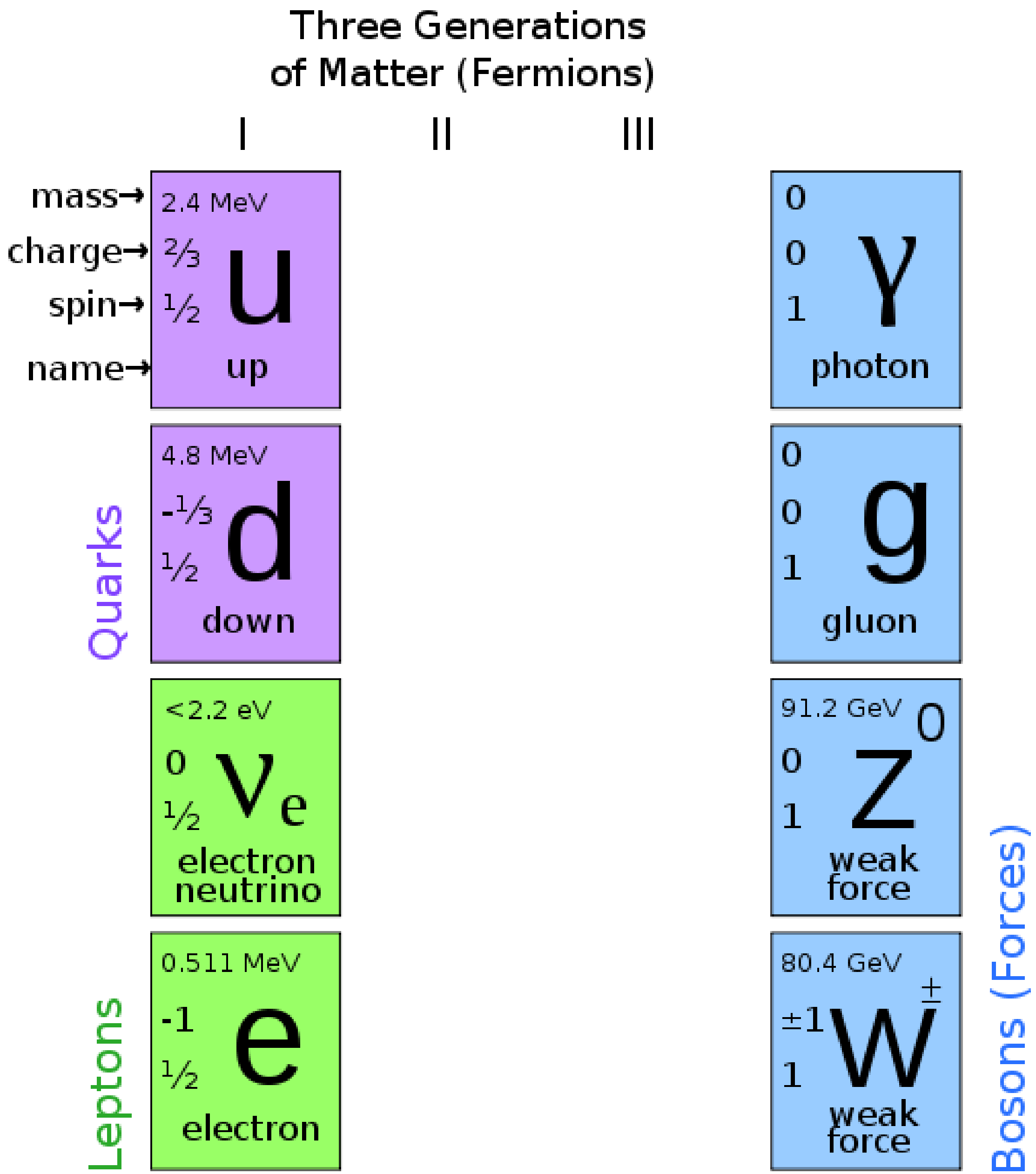
Future Colliders

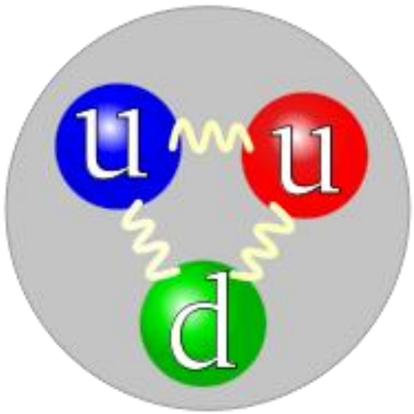
German Teachers Program

Frank Tecker – CERN

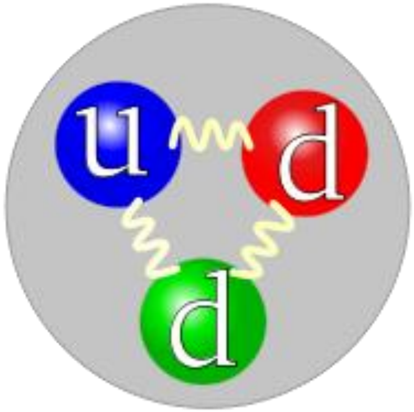
- Physics Motivation
- Hadron Colliders - Rings
  - LHC => HL-LHC
  - FCC-hh
- Lepton Colliders
  - Ring: FCC-ee
  - Linear: ILC / CLIC

The Standard Model (SM)





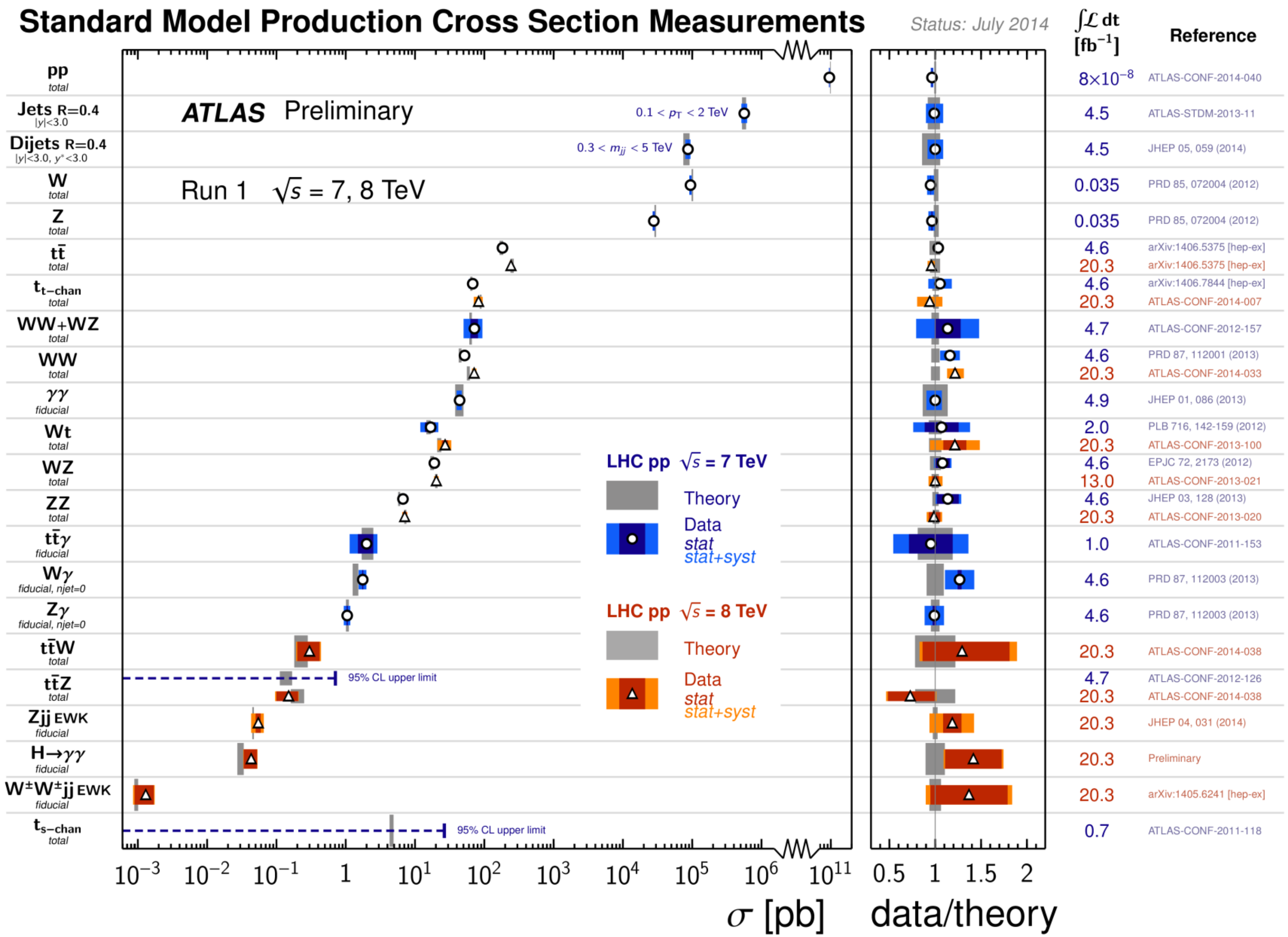
Proton



Neutron

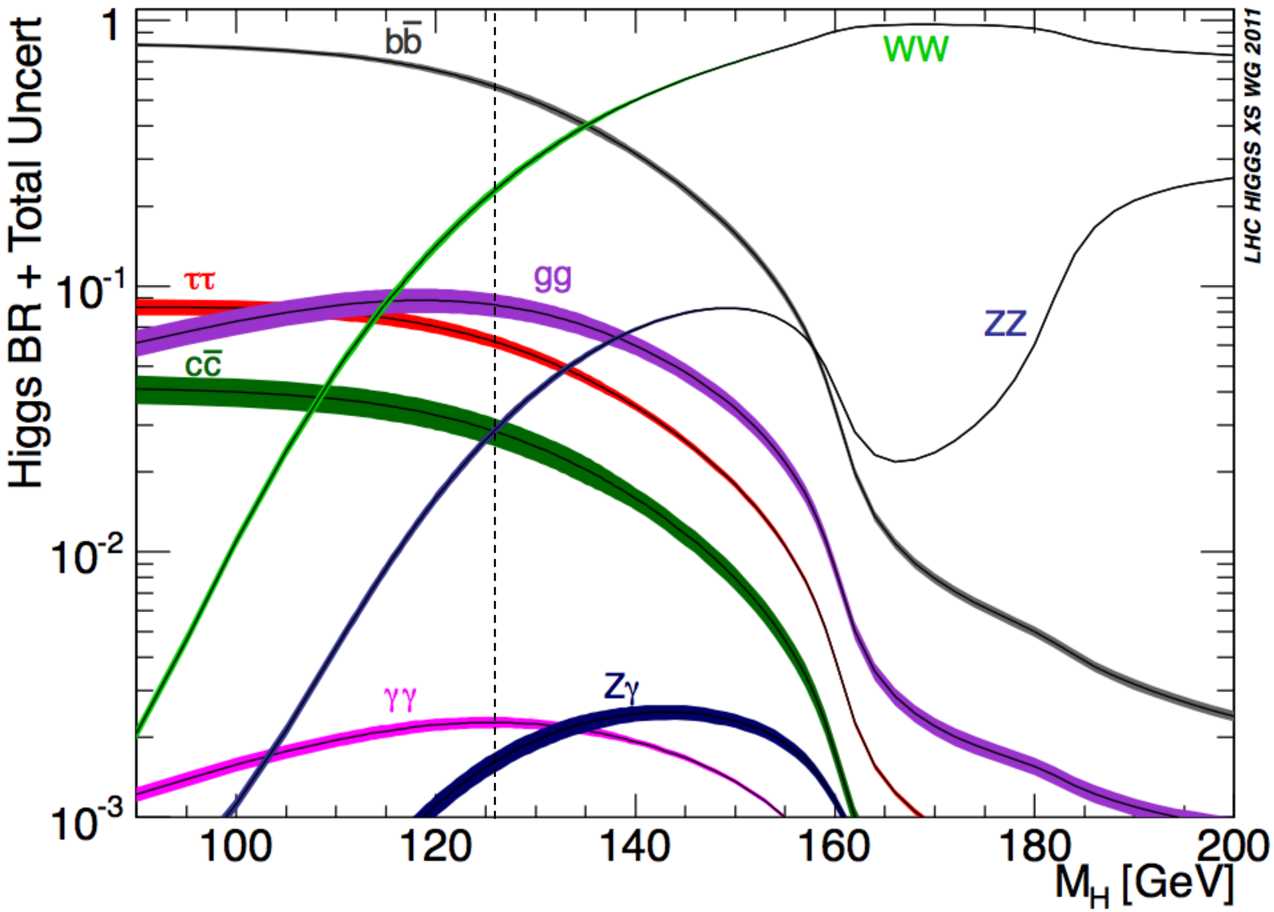
Precision Standard Model physics

- Predictions of Standard Model agree extremely well with measurements



The Higgs particle (in the SM)

- Predicted Higgs branching fractions



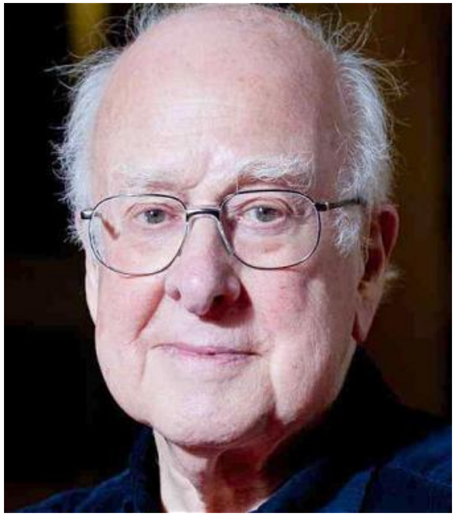
Higgs particle

- predicted in 1964 by Brout, Englert and Higgs

- gives mass to the particles

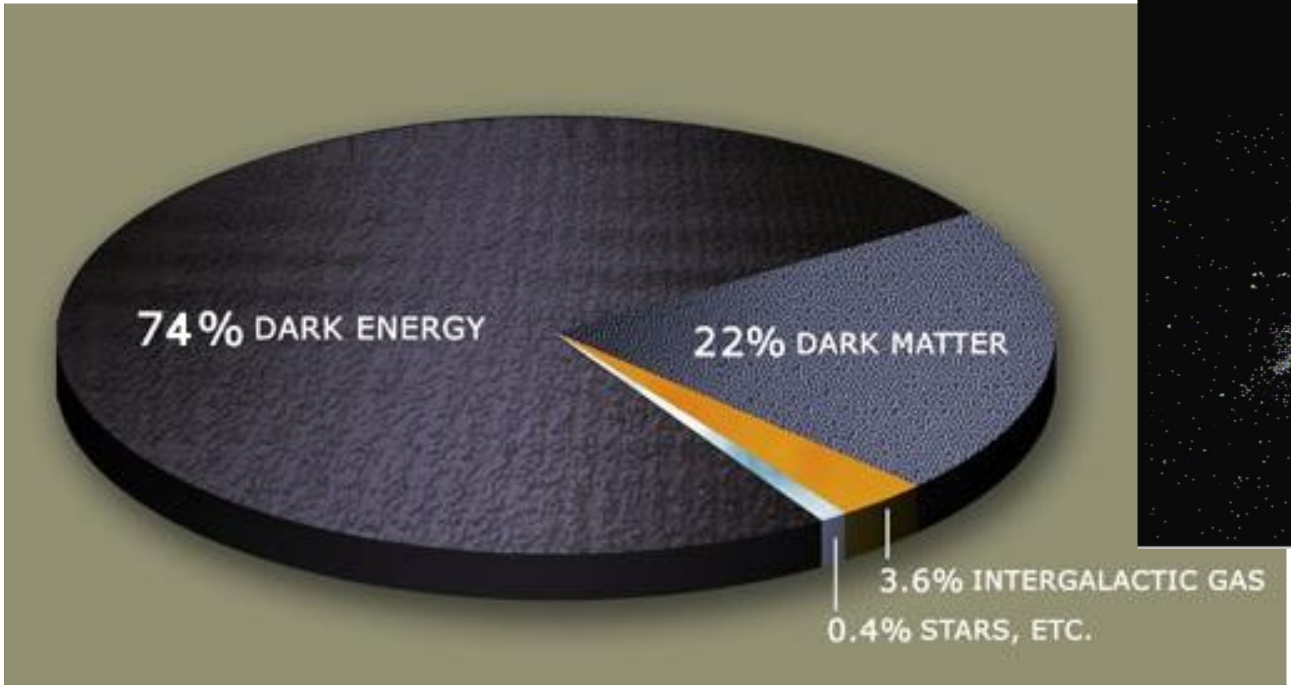
- discovered in 2012 at the LHC

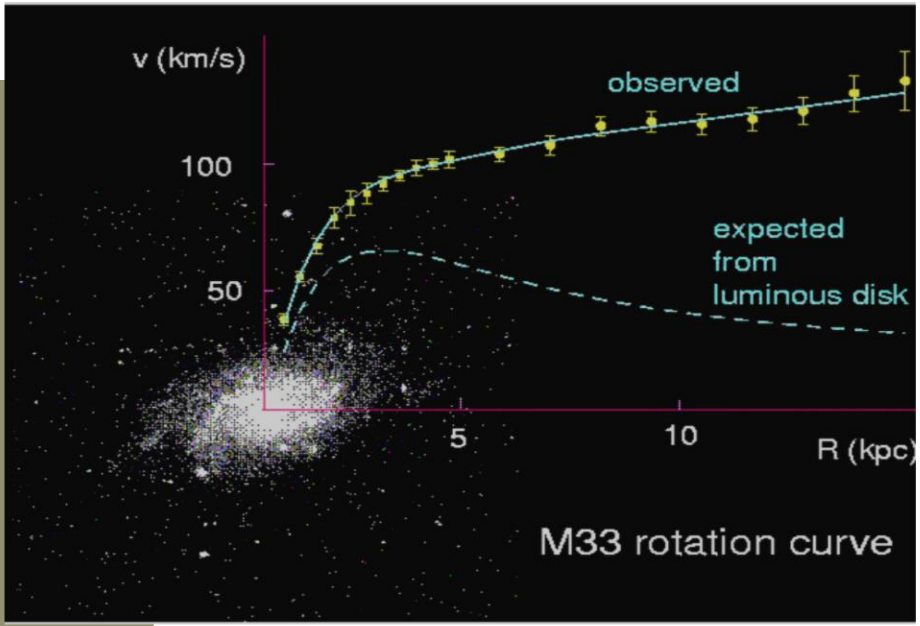
- m_H = 126 GeV is a very good place to be for precision measurements !
  - All decay channels open and measurable – can test new physics from many angles



The Dark Side of the Universe

- Only 4% of the universe is 'ordinary' matter (SM particles)





Dark (invisible) matter!

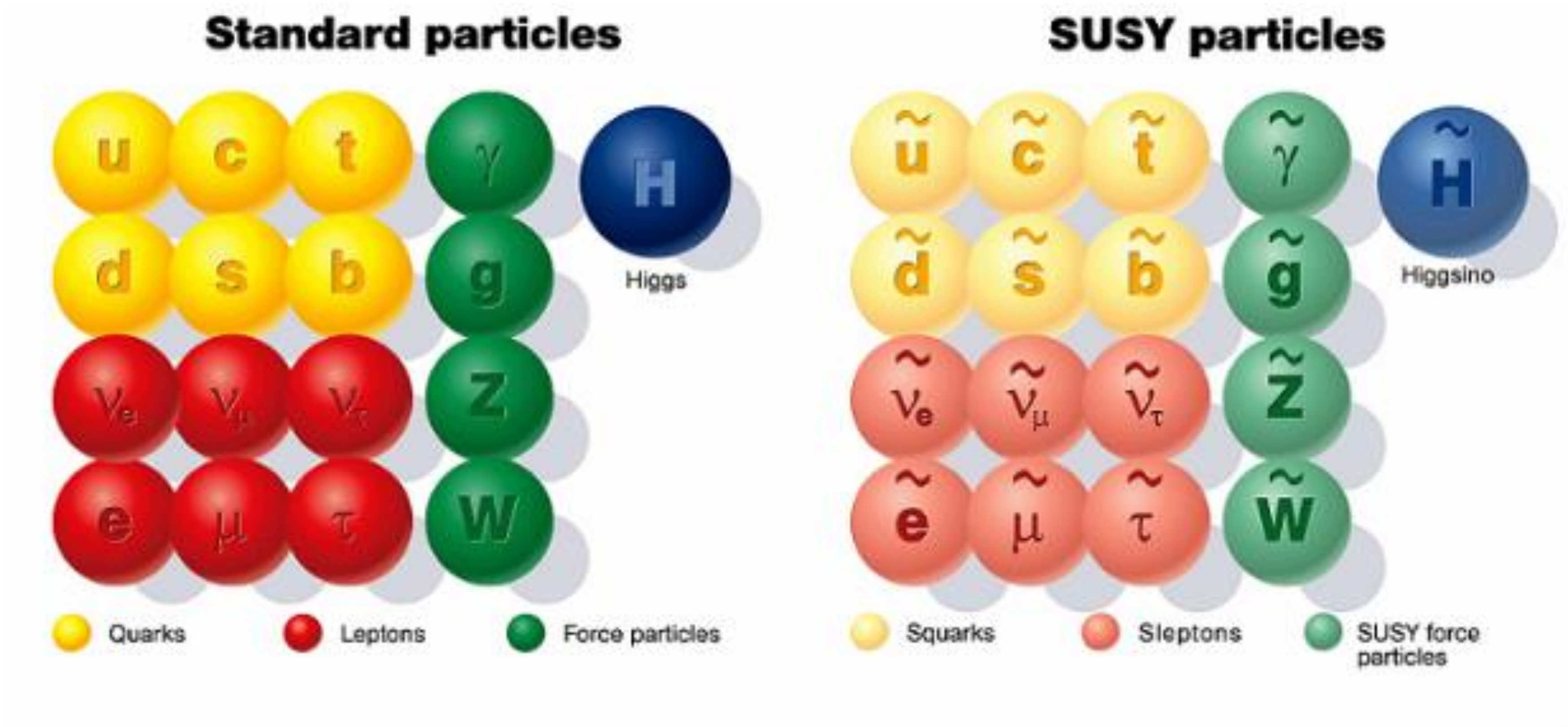
Interacts gravitationally but does not shine

Dark Matter appears to be made of weakly interacting massive particles.

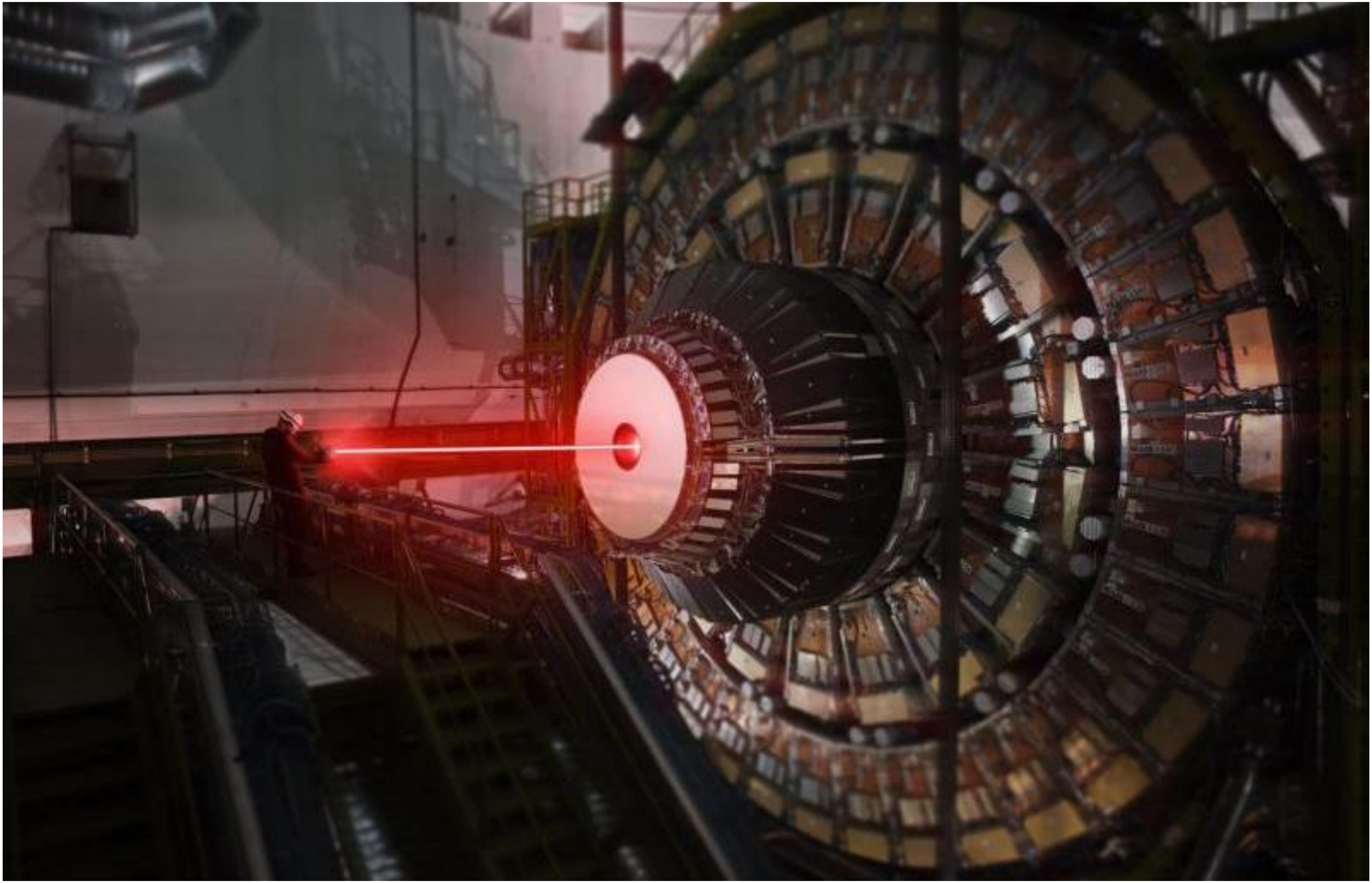
Lightest super-symmetric-particle has these properties !

Supersymmetry - SUSY

- SUSY (super-symmetry):
  for every SM particle, there is a super-partner with spin 1/2 difference
- none of the super-particles seen so far…



The force discovered!!!



Conclusions for Physics

- The LHC Run 1 brought the last experimental proof of the Standard Model ✔
  - The Higgs particle was found
  - Many of its properties measured
  - New physics with a scale below 1 TeV has become quite unlikely
- Upcoming LHC Run 2 and Run 3 with the 8 → 14 TeV increase promises to be thrilling
  - The mass reach for new physics will increase by a factor 2
  - The measurement precision will improve by a factor ~4-5
  - The lighter particle of the new physics spectrum may even be discovered

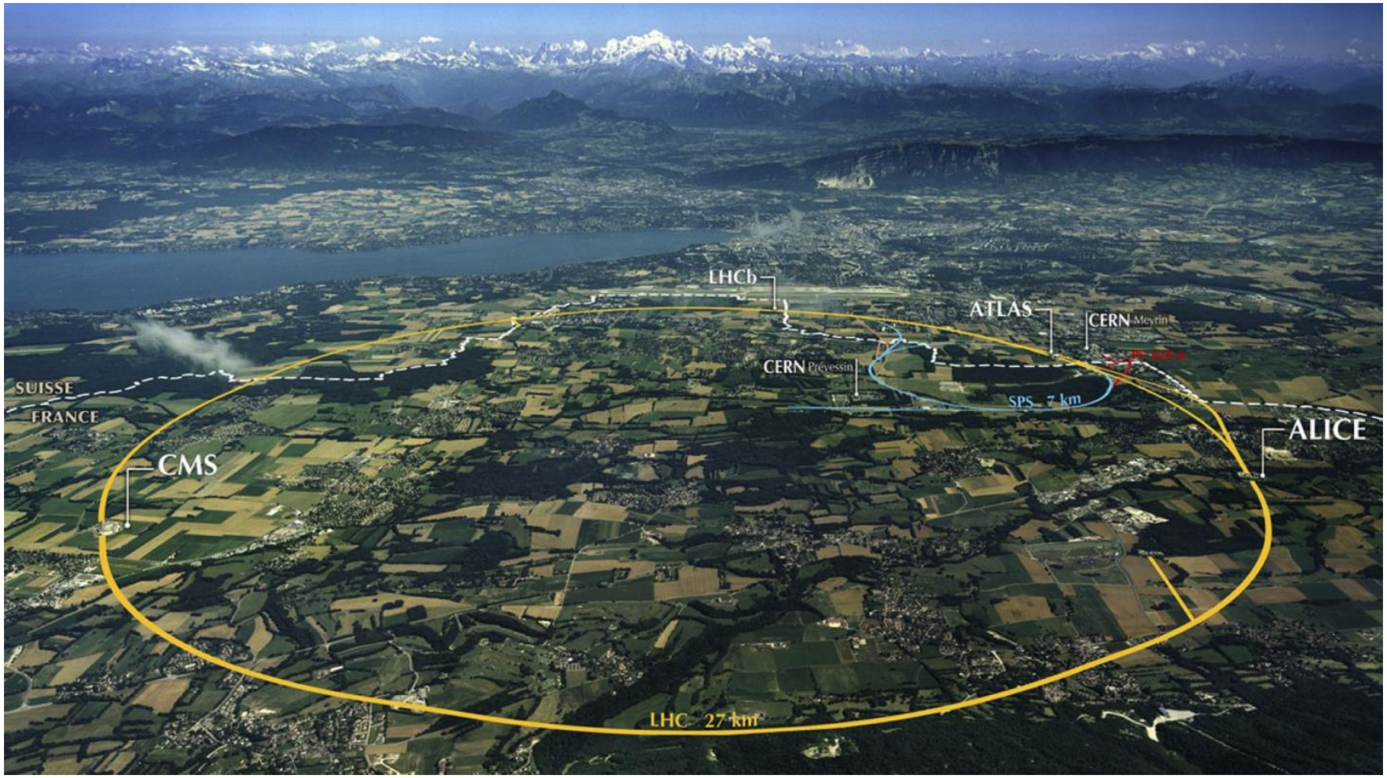
! ! !

- There is for sure something new out there!
- But we are not sure if we will be able to discover it.
- The discoveries / no discoveries at the LHC will set the directions for any future collider

? ? ?

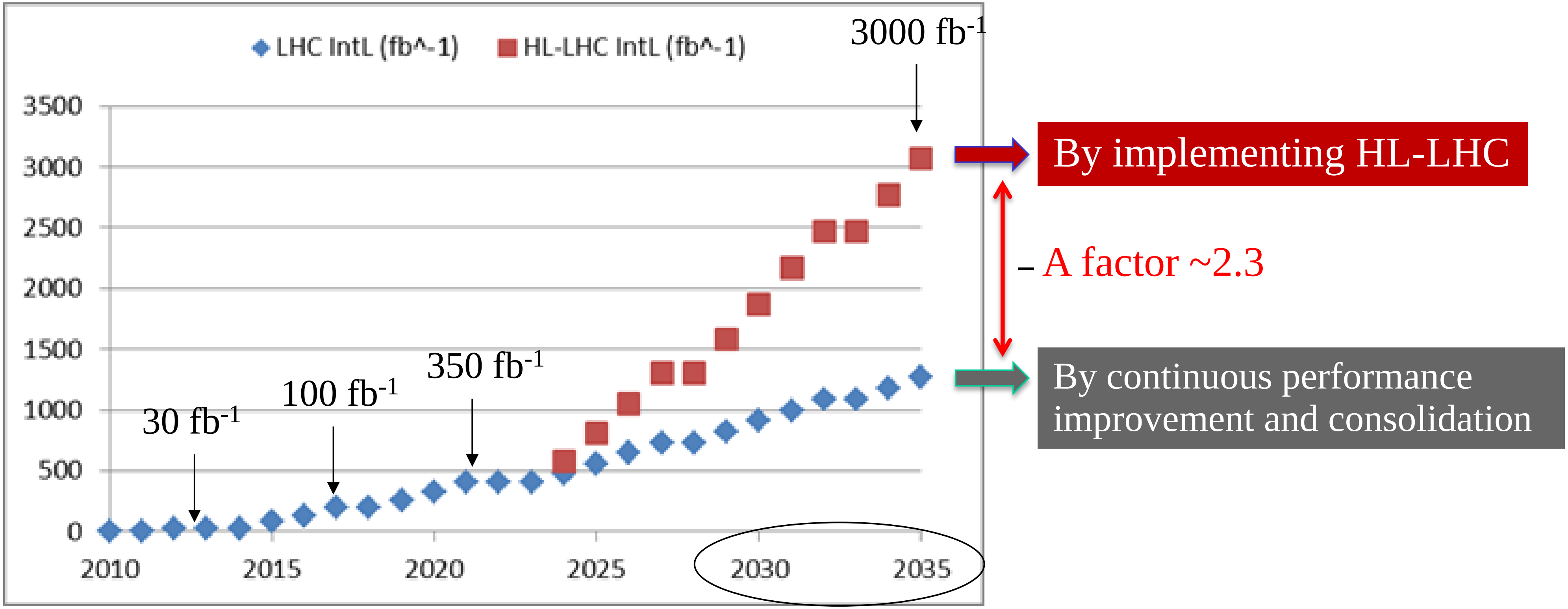
Short-term perspectives (2020-2030)

- European Strategy for Particle Physics (2013) (very similar statements from US)
  - Exploit the full potential of the LHC until ~2030 as the highest priority
    - Get 75-100 fb^{-1} at 13-14 TeV by 2017 (LHC Run2: approved)
    - Get ~350 fb^{-1} at 14 TeV by 2022 (LHC Run3: approved)
    - Upgrade machine and detectors to get 3 ab^{-1} at 14 TeV by 2035 (HL-LHC: project)
      - Addresses both energy and precision frontier

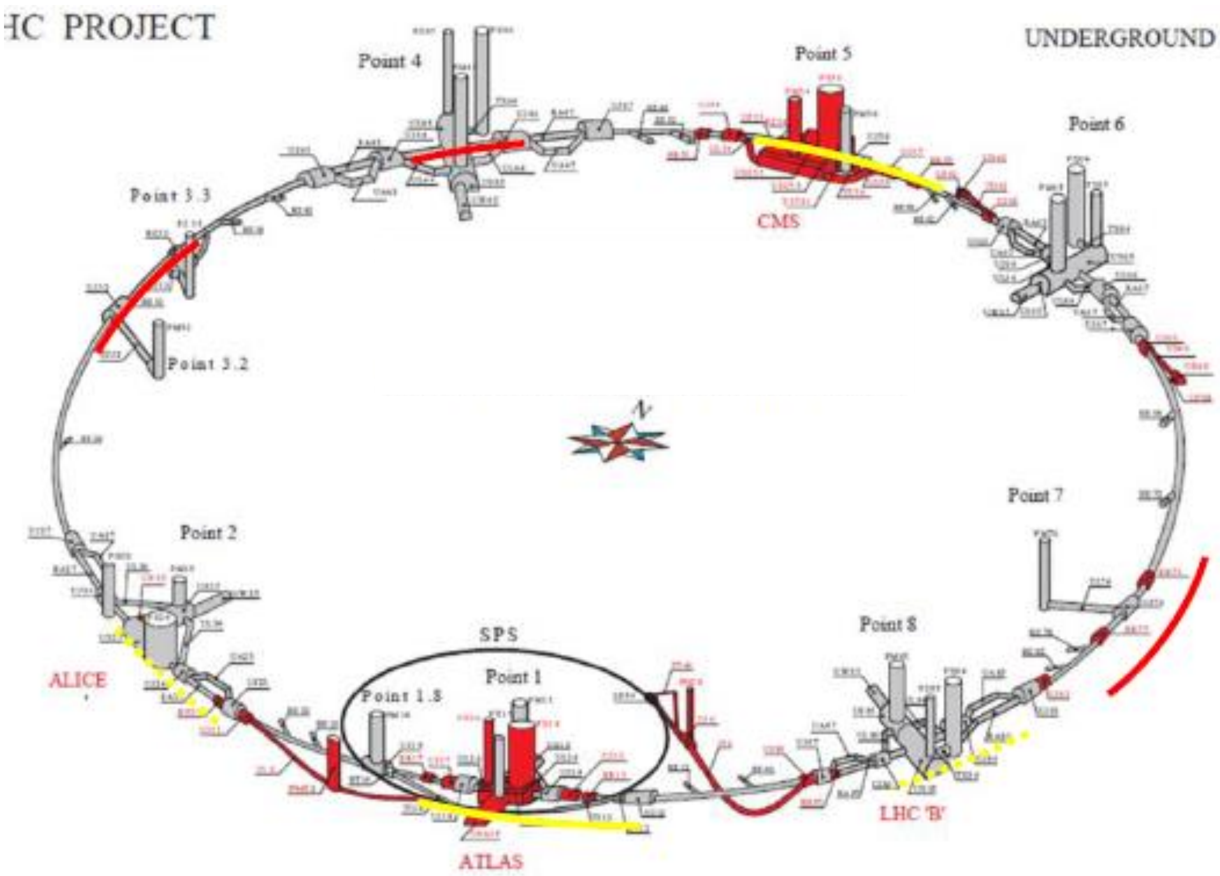


Note on integrated luminosity

- The High Lumi upgrade of the LHC is an ambitious project
  - Target is to deliver ~10 times more luminosity (3 ab^{-1}) than the first 10 LHC years



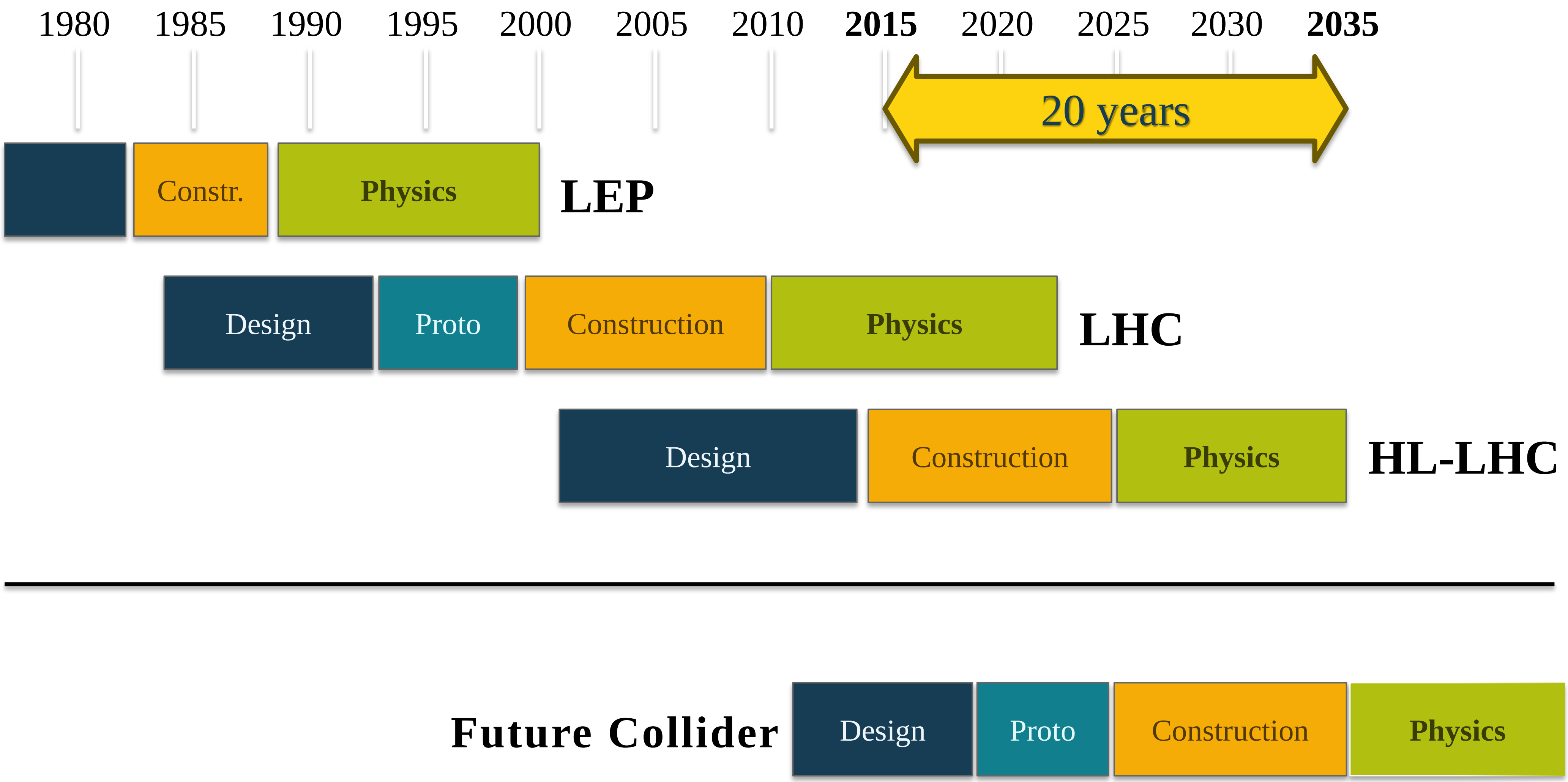
The HL-LHC Project



- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC !!!

CERN Colliders timescale



FCC – Future Circular Collider

International collaboration and study for:

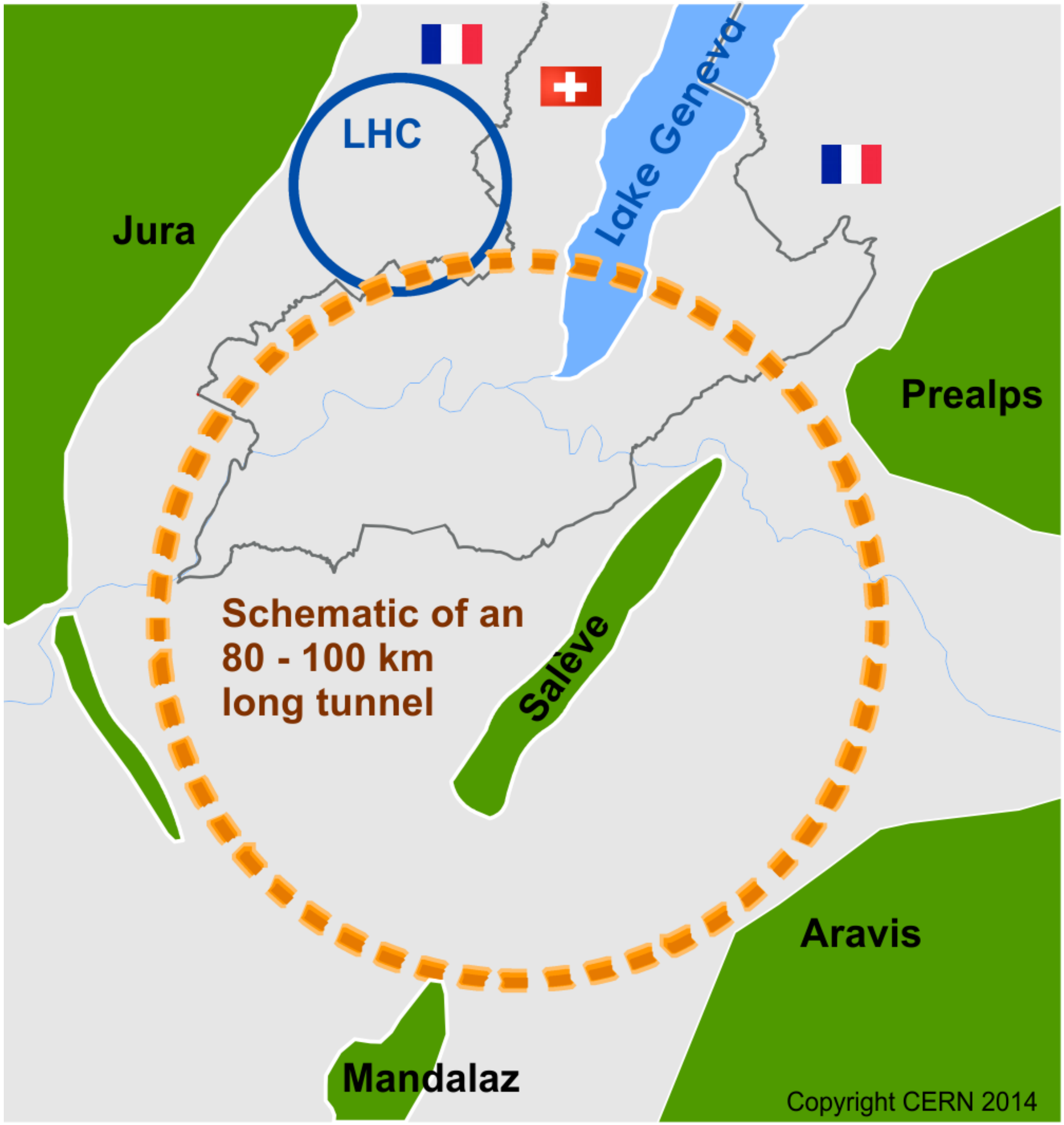
- ***proton-proton*-collider** (***FCC-hh***)

  100 TeV cms energy (80-100 km circumference)

  ⇒ defining infrastructure requirements

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step

- ***p-e*** **(*FCC-he*) option**



FCC Study - Collaboration

FCC Kick-off Meeting
University of Geneva
12-15 February 2014

>340 participants

FCC Collaboration Status

- 51 institutes
- 19 countries
- EC participation

FCC-hh: The Key Challenges

- Energy
  - Limited by the machine size and the strength of the bending dipoles
  => maximise the magnet strength

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

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

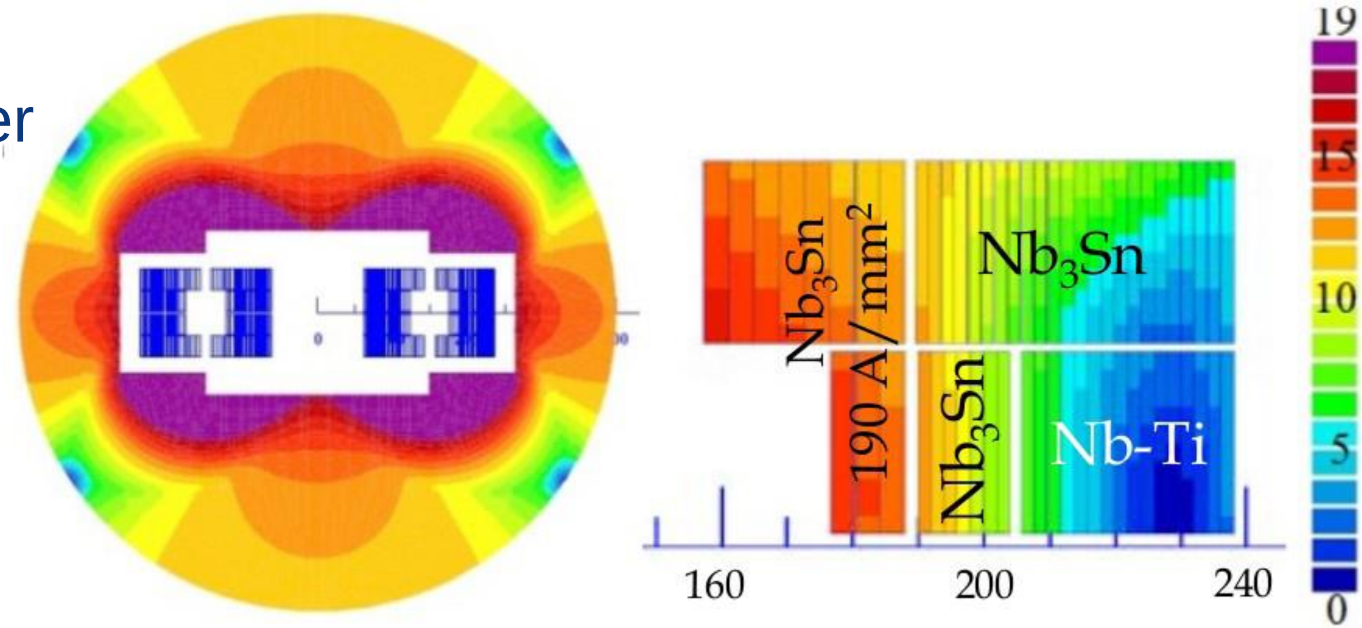
- Cost
  - The total cost is a concern => push everything to the limit to reduce cost

FCC-hh Challenges: Magnets

Arc dipoles are the main cost and parameter driver

Baseline: Nb_3Sn at 16T

HTS at 20T also will be studied as alternative



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

Field level is a challenge but many additional questions:

- Length, weight and cost
- Aperture
- Field quality
- Separation
- Stored energy: O(160GJ) in magnets, O(20) times LHC

  => Serious protection issue

Synchrotron Radiation and Beam Screen

- Protects superconducting magnets from synchrotron radiation

Synchrotron radiation power:
~30W/m/beam in arcs (E_{crit}=4.3keV)
total 5 MW (LHC 7kW)

⇒ Cooling challenge

⇒ Vacuum challenge

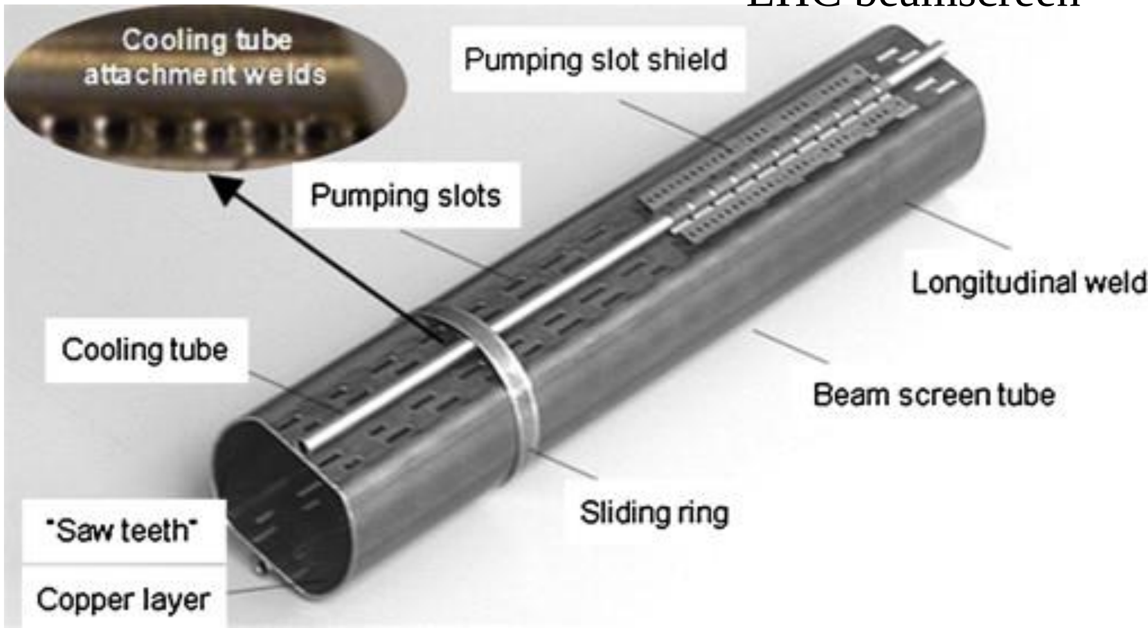
⇒ Impedance challenge

⇒ Mechanical challenge

⇒ Electron cloud

⇒ Cost challenge

LHC beamscreen



Choice of beamscreen temperature is 50K

Good vacuum between 40-60K

5MW synchrotron radiation => 100MW of cooling power

FCC-hh challenges

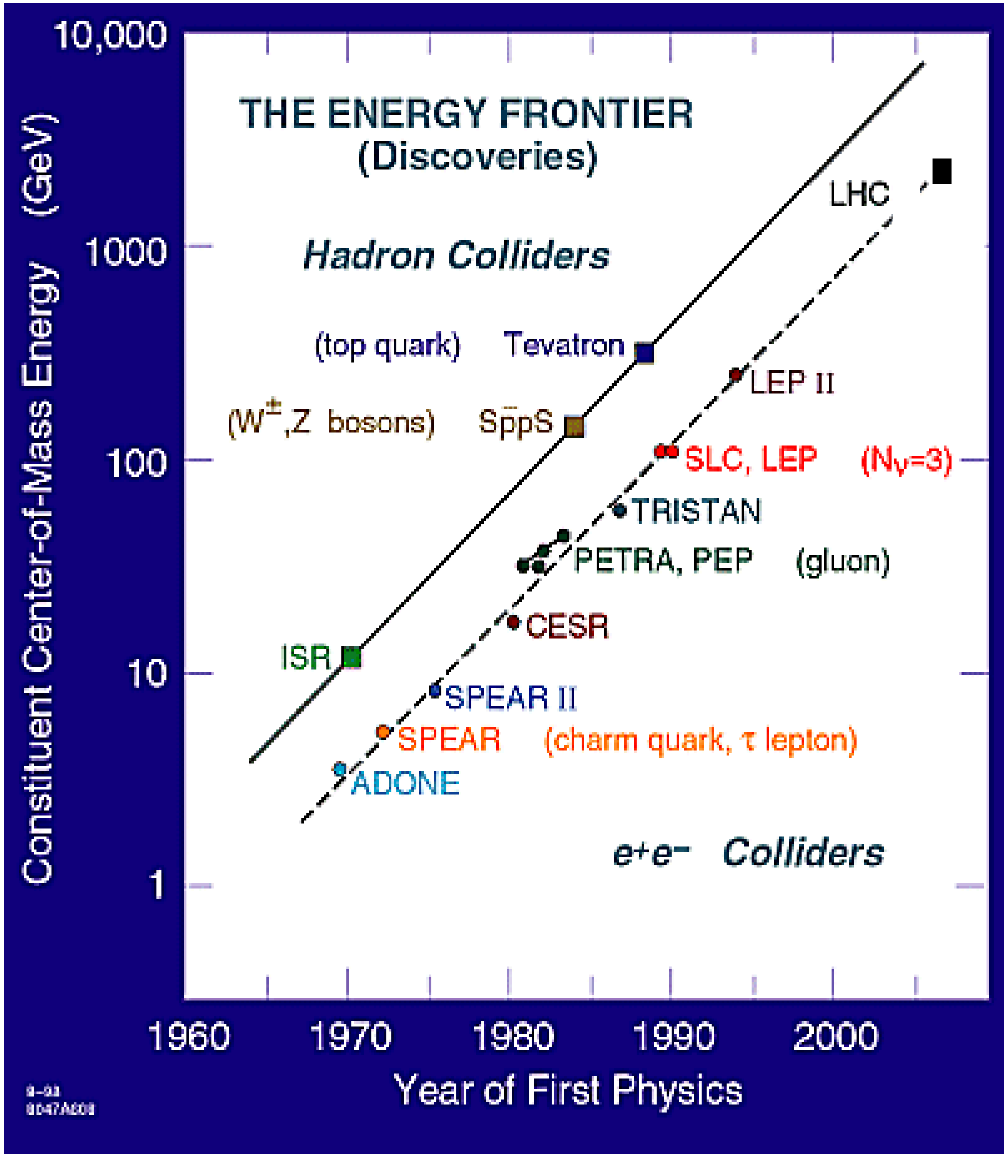
- Stored energy 8 GJ per beam, 16 GJ total
  - 20 times higher than LHC
  - 2000 kg TNT per beam, can melt 12 tons of copper
  - Equivalent to A380 (560 t) at nominal speed (850 km/h)

- => Collimation, control of beam losses and radiation effects very important
- Injection, beam transfer and dump very critical
- Machine protection issues to be addressed early on!

- so far for protons…

- now to leptons…

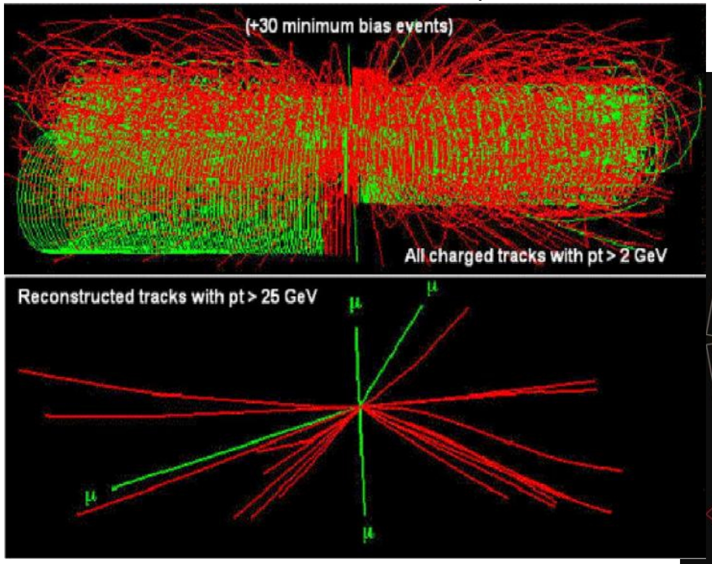
Path to higher energy

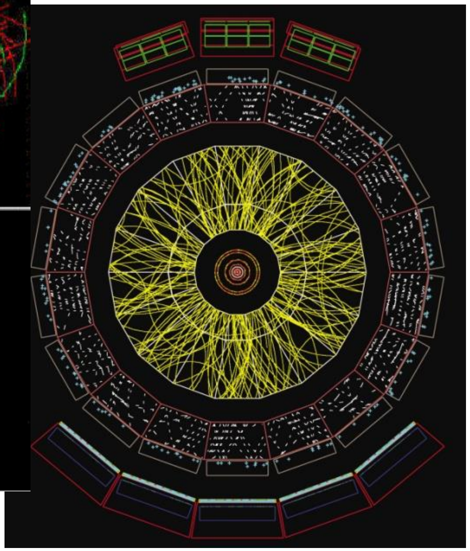


- History:
  - Energy constantly increasing with time
  - Hadron Colliders at the energy frontier
  - Lepton Colliders for precision physics
- LHC has found the Higgs with $m_H = 126\ GeV/c^2$
- A future Lepton Collider would complement LHC physics

Hadron vs. Lepton Collisions

LHC: H $\rightarrow$ ZZ $\rightarrow$ 4μ

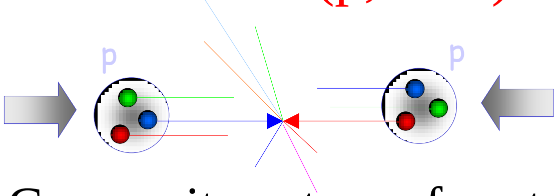




ALICE: Ion event

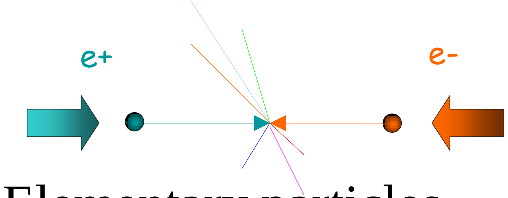
LEP event: $Z^0 \rightarrow$ 3 jets

- Hadron Collider (p, ions):



  - Composite nature of protons
  - Can only use p_t conservation
  - Huge QCD background

- Lepton Collider:

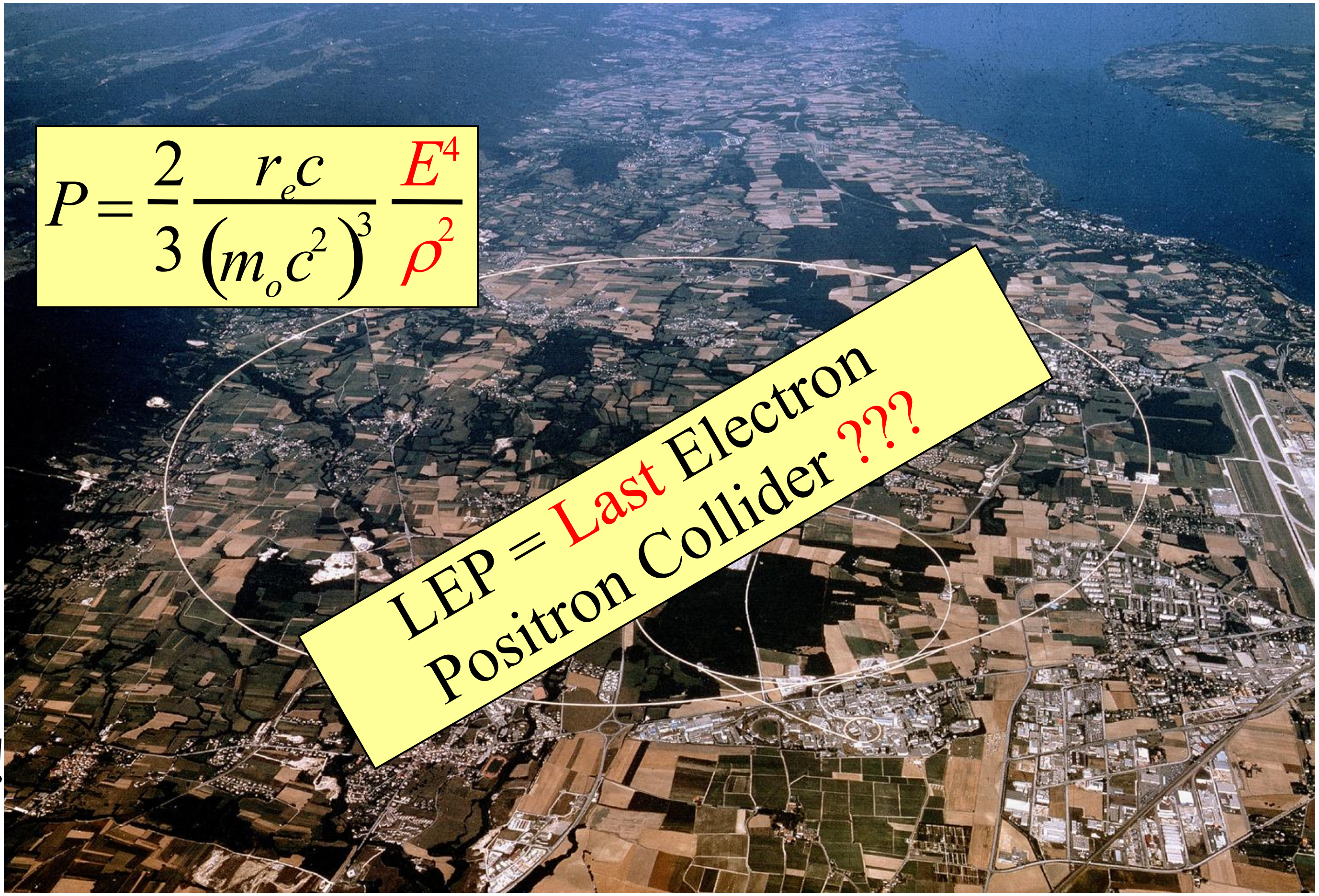


  - Elementary particles
  - Well defined initial state
  - Beam spin polarization
  - produces particles democratically
  - Momentum conservation eases decay product analysis

Much more precise analysis with leptons => precision measurements of particle properties

The LEP collider

- LEP (Large Electron Positron collider) was installed in LHC tunnel
  - e+ e- circular collider (27 km) with E_{cm}=200 GeV
- Problem for any ring: Synchrotron radiation
- Emitted power: scales with E^4 !! and $1/m_0^3$ (much less for heavy particles)
- This energy loss must be replaced by the RF system !!
- particles lost 3% of their energy each turn!



FCC-ee: physics requirements

- Electron-Positron Collider in the ~100km FCC tunnel:

- highest possible luminosity
- *beam energy range from 45 GeV to 175 GeV*
- main physics programs / energies:
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *W (80 GeV): W pair production threshold, high precision M_W*
  - *H (120 GeV): ZH production (maximum rate of H's),*
  - *t (175 GeV): threshold*
- some polarization up to ≥80 GeV for beam energy calibration
- optimized for operation at 120 GeV?! (2nd priority "*Tera-Z*")

preliminary FCC-ee parameters

parameter	FCC-ee	LEP2
energy/beam	45 – 175 GeV	105 GeV
bunches/beam	**60000 – 50**	4
beam current	**1450 – 6.6 mA**	3 mA
hor. emittance	**~2 nm**	~22 nm
emittance ratio $\varepsilon_y/\varepsilon_y$	**0.1%**	1%
vert. IP beta function β_y^*	**1 mm**	50 mm
luminosity/IP	**280 - 1.5** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$
energy loss/turn	0.03-7.55 GeV	3.34 GeV
synchrotron radiation power	**100 MW**	23 MW
RF voltage	0.3 – **11 GV**	3.5 GV

- Large number of bunches at Z and WW and H requires **2 rings**.
- High luminosity means short beam lifetime (few mins) and requires continuous injection (**top up**).

FCC-ee key technology: SRF

- Powerful Superconducting RF (SRF) system required to replace the synchrotron radiation losses!!!

range of requirements:

Higgs, high RF voltage

- RF power: 50 MW per beam
- 5.5 GV total
- Energy loss: 1.67 GV/turn
- I_{beam} = 30 mA

Z, high beam current

- RF power: 50 MW per beam
- 0.5 - 2.5 GV total
- Energy loss: 0.03 GV/turn
- I_{beam} = 1450 mA

preliminary design assumptions

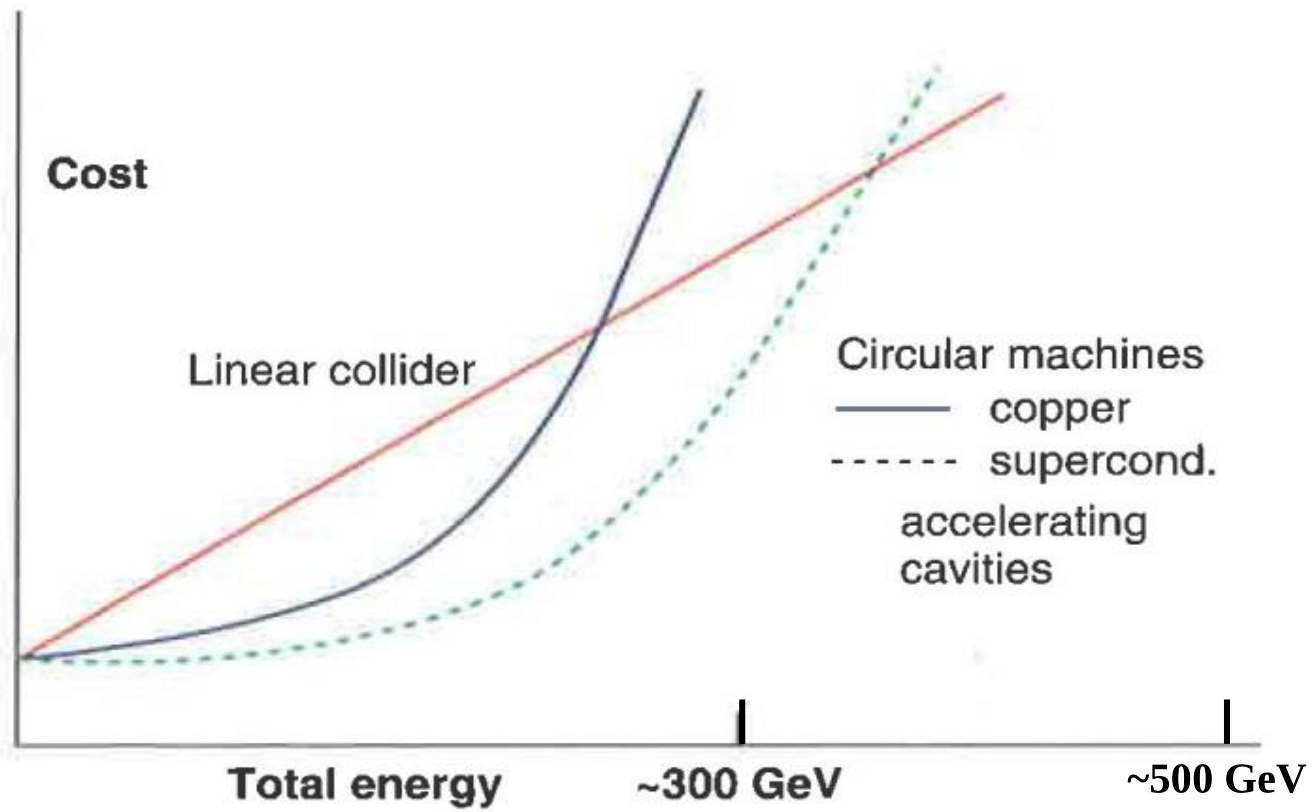
about 1200 Nb/Cu cells (300 modules?) operating at 12 MV/m

input power ≈ 40 kW / cell

efficient RF power sources

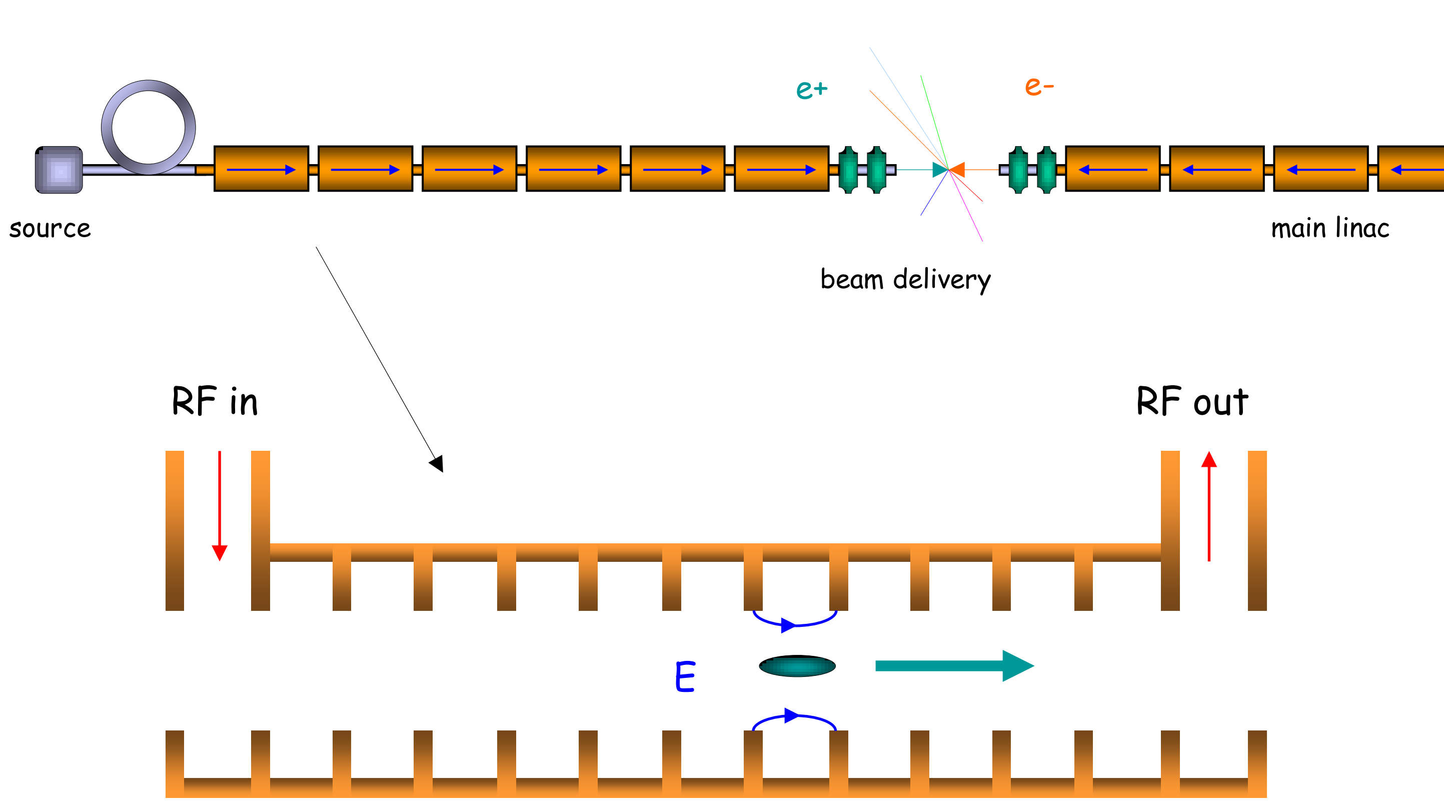
Linear or Circular ?

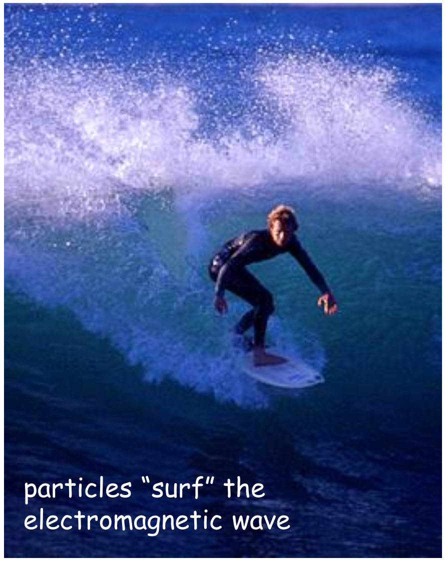
- If we want to go to higher energies with e+e- colliders?
  - Synchrotron radiation in circular machines
    - Energy lost per turn grows like $\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$, e.g., 3.5 GeV/turn at LEP2
      - Must compensate with R and accelerating cavities   Cost grows like ~E^2
  - A high energy e^+e^- collider can only be linear. Cost of a circular collider is prohibitive.



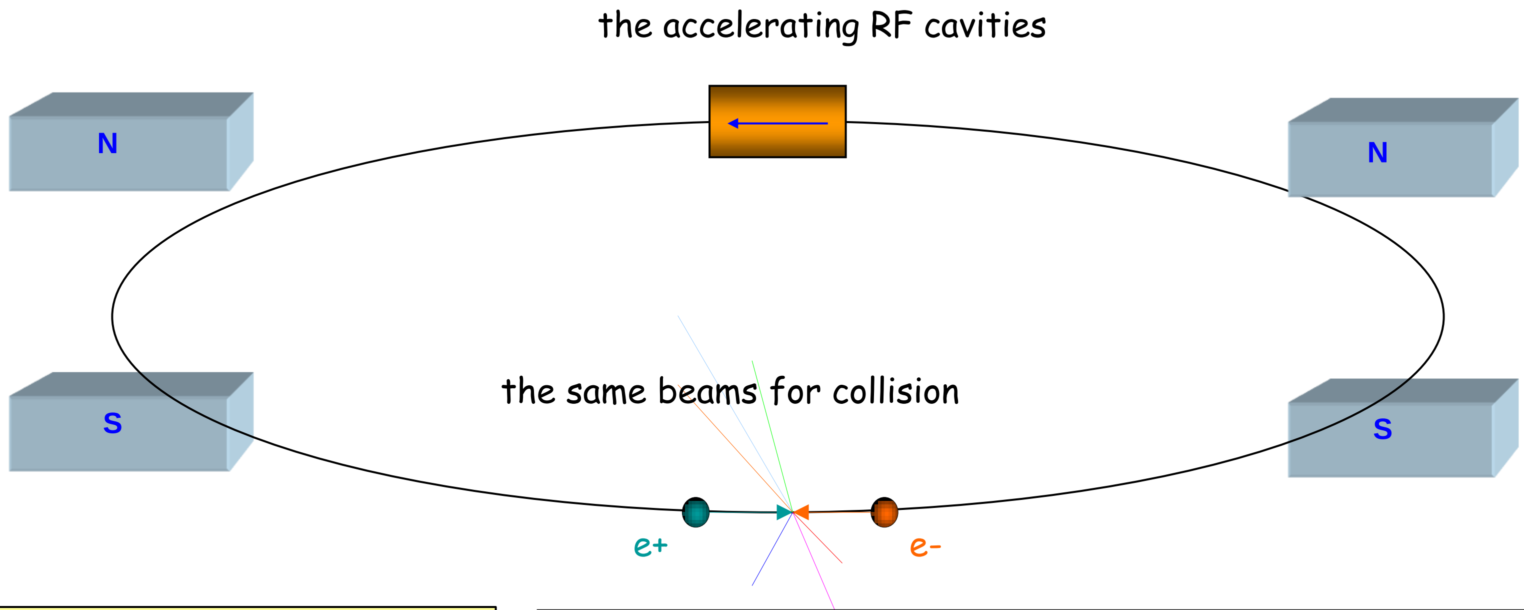
The next lepton collider

- Solution: LINEAR COLLIDER
- avoid synchrotron radiation
- no bending magnets, huge amount of cavities and RF





Linear Collider vs. Ring

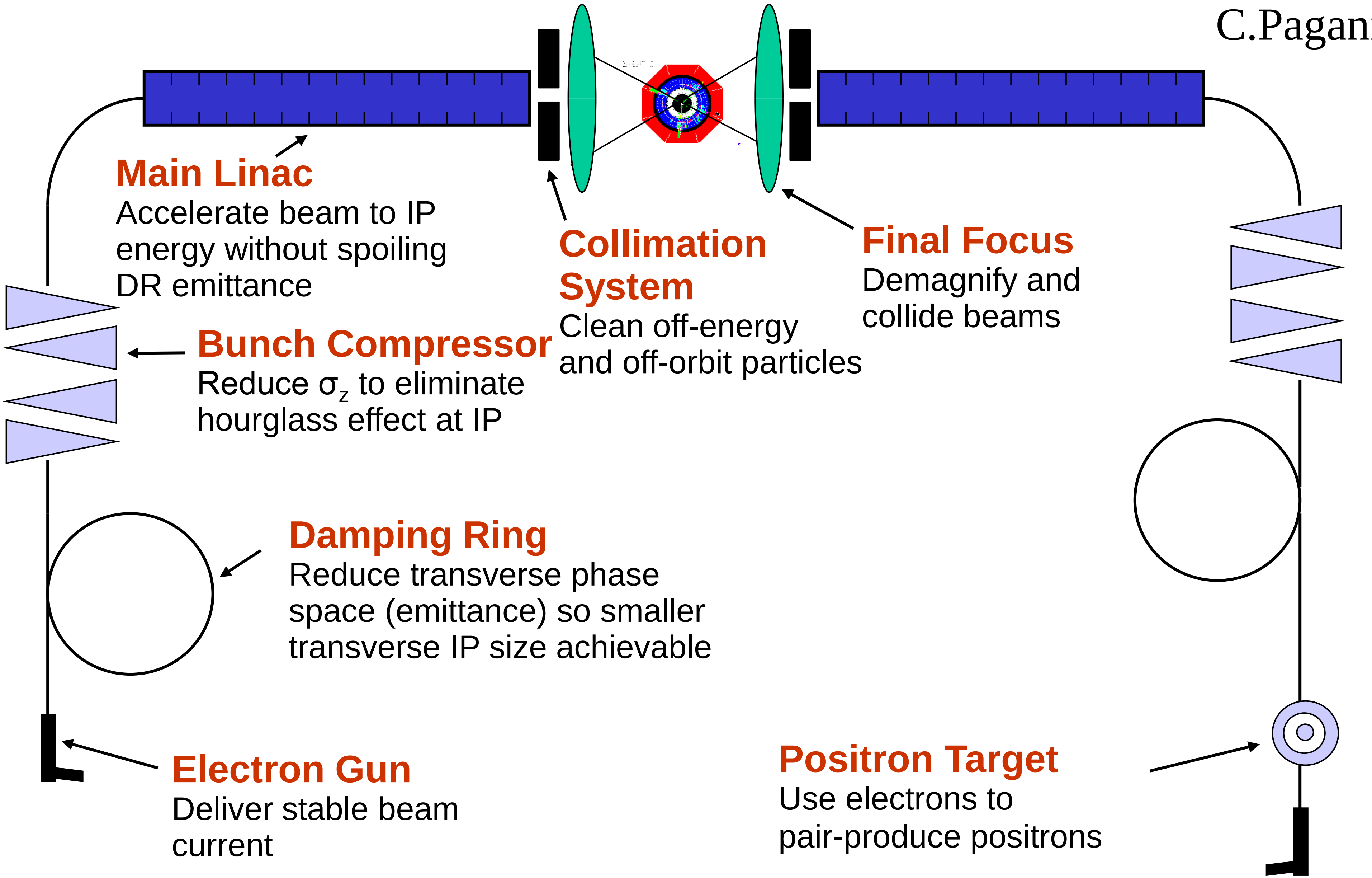


- **Storage rings:**
  - accelerate + collide every turn
  - 're-use' RF + 're-use' particles
- => efficient

- **Linear Collider:**
  - one-pass acceleration + collision => need
  - high gradient (acceleration)
  - small beam size

to reach high luminosity *L* (event rate)

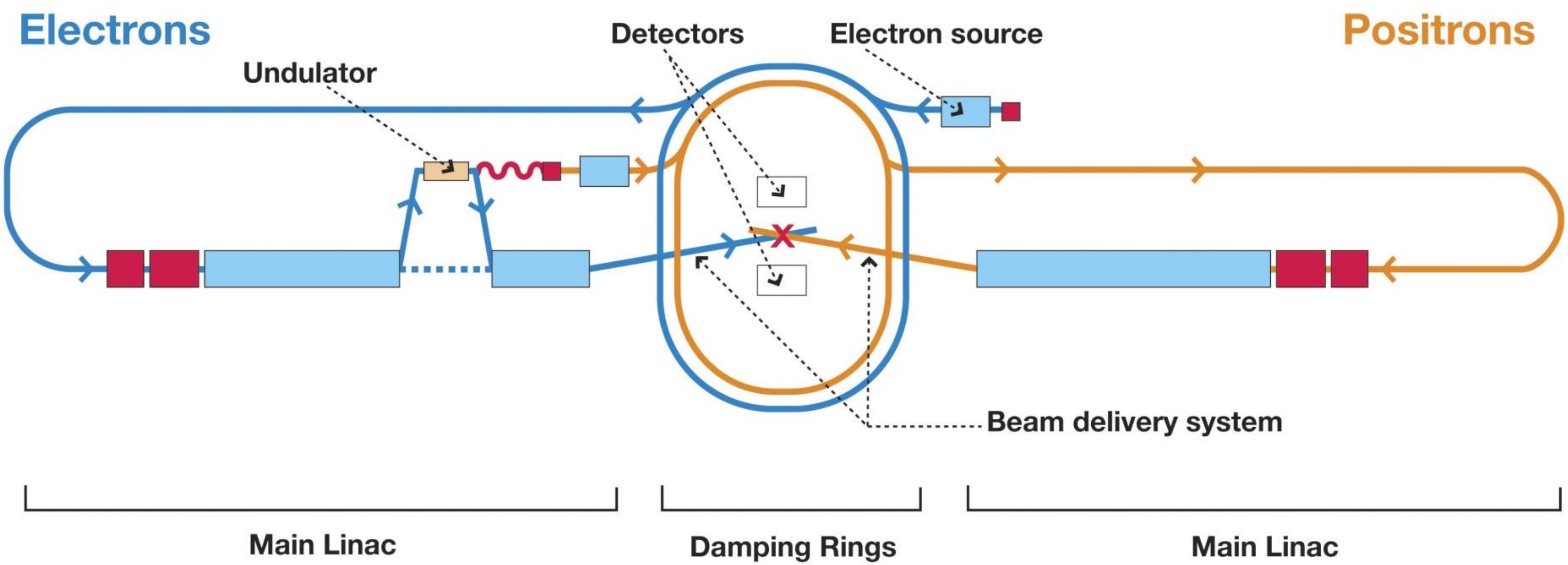
Generic Linear Collider



Linear Collider projects

- ILC (International Linear Collider) www.linearcollider.org
  - Superconducting technology
  - 1.3 GHz RF frequency
  - ~31 MV/m accelerating gradient
  - 500 GeV centre-of-mass energy
  - upgrade to 1 TeV possible
- CLIC (Compact Linear Collider)
  - normalconducting technology
  - multi-TeV energy range (nom. 3 TeV)

~35 km total length

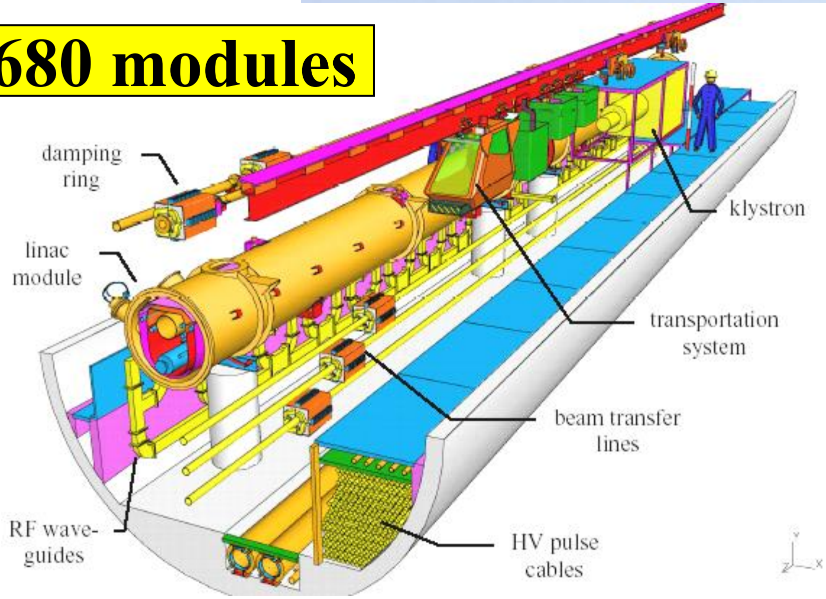


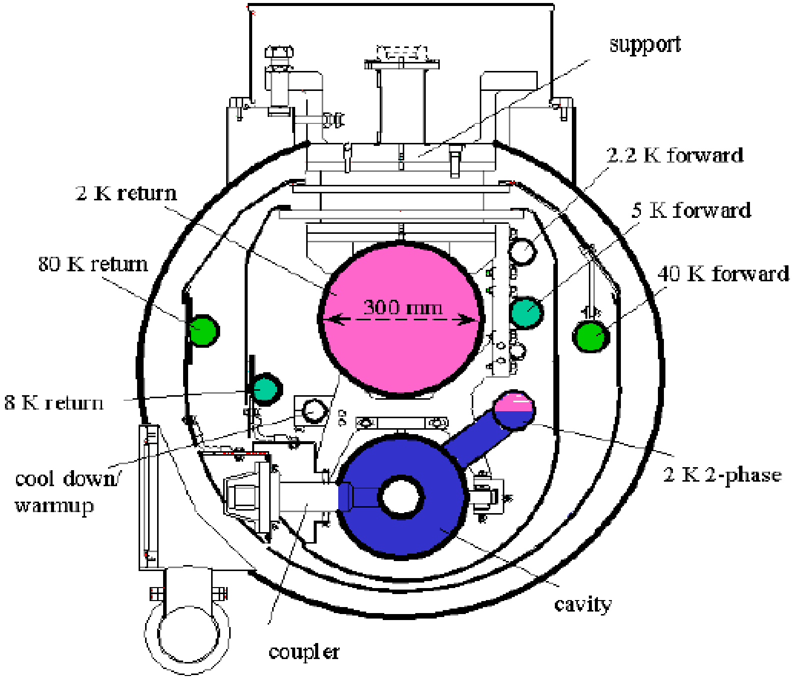
ILC Super-conducting technology

The core technology for the ILC is 1.3GHz superconducting RF cavity intensely developed in the TESLA collaboration, and recommended for the ILC by the ITRP on 2004 August.
The cavities are installed in a long cryostat cooled at 2K, and operated at gradient 31.5MV/m.

14560 cavities

1680 modules

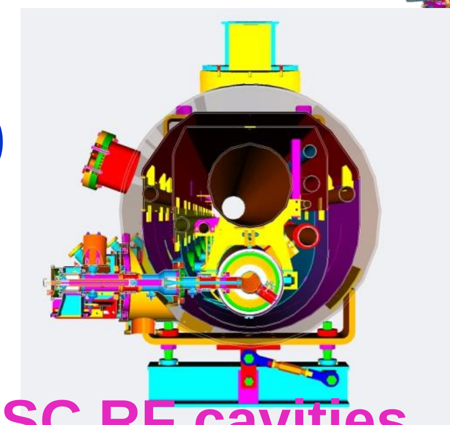


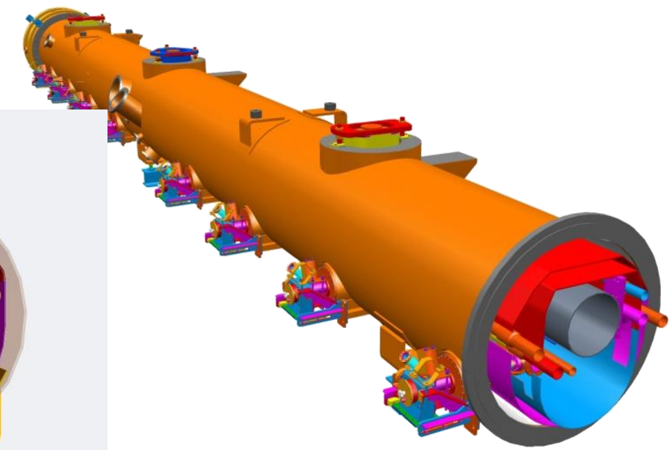


ILC Main Linac RF Unit

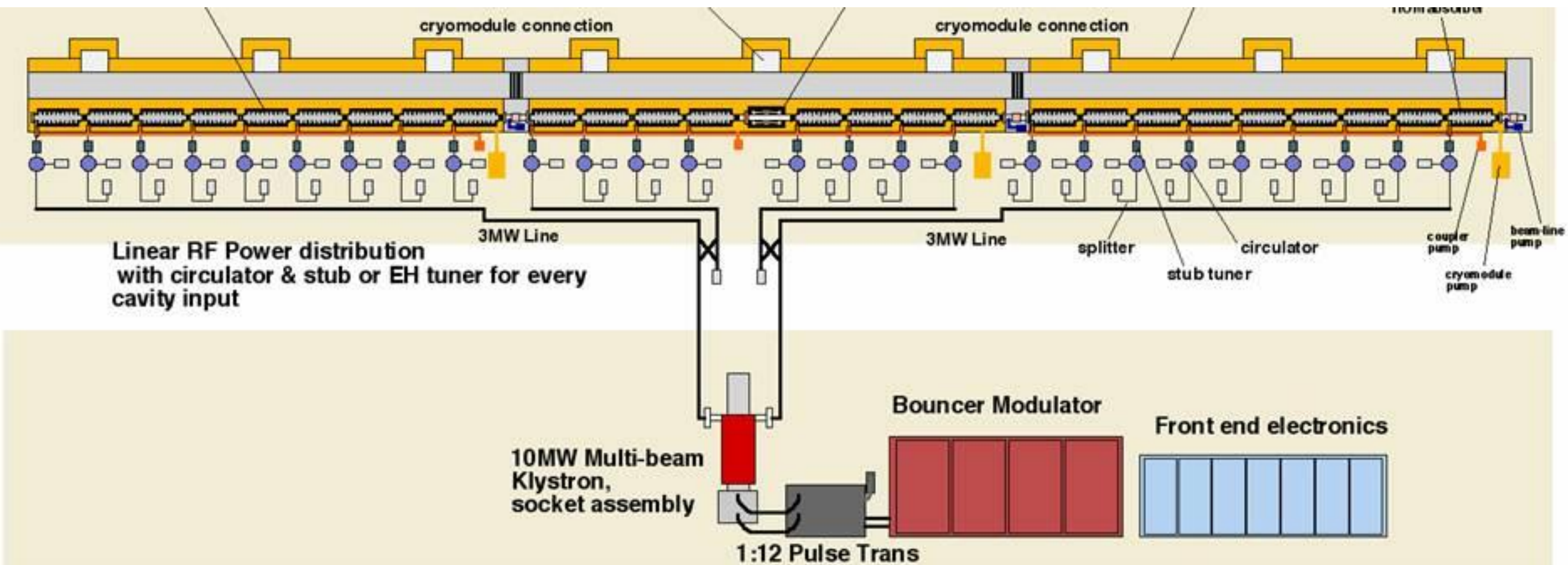
560 RF units each one composed of:

- **1 Bouncer type modulator**
- **1 Multibeam klystron (10 MW, 1.6 ms)**
- **3 Cryostats (9+8+9 = 26 cavities)**
- **1 Quadrupole at the center**





Total of 1680 cryomodules and 14 560 SC RF cavities



Note: Cryogenics

Cavities have small losses

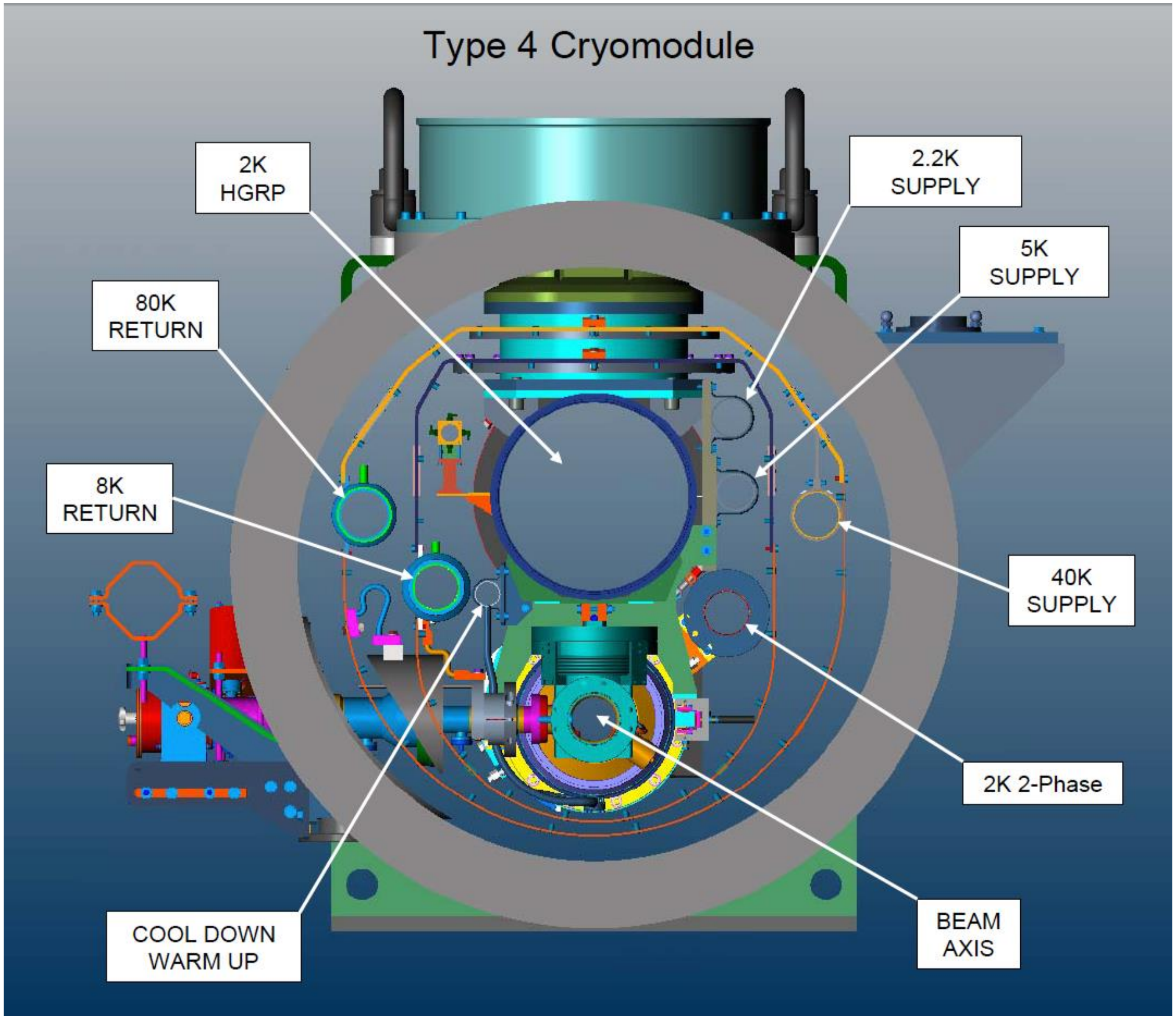
$$P_{loss} = const \frac{1}{Q_0} \times G^2$$

But cooling costly at low temperatures

Remember Carnot:

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

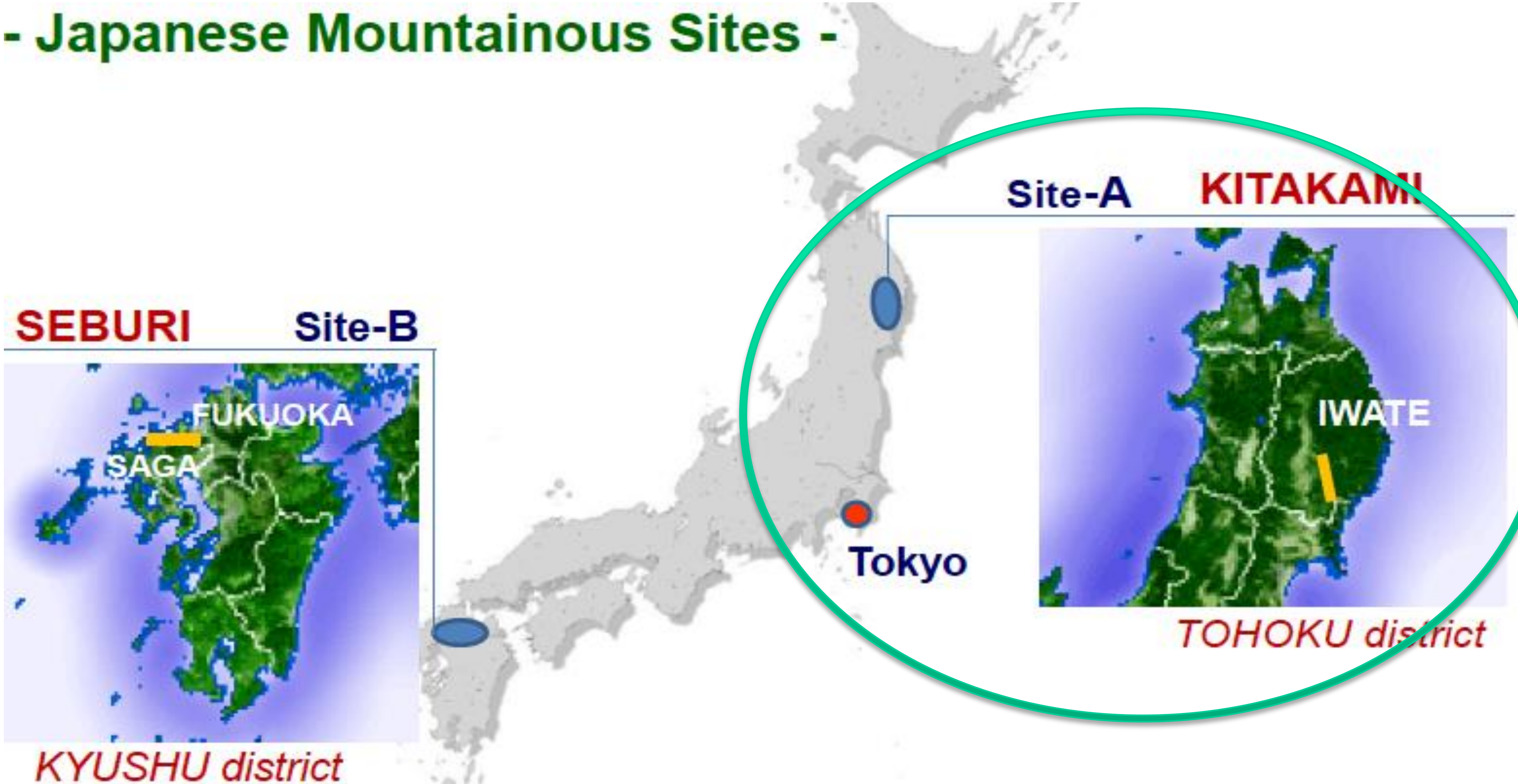
$$P_{cryo} \approx 700 \times P_{loss}$$



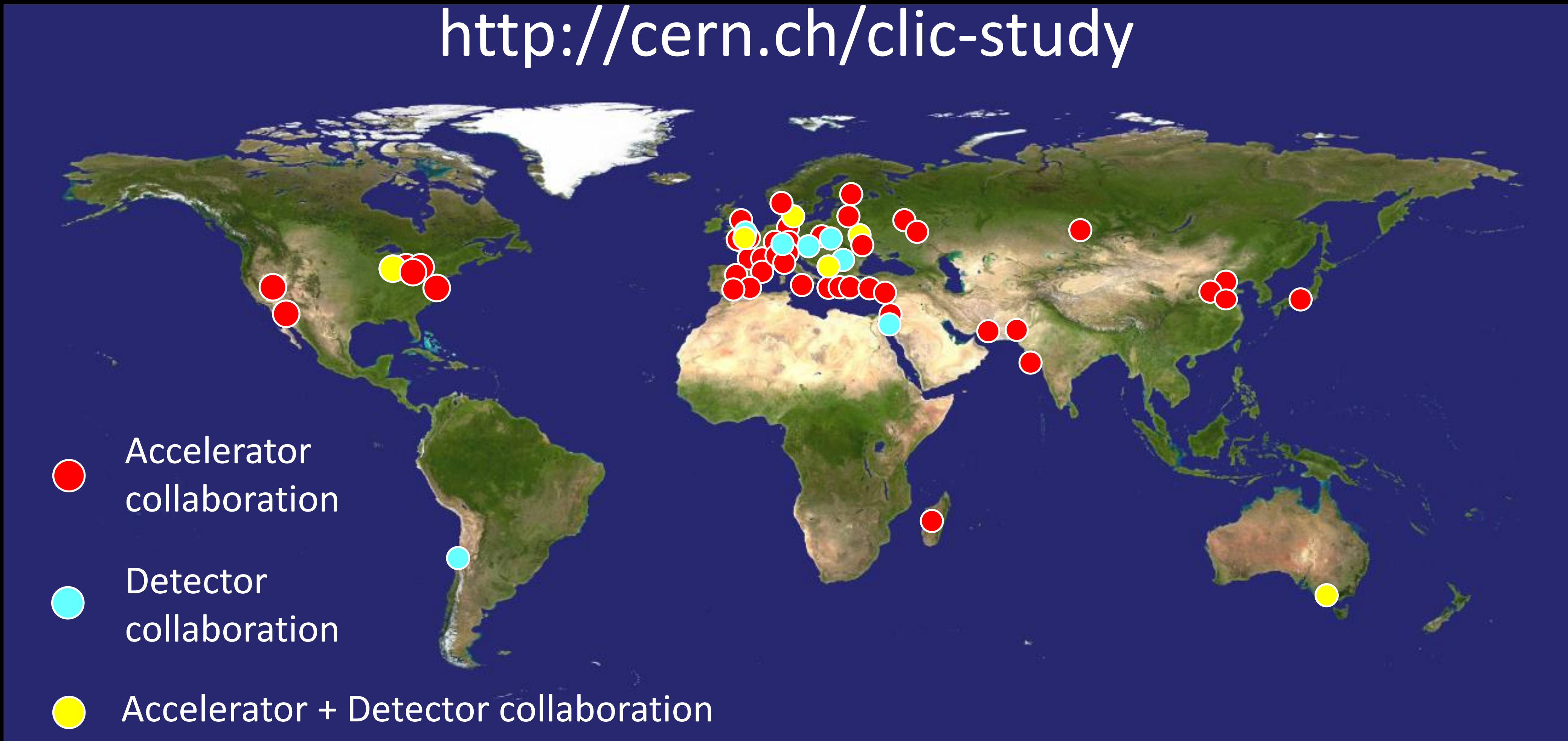
The typical heat load of 1 W/m => ~ 1 kW/m for cryogenics

ILC Site Choice

- Japan is pushing to host ILC, possible site selected
- Project is being evaluated but no decision yet

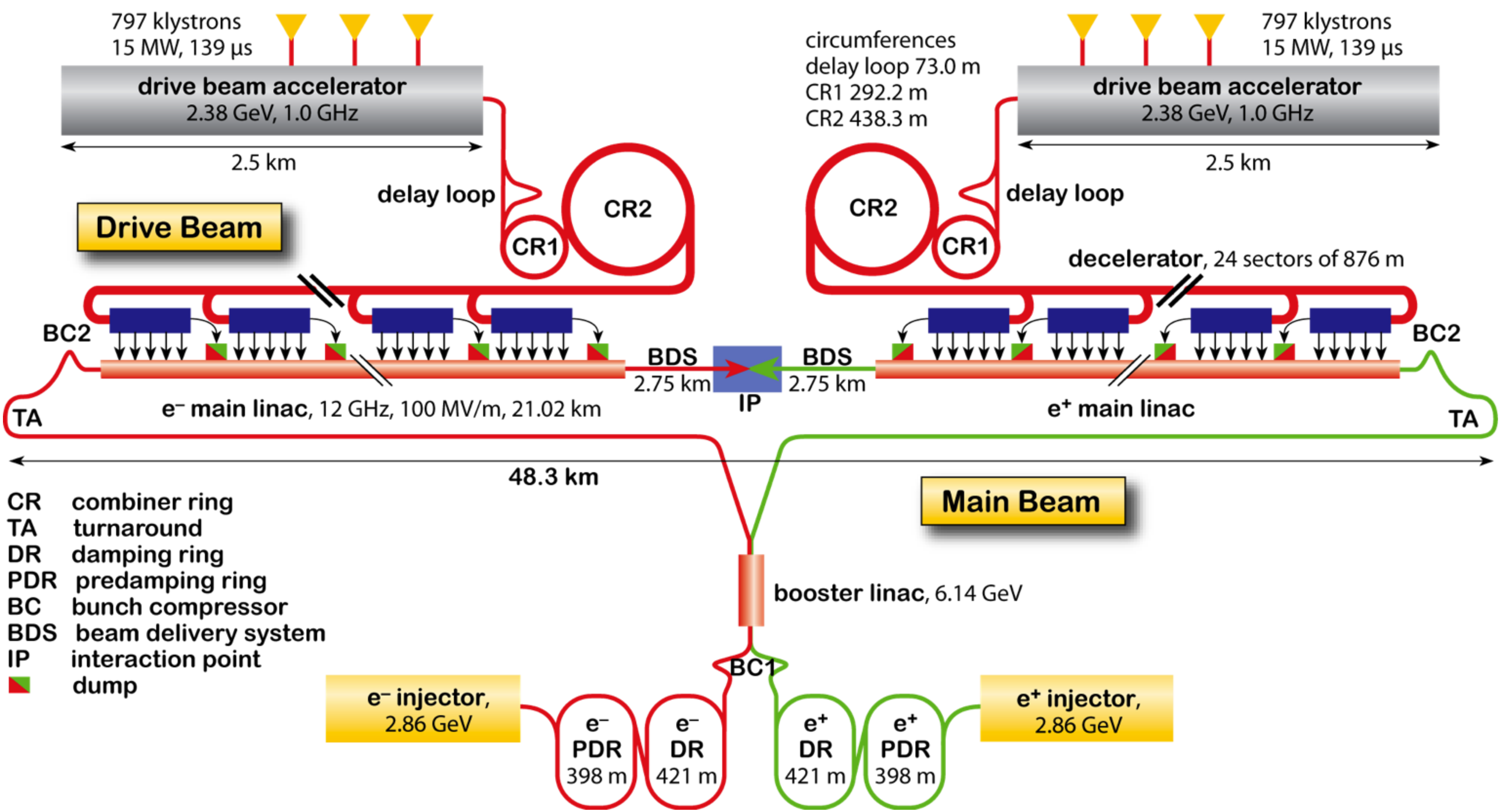


CLIC Collaboration: 31 Countries – over 70 Institutes



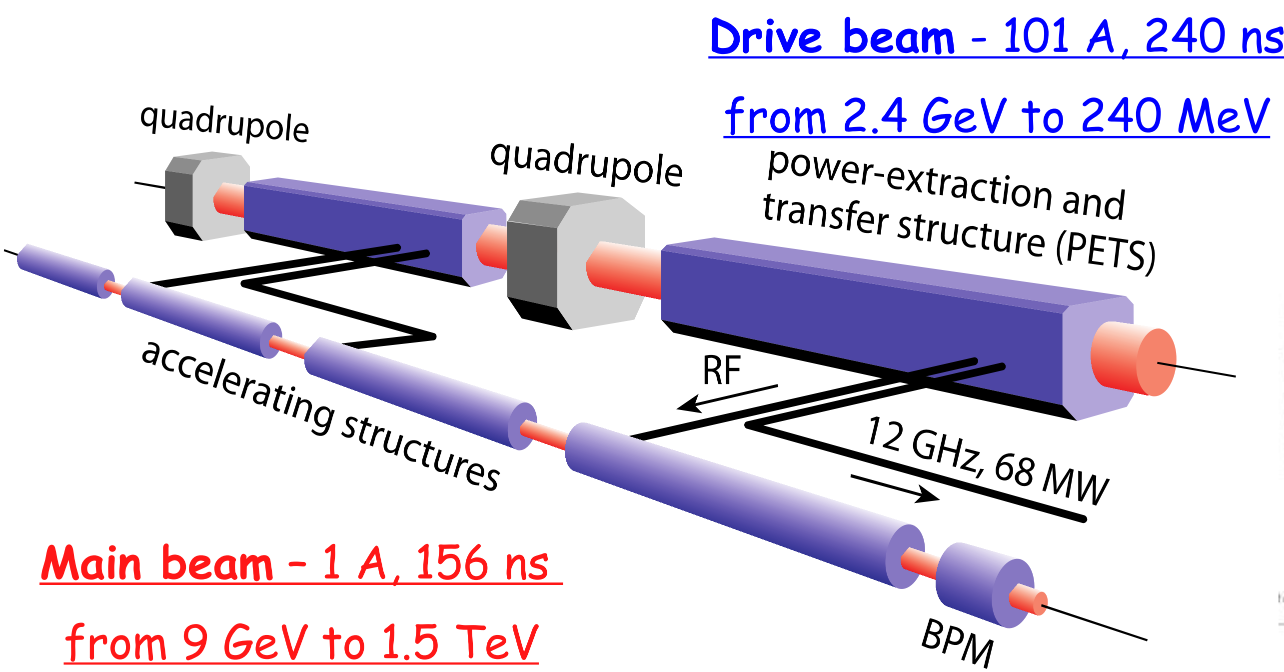
CLIC – overall layout – 3 TeV

- **CLIC** (Compact Linear Collider): only multi-TeV design
  3 TeV, 100 MV/m, warm technology, 12 GHz, two beam scheme

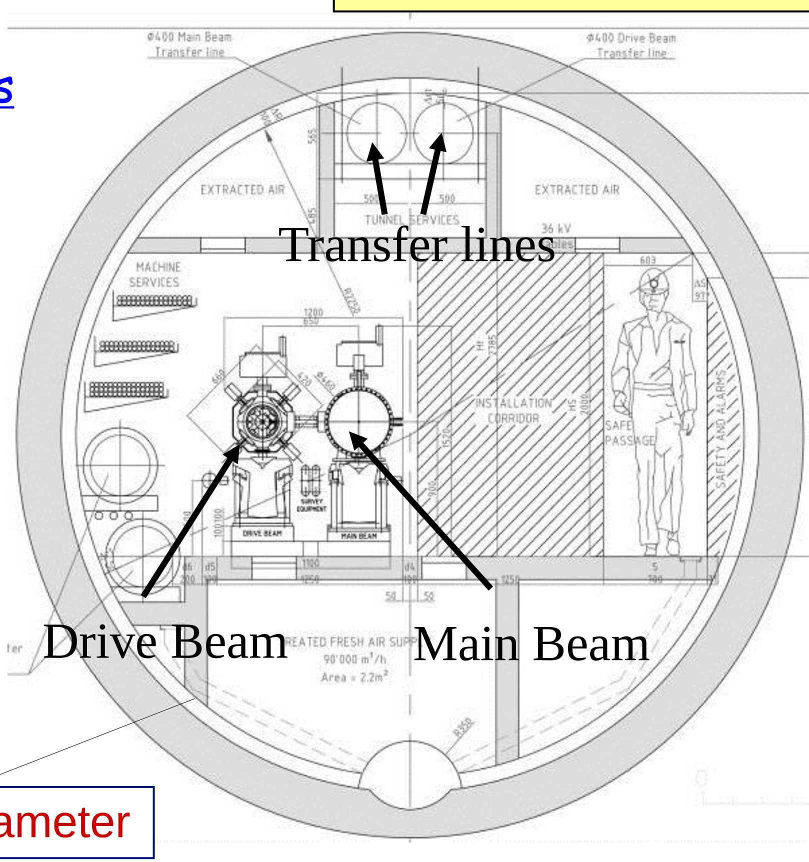


CLIC two beam scheme

- High charge Drive Beam (low energy)
- Low charge Main Beam (high collision energy)
- => Simple tunnel, no active elements
- => Modular, easy energy upgrade in stages

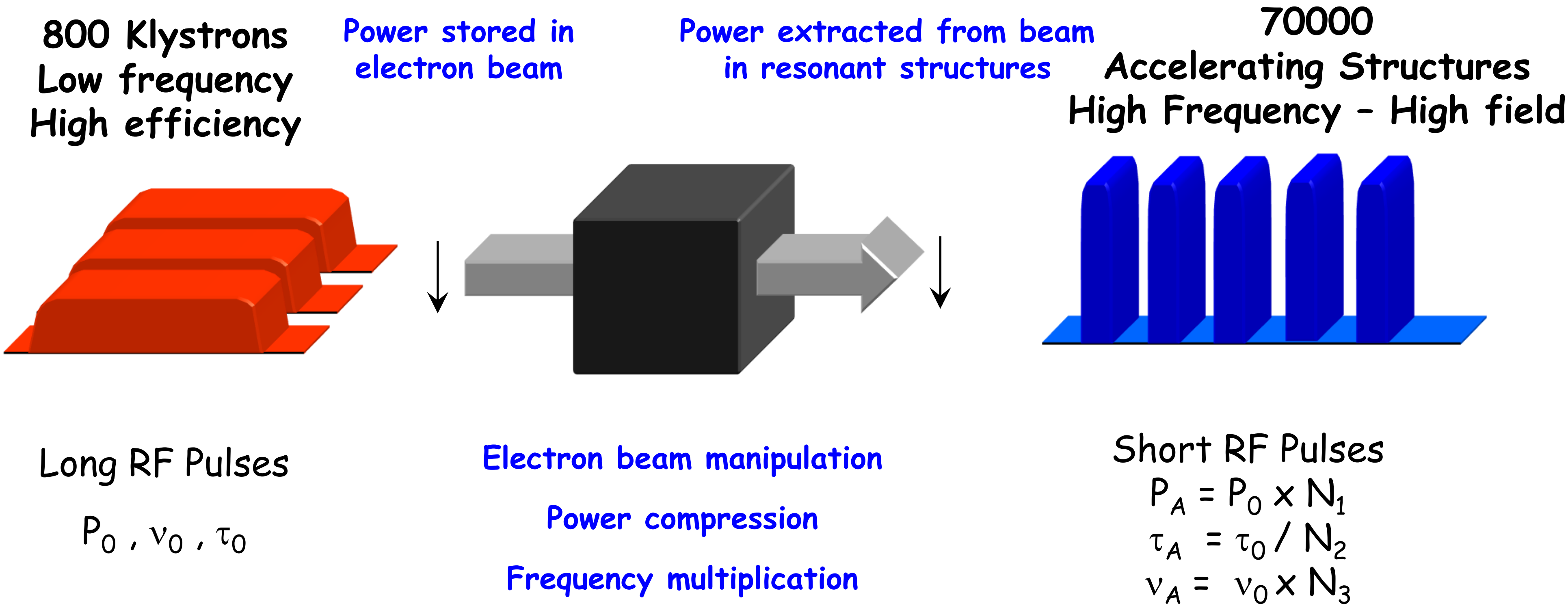


CLIC TUNNEL CROSS-SECTION



CLIC scheme

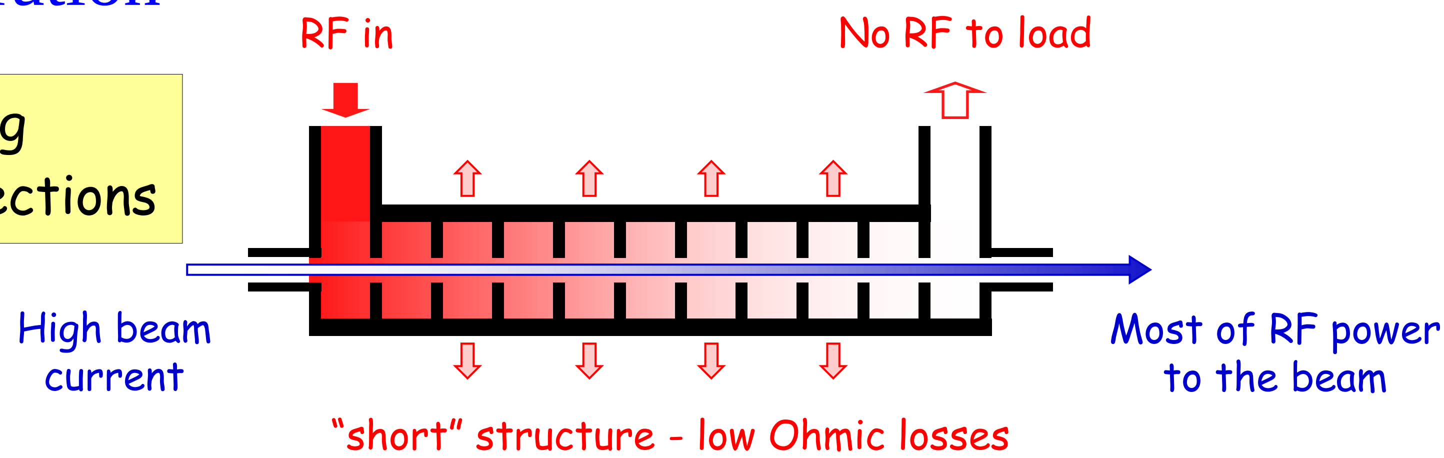
- Very high gradients possible with NC accelerating structures at high RF frequencies (12 → 30 GHz) for short RF pulses
- Extract RF power from an intense electron "drive beam"
- Generate efficiently long pulse and compress it (in power + frequency)



Drive beam generation basics

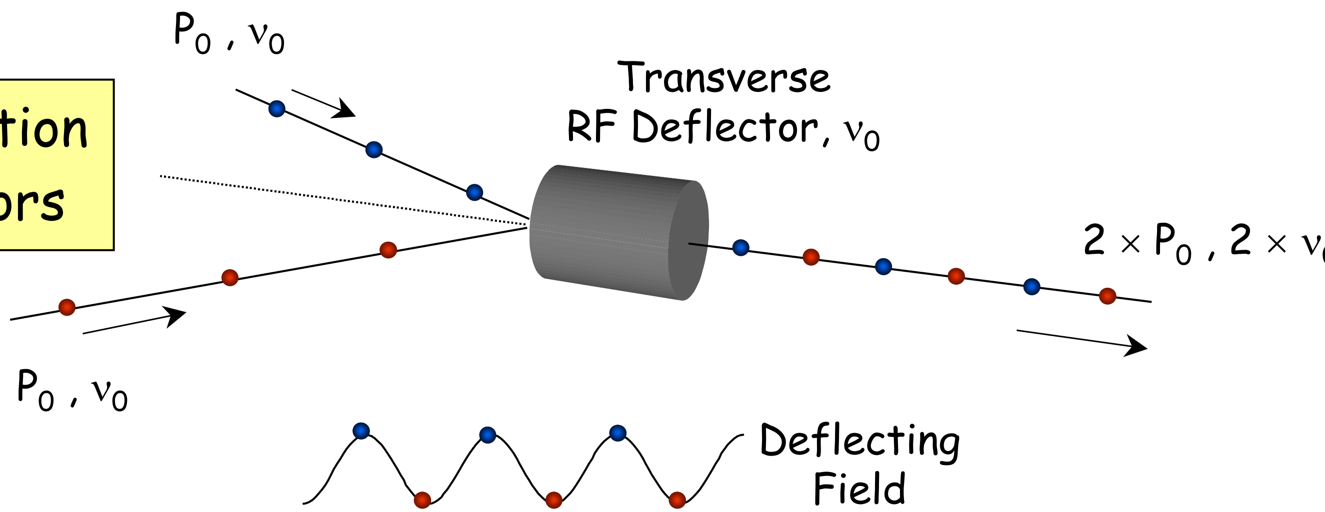
- Efficient acceleration

Full beam-loading acceleration in TW sections

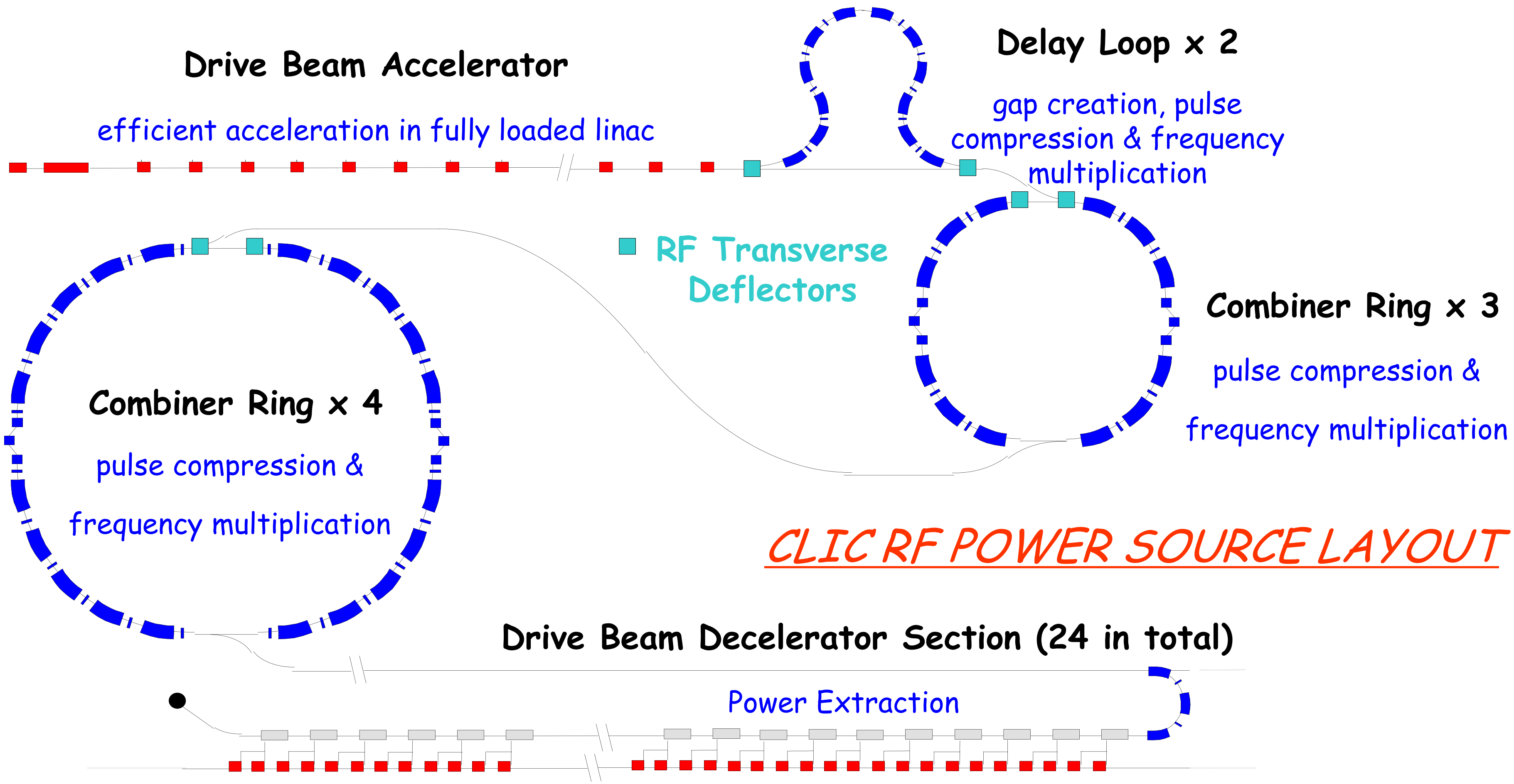


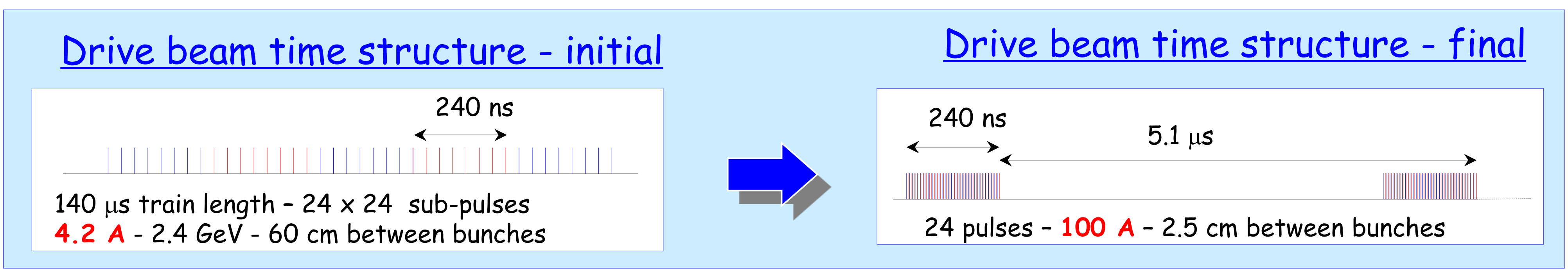
- Frequency multiplication

Beam combination/separation by transverse RF deflectors



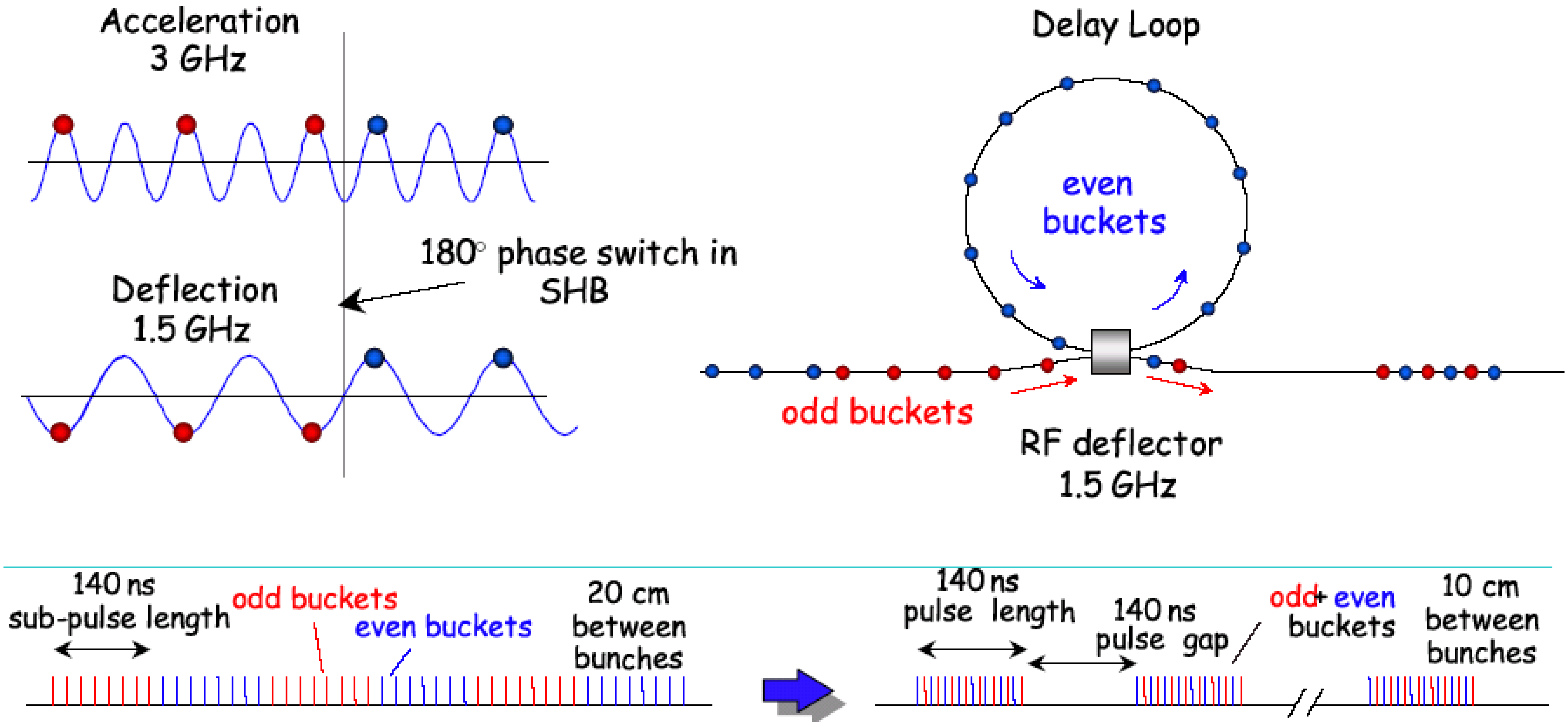
CLIC Drive Beam generation





Delay Loop Principle

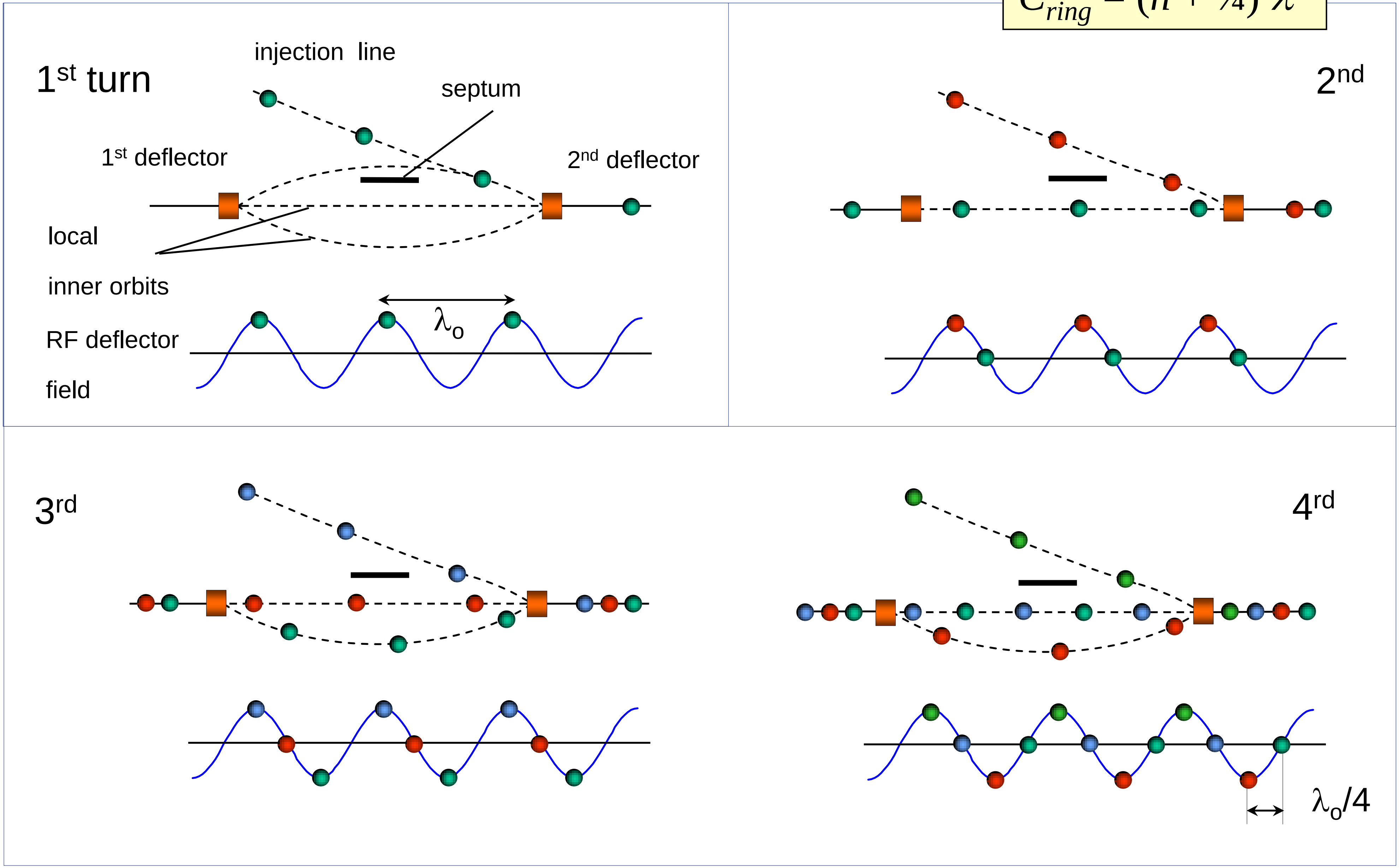
- **double repetition frequency and current**
- parts of bunch train delayed in loop
- RF deflector combines the bunches



RF injection in combiner ring

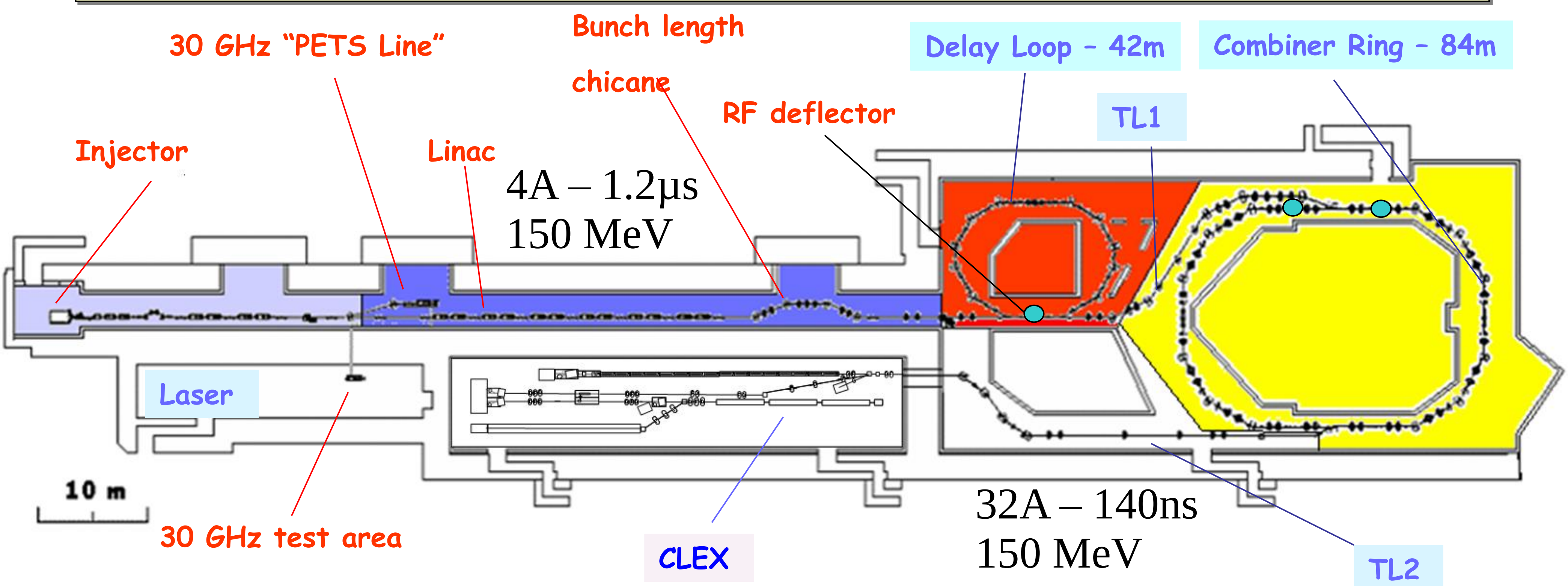
- combination factors up to 5 reachable in a ring

$C_{ring} = (n + 1/4)\,\lambda$



CTF 3

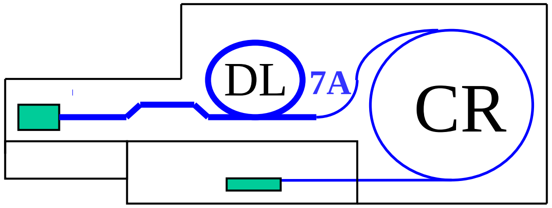
- demonstrate remaining CLIC feasibility issues, in particular:
  - Drive Beam generation (fully loaded acceleration, bunch frequency multiplication)
  - CLIC accelerating structures
  - CLIC power production structures (PETS)

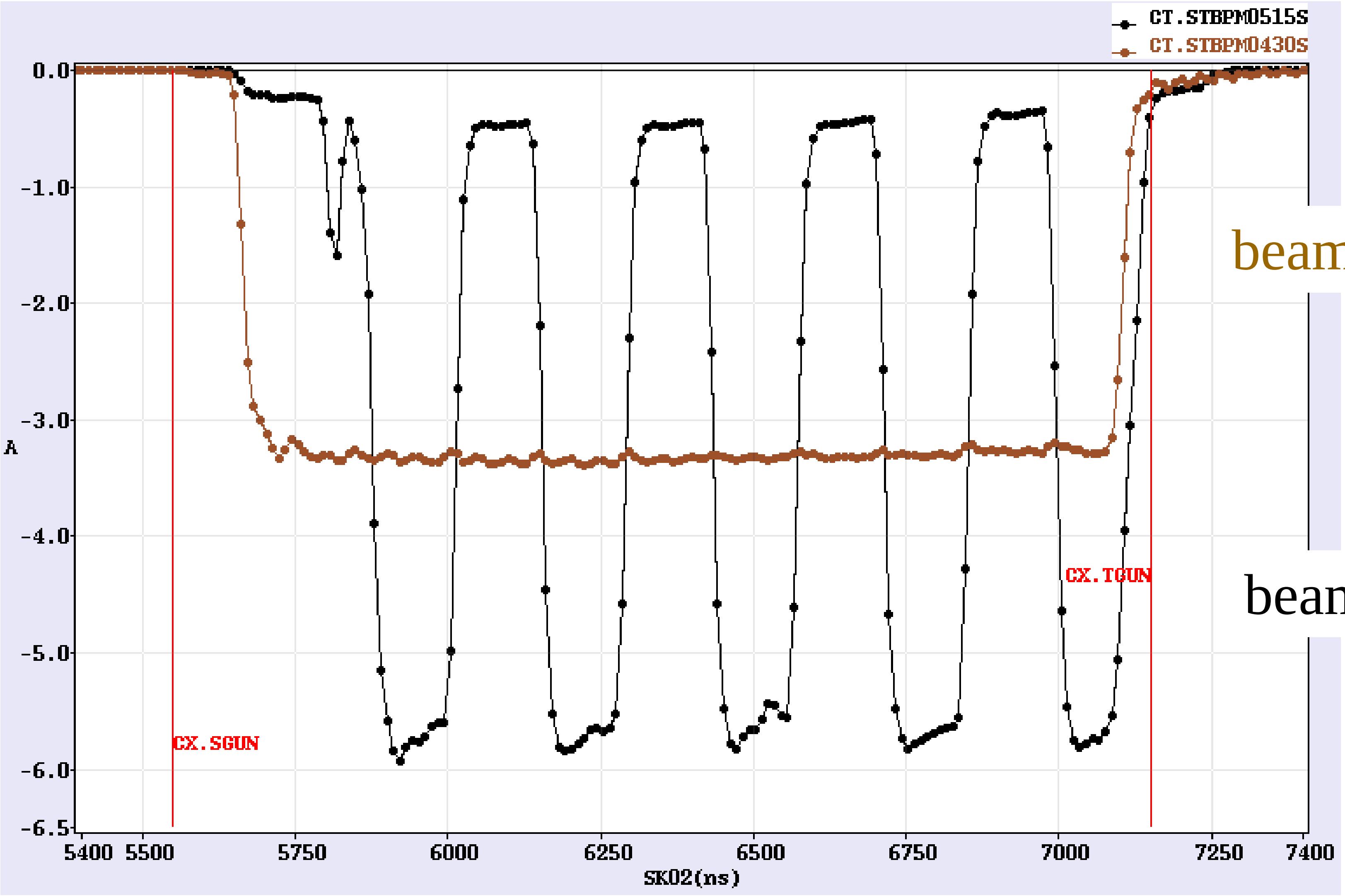


CTF3 Delay Loop

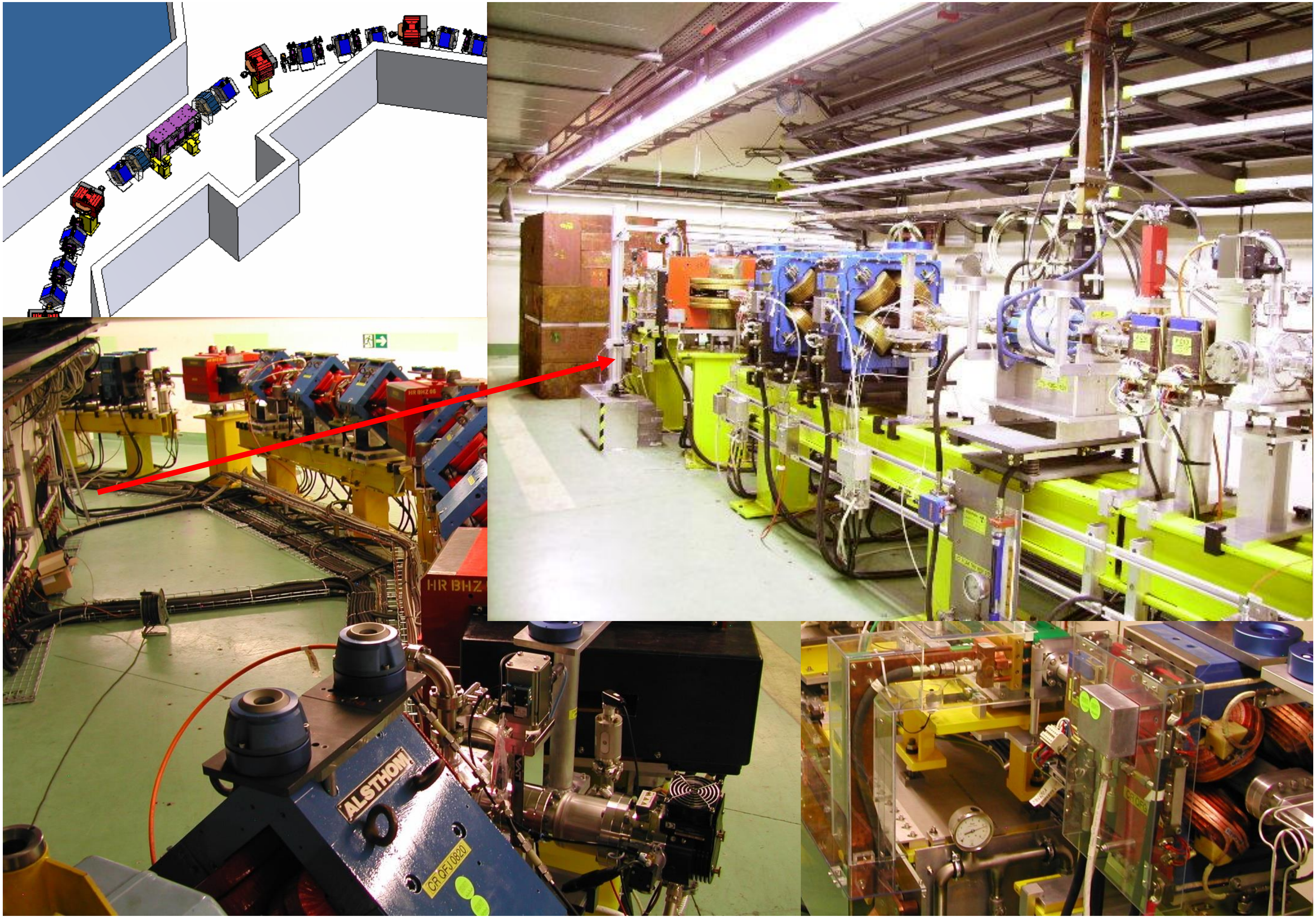
Delay Loop – full recombination

- 3.3 A after chicane =>
  < 6 A after combination (satellites)



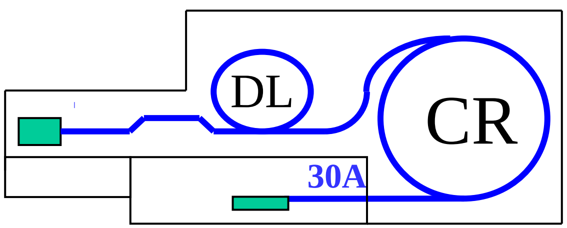


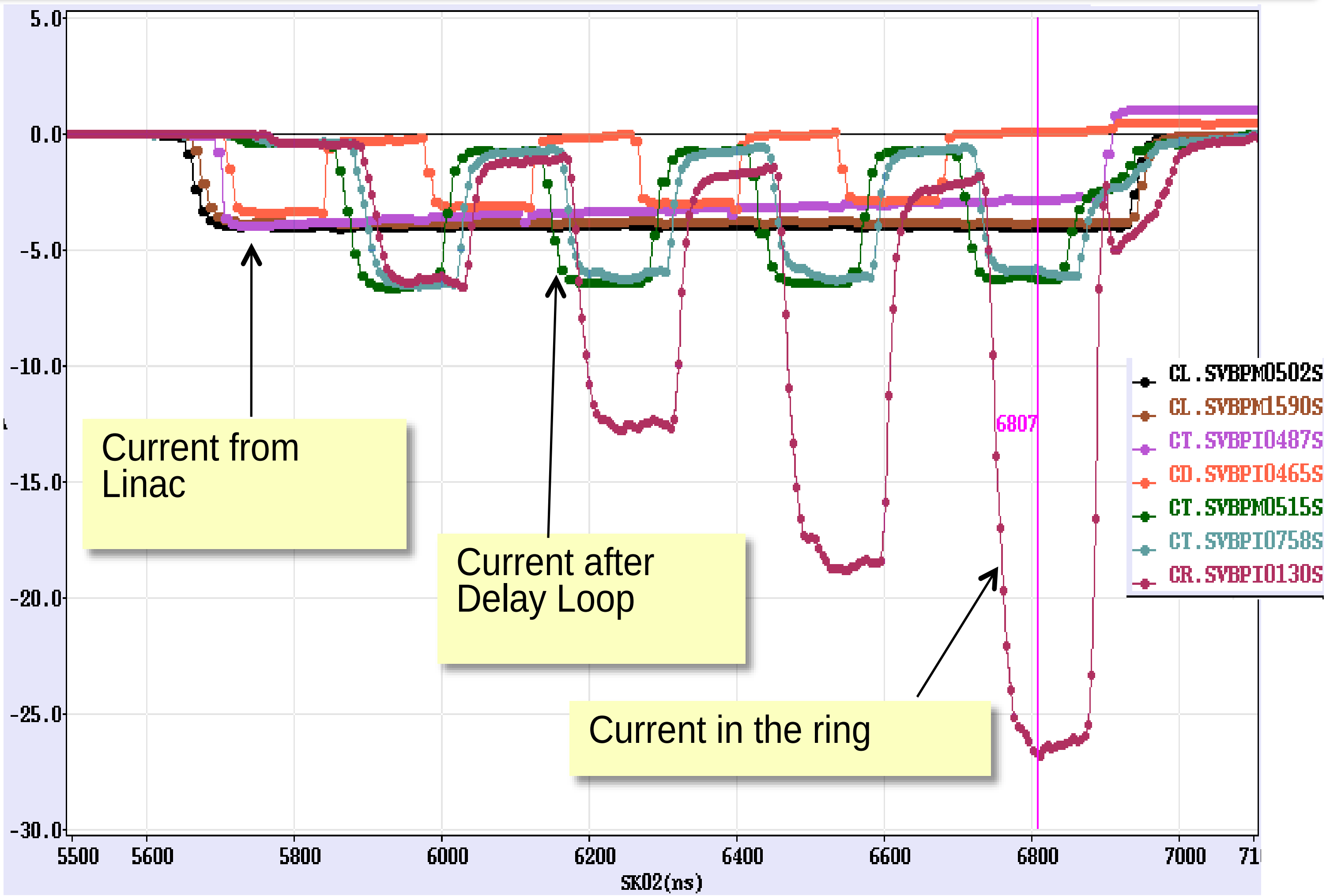
CTF3 combiner ring



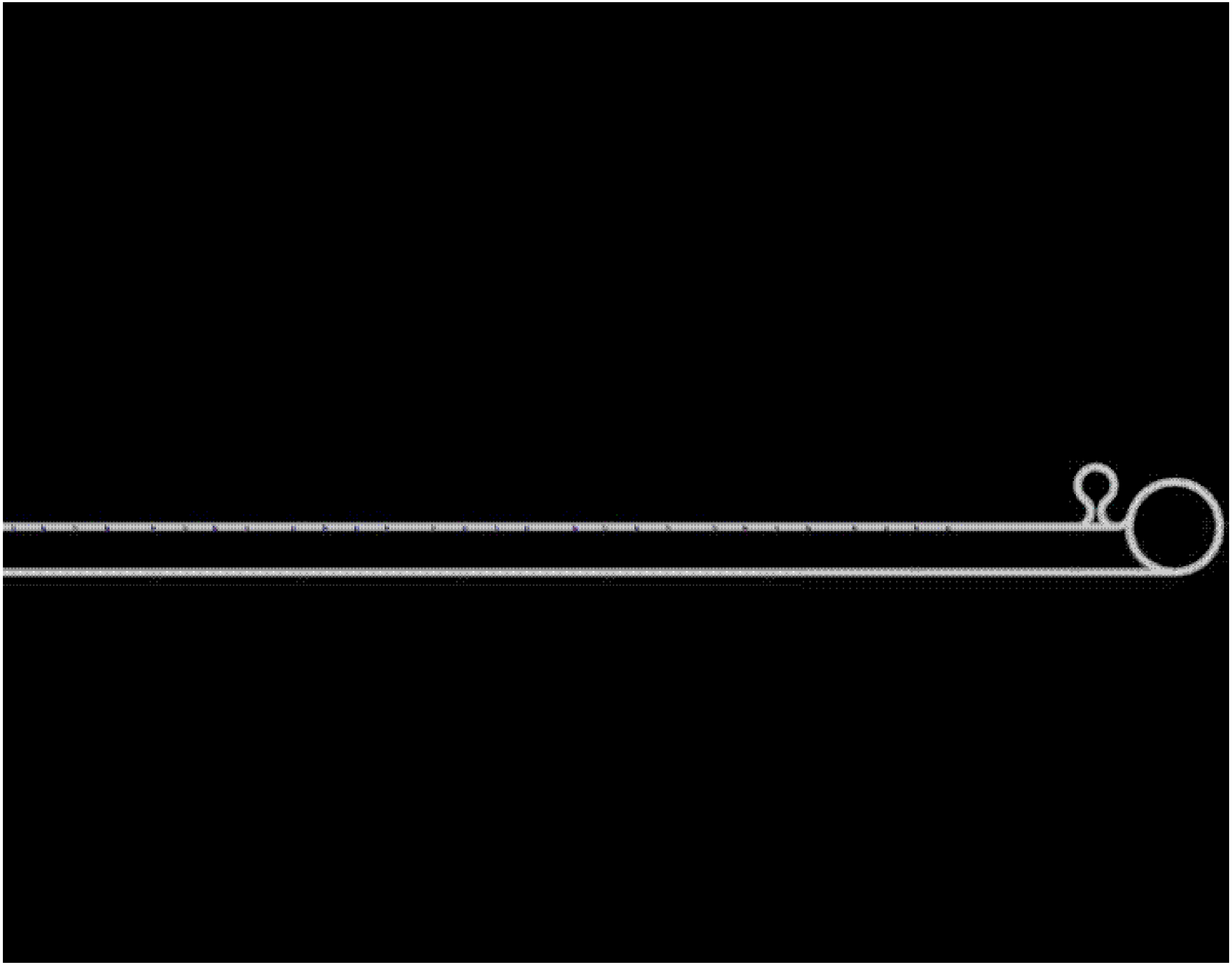
Drive beam generation achieved

- combined operation of Delay Loop and Combiner Ring (factor 8 combination)
- ~26 A combination reached, nominal 140 ns pulse length
- => **Full drive beam generation achieved** in 2009





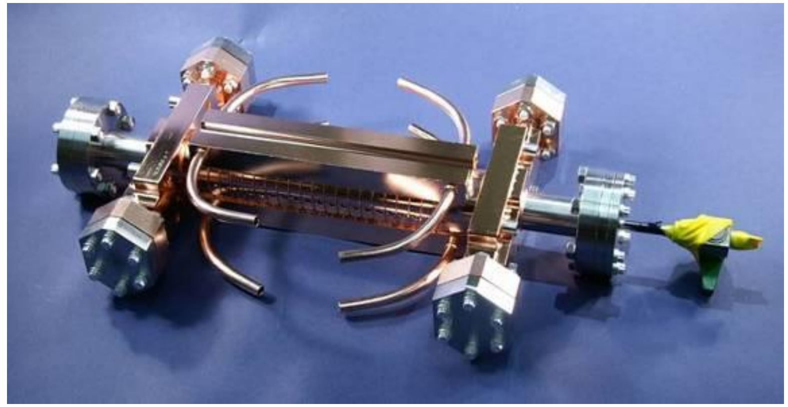
Lemmings Drive Beam

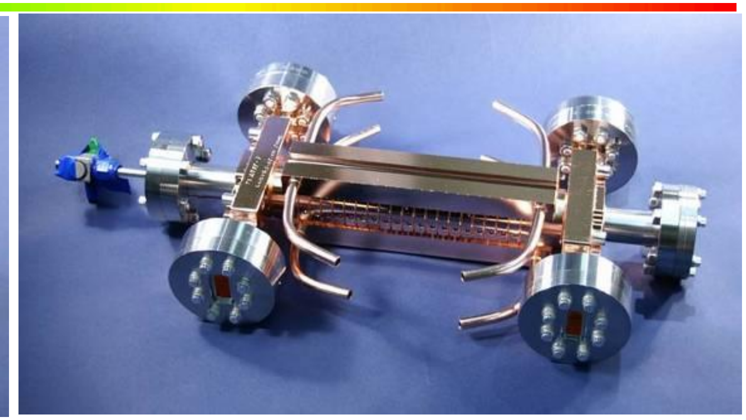


Alexandra Andersson

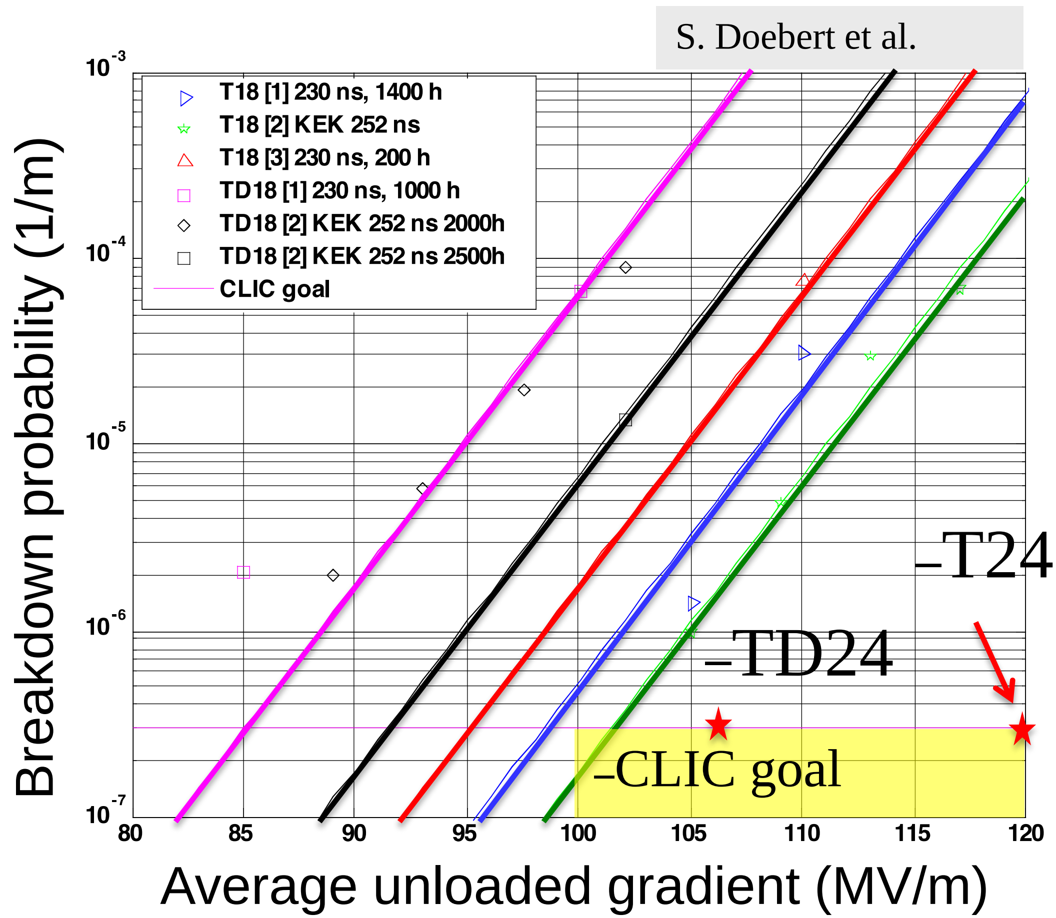
Accelerating Structure Results

- RF breakdowns can occur
  => no acceleration and deflection

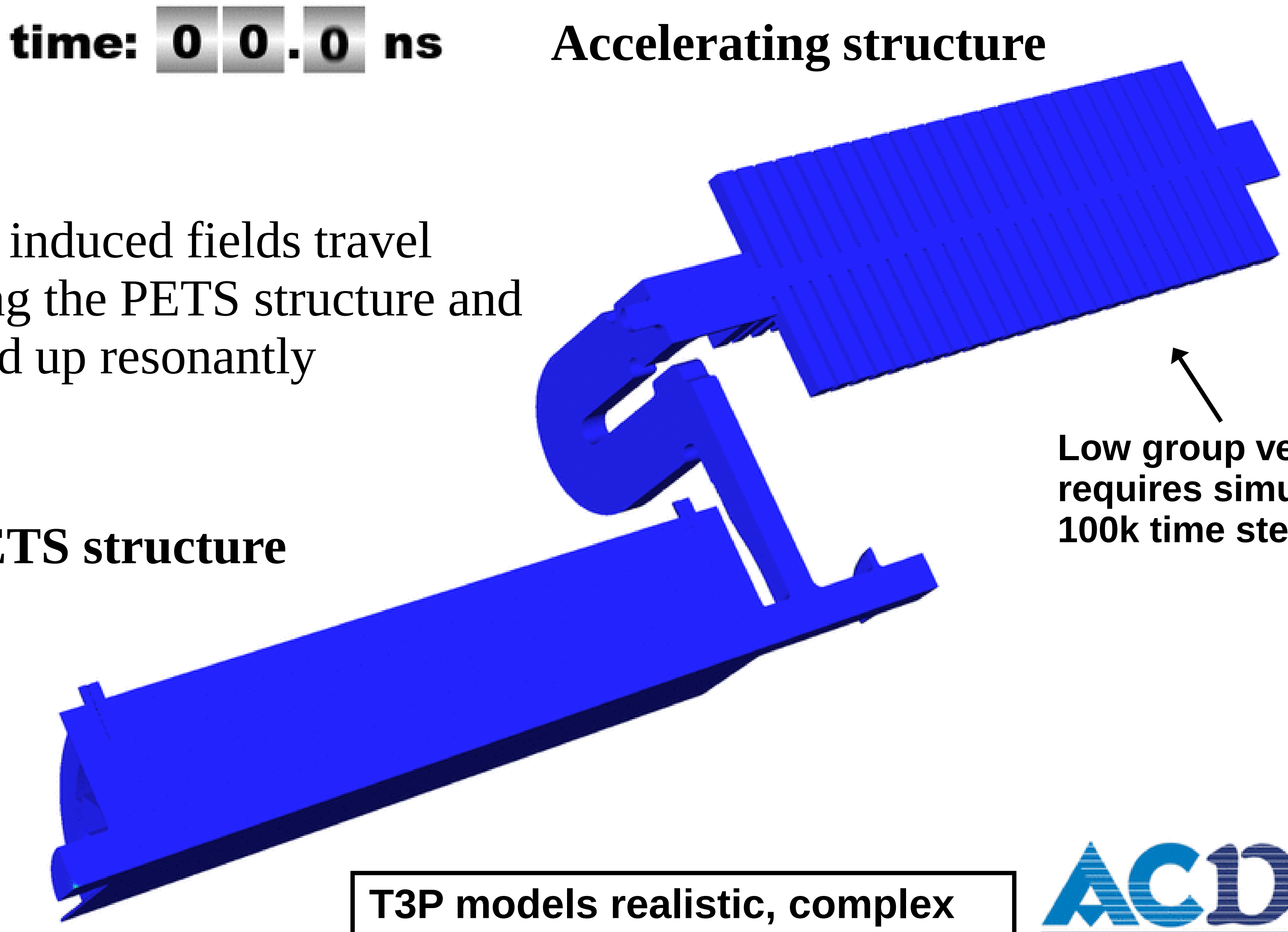




- Goal: 3 10^{-7}/m breakdowns
  at 100 MV/m loaded gradient
  at 230 ns pulse length
- latest prototypes (T24 and TD24) tested (SLAC and KEK)
- => TD24 reached 106 MV/m at nominal CLIC breakdown rate (without damping material)
- Undamped T24 reaches 120MV/m



Simulation of RF Power Transfer



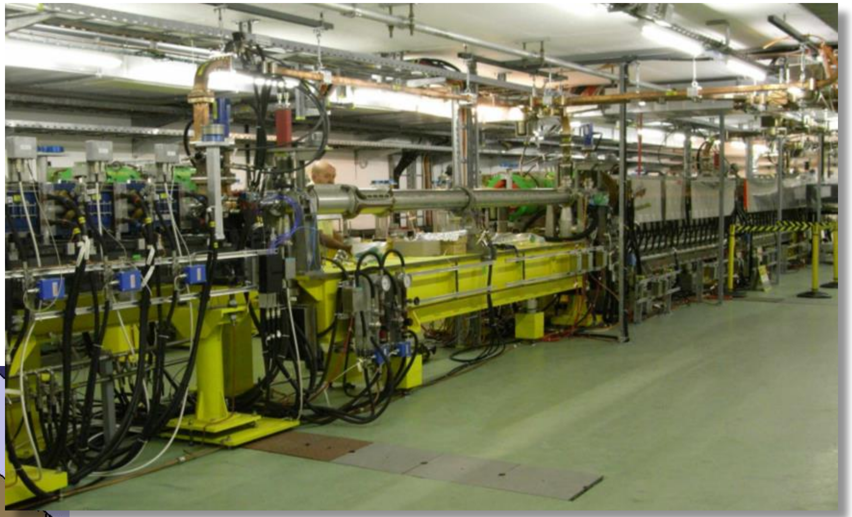
- The induced fields travel along the PETS structure and build up resonantly

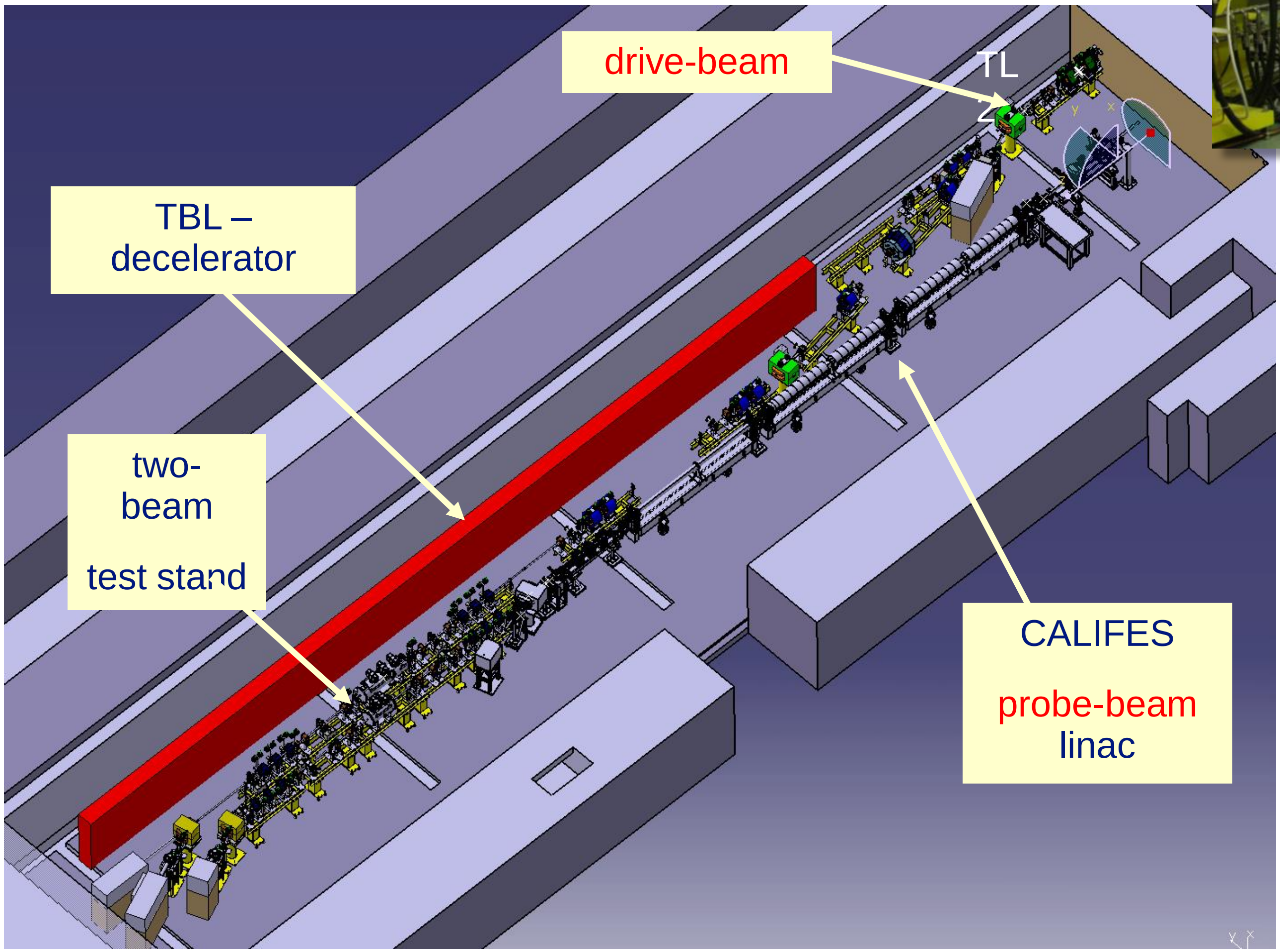
T3P models realistic, complex accelerator structures with unprecedented accuracy

Arno Candel, SLAC

CLEX test area in CTF3

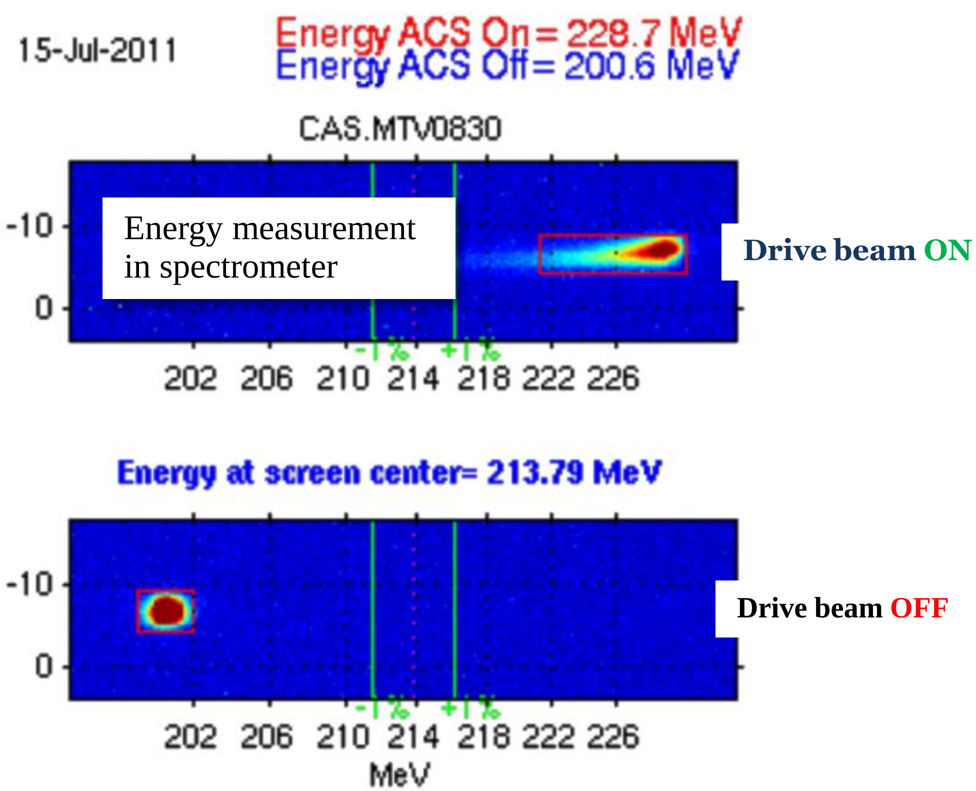
- Deceleration and two-beam tests
- High power tests of PETS and accelerating structures

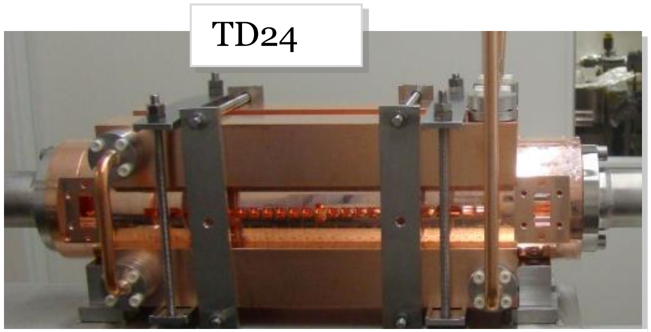


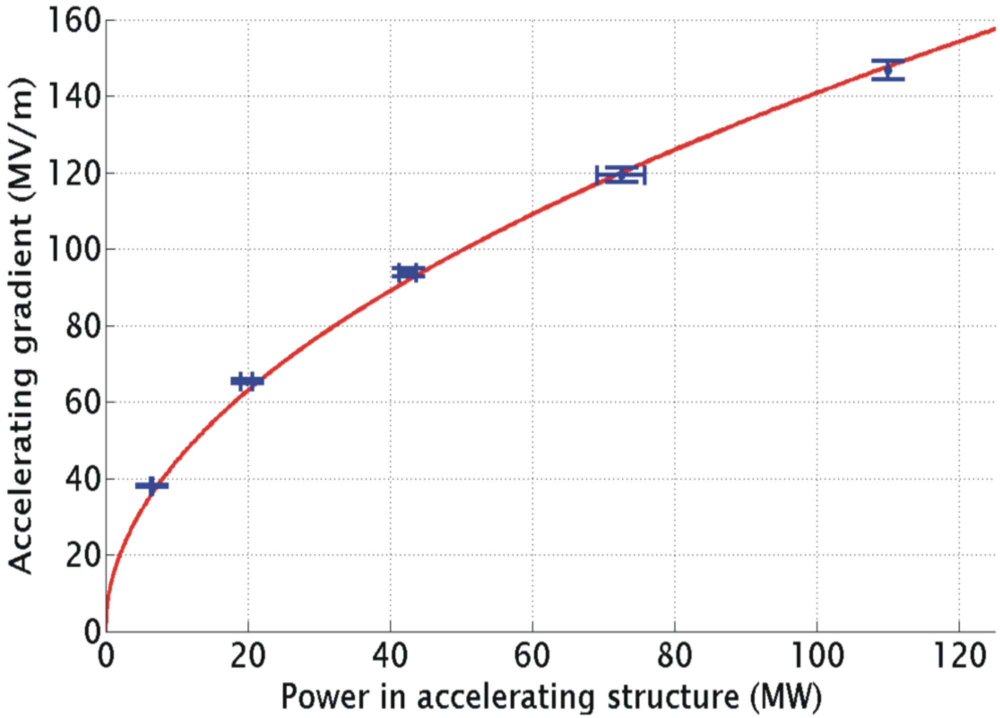


Achieved Two-Beam Acceleration in CTF3

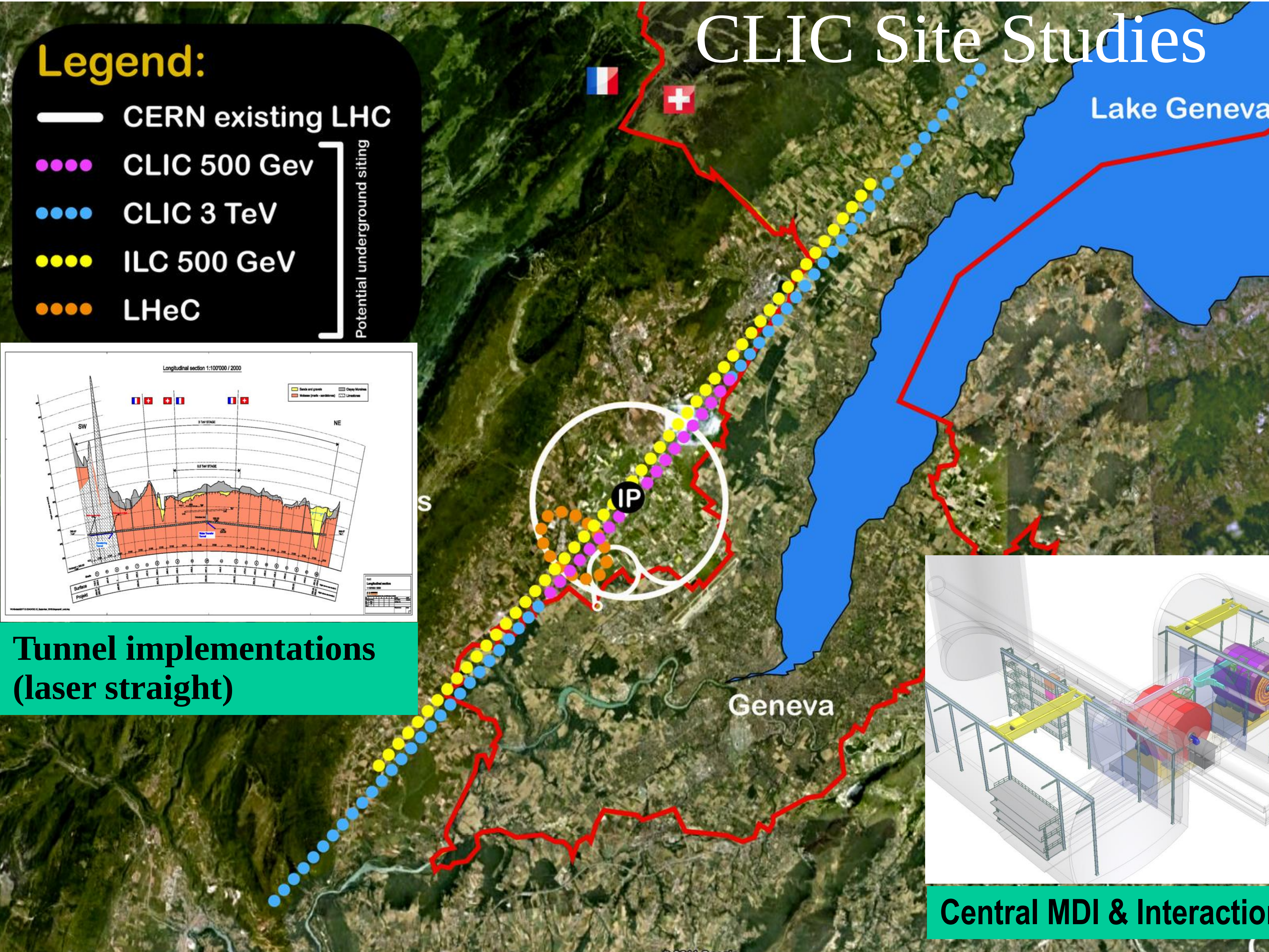
- Maximum probe beam acceleration measured: 31 MeV
  - Corresponding to a gradient of 145 MV/m







CLIC Site Studies



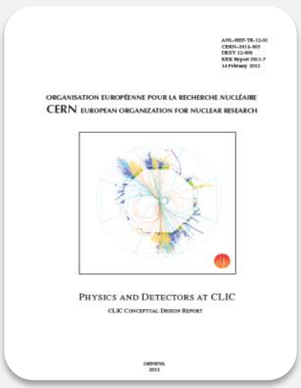
Tunnel implementations (laser straight)

Central MDI & Interaction

CLIC CDRs published

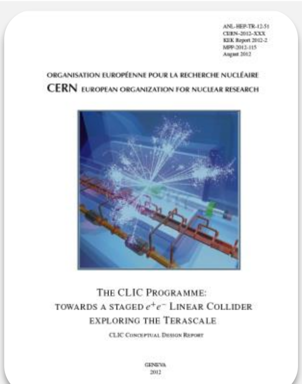
Vol 1: The CLIC accelerator and site facilities (H.Schmickler)

- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- Complete, presented in SPC in March 2011, in print: https://edms.cern.ch/document/1234244/



Vol 2: Physics and detectors at CLIC (L.Linssen)

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- Completed and printed, presented in SPC in December 2011 http://arxiv.org/pdf/1202.5940v1



Vol 3: "CLIC study summary" (S.Stapnes)

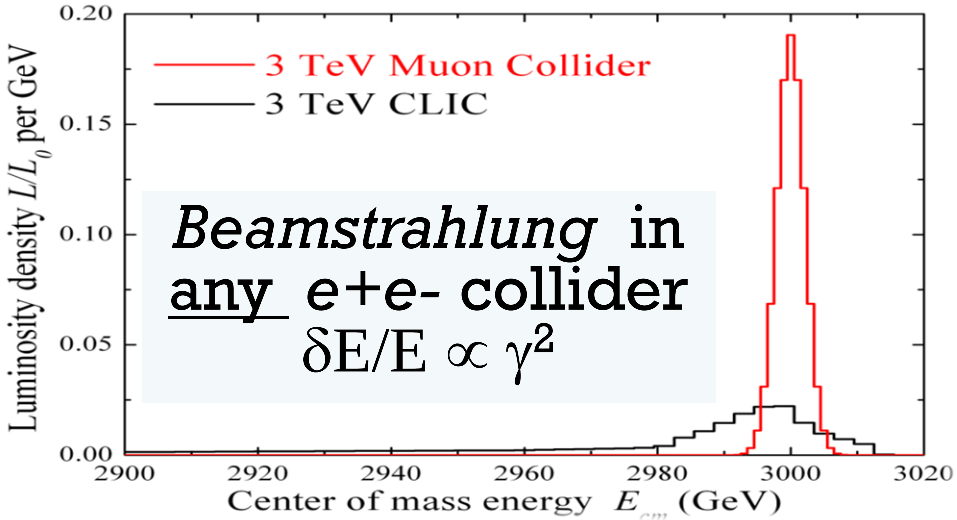
- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- Completed and printed, submitted for the European Strategy Open Meeting in September http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at:

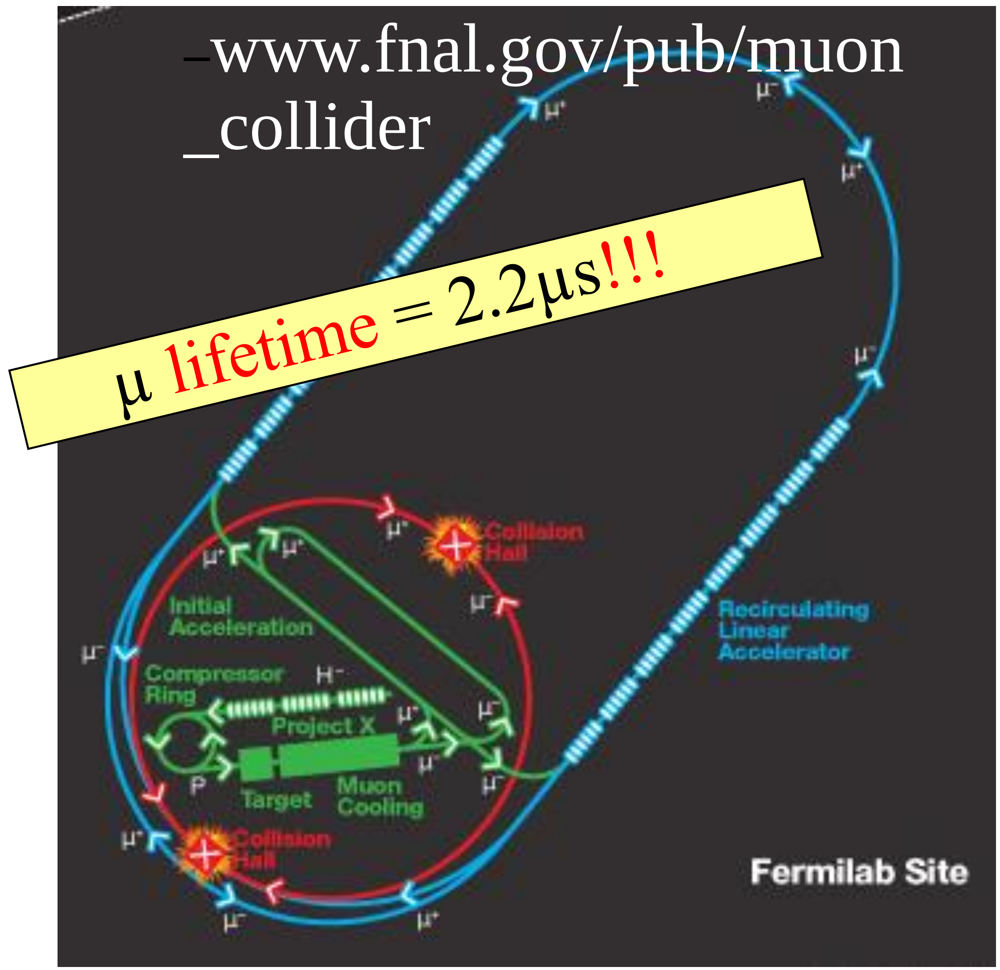
http://arxiv.org/pdf/1208.1402v1

Muon Collider

- Much less synchrotron radiation than e+e-
- Attractive ‘clean’ collisions at full E_{cms}



- High production cross section for Higgs
- The challenge: Cooling the μ beam!!
  + multi MW proton driver
- Emittance reduction 10^{-7}
  - ~1000 in each transverse plane
  - ~40 in longitudinal
  - => Ionisation cooling
  - requires 30-40T solenoids
    + high gradient RF cavities
- 6-year Feasibility Assessment Program



Compressor Ring
Reduce size of beam (2±1 ns).

Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate μ to 20 GeV

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to Multi-TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100m underground.

Plasma acceleration

Plasma accelerators:

Transform transverse fields into longitudinal fields

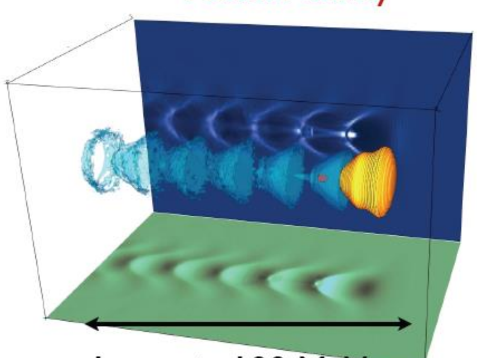
- **Laser driven**
- **e- driven**
- **p driven**
- **Dielectric wakefields**

RF Cavity

1 m => 100 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



1mm => 100 MeV

Electric field > 100 GV/m

V. Malka *et al.*, Science **298**, 1596 (2002)

Demonstrated accelerating gradients up to 3 orders of magnitudes beyond presently used RF technologies.

Still far away from possible future collider project

Plasma acceleration collider

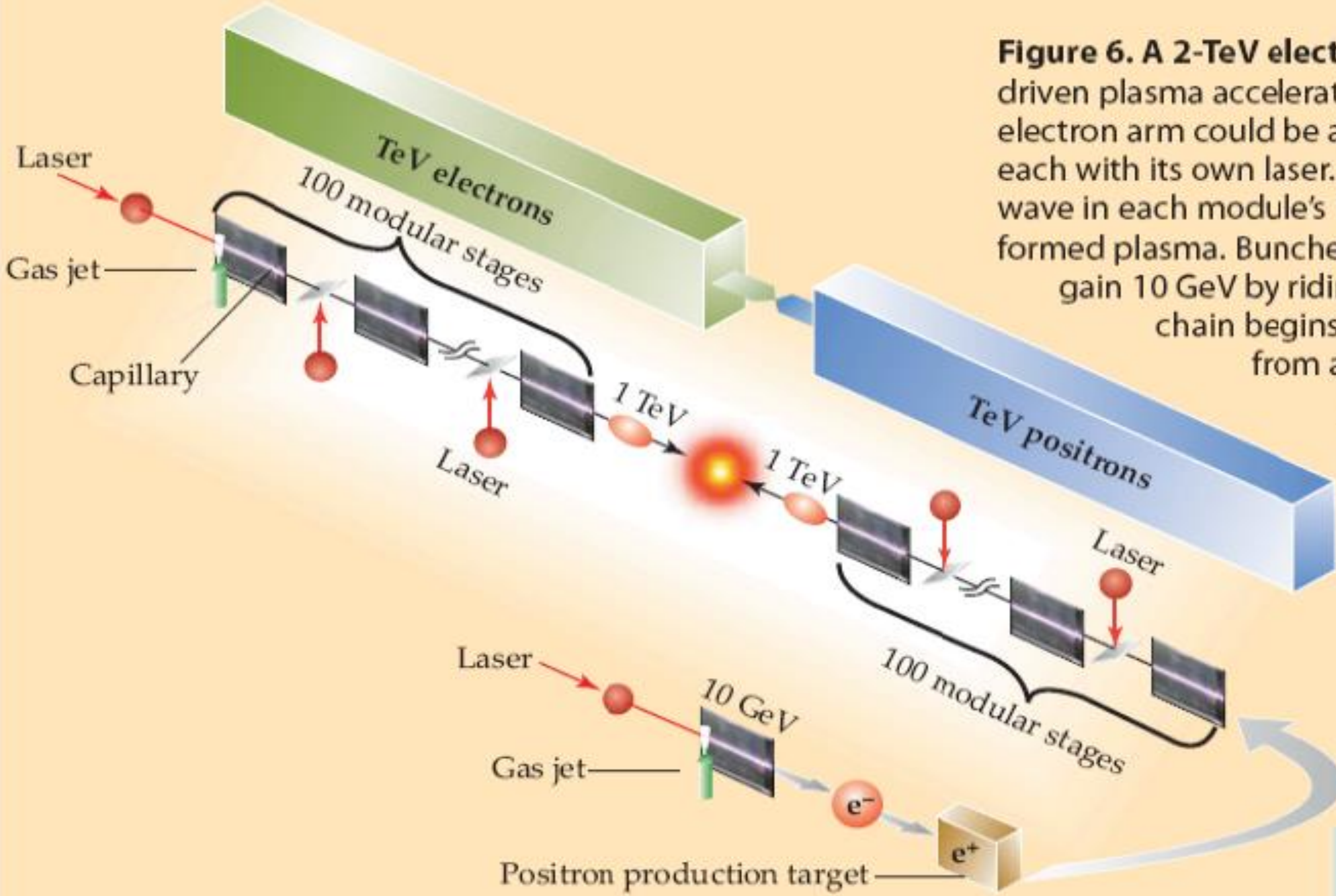


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans, et al.,

many challenges:

wall-plug efficiency:10^{-3}-10^{-4}! => 1-10 GW power for 1 MW e-, e+ beam

100 of kHz-PW Laser reliability, fs synchronisation, e+ acceleration, etc…

Summary

- CERN is presently exploiting the physics potential of the LHC
  - After the long shutdown LS1 the LHC will operate at 13 TeV in 2015 and later towards 14 TeV (2016-2023). Goal 300 fb^{-1} integrated luminosity
  - The high luminosity project HL-LHC will allow to collect ten times more data (2025 - mid 2030ies). Goal of 3'000 fb^{-1}
- CERN is hosting a study performed in international collaboration for a Future Circular Collider in the Geneva area with 80–100 km circumference:
  - proton-proton-collider (FCC-hh) defining the infrastructure requirements
  - e+e- collider (FCC-ee) as potential intermediate step
- Depending on the physics findings of the LHC "precision" e+e- linear colliders might be built in Japan (ILC) or at CERN (CLIC)
- Other more exotic projects (plasma, muons, …) are far future

Prediction is very difficult, especially if it's about the future. (Niels Bohr)

- Thank you very much for your attention!!!

Acknowledgements

- I would like to thanks everyone of whom I took some slides:

(in random order and I'm sure I forgot someone)

- C.Biscari, L.Rossi, F.Zimmermann, F.Bordry, M.Benedikt, P.Janot, D.Schulte, S.Stapnes, L.Evans, R.Assmann, V.Malka, plus everyone mentioned on the slides