10^6$ e+e- → ZH**	**Never done**
$t\bar{t}$ threshold	**E_{cm} : >350 GeV**	**2 10^6 e+e- → $t\bar{t}$**	**Never done**



FCC-ee

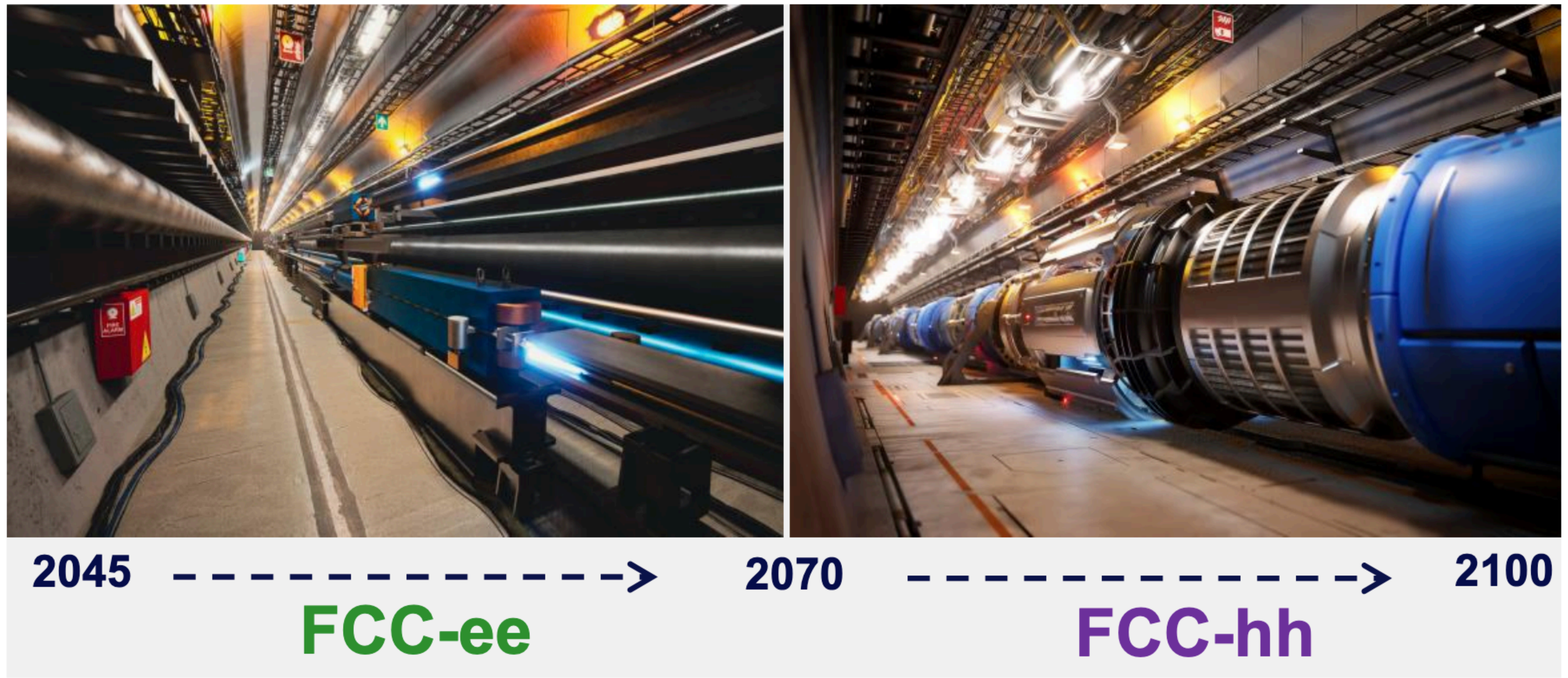
Precision measurements of SM parameters

FCC-hh

Direct Discoveries 100 TeV

FCC Goals & Feasibility Study (2021-2025)

- **Demonstrate geological, technical, environmental, and administrative feasibility** of subsurface and surface elements and optimise the placement of the ring
- Together with the Host States, **identify and address administrative processes** required for project approval
- **Advance collider and injector design**
- **R&D for key technologies**
- **Consolidate physics case**
- **Develop detector concepts**
- **Develop a sustainable operational model** (environmental, financial, societal)
- **Consolidate cost estimates**

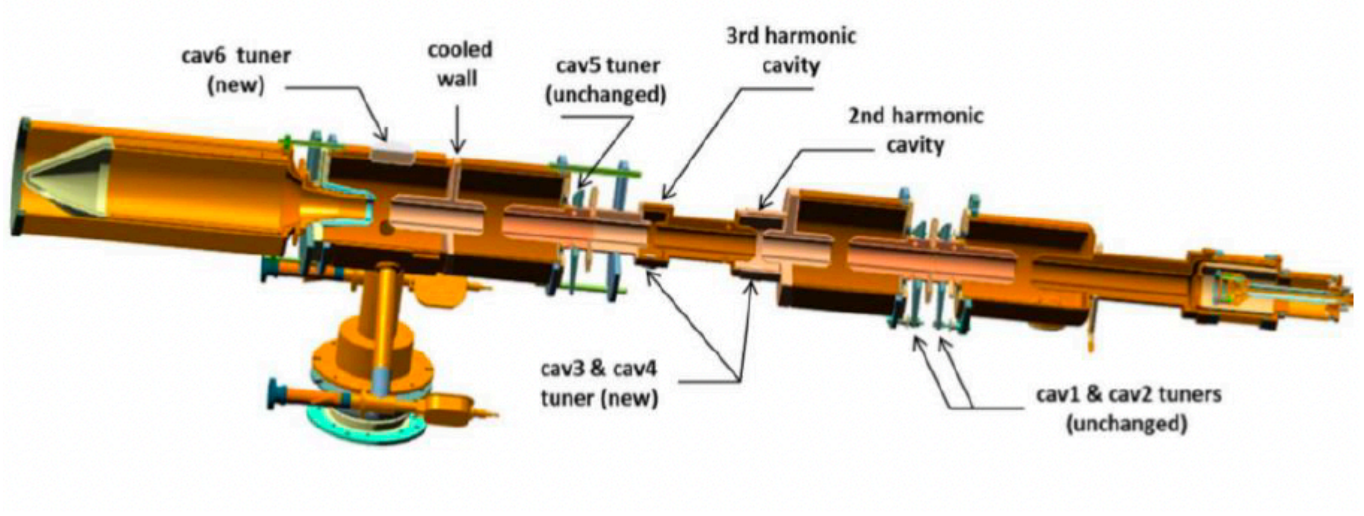


Results are being summarised in a Feasibility Study Report to be released by March 2025

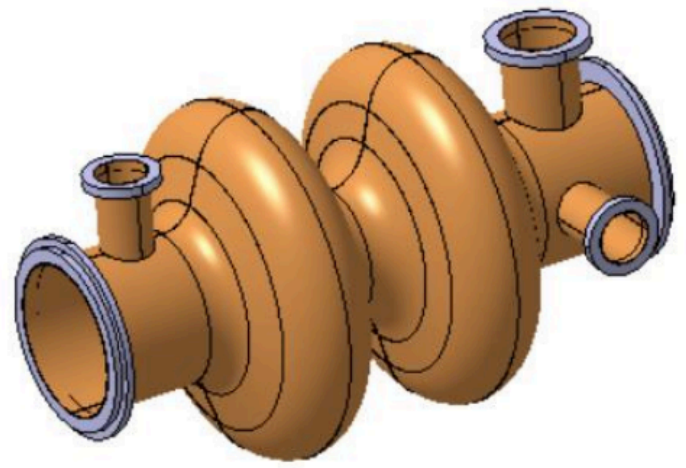
Technical Challenges - R&D Examples

- **High-luminosity requirements:** Requires advanced RF systems and twin-aperture magnets
- **Power efficiency:** Optimization of superconducting RF cavities (400MHz & 800MHz) to reduce energy losses

efficient RF power sources
(400 & 800 MHz)



400 MHz cavities



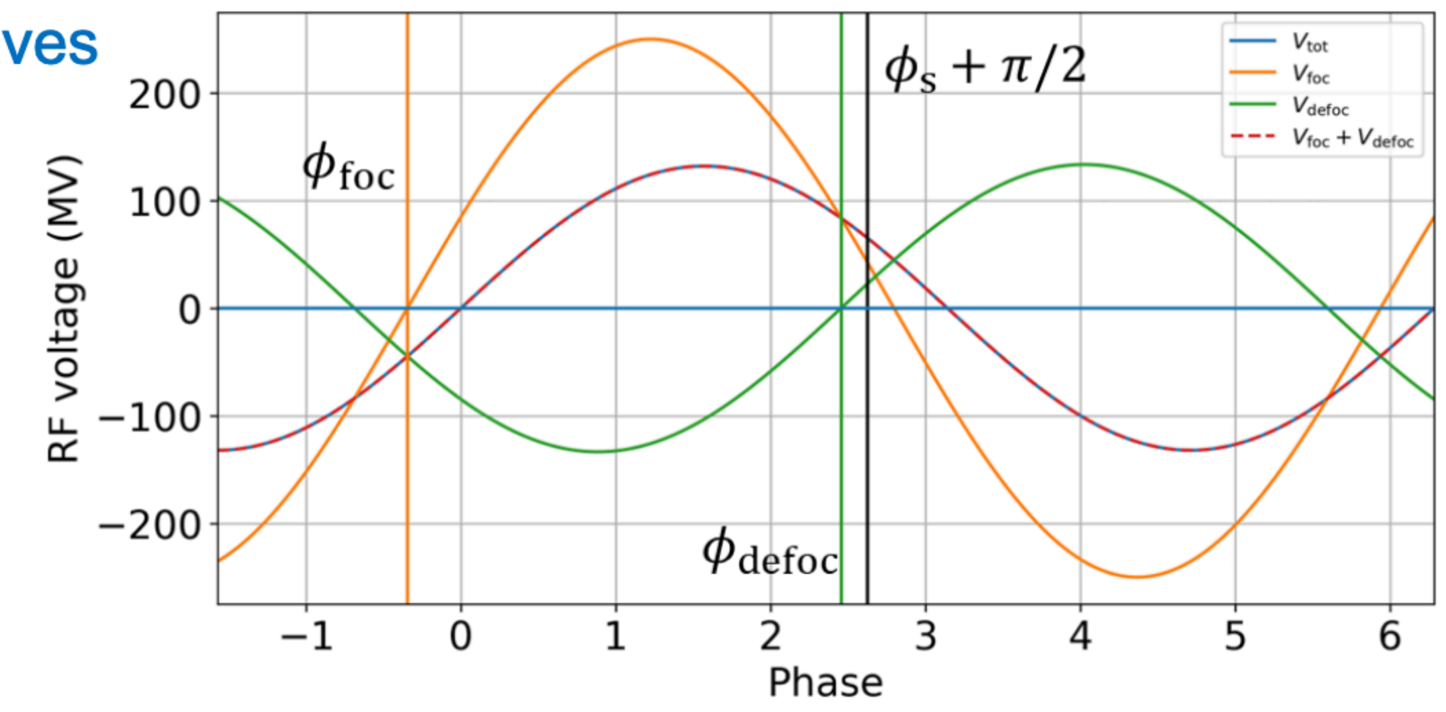
Z, W, ZH

X 264

400 MHz 2-cell cavity
Niobium thin film on Copper,
Operation at 4.5 Kelvin
Max. accel. gradient E_{acc} = 13 MV/m
Quality factor Q_0 = 3.3 x 10^9

- **Beam dynamics:**
  - Need for large momentum acceptance
  - Reducing synchrotron radiation losses
  - Ensuring stable and efficient beam injection (top-up injection system)

RF waves

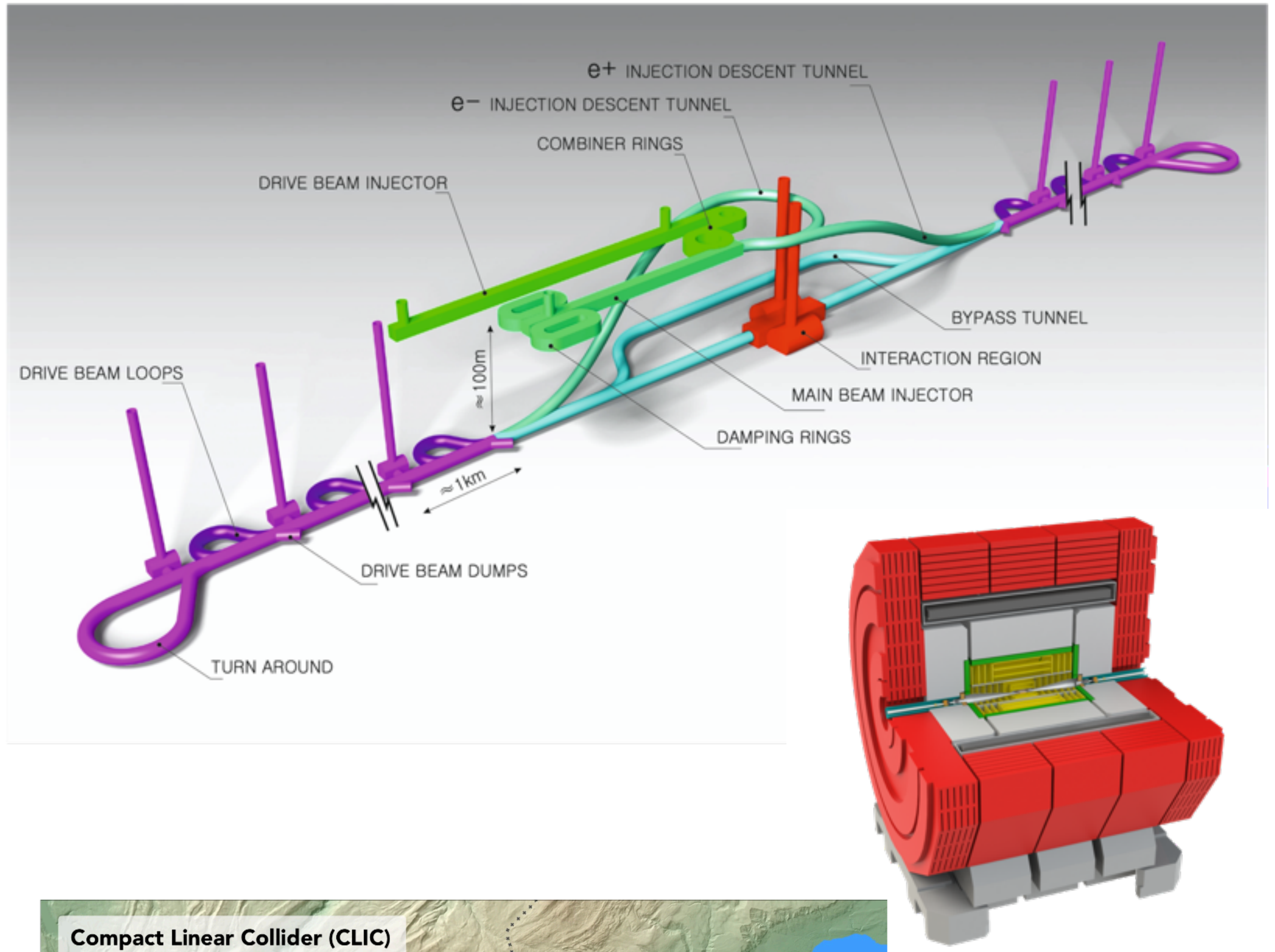


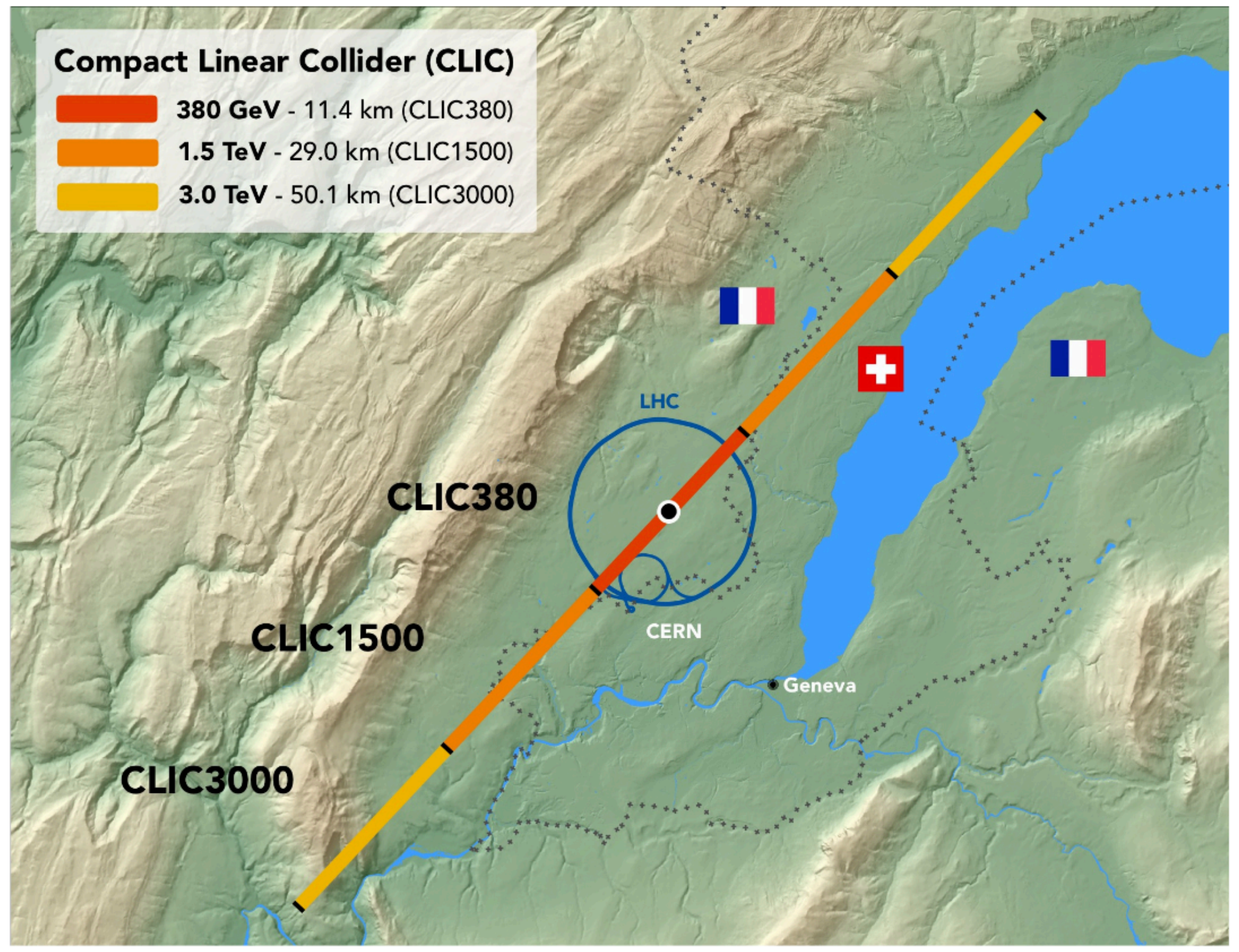
- **High-Field Magnets (HFM):**
  - FCC-hh goal: 14T hybrid Nb_3Sn/HTS magnets for 85 TeV c.o.m. energy (link)
  - Prototyping and industrial-scale production to reduce costs

One of the first 7-m long Nb_3Sn magnets

The Compact Linear Collider (CLIC)

- Electron-positron linear colider at CERN for the era beyond HL-LHC
- Planned for construction at CERN for three energy stages:
  - 380 GeV, focusing on precision Higgs boson and top-quark physics
  - 1.5 and 3 TeV, expanding Higgs and top studies including Higgs self-coupling, and opening higher direct and indirect sensitivity to BSM
- Nominal physics programme lasts for 25-30 years; approvable in stages
- Comprehensive Detector and Physics Studies
- Key Advantage of a linear machine:
  - Flexible Staging: The machine length and energy can be adapted in response to evolving physics goals

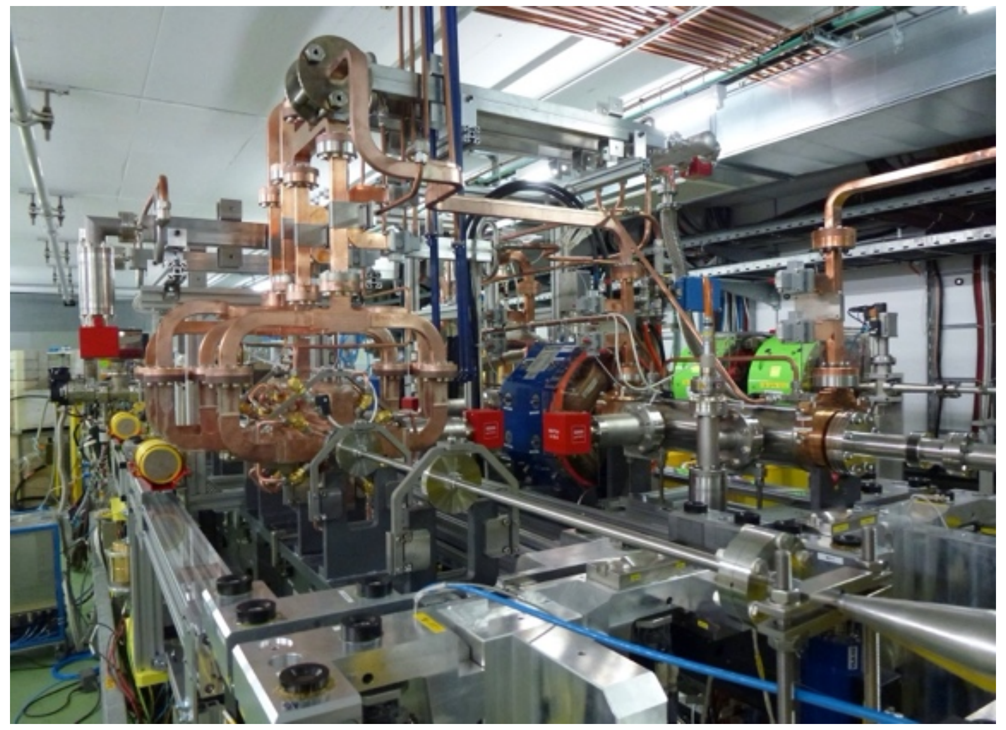


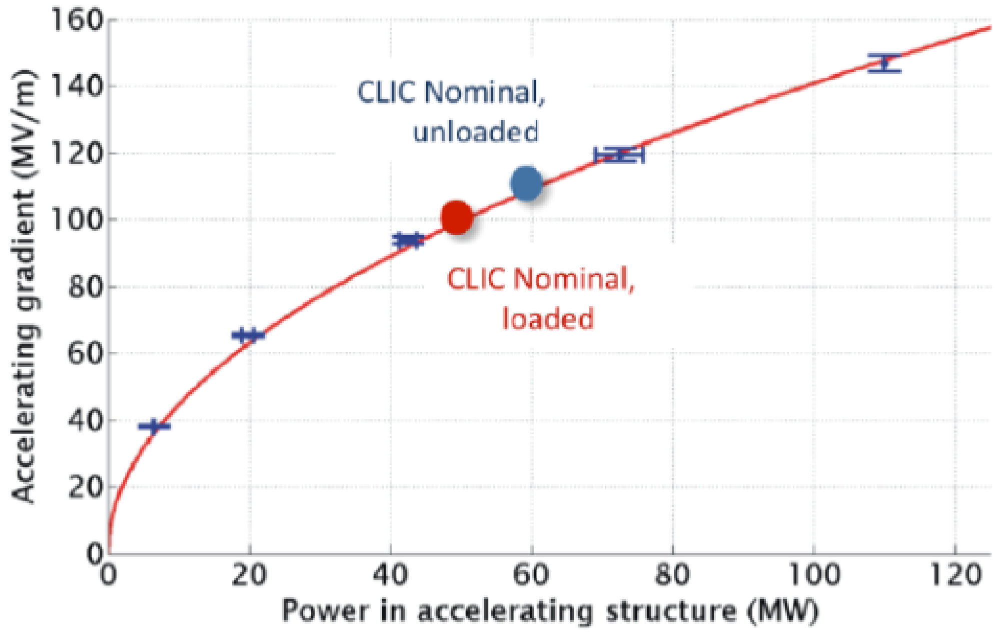


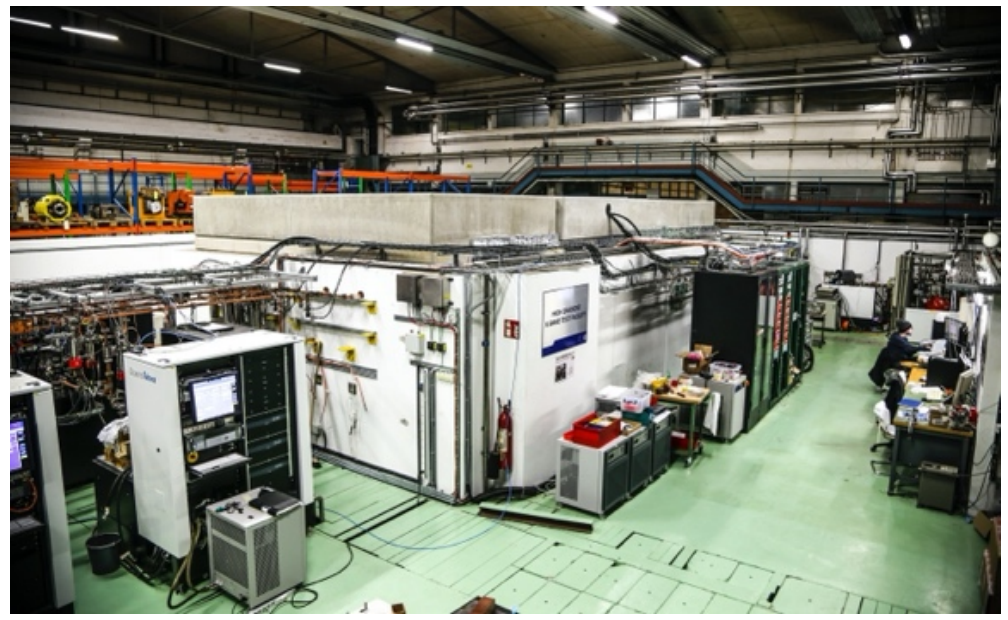
Accelerator challenges & Technologies

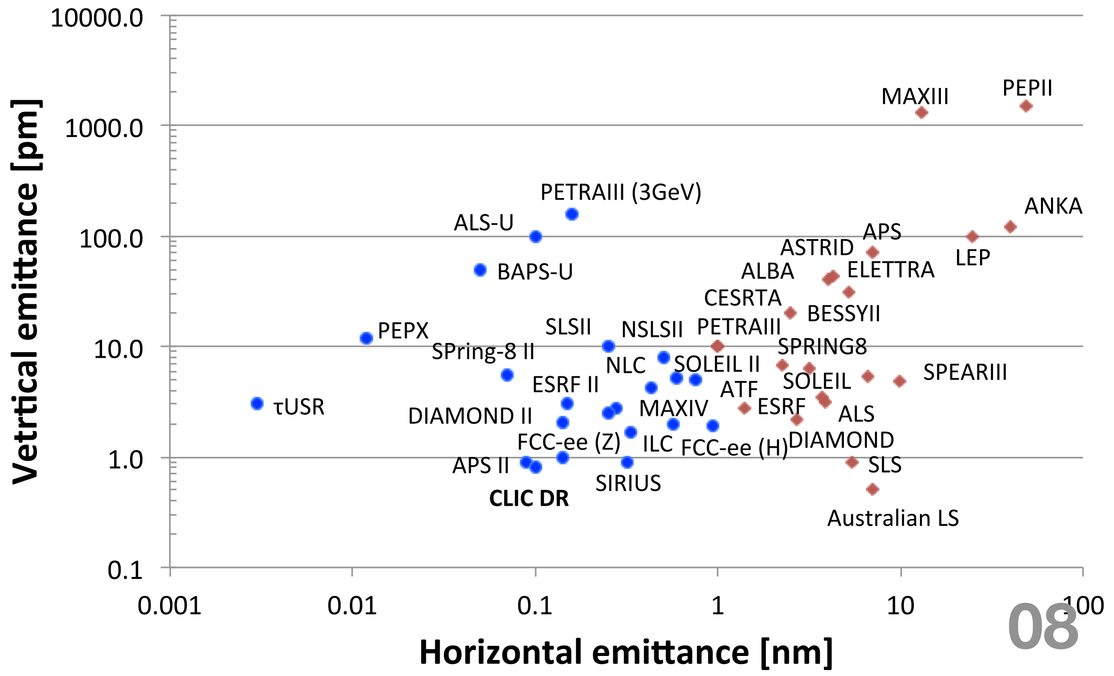
- **Four main challenges:**
  1. High-current drive beam bunched at 12 GHz
  2. Power transfer and main-beam acceleration, efficient RF power
  3. Towards 100 MV/m gradient in main-beam X-band cavities
  4. Alignment and stability ("nano-beams")

- **CTF3** (CLIC Test Facility at CERN) program addressed all drive-beam production issues
- Other **critical technical systems** (beam delivery, alignment etc) addressed via design and test-facility demonstrators
- **X-band technology** developed and verified with prototyping, test-stands and use in smaller systems and linacs
- **Two C-band XFELS (SACLA and SwissFEL)** now operational:
  - Large-scale demonstration of normal-conducting, high-frequency, low-emitance linacs



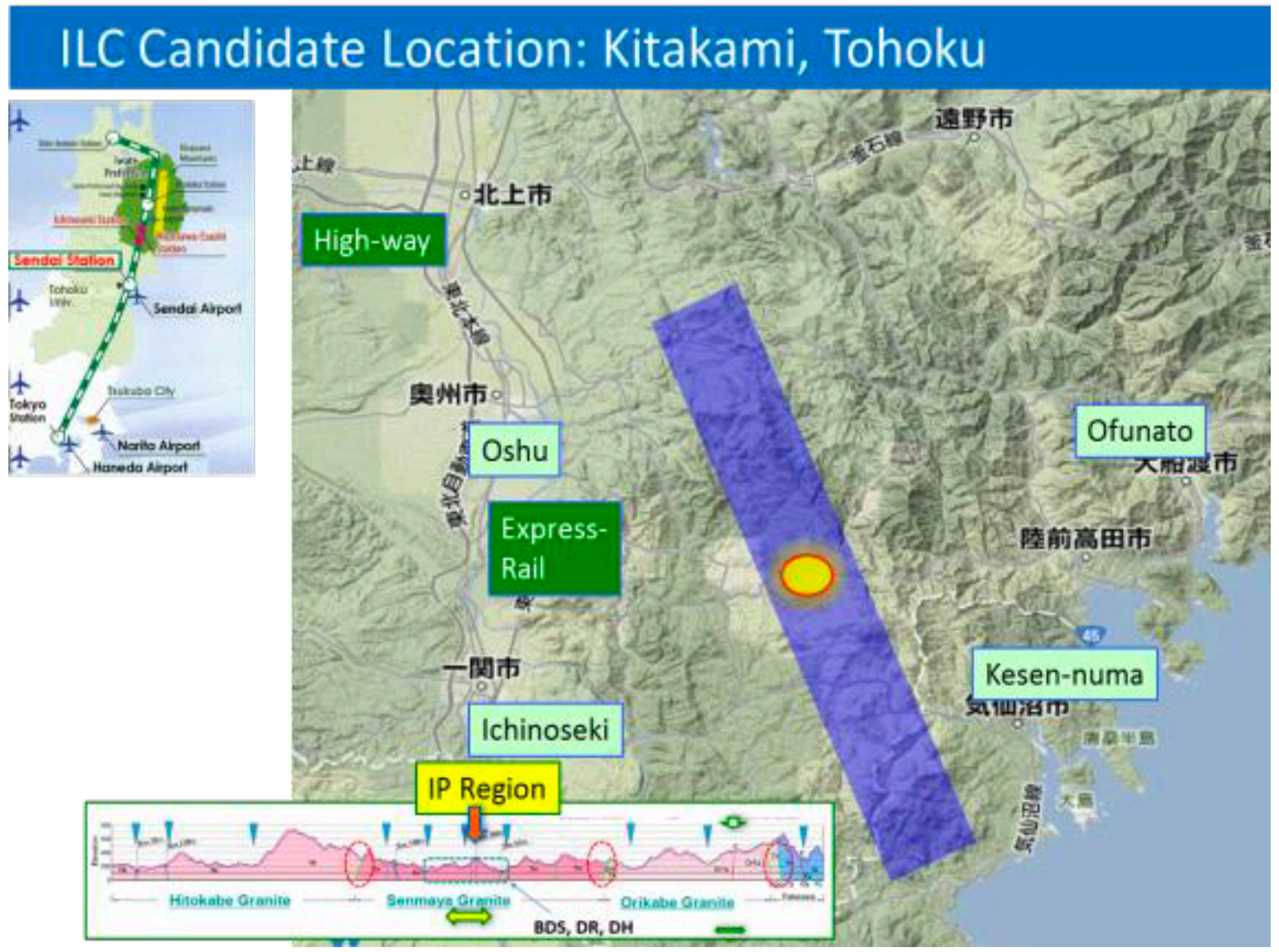


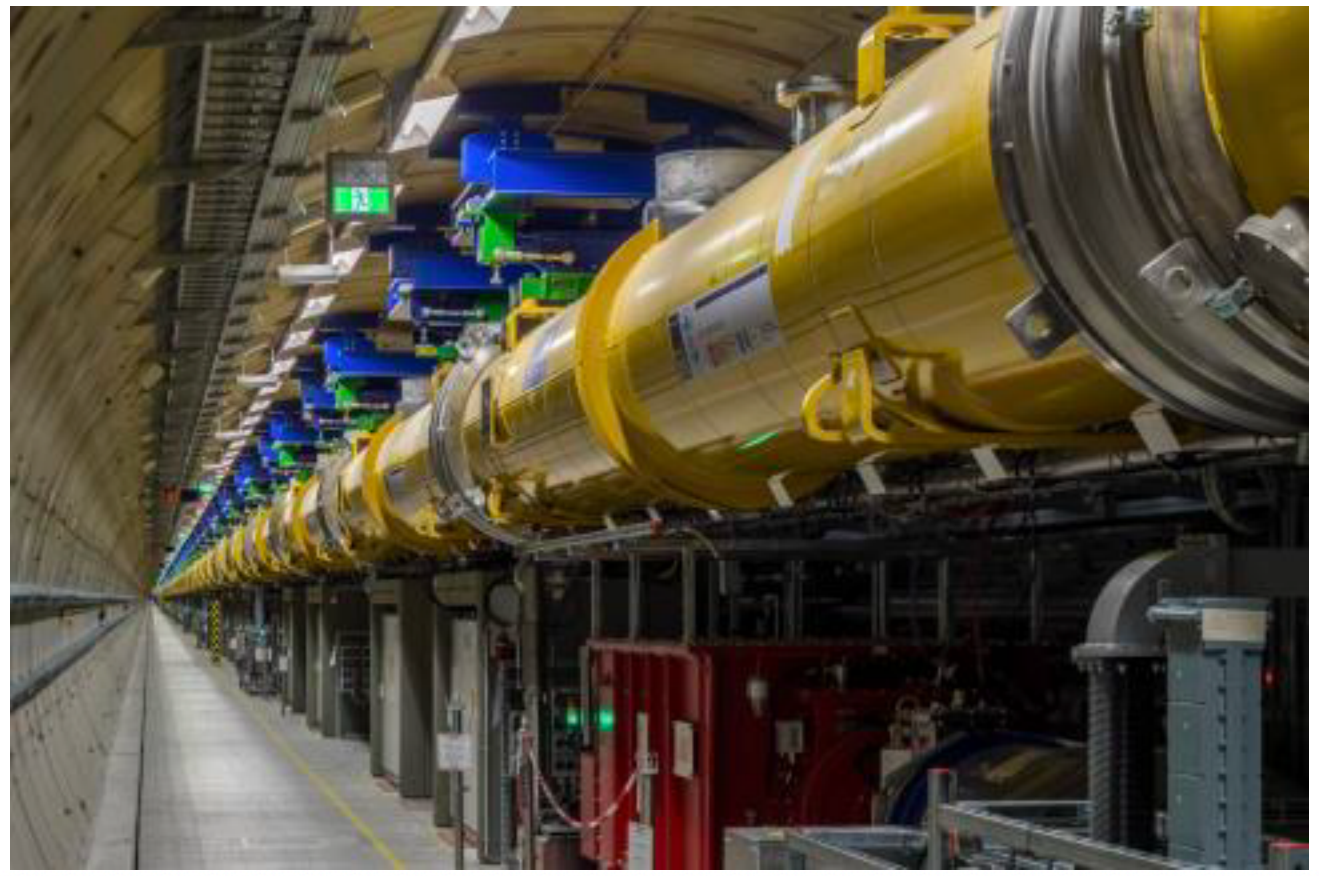


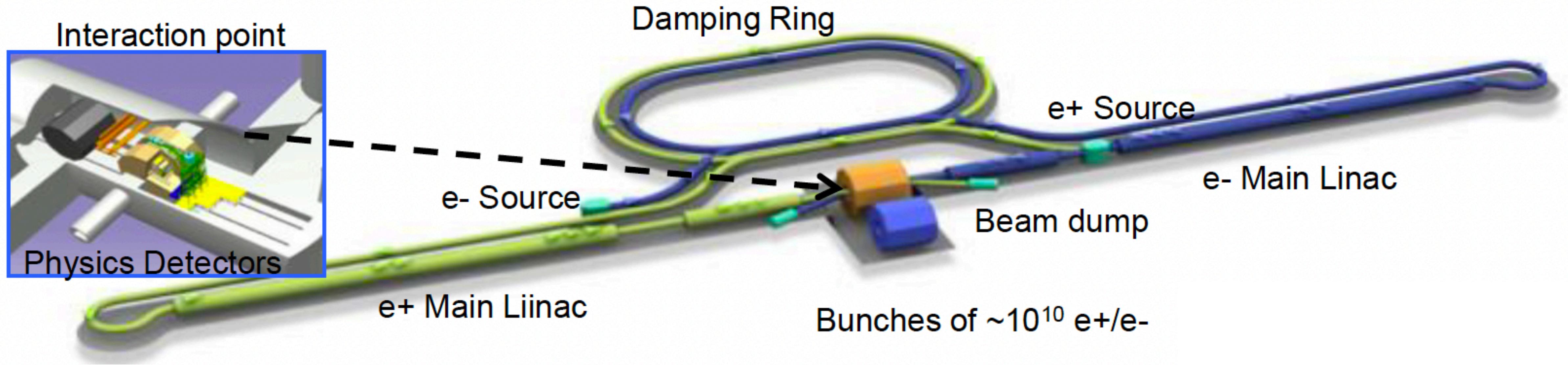


ILC

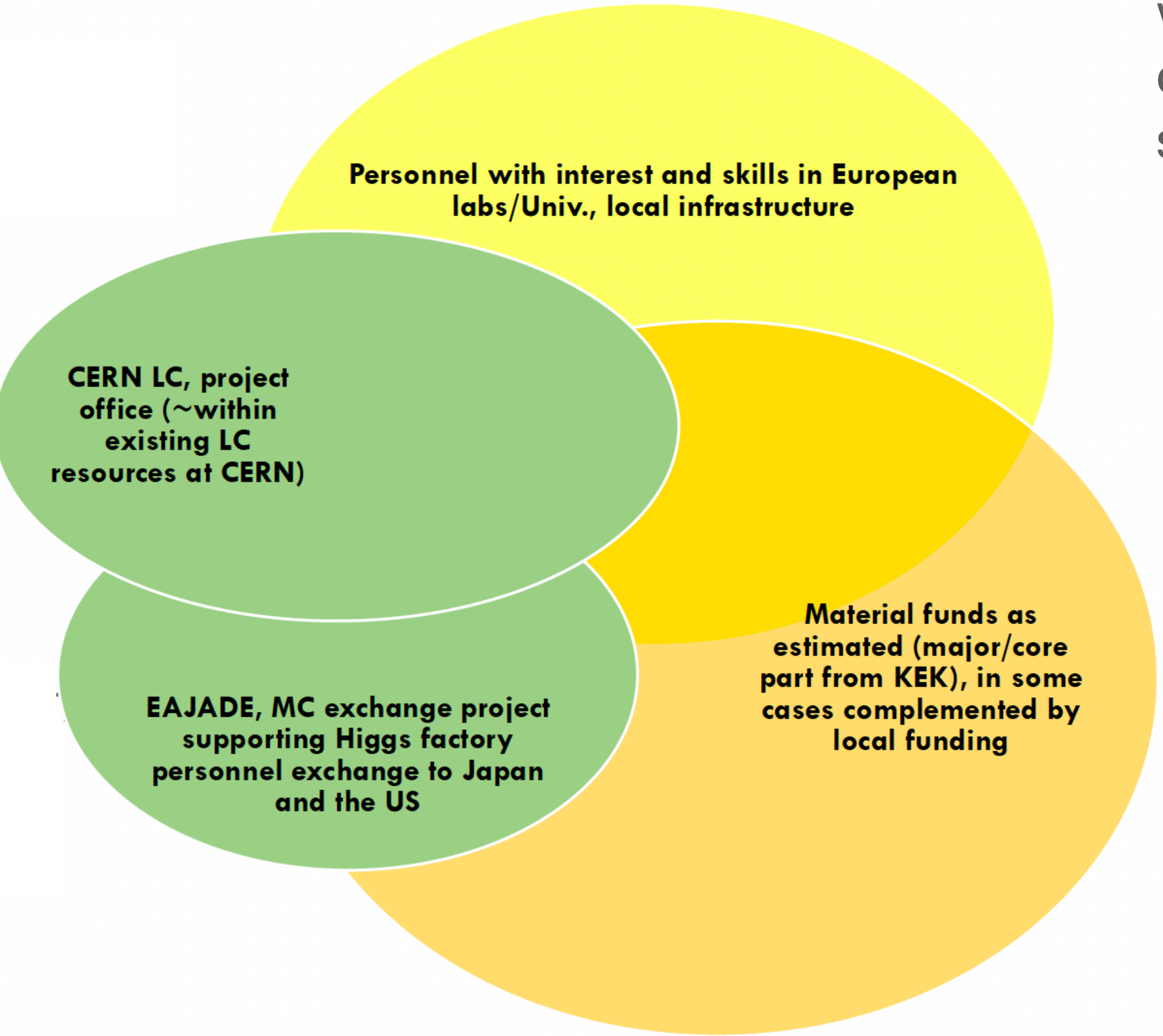
- **Two linear accelerators, each spanning ~20 km, employing superconducting radio frequency (SCRF) cavities cooled to ~2 K**
- **Capable of accelerating e$^-$ and e$^+$ beams to a 250 GeV c.o.m.**
    - Upgradable to 500 GeV or 1 TeV
- **Beam Operation:**
    - High-quality beams refined in damping rings before final acceleration
    - Repetition rate of ~5Hz, with multiple bunches per pulse
    - ~7000 collisions/s at the interaction point
- **Performance and Detectors**
    - Designed for high lumi (~10^{34} cm^{-2}s^{-1})
    - Precision tracking and calorimetry
    - Low background environment







ILC Ongoing Technical Developments



Personnel with interest and skills in European labs/Univ., local infrastructure

CERN LC, project office (~within existing LC resources at CERN)

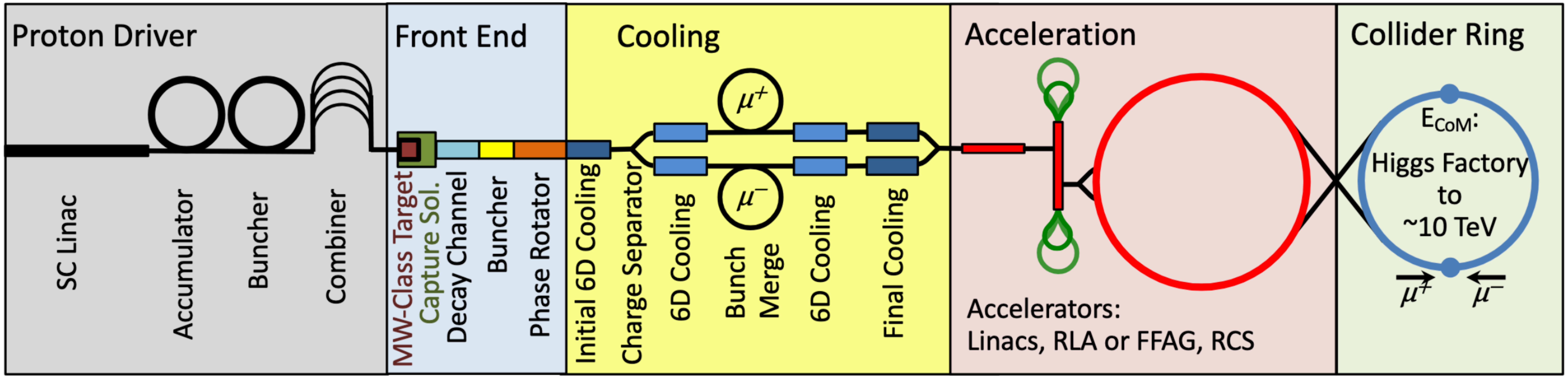
Material funds as estimated (major/core part from KEK), in some cases complemented by local funding

EAJADE, MC exchange project supporting Higgs factory personnel exchange to Japan and the US

- Within the overall ILC preparation phase, a subset of critical technical activities has been identified. These are being advanced with increased funding support from MEXT. European ILC studies, organised into five main areas, will focus (on the accelerator side) specifically on these key technical tasks (**A**ctivities):
  - **A1 with three SC RF related tasks**
    - SRF: Cavities, Module, Crab-cavities
  - **A2 Sources**
    - Concentrate on undulator positron scheme - fast pulses magnet, consult on conventual one (used by CLIC and FCCee)
  - **A3 Damping Ring including kickers**
    - Low Emittance Ring community
  - **A4 ATF activities for final focus in nanobeams**
    - Many European groups active in ATF
  - **A5 Implementation including Project Office**
    - Dump, CE, Cryo, Sustainability, MDI, others

Muon Collider

- **Muon collider R&D has been pursued in the US (MAP), experiments have been conducted in the UK (MICE) and alternative approaches have been explored at INFN (LEMMA)**
- **Renewed interest, driven by technological and design progress, along with the goal of achieving very high energy and high luminosity lepton collisions**
- **Would be much simpler if muons were stable - limited lifetime ($\tau = \gamma \times 2.2\ \mu s$)**



Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Main Challenges

Major technical challenges

- Supported by EU Design Study MuCol

1) Beam-induced backgrounds (BIB)

2) Dense neutrino flux mitigated by mover system and site selection

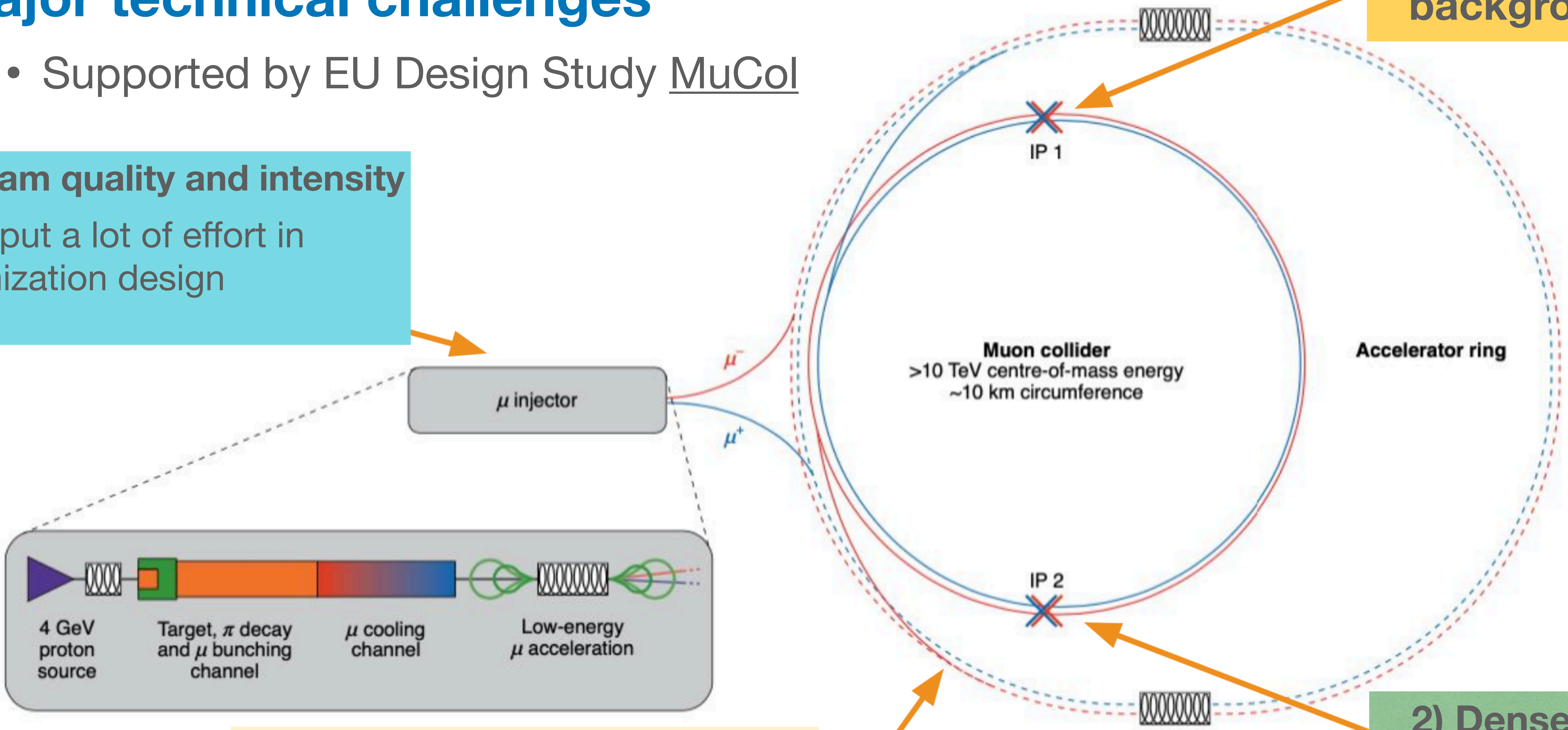
3) Beam quality and intensity

MAP put a lot of effort in optimization design

4) Cost and power consumption

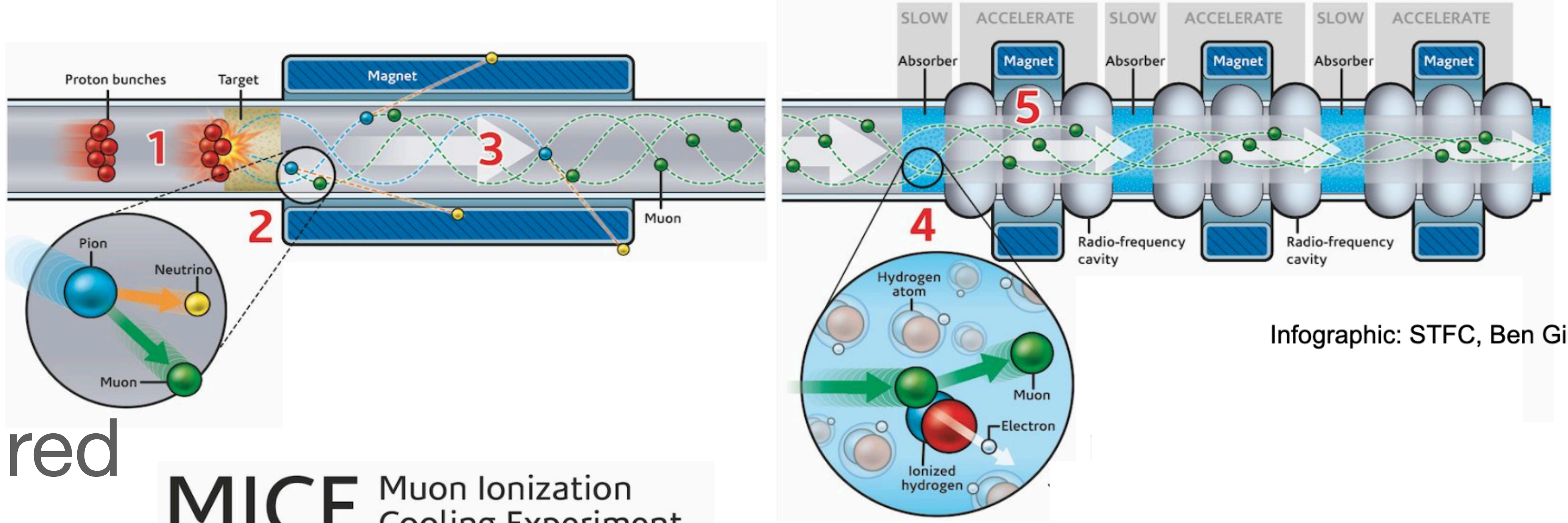
Limit energy reach

It also affects **beam quality**



Muon Collider R&D Examples

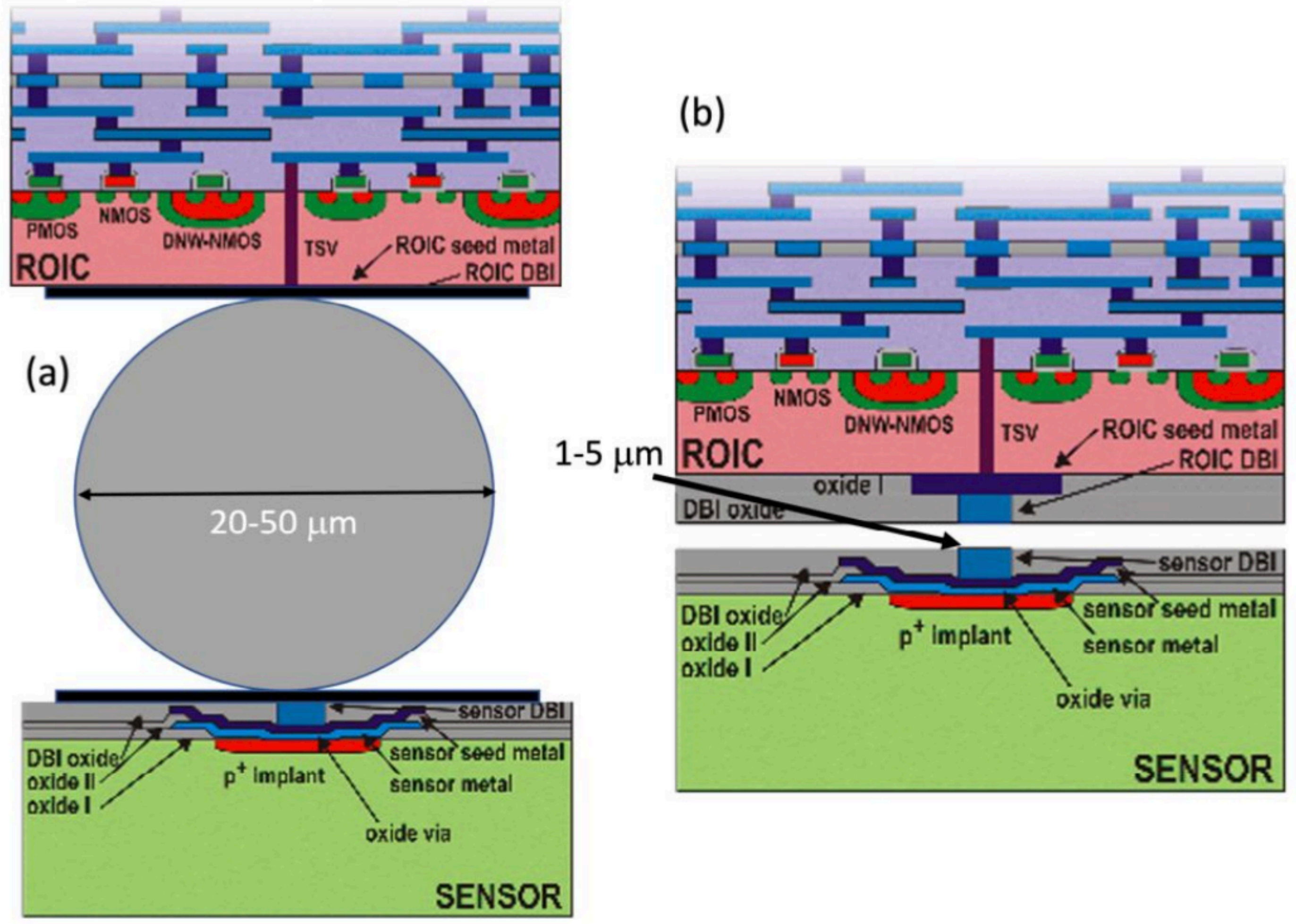
- **Cooling Cell Design** (1907.08562)
  - Cooling in matter demonstrated in MICE
  - **Need 10^6 emmitance reduction**
    - Demonstrator with RF and more that one stage required



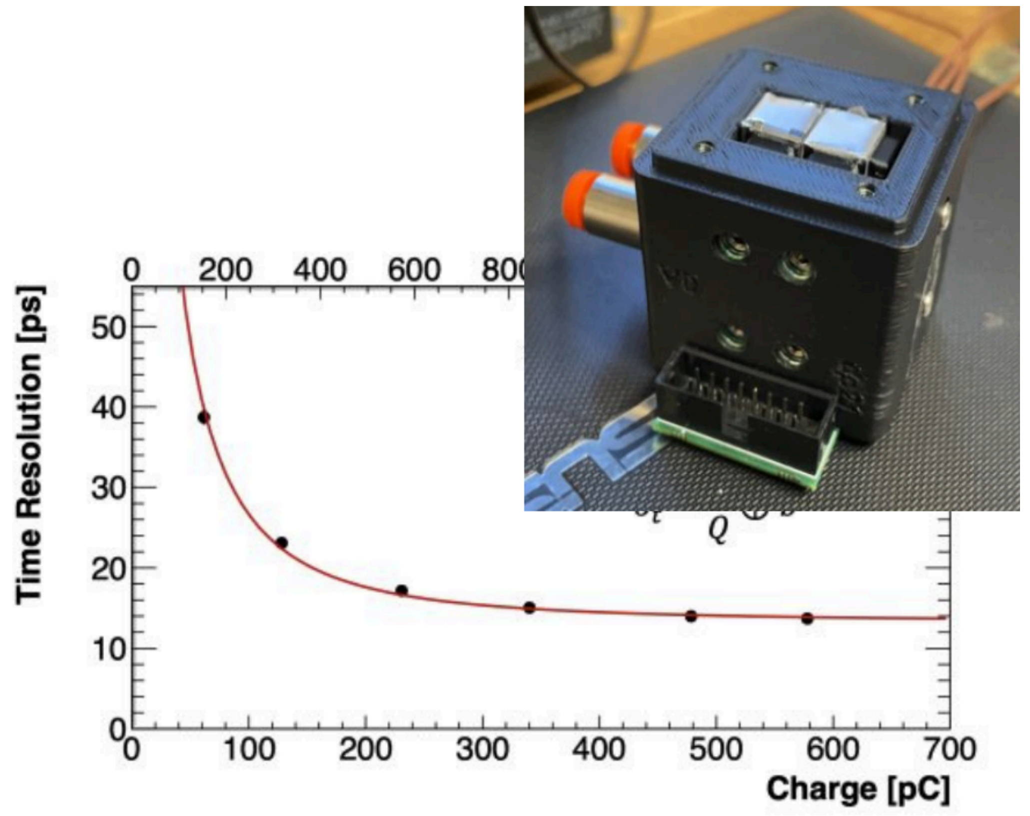
Infographic: STFC, Ben Gilliland

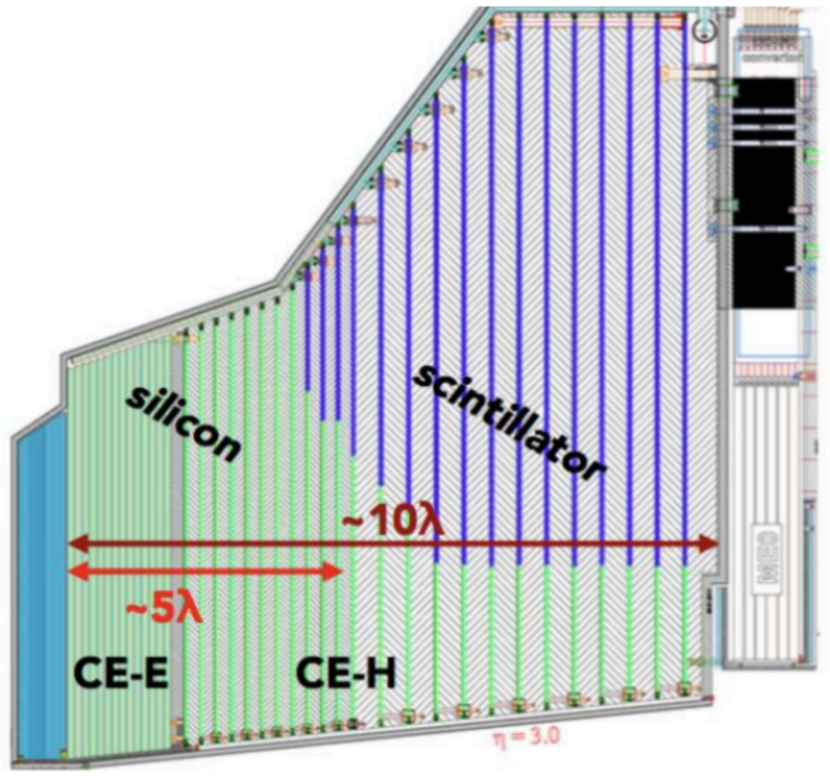
MICE Muon Ionization Cooling Experiment

- **4D tracking detectors** (2203.07224)
  - **Promising technologies exist**
    - Example: Advanced hybrid bonding tech can give < 5μm pitch and low input capacitance; 20-30ps time resolution



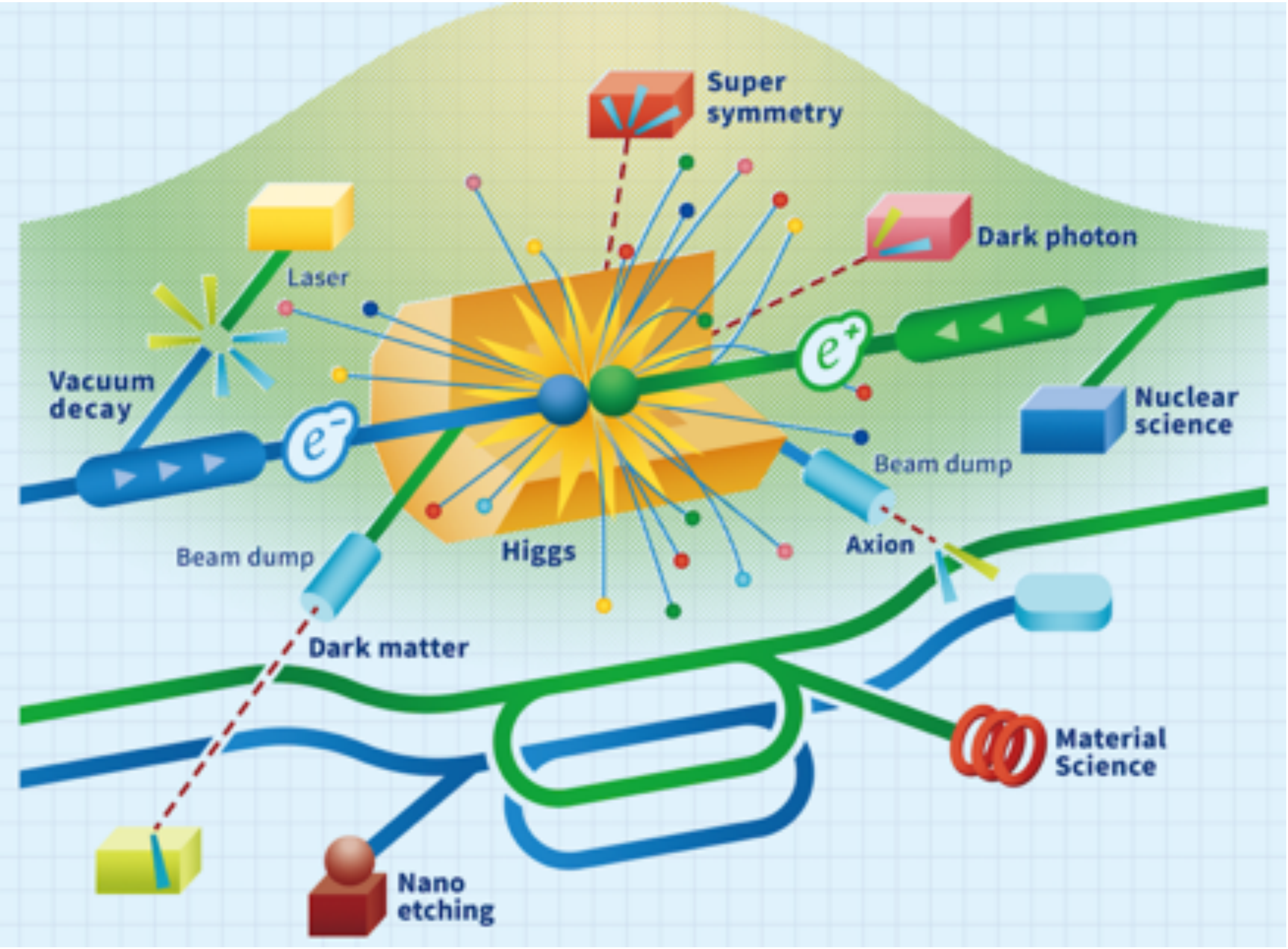
- **R&D and HL-LHC "technology transfer"**
  - **Crilin calorimeter**
    - Semi-homogeneous calorimeter based on PbF_2 crystals
  - **CMS High-granularity Calorimeter**
    - Mix of silicon and scintilator-based high-granularity cells (6.5M channels)





LC Vision

Linear Collider Vision

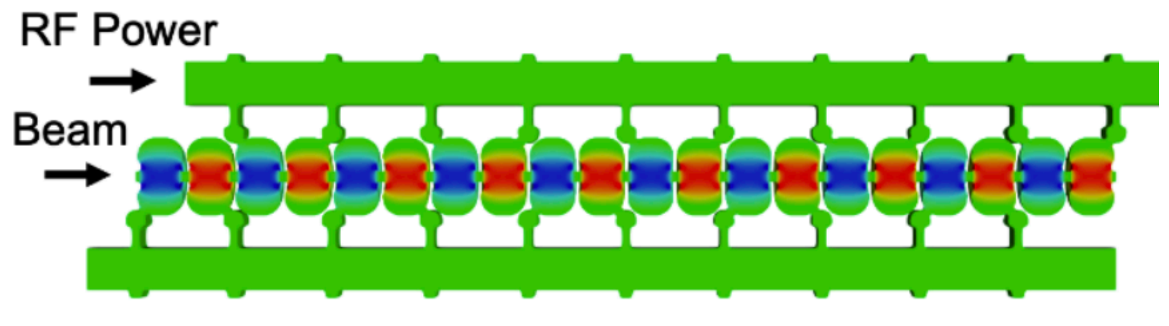


- A **coherent LC roadmap** with a long-term physics programme covering an energy rage of **~100 GeV** to **~1 TeV and beyond**, as well as with **beam dump and fixed target facility**
- Starting as a **Higgs (top) factory with the superconducting RF technology a la ILC**, $L \sim 10^{34}$, **benefiting from the matured industrialization worldwide**, is an attractive solution
- **Energy upgrade path**
  - Short-term solution in hand; adding more acceleration elements (extending the tunnel if needed)
  - Long-term solution with R&D; adopting higher gradient technologies, more performant SRF cavities with standing wave and ultimately plasma

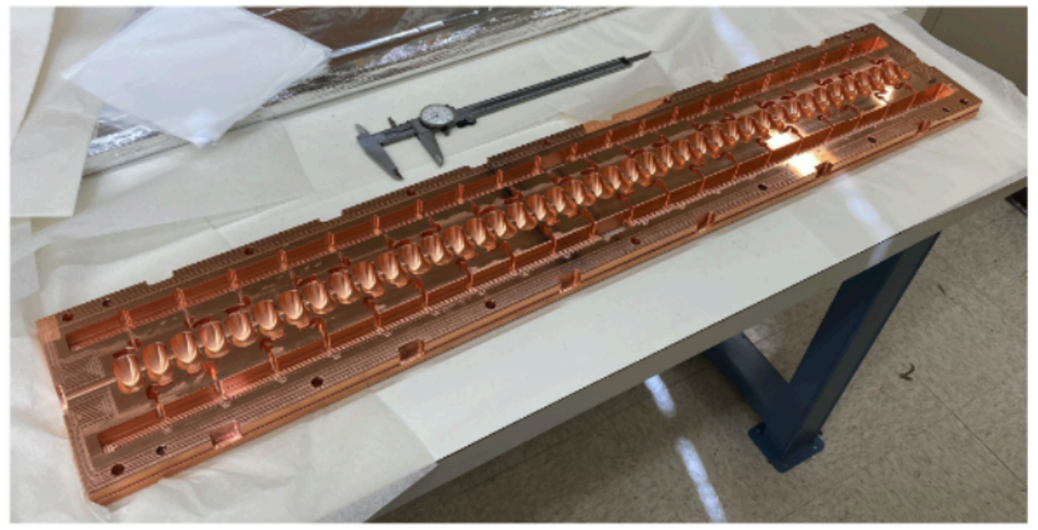
https://newsline.linearcollider.org/?p=39507
https://newsline.linearcollider.org/?p=39512
https://newsline.linearcollider.org/?p=39515
https://newsline.linearcollider.org/?p=39509

Additional Proposals: C^3 and LHeC/FCC-eh

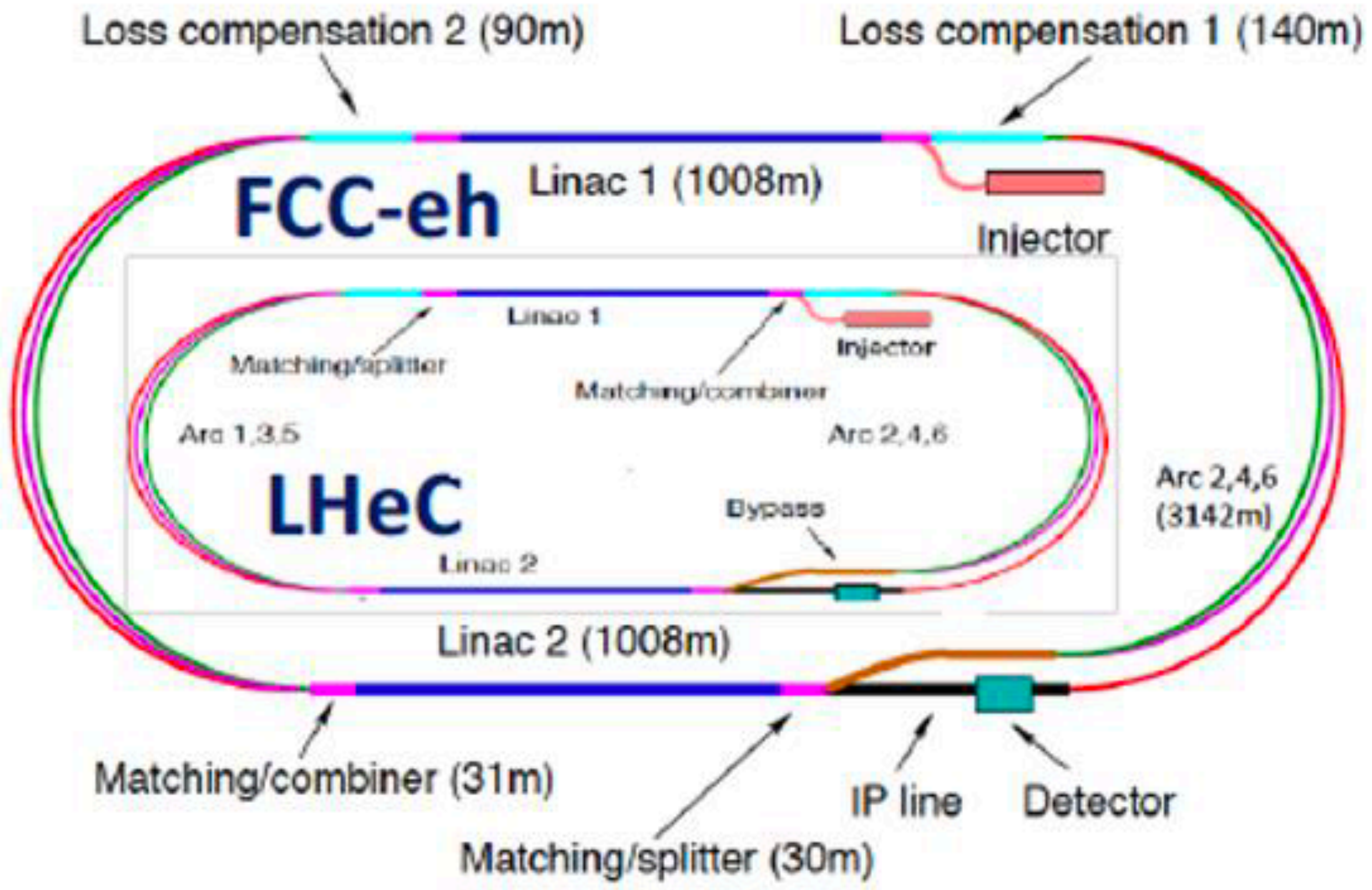
- **Cool Copper Collider (C^3) link**
    - High-energy e^+e^- linear collider concept
    - Utilizes a *cryogenic copper distributed-coupling* accelerating structure
    - Aimed at reducing operating costs and creating an efficient, compact and cost-effectice machine
    - Planned operation at 250/550 GeV c.o.m. for detailed Higgs studies
    - Energy upgrades require only additional RF power sources (no major structural changes)



Electric field magnitude for equal power from RF manifold



- **LHeC and FCC-eh: twin machines**
    - Collider electron from linac with LHC/FCC hadron beam
    - Recirculating linac allows to recover beam energy
    - 800 MW beam power for 100 MW power consumption



$\sqrt{s_{ep}}$ = 1-4 TeV

L(HERA) x 1000
(ERL and LHC)

1206.2913, JPhysG
2007.14491, JPhysG

f=802Mz,
3+3 passes: 20mA x 6
20 MV/m, $Q_0 > 10^{10}$

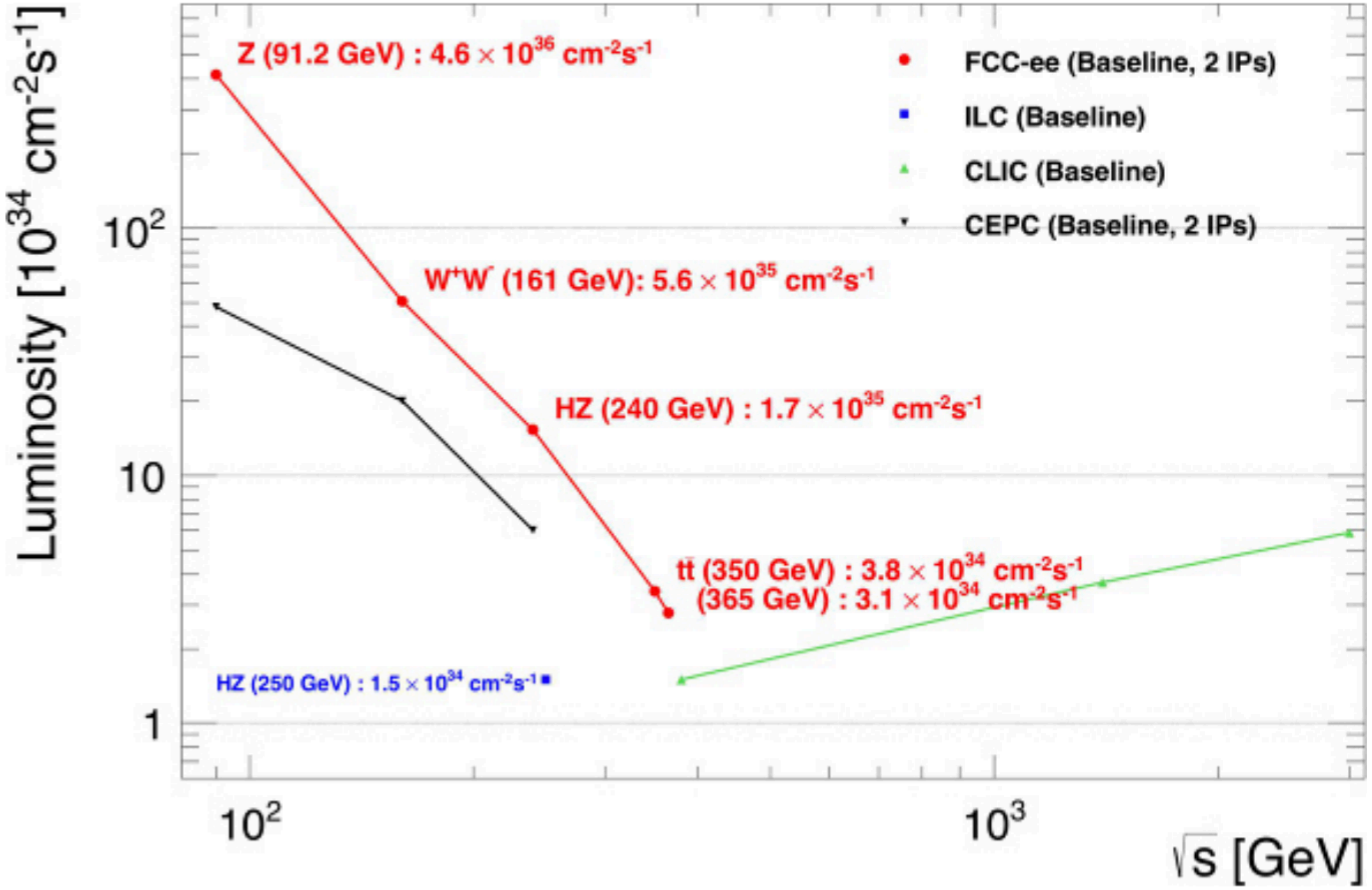
Summary & Outlook

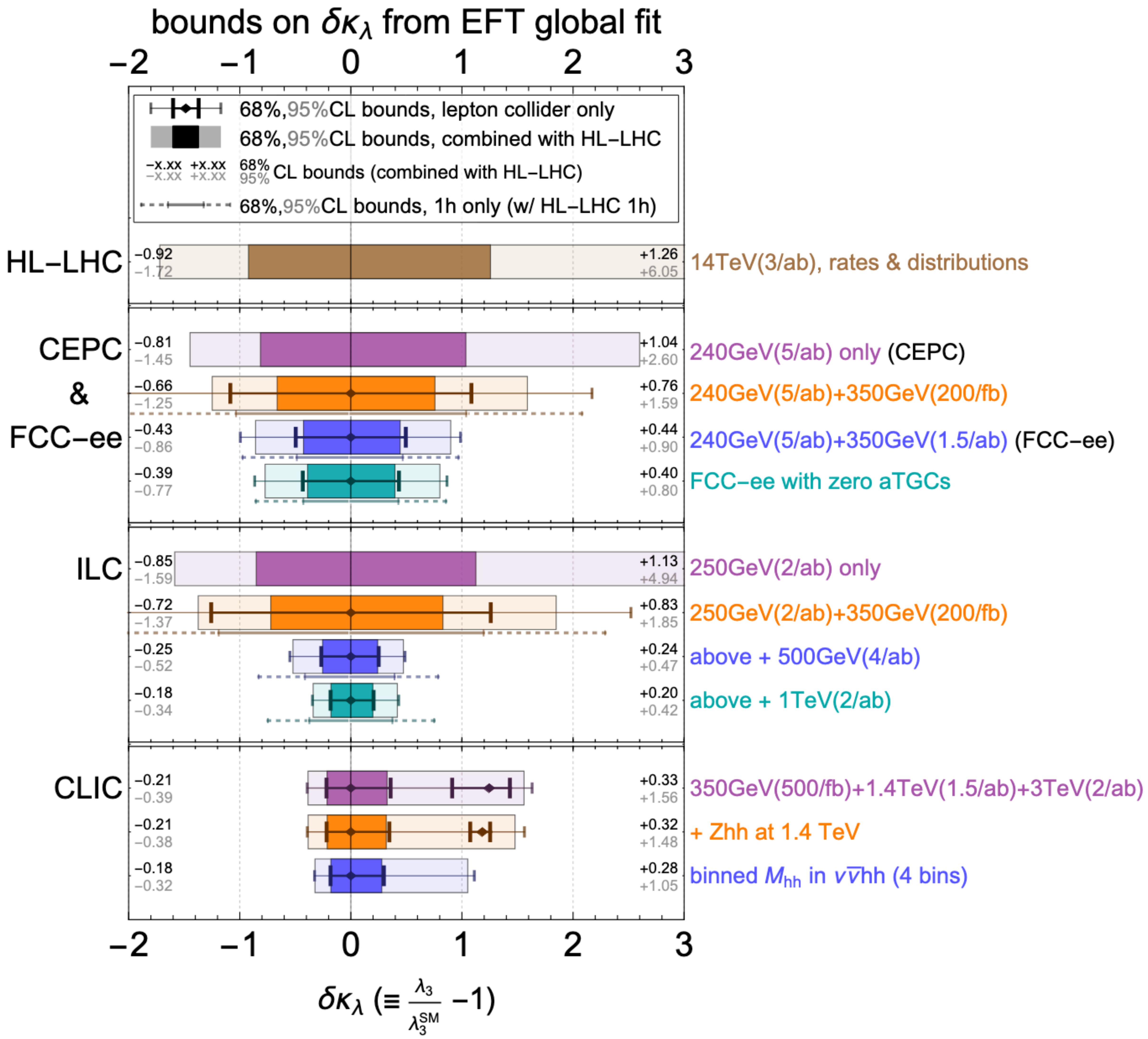
- ◉ **Colliders drive advancements in accelerator physics and technology**
- ◉ **Next-generation machines are not simply scaled-up versions of existing ones; many questions remain open**
- ◉ **Each project has unique advantages, challenges, and levels of risk**
- ◉ **Current proposals push technology R&D in multiple ways:**
  - **Rethinking established designs (e.g., Nb_3Sn cables)**
  - **Using new materials (e.g., high-temperature superconductors)**
  - **Exploring advanced concepts (e.g. muon cooling)**
  - **Designing for new constraints (environmental impact, power consumption, efficiency, societal benefits)**

Training the next generation of accelerator physicists and engineers is crucial for continued progress.

Backup Slides

Physics Programme

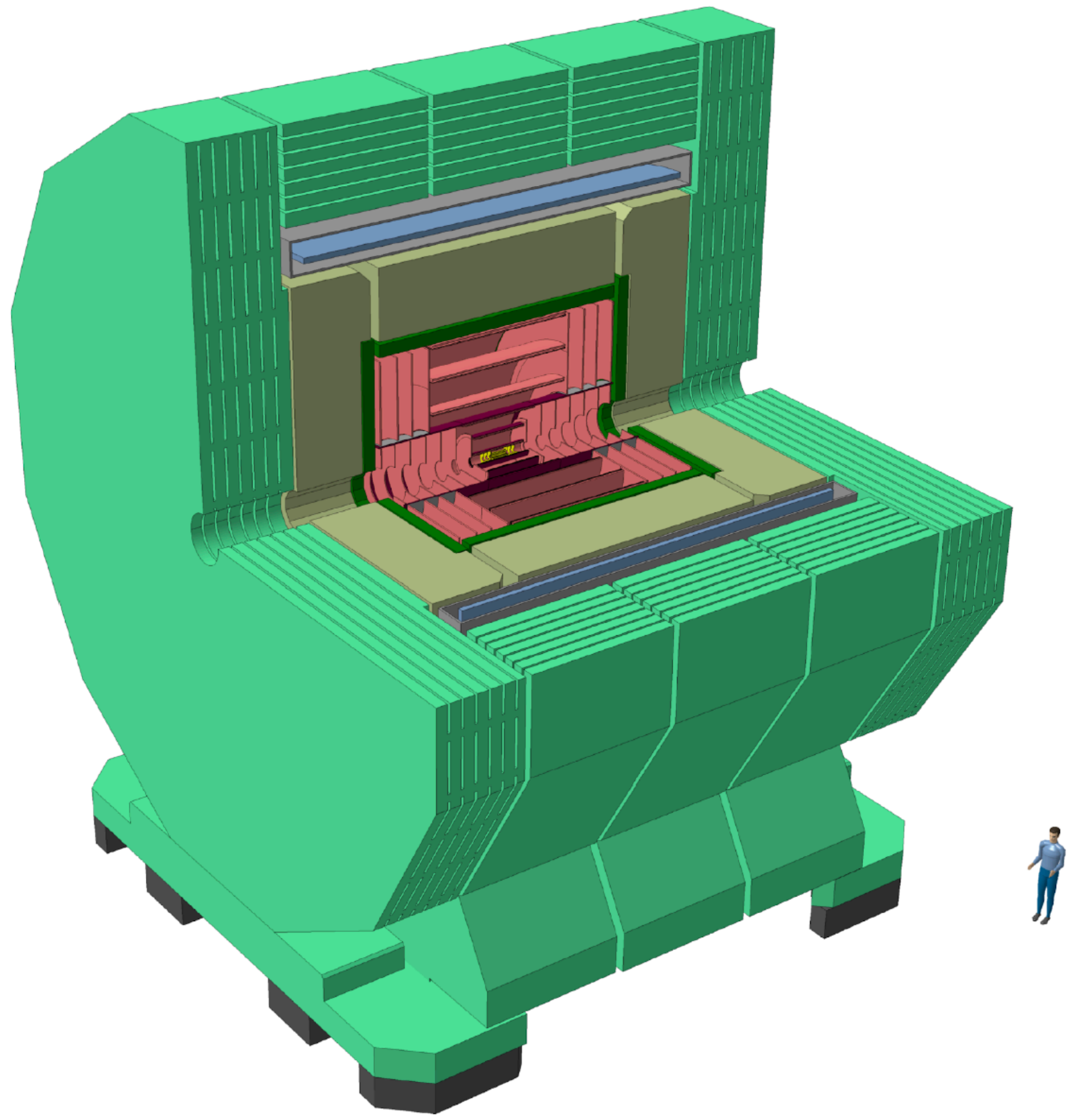




Detector concepts at the FCC-ee

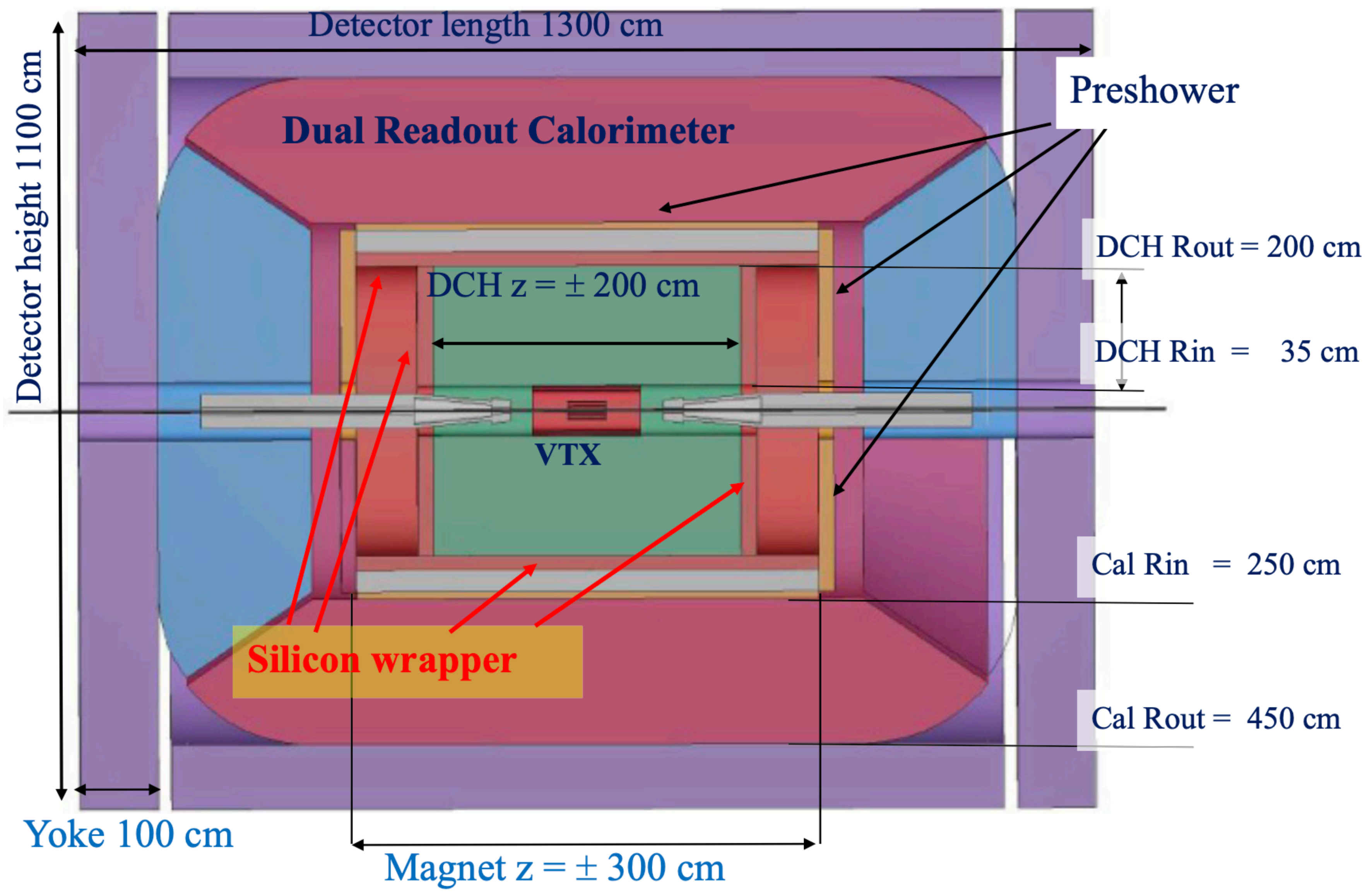
CLIC-like Detector (CLD)

- Full silicon vertex-detector+ tracker
- 3D HG calorimeter
- Solenoid outside calorimeter



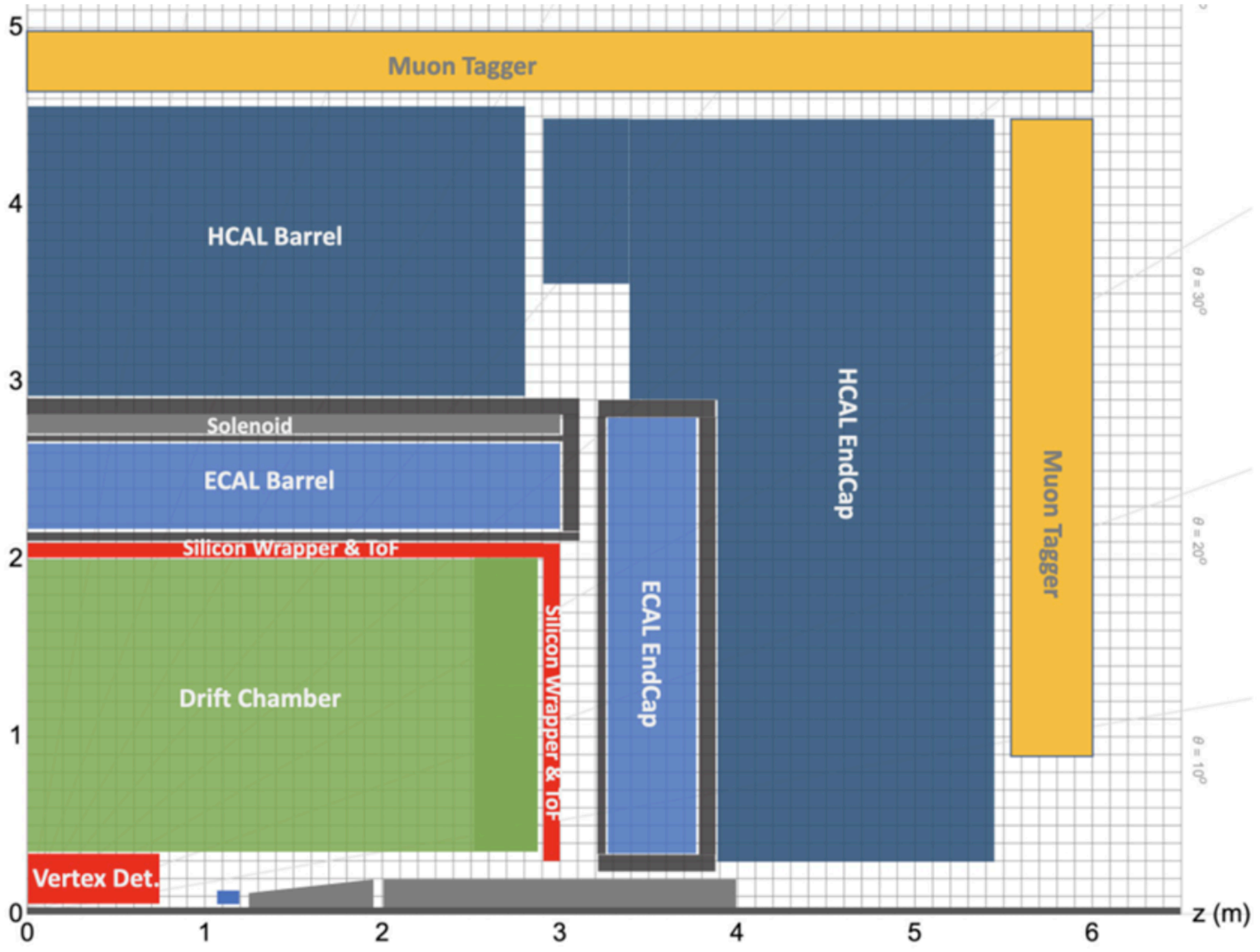
Innovative Detector for an Electron-Positron Accelerator (IDEA)

- Silicon vertex detector
- Short-drift chamber tracker
- Dual-readout calorimeter

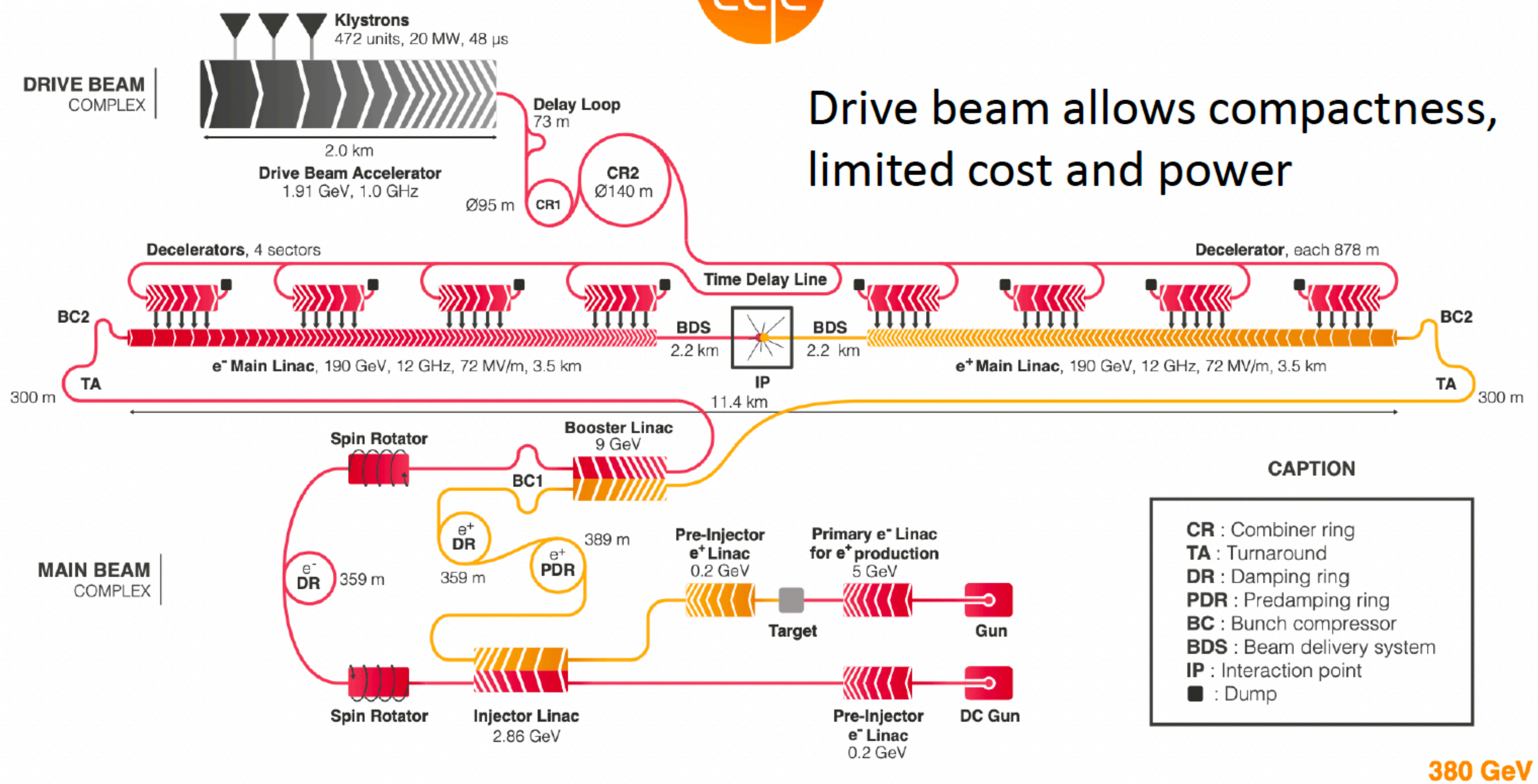


Allegro

- HG noble liquid calorimeter
- LAr or Lar + Lead or Tungsten absorber
- Latest proposal



CLIC

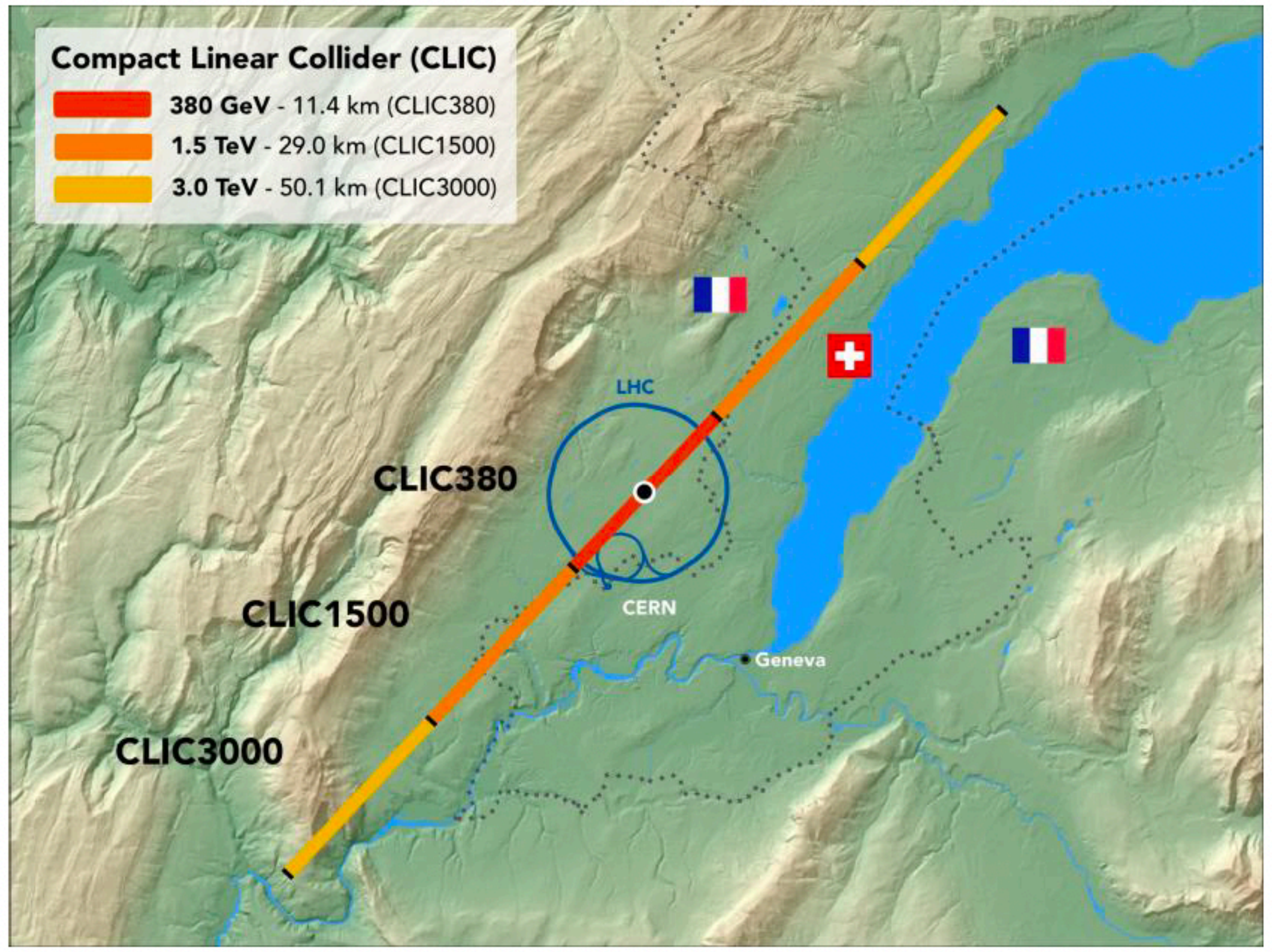


Drive beam allows compactness, limited cost and power

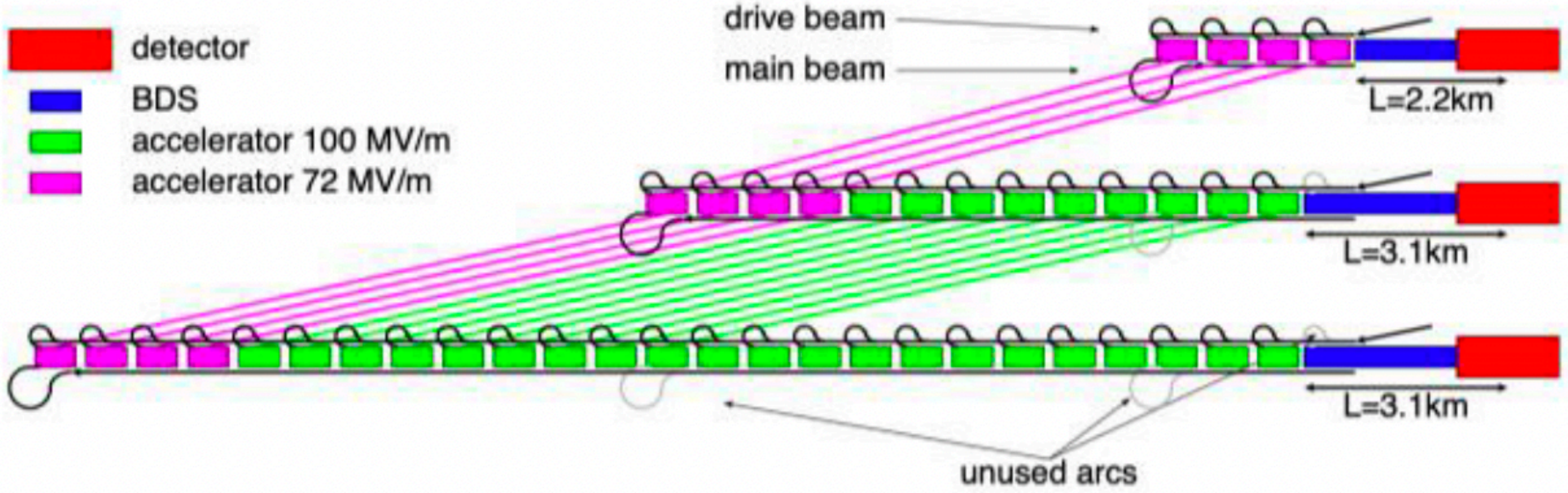
CAPTION

CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

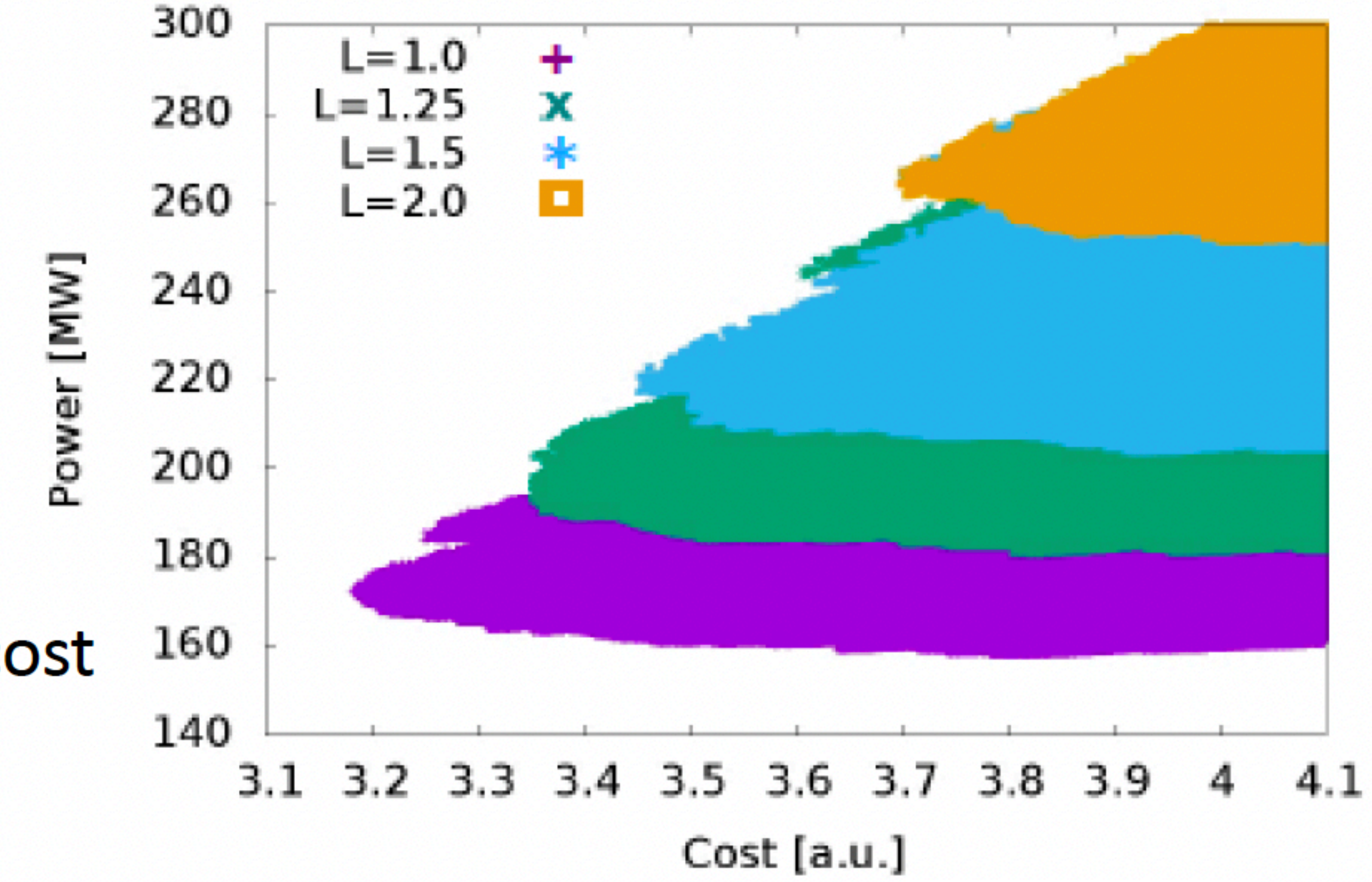
380 GeV



Stages possible: 0.38, 1.5 and 3 TeV

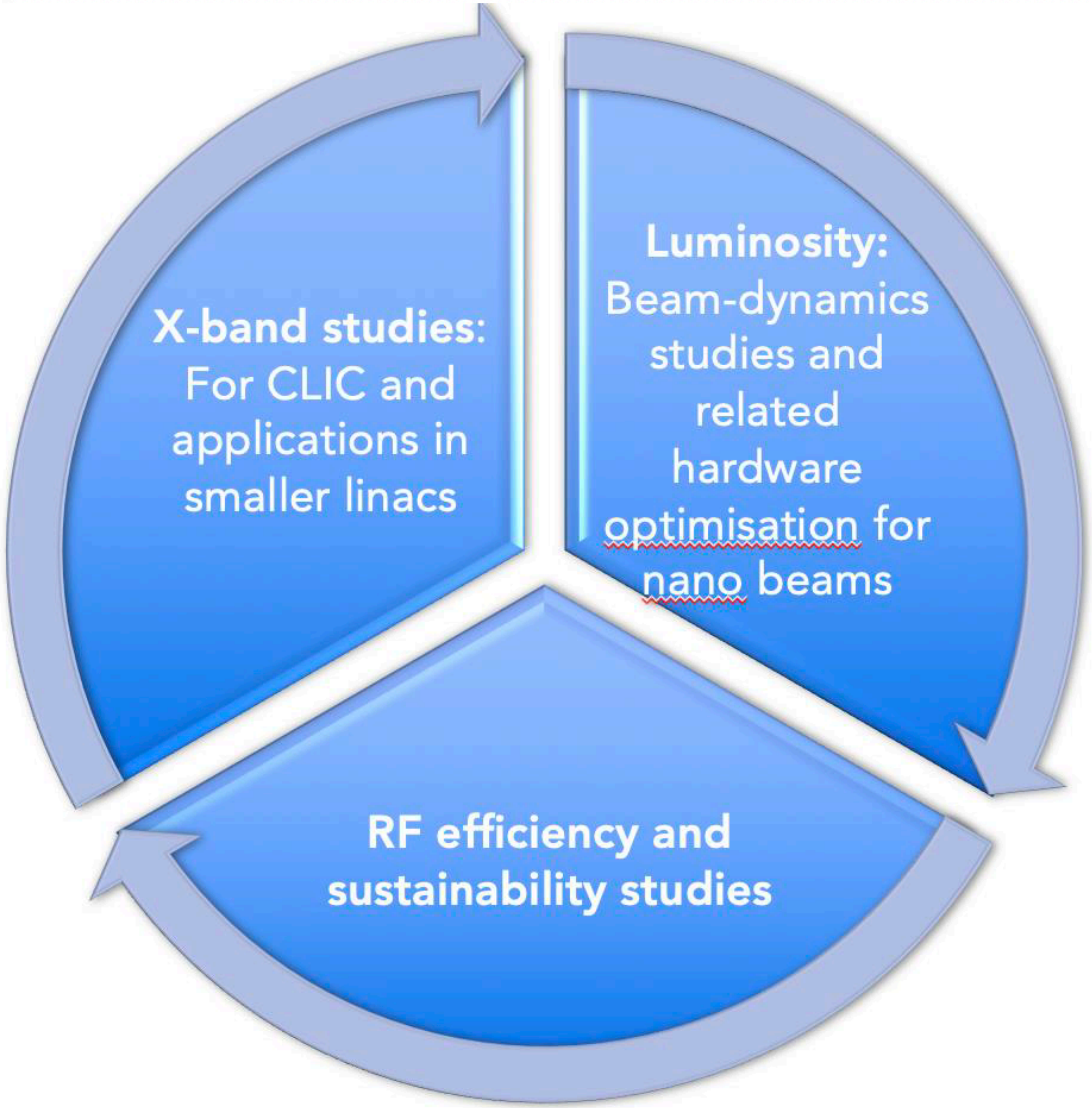


Optimised for cost and power



CLIC Work

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



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

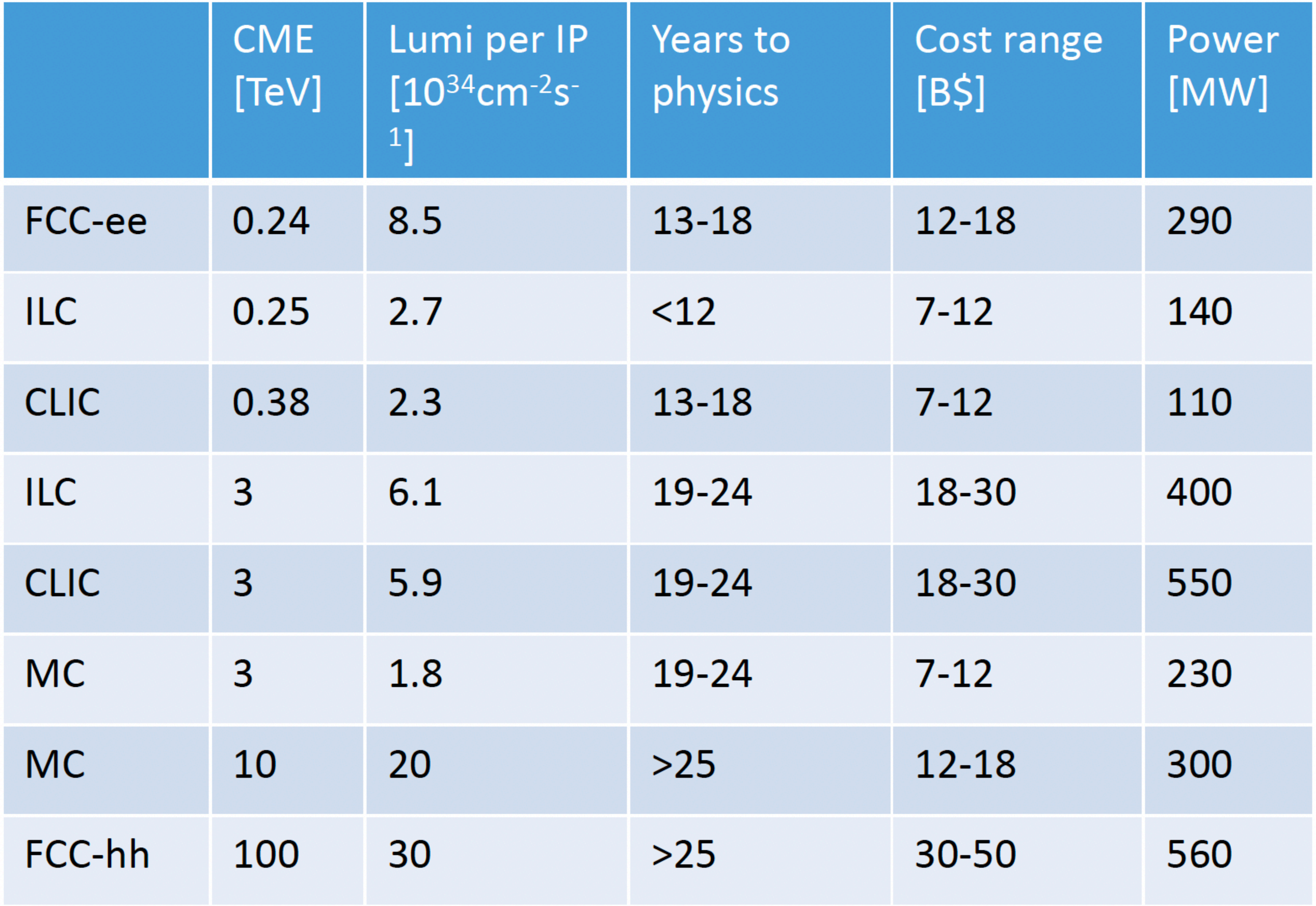
Luminosity: Beam-dynamics studies and related hardware optimisation for nano beams

RF efficiency and sustainability studies

LC Vision

- **Luminosity upgrade path**
  - A short-term solution in hand: increasing the RF power and doubling the collision frequency
  - Long-term solution with R&F: energy and positron recovery and CW mode up to two orders of magnitude, $\gtrsim 10^{36}$
- **If at CERN**
  - Starting machine as 250 GeV Higgs factory (20 km tunnel), $L \approx 1.4 \times 10^{34}$ with two separate collision points could be below 10 BCHF. Energy at 250 GeV with an extended tunnel (30 km) for the future energy upgrade and with luminosities of 3-5 $\times 10^{34}$ could still be just below 10 BCHF. (Cost estimate for a CERN implementation is in progress, where the cost of the accelerator part is based on the updated 2024 ILC cost for a Japanese site.)

Future Colliders Comparisons & Cost Estimates



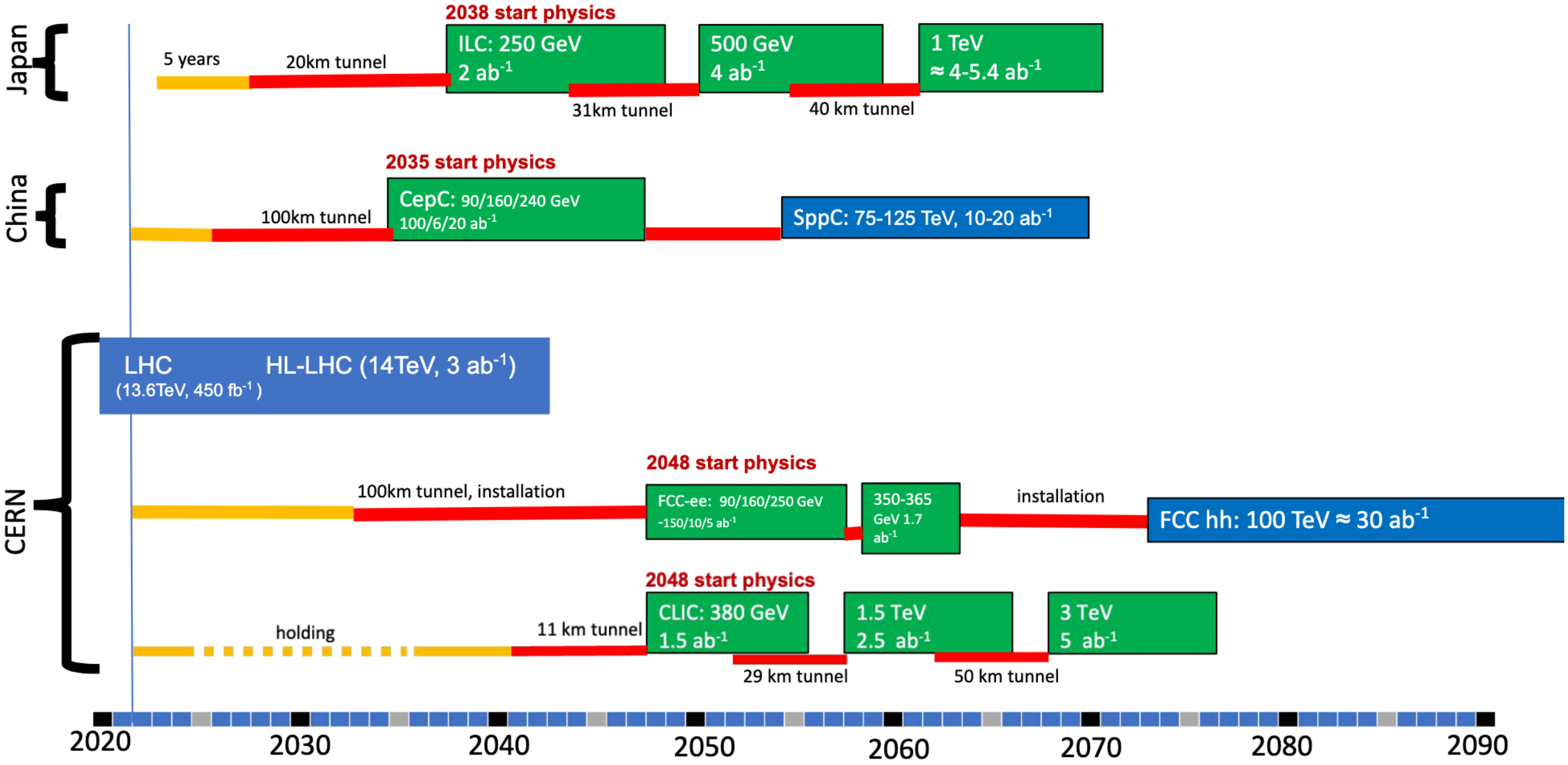
	CME [TeV]	Lumi per IP [$10^{34}cm^{-2}s^{-1}$]	Years to physics	Cost range [B$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
ILC	0.25	2.7	<12	7-12	140
CLIC	0.38	2.3	13-18	7-12	110
ILC	3	6.1	19-24	18-30	400
CLIC	3	5.9	19-24	18-30	550
MC	3	1.8	19-24	7-12	230
MC	10	20	>25	12-18	300
FCC-hh	100	30	>25	30-50	560

Timelines in Snowmass Energy Frontier Summary (I)

Original from ESG 2020 by UB
Updated July 25, 2022 by MN

🟦 Proton collider
🟩 Electron collider
🟧 Muon collider

🟥 Construction/Transformation
🟨 Preparation / R&D



Japan

5 years

20km tunnel

2038 start physics

ILC: 250 GeV
2 ab^{-1}

31km tunnel

500 GeV
4 ab^{-1}

40 km tunnel

1 TeV
≈ 4-5.4 ab^{-1}

China

100km tunnel

2035 start physics

CepC: 90/160/240 GeV
100/6/20 ab^{-1}

SppC: 75-125 TeV, 10-20 ab^{-1}

CERN

LHC
(13.6TeV, 450 fb^{-1})

HL-LHC (14TeV, 3 ab^{-1})

100km tunnel, installation

2048 start physics

FCC-ee: 90/160/250 GeV
-150/10/5 ab^{-1}

350-365
GeV 1.7
ab^{-1}

installation

FCC hh: 100 TeV ≈ 30 ab^{-1}

holding

11 km tunnel

2048 start physics

CLIC: 380 GeV
1.5 ab^{-1}

29 km tunnel

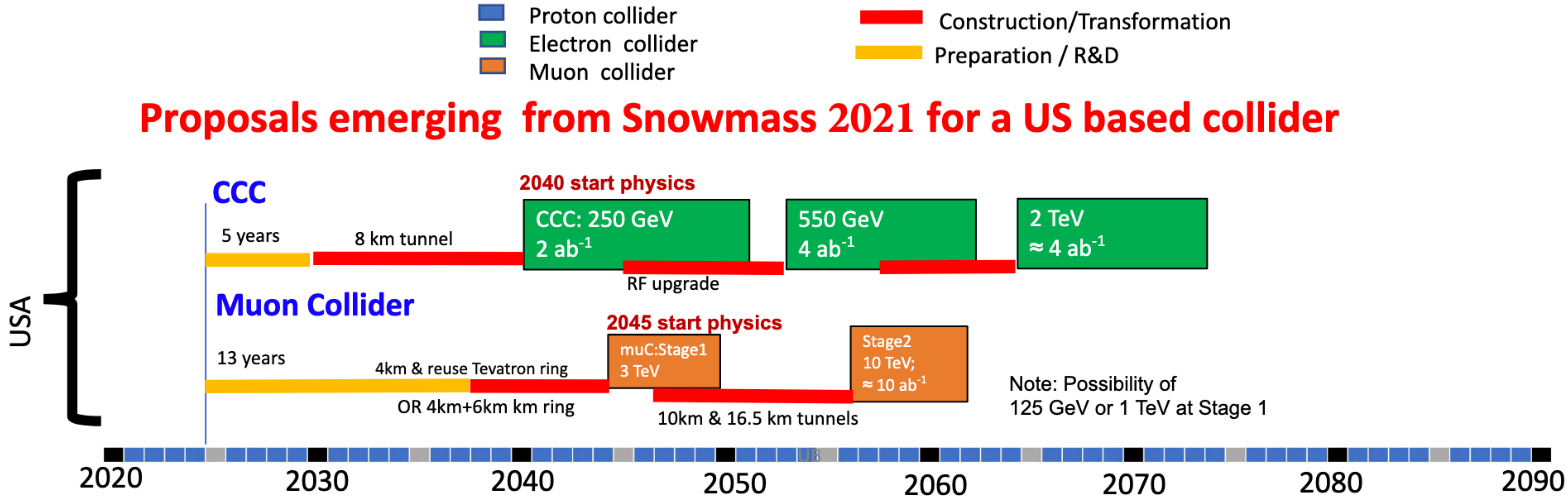
1.5 TeV
2.5 ab^{-1}

50 km tunnel

3 TeV
5 ab^{-1}

2020 2030 2040 2050 2060 2070 2080 2090

Timelines in Snowmass Energy Frontier Summary (II)



🟦 Proton collider
🟩 Electron collider
🟧 Muon collider

🟥 Construction/Transformation
🟨 Preparation / R&D

Proposals emerging from Snowmass 2021 for a US based collider

USA

CCC

5 years

8 km tunnel

2040 start physics

CCC: 250 GeV
2 ab^{-1}

RF upgrade

550 GeV
4 ab^{-1}

2 TeV
≈ 4 ab^{-1}

Muon Collider

13 years

4km & reuse Tevatron ring

OR 4km+6km km ring

2045 start physics

muC:Stage1
3 TeV

10km & 16.5 km tunnels

Stage2
10 TeV;
≈ 10 ab^{-1}

Note: Possibility of
125 GeV or 1 TeV at Stage 1