Hosting institutions

Elettra Sincrotrone Trieste

Istituto Nazionale di Fisica Nucleare

IPAC23

14th International Particle Accelerator Conference

IPAC '23

7 - 12 May 2023

VENICE, ITALY

Physics of linear accelerators / colliders

Louis Rinolfi / CERN / ESI-European Scientific Institute

The idea is to provide the basic notions in order to follow and understand the various concepts and parameters presented during the IPAC conference.

This is not a course but a tutorial to enter in the attractive world of linear accelerators and (future) linear colliders.

The various applications of these accelerators could be discussed with the questions

Don’t hesitate to interrupt the speaker when something is not clear

LIL*: A linear accelerator at CERN

This accelerator was producing and accelerating electrons and positrons up to:

(e^-) 500 MeV
(e^+) 500 MeV

100 m long

f = 2.99855 GHz

LEP operation: 1989- 2000

LEP = Large Electron Positron collider

* *LIL = LEP Injector Linac*
This linac was designed and built by LAL / Orsay

SLC*: A linear collider at SLAC - USA


J. Sheppard

This accelerator was producing electrons and positrons up to:
e^- (45.6 GeV) and e^+ (45.6 GeV)

3.2 km (2 miles) long
f = 2.856 GHz

** SLC = Stanford Linear Collider*

It was the first and only Linear Collider running with a beam

Operation: 1989-1998

SLAC = Stanford Linear Accelerator Center

What is a linear accelerator ?

A Linear Accelerator is a device where charged particles acquire energy moving on a linear path.
Such device is called **Linac**

A Linac should accelerate charged particle beams in controlled conditions:
=> Generate a flux of particles at precise energy and in a small volume in space.

The beam dynamics will define how to accelerate and how to focus the beam

The main parameters of a Linac are:

- Types of charged particles
- Output energy
- Beam current
- Frequency
- Pulse length
- Repetition rate

A word about some frequency bands used in the world of particle accelerators

Band names	Approx. range of wavelengths λ (cm)	Approx. frequencies f (GHz)
L	30 – 15	1 – 2 GHz
S	15 – 7.5	2 – 4 GHz
C	7.5 – 3.75	4 – 8 GHz
X	3.75 – 2.4	8 – 12 GHz
K	2.4 – 0.75	12 – 40 GHz

Beam dynamics for a linear accelerator

Vectorial product

Lorentz force and
Newton equation:

$$\frac{d^2\vec{z}}{dt^2} = \frac{q}{m}\cdot\left(\vec{E} + \frac{d\vec{z}}{dt}\times\vec{B}\right)$$

Type of the accelerated particles:

- Charge
- Mass

Electrons
Positrons
Protons
Antiprotons
Ions (light and heavy)
Muons

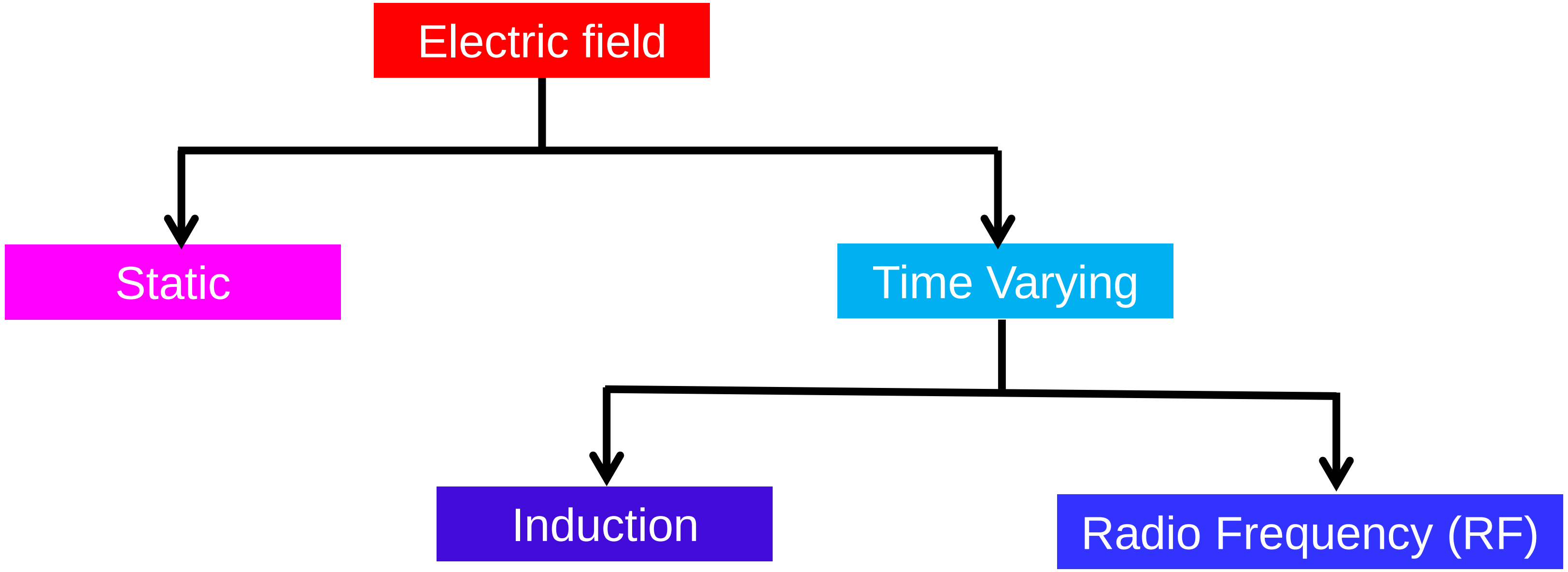
Type of the fields:

- Electric field
- Magnetic field

Different types of linear accelerator

Acceleration of charged particles is based on electric field


750 kV source at CERN


Electric field

Static

Time Varying

Induction

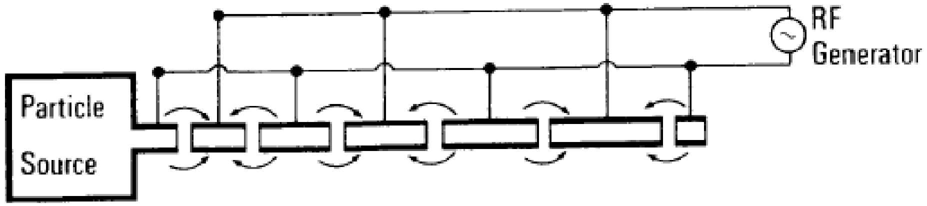
Radio Frequency (RF)


DAPHNE Linac Frascati

A varying magnetic field can generate an electric field.


The FXR at LLNL

$$V_0 = \oint \vec{E}.d\vec{l} = \iint_S \frac{d\vec{B}}{dt}.d\vec{S}$$



First RF linac design – Wideroe Linac in 1928

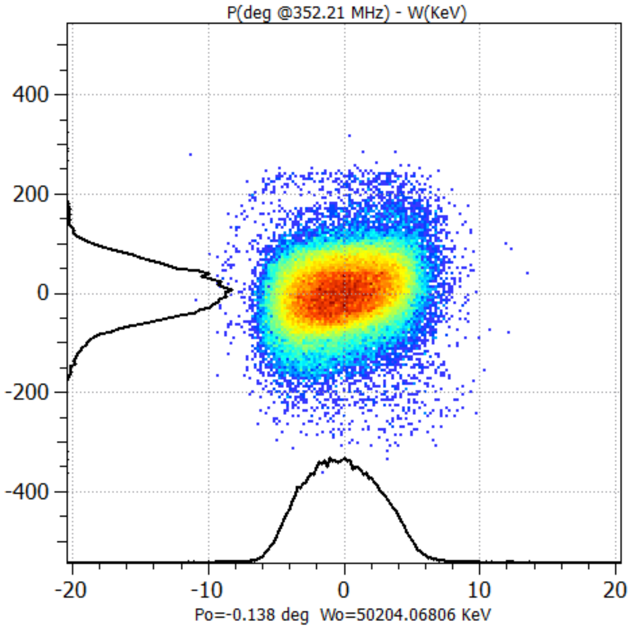
Longitudinal beam dynamics and transverse beam dynamics

$$\frac{d^2\vec{z}}{dt^2} = \frac{q}{m}.\left(\vec{E} + \frac{d\vec{z}}{dt}\times\vec{B}\right)$$

Electric field for acceleration

Magnetic field for focusing

Simulation in the longitudinal phase plane

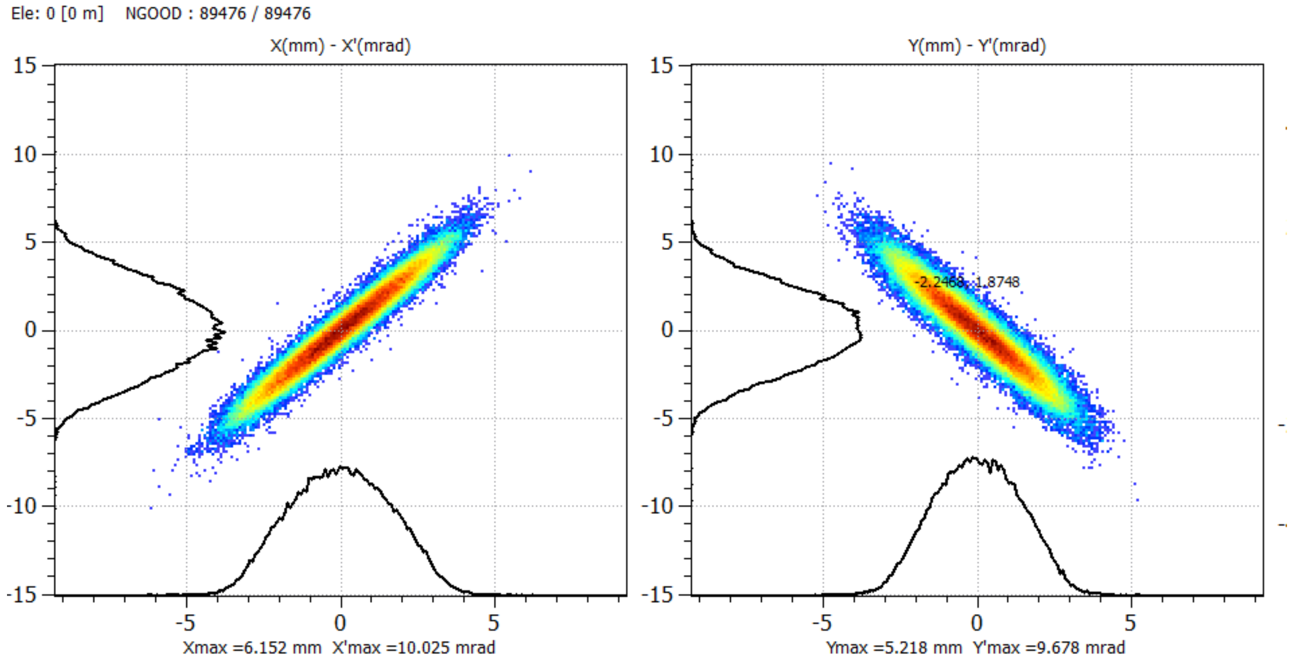


A bunch of particles is characterized by its distribution in the 6D-phase space.

Simulation in the transversal phase planes

Horizontal

Vertical



Main users for “scientific” linacs

The numbers of linacs around the world is estimated to be around 20 000.
The scientific linacs (for the research) represent roughly 1 % of this total. Among them, we give, below, only 3 important applications

1) Linacs used as injectors for downstream accelerators (which will increase the energy, in general), for synchrotron light sources, for FEL, …

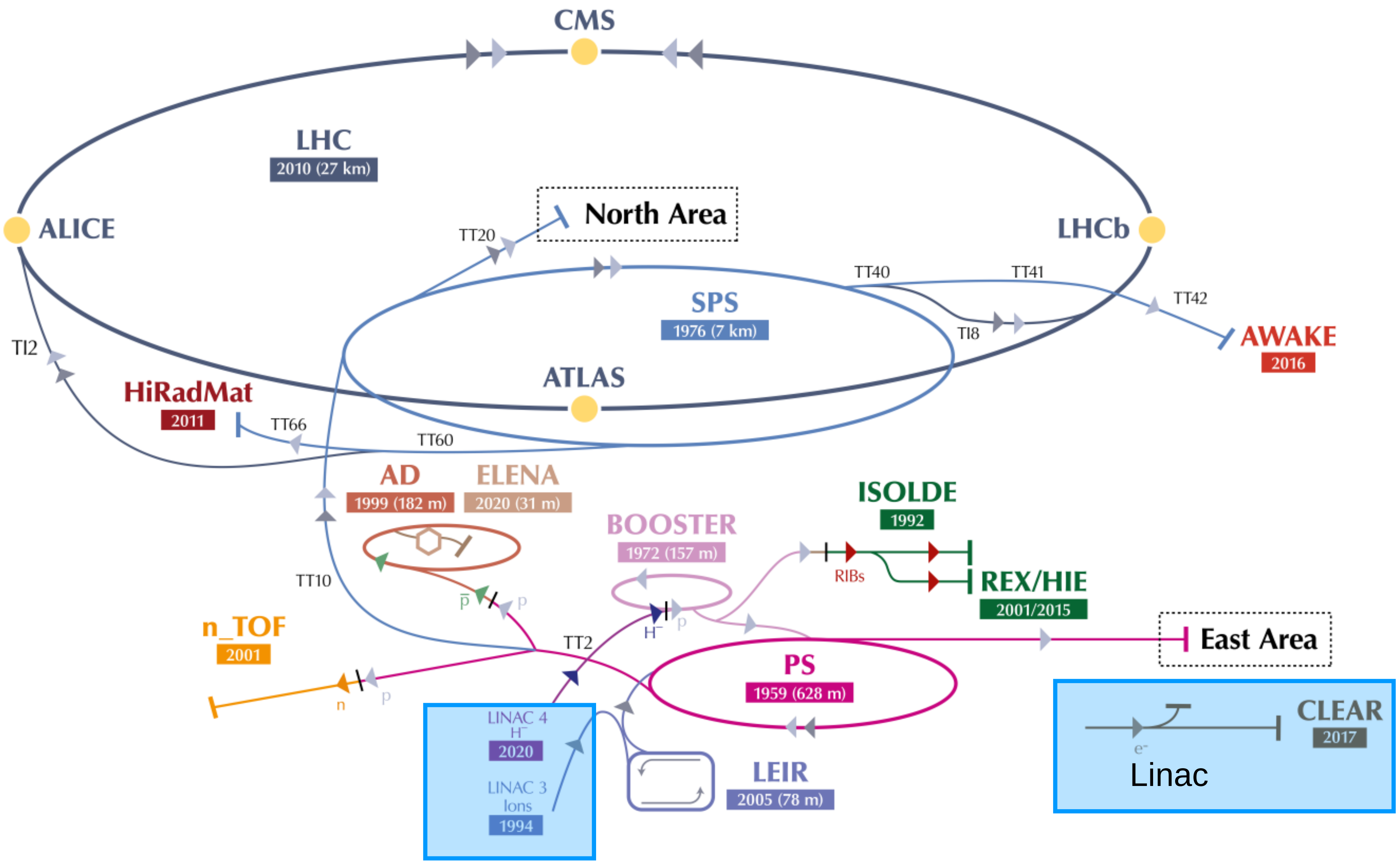
2) Linacs used as primary beams on targets

European Spallation Source ESS (Lund), Japan-Proton Accelerator Research Complex J-PARC, Spallation Neutron Source SNS (Oak Ridge), SPIRAL 2 (Caen), etc ……

3) Linacs used as linear colliders

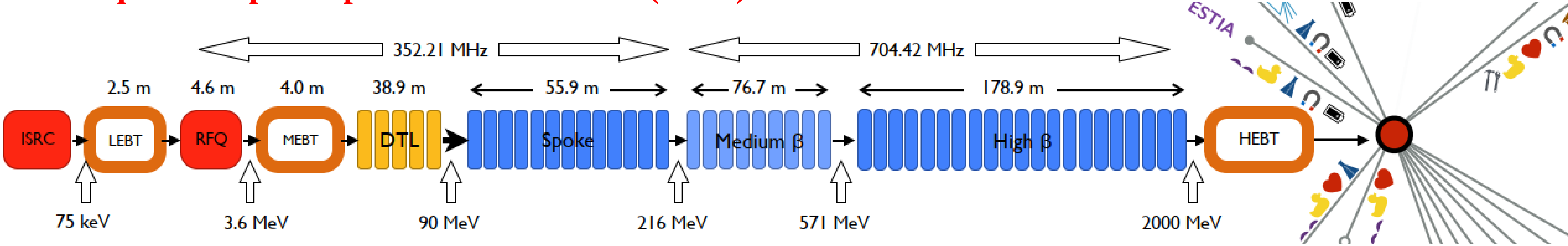
See following slides

1) Linacs used as injectors for CERN accelerators



2) Linacs used as high power primary beam

Example: European Spallation Source ESS (Lund):



$$\text{Beam Power (MW)} = \text{Current (A)} \times \text{Energy (MeV)} \times \underbrace{\text{Repetition rate (Hz)} \times \text{Pulse length (s)}}_{\text{Duty cycle (\%)}}$$

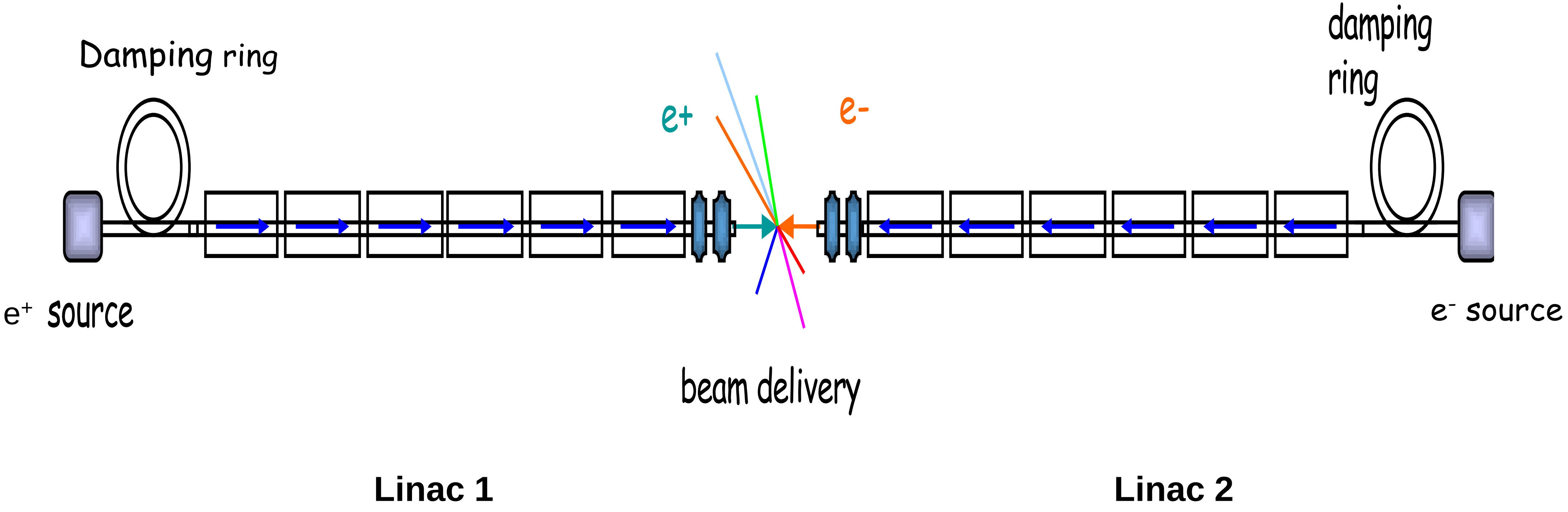

M. Esrhaqi

<u>ESS parameters:</u>

I = 62.5 mA
E = 2 GeV
Rep. rate = 14 Hz
Pulse length = 2.86 ms

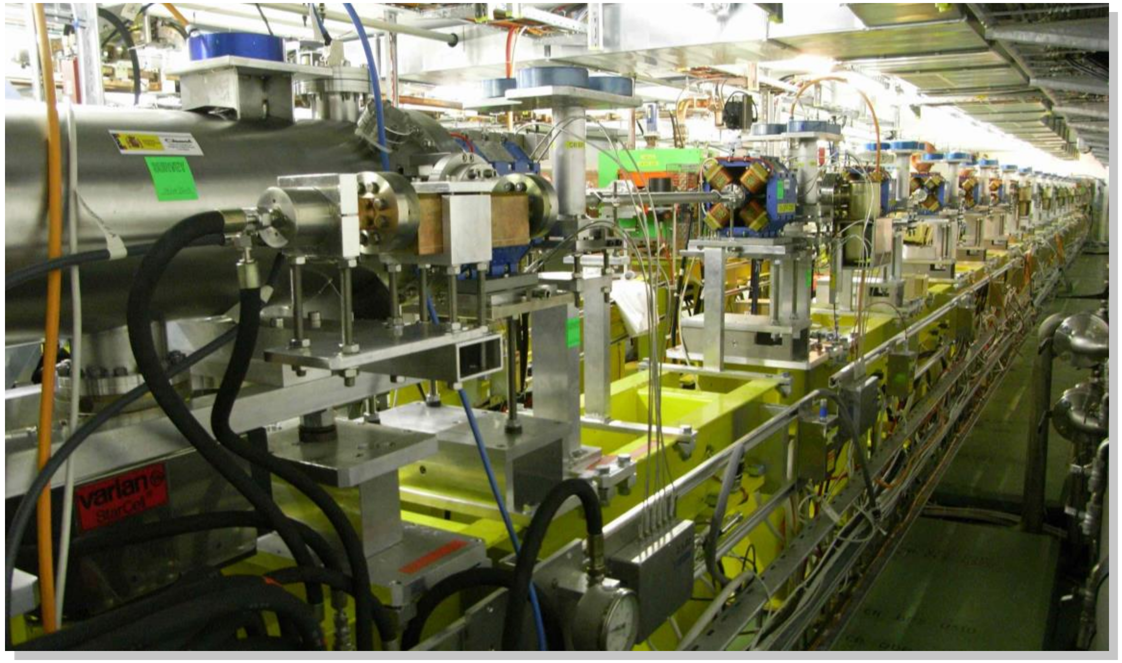
$$P_{\text{beam}} = 5\ \text{MW}$$

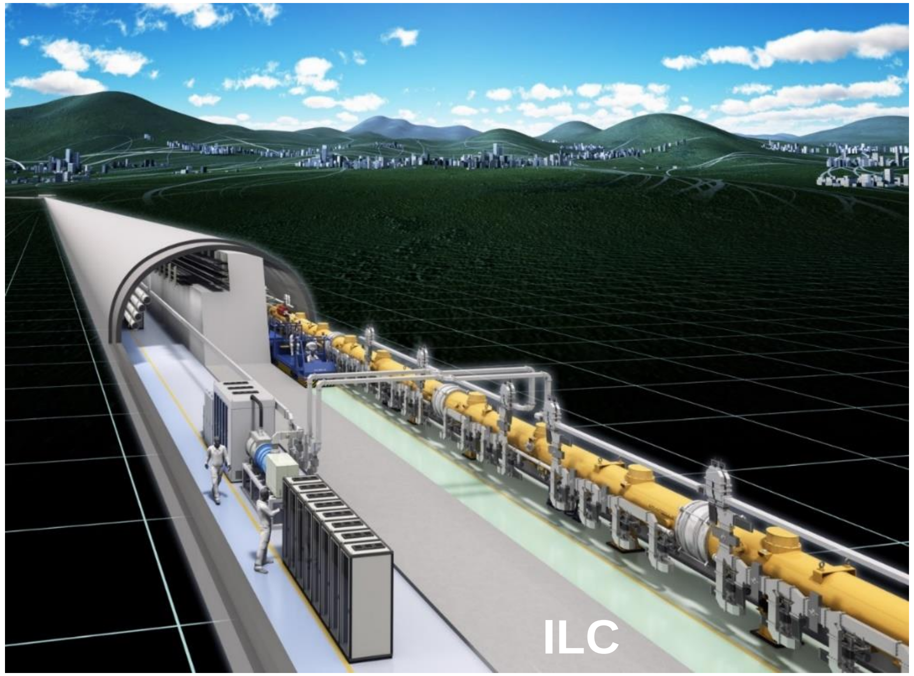
3) Linacs used as (future) linear colliders



Linac beam dynamics are identical to those of linear accelerators (previous slides) but here one has more beam dynamics related to the damping rings, beam delivery in the interaction point, etc…

From linear accelerators to linear colliders





Why a collider ?

E_{FT} = Energy of one accelerator used for a fixed target

E_C = Energy of one accelerator used as collider

If we want the same energy, E_{cm} in the center of mass (CM), the energy required for an accelerator working in fixed target is much higher than the energy required for an accelerator working as collider

$$E_{FT} = 2\,\gamma_C\,E_C$$

Example:

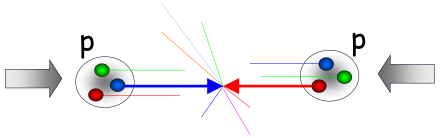
Electrons at 500 MeV

=> $\gamma_C = E_c/E_0 = 500 / 0.511 \simeq 1000$

$$\left.\begin{array}{l} E_{FT} = 2 \times 1000 \times 500 \text{ MeV} = 1 \text{ TeV} \\ E_C = 500 \text{ MeV} \end{array}\right\}$$

For the same E_{cm}
0.5 + 0.5 = 1 GeV

Hadrons versus leptons



6 quarks

In circular colliders

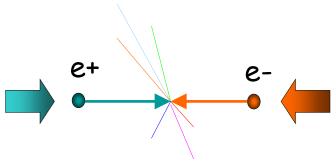
Limited by the dipole field available and the ring size

$$p\ [\mathrm{GeV/c}] \approx 0.3\ B\ [\mathrm{T}]\ \ \rho[\mathrm{m}]$$

Go to higher magnetic fields (=> Superconducting) or/and large circumferences (=> ten's km)

hadron collider => frontier of physics

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



2 leptons

In circular colliders

Limited by the synchrotron radiation

$$W\ [\mathrm{eV}] \approx E^4\ [\mathrm{GeV}]\ /\ \rho[\mathrm{m}]\ (E_o)^4\ [\mathrm{GeV}]$$

Go to linear colliders
(or heavier particles)

lepton collider => precision physics

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

Brief history of high energy linear colliders $e^+ e^-$ (1)

1985:	**CLIC** = CERN Linear Collider	30 GHz, normal conducting	CERN (Switzerland)
1989:	**SLC = Stanford Linear Collider**	3 GHz, normal conducting	SLAC (California)

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

➢ TESLA	1.3 GHz, superconducting	DESY (Germany)
➢ SBLC (S-Band Linear Collider)	3 GHz, normal conducting	DESY (Germany)
➢ NLC (Next Linear Collider)	11.4 GHz, normal conducting	SLAC (California)
➢ JLC (Japan Linear Collider) ⇒ Joint Linear Collider	11.4 GHz, normal conducting	KEK (Japan)
➢ VLEPP	14 GHz, normal conducting	Novosibirsk (Russia)
➢ CLIC (CERN Linear Collider) => Compact Linear Collider	30 GHz, normal conducting	CERN (Switzerland)

Brief history of high energy linear colliders $e^+ e^-$ (2)

2004: Decision for a ILC (International Linear Collider) based on TESLA technology
=> Only two major linear collider studies**:** **ILC (**SC RF cavities**)** and **CLIC (**NC RF cavities**)**

2007: ***Major CLIC changes*****:** 30 GHz => **12 GHz** and 150 MV/m => **100 MV/m**

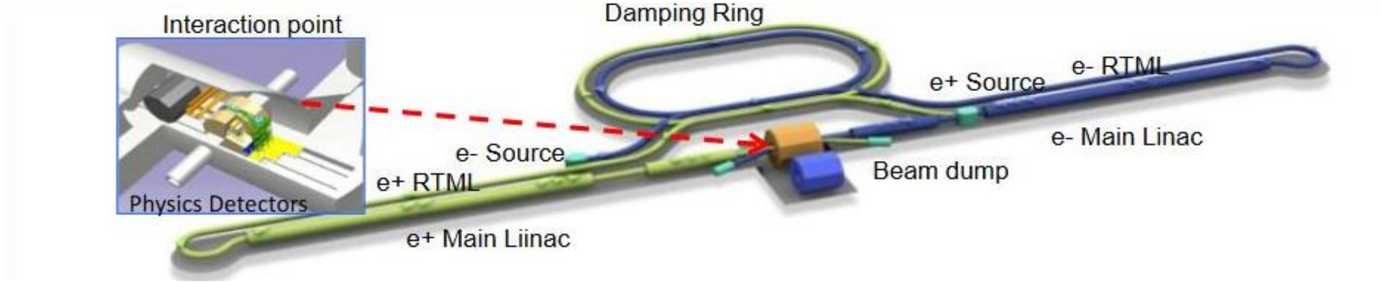
2012: Publication of Conceptual Design Report for CLIC (12 GHz)

2013: Publication of Technical Design Report for **ILC (1.3 GHz)**

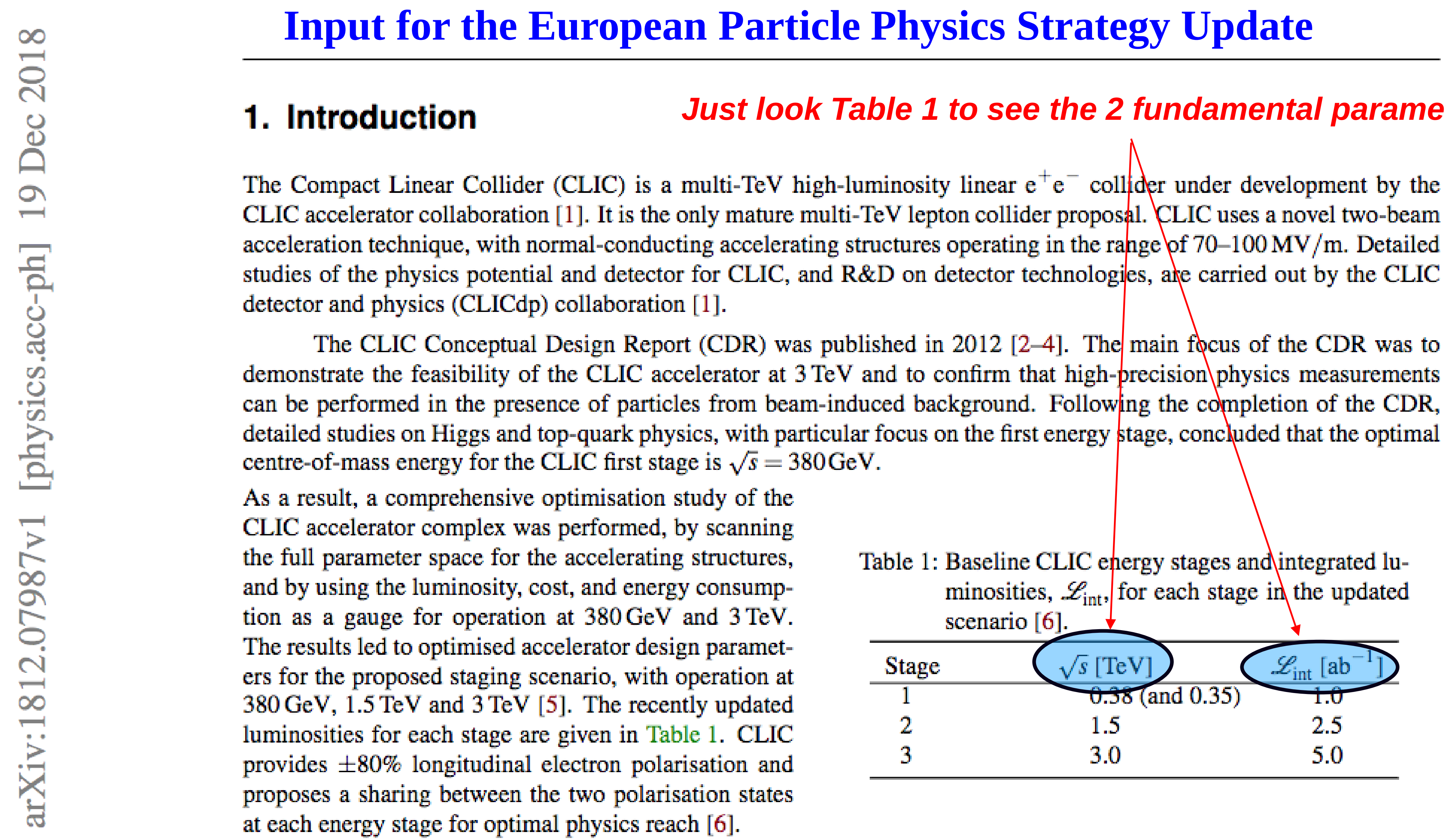
2023: Both ILC and CLIC are mature projects: **waiting for a decision to be approved**

~ 40 years of research and works for future high energy linear colliders

An overview of the required physics in linear colliders



❖ Create beams - Polarized electron (and polarized positron when possible)	Sources
❖ High quality beam - Low emittances - Small beam size, small energy spread	Damping rings
❖ Beam transport - Transport small emittances - Bunch compressor	RTML (Return To Main Linac)
❖ Acceleration - RF cavities (Room temperature) - RF cavities (superconducting)	Main Linac
❖ Bring to collision at Interaction Point (IP) - Nanometers beams	Final focus
❖ After collisions - Radiation issues	Beam dumps



Input for the European Particle Physics Strategy Update

1. Introduction

Just look Table 1 to see the 2 fundamental parameters

The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider under development by the CLIC accelerator collaboration [1]. It is the only mature multi-TeV lepton collider proposal. CLIC uses a novel two-beam acceleration technique, with normal-conducting accelerating structures operating in the range of 70–100 MV/m. Detailed studies of the physics potential and detector for CLIC, and R&D on detector technologies, are carried out by the CLIC detector and physics (CLICdp) collaboration [1].

The CLIC Conceptual Design Report (CDR) was published in 2012 [2–4]. The main focus of the CDR was to demonstrate the feasibility of the CLIC accelerator at 3 TeV and to confirm that high-precision physics measurements can be performed in the presence of particles from beam-induced background. Following the completion of the CDR, detailed studies on Higgs and top-quark physics, with particular focus on the first energy stage, concluded that the optimal centre-of-mass energy for the CLIC first stage is $\sqrt{s} = 380\,\text{GeV}$.

As a result, a comprehensive optimisation study of the CLIC accelerator complex was performed, by scanning the full parameter space for the accelerating structures, and by using the luminosity, cost, and energy consumption as a gauge for operation at 380 GeV and 3 TeV. The results led to optimised accelerator design parameters for the proposed staging scenario, with operation at 380 GeV, 1.5 TeV and 3 TeV [5]. The recently updated luminosities for each stage are given in Table 1. CLIC provides ±80% longitudinal electron polarisation and proposes a sharing between the two polarisation states at each energy stage for optimal physics reach [6].

Table 1: Baseline CLIC energy stages and integrated luminosities, $\mathscr{L}_{\text{int}}$, for each stage in the updated scenario [6].

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

Center-of-mass energy

The total mass of the system is often called the center-of-mass energy and its square is usually denoted by “s”.
The invariance of this quantity is very useful

$$\boxed{E_{cm} = \sqrt{s}}$$

Unit: eV
“electronVolt”

1 eV = 1,6 10^{-19} J

1 TeV = 10^{12} eV

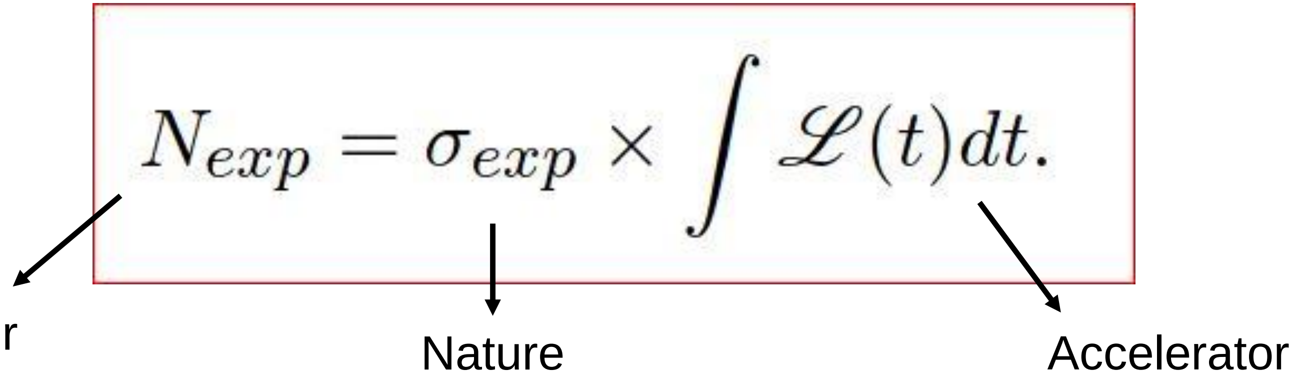
For a linear collider

Energy (center of mass) $$\underset{\text{MeV}}{E_{cm}} = 2\, F_{fill}\, \underset{\text{m}}{L_{linac}}\, \underset{\text{MV/m}}{E_{RF}}$$

F_{fill} = Filling factor of the Linac; L_{linac} = Length of the linac; E_{RF} = accelerating electric field

Luminosity

The number of events, N_{exp}, is the product of the cross-section of interest, σ_{exp}, and the time integral over the instantaneous luminosity $\mathscr{L}$



$$\boxed{N_{exp} = \sigma_{exp} \times \int \mathscr{L}(t)dt.}$$

$\mathscr{L}(t)$ → Design by accelerator physicist

$\int \mathscr{L}(t)dt.$ → Fundamental to accumulate statistics and make a discovery

Unit:

Integrated luminosity over the time uses a conventional unit called inverse “barn”

1 barn $=10^{-28}$ m^2 = 10^{-24} cm^2 and 1 ab^{-1} = 10^{46} m^{-2} = 10^{42} cm^{-2} (inverse attobarn)

Basic expression for instantaneous Luminosity

Hz

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

$cm^{-2}\ s^{-1}$

cm

n_b = number of bunches; N = number of particles per bunch; f_{rep} = frequency repetition rate;
σ_x, σ_y = rms transverse beam sizes;

Luminosity challenges

Future high energy linear colliders are based on experience:

- SLC (Stanford Linear Collider)
- FELs (Free Electron Lasers)
- Lights sources (Many radiation synchrotron machines in the world)

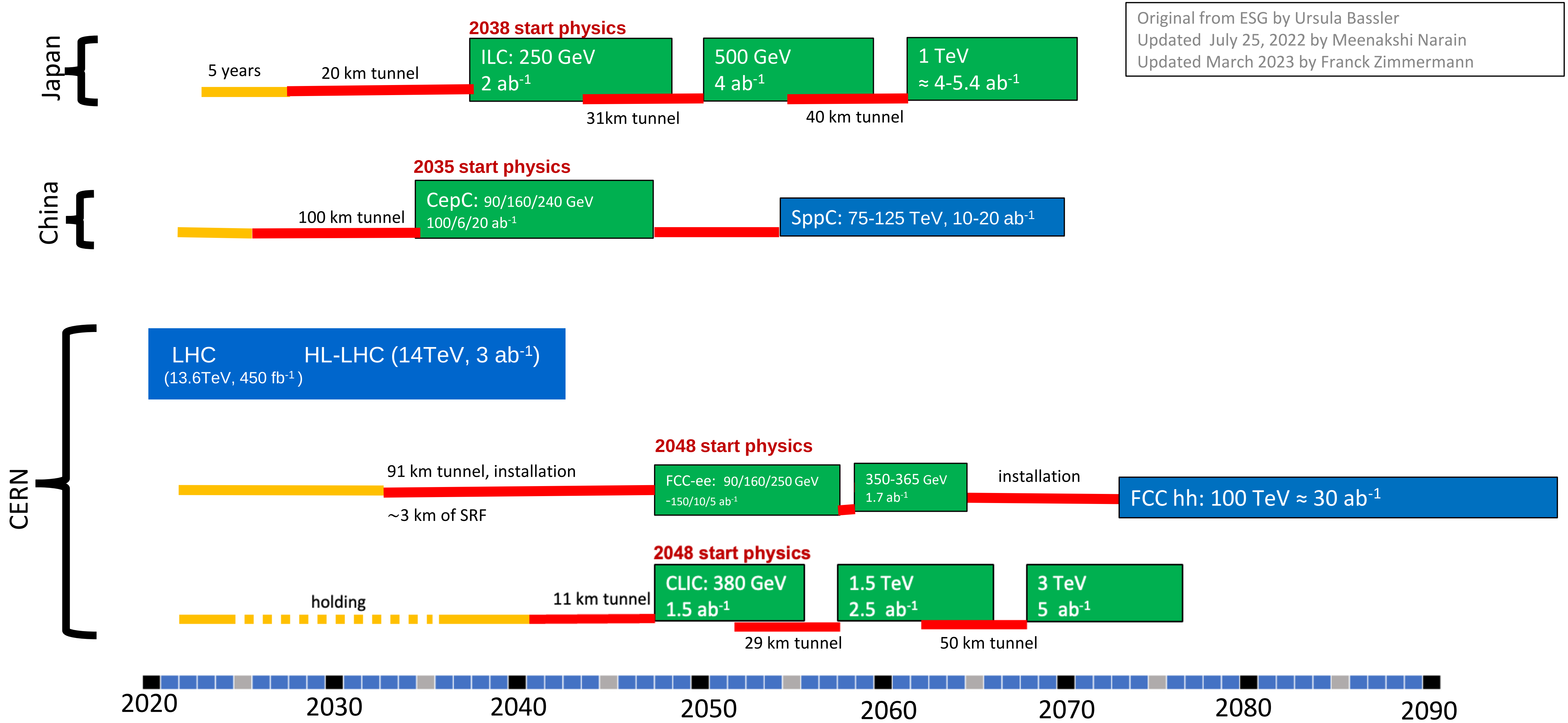
BUT the performance goal are more ambitious:

- beam size of nm scale,
- beam emittances extremely small,
- stabilization,
- alignments,
- **energy management**,…..

Indicative scenarios of future colliders [considered by ESG]

🟦 Proton collider
🟩 Electron collider
🟥 Construction/Transformation
🟨 Preparation / R&D

Original from ESG by Ursula Bassler
Updated July 25, 2022 by Meenakshi Narain
Updated March 2023 by Franck Zimmermann



Japan

5 years

20 km tunnel

2038 start physics

ILC: 250 GeV
2 ab^{-1}

31km tunnel

500 GeV
4 ab^{-1}

40 km tunnel

1 TeV
≈ 4-5.4 ab^{-1}

China

100 km tunnel

2035 start physics

CepC: 90/160/240 GeV
100/6/20 ab^{-1}

SppC: 75-125 TeV, 10-20 ab^{-1}

CERN

LHC
(13.6TeV, 450 fb^{-1})

HL-LHC (14TeV, 3 ab^{-1})

91 km tunnel, installation

~3 km of SRF

2048 start physics

FCC-ee: 90/160/250 GeV
-150/10/5 ab^{-1}

350-365 GeV
1.7 ab^{-1}

installation

FCC hh: 100 TeV ≈ 30 ab^{-1}

holding

11 km tunnel

2048 start physics

CLIC: 380 GeV
1.5 ab^{-1}

29 km tunnel

1.5 TeV
2.5 ab^{-1}

50 km tunnel

3 TeV
5 ab^{-1}

International Workshop on Future Linear Colliders

15-19 May 2023

America/Los_Angeles timezone

Acknowledgments

(slides and discussions)

Special thanks to Elias Métral for very fruitful discussions

D. Alesini, U. Amaldi, R. Assmann, U. Bassler, P. Burrows, R. Corsini, G. D'Auria, M. Esrhaqi, J.B. Lallement, A. Latina, P. Lebrun, S. Michizono, T. Omori, D. Schulte, S. Stapnes, M. Vretenar, M. Yoshioka, F. Zimmermann

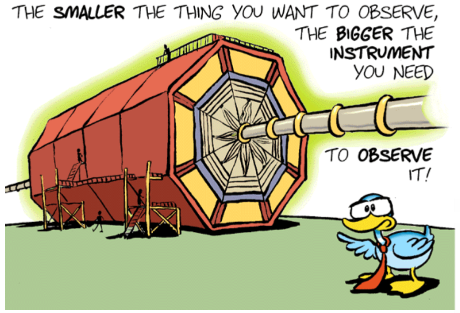
A citation as conclusion

In the book of U. Amaldi

“Viki” Wiesskopf, Director General of CERN 1961-1965 wrote:

“ There are three kinds of physicists, namely the machine builders, the experimental physicists, and the theoretical physicists.

If we compare this with the discovery of America, the machine builders correspond to captains and ship builders who really developed the techniques at that time.



The experimentalists were those fellows on the ships who sailed to the other side of the world and then landed on the new islands and wrote down what they saw.

The theoretical physicists are those who stayed behind in Madrid and told Columbus that he was going to land in India.”

You are the machine builders …..

…. for future linear accelerators and high energy colliders

Thank you for your attention

Appendix

If you wish to discuss some points:

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Electric field in a cavity

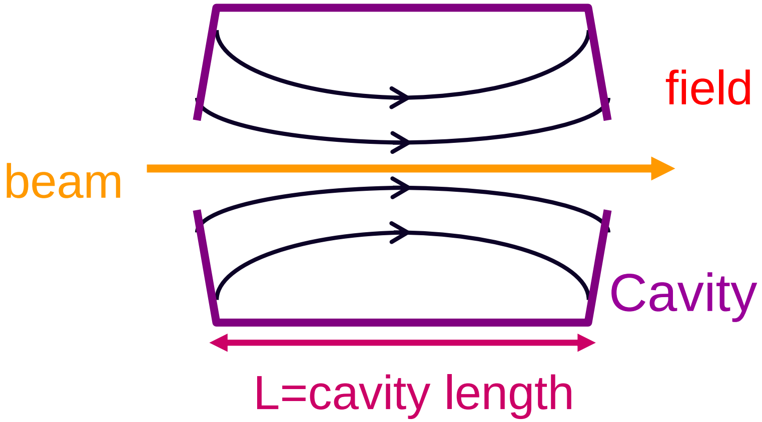
We assume that the solution of the wave equation in a bounded medium can be written as:

$$E(x,y,z,t) = E(x,y,z).e^{-j\omega t}$$

Function of space

Function of time
Oscillating at frequency $\omega/2\pi$

One should concentrate the RF power on the beam path in the most efficient way. Tailor development of the function of space $E(x,y,z)$ allows choosing the appropriate cavity geometry



Some cavity parameters:

1. Average electric field
2. Shunt impedance
3. Quality factor
4. Filling time
5. Transit time factor

Average electric field

Average electric field: **E_0** is measured in V/m.
Average electric field on beam axis in the direction of the beam propagation at a given moment in time when E(t) is maximum.

$$E(x,y,z,t) = E(x,y,z).e^{-j\omega t}$$

Integration done on z axis: x=0, y=0, z from 0 to L (cavity length)

$$E_0 = \frac{1}{L}\int_0^L E(0,0,z)dz$$

Measure how much field is available for acceleration
Depends on the cavity shape, resonating mode and frequency

Shunt impedance

Shunt impedance (per unit of length): **Z** measured in Ω/m.

Defines the ratio of the average electric field squared (E_0^2) to the power (P) per unit of length (L) dissipated on the walls surface.

$$Z = E_0^2 . \frac{L}{P}$$

Measure how well the RF power is concentrated in the useful region.

It is independent on the field level and cavity length. Depends on cavity mode and geometry.

Quality factor

Quality factor: **Q** dimension-less.

Defines the ratio of the stored energy (U) to the power lost on the wall (P) in one RF cycle (f = frequency).

$$Q = \frac{2\pi . f}{P} . U$$

Q is a function of the geometry and of the surface resistance of the cavity material.

Examples at 700 MHz:

Superconducting (niobium): $Q=10^{10}$ (depends on temperature)

Normal conducting (copper): $Q=10^{4}$ (depends on cavity mode)

Filling time

Filling time: **t_F** measured in seconds

Two different definitions for traveling wave (TW) structures or standing wave (SW) structures.

- For TW: Time needed for the electromagnetic energy to fill the cavity of length L

$$t_F = \int_0^L \frac{dz}{v_g(z)}$$

Velocity at which the energy propagate thru the cavity

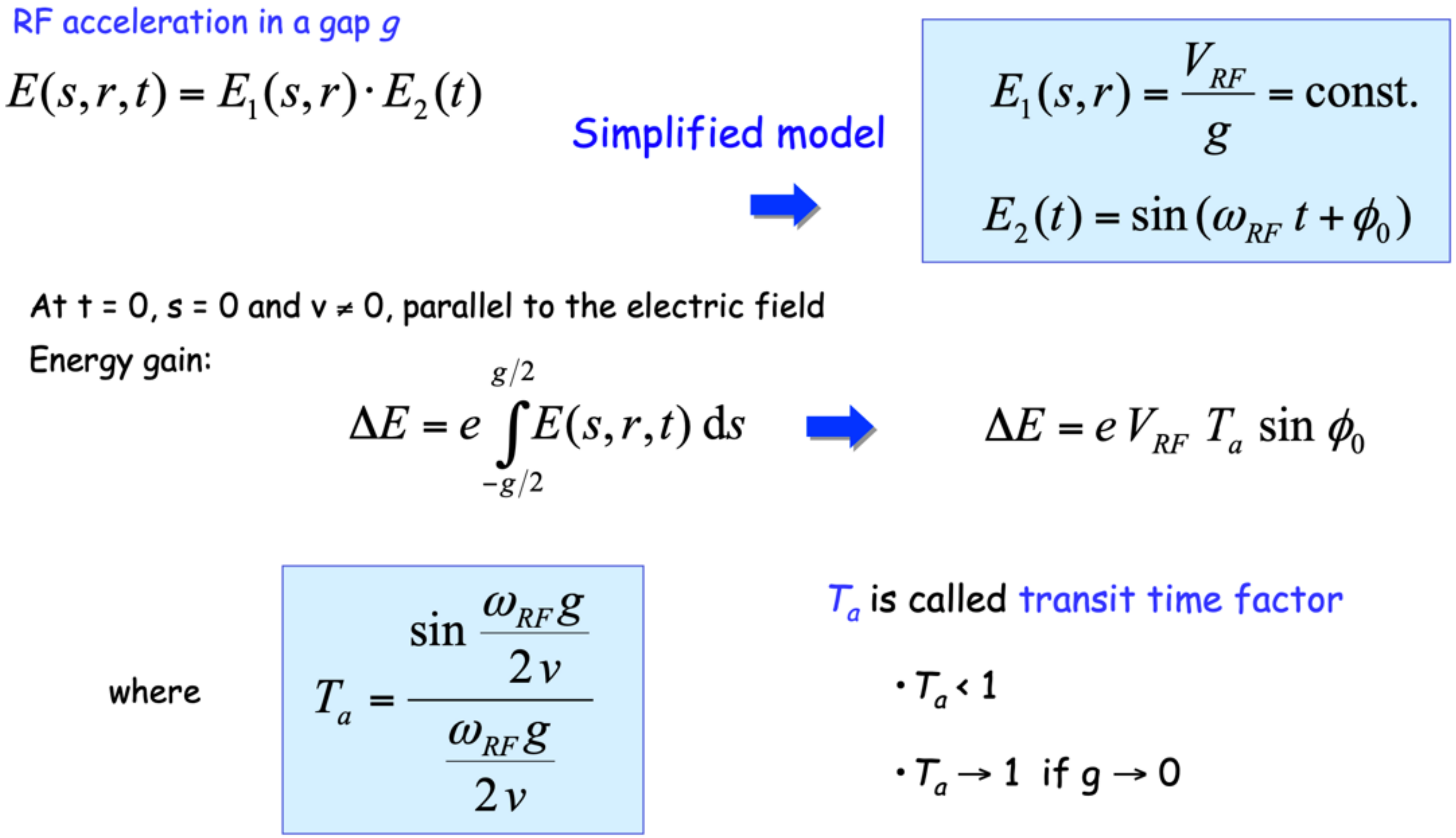
- For SW: Time it takes for the field to decrease by 1/e after the cavity has been filled.

$$t_F = \frac{2Q}{\omega}$$

How fast the stored energy is dissipated to the wall

Transit time factor

Transit time factor: **T** dimension-less.



RF acceleration in a gap g

$$E(s,r,t) = E_1(s,r) \cdot E_2(t)$$

Simplified model ➡

$$E_1(s,r) = \frac{V_{RF}}{g} = \text{const.}$$

$$E_2(t) = \sin(\omega_{RF}\, t + \phi_0)$$

At t = 0, s = 0 and v ≠ 0, parallel to the electric field

Energy gain:

$$\Delta E = e \int_{-g/2}^{g/2} E(s,r,t)\, \mathrm{d}s \;\; \Rightarrow \;\; \Delta E = e\, V_{RF}\, T_a \sin\phi_0$$

where

$$T_a = \frac{\sin \dfrac{\omega_{RF}\, g}{2v}}{\dfrac{\omega_{RF}\, g}{2v}}$$

T_a is called transit time factor

- $T_a < 1$
- $T_a \to 1$ if $g \to 0$

Defines the ratio of the energy gained in the time varying RF field to that in a DC field.
T is a measure of the reduction in energy gain caused by the sinusoidal time variation of the field in the gap.

Longitudinal phase space

Energy gain for the synchronous particle $\Delta W_s = qE_0 LT\cos(\phi_s)$

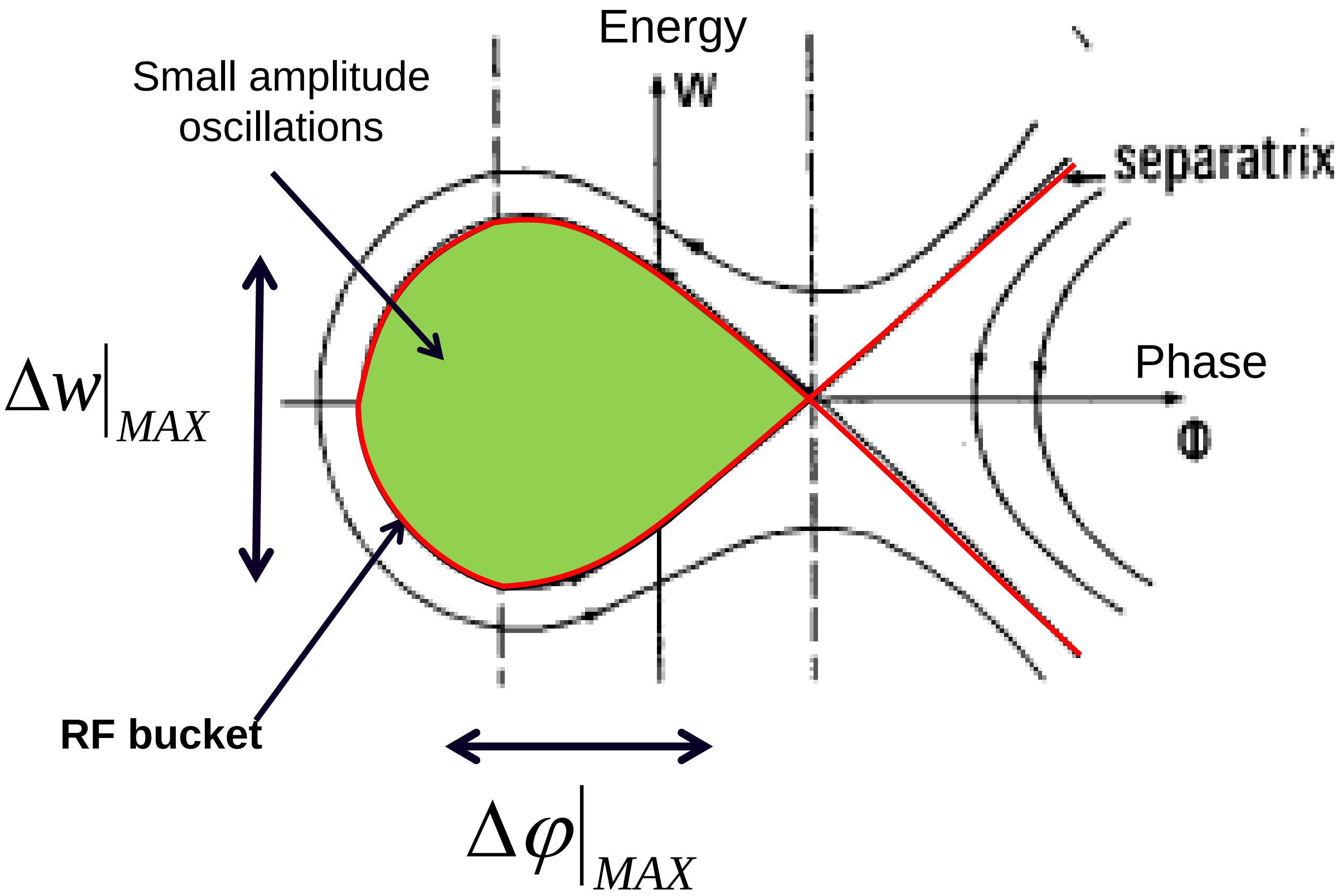
Energy gain for a particle with phase ϕ $\Delta W = qE_0 LT\cos(\phi)$

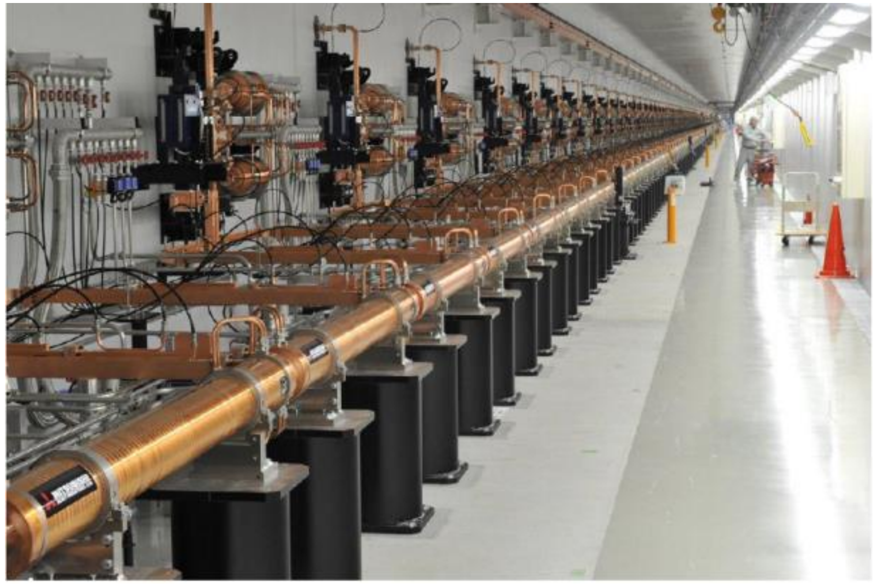
E_o *electric field*

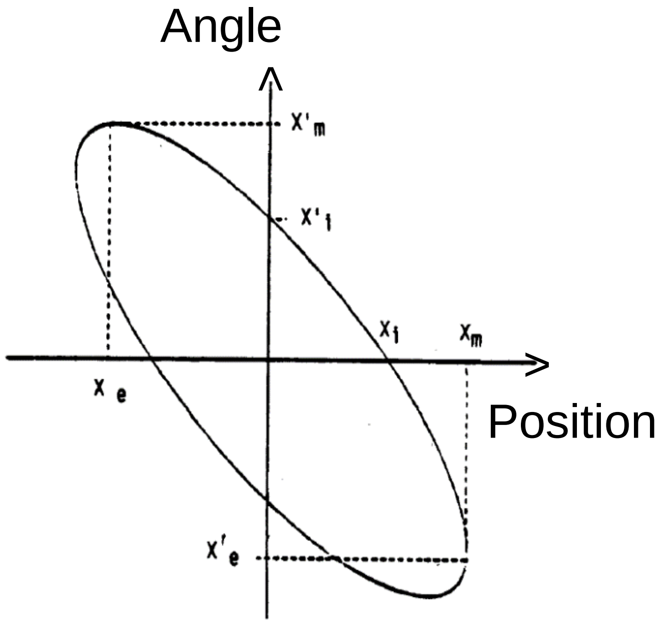
L cavity length

T transit time factor

ϕ_s *phase of the synchronous particle*







Transverse phase space

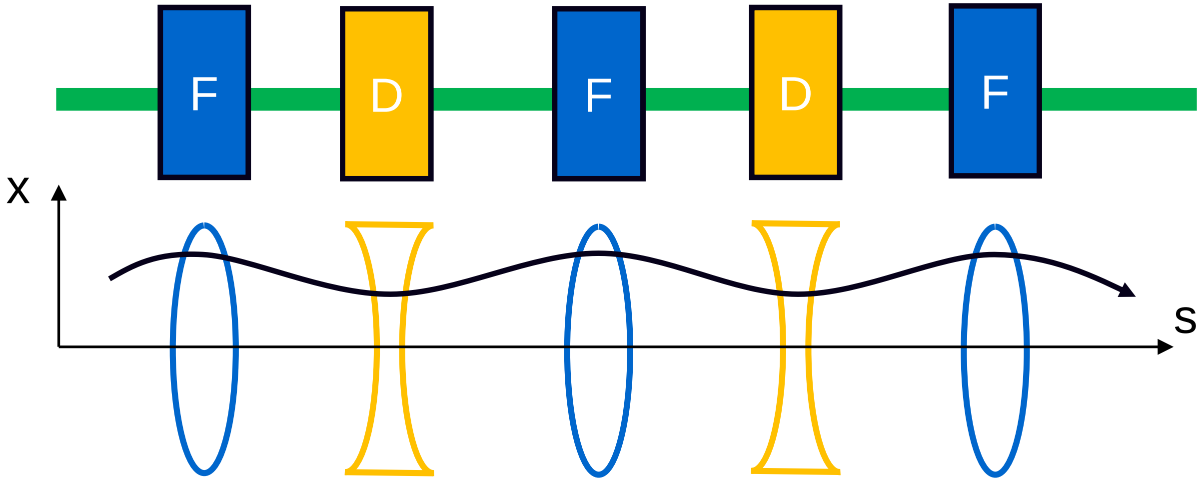
The ellipse equation used in beam dynamics is:

$$\gamma x^2 + 2\alpha x x' + \beta (x')^2 = \varepsilon$$

α, β, γ are the Twiss parameters

ε is called emittance of the beam. It’s equal to the ellipse area divided by π

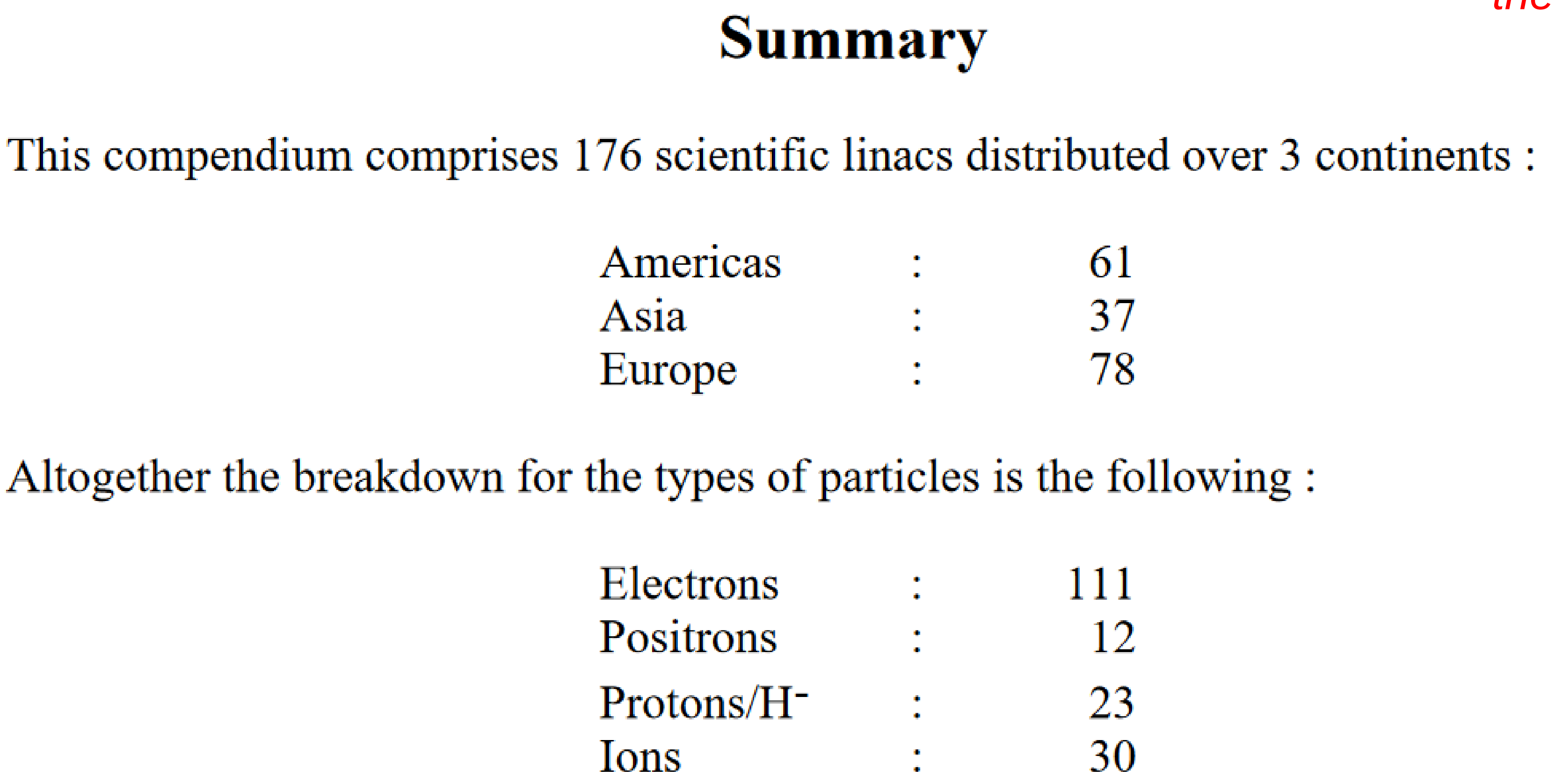
F and D are focusing and defocusing quadrupoles respectively



Scientific Linacs in the world

http://linac96.web.cern.ch/Compendium/COMPENDI.PDF

A complete review was made for the Linac Conference in 1996



Summary

This compendium comprises 176 scientific linacs distributed over 3 continents :

Americas : 61
Asia : 37
Europe : 78

Altogether the breakdown for the types of particles is the following :

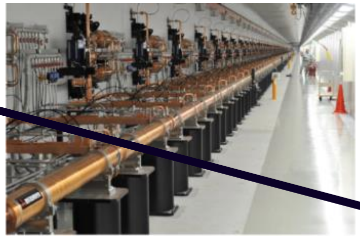
Electrons : 111
Positrons : 12
Protons/H$^-$: 23
Ions : 30

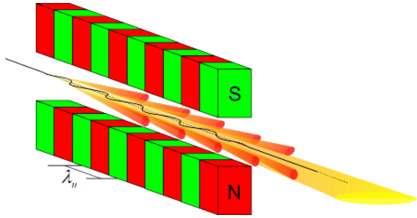
LINAC APPLICATIONS

D. Alesini / INFN

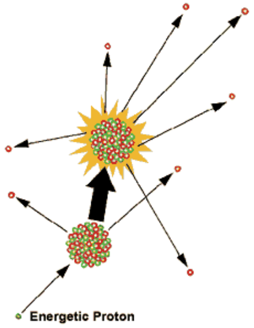
Injectors for synchrotrons

Free Electron Lasers



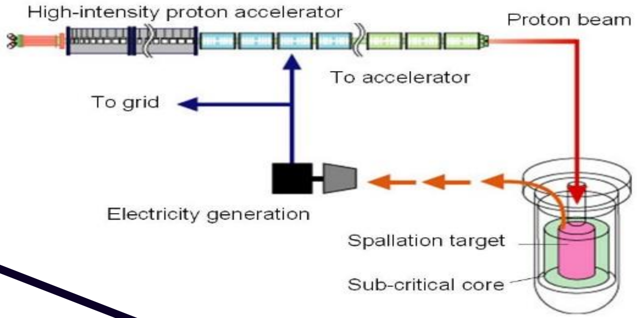


Spallation sources for neutron production



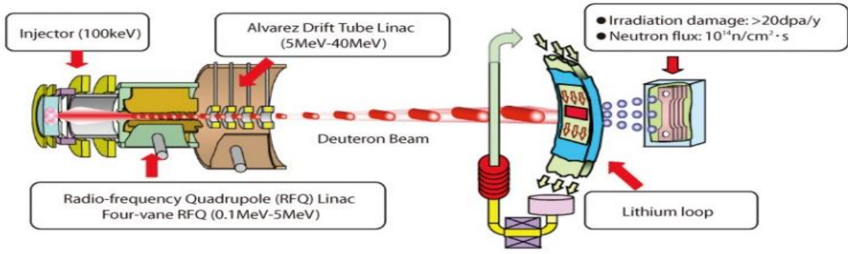
Medical applications: radiotherapy

Nuclear waste treatment and controlled fission for energy production (ADS)

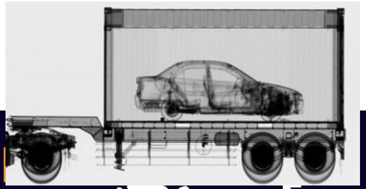


Industrial applications

Material testing for fusion nuclear reactors

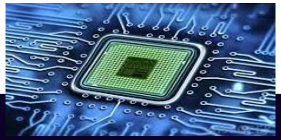


National security



Material treatment

Ion implantation



Material/food sterilization

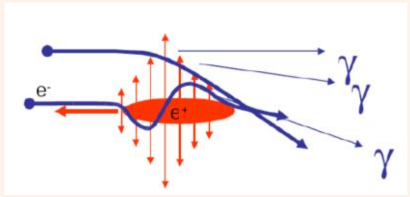
Another expression of luminosity for colliders

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

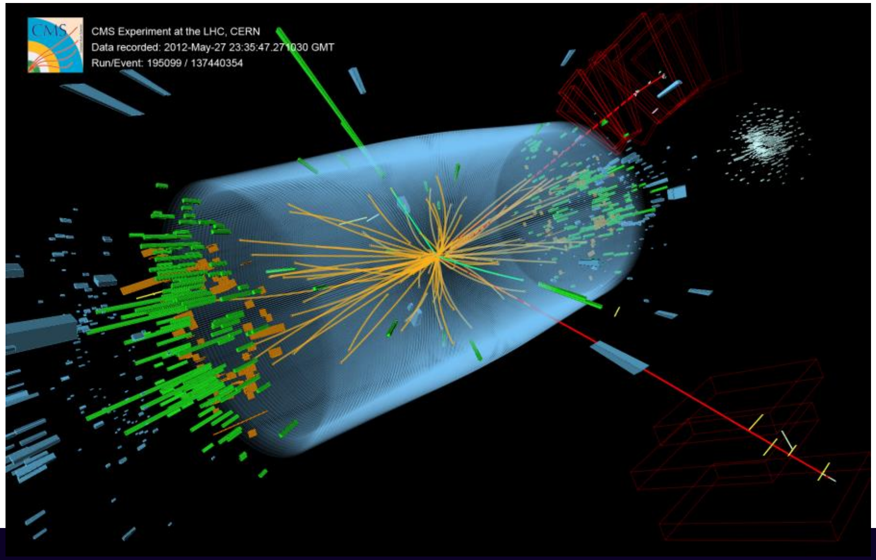
Luminosity spectrum
(Physics)

Beam current
(RF Power limited)

Beam Quality
(Optics, emittance,…)



H_D = luminosity enhancement factor



Higgs candidate: H->ZZ-> 2e2μ

Luminosity

The unit of the cross-section (σ_{event}) is the barn:

$\Rightarrow$ 1 barn $= 10^{-28}$ m^2 = 10^{-24} cm^2

$\Rightarrow$ 1 barn^{-1} = 10^{28} m^{-2} = 10^{24} cm^{-2}

$\Rightarrow$ 1 μb^{-1} = 10^{34} m^{-2} = 10^{30} cm^{-2}

$\Rightarrow$ 1 pb^{-1} = 10^{40} m^{-2} = 10^{36} cm^{-2}

$\Rightarrow$ 1 fb^{-1} = 10^{43} m^{-2} = 10^{39} cm^{-2}

$\Rightarrow$ 1 ab^{-1} = 10^{46} m^{-2} = 10^{42} cm^{-2}

The inverse femtobarn (fb^{-1}) is the unit typically used to measure the number of particle collision events per femtobarn of target cross-section, and is the conventional unit for time-integrated luminosity.
Thus if a detector has accumulated 100 fb^{-1} of integrated luminosity, one expects to find 100 events per femtobarn of cross-section within these data.

Luminosity at SLC

SLC collider ran over the last 2 years (1997-1998) with the following parameters:

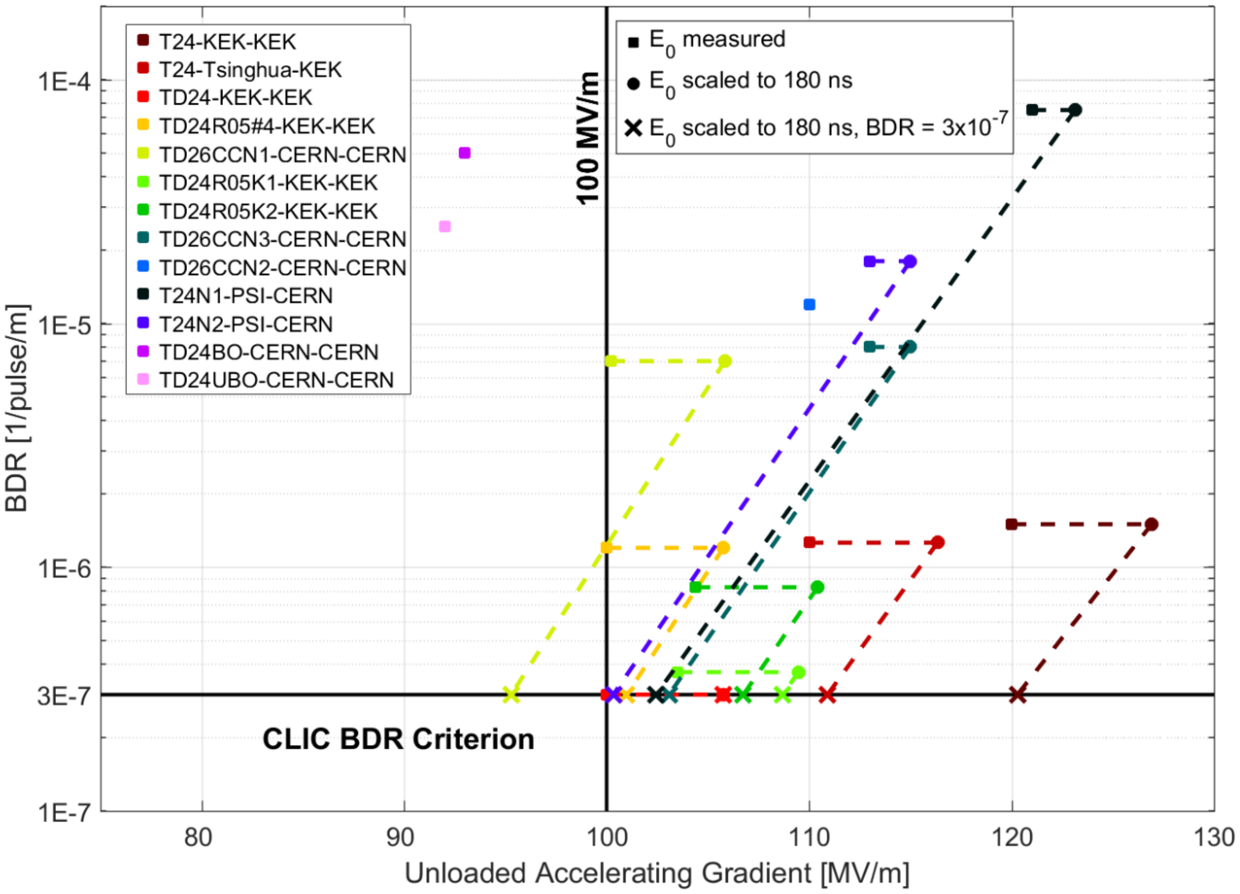
For ~ 28 10^6 seconds, the instantaneous luminosity was:
2×10^{30} $\text{cm}^{-2}\cdot\text{s}^{-1}$ = 2 $\mu\text{b}^{-1}\cdot\text{s}^{-1}$ = 2.10^{-6} $\text{pb}^{-1}\cdot\text{s}^{-1}$,

⇒integrated luminosity of $2\text{x}10^{-6}\text{x}28\text{x}10^{6}$ pb^{-1} = 56 pb^{-1} = 0.056 fb^{-1} during this period.

⇒multiplied by the cross-section of σ_{event}, then a dimensionless number is obtained which is the number of expected scattering events

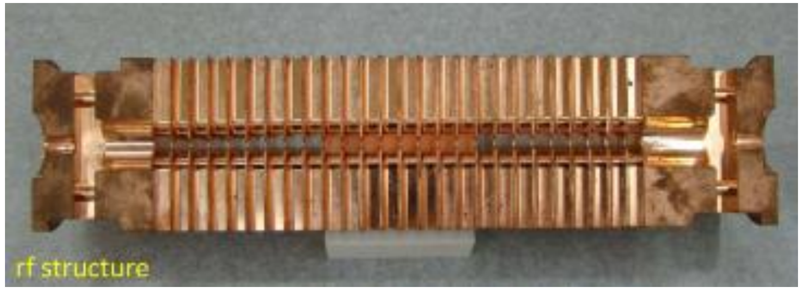
⇒ It's found 350 000 Zo collected over two years

Energy challenge: the electric field for normal conducting cavities



Break Down Rate (BDR) means pulses lost because of vacuum arcing in the structure.

Many tests done by CLIC study within a large international collaboration to understand the physics of breakdown phenomena.

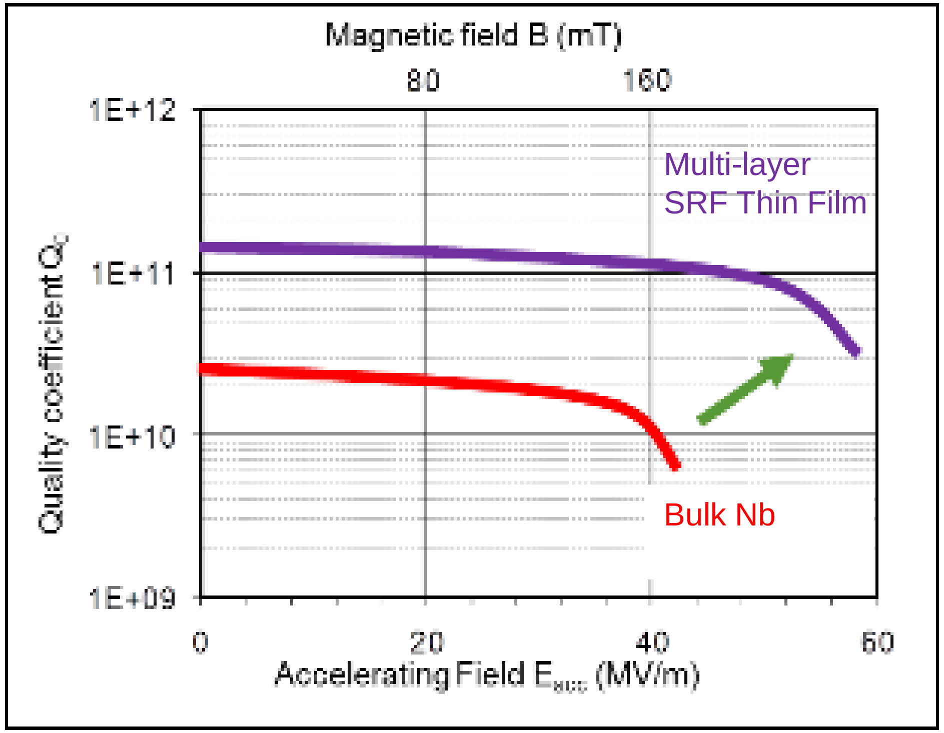


RF cavity: X-band, 12 GHz

100 MV/m gradient have been demonstrated
150 MV/m have been achieved with a lot of BDR

High frequencies means smaller dimensions.
The power scales as the square of the gradient
=> High gradient means higher power consumption.

Energy challenge: the electric field for superconducting cavities



31 MV/m gradient have been demonstrated
60 to 90 MV/m is a long-term goal

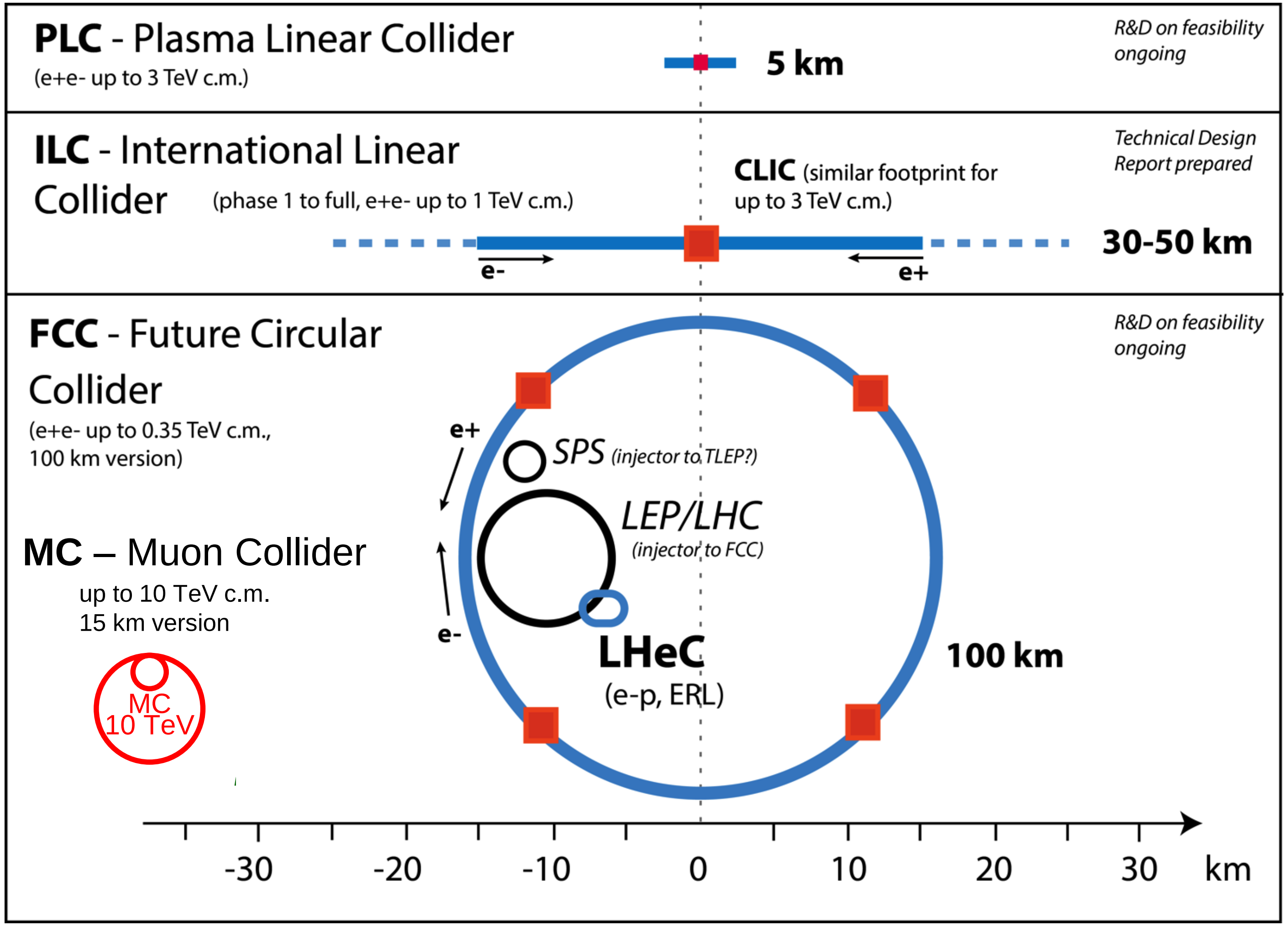
RF cavity: L-band, 1.3 GHz

Various techniques investigated:

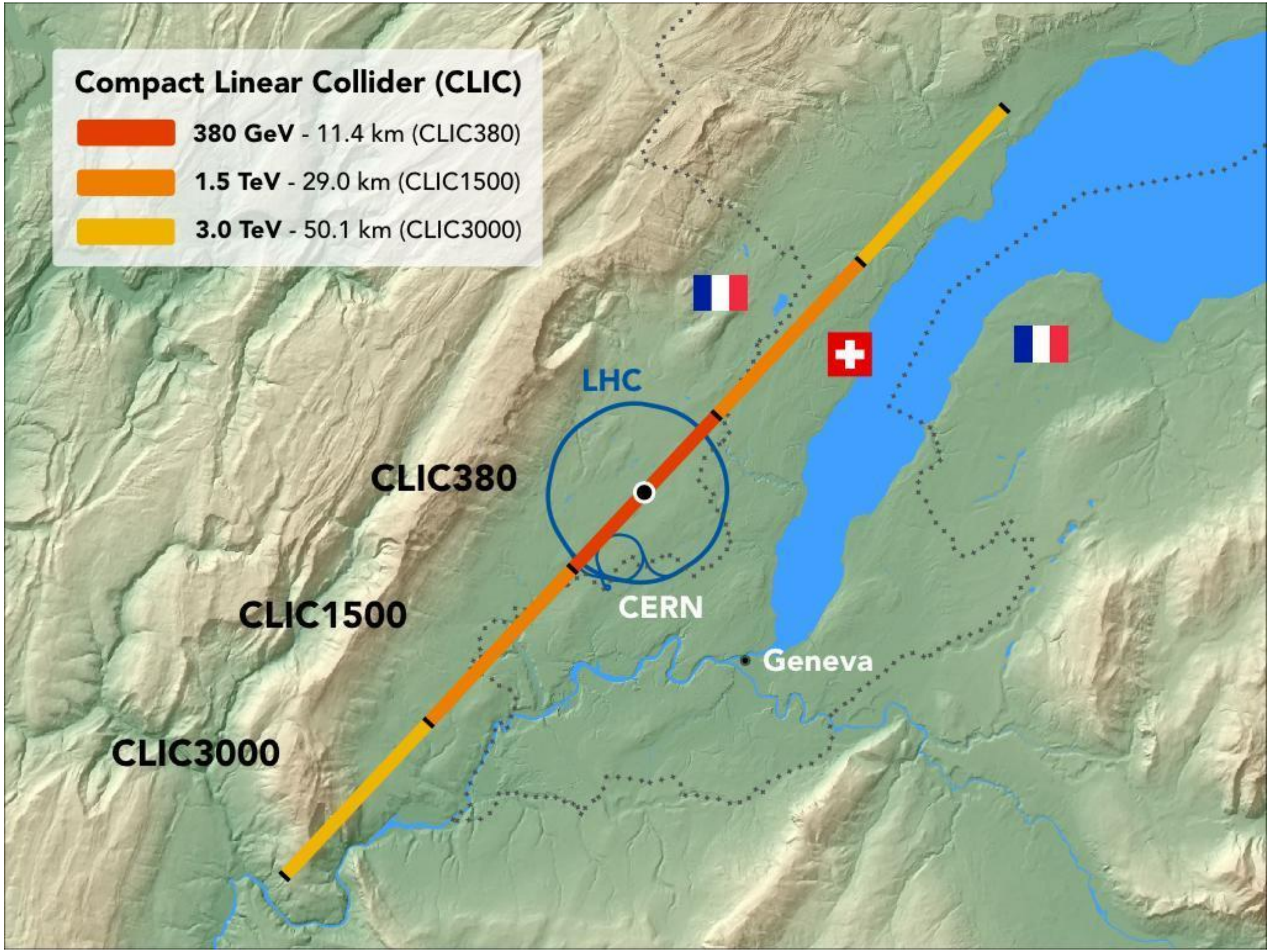
Nitrogen infusion process (FNAL)
=> high Q operation, gradients ~45 MV/m

Coating of Nb with a thin layer of Nb_3Sn
=> allows operation at larger T, improved cryogenic efficiency

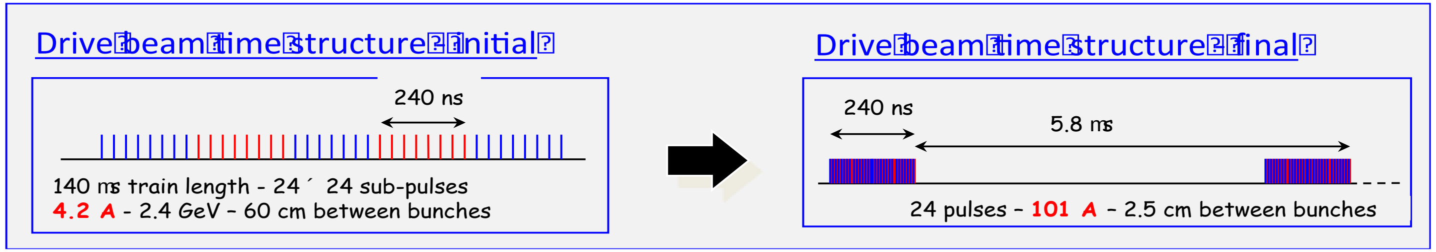
Which collider ?



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 3 TeV and Two beam concept



Drive beam time structure - initial

240 ns

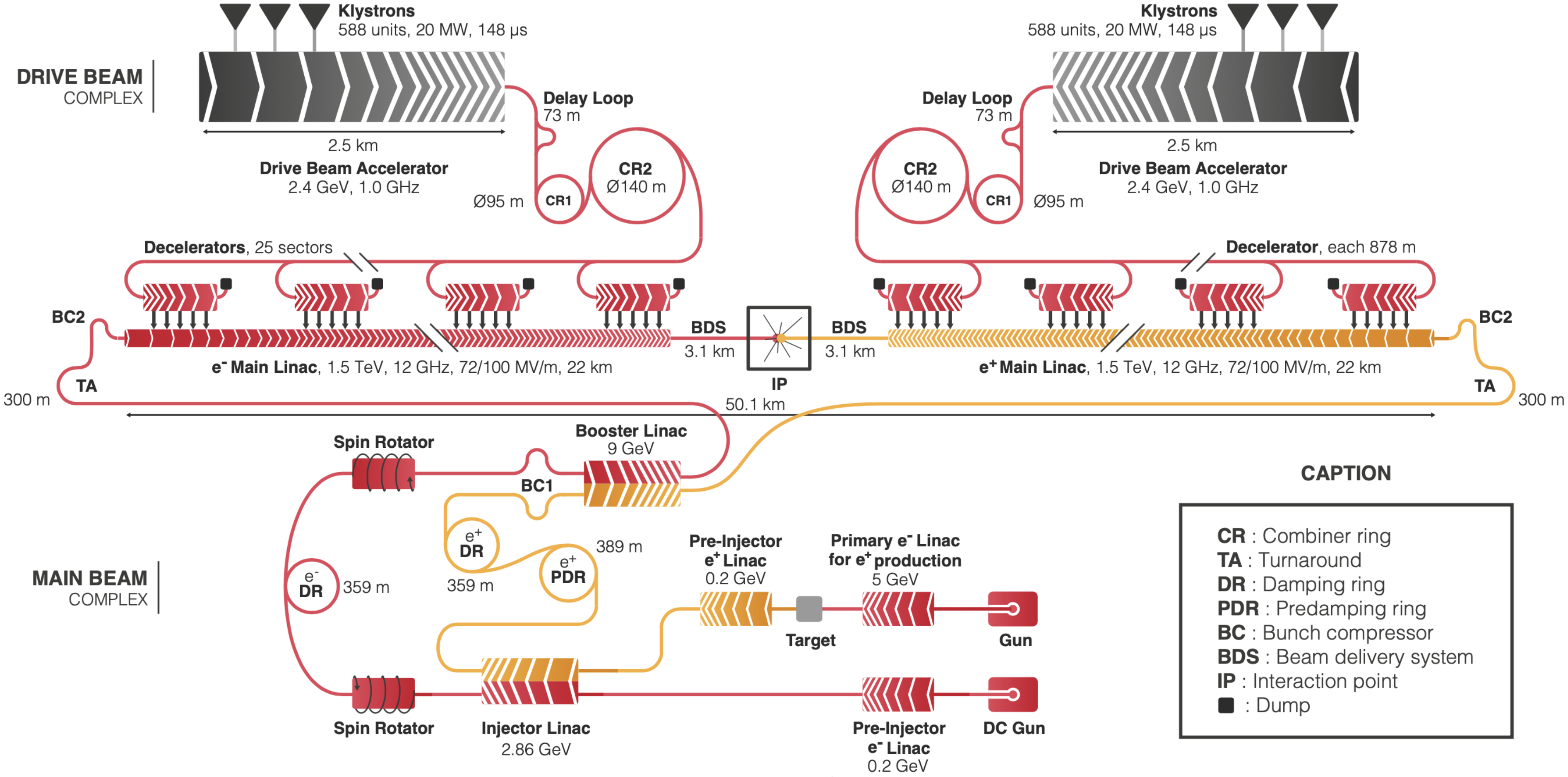
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final

240 ns

5.8 μs

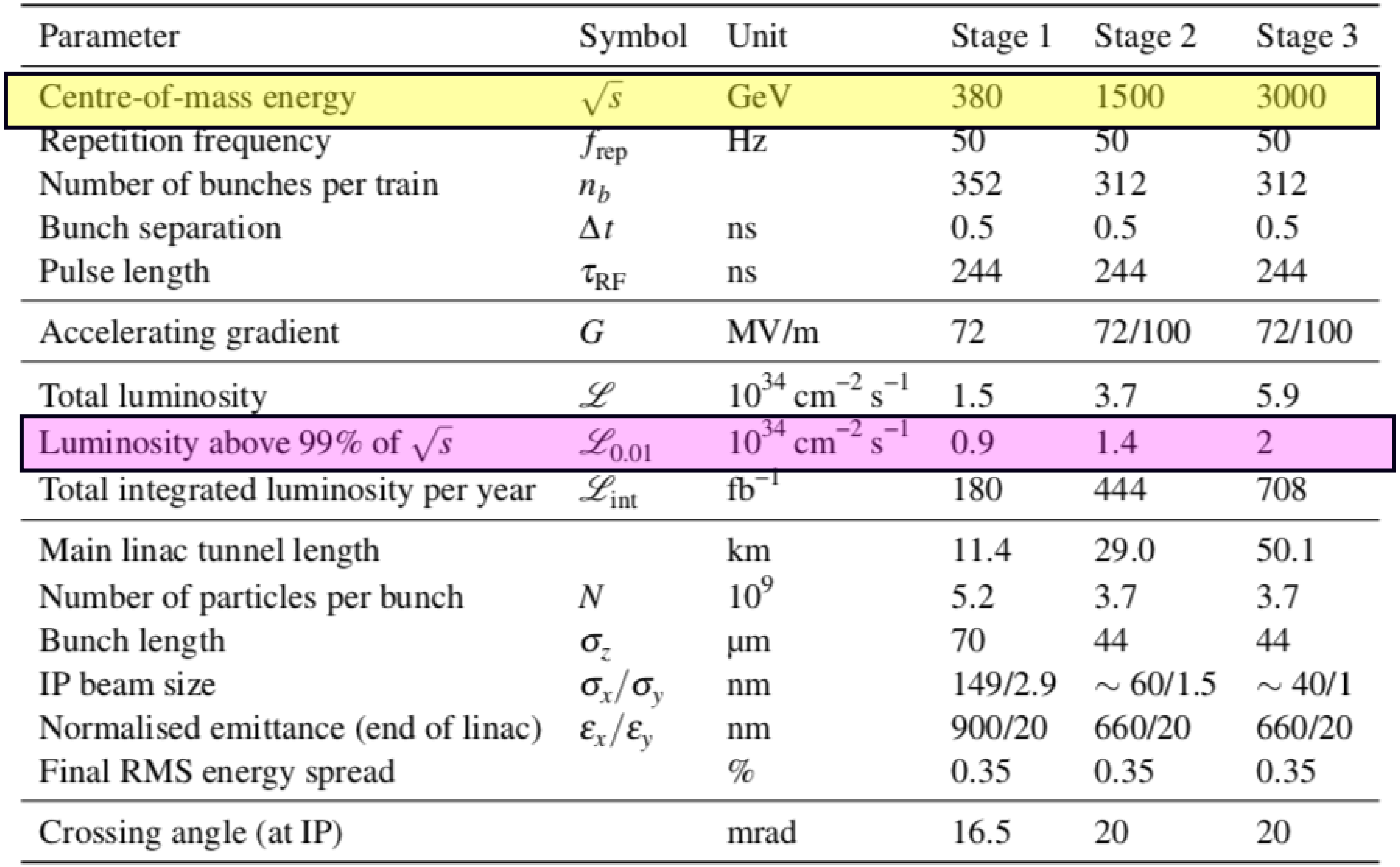
24 pulses – 101 A – 2.5 cm between bunches



CAPTION

CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

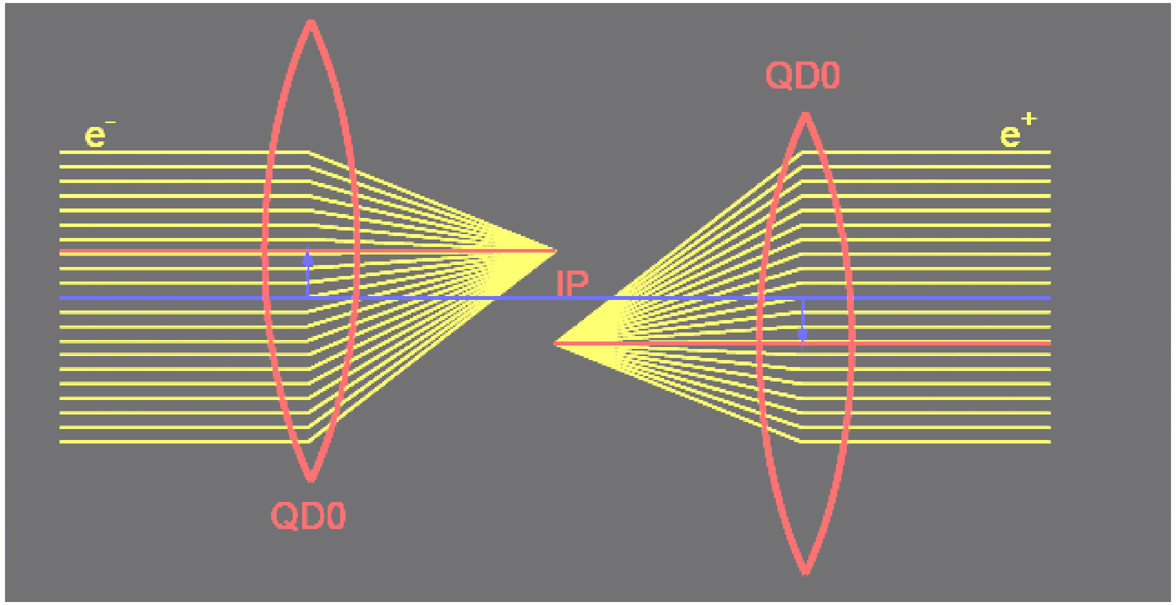
CLIC parameters



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

Another challenge: the beam size

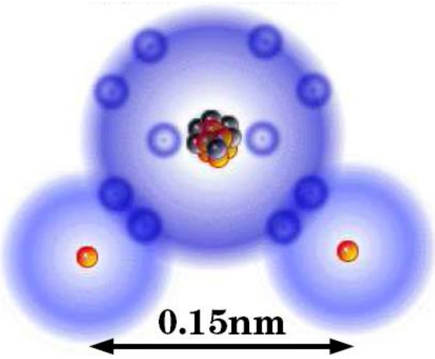
Vertical spot size at IP (Interaction Point) is 1 nm (for CLIC)



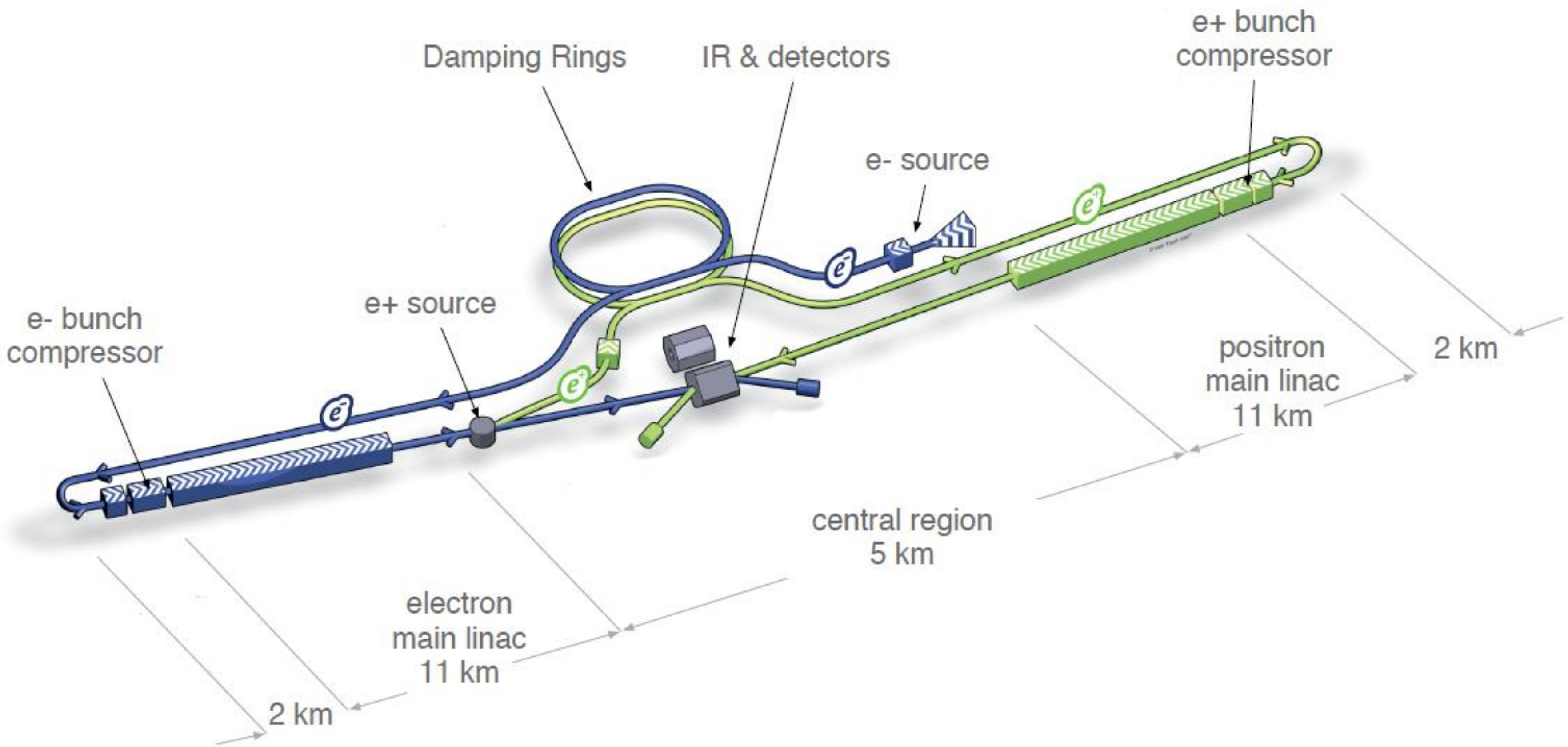
Stability requirements for a 2% loss in luminosity

Magnet	**Horizontal jitter**	**Vertical jitter**
Linac (2600 quads)	14 nm	1.3 nm
Final Focus (2 quads) QD0	4 nm	0.15 nm

H_2O molecule



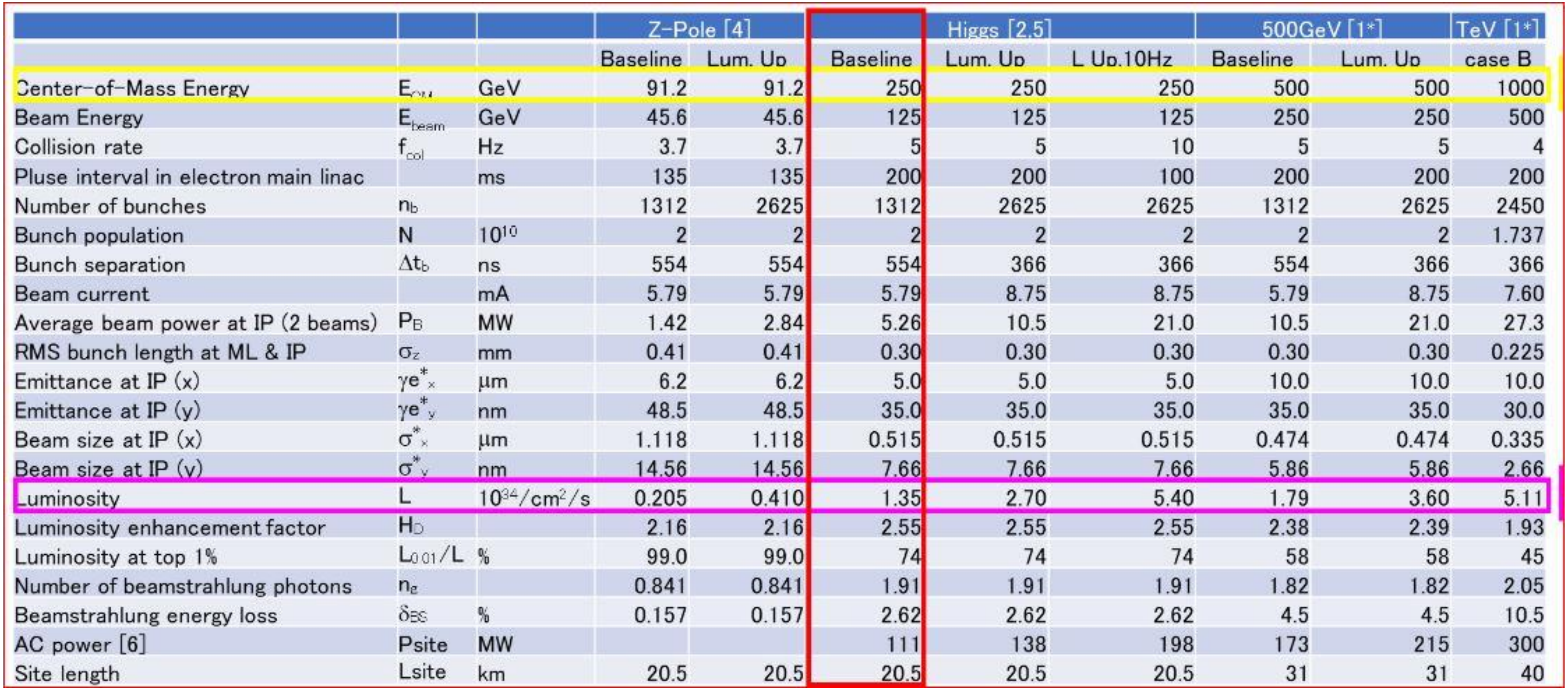
ILC layout



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

ILC parameters

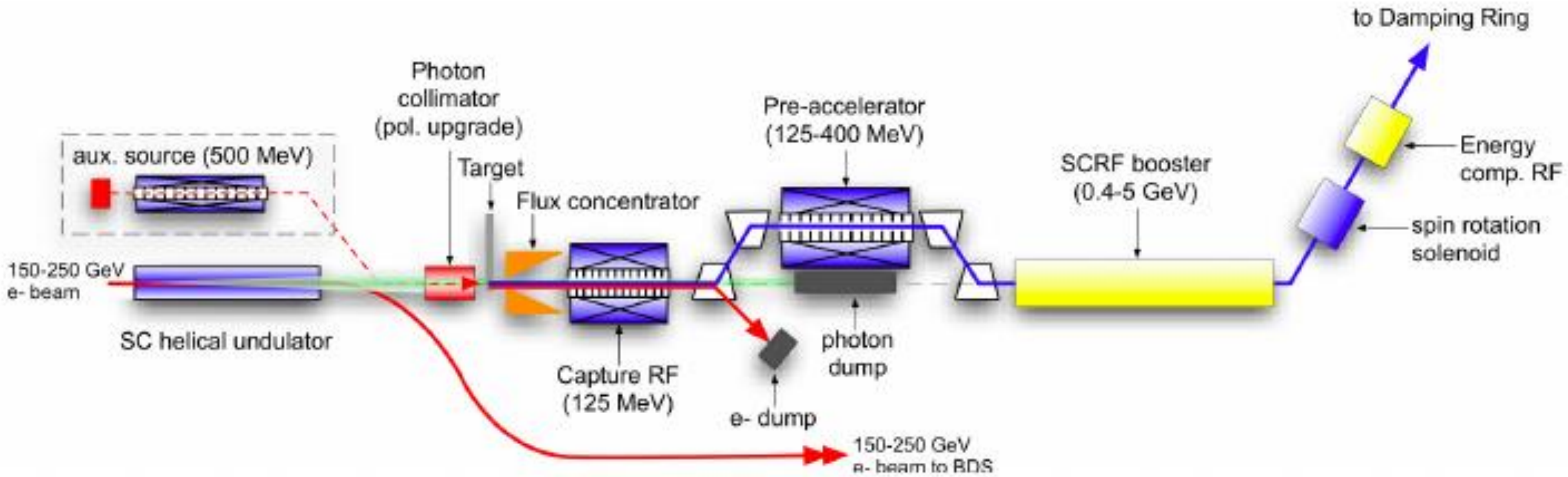
October 2020



			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]	Psite	MW			111	138	198	173	215	300
Site length	Lsite	km	20.5	20.5	20.5	20.5	20.5	31	31	40

Another challenge: the e^+ source

Design a Super-Conducting helical undulator to produce polarized photons
The same main electron beam is used for the Physics and for the e^+ production, for ILC



The main electron beam go through the helical undulator => polarized photons

The photon beam is sent onto a target to produce e^+e^- pairs.

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

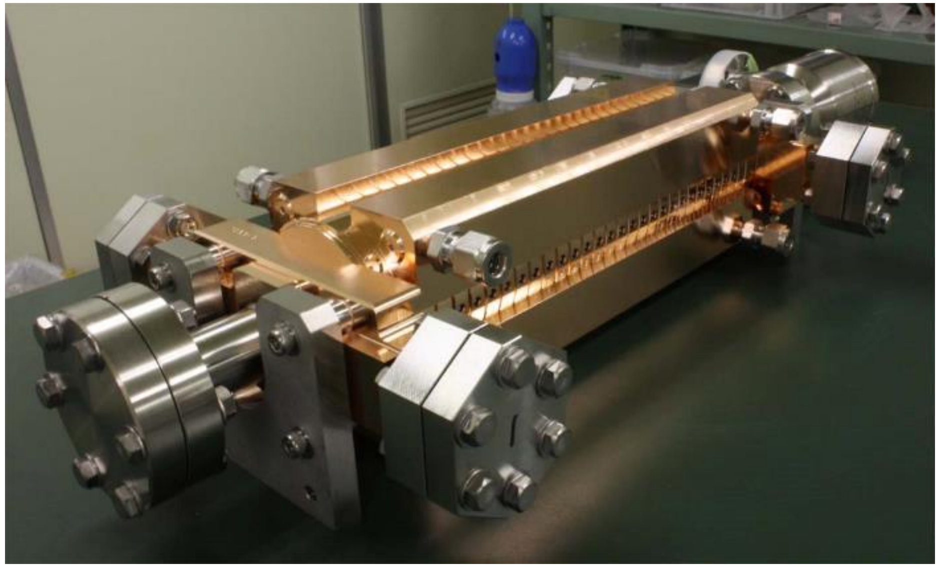
The crucial energy management

Summary of electric power situation in Tohoku

- Power generation facility capacity: Total 27.5GW
  - Total renewable power: 32 %
  - ILC peak power: 0.5 % of total capacity
- Electricity sales volume in 2017: 72 TWh/year
  - Total sustainable power: 22 %
  - Nuclear power: 0 %
  - ILC power demand: 1 % of total sales

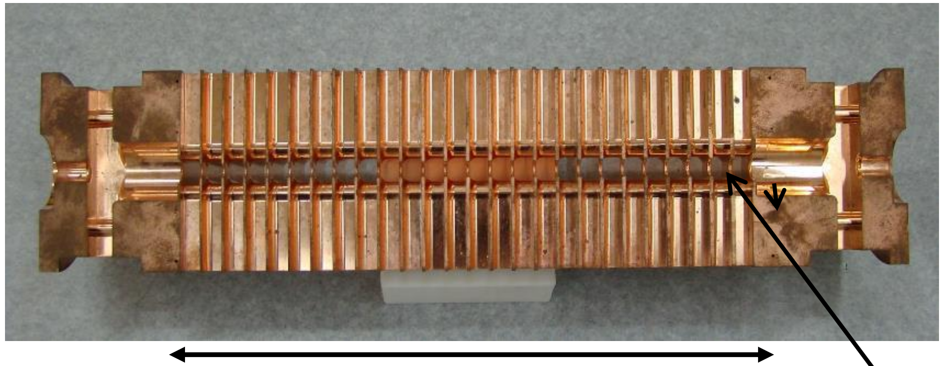
CLIC accelerating structure

Outside



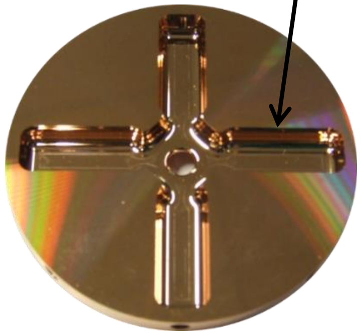
f = 11.994 GHz X-band
E = 100 MV/m
Input power ≈50 MW
Pulse length ≈240 ns
Repetition rate 50 Hz

Inside



25 cm

6 mm diameter beam aperture



HOM damping waveguide

Micron–precision disk

CLIC publications


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

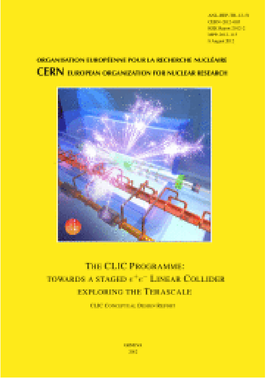
GENEVA
2012


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

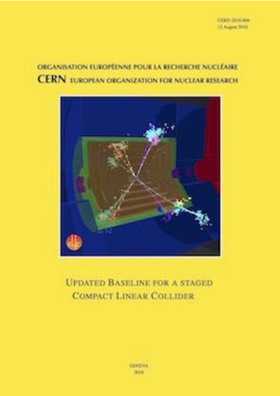
THE CLIC PROGRAMME:
TOWARDS A STAGED e^+e^- LINEAR COLLIDER
EXPLORING THE TERASCALE

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Conceptual Design Report CDR 2012

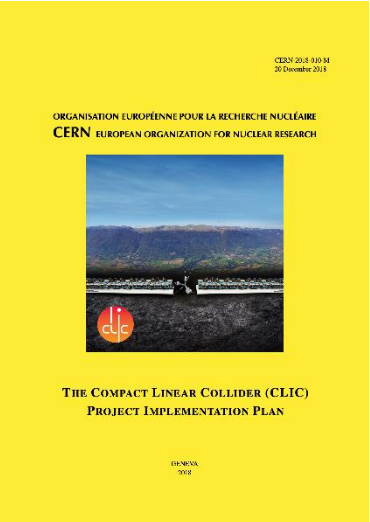
https://cds.cern.ch/record/1500095
https://cds.cern.ch/record/1425915
https://cds.cern.ch/record/1475225


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

GENEVA
2016

Updated Staging
Baseline 2016


CERN 2018-010-M
20 December 2018

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE COMPACT LINEAR COLLIDER (CLIC)
PROJECT IMPLEMENTATION PLAN

GENEVA
2018

Vol. 4 (2018): The Compact Linear Collider (CLIC) – Project Implementation Plan

The project status has been presented in a series of Yellow Reports
http://clic.cern/european-strategy

The CLIC project:
updated April 2022

https://arxiv.org/abs/2203.09186

ILC publications

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

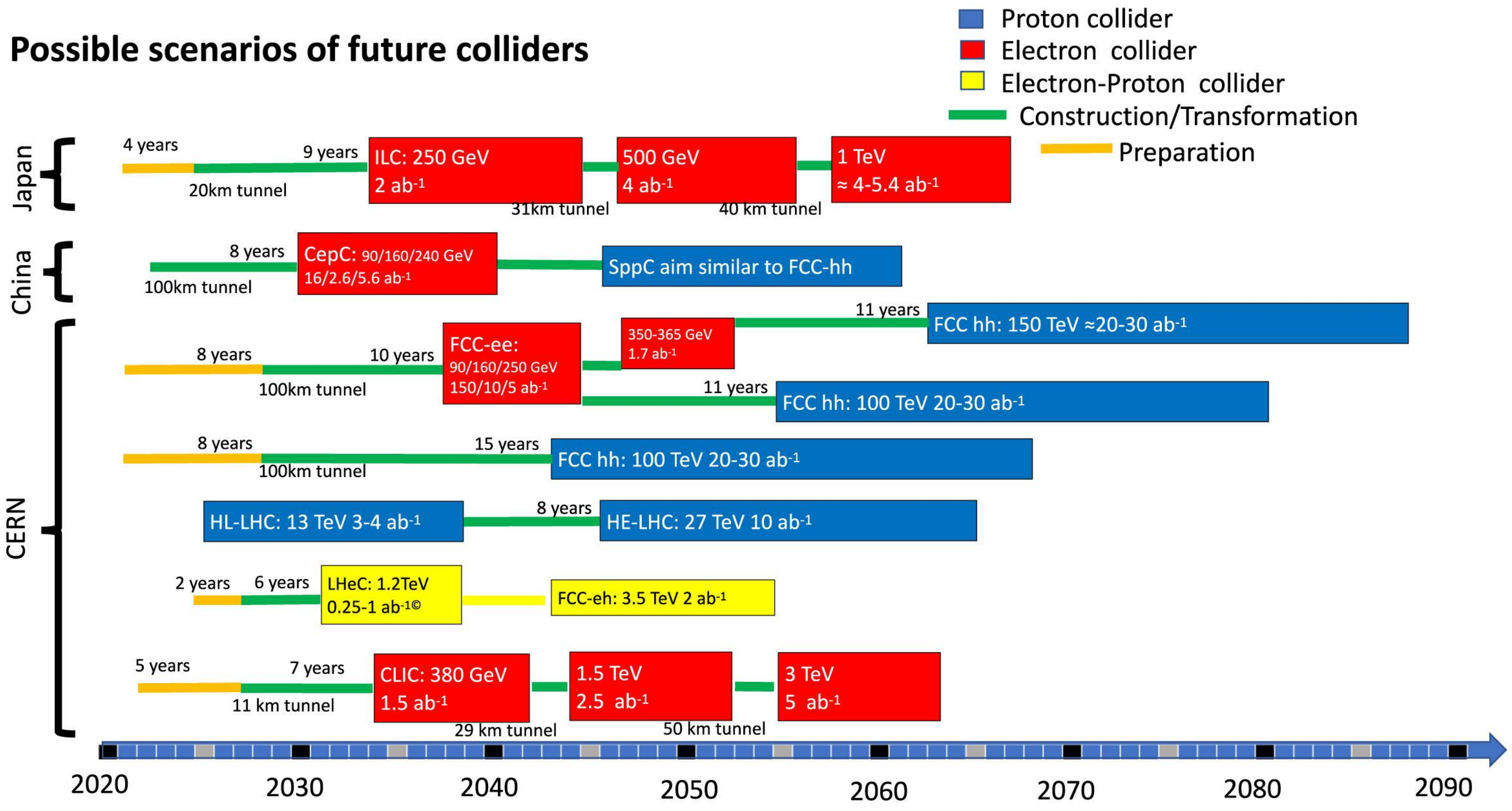
Download the pdf (66 MB)

From Design to Reality

Download the pdf (5.5 MB)

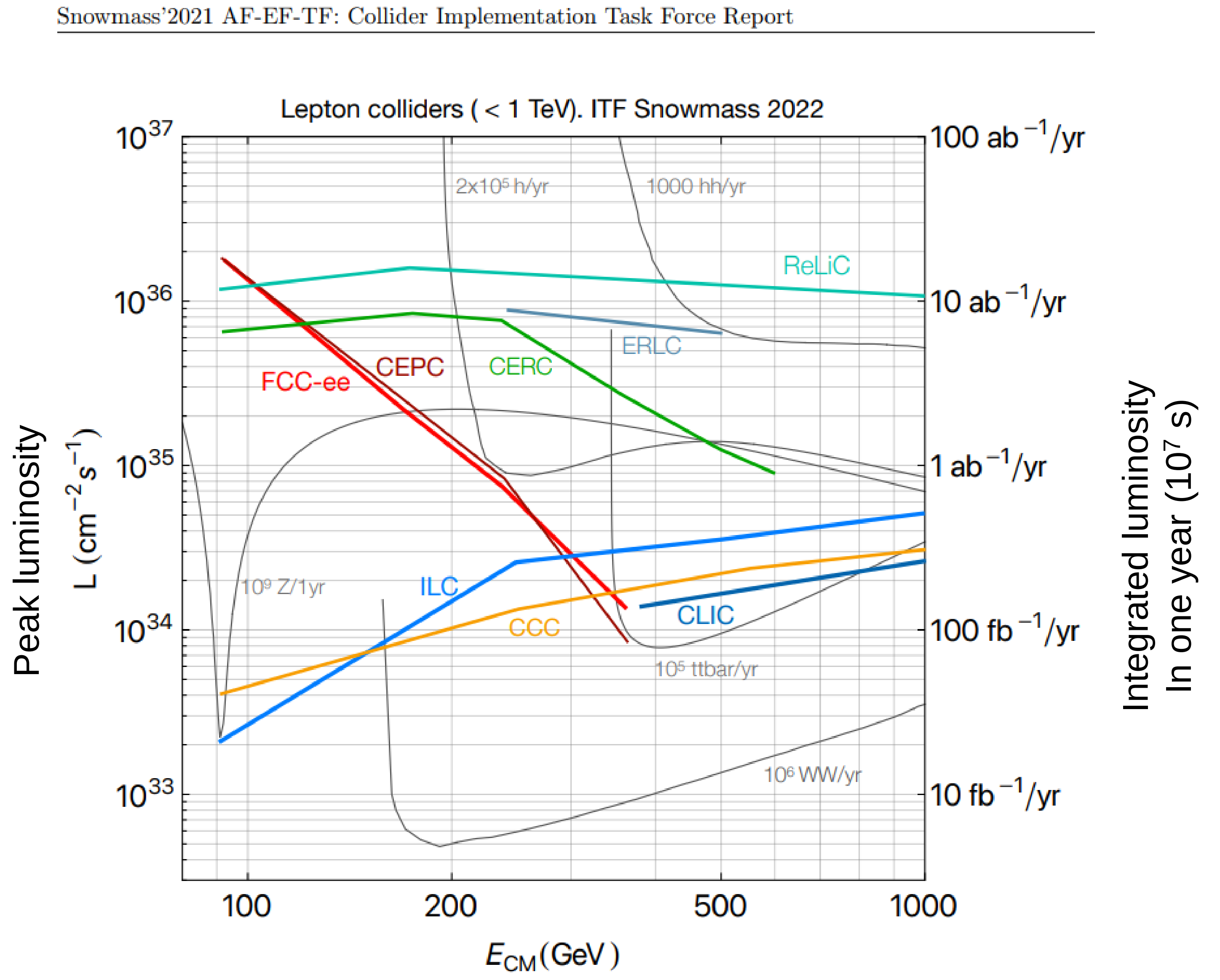
Visit the web site

Possible scenarios of future colliders



Ursula Bassler @ Granada open symposium – May 2019

Proposals of lepton colliders



Snowmass'2021 AF-EF-TF: Collider Implementation Task Force Report

Report of the Snowmass'21 Collider Implementation Task Force

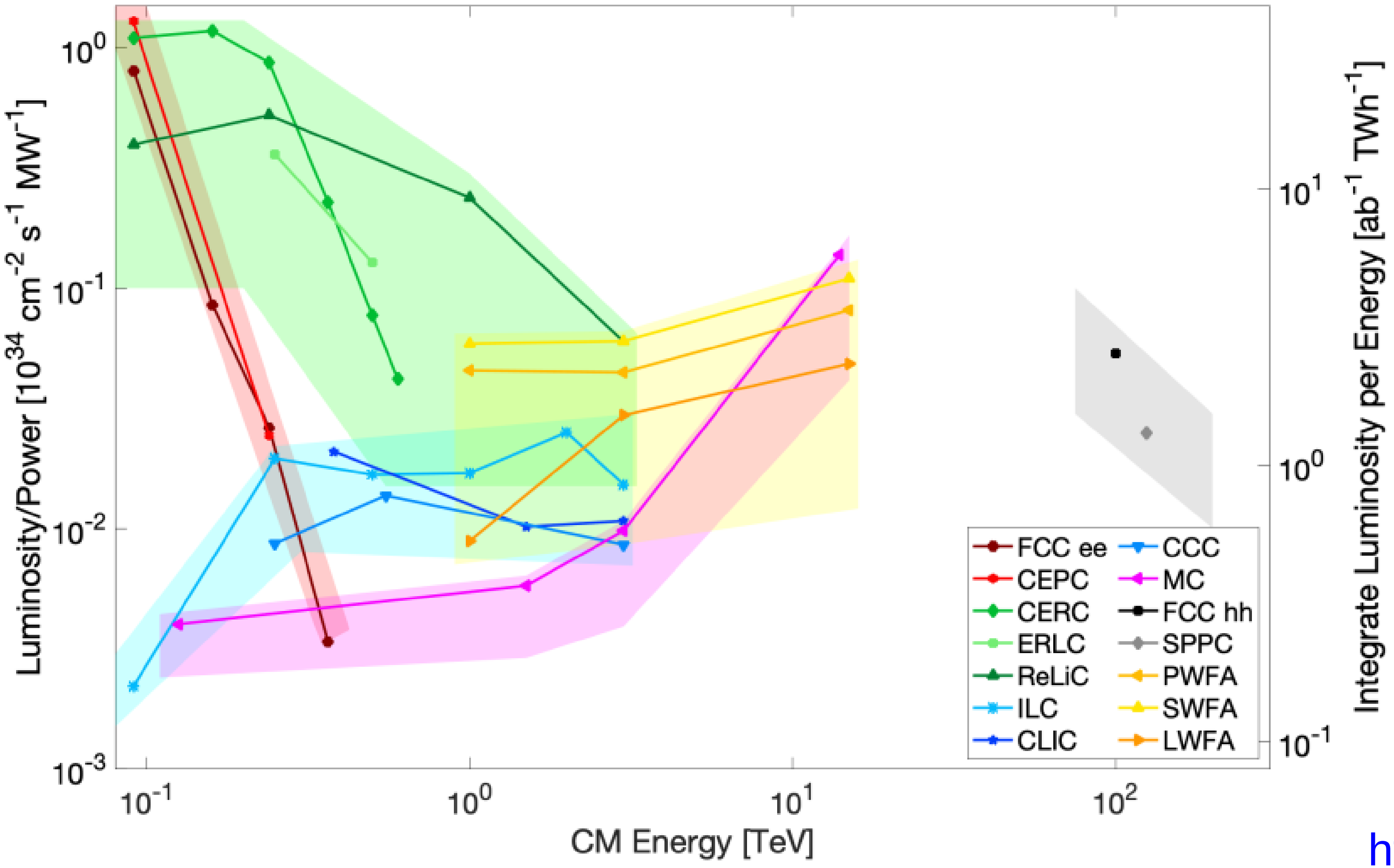
https://arxiv.org/pdf/2208.06030.pdf

Black lines represent yearly production rates of important processes related to elementary particles: Z, W, H, t quark, …

Present R&D :
Design and built a Higgs factory

=> A very large range of physics studies for future colliders

Figure-of-merit for peak luminosity and integrated luminosity for future colliders



The peak luminosity is normalized per input power.

The integrated luminosity is normalized per energy consumption

The bands around the data points reflect the power consumption uncertainty

Report of the Snowmass'21 Collider Implementation Task Force

https://arxiv.org/pdf/2208.06030.pdf

Colliders: 16 Options at Snowmass 2021

9:00 AM → 9:10 AM **Introduction: goals, format, etc**

9:10 AM → 9:25 AM **FCCee**
Speaker: Katsunobu Oide (KEK)

9:25 AM → 9:40 AM **CepC**
Speaker: Yu Chenghui

9:40 AM → 9:55 AM **ILC**
Speaker: Shinichiro MICHIZONO (KEK)

9:55 AM → 10:10 AM **CLIC**
Speaker: Steinar Stapnes (FNAL)

10:10 AM → 10:25 AM **EIC**
Speaker: Christoph Montag (BNL)

10:25 AM → 10:40 AM **LHeC**
Speaker: Oliver Bruning (CERN)

10:40 AM → 10:55 AM **HE-LHC**
Speaker: Frank Zimmermann (CERN)

10:55 AM → 11:10 AM **SppC**
Speaker: Jingyu Tang (Institute of High Energy Physics)

11:10 AM → 11:25 AM **FCChh**
Speaker: Michael Benedikt

9:00 AM → 9:10 AM **Introduction: gioals, format, etc**

9:10 AM → 9:30 AM **Cold NC-Linear Collider**
Speaker: Emilio Nanni (SLAC National Accelerator Laboratory)

9:30 AM → 9:50 AM **ERL based FCCee**
Speaker: Thomas Roser (BNL)

9:50 AM → 10:10 AM **Gamma-Gamma Higgs factories**
Speaker: Frank Zimmermann (CERN)

10:10 AM → 10:30 AM **Plasma-Laser WFA 1 TeV +**
Speaker: Carl Schroeder (Lawrence Berkeley National Laboratory)

10:30 AM → 10:50 AM **Plasma-Beam WFA 1 TeV +**
Speaker: Spencer Gessner

10:50 AM → 11:10 AM **Structure-beam WFA 1 Tev +**
Speaker: John Power (Argonne National Lab)

11:10 AM → 11:30 AM **Muon Coliders: Higgs Factory and 3-14 TeV**
Speaker: Daniel Schulte (CERN)

11:30 AM → 12:10 PM **Discussion/ Q&A**

Today vision

For future high energy colliders: four essential parameters:
1) increase the luminosity
2) increase energy
3) reduce the power consumption
4) reduce the cost

} as much as possible

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

What is the best type of particles: e^-/e^+? p / (pbar) ? $\mu^-\mu^+$? Plasma ?, ... ?

What is the best path: high intensity frontier ? high-energy frontier ?

Energy management for future linear colliders is crucial:
=> energy efficiency and sustainability