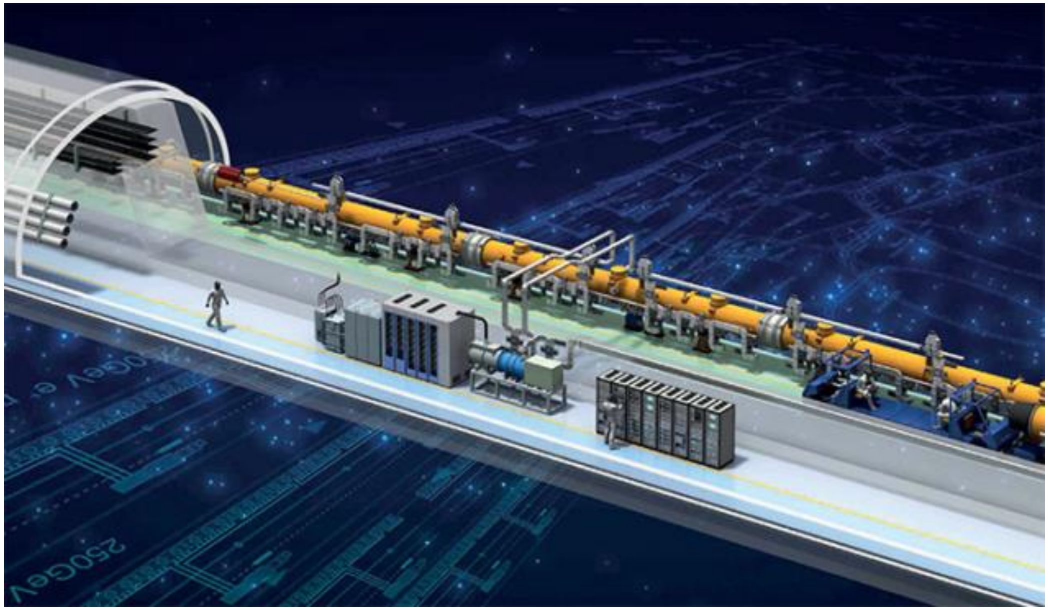
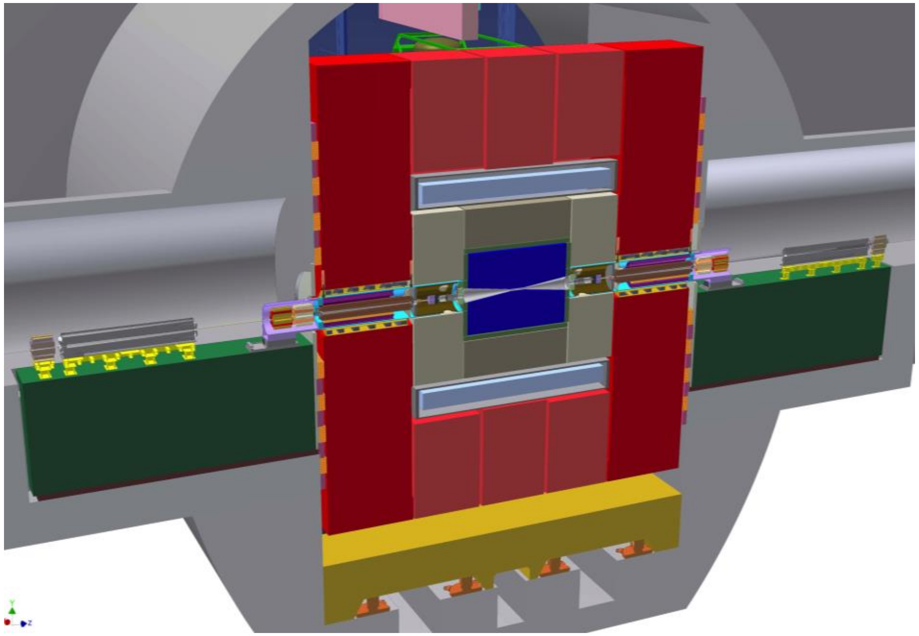
Future High Energy Linear Colliders

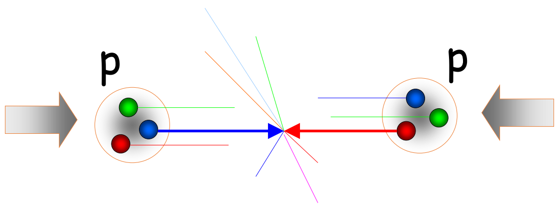
Louis Rinolfi

CERN





Hadrons versus leptons colliders

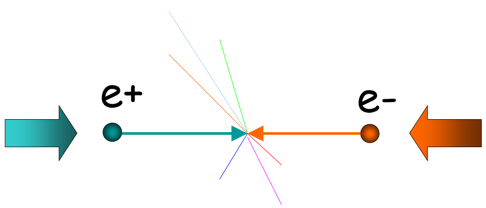


hadron collider => frontier of physics

- discovery machine
- collisions of quarks
- not all nucleon energy available in collision
- huge background

Limited by the dipole field available

p (GeV/c) ≈ 0.3 B (T) ρ (m)



lepton collider => precision physics

- study machine
- elementary particles collisions
- well defined CM energy
- polarization possible

Limited by the synchrotron radiation

W (eV) ≈ E^4 (GeV) / ρ (m)

Brief history of high energy linear colliders $e^+ e^-$

1985: **CLIC =** CERN Linear Collider **=>** Compact Linear Collider

1989: **SLC = Stanford Linear Collider**
Start operation with the beam

1995: **Six linear colliders studies at high energy, in parallel:**

=> TESLA	(1.3 GHz, superconducting)	DESY (Germany)
=> SBLC	(3 GHz, normal conducting)	DESY (Germany)
=> NLC	(11.4 GHz, normal conducting)	SLAC (California)
=> JLC	(11.4 GHz, normal conducting)	KEK (Japan)
=> VLEPP	(14 GHz, normal conducting)	Novosibirsk (Russia)
=> CLIC	(30 GHz, normal conducting)	CERN (Switzerland)

2004: International Technology Recommendation Panel selects the Superconducting RF technology versus room temperature technology
=> ILC (International Linear Collider) based on TESLA technolgy

2020: CLIC (12 GHz) and ILC (1.3 GHz) studies are ongoing

R&D on future high energy linear colliders:

ILC: 2004 to 2020: 16 years

CLIC: 1985 to 2020: 35 years

Recommendation (decision ?) expected this year 2020
if a linear collider should be constructed and which one

Vision 20 years ago
on future high energy colliders

LONGITUDINAL BEAM DYNAMICS

Application to synchrotron

CERN/PS 2000-008 (LP)

Course given at JUAS (Joint Universities Accelerator School) at Archamps (France)

January 2000

The milestones with a possible future scenario are given below:

1989: SLC first beam (50 GeV)

1989: LEP first beam (45 GeV)

1998: End of SLC (50 GeV with polarised electrons)

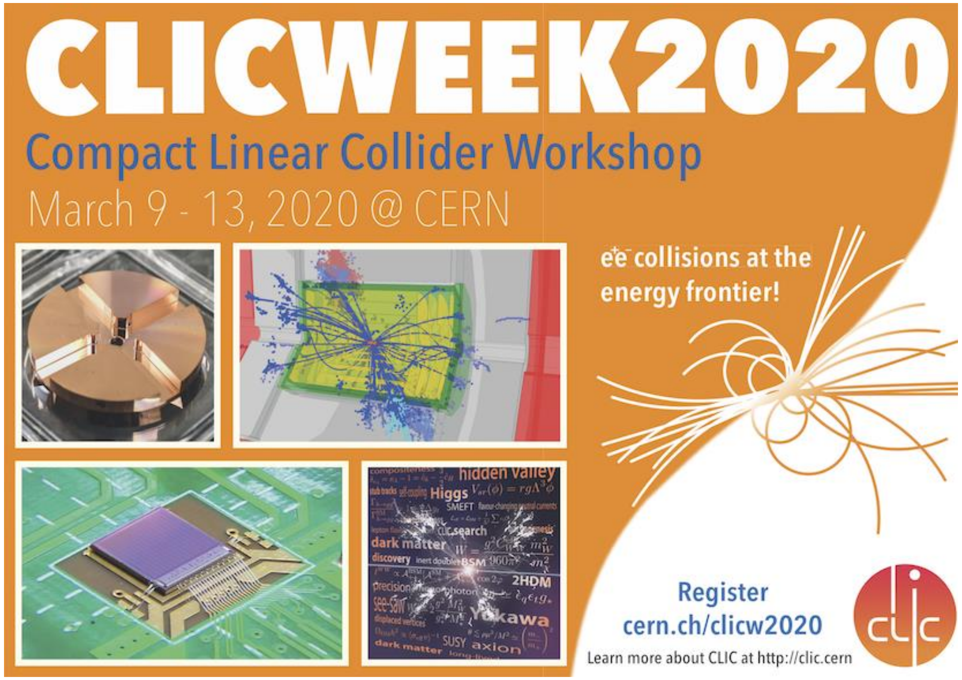
2000: End of LEP (104 GeV)

2005: LHC first beam p^+/p^+ (7 TeV)) (approved in 1994) → First beam 2010

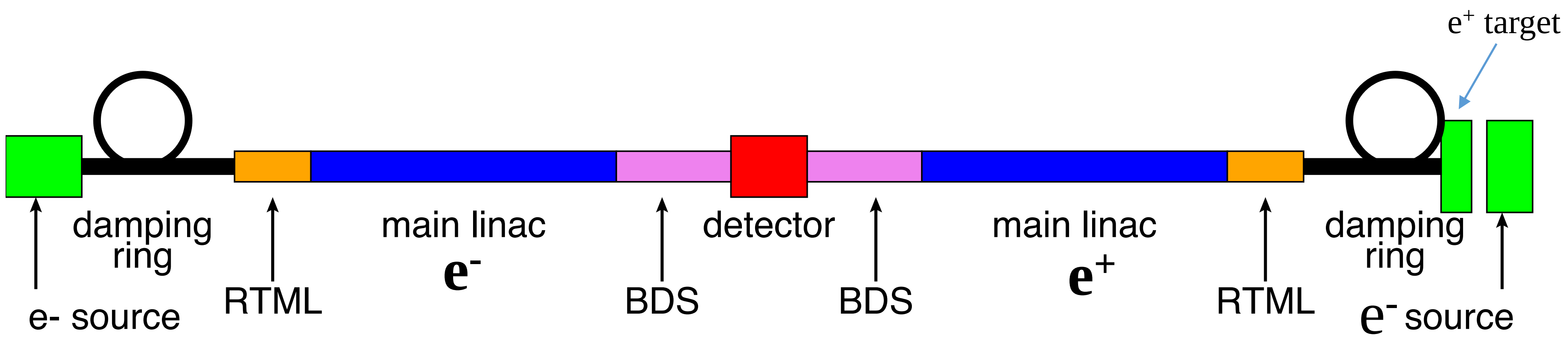
2010: Linear Collider e^-/e^+ (up to 3 TeV) (?) → Decision in 2020 hopefully

2030: Muons Collider μ^-/μ^+ (?) → R&D still for a long time

Workshops on high energy linear colliders



Basic Linear Collider



Reach the highest collision energy

Reach the highest luminosity

With a reduced power consumption and a minimum cost

BDS = Beam Delivery System
RTML = Return To Main Linac

Energy center of mass for linear colliders

Energy (center of mass) $E_{cm} = 2\, F_{fill}\, L_{linac}\, G_{RF}$

MeV m MV/m

F_{fill} = Filling factor of the Linac; L_{linac} = Length of the linac; G_{RF} = accelerating gradient

Luminosity

Number of events = σ_{event} x $\int L(t)\,dt$

σ_{event} is the probability of producing a particular event
$\int L(t)\,dt$ is a measure of the total number of interactions
with L the instantaneous luminosity

The unit of the cross-section (σ_{event}) is the barn (1 barn = 10^{-28} m^2)
=> 1fb = 10^{-43} m^2

Basic expression for luminosity

$$L = \frac{n_b\ N^+ N^-\ f_{rep}}{4\pi\,\sigma_x\,\sigma_y}$$

L: $cm^{-2}\,s^{-1}$; f_{rep}: Hz; σ_x, σ_y: cm

n_b = number of bunches; N = number of particles per bunch; σ_x, σ_y = rms transverse beam sizes

Re-write luminosity for linear colliders

$$L = \frac{n_b \; N^+ N^- \; f_r}{4 \pi \sigma_x \sigma_y}$$

$$\mathcal{L} \propto H_D \; \frac{N}{\sigma_x} \; N n_b f_r \; \frac{1}{\sigma_y}$$

Luminosity spectrum (Physics) → $\frac{N}{\sigma_x}$

Beam current (Power and RF limits, beam stability) → $N n_b f_r$

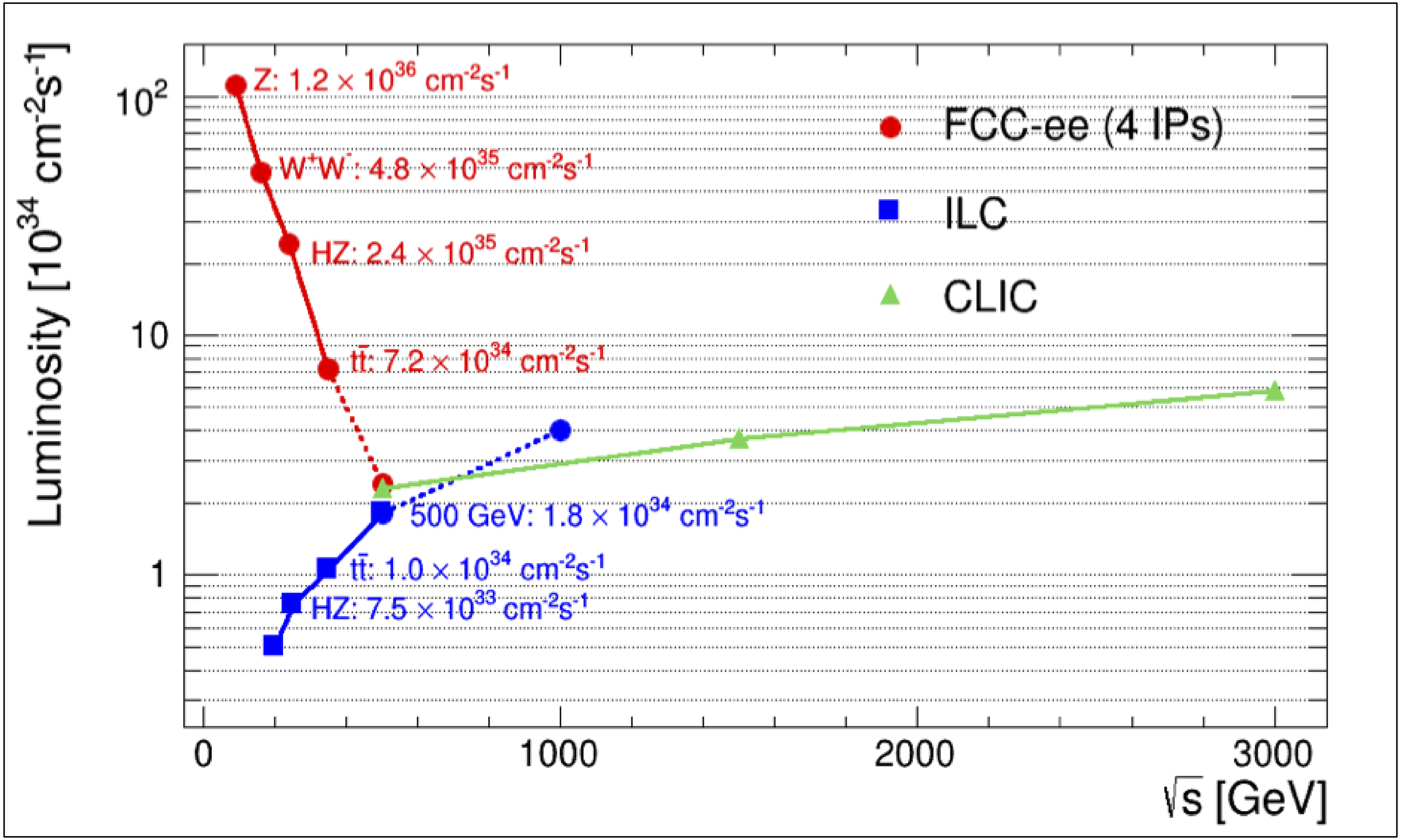
Beam Quality (Many systems) → $\frac{1}{\sigma_y}$

$$\mathcal{L} \propto \frac{P_{wall}}{E_{cm}} \; \frac{\eta}{\sigma_y} \; N_\gamma \; H_D$$

P_{wall} = total wall-plug power; E_{cm} = center mass energy;
η = efficiency of converting wall-plug power into beam power
$N\gamma$ = number of beamstrahlung photons emitted per e+/-
H_D = enhancement of luminosity due to the pinch effect during bunch crossing

Luminosity performance for e^+e^- colliders

D. Schulte



Note 1: Peak luminosity at SLC (92 GeV) was ~10^{30} cm^{-2}s^{-1}

Note2: Peak luminosity at LEP2 (209 GeV) was ~10^{32} cm^{-2}s^{-1}

SLC (Stanford Linear Collider) – California - USA

The first and only Linear Collider who was running with a beam
e^- (45.6 GeV) and e^+ (45.6 GeV)

3.2 km (2 miles) S-band linac

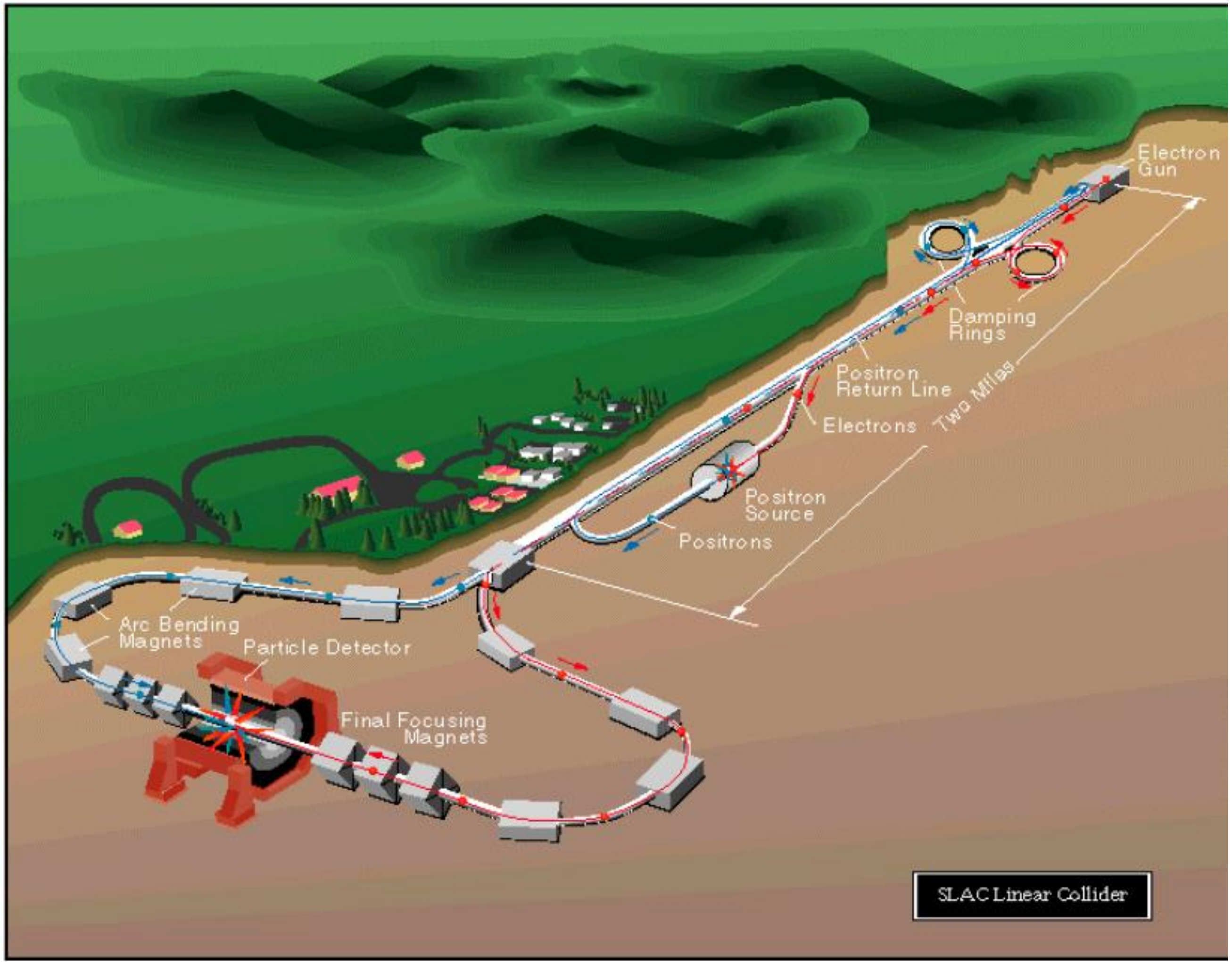
Operation: 1989-1998

SLC (Stanford Linear Collider) – California - USA

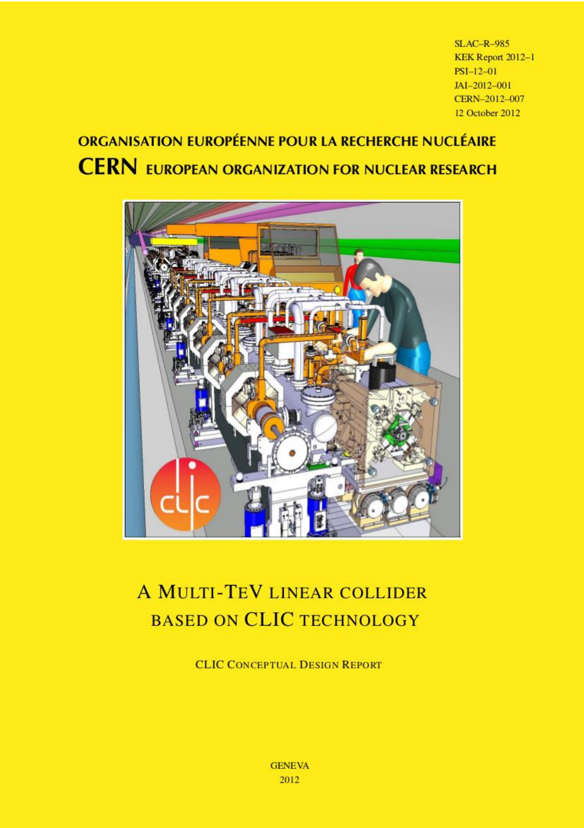
2 experiments: MARK II, SLD
Peak Luminosity: $2x10^{30} cm^{-2} s^{-1}$

Final beam energy
E_{cm} = 92 GeV

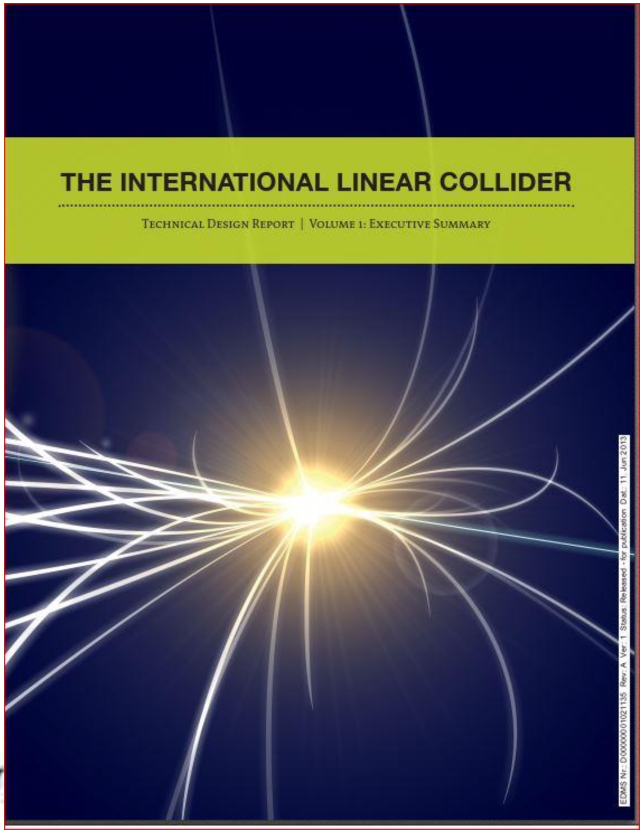
80% electron-beam polarization



The Linear Collider Collaboration



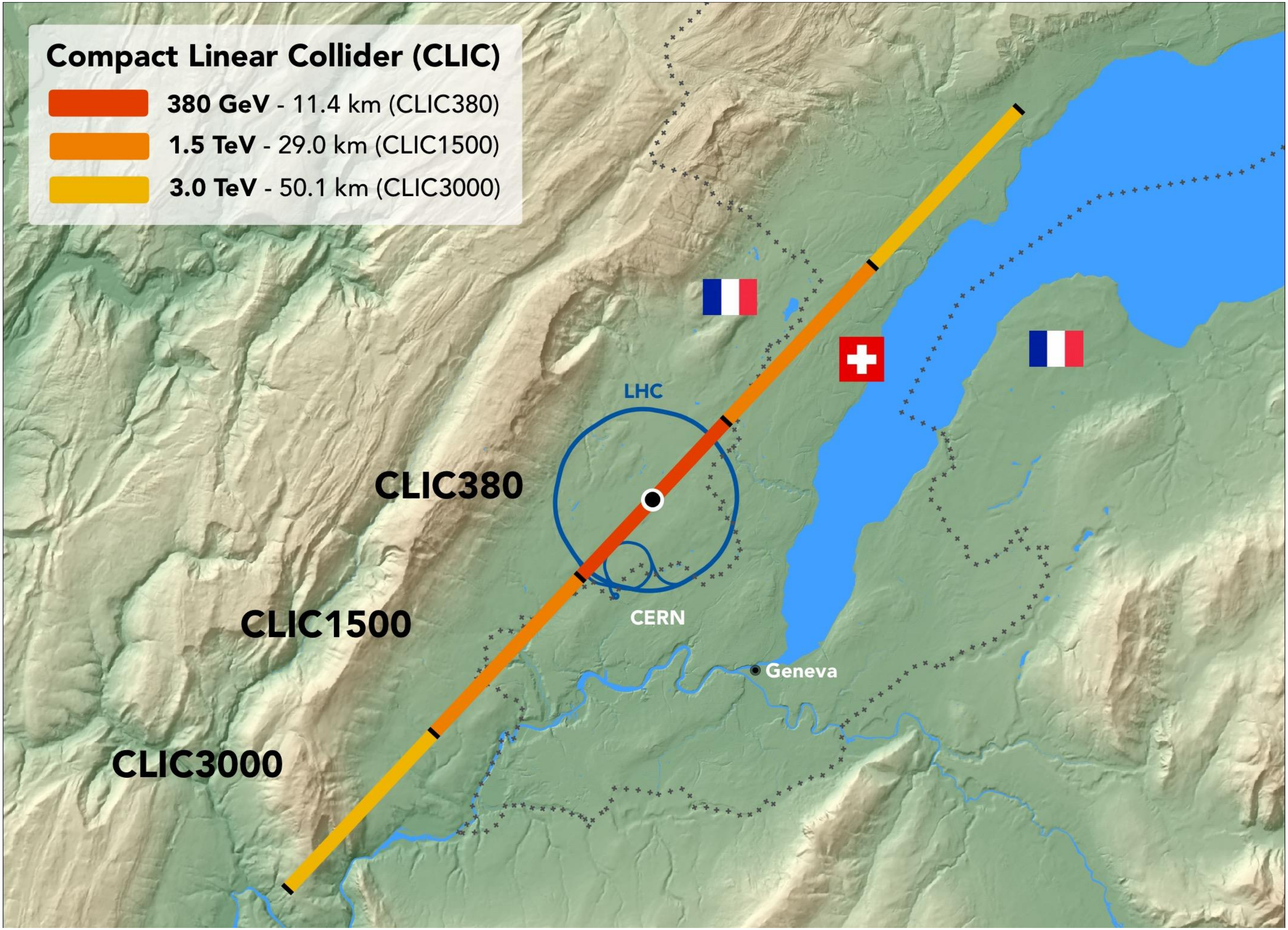
CLIC Conceptual Design Report published in 2012



ILC Technical Design Report published in 2013

LINEAR COLLIDER COLLABORATION 2012

CLIC at CERN



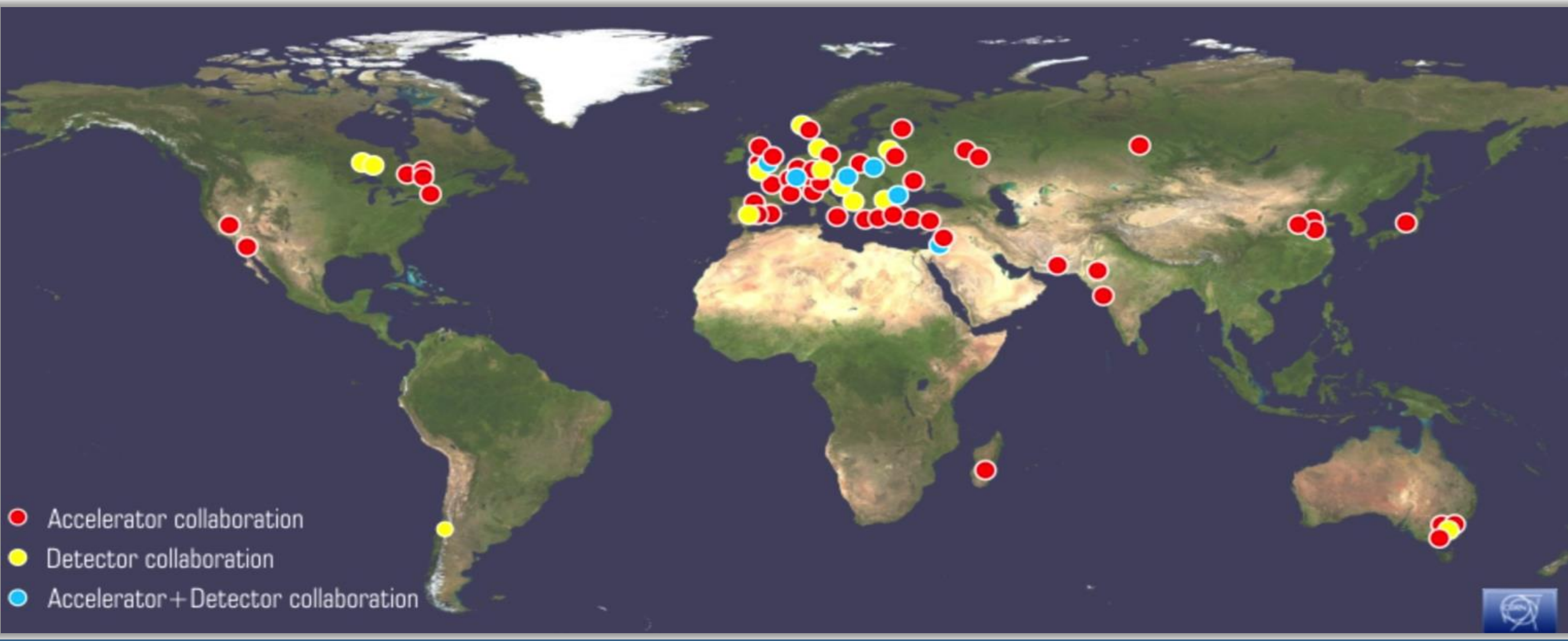
Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

CLIC Collaborations

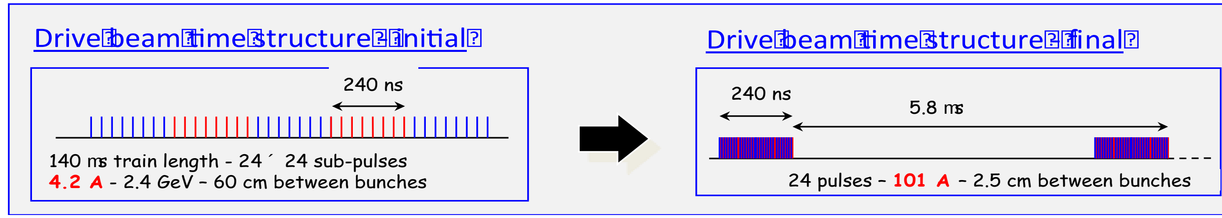
A. Latina

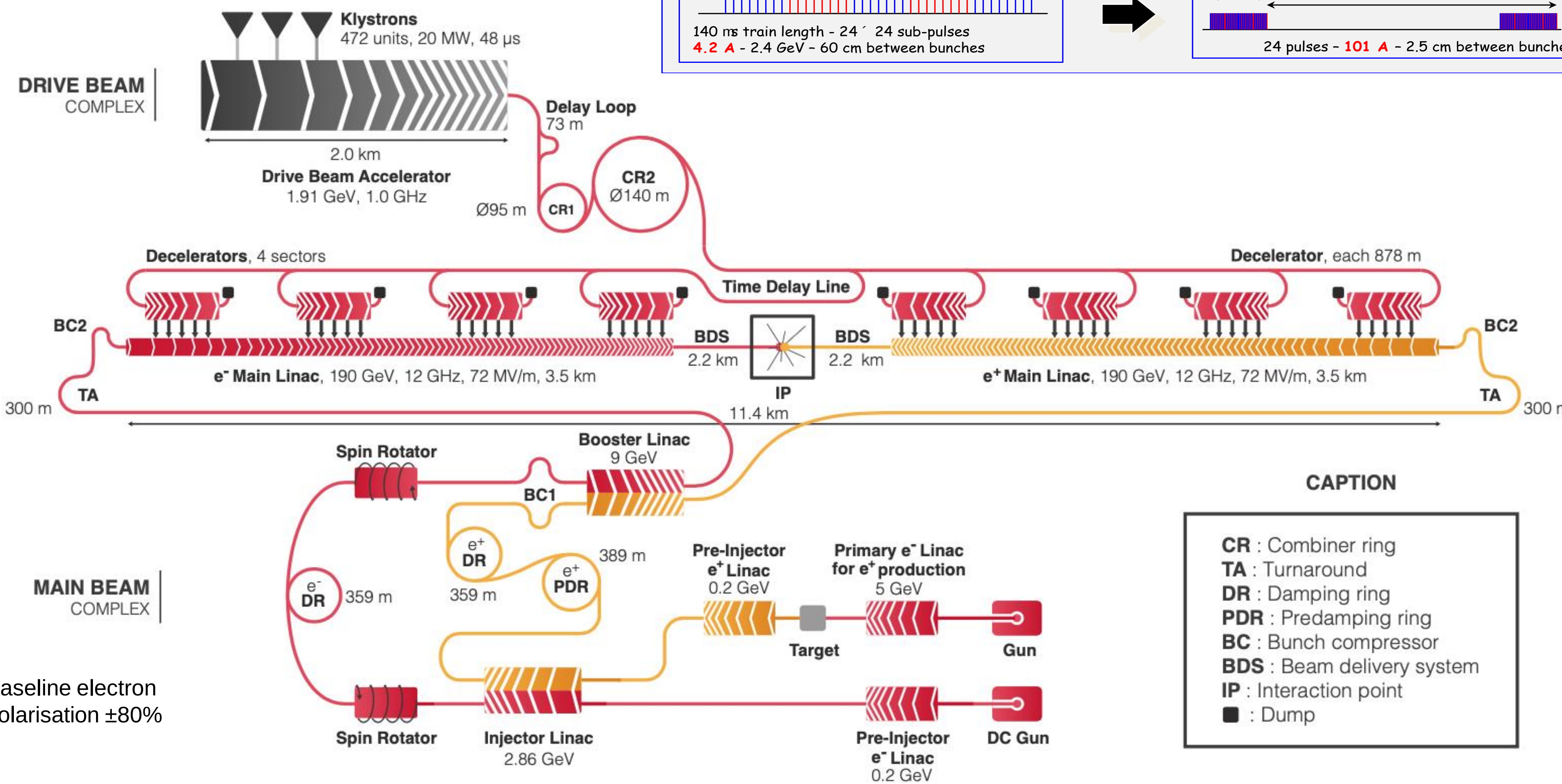
CLIC accelerator collaboration
70 institutes from **32 countries**

CLIC detector and physics (CLICdp)
30 institutes from **18 countries**



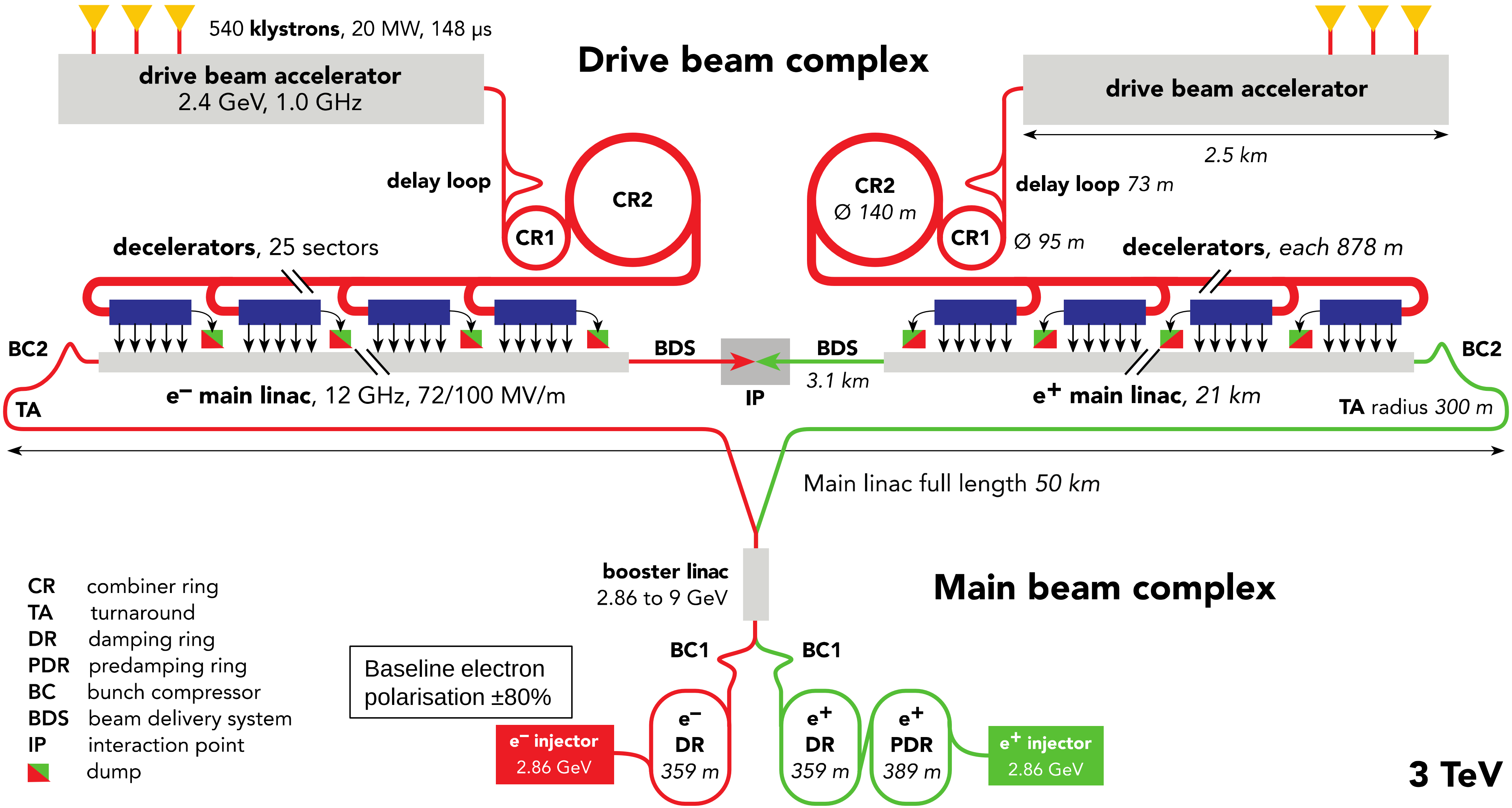
CLIC 380 GeV layout and power generation





Baseline electron polarisation ±80%

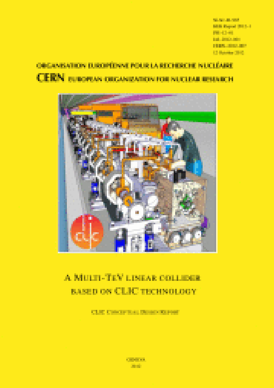
CLIC layout – 3TeV

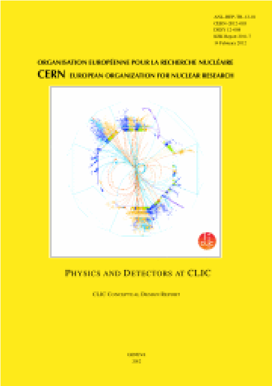


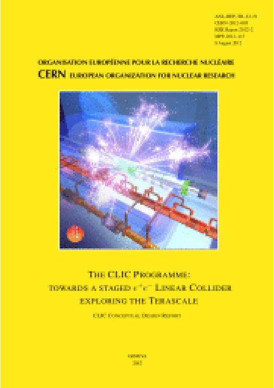
CLIC parameters

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	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	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)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

CLIC

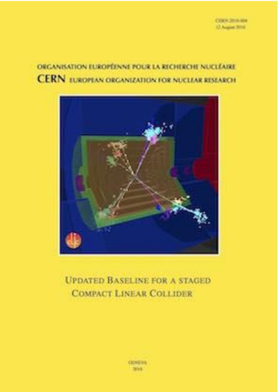






Conceptual Design Report CDR 2012

https://cds.cern.ch/record/1500095
https://cds.cern.ch/record/1425915
https://cds.cern.ch/record/1475225



Updated Staging Baseline 2016

http://dx.doi.org/10.5170/CERN-2016-004

Project Implementation Plan 2018

CLIC roadmap

S. Stapnes

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

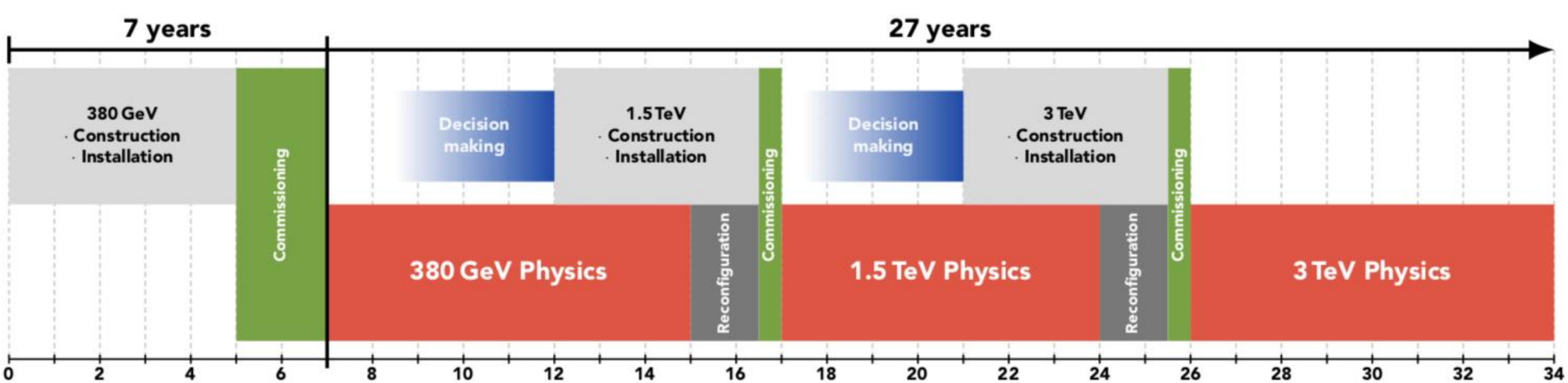
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

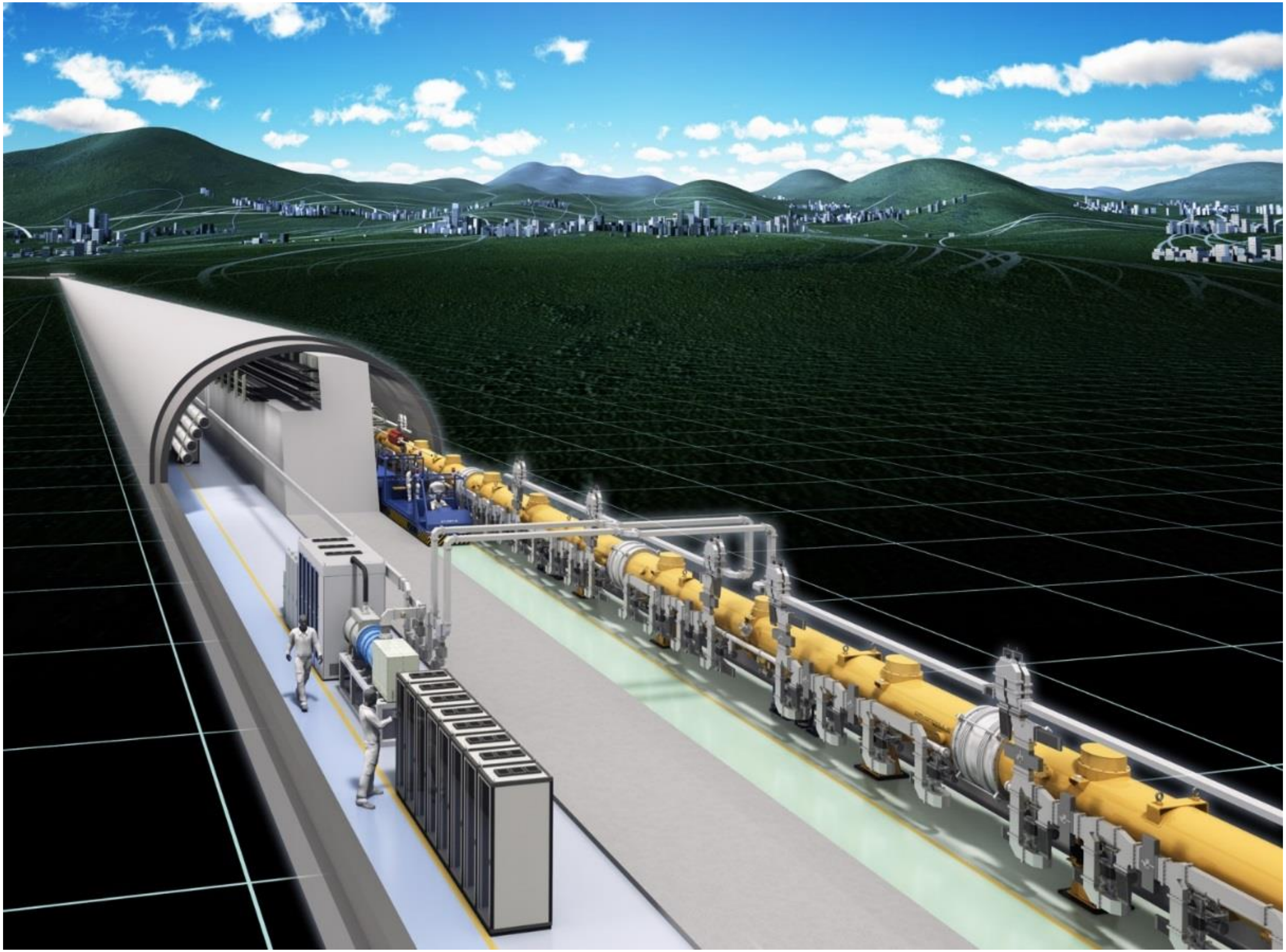
Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

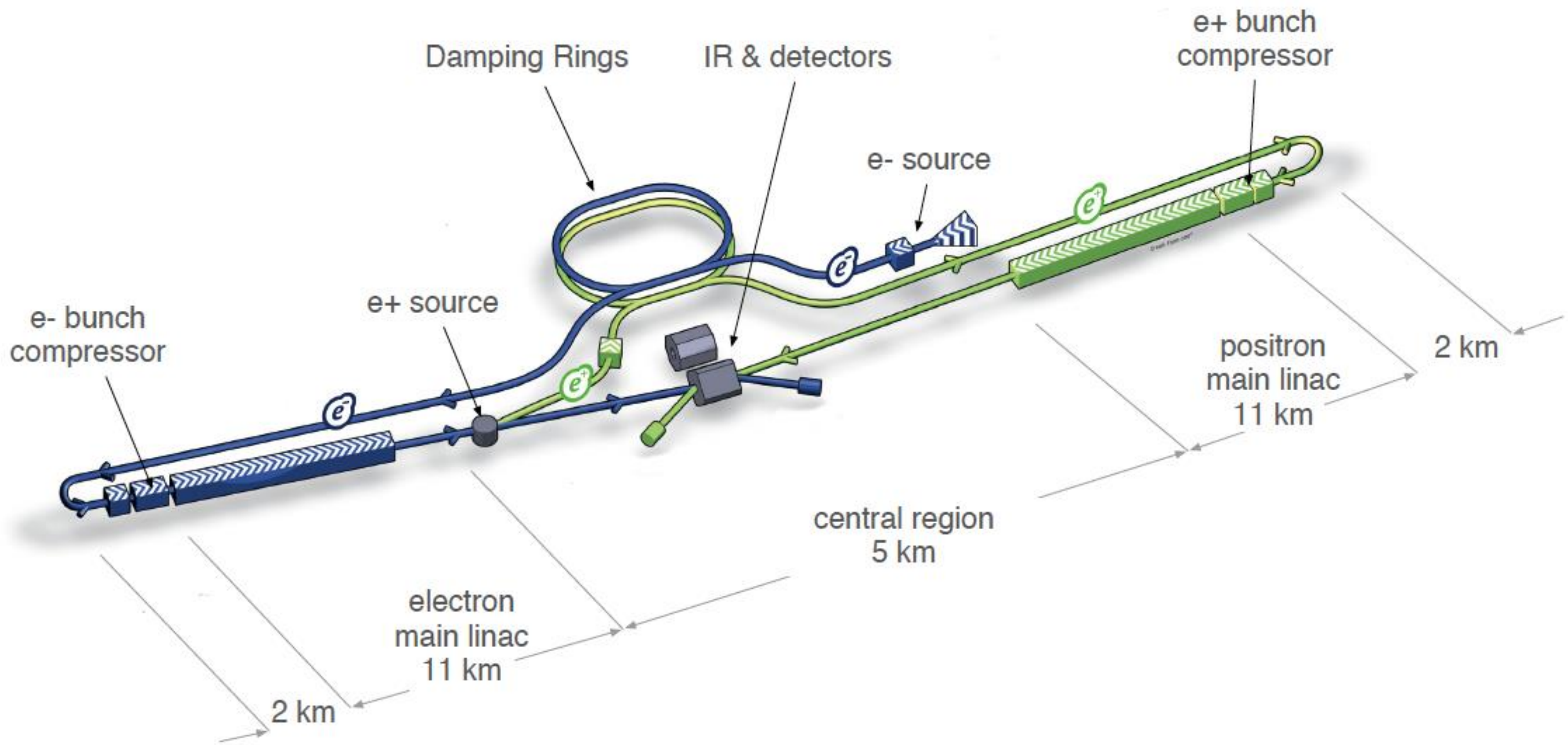


ILC in Japan



ILC Site and Collaborations

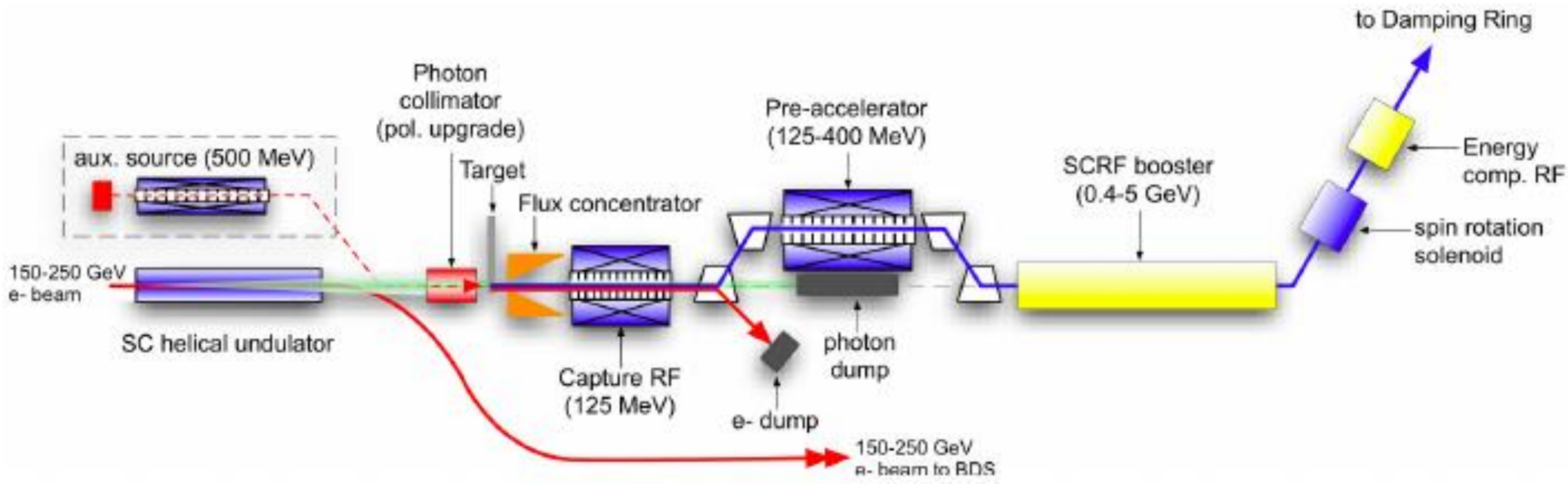
ILC layout



8370 superconducting cavities in 930 cryo-modules
Gradient 31.5 MV/m RF Frequency 1.3 GHz
Beam polarization: e- 80%, e+ 30%

ILC positron source

The main electron beam (> 125 GeV) should go through a SC helical undulator to produce polarized photons



The gamma-ray beam is sent onto a target to produce e+e- pairs.

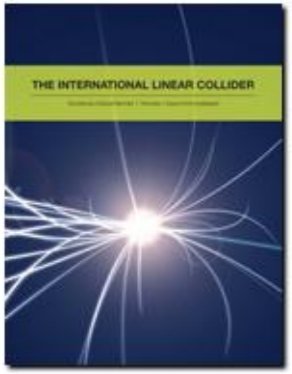
A e+ beam polarization (> 30 %) can be obtained.

ILC parameters

Quantity	Unit	ILC250	ILC500	ILC1000
Centre-of-mass energy	GeV	250	500	1000
Luminosity	$10^{34}cm^{-2}s^{-1}$	1.35	1.8	4.9
Repetition frequency	Hz	5	5	4
Bunches per pulse	1	1312	1312	2450
Bunch population	10^{10} e-	2	2	1.74
Linac bunch interval	ns	554	554	366
Beam current in pulse	mA	5.8	5.8	7.6
Beam pulse duration	s	727	727	897
Average beam power	MW	5.3	10.5	27.2
Norm. hor. emitt. at IP	μm	5	10	10
Norm. vert. emitt. at IP	nm	35	35	35
RMS hor. beam size at IP	nm	516	474	335
RMS vert. beam size at IP	nm	7.7	5.9	2.7
Site AC power	MW	129	163	300
Site length	km	20.5	31	40

ILC TDR

Volume 1 - Executive Summary



Download the pdf (9.5 MB)

Volume 2 - Physics

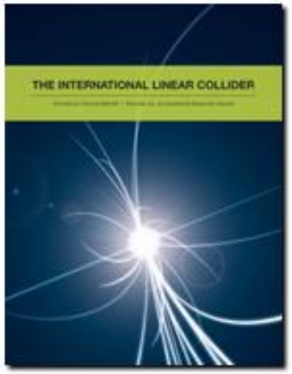
Download the pdf (9.5 MB)

Volume 3 - Accelerator

Part I:
R&D in the Technical Design Phase

Download the pdf (91 MB)

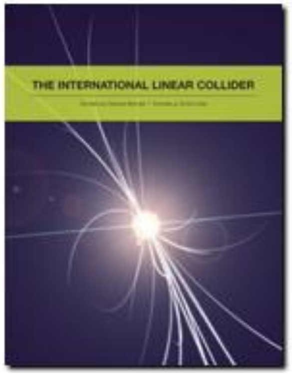
Volume 3 - Accelerator



Part II:
Baseline Design

Download the pdf (72 MB)

Volume 4 - Detectors



Download the pdf (66 MB)

From Design to Reality

Download the pdf (5.5 MB)
Visit the web site

Extendability built-in

Going fom 250 GeV to 1 TeV

ILC Site & Infrastructure

- 67 km maximal length of tunnel
- Beam dumps, etc designed for 1 TeV operation
- Overall recommended ILC power limit for the 1 TeV ILC : 300 MW

Luminosity upgrades

- Straightforward: Increasing the number of bunches from 1312 to 2624
- Power Increase 129 MW → 164 MW

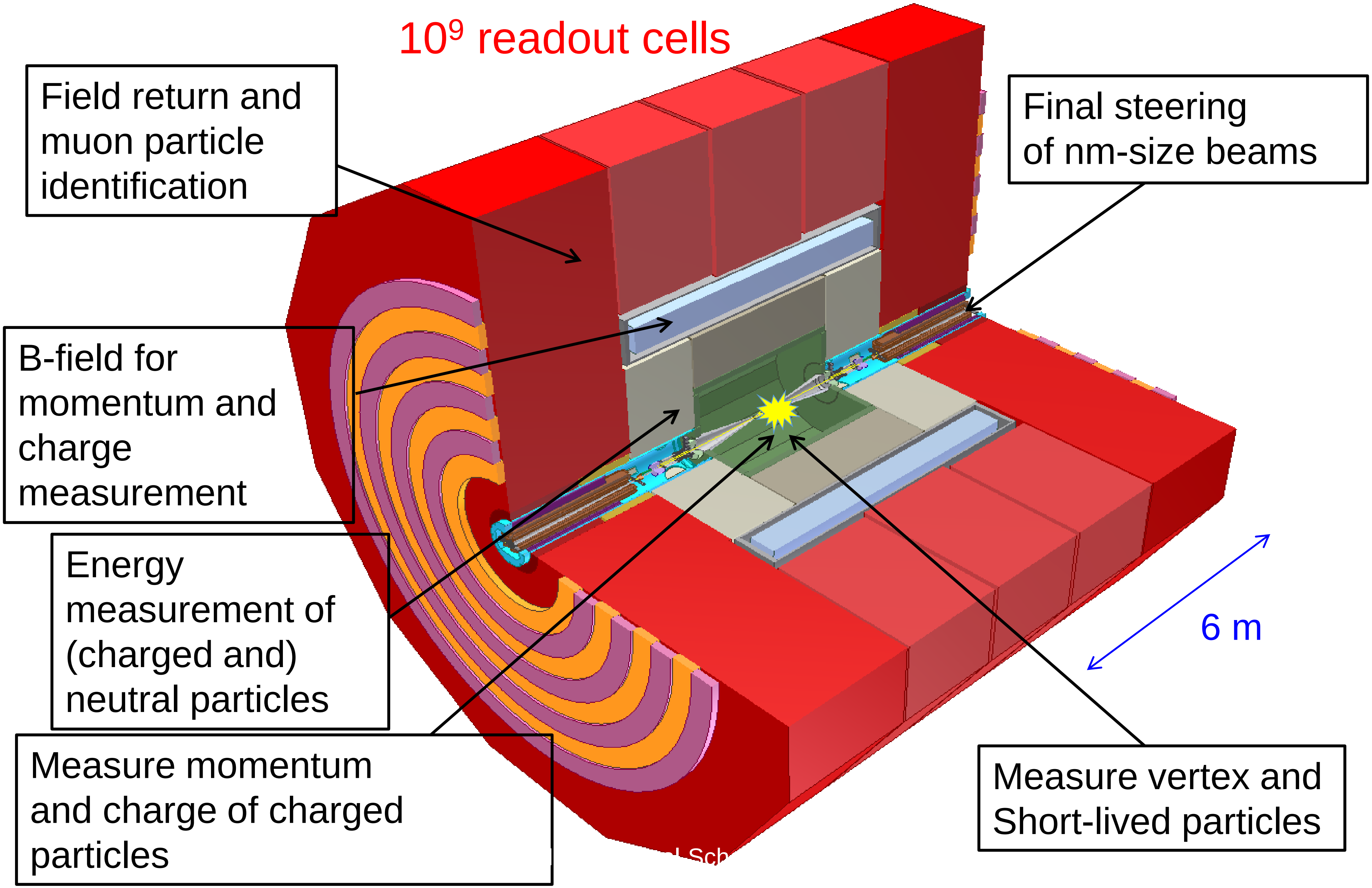
Energy upgrades

- Energy upgrades to 350 GeV ($t\bar{t}$ threshold) and ~500 GeV being discussed
- 1 TeV for longer-term plan

DESY. | ILC |103rd Plenary ECFA |Marcel Stanitzki

Linear Collider Experiment

L. Linssen



Comparison

Parameter	Symbol [unit]	SLC	ILC	CLIC
Centre of mass energy	E_{cm} [GeV]	92	500	3000
luminosity	L [$10^{34}cm^{-2}s^{-1}$]	0.0003	1.8	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	0.0003	1	2
Gradient	G [MV/m]	20	31.5	100
Particles per bunch	N [10^9]	37	20	3.72
Bunch length	σ_z [μm]	1000	300	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	474/5.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	3000	35	20
Bunches per pulse	n_b	1	1312	312
Distance between bunches	Δz [mm]	-	554	0.5
Repetition rate	f_r [Hz]	120	5	50

Why a future collider and why at CERN?

Gianotti / 14/01/2020

Physics case is very strong

- Higgs boson is a guaranteed deliverable: related to the most obscure and problematic sector of the Standard Model; it carries special quantum numbers and a new type of interaction
  → unique door into new physics, which can only be studied at colliders

- Unprecedented direct/indirect reach for new physics: up to ~100 TeV (details depend on whether it's CLIC or FCC). Note: no guarantee of discovery of new particles (*)
  (*) "*When theorists are more confused, it's time for more, not less, experiments*", Nima Arkani-Hamed.

- Precise measurements, as well as exclusion of unfounded theoretical scenarios, are as crucial as discoveries to make progress and redirect our theoretical thoughts and experimental exploration towards the most promising directions.

CERN should host an ambitious future collider

- strong scientific case for it (see above)
- to maintain Europe's leading role in fundamental physics and related technologies
- CERN has unique assets:
  - powerful infrastructure and outstanding personnel expertise, built over several decades
  - commitment of Member States → long-term budget stability
  - mission and tradition of international cooperation and open science, from founding Convention

→ essential pre-requisites for a large, global project

T. Omori / KEK

ILC 31st January 2020

This morning in Japan, the MEXT Minister and the Minister of State for Science and Technology Policy have spoken to the press about the ILC. You can read our translation below.

Translation of Q&A with Hon. Koichi Hagiuda,

Journalist:

Yesterday, the Science Council of Japan published its Master Plan for large infrastructure research projects, compiled every three years. The International Linear Collider (ILC) project, currently being promoted to be hosted in the Tohoku Region, was not selected to be among the high-priority projects. Please tell us about how you regard this result and the plan going forward.

Minister:

I understand that the ILC Project was not selected to be among the High-Priority Large Research Projects in the Master Plan 2020 published yesterday by the Science Council of Japan. This has been put together from the viewpoint of people representing the academic community, and we believe that it will serve as a reference for future discussions within the government. Being an international project, the ILC project requires broad support from both inside and outside the country. In light of the outcome of the Master Plan 2020, and observing the progress of other discussions such as the European Strategy for Particle Physics, we would like to carefully carry forward the discussions.

It should be stressed that the ILC project is not a domestic project that we can do alone, but it is an international project. It is often difficult to inform you of its prospects because the discussions of the financial cooperation from each country are yet to take place. For this reason, at this stage, I think that it is not so surprising that the ILC project was not included in the high-priority list.

We will cooperate firmly with international organizations. There are pending issues such as overall merits of the project, whether or not to host the project in Japan, and, if we decide in the affirmative, the location of the site. We would like to carefully examine these issues.

Other possible future linear colliders

LWFA = Laser Wake Field Accelerator
=> *Wakefields driven in plasma by intense laser beams*

PWFA = Plasma Wake Field Accelerator
=> *Wakefields driven in plasma by particle beams*

SWFA = Structure Wake Field Accelerator
=> *Wakefields driven in structures (*dielectric tubes*) by particle beams*

DLA = Dielectric Laser Accelerator
=> *Wakefields driven in dielectric structures by short-pulse laser*

https://agenda.infn.it/event/17304/overview

A study for a future linear collider

Based on accelerator gradient
> 1 GV/m

ALEGRO for Advanced LinEar collider study GROup, has been set up to coordinate preparation of **proposal for an Advanced Linear Collider in multi-TeV energy range**.

The Advanced and Novel Accelerator (ANA) community must meet towards ALIC, the Advanced LInear Collider (30 TeV in 2035).

Workshop at CERN 26-29 March 2019

https://indico.cern.ch/event/732810/overview

A muon collider as an optimal alternative

Carlo Rubbia / INFN /CERN / 2018

Muons combine a "point-like" electron-like nature with a larger mass immune to radiation.

A $\mu+\mu-$ collider is therefore highly preferable because of its small dimension which permits the utilization of an existing site.

However it demands a substantial R&D in order to produce adequate compression in 6D phase space of the muon beams.

To this effect an **additional experimental program based on a small Cooling Ring should be initiated.**

Muon Collider Workshop CERN

October 9-11, 2019

https://indico.cern.ch/event/845054/timetable/

Some links

JENAS

European Committee for Future Accelerators (ECFA), the Nuclear Physics European Collaboration Committee (NuPECC), and the Astroparticle Physics European Consortium (APPEC)

https://jenas-2019.lal.in2p3.fr/

Physics Beyond Colliders

https://cerncourier.com/a/physics-beyond-colliders-initiative-presents-main-findings/

European Strategy for Particle Physics

https://europeanstrategy.cern/

Final recommendations in May 2020

Today vision

For future high energy colliders: Three essential parameters:
1) increase the luminosity as much as possible
2) reduce the power consumption
3) reduce the cost

Higgs factory: what is the best implementation ? Linear vs circular.

What is the best path for the high intensity frontier vs. the high-energy frontier ?

Energy management for the future high-power accelerators ?
=> energy efficiency and sustainability are crucial for upcoming projects

Conclusion

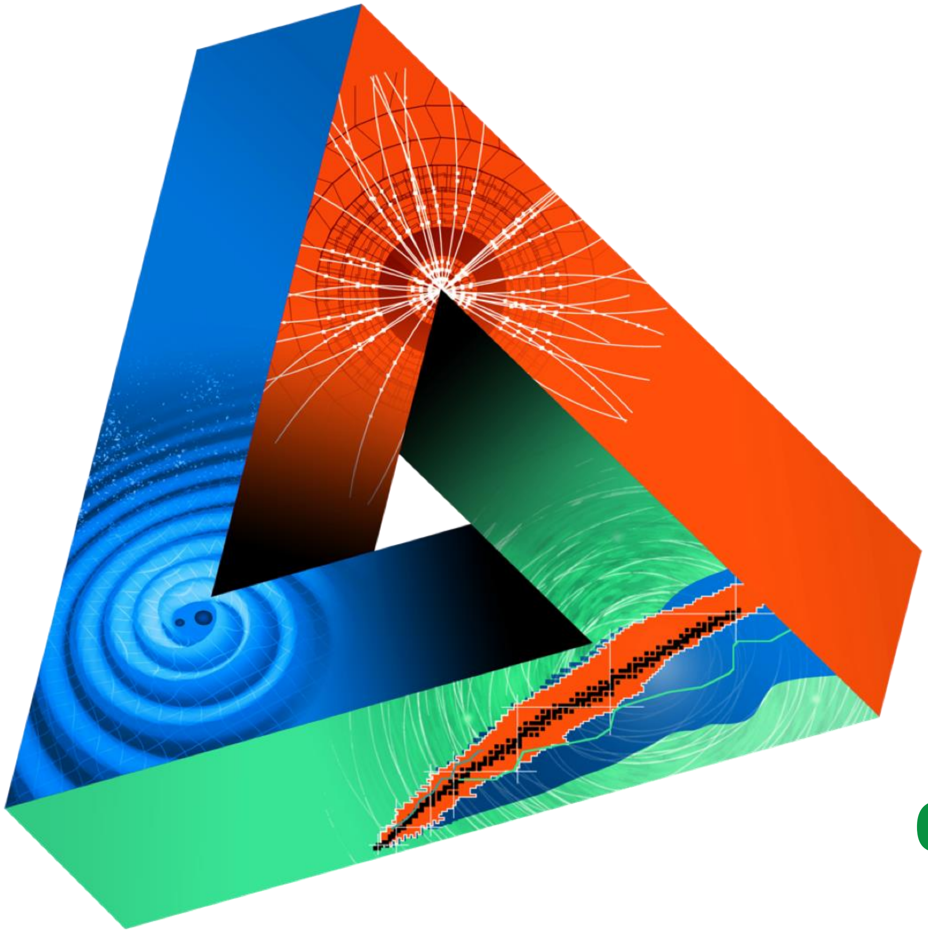
Fabiola Gianotti

PUZZLING: the SM is not a complete theory of particle physics, as several outstanding questions remain that cannot be explained within the SM

What is the composition of dark matter (~25% of the Universe) ?
What is the cause of the Universe's accelerated expansion (today: dark energy?; primordial: inflation?)
What is the origin of neutrino masses and oscillations ?
Why 3 fermion families ? Why do neutral leptons, charged leptons and quarks behave differently?
What is the origin of the matter-antimatter asymmetry in the Universe ?
Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?
Why is Gravity so weak ?
Etc. etc.

These questions require NEW PHYSICS
→ but where is the new physics in terms of E-scale and couplings to SM particles ???

The future of high energy physic is very exciting !!!



You
ESIPAP and JUAS students are the future machine designers and builders

Not impossibly tribal A Penrose triangle was used to symbolise how astroparticle, particle and nuclear physics are intertwined. Credit: JENAS

Spares

CLIC Cost

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**

ILC Cost

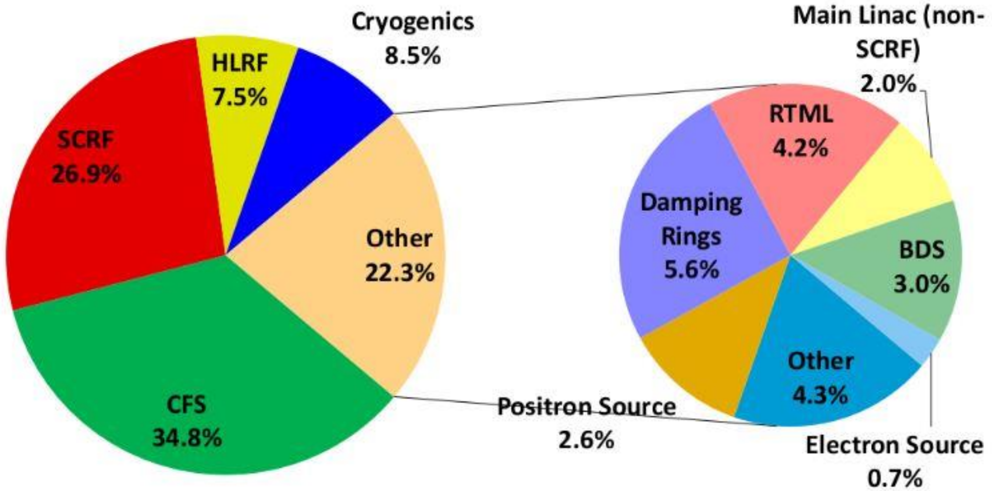
Accelerator Costing

ILC250 Baseline

ILC costing model

- Established for the TDR
  - Including set-up and learning curves
- TDR (500 GeV)
  - 7.98 Billion US-$
- Updates since
  - All experiences from the E-XFEL, ESS, LCLS-II
  - Higher Gradient Cavities
- ILC 250 baseline
  - 40% cost reduction
  - 1/3 Construction (CFS)

Primary cost drivers for the ILC



DESY. | ILC |103[rd] Plenary ECFA |Marcel Stanitzki   Page 19

Main challenges of a future collider

Gianotti / 14/01/2020

Financial feasibility

Cost of tunnel + first-stage machine (e.g. CLIC at 380 GeV: ~6 BCHF; FCC-ee: ~10 BCHF):
→ cannot be funded only from CERN's (constant) budget → need additional/innovative sources

Governance model for an unprecedented, global project

To be developed with international partners right from the beginning.

Technical and administrative feasibility of the tunnel

- ❑ highly-populated area; two countries with different legislative frameworks
- ❑ land expropriation and reclassification
- ❑ need to gain support of local populations (with a view to public surveys and debates)
- ❑ environmental aspects

Technologies of machine and experiments

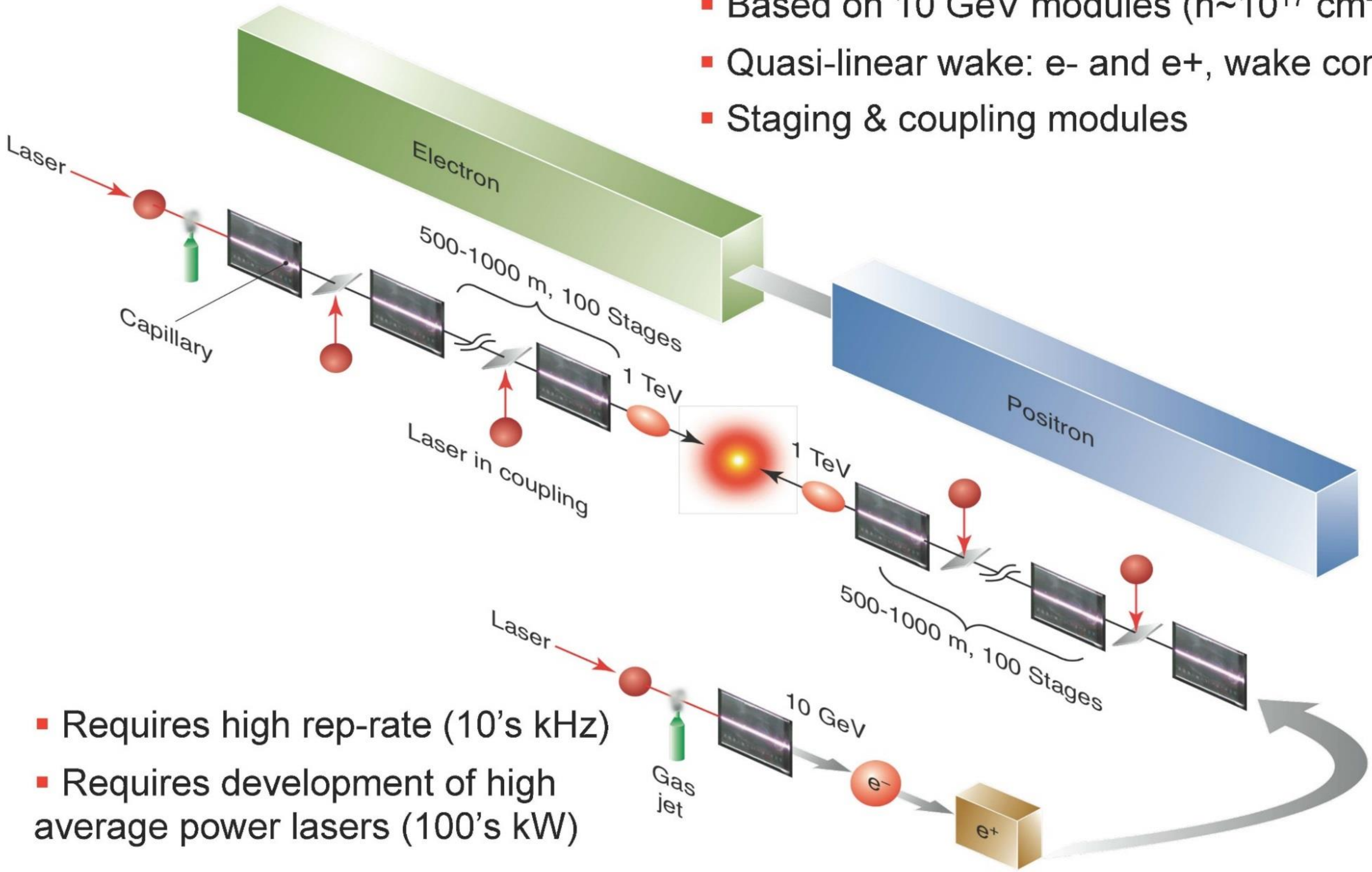
- ❑ huge challenges, but under control of our scientific community → "easier"
- ❑ environmental aspects (aim at "green collider"): power, energy, cooling, gases, etc.

Gathering political and societal support

→ requires "political work" and vast communication campaign for "consensus building" with governments and other authorities, scientists from other fields, general public (KT, Science Gateway, VIP and other visits, …)

Laser Wake Field linear collider

- Based on 10 GeV modules (n~10^{17} cm^{-3})
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

W.P. Leemans & E. Esarey, Physics Today, March 2009

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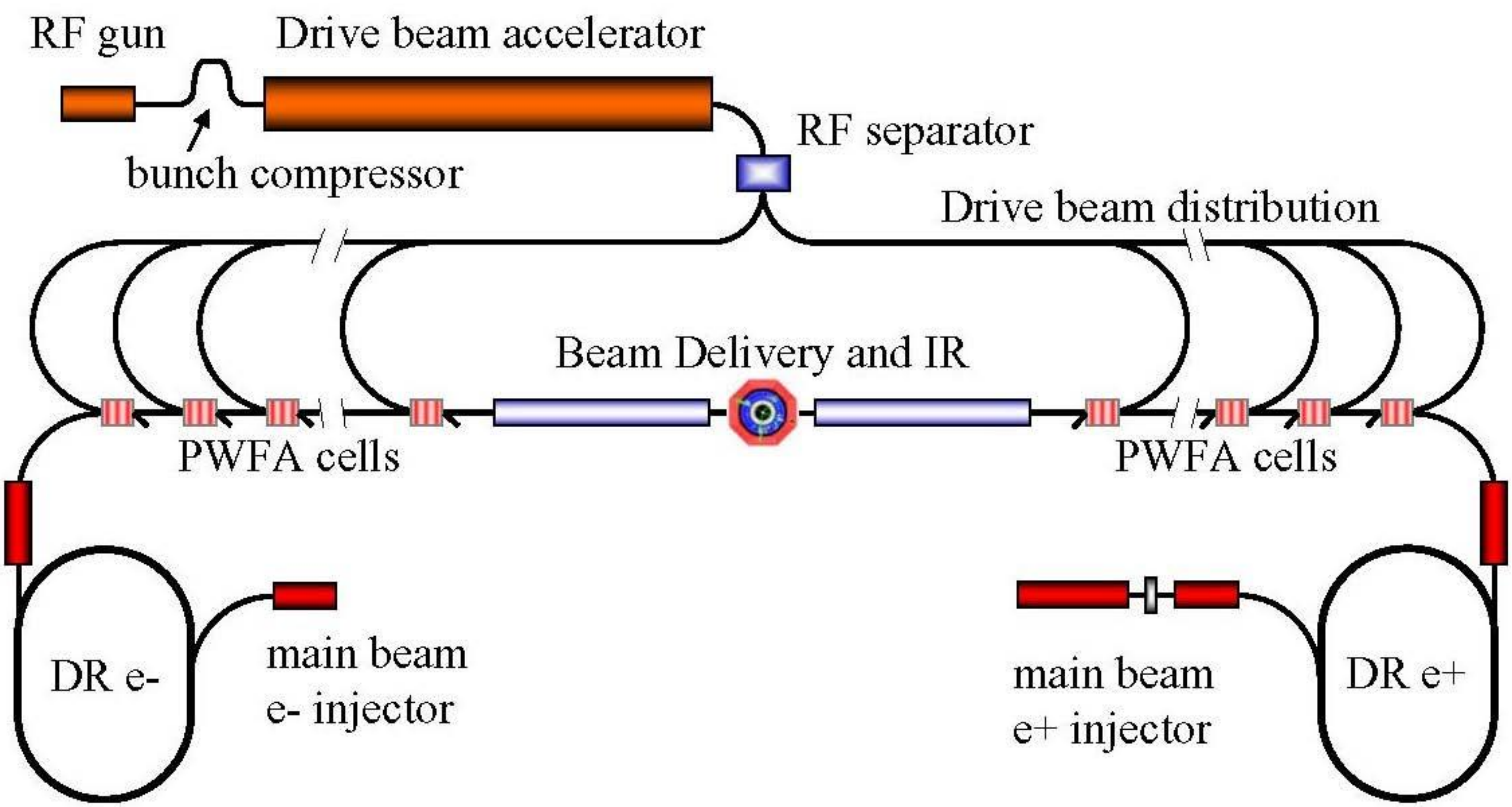
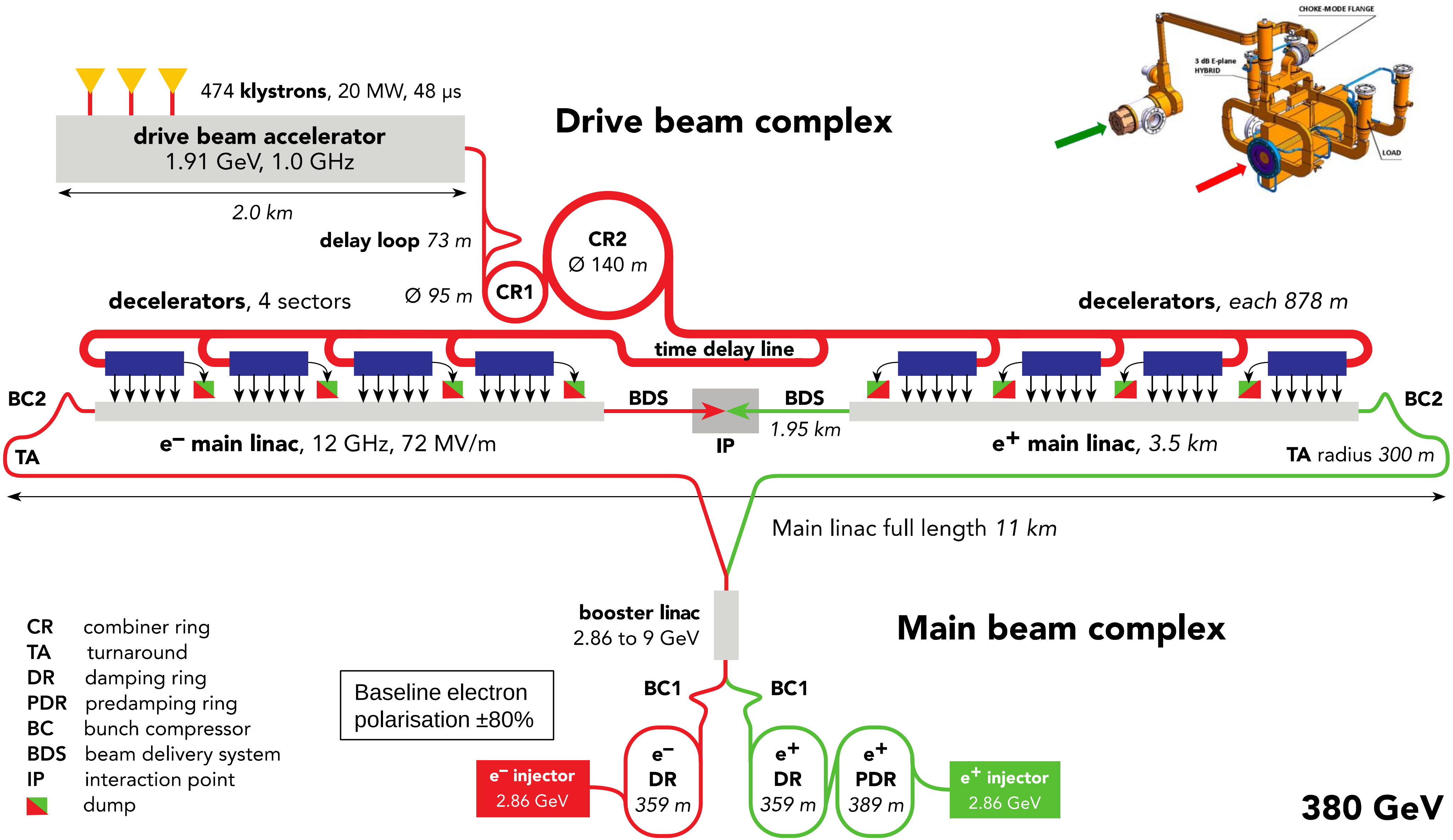
Plasma Wake Field linear collider



Concept for a multi-stage PWFA-based Linear Collider (A. Seryi, T. Raubenheimer et al., 2009)

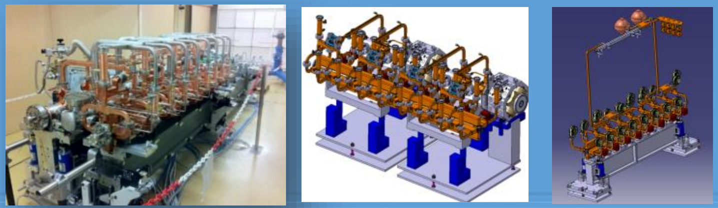
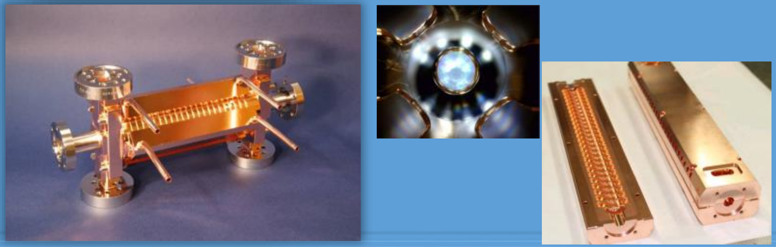
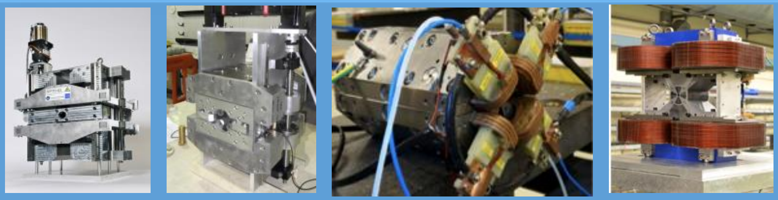
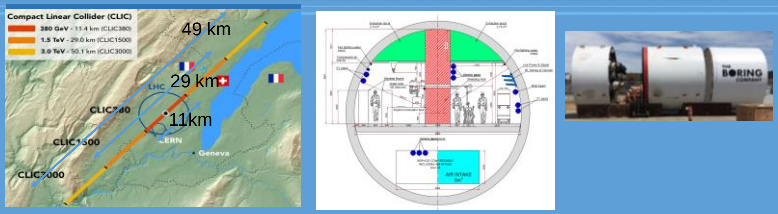
CLIC layout – 380 GeV



Applications of X-band linacs

SLAC	NLCTA+XTA	2x50 MW, 11 GHz	Operational
Eindhoven	Compact Compton source - 25 MeV	6 MW	Procurement
CERN	CLEAR – 50 MeV (from Xbox-1)	50 MW	Preparation
Tsinghua	Thompson source upgrade – 50 MeV	50 MW	Design
Frascati	XFEL, injector to plasma - 1 GeV	8x50 MW	CDR
Collaboration	CompactLight – 6 GeV	30x50 MW	Design Study
CERN	LDMX – 3.5 GeV	24x50 MW	Letter of intent submitted
Groningen	1.4 GEV XFEL Accelerator - 1.4 GeV		NL roadmap
CERN	CLIC – 380 GeV	5800x50 MW	CDR

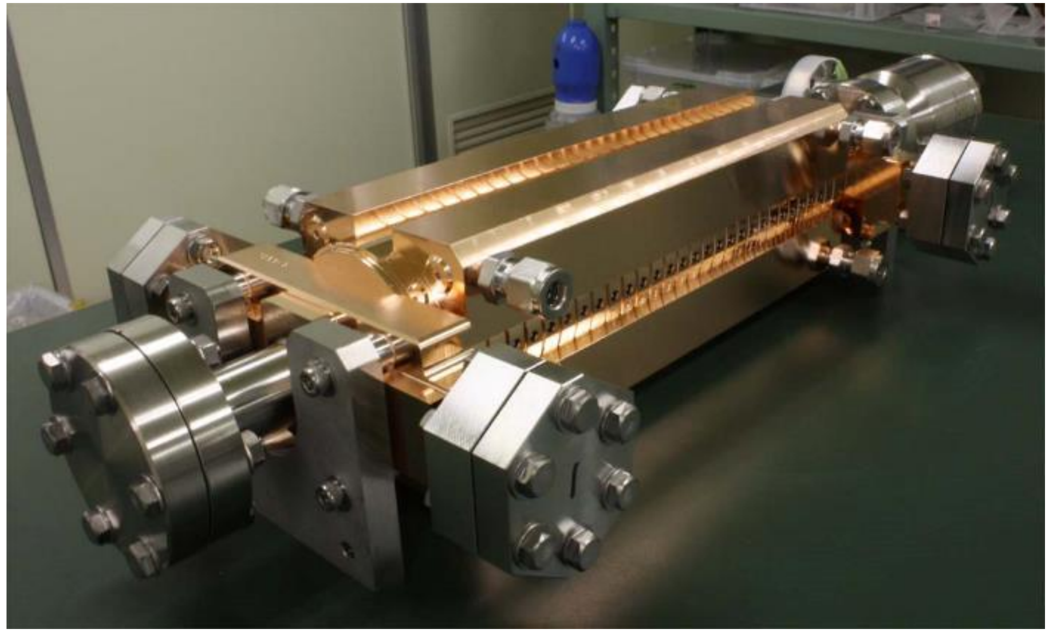
Technical developments

Modules (drive-beam, klystron type)		Final modules, from revised designs to industrial modules
Optimized structures		Use existing test-stands for testing, increase manufacturability, brazed, halves, conditioning
Klystrons and Modulators		Efficiency and costs, significant gains possible for efficiency, industrial cost-models and optimisation
Magnets		Permanent magnets, industrial capabilities
Civil engineering, infrastructure		Detailed site layout and CE/infrastructure designs

CLIC accelerating structure

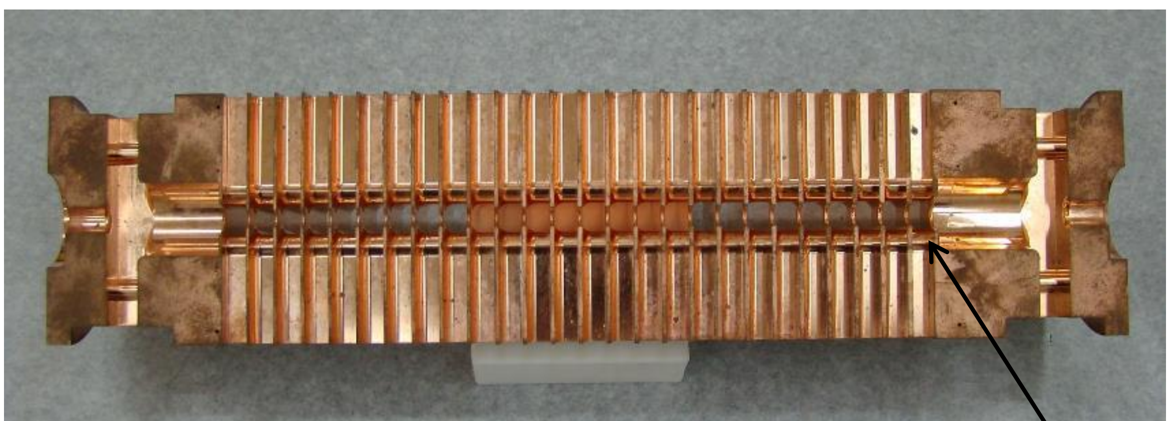
Outside

11.994 GHz X-band
100 MV/m
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz



HOM damping waveguide

Inside



25 cm

6 mm diameter beam aperture

Micron–precision disk