The CERN Accelerator School

Accelerator Issues Overview

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CERN, ATS-DO

The CERN Accelerator School

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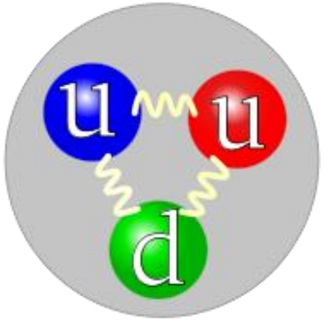
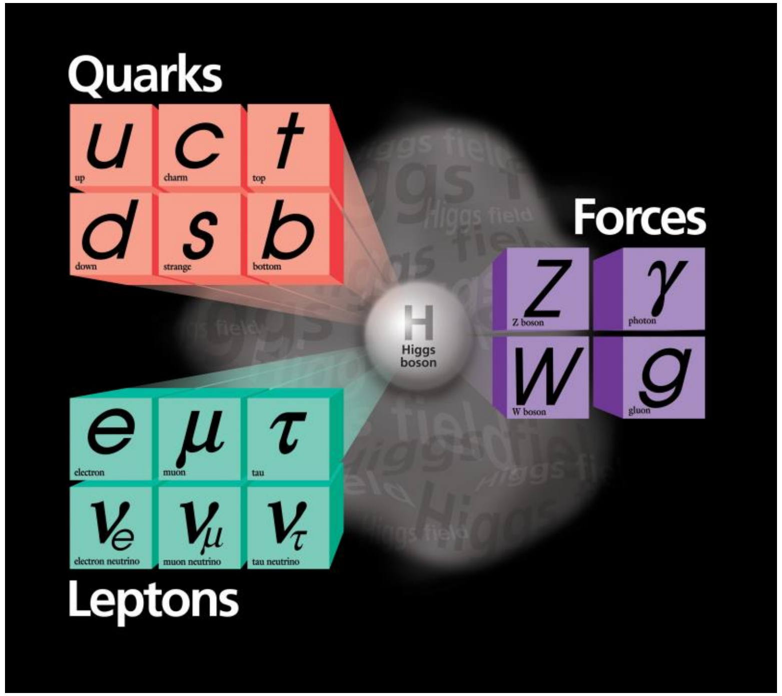
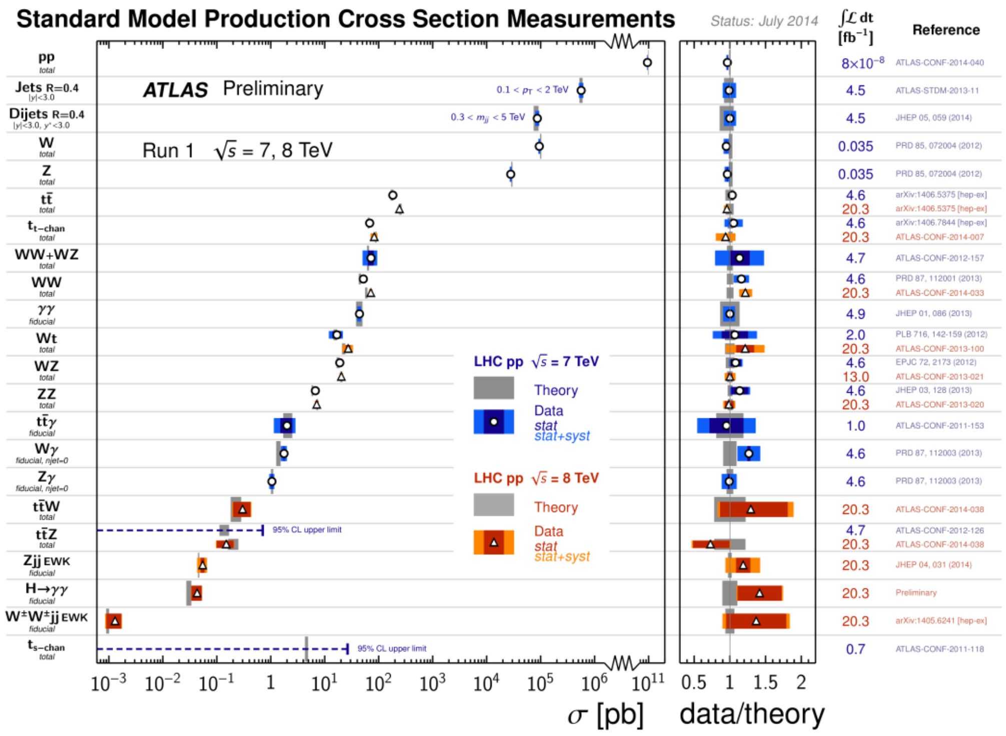
Introduction – The Standard Model

- The standard model describes extremely well the particle interactions



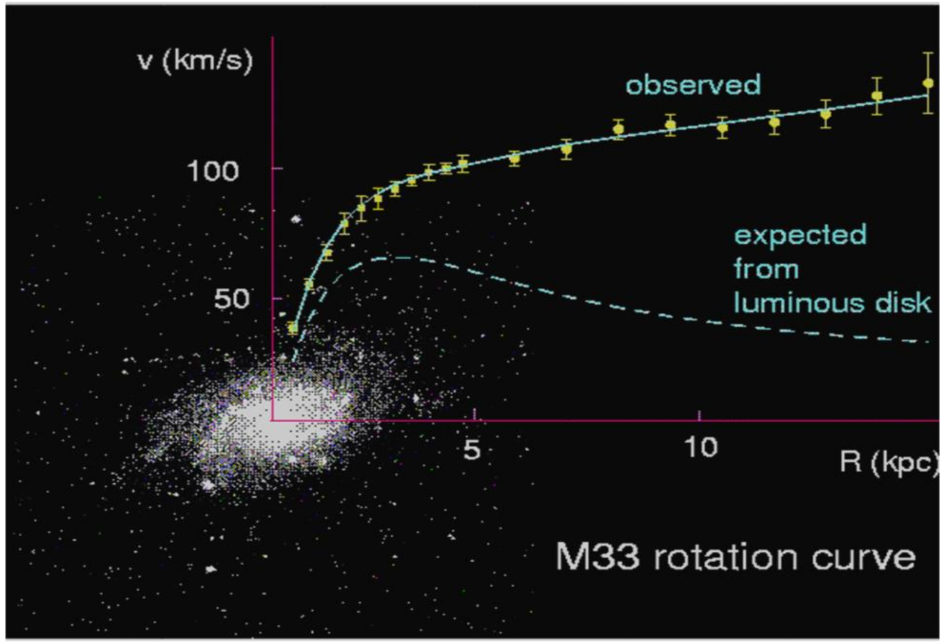
Proton

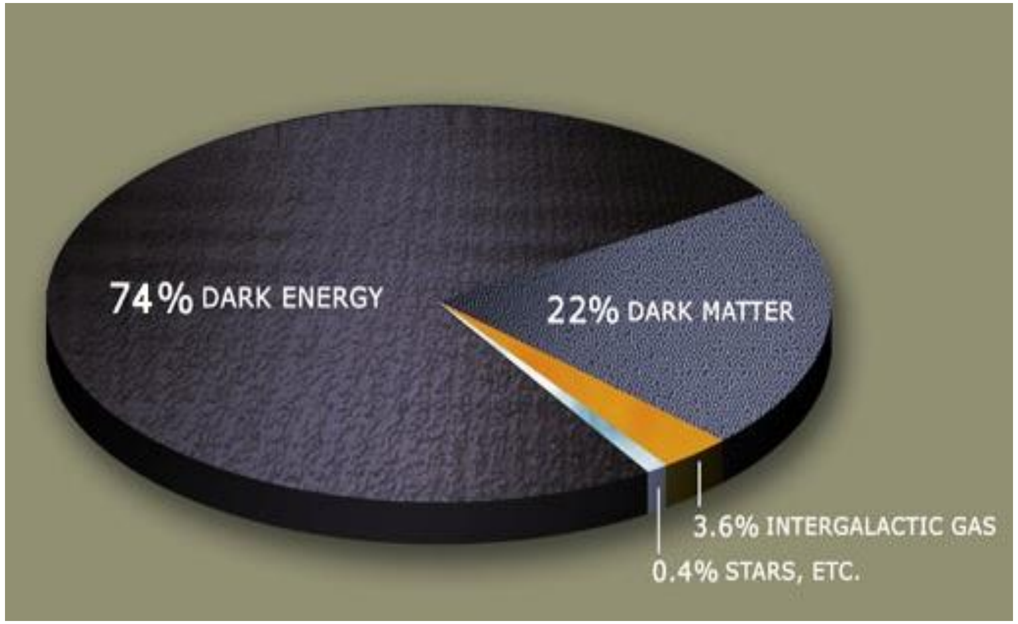




- BUT:
  - neutrino masses (explaining measured neutrino oscillations) not foreseen
  - a few parameters differ from expectations
    (anomalous magnetic dipole moment of the muon (g-2), W mass, B meson decay asymmetries)
  - matter/anti-matter inequality

The Dark Side of the Universe

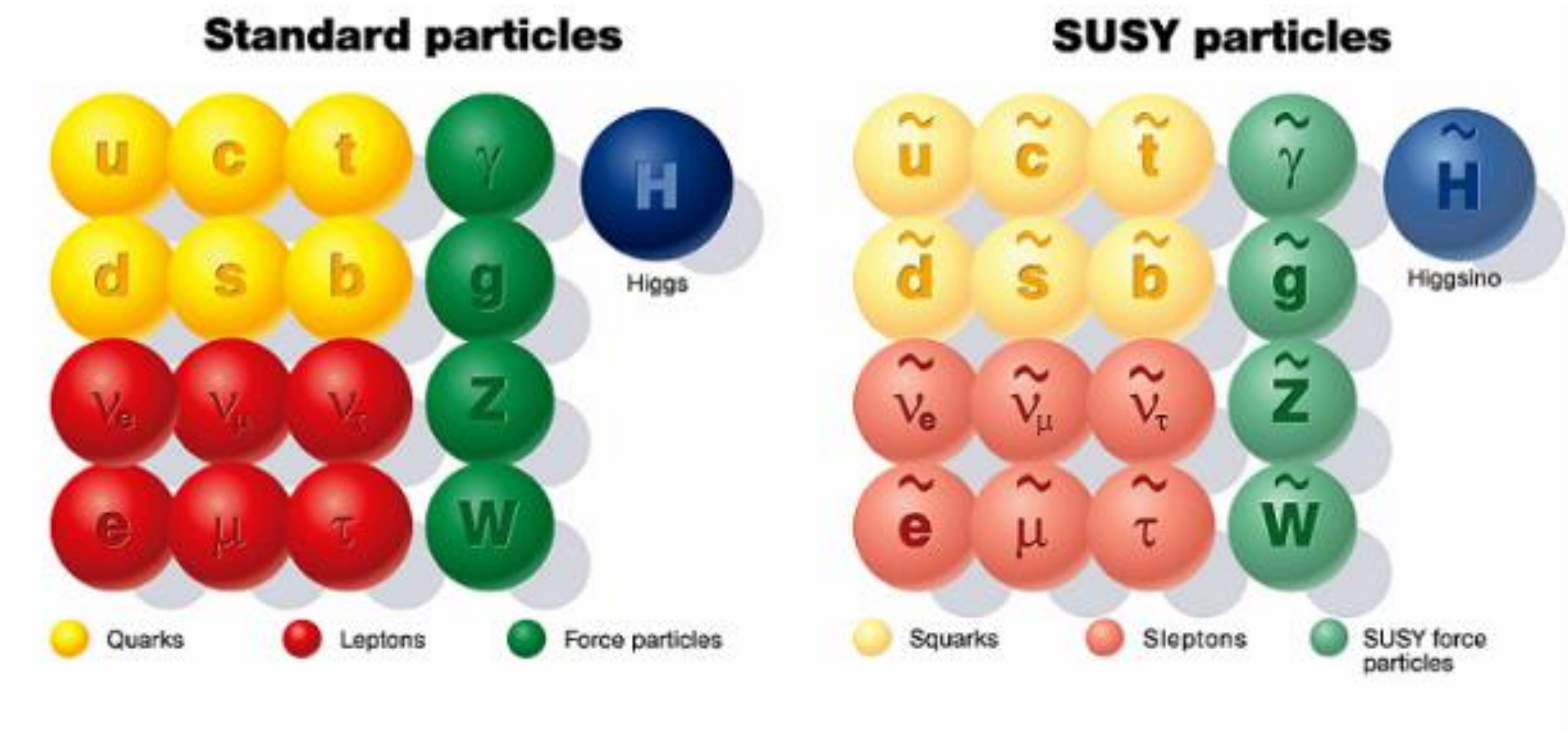




- Significant presence of dark (invisible) matter! Interacts gravitationally but does not shine
- Only 4% of the universe is 'ordinary' matter (SM particles)
- most of the universe is completely unexplained and not understood
- There is for sure something new out there! But we are not sure if we will be able to discover it.
- The discoveries / no discoveries at the LHC will set the directions for any future collider

Beyond the SM: Supersymmetry, …

- SUSY (super-symmetry) is one possible extension of the SM
  for every SM particle, there is a super-partner with spin 1/2 difference
- lightest SUSY particle could be dark matter candidate
- none of the super-particles seen so far… (but also still not excluded)
- other theories around (extra dimensions, little Higgs models, …)



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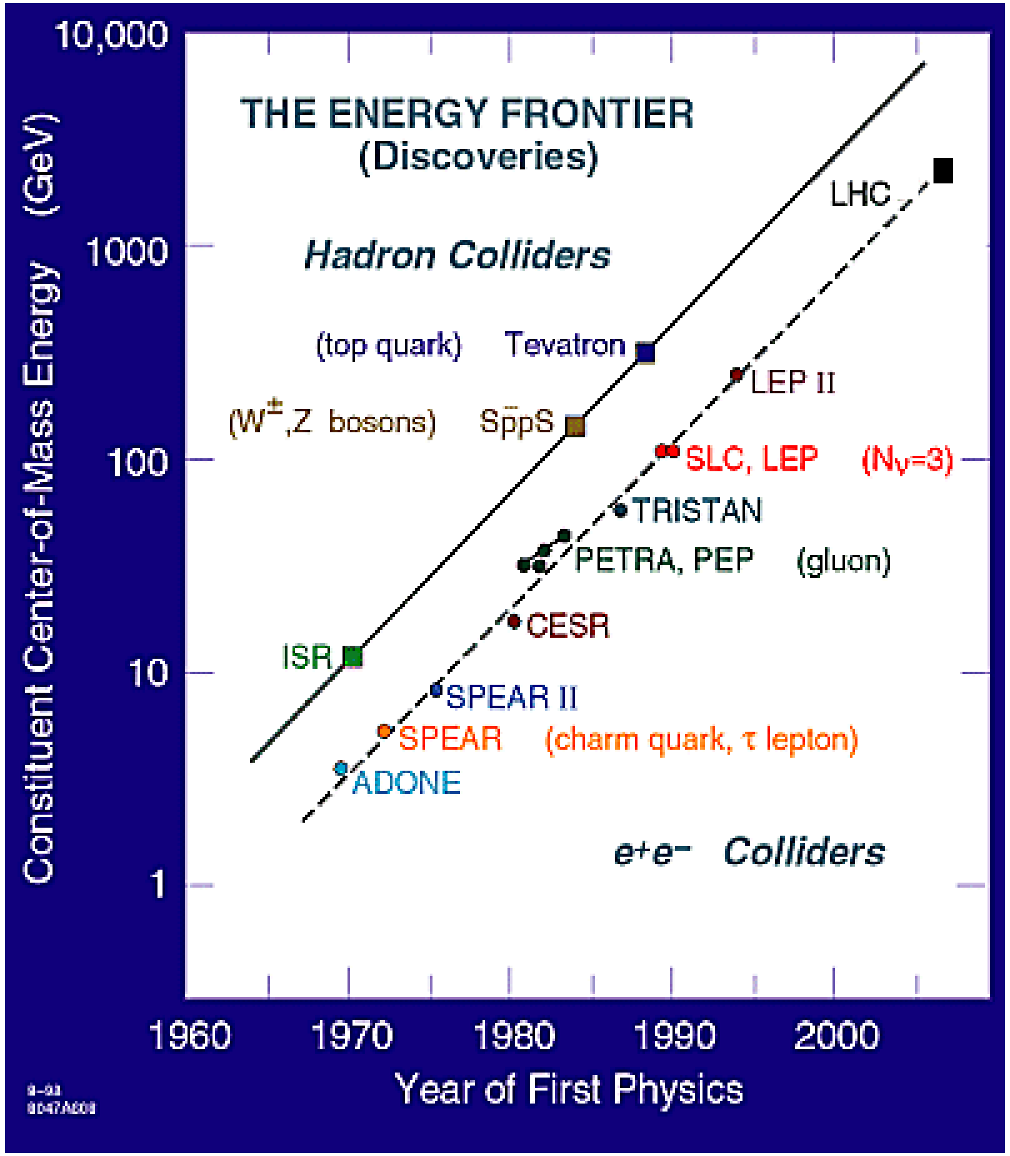
Path to discovery - higher energy

- **History of Colliders:**
  - **Hadron Colliders** at the energy frontier => direct discovery
  - **Lepton Colliders** for precision physics => deviations from SM expectations

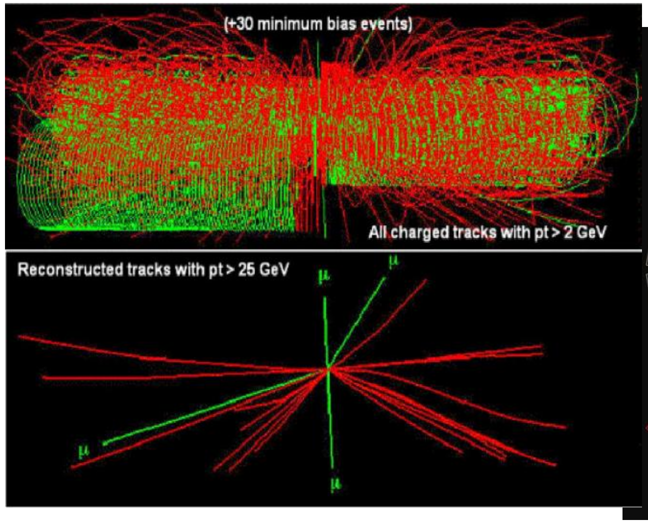
- LHC has found the Higgs with m_H = 126 GeV/c^2

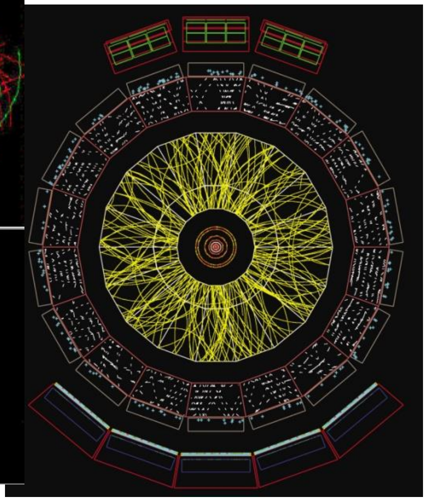
- What will be the next energy frontier machine?



Hadron vs. Lepton Collisions

LHC: H → ZZ → 4μ

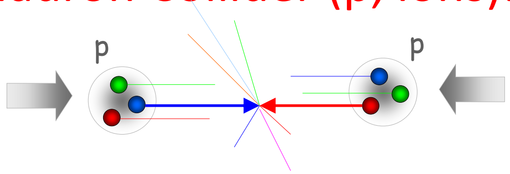




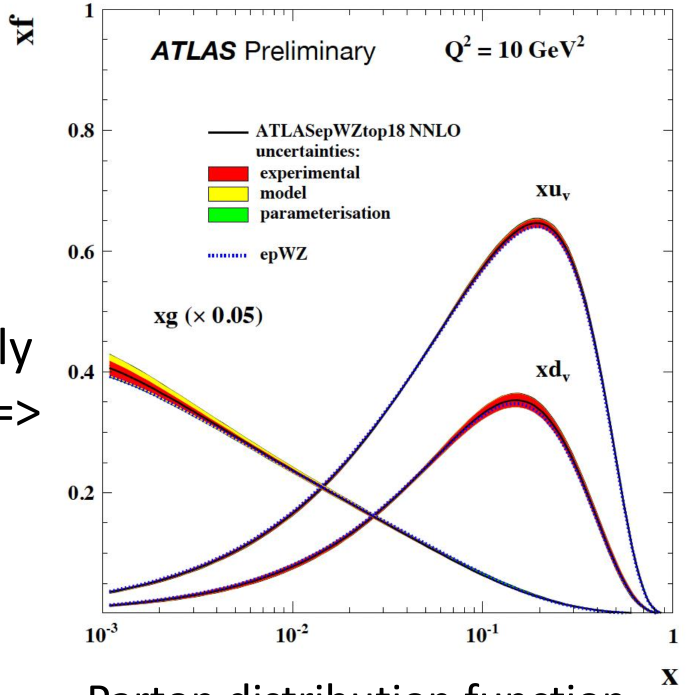
ALICE: Ion event

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

- Hadron Collider (p, ions):

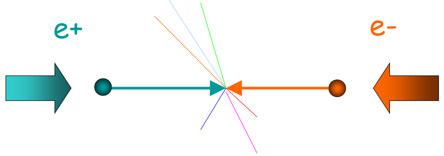


  - Composite nature of protons
  - Quarks (which collide) carry only fraction of the momentum =>
  - Can only use p_t conservation
  - Huge QCD background



Parton distribution function of the proton

- Lepton Collider:



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

Main High-Energy Frontier Collider Projects

Circular colliders:

- HL-LHC (CERN) – High-Luminosity upgrade of LHC
- FCC (CERN) (Future Circular Collider)
  - FCC-hh: 100 TeV proton-proton cms energy, ion operation possible
  - FCC-ee: 90-350 GeV e^+e^- collider as potential intermediate step
  - FCC-he: Lepton-hadron option
- CEPC / SppC (China) (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC : e^+e^- 240GeV cms
  - SppC : pp 70TeV cms
- Muon collider: 3-10 (14) TeV cms energy

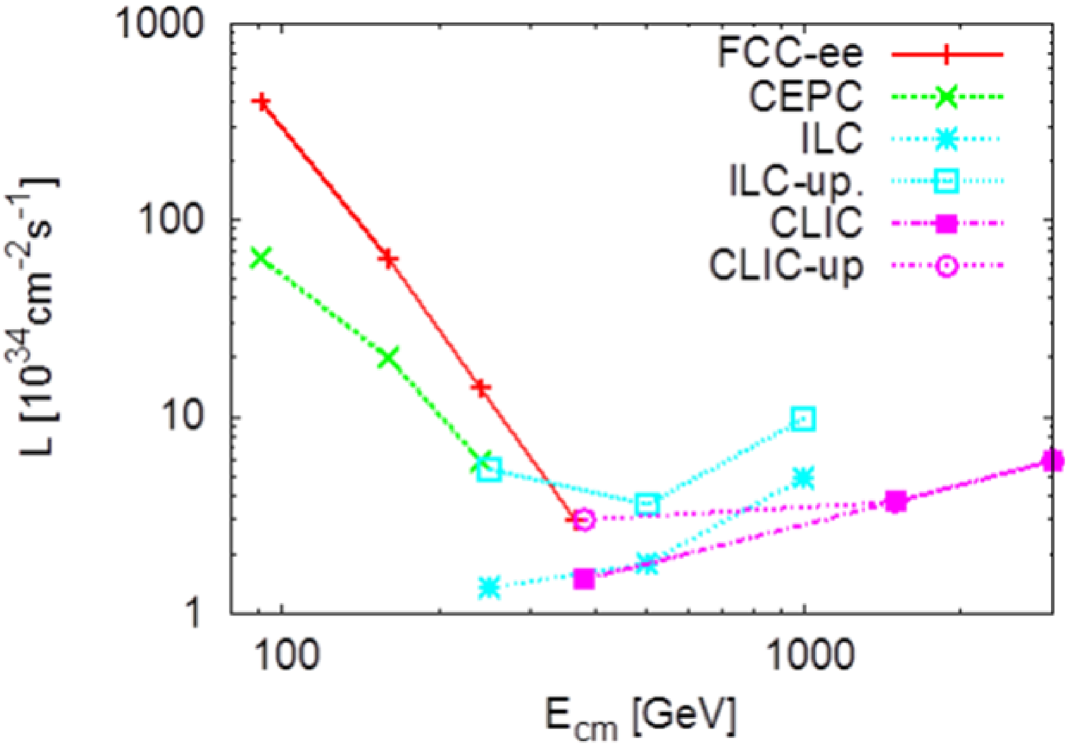
Linear colliders:

- ILC (International Linear Collider): e^+e^-, 250-500 GeV cms energy, SC technology
  Japan considers hosting project
- CLIC (Compact Linear Collider): e^+e^-, 380GeV-3TeV cms energy, NC technology
  CERN hosts collaboration

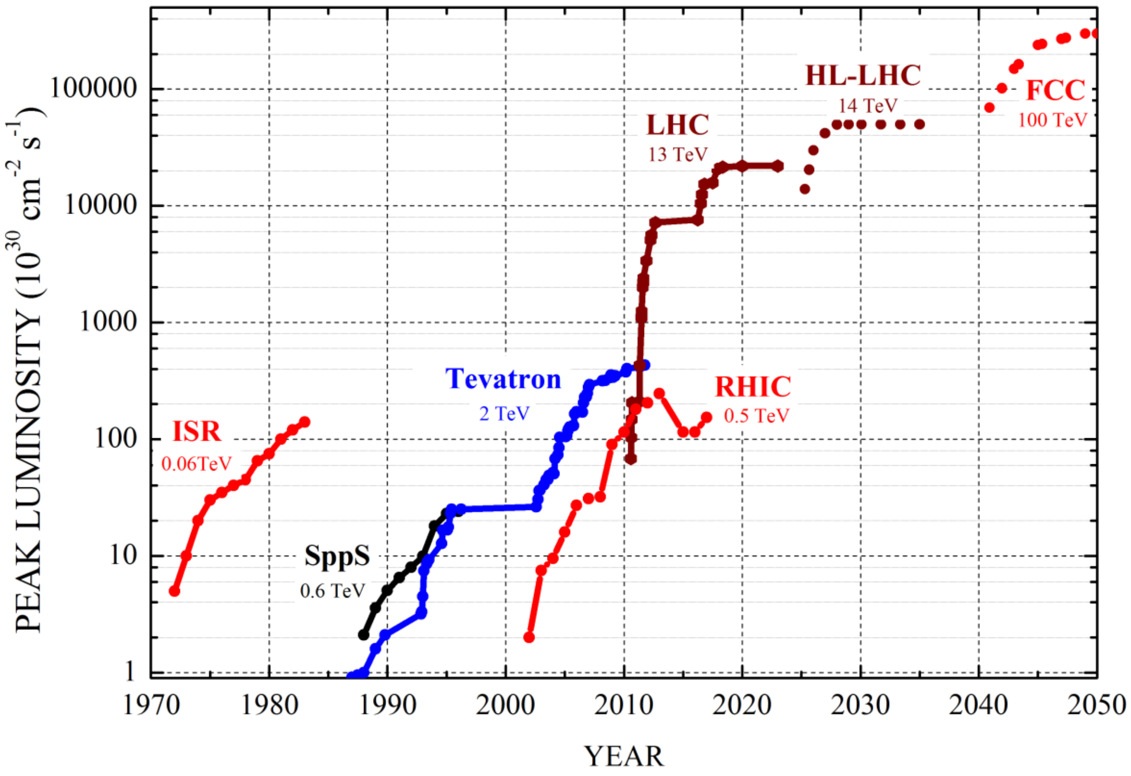
Collider Luminosity

L.Rossi

- Electron-Positron collider



- Hadron collider



Challenge: Energy

- **Ring collider:**
  - $p = q\,B\rho$
  - $E = \sqrt{p^2c^2 + m^2c^4} \approx pc$ (for $pc \gg mc^2$)

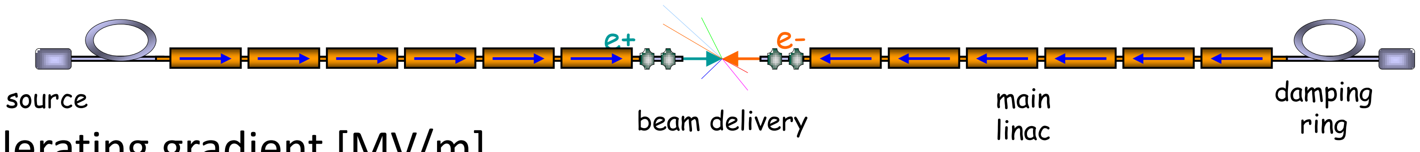
p : particle momentum
q : electric charge, typically e
B : magnetic field [T]
ρ : bending radius [m]

⇒ For a given size, the magnetic field determines the energy

⇒ **Limitation for hadron colliders** (not limiting lepton colliders)

⇒ need to develop **strong superconducting magnets**

- **Linear collider:**
  - $E = q\,G\,L$



G : accelerating gradient [MV/m]
L : length of the acceleration [m]

⇒ maximize the gradient for high energy reach

⇒ need to develop **high-gradient RF structures** (or alternative methods)

Challenge: Synchrotron radiation

$$P = \frac{e^2 c}{6\pi\varepsilon_0}\left(\frac{E}{m_0 c^2}\right)^4 \frac{\beta^4}{\rho^2}$$

- Emitted power P scales with γ^4 !
- Factor ~10^{13} between electron and proton (m_p/m_e=1836)
  - LEP-II, electrons
    - E = 100 GeV, ρ = 3026 m, I = 6 mA => U_0 = 2.9 GeV, P = 17.4 MW (!)
  - LHC, protons
    - E = 7 TeV, ρ = 2804 m, I = 580 mA => U_0 = 6.6 keV, P = 3.8 kW – not negligible!

- This is **limiting the energy for** high-energy **electron-positron storage rings**
- FCC-ee limits synchrotron radiation power in design to 50 MW/beam

- Muon-collider has the advantage of colliding elementary particles with less synchrotron radiation (m_μ/m_e=207)
  - but the muons are decaying => rapid acceleration and beam cooling

Challenge: Luminosity

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- The integrated luminosity is the figure of merit for a collider => physics results

Number of events: $N = \sigma \cdot \int \mathcal{L}\, dt$ σ production cross-section

$$\mathcal{L} = \frac{n_b N_{b1} N_{b2} f}{4\pi\sigma_x\sigma_y} F\, H_D$$

f : revolution frequency

n_b: number of colliding bunch pairs at that Interaction Point (IP)

N_{b1}, N_{b2}: bunch population

$\sigma_{x,y}$: transverse beam size at the collision point

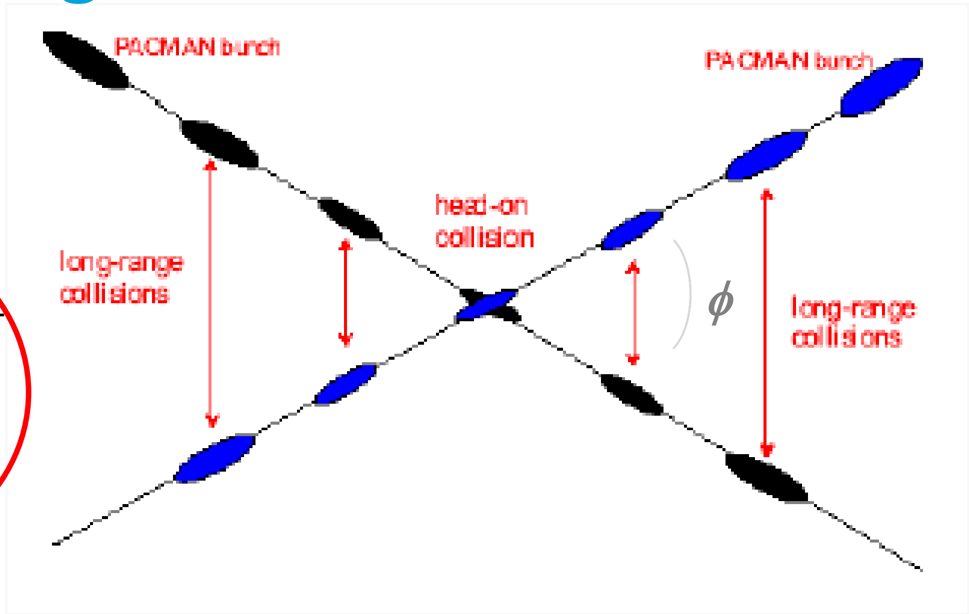
F: geometric reduction factors

- transverse offsets
- crossing angle
- hour-glass effect

H_D: beam-beam enhancement factor (linear colliders)

- In principle, we need
  - many intense bunches with high repetition frequency
  - well centered collisions
  - small beam sizes

Luminosity: Crossing angle



- Need crossing angle to avoid parasitic collisions and for beam extraction (linear collider)
- Luminosity reduced

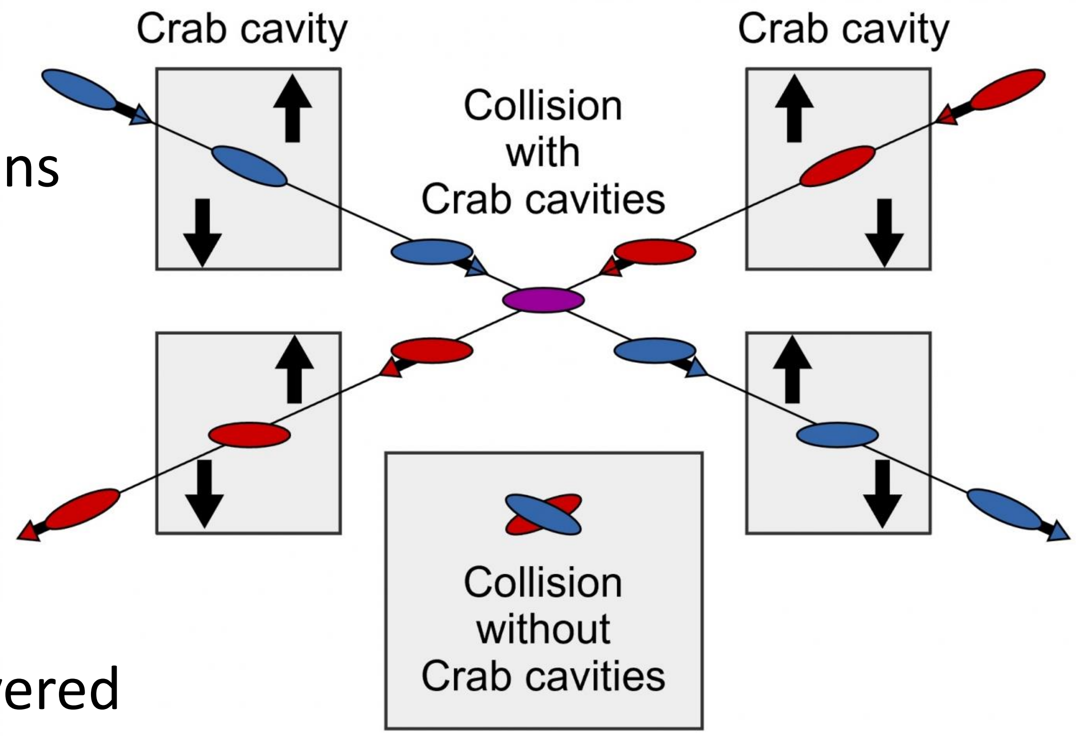
$$L = \frac{n_b N_{b1} N_{b2} f}{4\pi\sigma_x\sigma_y} \underbrace{\frac{1}{\sqrt{1+\left(\frac{\sigma_z}{\sigma_x}\tan\frac{\phi}{2}\right)^2}}}_{F}$$

$\frac{\sigma_z}{\sigma_x}\tan\frac{\phi}{2}$ is called "Piwinski angle"

- large angle for minimizing long-range beam-beam effect
- LHC: $\phi = 285$ μrad, $\sigma_z = 7.5\ cm$ => F=0.84
- HL-LHC: $\phi = 590$ μrad, $\sigma_z = 7.5\ cm$ => F=0.31
- ILC: $\phi = 14$ mrad, $\sigma_z = 300\ \mu m$, $\sigma_x = 730\ nm$ => F=0.33
- CLIC: $\phi = 16.5/20$ mrad (@0.38/3 TeV)

Luminosity: Crossing angle and Crab Cavities

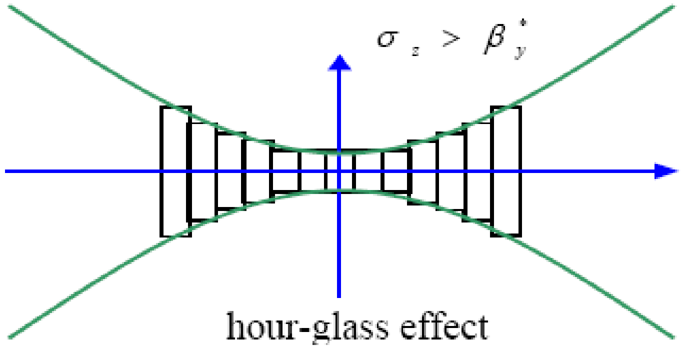
- oscillating transverse electric field kicks head and tail of the bunches in opposite directions
- transversely deflecting RF ”crab cavity” on both side of the IP
- 90 degrees betatron phase advance to IP
- bunches tilt on the way to the IP to collide quasi head-on
- => luminosity reduction from angle almost recovered



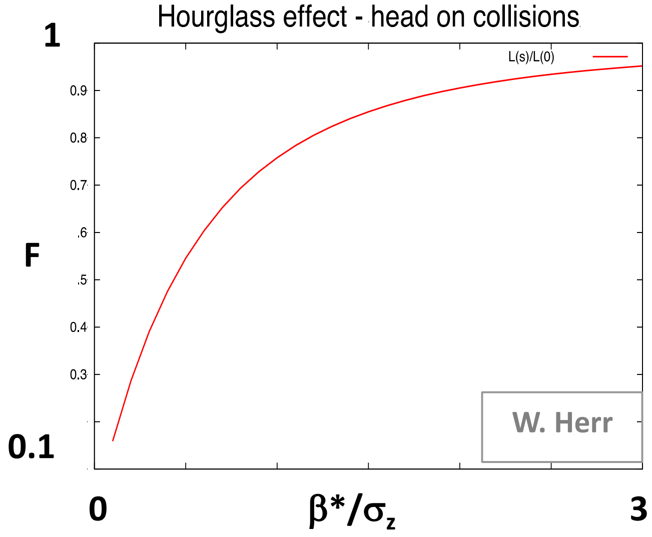
- Important for proton colliders and linear e+/e- colliders
- challenge for phase noise (luminosity reduction, emittance growth)

Luminosity: Hourglass effect

- Tiny beam sizes require small β* (β at the IP)
- β depends on longitudinal position s: $\beta(s) = \beta^* + \frac{s^2}{\beta^*}$
- so beam size $\sigma_{x,y}$ depends on s
  - if β* >> σ_z, effect is negligible
  - if β* ~ σ_z, collisions where β bigger than β*



- LHC: $\beta^* = 55$ cm, $\sigma_z = 7.5\ cm$ => F ~ 1
- HL-LHC: $\beta^* = 15$ cm, $\sigma_z = 7.5\ cm$ => F ~ 0.90
- FCC-ee: F: 0.53 - 0.73 (standard collision scheme)
- Linear colliders: very important, drives design to small σ_z

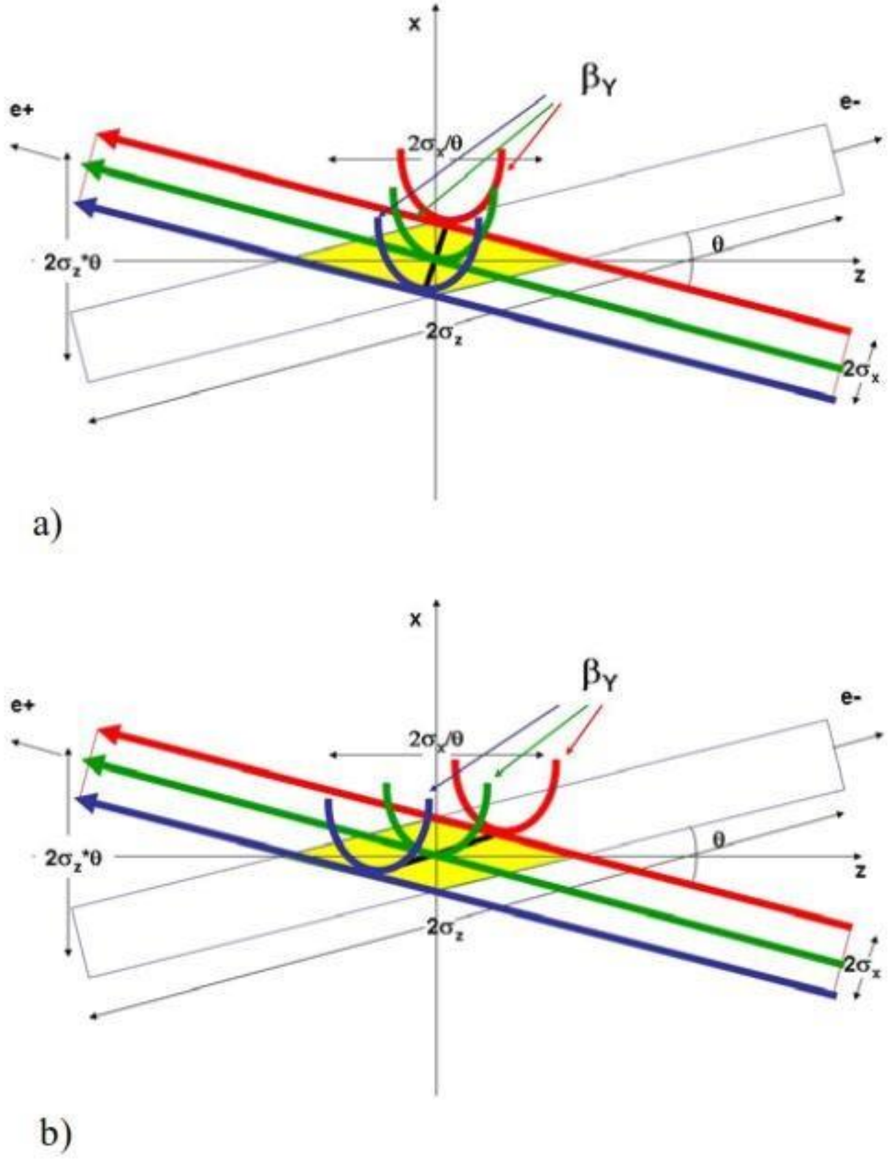


Luminosity: Crab-Waist scheme

- Increase crossing angle and decrease horizontal beam size => reduce beam-beam effects
- reduce vertical β function to overlap length (smaller than σ_z)
- β waist of one beam is oriented along the central trajectory of the other one
- sextupole magnets placed on both sides of the IP in phase with the IP in the horizontal plane and at π/2 in the vertical one

⇒ suppression of betatron resonances

- design for FCC-ee, SuperKEKB, SuperC-Tau factory, CEPC (China)



Luminosity: e+/e- Linear Collider vs Storage Ring

- **Ring collider**: 'efficient', as particles are accelerated over many turns and then can collide every turn, limited by beam-beam effect, synchrotron radiation for e+/e-
- **Linear Collider** (LC): one pass acceleration, less beam-beam limited

- Collider luminosity $\mathcal{L}$ (cm^{-2} s^{-1}) is

$$\mathcal{L} = \frac{n_b N_{b1} N_{b2} f}{4\pi\sigma_x\sigma_y} F\, H_D$$

- LHC ring f = 11 kHz
- LC f = few-100 Hz (power limited)

  ⇒ factor ~100-1000 in L already lost for the LC!
- Must push very hard on beam cross-section at collision:
- factor of 10^6 gain needed to obtain high luminosity of a few 10^{34} cm^{-2}s^{-1}
- Driven to extremely small beam sizes
- => **challenge for generating small emittance, alignment, stabilization**

LEP: $\sigma_x\sigma_y \approx 130 \times 6\ \mu m^2$

LC: $\sigma_x\sigma_y \approx (60\text{-}550) \times (1\text{-}5)\ nm^2$

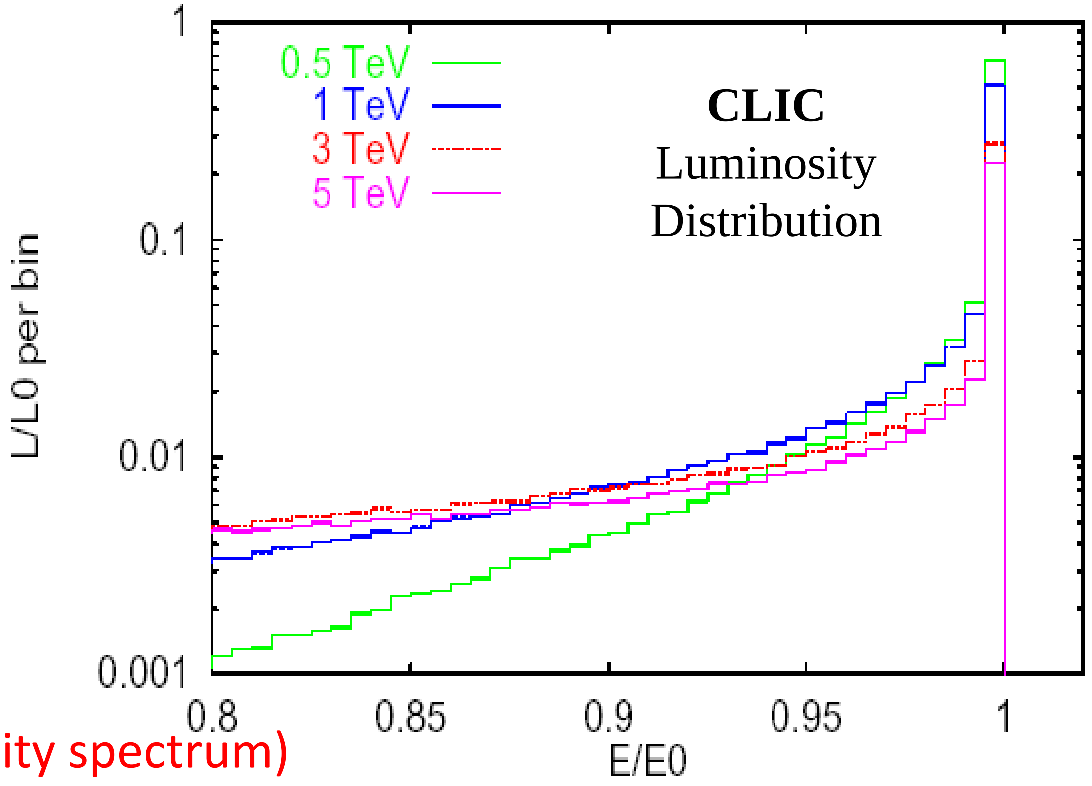
Luminosity - Beamstrahlung

- "synchrotron radiation" in the field of the opposing bunch

=> energy loss

- smears out luminosity spectrum
- creates e^+e^- pairs - background in detector
- RMS beamstrahlung energy loss:

$$\delta_{BS} \approx 0.86 \frac{r_e^3}{2m_0c^2}\left(\frac{E_{cm}}{\sigma_z}\right)\frac{N^2}{(\sigma_x+\sigma_y)^2}$$

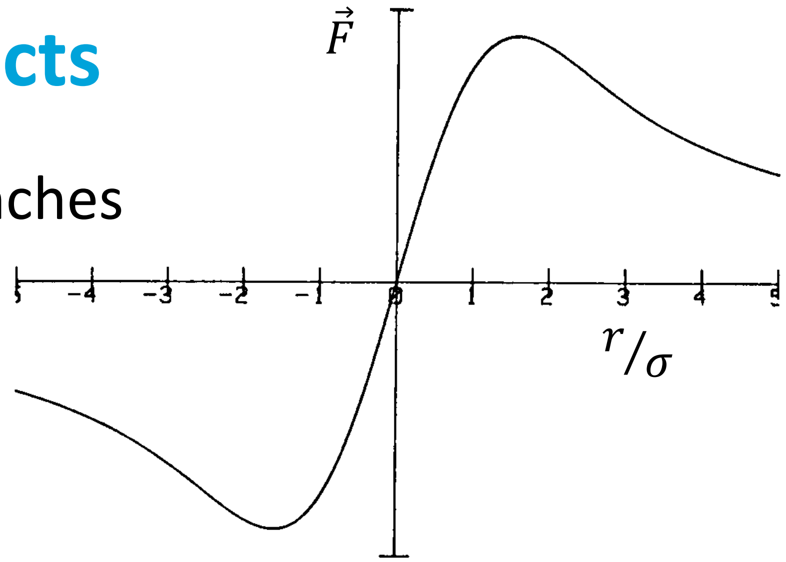


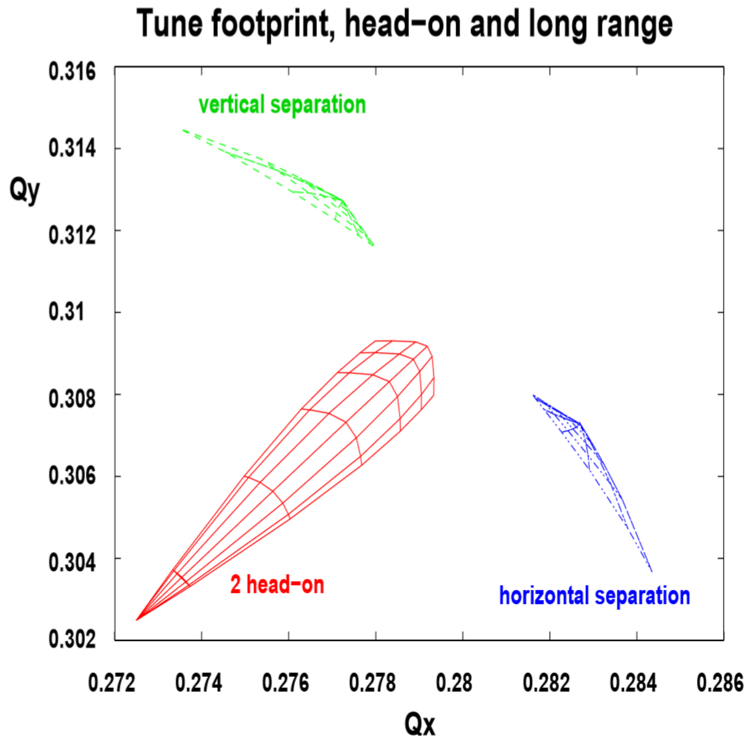
- we want
  - σ_x and σ_y small for high luminosity
  - $(\sigma_x + \sigma_y)$ large for small δ_{BS} (=> better luminosity spectrum)
- use **flat beams with $\sigma_x \gg \sigma_y$**

Challenge: Beam-beam effects

- In the collisions, particles see strong field of opposing bunches
- Field is highly non-linear
  - for small amplitudes:
    - almost linear, quadrupole like

    $\Rightarrow$ linear detuning, same sign in both planes
  - for large amplitudes:
    - amplitude dependent
    - opposite sign w.r.t. to the particle near the center
- ring colliders:
  - tune spread => crossing resonances
  - emittance growth and instabilities
- linear colliders:
  - beam extraction difficult
  - beam-beam deflection feedback





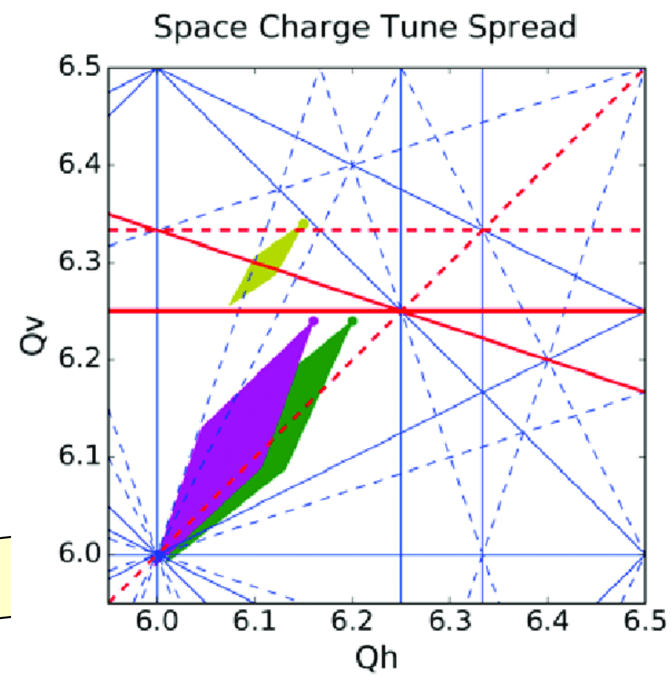
M. Bai
W. Herr

More in lecture by **Xavier Buffat**

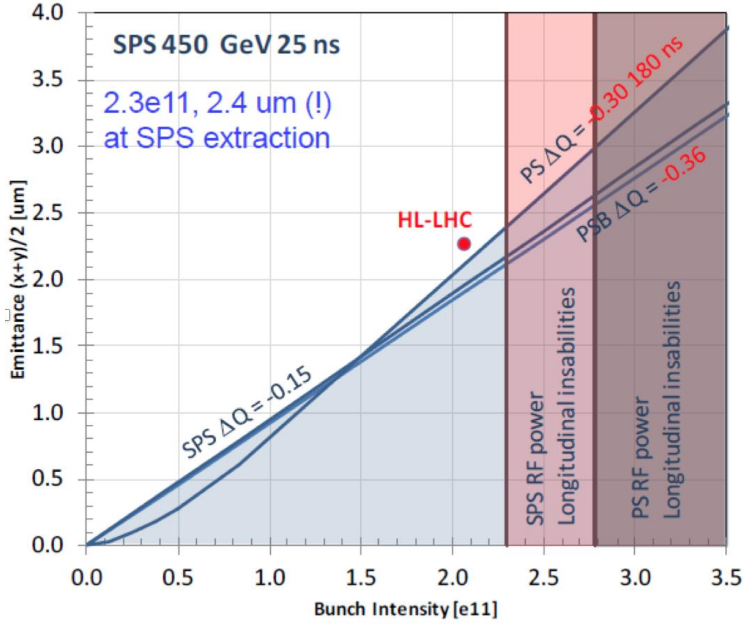
Challenge: Space Charge

- high-current beams needed
- effect from self fields inside the bunch and image fields
- tune spread ΔQ for bunched beams
- => particle cross resonance lines
- => losses and emittance growth
- $\Delta Q \sim \frac{N}{\varepsilon_{x,y}\beta^2\gamma^3}$
- space charge effect predominant at low energy

More in lectures by ***Massimo Ferrario***



- Limiting the brightness in the (HL-)LHC injector chain
- much less critical in presence of SR damping



Challenge: beam power

- **Linear collider:**
  - Average beam power $P_{beam} = \delta \, IE/e = f_{rep} \, N_{pulse} \, E$
  - Luminosity is proportional to beam power
  - $P_{beam} = P_{RF} \, \eta_{RF \rightarrow beam} = P_{mains} \, \eta_{mains \rightarrow RF} \, \eta_{RF \rightarrow beam}$
  - Power consumption proportional to beam power

  $\Rightarrow$ need to optimize overall efficiency η
  - develop efficient modulators and klystrons

δ: duty factor
I : beam current
E: beam energy
f_{rep}: repetition rate
N_{pulse}: total particles per pulse

- **Ring collider:**
  - large power loss through synchrotron radiation needs to be replaced for e+/e- rings

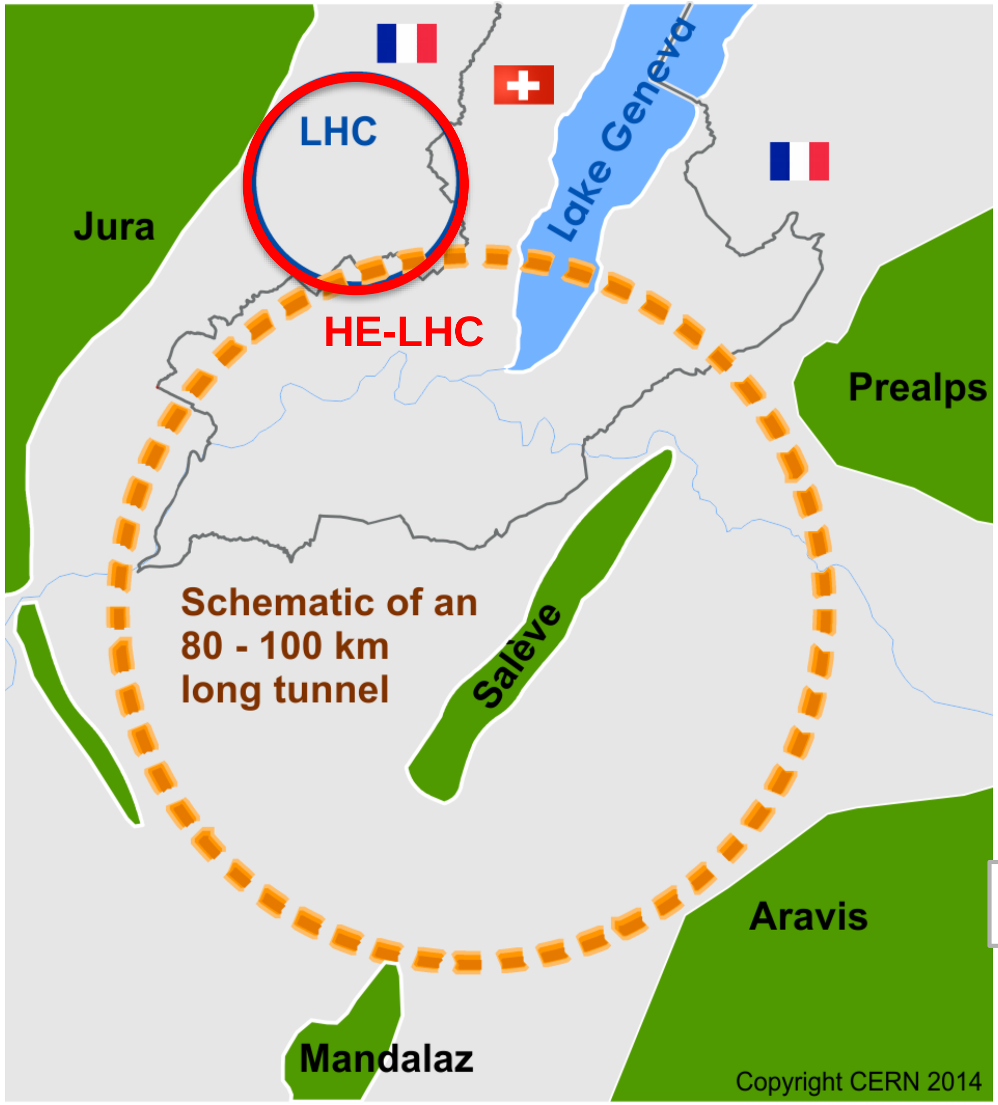
The different projects

Proton-Proton ring collider: HL-LHC

- Upgrade LHC operation for the period beyond 2025 up to 2040
- Goal: Increase LHC luminosity by a factor 10, total integrated luminosity of **3000 fb^{-1}**
- Limit the pile-up (number of collisions per bunch crossing) to **μ ≤ 140**
- **=> Luminosity levelling** required
- Modifications:
  - Lower beta* (~15 cm) => larger beam size in inner triplet magnets => larger crossing angle
    - New technology inner triplet magnets - wide aperture Nb_3Sn – radiation shielding necessary
  - more intense and brighter bunches from injector complex (from 1.15E11p / 3.4µm to 2.2E11p / 2µm emittance at SPS extraction)
  - Shielding and collimation upgrade (low impedance collimators) => beam stability
  - large crossing angle significantly reduces luminosity
    - compensation by crab cavities

More in lectures by
Markus Zerlauth** and **Oliver Brüning

CERN Future Circular Collider Study

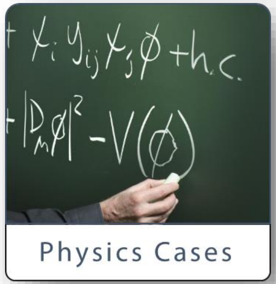


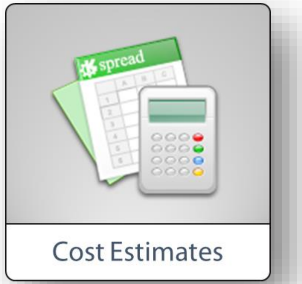
International FCC collaboration (CERN as host lab) to study:

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- ***e*⁺*e*⁻ collider (*FCC-ee*),** as potential first step
- ***pp*-collider (*FCC-hh*)** → long-term goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **lepton-hadron collisions** as options to FCC-hh





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 superconducting 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

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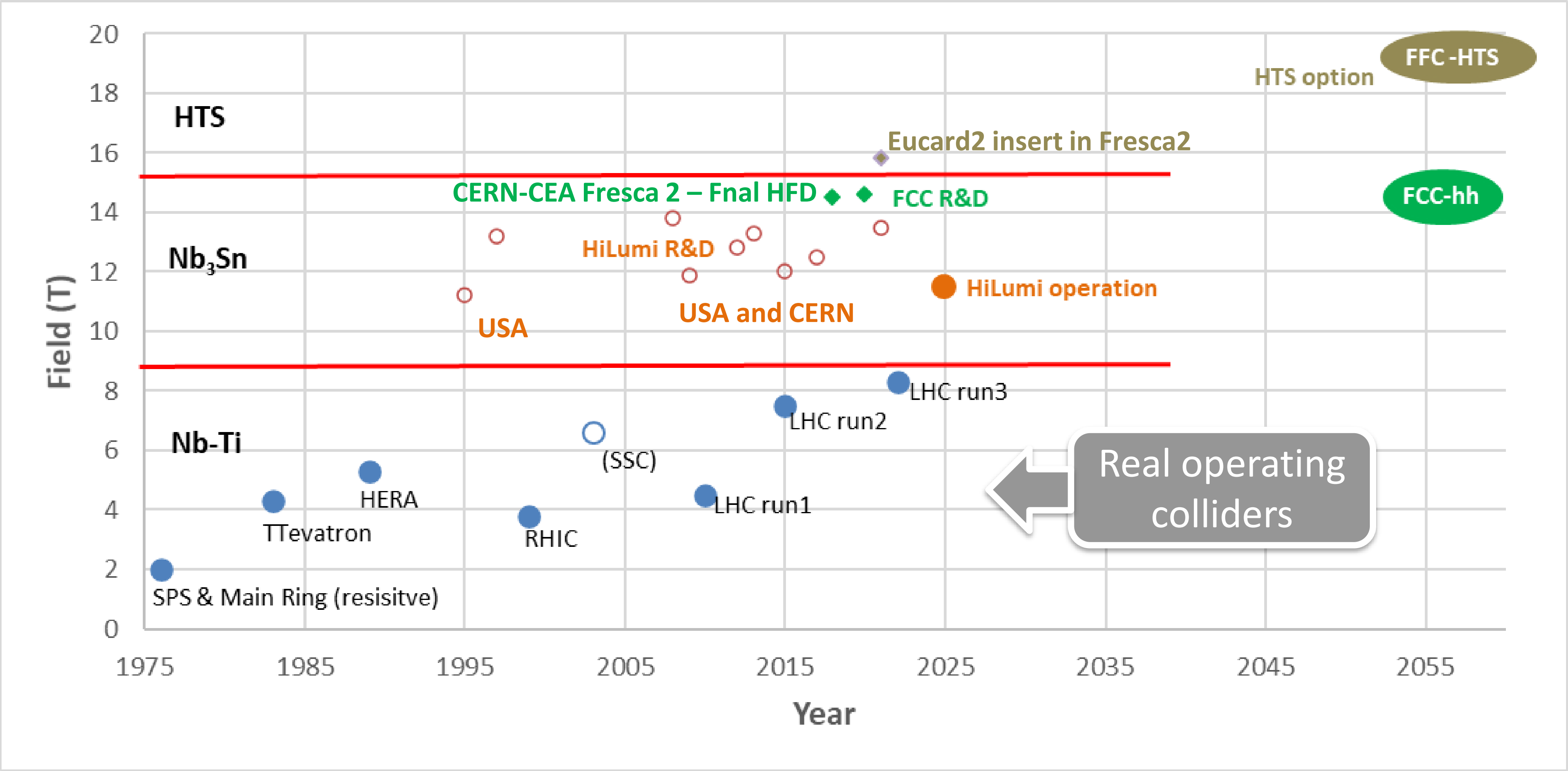
Maximum magnetic field in hadron collider

L.Rossi

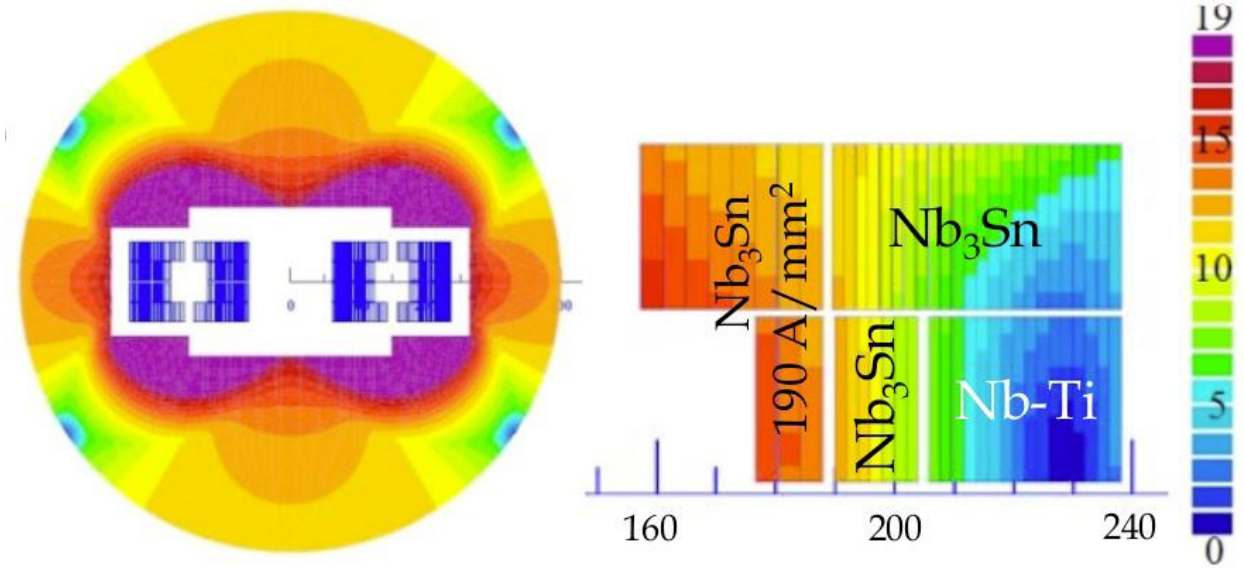


FCC-hh Challenges: Magnets

Arc dipoles are the main cost and parameter driver

Baseline: Nb_3Sn at 16T

HTS at 20T also studied as alternative

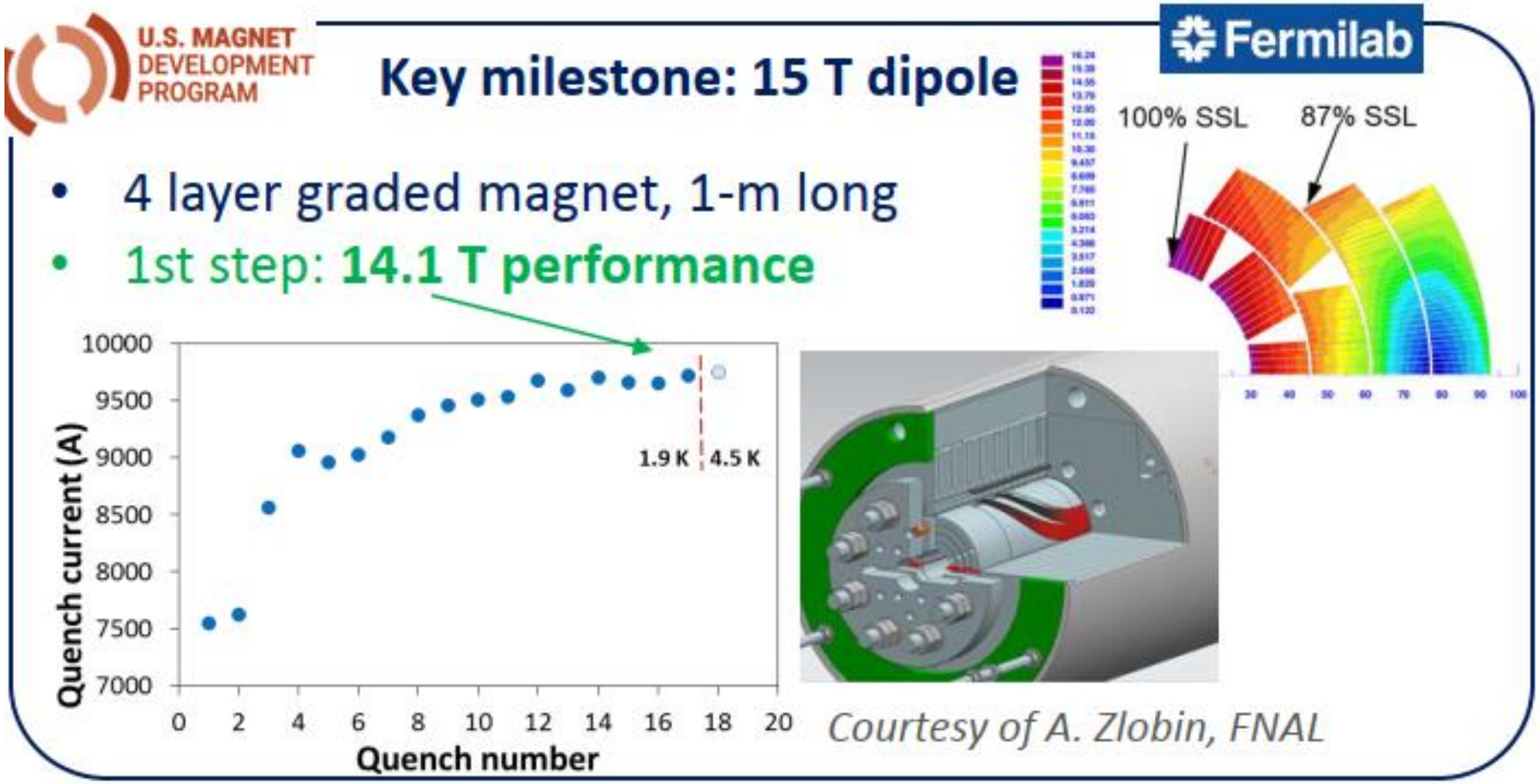


Coil sketch of a 15 T magnet with grading, E. Todesco

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

14 T magnet reached by US MDP cosϑ dipole at FNAL



- At > 15 T the magnet failed…
  => a 16 T 100 km accelerator requires still significant R&D

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!

More in lectures by **Stefano Redaelli**

FCC-hh: Synchrotron Radiation and Beam Screen

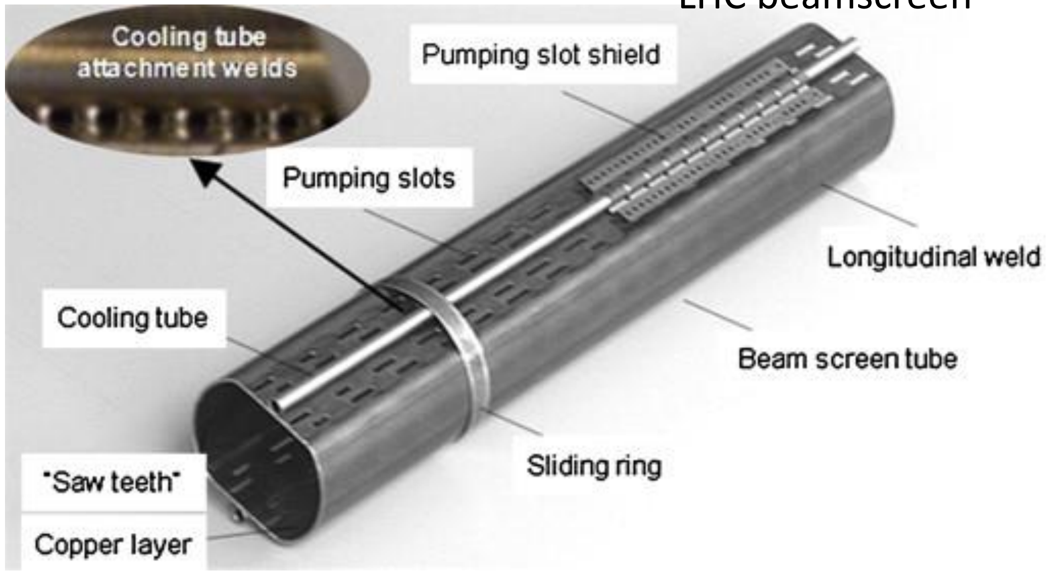
Synchrotron radiation power:

~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



- Beam screen protects superconducting magnets from synchrotron radiation

Choice of beam screen temperature is 50K (for reduced cooling power)

5MW synchrotron radiation => 100MW of cooling power

FCC-ee basic design choices

K. Oide et al.

double ring e⁺e⁻ collider ~100 km, **cms energies**:

Z (90 GeV), **W** (160 GeV), **H** (240 GeV), $\boldsymbol{t\bar{t}}$ (350 GeV)

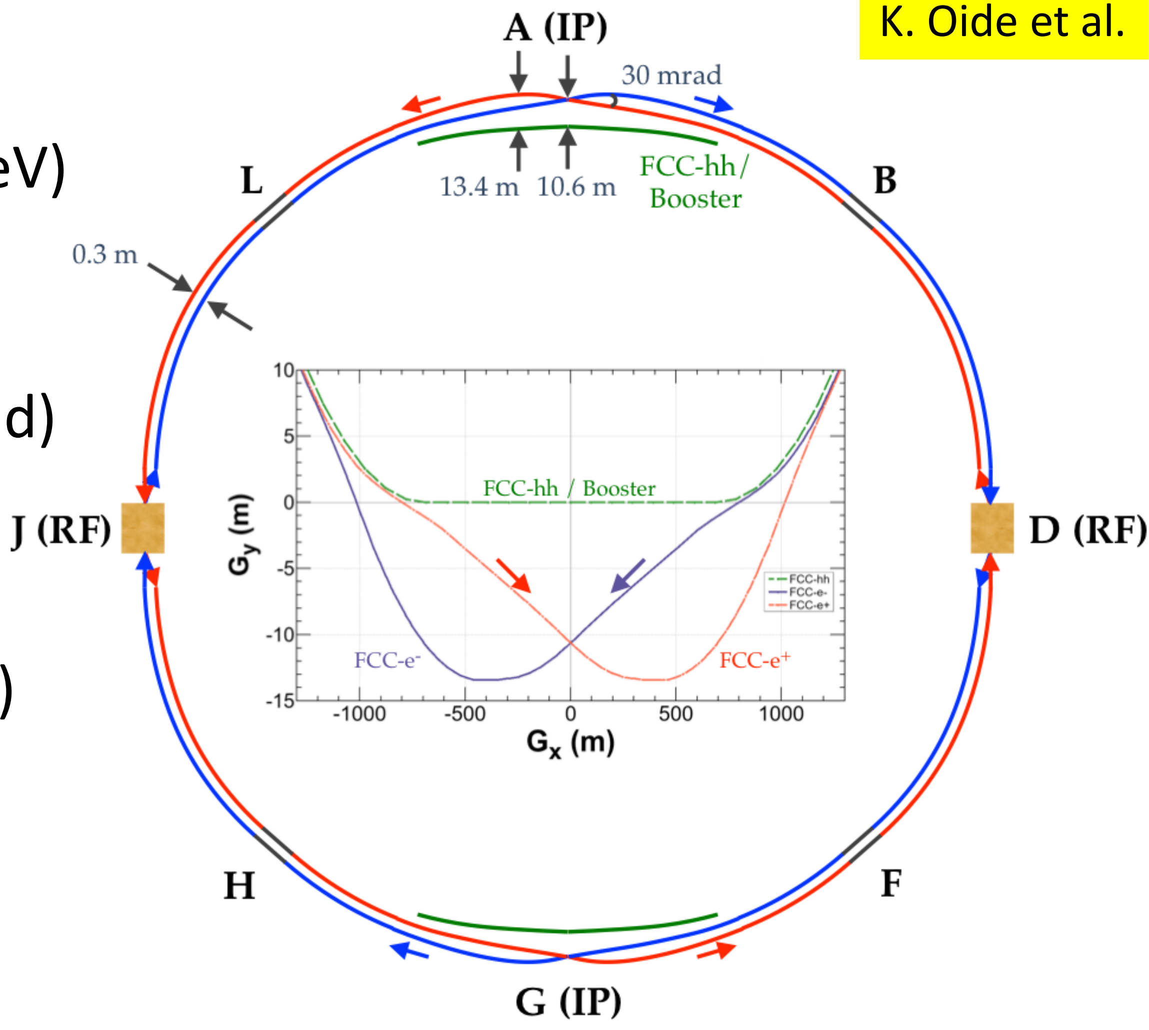
follows footprint of FCC-hh, except around IPs

asymmetric IR layout & optics to limit synchrotron radiation towards the detector (lower incoming bend)

- **large** horizontal crossing angle **30 mrad**
- **crab-waist optics**
- **presently 2 IPs** (alternative 3 or 4 IPs under study)

synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy

top-up injection requires booster synchrotron in collider tunnel



FCC-ee: The Lepton Collider, **Eur. Phys. J. Spec. Top. 228**, 261–623 (2019)
K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

FCC-ee: RF challenge

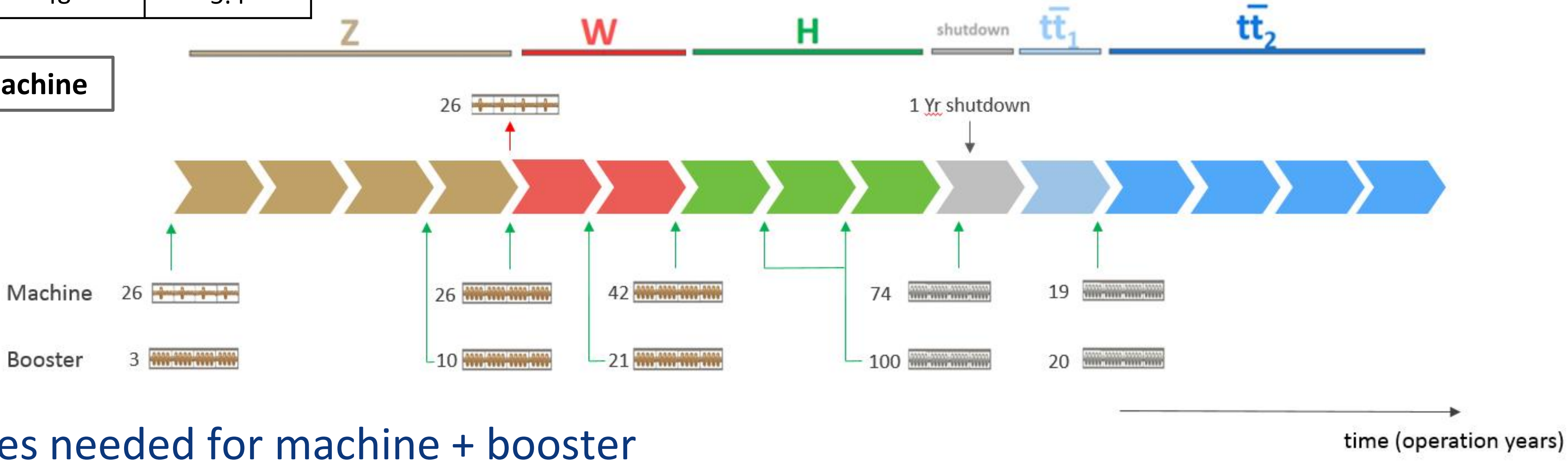
"Ampere-class" machine

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

"high-gradient" machine

three sets of RF cavities to cover all options for FCC-ee & booster:

- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**
- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**

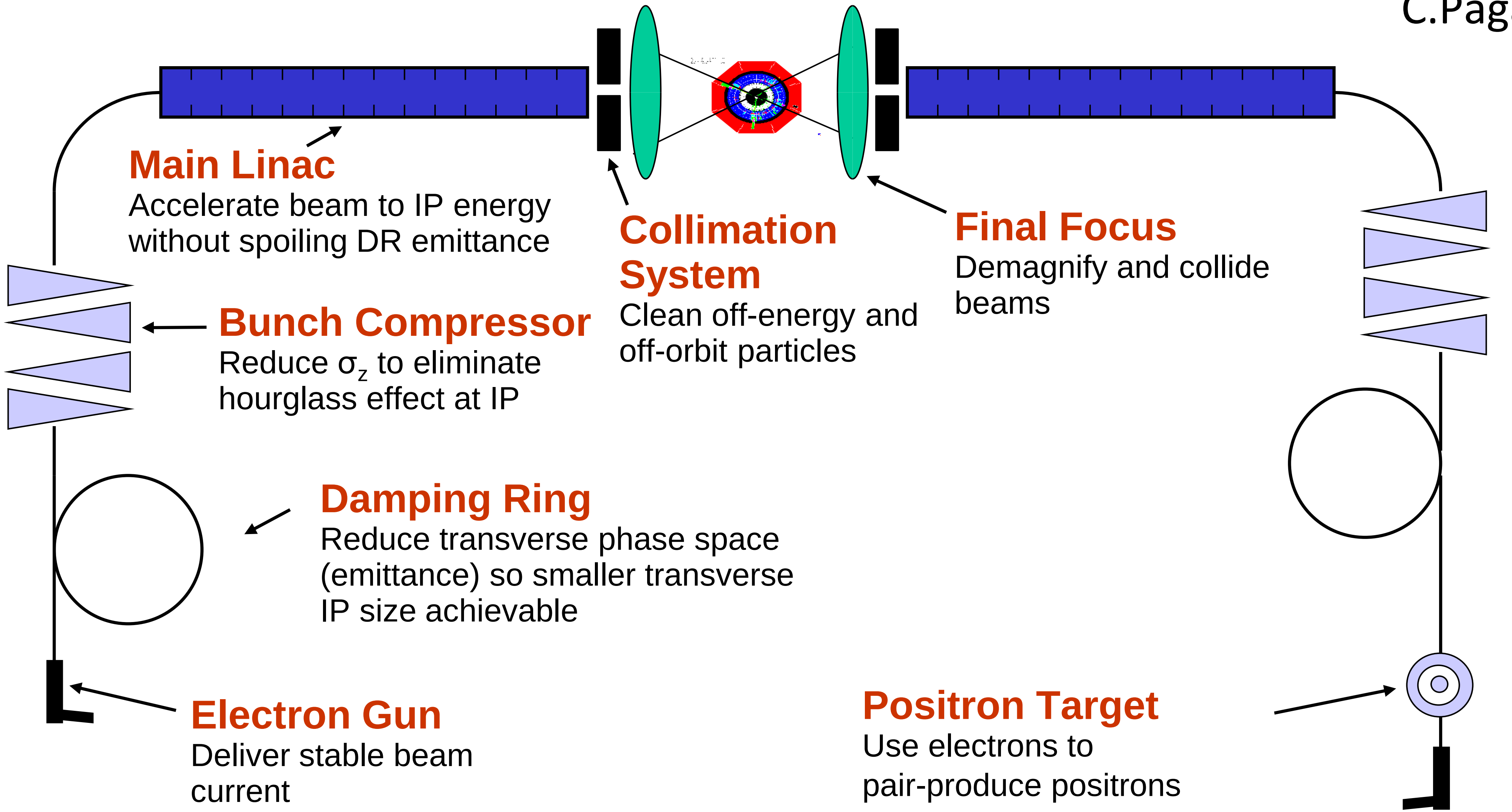


>1200 cavities needed for machine + booster

R&D aimed at improving performance & efficiency and reducing cost

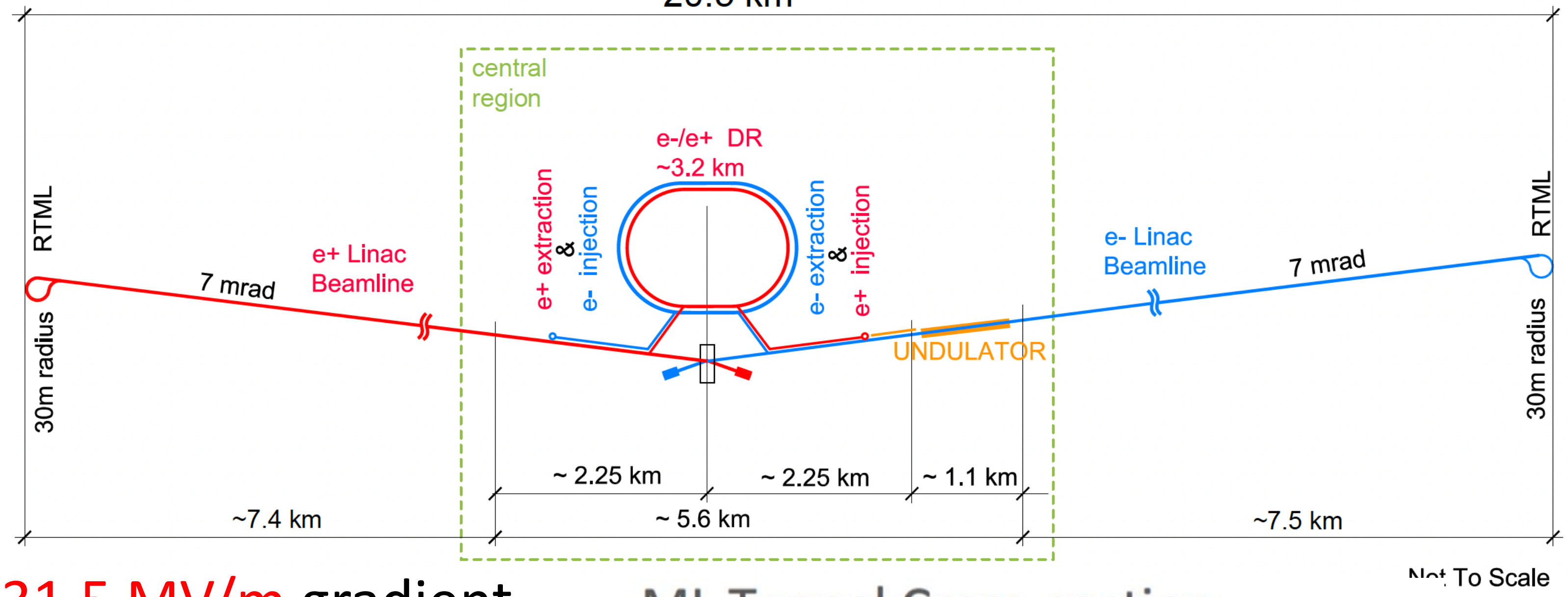
Challenges - Linear Colliders

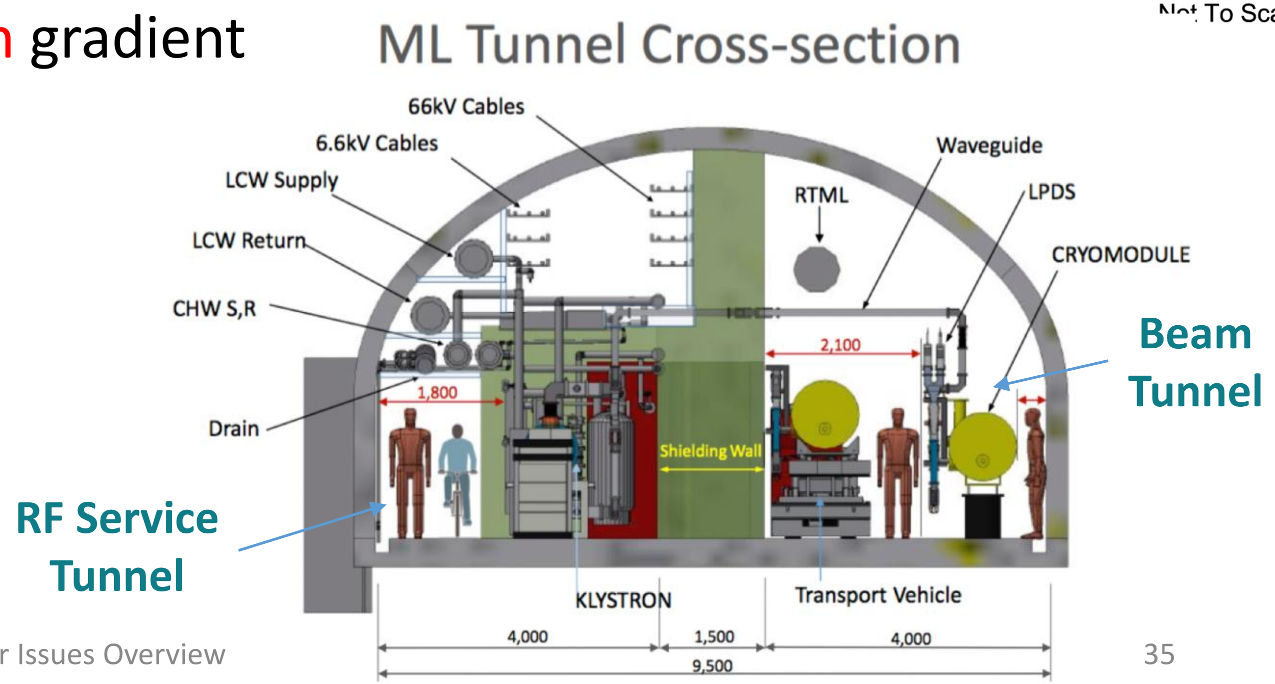
C.Pagani



Linear Collider: ILC

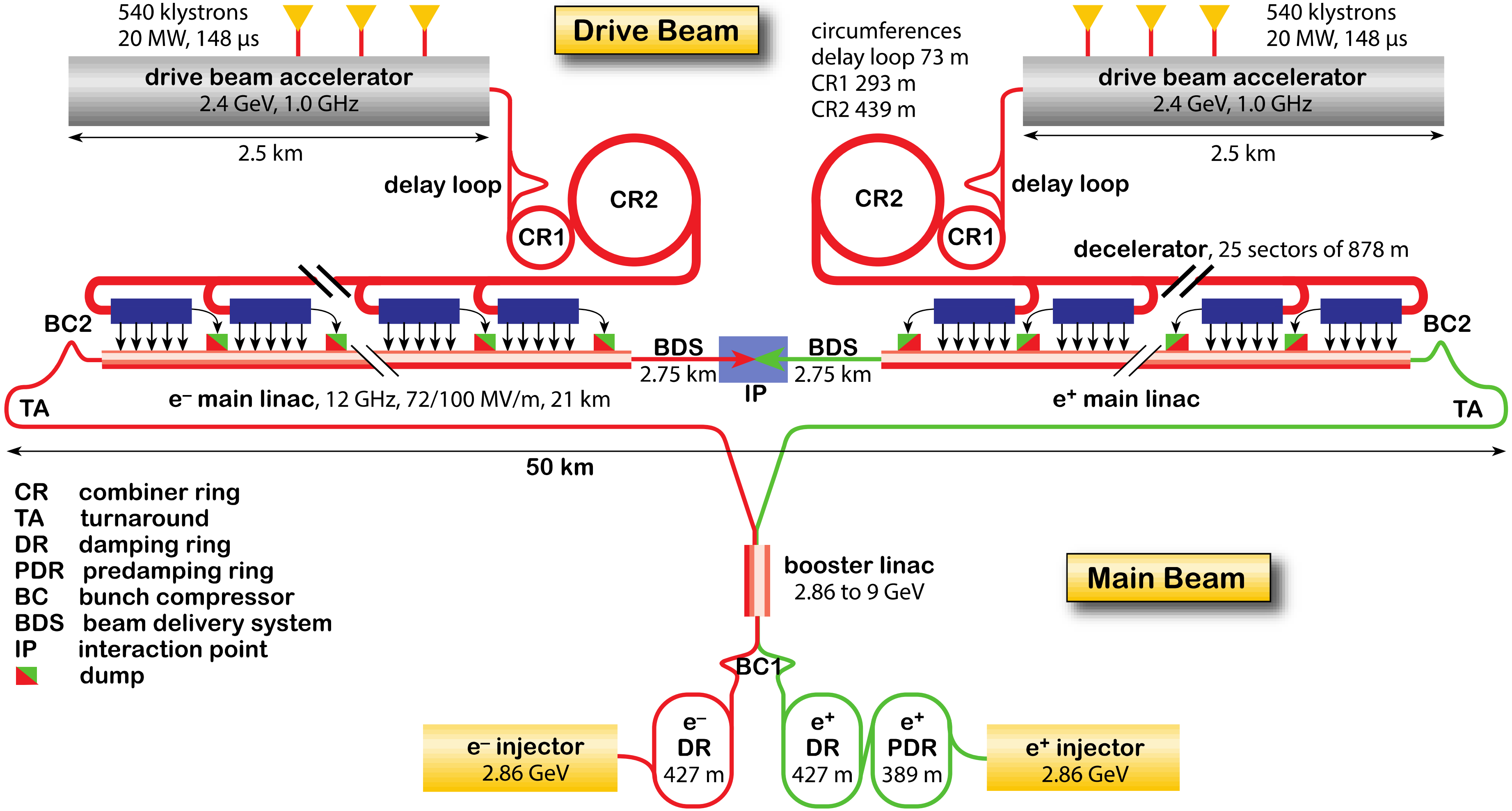
- 2 x 125 Gev linacs to produce nearly head-on e+e- collisions 2 x 250 GeV later
  - Single IR with 14 mrad crossing angle, crab cavities essential
- Superconducting cavities with 31.5 MV/m gradient
- Centralized injector
  - Circular 3.2 km damping rings
  - Undulator-based positron source
- Beam/service tunnel configuration





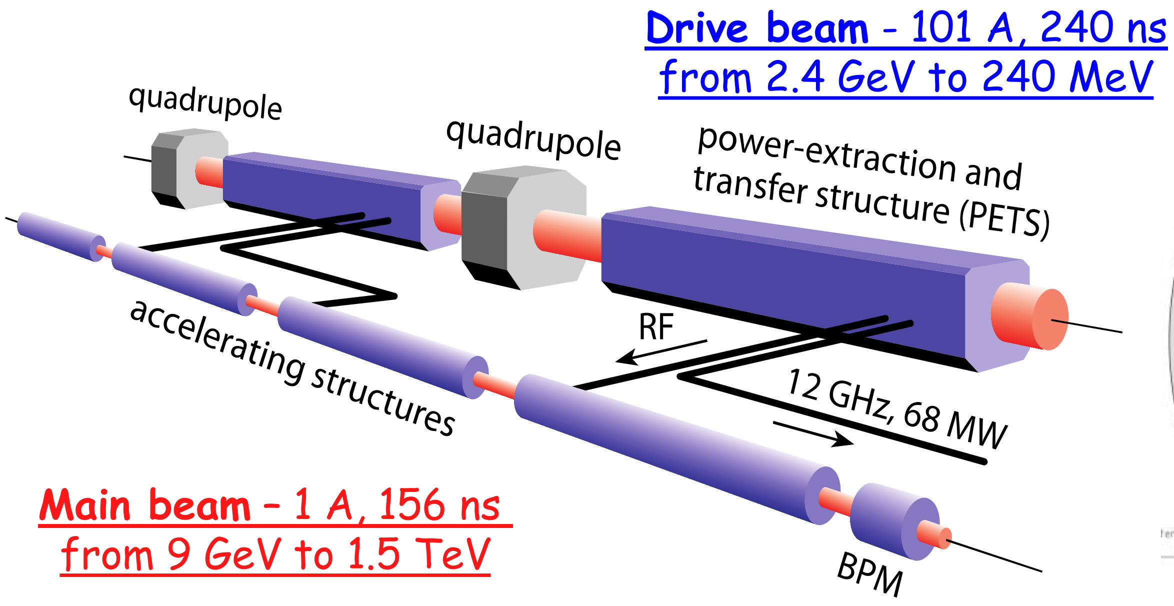
CLIC – overall layout – 3 TeV

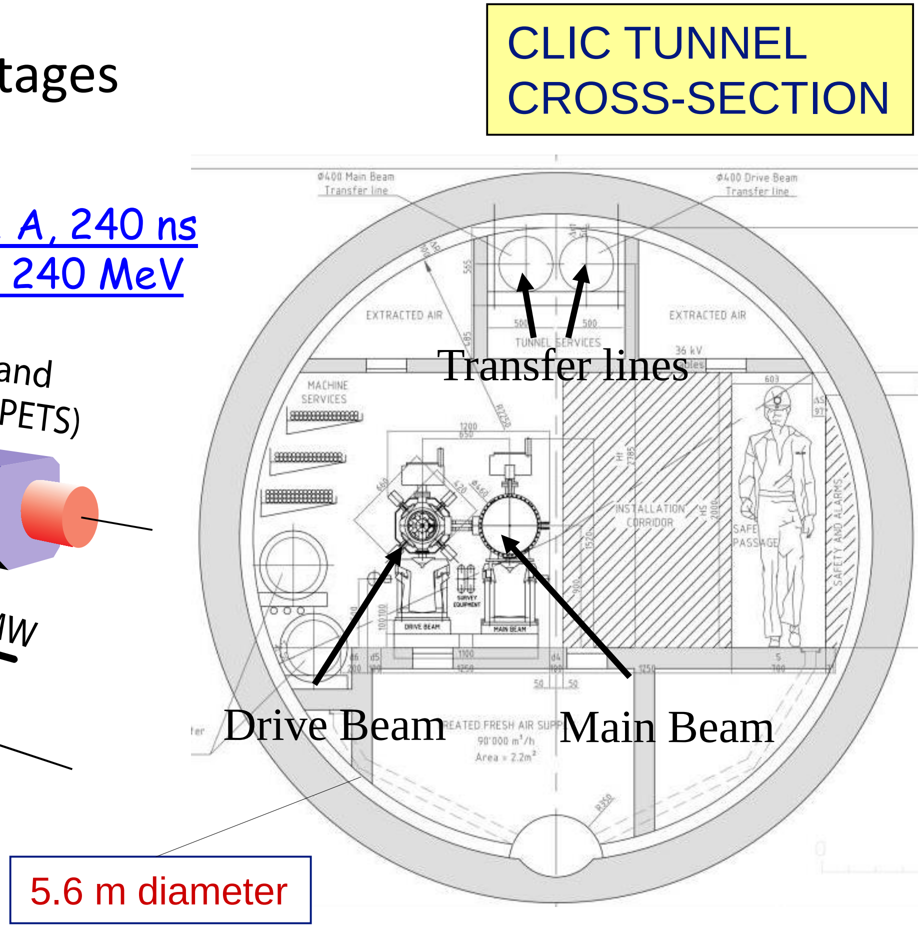
- **CLIC** (Compact Linear Collider):
- 380 GeV - 3 TeV
- 100 MV/m
- warm technology
- 12 GHz
- two beam scheme



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
  380 GeV => ~1.5 TeV => 3 TeV





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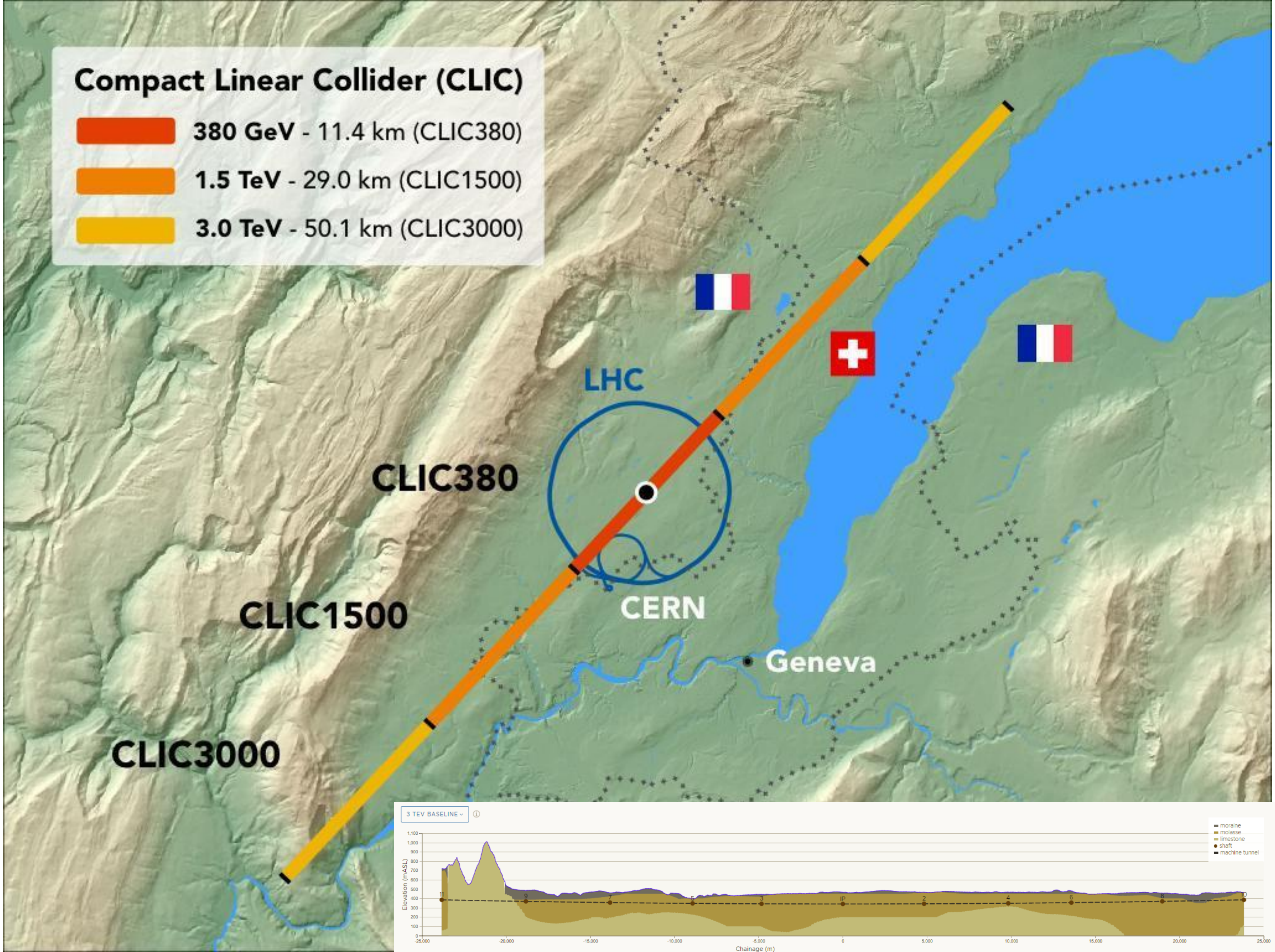
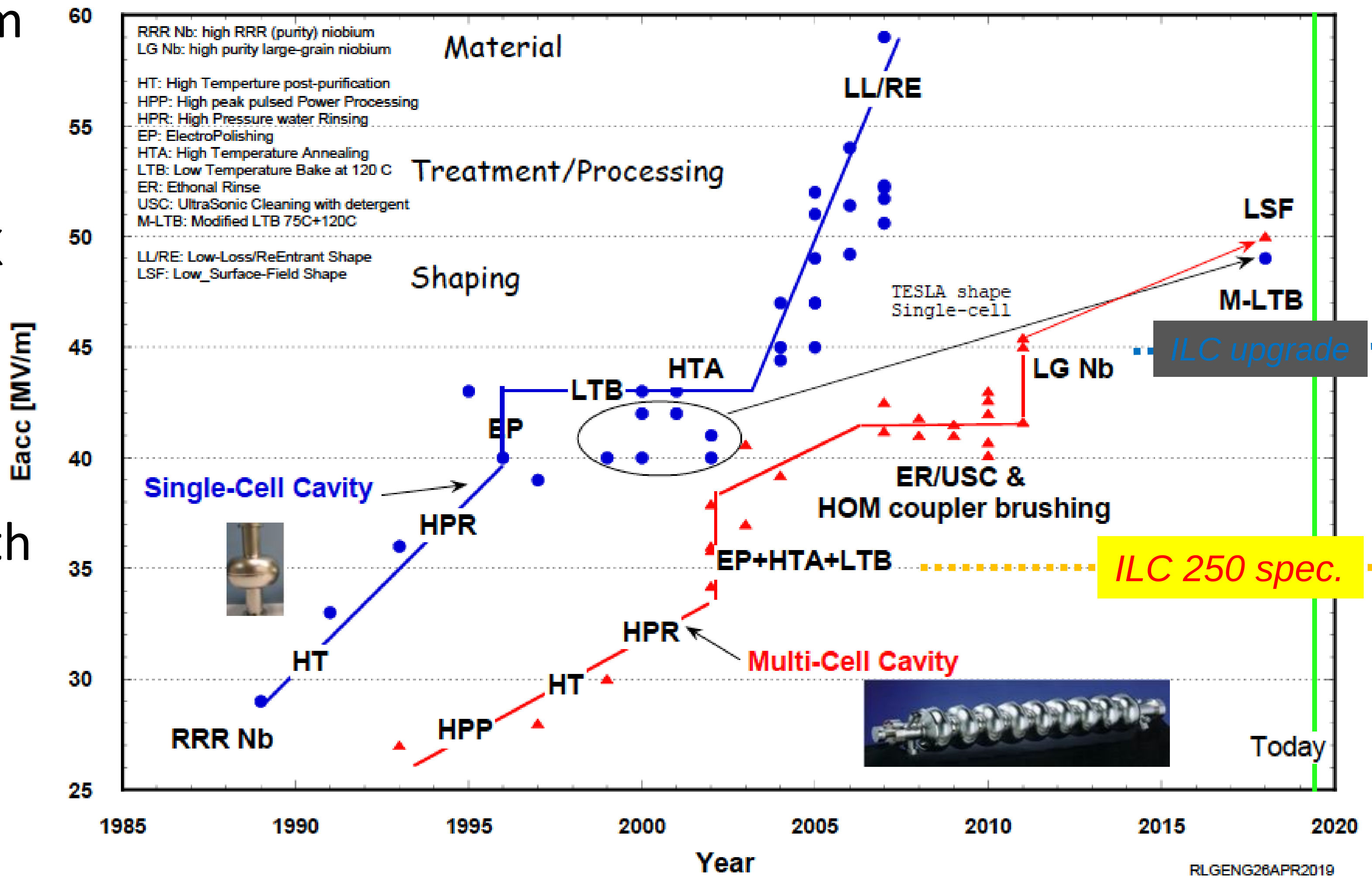


Challenge: Accelerating gradient SC

Courtesy: Rong Li Geng

- Impressive progress in SC accelerating structures
- ILC design gradient 31.5 MV/m
- European XFEL 23.6 MV/m operational running
- Cryomodules at Fermilab/KEK exceeded 32 MV/m with beam
- => established technology with large potential gains



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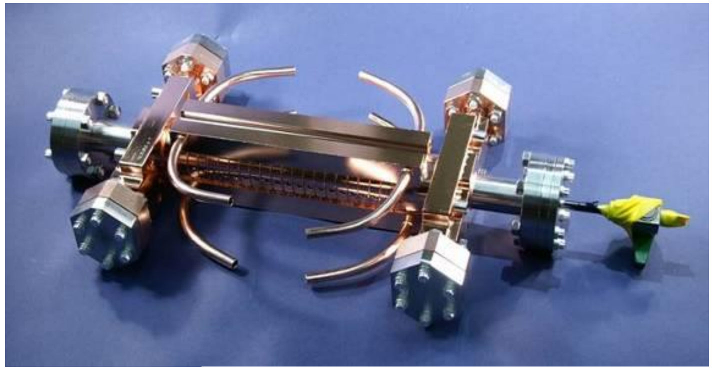
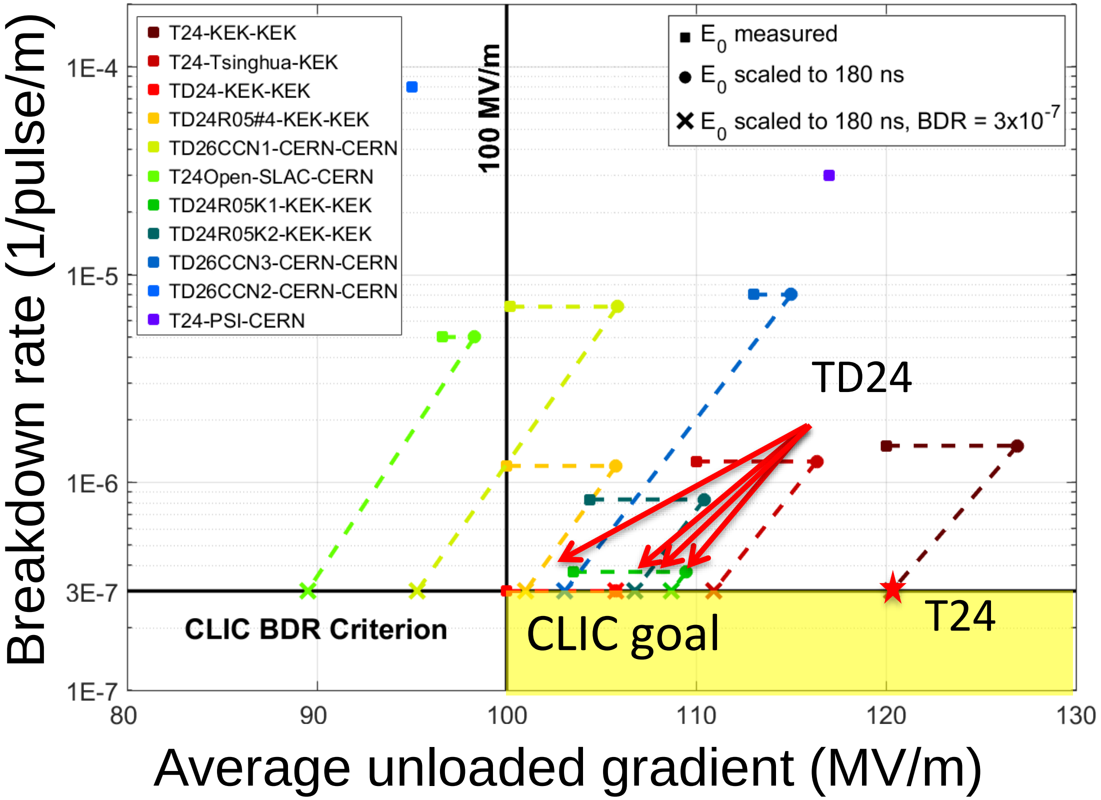
Challenge: Accelerating gradient NC (CLIC)

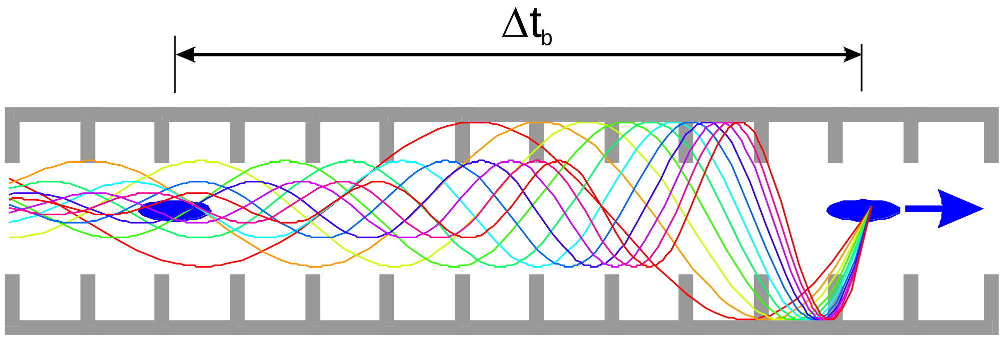
- RF breakdowns can occur
  => no acceleration and deflection
- Goal: 3 10^{-7}/m breakdowns
  at 100 MV/m loaded gradient
  at 230 ns pulse length
- scales very strongly with electric field and pulse length
- => drives NC linac to very short pulses

- => TD24 reach up to 108 MV/m at nominal CLIC breakdown rate (without damping material)
- Undamped T24 reaches 120MV/m





Linac: transverse wakefields

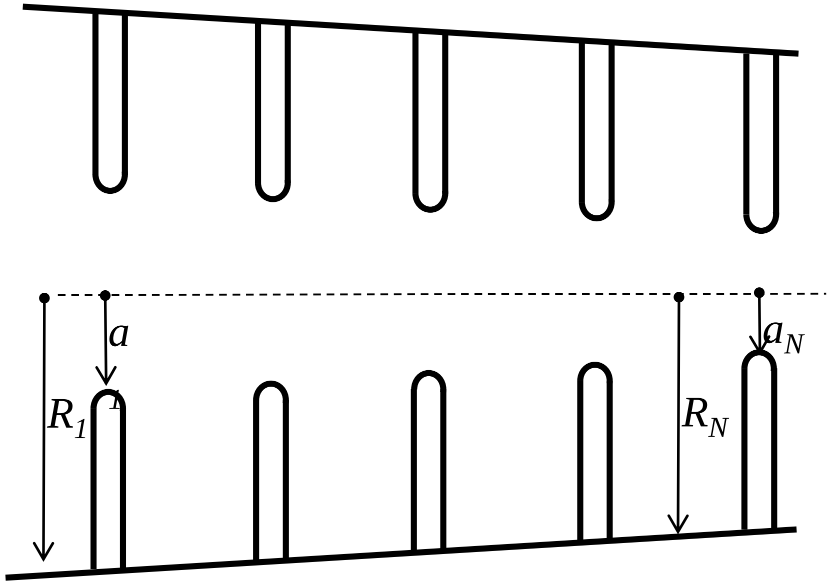


- Bunches induce field in the cavities
- Later bunches are perturbed by these fields
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Fields can build up resonantly
- Later bunches are kicked transversely
- => multi- and single-bunch beam break-up (MBBU, SBBU)
- Emittance growth!!!

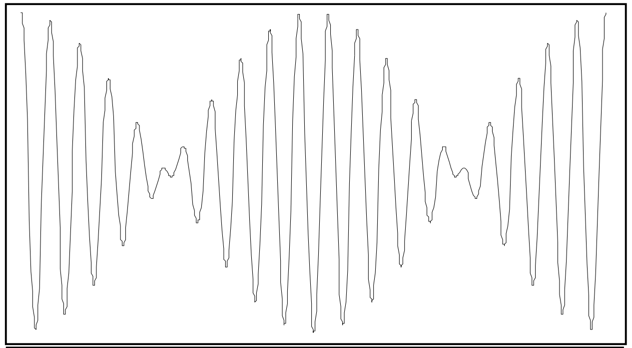
More in lectures by ***Giovanni Rumolo***

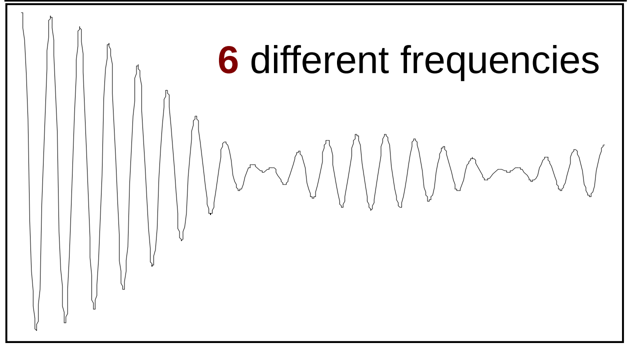
Transverse wakefields

- Effect depends on a/λ (a iris aperture) and structure design details
- transverse wakefields roughly scale as $W_\perp \propto f^{\,3}$
- less important for lower frequency:
  Super-Conducting (SW) cavities suffer less from wakefields
- Long-range minimised by structure design
- Dipole mode detuning



Long range wake of a dipole mode spread over **2** different frequencies





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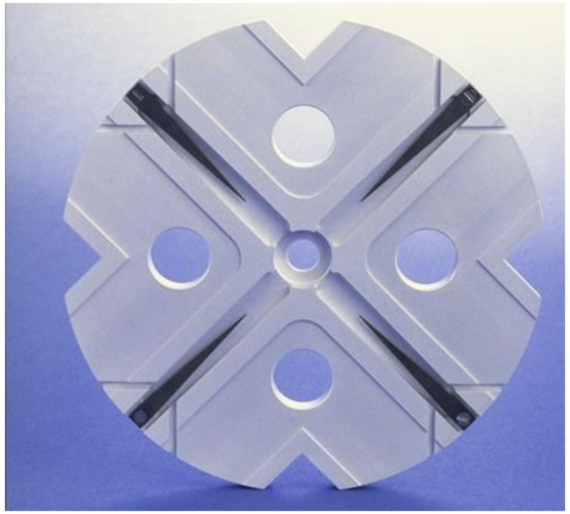
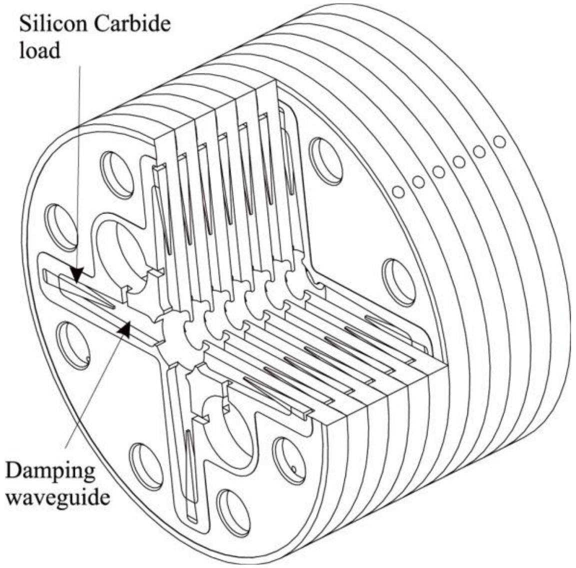
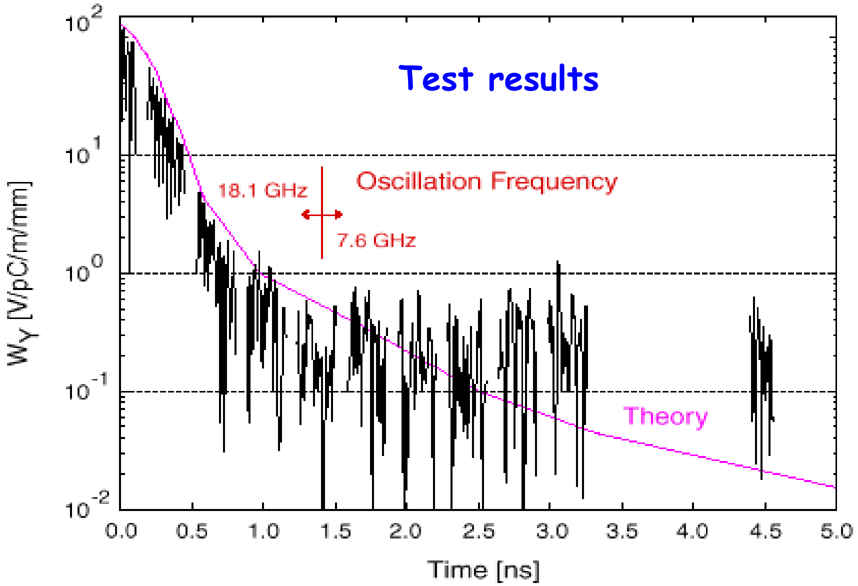
HOM damping



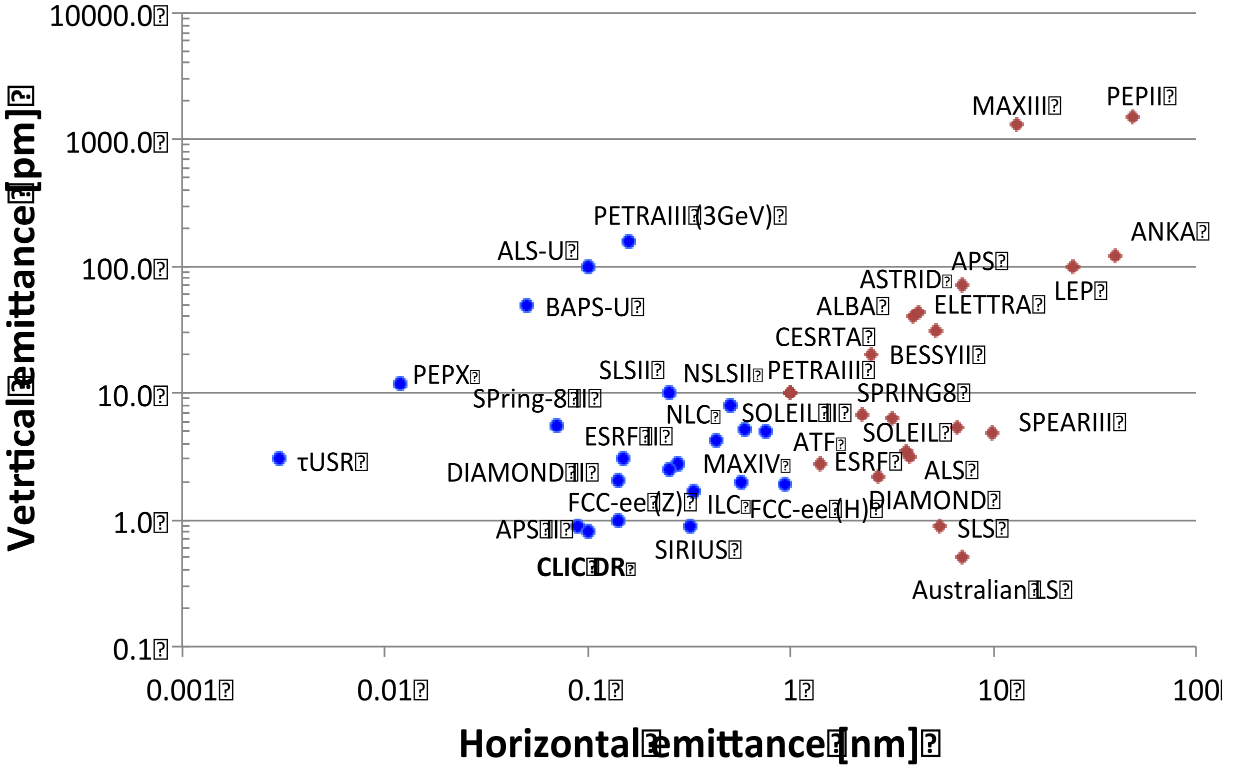


- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- HOM enter WG
- Long-range wake efficiently damped



Damping rings/Light sources: emittance limits

- Lights sources require small emittances for high brilliance
- Horizontal emittance ε_x defined by lattice
  - multibend achromats, longitudinal gradient bend
- theoretical vertical emittance ε_y limited by
  - space charge
  - intra-beam scattering (IBS)
  - photon emission opening angle

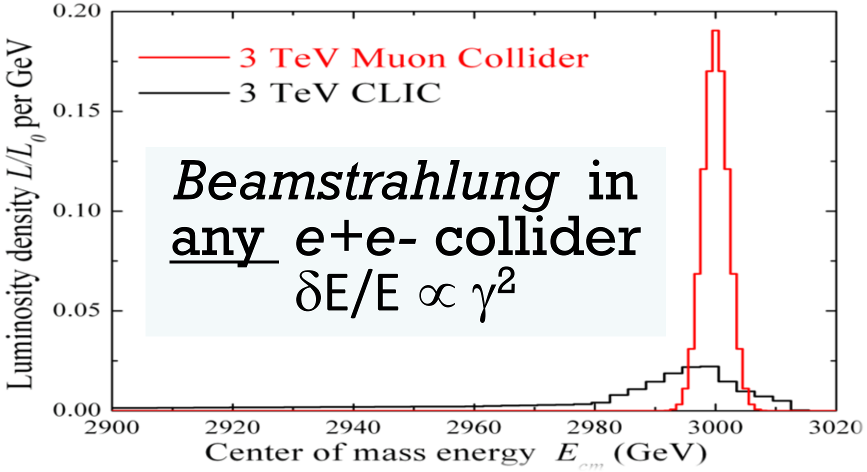


- In practice, ε_y limited by magnet alignment errors [cross plane coupling by tilted magnets]
- typical vertical alignment tolerance: $\Delta y \approx 30\ \mu m$
  $\Rightarrow$ requires beam-based alignment techniques!

More in lectures by
Massimo Ferrario** and **Andy Wolski

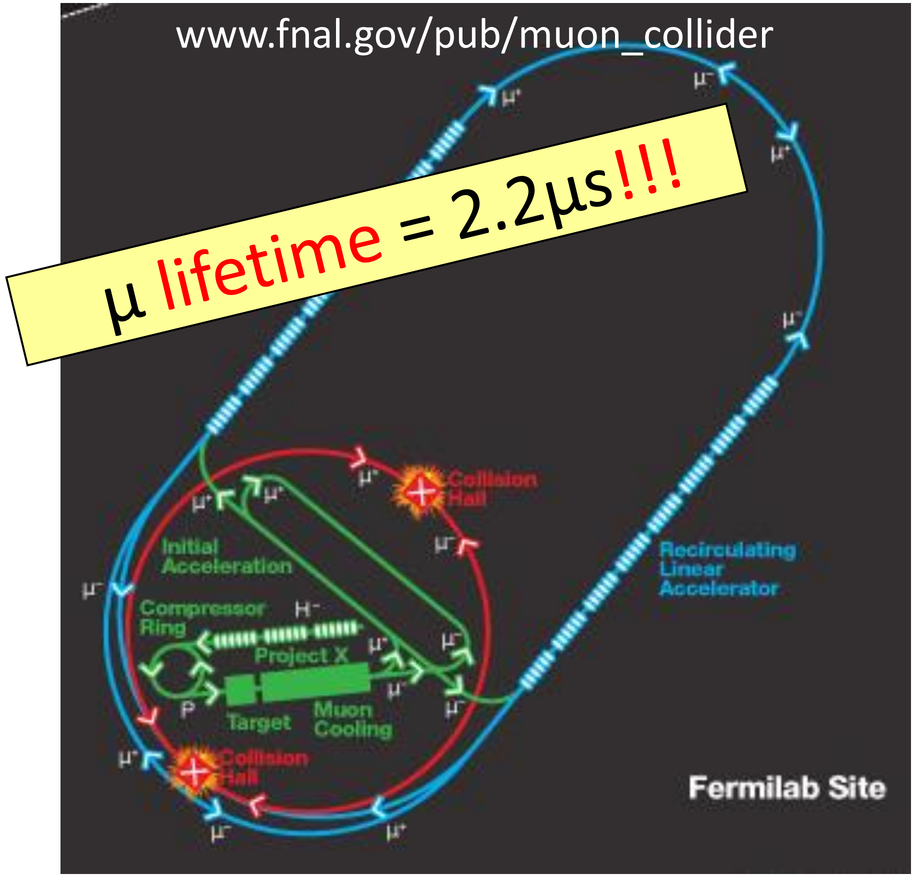
Muon Collider

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



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

More in lectures by ***Chris Rogers***



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.

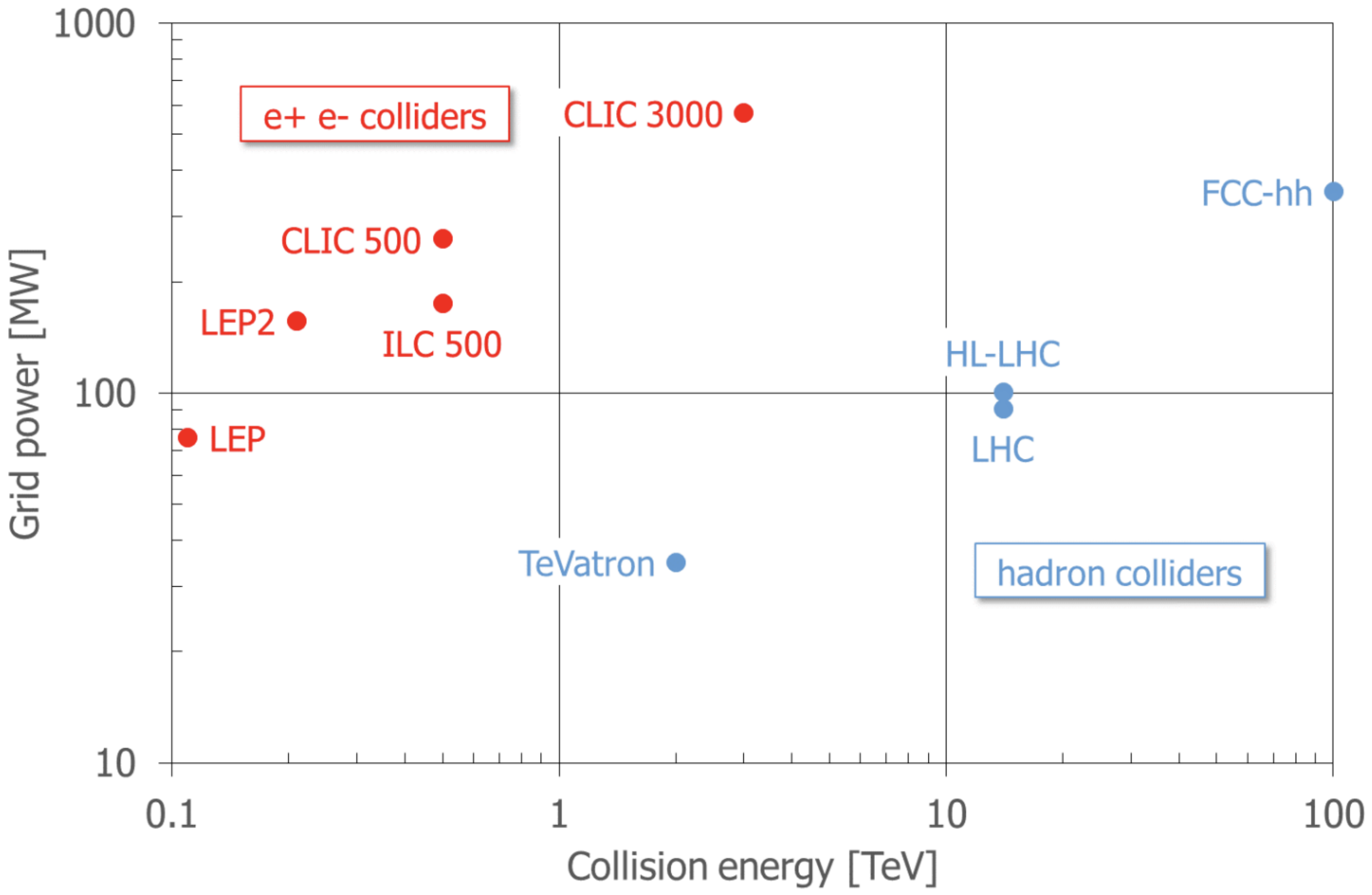
Initial Acceleration
In a dozen turns, accelerate μ to 20 GeV

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.

Challenge: Power consumption of high-energy colliders

Ph.Lebrun



- The bad news: future projects need hundreds of MW grid power
- The good news: power consumption grows slower than collision energy

Approach to reduce energy footprint

Ph.Lebrun

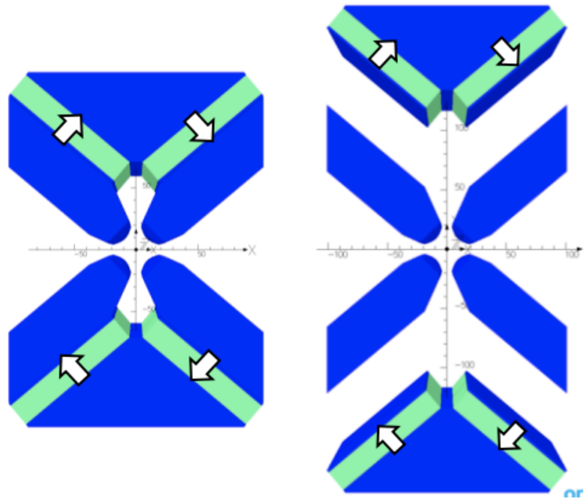
- Understand relations between
  - Performance parameters
    - Particle energy E
    - Luminosity $\mathcal{L}$
  - Beam parameters
    - Beam power P_{beam}
    - Beam stored energy W_{beam}

- Analyse sources of losses
  - "Intrinsic" losses
    - Synchrotron radiation
    - Beam image currents
  - Accelerator systems efficiency
    - RF
    - Magnets
    - Vacuum
    - Beam instrumentation
    - …
  - Infrastructure
    - Electrical distribution
    - Cooling & ventilation
    - Cryogenics
    - …

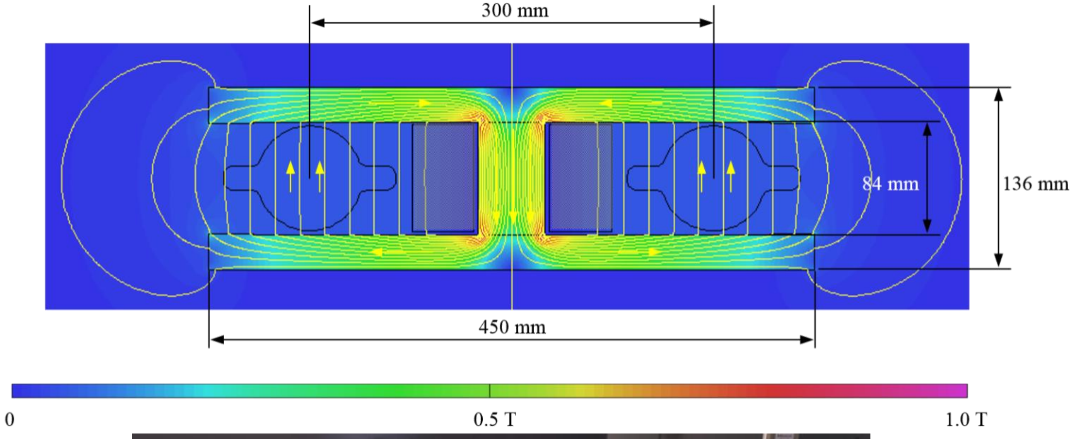
Energy saving example - Magnets

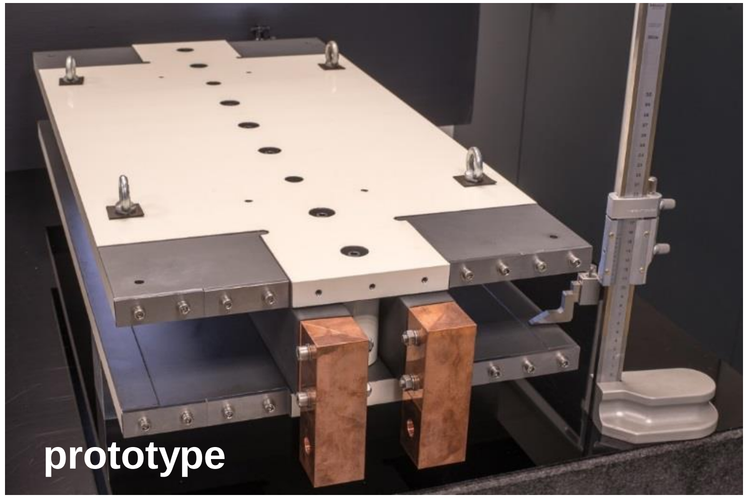
- Innovative designs
- Permanent/hybrid magnets

Tunable quadrupole for CLIC drive beam (B. Sheperd STFC)



FCC-ee twin-dipole design: 2× power saving 16 MW (at 175 GeV), with Al busbars





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Main High-Energy Frontier Collider Challenges

Hadron colliders (HL-LHC, FCC-hh, SppC)**:**

- High-field dipoles: SC magnet R&D with new materials (Nb_3Sn, HTS), large stored energy in magnets requires quench protection
- Stored energy in beam: sophisticated collimation system and machine protection

e+/e- ring colliders (FCC-ee, CEPC)**:**

- Synchrotron radiation power limits the energy reach
  - FCC-ee has 10.9 GV energy loss/turn at 350 GeV cms
  - huge installation with SC RF cavities

Linear colliders:

- ILC: SC RF technology developments, nano-beam stability
- CLIC: NC structures with low RF breakdown rate, nano-beam, alignment (RF structures and magnets) and stability

Muon collider:

- fast muon cooling

Power and Energy consumption

Acknowledgements

- I would like to thank the following people of whom I have used material from:
  - Mei Bai
  - Michael Benedikt
  - Xavier Buffat
  - Rong-Li Geng
  - Werner Herr
  - Philippe Lebrun
  - Edouard Prat
  - Lucio Rossi
  - Hermann Schmickler
  - Markus Zerlauth

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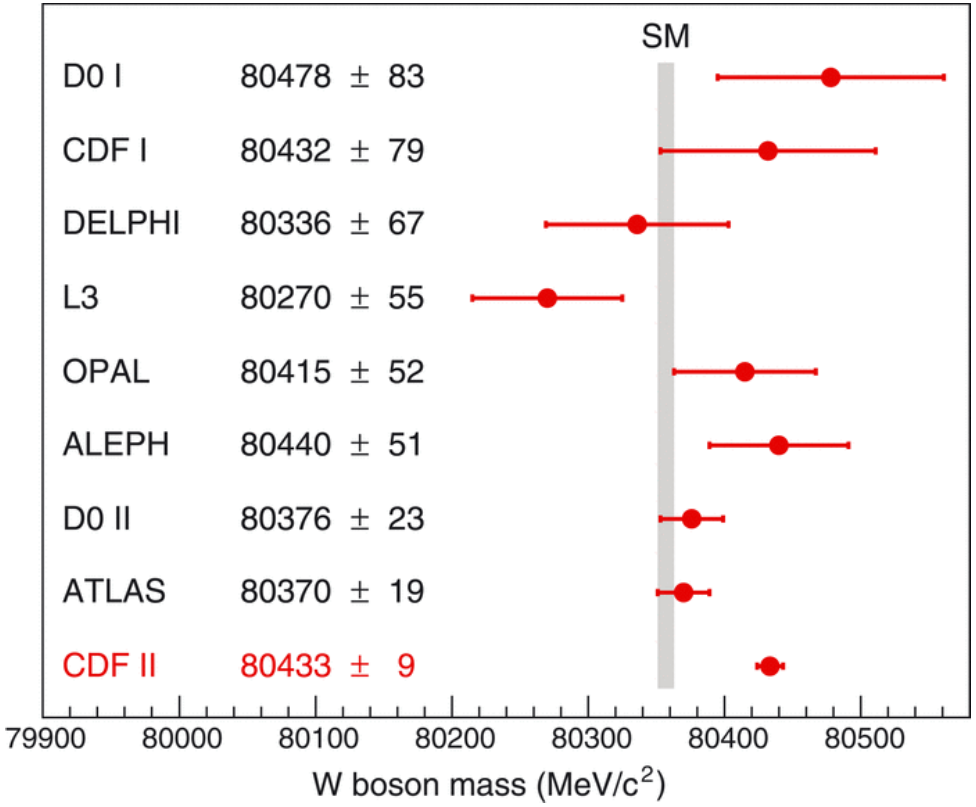
Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Value [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology (Lucio Rossi)
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS (HTS): Jc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10~20 (0.4 / 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 (~ 40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	< 5.3 > (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

Appendix: W boson mass



High-precision measurement of the W boson mass with the CDF II detector, Volume: 376, Issue: 6589, Pages: 170-176, DOI: (10.1126/science.abk1781)