John Adams Institute for Accelerator Science

Royal Holloway University of London

YETI 2021
The Future of Lepton Colliders

# Future Collider Technologies and their challenges


*Stephen Gibson*

*RHUL*


*9th July 2021*

HiLumi HL-LHC PROJECT

ilc

clic

FCC hh ee he

# Overview

- ***Motivation***
  - *Accelerators drive discoveries*
  - *What technologies will improve the state-of-the-art?*
- ***Near-future***
  - *High-Luminosity LHC*
  - *Technical capabilities to address future challenges*
- ***Mid-future***
  - *Linear Colliders: ILC & CLIC*
  - *Future Circular Colliders: FCCee & CEPC*
- ***Further-future***
  - *Muon Collider*
  - *Advanced acceleration:*
    - *Laser & beam driven wakefield; THz; dielectric...*
- ***Dream beams***

# Motivation

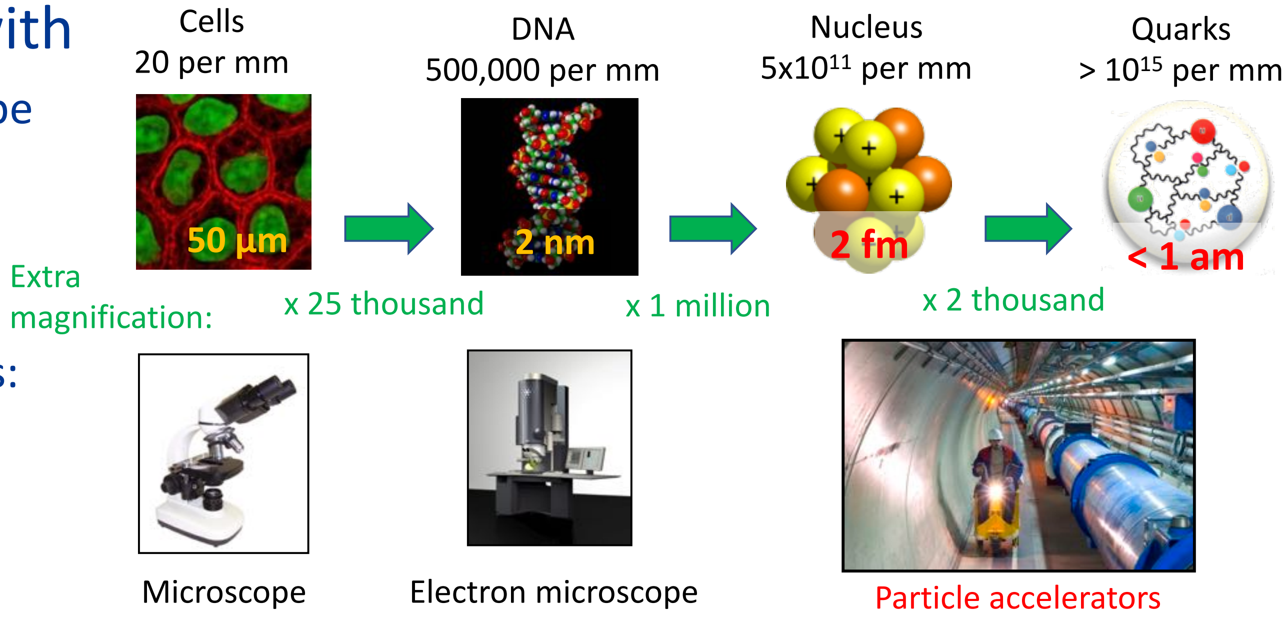
- ***How to address the fundamental questions of particle physics?***
  - *Why do we observe three generations of quarks and leptons?*
  - *Are there particles or interactions Beyond the Standard Model?*
  - *Why is there a matter-antimatter asymmetry in the universe?*
  - *What is mass? How exactly is electroweak symmetry broken?*
  - *What is the nature of Dark Matter? Are there Extra Dimensions?*

- **Accelerators** enable us to collide particles with
  - the **energy** to create new, massive particles, or to probe matter at the smallest length scales,

    De Broglie wavelength $\lambda = \frac{h}{p}$

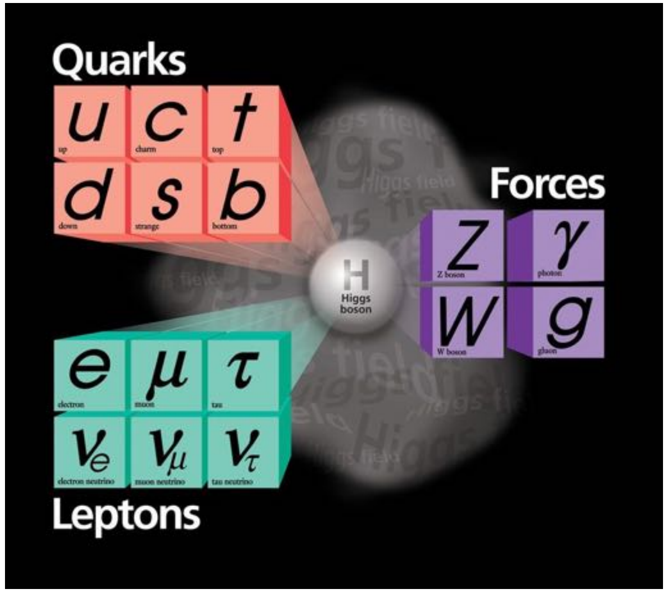
  - and the **luminosity** required to observe rare processes:

$$\mathcal{L} = \frac{1}{\sigma}\frac{dN}{dt} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$



# Motivation: accelerating discoveries…

- ***Advancement in accelerator technology drives discoveries, e.g.:***



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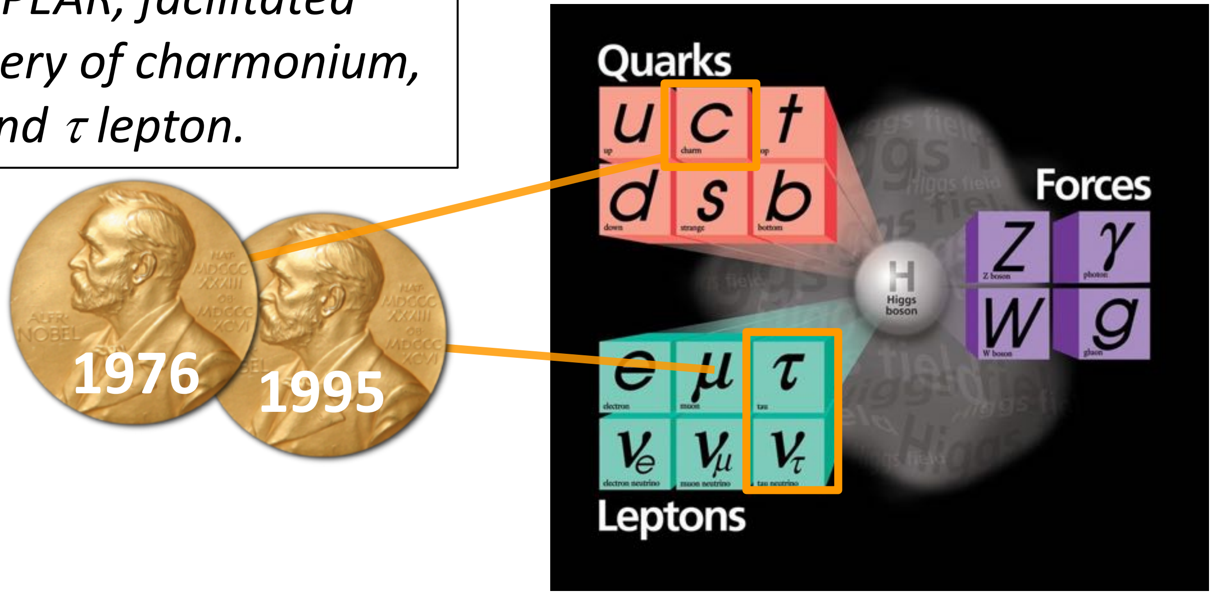
*Electron-positron storage ring, SPEAR, facilitated discovery of charmonium, J/$\psi$, and $\tau$ lepton.*



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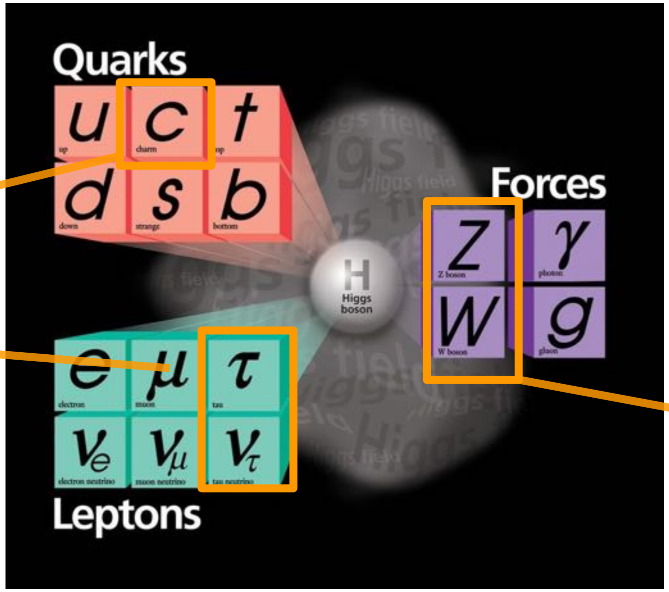


*Stochastic cooling at the CERN Super-Proton-Synchrotron led to discovery of the W/Z bosons.*


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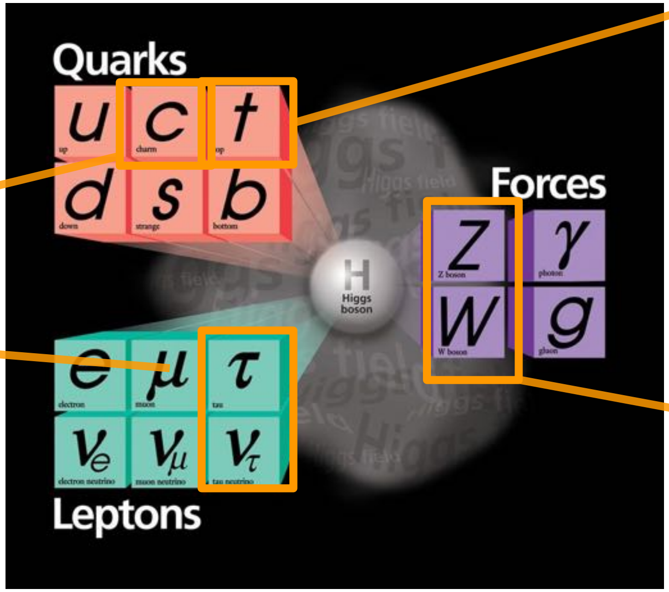


*Powerful superconducting coils at the Tevatron enabled the top quark discovery*

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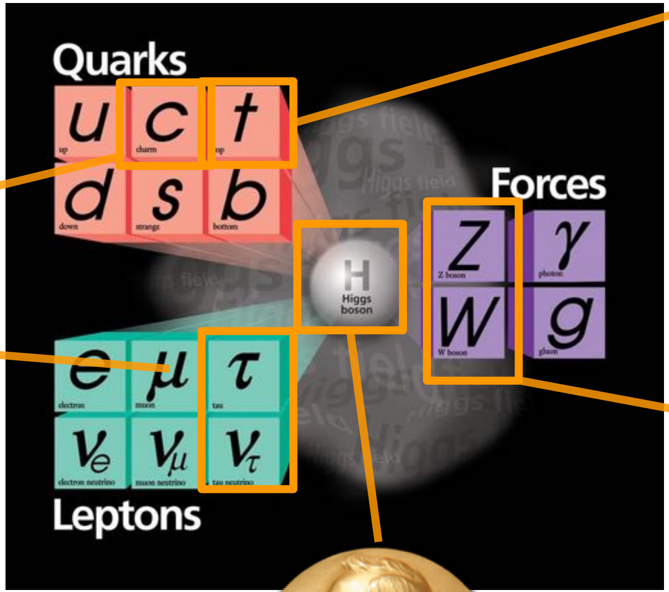



*Stochastic cooling at the CERN Super-Proton-Synchrotron led to discovery of the W/Z bosons.*

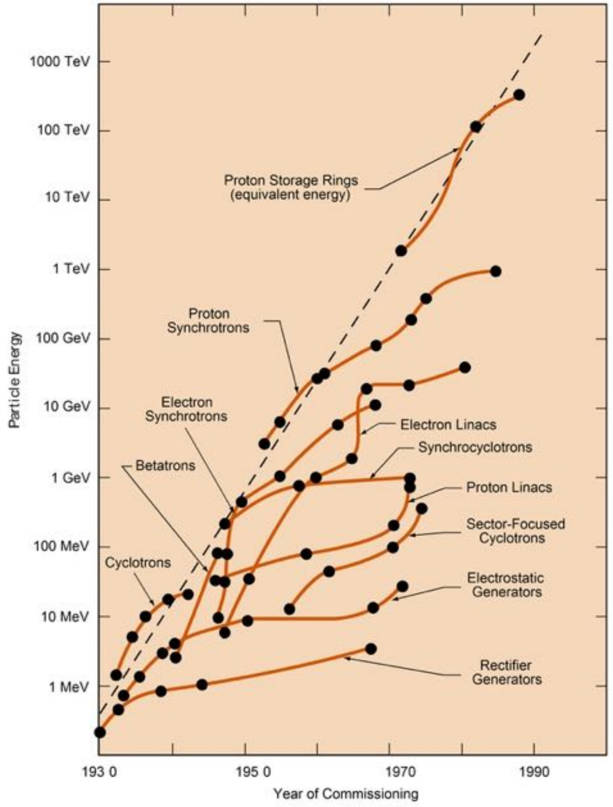

Simon van der Meer and Carlo Rubbia share the 1984 Nobel Prize.

*A giant leap in **energy** and **luminosity** at the Large Hadron Collider delivered the long-awaited Higgs Boson*


Peter Higgs and Francois Englert share the 2013 Nobel Prize

# “Livingston” plots of accelerator development

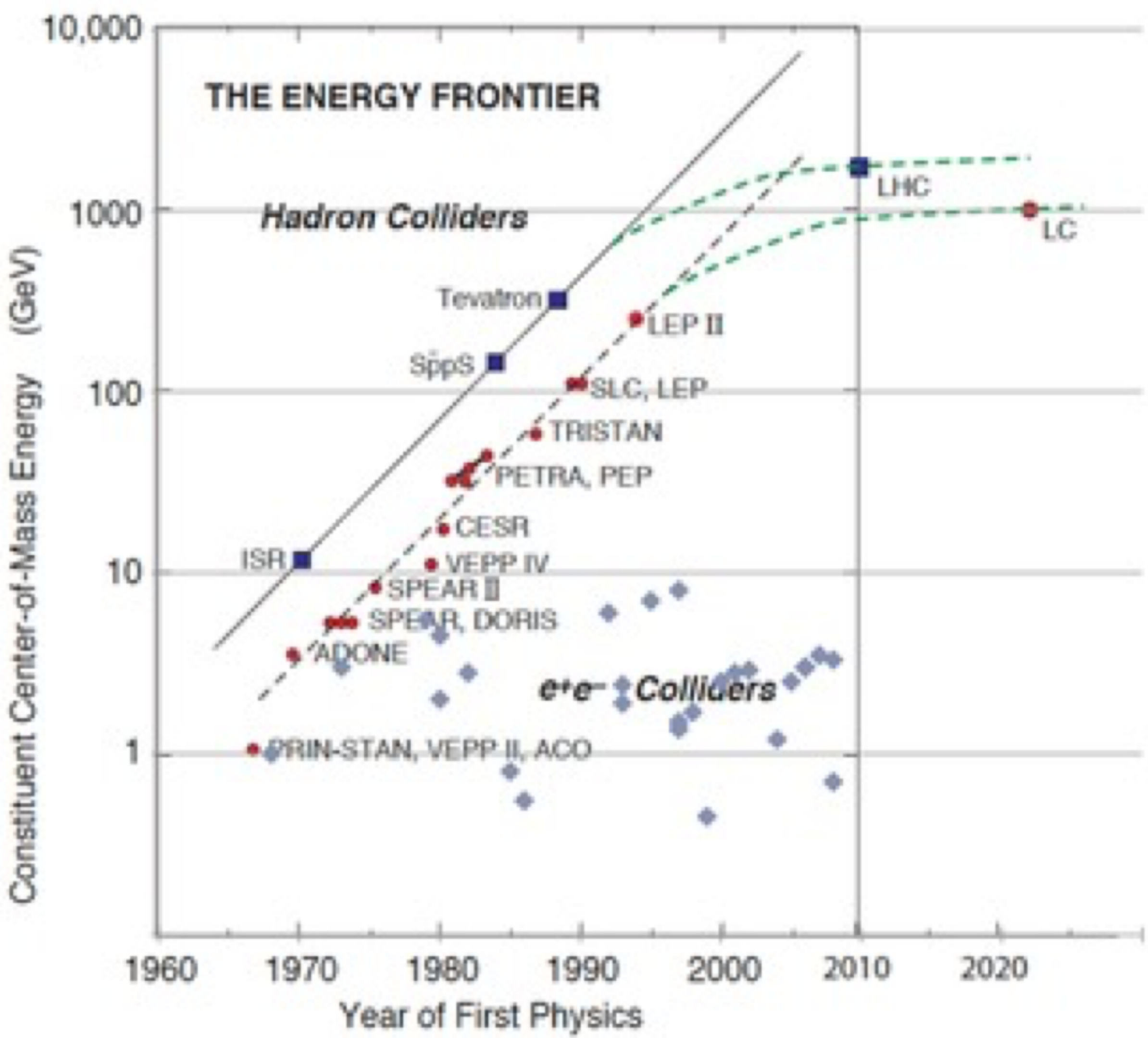
- *Since 1930 there has been about a factor 10 increase in equivalent fixed-target energy, every 6-8 years:*




From W.K.H. Panofsky, “Evolution of Particle Accelerators and Colliders 1997.

- *As one technology “ran out of steam”, another technology took over!*

- *Recently, this trend has softened:*
- ***What limits the energy reach of current machines?***
- ***What are the breakthrough technologies needed for future accelerators?***




Jordan Nash, Imperial College London, Current and Future Developments in Accelerator Facilities, 2010 IOP Meeting

# What limits the energy reach of circular colliders?



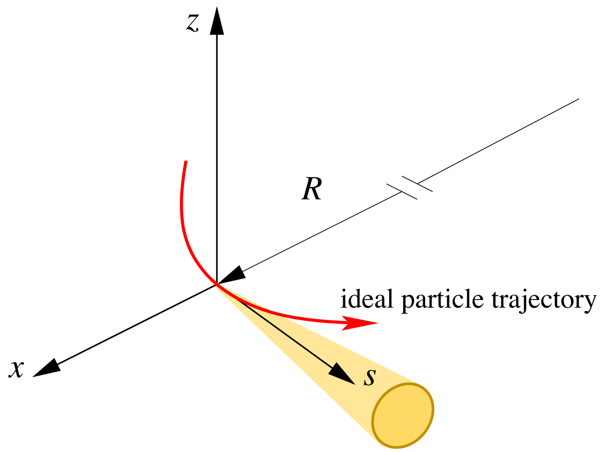
- ***Synchrotron radiation***
  - ***Charged particles accelerated transversely in a curved trajectory by a magnetic field emit synchrotron radiation:***
  - The total power radiated by synchrotron emission for a single charged particle, $P_s$ is:

$$P_{\rm s} = \frac{e^2 c}{6\pi\epsilon_0} \times \frac{\gamma^4}{R^2}.$$

*See Appendix 1.1 &1.2 of **Wilson** for derivation from retarded fields*

Where:
e is the electron charge
c is the speed of light
R is the radius of the charge particle's orbit
$\gamma = \frac{E}{m_0 c^2}$ is the ratio of the particle's total energy to its rest mass energy

$$P_s \propto \frac{\gamma^4}{R^2} \sim \frac{E^4}{m^4} \times \frac{1}{R^2}$$



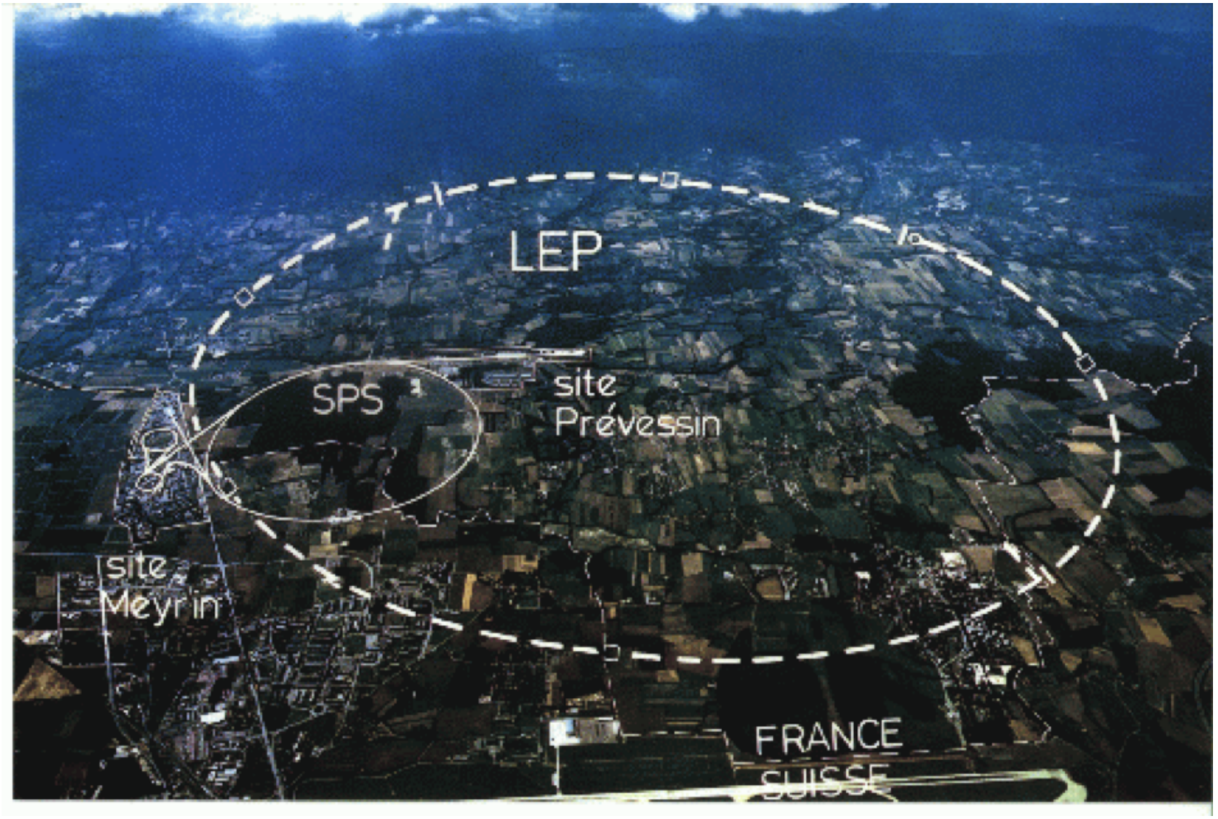

- ***Energy lost per turn:***

$$\Delta E_{\rm s} = \oint P_{\rm s}\, dt = P_{\rm s}\, t_{\rm b} = P_{\rm s} \frac{2\pi R}{c}$$

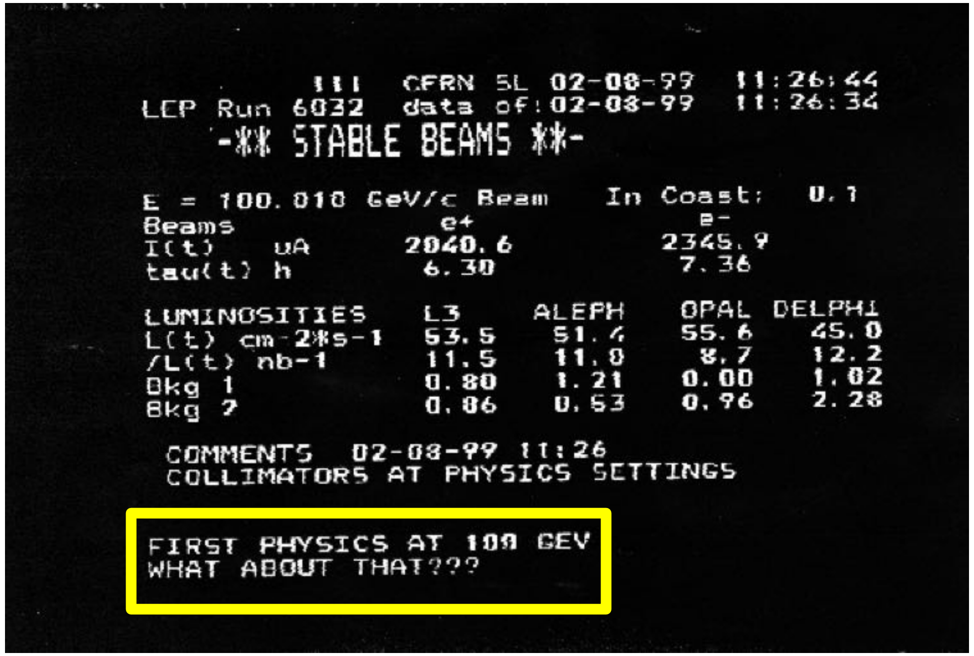
$$\Delta E_{\rm s} = \frac{e^2}{3\epsilon_0} \times \frac{E^4}{(mc^2)^4} \times \frac{1}{R}$$

- This lost energy must be replenished by further acceleration
- Synchrotron radiation limits the maximum energy that is attainable in high energy circular accelerators, particularly for electron synchrotrons, due to small $m_e$ 0.511 MeV/$c^2$

# The Large Electron-Positron Collider, 1989-2000




– *Excitement as LEP2 breaks the energy record, 100 GeV per beam: (while I was a summer student in 1999!)*




– *The LHC's predecessor was used for beautiful precision electroweak studies of the Z boson (45.5* ***GeV*** *per beam) and ultimately reached an energy of* ***104.5 GeV per beam*** *(still* not enough energy to find the Higgs boson)

# How to beat the synchrotron limit?

Synchrotron energy loss per turn

$$\Delta E_s = \frac{e^2}{3\epsilon_0} \times \frac{E^4}{(mc^2)^4} \times \frac{1}{R}$$

**increase R (and B)**

**Circular colliders, e.g.**

FCChh in 100 km tunnel requires **high-field magnets**

**Increase m, same R:** reuse LEP tunnel with protons -> **LHC,**

and in near future:

**switch to higher lepton mass**

Challenge is to produce and capture intense beams of short-lived muons

**set R to infinity**

**Linear colliders** require **high gradient acceleration:**
SCRF structures,
drive beams or
advanced accelerator concepts (plasma wakefield)

+ energy recovery linacs

# Key technologies for future accelerators

3 ! High-priority future initiatives

- ***Five technologies pillars were identified in the 2020 EU strategy and by CERN Council / SPC / LDG.***

  - ***High-field magnets***
  - ***High-gradient plasma / laser acceleration***
  - ***High-gradient RF structures***
  - ***Muon beams***
  - ***Energy-recovery linacs***

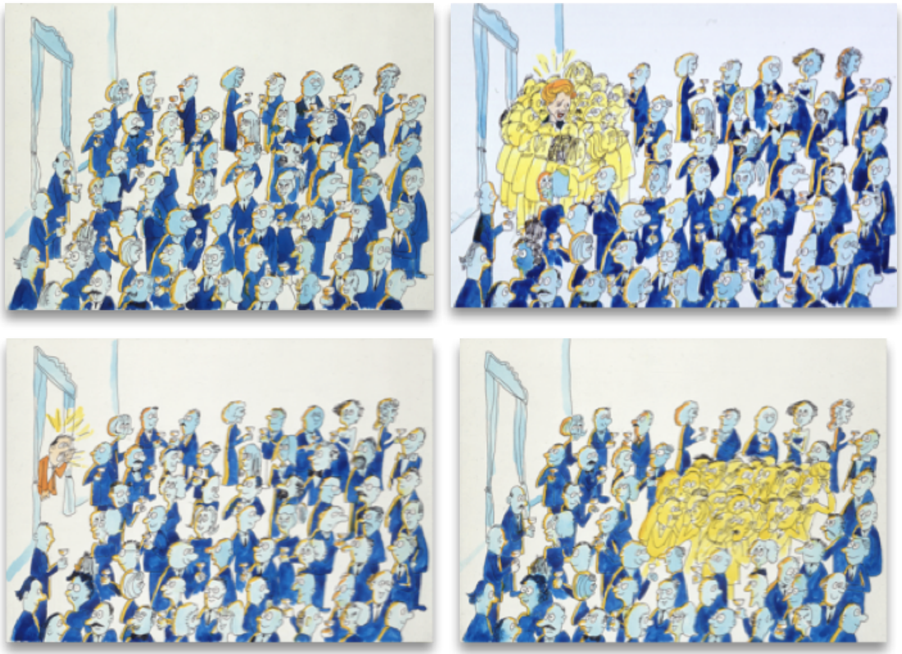
B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

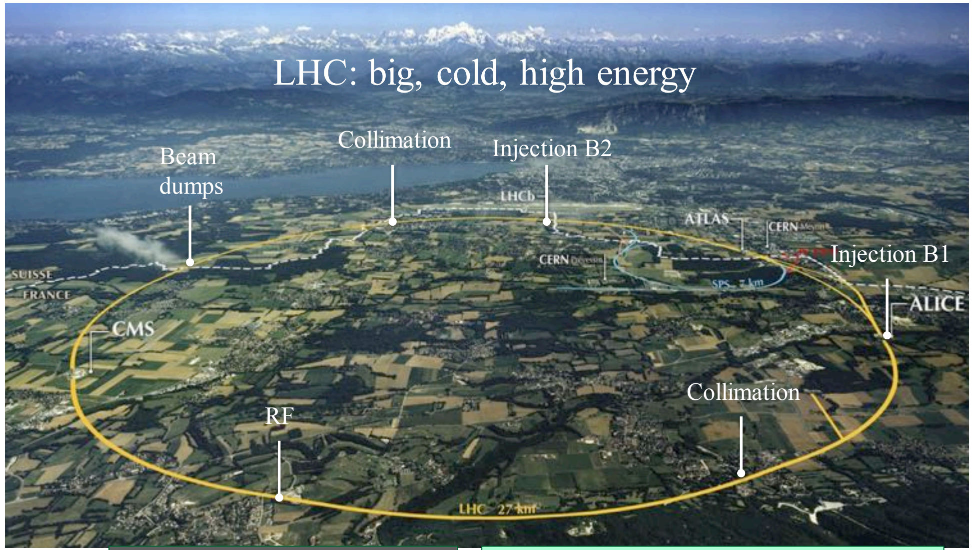
- *Current work towards the European accelerator R&D roadmap with an update for the HEP community taking place today:*
- *9th July 2021:* ***Symposium on the Accelerator R&D Roadmap for the HEP community***
  - *https://indico.cern.ch/event/1053889/*

# The political challenge…

***"My Lords, can my noble friend tell us what a Large Hadron Collider is, and whether a smaller one might not do?"* - LORD ELTON, July 1994**

speaking in the House of Lords debate on the LHC, Hansard, 18th July 1994.
The full transcript:
http://hansard.millbanksystems.com/lords/1994/jul/18/large-hadron-collider






1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
4000 Beam loss monitors

150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
370 MJ design and > 500 MJ for HL-LHC!
450 MJ magnetic energy per sector at 4 TeV
➔ ≈ 10 GJ total @ 7 TeV

Near future:

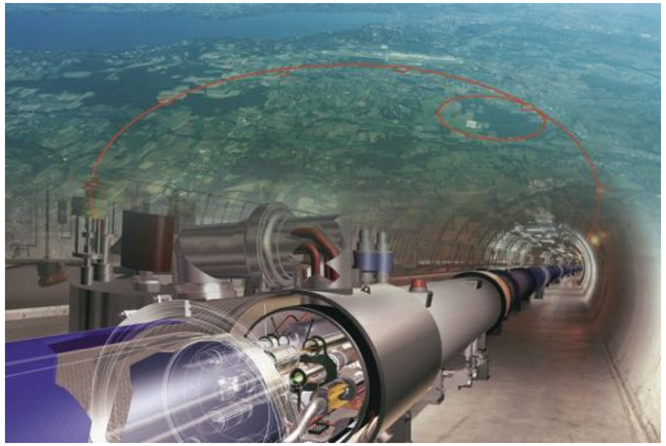
High-Luminosity LHC
and recently developed technologies
applicable to many future accelerators

# 2020 update of European Strategy


1 Major developments

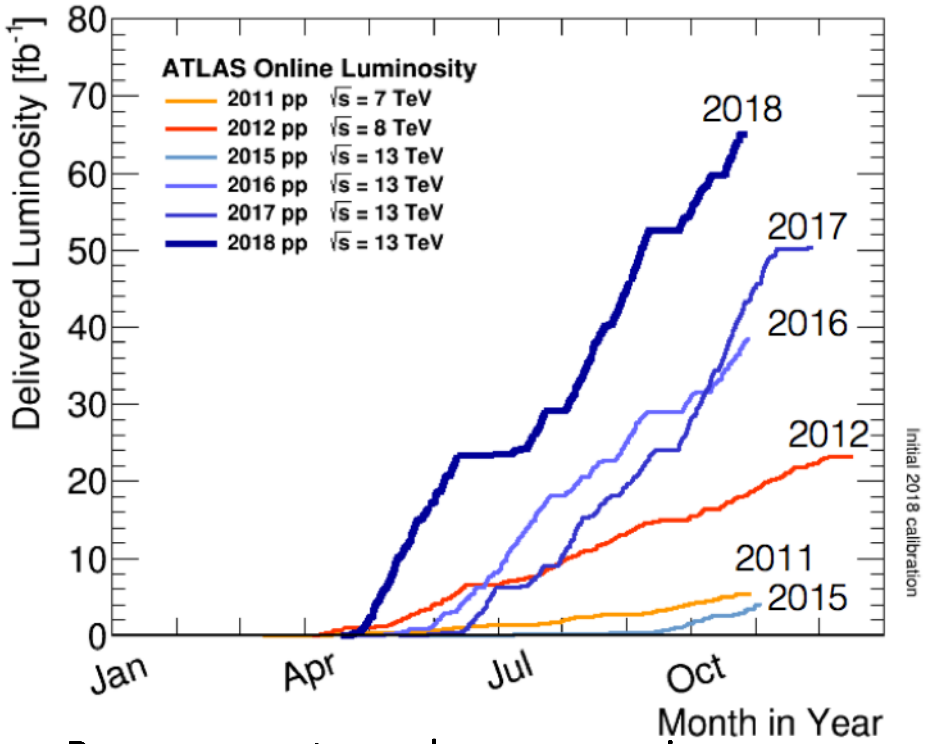
with the innovative experimental techniques developed at the LHC experiments and their planned detector upgrades, a significantly enhanced physics potential is expected with the HL-LHC. The required high-field superconducting $Nb_3Sn$ magnets have been developed. ***The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.***

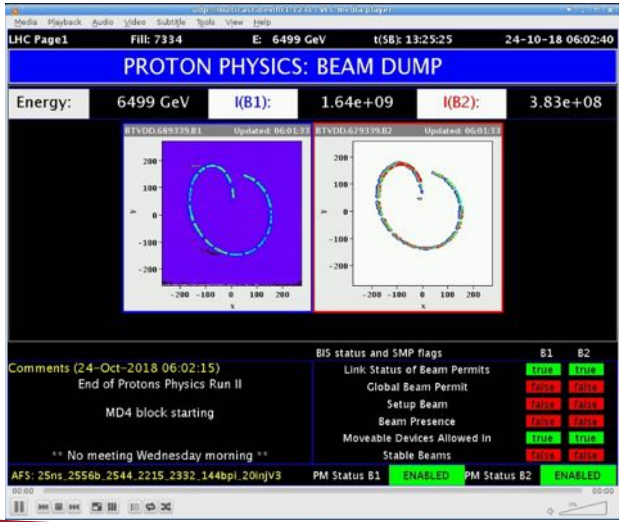
HiLumi HL-LHC PROJECT



# LHC performance and future

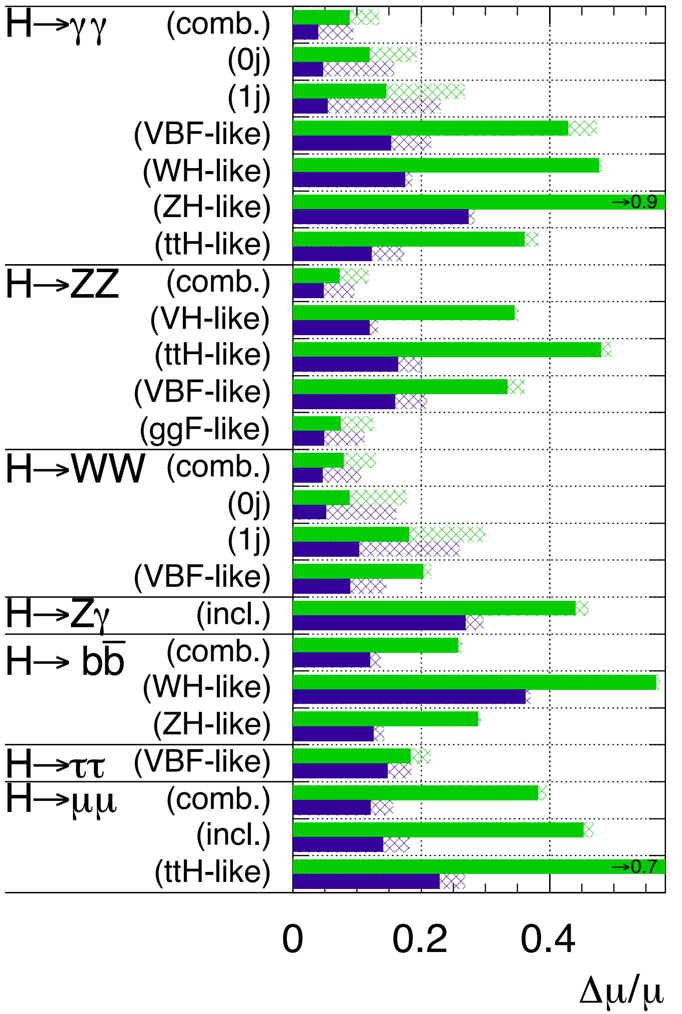
LHC performance has exceeded yearly targets in quest to measure Higgs Boson couplings and search for exotic physics:
Dark Matter, Extra Dimensions, Super symmetry, ...



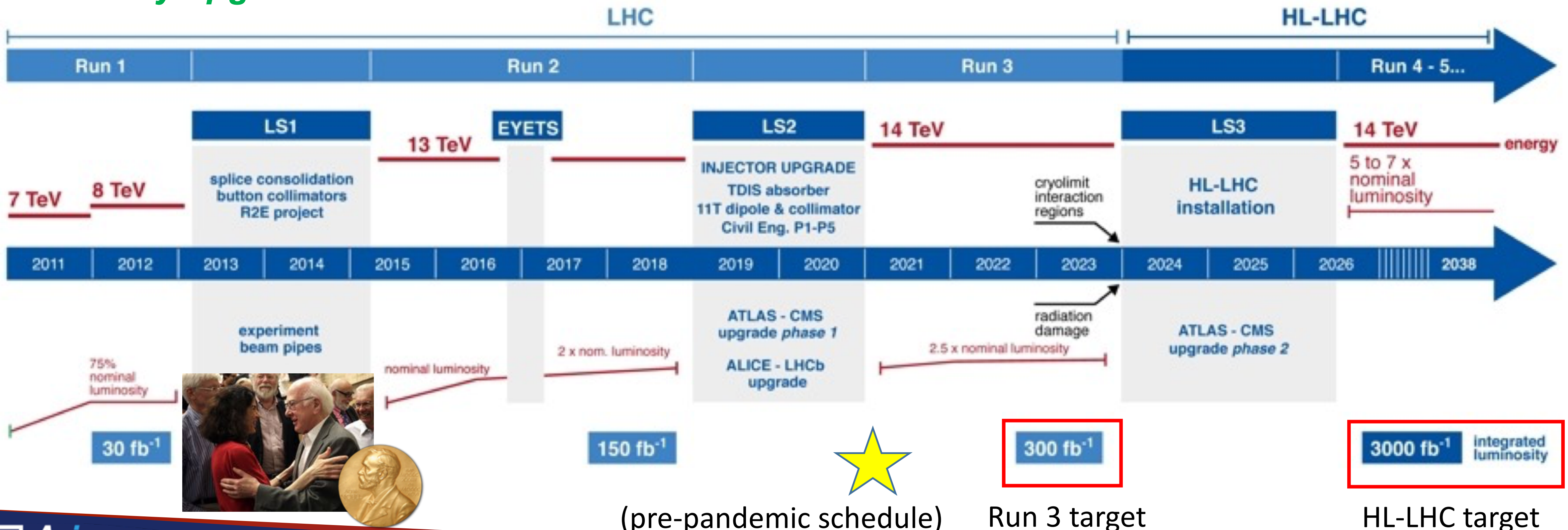

Processes extremely rare, requires many collisions = luminosity!

**160 fb$^{-1}$ achieved in Run II**



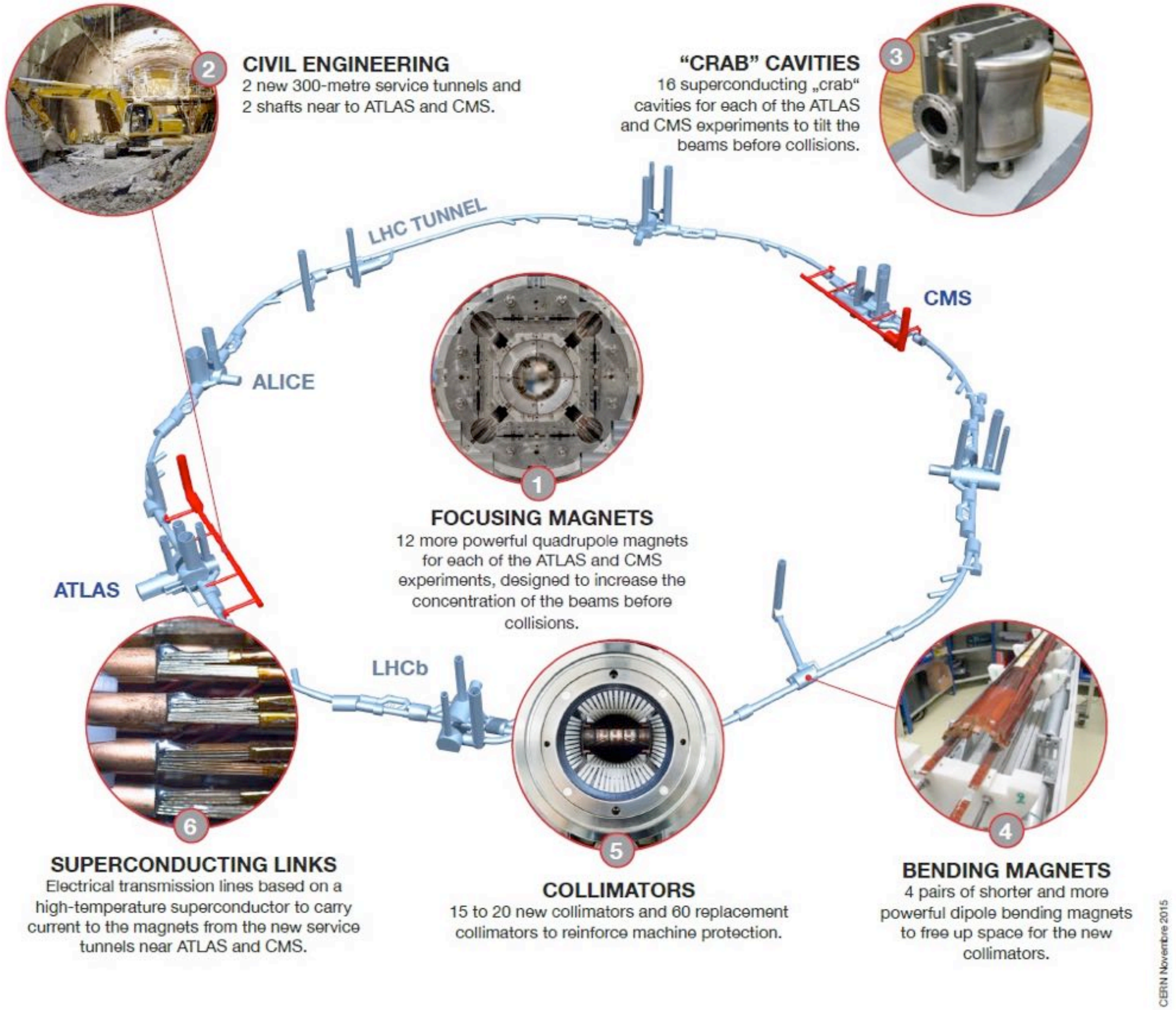
# The path to High Luminosity LHC

- LHC Run-II at 13 TeV, integrated luminosity of >160 fb$^{-1}$ delivered to ATLAS/CMS at end 2018.
- Plan to increase to 14 TeV after Long Shutdown 2.
- After LS3 ending 2026, enter HL-LHC: aim to reach **5 - 7x nominal luminosity**.
- ***Europe's top priority should be exploitation of the full potential of the LHC, including the high luminosity upgrade of the machine and detectors.***




(pre-pandemic schedule) Run 3 target HL-LHC target

# High Luminosity LHC – how?

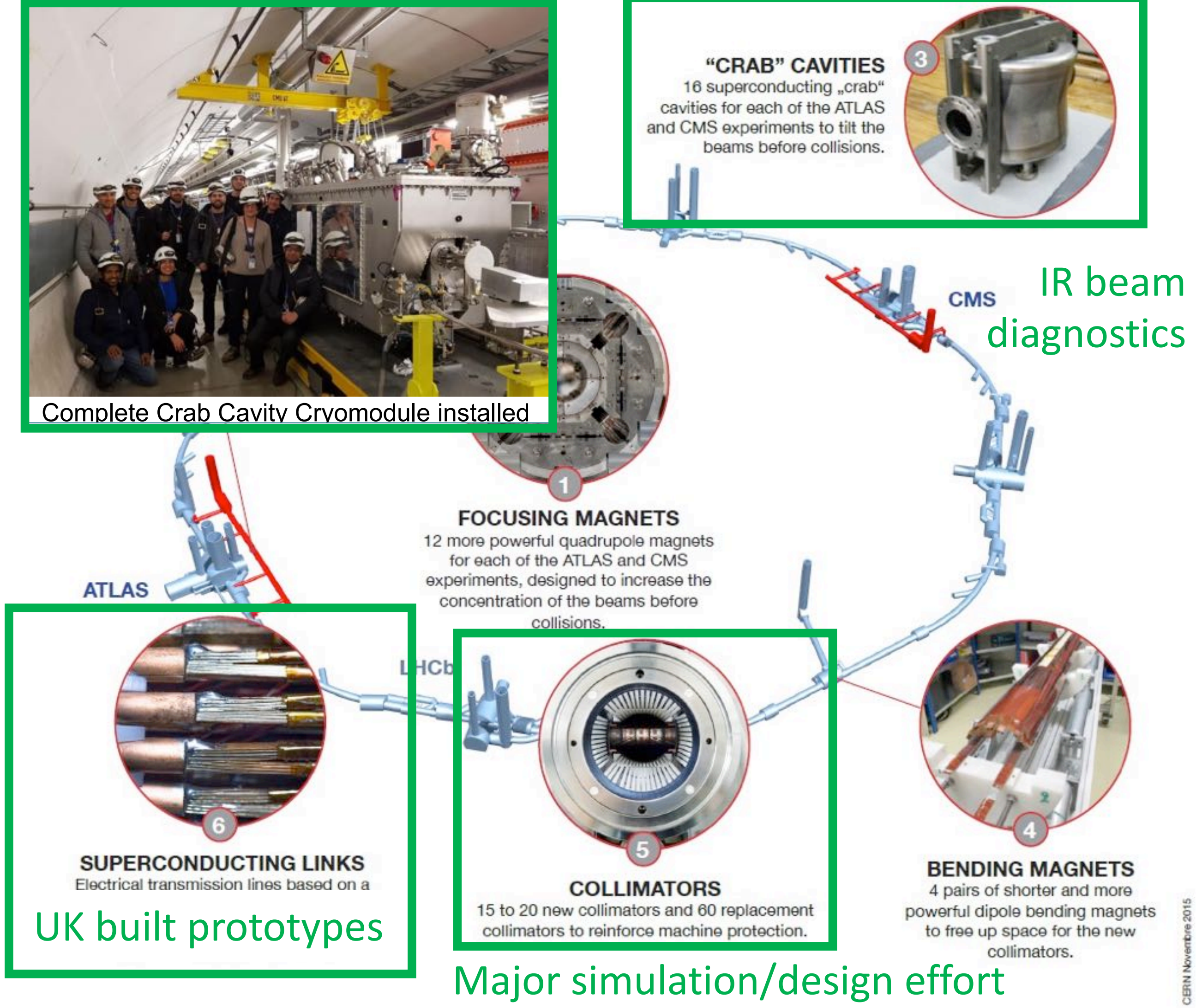



- **Lower beta* (~15 cm)**
  - New inner triplets - wide aperture $Nb_3Sn$
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
  - Long-range beam-beam compensation
- **Dealing with the regime**
  - Collision debris, high radiation
- **Beam from injectors**
  - Major upgrade of complex (LIU)
  - High bunch population, low emittance, 25 ns beam

# HL-LHC-UK phase I (2016-2020)

HiLumi HL-LHC PROJECT

UK delivered crab cavity prototype to SPS




IR beam diagnostics

UK built prototypes

Major simulation/design effort

UK institutes on ***HL-LHC-UK***

*£8M CERN-STFC investment in UK*

MANCHESTER 1824 The University of Manchester

The Cockcroft Institute of Accelerator Science and Technology

Lancaster University

UNIVERSITY OF LIVERPOOL

ROYAL HOLLOWAY UNIVERSITY OF LONDON

JAI John Adams Institute for Accelerator Science

UNIVERSITY OF Southampton

University of HUDDERSFIELD

ASTeC

LHC Injectors Upgrade

+ new injector diagnostics

Linac2:
50 MeV protons

Linac4:
160 MeV $H^-$ ions
http://home.cern/about/accelerators/linear-accelerator-4

# HL-LHC-UK phase II announced by STFC

https://stfc.ukri.org/news/project-to-upgrade-the-large-hadron-collider-now-underway/

## Upgrade to Large Hadron Collider underway

HiLumi
HL-LHC PROJECT

**11 September 2020**

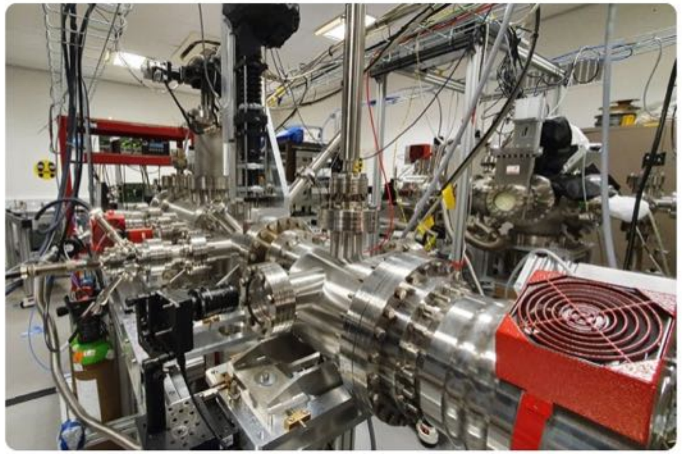
Scientists, engineers and technicians from the UK have embarked on a £26 million project to help upgrade the Large Hadron Collider (LHC) at CERN, on the French/Swiss border near Geneva.

The collaboration is between the Science and Technology Facilities Council (STFC), CERN, the Cockcroft Institute, the John Adams Institute, and eight UK universities. STFC is contributing £13.05 million.

Science Minister Amanda Solloway said:

"Ever since it first switched on in 2008, CERN's Large Hadron Collider has been working to answer some of the most fundamental questions of the universe.

"I am delighted that the UK's science and research industry will play a central role in upgrading what is the world's largest and highest energy particle collider, enabling leading physicists to continue making monumental discoveries."



Gas jet beam profile monitor setup at the Cockcroft Institute.

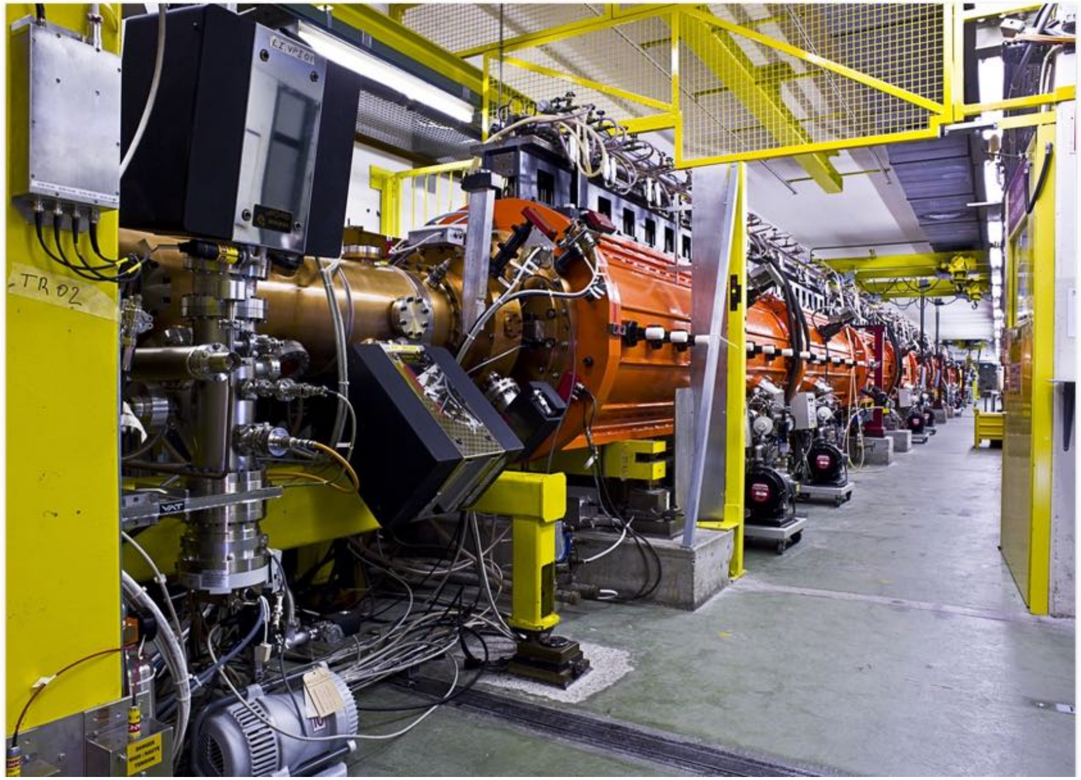
# Beam off at Linac2 –> Linac4, a new hope

LHC Injectors Upgrade

## So long, Linac2, and thanks for all the protons

After 40 years of service, the linear accelerator has shut down and passed the baton to Linac4, which will take over as the first link in the accelerator chain

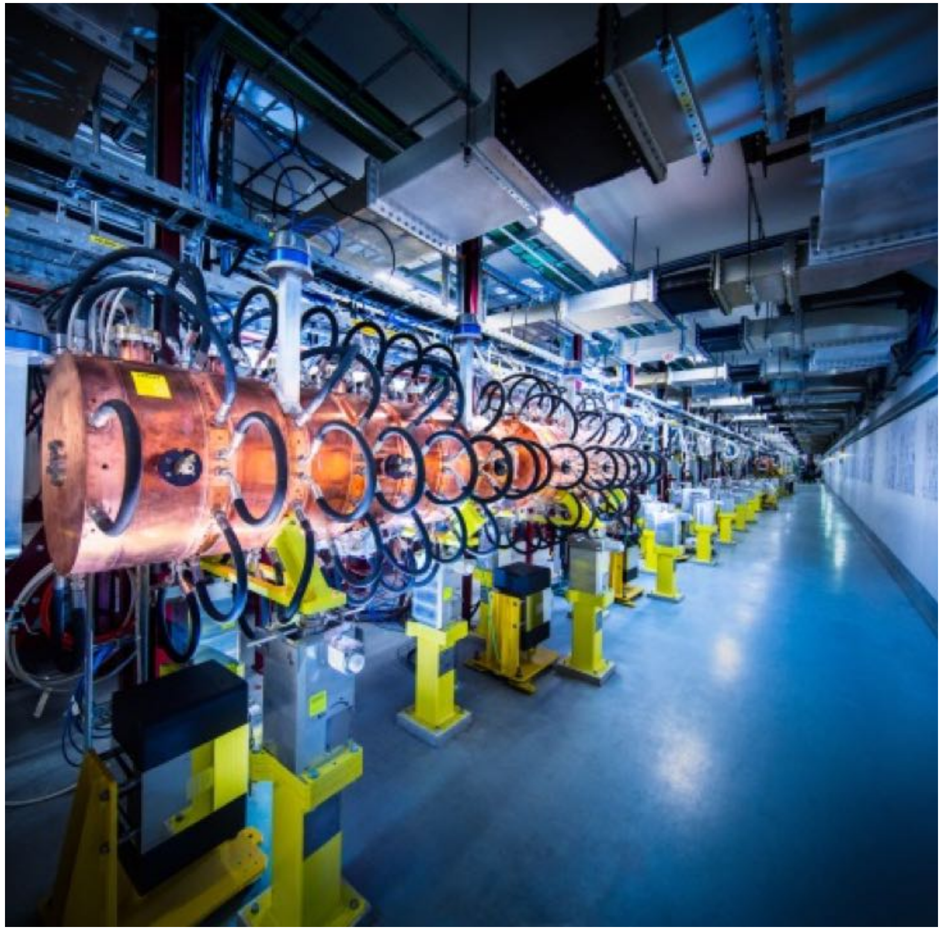
13 NOVEMBER, 2018 | By Corinne Pralavorio

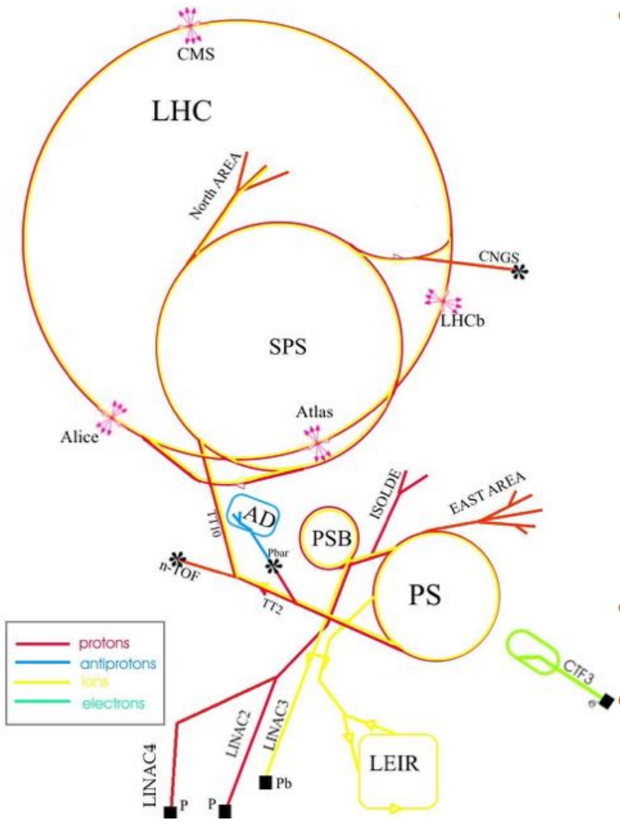



Frédérick Bordry, Director for Accelerators and Technology, switching off the Linac2 on 12 November. (Image: Nathan Schwerdtel/CERN)

# Beam off at Linac2 –> Linac4, a new hope

- ***Linac4 is now the main injector for LHC, connected to PSB in LS2 2019/20***






- *$H^-$ ions boosted to 160 MeV*
  - *3 MeV, 352MHz Radio-Frequency Quadrupole (RFQ)*
  - *50 MeV drift tube linacs (DTLs)*
  - *100 MeV coupled-cavity drift tube linacs (CCDTLs)*
  - *160 MeV Pi-mode structures (PIMS)*
- *Commissioned 160 MeV in 2016.*
- *Multi-turn H- charge exchange injection to PSB enables a more brilliant beam for HL-LHC.*

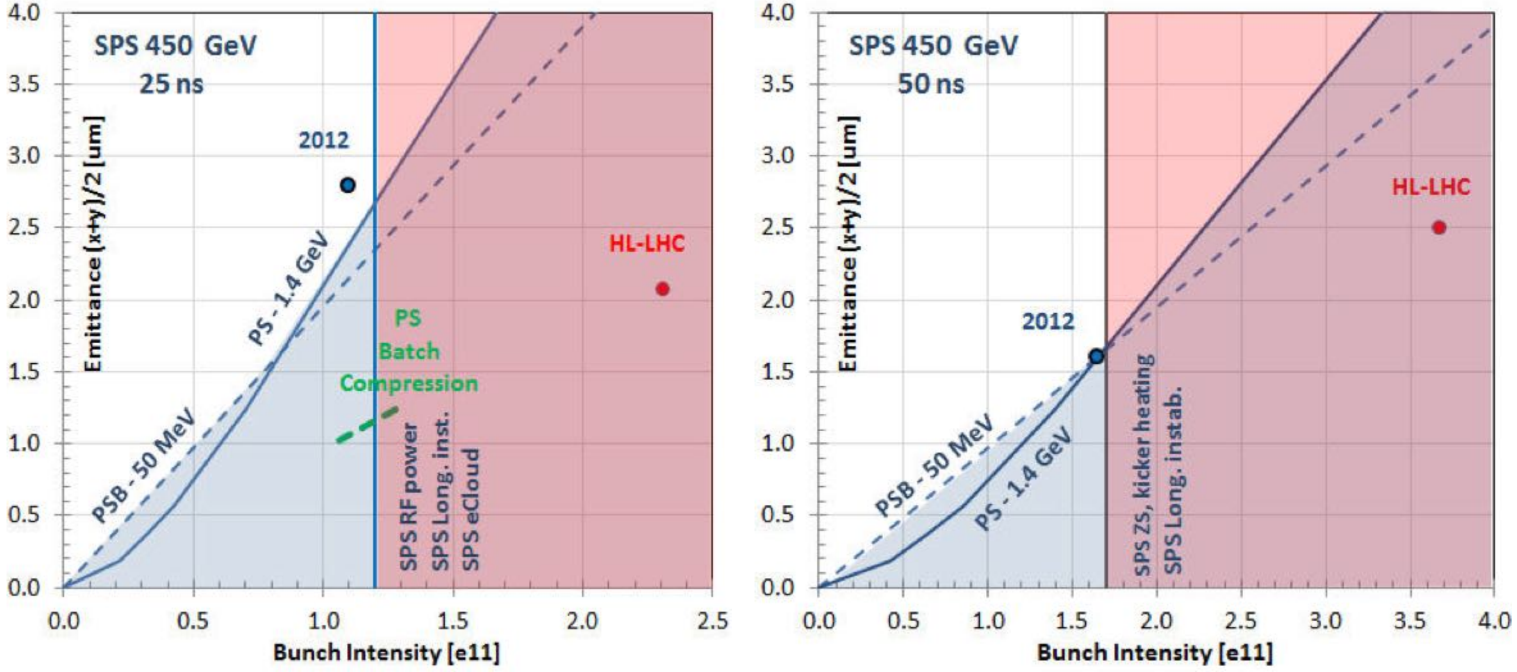
LHC Injectors Upgrade

John Adams Institute for Accelerator Science

# Why upgrade the injector?

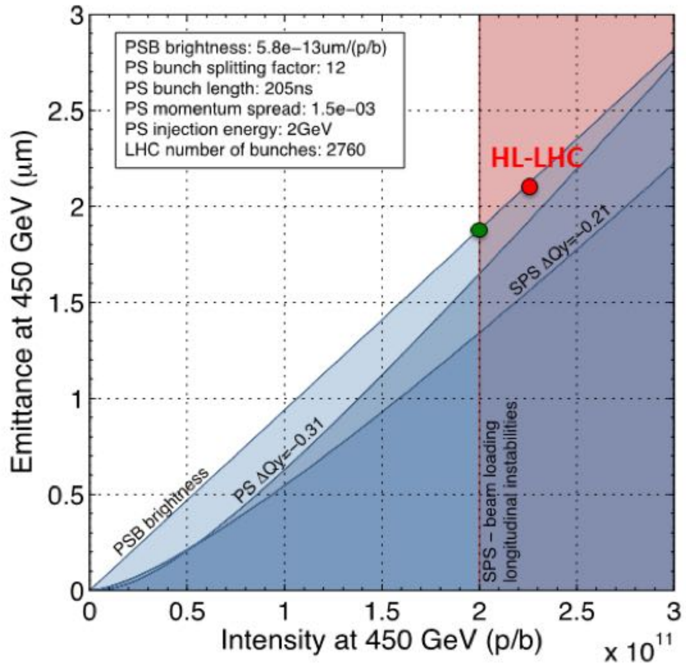
LHC Injectors Upgrade

- Emittance requirements for HL-LHC bunches cannot be reached with existing machines:




(a) (b)

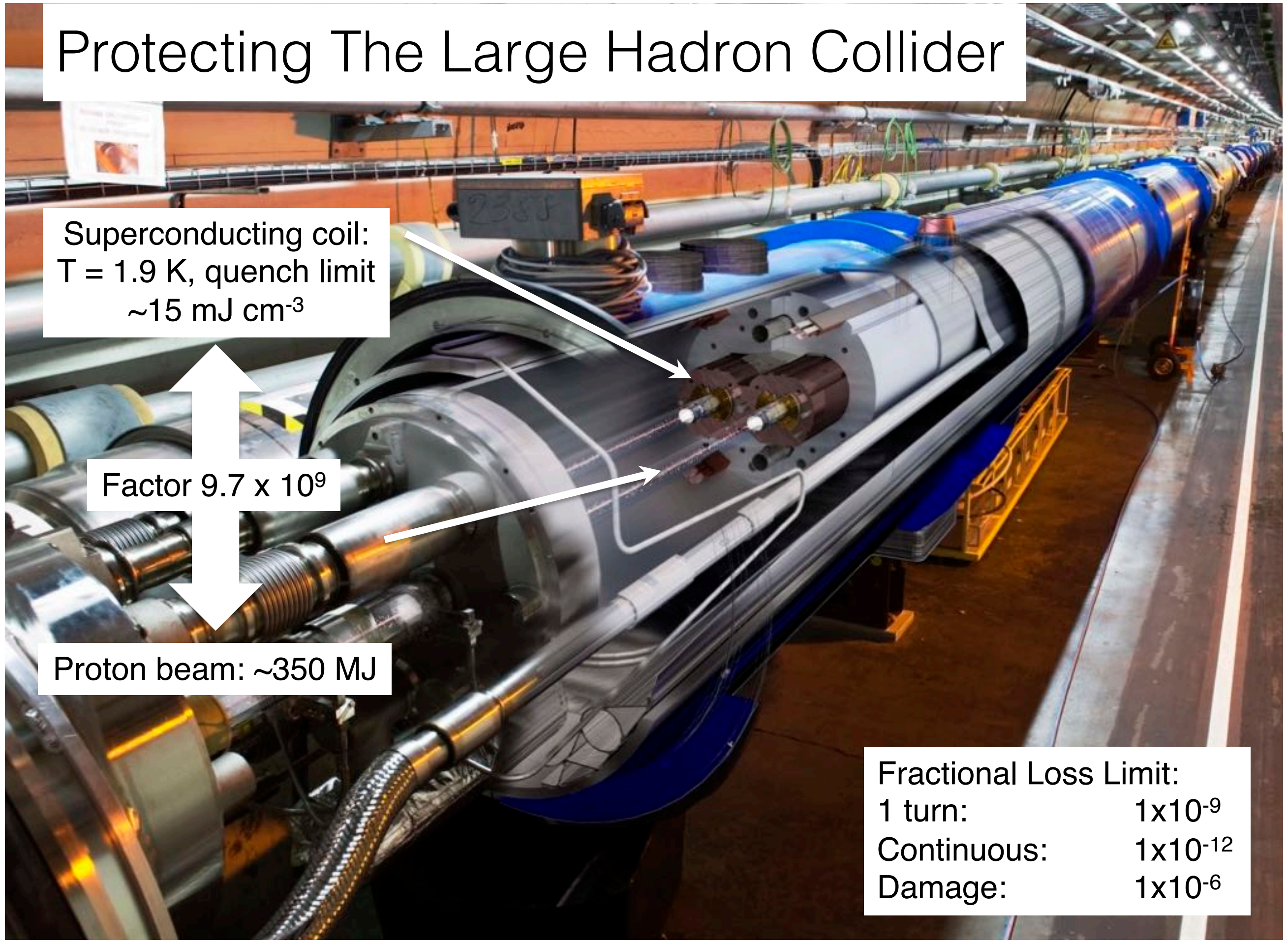
**Fig. 2.3:** Status and limitations of the beam characteristics of the LHC proton injector complex at SPS ejection, in 2012. (a) 25 ns bunch spacing; (b) 50 ns bunch spacing.

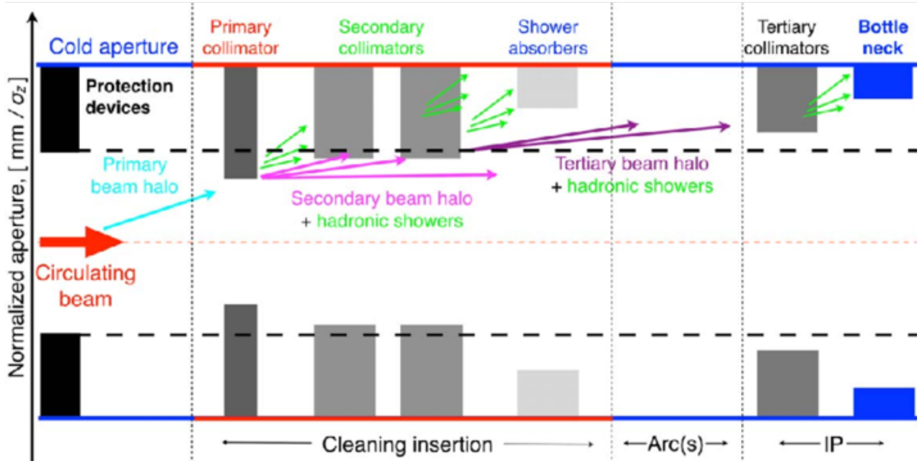



LIU: Technical Design Report, volume 1 protons CERN-ACC-2014-0337

# Machine Protection at the LHC, HL-LHC and FCC-hh

- ***Efficient cleaning of proton beam halo is vital to protect the sc magnets***




***Stored beam energy:***

– ***LHC ~ 350 MJ***

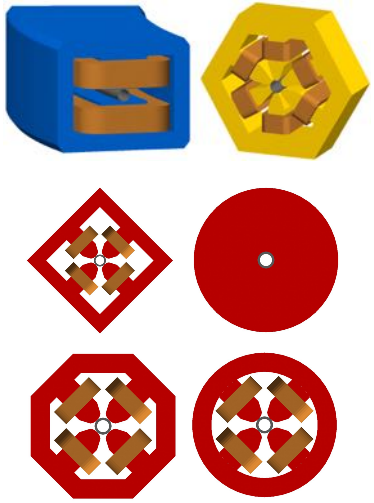
*TGV at 150km/h*

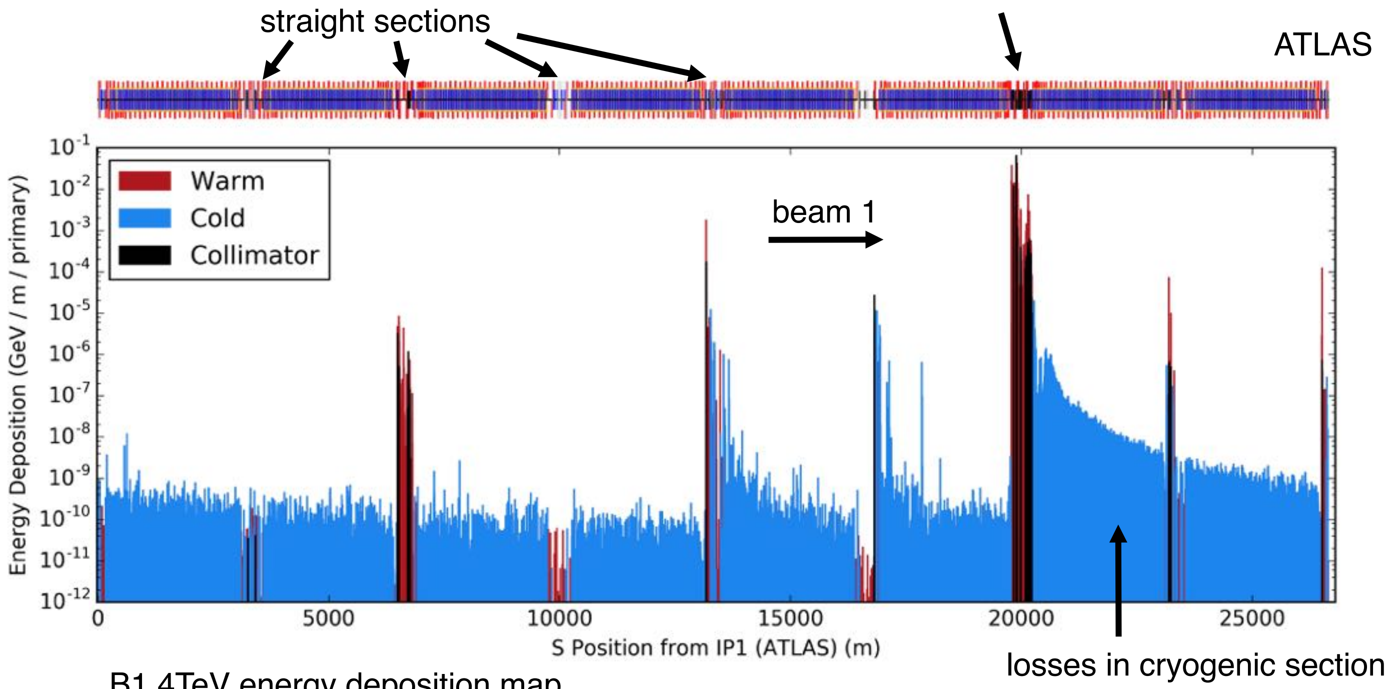
– ***FCC-hh = 8.4 GJ***

*Equivalent to AirBus A380 at 850 km/h*

# Collimation studies with BDSIM model of (HL-)LHC

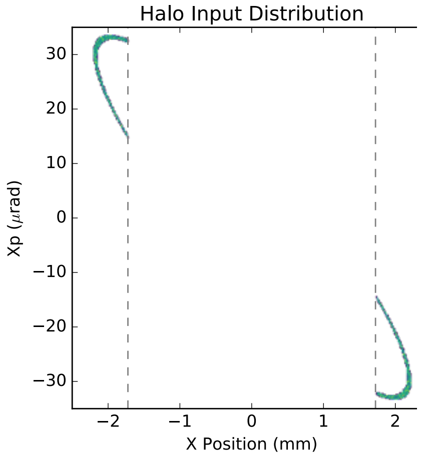
- BDSIM automatically builds a 3D, Geant4 model, from generic accelerator components.
- *LHC stores unprecedented energy in beams: 350 MJ (80kg of TNT) stored per beams at design energy (500MJ HL-LHC)*
- *Halo efficiently cleaned by collimation system*
- *LHC model developed to simulate collimation and energy deposition. Requires 1:10$^6$ precision*

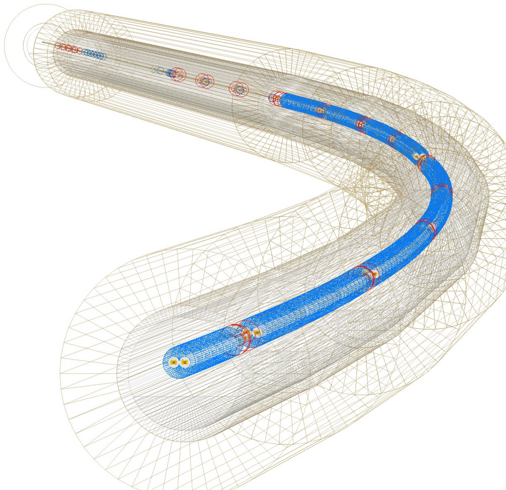





B1 4TeV energy deposition map

Example halo distribution



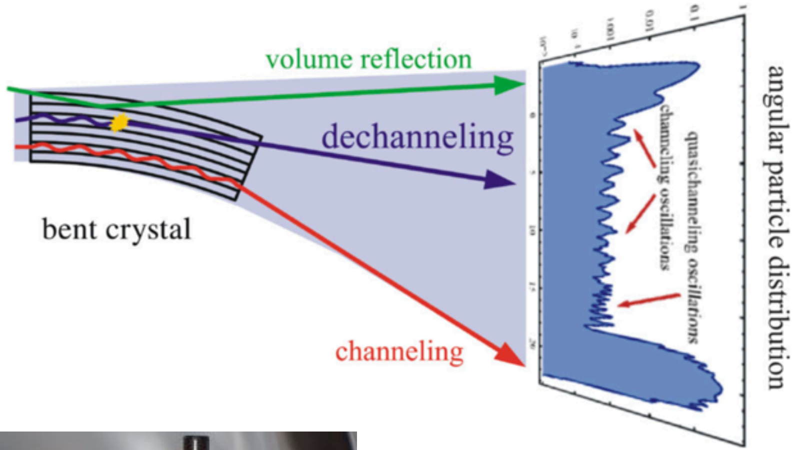



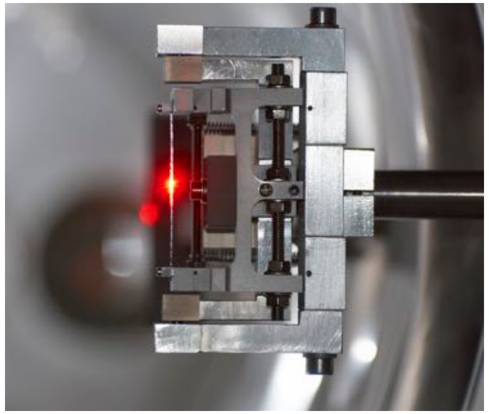
https://doi.org/10.1016/j.cpc.2020.107200

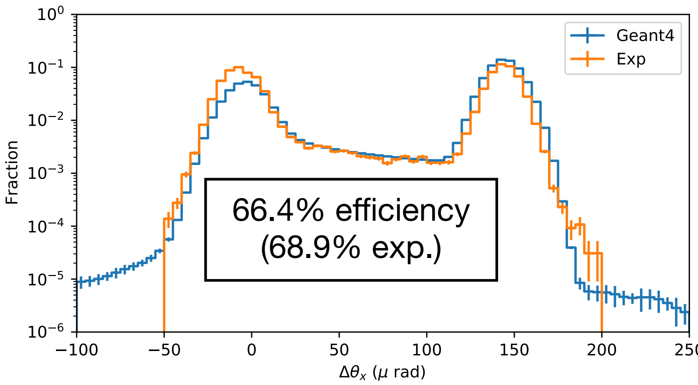
# Active halo control & novel collimation

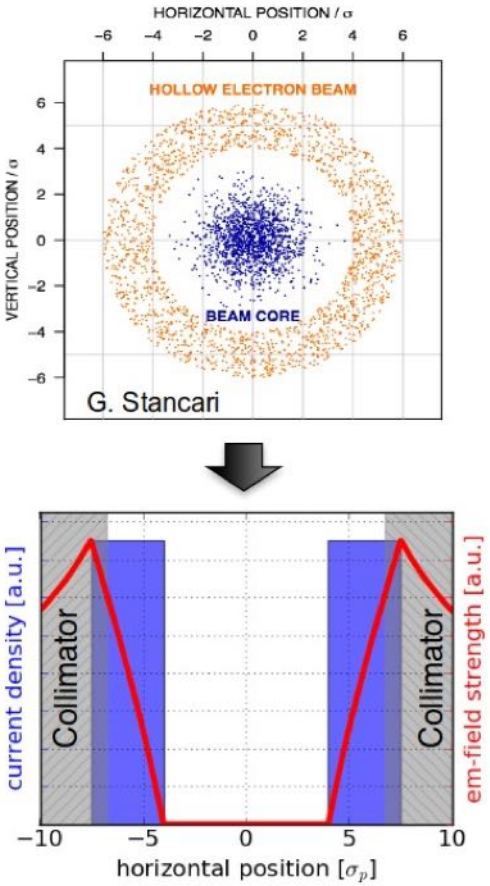


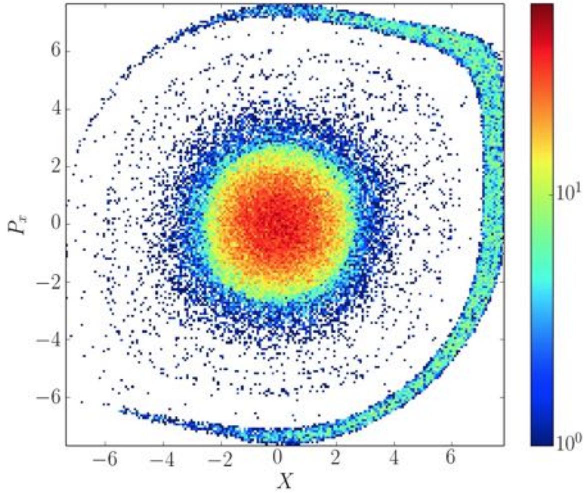
- *How can we **remove halo** particles **without affecting** the **core**?*
- *Novel collimation techniques being developed for HL-LHC:*
  - **Crystal collimation**
  - **Hollow electron lens**

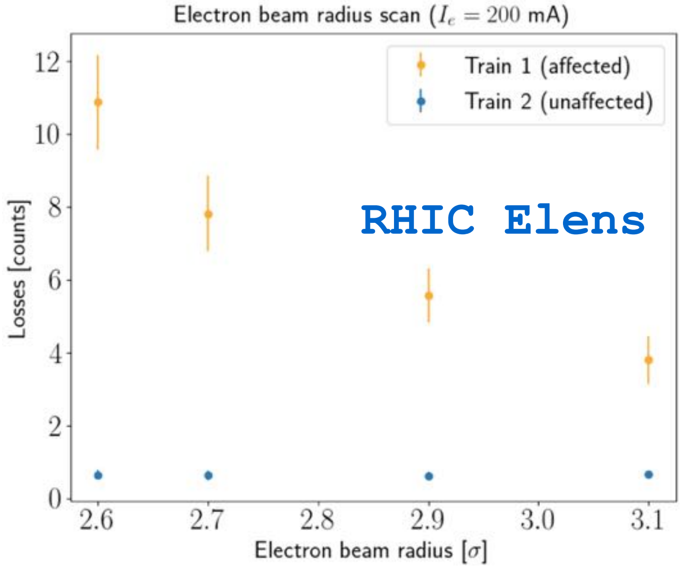




# Superconducting RF capabilities

Science and Technology Facilities Council

- ***ASTeC @ Daresbury hosts major facility for SRF design & fabrication for many projects***

Peter McIntosh, STFC Daresbury Laboratory

## 1 ERL SRF Linac
Optimised, high current, flexible CM development

## 2 Crab Cavity Cryomodule
Collaborative cavity, CM development and infrastructure

## 3 ESS SRF Contributions
High beta cavity testing and infrastructure

## 3 PIP-II SRF Contributions
Cavity testing, CM integration and infrastructure

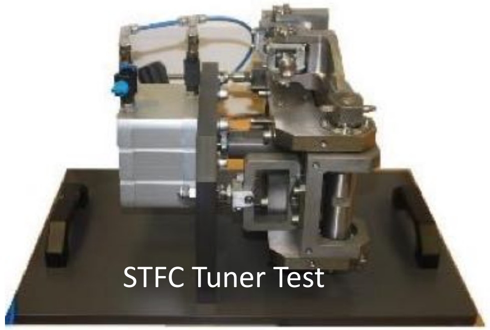
## 4 UK Industry SRF Developments
Cavity pressing, machining and EBW

## 5 EIC Opportunities

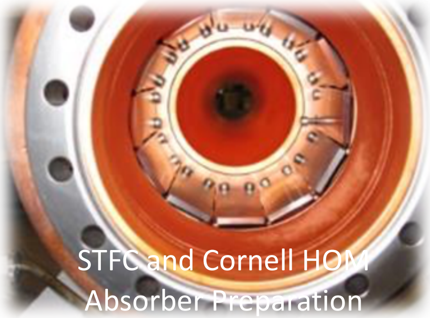

STFC, LBNL and Cornell Cavity Design

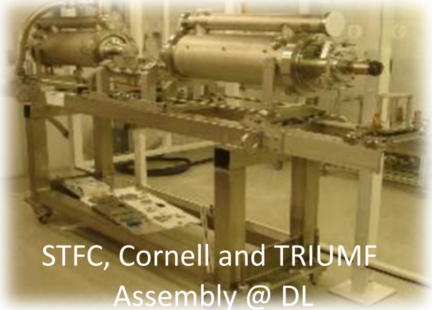

DESY TESLA Superstructure


Cornell Manufacture and Test


STFC Tuner Test


STFC Coupler Test


STFC and Cornell HOM Absorber Preparation

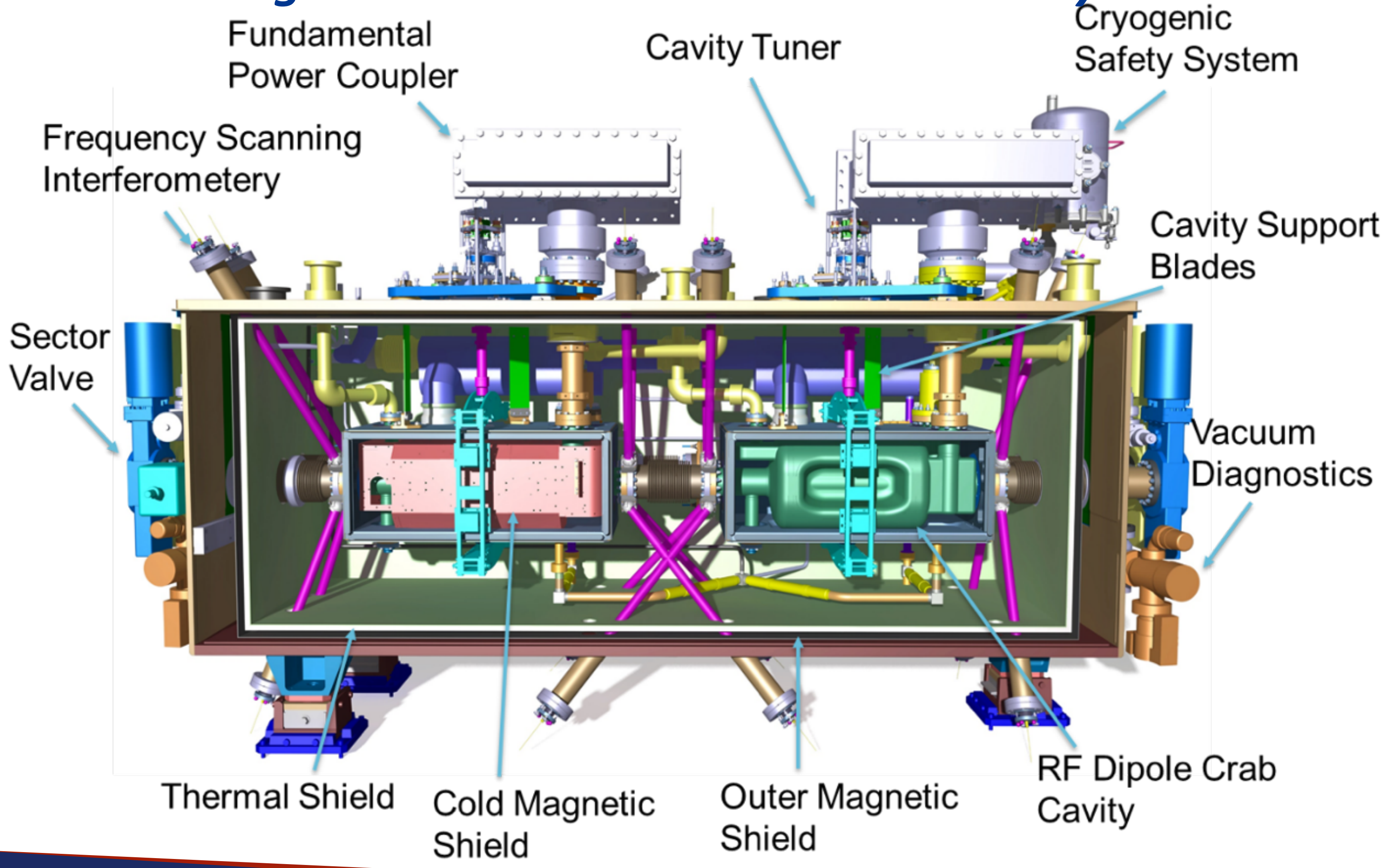

STFC, Cornell and TRIUMF Assembly @ DL

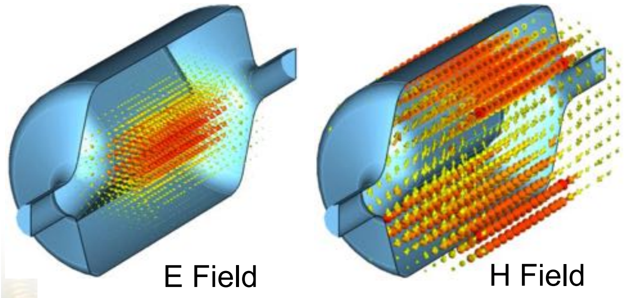

Stanford Outer Cryomodule


STFC Integration and Installation on ALICE

# Crab-cavity cryomodules for HL-LHC:

- ***UK contributing cryomodules for crab-cavities, which rotate the colliding bunches to increase the luminosity.***

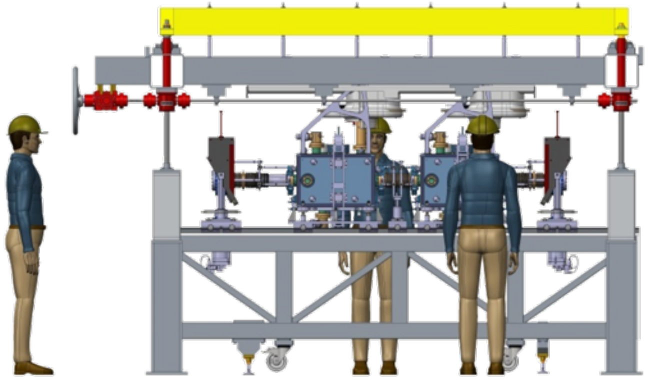



Graeme Burt et al

Cleanroom Assembly

Cryomodule Assembly

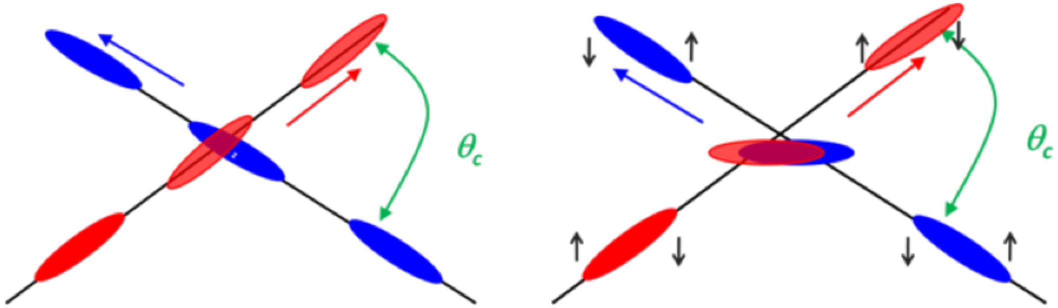


# Bunch crabbing for HL-LHC

- *LHC luminosity is currently limited by geometrical overlap, due the crossing angle (285mrad) between beams:*

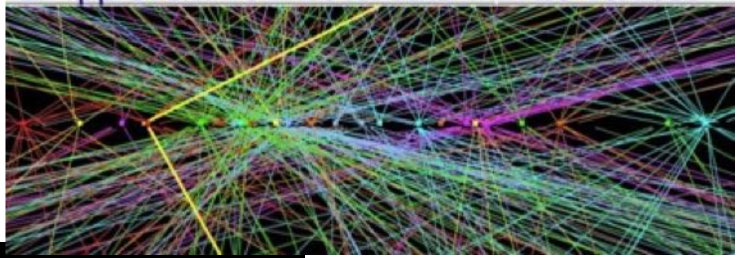
$$\mathcal{L} = \frac{N_1\, N_2\, f\, N_b}{4\pi\sigma_x\sigma_y} \qquad R(\theta) = \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x} tan\frac{\theta}{2})^2}}$$

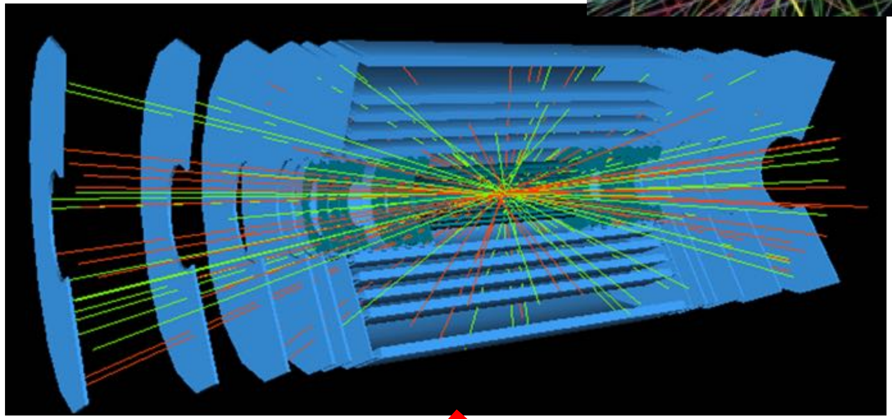
- *At HL-LHC, RF crab cavities will rotate the bunches to collide head on:*




**23** interactions per bunch crossing at nominal LHC

Z→μμ event from 2012 data with 25 vertices

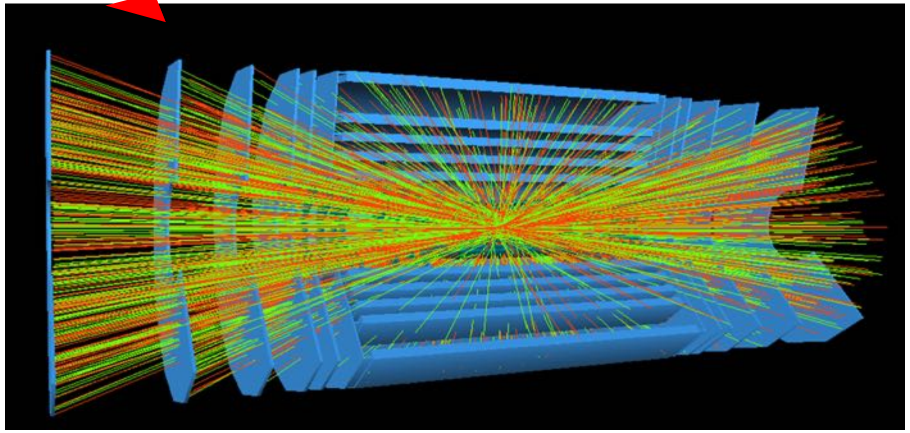




One bunch crossing in the ATLAS particle tracker

HL-LHC

HL-LHC: pile up increases to ~**140** vertices per crossing.

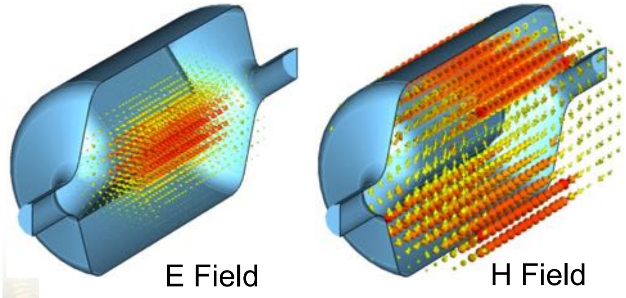


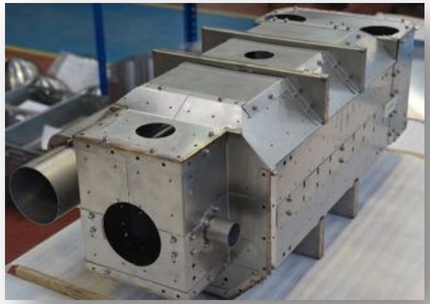
# Demonstration of HL-LHC crab-cavities

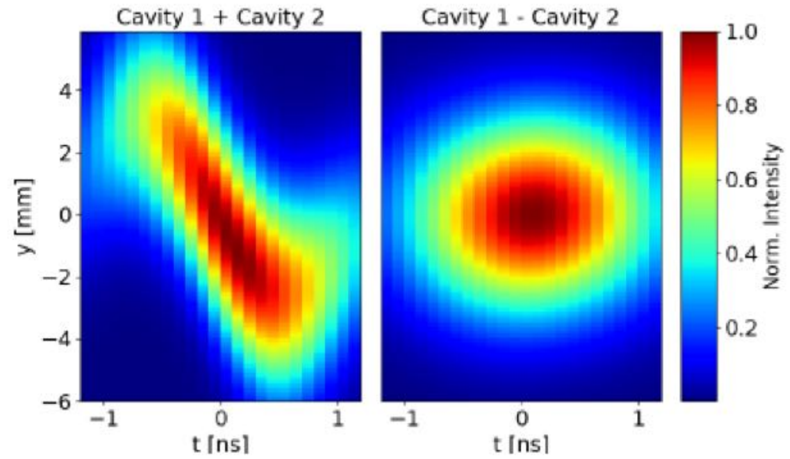
Graeme Burt et al

- First prototype cryomodule (DQW) tests completed on SPS in mid 2018.
- First ever evaluation of crab cavities with a proton beam!
- A 2-cavity pre-series RFD cryomodule in development + providing 4 production DQW cryomodules for LS3

UK team responsible for key elements of the design: cold shield, magnetic shield, thermal shield, vacuum vessel, transport modules, HOM coupler + SPS test: machine physics, impedance, diagnostics and played major roles in other areas (LLRF)

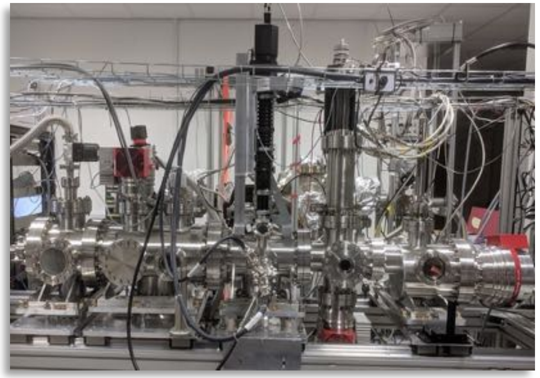


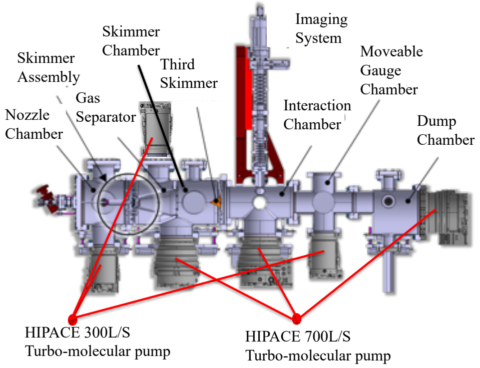



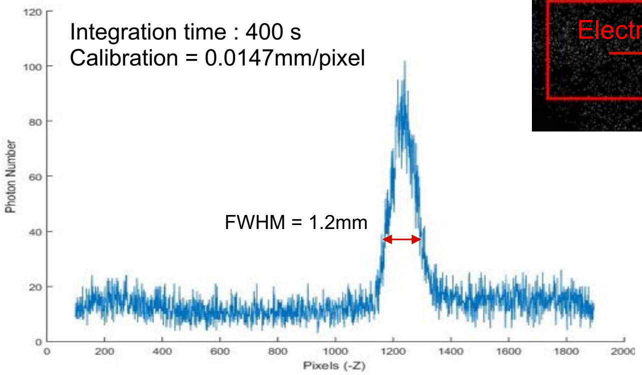


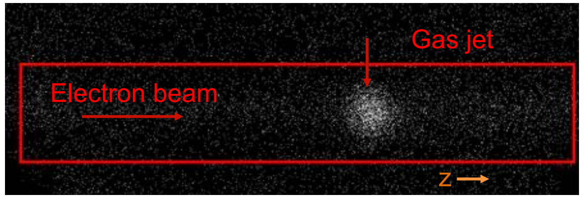
# Beam diagnostics for FCC-hh (developed for HL-LHC)

- ***Fully characterizing FCC-hh circulating beams with high intensity requires similar diagnostics to those being developed for HL-LHC. Examples include:***
- ***Beam-gas interactions:***
  - *Continuous, non-invasive 2D beam profile monitoring by a supersonic gas jet monitor for the hollow electron lens collimation.*






UNIVERSITY OF LIVERPOOL

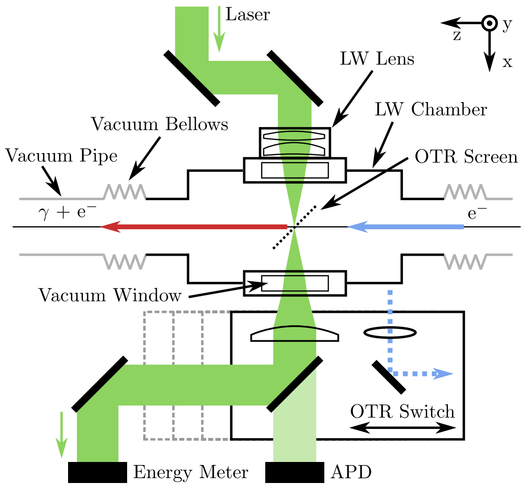
C Welsch et al

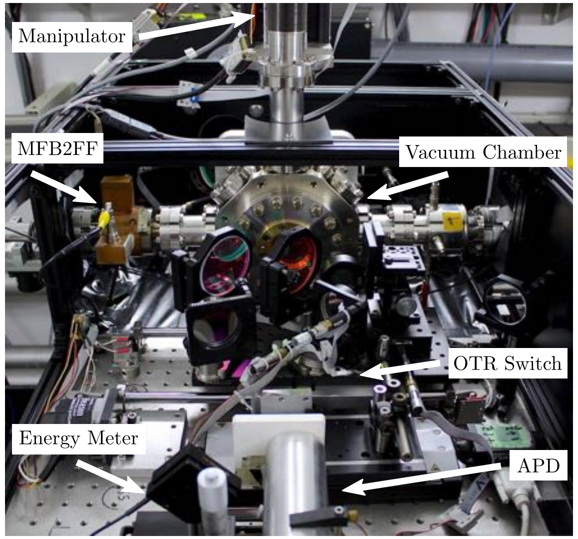
- ***Electro optics techniques:***
  - *Electro-optic BPM diagnostics for measurement of crabbed rotation of the hadron bunch [RHUL].*
  - *For FCC-ee, the electron bunch will require sub-ps e-o techniques, as pioneered at ASTeC.*

# Beam diagnostics for FCC-ee

- ***Small electron bunches at high energy, and sub ps resolution require novel approaches:***
  - *To measure small transverse beam sizes,* ***SR interferometric measurements*** *are under development at LHC, though need to be demonstrated for X-ray wavelengths.*
  - *Bunch lengths of ps, with resolution of 10 fs pose difficulties for streak cameras and e-o sampling techniques due to the relatively long bunch.*
  - *Non-invasive techniques based on* ***Čerenkov diffraction radiation*** *may results in a directional beam position monitor and for fast intra-bunch transverse instabilities.*

- ***FCC-ee requires polarimetry based on inverse-Compton scattering***
  - ***Similar to implementation at LEP and could leverage expertise on electron laserwires developed for Linear Collider at ATF2 in KEK.***

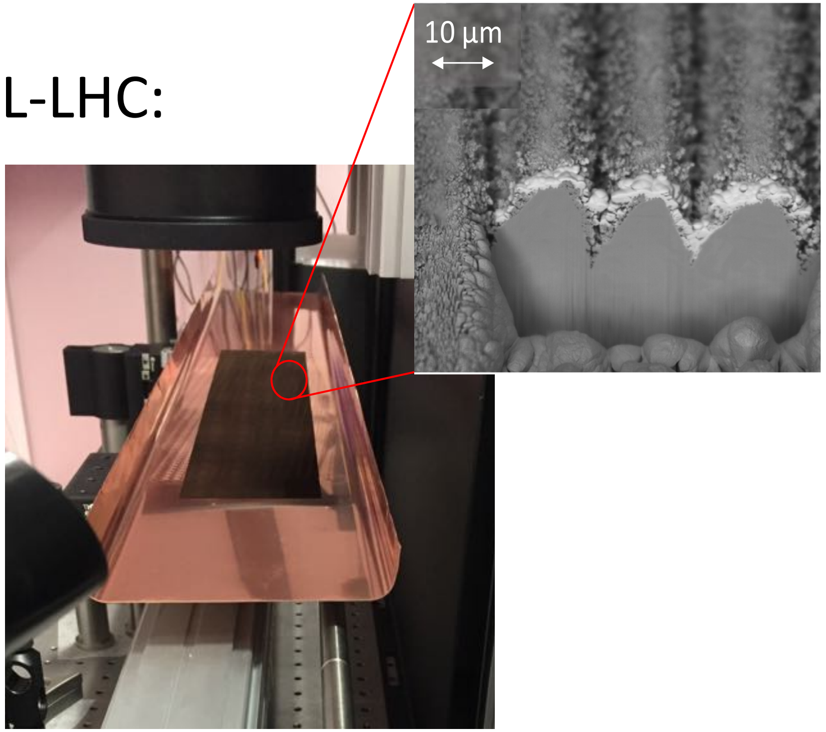



PRSTAB 17, 072802 (2014)

# Laser Engineered Surfaces

- **Electron cloud mitigation:**
  - intense electric field of the proton bunch can accelerate electrons into the beam pipe walls, which liberates secondary electrons. Exponential growth in electrons creating a cloud which heats the superconducting magnets and limits the machine intensity.
- Secondary electron yield can be suppressed by modifying the surface walls with a laser, creating channels to trap the electrons.
- Automated robot for in-situ treatment of beam-screens at HL-LHC:



# Capabilities in accelerators & enabling technology

***Developing a broad range of UK capabilities to address future technical challenges, including***

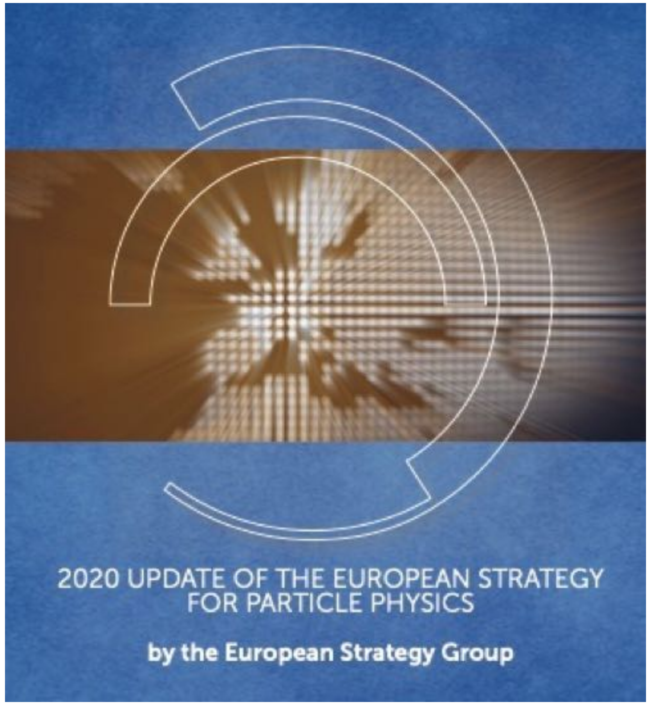
- ***Beam dynamics simulations; optical lattice design & optimisation***
- ***Novel collimation techniques: crystal, hollow electron lens.***
- ***Machine detector interface & accelerator backgrounds***
- ***Superconducting RF cavities, crab-cavities, high efficiency klystron development***
- ***Beam diagnostics, including non-invasive profile & bunch instability monitoring***
- ***Nanobeam control and fast feedback***
- ***Cryogenic systems, cold powering.***
- ***Vacuum systems & electron cloud mitigation***
- ***Accelerator alignment systems***
- ***Operational experience of low emittance electron storage rings & FEL test facilities…***

*ESPP2020 "Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. … **The European particle physics community must intensify accelerator R&D and sustain it with adequate resources**.*

# Mid-future: Higgs Factory:
# Linear Collider / Future Circular Collider

# 2020 update of European Strategy

3 | High-priority future initiatives

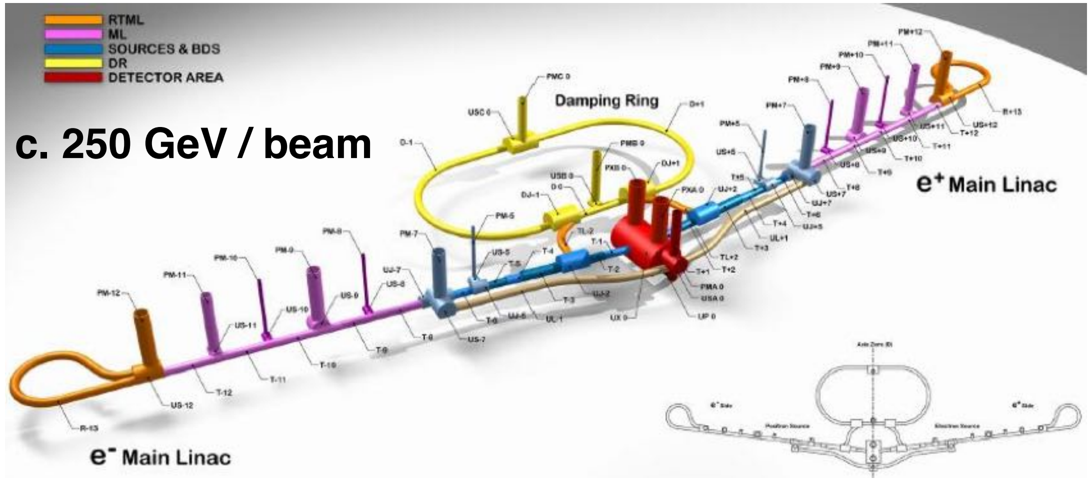



**The vision is to prepare a Higgs factory, followed by a future hadron collider** with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

***The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.***

***Higgs factory*** $e^+e^-$ collider for precise measurements of Higgs & top ++, complementary to ***LHC***



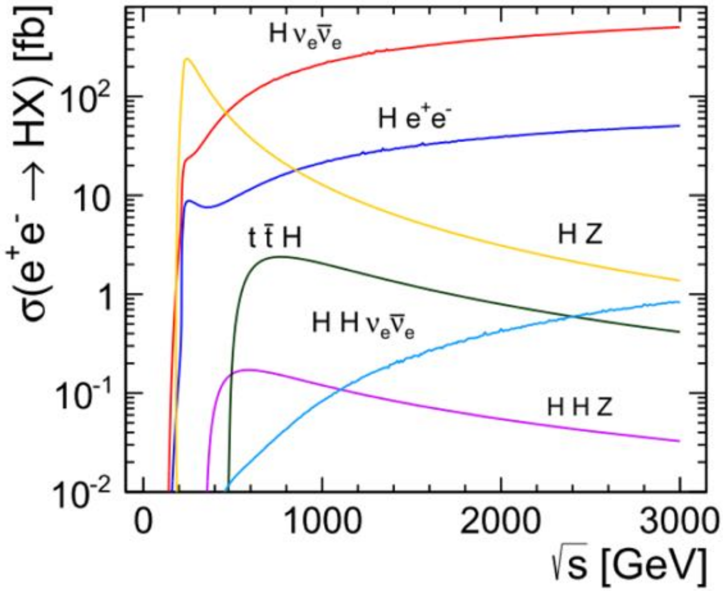

31 km

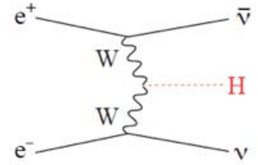
# e+e- Higgs Factory: the International Linear Collider

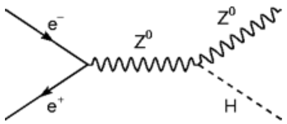
P. Burrows

- **ILC TDR complete, mature technology with many benefits:**
  - *Well defined centre of mass energy: 2E*
  - *complete control of event kinematics: p = 0, M = 2E*
  - *polarised beam(s)*
  - *clean experimental environment*


XFEL at DESY essentially
a 20 GeV prototype



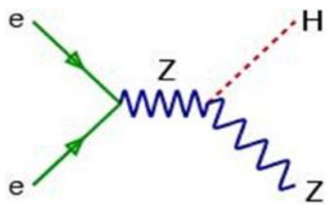




**e+e- annihilations:**

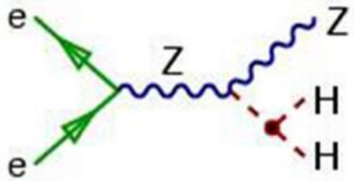
**E > 91 + 125 = 216 GeV**

**E ~ 250 GeV**




**E > 91 + 250 = 341 GeV**

**E ~ 500 GeV**




**250 GeV:**
- **Mass, Spin, CP nature**
- **Absolute measurement of HZZ**
- **BRs Higgs → qq, ll, VV**

**350-380 GeV:**
- **Absolute HWW measurements**
- **Top threshold: mass, width, anomalous couplings …**

**500 GeV:**
- **Higgs self coupling**
- **Top Yukawa coupling**

**→ 1000 GeV: as motivated by physics**

# International Linear Collider

P. Burrows

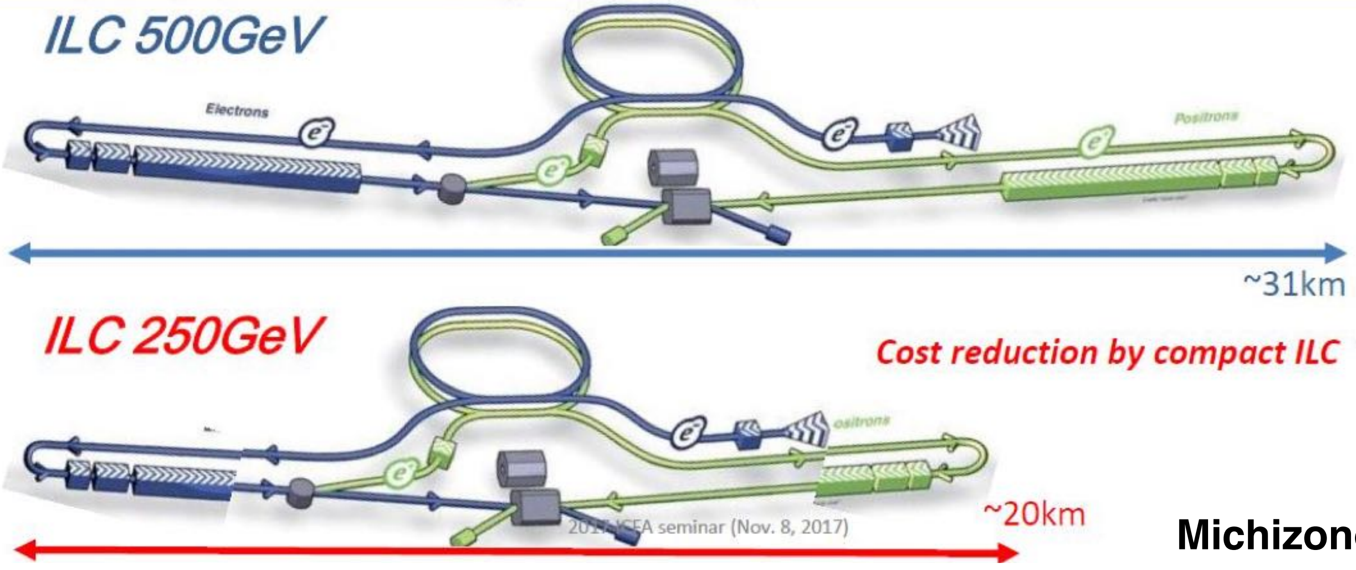
## US-Japan cost reduction R&D

*Cost reduction by technological innovation*

*Innovation of Nb (superconducting) material process: decrease in material cost*

*Innovative surface process for high efficiency cavity (N-infusion): decrease in number of cavities*

## Staging




*Cost reduction by compact ILC*

Michizono

## ILC in Japan?

meeting of Lyn Evans and Prime Minister Abe, March 27, 2013

## Beam parameters

| | ILC 250 | 500 | |
|---|---|---|---|
| Electrons/bunch | 2 | 2 | 10**10 |
| Bunches/train | 1312 | 1312 | |
| Bunch separation | 554 | 544 | ns |
| Train length | 727 | 727 | us |
| Train repetition rate | 5 | 4 | Hz |
| Horizontal IP beam size | 729 | 474 | nm |
| Vertical IP beam size | 8 | 6 | nm |
| Luminosity | 1.4 | 2 | 10**34 |

# International Linear Collider

P. Burrows

## Beam parameters

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## Like firing bullets to hit in middle …

## Except that …

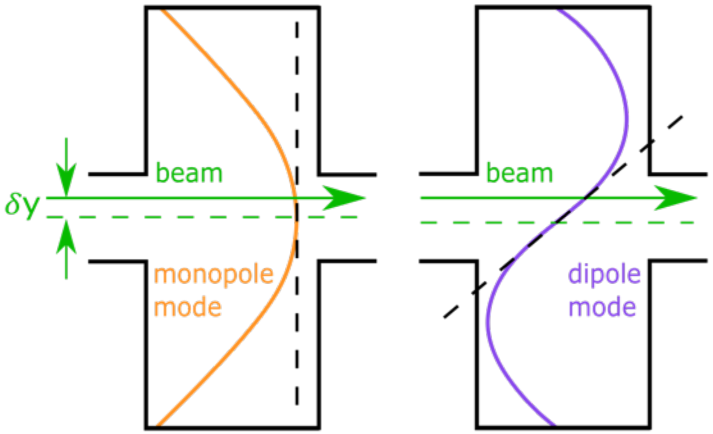
*Requires precise beam measurements at final focus and feedback on nanosecond timescales*

# Cavity BPMs & fast feedback

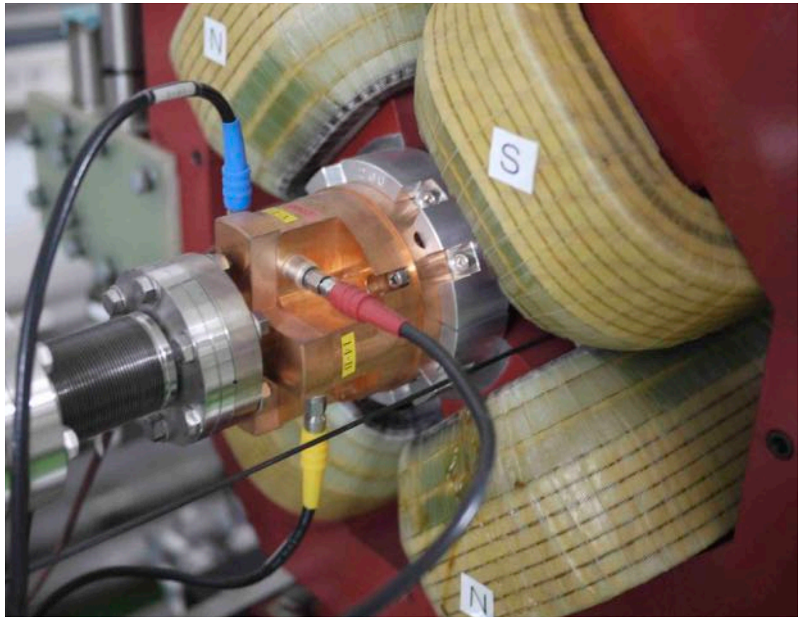
P Burrows et al

UNIVERSITY OF OXFORD

Separate cavities for the extraction of the monopole and dipole modes.
These high-frequency signals need down-mixing and mixing to produce a baseband signal proportional to only the bunch offset.




**ATF2 (6.5 GHz)**



**CLIC main beam/CTF3 (15 GHz)**

**Feedback On Nanosecond Timescales:**
Nanometer-resolution cavity BPMs used for fast digital + analogue feedback/feedforward systems

- ADCs to digitise I and Q waveforms at 357 MHz.
- DACs to provide analogue output to drive kicker, with a fast rise time 35 ns

| Resolution calculation method | Resolution (nm) Single sampling | Integration sampling |
|---|---|---|
| Geometric | 49 ± 1 | 21.5 ± 0.4 |
| Fitting I’ | 49 ± 1 | 19.9 ± 0.4 |
| Fitting I’, Q’ | 43 ± 1 | 19.5 ± 0.4 |
| Fitting I’, Q’, q | 43 ± 1 | 19.5 ± 0.4 |
| Fitting I’, Q’, q and x | 42 ± 1 | 19.2 ± 0.4 |

# International Committee for Future Accelerators

August 2, 2020

**ICFA announces a new phase towards preparation for the International Linear Collider**

At its 86th meeting held today, ICFA approved the formation of the International Linear Collider International Development Team as the first step towards the preparatory phase of the ILC project, with a mandate to make preparations for the ILC Pre-Lab in Japan.

A description of the mandate and structure of the ILC International Development Team was also approved by ICFA today.

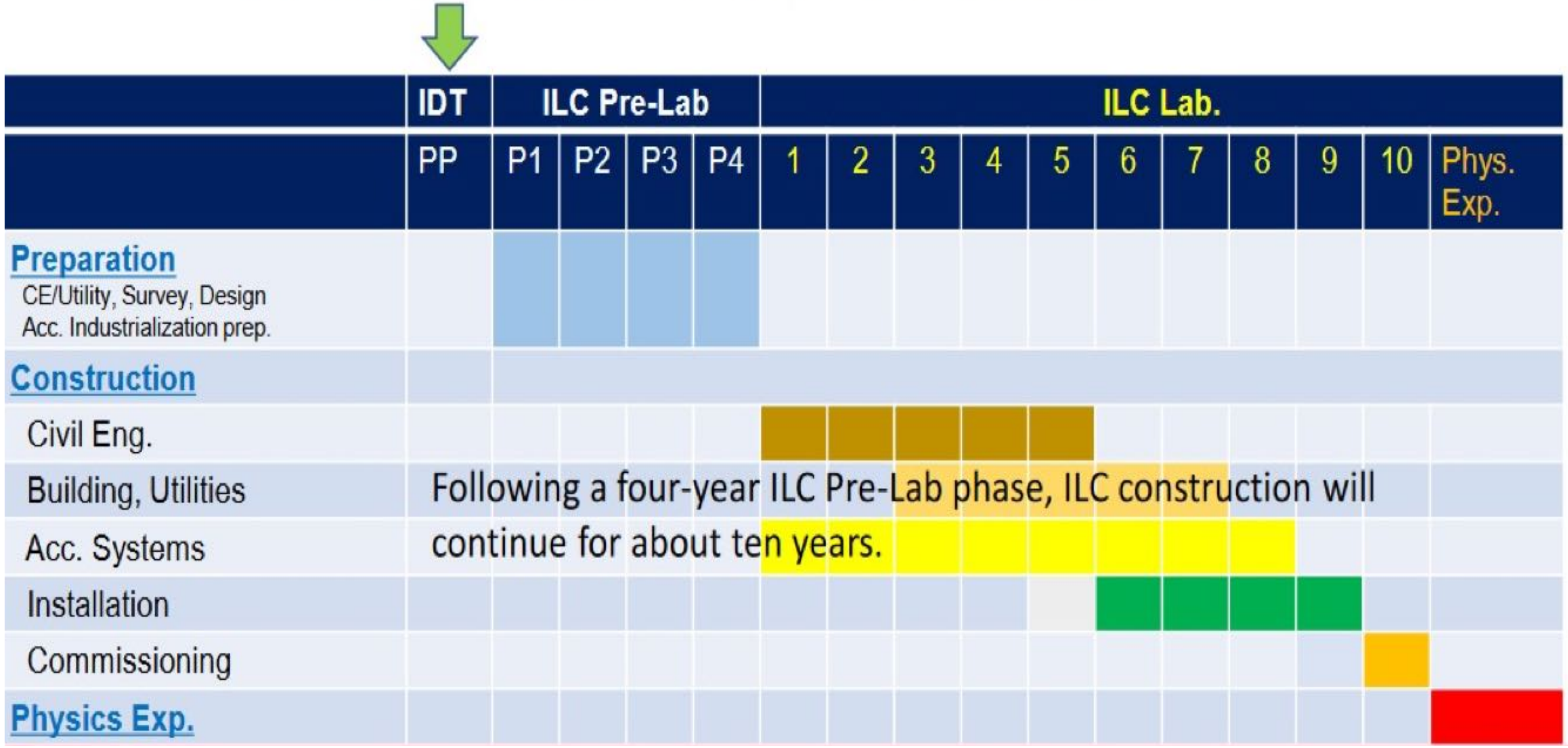
The Team will commence its work immediately and is expected to complete it by the end of 2021.

The ILC International Development Team will work towards making a timely realization of the ILC possible.

ICFA thanks the Linear Collider Collaboration led by Dr. Lyn Evans for its excellent work over the past several years.

Contacts:
Geoffrey Taylor (ICFA, Chair) - The University of Melbourne
Tatsuya Nakada (Chair, Executive Board, ILC International Development Team) - EPFL, Lausanne

# International Committee for Future Accelerators

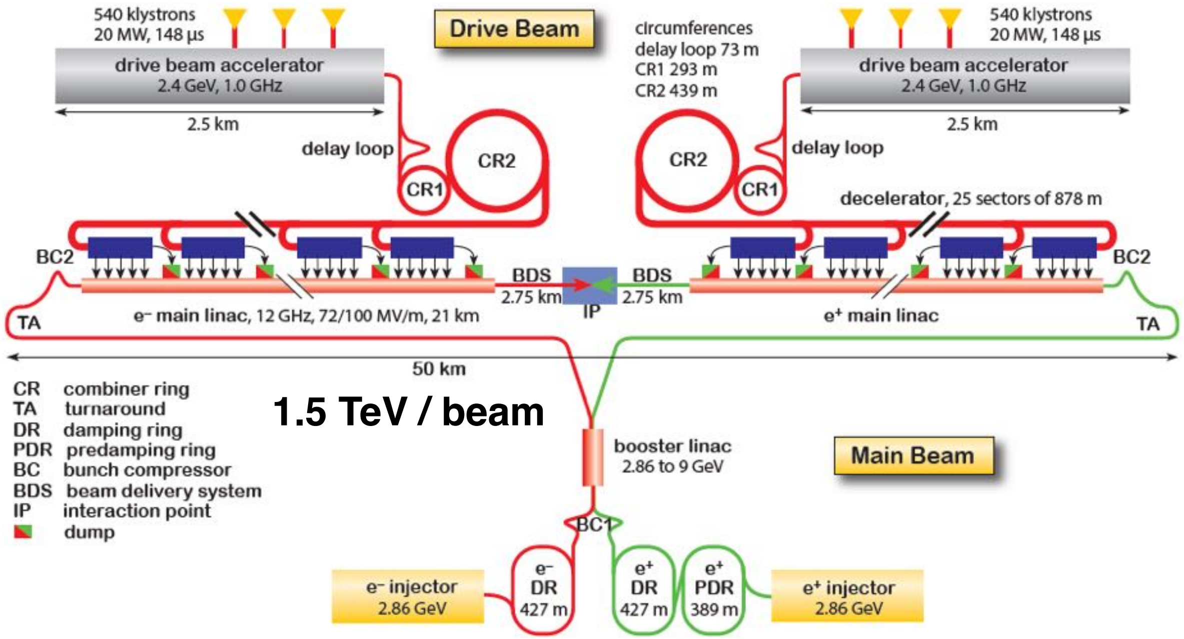


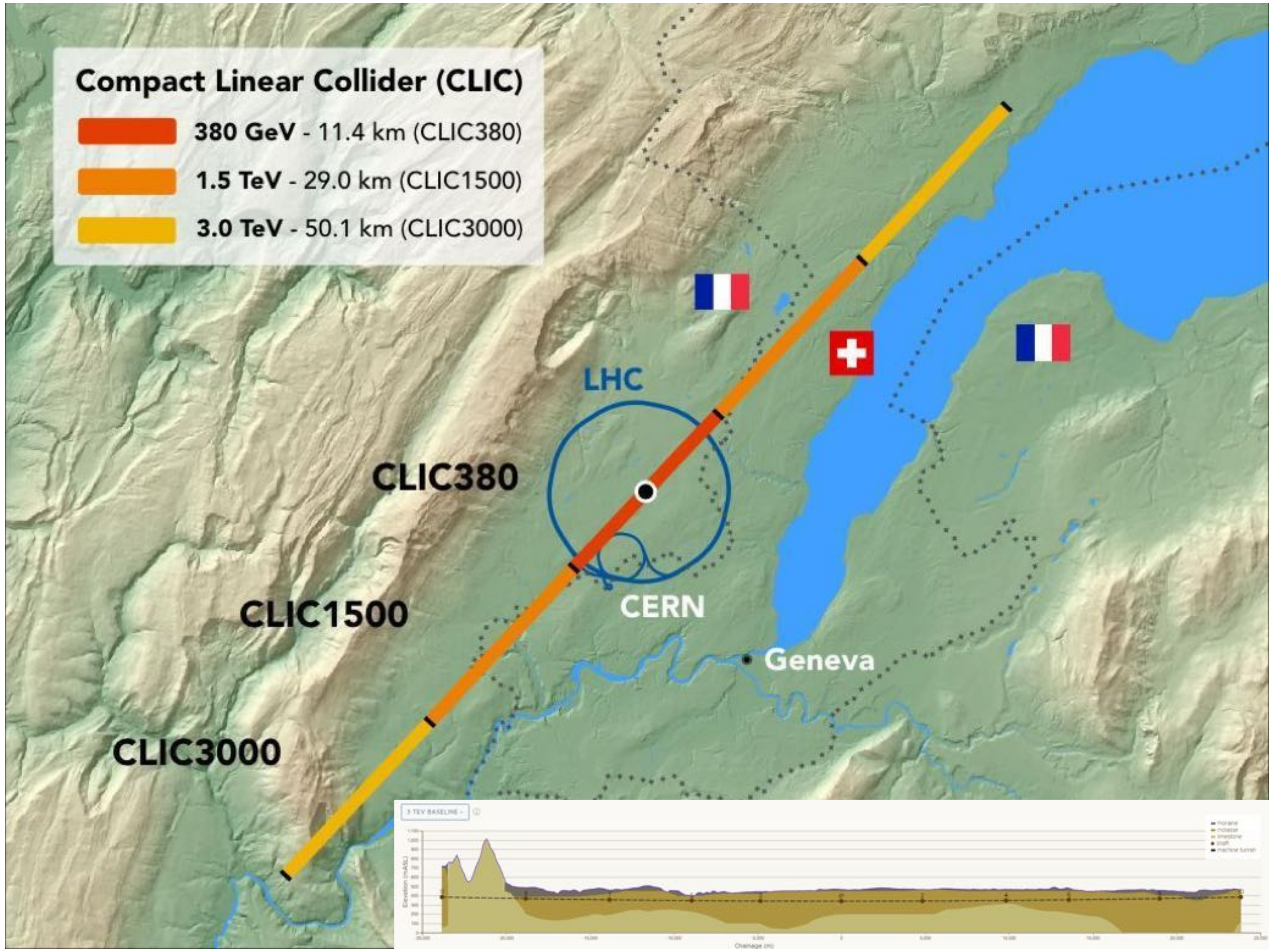

Following a four-year ILC Pre-Lab phase, ILC construction will continue for about ten years.


***Charge for WG1:*** prepare outlines schemes for submission initially for inclusion in document prepared by IDT Directorate for submission to Japanese MEXT ministry in context of KEK bid for Pre-lab funding in summer 2021.

# Compact Linear Collider: CLIC

- ***Drive beam technology demonstrated*** *at CTF3, CERN, acc. gradient upto 150 MV/m.*
- *Operation **100 MV/m**, 135 MW at 12 GHz.*
- Project staging to ***multi-TeV $e^+e^-$***
  - **380 GeV, 1.5 TeV ,3.0 TeV**




UK institutes contributed to design;
Phil Burrows – CLIC spokesperson

# Compact Linear Collider: CLIC

- ***Drive beam technology demonstrated** at CTF3, CERN, acc. gradient upto 150 MV/m.*
- *Operation **100 MV/m**, 135 MW at 12 GHz.*
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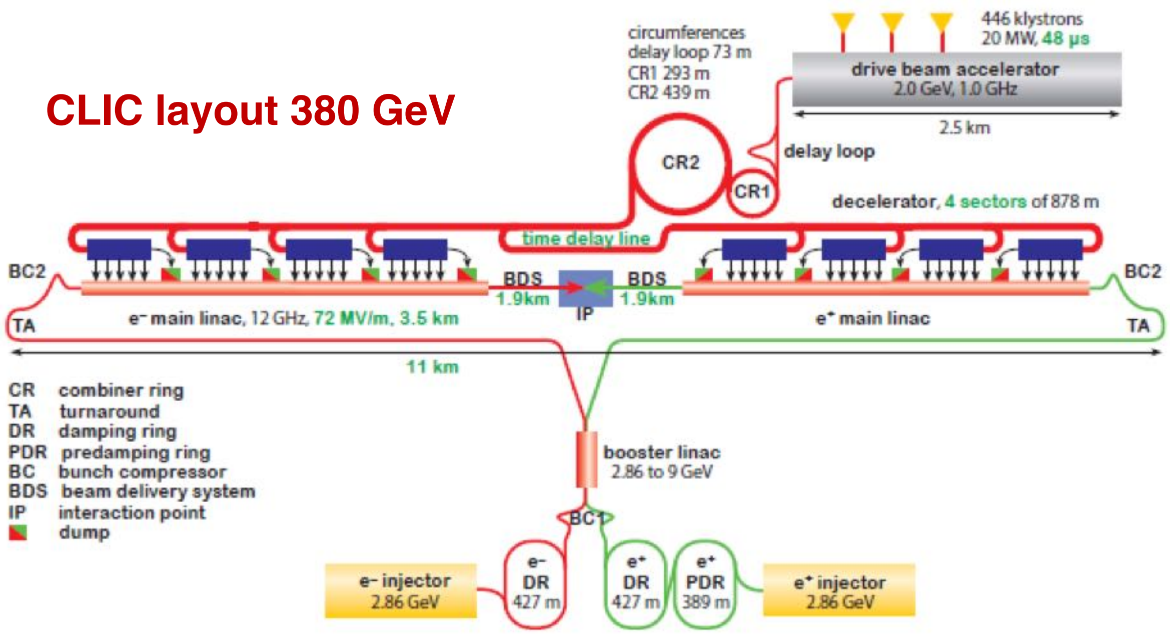
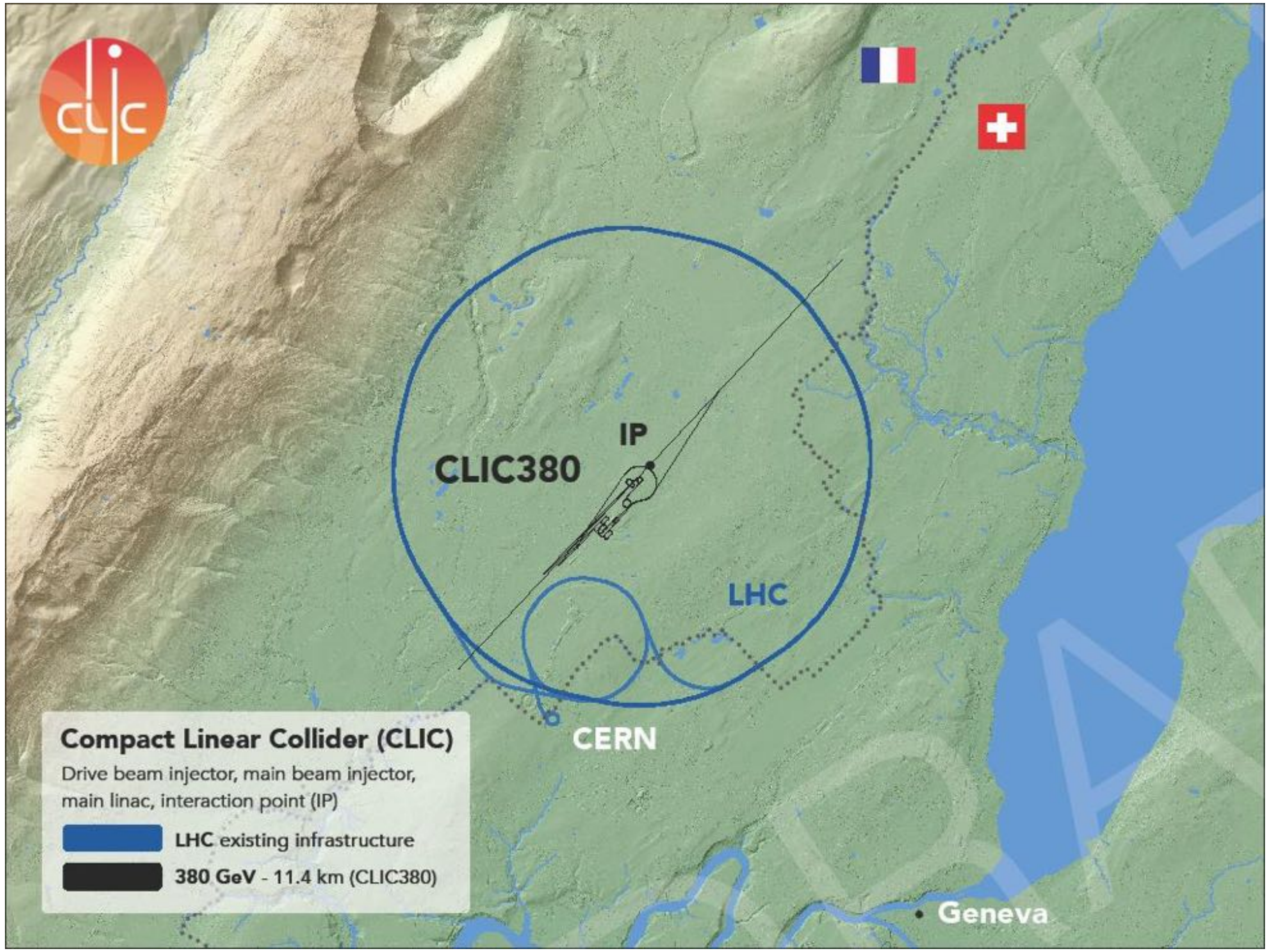
  - **380 GeV, 1.5 TeV ,3.0 TeV**

**CLIC layout 380 GeV**

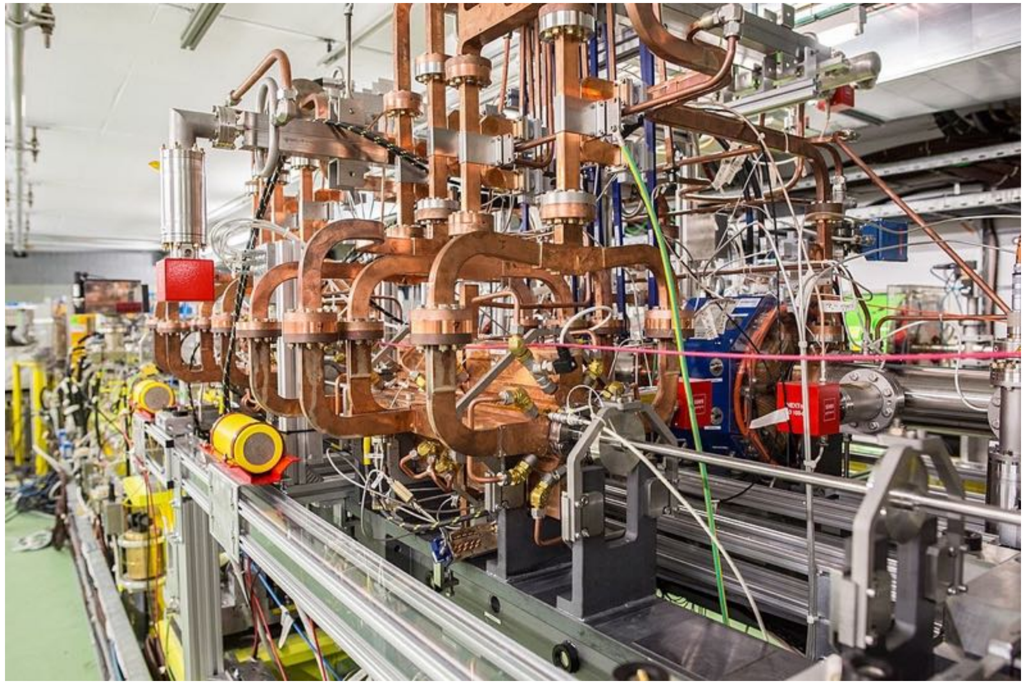


# CLIC demonstrator and machine parameters

Normal conducting high-frequency RF (X-band 12GHz)

Drive beam technology demonstrated at CLIC Test Facility (CTF3)

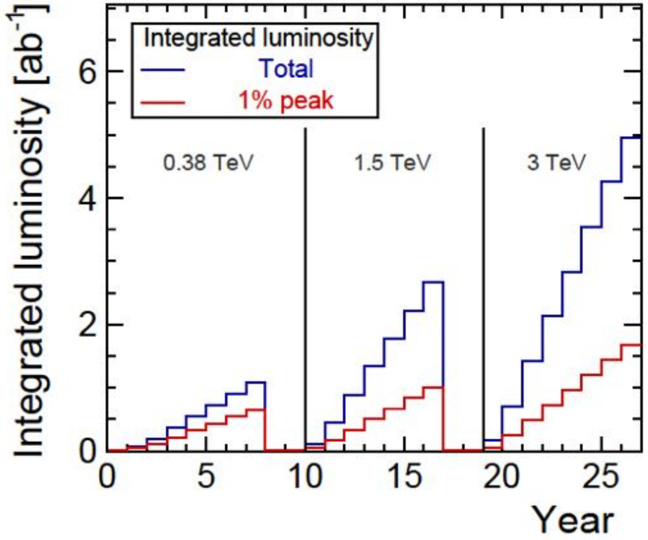


| Parameter | Symbol | Unit | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|---|---|
| Centre-of-mass energy | $\sqrt{s}$ | GeV | 380 | 1500 | 3000 |
| Repetition frequency | $f_{rep}$ | Hz | 50 | 50 | 50 |
| Number of bunches per train | $n_b$ | | 352 | 312 | 312 |
| Bunch separation | $\Delta t$ | ns | 0.5 | 0.5 | 0.5 |
| Pulse length | $\tau_{RF}$ | ns | 244 | 244 | 244 |
| Accelerating gradient | $G$ | MV/m | 72 | 72/100 | 72/100 |
| Total luminosity | $\mathscr{L}$ | $10^{34}$ cm$^{-2}$ s$^{-1}$ | 1.5 | 3.7 | 5.9 |
| Luminosity above 99% of $\sqrt{s}$ | $\mathscr{L}_{0.01}$ | $10^{34}$ cm$^{-2}$ s$^{-1}$ | 0.9 | 1.4 | 2 |
| Total integrated luminosity per year | $\mathscr{L}_{int}$ | fb$^{-1}$ | 180 | 444 | 708 |
| Main linac tunnel length | | km | 11.4 | 29.0 | 50.1 |
| Number of particles per bunch | $N$ | $10^9$ | 5.2 | 3.7 | 3.7 |
| Bunch length | $\sigma_z$ | μm | 70 | 44 | 44 |
| IP beam size | $\sigma_x/\sigma_y$ | nm | 149/2.9 | ~ 60/1.5 | ~ 40/1 |
| Normalised emittance (end of linac) | $\epsilon_x/\epsilon_y$ | nm | 900/20 | 660/20 | 660/20 |
| Final RMS energy spread | | % | 0.35 | 0.35 | 0.35 |
| Crossing angle (at IP) | | mrad | 16.5 | 20 | 20 |

# CLIC summary


- **Timeline:** e+e- linear collider at CERN for the era beyond HL-LHC
- **Compact:** novel and unique two-beam accelerating technique based on high-gradient room temperature RF cavities:

  first stage: 380 GeV, ~11km long, 20,500 cavities
- **Expandable:** staged collision energies from 380 GeV (Higgs/top) up to 3 TeV




| Stage | $\sqrt{s}$ [TeV] | $\mathcal{L}_{int}$ [ab$^{-1}$] |
|---|---|---|
| 1 | 0.38 (and 0.35) | 1.0 |
| 2 | 1.5 | 2.5 |
| 3 | 3.0 | 5.0 |

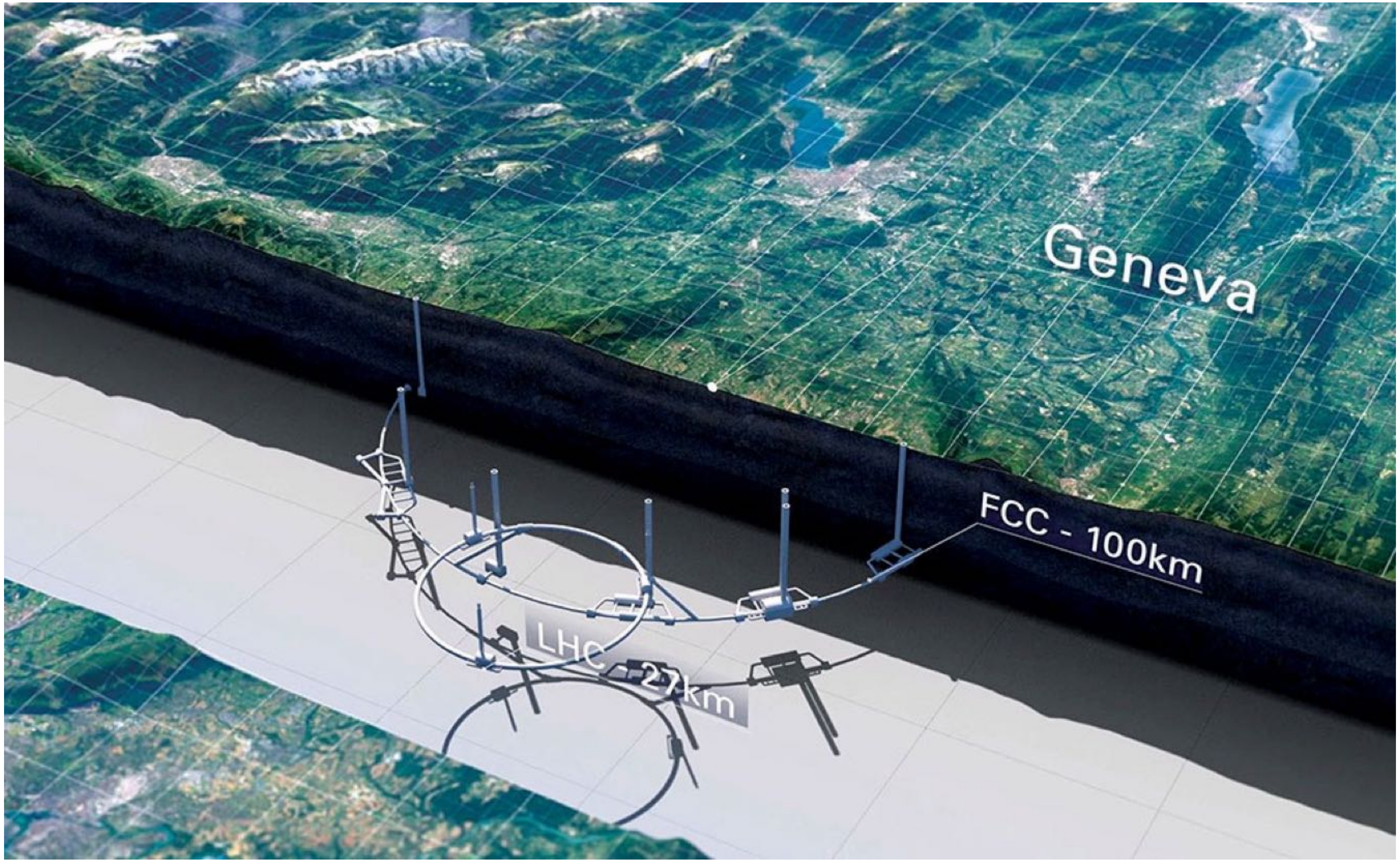
- **Conceptual Design Report published in 2012**
- **Project Implementation Plan released 2018**

  **Cost: 5.9 BChF for 380 GeV (stable w.r.t. CDR)**

  **Power: 168 MW at 380 GeV (significantly reduced since CDR)**

**Baseline polarisation scenario adopted:**
**electron beam (–80%, +80%) polarised in ratio (50:50) at √s=380GeV ; (80:20) at √s=1.5 and 3TeV**

# Future Circular Collider



# ESPP20 update and next steps for FCC

- ***EU Strategy 2020:*** *"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."*

- ***FCC Innovation Study (FCCIS) kickoff meeting in 9-13 November 2020 at CERN, including 4th Physics & Experiments workshop, beginning to address the ESPP20 mandate.***
  - https://indico.cern.ch/event/923801/
  - FCCIS will deliver a conceptual design and an implementation plan for a new research infrastructure, consisting of a 100 km long, circular tunnel and a dozen surface sites. It will initially host an electron-positron particle collider. With an energy frontier hadron collider as a second step, it can serve a world-wide community through the end of the 21st century. This project will validate the key performance enablers at particle accelerators.

- ***FCC collaboration met last week, in July***

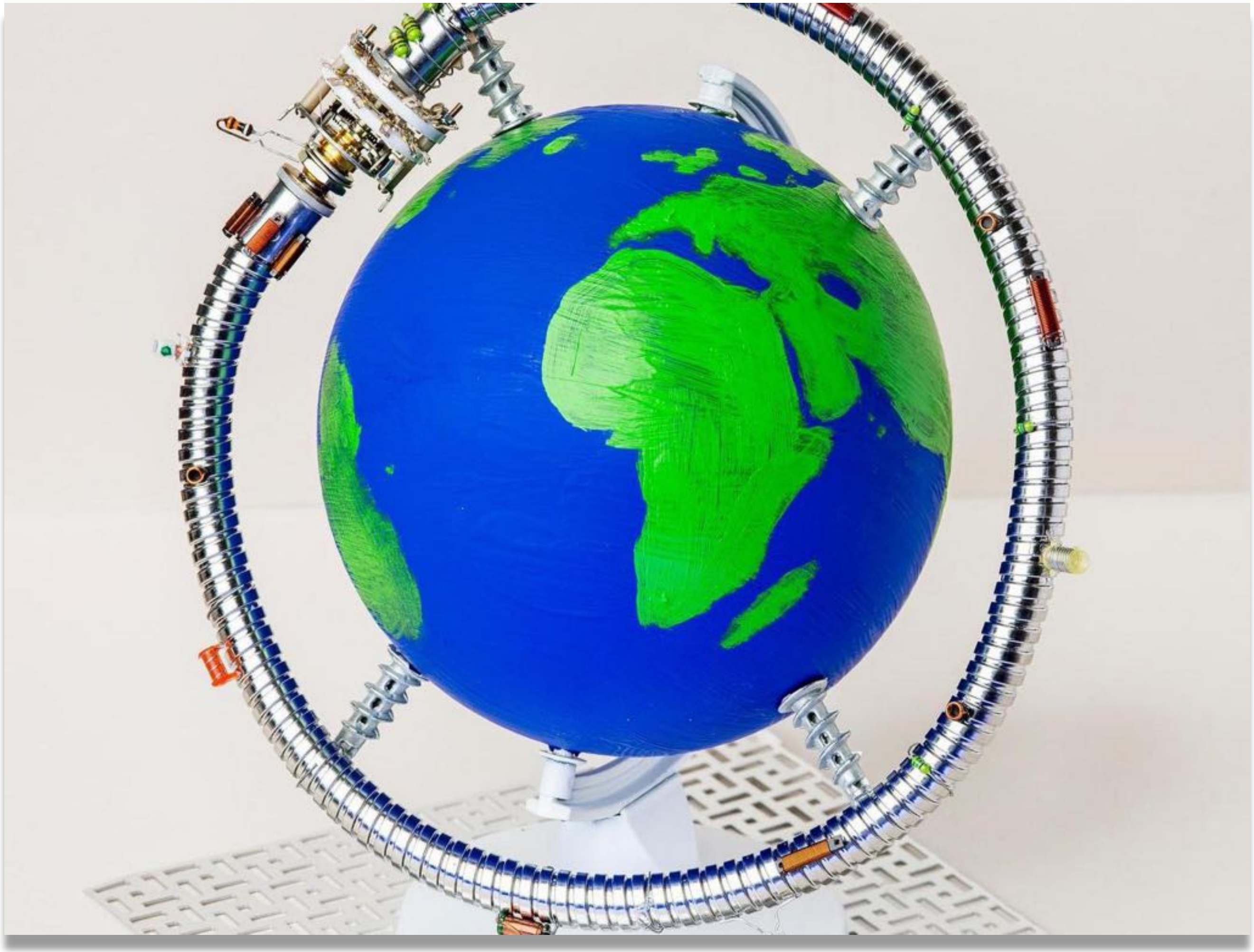
# FCC


| parameter | FCC-hh | HE-LHC | HL-LHC | LHC |
|---|---|---|---|---|
| collision energy cms [TeV] | 100 | 27 | 14 | 14 |
| dipole field [T] | 16 | 16 | 8.33 | 8.33 |
| circumference [km] | 97.75 | 26.7 | 26.7 | 26.7 |
| stored energy/beam [GJ] | 8.4 | 1.3 | 0.7 | 0.36 |

Big article in Dutch press:


deVolkskrant

Hoe moet de grootste deeltjesversneller op aarde eruit gaan zien?

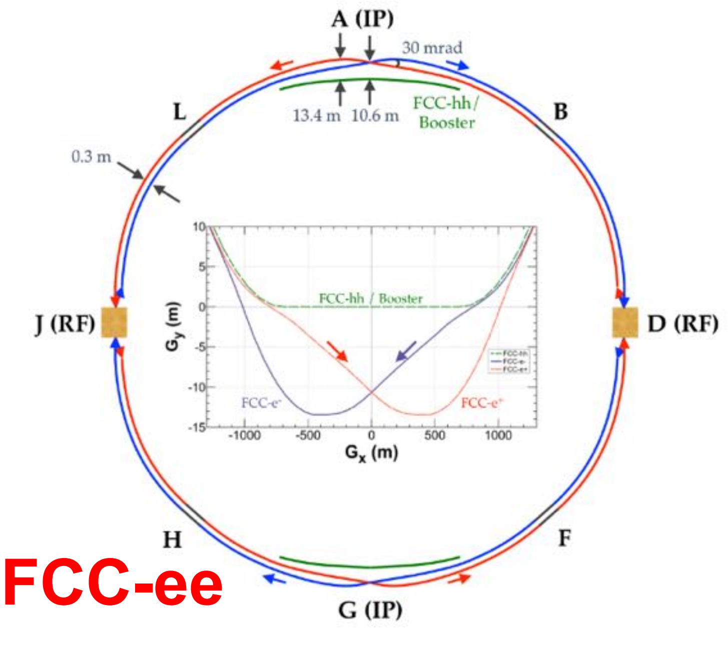


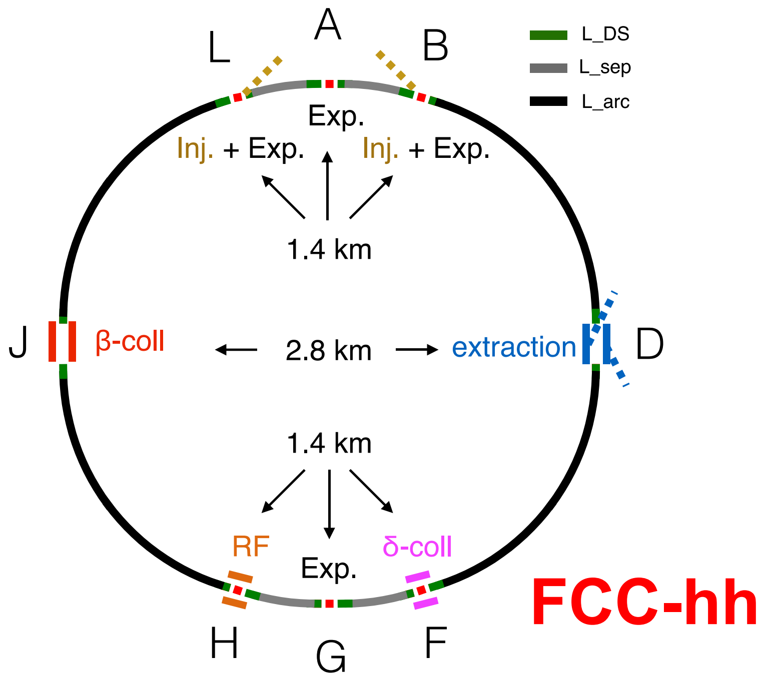
*"What might the largest particle accelerator on earth look like?"*

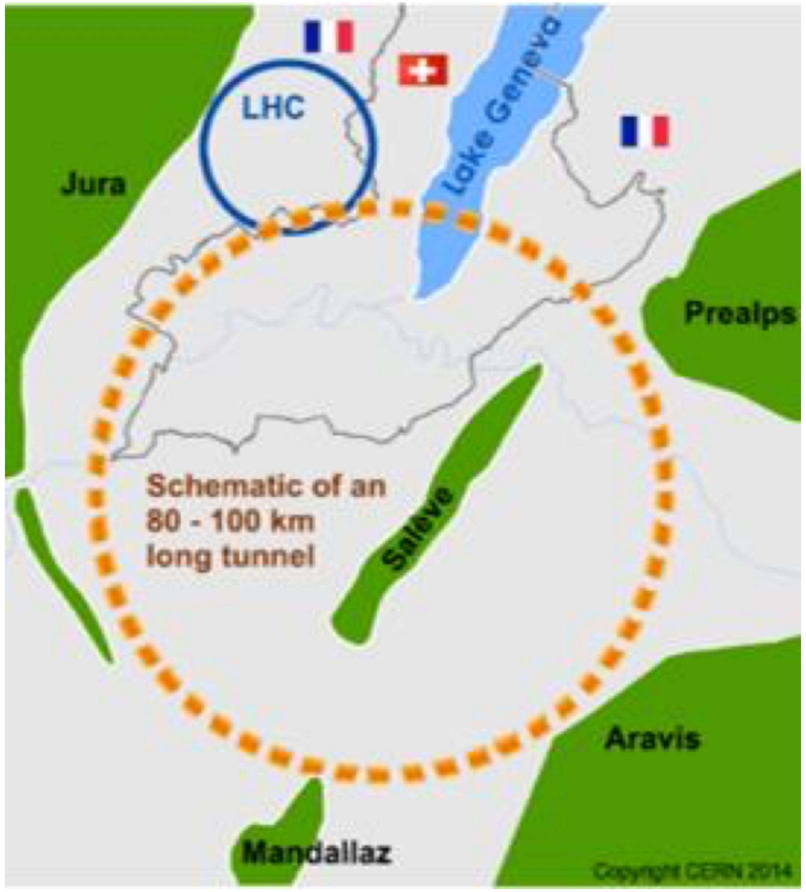
# FCC week 2021: FCC integrated program

## Comprehensive long-term program, maximizing physics opportunities

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC



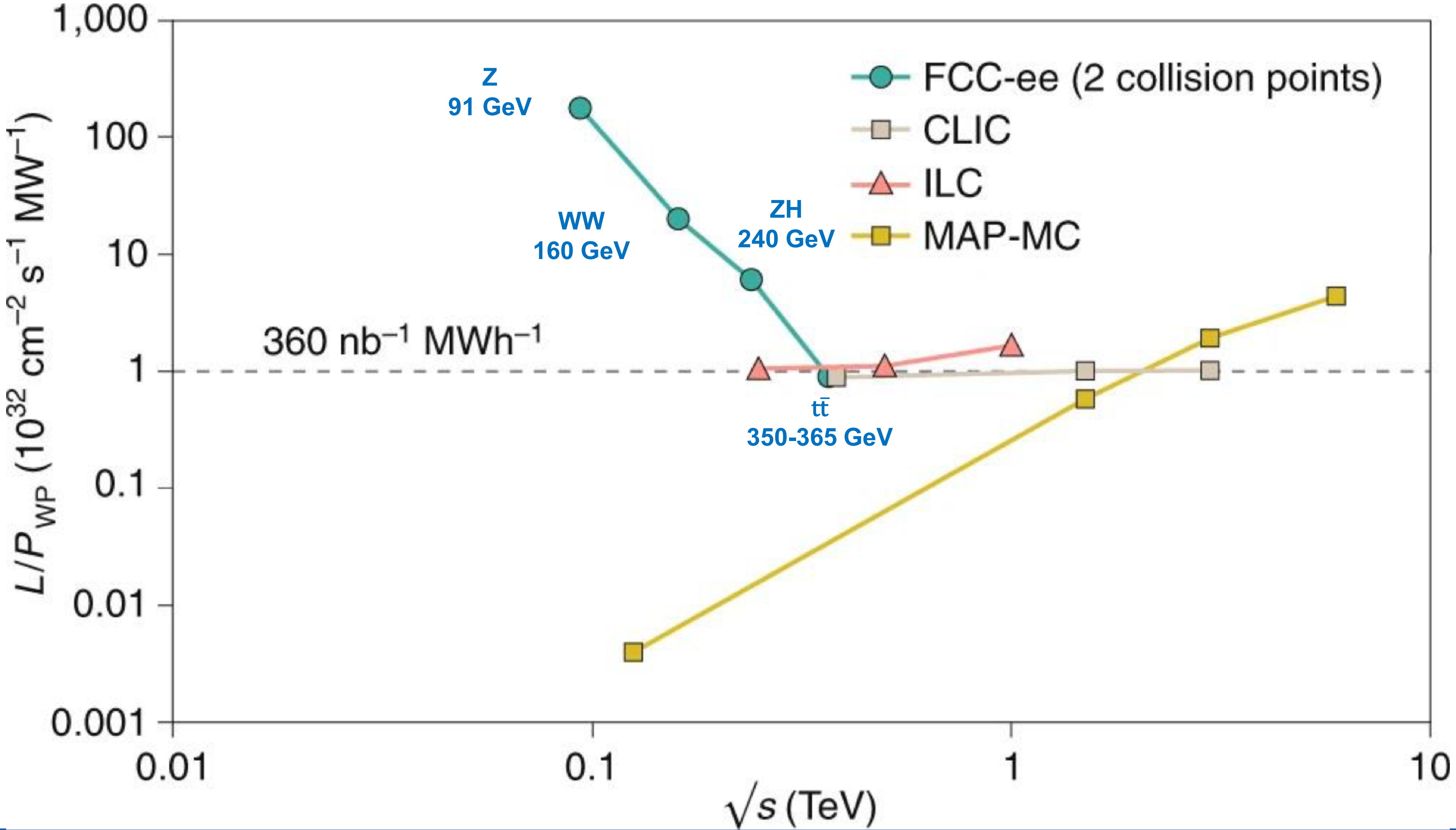



# FCC-ee collider parameters (stage 1)

| parameter | Z | WW | H (ZH) | ttbar |
|---|---|---|---|---|
| beam energy [GeV] | 45 | 80 | 120 | 182.5 |
| beam current [mA] | 1390 | 147 | 29 | 5.4 |
| no. bunches/beam | 16640 | 2000 | 393 | 48 |
| bunch intensity [$10^{11}$] | 1.7 | 1.5 | 1.5 | 2.3 |
| SR energy loss / turn [GeV] | 0.036 | 0.34 | 1.72 | 9.21 |
| total RF voltage [GV] | 0.1 | 0.44 | 2.0 | 10.9 |
| long. damping time [turns] | 1281 | 235 | 70 | 20 |
| horizontal beta* [m] | 0.15 | 0.2 | 0.3 | 1 |
| vertical beta* [mm] | 0.8 | 1 | 1 | 1.6 |
| horiz. geometric emittance [nm] | 0.27 | 0.28 | 0.63 | 1.46 |
| vert. geom. emittance [pm] | 1.0 | 1.7 | 1.3 | 2.9 |
| bunch length with SR / BS [mm] | 3.5 / 12.1 | 3.0 / 6.0 | 3.3 / 5.3 | 2.0 / 2.5 |
| luminosity per IP [$10^{34}$ $cm^{-2}s^{-1}$] | 230 | 28 | 8.5 | 1.55 |
| beam lifetime rad Bhabha / BS [min] | 68 / >200 | 49 / >1000 | 38 / 18 | 40 / 18 |

# FCC-ee: efficient Higgs/electroweak factory




luminosity $L$ per supplied electrical wall-plug power $P_{WP}$ is shown as a function of centre-of-mass energy for several proposed future lepton colliders

M. Benedikt, A. Blondel, P. Janot, et al., **Nature Physics 16**, 402-407 (2020), and **European Strategy** for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

# High efficiency Klystron design for FCC-ee

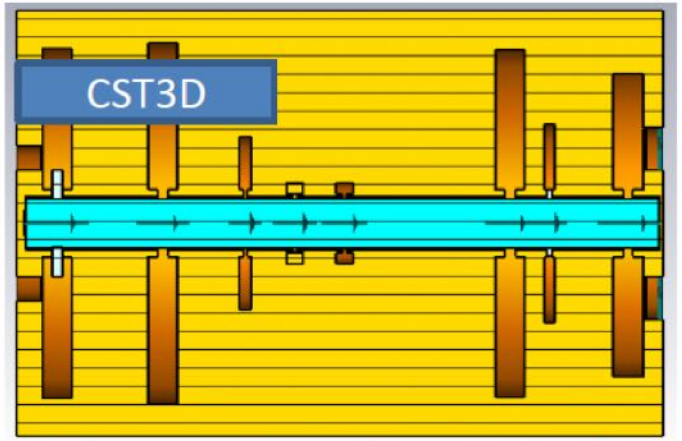
0.8GHz,133.9kV×12.5A×**80%**>1.3MW

Jinchi Cai & Graeme Burt

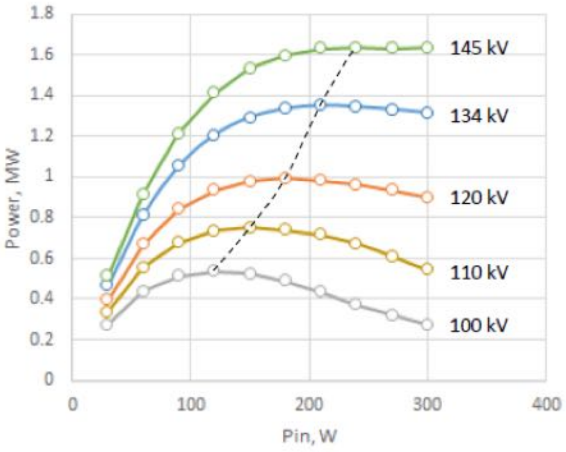
The klystron efficiency impact on the FCC power consumption.
Example of the efficiency upgrade from 60% to 80%.

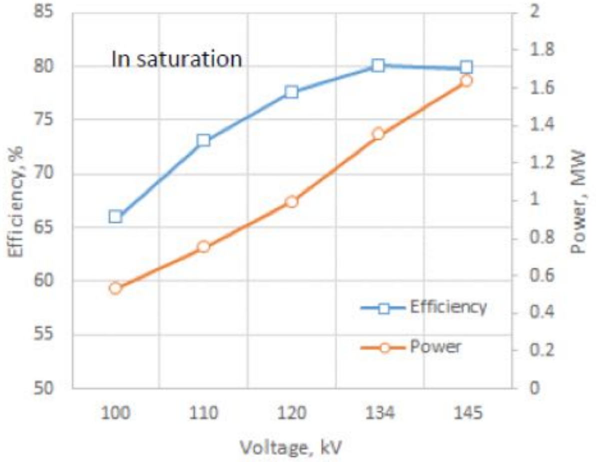
| | Klystron eff. 60% | Klystron eff. 80% | Difference |
|---|---|---|---|
| RF power needed for 3TeV CLIC | 105 MW | | |
| DC input power | 150 MW | 123 MW | -27MW |
| Waste heat | 45 MW | 18 MW | -27MW |
| Annual consumption (5500 h assumed) | 825 GWh | 676 GWh | -149 GWh |
| Annual cost (60 CHF/MWh assumed) | 49.5 MCHF | 40.5 MCHF | -9 MCHF |

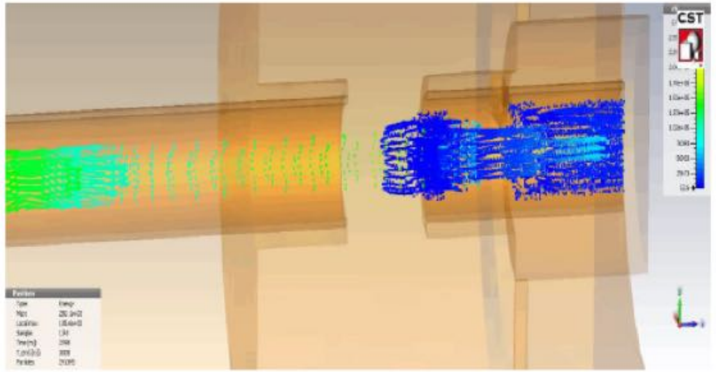
- FCC requires 105 MW of RF power, but the DC power is much higher due to limited efficiency
- Increasing the efficiency by just 20% would save CERN 9 MCHF / year by saving 149 GWh of electricity
- CERN and Lancaster are investigating new methods of increasing klystron efficiency




Efficiency=79%, Time cost=50h




$B_z$=0.07T (5xBr). **Efficiency 79%**

# FCCee

## FCC-ee operation model

| working point | luminosity/IP [$10^{34}$ cm$^{-2}$s$^{-1}$] | total luminosity (2 IPs)/ yr | physics goal | run time [years] |
|---|---|---|---|---|
| *Z* first 2 years | 100 | 26 ab$^{-1}$/year | **150 ab$^{-1}$** | **4** |
| *Z* later | 200 | 52 ab$^{-1}$/year | | |
| *W* | 25 | 7 ab$^{-1}$/year | **10 ab$^{-1}$** | **1-2** |
| *H* | 7.0 | 1.8 ab$^{-1}$/year | **5 ab$^{-1}$** | **3** |
| machine modification for RF installation & rearrangement: **1 year** | | | | |
| top 1st year (350 GeV) | 0.8 | 0.2 ab$^{-1}$/year | **0.2 ab$^{-1}$** | **1** |
| top later (365 GeV) | 1.4 | 0.36 ab$^{-1}$/year | **1.5 ab$^{-1}$** | **4** |

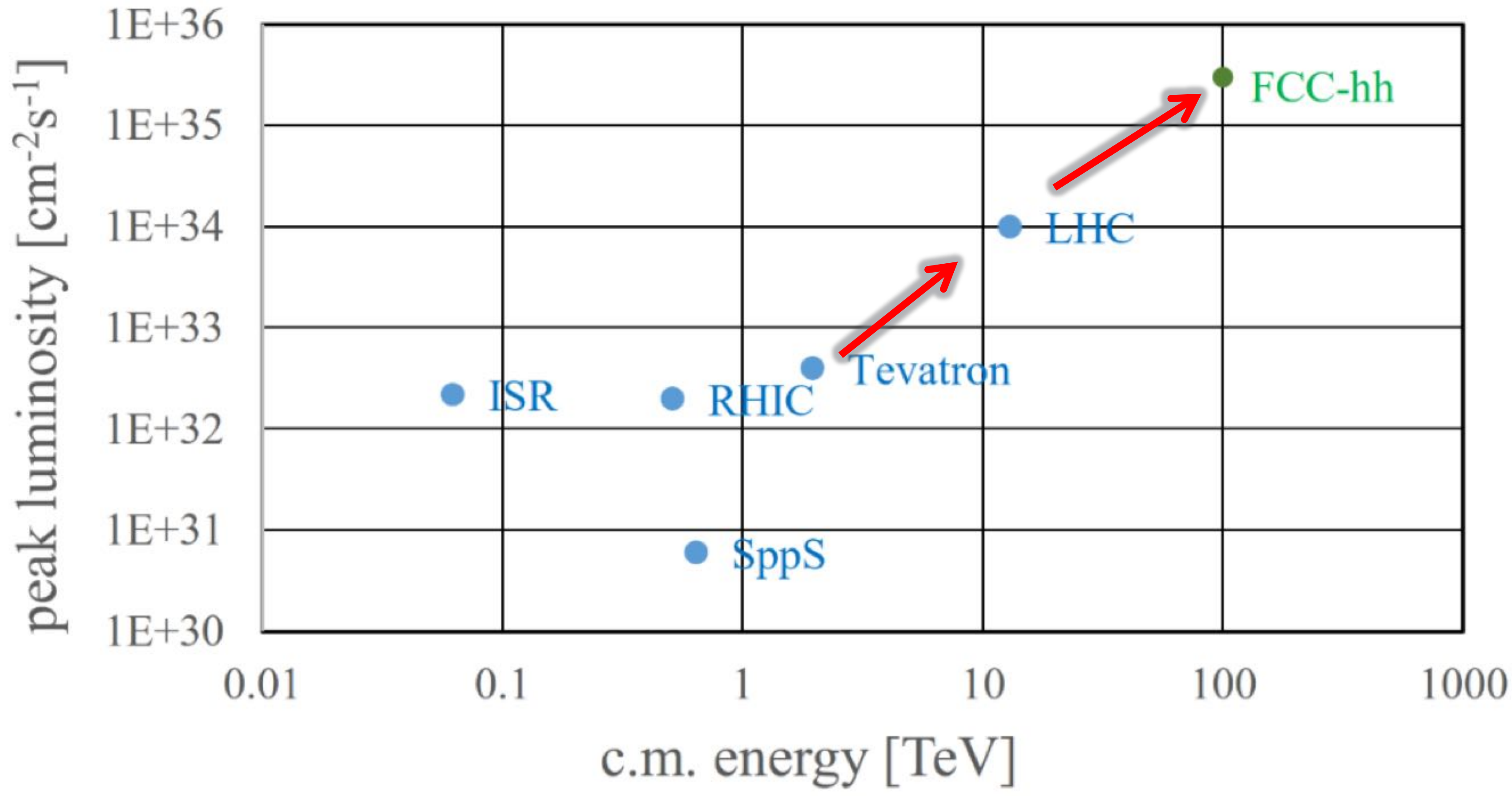
**total program duration: 14-15 years** - ***including machine modifications***
**phase 1 (*Z*, *W*, *H*): 8-9 years, phase 2 (top): 6 years**

PPAP 16/7/18 -- I. Shipsey

# FCC-hh (pp) collider parameters (stage 2)

| parameter | FCC-hh | | HL-LHC | LHC |
|---|---|---|---|---|
| collision energy cms [TeV] | 100 | | 14 | 14 |
| dipole field [T] | 16 | | 8.33 | 8.33 |
| circumference [km] | 97.75 | | 26.7 | 26.7 |
| beam current [A] | 0.5 | | 1.1 | 0.58 |
| bunch intensity [$10^{11}$] | 1 | 1 | 2.2 | 1.15 |
| bunch spacing [ns] | 25 | 25 | 25 | 25 |
| synchr. rad. power / ring [kW] | 2400 | | 7.3 | 3.6 |
| SR power / length [W/m/ap.] | 28.4 | | 0.33 | 0.17 |
| long. emit. damping time [h] | 0.54 | | 12.9 | 12.9 |
| beta* [m] | 1.1 | 0.3 | 0.15 (min.) | 0.55 |
| normalized emittance [μm] | 2.2 | | 2.5 | 3.75 |
| peak luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | 5 | 30 | 5 (lev.) | 1 |
| events/bunch crossing | 170 | 1000 | 132 | 27 |
| stored energy/beam [GJ] | 8.4 | | 0.7 | 0.36 |

# FCC-hh: big step in performance




**order of magnitude performance increase** in **energy & luminosity**

**100 TeV cm collision energy** (vs 14 TeV for LHC)

**20 $ab^{-1}$ per experiment collected over 25 years** of operation (vs 3 $ab^{-1}$ for LHC)

similar performance increase as from Tevatron to LHC

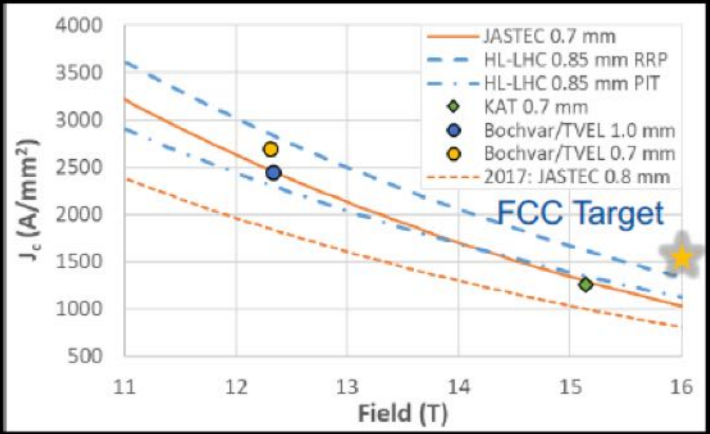
**key technology: high-field magnets**

# FCChh: High-Field Magnets

## Worldwide FCC $Nb_3Sn$ program

**Main development goal is wire performance increase:**
- $J_c$ (16T, 4.2K) > 1500 A/mm² → 50% increase wrt HL-LHC wire
- Reduction of coil & magnet cross-section


After only one year of development, **prototype Nb3Sn wires from several new industrial FCC partners already achieve HL-LHC performance**

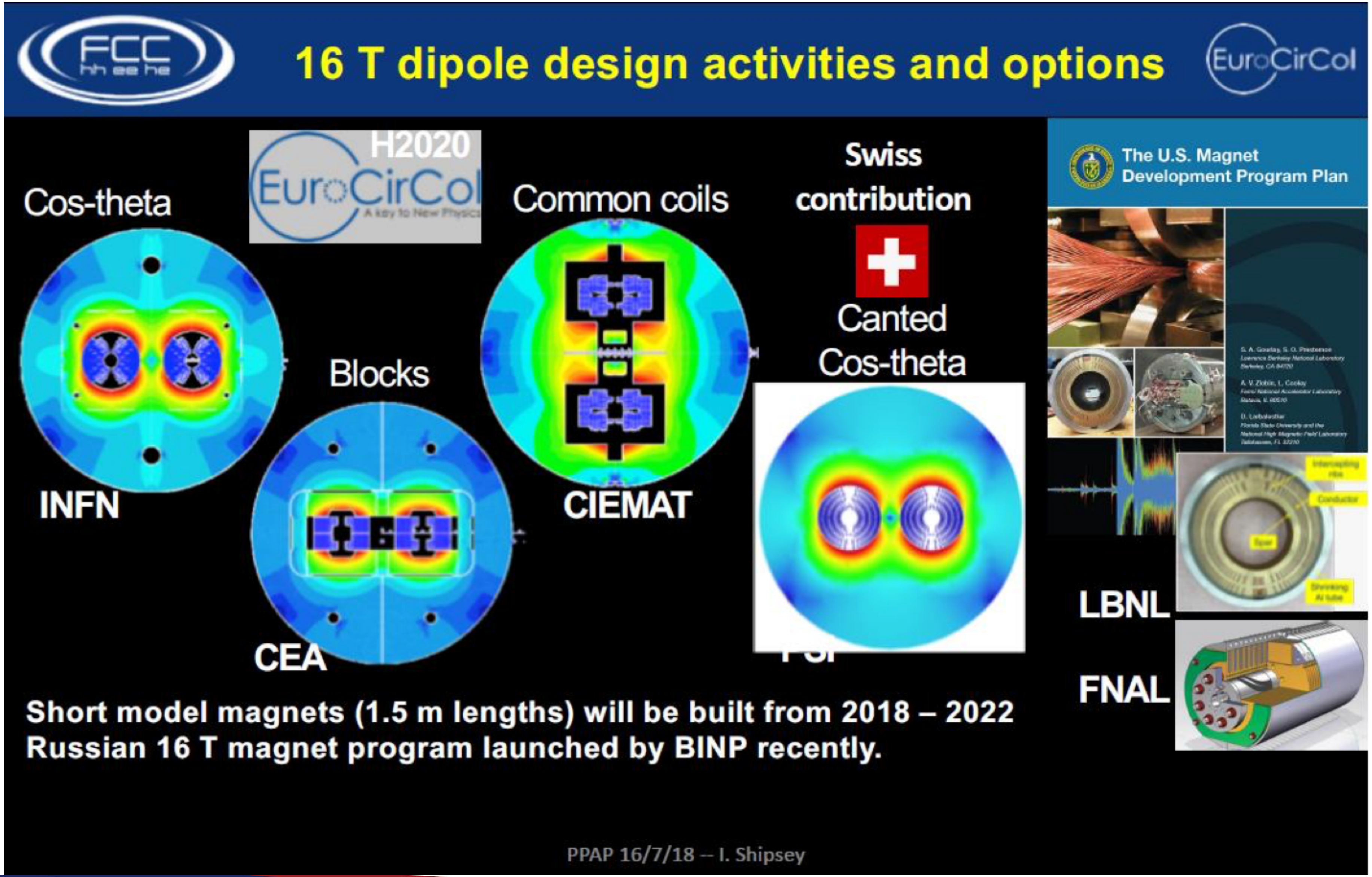



**Conductor activities for FCC started in 2017:**
- **Bochvar Institute** (production at **TVEL**), **Russia**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT, Korea**
- **Columbus, Italy**
- **University of Geneva, Switzerland**
- **Technical University of Vienna, Austria**
- **SPIN, Italy**
- **University of Freiberg, Germany**

**In addition, agreements under preparation:**
- **Bruker, Germany**
- **Luvata Pori, Finland**

PPAP 16/7/18 -- I. Shipsey

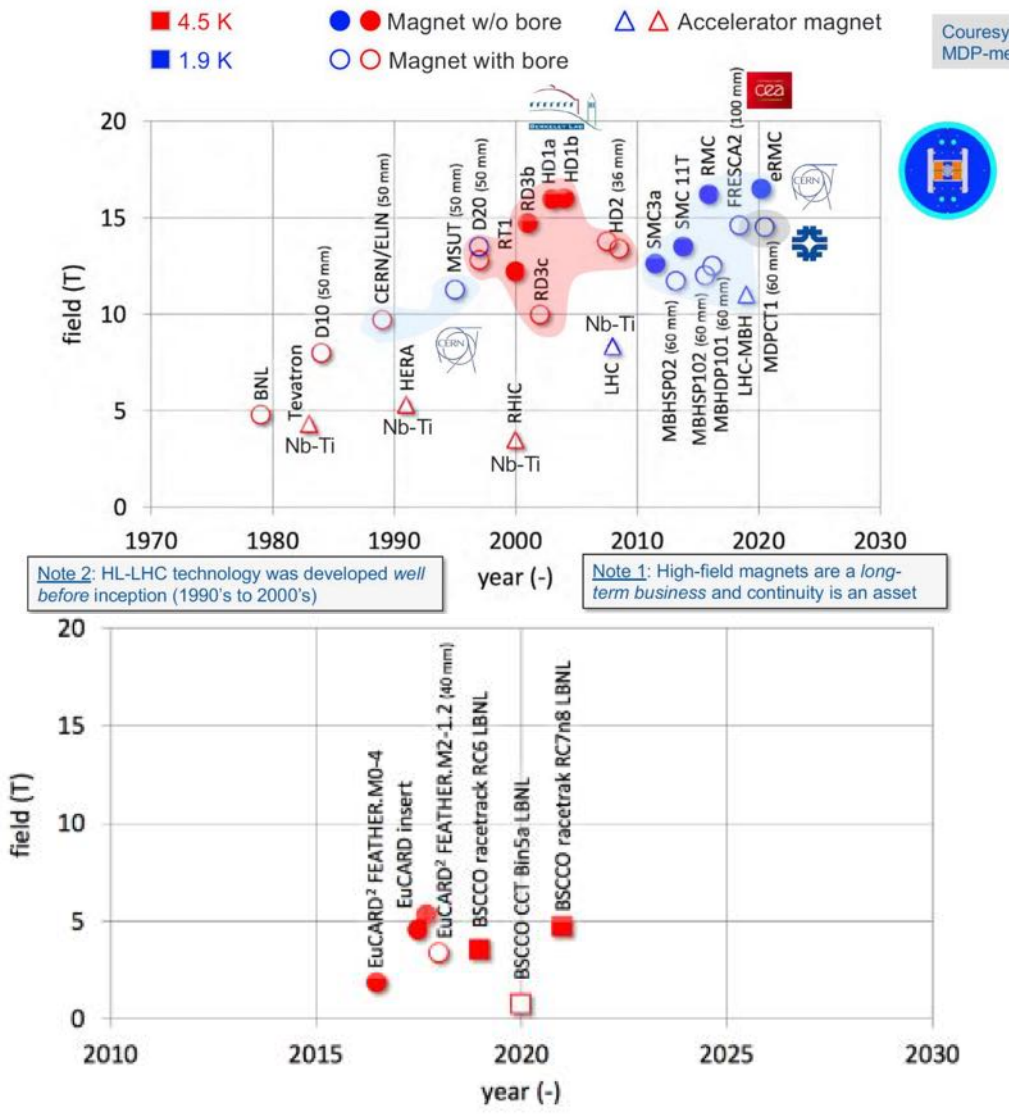
# FCChh: High-Field Magnets



# High-Field Magnets latest: Pierre Vedrine, on behalf of HFM Expert Panel
## High-Field Magnet R&D Status, 9 July 2021

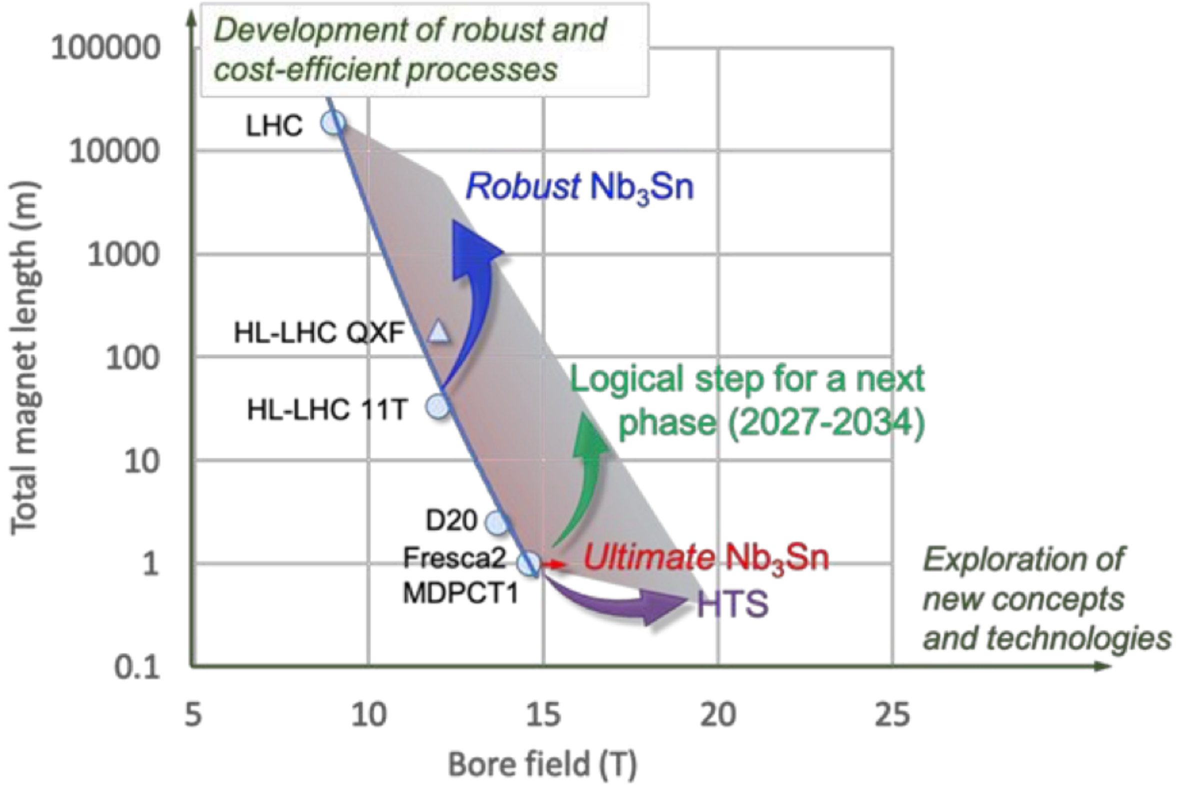
- **High Field Magnets (HFM) are among the key technologies** that will enable the search for new physics at the energy frontier.
- Approved projects (HL-LHC) and studies for future circular machines (FCC, SppC) call for the **development of superconducting magnets that produce fields beyond those attained in the LHC** .
- **Progress in highest field attained** in European and international programs (EU-FP6 CARE , EU-FP7 EuCARD, EuCARD2, HL-LHC , ARIES, on-going I-FAST, HFM & US-DOE programs)

Courtesy, L. Bottura MDP-meeting-2021



## Goals of a High Field Magnets R&D Program

- **Demonstrate $Nb_3Sn$ magnet technology for large scale deployment**, pushing it to its practical limits, both in terms of maximum performance as well as production scale
  - Demonstrate $Nb_3Sn$ full potential in terms of ultimate performance (target 16 T)
  - Develop $Nb_3Sn$ magnet technology for collider-scale production, through robust design, industrial manufacturing processes and cost reduction (benchmark 12 T)
- **Demonstrate suitability of HTS for accelerator magnet applications**, providing a proof-of-principle of HTS magnet technology beyond the reach of $Nb_3Sn$ (target in excess of 20 T)
- Implemented as a **focused, innovative, mission-style R&D** of collaborative nature




*See today's* ***Symposium on the Accelerator R&D Roadmap for the HEP community***
https://indico.cern.ch/event/1053889/

# FCC CDR and Study Documentation


>1350 contributors from > 350 institutes, a truly global effort as suggested by EPPSU 2013

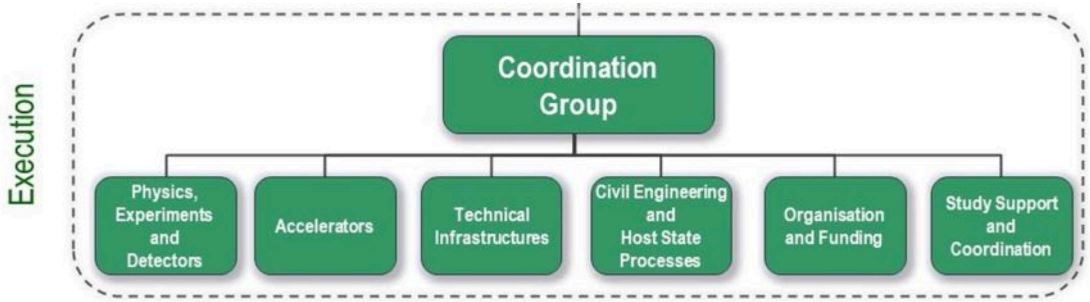
- **FCC-Conceptual Design Reports:**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

  EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

- **Summary documents provided to EPPSU SG**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

# FCC Feasibility Study

## Main deliverables and milestones (i):



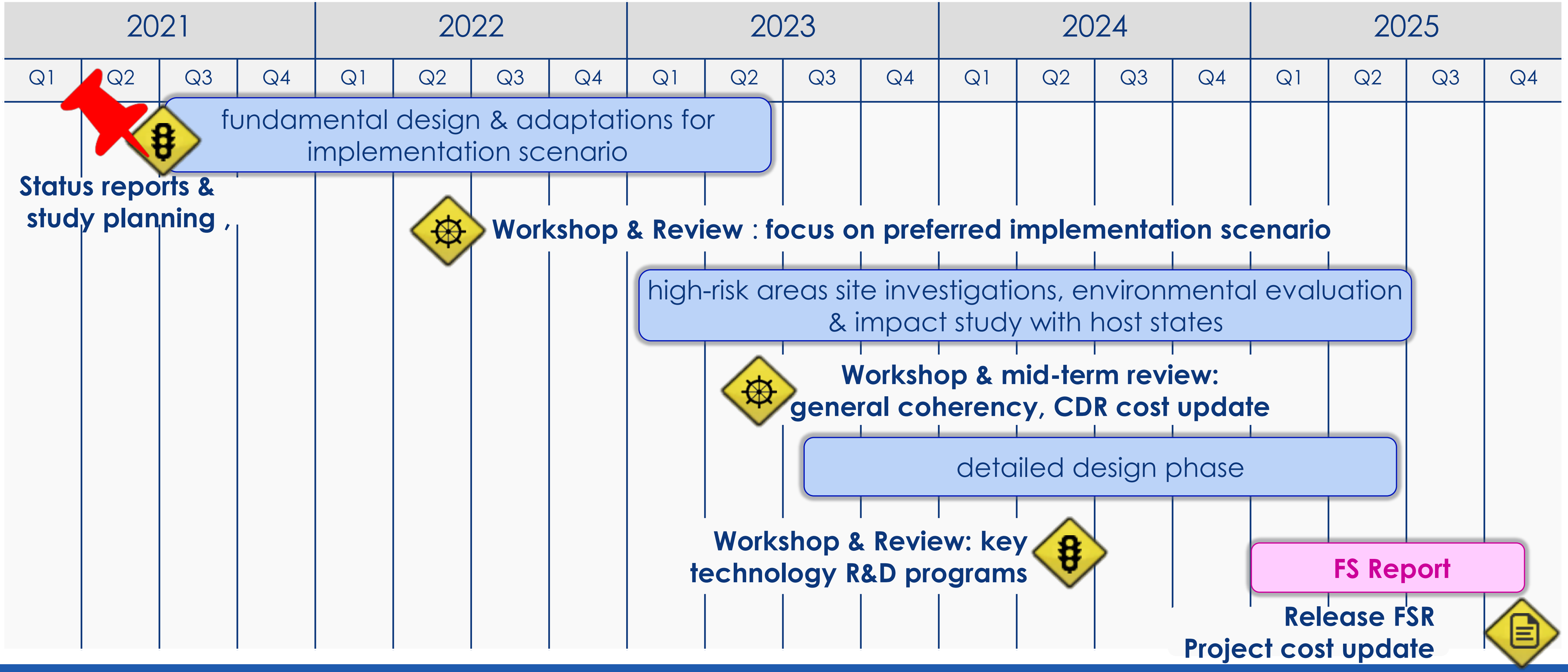

### Physics, experiments and detectors

- ❑ consolidation of physics case for full FCC programme;
- ❑ requirements on theoretical calculations, Monte Carlo generators and other software;
- ❑ detector concepts for FCC-ee and FCC-hh (also based on experience with Phase-2 upgrades);
- ❑ detector design and R&D (synergies with "R&D for future detectors" at CERN and ECFA Detector Roadmap);
- ❑ requirements on accelerator performance, technical infrastructure, computing and integration.

### Accelerators

- ❑ design of FCC-ee and FCC-hh, and their injectors;
- ❑ development of key technologies for both colliders, including high-field superconducting magnets, SCRF, high-efficiency power production, and other sustainable and environmentally-friendly technologies; milestones will be finalised once Accelerator R&D roadmap available;
- ❑ machine-detector interface for FCC-ee (final focus magnets and compensation solenoids).

# Feasibility study timeline



# Possible scenarios

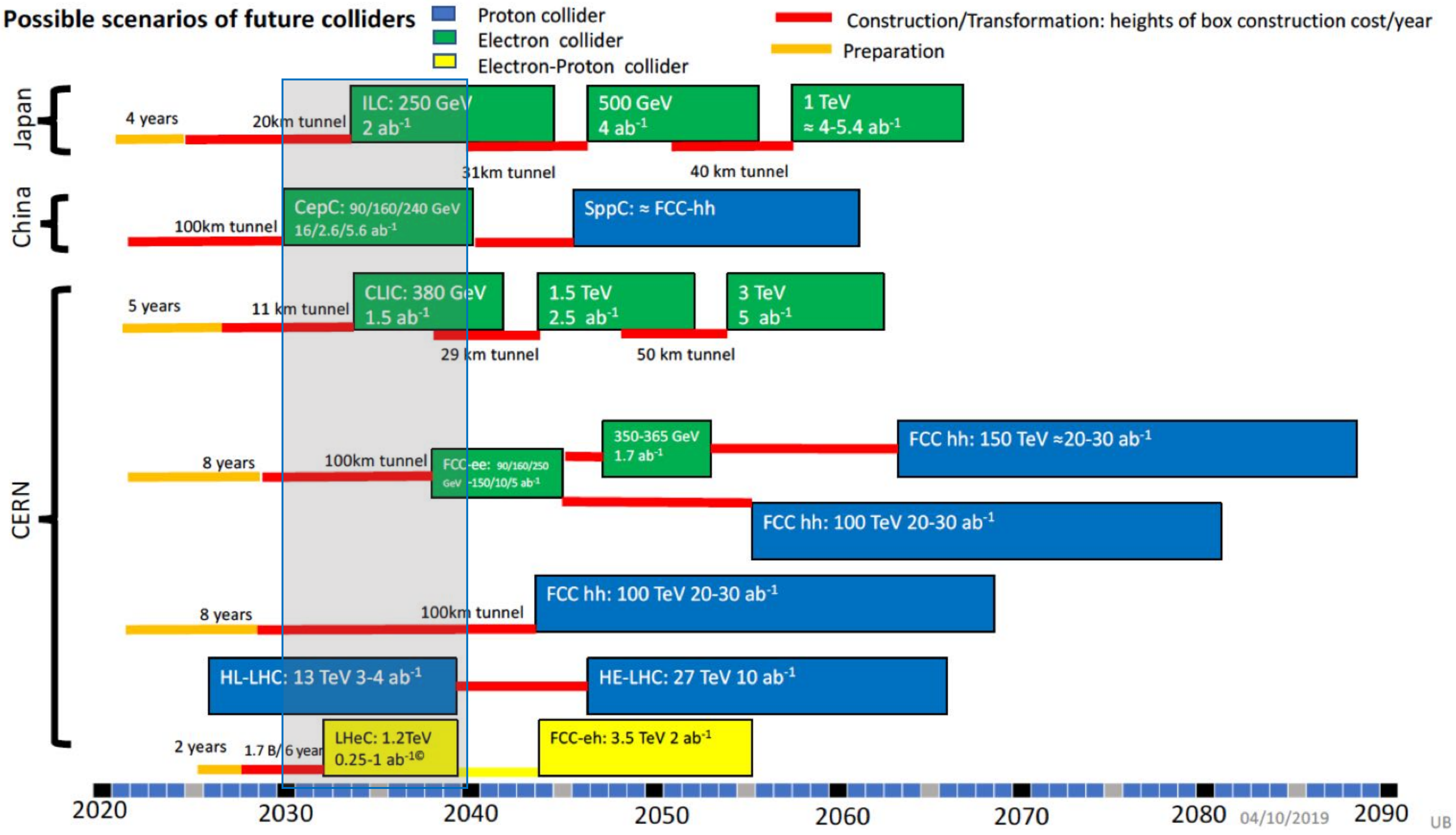



*Figure 1 Timeline of Future Colliders as extracted from the submitted inputs (by U. Bassler)*

CERN/ESG/05

Being updated by SPC/ECFA

# Higgs factory – which flavour?



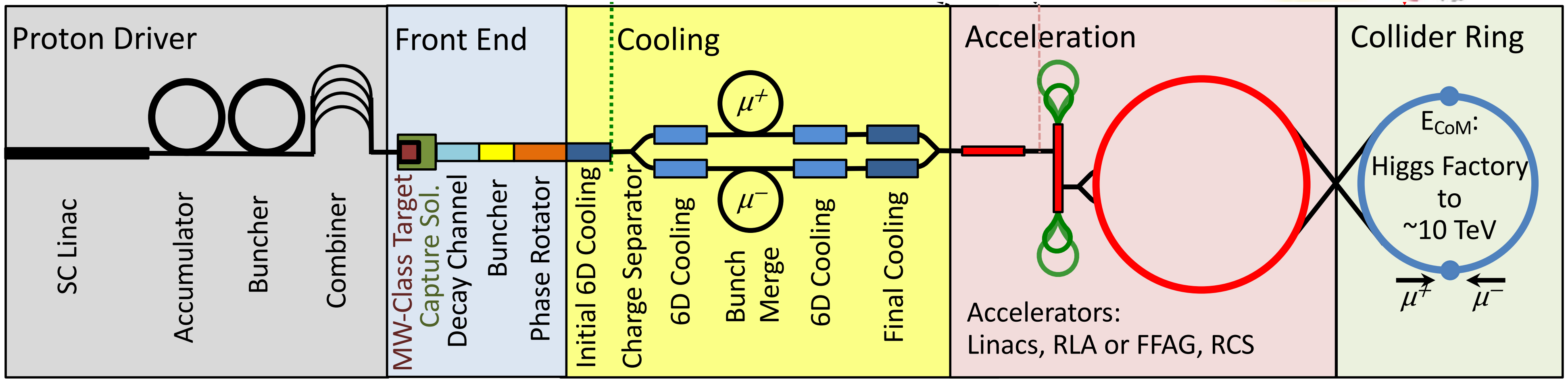
Lenny Rivkin

# Muon Collider: protons on target

- Main advantage of $\mu^+\mu^-$ compared to $e^+e^-$ is higher mass: $(0.115 \text{ MeV} / 105.658 \text{ MeV})^4$ less synchrotron radiation
  - *TeV collider fits in small ring!*

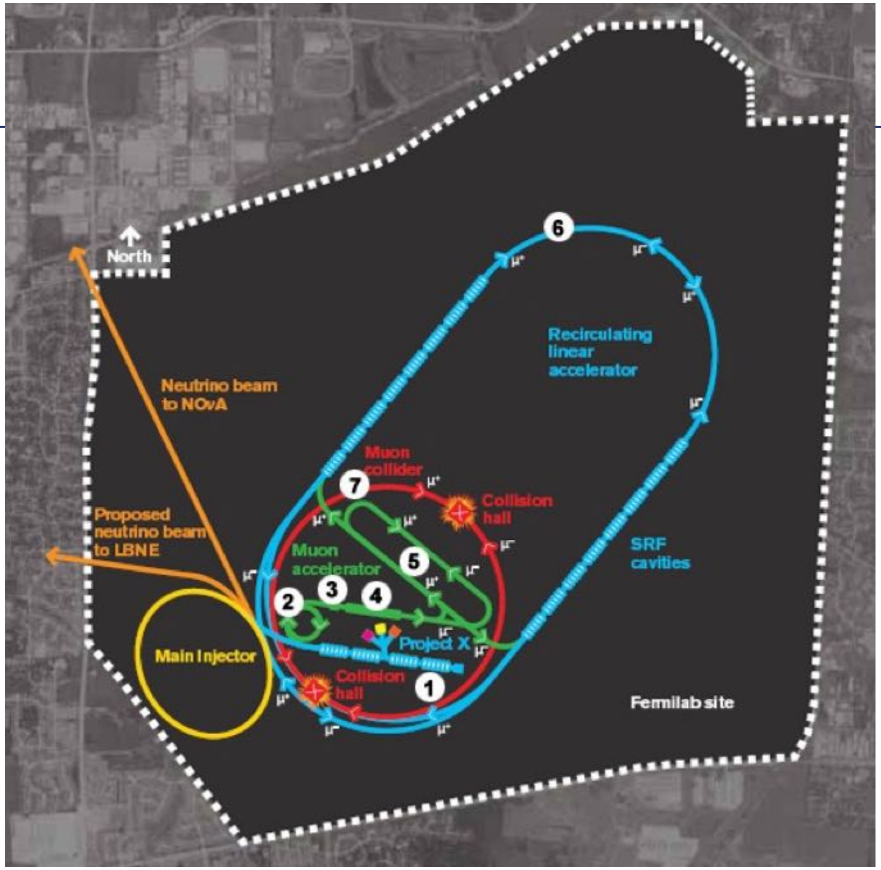
Challenges:

- Muon lifetime is only 2.197 μs.
  - *Need to rapidly accelerate muons to relativistic energies, so lifetime in lab frame is extended.*
- Muons created by protons on target & pion decay.

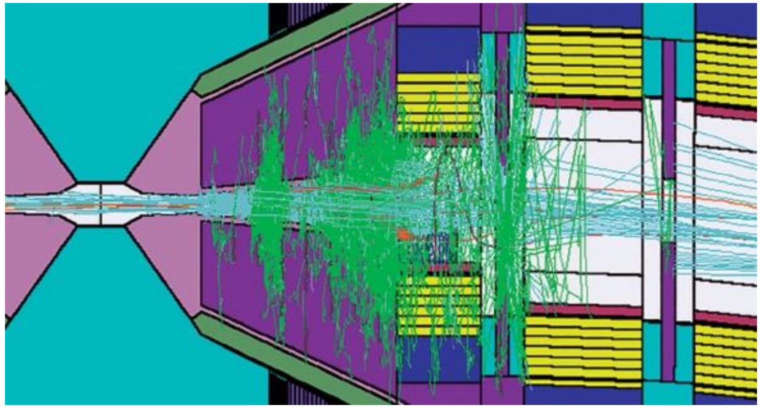
# Muon Collider

- 4 TeV muon collider would fit on the former Tevatron site at Fermilab
- A muon collider in the LHC tunnel could reach 14TeV CoM




Main technical challenges:

- Muon beam from target is produced with extremely large emittance:
  - *Need rapid cooling so short-lived muons can be captured (see next slides)*
- Beam quality, cost and power
- Machine Detector Interface:
  - *After acceleration, the muon beam decay products interact with the machine components tens of meters from the Interaction Point (IP), generating high fluxes of beam induced background (BIB) on the detector.*

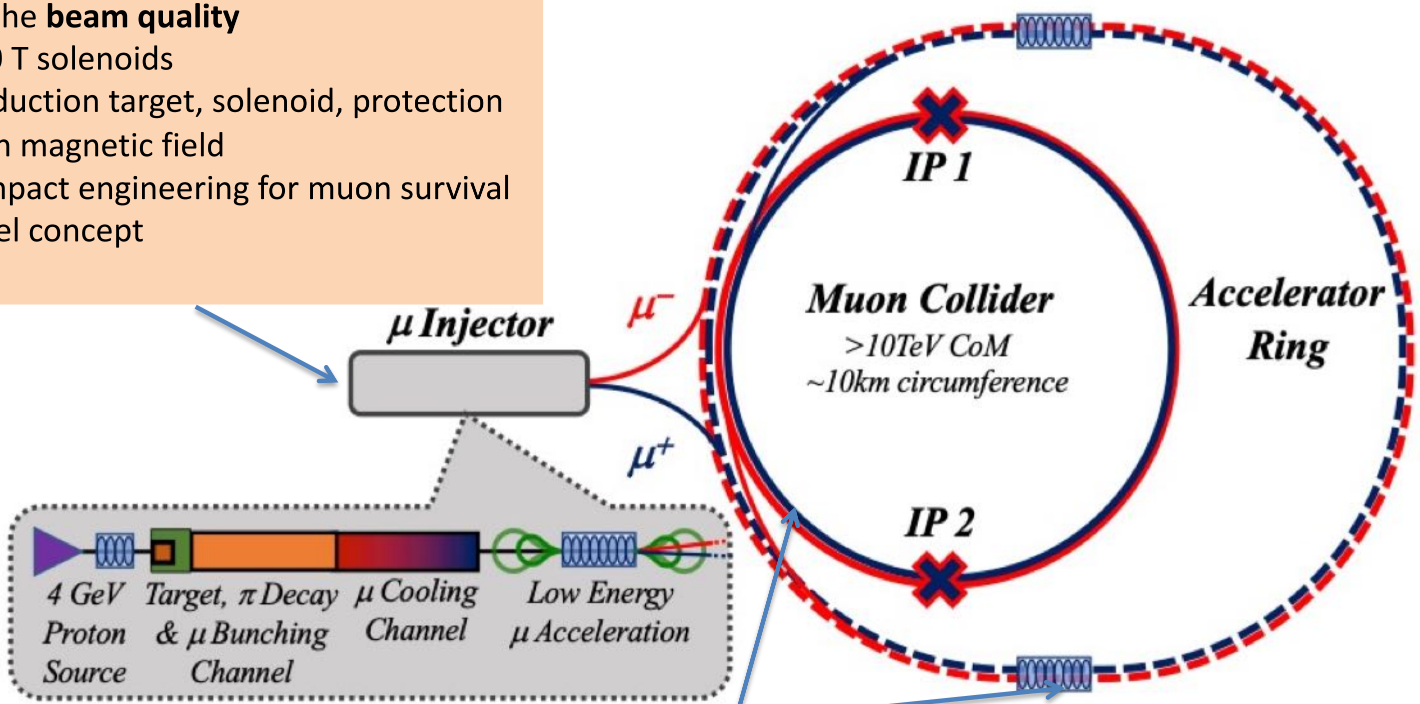


N Mokhov

# Muon Collider

## R&D Challenges

Drives the **beam quality**
- > 30 T solenoids
- Production target, solenoid, protection
- RF in magnetic field
- Compact engineering for muon survival
- novel concept
- …




**Cost** and **power** consumption limit energy reach
- Superconducting collider ring magnets
- Fast ramping magnets with energy recovery
- Efficient RF for high bunch charge
- FFA
- Protection of collider magnets from muon decays

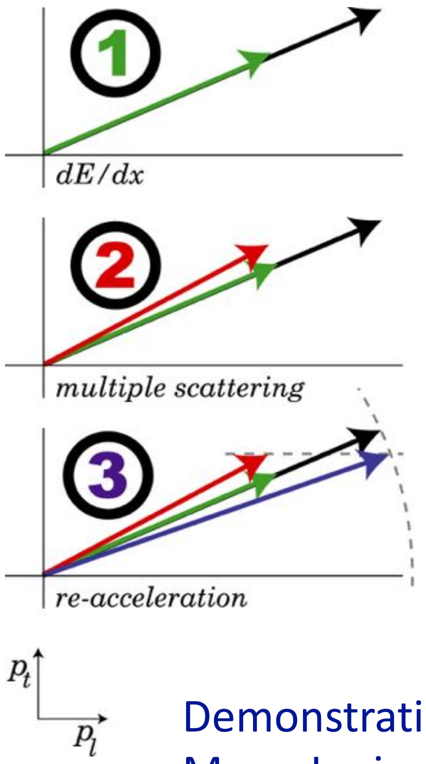
**Neutrino flux** and **MDI** limit energy reach
- Machine detector interface
- Neutrino flux on Earth surface (have mitigation idea)

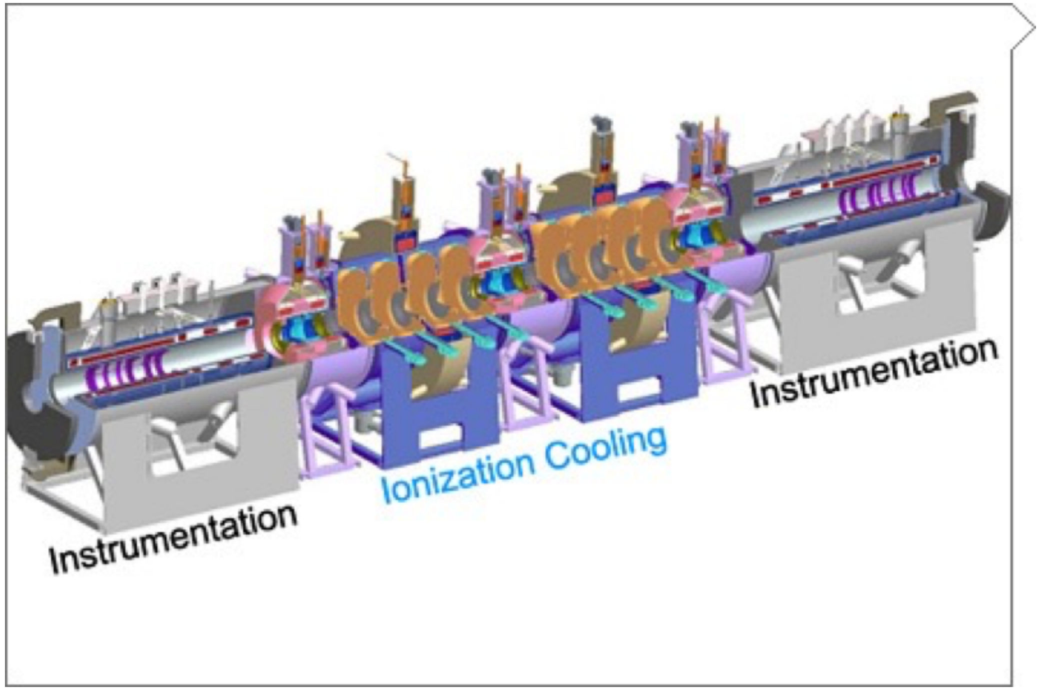
Integrated coherent concept/parameters

Muon beam panel, June 2021

# MICE experiment: cool demonstration

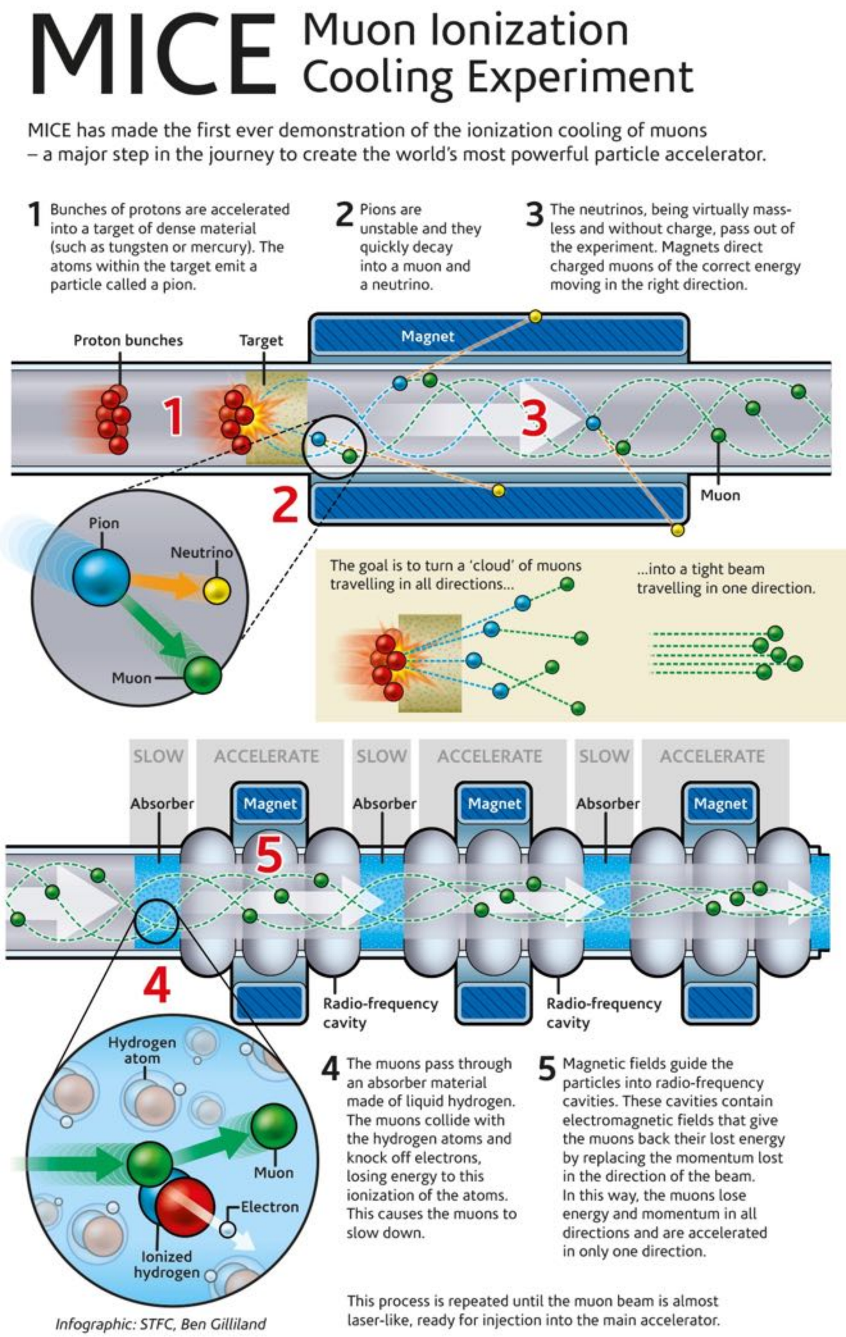
- High intensity protons on target generate pions that decay:
  - *Large 6D emittance beams must be cooled:*
  - *Muon ionization cooling demonstration by MICE.*




Demonstration of cooling by the
Muon Ionization Cooling Experiment

https://www.nature.com/articles/s41586-020-1958-9

# MICE experiment: cool demonstration

- High intensity protons on target generate pions that decay:
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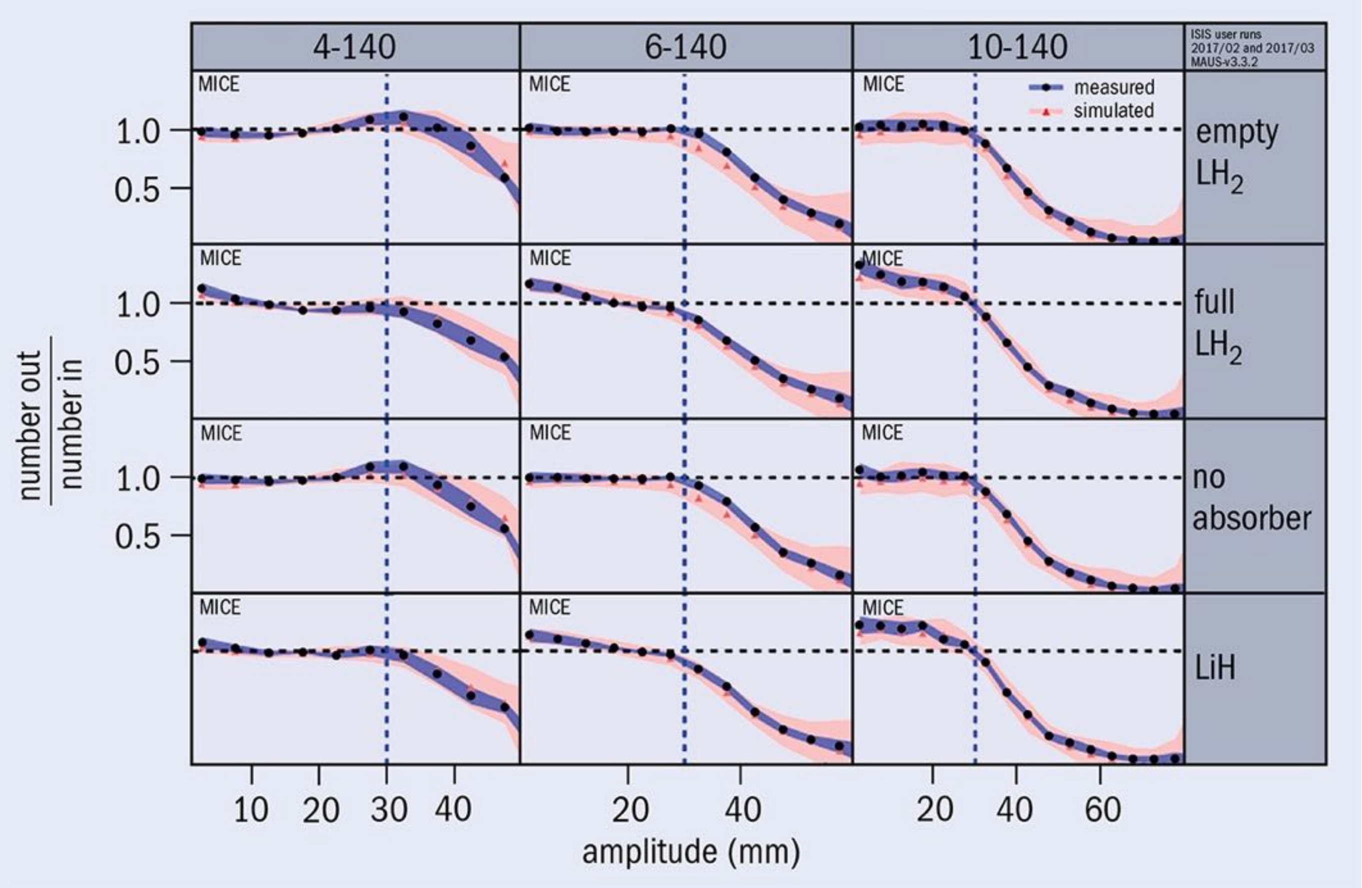
  - *Muon ionization cooling demonstration by MICE.*



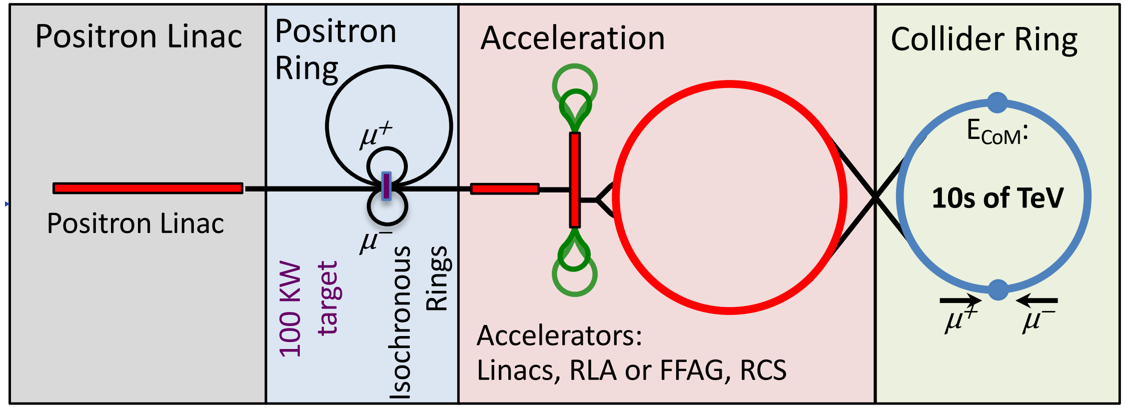

A ratio of greater than unity is observed with both the full LH2 absorber and the LiH absorber

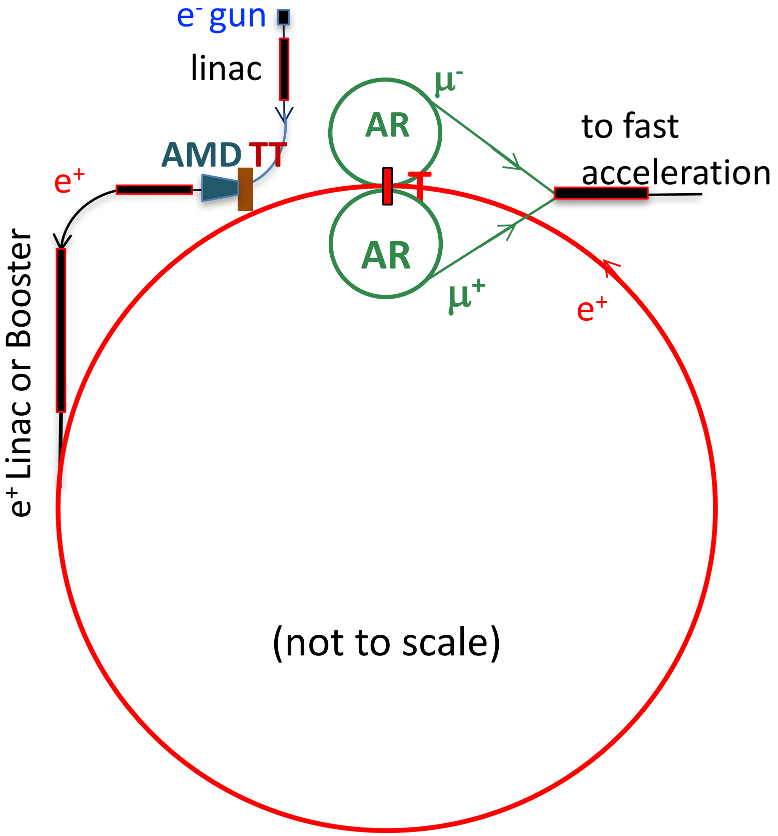
- https://www.nature.com/articles/s41586-020-1958-9

# Muon collider alternative schemes

- LEMMA: Low Emittance Muon Accelerator
  - *High intensity 45 GeV e+ beam hits thin target (0.01 rad length) collides with e- in target, giving muon pair just above threshold:*
  - *Small emittance and small energy spread, therefore no need for cooling.*
  - *6.2 km storage ring.*

$$e^+e^- \rightarrow \mu^+\mu^-$$



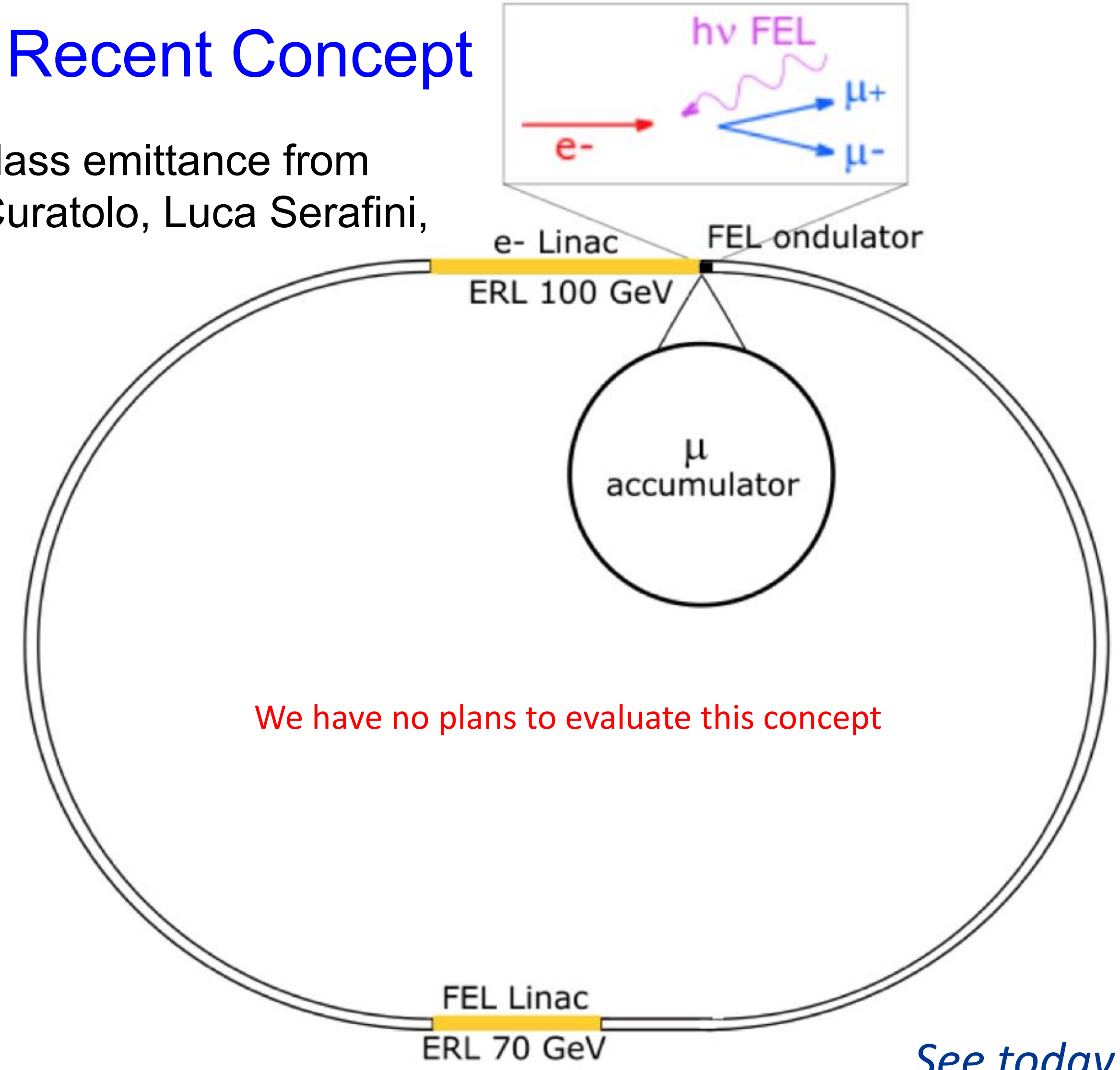
# Muon collider alternative schemes

## Very Recent Concept

- "GeV muon beams with picometer-class emittance from electron-photon collisions" Camilla Curatolo, Luca Serafini, https://arxiv.org/abs/2106.03255

- Concept of a 100 GeV eERL with X-Ray FEL as basis for a muon collider
- Muons are produced via the

  $e^- + \gamma \rightarrow e^- + \mu^+/\mu^-$ reaction
- The calculated geometric emittance is 10 picometer-radian
- Since only a small number of interactions occur, the energy of the electron beam is recovered in an ERL configuration

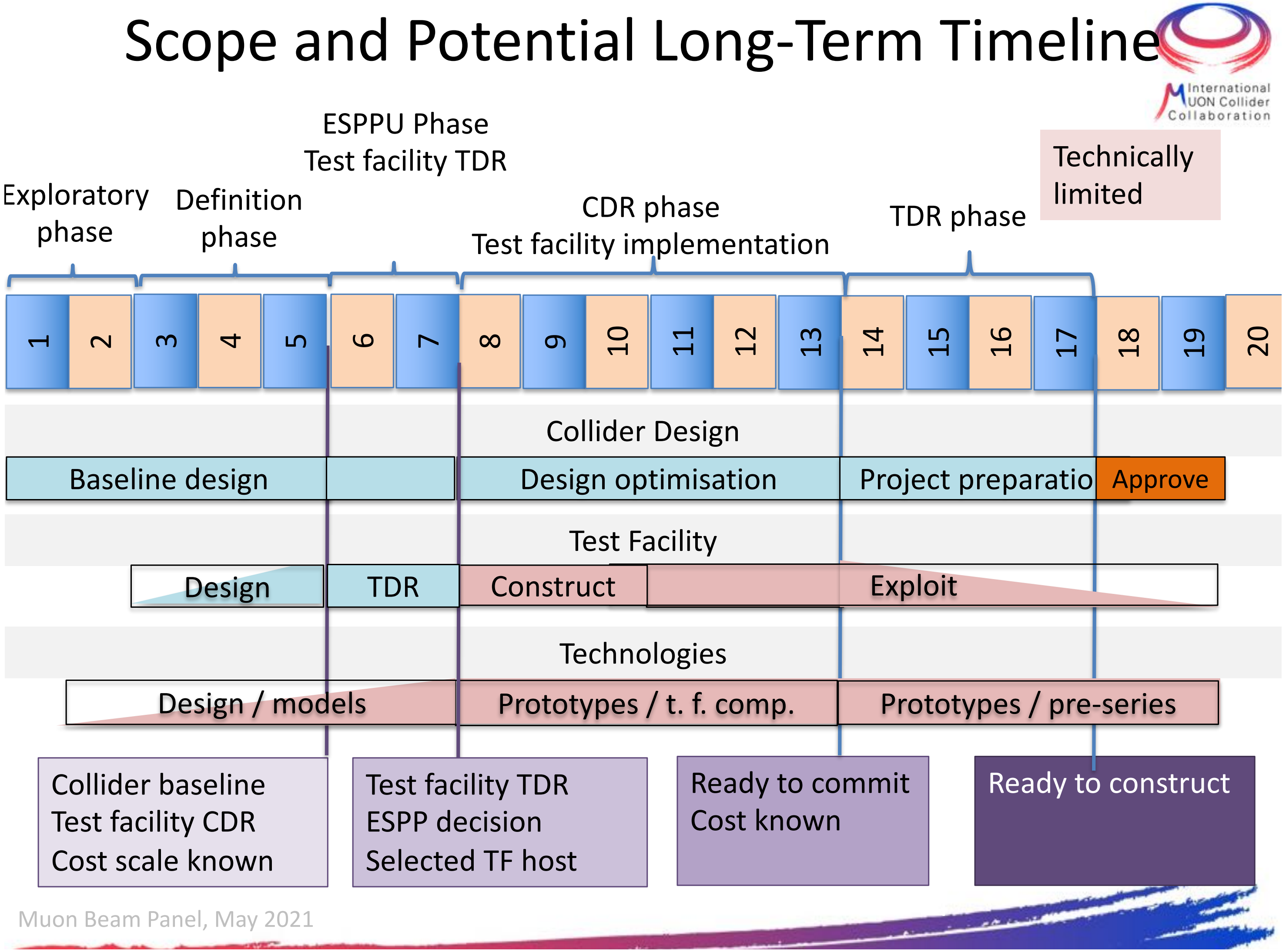



We have no plans to evaluate this concept

Symposium on the accelerator R&D roadmap for HEP community July 9, 2021

*See today's **Symposium***
*https://indico.cern.ch/event/1053889/*

# Muon collider outlook



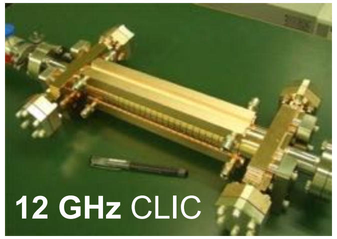

*See more details at today's*
***Symposium***
*https://indico.cern.ch/event/1053889/*

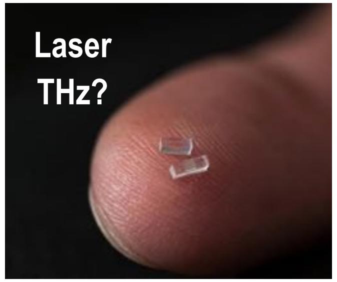
*and Muon Community Meeting next week, 12-14 July 21: https://indico.cern.ch/event/1043242/*

# Table top accelerators?

How to increase acceleration gradient beyond conventional RF 100 MV/m (CLIC technology)?

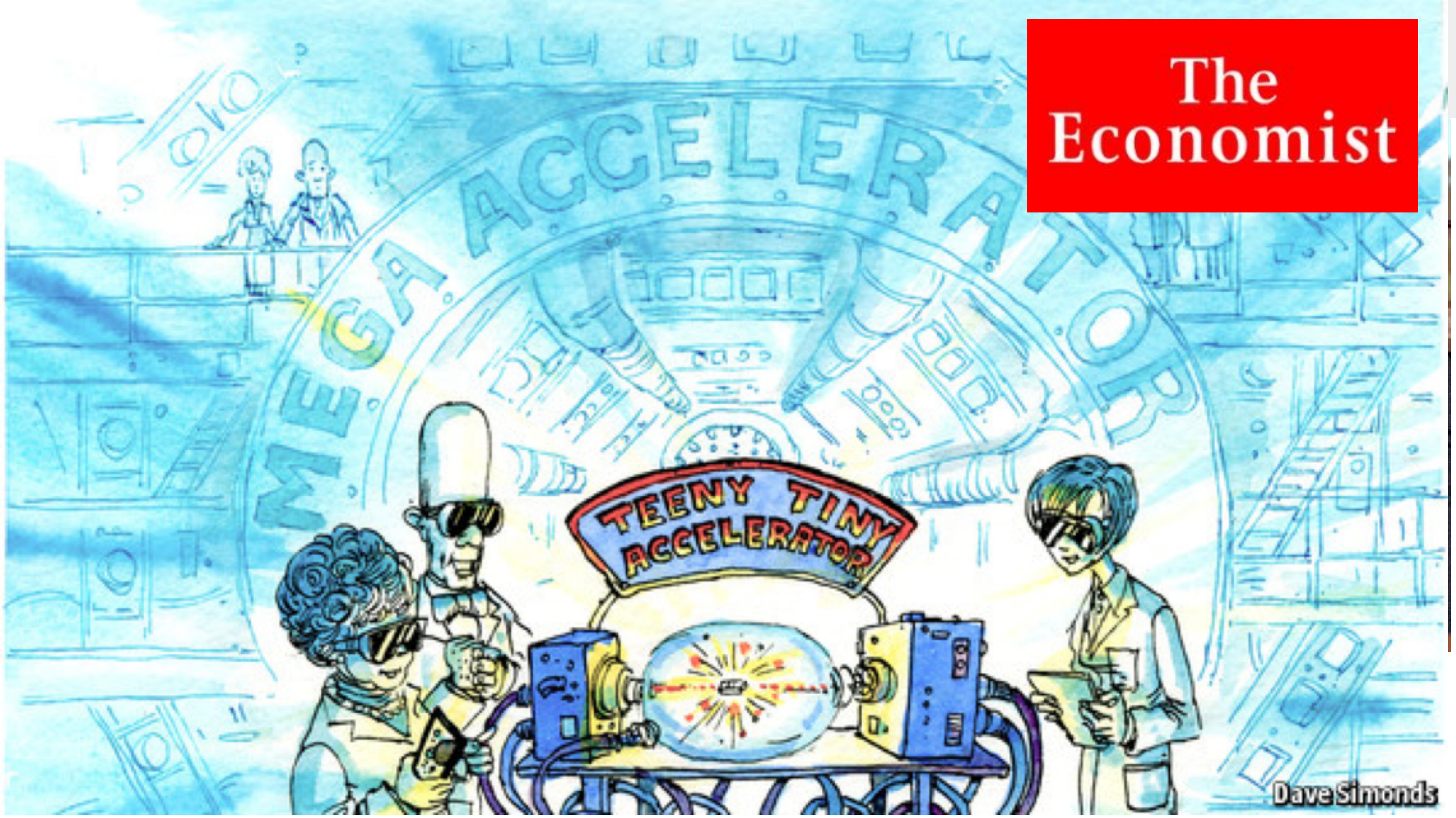
## RF Acceleration: scaling with frequency


GORDON AND BETTY MOORE FOUNDATION

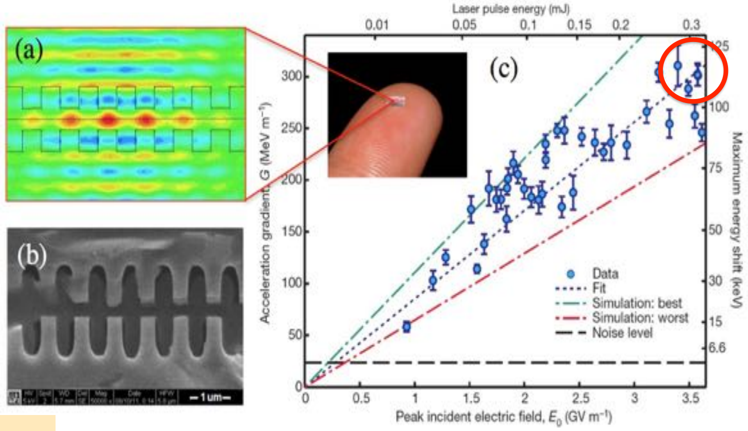
DESY EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG PAUL SCHERRER INSTITUT PSI SLAC NATIONAL ACCELERATOR LABORATORY



# Laser dielectric / THz

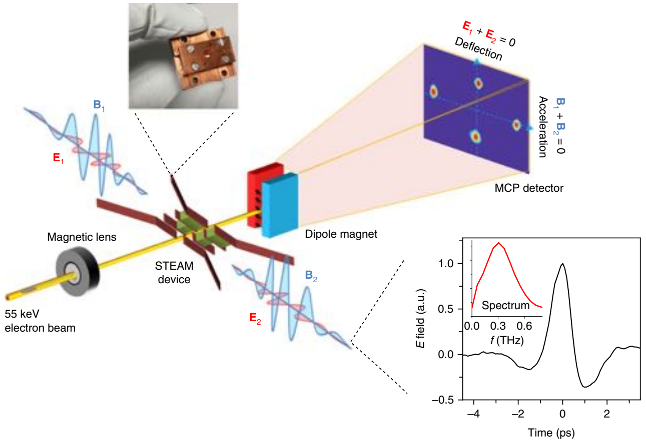
- ***Dielectric Laser Accelerators***
  - High electric field at optical wavelengths:
  - Gradients < 0.3-1 GeV/m
  - Staging rather inefficient, lowers average gradient
  - Laser efficiency -> high power requirements.

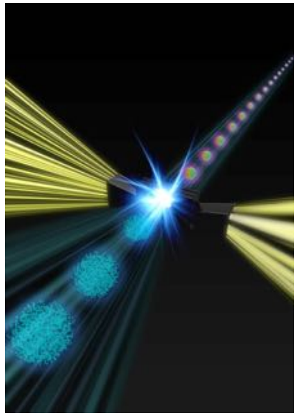
Peak gradient as a function of Laser Field




Peralta et al., Nature **503**, 91 (2013)

- ***THz structures***
  - Easier to manufacture / control at THz wavelength.
  - Recent demonstration of THz accelerated beams (>30 keV so far):



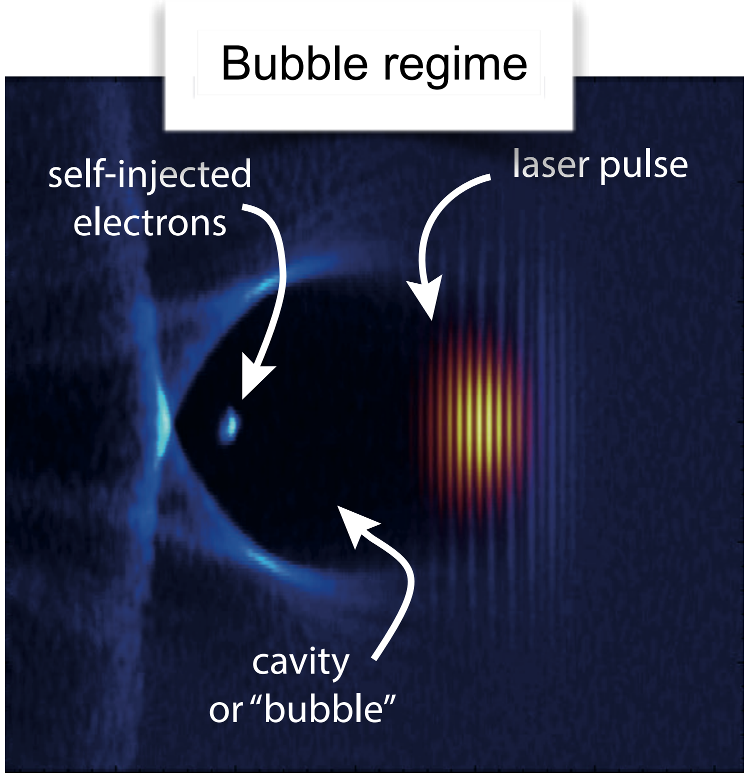
nature photonics ARTICLES
https://doi.org/10.1038/s41566-018-0138-z

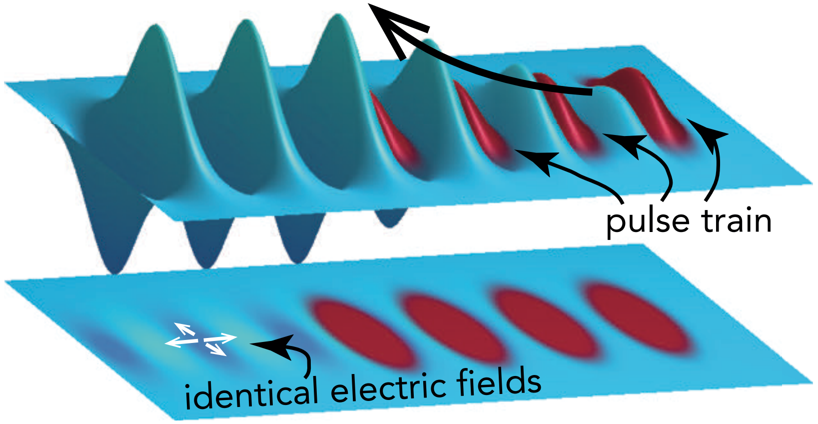
**Segmented terahertz electron accelerator and manipulator (STEAM)**

Dongfang Zhang[1,2,5]*, Arya Fallahi[1,5], Michael Hemmer[1], Xiaojun Wu[1,4], Moein Fakhari[1,2], Yi Hua[1], Huseyin Cankaya[1], Anne-Laure Calendron[1,2], Luis E. Zapata[1], Nicholas H. Matlis[1] and Franz X. Kärtner[1,2,3]

# Laser-plasma wakefield

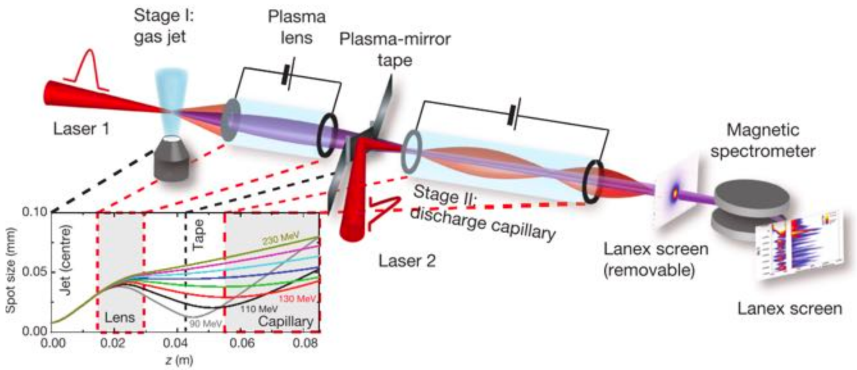
- ***Laser-plasma accelerators*** *(8 GeV demonstrated)*
  - Laser pulse in plasma filled capillary enables electrons to surf a plasma density wave.
  - Recent exciting developments in multi-pulse schemes and staging at low energies.




S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

LBNL have demonstrated staging at low energies (~200 MeV increased to ~300 MeV).



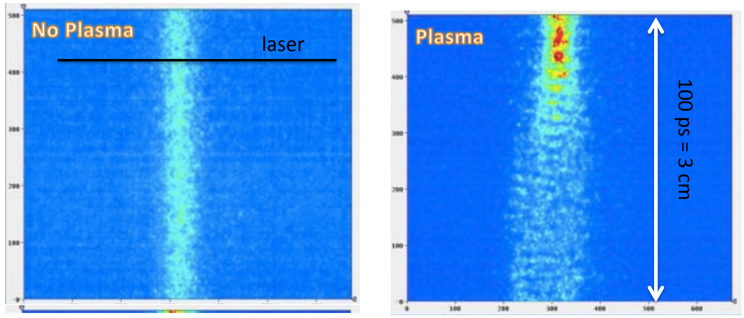

Steinke, S. et al. Multistage coupling of independent laser-plasma accelerators. Nature 530, 190–193 (2016).

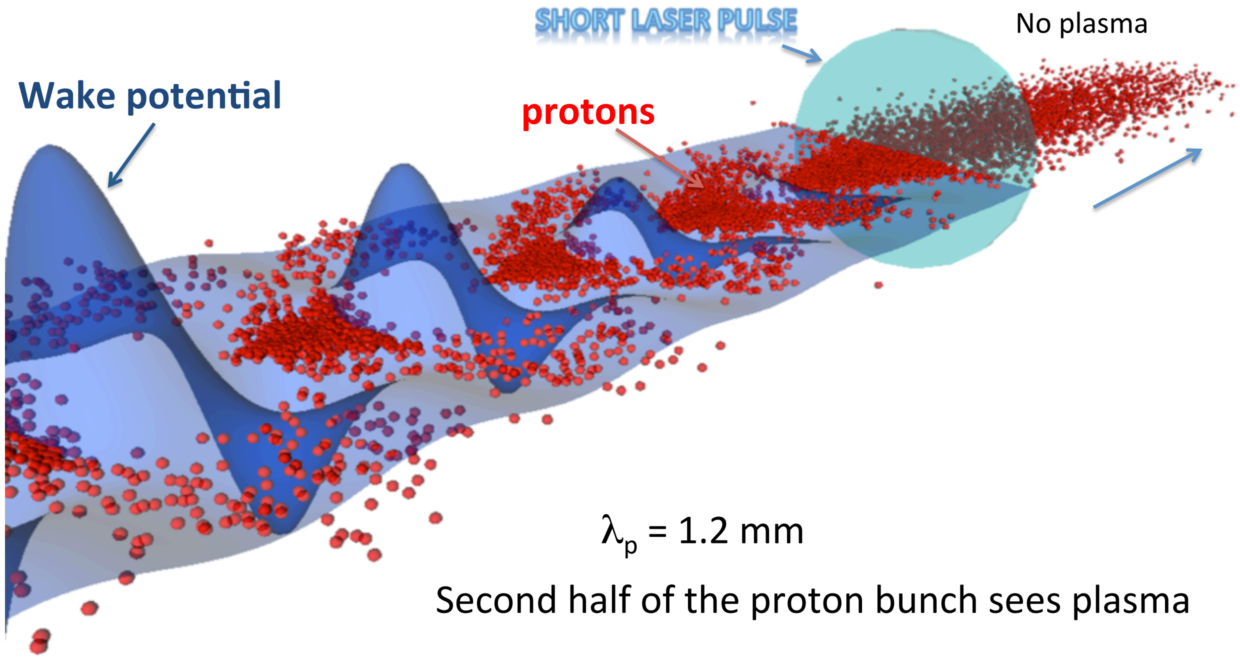
Van Tilborg, J. et al. Active Plasma Lensing for Relativistic Laser-Plasma-Accelerated Electron Beams. Phys. Rev. Lett. 115, 184802 (2015).

# Beam drive plasma wakefield: AWAKE experiment

- ***Proton driven plasma wakefield***
  - 12cm, $3\times10^{11}$ proton bunch drives plasma wakefield in cell at SPS.
  - Successful observation of self-modulation in LHC Run II
  - Successful acceleration of 15 MeV injected e- to 0.8 GeV.

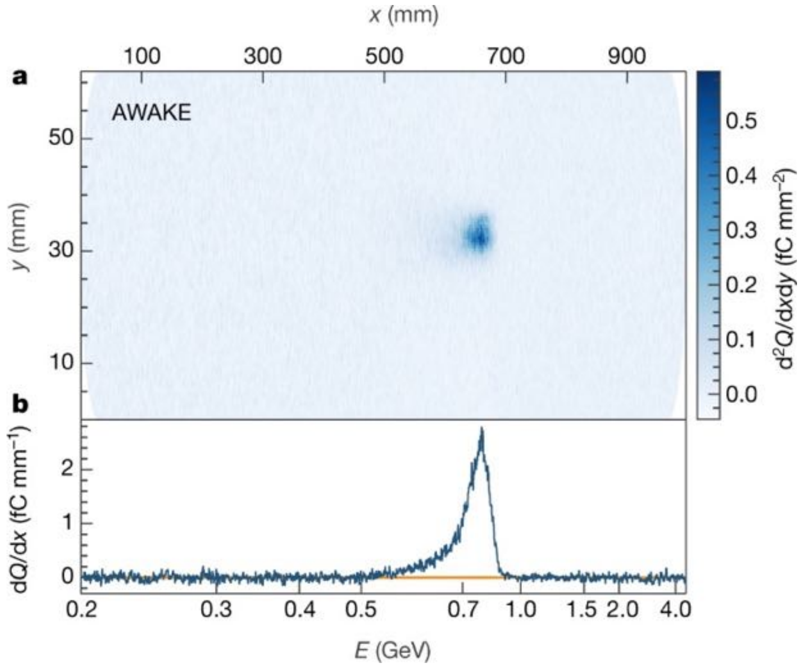
**Self-modulated proton bunch** resonantly driving plasma wakefields.



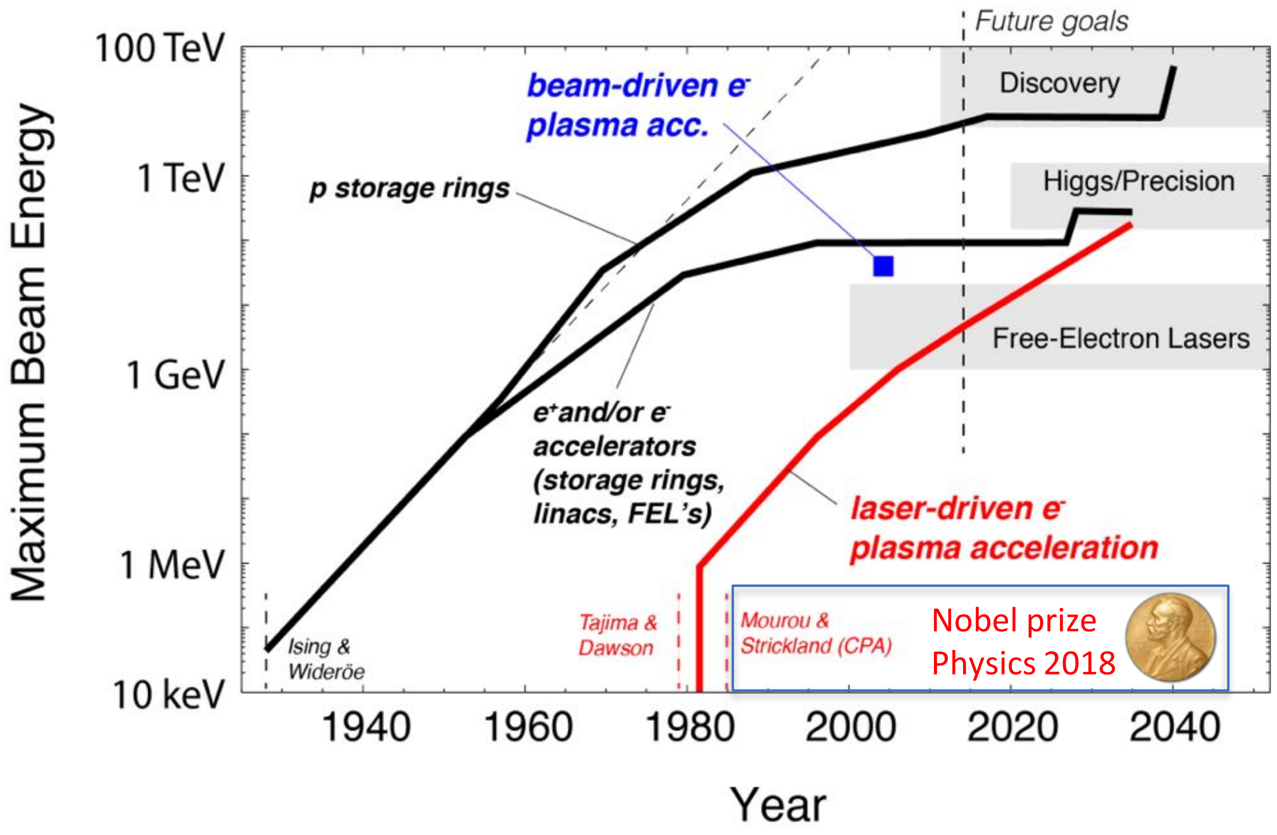

$\lambda_p$ = 1.2 mm

Second half of the proton bunch sees plasma

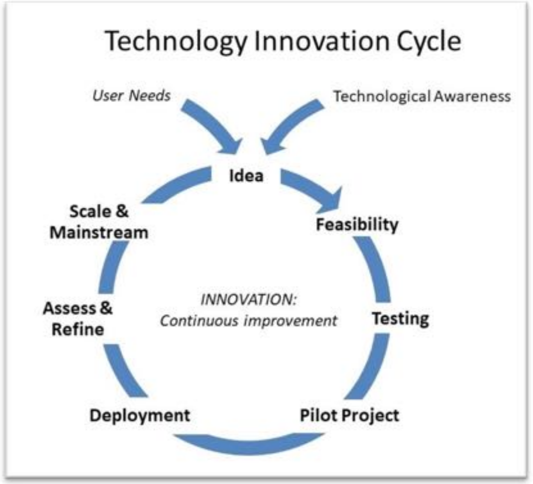



https://doi.org/10.1038/s41586-018-0485-4

# Plasma and Laser Accelerators: New Livingston Curve




- Examples of **new ideas and solutions**: RF, strong focusing, beta squeeze, stochastic cooling, polarized beams, super-conducting magnets/RF, advanced materials for vacuum/collimators, plasma / laser accelerators, …
- **Particle physics in the driver seat** for most of those developments



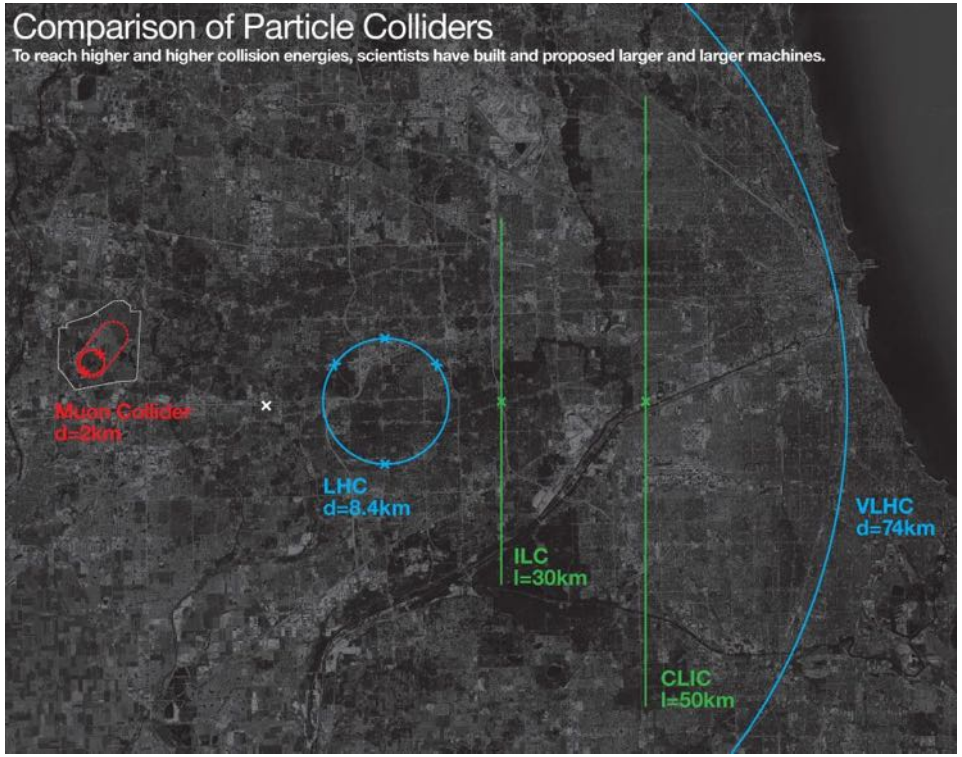

A. Walter Dorn, Unite Paper 2021(1)
https://walterdorn.net/home/295-tech-innovation-model-for-un-2

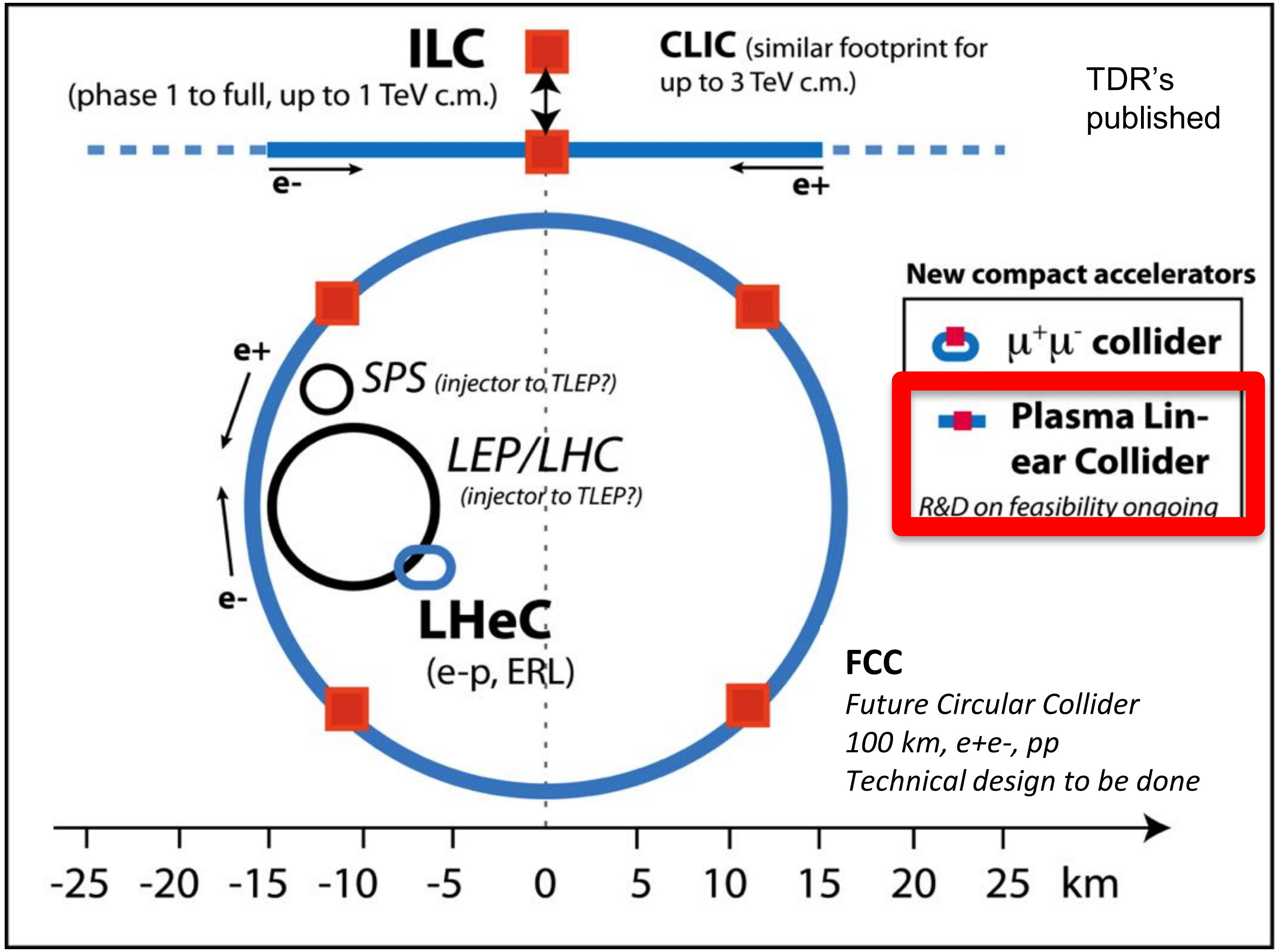
Accelerators are in a **continuous technology innovation cycle** to be successful:

E. Gschwendtner, R. Assmann

https://indico.cern.ch/event/1053889/

# Is A Compact Plasma/Laser Collider Feasible?




**Devil is in the details!** Answer requires detailed simulation, calculations, designs and tests!

E. Gschwendtner, R. Assmann 13

https://indico.cern.ch/event/1053889/

# Moon beams ?



## A very high energy hadron collider on the Moon

James Beacham[1,*] and Frank Zimmermann[2,†]

[1] *Duke University, Durham, N.C., United States*

[2] *CERN, Meyrin, Switzerland*

(Dated: June 17, 2021)

The long-term prospect of building a hadron collider around the circumference of a great circle of the Moon is sketched. A Circular Collider on the Moon (CCM) of ~11000 km in circumference could reach a proton-proton center-of-mass collision energy of 14 PeV — a thousand times higher than the Large Hadron Collider at CERN — optimistically assuming a dipole magnetic field of 20 T. Siting and construction considerations are presented. Machine parameters, powering, and vacuum needs are explored. An injection scheme is delineated. Other unknowns are set down. Through partnerships between public and private organizations interested in establishing a permanent Moon presence, a CCM could be the (next-to-) next-to-next-generation discovery machine and a natural successor to next-generation machines, such as the proposed Future Circular Collider at CERN or a Super Proton-Proton Collider in China, and other future machines, such as a Collider in the Sea, in the Gulf of Mexico. A CCM would serve as an important stepping stone towards a Planck-scale collider sited in our Solar System.

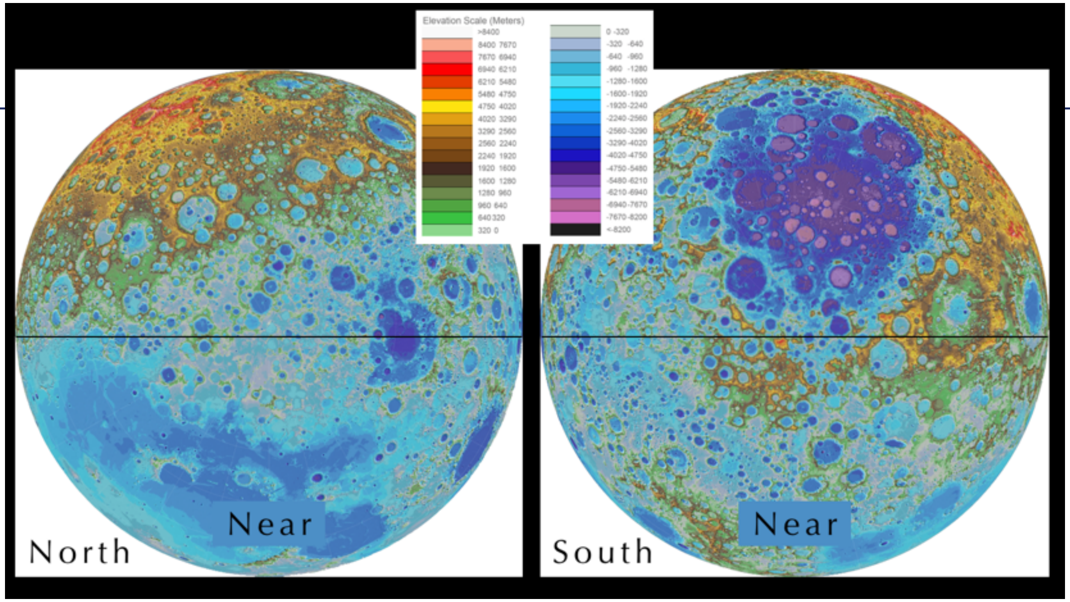



FIG. 2. Schematic possible trajectory (black line) of a Circular Collider on the Moon (CCM) that could potentially avoid several major elevation changes, though not all. In the left image the north pole of the Moon is centered, while in the right image the south pole is centered. Images modified from Ref. [31]; the originals were constructed with data collected by the Lunar Reconnaissance Orbiter [32–36].

| Parameter | CCM | FCC-hh | HL-LHC |
|---|---|---|---|
| Max. beam energy $E_{\rm beam}$ [TeV] | 7,000 | 50 | 7 |
| Circumference $C$ [km] | 11,000 | 97.8 | 26.7 |
| Arc dipole magnet field $B_{\rm dip}$ [T] | 20 | 16 | 8.3 |
| Luminosity / IP $L$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | ~20,000 | ~30 | 5 (leveled) |
| Number of events/crossing (pile-up) | ~$10^6$ | ~1000 | 135 |
| Max. integrated lum./experiment [ab$^{-1}$/y] | ~2000 | 1.0 | 0.35 |

TABLE I. Tentative proton-proton parameters for CCM, compared with FCC-hh and HL-LHC [40].

# Summary

- *Technology developments for HL-LHC are applicable at future lepton and hadron colliders:*
  - *Novel collimation, SCRF, crab-cavities, diagnostics, cold powering, laser of engineering surfaces...*
- *The EU strategy update has helped to launch several feasibility studies, especially towards finding the near term technical solutions to create a Higgs Factory.*
- *Much progress has been made and further innovation is needed to address challenges across 5 technology pillars for future machines:*
  - *High-field magnets; High-gradient plasma/laser, high-gradient RF structures; muon beams, ERLs.*
  - *Community feedback is welcome to the Accelerator Roadmap: https://indico.cern.ch/event/1053889/*

***Thanks to the YETI21 organisers and all who contributed slides!***