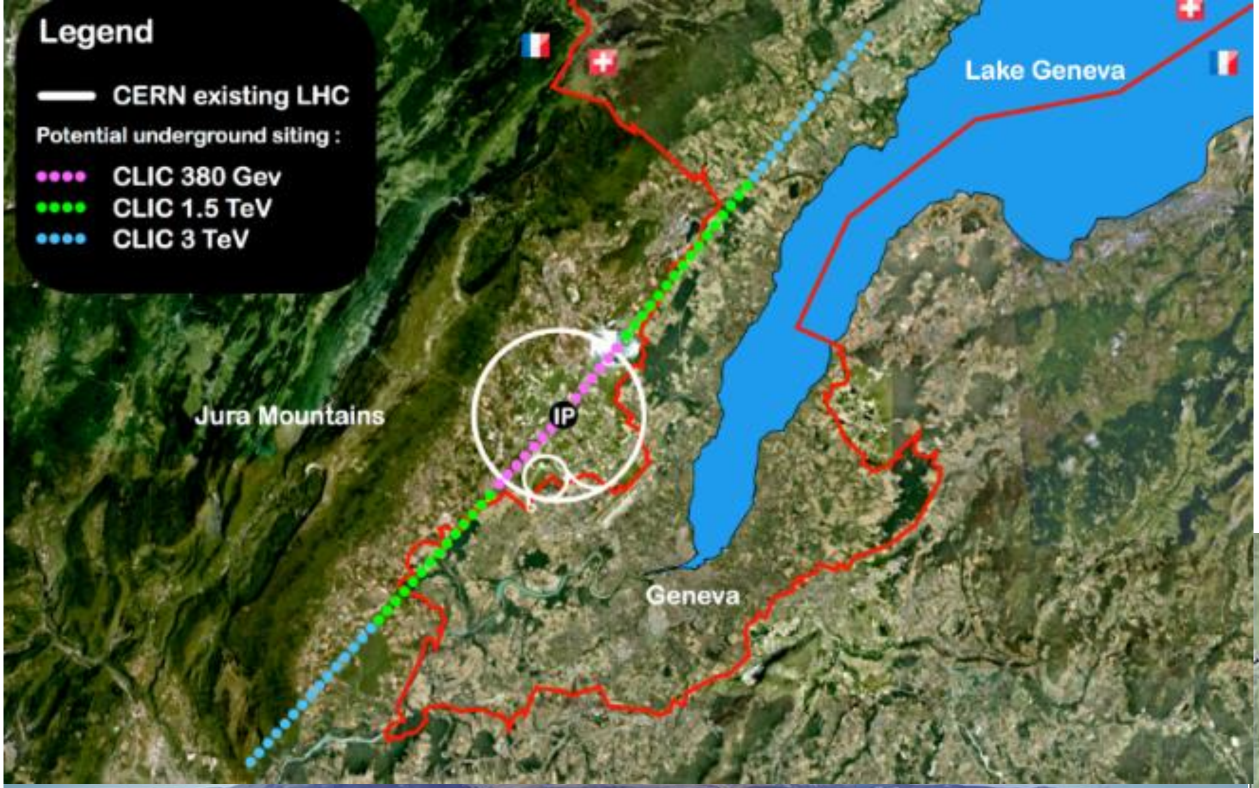


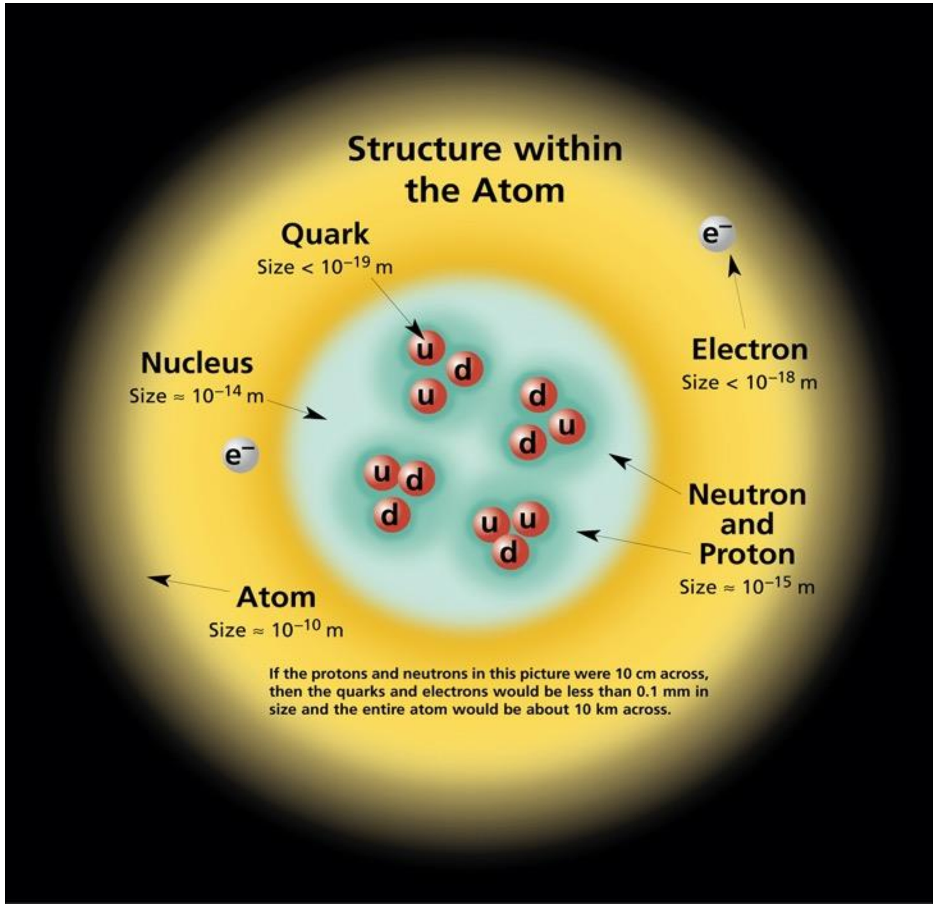
Future Linear Colliders

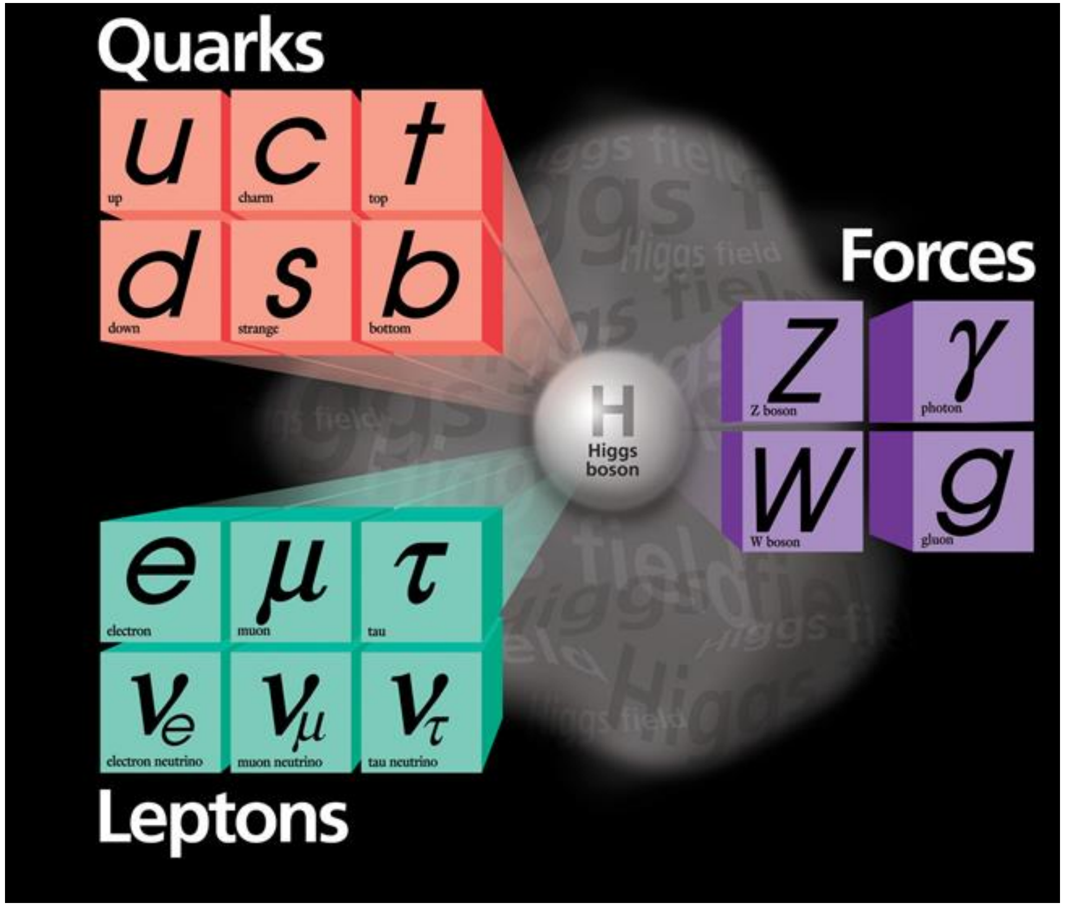
Outline:

- Physics -> Higgs factory
- Linear Accelerators (e+e-)
- CLIC
- ILC

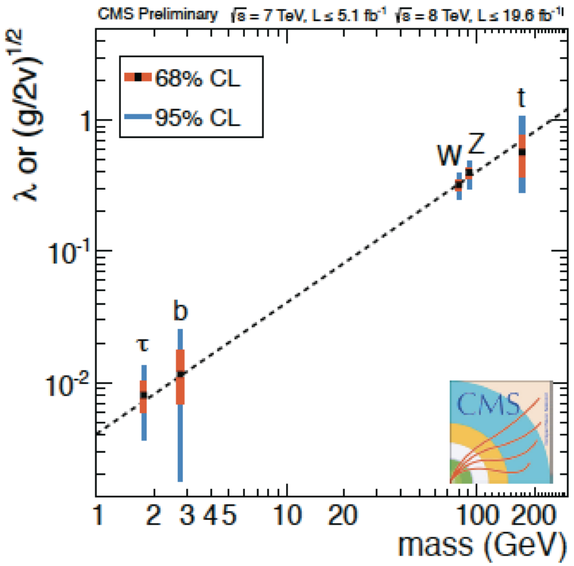
The CERN Accelerator School

The physics landscape





Higgs and Beyond the Standard Model

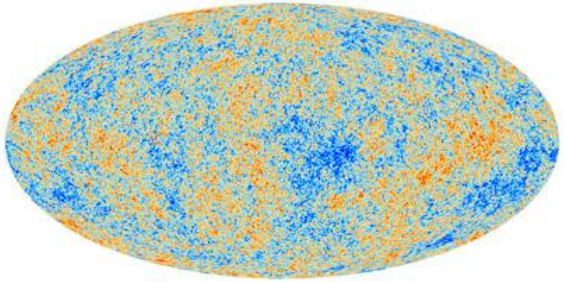


Unknowns:

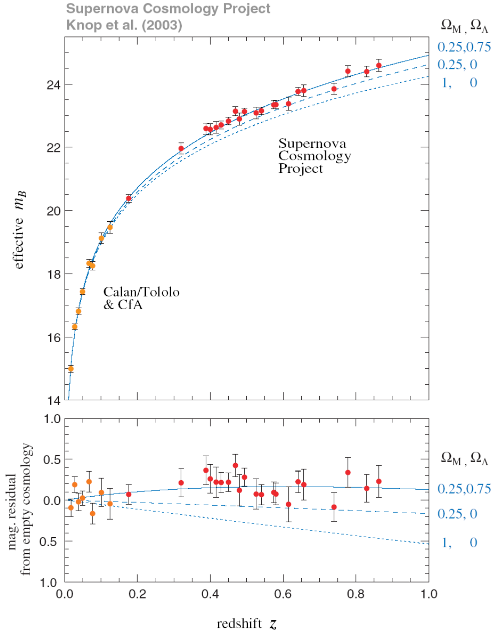
- Flavour structure
- Matter-antimatter
- Why is the Higgs so light
- Forces merging ?

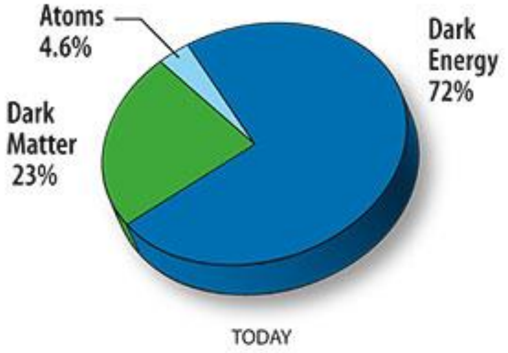
- General Relativity versus Quantum Field Theories
- Dark Matter and Energy

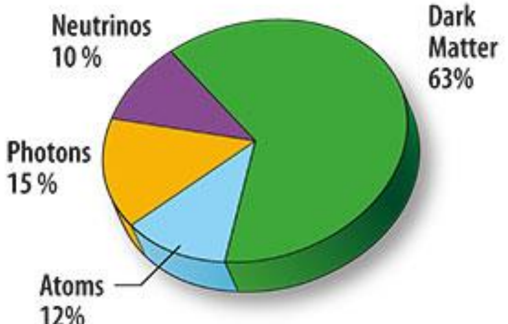
The Higgs is new, it is special, we believe studying it in detail can be a portal to new physics



The universe as seen by Planck

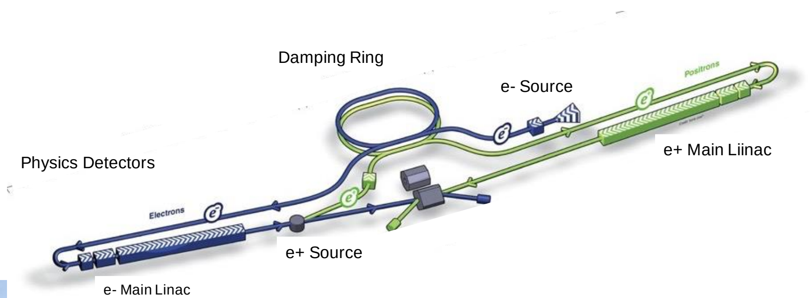


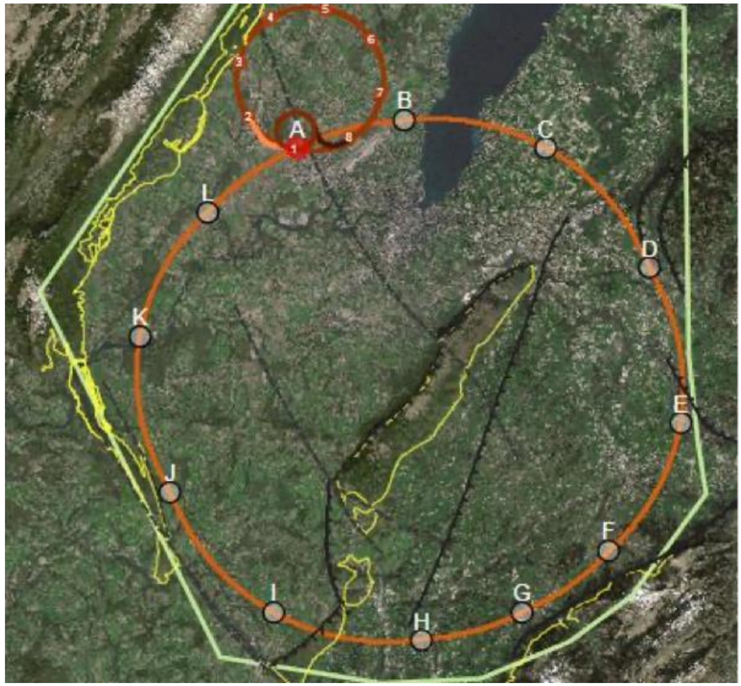




13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Next: A Higgs factory





Need e+e- collisions at least at 250 GeV, four alternatives:

ILC in Japan (linear)

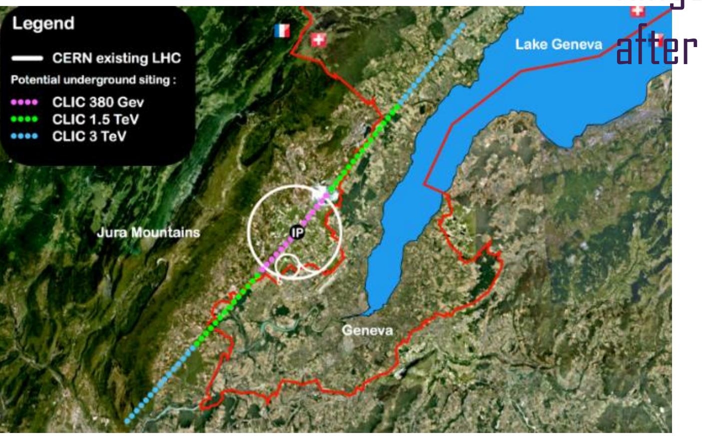
FCC at CERN (ring)

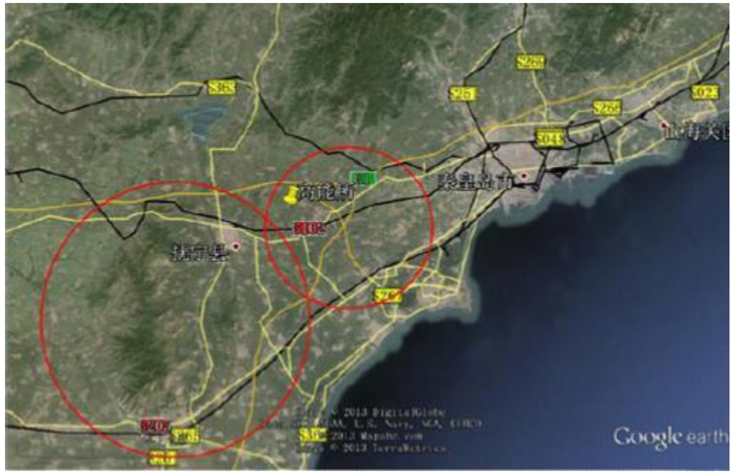
CLIC at CERN (linear)

CEPC in China (ring)

Linear colliders: 13 (Higgs) -> 50 (max) km

Rings ~100km, can be used for protons after





Particle types to accelerate

Not so many choices:

- Need stable charges particles: protons, electrons, (muons), ions – most used: electrons and protons
- Secondary beams: photons, pions, kaons, neutrons, neutrinos, ...

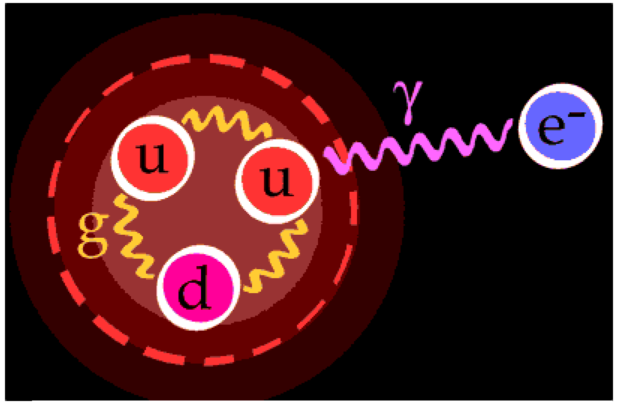
Proton collisions: compound particles

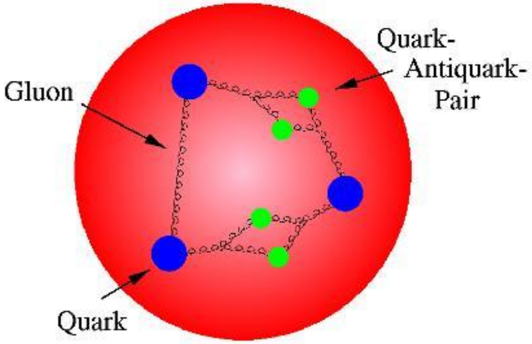
- Mix of quarks, anti-quarks and gluons: variety of processes
- Parton energy spread
- QCD processes large background sources

Electron/positron collisions: elementary particles

- Collision process known
- Well defined energy
- Background from other physics limited

Muons: elementary particle, but lifetime only 2.2 μs





$$\frac{\text{proton mass}}{\text{electron mass}} \approx 2000$$

Circular versus linear

High energy limited by how strong electric fields you can have inside metallic structures:

- Make accelerators circular, then we become limited by magnetic fields for bending – as in LHC, accelerating protons
- It also allows us to re-collide "bunches" for hours

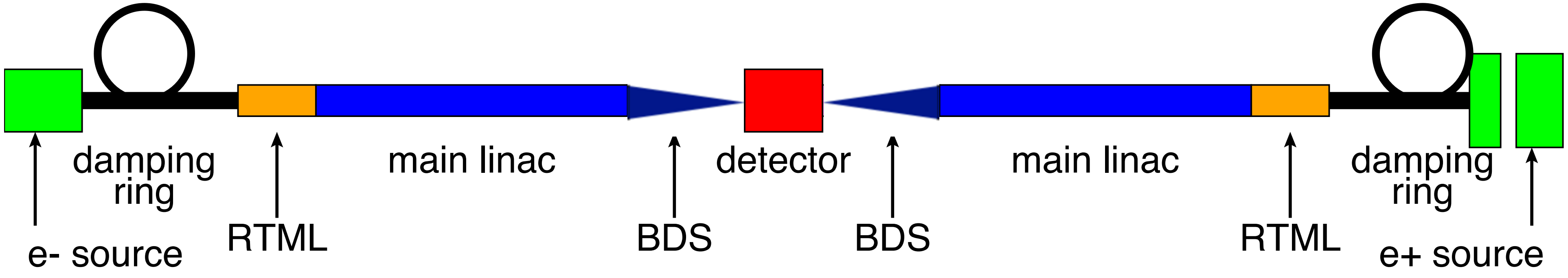
For electrons also limited by synchrotron radiation when bending a particle, at some point cannot provide enough energy in a circle to compensate for these losses, go back to linear accelerators (CLIC/ILC designed for 3/1 TeV at ~50km)

CLIC is ~11km (380 GeV), ILC ~20km (250 GeV), FCC/CEPC ~100km (~350 GeV)

$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

Generic Linear Collider

The key parameters: Energy and luminosity



The critical steps:

Create low emittance beams (sources, injector, damping rings, ring to main linac - RTML)

1) Acceleration in main linac (energy increase per length)
2) Supply energy as efficient as possible to beam (high power at 1, 1.3 and 12 GHz)
3) Nano-beams: Squeeze the beam (Beam Delivery System- BDS), i.e. reduce β

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r \qquad \sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$

Beam-beam Effect

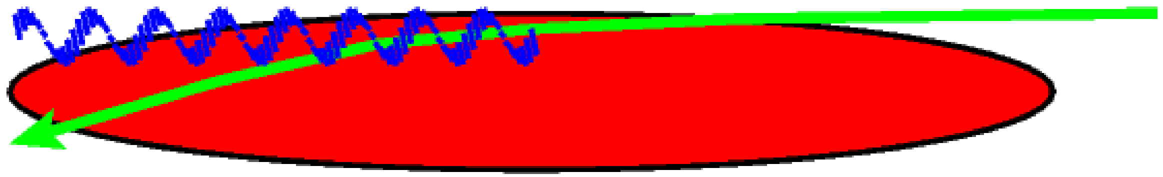
Bunches are squeezed strongly to maximise luminosity

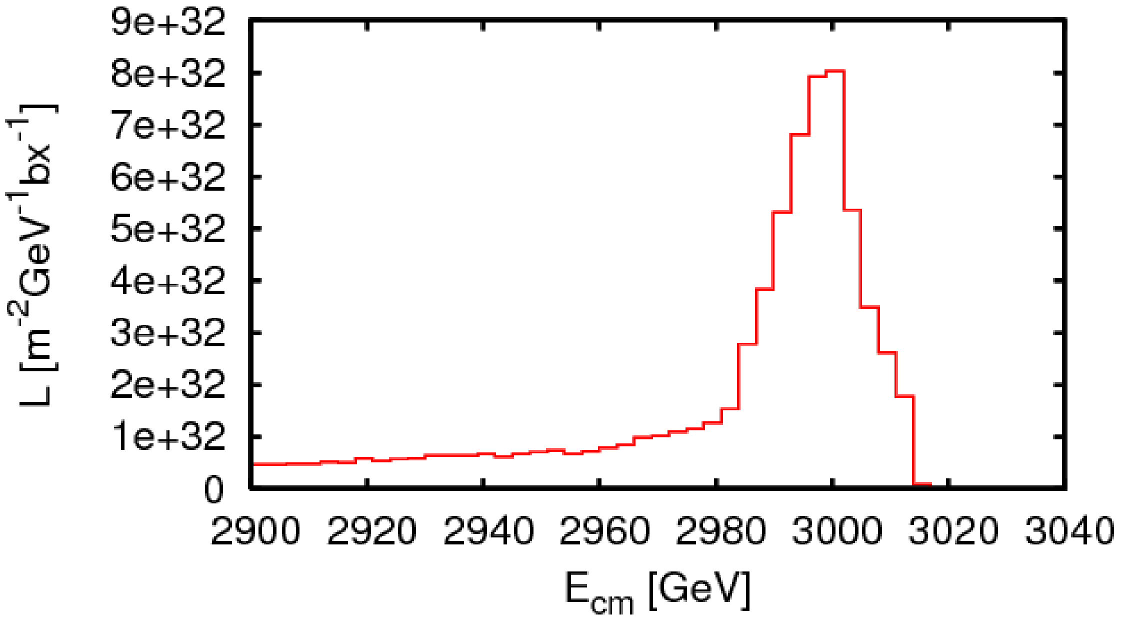
Electron magnetic fields are very strong

Beam particles travel on curved trajectories

They emit photons (O(1)) (beamstrahlung)

They collide with less than nominal energy





Beamstrahlung Optimisation

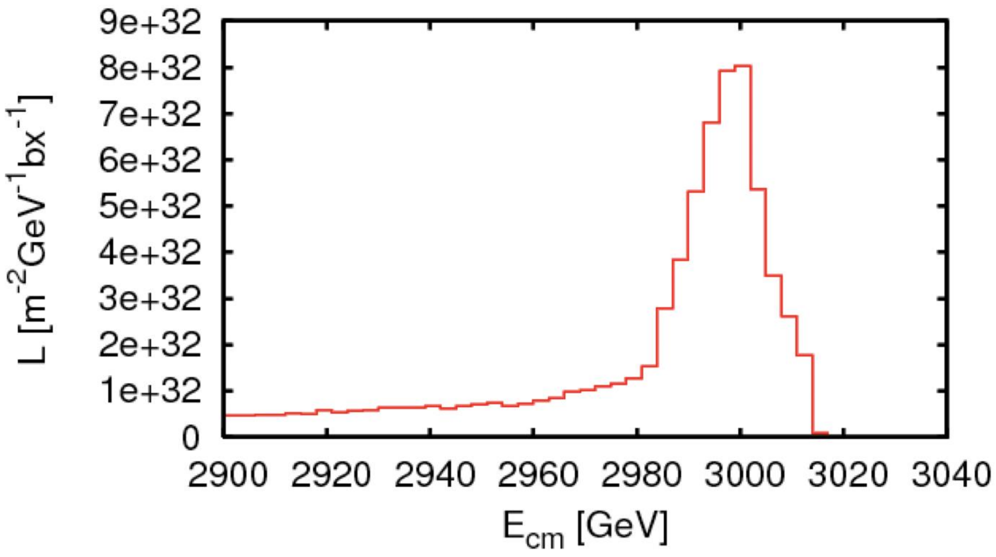
$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

+

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \quad I_{beam}$$

↓

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$

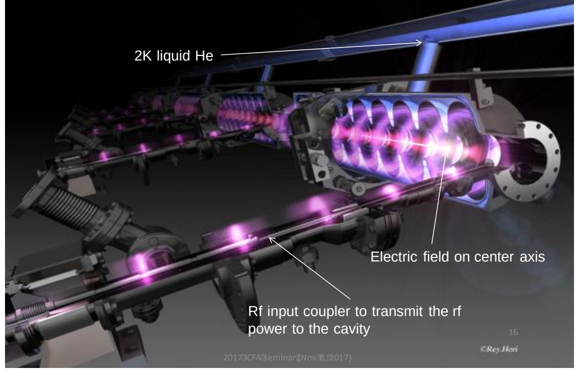


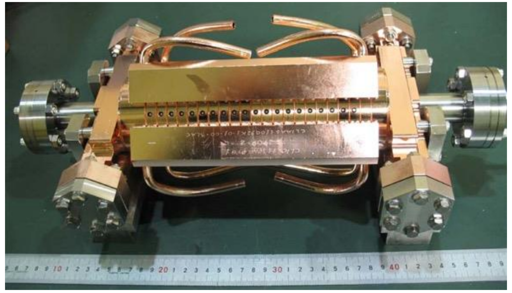
Lorentz equation

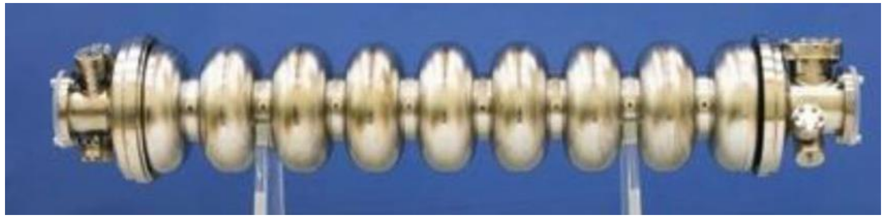
- The two main tasks of an accelerator
  - Increase the particle energy
  - Change the particle direction (follow a given trajectory, focusing "bunches" of particles)
- Lorentz equation:

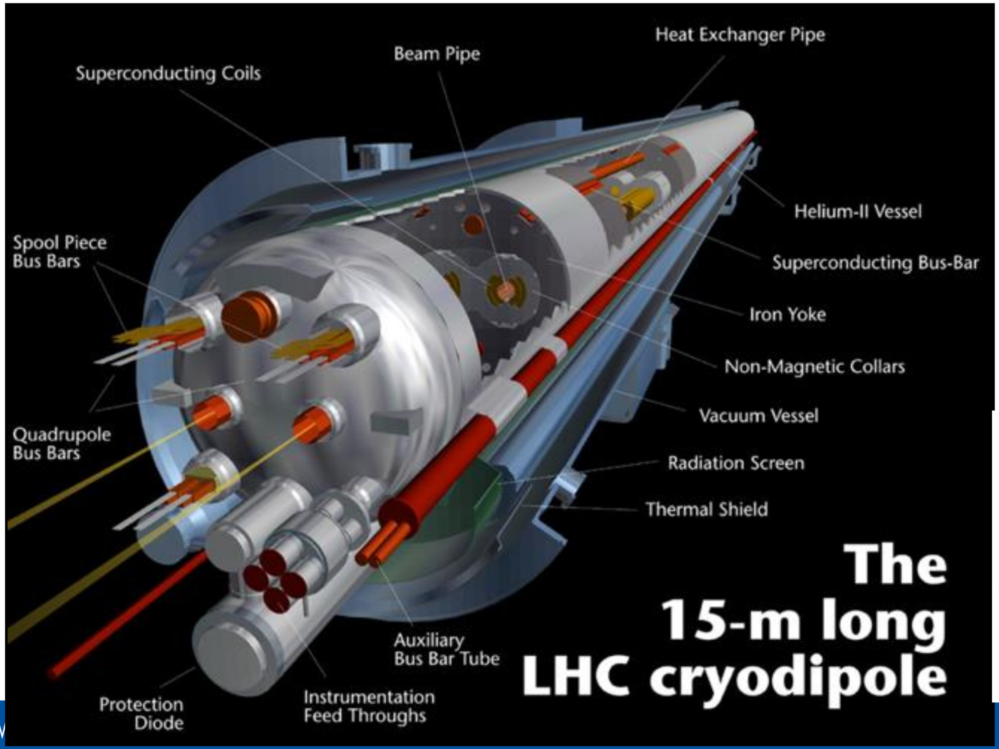
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) = q\vec{E} + q\vec{v} \times \vec{B} = \vec{F}_E + \vec{F}_B$$

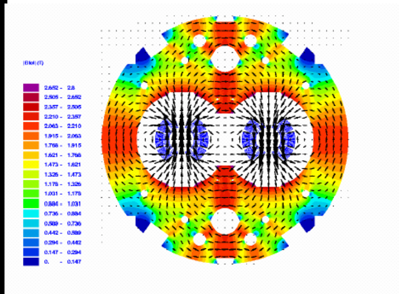
- $F_B \perp v \;\; \Rightarrow F_B$ does no work on the particle
  - Only F_E can increase the particle energy
- F_E or F_B for deflection? $v \approx c \Rightarrow$ Magnetic field of 1 T (feasible) same bending power as en electric field of $3{\cdot}10^8$ V/m (NOT feasible)
  - F_B is by far the most effective in order to change the particle direction







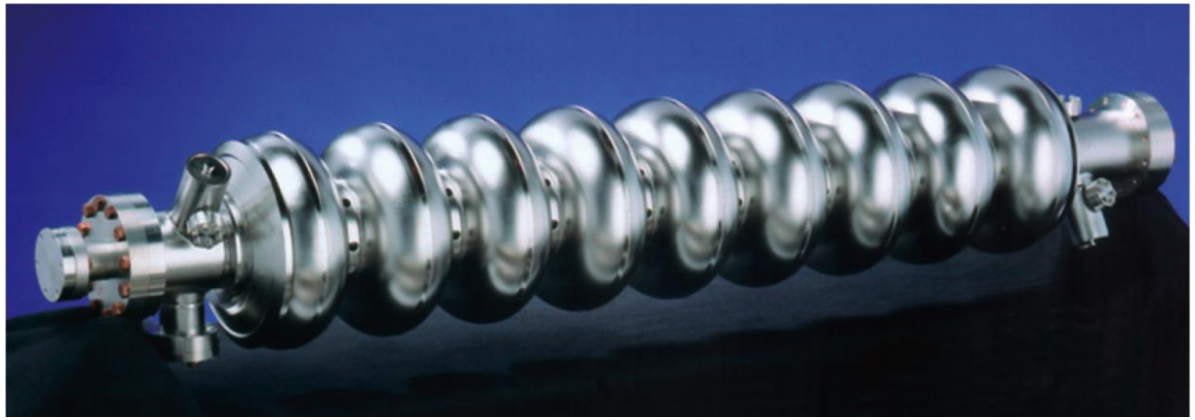




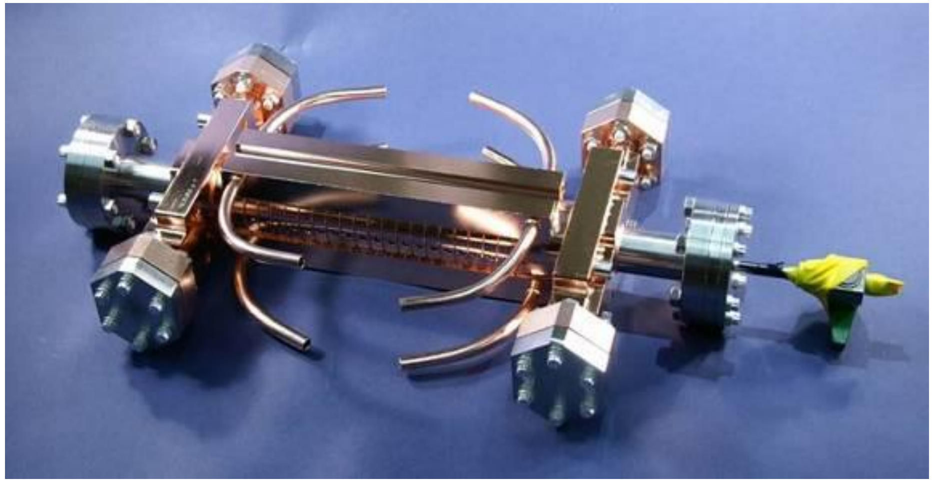
Cavity/Accelerating Structure

ILC cavity

1.3 GHz, superconducting
Target effective operational 31.5MV/m
Target gradient 35MV/m
$Q_0 \approx 10^{10}$



Long pulse => low peak power
Large structure dimensions => low WF (wakefields)
Very long pulse train => feedback within train
SC structures => high efficiency
Gradient limited => longer linac
Large number of e+ per pulse
Large DR

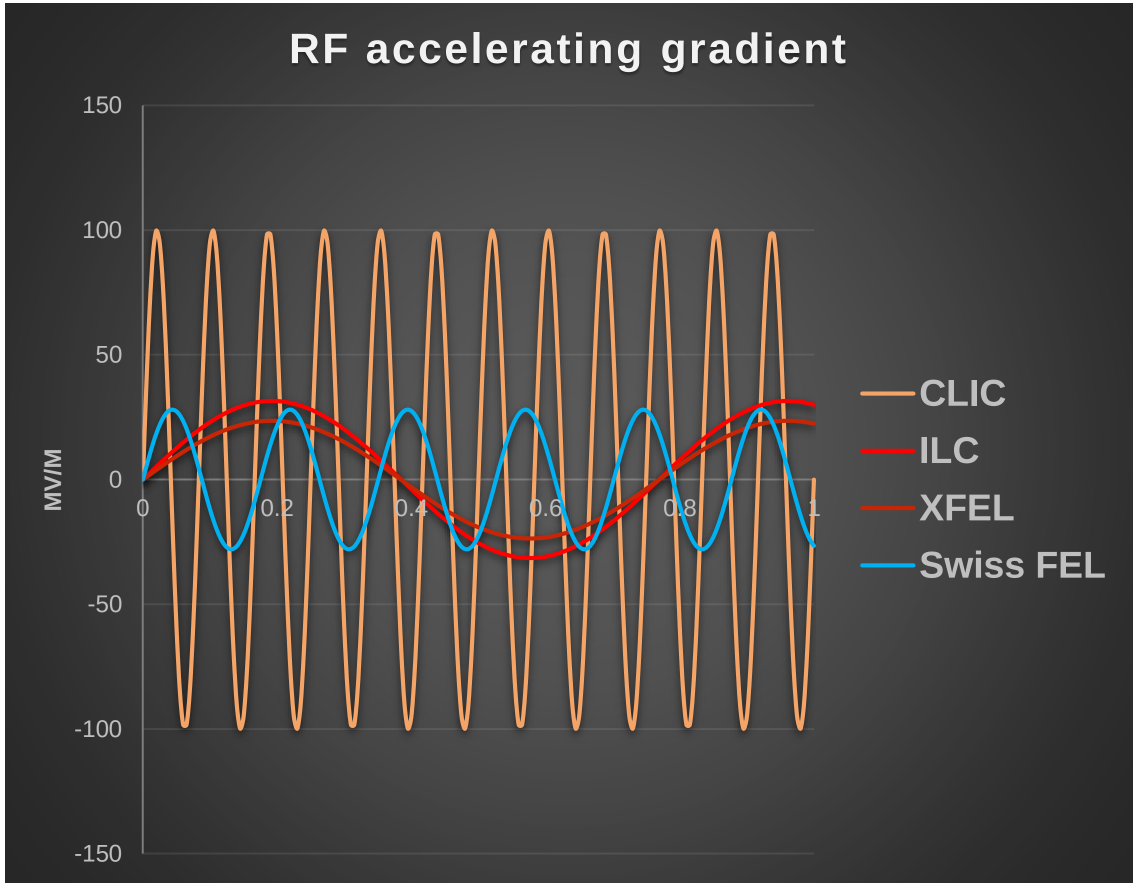


CLIC accelerating structure

12 GHz, normal conducting
Target loaded gradient 100MV/m
Target unloaded gradient 120MV/m
$Q_0 \approx 6\ 10^3$

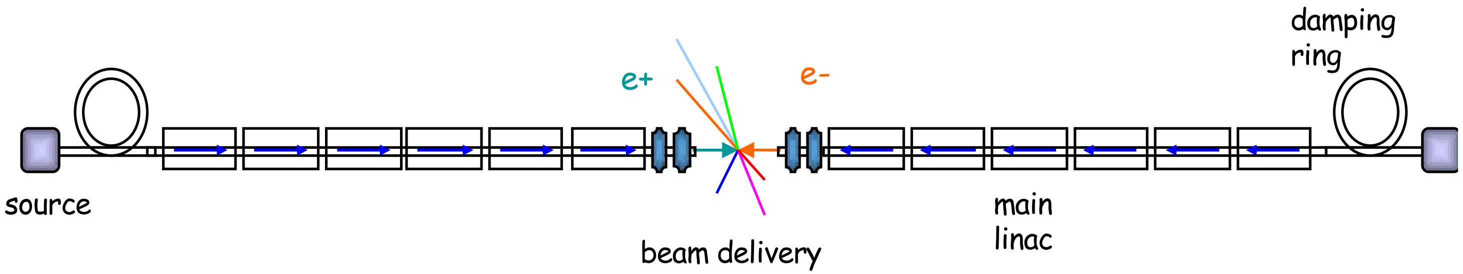
High gradient => short linac
Small structures => strong wakefields
Generation of high peak RF power (drivebeam)

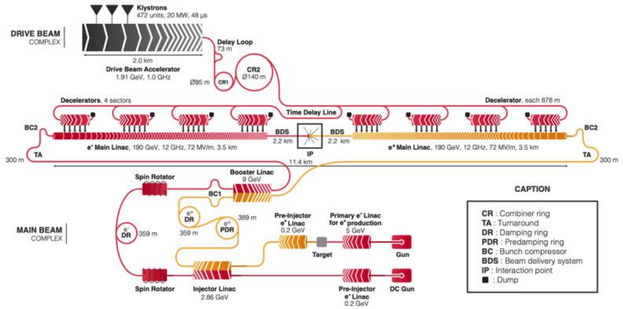
Gradients and frequencies

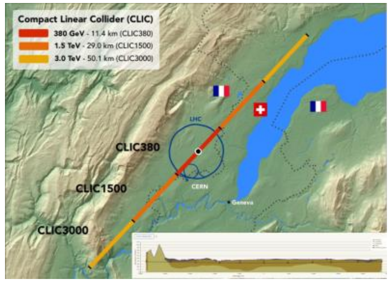


e+e-: Linear Colliders

Linear Collider (LC) proposals for CLIC and ILC are very mature: parameters & design, technically developments, in term of performance verifications, project planning – with strong communities behind

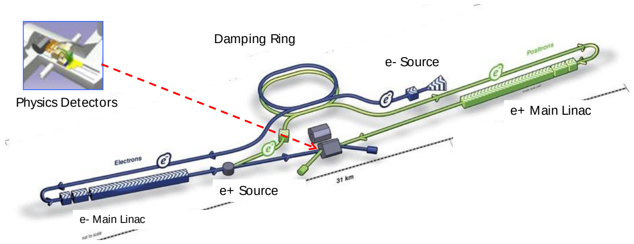






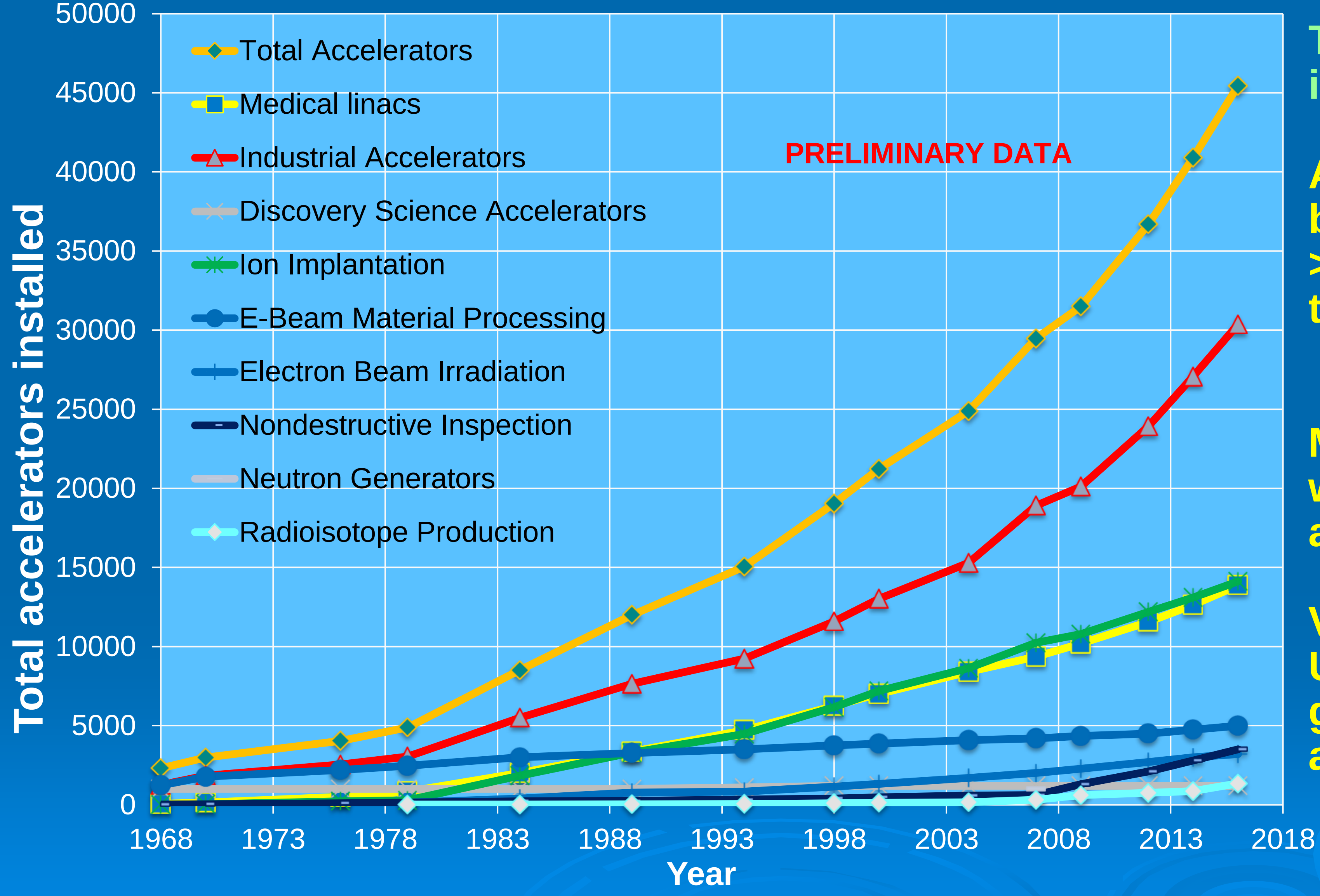
Key features and technical focus of studies:

- Initial stages with costs and power similar to LHC, further investments will be staged
- Expandable to higher energies – with existing, improved or new RF technologies (as novel acc. technologies) - and in some cases also increased luminosities
- RF (energy) and nanobeams (luminosity) main challenges
- Strong connection and synergies with light-sources and FEL linacs
- Polarized beams foreseen
- Can also run a lower energies (Z) and gamma-gamma is possible



Can we hope that Novel Acc. technologies will provide compact (translating into construction timescales that are not many decades) and relatively cheap high gradient acceleration ?

Accelerators Installed Worldwide



Total sales of accelerators is ~US$5B annually

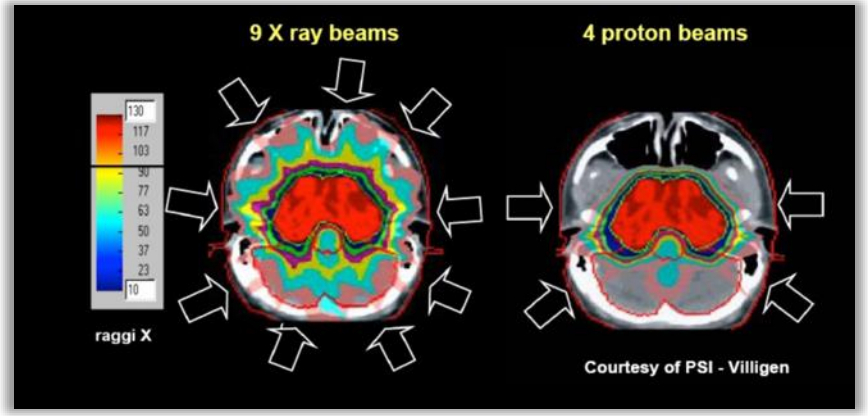
About 47,000 systems have been sold,
> 40,000 still in operation today

More than 100 vendors worldwide are in the accelerator business.

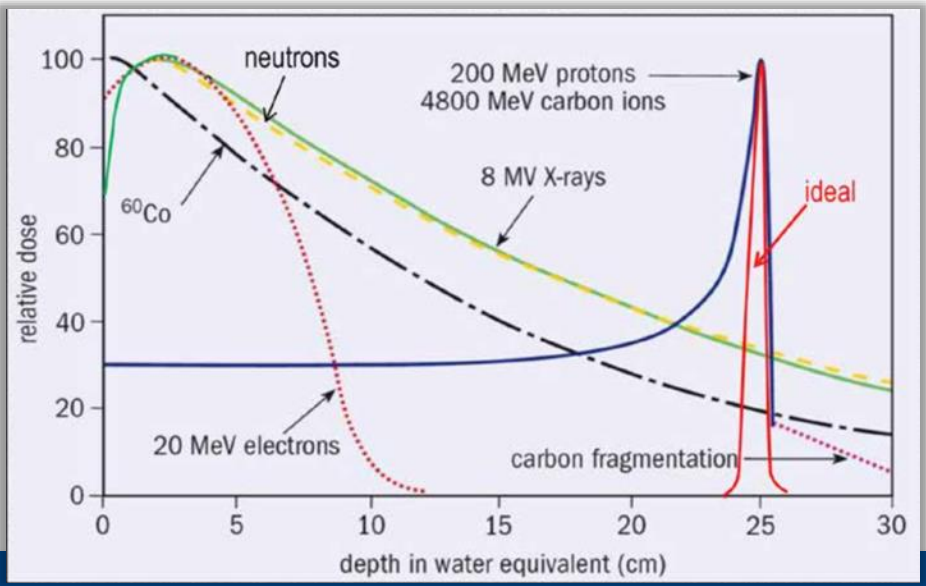
Vendors are primarily in US, Europe and Japan, but growing in China, Russia and India

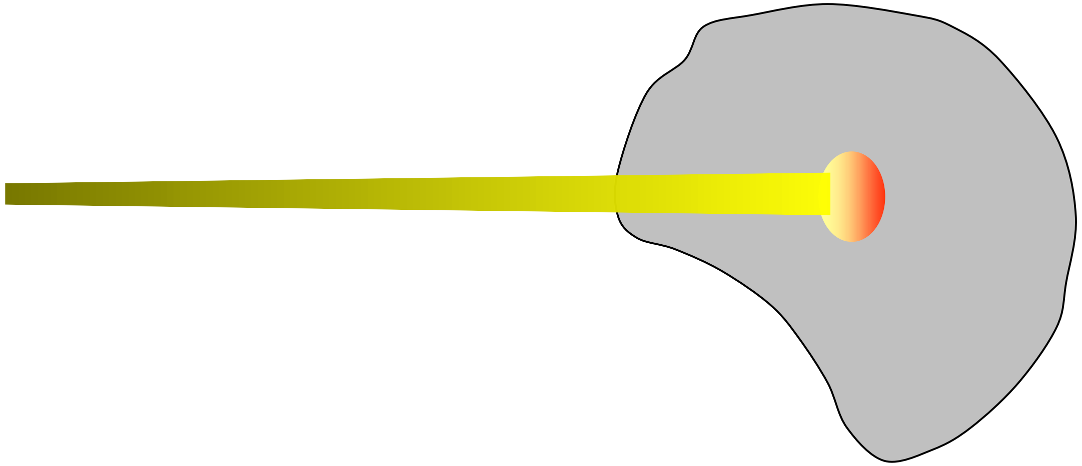
R. Hamm, Accelerator-Industry Co-Innovation Workshop, Feb 6, 2018, Brussels, Belgium

Photon (from electrons) and hadron therapy (protons and ions)

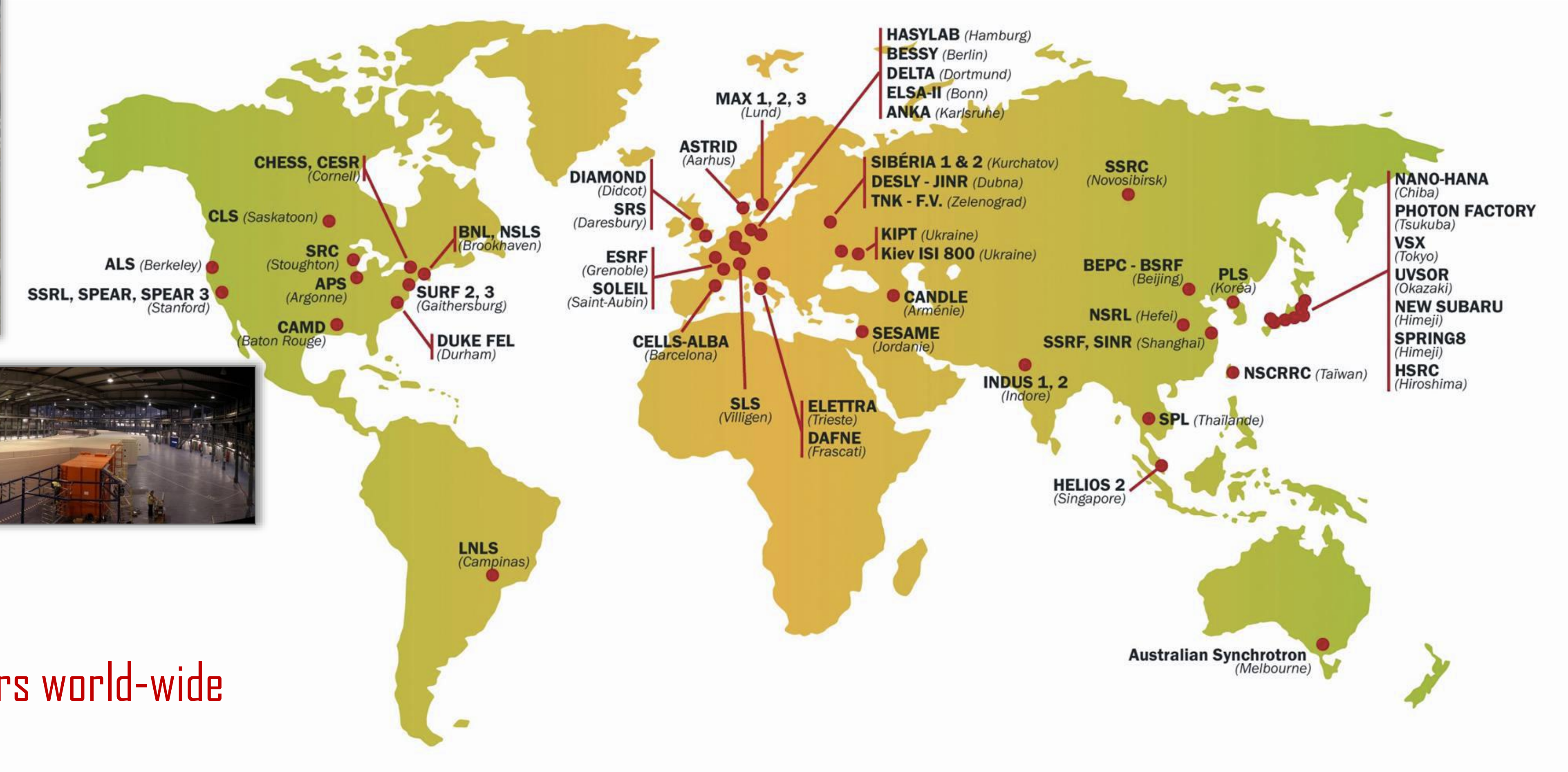


50 mill patients treated with photons





Synchrotron Light Sources: about 50 storage ring based



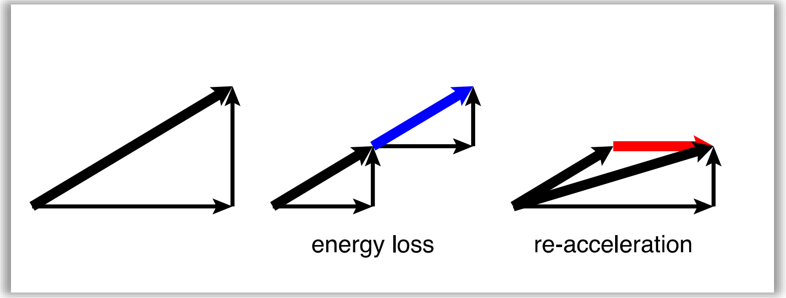
60'000 users world-wide

Established, mature technology

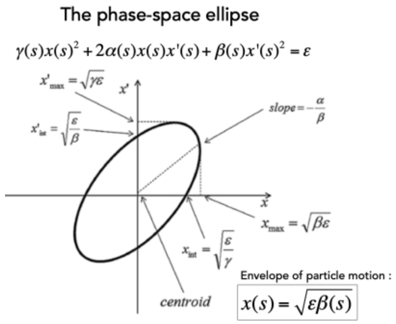
From L.Rivkin EPFL

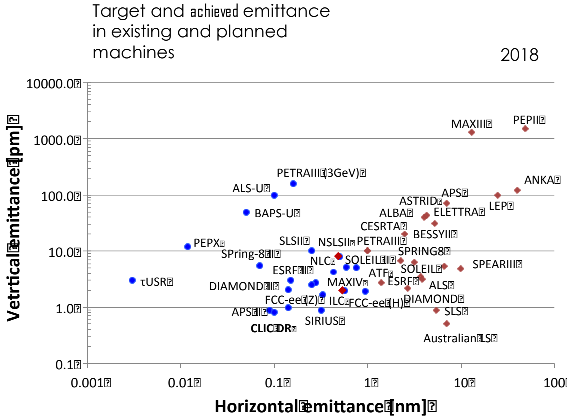
Damping ring, experience from light sources

The damping rings reduce the phase space (emittance $\varepsilon_{x,y}$) of the beam – wigglers to stimulate energy losses (SR)



Light-sources need similar beams (picture: ALBA)





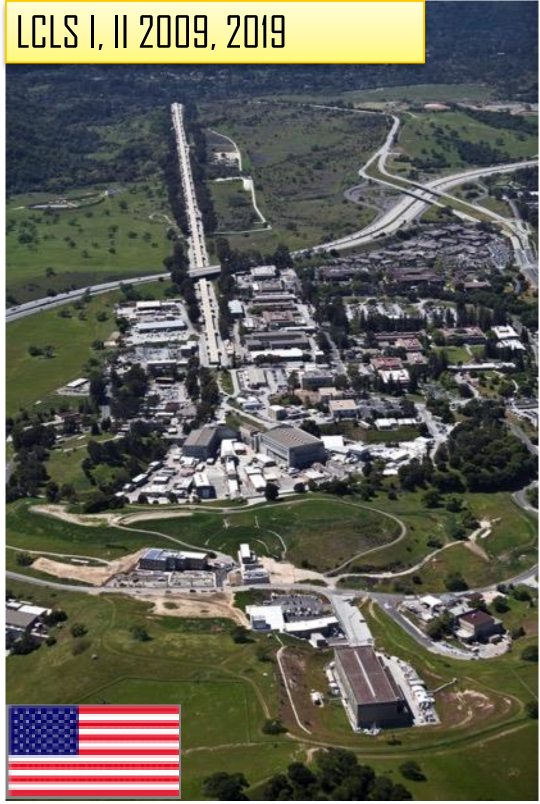
X-Ray Free Electron Lasers

From L.Rivkin EPFL

PAL XFEL 2016

SACLA 2011
8.5 GeV, 60 Hz NC

SwissFEL 2017



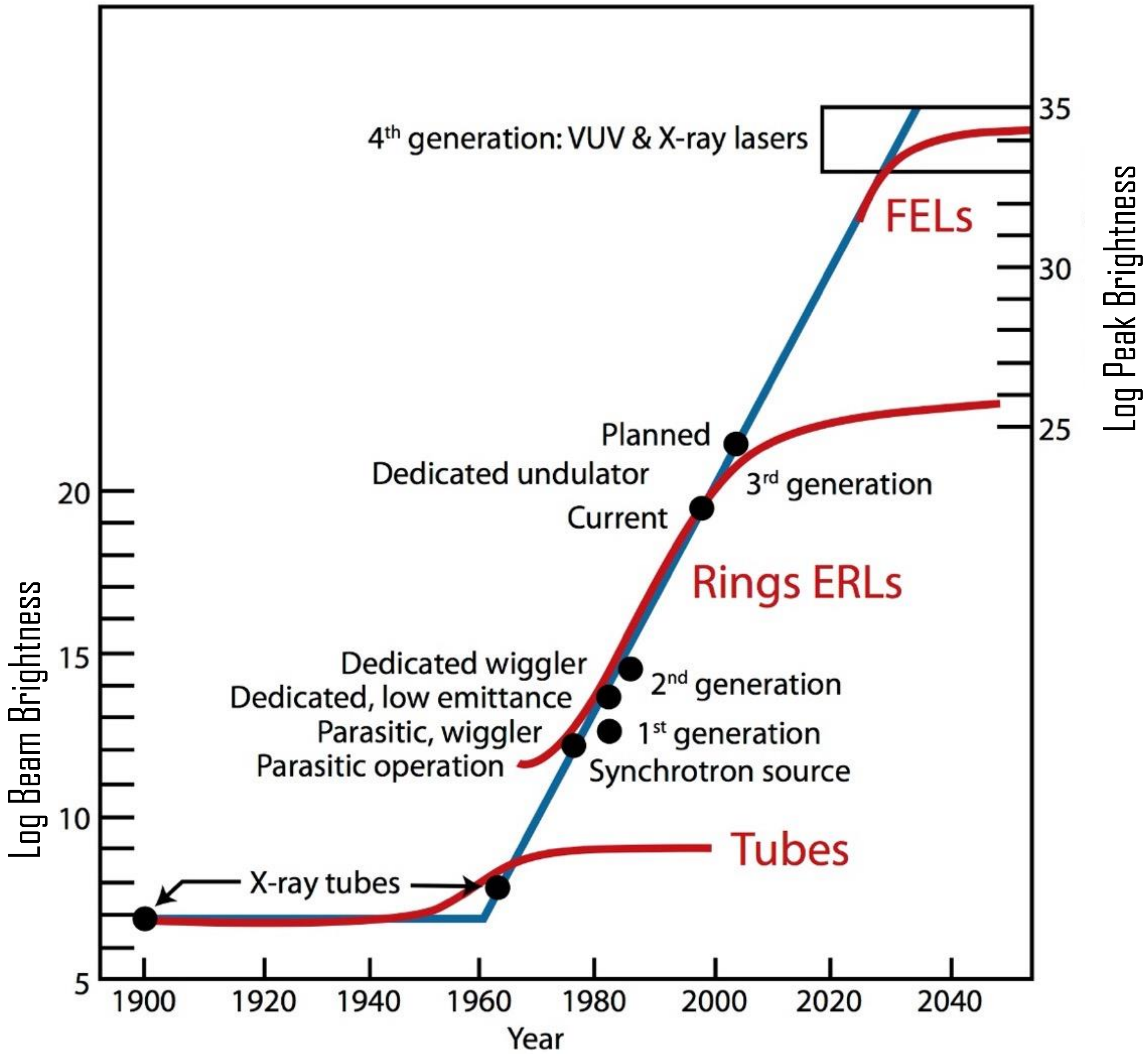
LCLS I, II 2009, 2019

European XFEL 2017
DESY, Hamburg

SHINE, Shanghai, under construction

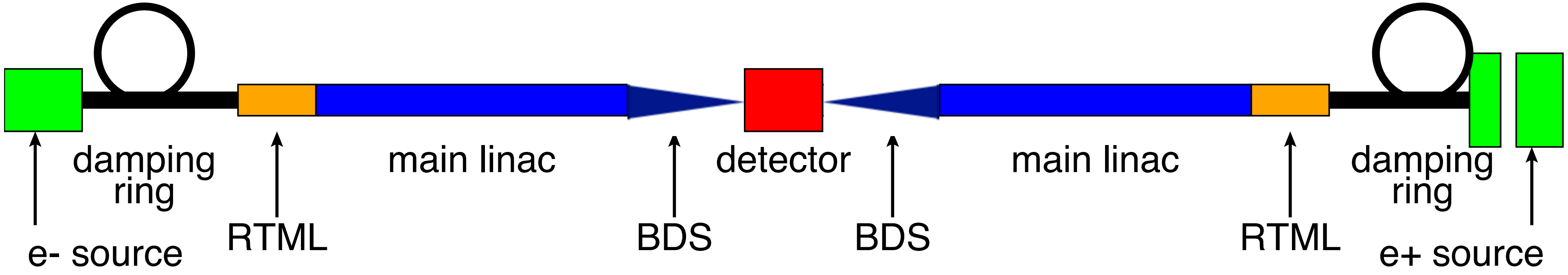
Brightness: disruptive change

- X-ray Tubes
- Storage Rings
- FELs
- ? Compact sources ?



Generic Linear Collider

The key parameters: Energy and luminosity

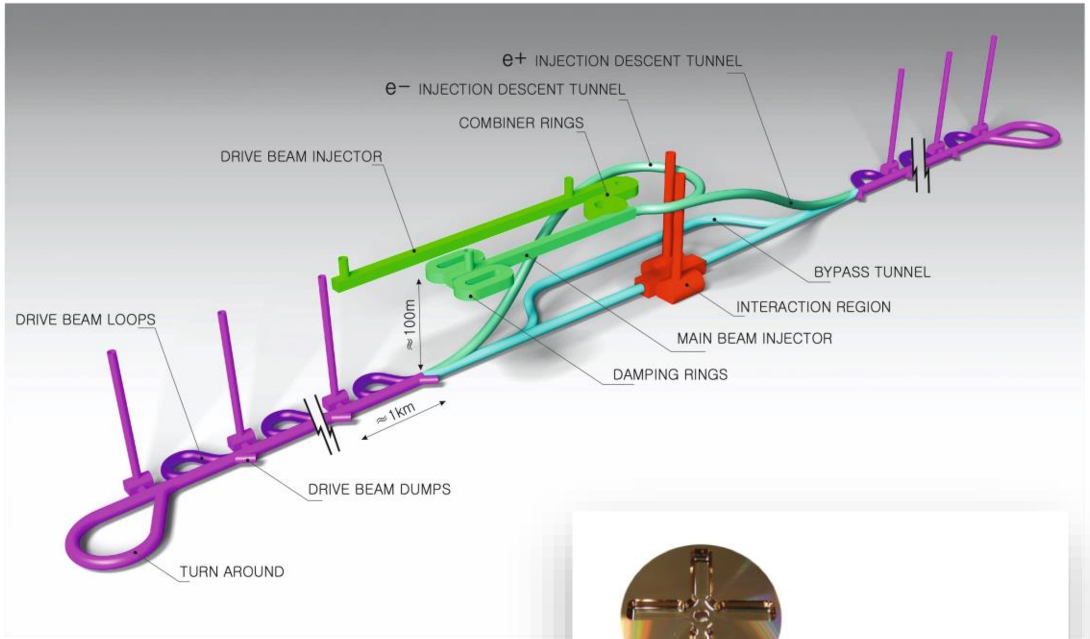


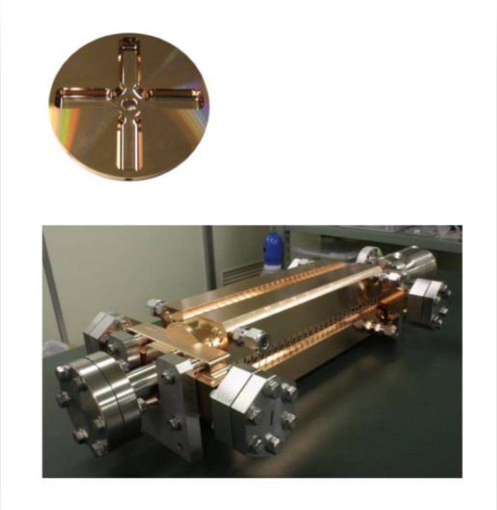
Light-sources (DR) and FEL linacs (ML) are heavily invested in

Very important to work closely with such projects, for common technology development, construction and operation experience – and also for industry capabilities

In particle physics we have some special challenges: scale, luminosities, positrons

Proposed e^+e^- linear colliders – CLIC





Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)

The Compact Linear Collider (CLIC)

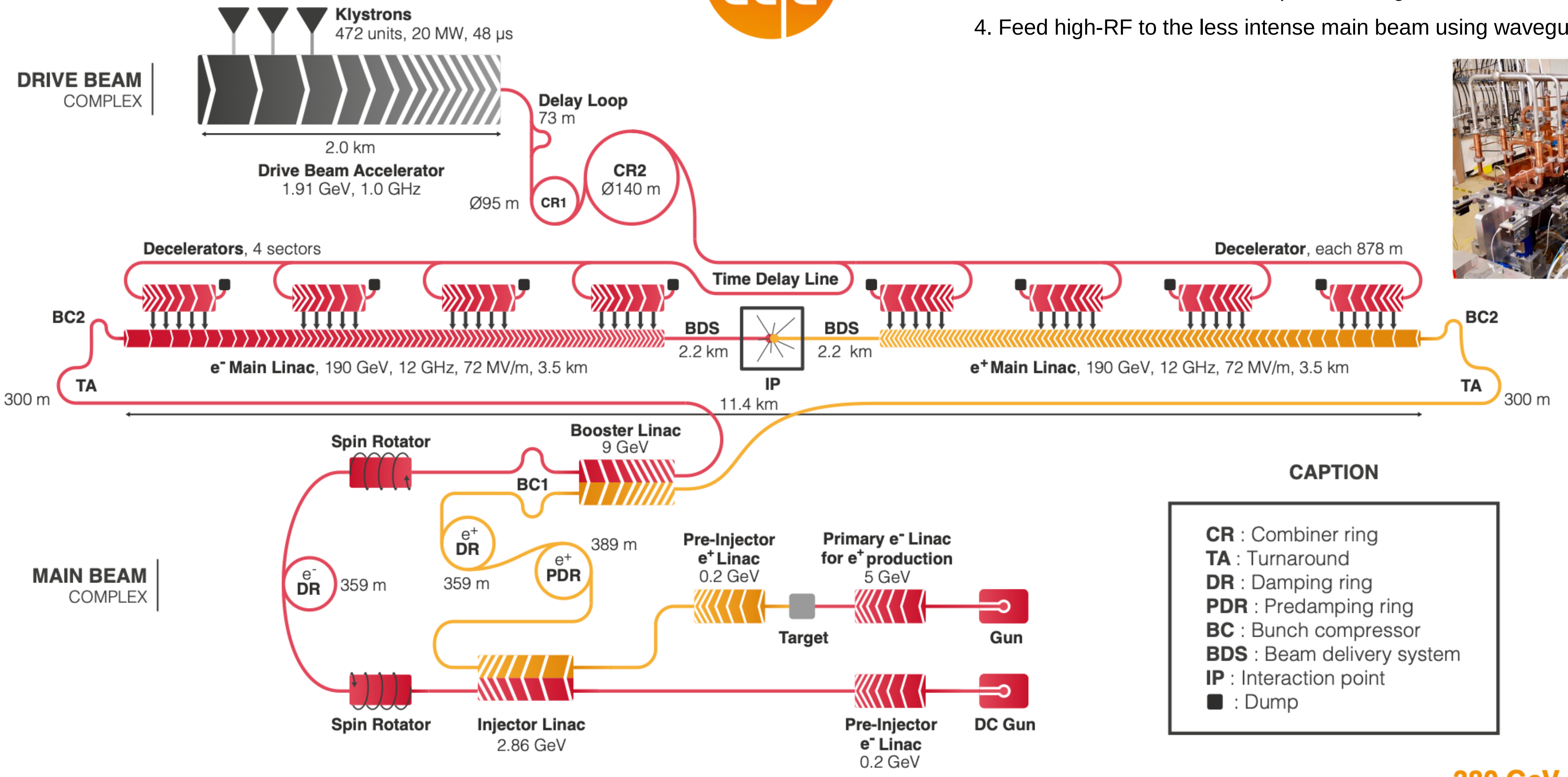
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC (~2035 Technical Schedule)
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 cavities at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

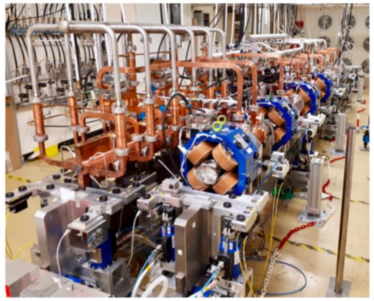
- CDR in 2012. Updated project overview documents in 2018 (Project Implementation Plan). See resource slide.

- **Cost:** 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power:** 168 MW at 380 GeV (reduced wrt 2012), some further reductions possible

- Comprehensive **Detector and Physics** studies

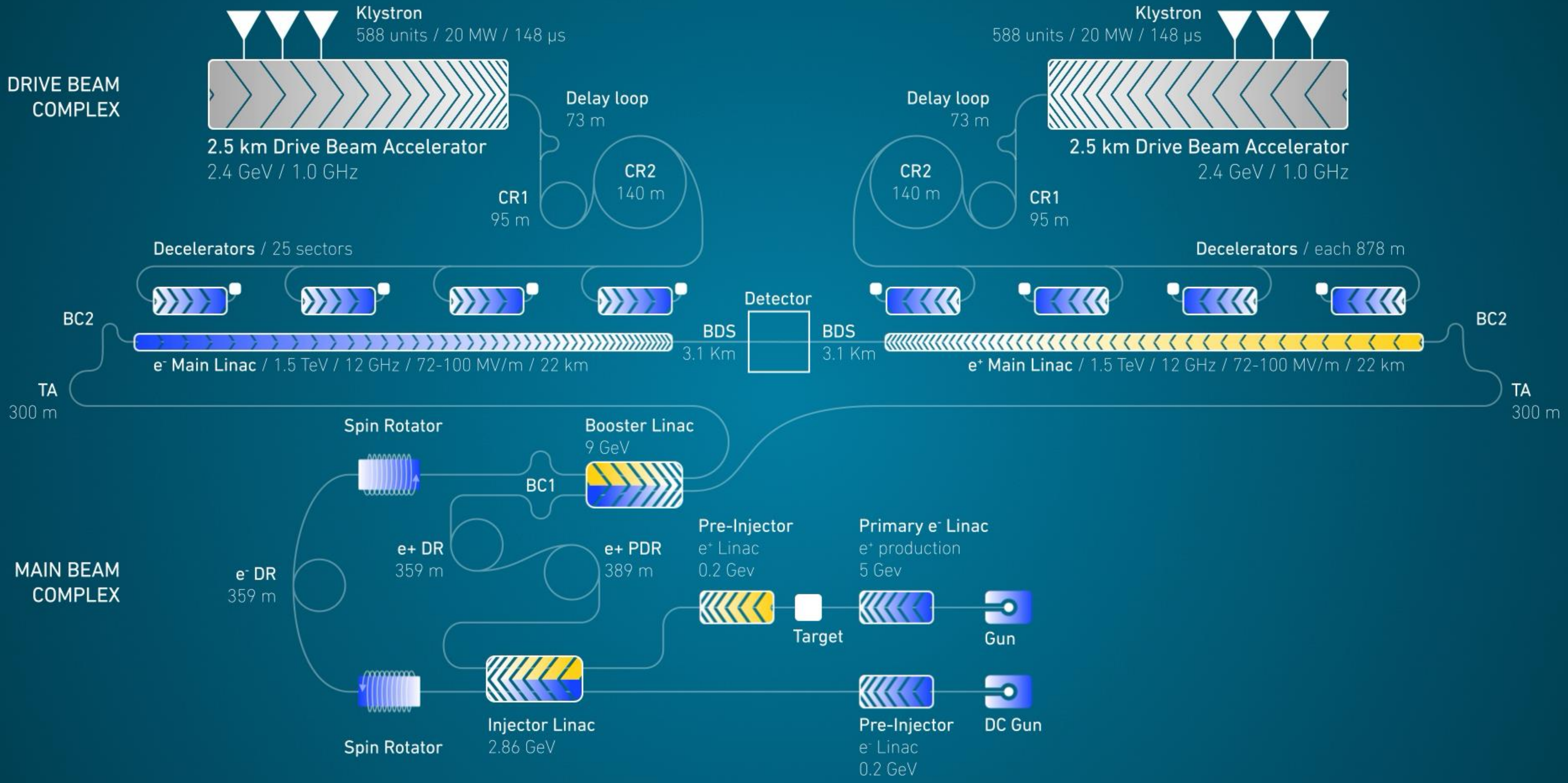
1. Drive beam accelerated to ~2 GeV using conventional klystrons
2. Intensity increased using a series of delay loops and combiner rings
3. Drive beam decelerated and produces high-RF
4. Feed high-RF to the less intense main beam using waveguides

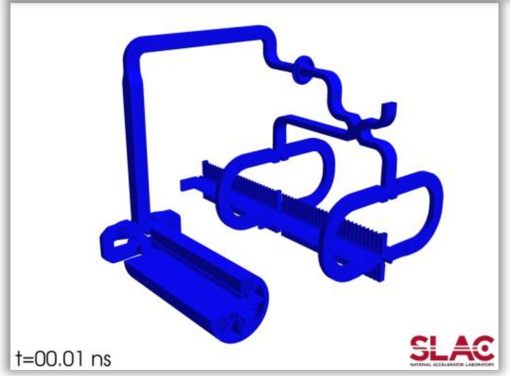




CLIC parameters

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	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{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	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	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


DRIVE BEAM COMPLEX
Klystron
588 units / 20 MW / 148 μs
2.5 km Drive Beam Accelerator
2.4 GeV / 1.0 GHz
Delay loop
73 m
CR1
95 m
CR2
140 m
Decelerators / 25 sectors
Decelerators / each 878 m
Detector
BDS
3.1 Km
BC2
TA
300 m
e- Main Linac / 1.5 TeV / 12 GHz / 72-100 MV/m / 22 km
e+ Main Linac / 1.5 TeV / 12 GHz / 72-100 MV/m / 22 km
MAIN BEAM COMPLEX
Spin Rotator
Booster Linac
9 GeV
BC1
e+ DR
359 m
e+ PDR
389 m
e- DR
359 m
Pre-Injector
e+ Linac
0.2 Gev
Primary e- Linac
e+ production
5 Gev
Target
Gun
Injector Linac
2.86 GeV
Pre-Injector
e- Linac
0.2 GeV
DC Gun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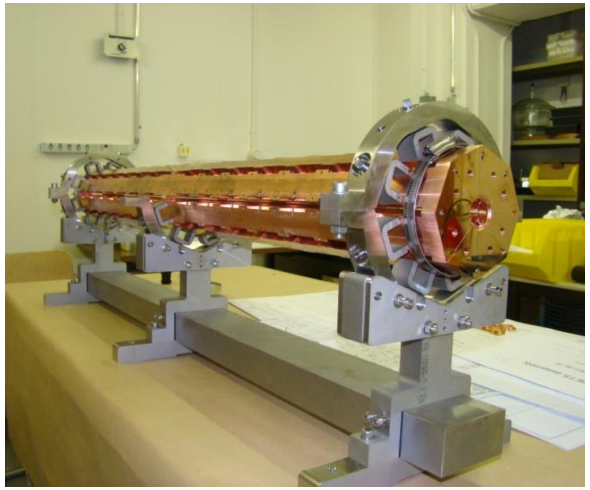
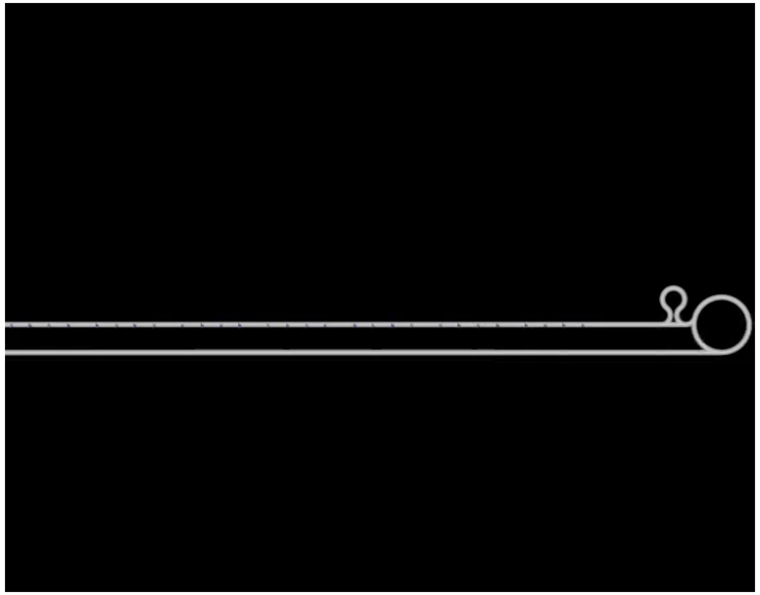
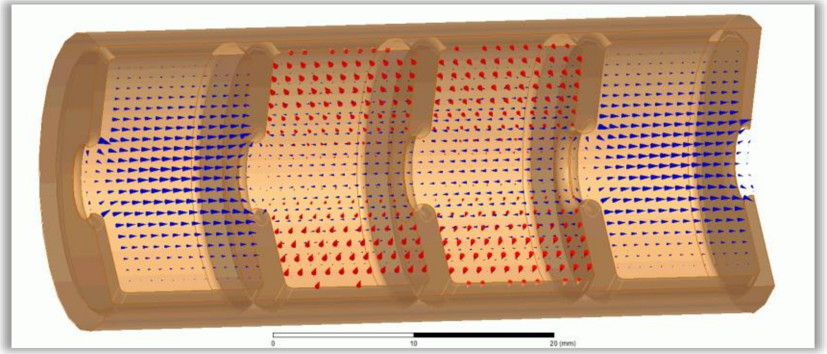





0
10
20 (mm)

Limitations of CLIC gradient E_{acc}

Surface magnetic field

Pulsed surface heating => material fatigue => cracks

Field emission due to surface electric field

RF break downs

Break down rate => Operation efficiency

Local plasma triggered by field emission => Erosion of surface

Dark current capture
=> Efficiency reduction, activation, detector backgrounds

RF power flow

RF power flow and/or iris aperture have a strong impact on achievable E_{acc} and on surface erosion.

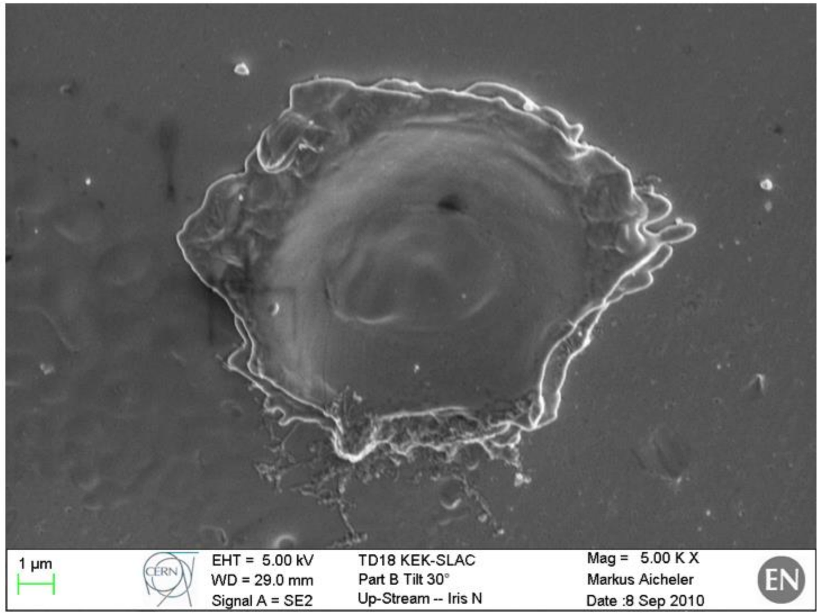


Figure 4.1.: Electron micrograph by Markus Aicheler [4] of the crater left behind from a breakdown on the iris of a TD18 accelerating structure.

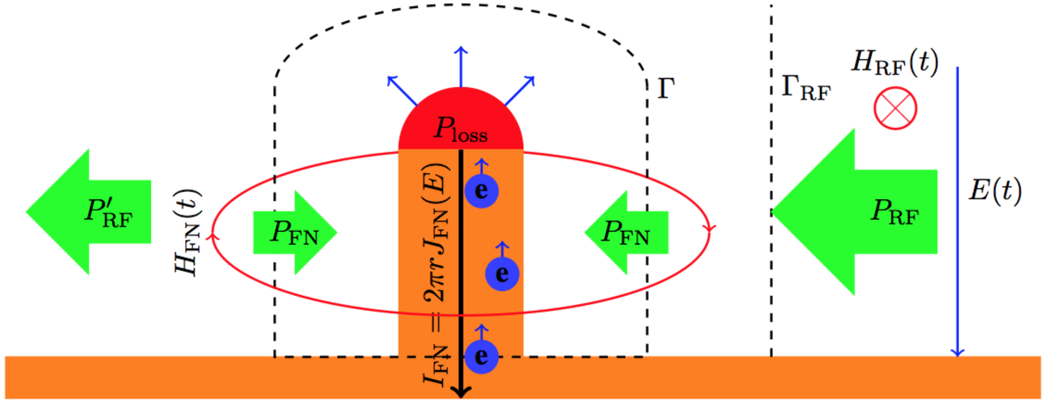
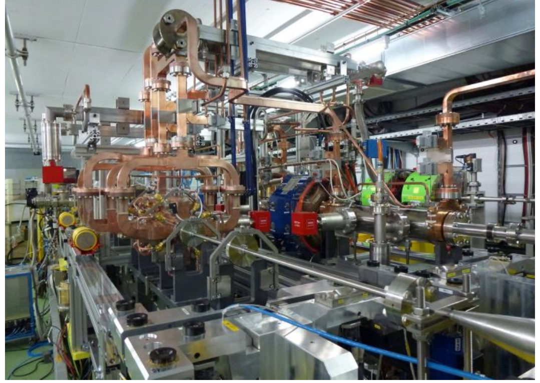


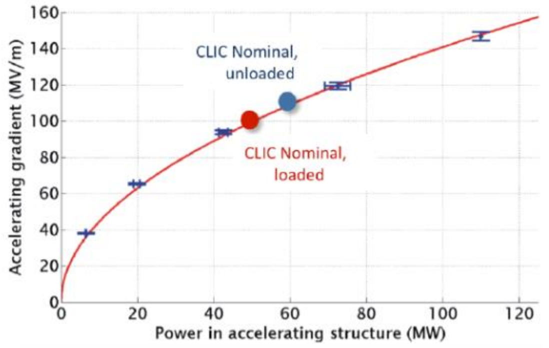
Figure 4.3.: Power flows around a field emitter tip in an RF cavity.

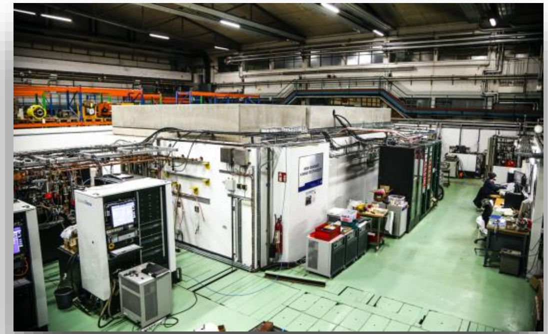
CLIC Accelerator challenges

Details in PIP, DOI: http://dx.doi.org/10.23731/CYRM-2018-004

- CLIC baseline – a drive-beam based machine with an initial stage at 380 GeV
- Four main challenges
  1. High-current drive beam bunched at 12 GHz
  2. Power transfer and main-beam acceleration
  3. Towards 100 MV/m gradient in main-beam cavities
  4. Alignment and stability (“nano-beams”)
- The CTF3 (CLIC Test Facility at CERN) programme addressed all drive-beam production issues
- Other critical technical systems (alignment, damping rings, beam delivery, etc.) addressed via design and/or test-facility demonstrations
- X-band technology developed and verified with prototyping, test-stands, and use in smaller systems
- Two C-band XFELS (SACLA and SwissFEL – the latter particularly relevant) now operational: large-scale demonstrations of normal-conducting, high-frequency, low-emittance linacs

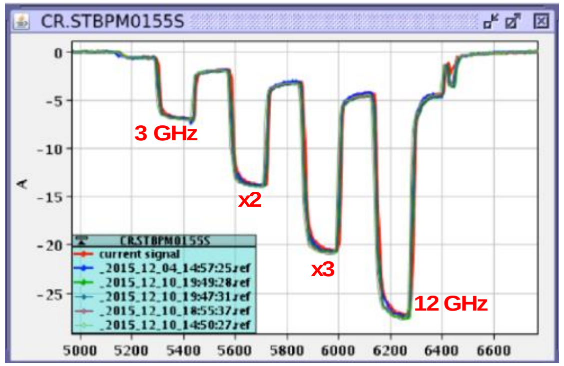


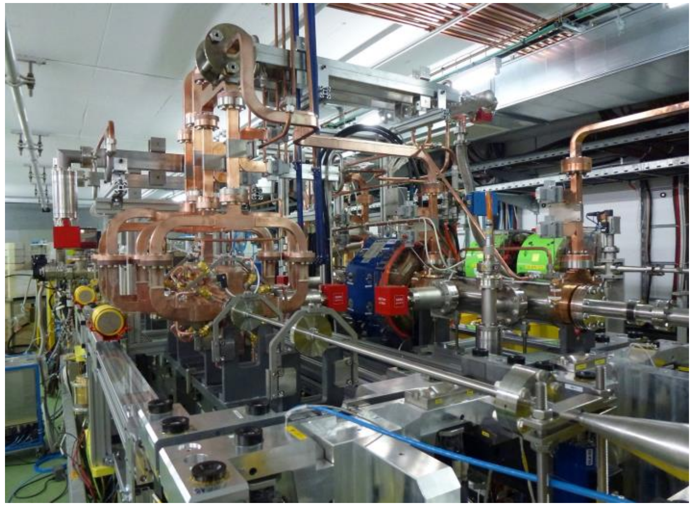




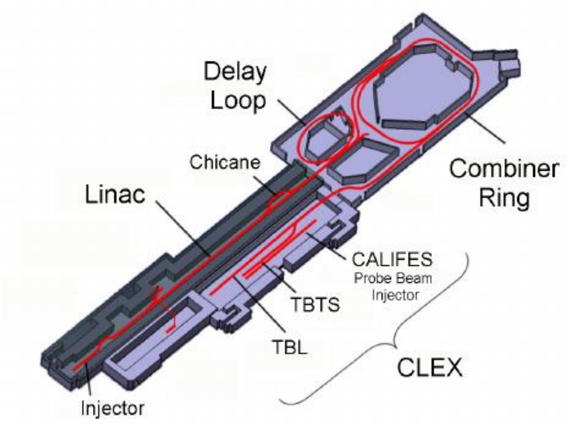
Two beam acceleration

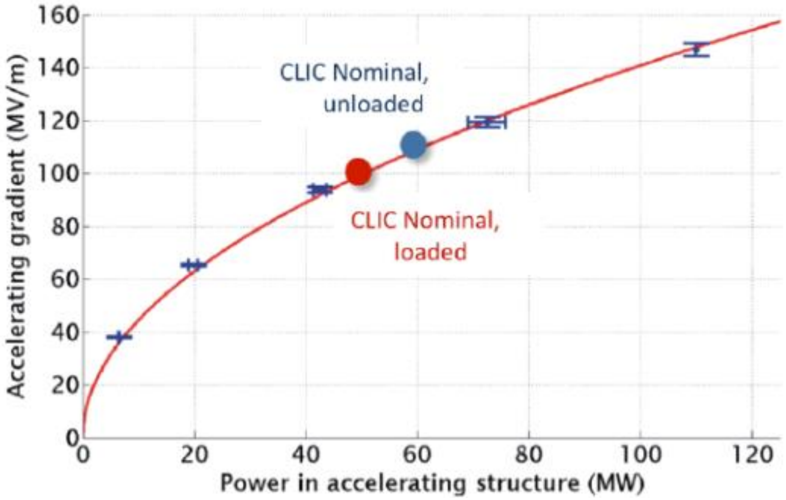
Demonstrated 2-beam acceleration

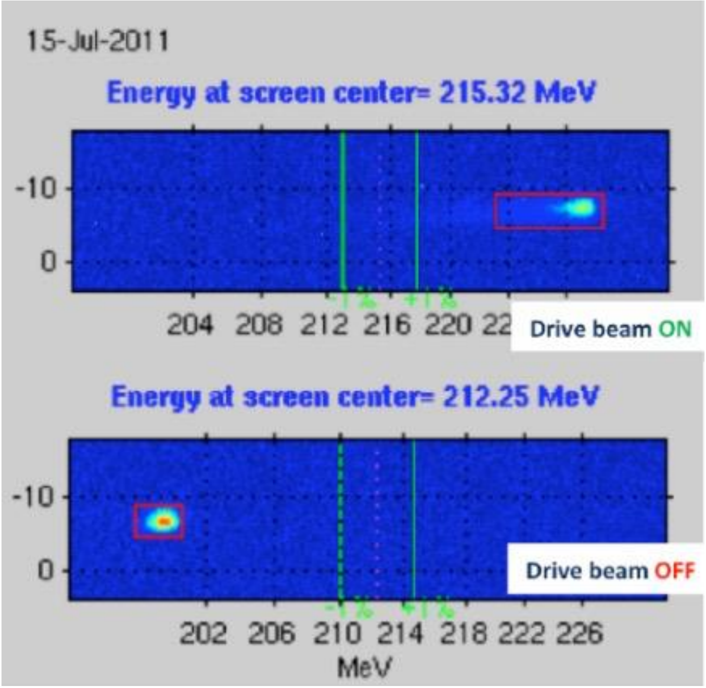


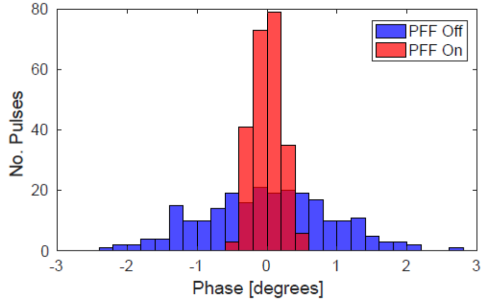


31MeV = 145MV/m





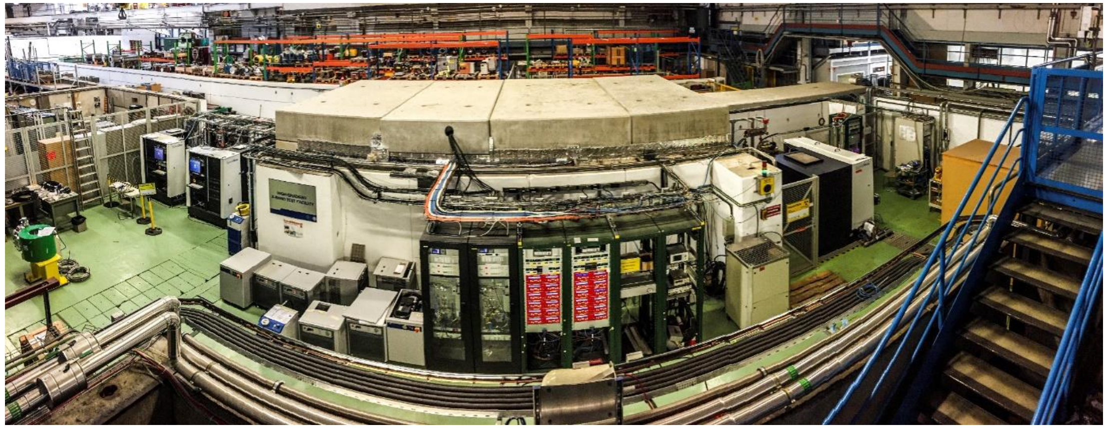




Status

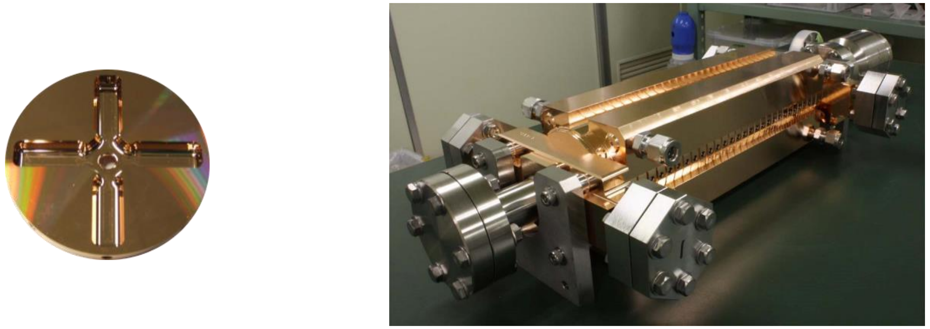
Achieved 100 MV/m gradient in main-beam RF cavities

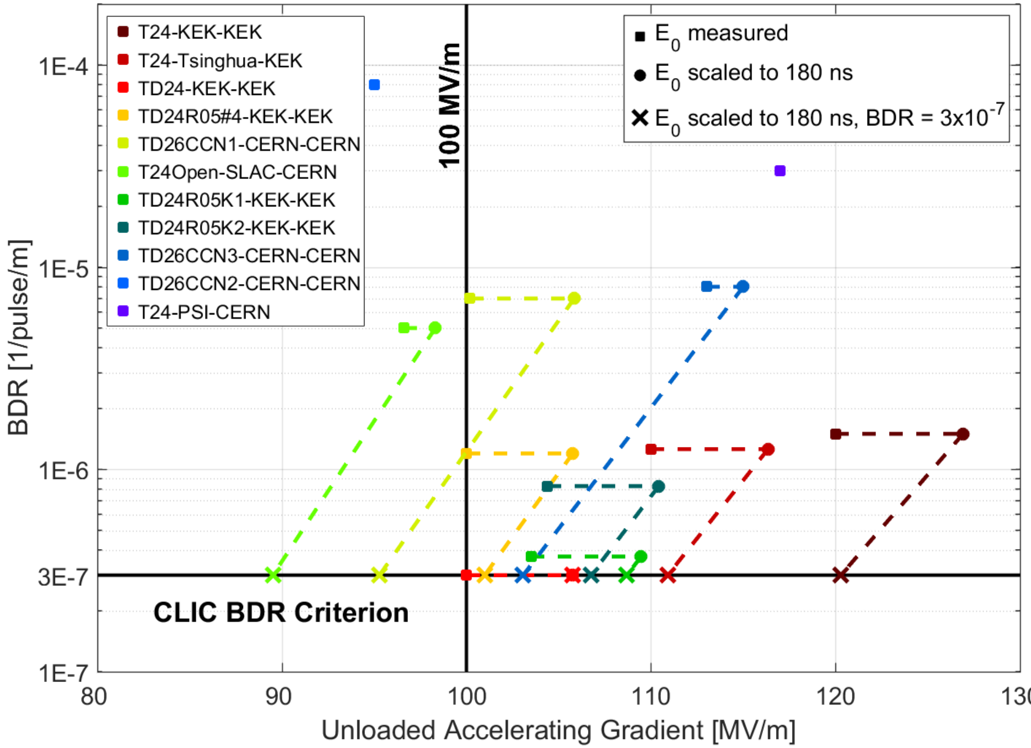
6 MW klystron pairs



50 MW klystron

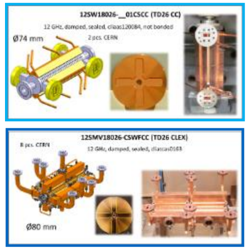
XBox-3 XBox-2

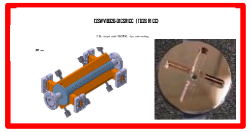




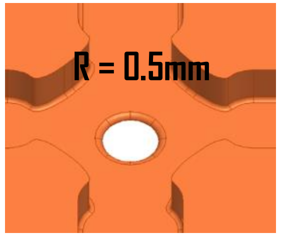
X-band structures for CLIC

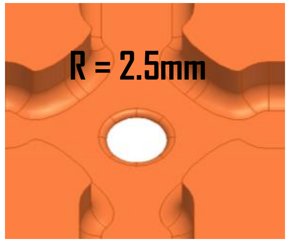
Baseline: Machines disks, damping structures, bonding steps





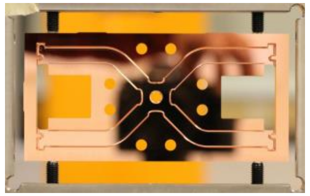
3 TeV structure
CLIC G*
(optimised)

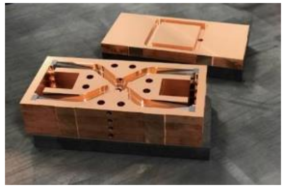




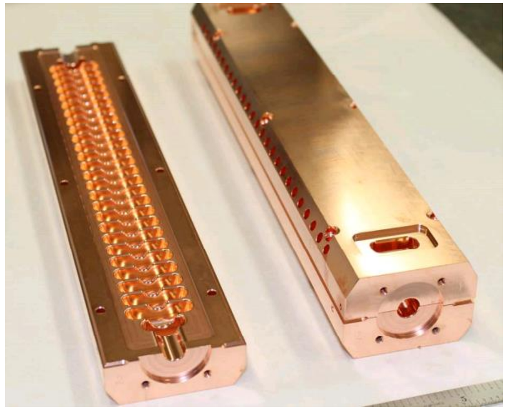
SwissFEL Assembly (brazing)

Rectangular (manufacturing)

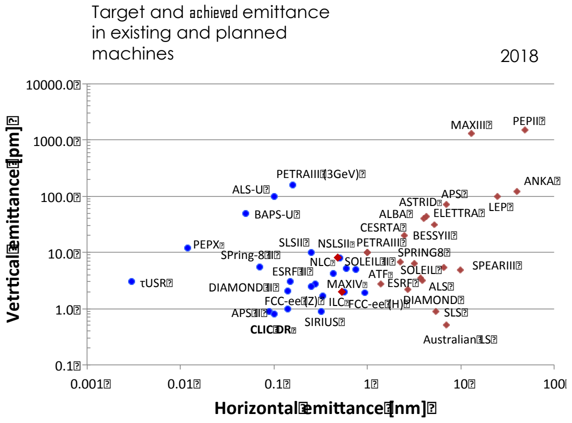


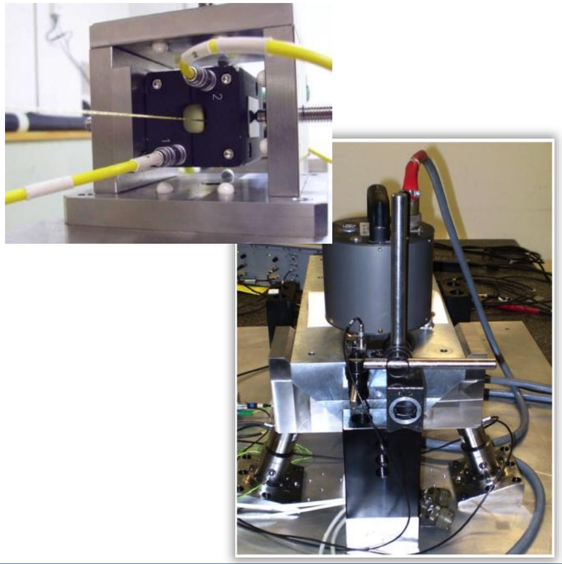


Halves: SLAC/CERN



Low emittance generation and preservation





Low emittance damping rings

Preserve by

- Align components (10 μm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Beam based measurements
  – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks

- Experimental tests in existing accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

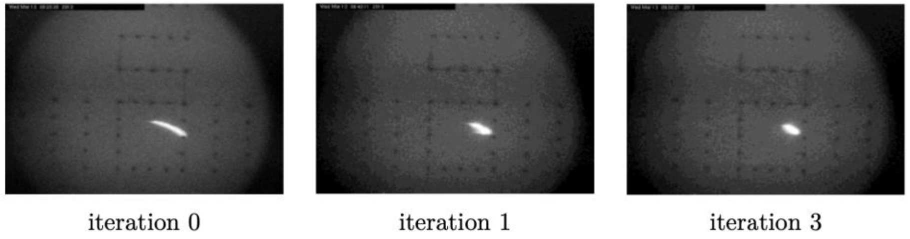
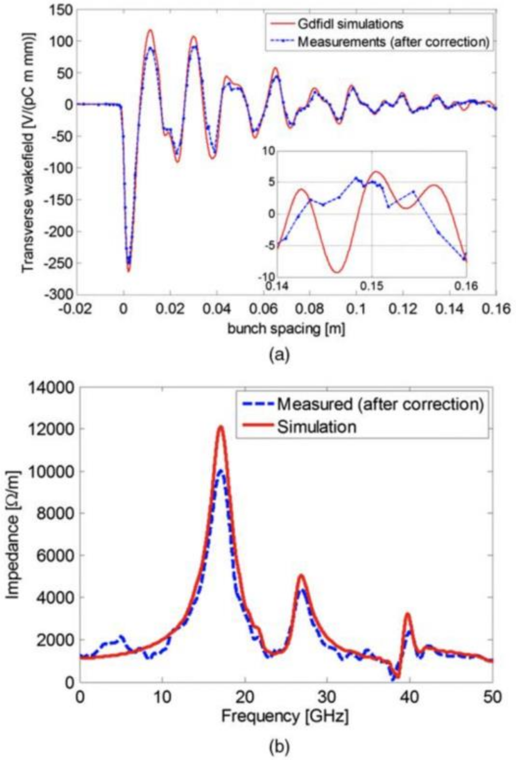


Figure 8.10: Phosphorous beam profile monitor measurements at the end of the FACET linac, before the dispersion correction, after one iteration step, and after three iteration steps. Iteration zero is before the correction.



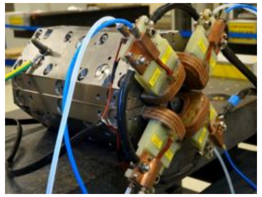
Wake-field measurements in FACET

(a) Wakefield plots compared with numerical simulations.
(b) Spectrum of measured data versus numerical simulation.

Information about some relevant suppliers and subcontractors participating to prototypes procurement for the CLIC Magnets R&D phase

Note: majority of coils and of other components manufacturing, magnet assembly, was done by CERN apart for the DBQ magnets (EM and PM versions).

1) **Main Beam Quadrupoles. 4 prototypes** procured: 3 Type1 (the shorter), 1 Type4 (the longer)



Relevant procurements:

- *Coils:* **TESLA** Engineering LTD, Storrington, West Sussex - UK
- *High Precision quadrants machining:*
- **DMP** 20850 Mendaro, Gipuzkoa - ES

2) **Drive Beam Quadrupoles** (EM version): **8 prototypes** procured:

Relevant manufacturers:

- *Complete manufacturing:*

Danfysik A/S 2630 Taastrup, DK

3) **Drive Beam Quadrupoles** (PM version): **2 prototypes** procured by Daresbury Laboratory

Relev

-*Des*

-*PM*

Hana

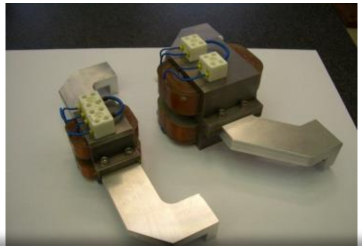
-*Hig*

-**SEN**

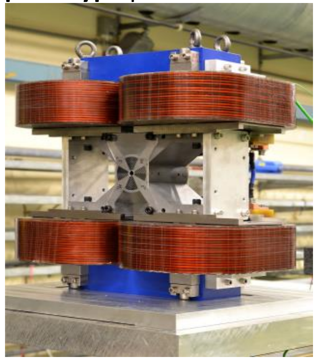
-**TSV**

-**Mc**

4) **Main Beam Steering Dipoles**: **2 prototypes** procured



5) **Final Focus Quadrupole QD0**: **1 prototype** procured



Relevant manufacturers:

- *PM blocks, Permendur EDM machining:* **Vacuumschmelze** GmbH & Co. KG, Hanau - D

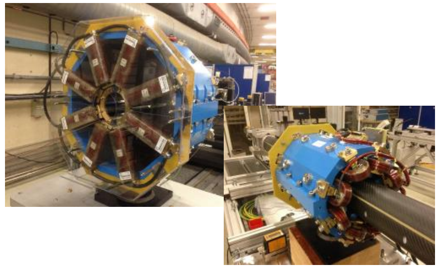
6) **Final Focus Sextupoles SD0:** *(**1 prototype** procurement **on-going**)*

Relevant manufacturers:

- *Permendur and PM blocks procurement:*

VDL Groep BV, Eindhoven - NL

7) **Octupoles for ATF** facility at KEK, Japan: **2 magnets** procured



Relevant manufacturers:

- *Coils:* **S.E.F.** Sarl, Labège - F
- *Iron Yokes EDM Machining:*

Röttgers Værktøj A/S Odense - DK

Technical Developments

Collaborations

CLIC accelerator

- ~50 institutes from 28 countries
- CLIC accelerator studies
- CLIC accelerator design and development
- Construction and operation of CLIC Test Facility, CTF3

CLIC detector and physics (CLICdp)

- 30 institutes from 18 countries
- Physics prospects & simulations studies
- Detector optimisation + R&D for CLIC

+ strong participation in the CALICE and FCAL Collaborations and in AIDA-2020

Technology use

Photo: SwissFEL/PSI

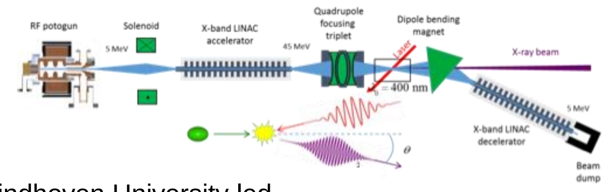
SwissFEL: C-band linac

- 104 x 2 m-long C-band (5.7 GHz) structures (beam up to 6 GeV at 100 Hz)
- Similar µm-level tolerance
- Length ~ 800 CLIC structures

CompactLight

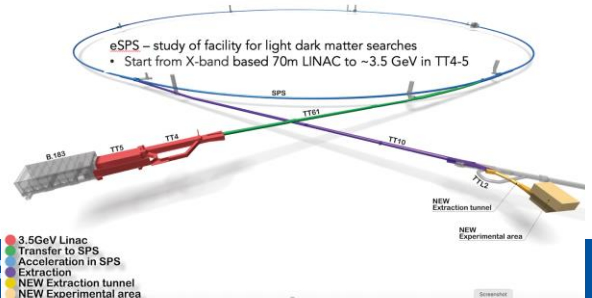
CLIC technology for different applications

- EU co-funded FEL design study
- 1 GeV linac at INFN-LNF
- …many other small systems…



Eindhoven University led SMART*LIGHT Compton Source

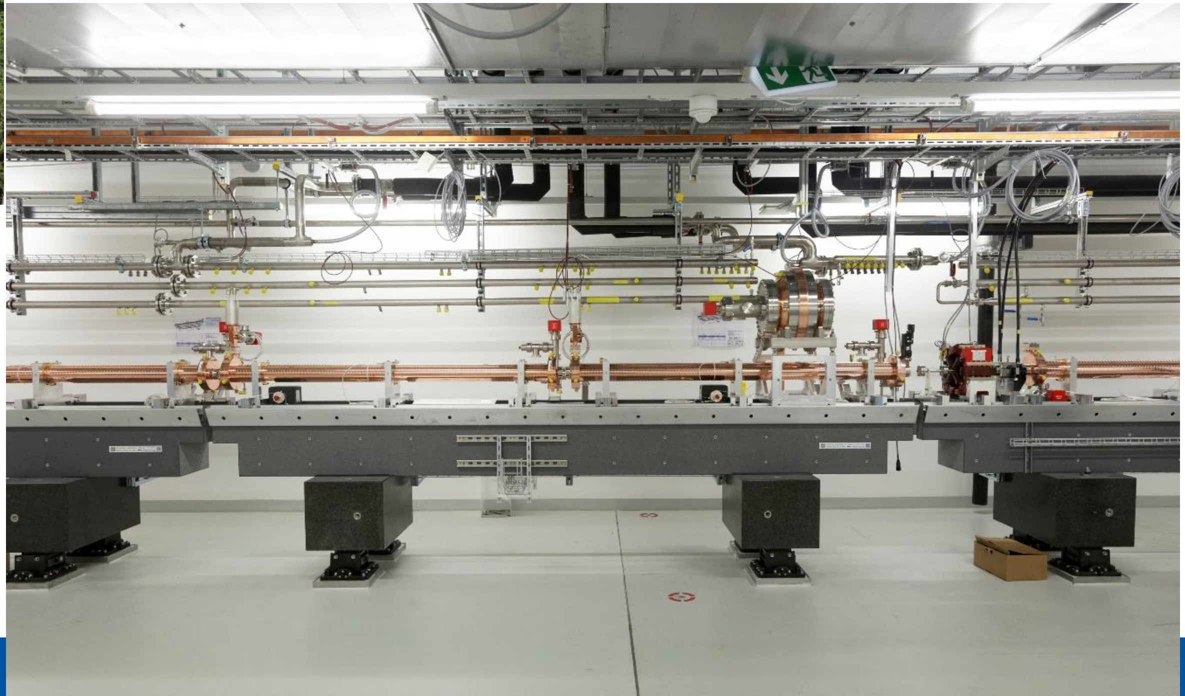
INFN Frascati advanced acceleration facility EuPRAXIA@SPARC_LAB



CERN: eSPS study (3.5 GeV X-band linac)

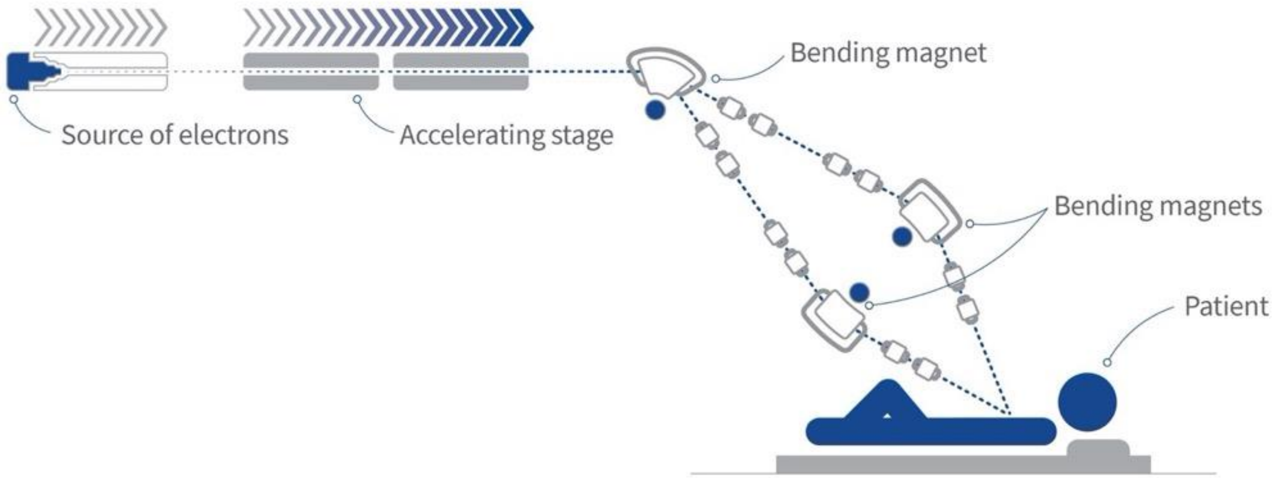
SwissFEL

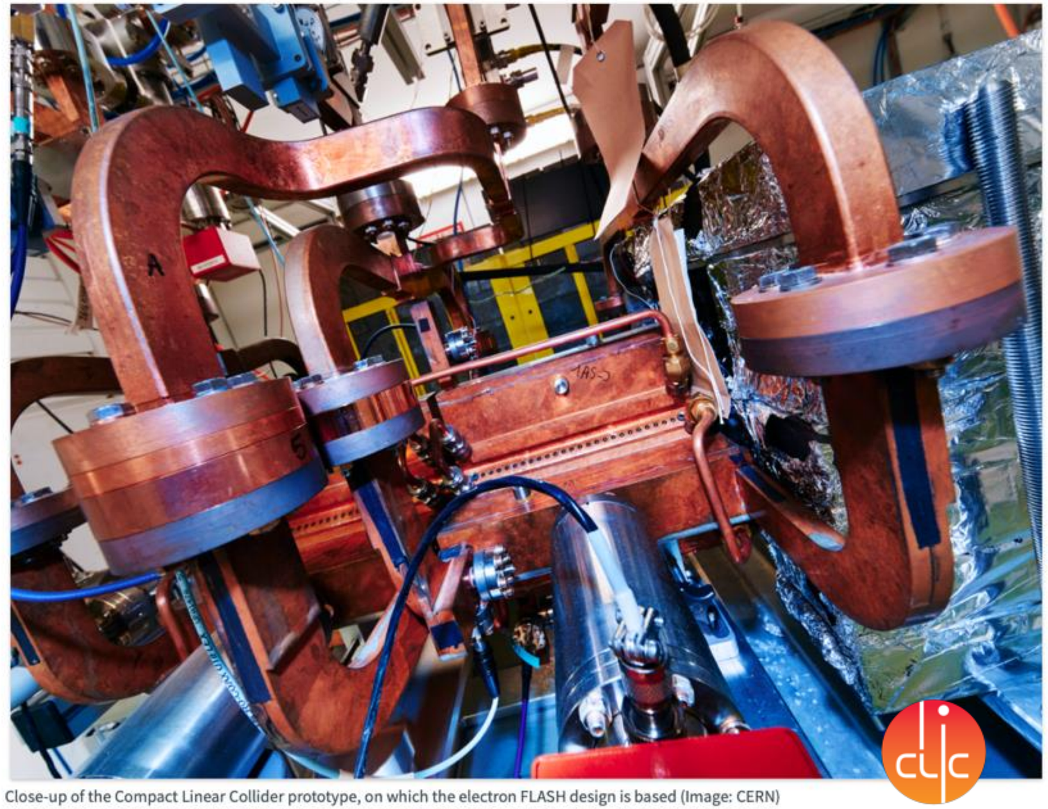
- 104 x 2m-long C-band structures (beam → 6 GeV @ 100 Hz)
- Similar um-level tolerances
- Length ~ 800 CLIC structures



FLASH VHEE (very high energy electron) therapy

CLIC technology for a FLASH VHEE facility being designed in collaboration with Lausanne University Hospital (CHUV)





Close-up of the Compact Linear Collider prototype, on which the electron FLASH design is based (Image: CERN)

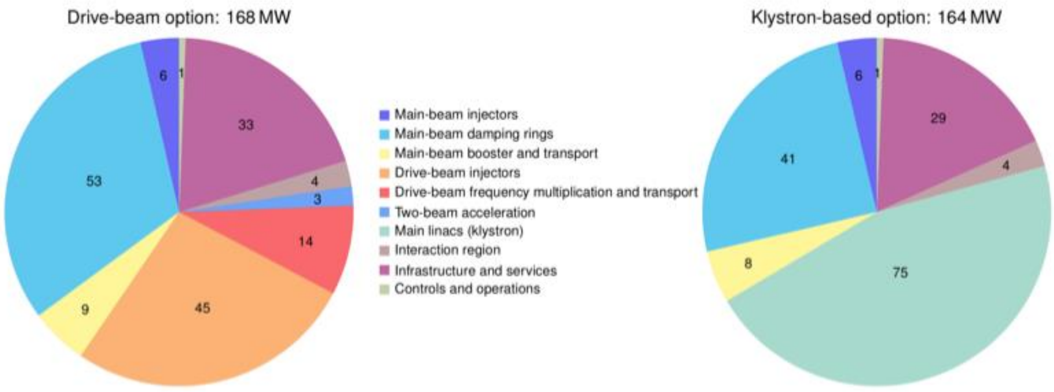
An intense beam of electrons is produced in a photoinjector, accelerated to around 100 MeV and then is expanded, shaped and guided to the patient.

Flash: Very short and intense radiation, sparing of healthy tissue

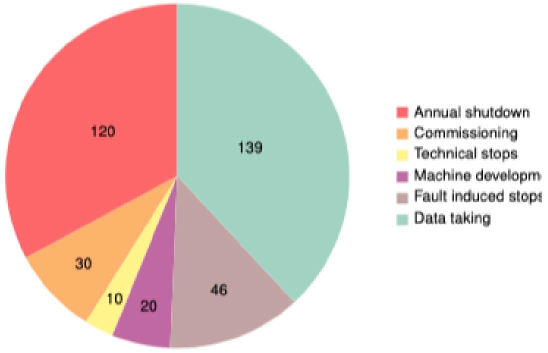
CLIC implementation

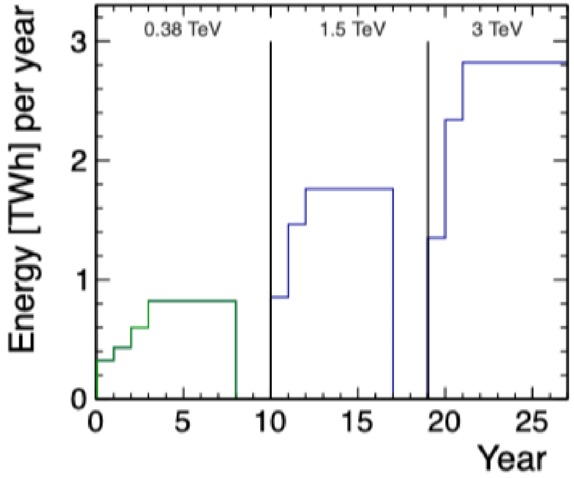
Schedules, cost, power for CLIC in the next slides – for information

Power and energy



Collision Energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	168	25	9
1500	364	38	13
3000	589	46	17





Power estimate bottom up (concentrating on 380 GeV systems)

- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimisation, etc

Further savings possible, main target damping ring RF

From running model and power estimates at various states – the energy consumption can be estimated

CERN is currently consuming ~1.2 TWh yearly (~90% in accelerators)

Will look also more closely at 1.5 and 3 TeV numbers next (in blue in figure to illustrate not optimized as for 380 GeV), Hi-Eff L-band klystrons development (see later), damping ring RF as mentioned, include reduction using permanent magnets

Energy studies - I
(Fraunhofer)

Topic 1:

CLIC is normal conduction, single pass, can change off-on-off quickly, at low power when not pulsed

Specify state-change (off-standby-on) times and power uses for each – see if clever scheduling using low cost periods, can reduce the energy bill

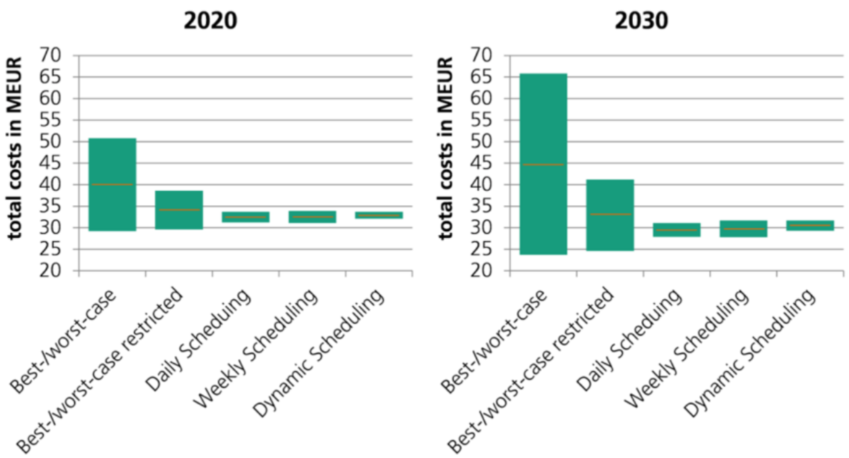


Figure 7.13: Relative energy cost by no scheduling, avoiding the winter months (restricted), daily, weekly and dynamic scheduling. As explained in the text the central values of the ranges shown should be considered the best estimates. The absolute cost scale will depend on prices, contracts and detailed assumption about running times, but the relative cost differences indicate that significant cost-reductions could be achieved by optimising the running schedule of CLIC to avoid high energy cost periods, also outside the winter shut-down periods. (image credit: Fraunhofer)

Energy studies - II
(Fraunhofer)

Topic 2:

- It is possible to fully supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators, at a cost of slightly more than 10% of the CLIC 380 GeV cost)
- However, self-sufficiency during all times can not be reached and only 54% of the time CLIC could run independently from public electricity supply with the portfolio simulated.
- About 1/3 of the generated PV and wind energy will be available to export to the public grid even after adjusting the load schedule of CLIC.
- Additional, the renewables are most efficient in summer, when prices are low anyway

Topic 3:

- The use of waste heat to generate electricity is technically difficult due to the low temperature of the waste heat. The heat would have to be raised to a significantly higher level and more electricity would be consumed than can be generated again in the later process.
- A reasonable option is to use the waste heat to provide space heating. Also for this option, the temperature must be raised via a heat pump and thus additional electricity must be used.
- Another possibility would be the research of further innovative concepts for the use of waste heat with very low temperature (for example very low temperature ORCs, thermoelectric generators or the storage of heat in zeolites).
- The fact that the maximum energy need locally is during the winter, when it is favourable of energy cost reasons to not run the accelerator, also makes is more difficult today to envisage efficient large scale energy recovery strategies.

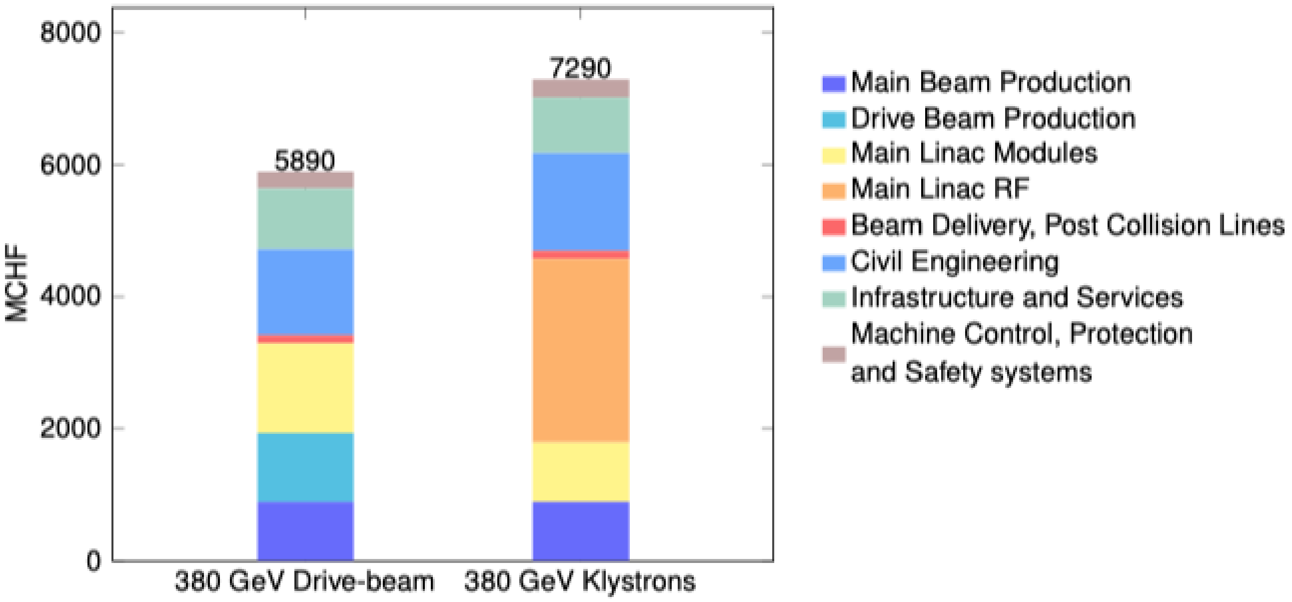
More in chapter 7.4.3 of the CLIC project plan (link)

Cost - I

Machine has been re-costed bottom-up in 2017-18

- Methods and costings validated at review on 7 November 2018 – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated

Domain	Sub-Domain	Cost [MCHF] Drive-Beam	Cost [MCHF] Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**



$$\text{CLIC 380 GeV Drive-Beam based:} \quad 5890^{+1470}_{-1270}\,\text{MCHF};$$

$$\text{CLIC 380 GeV Klystron based:} \quad 7290^{+1800}_{-1540}\,\text{MCHF}.$$

Cost - II

Other cost estimates:

Construction:

- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction

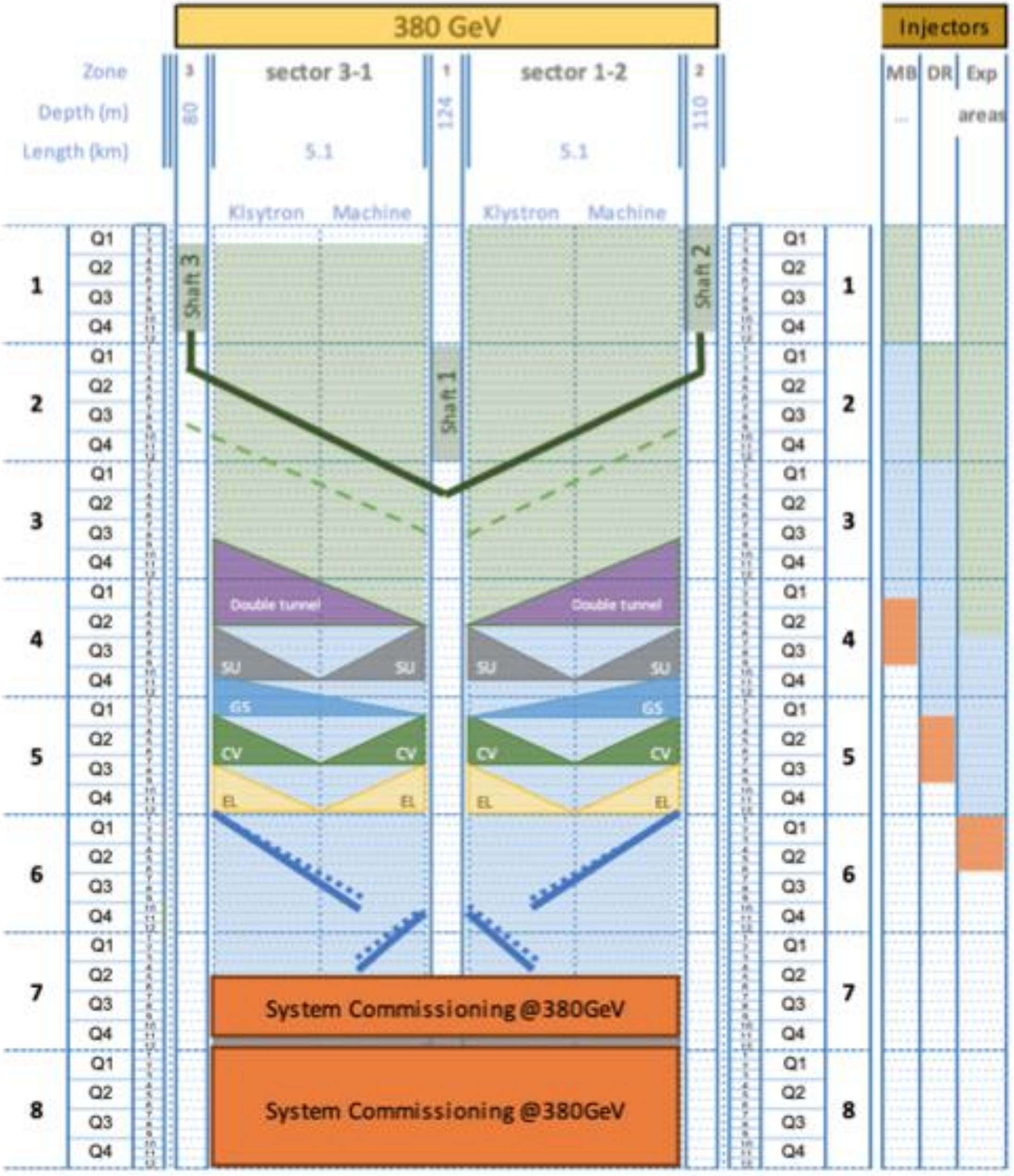
Operation:

- 116 MCHF (see assumptions in box below)
- Energy costs

– 1% for accelerator hardware parts (e.g. modules).
– 3% for the RF systems, taking the limited lifetime of these parts into account.
– 5% for cooling, ventilation and electrical infrastructures etc. (includes contract labour and consumables)

These replacement/operation costs represent 116 MCHF per year.

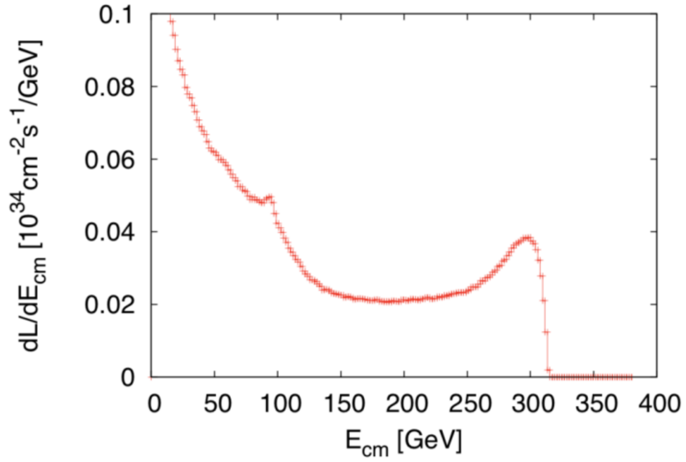
Based on detailed breakdown of tasks, rates, access/zoning/transport, prod. rates, etc



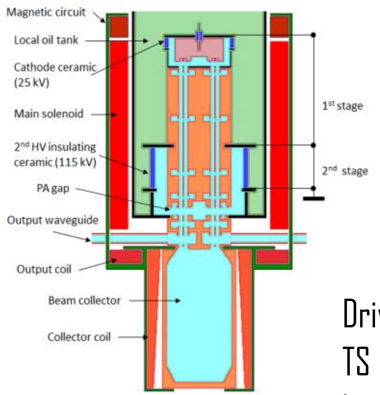
CLIC acc. studies 2019/20 – some examples

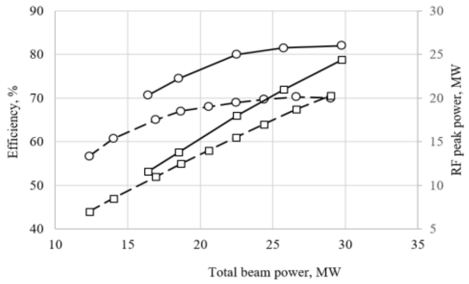
Further work on luminosity performance, possible improvements and margins, operation at the Z-pole and gamma-gamma

- Z pole performance, 2.3×10^{32} – 0.4×10^{34} cm^{-2} s^{-1}
  - The latter number when accelerator configured for Z running (e.g. early or end of first stage)
- Gamma – Gamma spectrum (example)
- Luminosity margins and increases
  - Baseline includes estimates static and dynamic degradations from damping ring to IP: 1.5 x 10^{34} cm^{-2} s^{-1}, a “perfect” machine will give : 4.3 x 10^{34} cm^{-2} s^{-1}, so significant upside
  - In addition: doubling the frequency (50 Hz to 100 Hz) would double the luminosity, at a cost of +50 MW and ~5% cost increase
- CLIC note about these studies

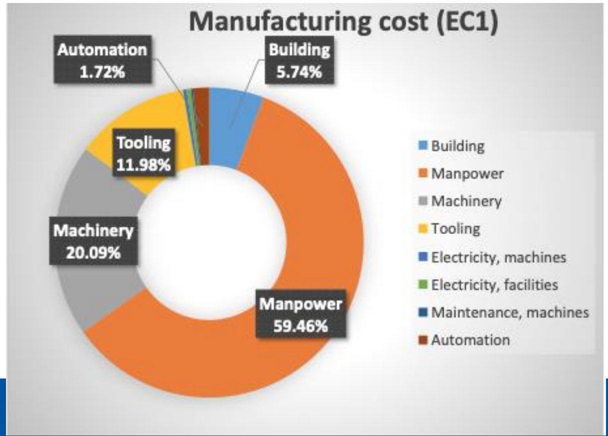


Industrial questionnaire:
Based on the companies feedback, the preparation phase to the mass production could take about five years. Capacity clearly available.





Drivebeam klystron: The klystron efficiency (circles) and the peak RF power (squares) simulated for the CLIC TS MBK (solid lines) and measured for the Canon MBK E37503 (dashed lines) vs total beam power. See more later.
Publication: https://ieeexplore.ieee.org/document/9115885



LC studies CERN 2021-26

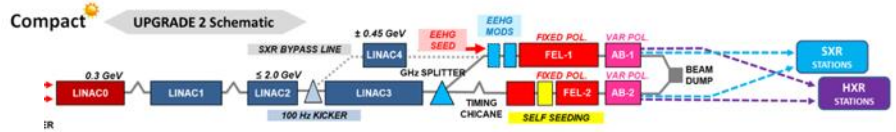

CLIC and High Gradient technology:

- Design and manufacturing of X-band structures and components, system interfaces
- Study structures breakdown limits and optimization, operation and conditioning
- Beam-dynamics and parameters: Nanobeams (focus on beam-delivery), pushing multi-TeV region (parameters and beam structure vs energy efficiency)
- Tests in CLEAR (wakefields, instrumentation) and other facilities (e.g. ATF2)

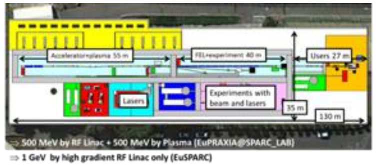
See talks by Phil Burrows (CLIC), Nuria Catalan (Nanobeams), Chetan Gohil (Luminosity Performance)

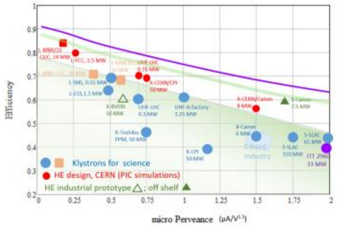
Application of X-band technology (examples):

- A compact FEL (CompactLight: EU Design Study 2018-21)
- Compact Medical linacs (proton and electrons)
- Inverse Compton Scattering Source (Smart-Light)
- Linearizers and deflectors in FELs (PSI, DESY, more)
- 1 GeV X-band linac at LNF

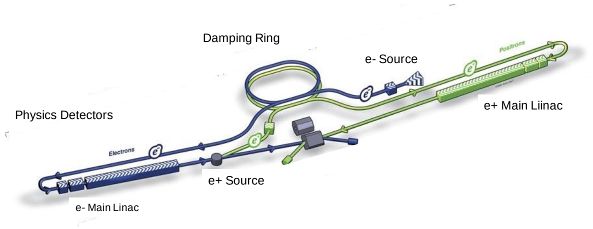








See talk by Walter Wuensch (Applications of High Gradient Technologies)



ILC related R&D and Pre-lab Planning

- Positron flux concentrator, ATF2/3, Hi-klystrons, various SRF topics, cryo, dumps, beam-dynamics, DR, etc
- IDT participation and Common Fund contributions.
- Numerous ILC and/or KEK collaborative R&Ds, linking to CLIC, generic R&D or SRF for HL LHC and FCC and other CERN activities.

See talks by Joachim Mnich and Steinar Stapnes (CERN and European reports)

CLIC Project Readiness Report (PRR)

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

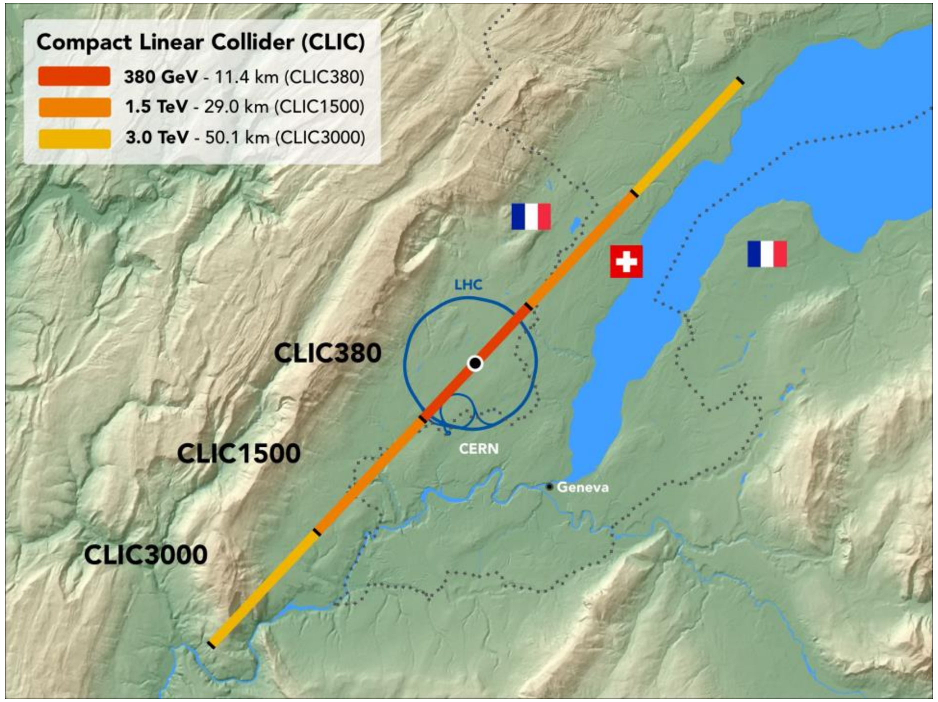
Focusing on:

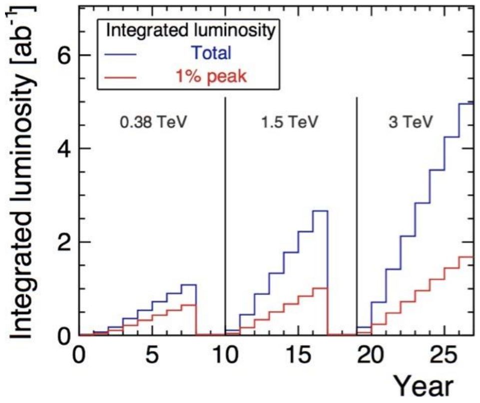
- The X-band technology readiness for the 380 GeV CLIC initial phase
- Optimizing the luminosity at 380 GeV
- Improving the power efficiency for both the initial phase and at high energies

More details:

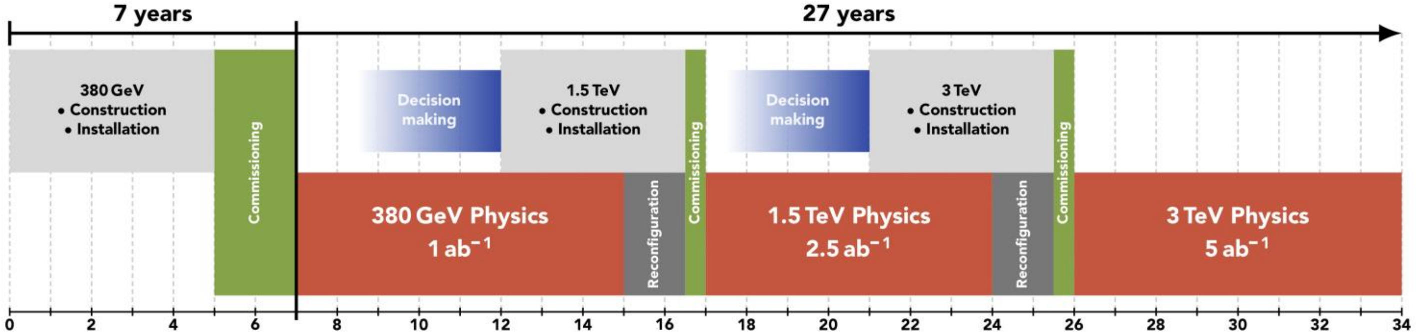
- X-band studies: Structure manufacturability and optimized conditioning, interfaces to all connecting systems for large scale production, designs for and support of use in applications from the 1 GeV linac at LNF to medical linacs
- Luminosity: beamdynamics studies and related hardware optimisation for nano beams from damping rings to final focus (mechanical and thermal stability, alignment, instrumentation, vacuum systems, stray field control, magnet stability, etc)
- Improving damping ring and drive beam RF efficiency, study parameter changes to reduce power at multi-TeV energies maintaining high luminosities

CLIC timeline





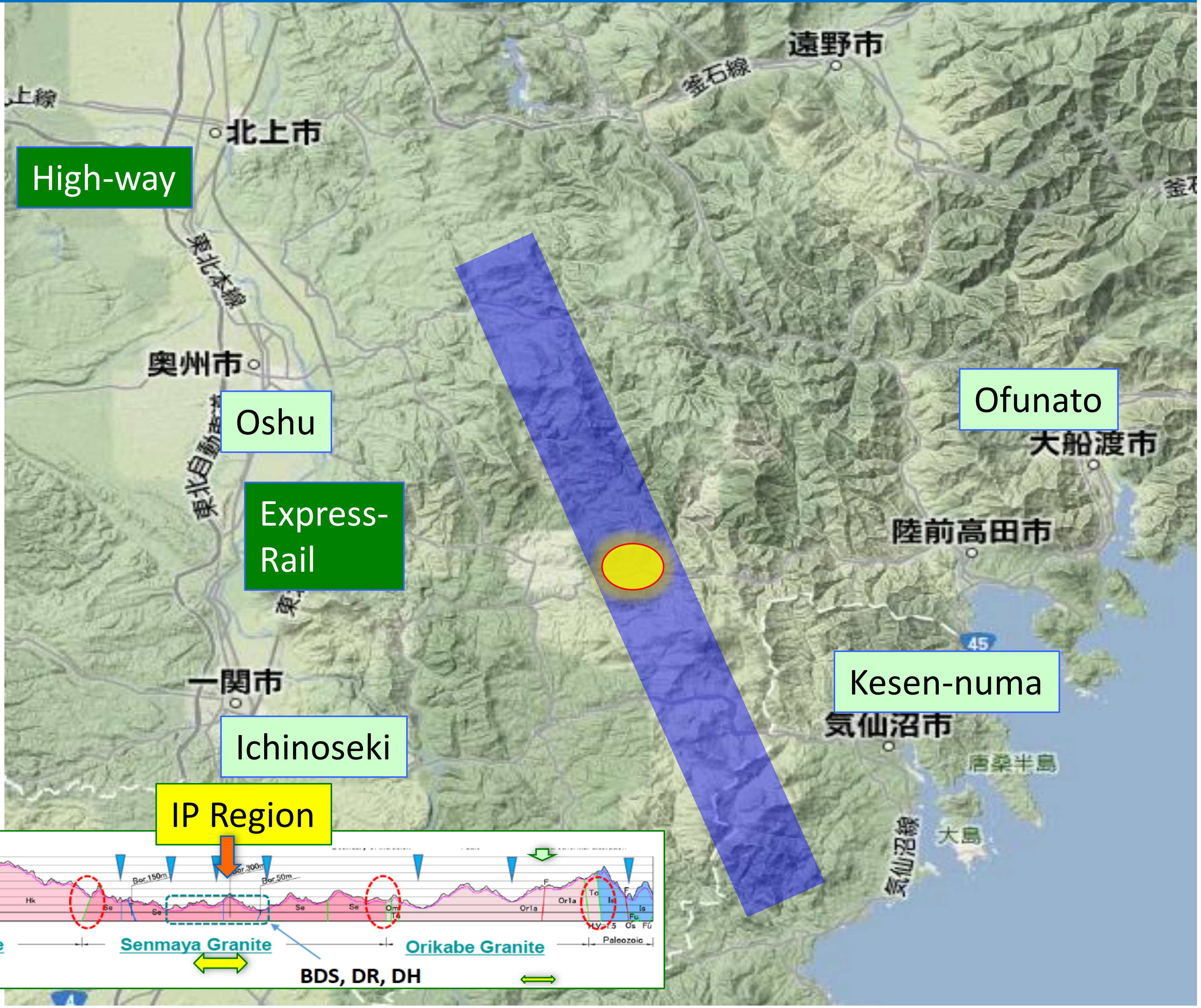
Ramp-up and up-time assumptions: arXiv:1810.13022, Bordry et al.



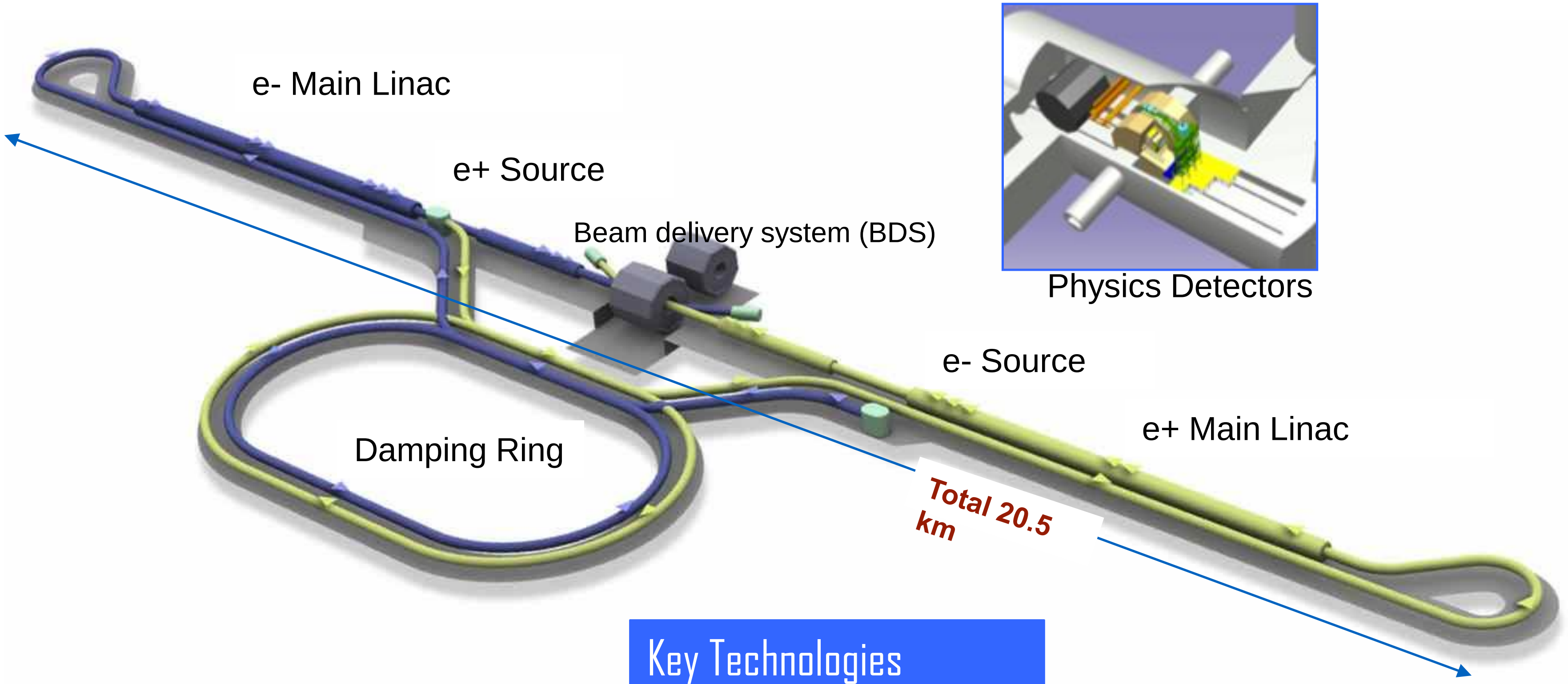
Technology Driven Schedule from start of construction shown above.

A preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)

ILC Candidate Location: Kitakami, Tohoku



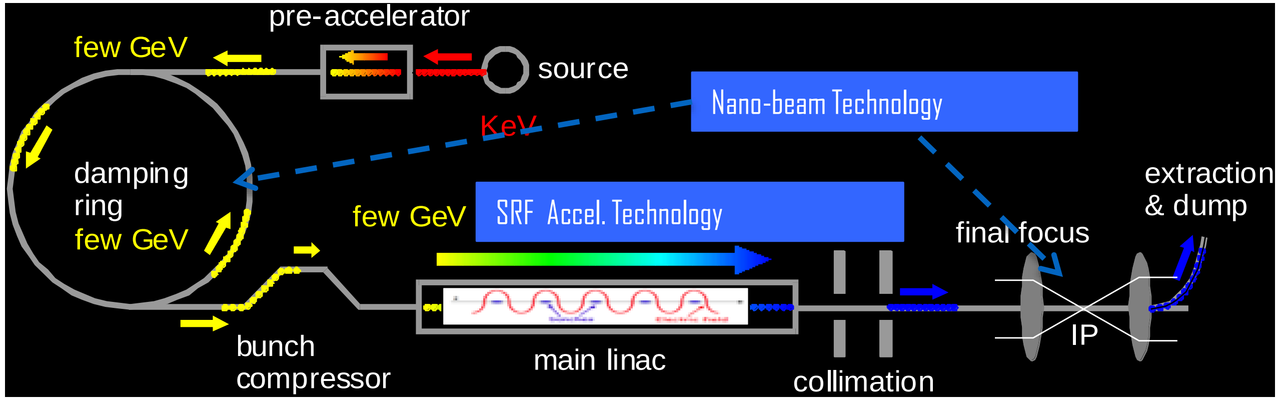
Design outline: ILC250 accelerator facility



Physics Detectors

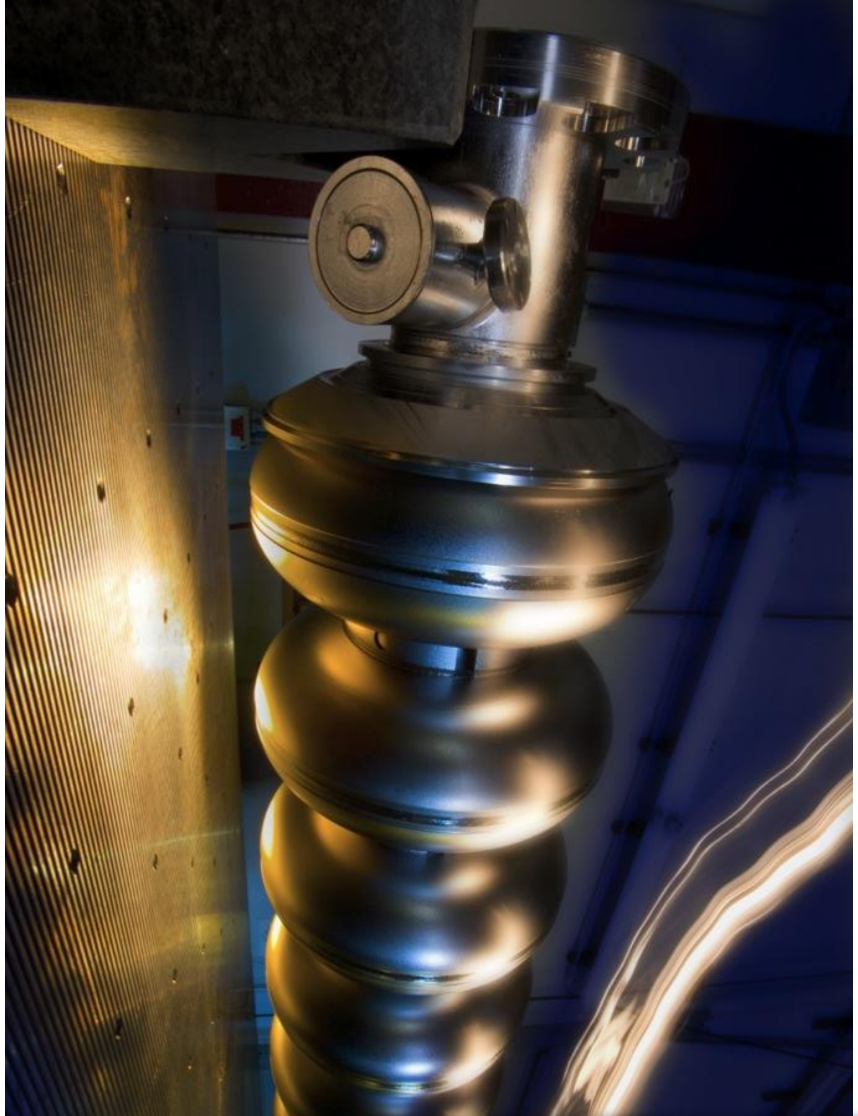
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 $\times10^{34}$ $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) $Q_0 = 1\times10^{10}$

Key Technologies



- Costs ~5 B$, power ~120 MW
- Will concentrate on SRF
- Nanobeam similar as for CLIC but a few words about ATF

ILC: SCRF

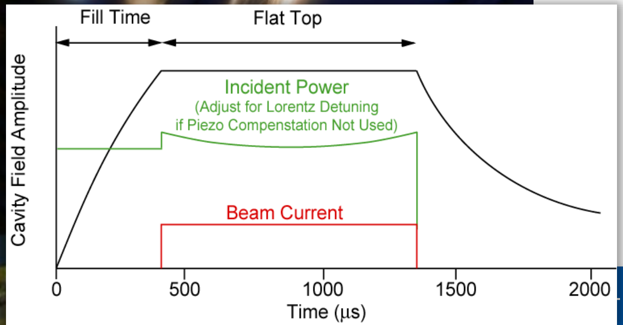


Ultra-high Q_0 (~10^{10})

- Almost zero power (heat) in cavity walls (in SC RF the main efficiency issues related to fill factors and cryogenics)
- Standing wave cavities with low peak power requirements
- Long beam pulse (~1 ms) - favorable for feed-backs within the pulse train

Low impedance

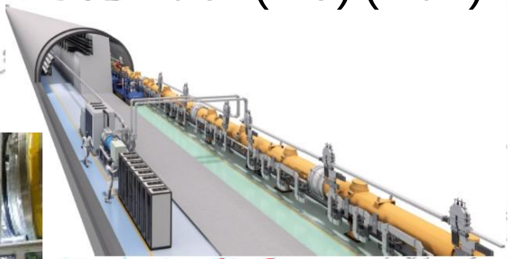
- beam generates low "wakefields"
- relatively large structures (1.3 GHz)



Worldwide large scale SRF accelerators

European XFEL

International Linear Collider (ILC) (Plan)



Euro-XFEL
Operation started from 2017
- -100 cryomodules
- -800 cavities
- -17.5 GeV (Pulsed)

DESY

LAL/Saclay

INFN

LCLS-II + HE (under construction)
- -35 + 20 cryomodules
- -280 + 160 cavities
- - 4 + 4 GeV (CW)

Cornell

FNAL

SLAC

JLab

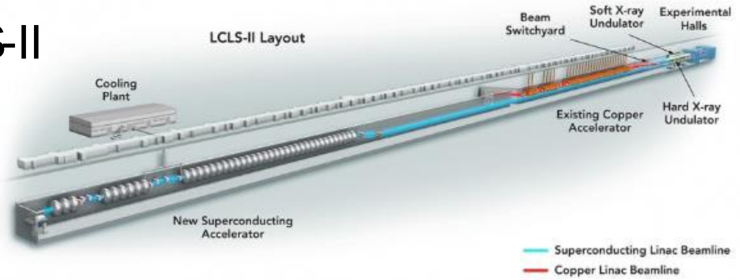
ILC
- -900 cryomodules
- -8,000 cavities
- -250 GeV (Pulsed)

KEK

SINAP

SHINE (under construction)
- -75 cryomodules
- -~600 cavities
- - 8 GeV (CW)

LCLS-II



1.3GHz 9 cell cavity

Potential for upgrades

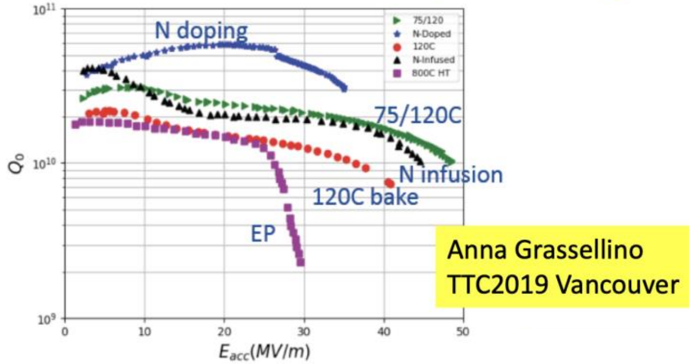
The ILC can be upgraded to higher energy and luminosity.

			Z-Pole [4]		Higgs [2,5]			500GeV [1*]		TeV [1*]
			Baseline	Lum. Up	Baseline	Lum. Up	L Up,10Hz	Baseline	Lum. Up	case B
Center-of-Mass Energy	E_{CM}	GeV	91.2	91.2	250	250	250	500	500	1000
Beam Energy	E_{beam}	GeV	45.6	45.6	125	125	125	250	250	500
Collision rate	f_{col}	Hz	3.7	3.7	5	5	10	5	5	4
Pluse interval in electron main linac		ms	135	135	200	200	100	200	200	200
Number of bunches	n_b		1312	2625	1312	2625	2625	1312	2625	2450
Bunch population	N	10^{10}	2	2	2	2	2	2	2	1.737
Bunch separation	Δt_b	ns	554	554	554	366	366	554	366	366
Beam current		mA	5.79	5.79	5.79	8.75	8.75	5.79	8.75	7.60
Average beam power at IP (2 beams)	P_B	MW	1.42	2.84	5.26	10.5	21.0	10.5	21.0	27.3
RMS bunch length at ML & IP	σ_z	mm	0.41	0.41	0.30	0.30	0.30	0.30	0.30	0.225
Emittance at IP (x)	γe^*_x	µm	6.2	6.2	5.0	5.0	5.0	10.0	10.0	10.0
Emittance at IP (y)	γe^*_y	nm	48.5	48.5	35.0	35.0	35.0	35.0	35.0	30.0
Beam size at IP (x)	σ^*_x	µm	1.118	1.118	0.515	0.515	0.515	0.474	0.474	0.335
Beam size at IP (y)	σ^*_y	nm	14.56	14.56	7.66	7.66	7.66	5.86	5.86	2.66
Luminosity	L	$10^{34}/cm^2/s$	0.205	0.410	1.35	2.70	5.40	1.79	3.60	5.11
Luminosity enhancement factor	H_D		2.16	2.16	2.55	2.55	2.55	2.38	2.39	1.93
Luminosity at top 1%	$L_{0.01}/L$	%	99.0	99.0	74	74	74	58	58	45
Number of beamstrahlung photons	n_γ		0.841	0.841	1.91	1.91	1.91	1.82	1.82	2.05
Beamstrahlung energy loss	δ_{BS}	%	0.157	0.157	2.62	2.62	2.62	4.5	4.5	10.5
AC power [6]	P_{site}	MW			111	138	198	173	215	300
Site length	L_{site}	km	20.5	20.5	20.5	20.5	20.5	31	31	40

Increase in energy and luminosity foreseen already at TDR times (see table)

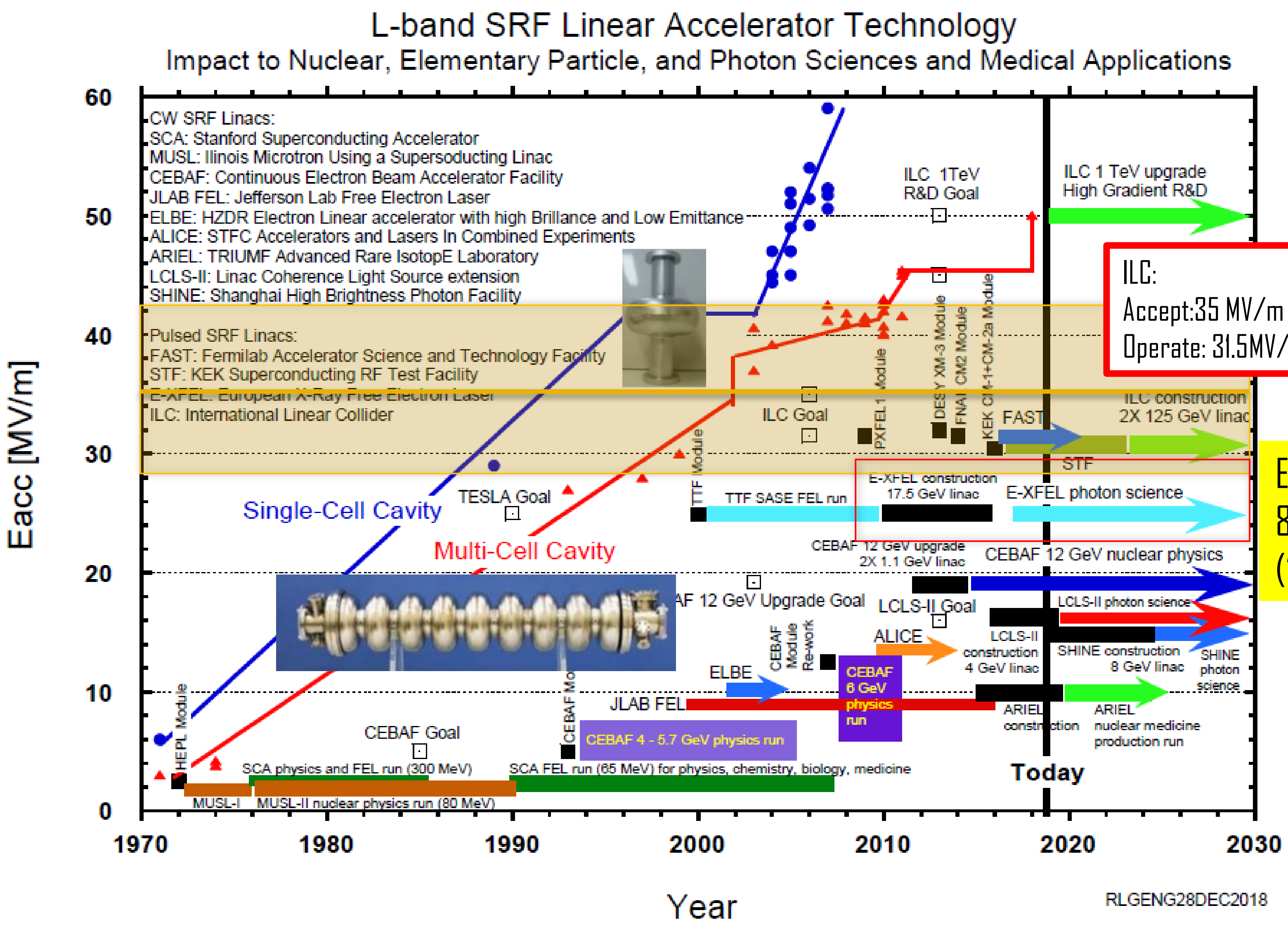
New cavity results open for further optimization (reduce costs, increase energy, increase luminosity …)

- Surface treatments for high-Q and high-G



*There were several typos in the values of the luminosities in the TDR. They have been fixed by CR-0005. https://edmsdirect.desy.de/item/D00000001100895

Technology timeline and prospects for improvements



ILC:
Accept:35 MV/m +/-20%
Operate: 31.5MV/m +/-20%

European XFEL
800 cavities
(10% of ILC ML)

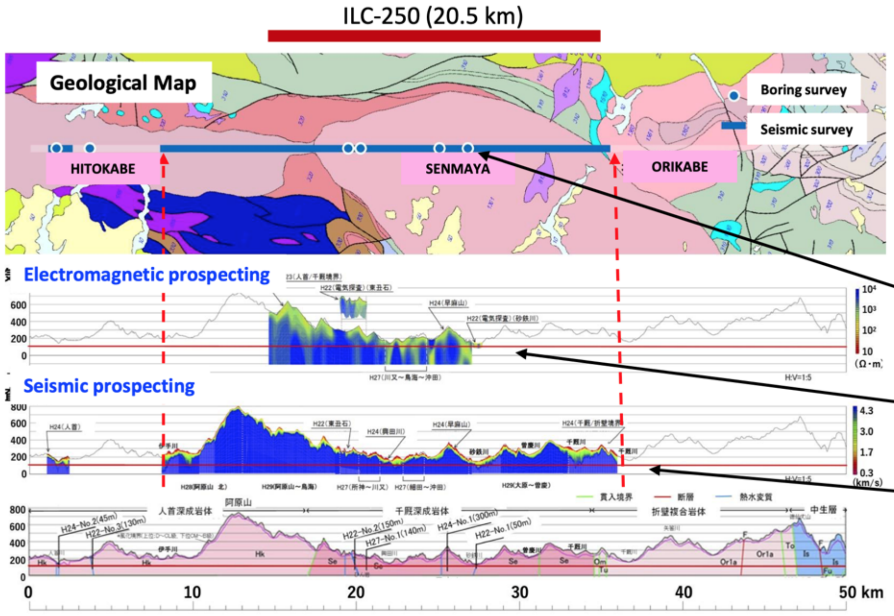
R. Geng (JLAB)

Tohoku ILC Project Development Center

(https://tipdc.org/)

- Local governments and universities in Tohoku area established Tohoku ILC Project Development Center this summer to solve issues that should be handled by the region regarding the construction of research facilities and environmental improvement around the ILC candidate site.
- Mandate of the center
  - Examination of the impact of ILC construction on the natural environment, society, and economy
  - Utilization of local resources associated with the location of research facilities and examination for regional promotion
  - Examination of system and town development corresponding to acceptance and settlement of researchers and families

Geological survey of the ILC candidate site



- Continuous **granite region**
  HITOKABE, **SENMAYA** and **ORIKABE** bedrock
- **Have capability to extend the ILC up to 50 km in future**
- **Boring geological survey**
  → Direct sampling down to the accelerator depth
- **Electromagnetic prospecting**
  → Cracks in the rock
- **Seismic prospecting**
  → Rock hardness

ICFA

ILC International Development Team

Executive Board

Americas Liaison	Andrew Lankford (UC Irvine)
Working Group 2 Chair	Shinichiro Michizono (KEK)
Working Group 3 Chair	Hitoshi Murayama (UC Berkeley/U. Tokyo)
Executive Board Chair and Working Group 1 Chair	Tatsuya Nakada (EPFL)
KEK Liaison	Yasuhiro Okada (KEK)
Europe Liaison	Steinar Stapnes (CERN)
Asia-Pacific Liaison	Geoffrey Taylor (U. Melbourne)

Working Group 1
Pre-Lab Setup

Working Group 2
Accelerator

Working Group 3
Physics & Detectors

Overall timeline

ILC IDT (~1.5 years)

- Prepare the work and deliverables of the ILC Pre-laboratory and work out, with national and regional laboratories, a scenario for their contributions
- Prepare a proposal for the organisation and governance of the ILC Pre-laboratory

ILC Pre-laboratory (~4 years)

- Complete all the technical preparation necessary to start the ILC project (infrastructure, environmental impact and accelerator facility)
- Prepare scenarios for the regional contributions to and organisation for the ILC.

ILC laboratory

- Construction and commissioning of the ILC (~9-10 years)
- Followed by the operation of the ILC
- Managing the scientific programme of the ILC

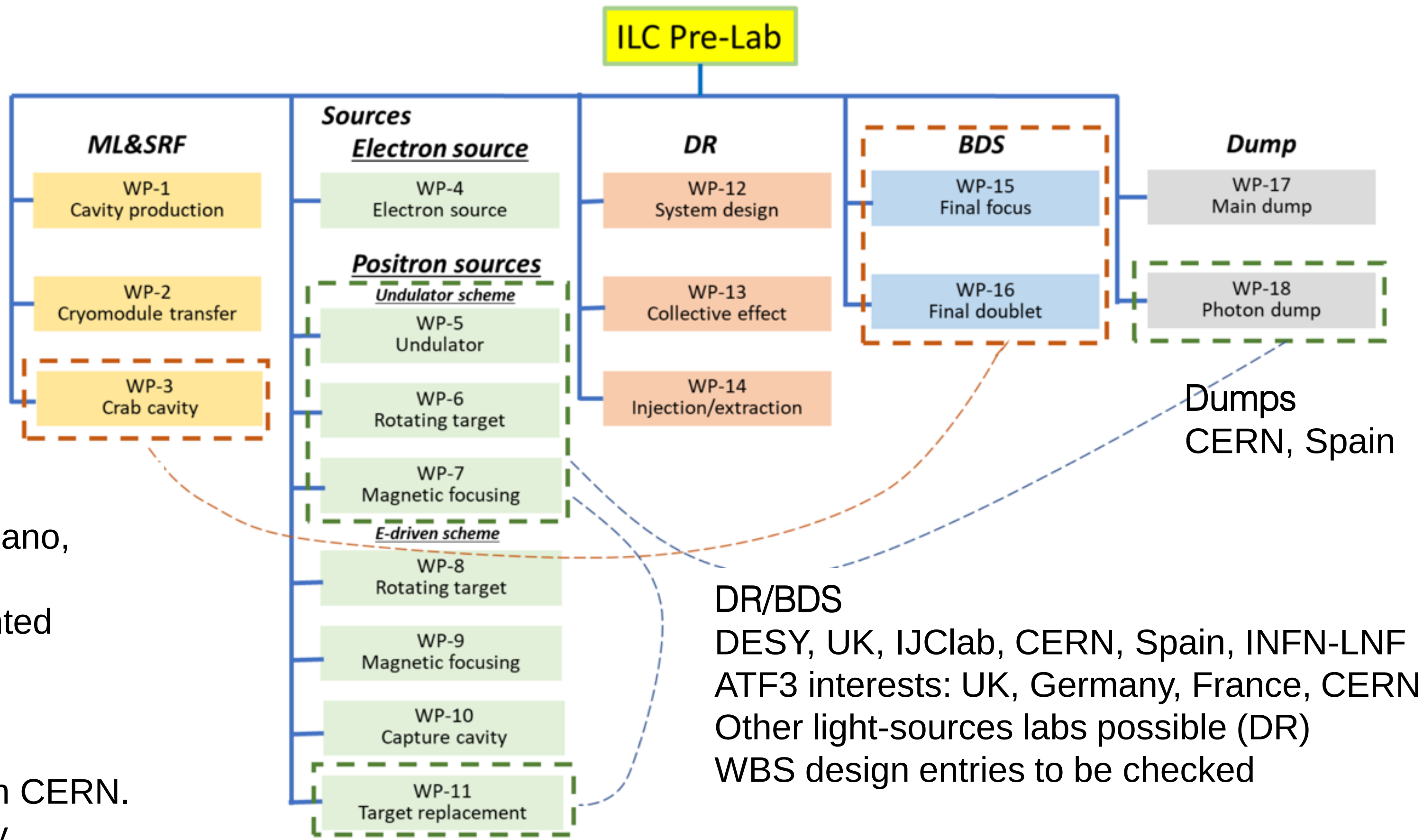
ILC development in Japan

ATF: Technology to handle nano-size beam
STF: Technology to assemble and operate superconducting cavities
CFF: Technology to manufacture superconducting cavities

Large Japanese activity in at least five areas:

- Work towards Japanese funding of the ILC Pre-lab
- Central role in Pre-lab planning discussions and leadership in many aspects of the technical work followed up in the IDT WGs, and KEK hosts the IDT
- Collaborative projects with many partners across the world and associated agreements
- Activities towards the wider Japanese physics and general community
- Work with Tohoku ILC Project Development Center for site preparation

Pre-lab work-packages – European participation in planning



Dumps
CERN, Spain

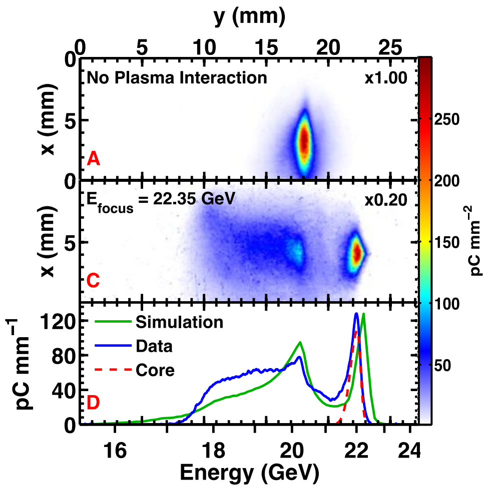
ML & SRF
CEA, CERN, CIEMAT, UK, INFN Milano, DESY
Not all European SRF labs represented

Additionally (in WBS but not in workpackages):
- Long term cryo collaboration with CERN.
- HiEff RF another relevant activity
- SRF “basic” R&D for fabrication improvements or long term performance improvements (i.e. for upgrades)

DR/BDS
DESY, UK, IJClab, CERN, Spain, INFN-LNF
ATF3 interests: UK, Germany, France, CERN, Spain
Other light-sources labs possible (DR)
WBS design entries to be checked

Sources
DESY, UK, CERN
IJCLab also, other groups also possible (FCC-ee, Dafne)

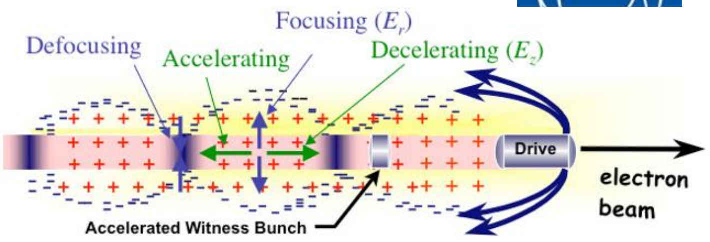
Towards TeV beams with new technology ?



1.7 GeV energy gain in 30 cm of pre-ionized Li vapor plasma.

2% energy spread

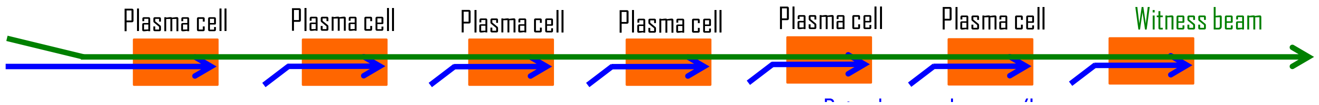
Up to 30% wake-to-bunch energy transfer efficiency (mean 18%).



A possible witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

Existing driver beams options :
Lasers: up to 40 J/pulse
Electron driver: up to 60 J/bunch
Proton driver: SPS 19 kJ/bunch, LHC 300 kJ/bunch

While GeV acceleration in plasmas has been demonstrated for with both lasers and electron beams, reaching TeV scales requires staging of many drivers and plasma cells. Challenging.



Current focus on "small scale" applications – for LCs a long way to go:
Electrons and Positrons, staging, energy efficiency, suitable beam-parameters and luminosity
However – disruptive technologies so (always) very important to pursue (and cost in this case likely less)

Mostly from E.Adli

Key points

Two linear collider projects are being pursued **(ILC and CLIC)** – with large collaborative effort

- Both are mature, have a clear physics case, are (each) affordable (similar in cost to LHC)
- CERN has a leading role in CLIC, but also taking a coordinating role in European planning for ILC.
- ILC next step would be a Pre-lab (2022-2025) before construction, CLIC is working on a timeline for updated baseline parameters and technology developments for the next European strategy ~2026

The developments (design, technical developments, tests of single elements or systems, industrial (pre)-productions – and also civil engineering, conventional systems, power and cost optimizations, are done **by international teams/collaborations**, usually led a major lab with special interest in the project but with world-wide participation since the technology developments and knowledge are transferable to/from **local or regional projects (as light-sources, FEL linacs, etc)**

Related: linear accelerator technology and development are currently strongly taking part outside particle physics – very beneficial in both directions and easy to show societal impact

Any linear collider facility is likely to host future machines. It can be **extended** – and/or equipped with new technology in the future …

Thanks to many colleagues from all over world, a few names mentioned directly in the slides, also several slides from Nuria Catalan, Walter Wuensch, Daniel Schulte, Shin Michizono, and many more directly or indirectly

ILC: https://linearcollider.org
CLIC: https://clic.cern