UPPSALA UNIVERSITET

Future Accelerators

Roger Ruber
FREIA Laboratory
Dept. of Physics and Astronomy
Uppsala University

October 2015

Course Layout

This Lecture

- technologies for a future collider
- highlights of related research

Sections

1. Circular versus Linear
2. International Linear Collider (ILC)
3. Compact Linear Collider (CLIC)
4. Future Circular Collider (FCC)

Accelerator History

A question of

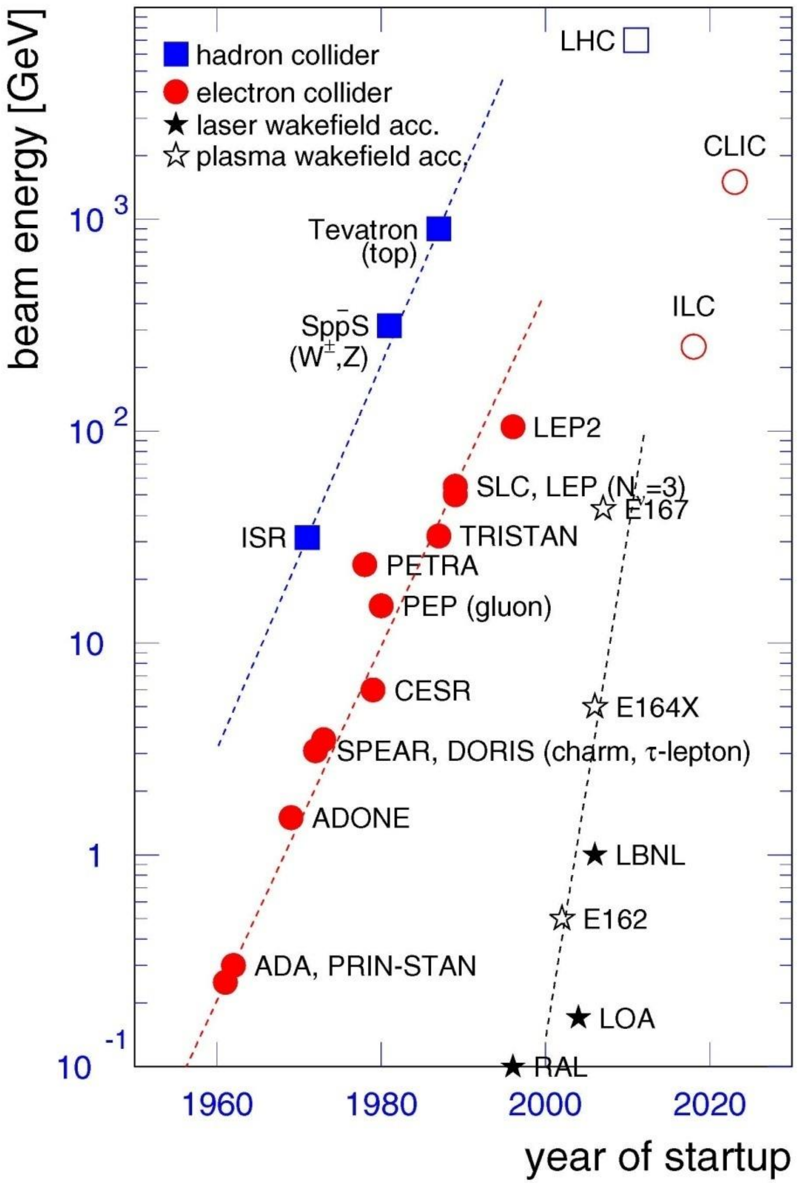
- linear vs circular
- lepton vs hadron
- acceleration technology
  - DC, RF, wakefield

Project ideas

- linear electron collider
- circular electron or proton collider
- circular electron – proton collider

But also

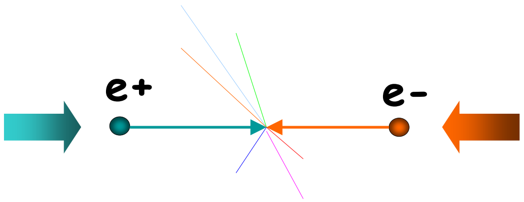
- non-HEP use of accelerators

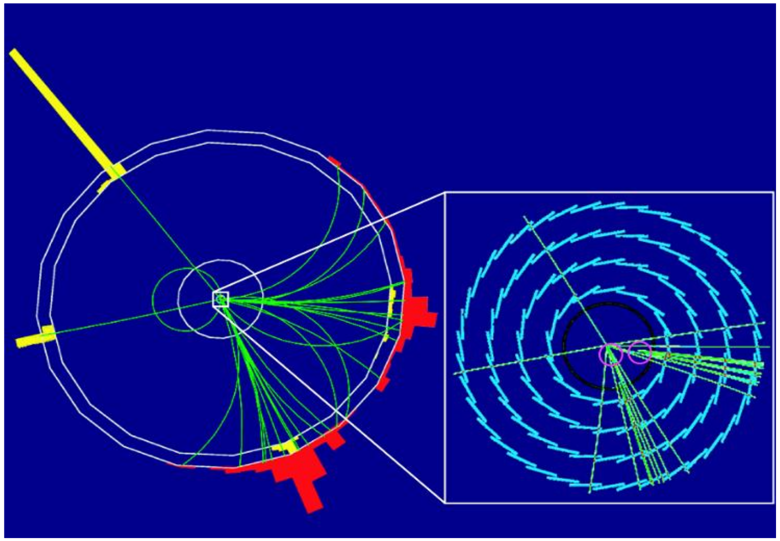


Lepton versus Hadron Collissions

Leptons

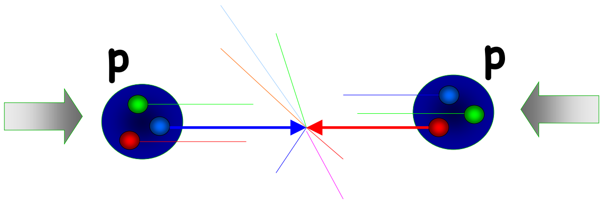
- for precision physics
- well defined CM energy
- polarization possible

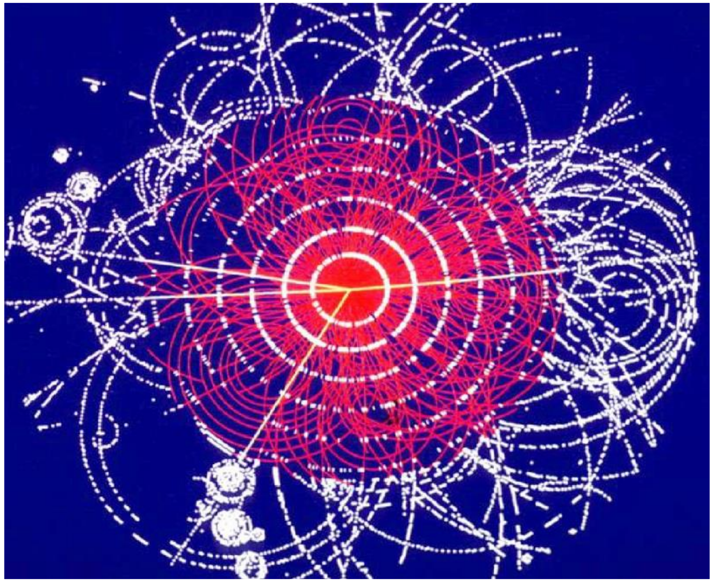




Hadrons

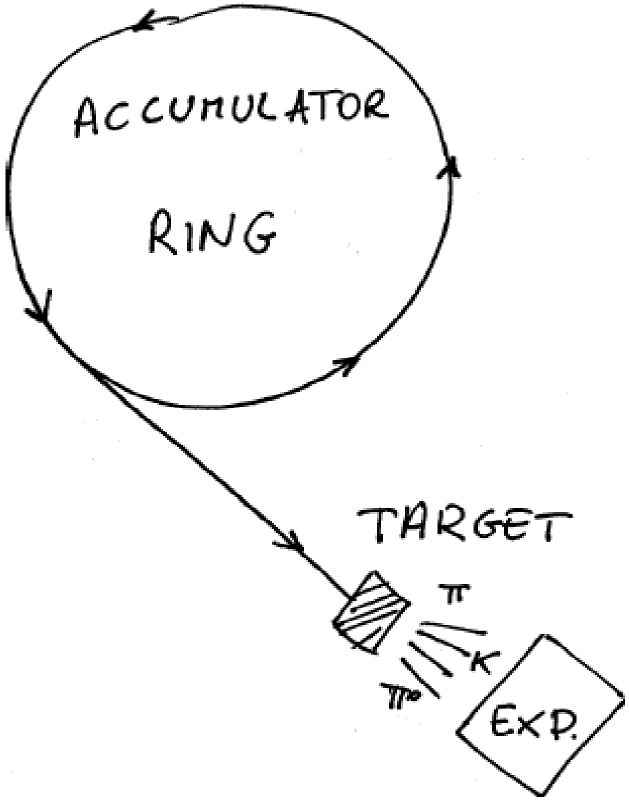
- at the frontier of physics
- huge QCD background
- not all nucleon energy available in collision



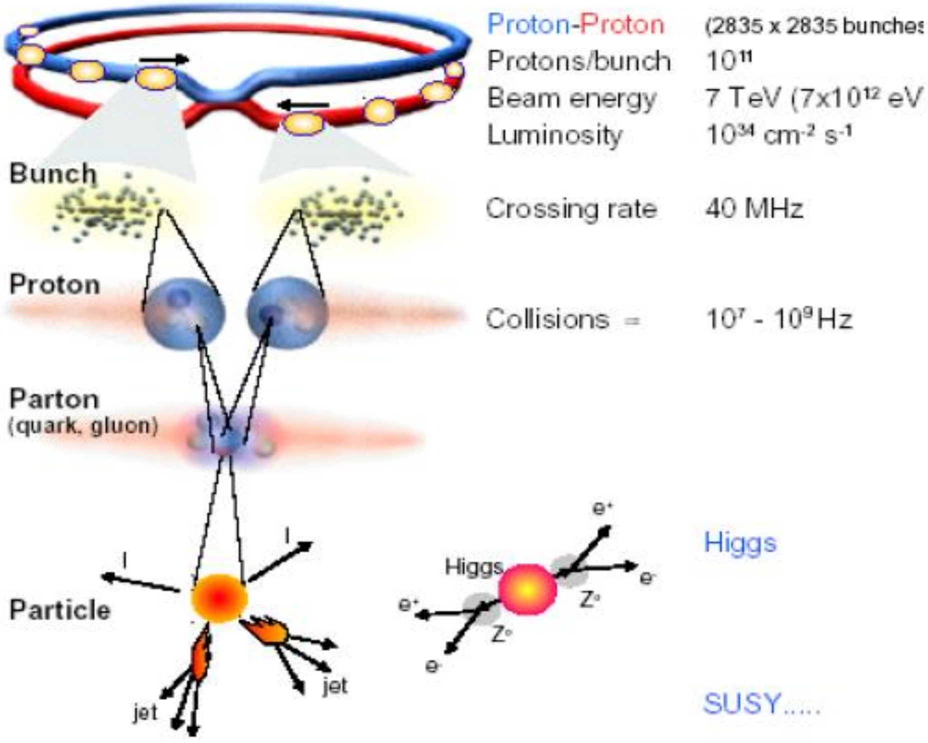


Particle Accelerators and Collissions

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 Collider

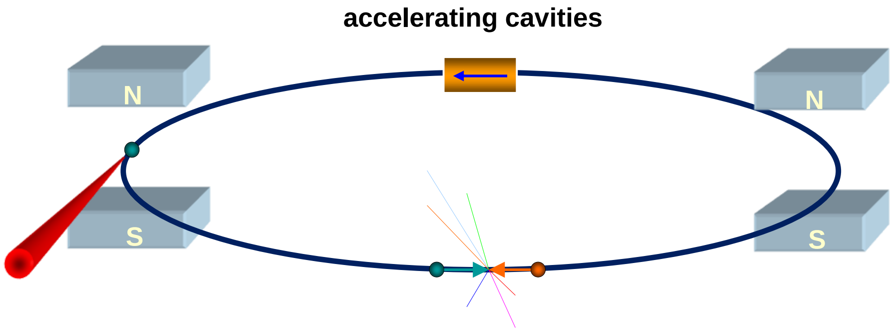
Circular Collider

many magnets, few cavities → need strong field for smaller ring

multi-pass → high bunch repetition rate for high luminosity

ring → synchrotron radiation losses

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



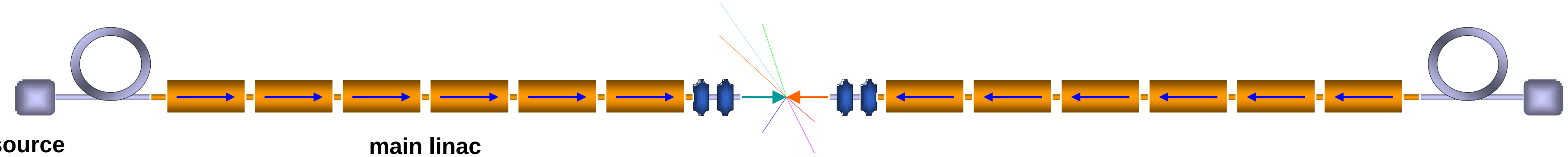
Linear Collider

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:

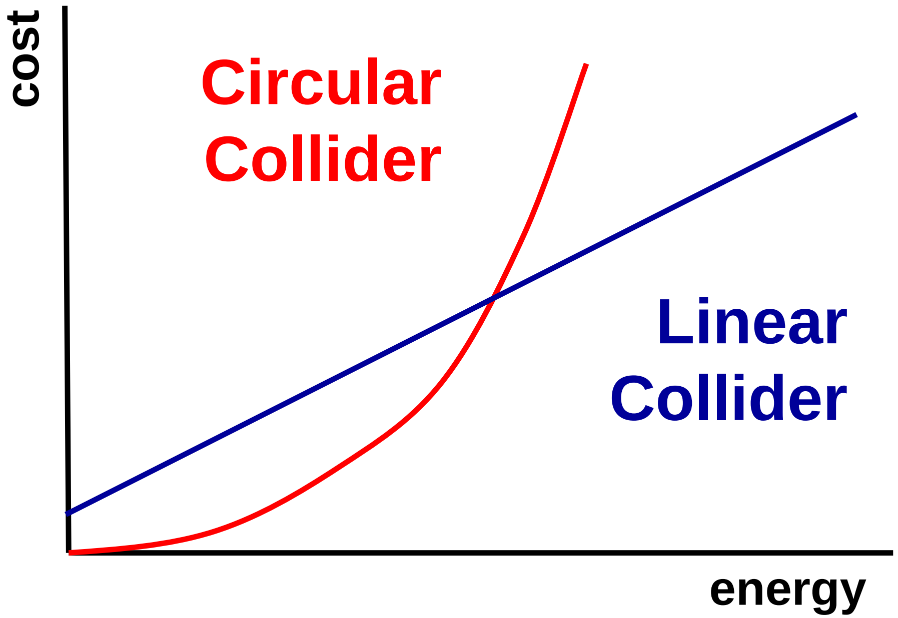
(exceptional beam quality, alignment and stabilization)



Linear versus Circular Collider: Cost

Linear Collider

- E ~ L
- cost ~ aL



Circular Collider

- ΔE_{turn} ~ (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

Future Accelerator Projects

Linear

- Particle physics
  - high energy electrons
    - ILC
    - CLIC
  - high intensity protons
    - ESSnuSB, LBNE: neutrino beams
- Other physics research
  - high intensity protons/deuterons
    - ESS: neutron spallation source for material research
    - IFMIF: material irradiation for ITER
    - MYRRHA, C-ADS, ….: accelerator driven nuclear power systems
    - LCLS-II: FEL for material research

Circular

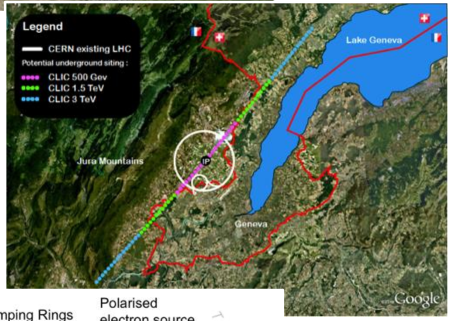
- Particle physics
  - high energy electrons/protons/ions
    - FCC-ee/pp/ep
  - high energy muons
    - MAP and MICE studies for muon collider technologies
- Other physics research
  - synchrotron radiation
    - MAX-IV: material research

European Strategy

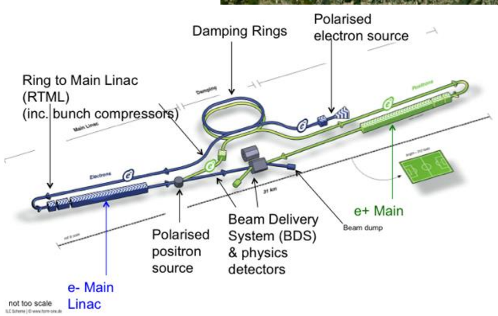
Approved by CERN council (May 2013), ESFRI roadmap

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

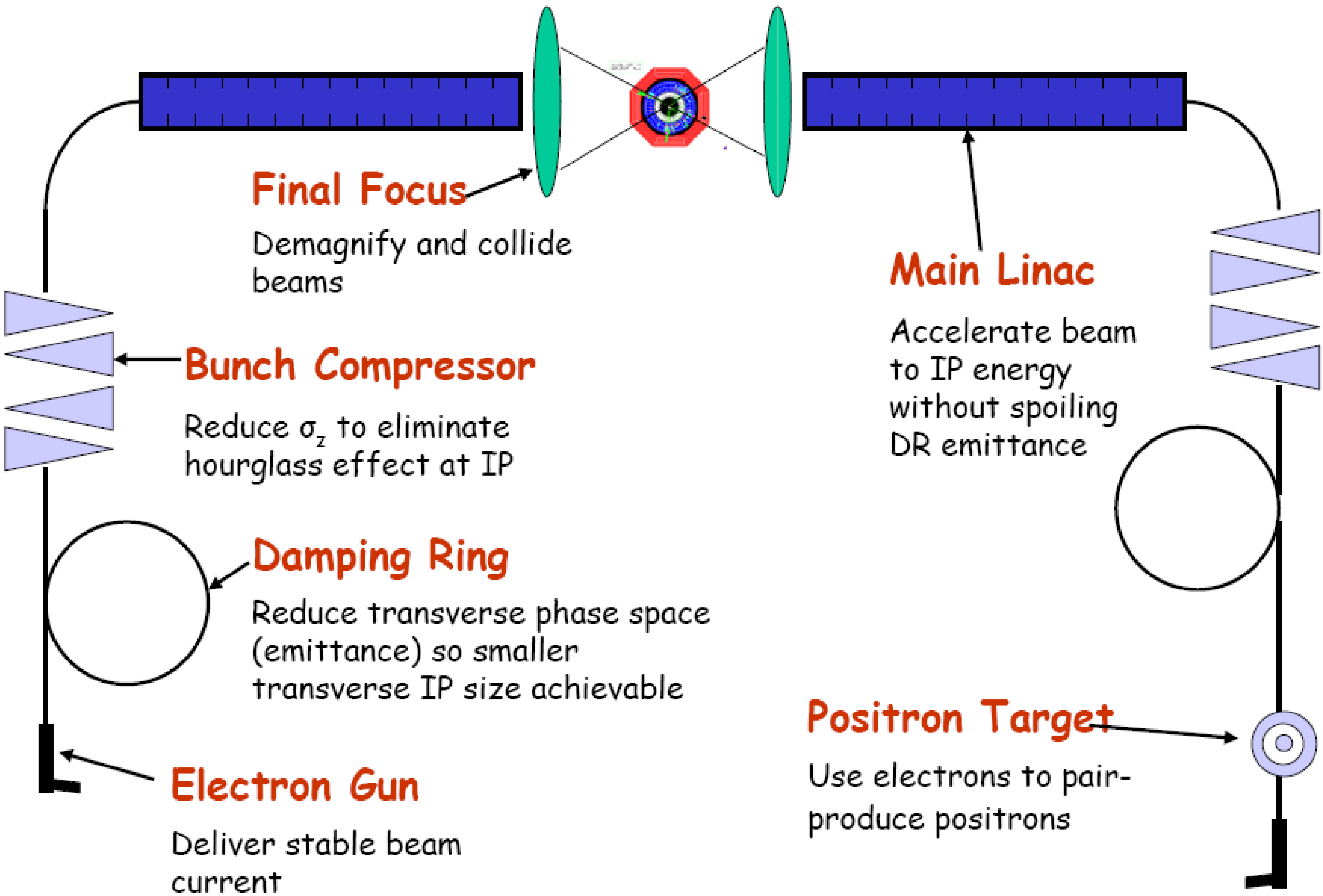


- Europe welcomes Japan to make a proposal to host ILC

- Long baseline neutrino facility

Linear Colliders

Basic Layout of a Linear Collider



Studies and Project Proposals

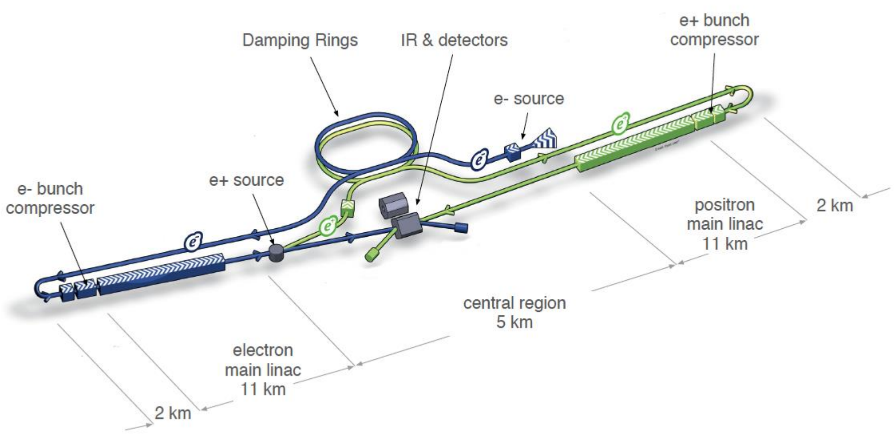
LINEAR COLLIDER COLLABORATION

UPPSALA UNIVERSITET

International Linear Collider: ILC

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

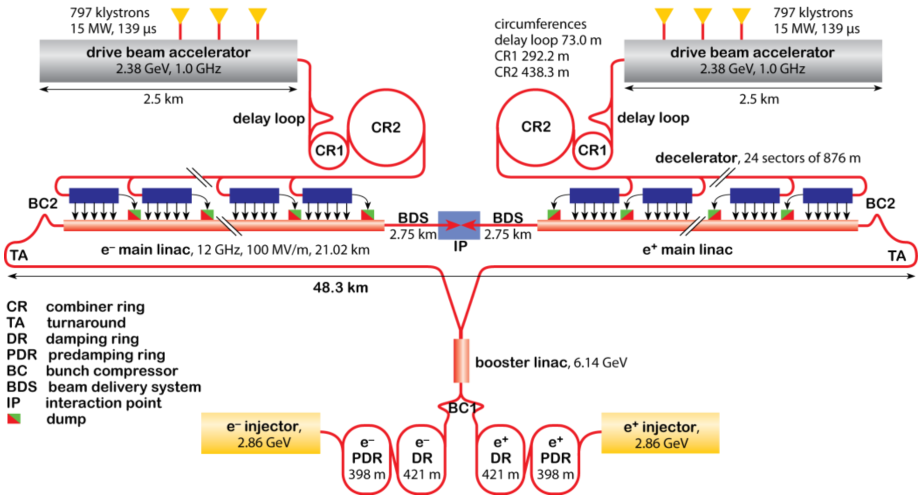
international linear collider



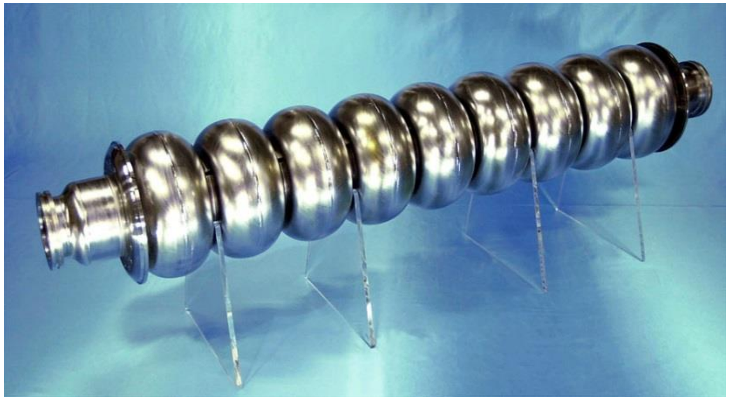
Compact Linear Collider: CLIC

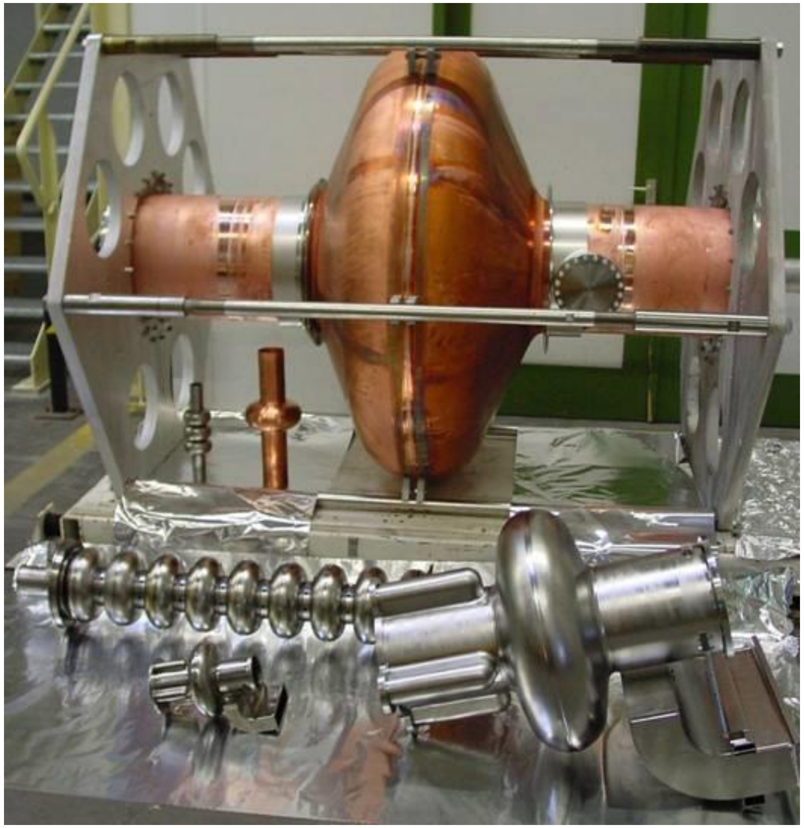
- normal conducting technology
- 12 GHz
- 100 MV/m
- E_{CM} = 3 TeV
- start at 500 GeV with stepwise upgrading

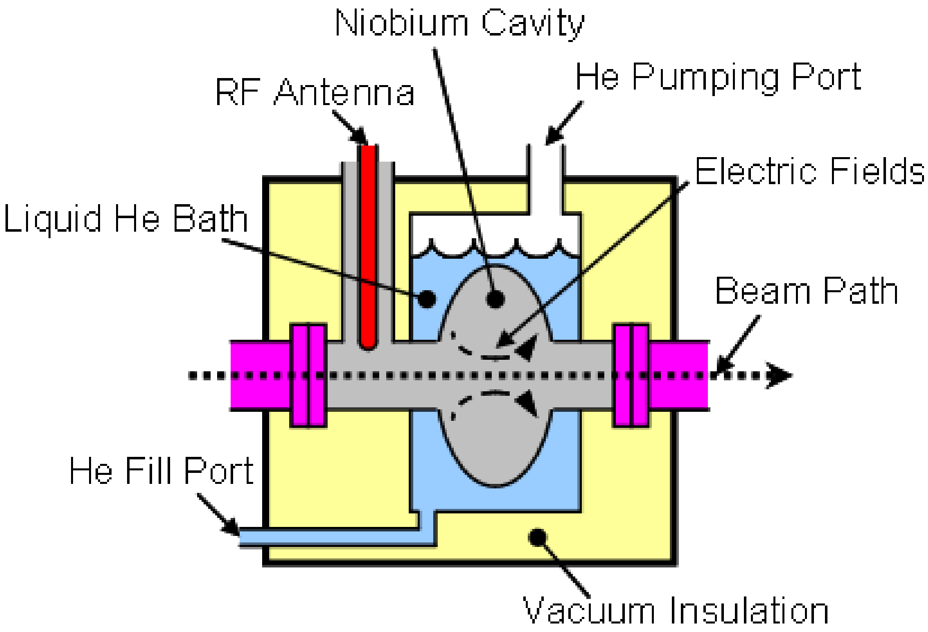
Compact Linear Collider



Superconducting RF Cavities (SRF)







Advantages of SRF

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

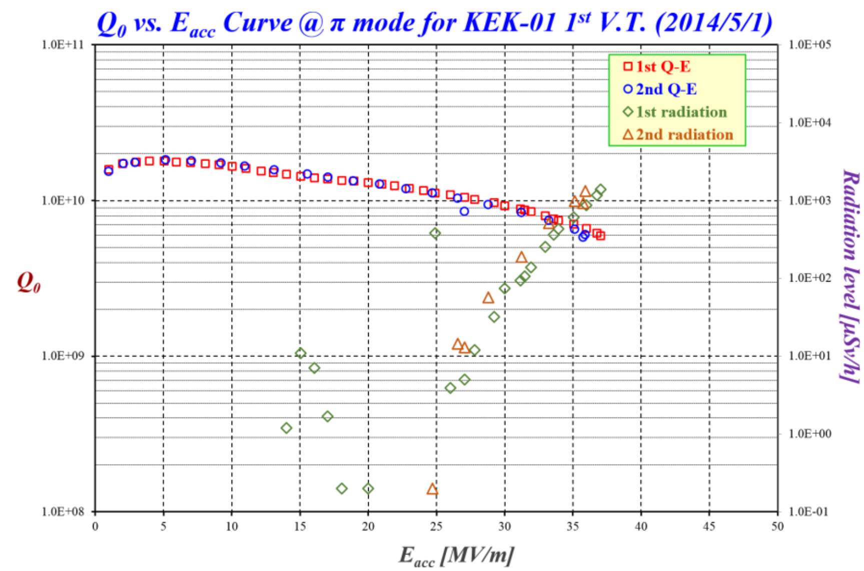
$$P_{loss} = const \frac{1}{Q_0} \times G^2$$

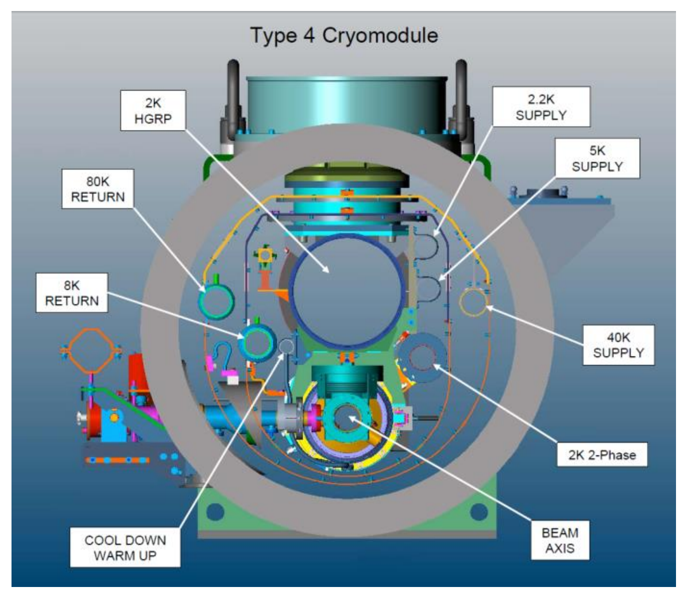
  - but expensive cryo-cooling

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

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

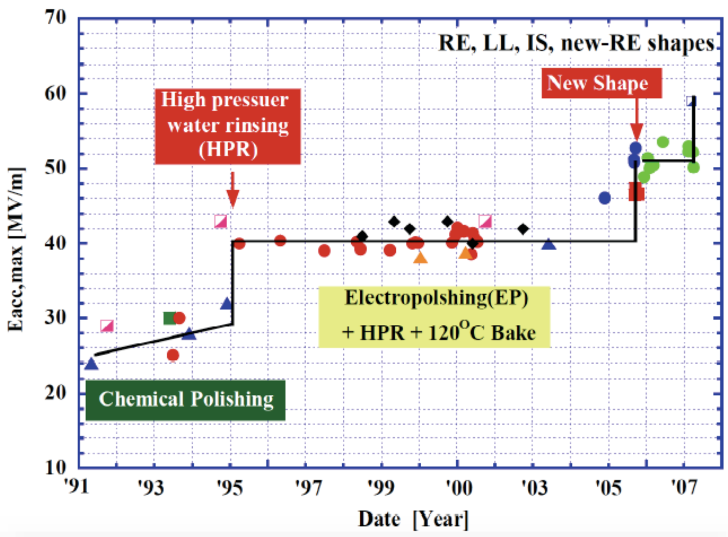
- High efficiency
- Long pulse trains possible
  - favourable for in-pulse feed-back
- Low frequency
  - large dimensions (larger tolerances) large aperture and small wakefields
  - important accelerator design implications



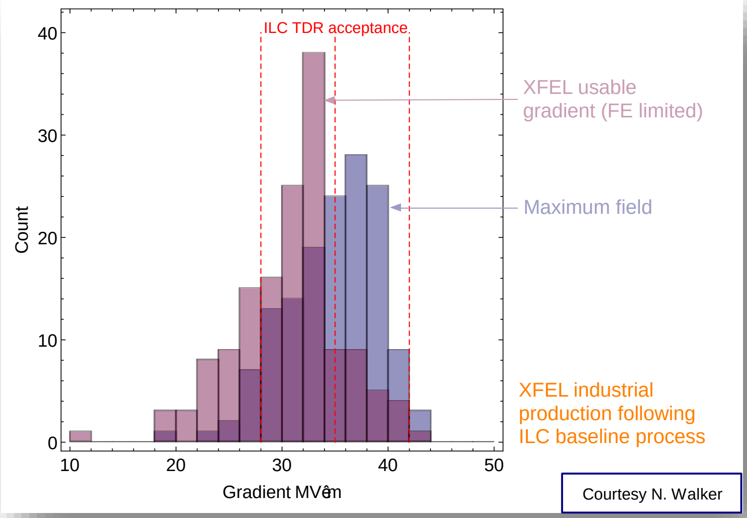


Progress in SRF Development

- Record **59 MV/m** achieved with single cell cavity at 2K
- 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



- Example 9 cell cavities in operation
  - at DESY (FLASH/XFEL):
    - R&D Status ~30-35 MV/m
  - DESY XFEL requires <23.6> MV/m
  - ILC requires <31.5> MV/m



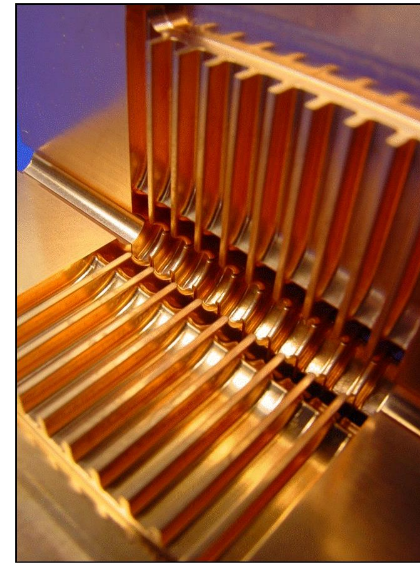
Normal Conducting RF

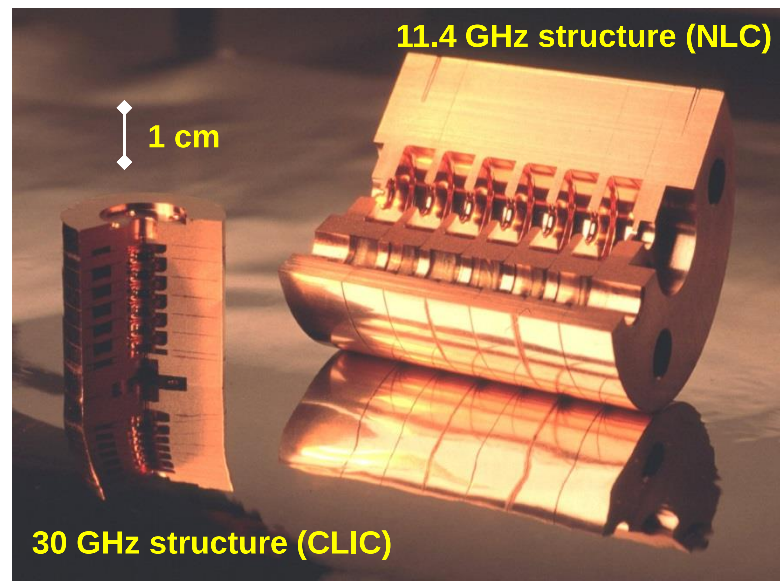
- Normal conducting = resistive

- Higher gradients than SCRF cavities possible, but only if
  - high frequency: >10 GHz
  - short pulse lengths: < 1μs
  - E_{acc} limited by breakdown RF-field: > 60 MV/m

- high ohmic losses
  ⟶ travelling wave
  (unlike standing wave in SCRF)

- fill time $t_{fill} = \int 1/v_G \, dz$
  order <100 ns (~ms for SCRF)





Advantages of Normal Conducting RF

- Higher gradients
  - shorter accelerator thus cheaper real estate costs

- Easier operation
  - water cooling instead of cryogenic fluids
  - stiffer thus less effected by Lorentz force detuning (in pulsed mode)

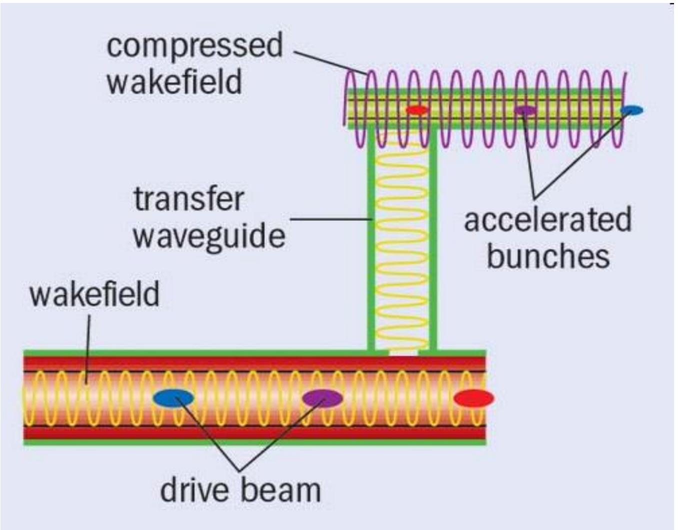
- Easier manufacturing
  - unlike SRF, no special chemical procedures, no clean room
  - direct machining instead of form shaping
  - better accuracy thus higher frequency possible

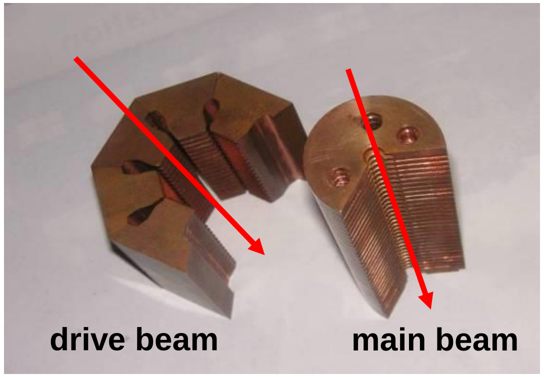
- Well suited for small accelerators
  - industrial and medical applications
  - university

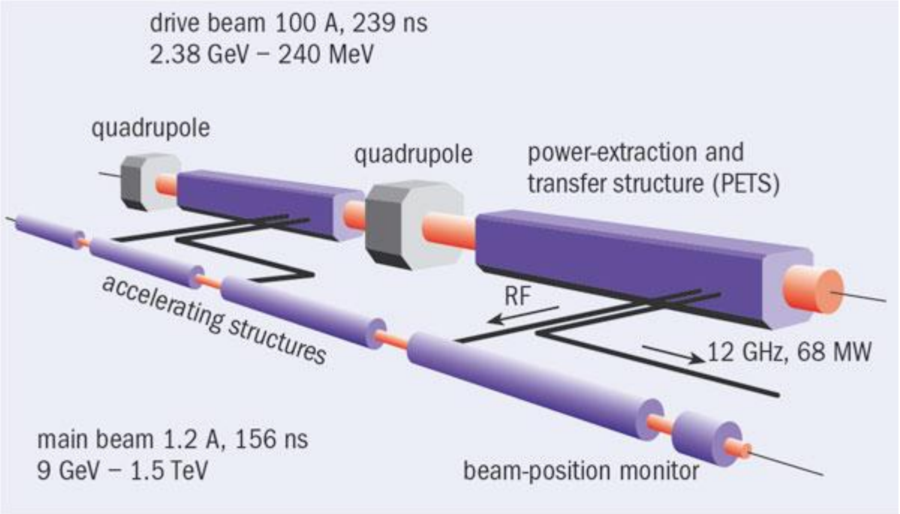
CLIC Two-beam Acceleration Concept

- acceleration by wakefield of drive-beam
  - 12 GHz modulated and high power drive beam
  - RF power extraction in a special structure (PETS)
  - use RF power to accelerate main beam

- only passive elements
- compress energy density

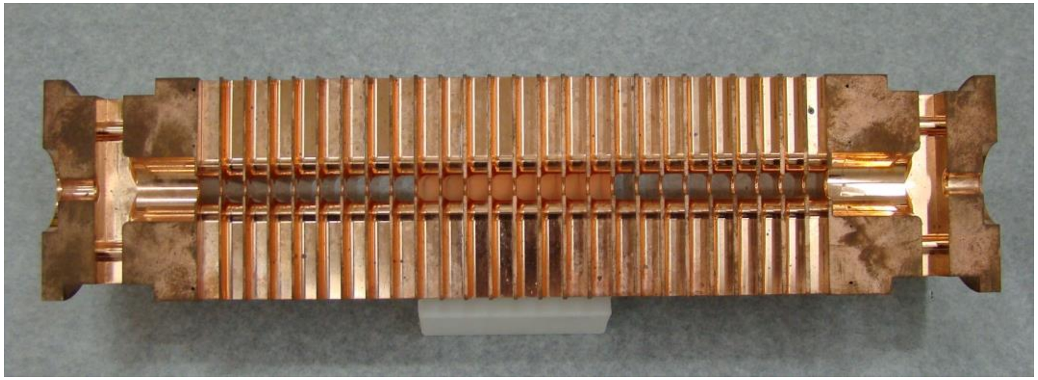


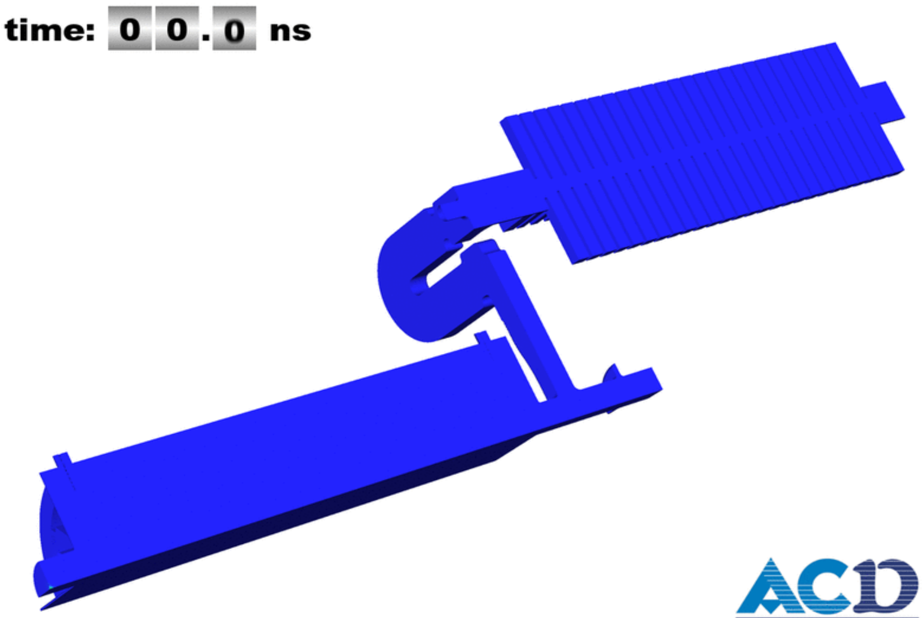




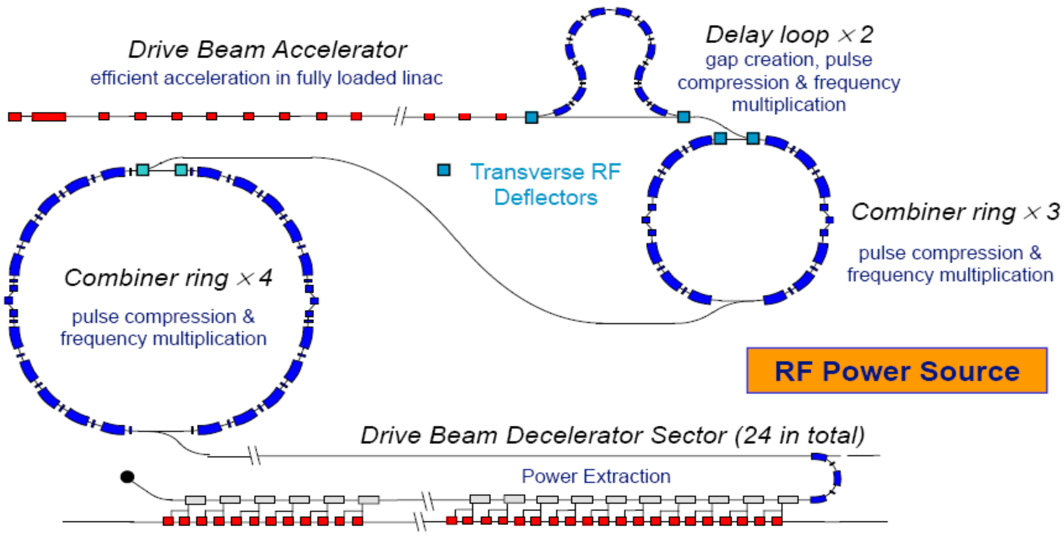
CLIC Accelerating Structure

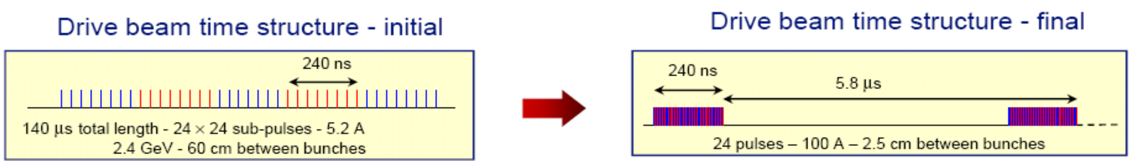
- Main parameters
  - E_{acc} = >100 MV/m
  - 11.424 GHz
  - 230 ns pulse length
  - <10^{-6} breakdown rate (BDR)

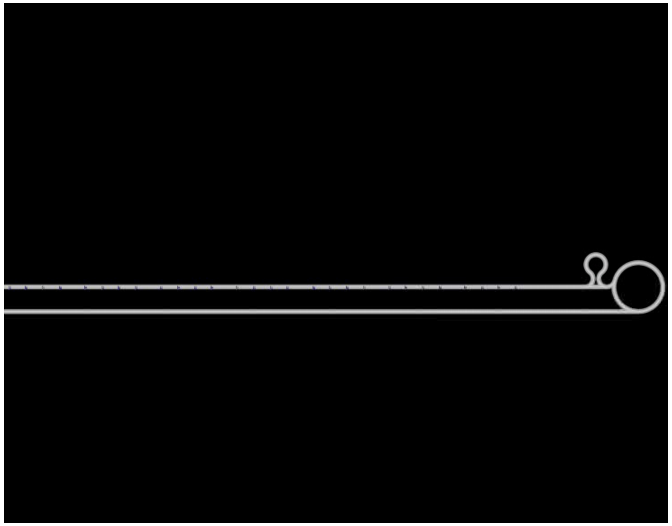




Drive Beam Generation







Courtesy A. Andersson

Circular Colliders

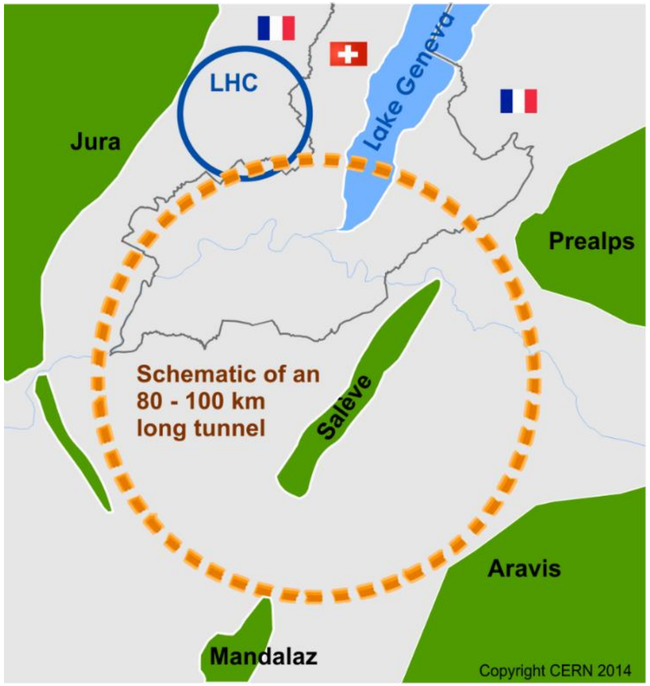
The Future Circular Collider (FCC) Study

- The main emphasis is the long-term goal of a hadron collider (**FCC-hh**) with a centre-of-mass energy of the order of **100 TeV** in a new tunnel of **80 - 100 km circumference** for the purposes of studying physics at the highest energies.

- Includes a lepton collider (**FCC-ee**) and its detectors, 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**) and their impact on the infrastructure are studies at conceptual level.

- The study includes cost and energy optimisation, industrialisation aspects and provides implementation scenarios, including schedule and cost profiles



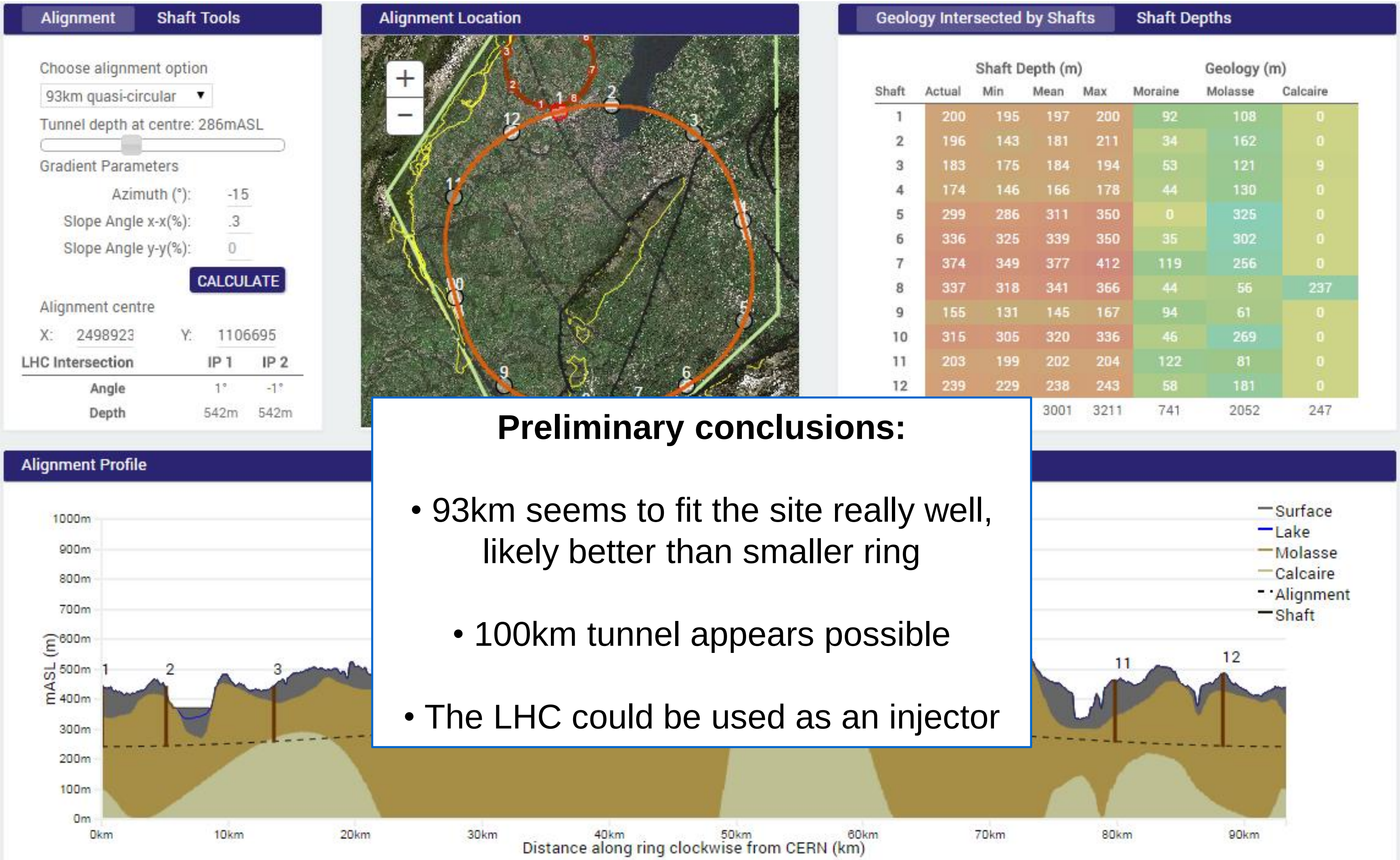
FCC-hh Parameters

	LHC	HL-LHC	FCC-hh
CMS energy [TeV]	14	14	100
Luminosity [$10^{34} cm^{-2} s^{-1}$]	1	5	5
Bunch distance [ns]	25	25	25
Background events/bx	27	135	170
Bunch length [cm]	7.5	7.5	8

- Baseline parameter list exists:
  - http://indico.cern.ch/event/282344/material/3/
- Two main experiments
  - Two reserve experimental areas
- 80% of circumference filled with bunches

Site Study (Example)

PRELIMINARY



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
  - ⇒ Have to maximise the magnet strength

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

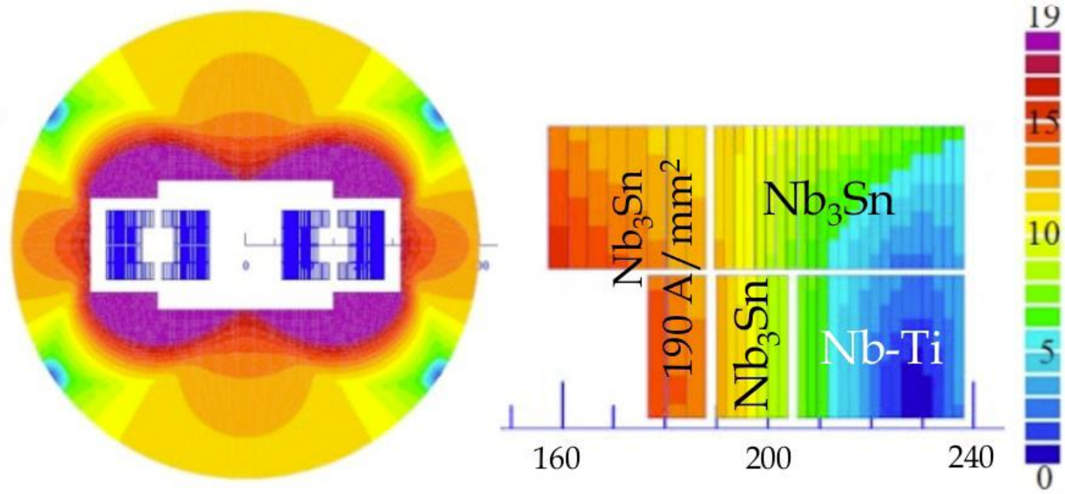
- Beam power handling: The beam can damage the machine
  - – Quench the magnets
  - – Create background in the experiments
  - ⇒ Need a concept to deal with the beam power

- 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

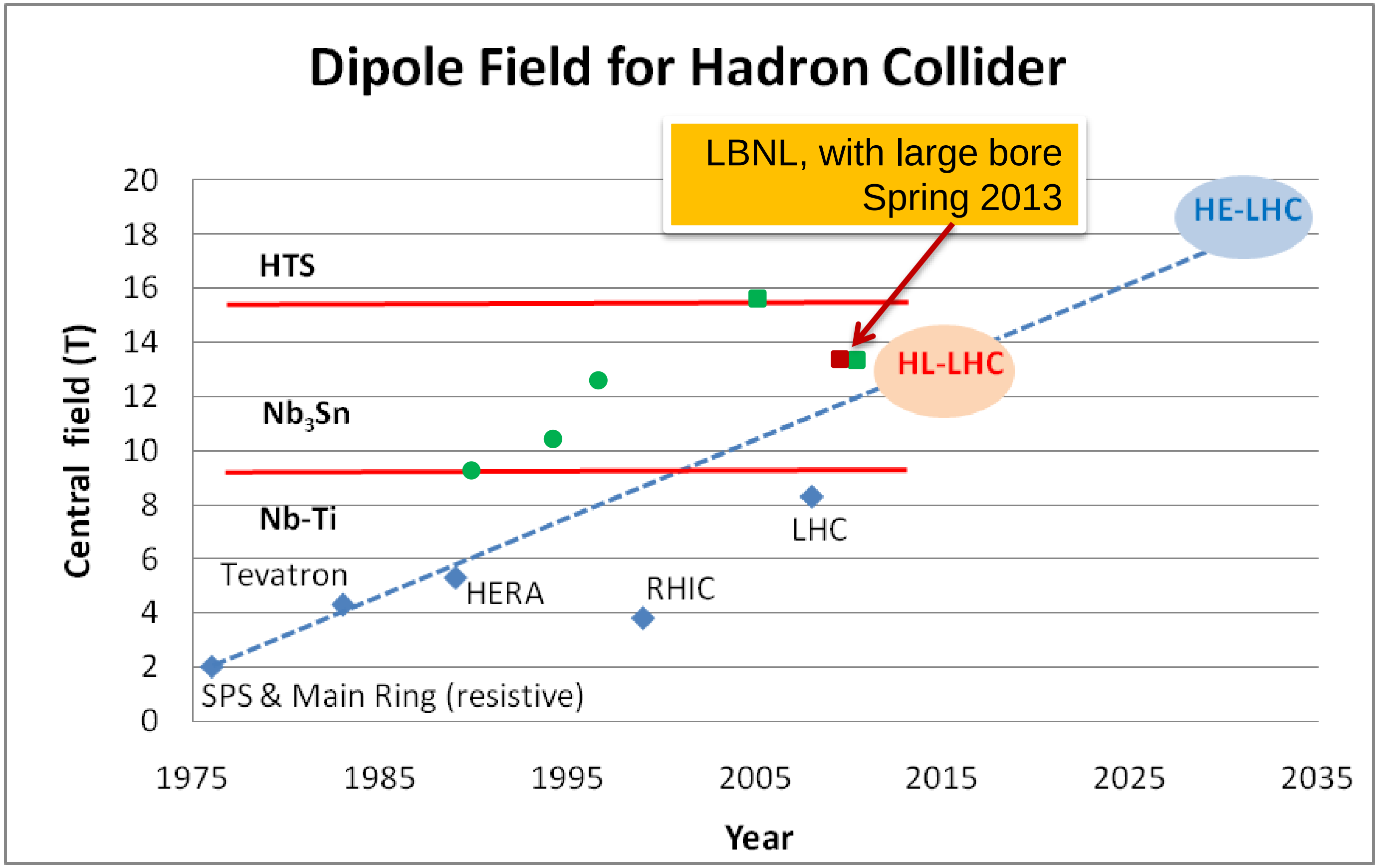
- baseline is Nb3Sn at 16T
- alternative HTS at 20T



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

- Field level is a challenge but many additional questions:
  - aperture
  - field quality
- Different design choices (e.g. slanted solenoids) should be explored
- Prototype development ongoing in all regions (America, Asia, Europe)

Development of Dipole Magnets



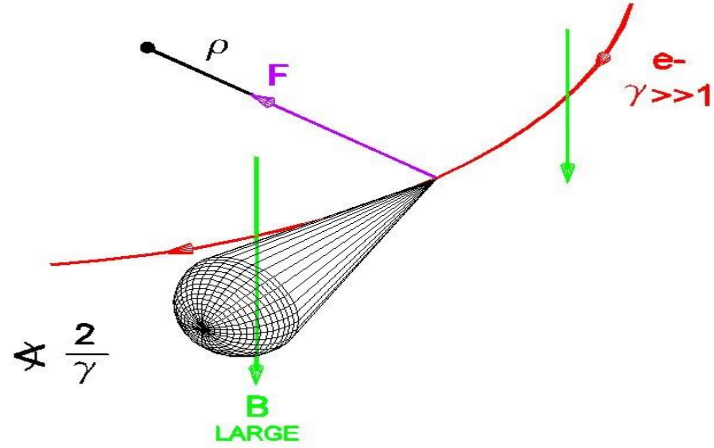
Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) **the practical limit is around 20 T**. Such a challenge is similar to a 40 T solenoid.

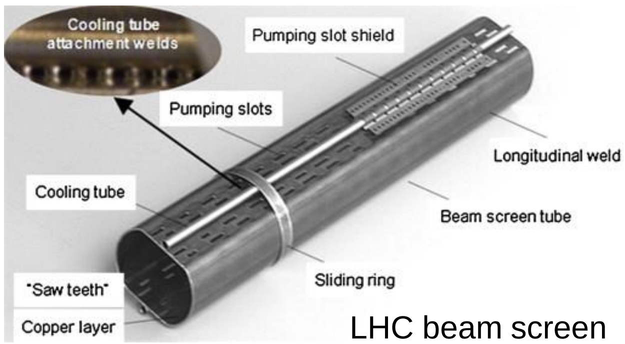
◆ **Nb-Ti operating dipoles;** ● **Nb3Sn cosϑ test dipoles** ■ **Nb3Sn block test dipoles**

Synchrotron Radiation

- At 100 TeV even protons radiate significantly
  - Total power of 5 MW (LHC 7kW)

$\Rightarrow$ 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



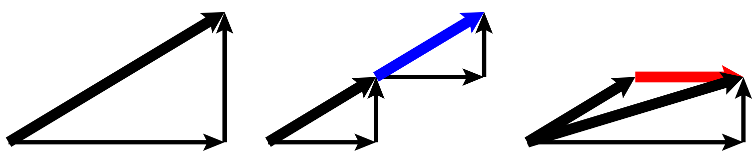


LHC beam screen

- Protons loose energy

$\Rightarrow$ They are damped

$\Rightarrow$ Emittance improves with time
- Typical transverse damping time 1 hour



energy loss re-acceleration

FCC-ee Parameters

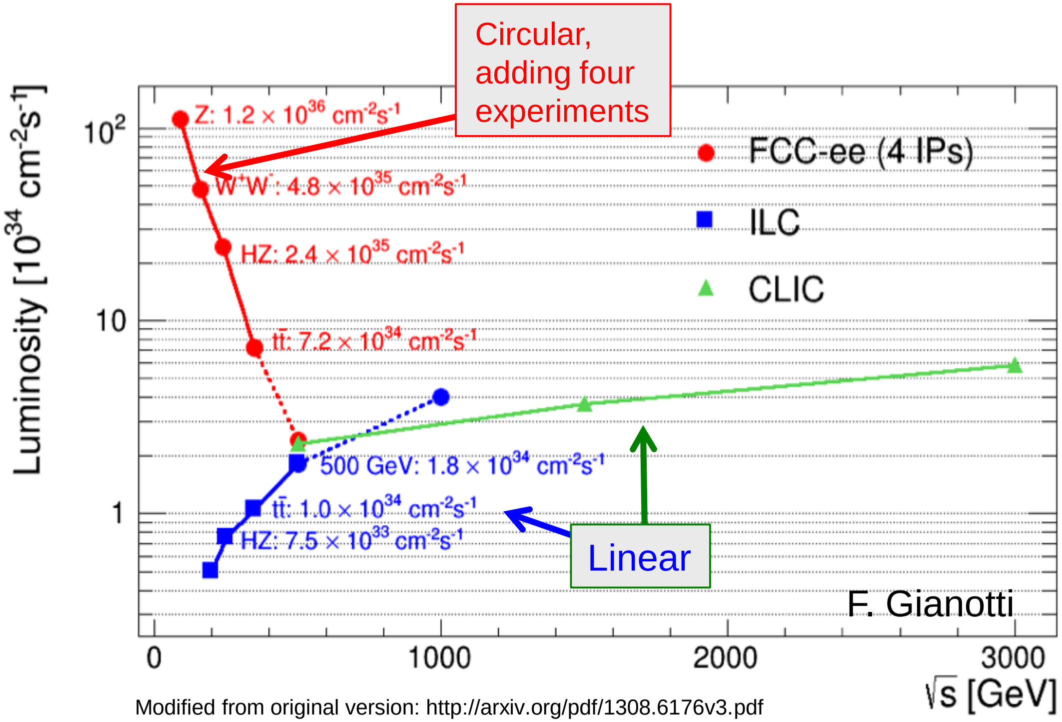
Parameter	Z	W	H	t	LEP2
E (GeV)	45	80	120	175	104
I (mA)	1400	152	30	7	4
No. bunches	16'700	4'490	1'330	98	4
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	1000 / 1	1500 / 50
ε_x (nm)/ε_y (pm)	29/60	3.3/7	1/2	2/2	30-50/~250
σ_x(μm)/σ_y(nm)	120/250	40/84	22/45	45/45	250/3500
ξ_y	0.03	0.06	0.09	0.09	0.07
L (10^{34} cm^{-2}s^{-1})	28	12	6.0	1.8	0.012

- Four experiments foreseen

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

RF System Challenge

- Requirements are characterized by two different regimes.
  - High gradients for H and $t\bar{t}$ – up to ~11 GV.
  - High beam loading with currents of ~1.5 A at the Z pole.

- Must be distributed over the ring to minimize energy excursions
  - ~4.5% energy loss at 175 GeV,
  - optics errors driven by energy offsets.

- Aiming for SC RF cavities
  - with gradients of ~20 MV/m.
  - frequency of 400 or 800 MHz (current baseline).
    - nano-beam / crab waist favours lower frequency, e.g. 400 MHz.

- Conversion efficiency (wall plug to RF power) is critical:
  - Aiming for 75% or higher → needs R&D !
  - An important item for the FCC-ee power budget.~65% was achieved for LEP2.

FCC-he Parameters

Parameters	$e^{\pm}$ scenarios			protons
Species	$e^{\pm}$ (polarized)	$e^{\pm}$	$e^{\pm}$	p
Beam energy [GeV]	80	120	175	50000
Luminosity [$10^{34}cm^{-2}s^{-1}$]	2.3	1.2	0.15	
Bunch intensity [10^{11}]	0.7	0.46	1.4	1.0
#bunches per beam	4490	1360	98	10600
Beam current [mA]	152	30	6.6	500
$\sigma_{x,y}$* [micron]	4.5, 2.3			

- Tentative design choice: beam parameters as available from hh and ee
  - Max. e± beam current at each energy determined by 50 MW SR limit.
  - one (1) physics interaction point (IP), optimization at each energy
- Could consider linac-ring design

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