Future Accelerators for Particle Physics

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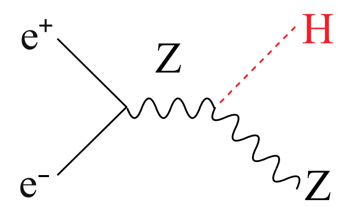
3 main complementary ways to search for (and study) new physics at accelerators

F. Gianotti

Direct

production of a given (new or known) particle

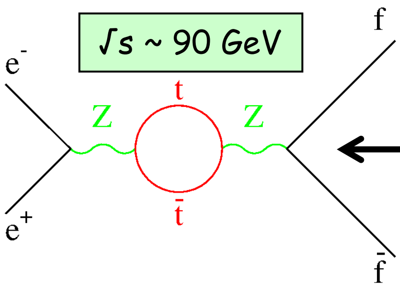
e.g.: Higgs production at future e^+e^- linear/circular colliders at $\sqrt{s}$ ~ 250 GeV through the HZ process
→ need high E and high L



Indirect

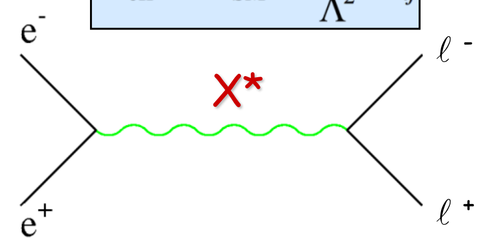
precise measurements of known processes

→ look for (tiny) deviations from SM expectation from quantum effects (loops, virtual particles)
→ sensitivities to E-scales Λ>> $\sqrt{s}$ → need high E and high L



E.g. top mass predicted by LEP1 and SLC in 1993: m_{top} = 177 ± 10 GeV; first direct evidence at Tevatron in 1994: m_{top} = 174 ± 16 GeV

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{C_{\rm NP}}{\Lambda^2} O_{ij}$$

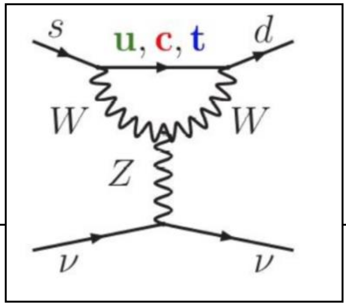


Rare processes

suppressed in SM → could be enhanced by New Physics

e.g. neutrino interactions, rare decay modes → need intense beams and/or ultra-sensitive (massive) detectors ("intensity frontier")

E.g. $K^+ \to \pi^+ \nu\nu$ decay (NA62 experiment)
Proceeds via loops → suppressed in the SM : BR~ 10^{-10}
Can be enhanced by new particles running in the loop.
Theoretically very clean.



Accelerator History for Particle Physics

Different options

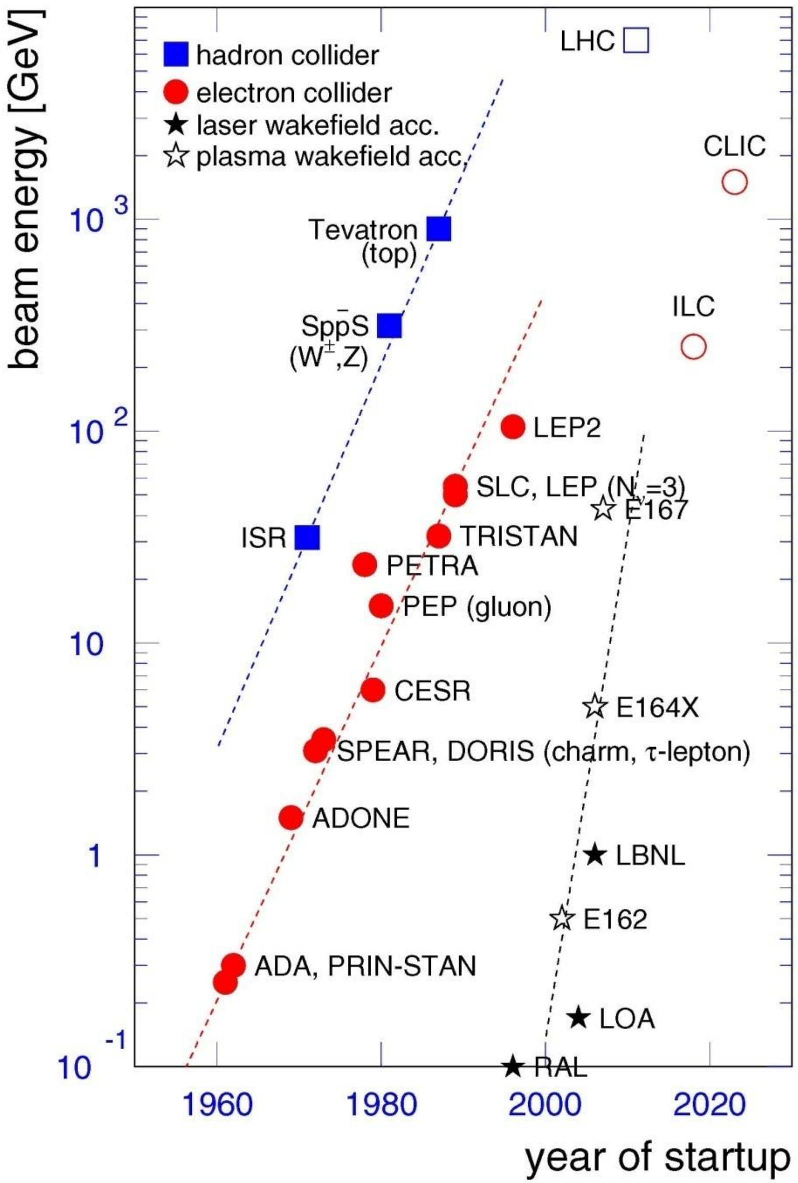
- what to collide: lepton vs hadron
- how to collide:
  - fixed target or colliding beams
  - linear vs circular
  - acceleration technology
    - DC, RF, wakefield

Project ideas

- linear electron collider: SC or NC
- circular electron or proton collider
- circular electron – proton collider

But also

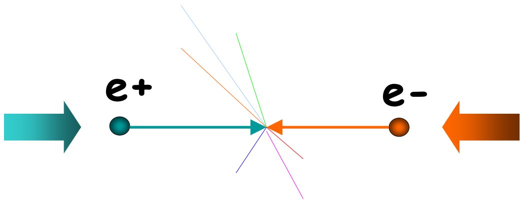
- non-HEP use of accelerators

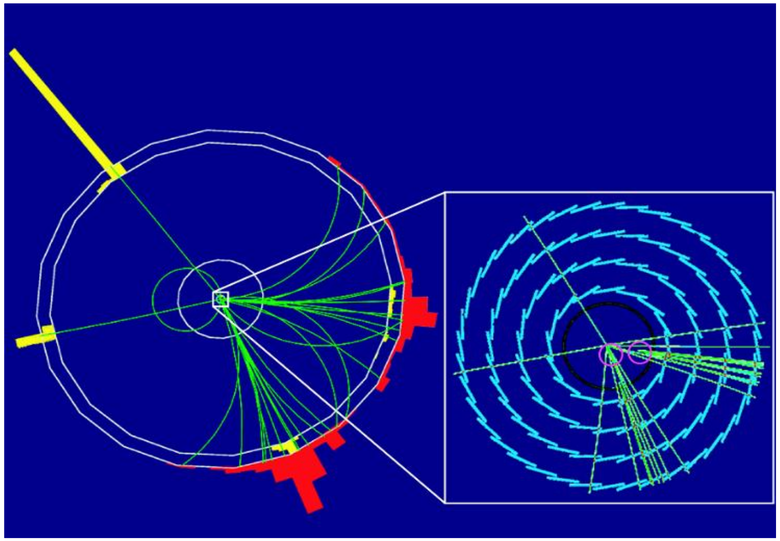


Lepton versus Hadron Collisions

Leptons

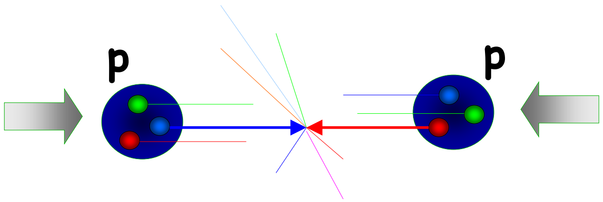
- for precision physics
- well defined CM energy
- polarization possible

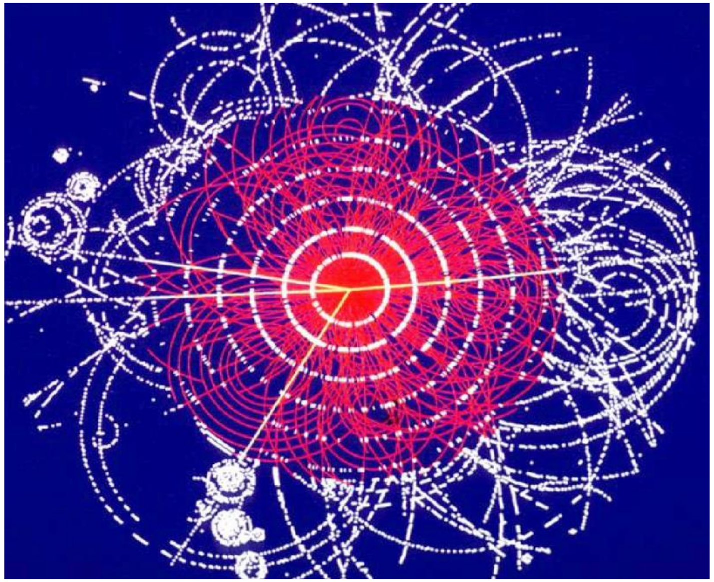




Hadrons

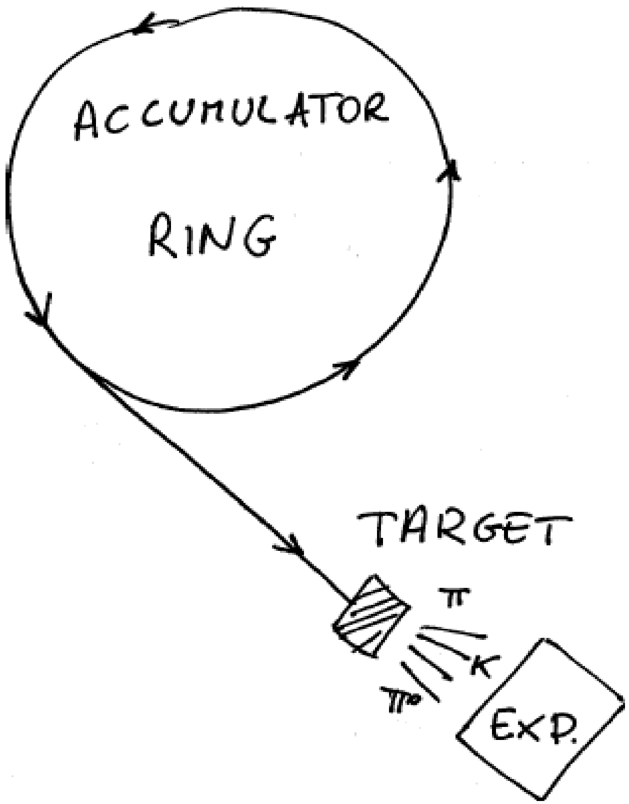
- at the frontier of physics
- huge QCD background
- not all nucleon energy available in collision



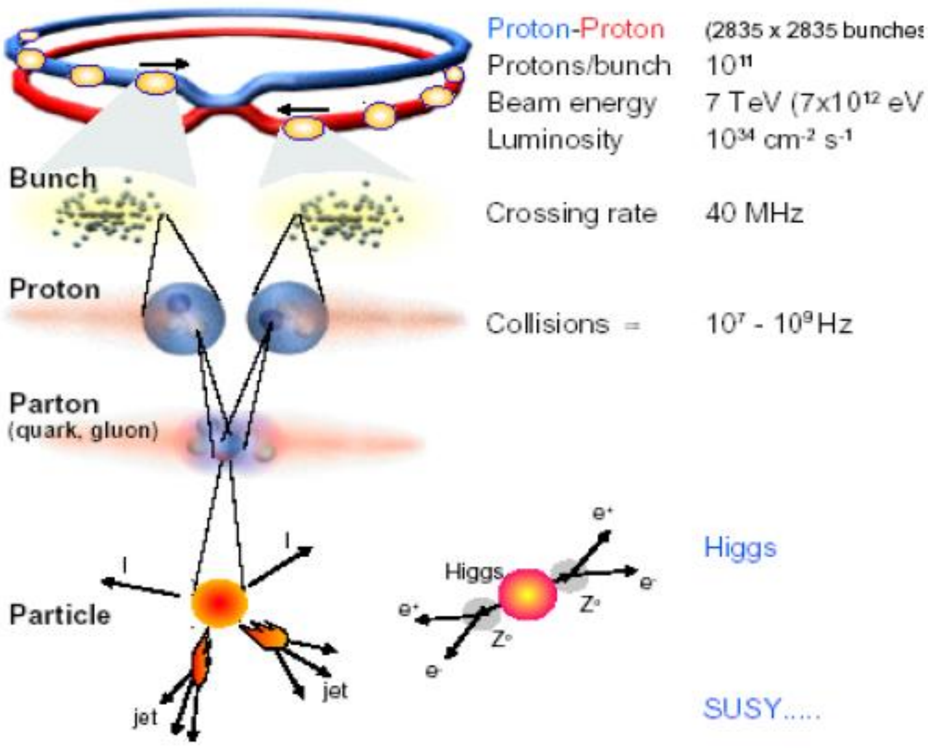


Particle Collisions

Fixed Target



Collider



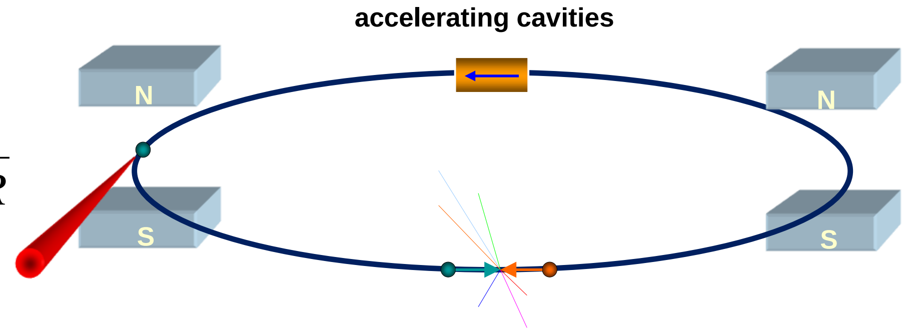
$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

Linear versus Circular

Circular Collider

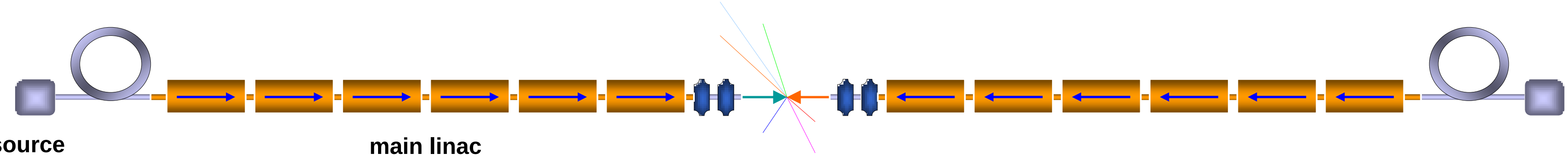
many magnets, few cavities → need strong field for smaller ring
multi-pass → high bunch repetition rate for high luminosity
ring → synchrotron radiation losses

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$



Linear Collider

few magnets, many cavities → need efficient RF power production
single pass → need higher gradient for shorter linac
single pass → need small transverse beam for high luminosity:
(exceptional beam quality, alignment and stabilization)



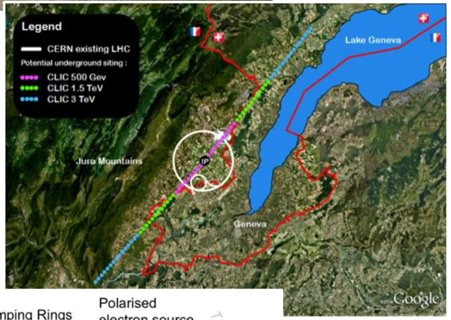
Projects for Future Accelerators

	Electrons Linear	Electrons Circular	Hadrons Linear	Hadrons Circular
Particle Physics	ILC		LBNF / PIP-II	
	CLIC		ESSnuSB	
		FCC-ee		FCC-hh
		CepC		SppC
Material Science	LCLS-II		ESS	
	ERL Berlin		IFMIF (Japan)	
	ERL Cornell		CSNS (China)	
Nuclear Energy			MYRRHA	
			C-ADS	

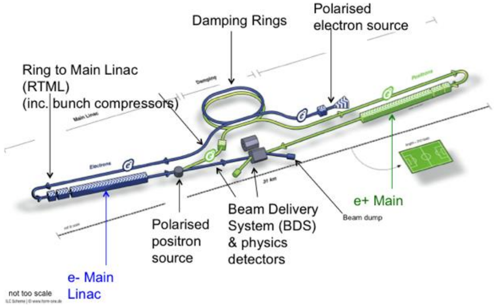
European Strategy 2013 → Update in 2020

Approved by CERN council (May 2013),
ESFRI roadmap

Identified four highest priorities:



- Highest priority is exploitation of the LHC including luminosity upgrades
  - HiLumi LHC upgrade project
- Europe should be able to propose (by 2018-2019) an ambitious project at CERN after the LHC
  - circular proton collider (FCC-hh) → high-field magnets
  - linear electron collider (CLIC) → high-gradient acceleration
- Europe welcomes Japan to make a proposal to host ILC

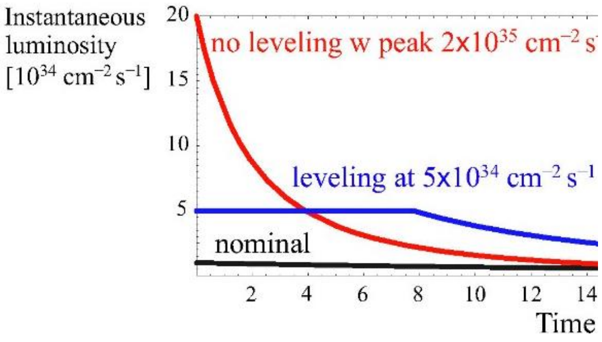


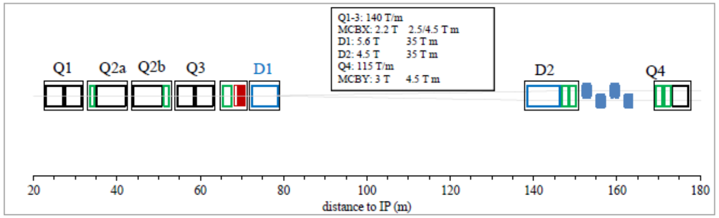
- Long baseline neutrino facility

Circular Colliders

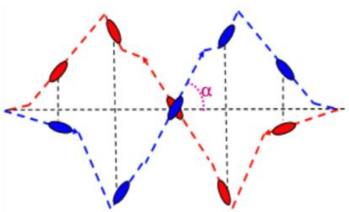
High Luminosity LHC Upgrade Project

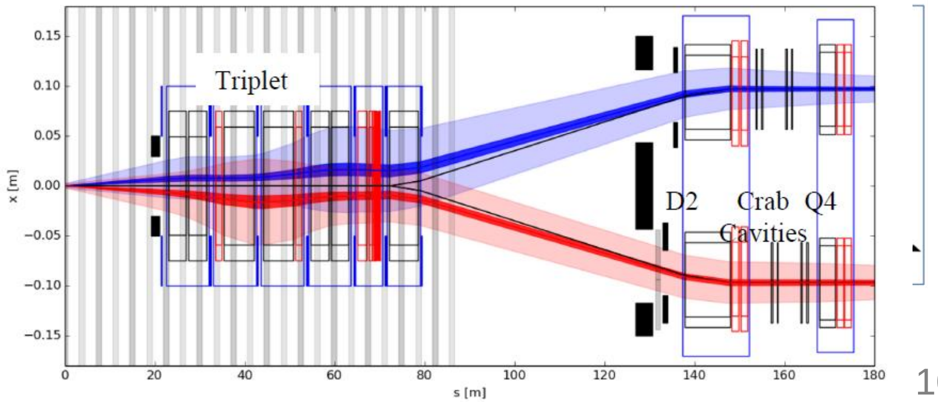
- Increase the LHC luminosity with a factory 5
  - peak luminosity to $5\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ with levelling
    - $\mathcal{L} = \text{f}\frac{N^2}{4\pi\sigma^2}$
  - allowing integrated $\mathcal{L}$ of 250 fb^{-1} per year
    - integrated over time in units of the relevant X-section



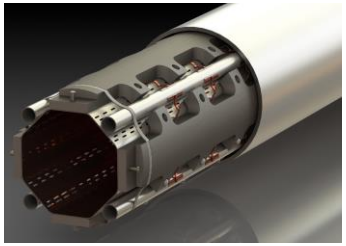


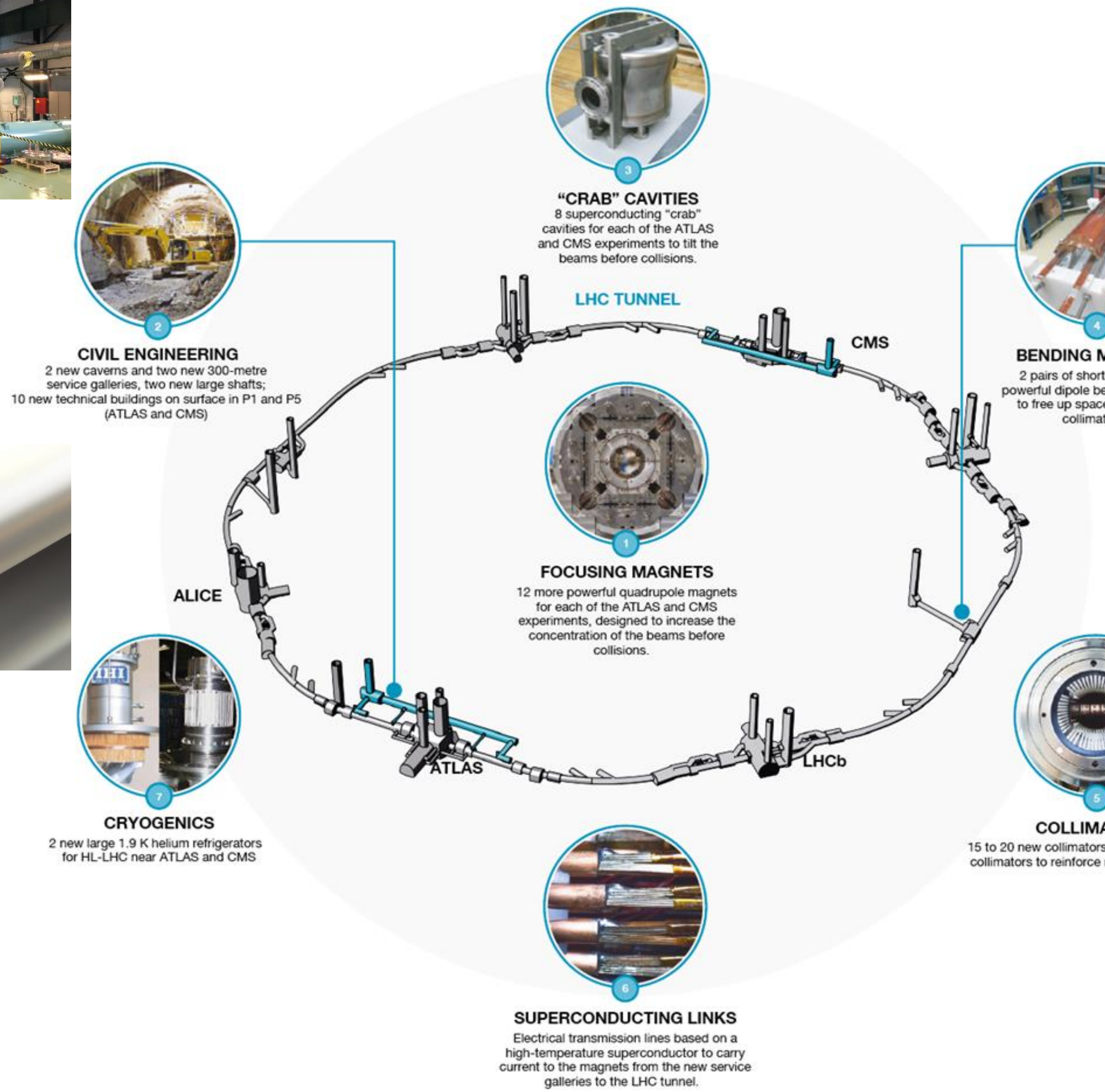
- Increasing the beam brightness by reduced β* and crabbing
  - reduce envelop $\sigma^2 = \varepsilon\beta$; emittance $\varepsilon \propto {}^1/_p$
  - crab cavities to compensate for crossing angle
  - replace inner triplet magnets to increase aperture
  - modify some collimators & bending dipoles

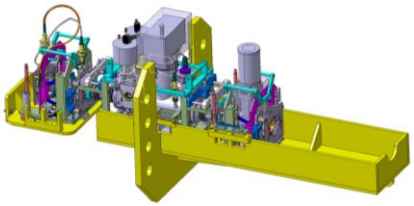




High Luminosity LHC Technical Highlights

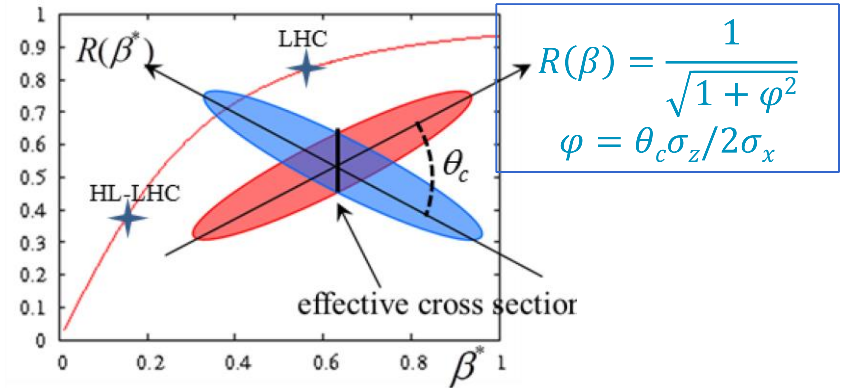




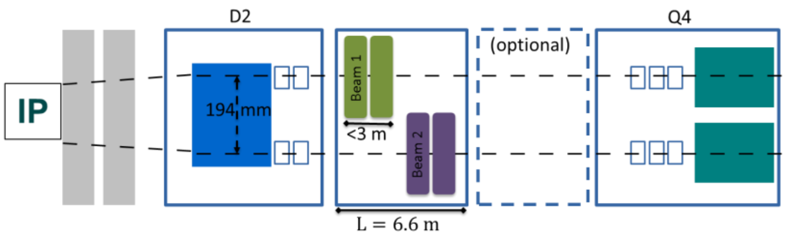


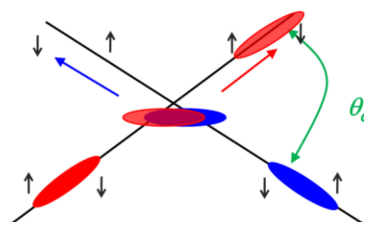
Crabbing Cavities

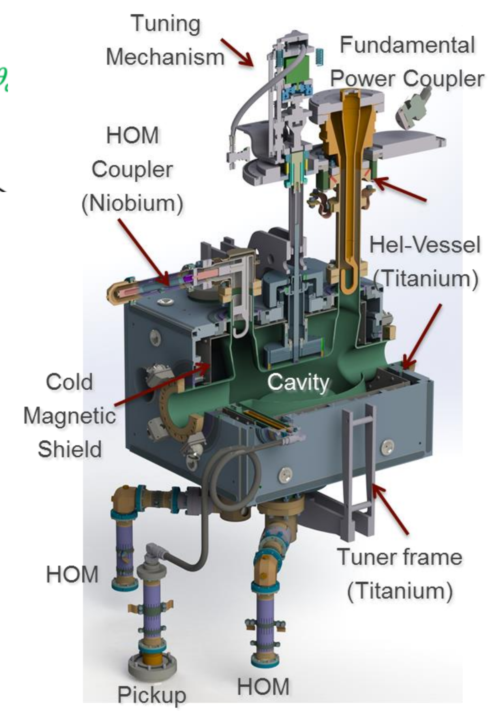
- Increase effective overlap
  - $\sigma_{\text{eff}} = \sqrt{\sigma_z^2 + \sigma_z^2\theta_c^2}$



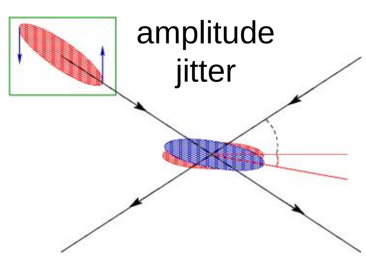
- RF deflector
  - before and after the crossing point

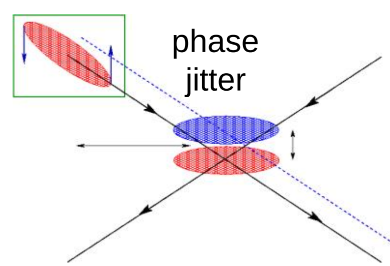






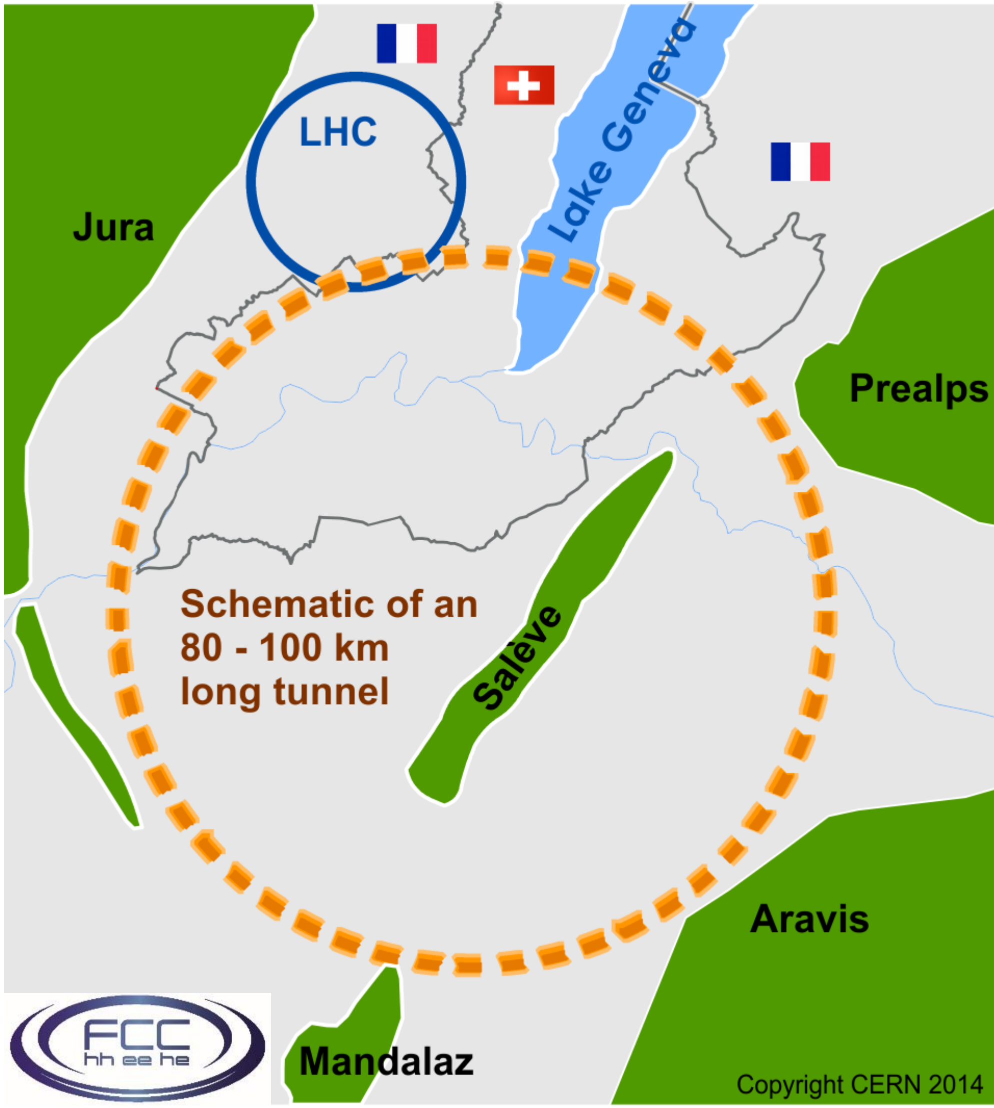
- RF noise
  - amplitude jitter
  - phase jitter





Future Circular Collider (FCC) Study

- International FCC collaboration (CERN as host lab) to study:
  - pp-collider (FCC-hh)
    → main emphasis, defining infrastructure requirements
- **~16 T ⇒ 100 TeV *pp* in 100 km**
  - ~100 km tunnel infrastructure in Geneva area, site specific
  - e+e- collider (FCC-ee), as potential first step
    → **start operation 2039**
  - HE-LHC with FCC-hh technology
    → **start operation 2040**
  - p-e (FCC-he) option, IP integration, e- from ERL

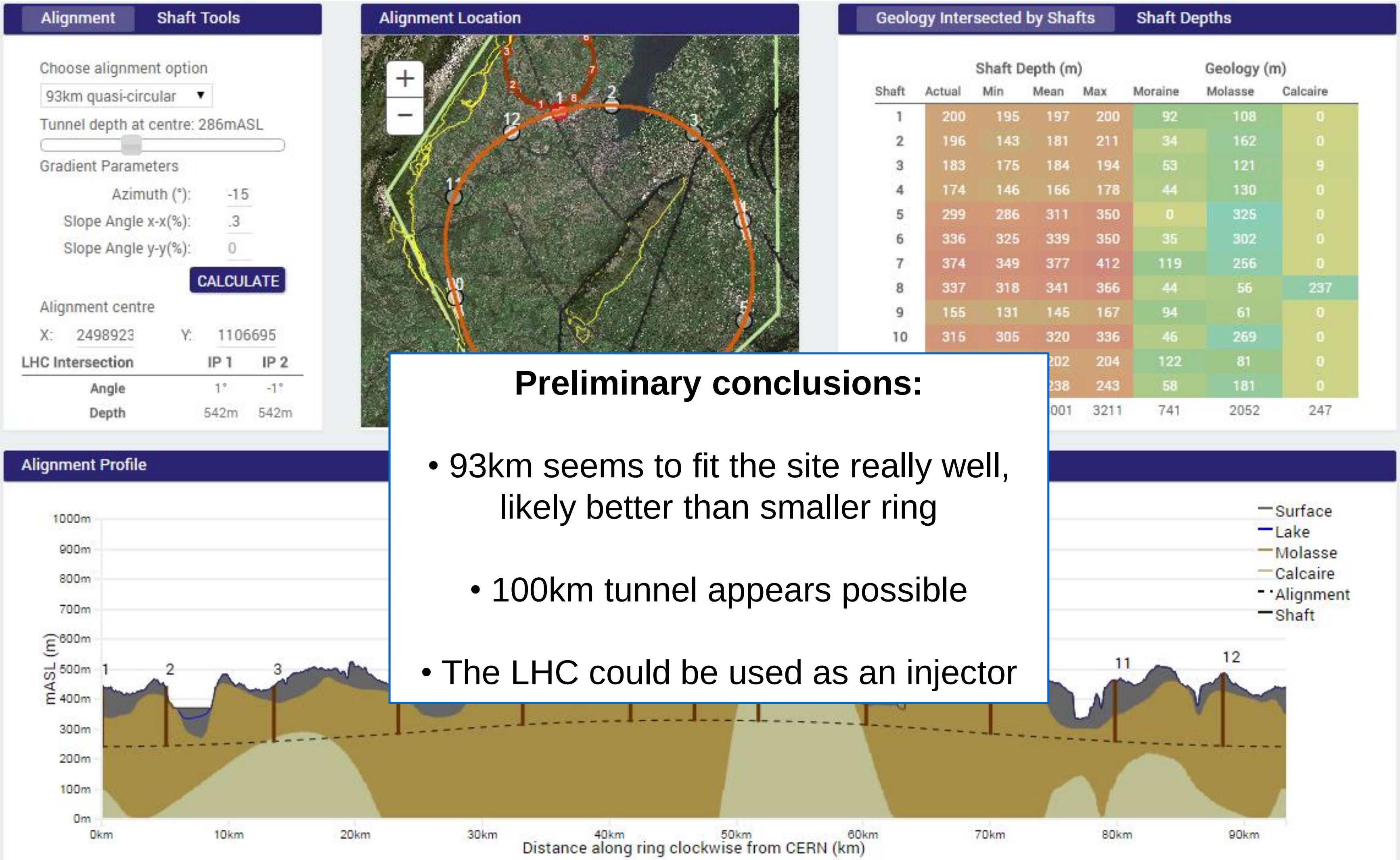


Future Circular Collider (FCC) Study

- **FCC-ee:**
  - c.m. energy from 45 to 183 GeV for Z, WW, H and ttbar production
  - Exploration of 10 to 100 TeV energy scale via couplings with precision measurements
  - ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) (m_Z, m_W, m_{top}, $\sin^2\theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$, $\alpha_s(m_z\ m_W\ m_\tau)$, Higgs and top quark couplings)
  - Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points
- **FCC-hh:**
  - Highest centre of mass energy for direct production up to 20 - 30 TeV
  - Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks
  - Machine design for 100 TeV c.m. energy & integrated luminosity ~ $20ab^{-1}$ within 25 years
- **HE-LHC:**
  - Doubling LHC collision energy with FCC-hh 16 T magnet technology
  - c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC
  - Machine design within constraints from LHC civil engineering and based on HL-LHC and FCC technologies

Future Circular Collider (FCC) Site Study Example

PRELIMINARY



Preliminary conclusions:

- 93km seems to fit the site really well, likely better than smaller ring
- 100km tunnel appears possible
- The LHC could be used as an injector

J. Osborne & C. Cook

Future Circular Collider (FCC) Key Challenges

- Energy
  - Limited by the machine size and the strength of the bending dipoles
  - ⇒ Have to maximize the magnet strength.
  - ⇒ Challenge to build 16T magnets! Will they be ready in time?

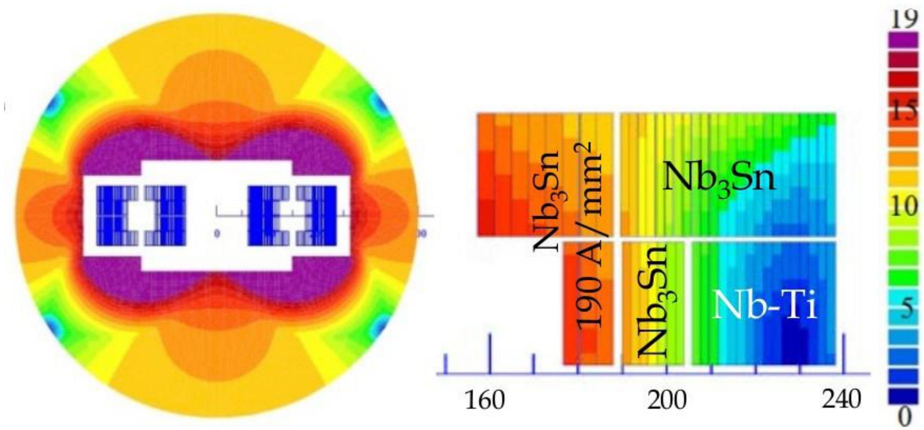
- Luminosity
  - ⇒ Need to maximize the use of the beam for luminosity production

- Beam power handling: The beam can damage the machine
  - Quench the magnets
  - Create background in the experiments
  - ⇒ Need a concept to deal with the beam power

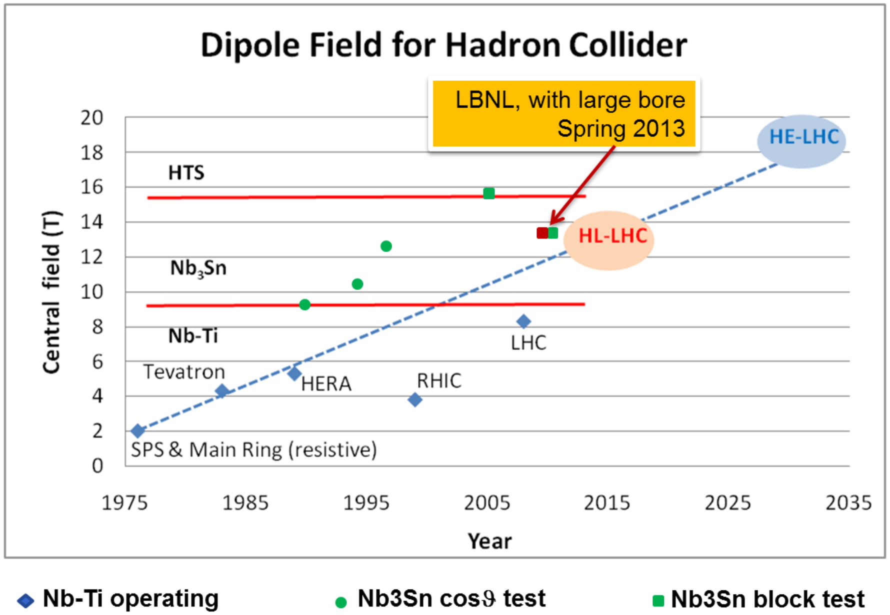
- Cost
  - The total cost is a concern, so we have to push everything to the limit to reduce cost
  - ⇒ Most things will become difficult

Dipole Magnet Challenge

- Arc dipoles are the main cost and parameter driver
  - baseline is Nb3Sn at 16T
  - alternative HTS at 20T
- Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) the practical limit is around 20 T.
  - Such a challenge is similar to a 40 T solenoid.
- Field level is a challenge but many additional questions:
  - aperture
  - field quality



Coil sketch of a 15 T magnet with grading, E. Todesco



Synchrotron Radiation

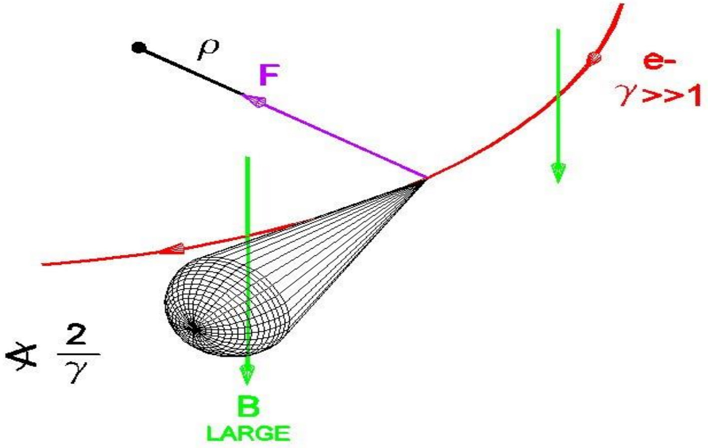
- Synchrotron radiation power
  - $P_\gamma \propto \frac{(\beta\gamma)^4}{\rho^2} \propto \frac{{m_0}^4}{\rho^2}$ $\quad \beta = \frac{v}{c} \quad \gamma = \frac{E}{E_0}$
- 100 TeV protons radiate significantly
  - Total power of 5 MW (LHC 7kW)

⇒ Needs to be cooled away
  - Equivalent to 30W/m per beam in the arcs
    - LHC <0.2W/m, total heat load 1W/m
- Current goal
  - beam aperture: 2x13mm
  - magnet aperture: 2x20mm
  - space for shielding: 7mm
- Protons loose energy

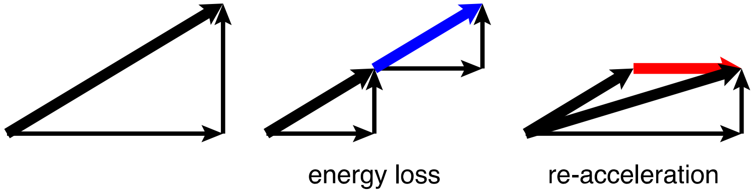
⇒ They are damped

⇒ Emittance improves with time

- Typical transverse damping time 1 hour



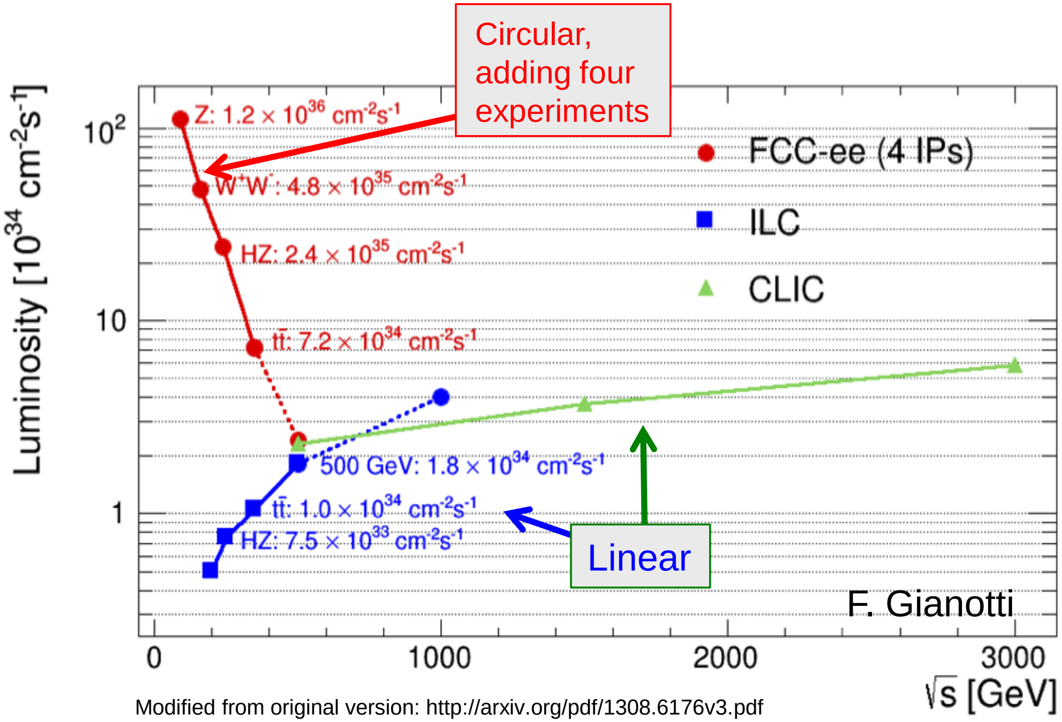
LHC beam screen



The FCC-ee Rational

- Can use FCC-hh tunnel
  - Tunnel cost has to be paid only once
- Can operate at different energies
  - 90 GeV (“Tera-Z”), 160GeV (W pairs), 240GeV (Higgs via Zh)
  - 350GeV (top threshold, higgs productions via Zh and WW)

- Limited energy reach
  - But proton collider takes care of high energies
- Limited beam lifetime
  - due to large particle energy loss in IPs and limited energy acceptance (2%)
  - need continuous top-up



Modified from original version: http://arxiv.org/pdf/1308.6176v3.pdf

Conceptual design report

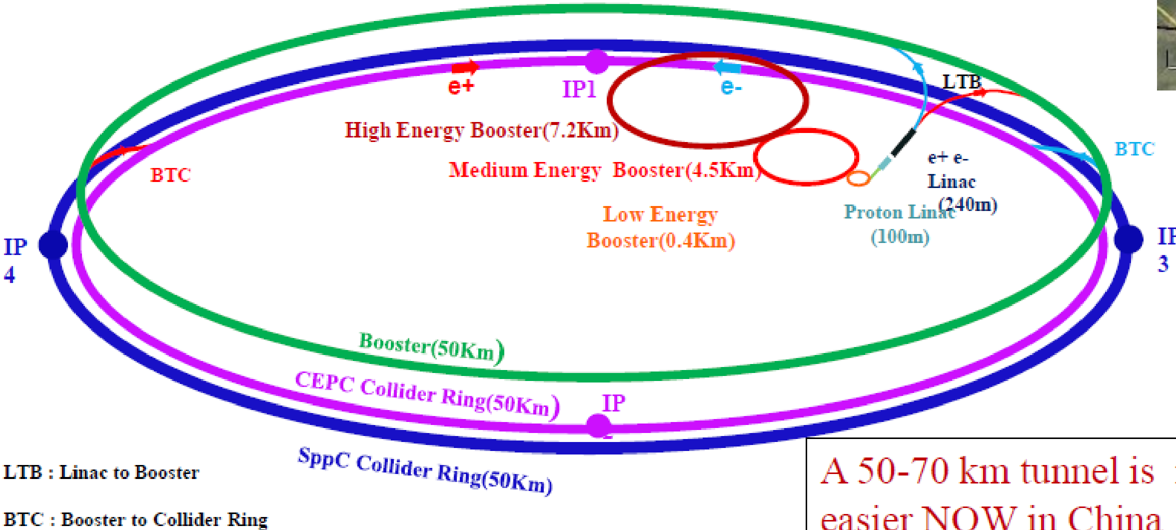
Study Documentation:

- 4 CDR volumes published in European Physical Journal in December 2018.
  - –FCC Physics Opportunities
  - –FCC-ee
  - –FCC-hh
  - –HE-LHC
  - –Preprints available, free to read http://fcc-cdr.web.cern.ch/

Chinese R&D: CepC and SppC

Effort led by IHEP, Beijing*

- e+e- Higgs factory (CEPC) 240 GeV, 54 km
- continuation of BEPC → BEPCII → CEPC
  - fits strategic needs, experience, resources
- pp collider (SppC) 70 TeV, in the same tunnel
  - gain sufficient time for magnet R&D and wait for technological improvements



A 50-70 km tunnel is relatively easier NOW in China

*) Y. Wang (IHEP) IPAC'2015
http://accelconf.web.cern.ch/AccelConf/IPAC2015/talks/frygb2_talk.pdf

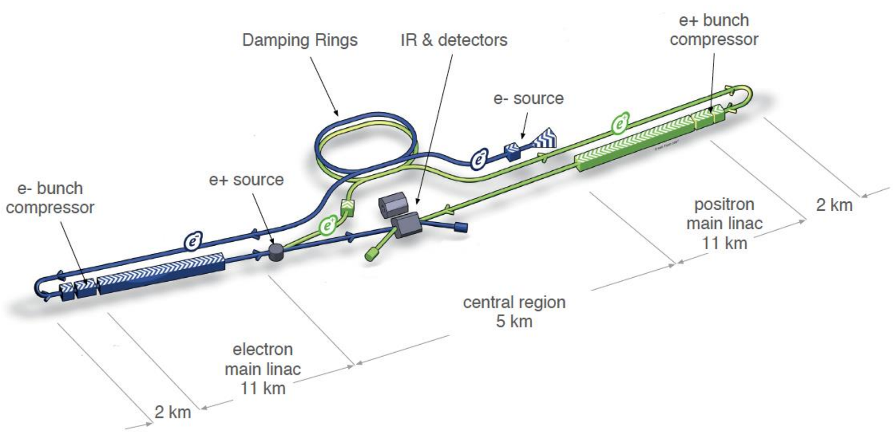
Linear Colliders

Linear Collider Studies

International Linear Collider: ILC

- superconducting technology
- 1.3 GHz
- 31.5 MV/m
- E_{CM} = 500 GeV
- upgrade to 1 TeV

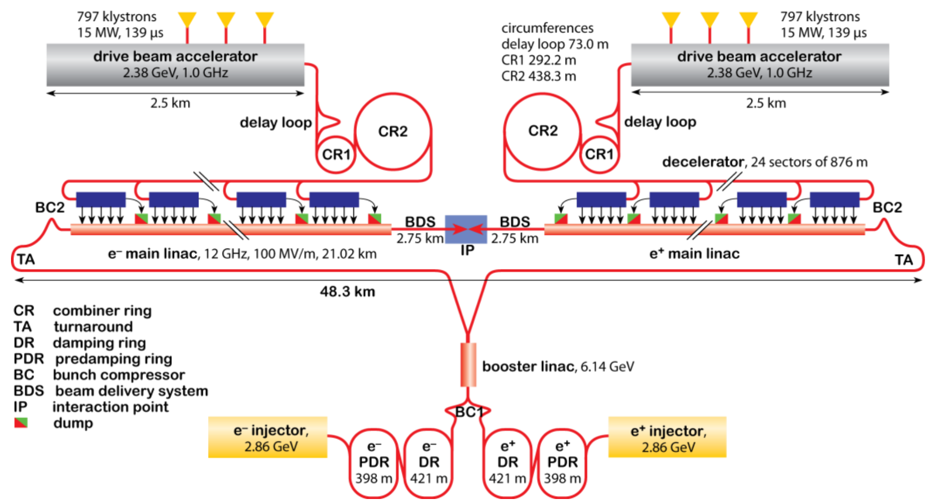
international linear collider



Compact Linear Collider: CLIC

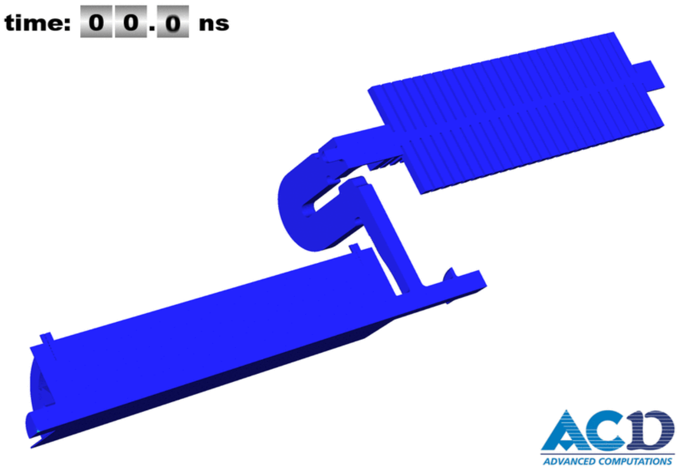
- normal conducting technology
- 12 GHz
- 100 MV/m
- E_{CM} = 3 TeV
- start at 500 GeV with stepwise upgrading

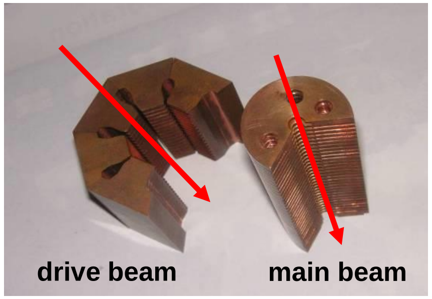
Compact Linear Collider

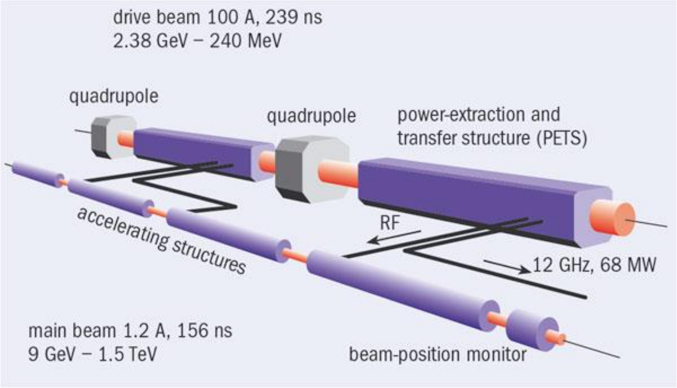


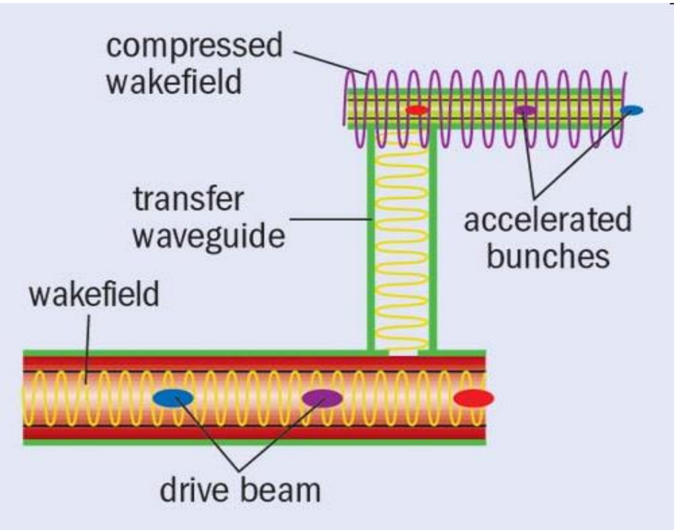
CLIC Two-beam Acceleration Concept

- acceleration by wakefield of drive-beam
  - energy extraction and compression from high power drive beam
  - only passive elements
- Main parameters
  - E_{acc} = >100 MV/m
  - 11.424 GHz
  - 230 ns pulse length
  - <10^{-6} breakdown rate (BDR)

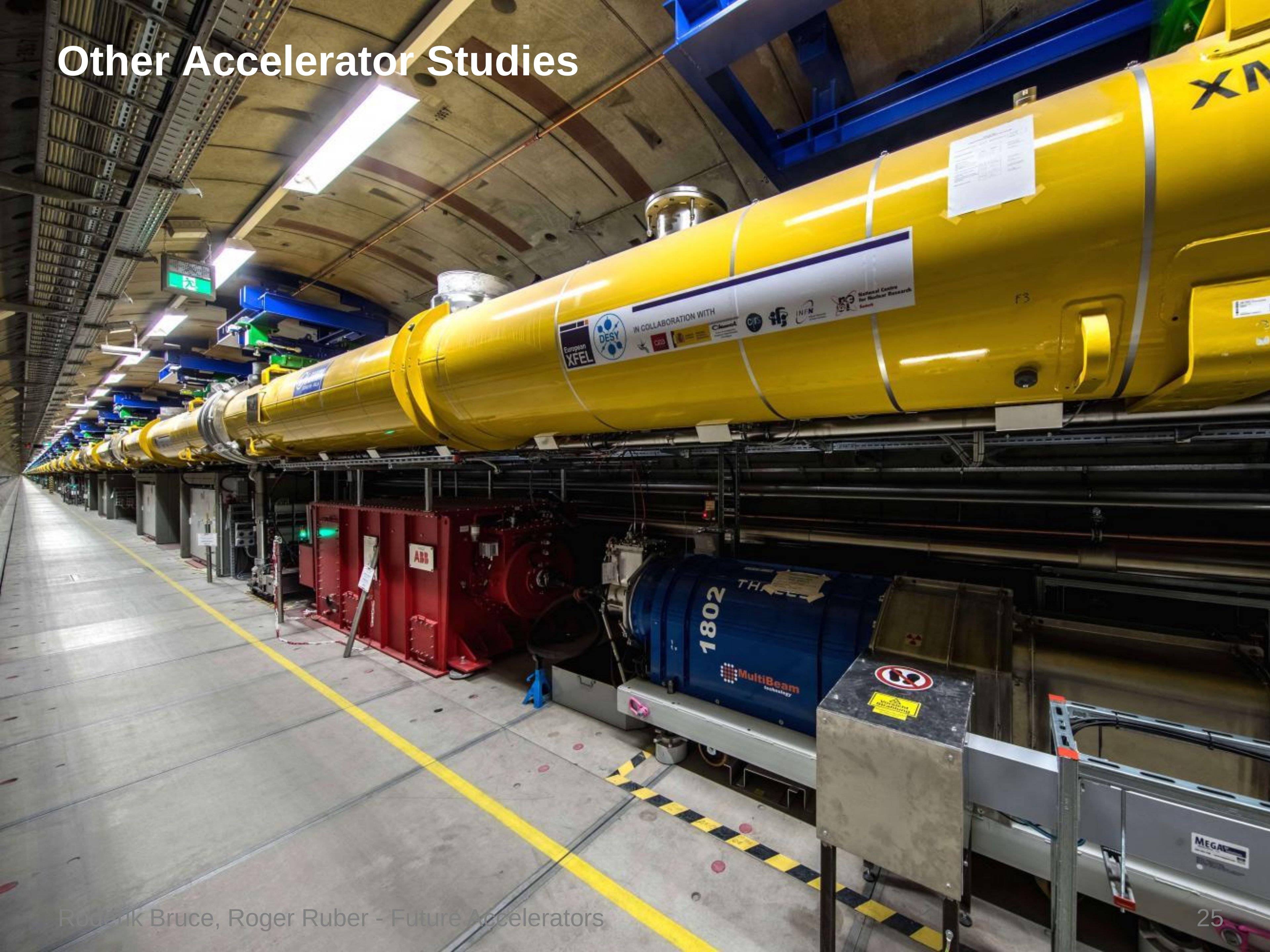








Other Accelerator Studies



Physics beyond colliders

Physics Beyond Colliders study group set up in 2016 to explore the opportunities offered by the CERN accelerator complex and other scientific infrastructure to get new insight into some of today's outstanding questions in particle physics through projects complementary to high-energy colliders (i.e. projects requiring different types of beams and experiments) and other initiatives in the world. Projects should exploit the uniqueness of CERN accelerator complex and infrastructure.

QCD measurements
COMPASS++, DIRAC++
NA61++, NA60++
Fixed target (gas, bending crystals) in ALICE and LHCb

Hidden sector with "beam dump"
NA64++ (e,μ)
NA62++
Beam Dump Facility at North Area (SHiP)
LDMX@eSPS
AWAKE++

Rare decays and precise measurements
KLEVER ($K^0_L \rightarrow \pi^0 \nu\nu$)
TauFV@BDF: $\tau \rightarrow 3\mu$
REDTOP (η decays)
MUonE (hadronic vacuum polarization for $(g\text{-}2_\mu)$)
Proton EDM

Long-lived particles from LHC collisions
FASER, MATHUSLA, CODEX-b, milliQAN

Other facilities:
γ-factory from Partially Stripped Ions; nuSTORM

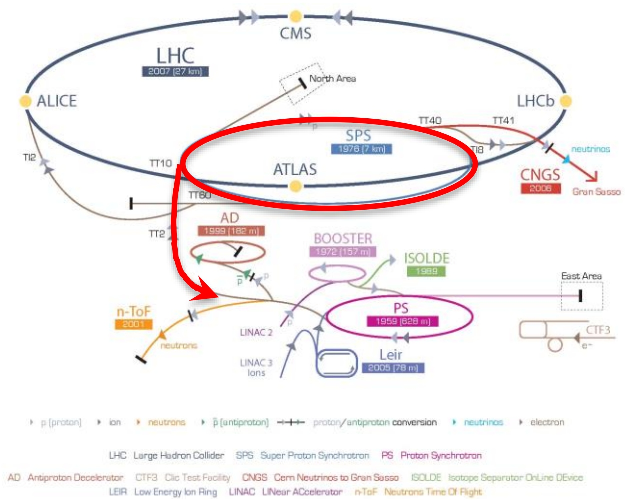
Non-accelerator projects
Exploit CERN's technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)

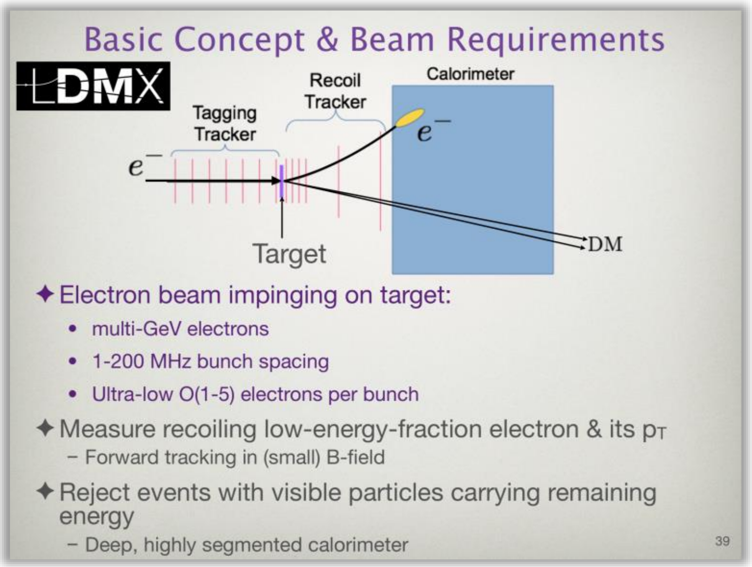
→ Report submitted to the ESPP

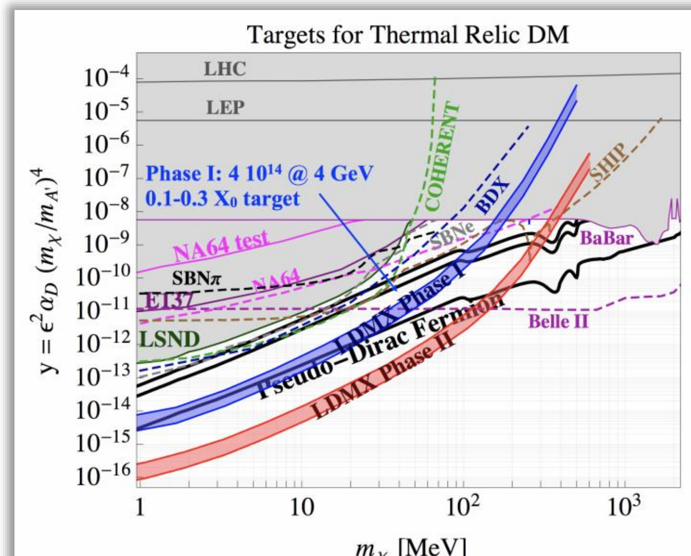
F. Gianotti

CERN e-beam Facility for DM Searches

- **Implementation of an LDMX type beam**
  - X-band based 60m LINAC to 3 GeV in TT4-5
  - Fill the SPS in 2s (bunches 5ns apart) via TT60
  - Accelerate to ~10 GeV in the SPS
  - Slow extraction to experiment in 10s as part of the SPS super-cycle
  - Experiment(s) considered in UA2 area or bring beam back on Meyrin site using TT10

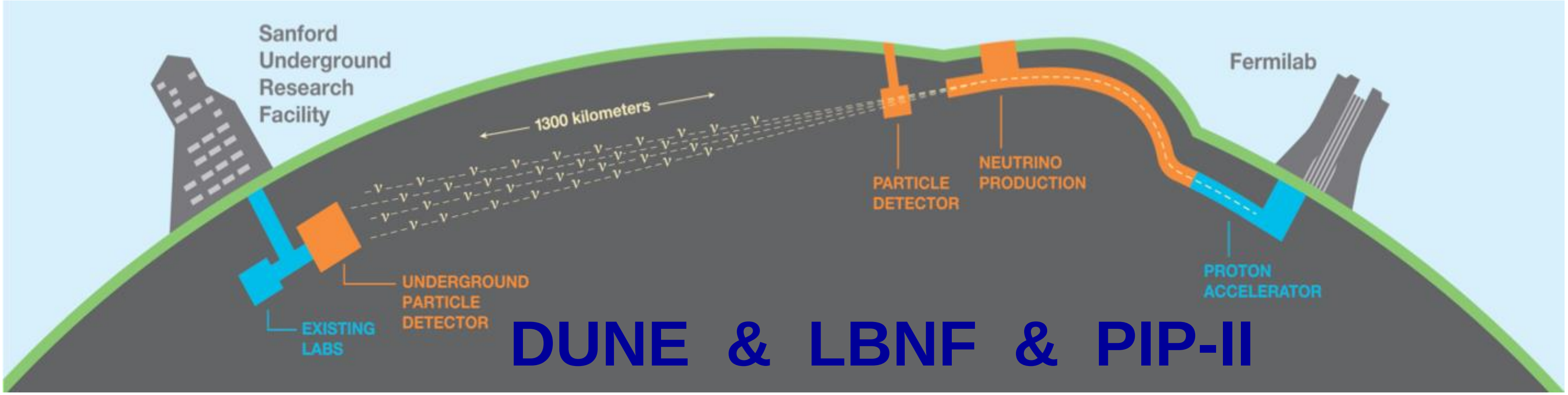






LBNF/DUNE

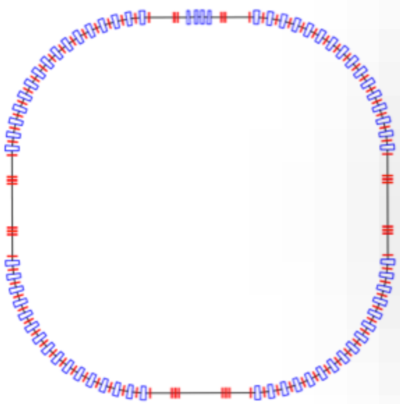
- American project, with proton accelerator at Fermilab, sending neutrinos through the Earth to a detector 1300 km away

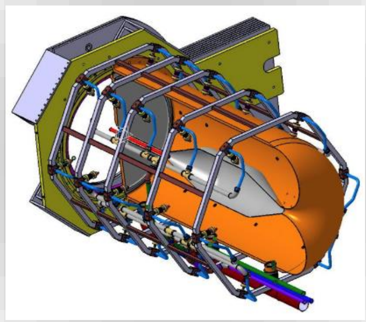


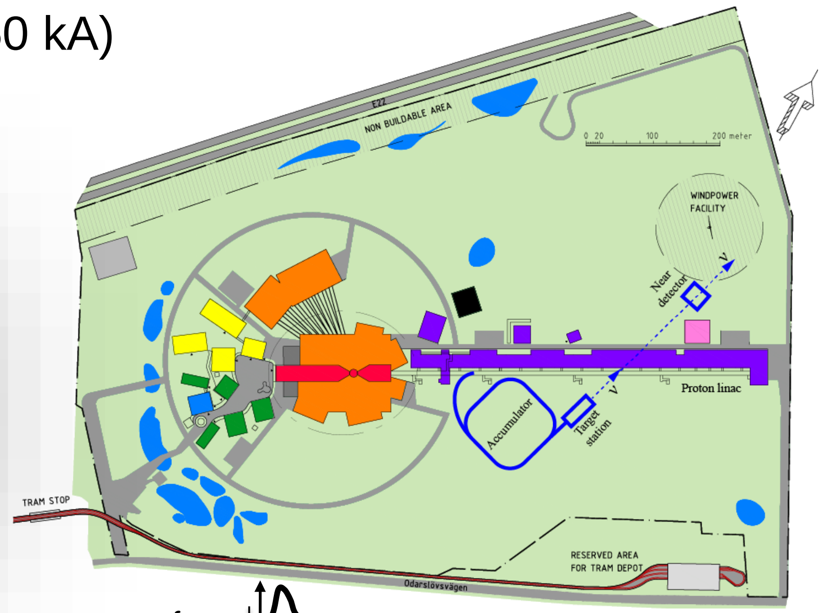
- Status:
  - **Far site:** Construction at started Nov 2018. Currently building or refurbishing ~100 year old rock handling systems at former gold mine to be able to move ~800k tons of excavated rock to surface
  - **Near Site**: site preparation construction contract awarded last month, design of facilities and neutrino beamline underway.
  - **DUNE**: two prototype detector models constructed and operating at CERN.

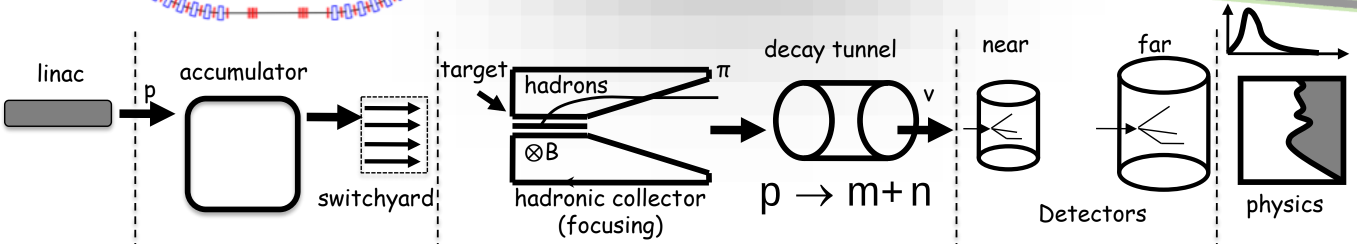
ESS Neutrino Super Beam (ESSnuSB)

- Doubling the ESS beam power for a second target
  - linac duty cycle doubling to 8 % (RF sources, cooling)
    - using new H^- source
  - accumulator ring (~400 m circ.) compress 2.86 ms beam pulse to few µs
    - multi-turn injection, stripping $H^- \rightarrow H^+$
  - 2nd target station with magnetic horn (350 kA)
    - to deliver ~300 MeV neutrinos









Summary and Info

Summary

- Several studies ongoing with complementary technologies and goals
  - all studies are world-wide collaborative efforts
- ILC study is ready to prepare a proposal
  - Proven technology, in use for FLASH, coming up for EuXFEL
- CLIC study has produced a Conceptual Design Report
  - now focusing on the optimisation and industrialisation of the technology
- FCC study has produced a Conceptual Design Report
  - can use the vast experience and technology from LHC
  - but challenges due to high beam energy and luminosity
- Update of the European strategy for particle physics due next year – should indicate directions for future direction of CERN accelerators

Let us hope that the LHC will find exciting new physics and guide our choice between the machines.

Acknowledgements

With material from many colleagues

- Alex Andersson, Erik Adli, Erk Jensen, Hans Braun, Andrea Palaia, Daniel Schulte, Frank Tecker, Wilfrid Farabolini, Walter Wünsch, Akira Yamamoto and Volker Ziemann

Some illustrations and photos courtesy

- CERN, KEK and Symmetry Magazine

Backup

Superconducting RF Cavities (SRF)

- High efficiency due to low $R_{surface}$
  - standing wave cavities with low peak power requirements

$$P_{loss} = const \frac{1}{Q_0} \times G^2$$

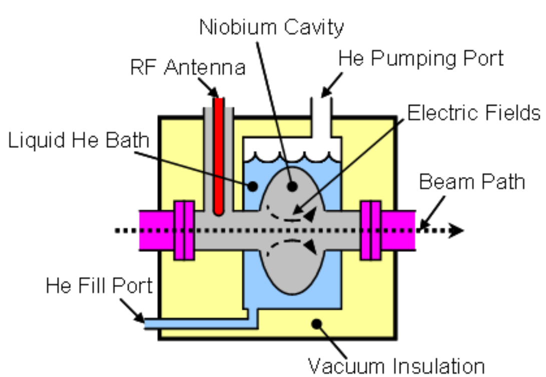
  - but expensive cryo-cooling

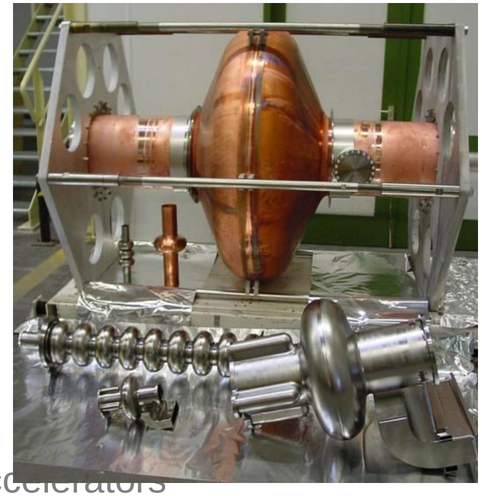
$$P_{cryo} = \frac{1}{\eta} \frac{T_{room} - T_{source}}{T_{source}} \times P_{loss}$$

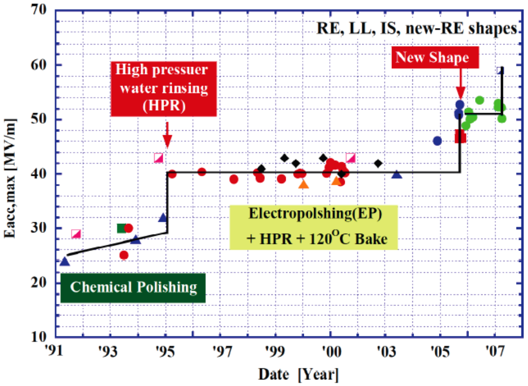
$$P_{cryo} \approx 700 \times P_{loss}$$

- Long pulse trains (long fill time)
  - favourable for in-pulse feed-back

- Record **59 MV/m** achieved with single cell cavity at 2K (1.3 GHz)
  - multi-cell in operation ~30-35 MV/m
- Limitations:
  - Field Emission
    - due to high electric field around iris
  - Quench
    - surface heating from dark current, or
    - magnetic field penetration at "Equator"
  - Contamination
    - during assembly → improve surface treatment



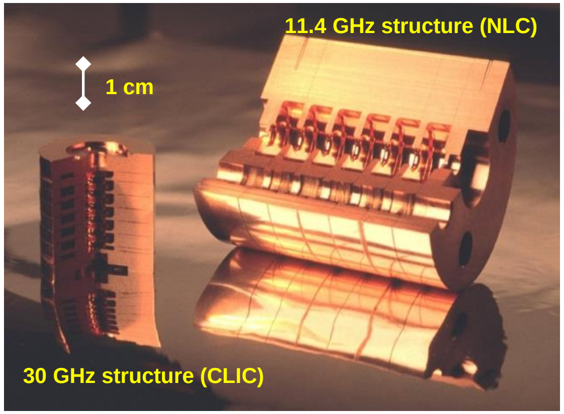


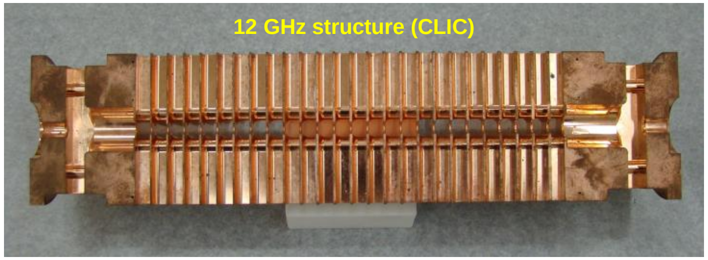


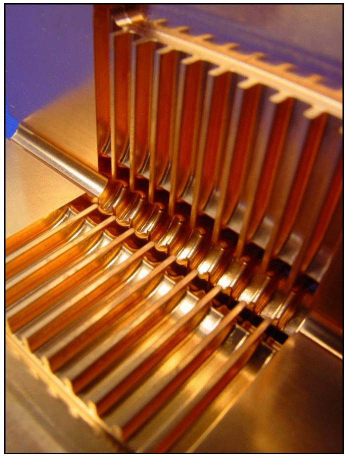
Normal Conducting (Resistive) RF

- High ohmic losses
  – but use water cooling
- Standing or travelling wave
- Easier manufacturing
  – unlike SRF, no special chemical procedures, no clean room
- Short fill time $t_{fill} = \int 1/v_G \, dz$
  – order <100 ns (~ms for SCRF)

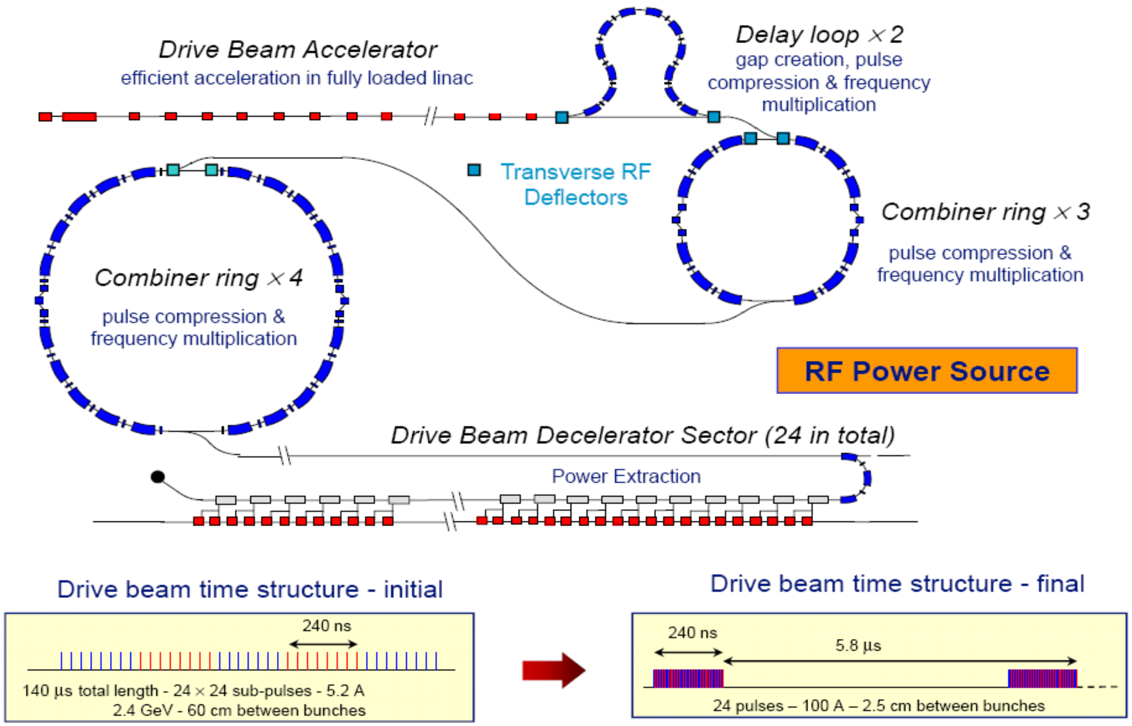
- High gradients, but only if
  – high frequency
  – short pulse lengths: < 1μs
  – limited by RF breakdown: > 60 MV/m
- Higher frequencies
  – smaller structures cq. equipment
- Well suited for small accelerators
  – industrial and medical applications
  – university

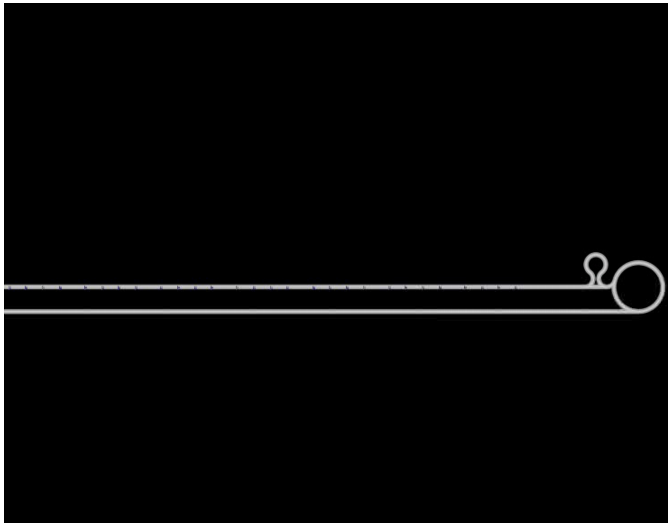






Drive Beam Generation





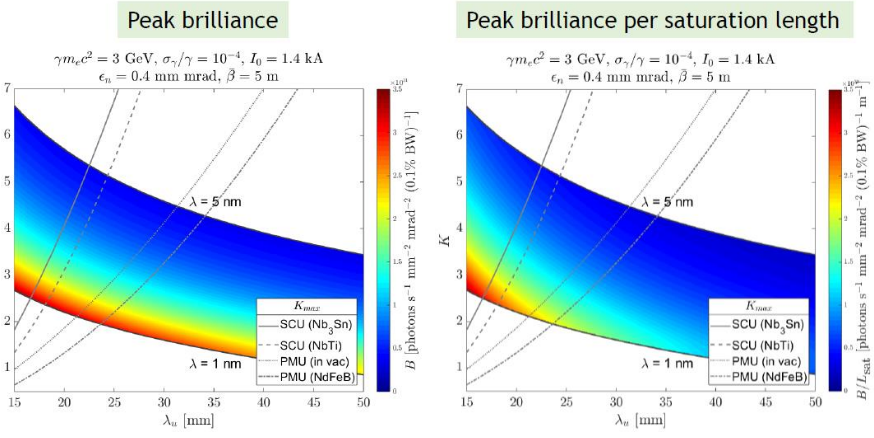
Courtesy A. Andersson

Soft X-ray FEL Studies

MAX IV Soft X-ray FEL

- Baseline SXL design with state-of-the-art undulator technology
  - generation of short pulses (<1 fs)
  - double pulses for pump-probe experiments
  - strong-field single-cycle THz source
  - microbunching instability

Large undulator strength for short period gives a huge improvement in FEL brightness.



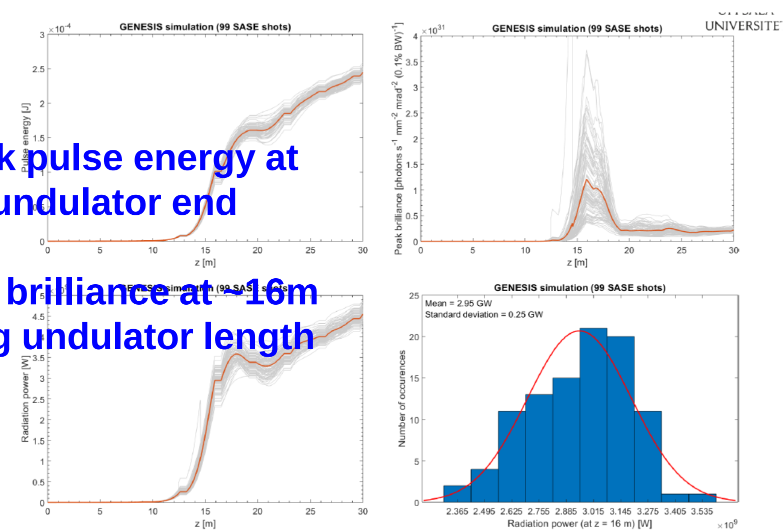
K_{max} curves assume a minimum gap of 7.5 mm (5.7 mm for in-vacuum undulators), and are interpolated from data presented by Paul Emma at the SCU R&D Review of SLAC in 2014.

CompactLight

- Impact of undulator technology on FEL performance:
  - analytical computation of FEL performance parameters
  - dependence on λ_u & K of undulator
- Simulation studies of soft x-ray FEL
  - baseline design – SASE operation
  - production of attosecond light pulses
  - Harmonic-lasing self-seeding (HLSS)

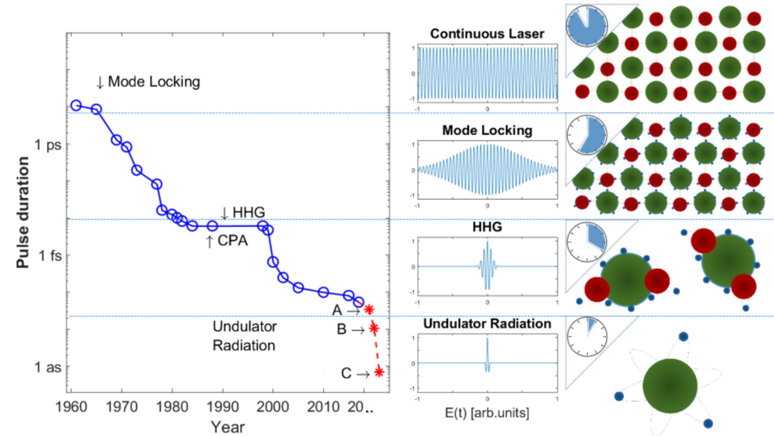
Peak pulse energy at undulator end

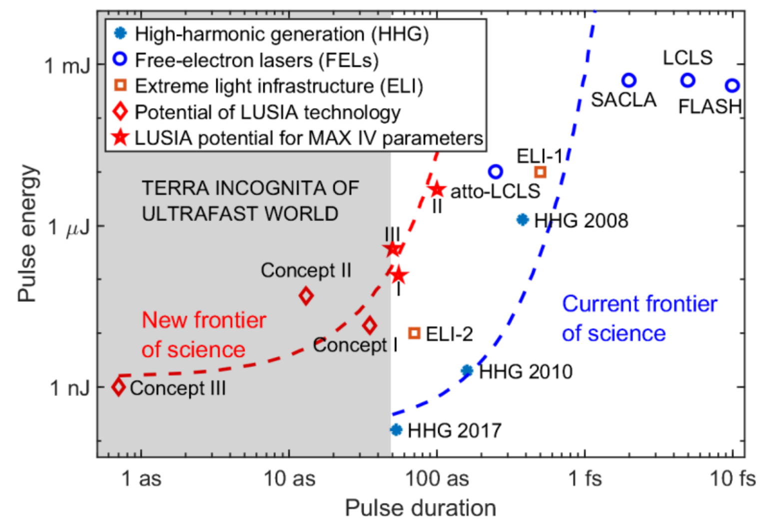
Peak brilliance at ~16m along undulator length

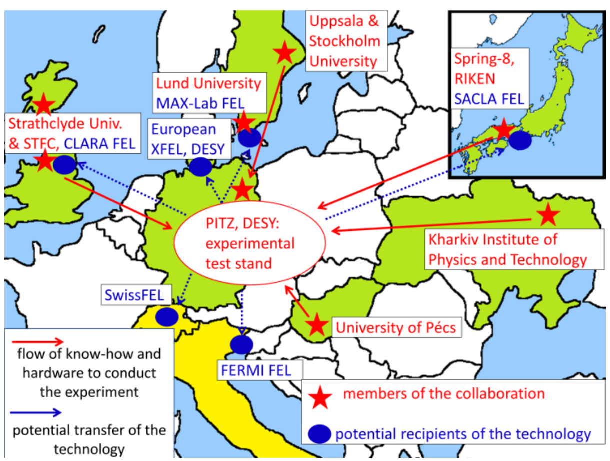


Ultrashort Light Pulse Generation

- High-Harmonic Generation (HHG) sources are facing saturation
  - Undulator light source is a promising way to the attosecond region
- **LUSIA Collaboration**
  - **A**ttosecond **SI**ngle-cycle **U**ndulator **L**ight
  - explore novel concepts for generation of attosecond pulses with on a µJ energy scale
  - coherent few-cycle light pulses down to a single-cycle by tailoring light wavefronts in an undulator

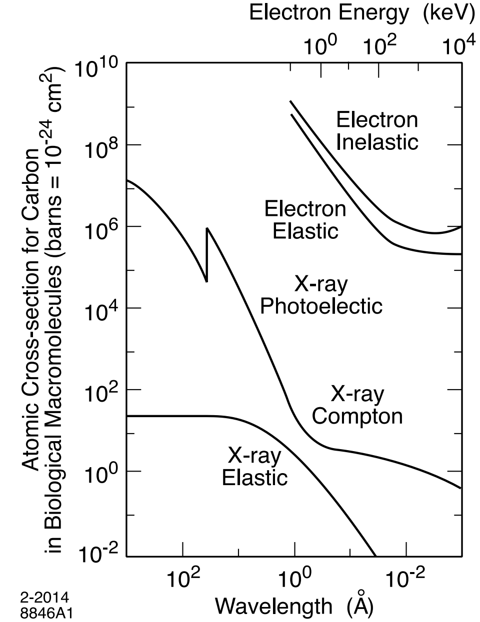




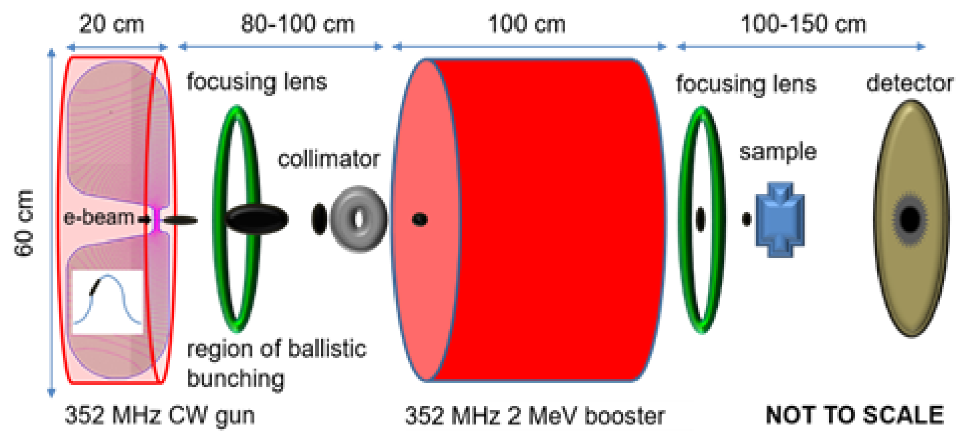


Ultra-fast Electron Diffraction

- X-ray FELs generate laser-like x-ray pulses
  - with wavelengths from 10's nm to sub-Å region
- **Ultra-short electron pulse**
  - offer much higher elastic scattering cross sections
  - an ideal tool to probe structural dynamics
- Science case
  - chemical reactions in water and liquid environments
  - structural dynamics in biological systems
  - controlling the non-equilibrium pathways toward materials' functionality



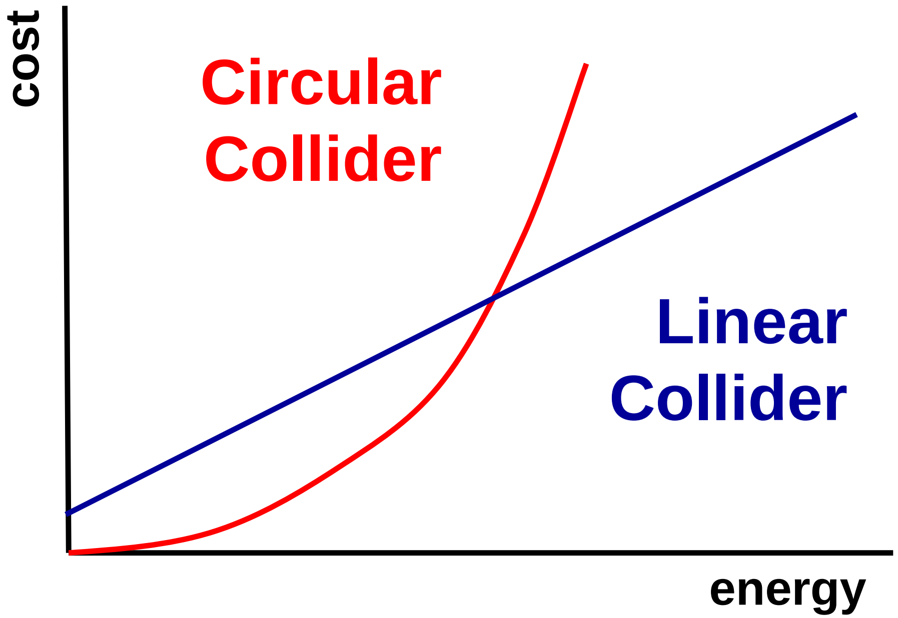
- Proposed **FREIA-UED**
  - variable pulse lengths (0.1-10 ps),
  - high electron flux (CW/1 MHz),
  - excellent coherence,
  - electron energy 250 keV - 2 MeV,
  - collaboration with Stanford



Linear versus Circular: Cost

Linear Collider

- E ~ L
- cost ~ aL



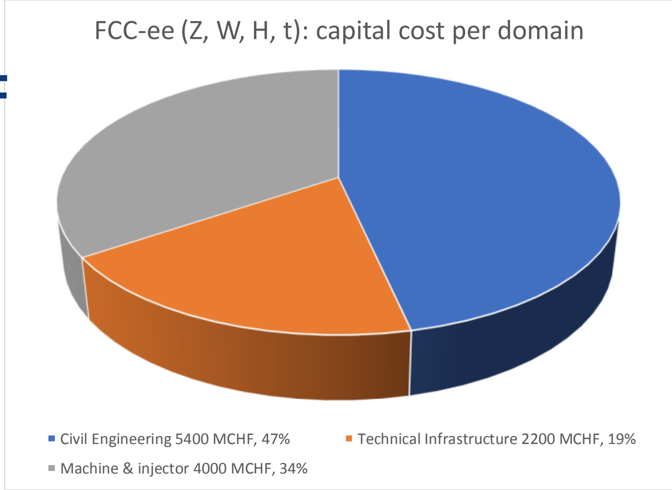
Circular Collider

- $\Delta E_{turn} \sim (q^2 E^4/m^4 R)$
- cost ~ aR + b ΔE
- optimization: $R \sim E^2 \rightarrow$ cost ~ cE^2
- examples:
  - LEP200: ΔE ~ 3%; 3640 MV/turn
  - LHC: Bmag limited

FCC integrated project cost estimate

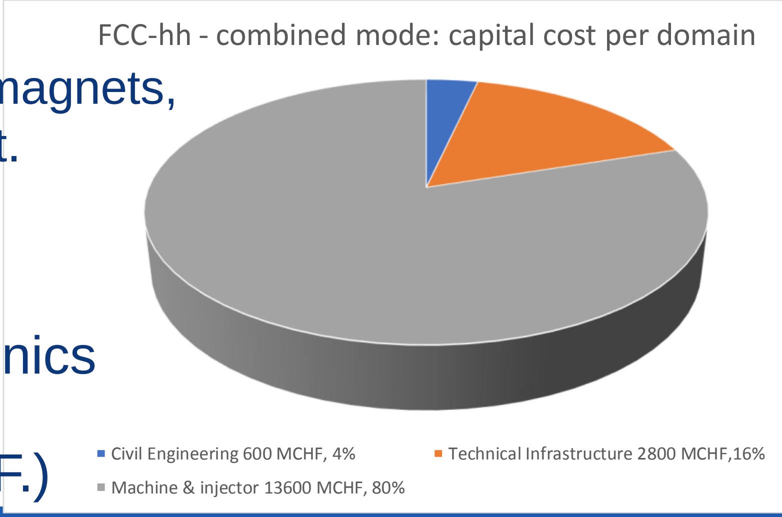
Construction cost phase1 (FCC-ee) is 11,6 BCHF

- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)



Construction cost phase 2 (FCC-hh) is 17,0 BCHF.

- 13,6 BCHF accelerator and injector (57%)
  - Major part for4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,4 BCHF, targeting 2 MCHF/magnet.
- CE and TI from FCC-ee re-used, 0,6 BCHF for adaptation
- 2,8 BCHF for additional TI, driven by cryogenics



(Cost FCC-hh stand alone would be 24,0 BCHF.)