



The CERN Accelerator School

# Accelerator Issues Overview

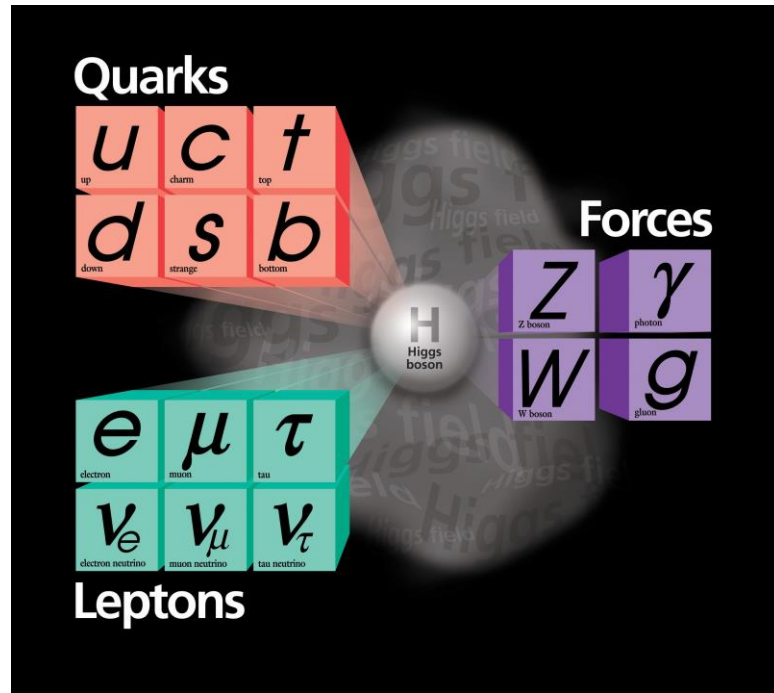
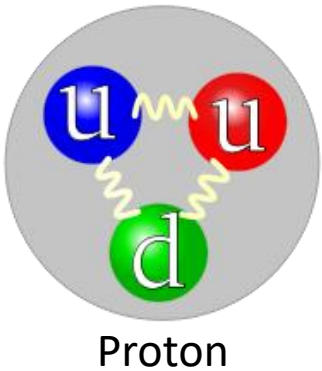
Frank Tecker

CERN, ATS-DO

- Introduction and physics scope
- High-Energy Collider Project Challenges
  - Energy
  - Luminosity
- The different projects
  - HL-LHC
  - FCC
  - Linear Colliders (ILC, CLIC)
  - Muon Collider
- Energy efficiency
- Conclusion

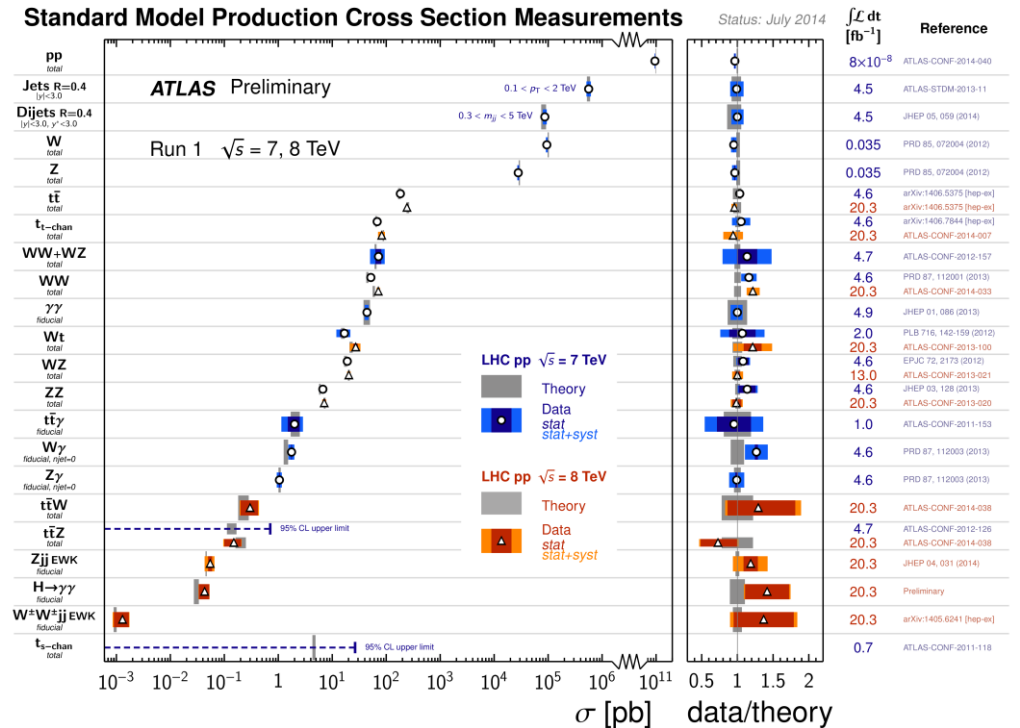
# Introduction – The Standard Model

- The standard model (SM) describes extremely well the particle interactions

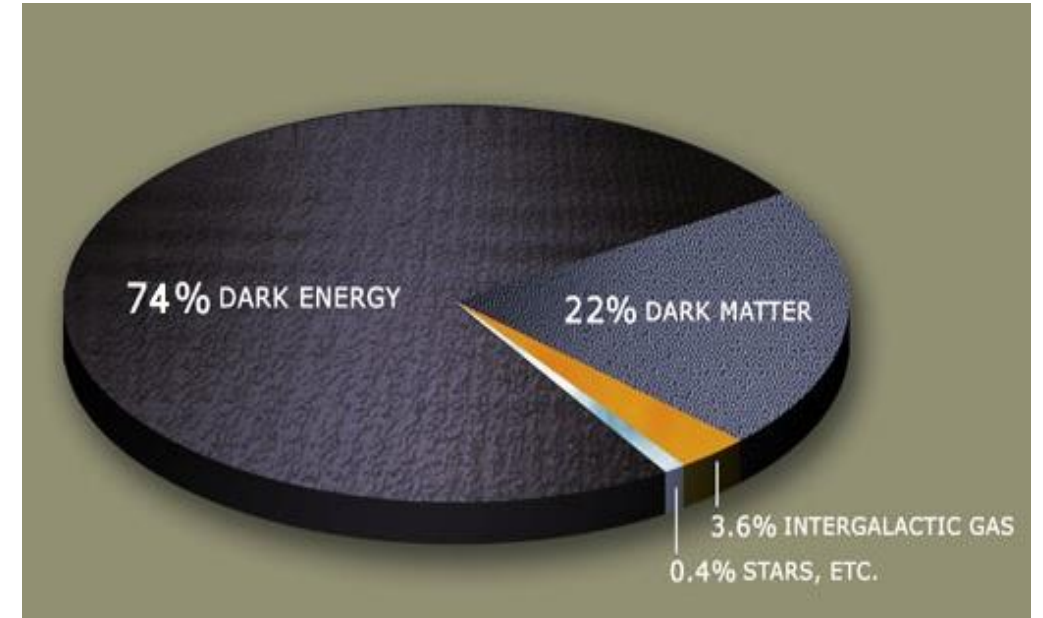
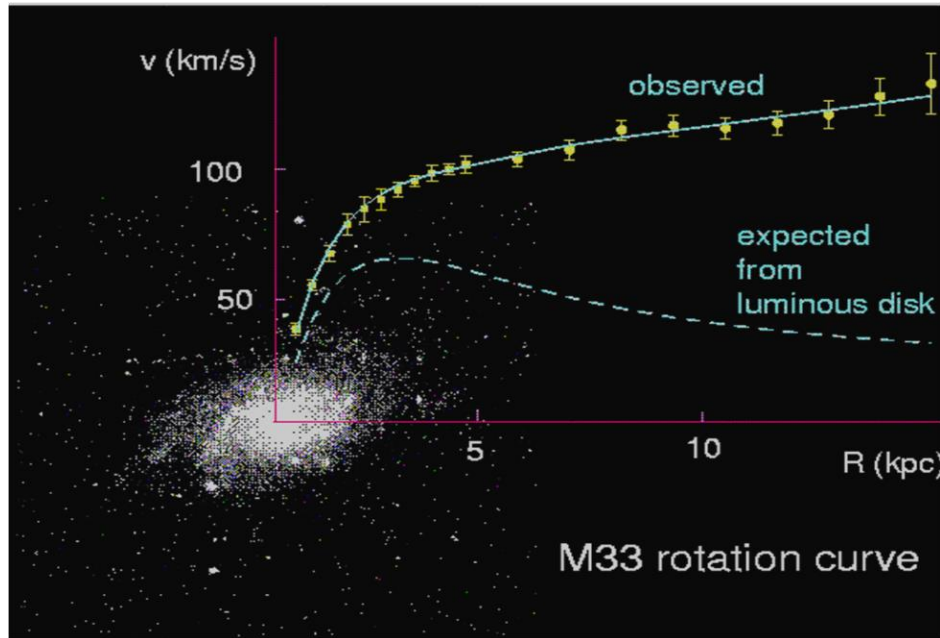


BUT:

- 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



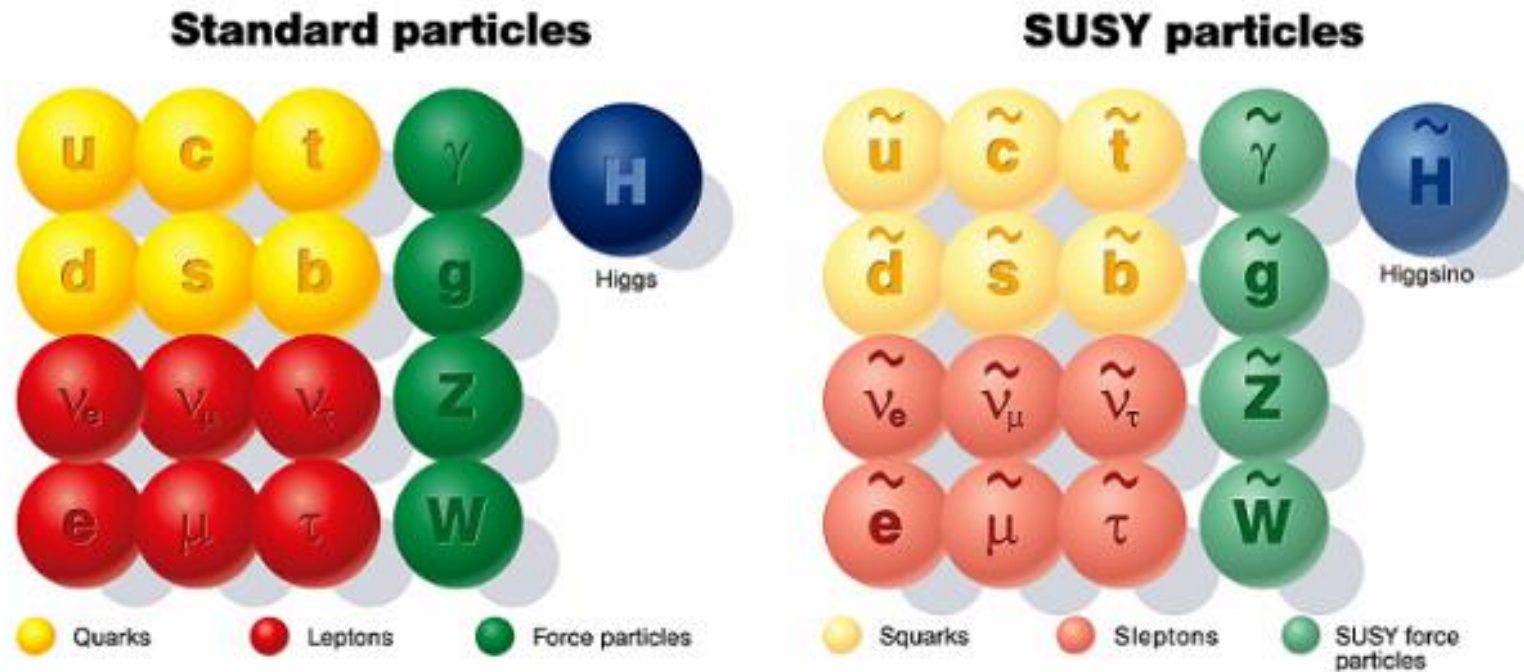
# The Dark Side of the Universe



- 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, ...

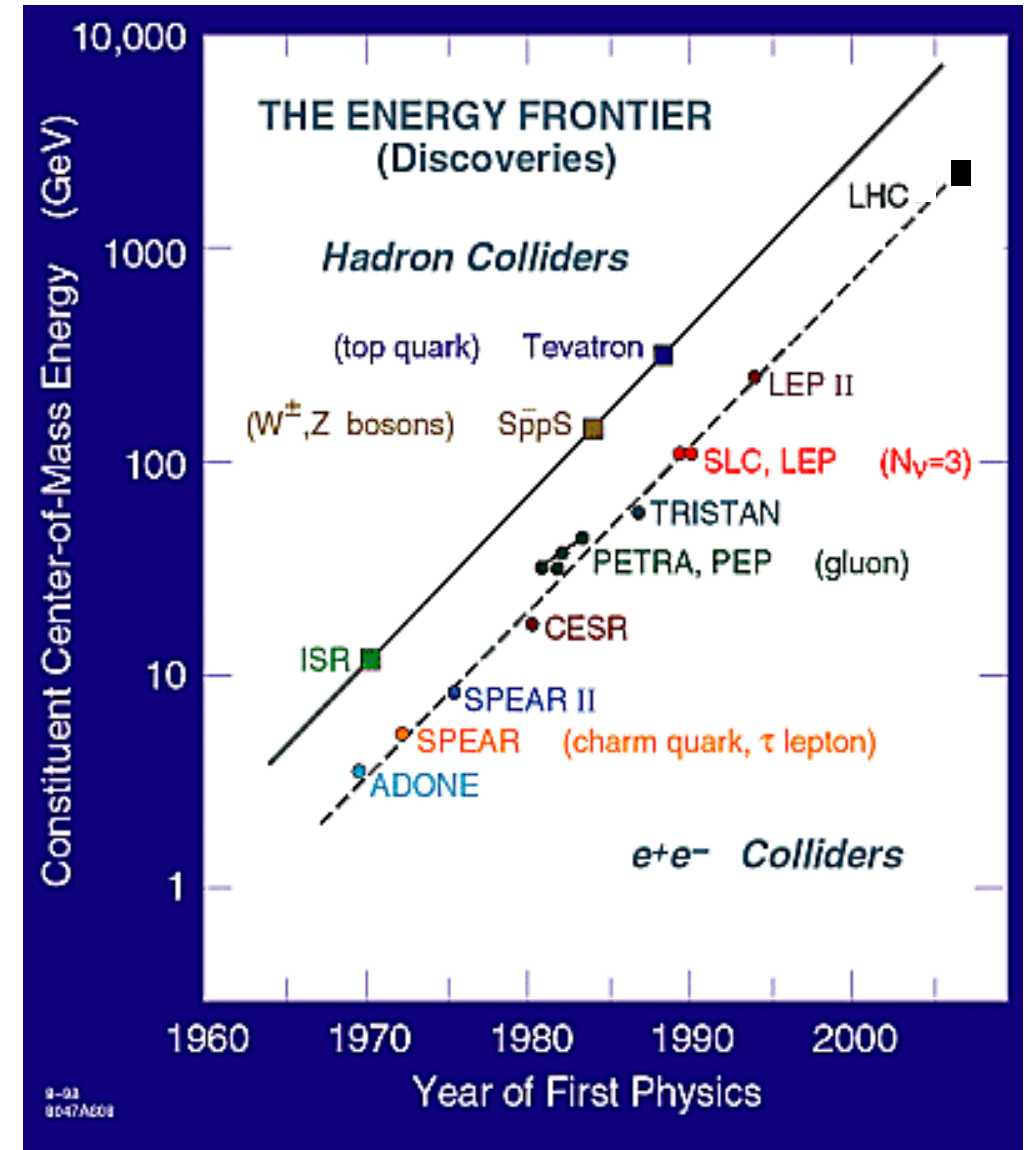
- **SUSY (super-symmetry)** is one possible extension of the SM  
for every SM particle, there is a super-partner with spin 1/2 difference
- lightest SUSY particle could be dark matter candidate
- none of the super-particles seen so far... (but also still not completely excluded)
- other theories around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



# Path to discovery - higher energy

## History of Colliders:

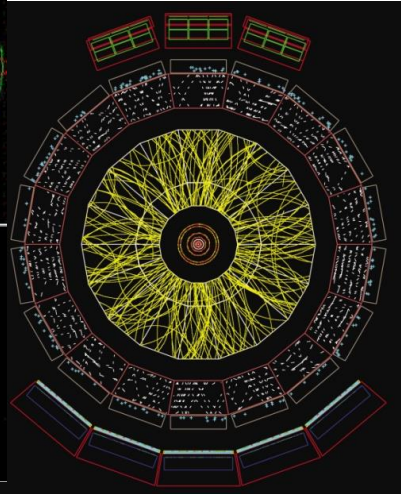
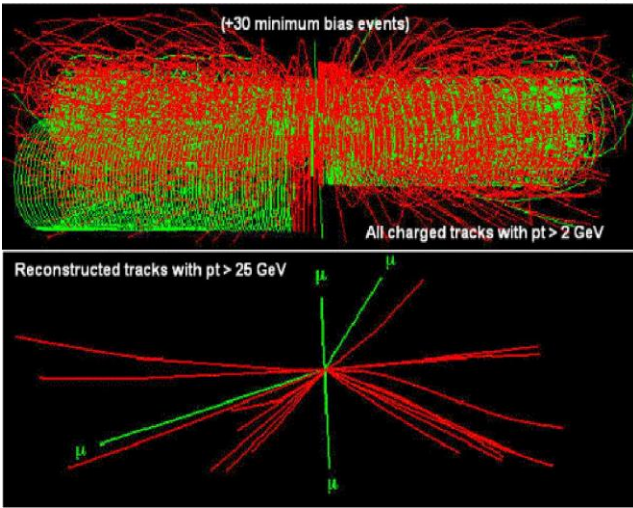
- **Hadron Colliders** at the **energy frontier**  
=> **direct discovery**
- **Lepton Colliders** for **precision physics**  
=> **deviations from SM expectations**
- LHC has discovered the Higgs in 2012  
with  $m_H = 126 \text{ GeV}/c^2$
- What will be the next energy frontier machine?





# Hadron vs. Lepton Collisions

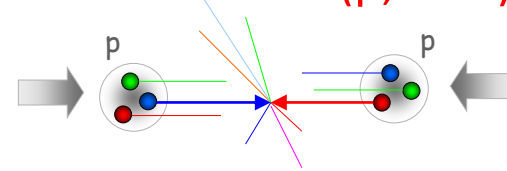
LHC:  $H \rightarrow ZZ \rightarrow 4\mu$



LEP event:  $Z^0 \rightarrow 3 \text{ jets}$

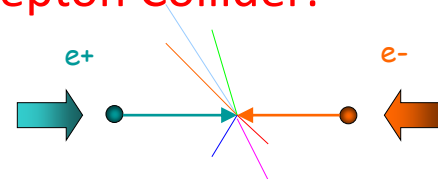
ALICE: Ion event

## Hadron Collider (p, ions):

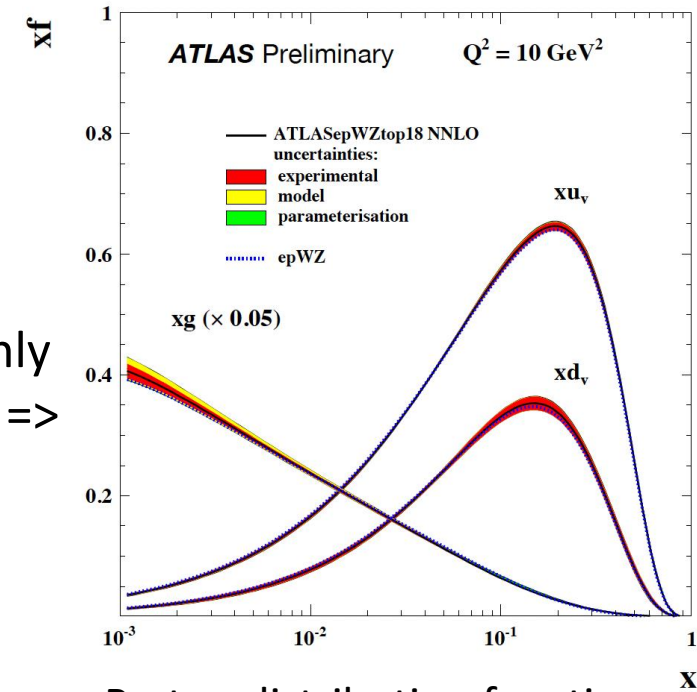


- Composite nature of protons
- Quarks (which collide) carry only fraction of the momentum  $\Rightarrow$
- Can only use  $p_t$  conservation
- Huge QCD background

## Lepton Collider:



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



Parton distribution function of the proton

# Main High-Energy Frontier Collider Projects

## Circular colliders:

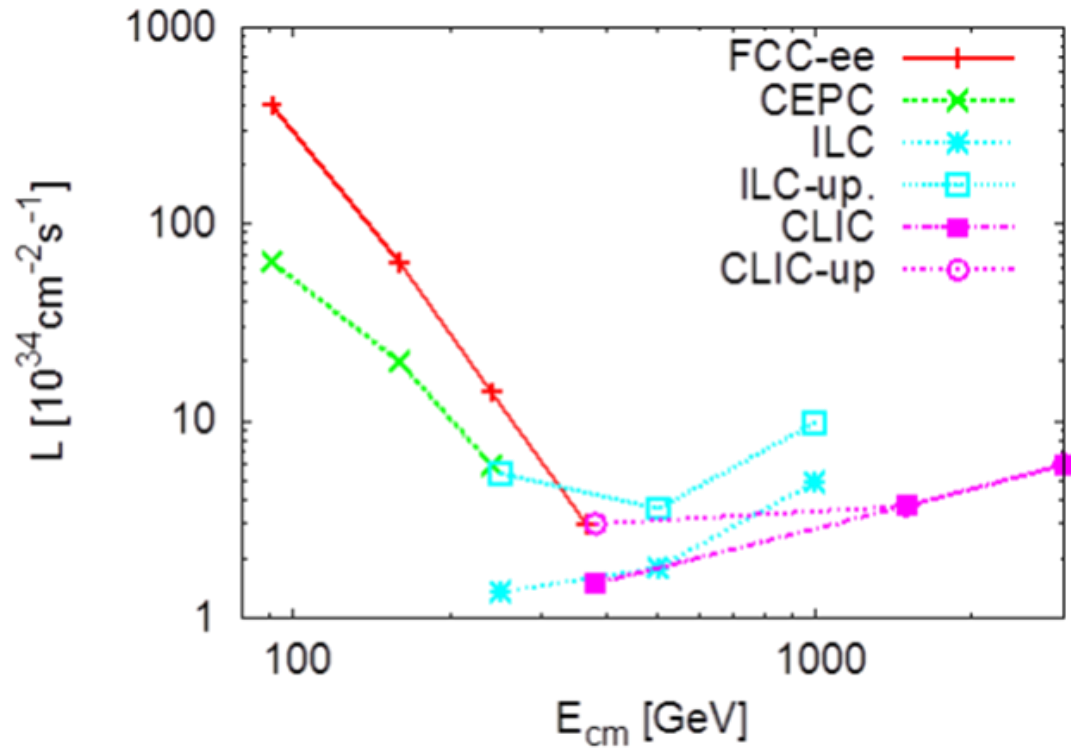
- **HL-LHC** (CERN) – High-Luminosity upgrade of LHC
- **FCC** (CERN) (Future Circular Collider)
  - FCC-hh: 100 TeV proton-proton cms energy, ion operation possible
  - FCC-ee: 90-350 GeV  $e^+e^-$  collider as potential intermediate step
  - FCC-he: Lepton-hadron option
- **CEPC / SppC** (China) (Circular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

## Linear colliders:

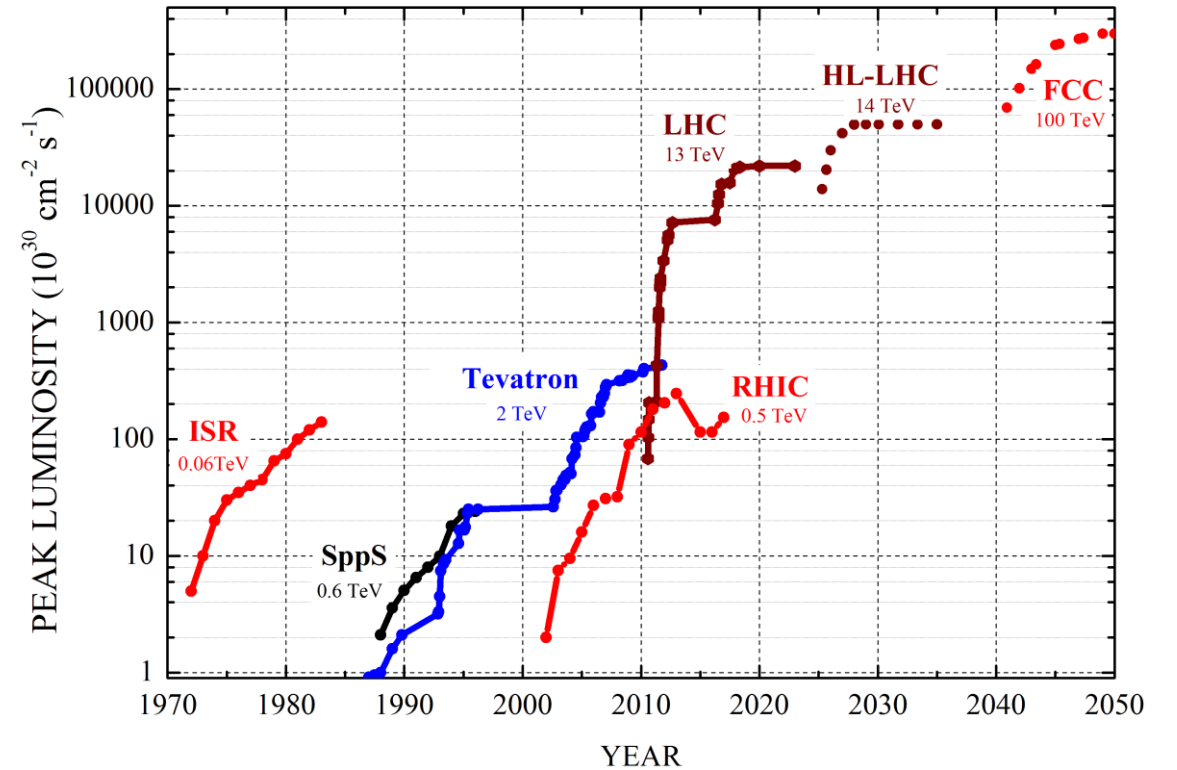
- **ILC** (International Linear Collider):  $e^+e^-$ , 250-500 GeV cms energy, SC technology  
Japan considers hosting project
- **CLIC** (Compact Linear Collider):  $e^+e^-$ , 380GeV-3TeV cms energy, NC technology  
CERN hosts collaboration



- Electron-Positron collider



- Hadron collider



# Challenge: Energy

- **Ring collider:**

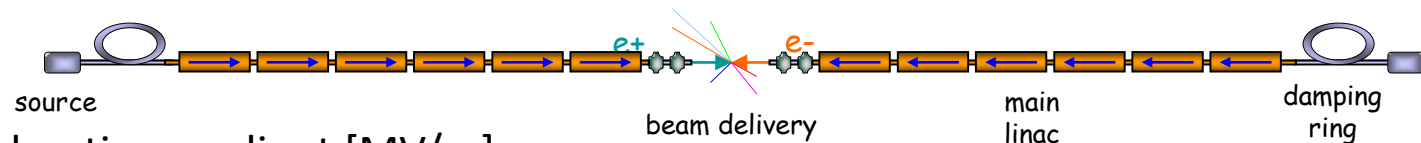
- $p = q B \rho$
  - $E = \sqrt{p^2 c^2 + m^2 c^4} \gg pc$  (for  $pc \gg mc^2$ )

$p$  : particle momentum  
 $q$  : electric charge, typically  $e$   
 $B$  : magnetic field [T]  
 $\rho$  : 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

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

$$P = \frac{e^2 c}{6\pi\epsilon_0} \left( \frac{E}{m_0 c^2} \right)^4 \frac{\beta^4}{\rho^2}$$

- 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 ( $m_\mu/m_e=207$ )
  - but the muons are decaying  $\Rightarrow$  rapid acceleration and beam cooling

# Challenge: Luminosity

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

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

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

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)

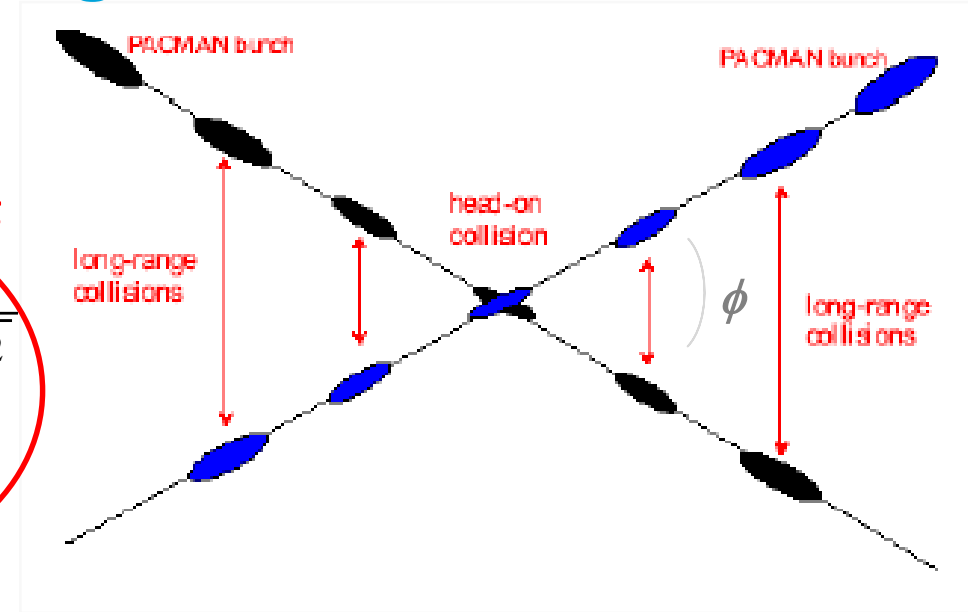
- In principle, we need
  - many intense bunches with high repetition frequency
  - well centered collisions
  - small beam sizes

# Luminosity: Crossing angle

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

$$L = \frac{n_b N_{b1} N_{b2} f}{4\rho S_x S_y} \frac{1}{\sqrt{1 + \left(\frac{S_z}{S_x} \tan \frac{f}{2}\right)^2}} \quad F$$

$\frac{S_z}{S_x} \tan \frac{f}{2}$  is called "Piwinski angle"

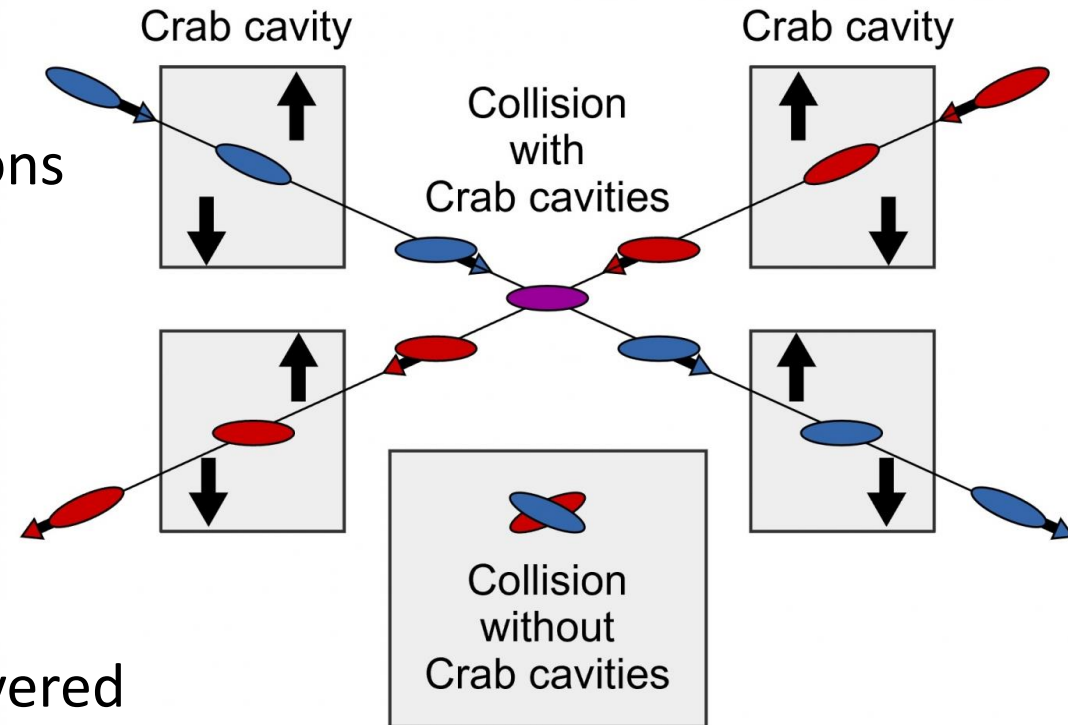


- large angle for minimizing long-range beam-beam effect
- LHC:  $\phi = 285 \mu\text{rad}$ ,  $\sigma_z = 7.5 \text{ cm}$   $\Rightarrow F=0.84$
- HL-LHC:  $\phi = 590 \mu\text{rad}$ ,  $\sigma_z = 7.5 \text{ cm}$   $\Rightarrow F=0.31$
- ILC:  $\phi = 14 \text{ mrad}$ ,  $\sigma_z = 300 \mu\text{m}$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



# Luminosity: Crossing angle and Crab Cavities

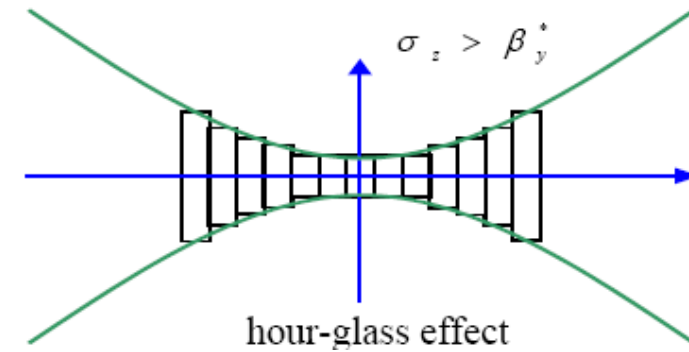
- oscillating transverse electric field kicks head and tail of the bunches in opposite directions
- transversely deflecting RF "crab cavity" on both side of the IP
- 90 degrees betatron phase advance to IP
- bunches tilt on the way to the IP to collide quasi head-on
- => luminosity reduction from angle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



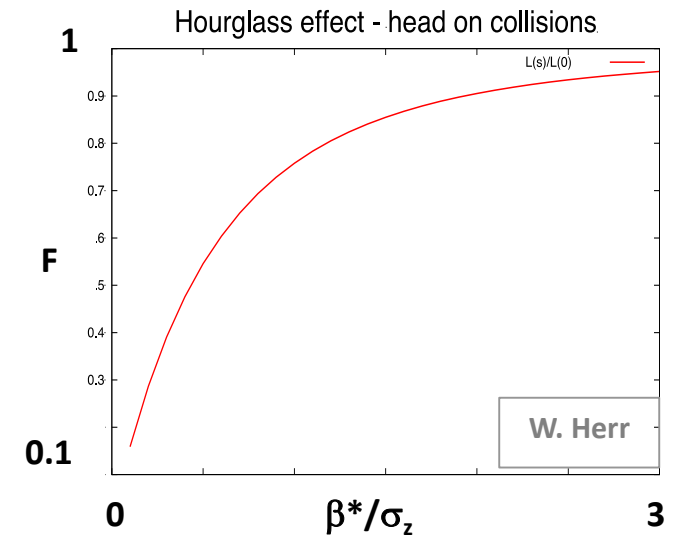
- Important for proton colliders and linear e<sup>+</sup>/e<sup>-</sup> colliders
- challenge for phase noise (luminosity reduction, emittance growth)

# Luminosity: Hourglass effect

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

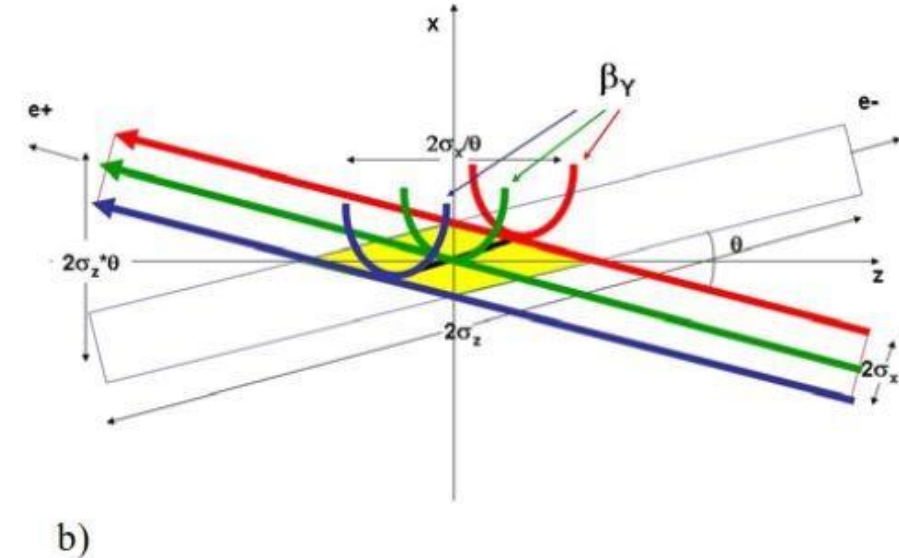
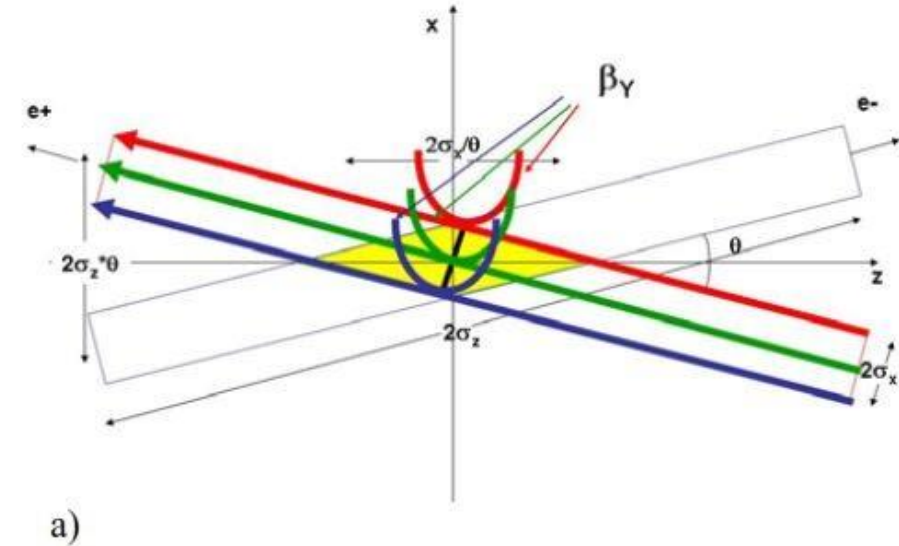


- LHC:  $\beta^* = 55 \text{ cm}$ ,  $\sigma_z = 7.5 \text{ cm}$   $\Rightarrow F \sim 1$
- HL-LHC:  $\beta^* = 15 \text{ cm}$ ,  $\sigma_z = 7.5 \text{ cm}$   $\Rightarrow F \sim 0.90$
- FCC-ee:  $F: 0.53 - 0.73$  (standard collision scheme)
- Linear colliders: very important, drives design to small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



# Luminosity: Crab-Waist scheme

- Increase crossing angle and decrease horizontal beam size => reduce beam-beam effects
  - reduce vertical  $\beta$  function to overlap length (smaller than  $\sigma_z$ )
  - $\beta$  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  $\pi/2$  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  $\mathcal{L}$  ( $\text{cm}^{-2} \text{s}^{-1}$ ) is

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

- LHC ring  $f = 11 \text{ kHz}$

- LC  $f = \text{few-100 Hz (power limited)}$

$\Rightarrow$  **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  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

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

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

- Driven to extremely small beam sizes

- $\Rightarrow$  **challenge for generating small emittance, alignment, stabilization**

# Luminosity - Beamstrahlung

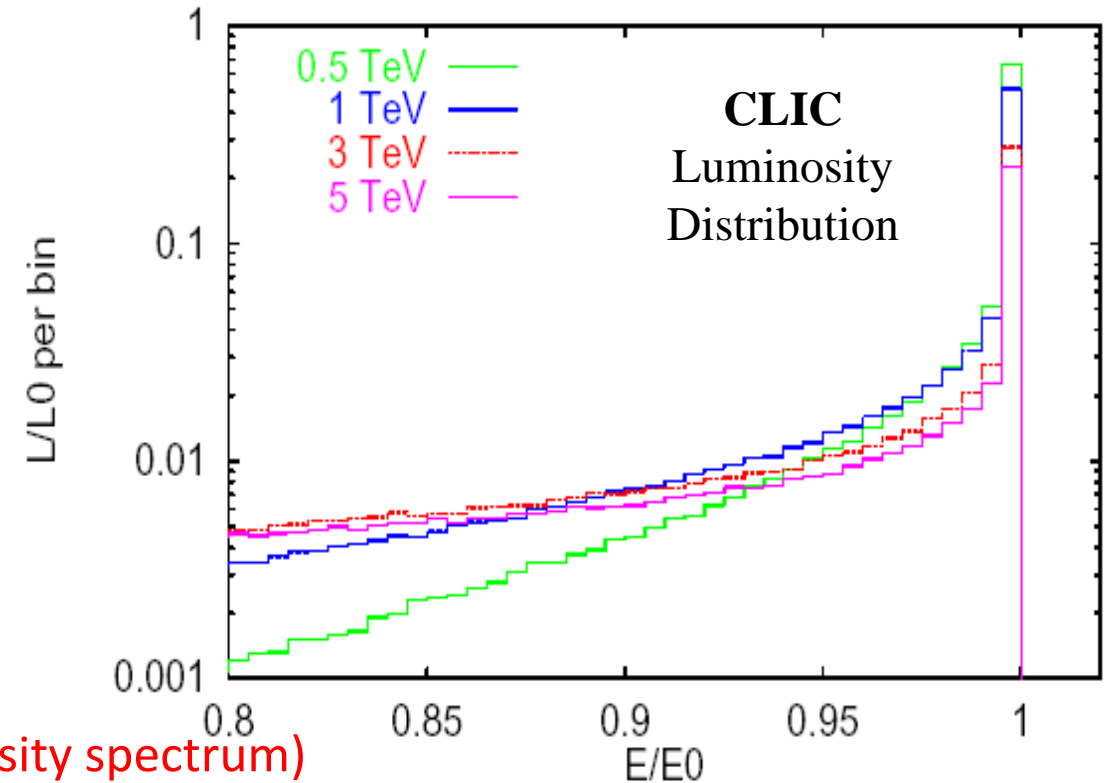
- “synchrotron radiation” in the field of the opposing bunch

=> energy loss

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

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

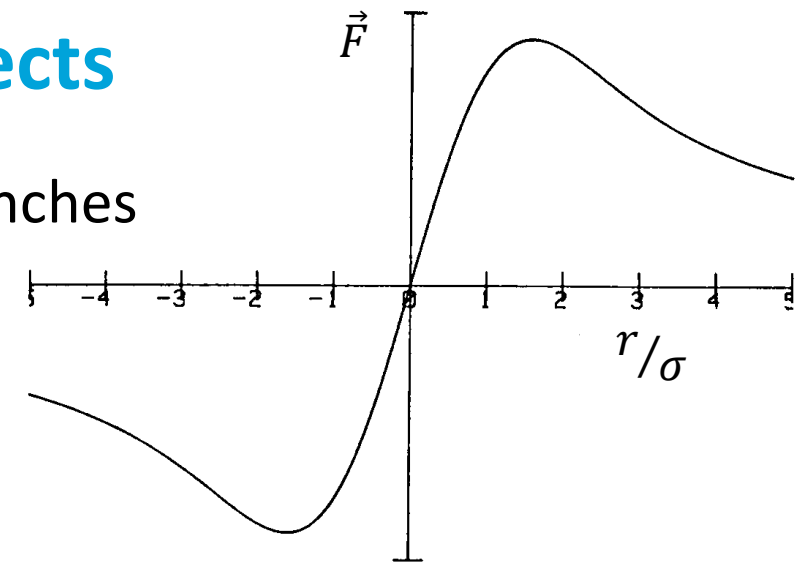
- we want
  - $\sigma_x$  and  $\sigma_y$  **small** for high **luminosity**
  - $(\sigma_x + \sigma_y)$  **large** for small  $\delta_{BS}$  (**=> better luminosity spectrum**)
- use **flat beams with  $\sigma_x \gg \sigma_y$**



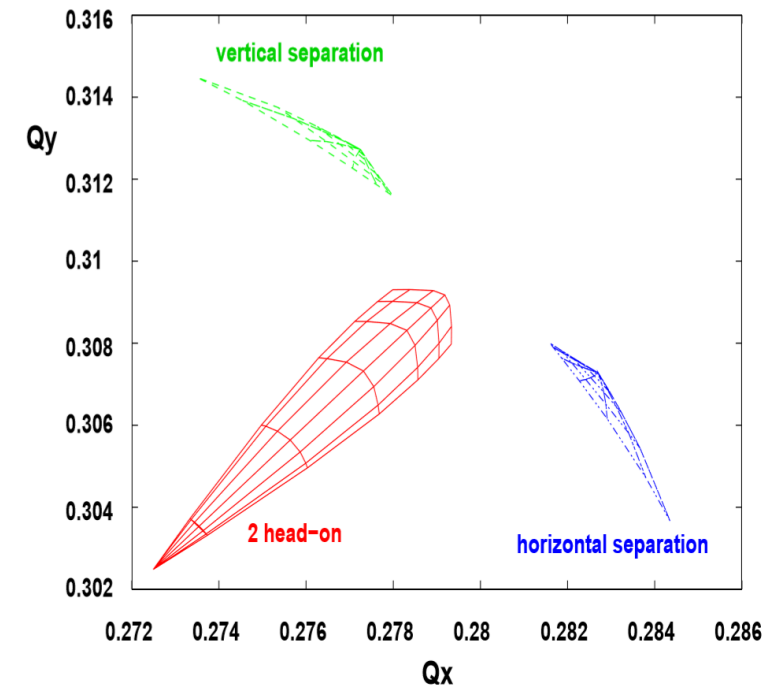


# Challenge: Beam-beam effects

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



Tune footprint, head-on and long range



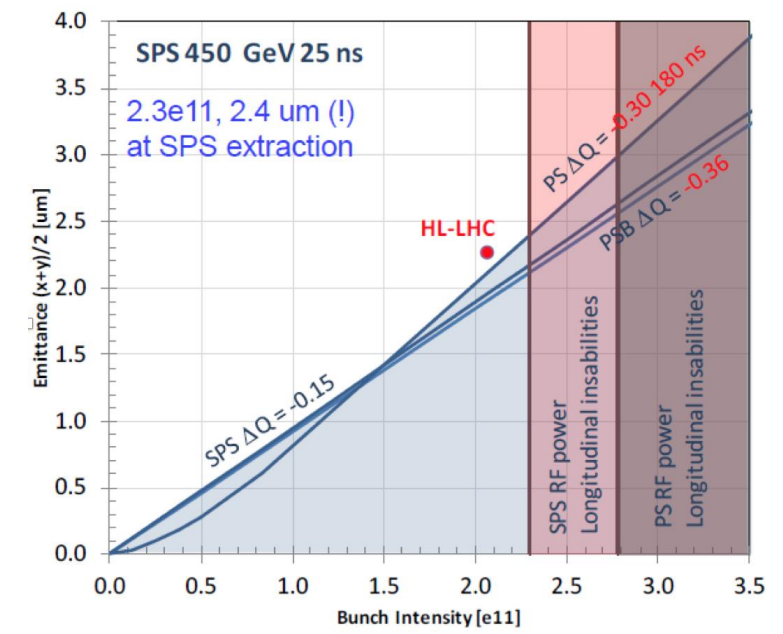
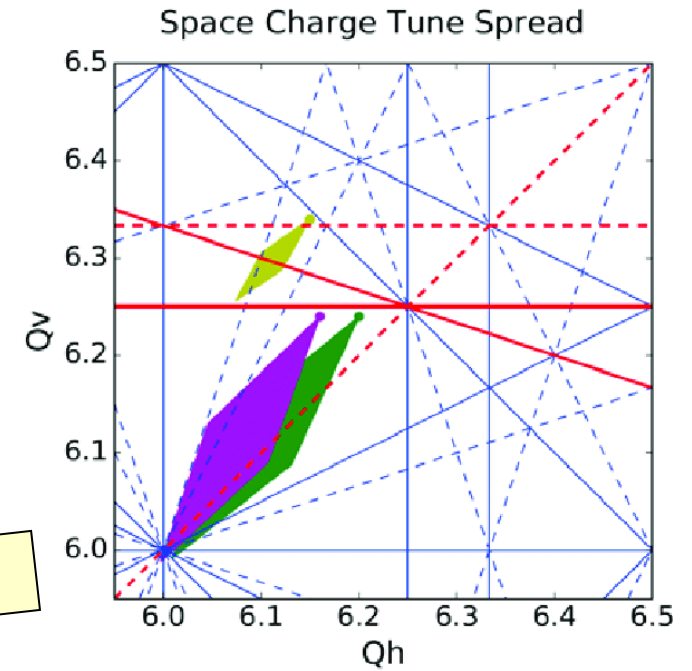
M. Bai  
W. Herr

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

More in lectures by Massimo Ferrario



# Challenge: beam power

- **Linear collider:**

- Average beam power  $P_{beam} = \delta IE/e = f_{rep} N_{pulse} E$
- Luminosity is proportional to beam power (at given energy)
- $P_{beam} = P_{RF} \eta_{RF \rightarrow beam} = P_{mains} \eta_{mains \rightarrow RF} \eta_{RF \rightarrow beam}$
- Power consumption proportional to beam power
- ⇒ need to optimize overall efficiency  $\eta$
- develop efficient modulators and klystrons

- **Ring collider:**

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

$\delta$ : duty factor

$I$ : beam current

$E$ : beam energy

$f_{rep}$ : repetition rate

$N_{pulse}$ : total particles per pulse

# The different projects

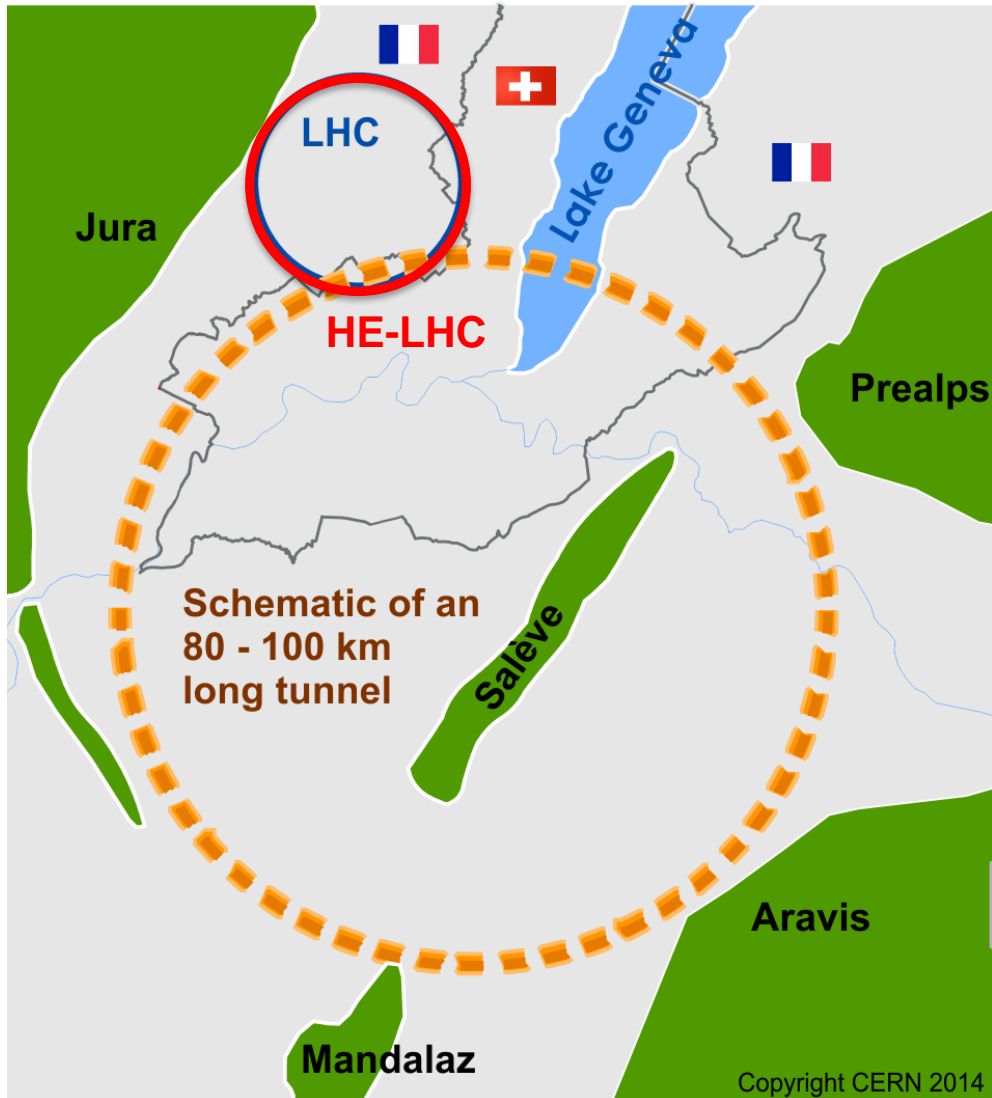
# Proton-Proton ring collider: HL-LHC

- 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<sup>-1</sup>**
- Limit the pile-up (number of collisions per bunch crossing) to  **$\mu \leq 140$**
- => **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<sub>3</sub>Sn – 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 lecture by  
Markus Zerlauth*



# CERN Future Circular Collider Study

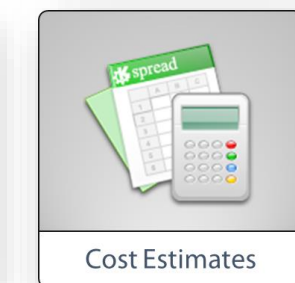
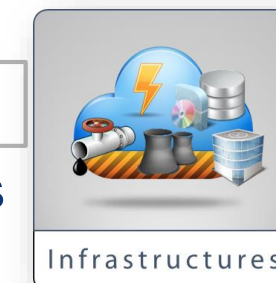
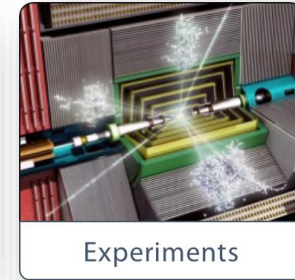
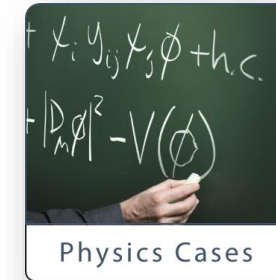


## International FCC collaboration (CERN as host lab) to study:

- ~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  $\Rightarrow$  100 TeV  $pp$  in 100 km**

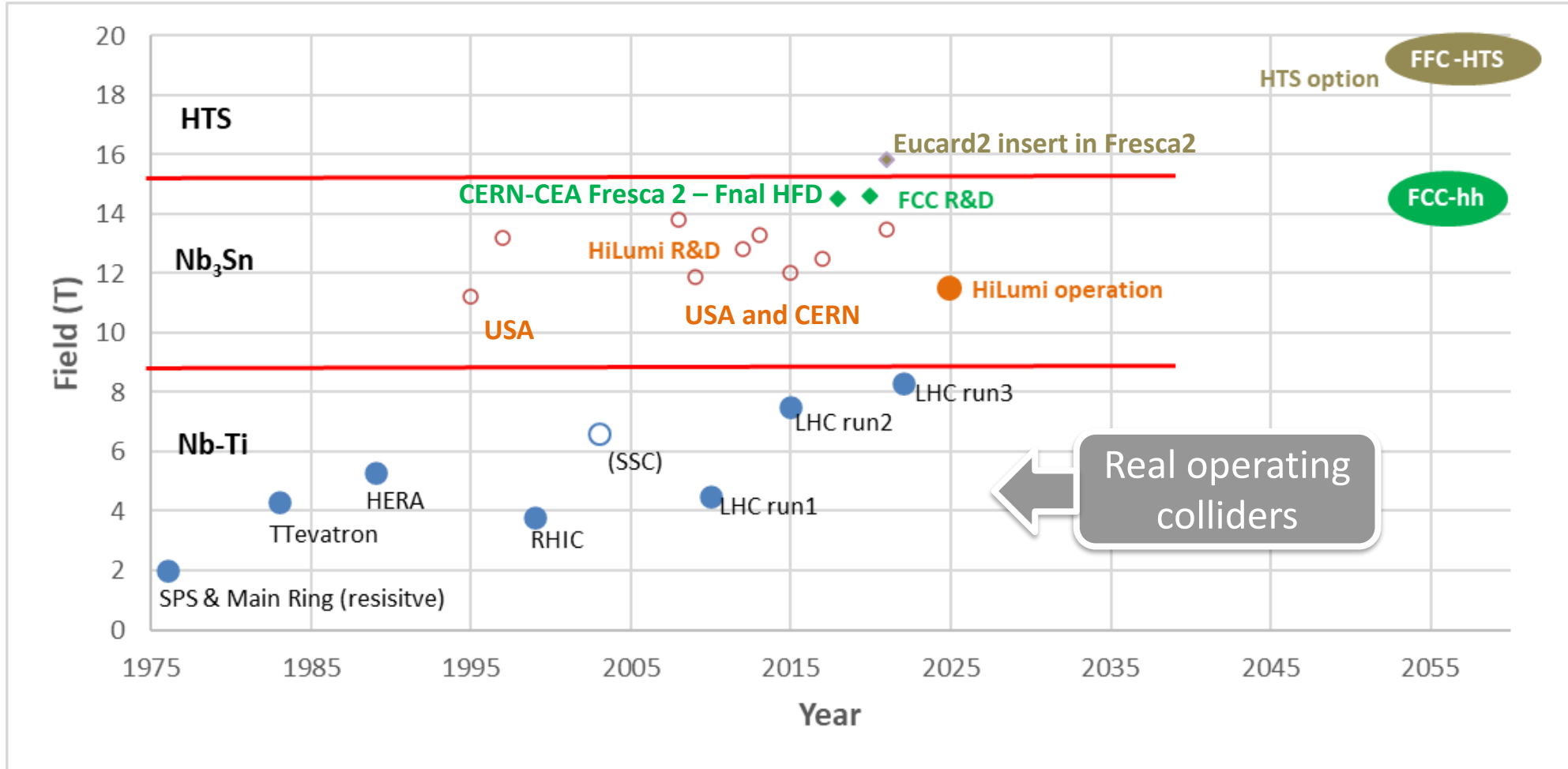
- lepton-hadron collisions as options to FCC-hh



# 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 (16 GJ total energy stored in beams)
  - 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

# Maximum magnetic field in hadron collider

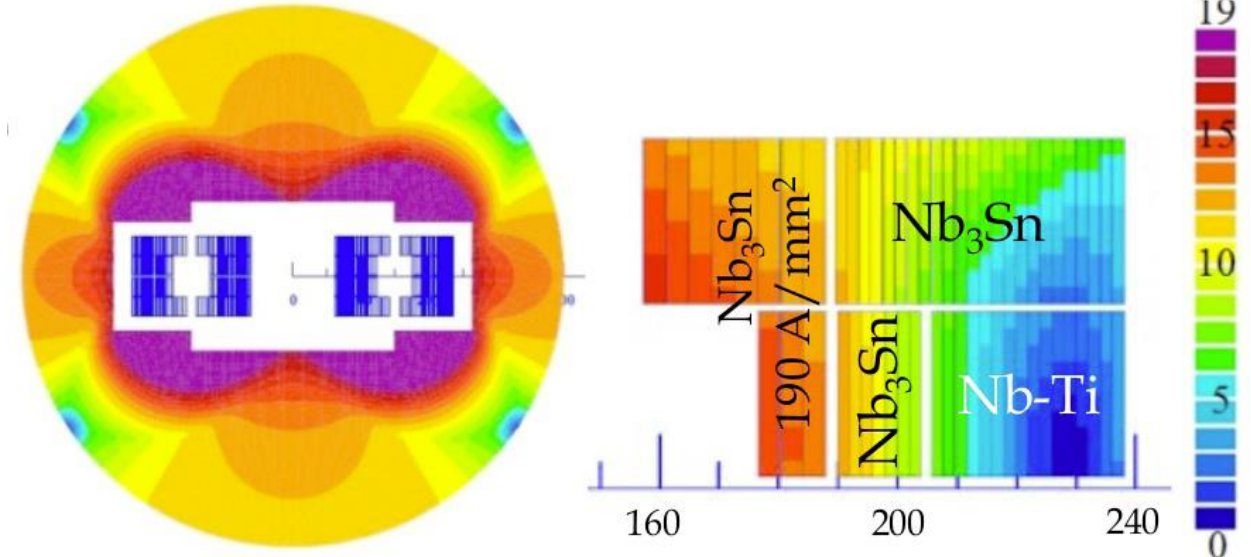


# FCC-hh Challenges: Magnets

Arc dipoles are the main cost and parameter driver

**Baseline: Nb<sub>3</sub>Sn at 16T**

HTS at 20T also studied as alternative

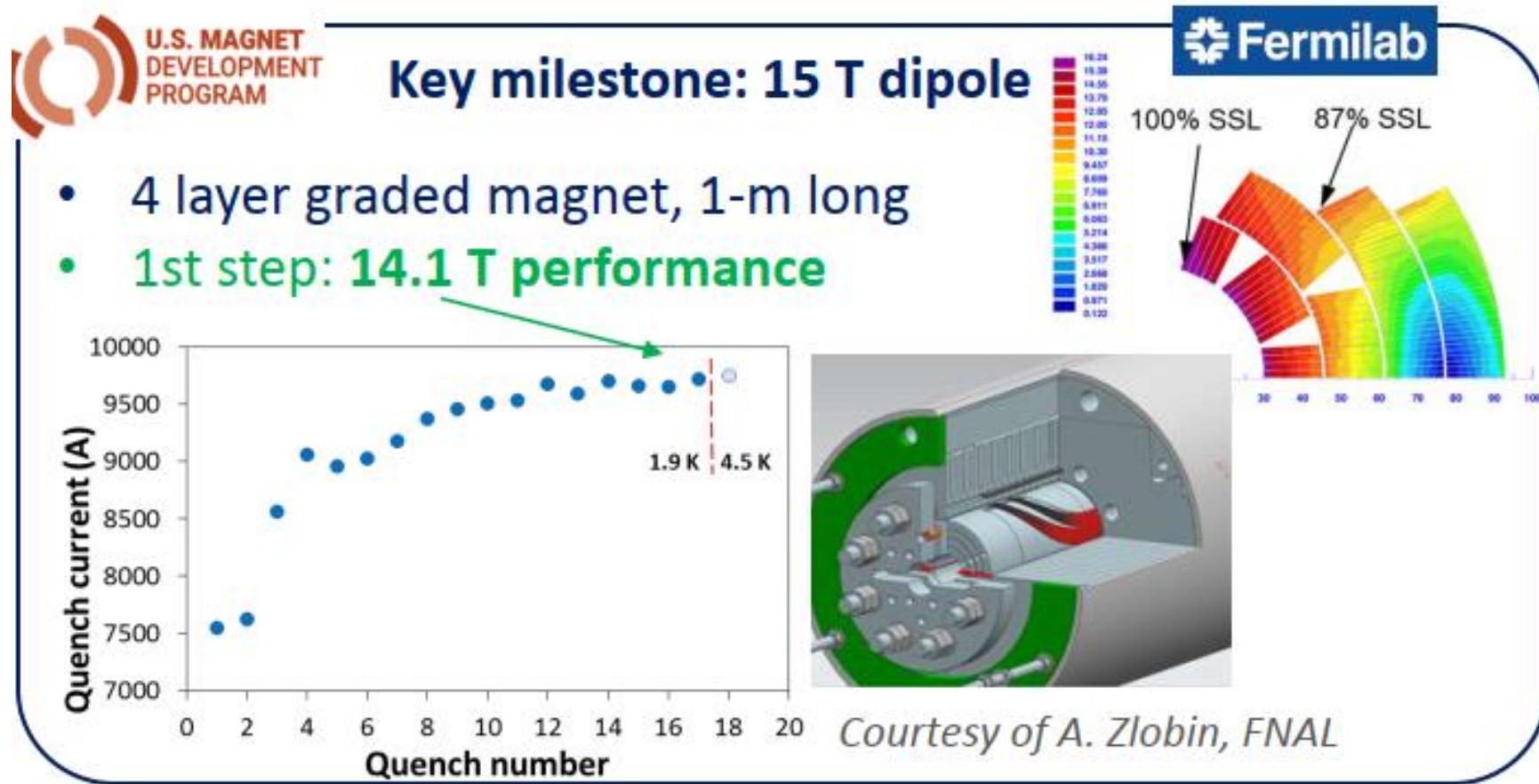


Coil sketch of a 15 T magnet with grading, E. Todesco

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 cos $\theta$ 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:

$\sim 30\text{W/m/beam}$  in arcs ( $E_{\text{crit}} = 4.3\text{keV}$ )

$\Rightarrow$  **total 5 MW** (LHC 7kW)

- $\Rightarrow$  Cooling challenge
- $\Rightarrow$  Vacuum challenge
- $\Rightarrow$  Impedance challenge
- $\Rightarrow$  Mechanical challenge
- $\Rightarrow$  Electron cloud
- $\Rightarrow$  Cost challenge

- Beam screen protects superconducting magnets from synchrotron radiation

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

5MW synchrotron radiation  $\Rightarrow$  **100MW** of cooling power



# FCC-ee basic design choices

K. Oide et al.

**double ring  $e^+e^-$  collider  $\sim 100$  km, cms energies:**

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

**follows footprint of FCC-hh, except around IPs**

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

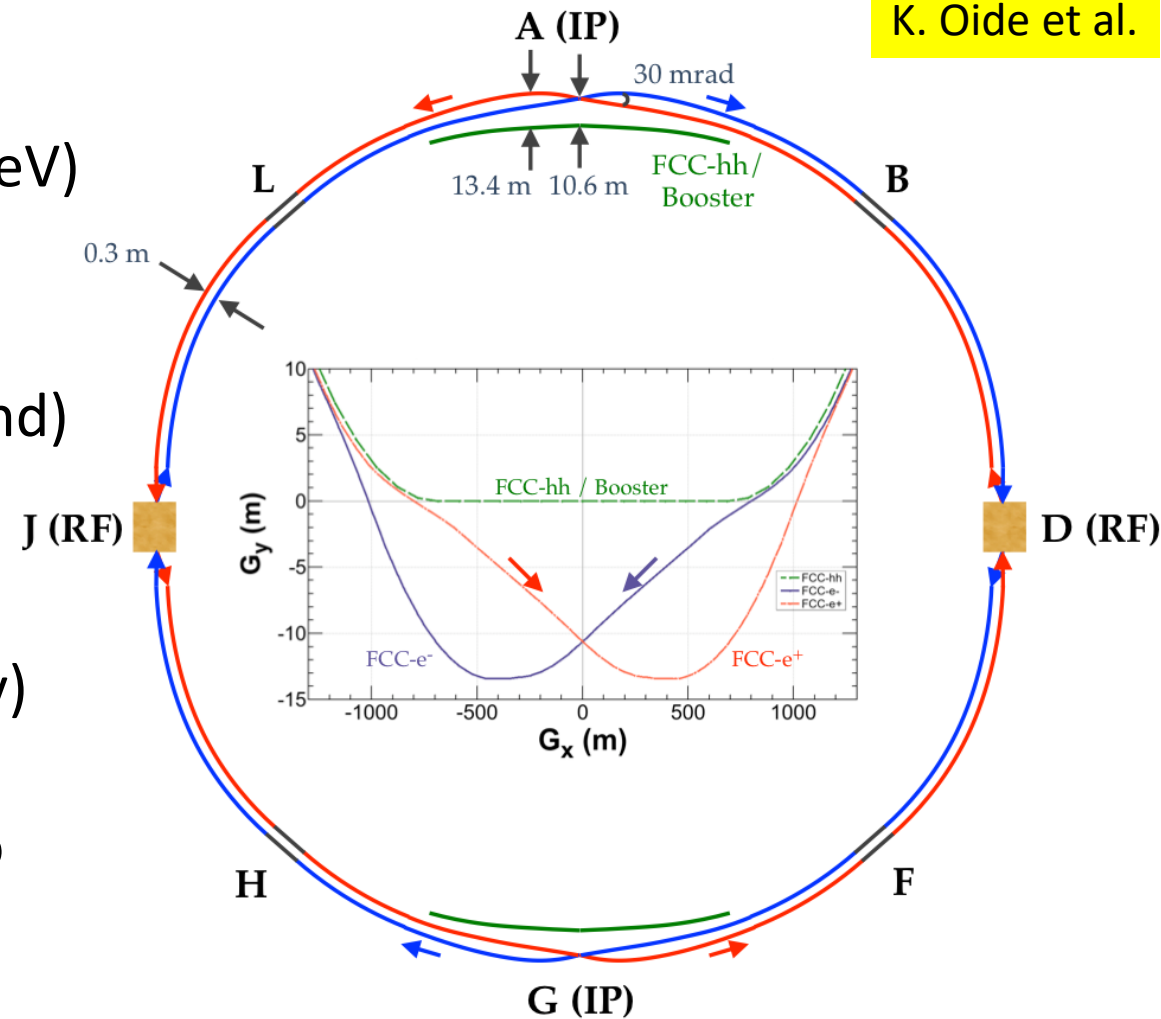
**large horizontal crossing angle 30 mrad**

**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: RF challenge

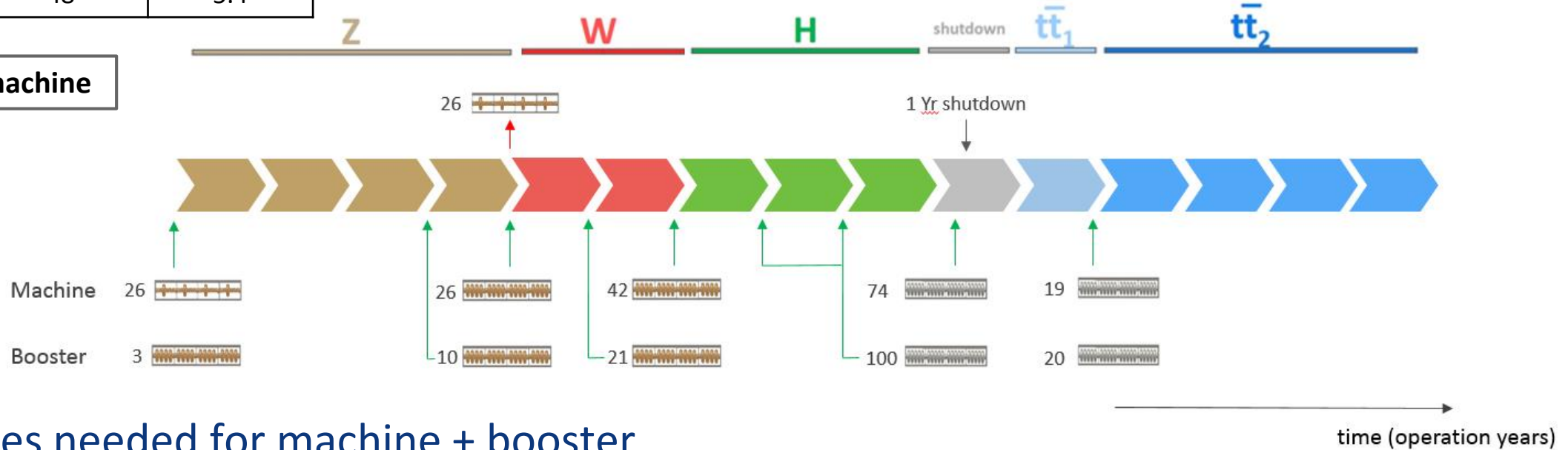
“Ampere-class” machine

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

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 ( $\approx 30$  CM/shutdown)

“high-gradient” machine

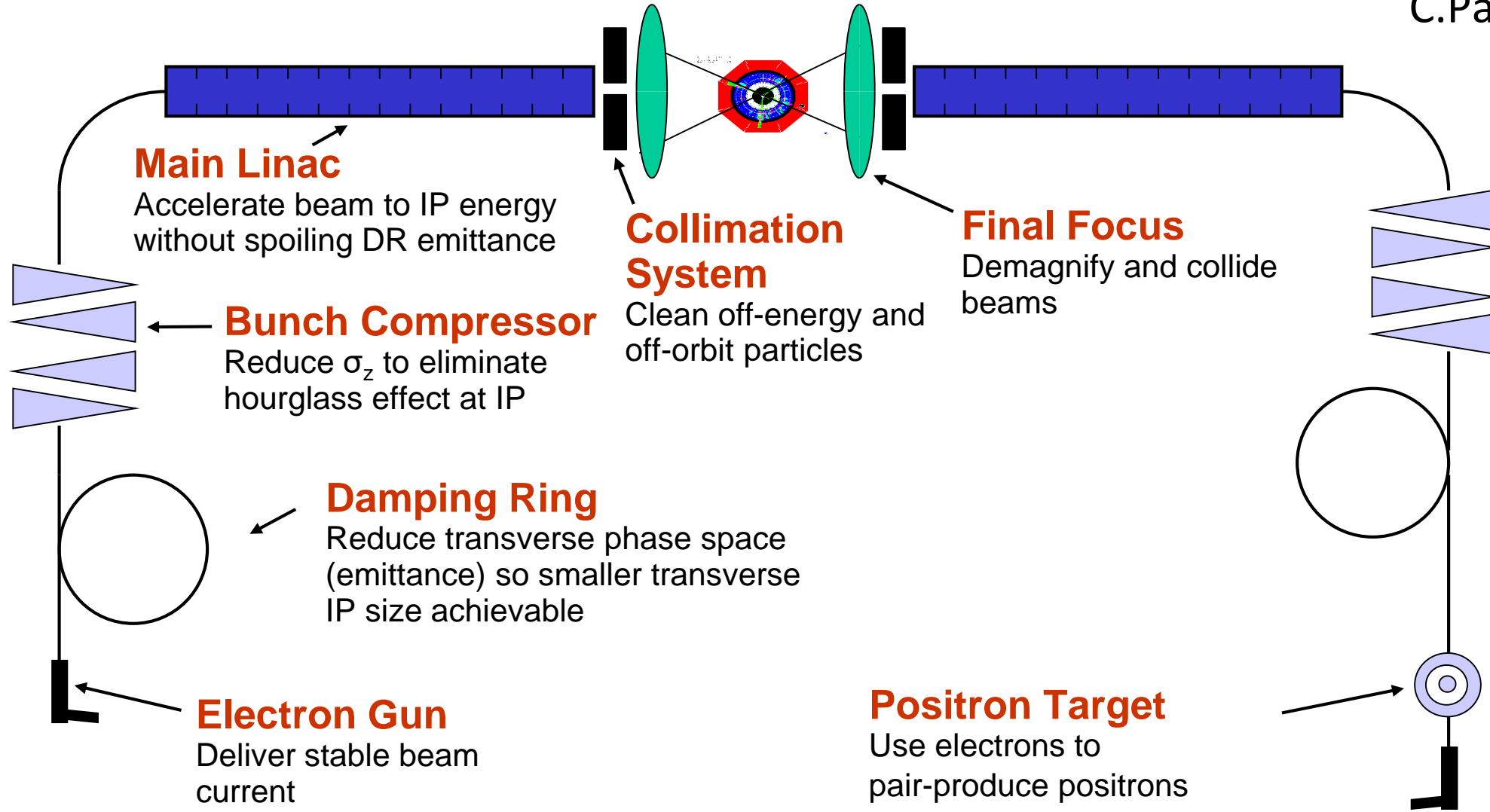


>1200 cavities needed for machine + booster

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

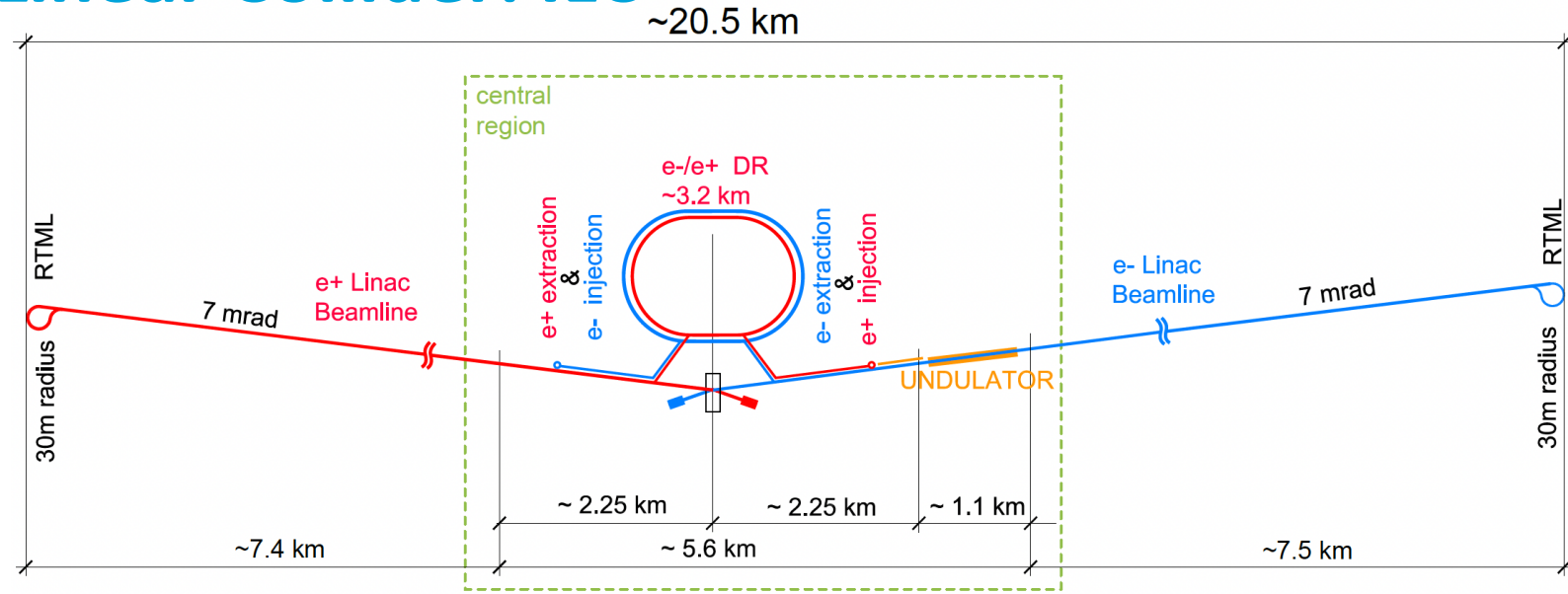
# Challenges - Linear Colliders

C.Pagani

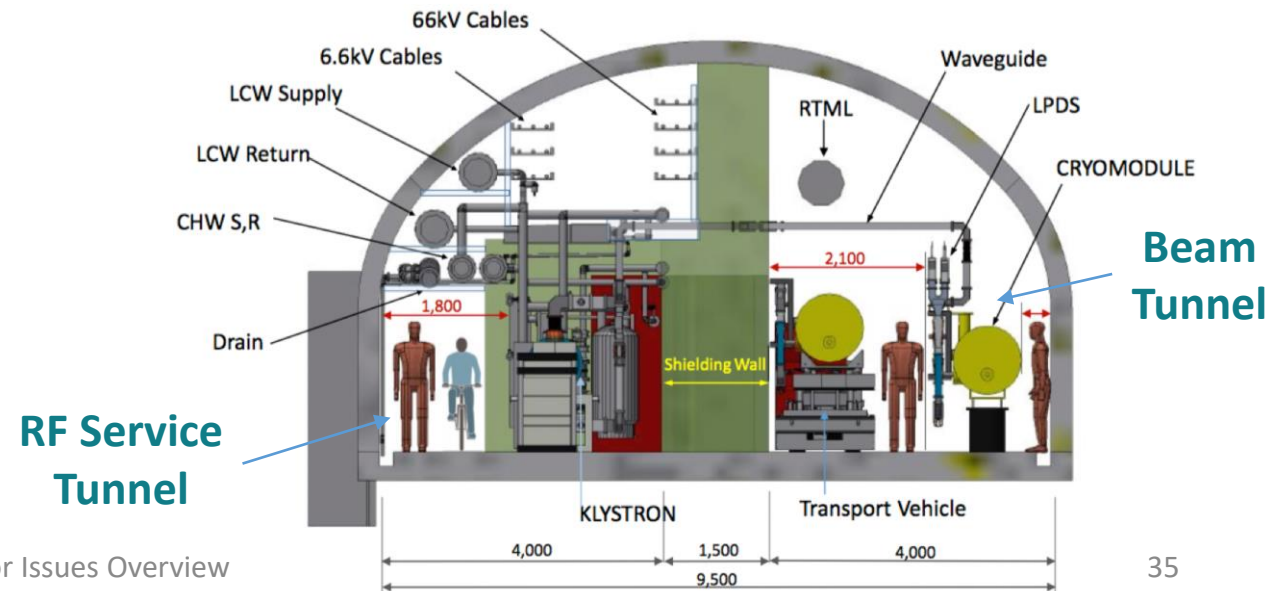


# Linear Collider: ILC

- **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



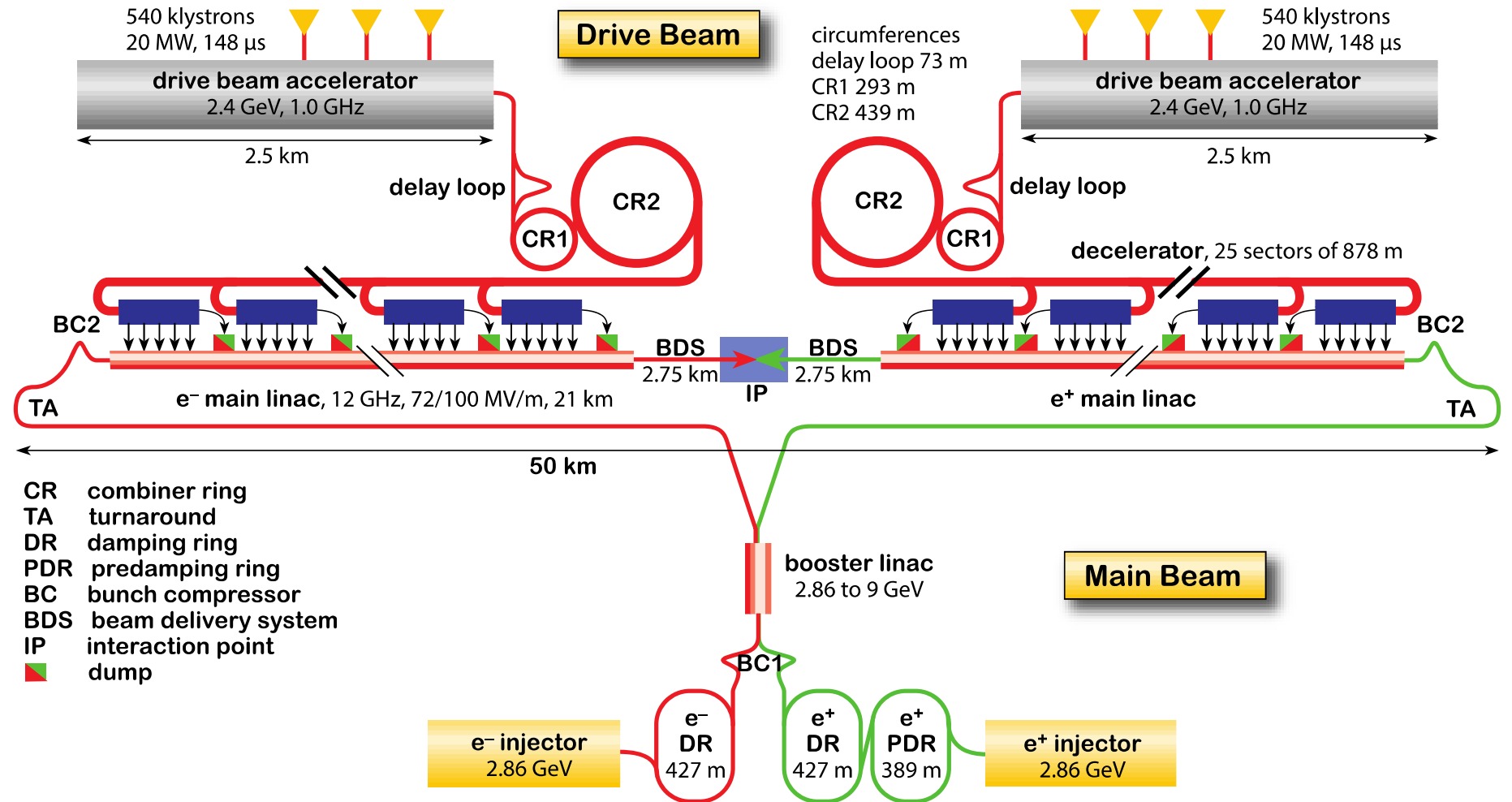
ML Tunnel Cross-section



# CLIC – overall layout – 3 TeV

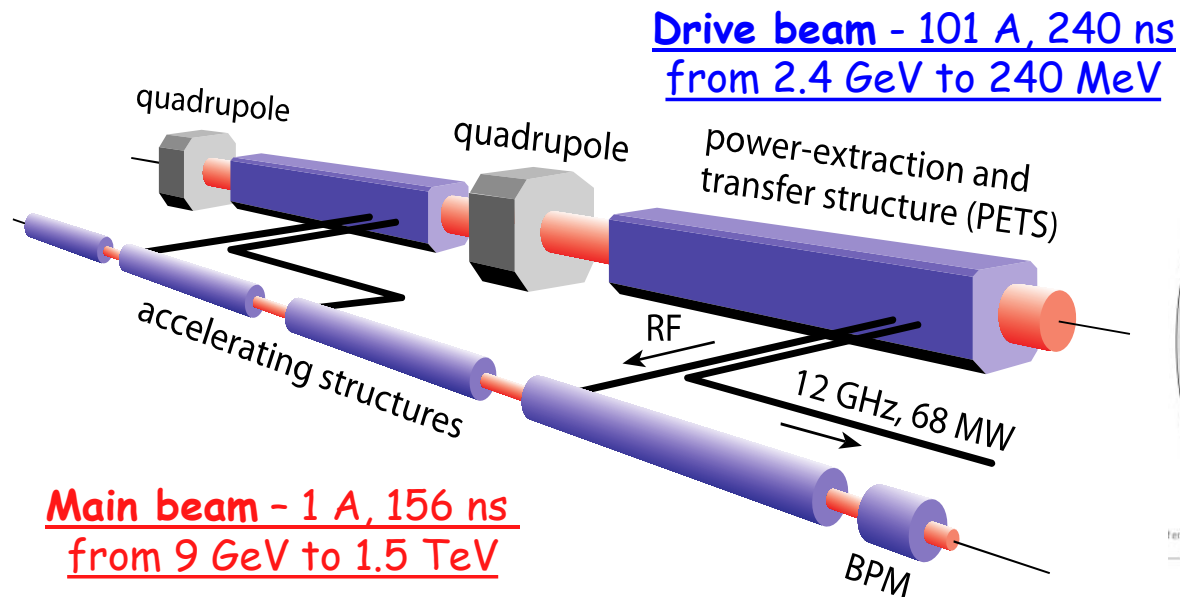
## CLIC (Compact Linear Collider):

- 380 GeV - 3 TeV
- 100 MV/m
- warm technology
- 12 GHz
- two beam scheme



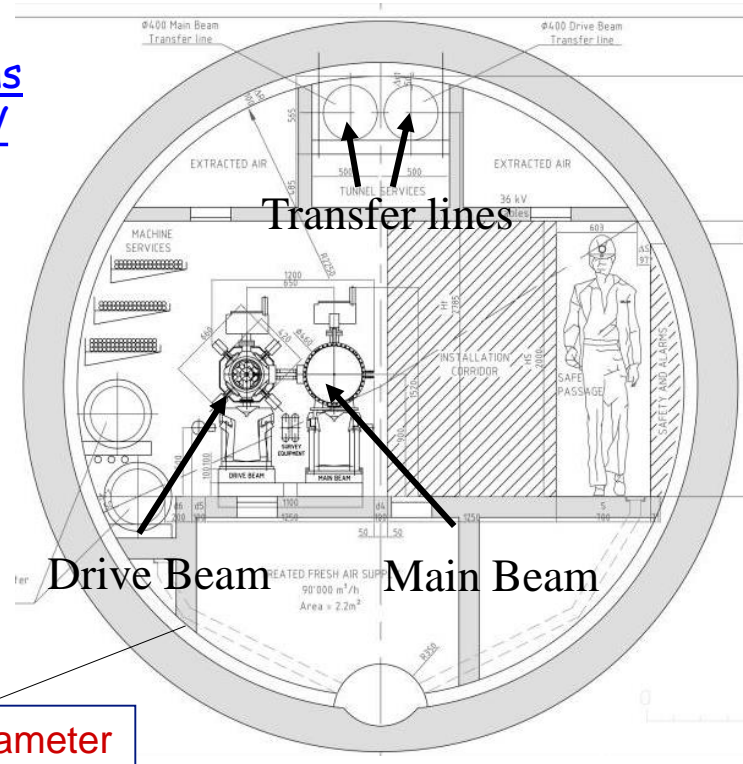
# CLIC two beam scheme

- 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




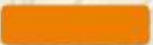

5.6 m diameter

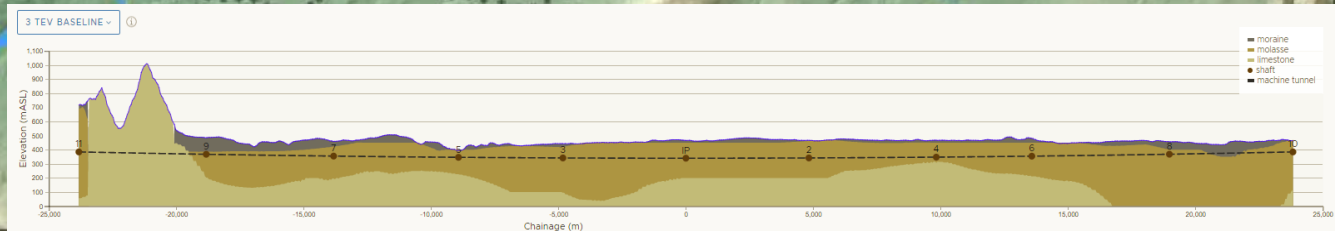
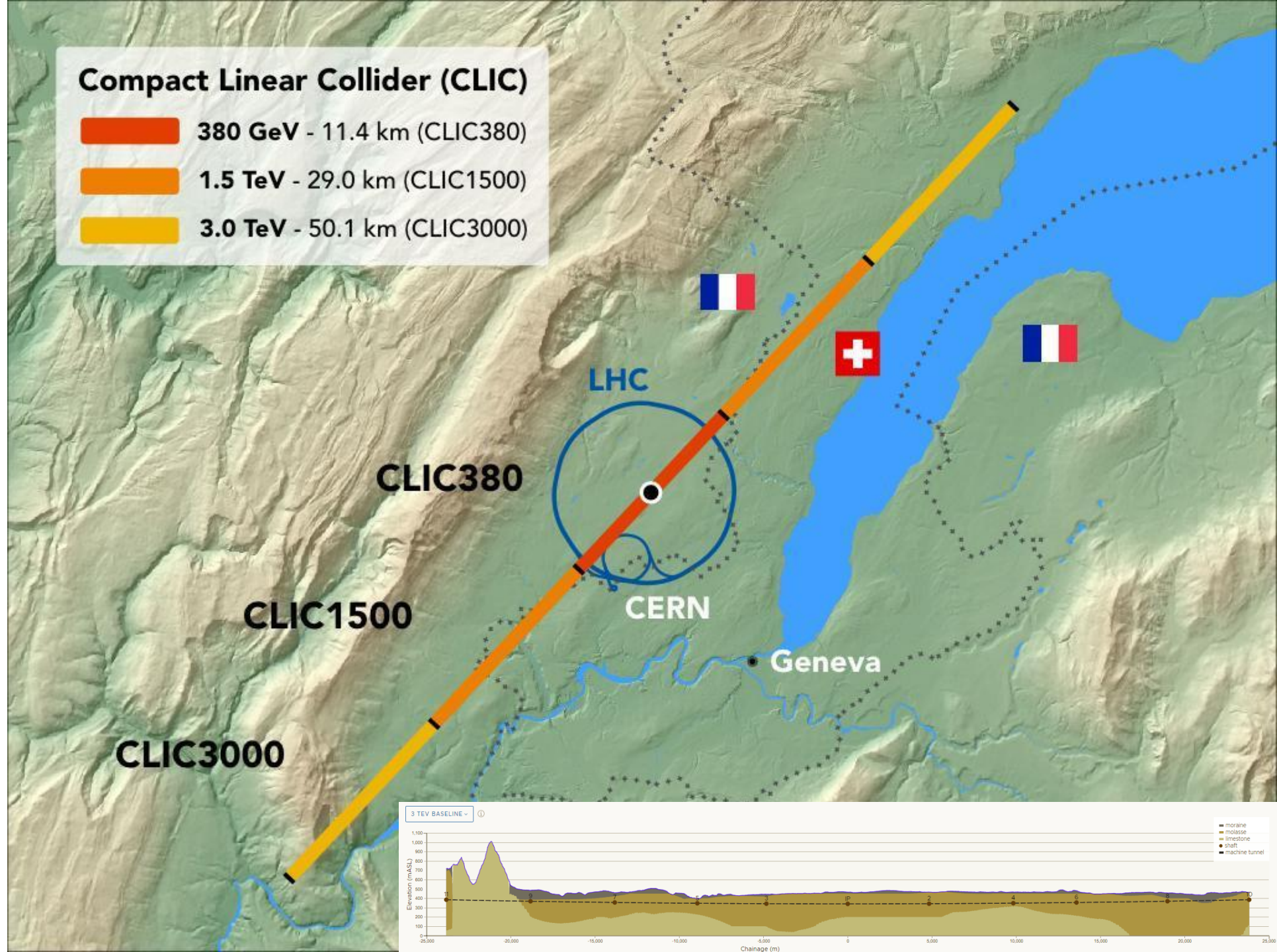
CLIC TUNNEL CROSS-SECTION



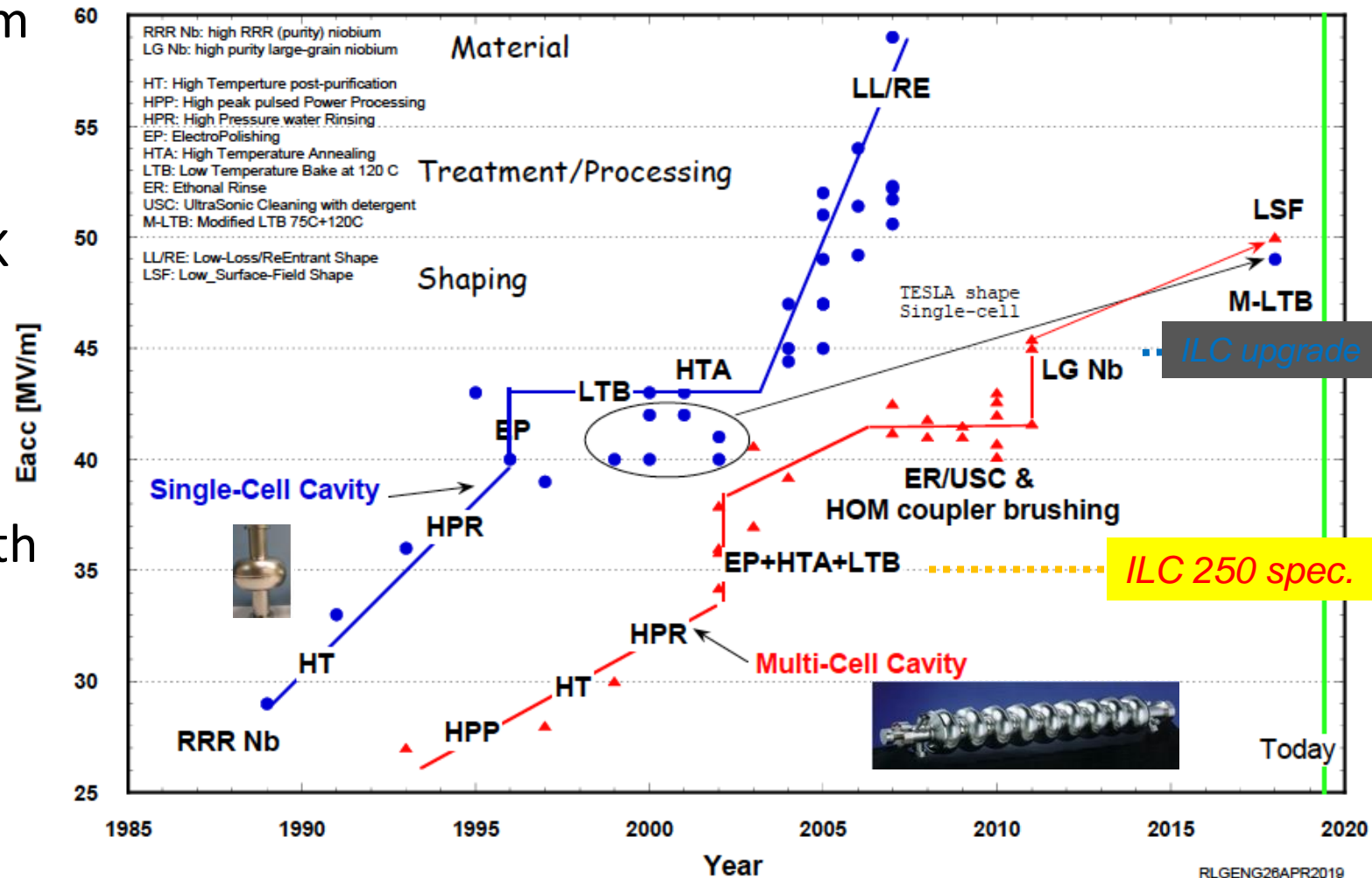


## Compact Linear Collider (CLIC)

-  **380 GeV - 11.4 km (CLIC380)**
-  **1.5 TeV - 29.0 km (CLIC1500)**
-  **3.0 TeV - 50.1 km (CLIC3000)**



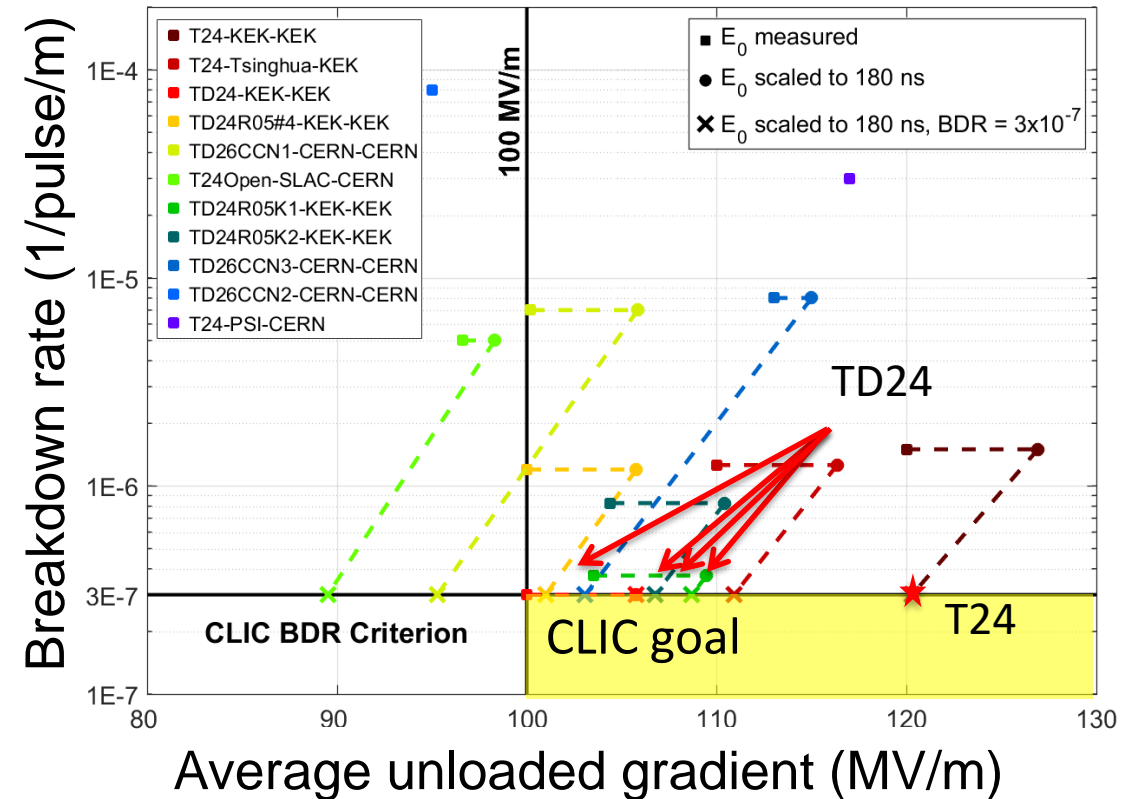
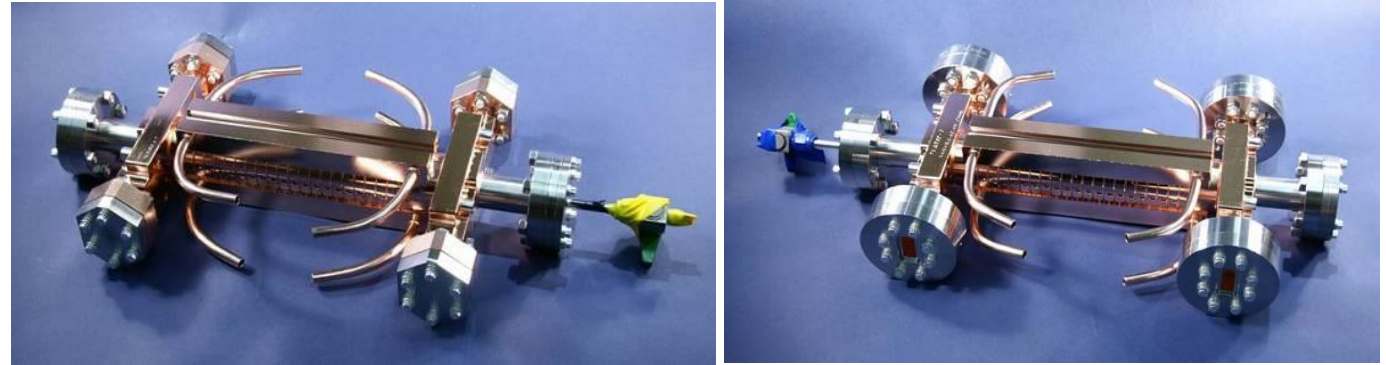
- Impressive progress in SC accelerating structures
- ILC design gradient 31.5 MV/m
- European XFEL 23.6 MV/m operational running
- Cryomodules at Fermilab/KEK exceeded 32 MV/m with beam
- => established technology with large potential gains





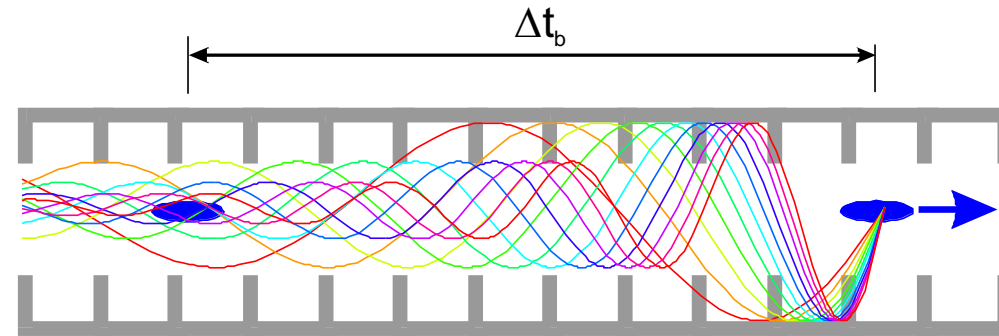
# Challenge: Accelerating gradient NC (CLIC)

- **RF breakdowns** can occur  
=> no acceleration and deflection
- Goal:  $3 \cdot 10^{-7}/\text{m}$  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

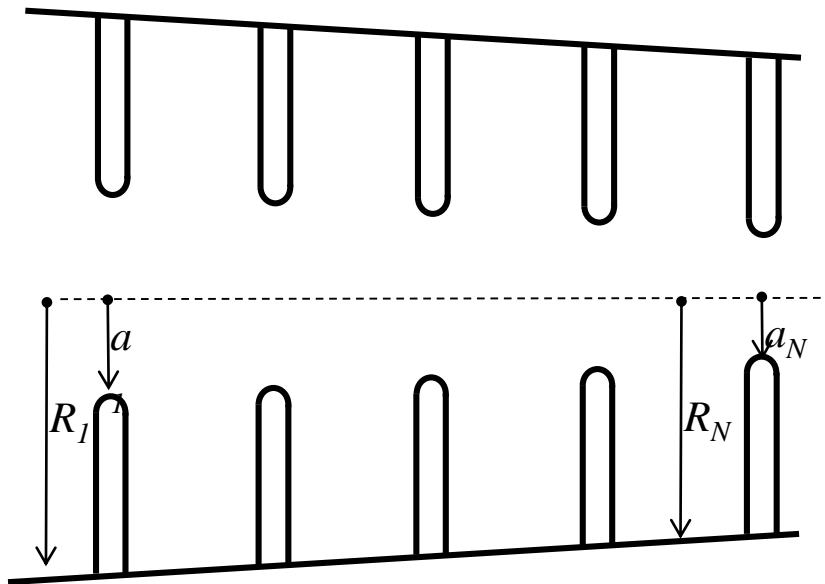


- Bunches **induce field** in the cavities
- **Later bunches** are **perturbed** by these fields
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Fields can build up resonantly
- Later bunches are kicked transversely
- => multi- and single-bunch beam break-up (MBBU, SBBU)
- **Emittance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

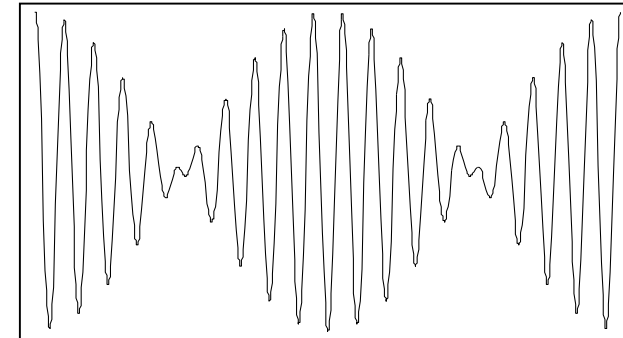
More in lectures by **Giovanni Rumolo**

# Transverse wakefields

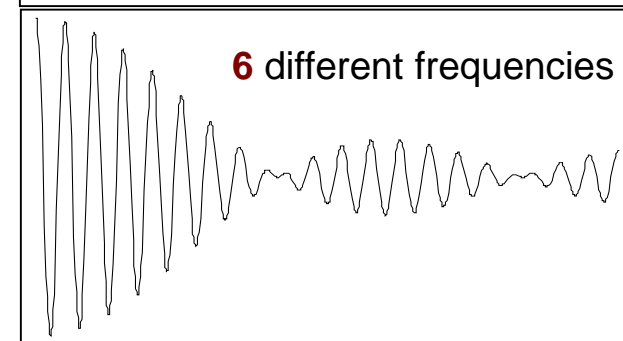
- Effect depends on  $a/\lambda$  ( $a$  iris aperture) and structure design details
- transverse wakefields roughly scale as  $W_{\perp} \propto f^3$
- less important for lower frequency:  
Super-Conducting (SW) cavities suffer less from wakefields
- **Long-range minimised by structure design**
- Dipole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



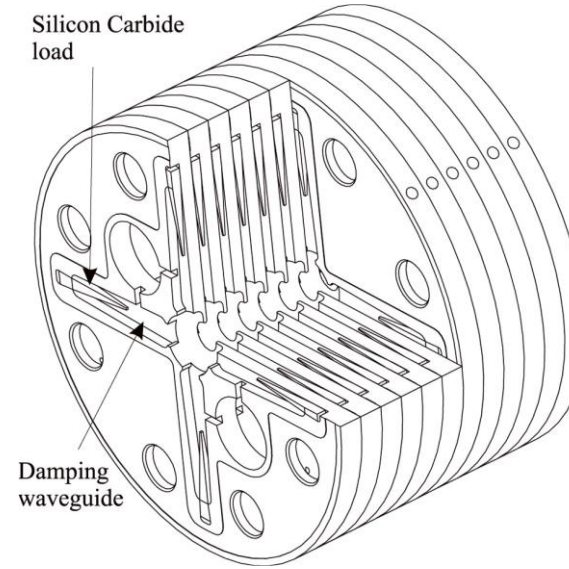
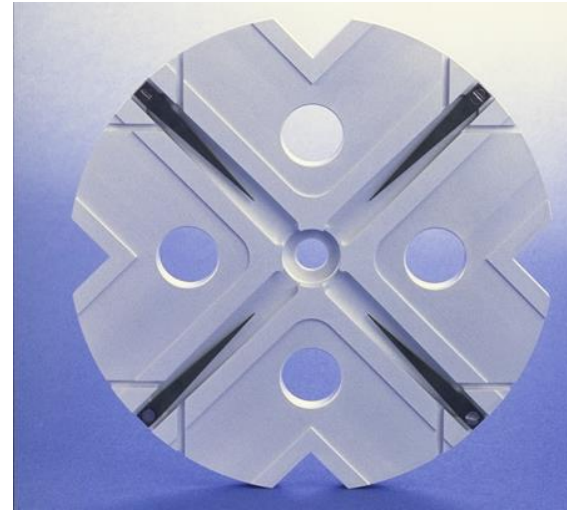
Long range wake of a dipole mode spread over **2** different frequencies



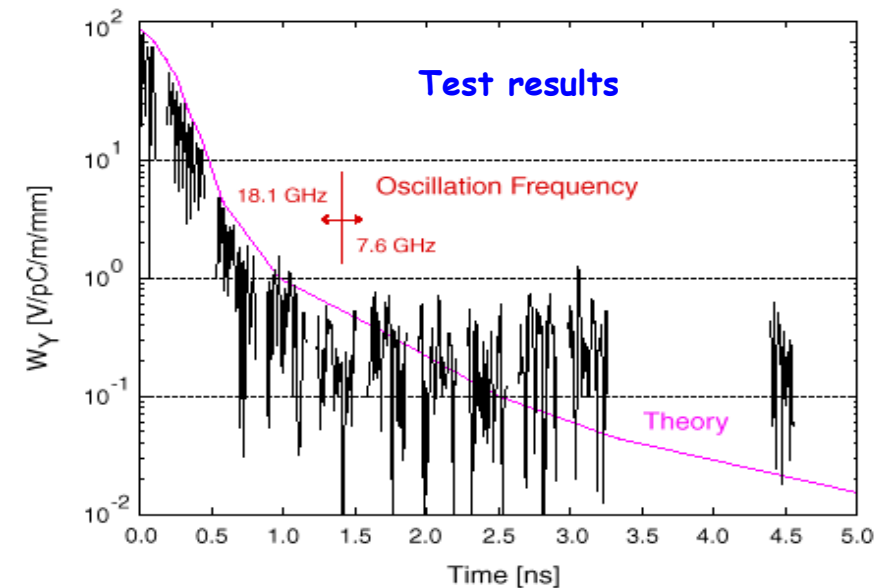
**6** different frequencies



# HOM damping



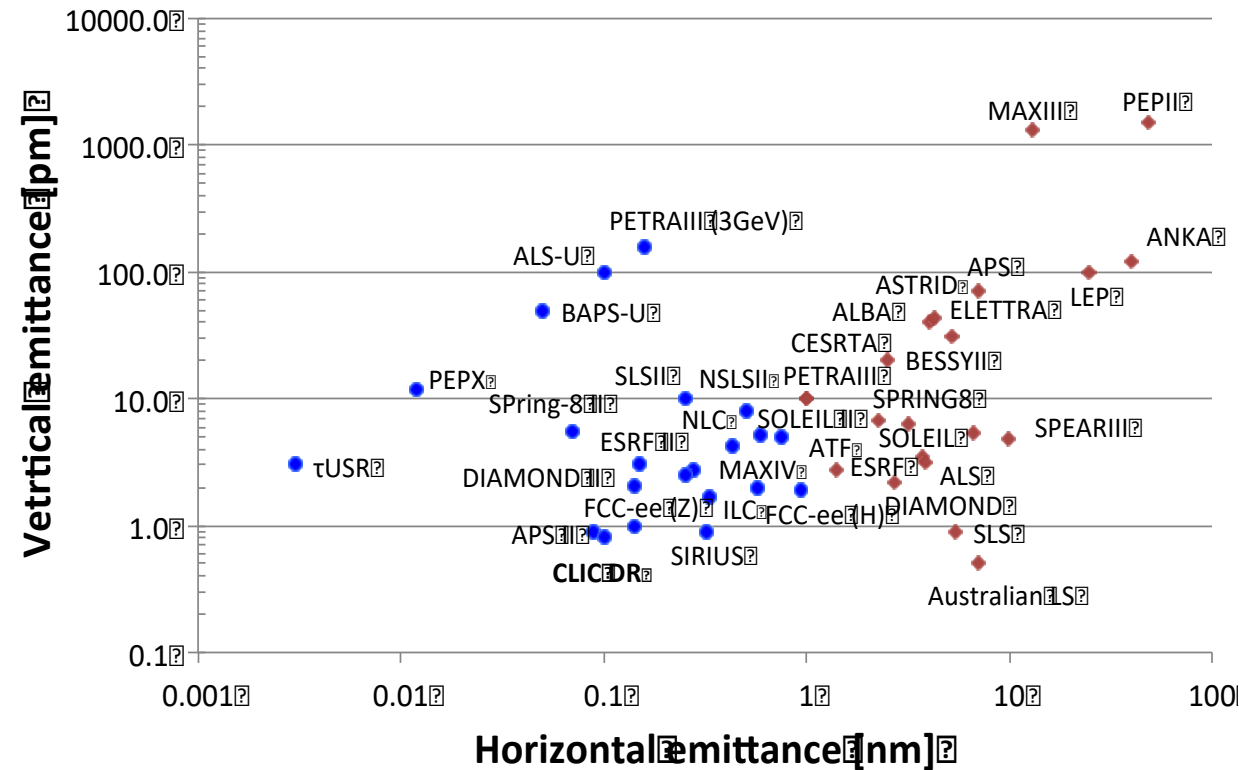
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- HOM enter WG
- Long-range wake efficiently damped



# Damping rings/Light sources: emittance limits

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

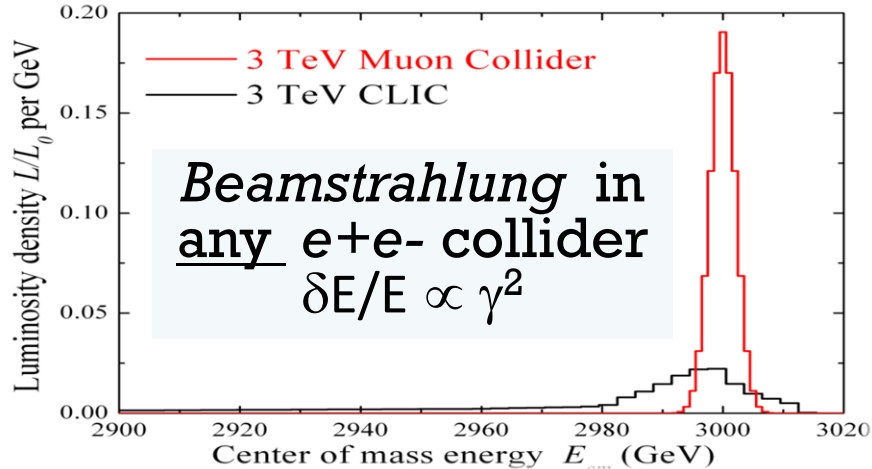
- In practice,  $\epsilon_y$  limited by magnet alignment errors [cross plane coupling by tilted magnets]
- typical vertical alignment tolerance:  $\Delta y \approx 30 \mu\text{m}$   
 $\Rightarrow$  requires beam-based alignment techniques!



More in lectures by  
 Massimo Ferrario and Ian Martin

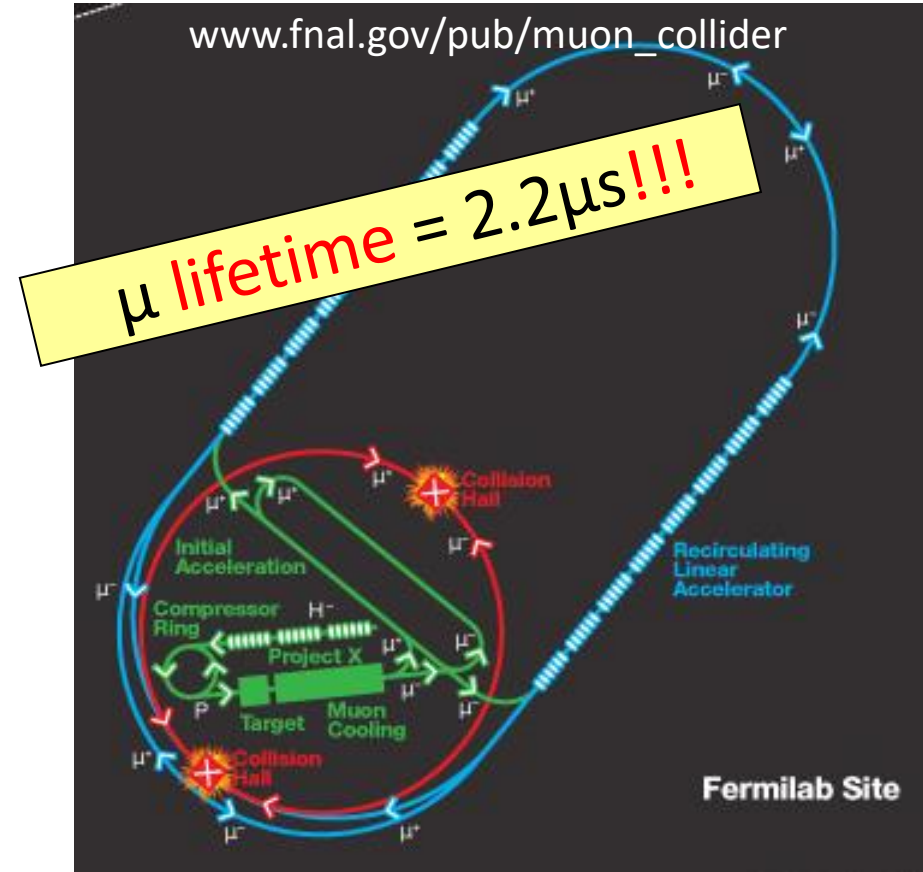
# Muon Collider

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



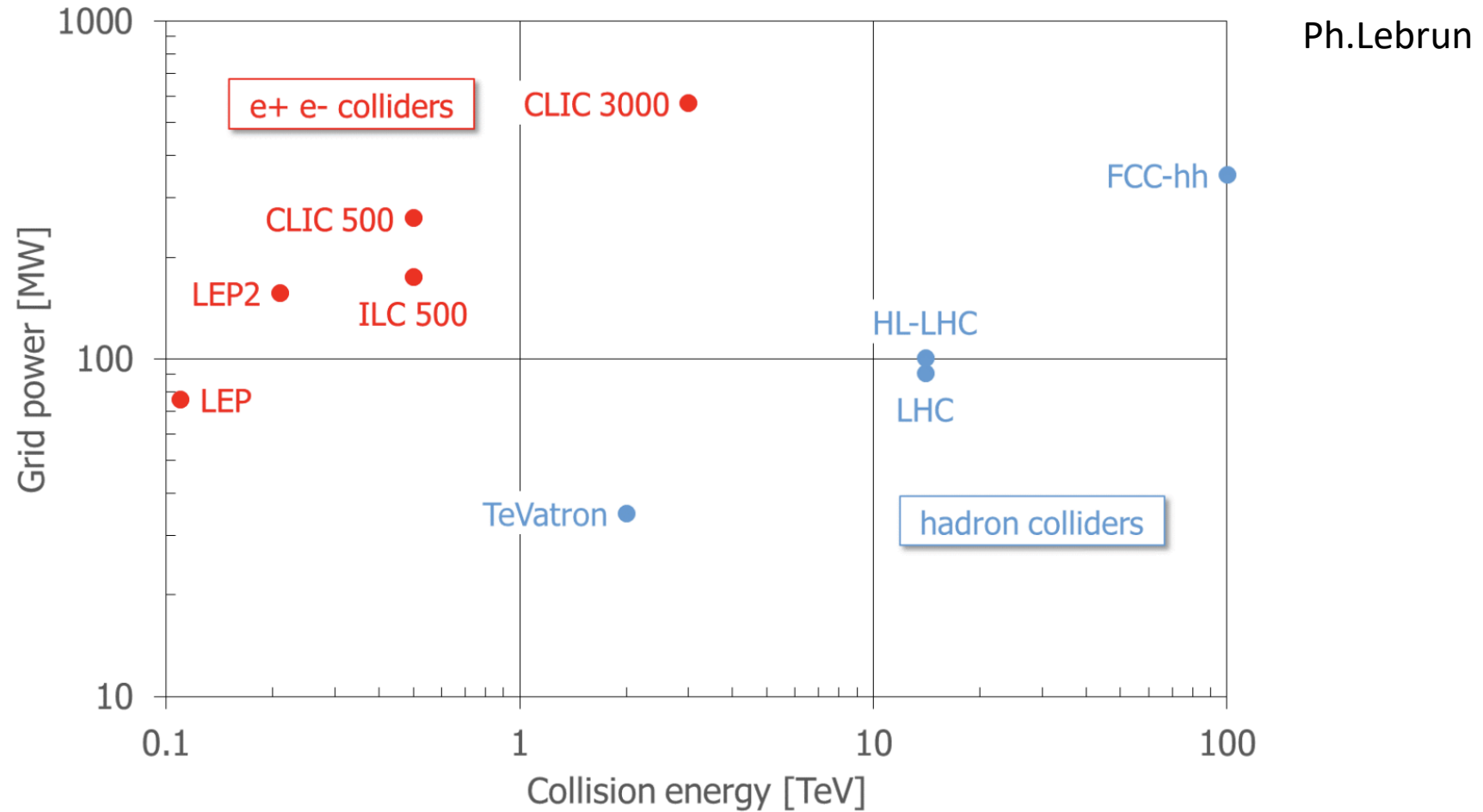
- High production cross section for Higgs
- **The challenge:** multi MW proton driver + Cooling the  $\mu$  beam!!
- Emittance reduction  $10^{-7}$ 
  - ~1000 in each transverse plane
  - ~40 in longitudinal
  - => Ionisation cooling
  - requires 30-40T solenoids + high gradient RF cavities

*More in lectures by Chris Rogers*



<p><b>Compressor Ring</b> Reduce size of beam (<math>2 \pm 1</math> ns).</p> <p><b>Target</b> Collisions lead to muons with energy of about 200 MeV.</p> <p><b>Muon Capture and Cooling</b> Capture, bunch and cool muons to create a tight beam.</p>	<p><b>Initial Acceleration</b> In a dozen turns, accelerate <math>\mu</math> to 20 GeV</p> <p><b>Recirculating Linear Accelerator</b> In a number of turns, accelerate muons up to Multi-TeV using SRF technology.</p> <p><b>Collider Ring</b> Bring positive and negative muons into collision at two locations 100m underground.</p>
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# Challenge: Power consumption of high-energy colliders



- 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

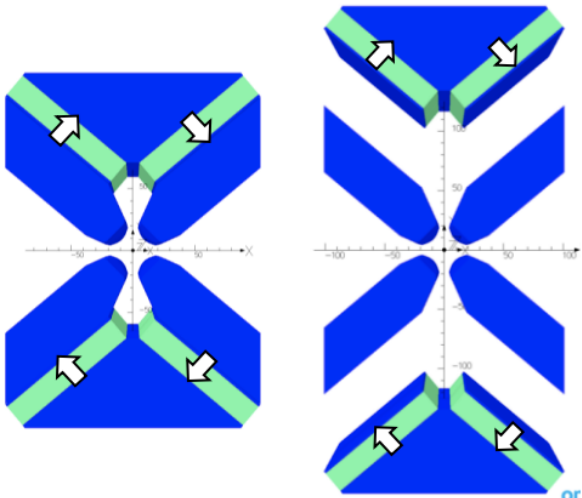
- Understand relations between
  - Performance parameters
    - Particle energy  $E$
    - Luminosity  $\mathcal{L}$
  - Beam parameters
    - Beam power  $P_{beam}$
    - Beam stored energy  $W_{beam}$
- Analyse sources of losses
  - “Intrinsic” losses
    - Synchrotron radiation
    - Beam image currents
  - Accelerator systems efficiency
    - RF
    - Magnets
    - Vacuum
    - Beam instrumentation
    - ...
  - Infrastructure
    - Electrical distribution
    - Cooling & ventilation
    - Cryogenics
    - ...



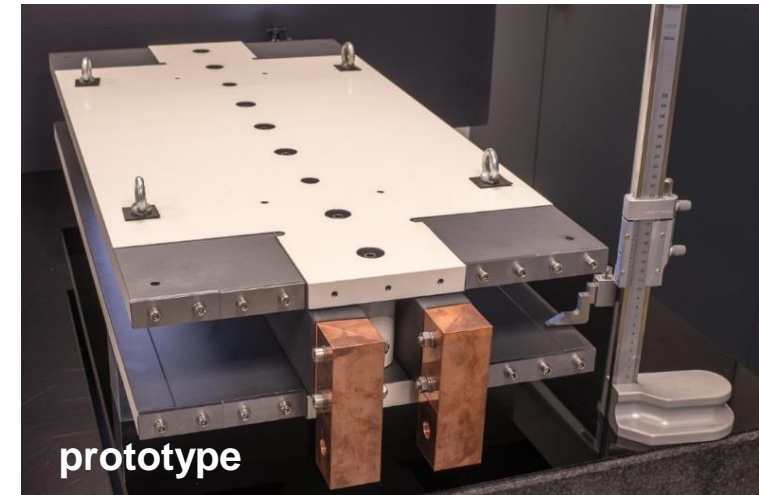
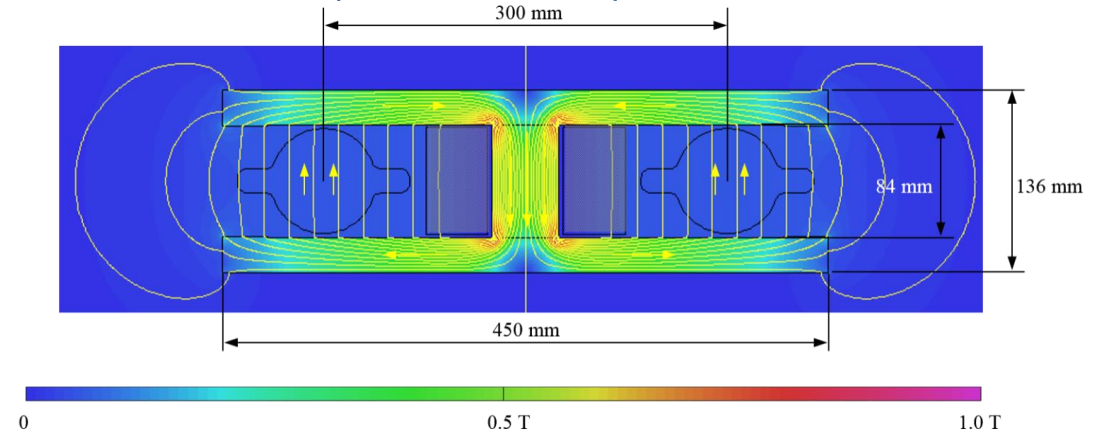
# Energy saving example - Magnets

- Innovative designs
- Permanent/hybrid magnets

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



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





# Main High-Energy Frontier Collider Challenges

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

- **High-field dipoles:** SC magnet R&D with new materials ( $\text{Nb}_3\text{Sn}$ , 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:
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  - Markus Zerlauth

