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Future Accelerators for Particle Physics

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31 October 2017

Accelerator History for Particle Physics

Different options

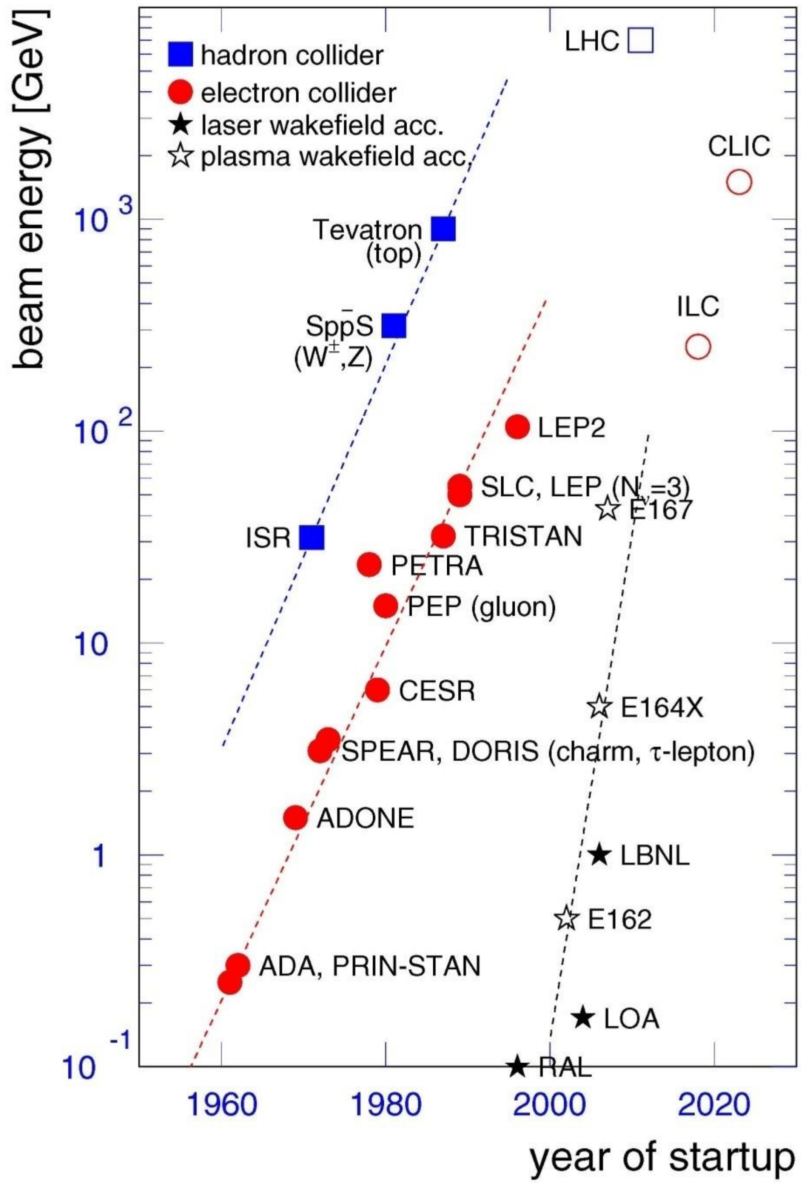
- what to collide: lepton vs hadron
- how to collide:
  - fixed target or colliding beams
  - linear vs circular
  - acceleration technology
    - DC, RF, wakefield

Project ideas

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

But also

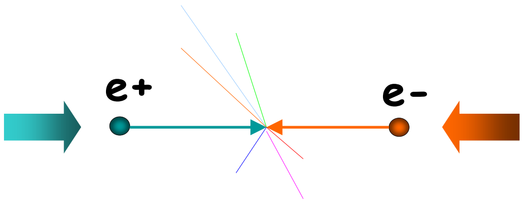
- non-HEP use of accelerators

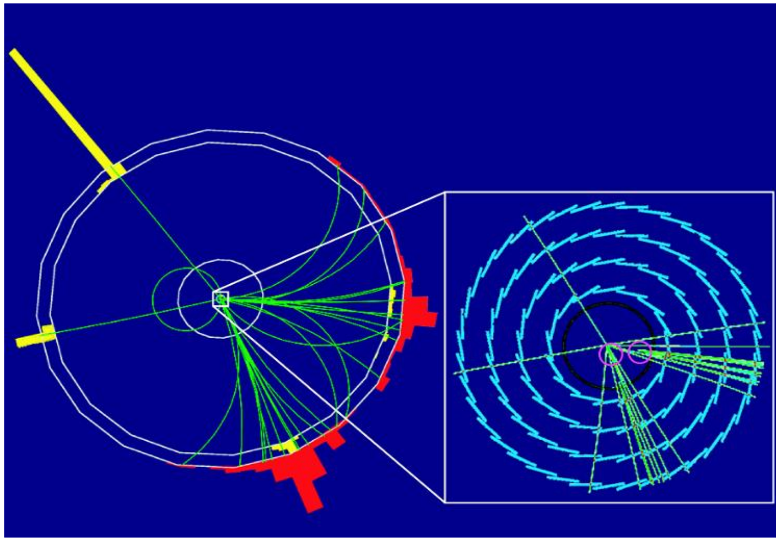


Lepton versus Hadron Collisions

Leptons

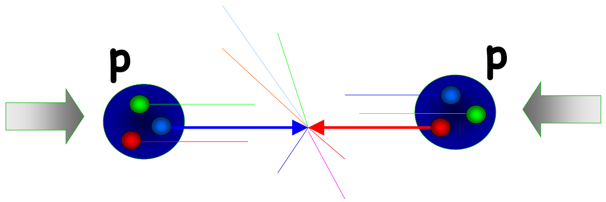
- for precision physics
- well defined CM energy
- polarization possible

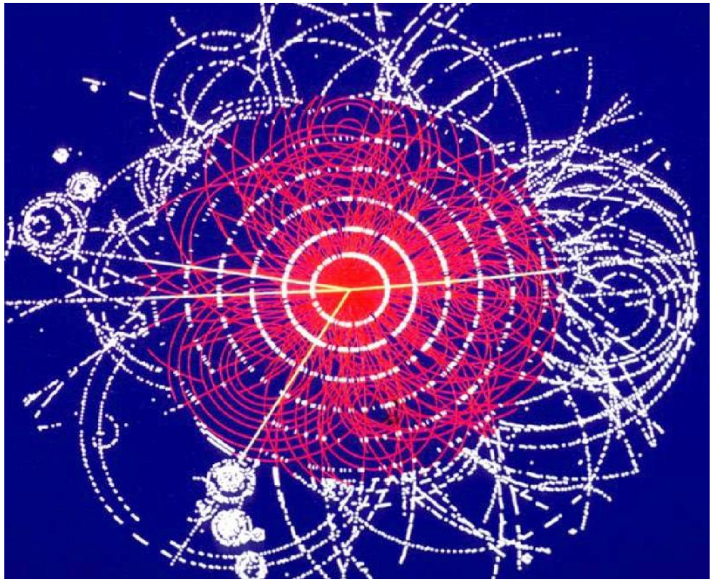




Hadrons

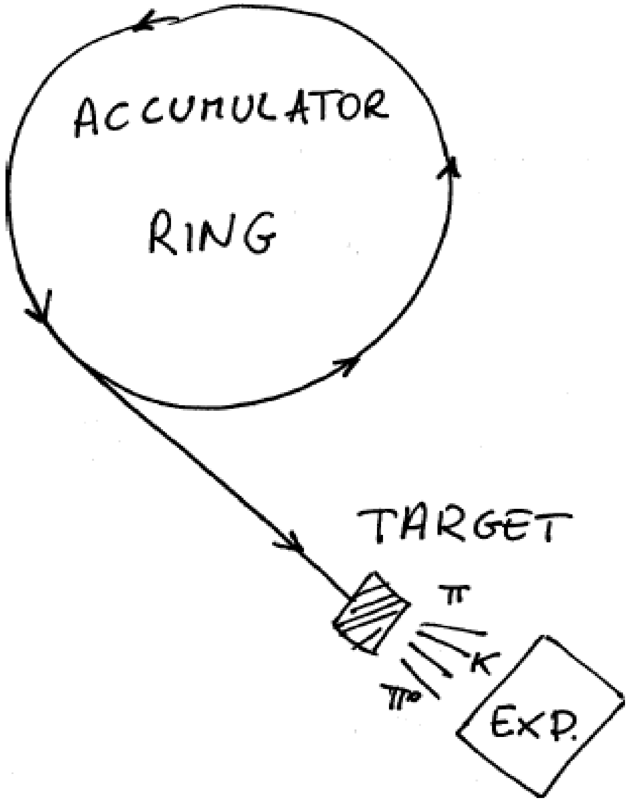
- at the frontier of physics
- huge QCD background
- not all nucleon energy available in collision



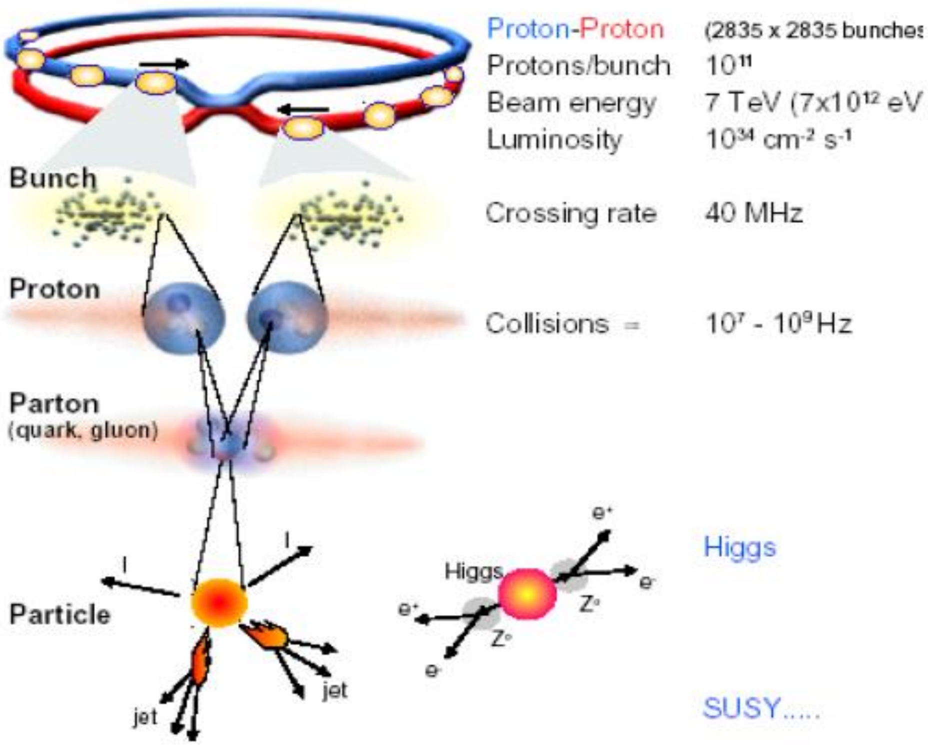


Particle Collisions

Fixed Target



Collider



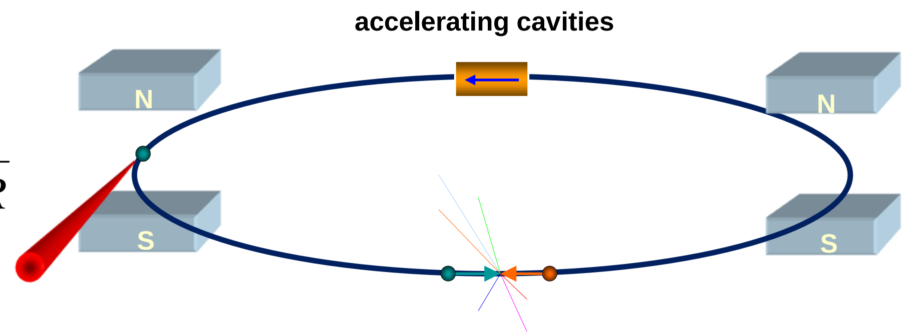
$$E_{CM} = \sqrt{2\left(E_{beam} mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

Linear versus Circular

Circular Collider

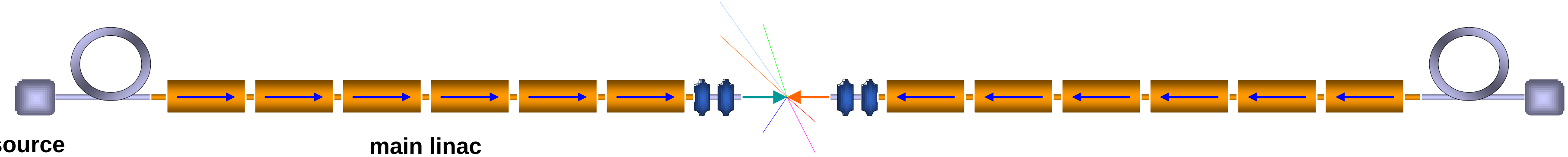
many magnets, few cavities → need strong field for smaller ring
multi-pass → high bunch repetition rate for high luminosity
ring → synchrotron radiation losses

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



Linear Collider

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



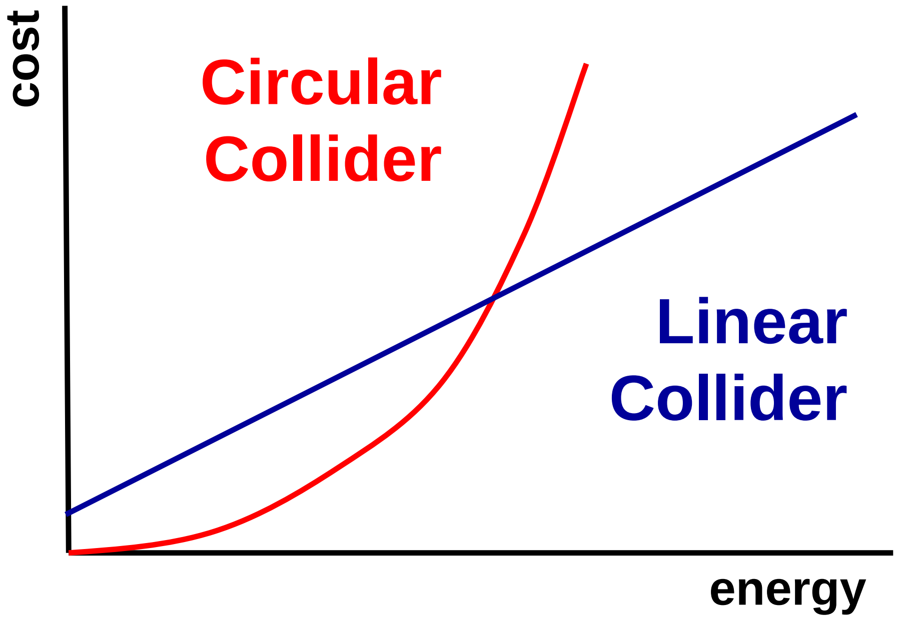
Linear versus Circular: Cost

Linear Collider

- E ~ L
- cost ~ aL

Circular Collider

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



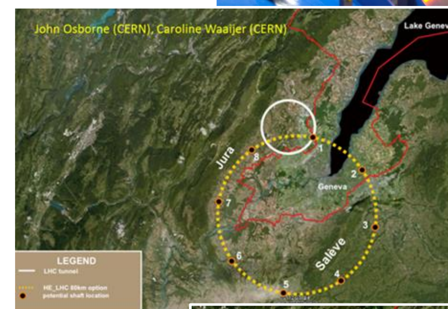
Projects for Future Accelerators

	Electrons Linear	Circular	Hadrons Linear	Circular
Particle Physics	ILC		LBNE	
	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/ADANES	

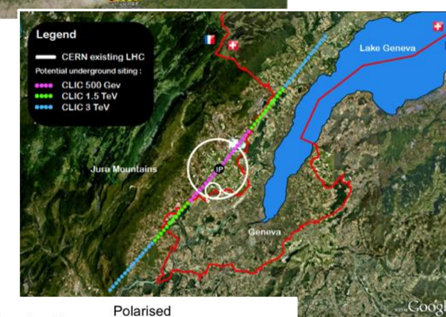
European Strategy

Approved by CERN council (May 2013),
ESFRI roadmap

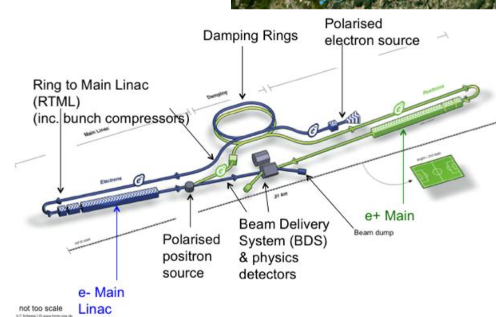
Identified four highest priorities:



- 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



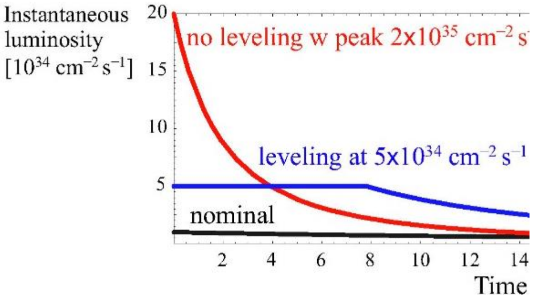
- Europe welcomes Japan to make a proposal to host ILC

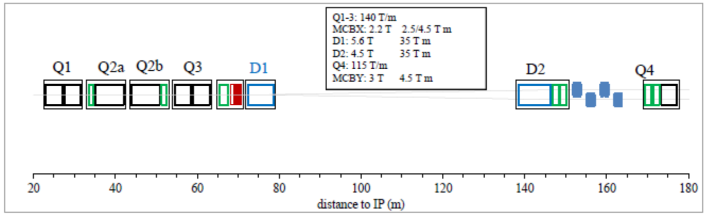
- Long baseline neutrino facility

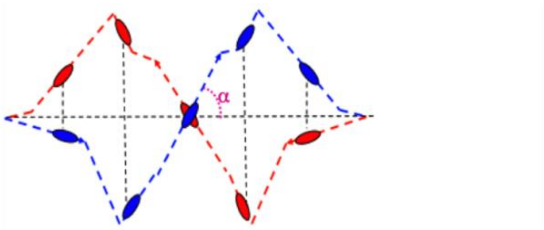
Circular Colliders

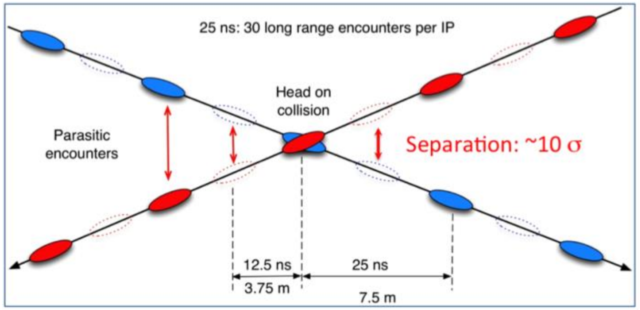
High Luminosity LHC Upgrade Project

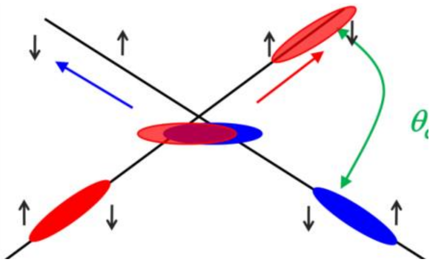
- to increase the luminosity to $5\mathrm{x}10^{34}$ from $1.5\mathrm{x}10^{34}$
  - $\mathcal{L} = \mathrm{f}\frac{N^2}{4\pi\sigma^2}$
  - integrated $\mathcal{L}$ [fb^{-1}]: integrated over time in units of the relevant X-section
- by increasing the beam brightness
  - reduce envelop $\sigma^2 = \varepsilon\beta$; emittance $\varepsilon \propto {}^1/_p$
  - crab cavities to compensate for crossing angle
  - replace inner triplet magnets to increase aperture

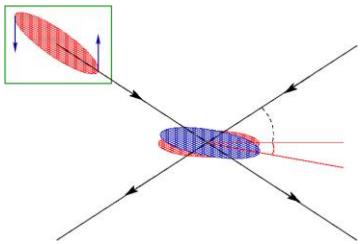


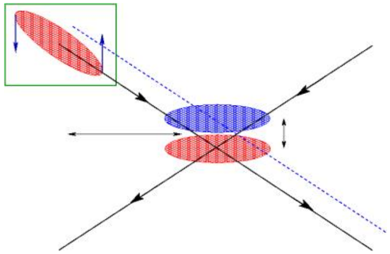






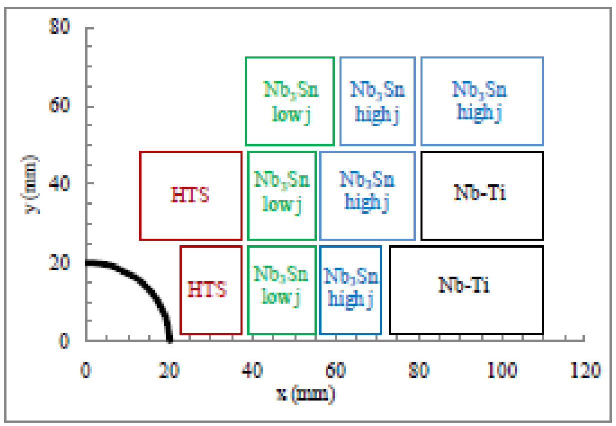


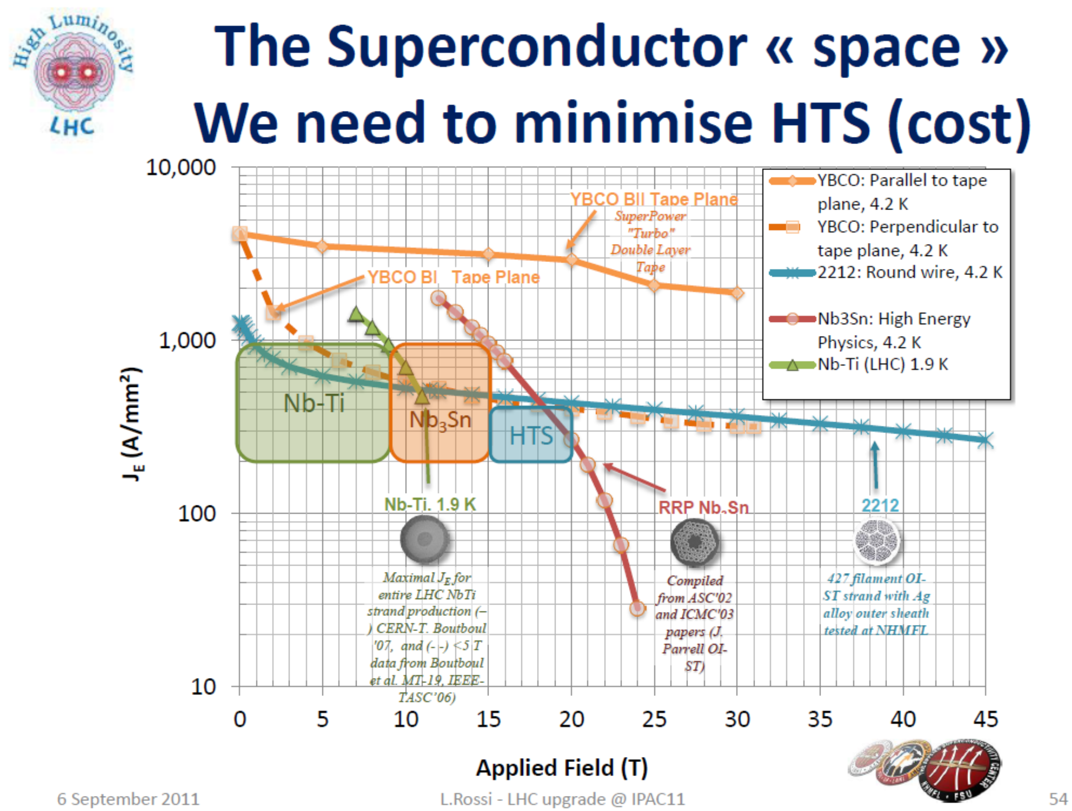




High Energy LHC Upgrade Project

- study project to upgrade the LHC energy
  - replace main bending dipoles by 20 T magnets as compared to 8.3 T
  - collision energy 33 TeV as compared to 14 TeV
- EU supported study program to
  - prototype 16 T by 2018
  - use Nb_3Sn wire
- 20 T design requires HTS

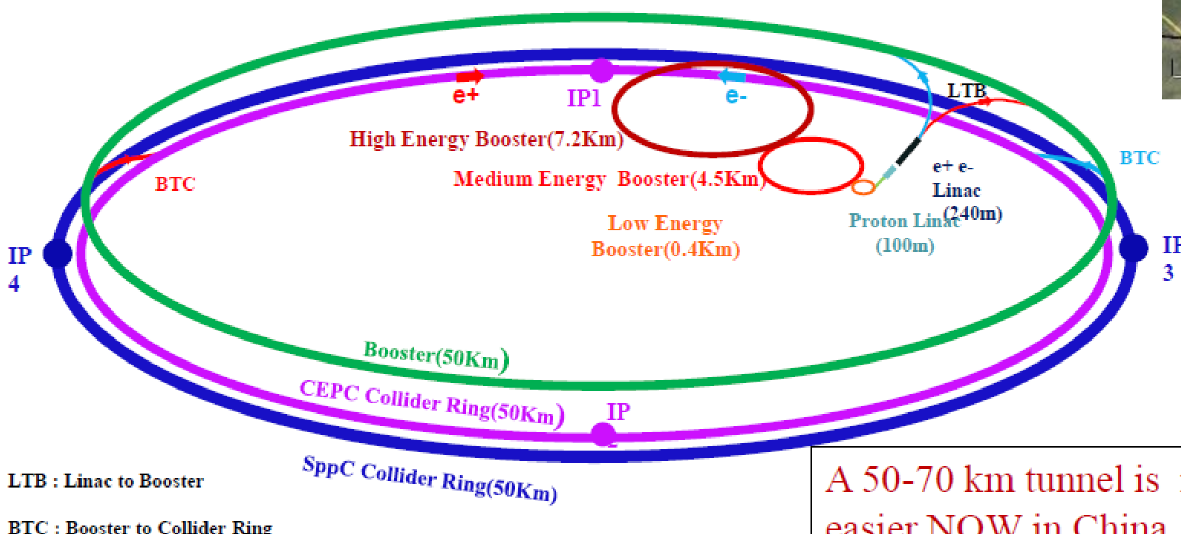




Chinese R&D: CepC and SppC

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

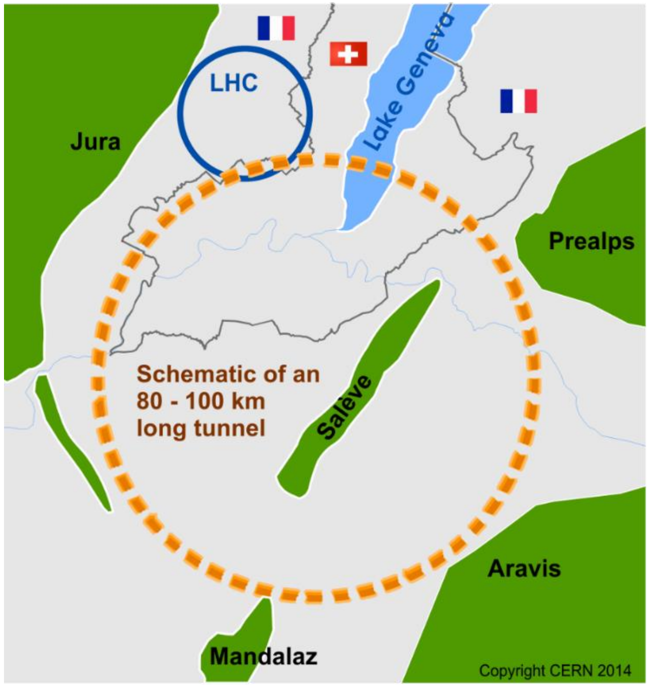


A 50-70 km tunnel is relatively easier NOW in China

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

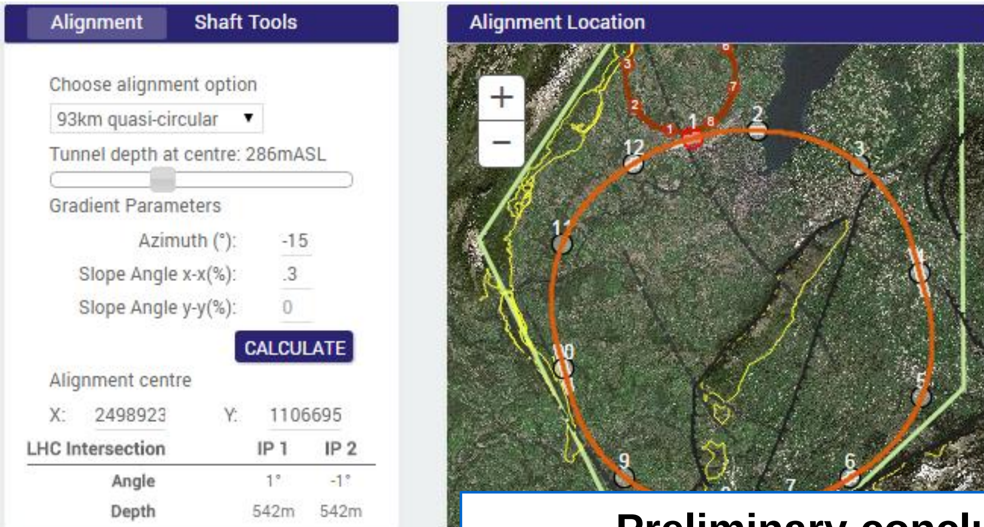
The Future Circular Collider (FCC) Study

- Hadron collider (**FCC-hh**)
  - centre-of-mass energy of the order of **100 TeV**
  - new tunnel of **80 - 100 km circumference** for physics at the highest energies.
- Lepton collider (**FCC-ee, ~300 GeV**)
  - as a potential intermediate step towards realization of the hadron facility.
  - potential synergies with linear collider detector designs are considered.
- Options for e-p scenarios (**FCC-he**)
  - impact on the infrastructure are studies at conceptual level.
- Study includes
  - cost and energy optimisation,
  - industrialisation aspects
  - implementation scenarios, including schedule and cost profiles



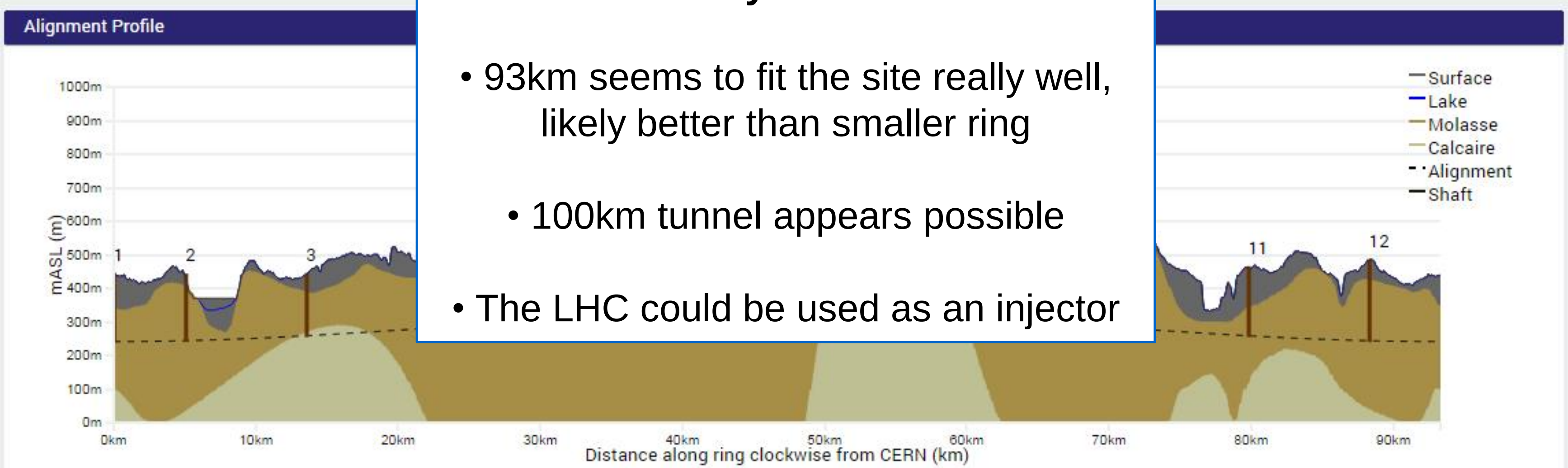
Site Study (Example)

PRELIMINARY



Geology Intersected by Shafts | Shaft Depths

Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
			3001	3211	741	2052	247



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

The Key Challenges

- Energy
  - Limited by the machine size and the strength of the bending dipoles
  - $\Rightarrow$ Have to maximize the magnet strength

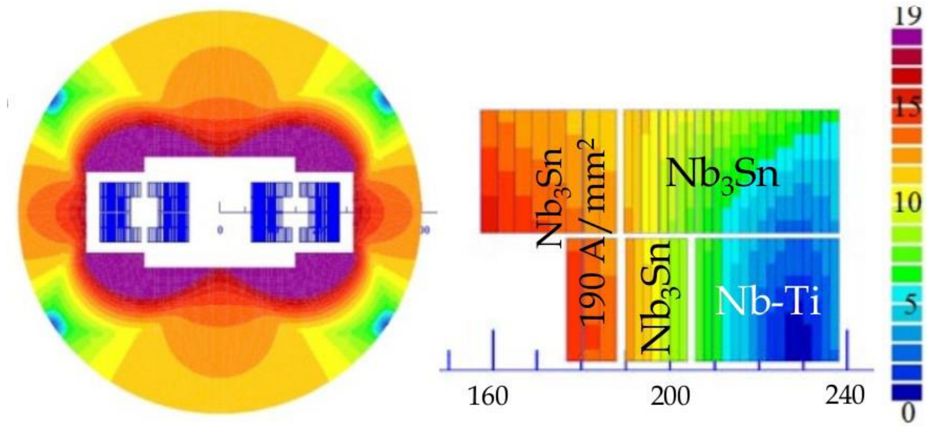
- Luminosity
  - $\Rightarrow$ Need to maximize the use of the beam for luminosity production

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

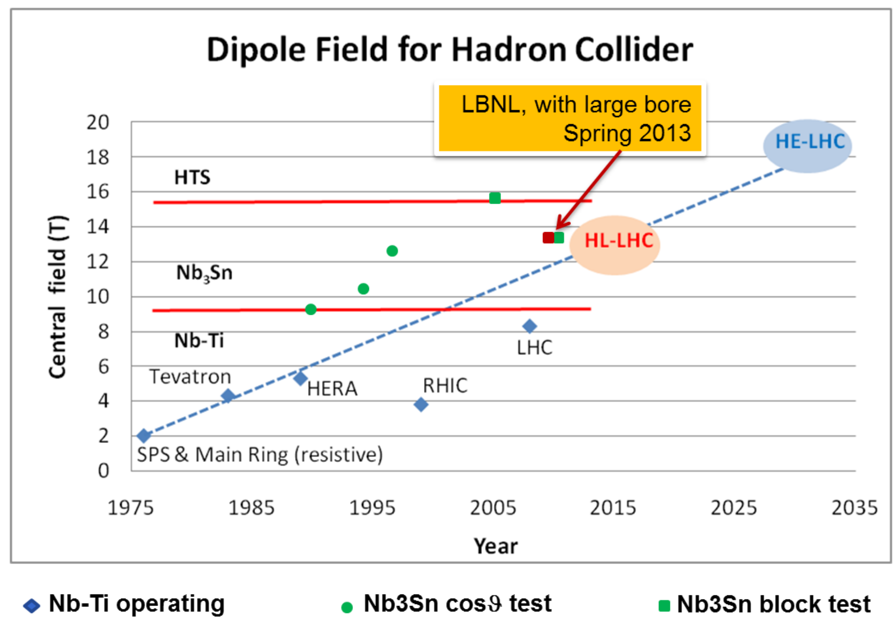
- Cost
  - The total cost is a concern, so we have to push everything to the limit to reduce cost
  - $\Rightarrow$ Most things will become difficult

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

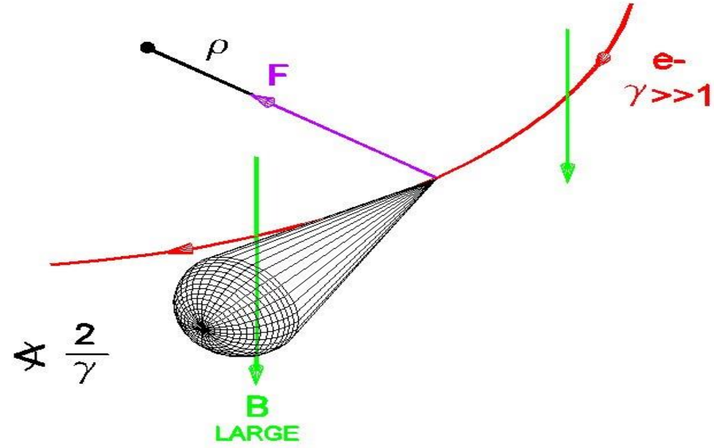
- Synchrotron radiation power
  - $P_\gamma \propto \frac{(\beta\gamma)^4}{\rho^2} \propto \frac{{m_0}^4}{\rho^2}$ $\beta = \frac{v}{c}$ $\gamma = \frac{E}{E_0}$
- 100 TeV protons radiate significantly
  - Total power of 5 MW (LHC 7kW)

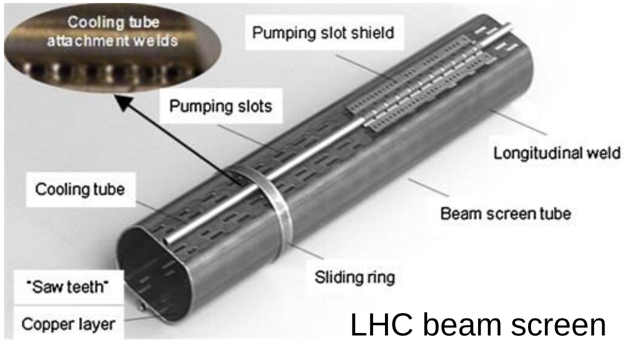
⇒ Needs to be cooled away
  - Equivalent to 30W/m per beam in the arcs
    - LHC <0.2W/m, total heat load 1W/m
- Current goal
  - beam aperture: 2x13mm
  - magnet aperture: 2x20mm
  - space for shielding: 7mm
- Protons loose energy

⇒ They are damped

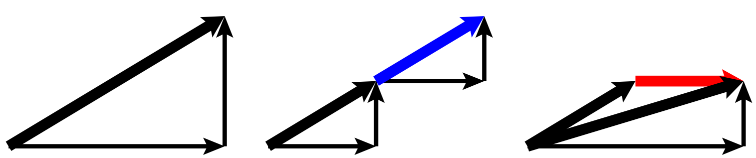
⇒ Emittance improves with time

- Typical transverse damping time 1 hour





LHC beam screen

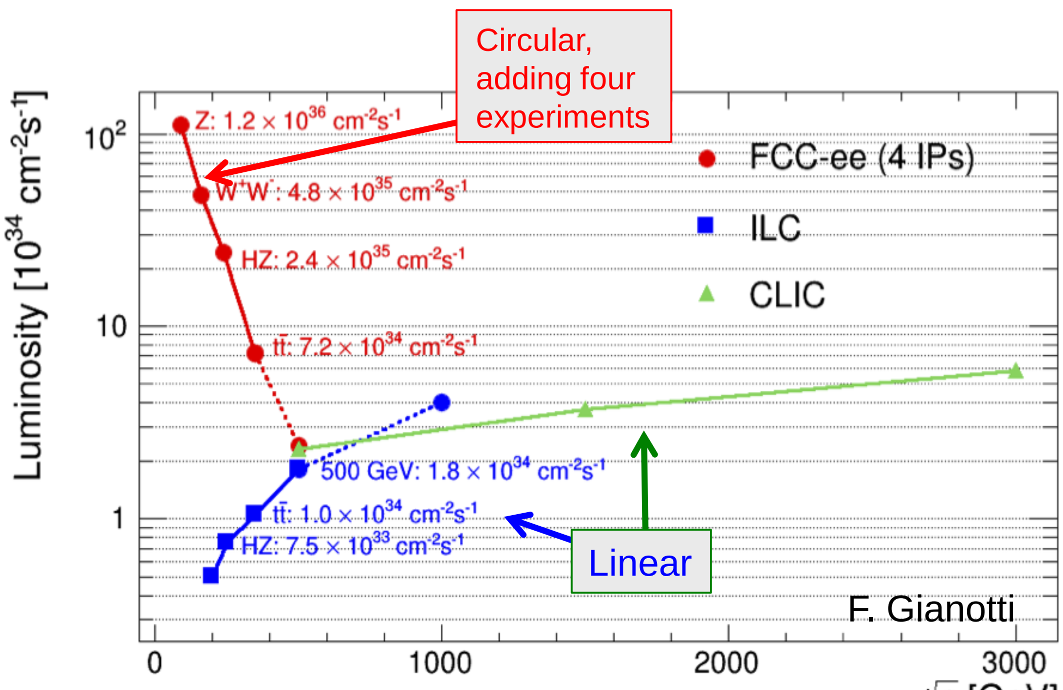


energy loss   re-acceleration

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)

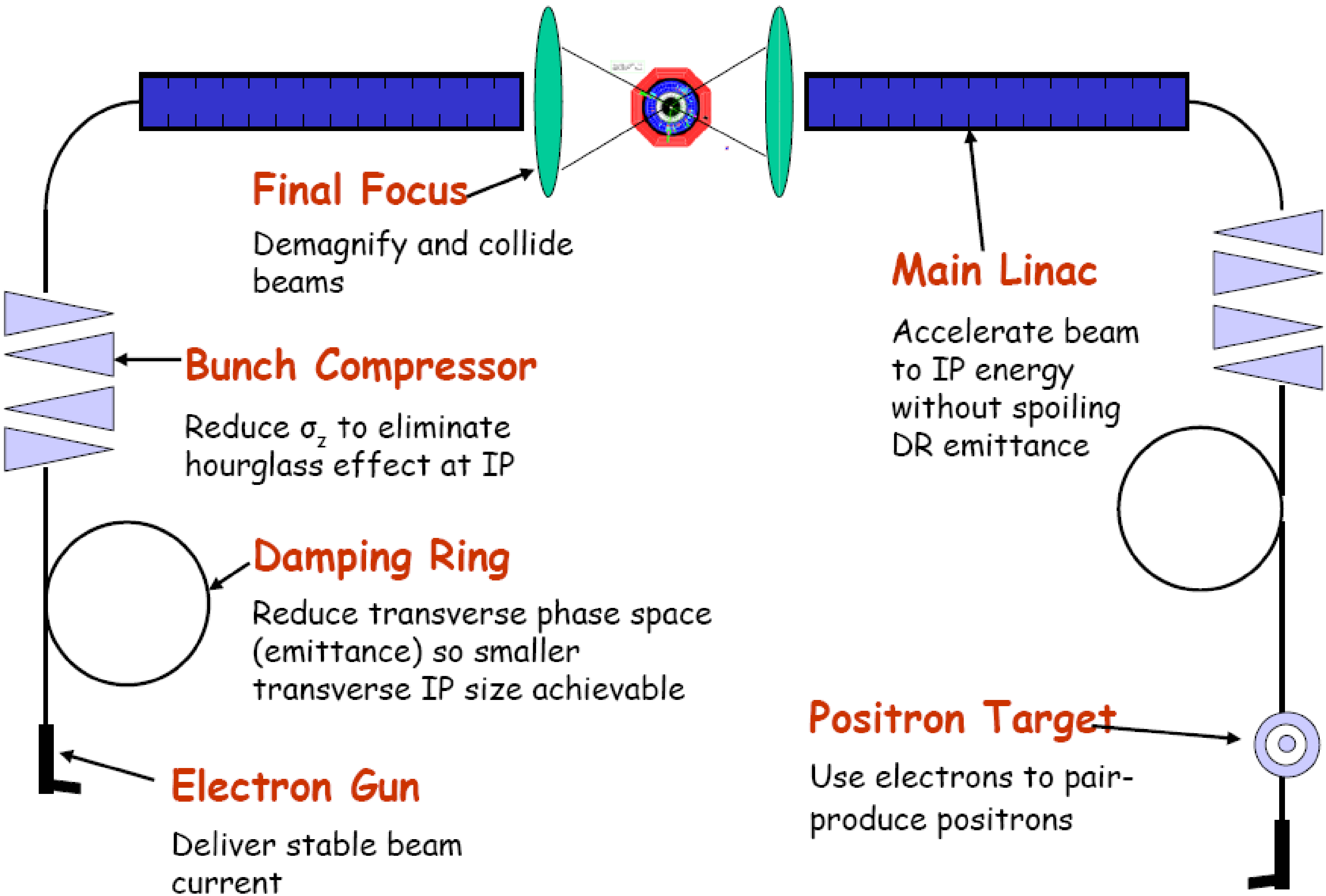
- Limited energy reach
  - But proton collider takes care of high energies
- Limited beam lifetime
  - due to large particle energy loss in IPs and limited energy acceptance (2%)
  - need continuous top-up



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

Linear Colliders

Basic Layout of a Linear Collider



Studies and Project Proposals

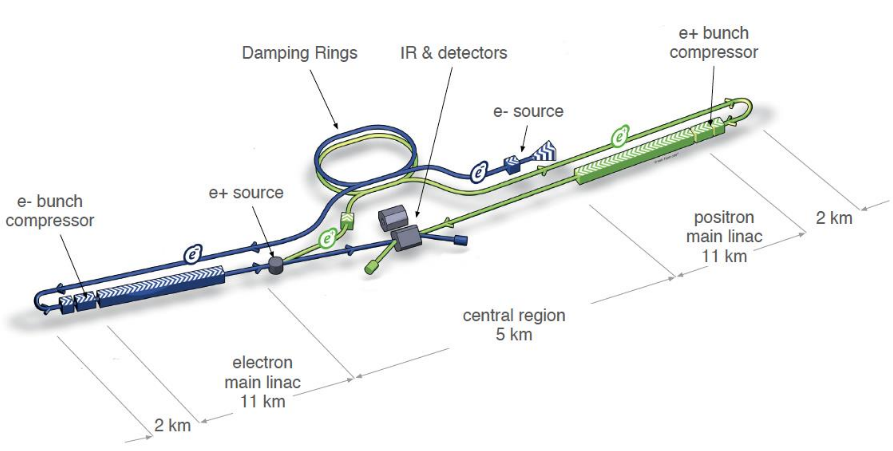
International Linear Collider: ILC

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

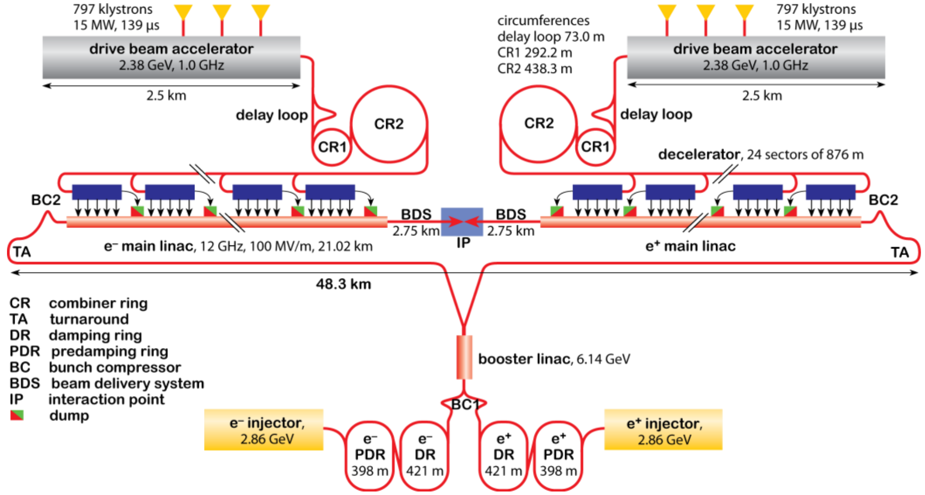
Compact Linear Collider: CLIC

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

international linear collider



Compact Linear Collider



Superconducting RF Cavities (SRF)

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

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

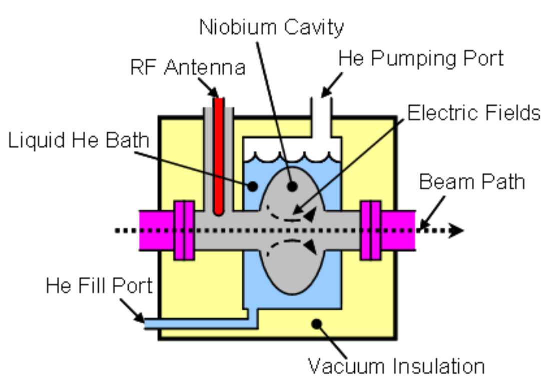
  - but expensive cryo-cooling

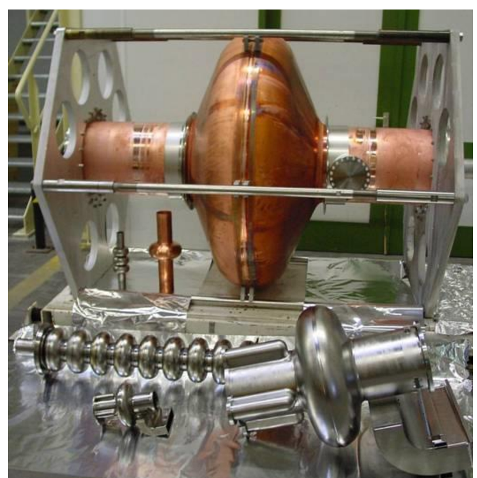
$$P_{cryo} = \frac{1}{\eta} \frac{T_{room} - T_{source}}{T_{source}} \times P_{loss}$$

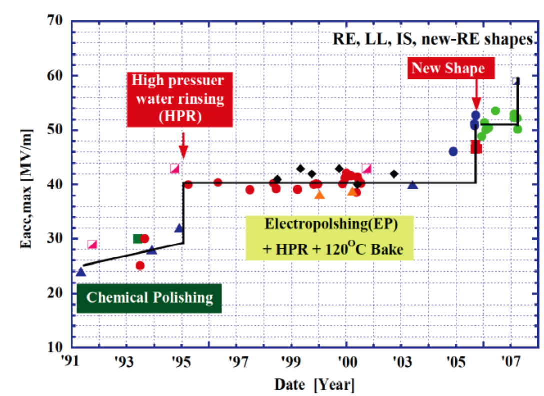
$$P_{cryo} \approx 700 \times P_{loss}$$

- 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

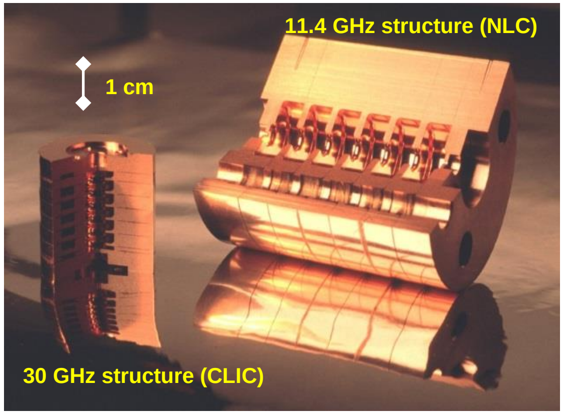


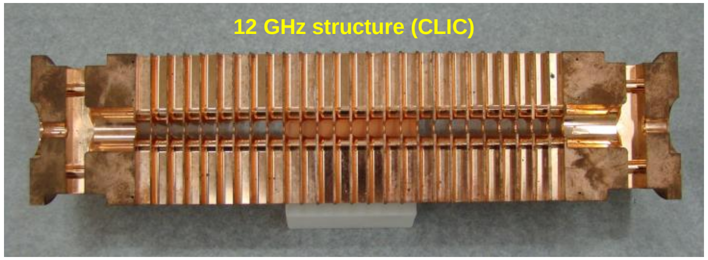


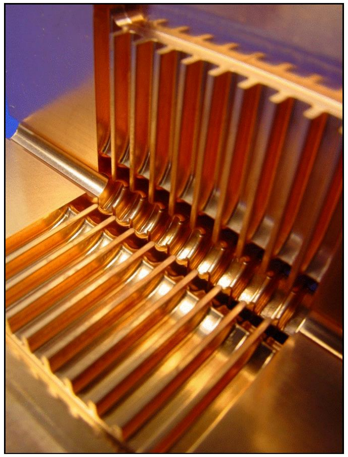


Normal Conducting (Resistive) RF

- 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

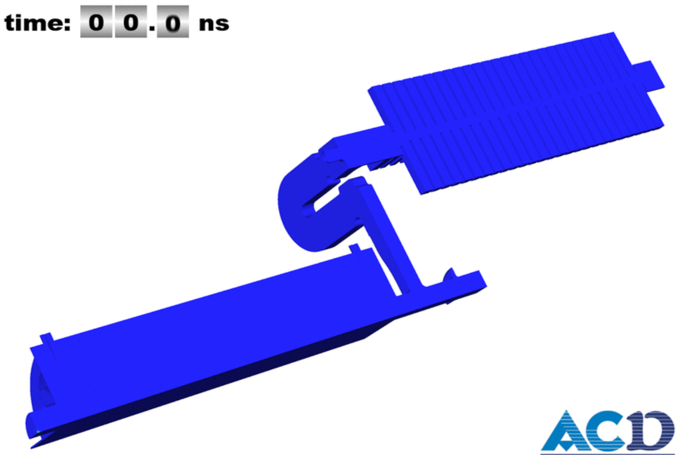


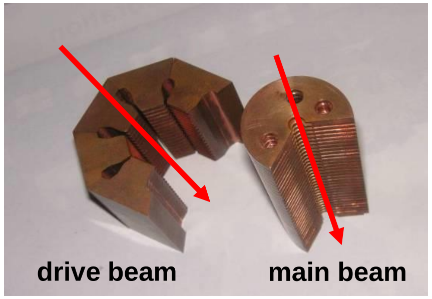


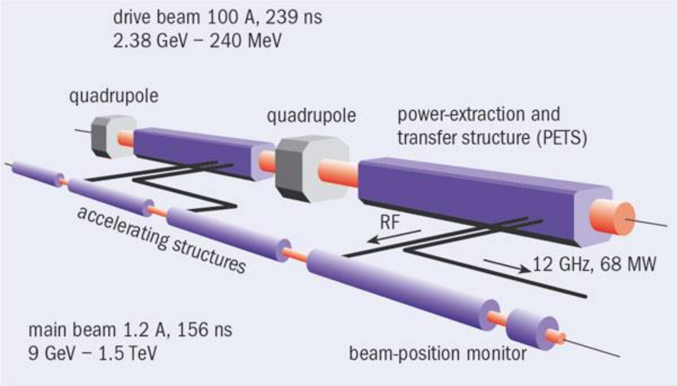


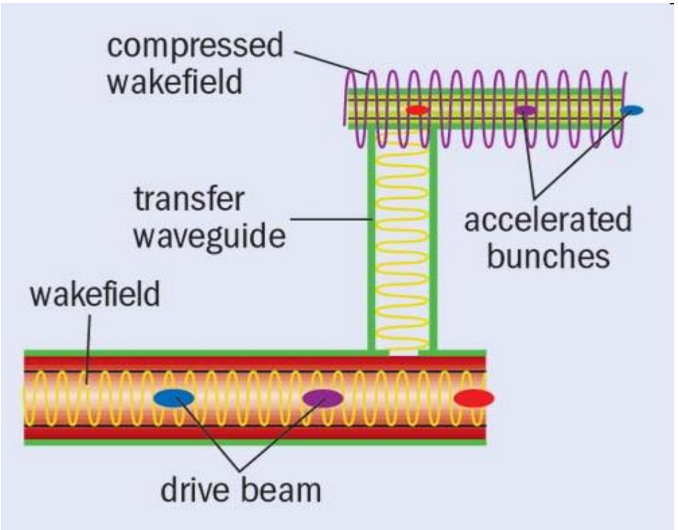
CLIC Two-beam Acceleration Concept

- 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)

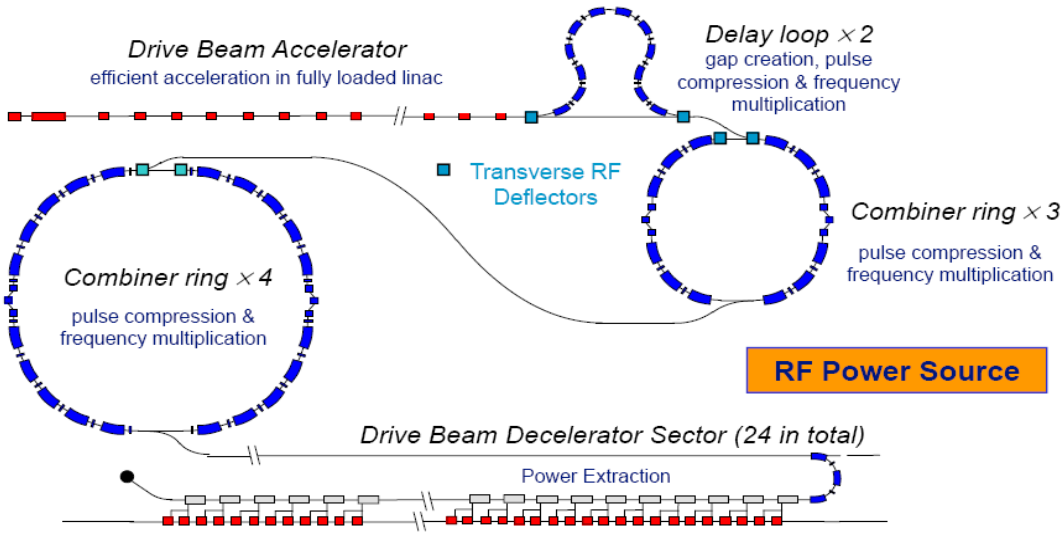






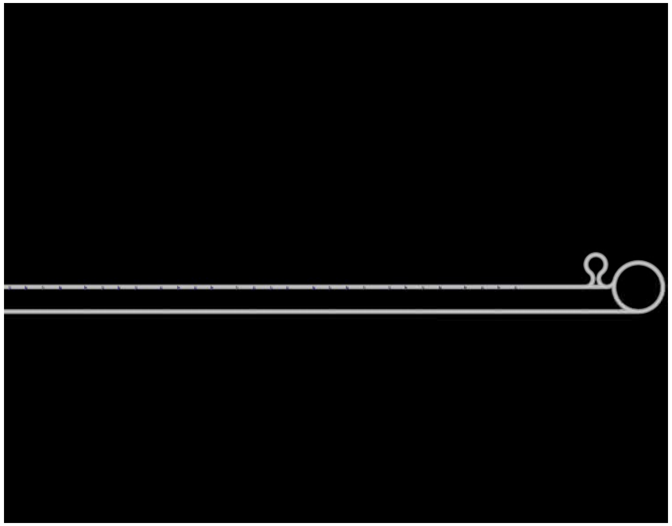


Drive Beam Generation



Drive beam time structure - initial

Drive beam time structure - final



Courtesy A. Andersson

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 CDR
  - now focusing on the optimisation and industrialisation of the technology
- FCC study is working towards a CDR in 2018
  - can use the vast experience and technology from LHC
  - but challenges due to high beam energy and luminosity

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