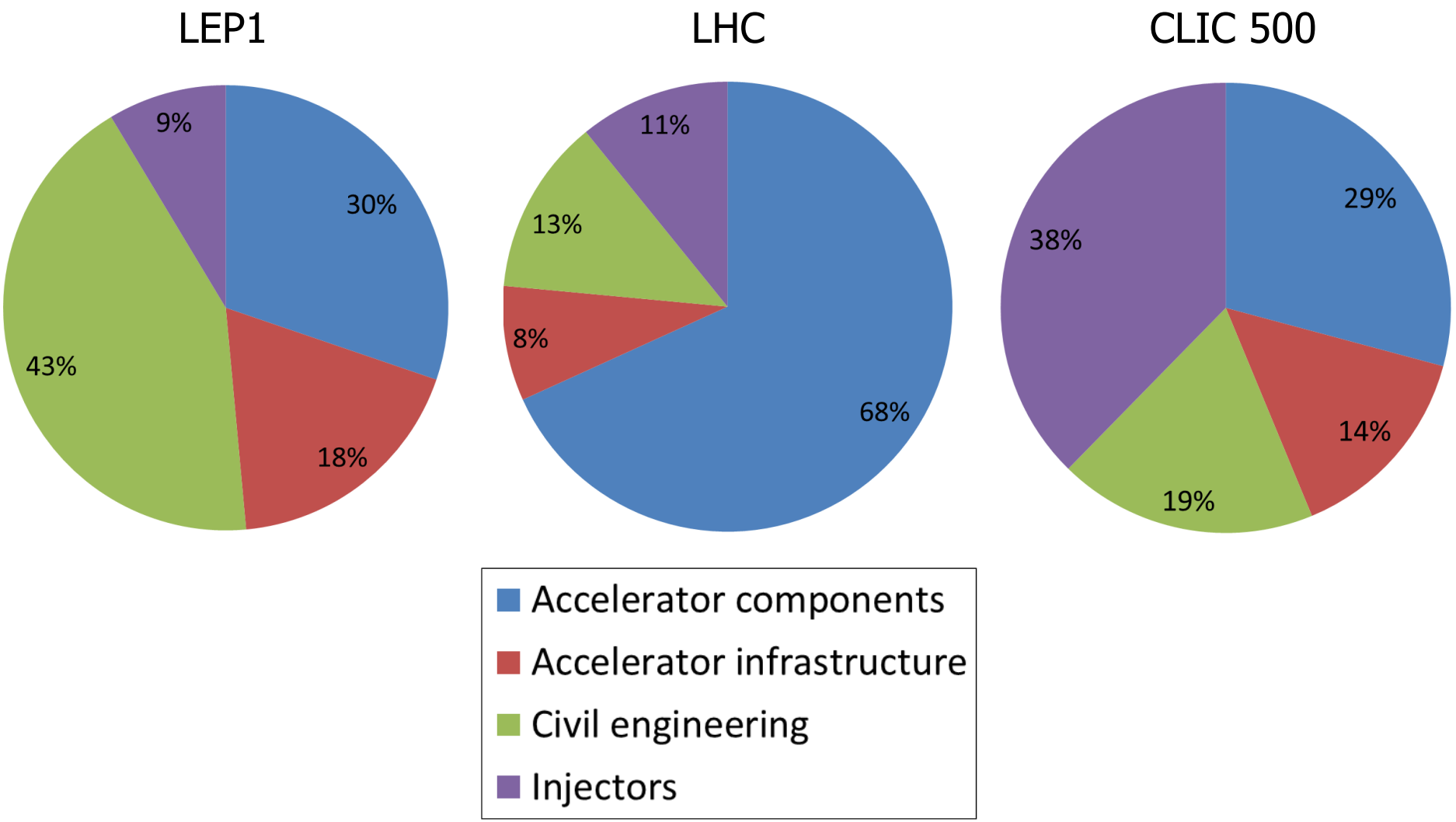
Unconventional issues in conventional facilities for very large circular colliders

Philippe Lebrun
CERN

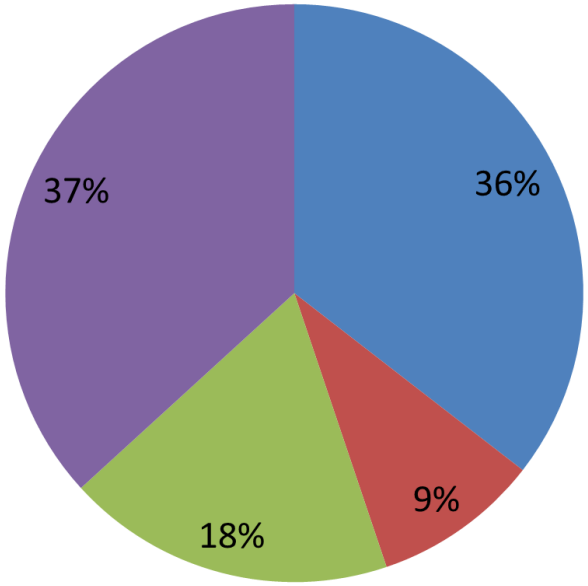
FCC Study Kick-off Meeting
University of Geneva, 12-15 February 2014

Cost structure of large accelerator projects

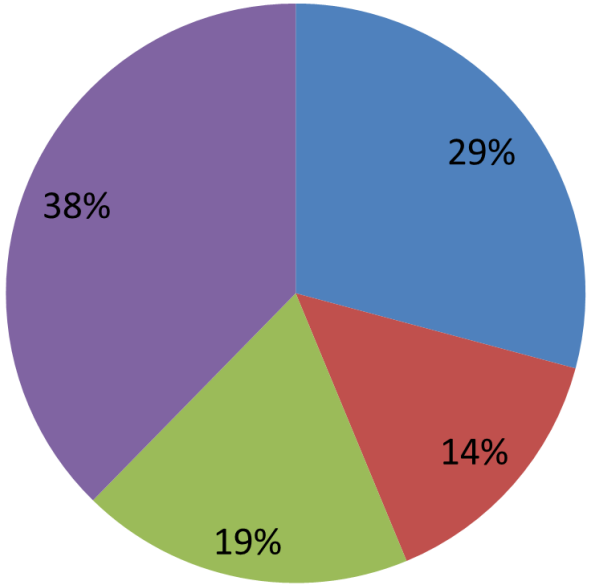


"Green field" cost of large accelerator projects

LHC "green field" (reconstructed)

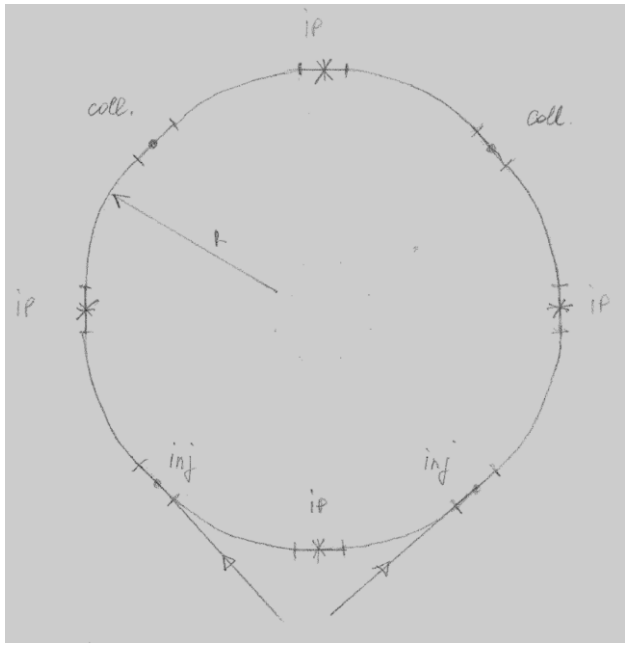


CLIC 500 ≡ "green field"

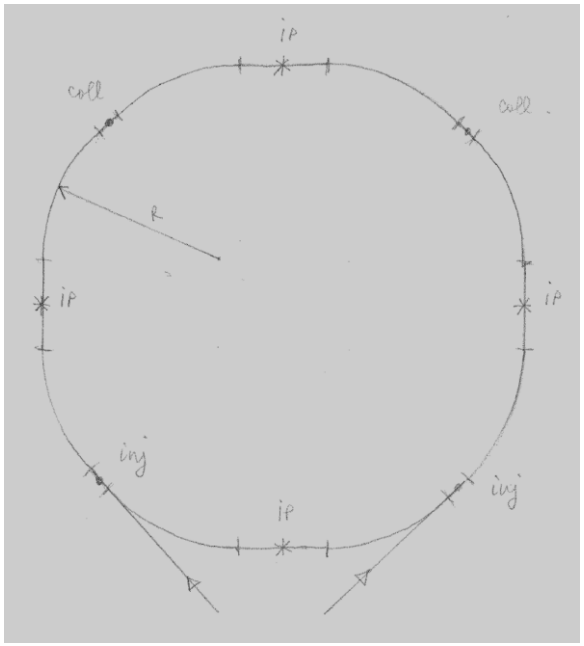


- Accelerator components
- Accelerator infrastructure
- Civil engineering
- Injectors

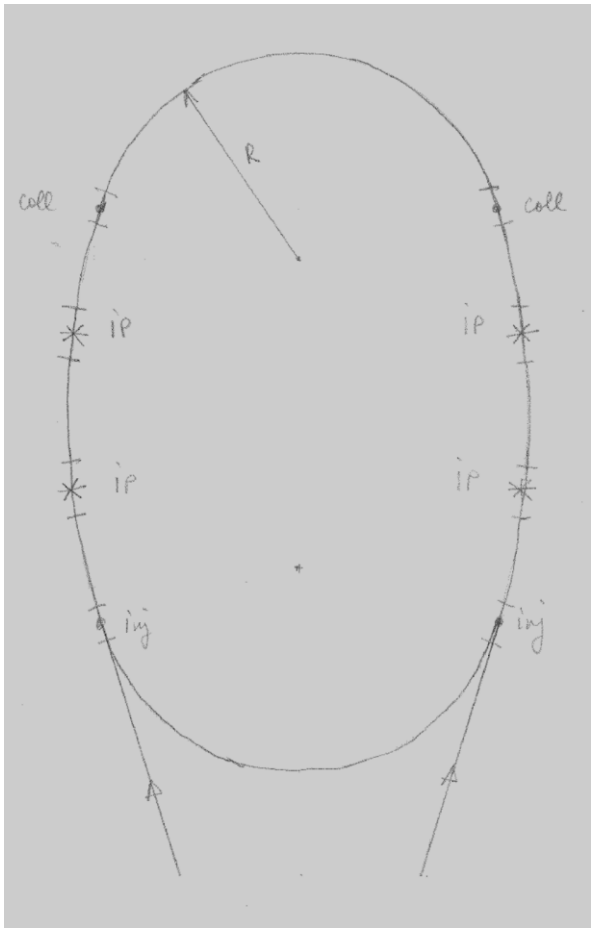
Basic footprint



"Quasi-circular" (LEP/LHC)
8^{th} (12^{th}) order symmetry
8 (12) equal arcs
8 (12) equal LSS

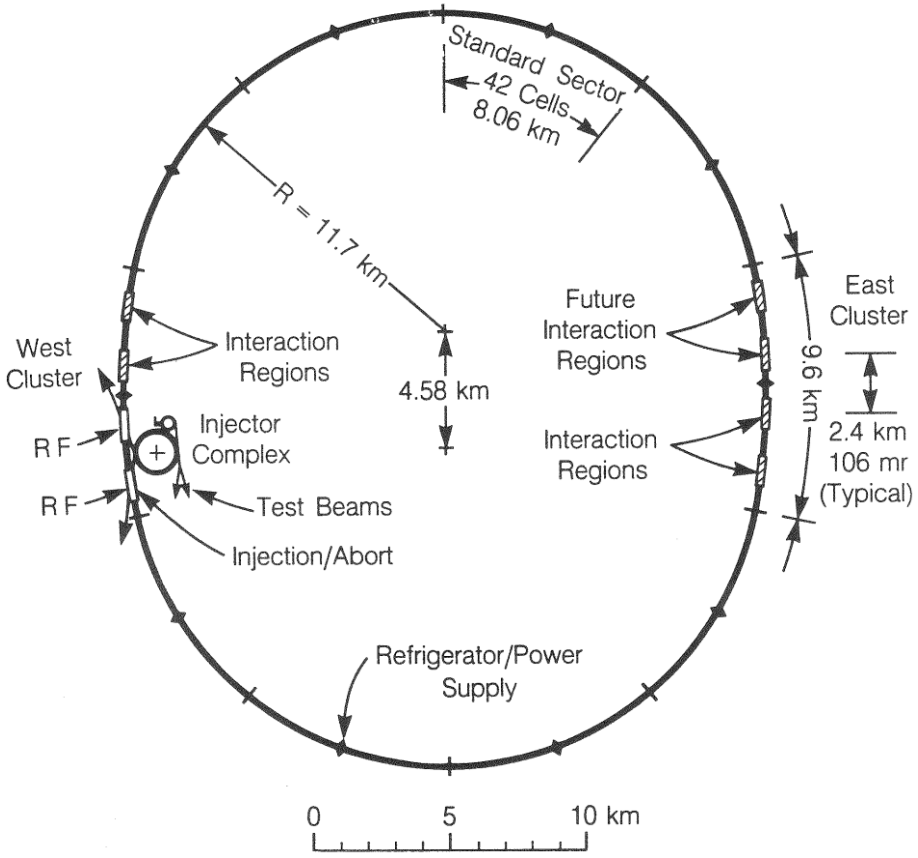


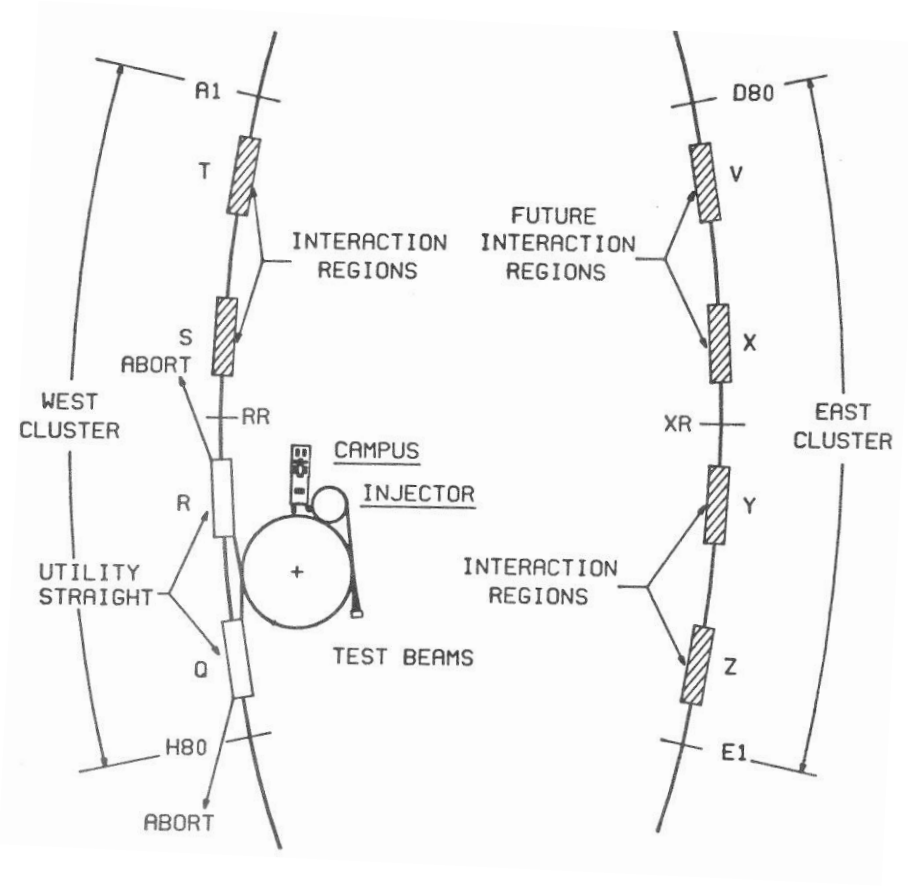
Modified "quasi-circular"
4^{th} order symmetry
8 (12) equal arcs
4 long LSS
4 (8) short LSS



"Quasi-racetrack" (SSC)
2^{nd} order symmetry
2 equal arcs

A 83 km circular collider: the SSC





Evenly distributed vs clustered IRs
From SSC Design report

Evenly distributed

- Higher superperiodicity i.e. fewer resonances in tune space
- Chromaticity accumulates in IRs, reset in neighbouring arcs
- Smaller beam energy sawtoothing for TLEP (even compensation of synchrotron losses around ring)

Clustered

- Superperiodicity broken in large SC machines anyway (magnetic field & alignment errors)
- Optimal use of LSS length leading to higher overall filling factor
- Economy in CE and infrastructure
- Better access for servicing

Beam scraping/ collimation necessary on either side of IPs anyway

Machine perimeter

- **Perimeter**

$$\Pi = 2\pi R/f + N_{exp}\, L_{exp} + N_{tech}\, L_{tech}$$

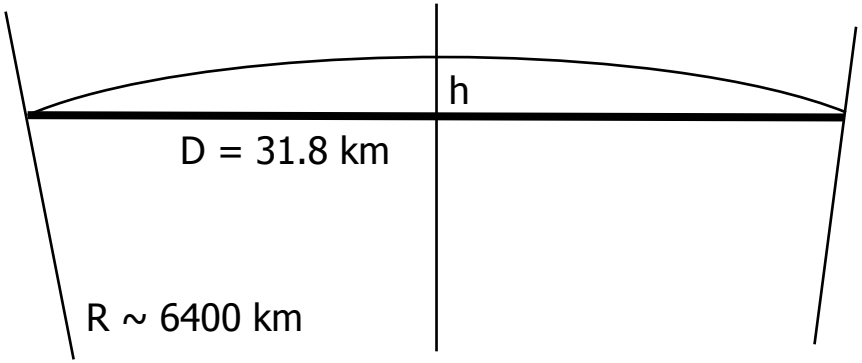
  - R bending radius
  - f arc filling factor
  - N_{exp} number of experiment LSS
  - L_{exp} length of experiment LSS
  - N_{tech} number of technical LSS
  - L_{tech} length of technical LSS

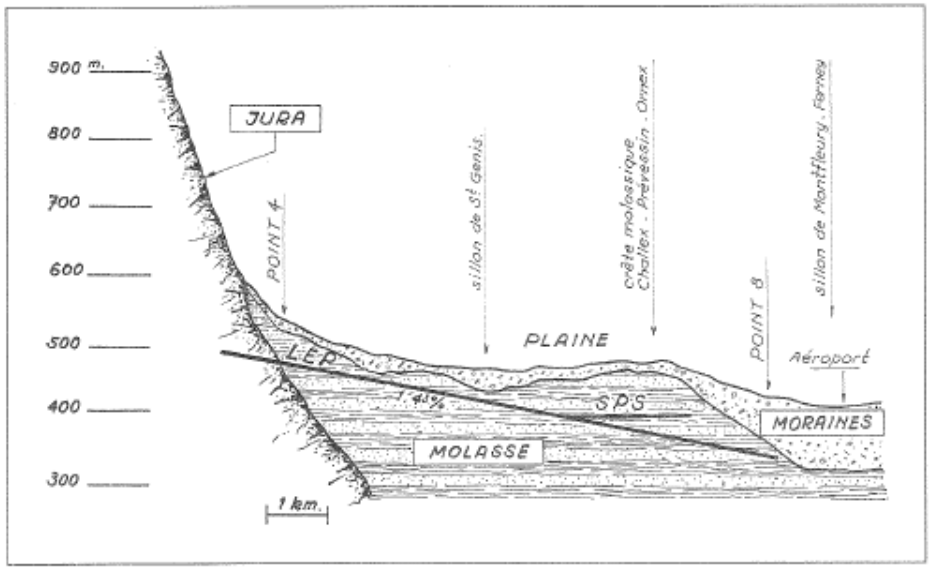
- Minimize machine perimeter to limit
  - Cost
  - Beam stored energy (for given current/luminosity)
  - Beam impedance

Sensitive parameters other than bending field

- **Arc filling factor**
  - E [TeV] ~ 0.3 B [T] R [km]
  - Hence dB/B ~ - df/f
  - Increasing f by 5 % is equivalent to reducing B by 5 %, i.e. 1 T at 20 T
- **Long straight sections**
  - Consider 100 km machine with 12 LSS of 2 km each, f = 0.8
  - $2\pi R/f$ = 76 km and R = 9.7 km
  - Consider 100 km machine with 8 LSS of 2 km each, f = 0.8
  - $2\pi R/f$ = 84 km and R = 10.7 km
  - dR/R = -dB/B ~ -10 %, i.e. 2 T at 20 T

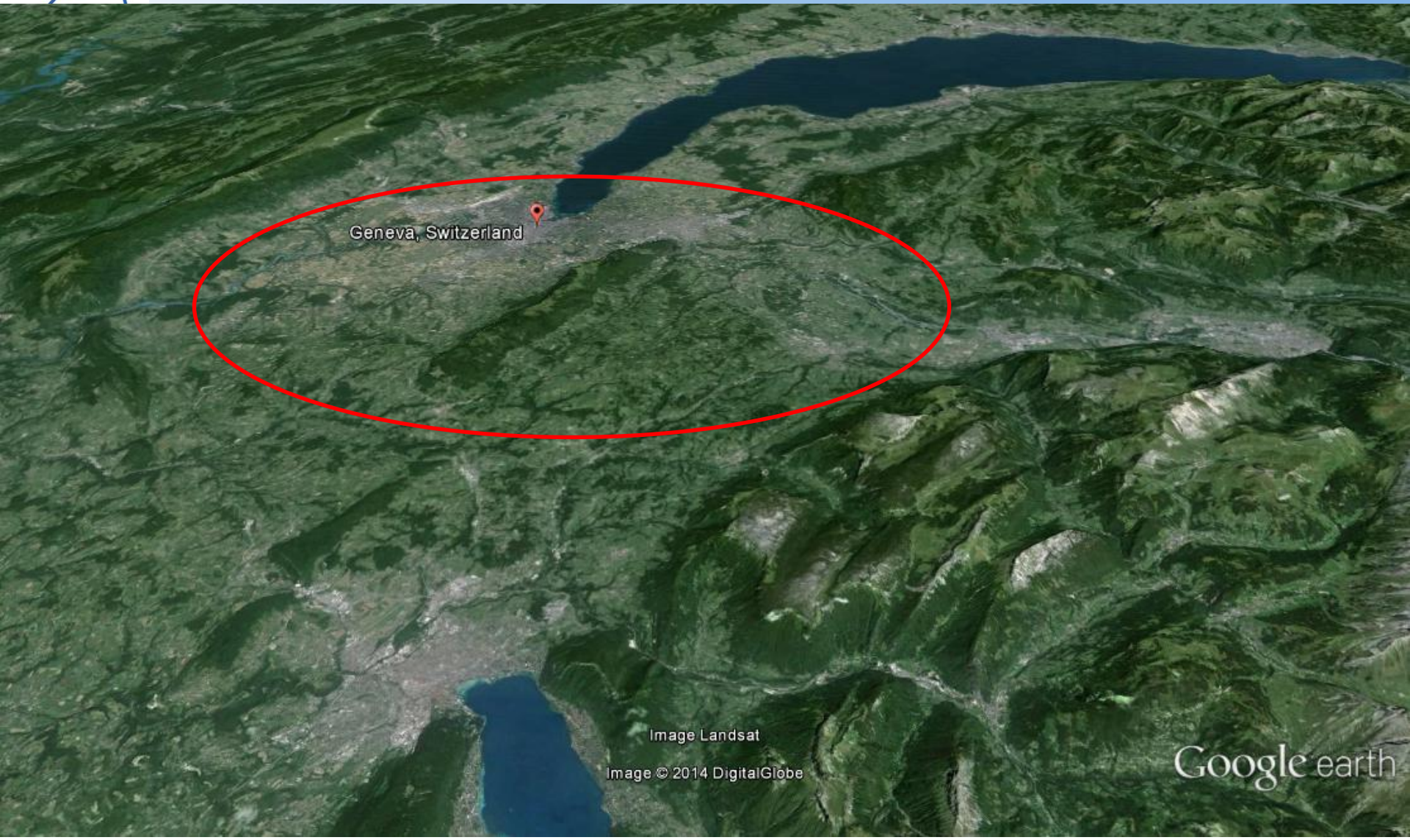
Tunnel orientation and planarity





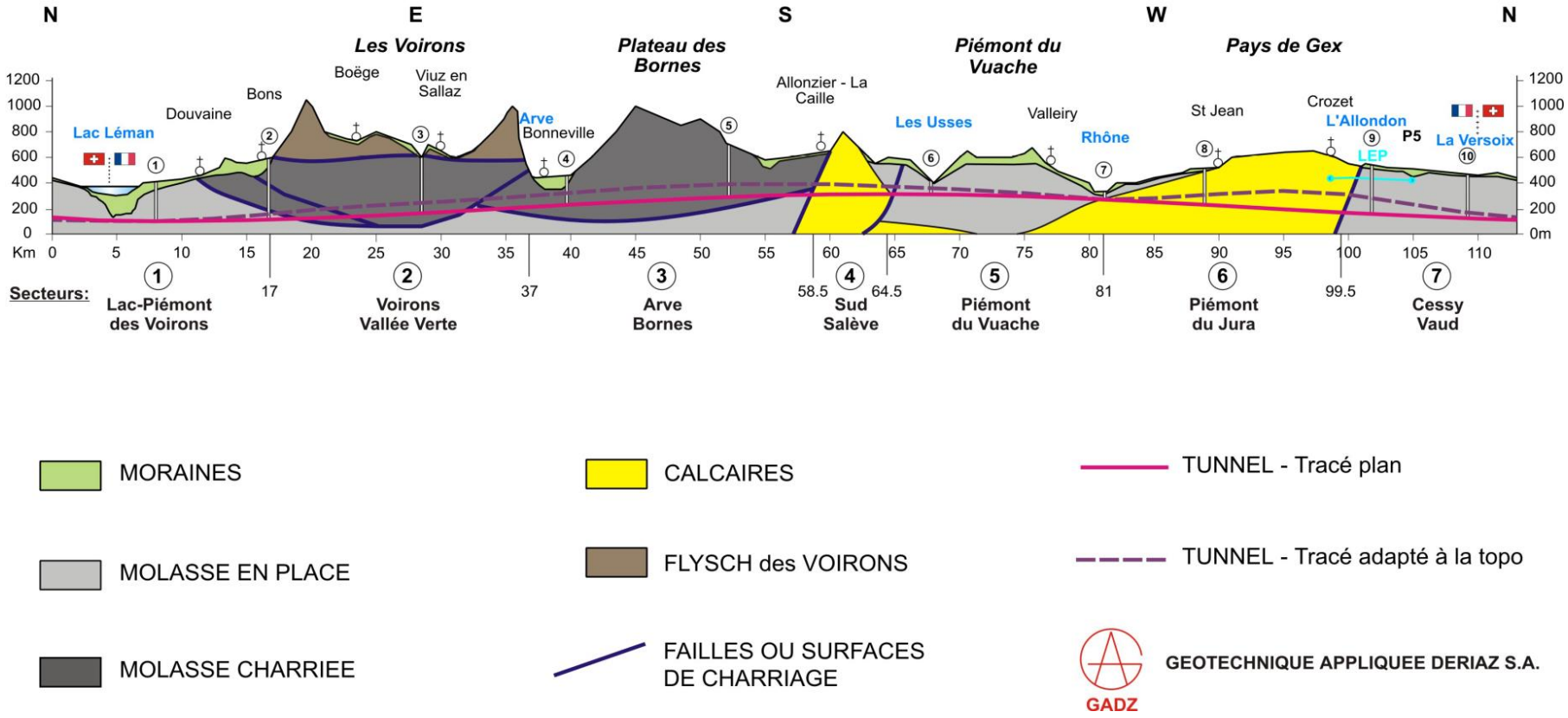
- A "horizontal" tunnel?
  - Earth ~ sphere / ellipsoid
  - D = 100/π = 31.8 km
  - h ~ 20 m
  - Deviation of vertical ~ 0.28 deg
- A tunnel on a sloping plane?
  - Solution retained for LEP/LHC
  - Elevation difference for FCC is 320 m per % slope
- A non-planar tunnel?
  - To limit overburden and depth of shafts
  - Dihedral (SSC)
  - Terrain-following

Getting closer to the Alps



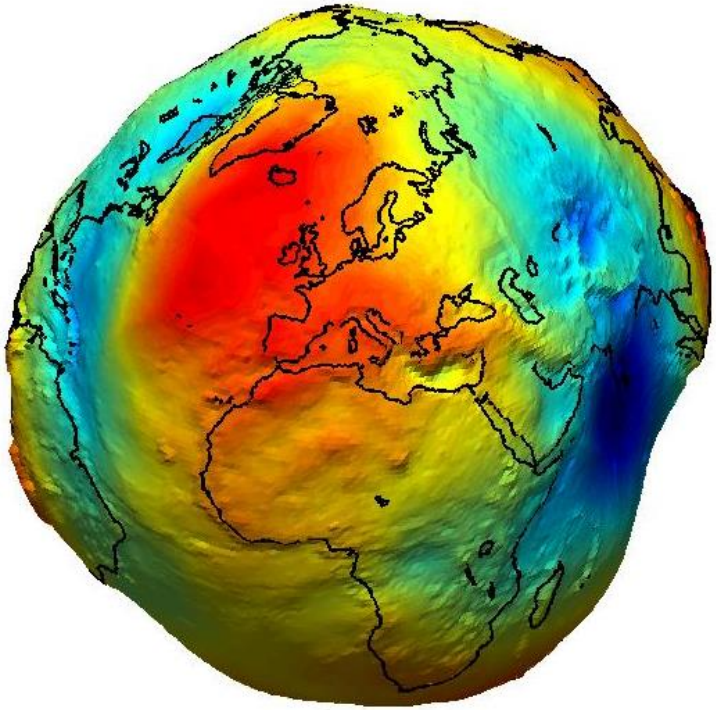
Tunnel geology
Depart from current wisdom of "staying in Molasse"

See forthcoming presentation by J. Osborne

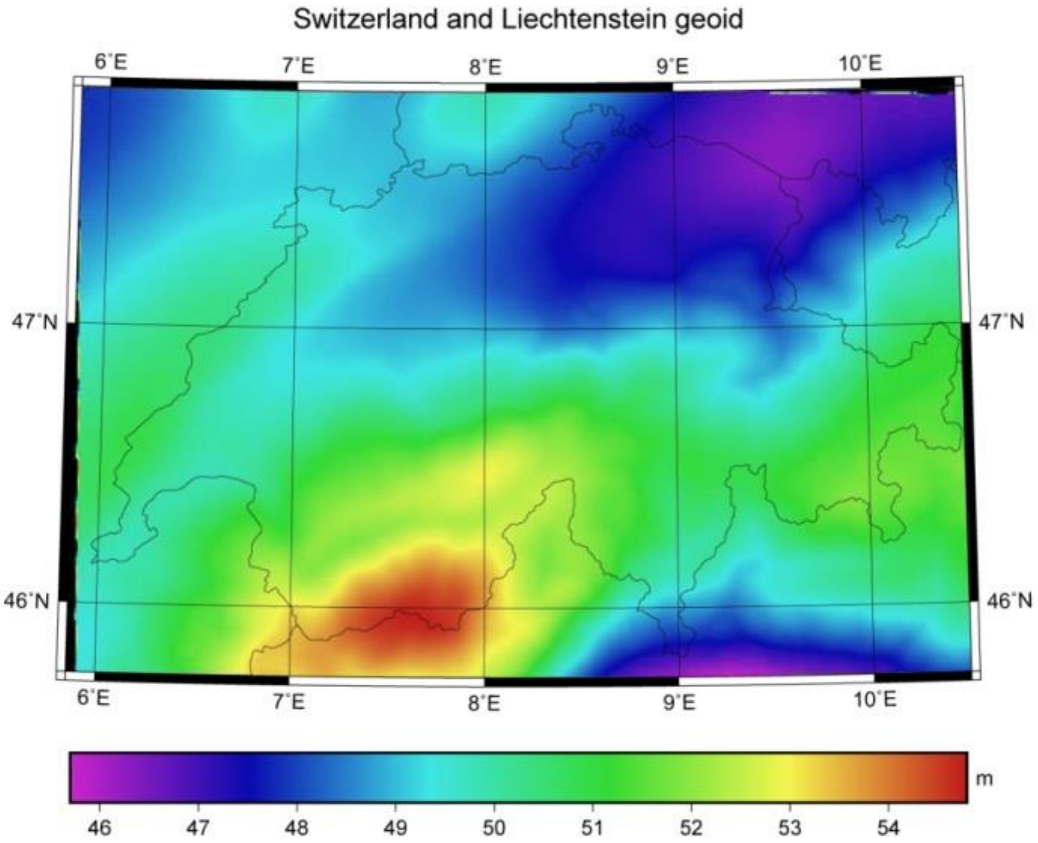


The Earth is neither a sphere nor an ellipsoid

The geoid from GOCE satellite's observations

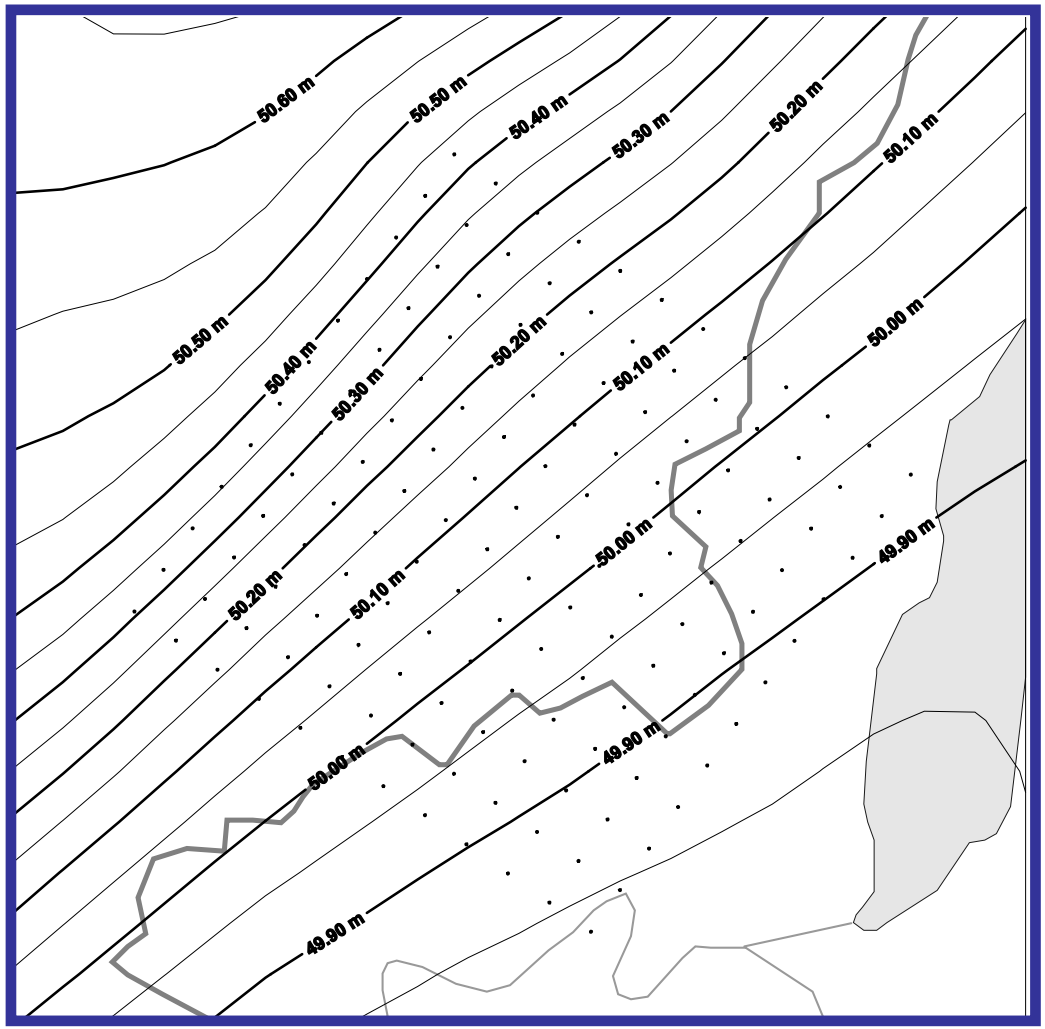


The geoid in Switzerland (CHGEO98)

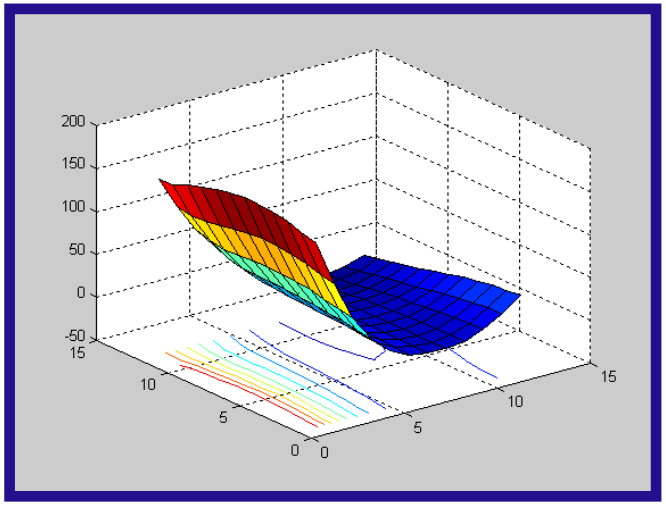


Elevation above the reference ellipsoid

Local models of the geoid
Will need to be extended towards the Alps

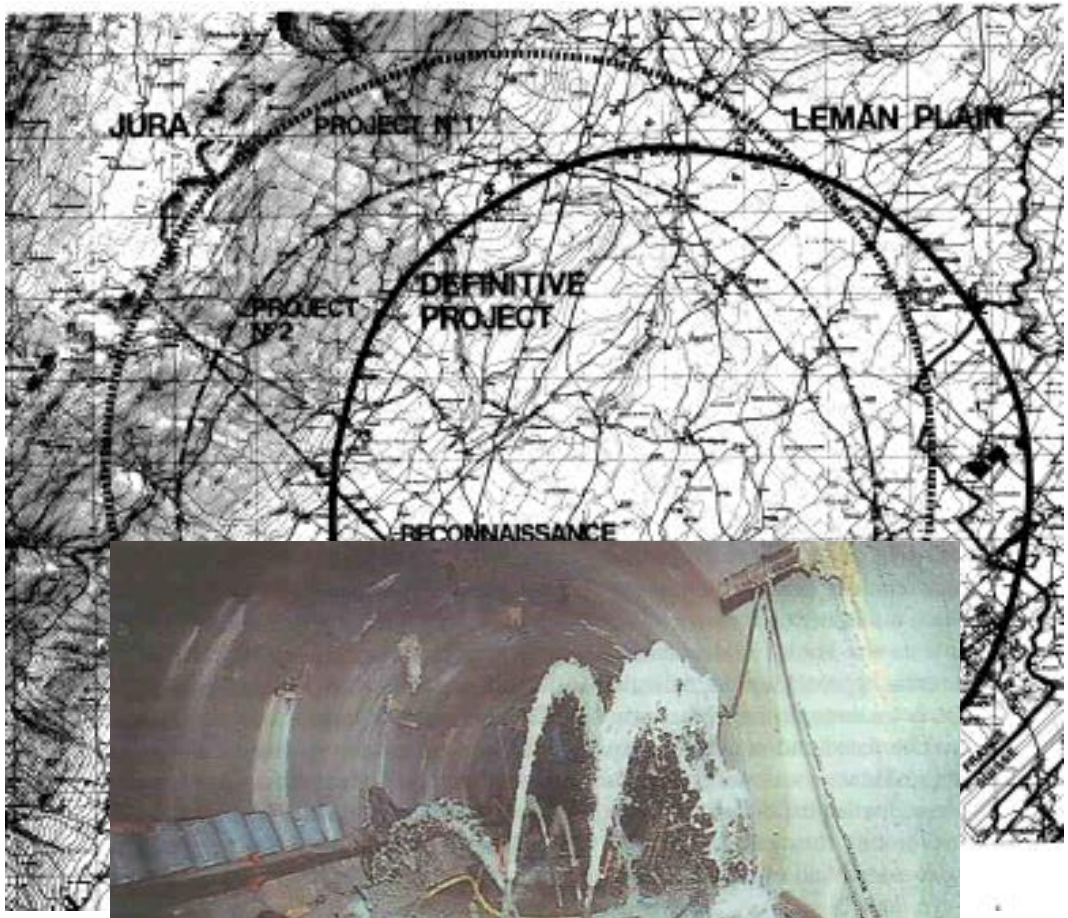


CHGEO98: cotes rapportées à l'ellipsoïde

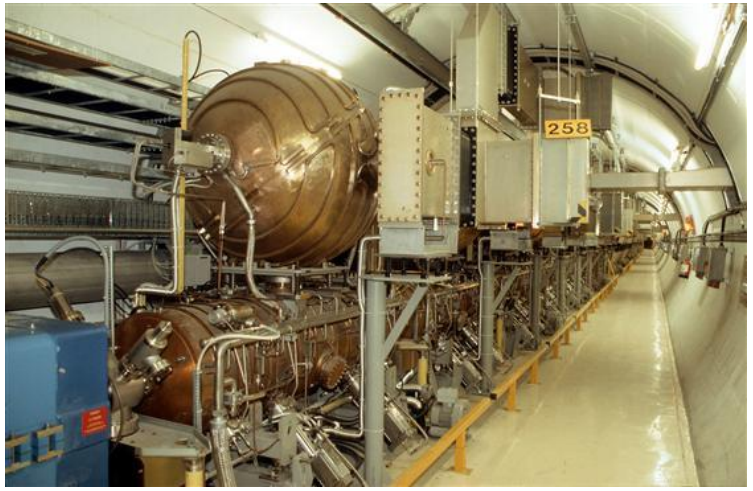


CERN Geoïde 2000

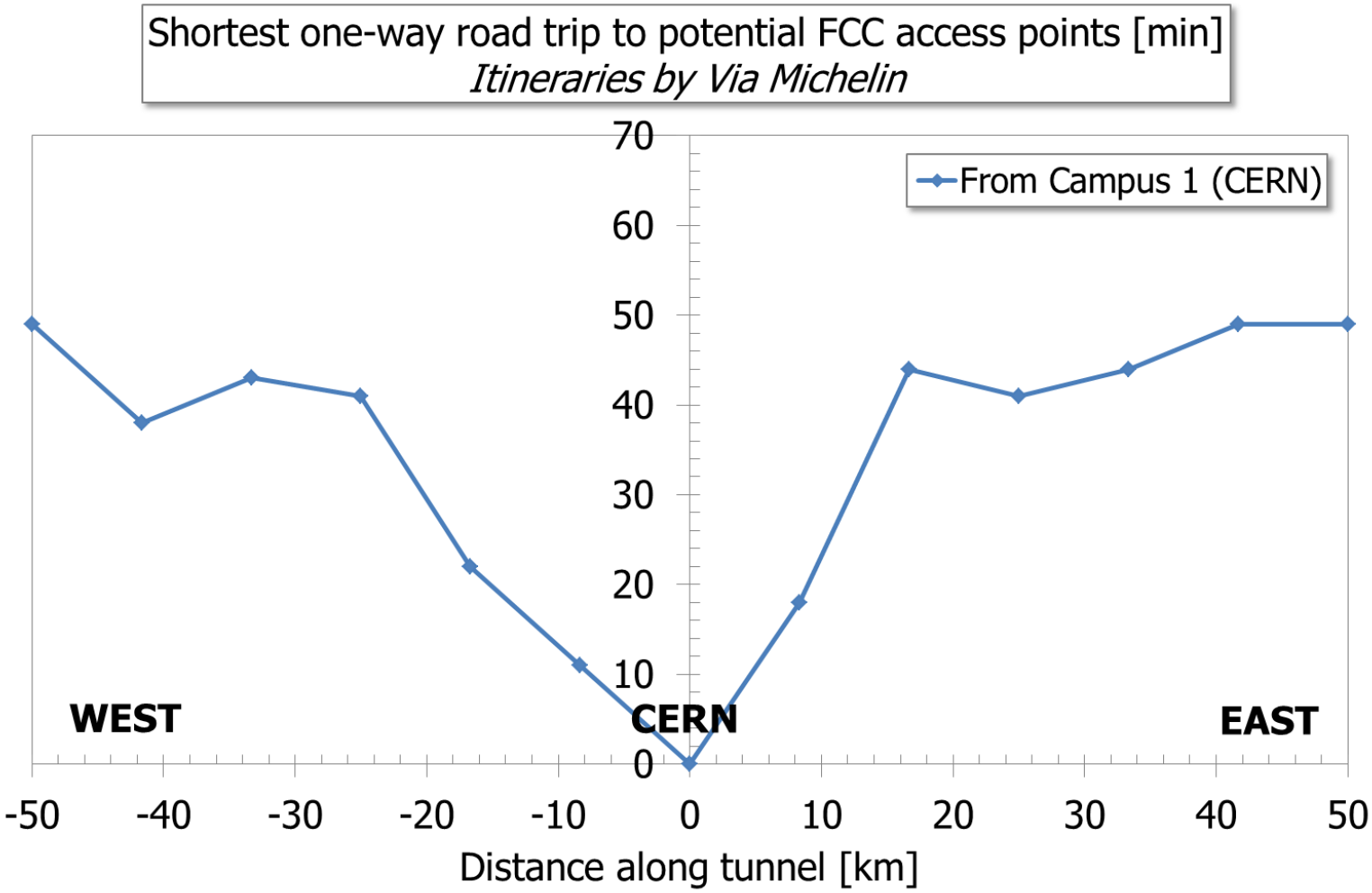
Site/size optimization: the case of LEP



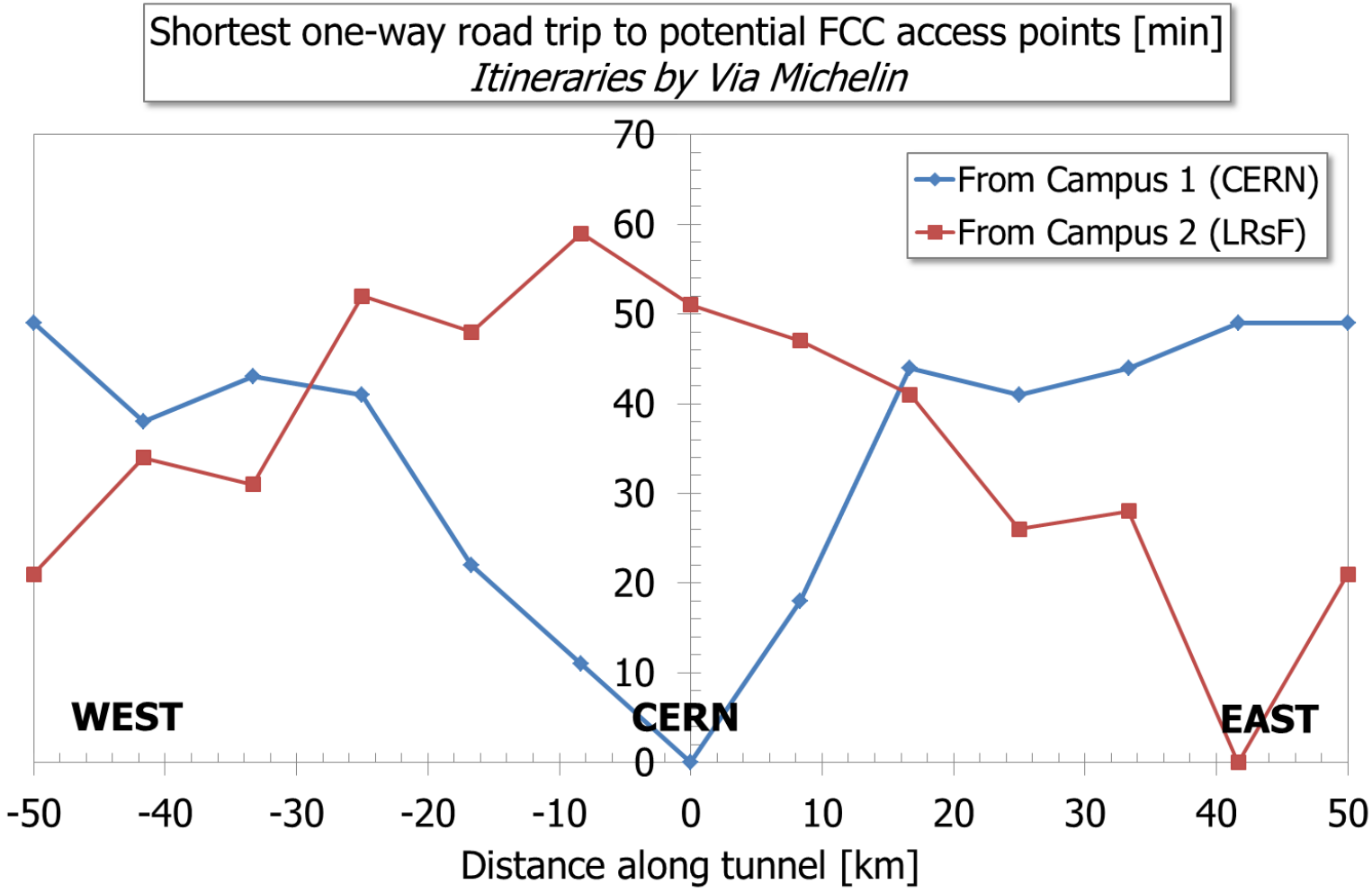
- **Geology**: stay out of Trias
- **Hydrology**: preserve springs at piedmont of Jura
- **Geotechnical**: maximize tunnel in "molasse" (1.41 % slope)
- **Topography**: limit overburden
- **Neighbourhood**: integration of surface buildings, noise, road traffic
- **Cost**
- **Performance**: trade-off CE vs accelerator technology



Access for servicing from CERN main campus

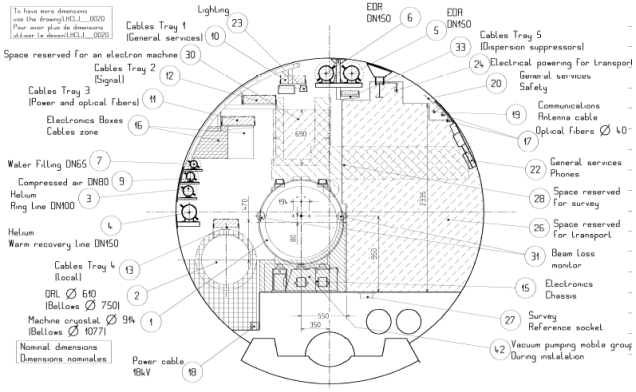


A second campus?



Tunnel cross-section
Accelerator components only

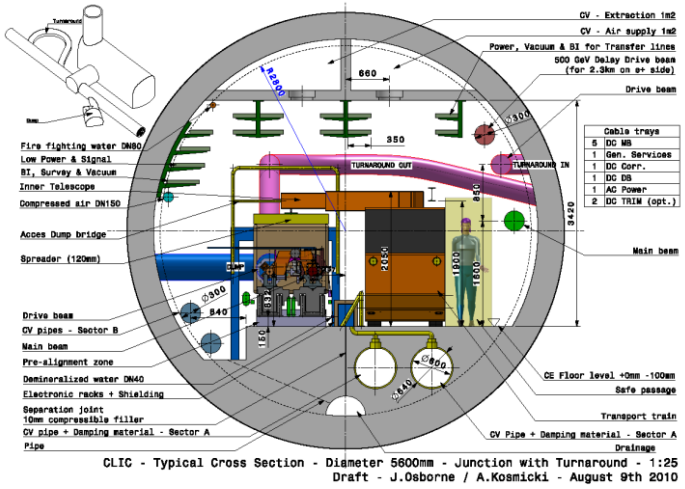
LEP/LHC



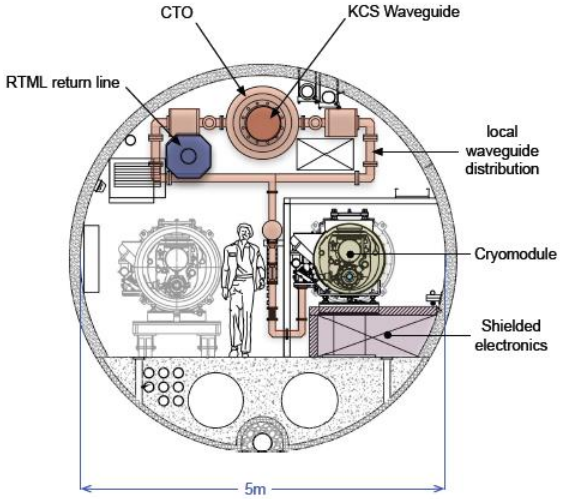
All tunnels drawn at same scale

2 m

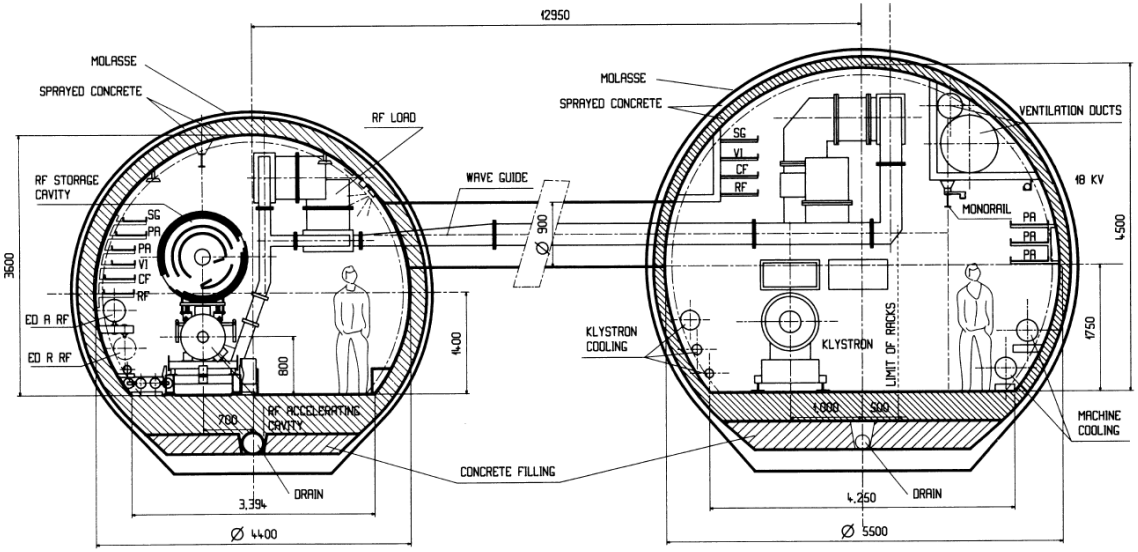
CLIC



ILC "klystron cluster"



Tunnel cross-section
Accelerator components & technical systems

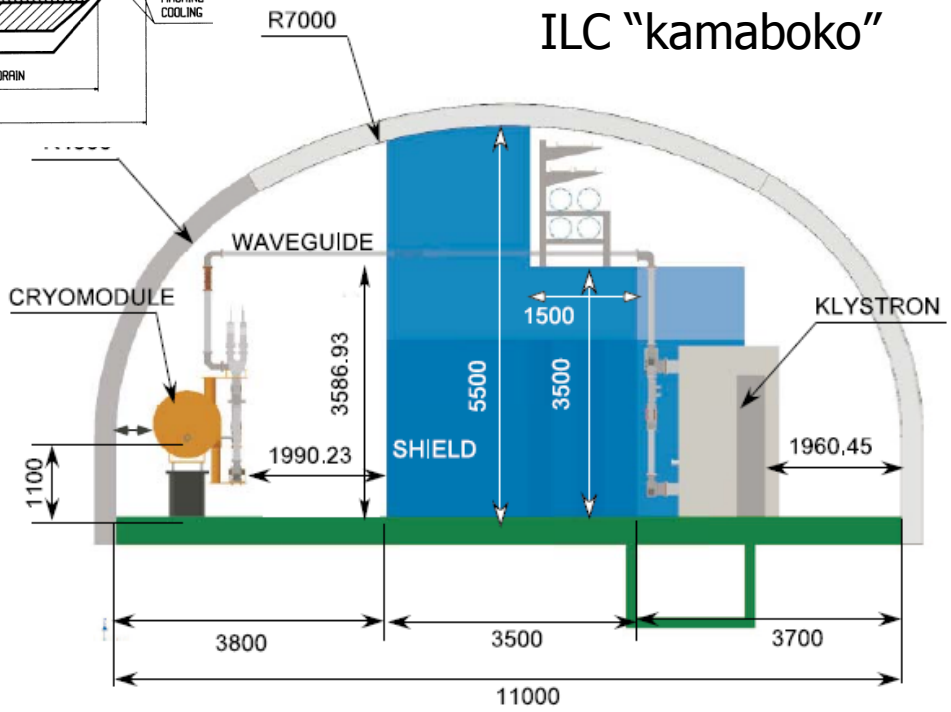


LEP

All tunnels drawn at same scale

2 m

ILC "kamaboko"

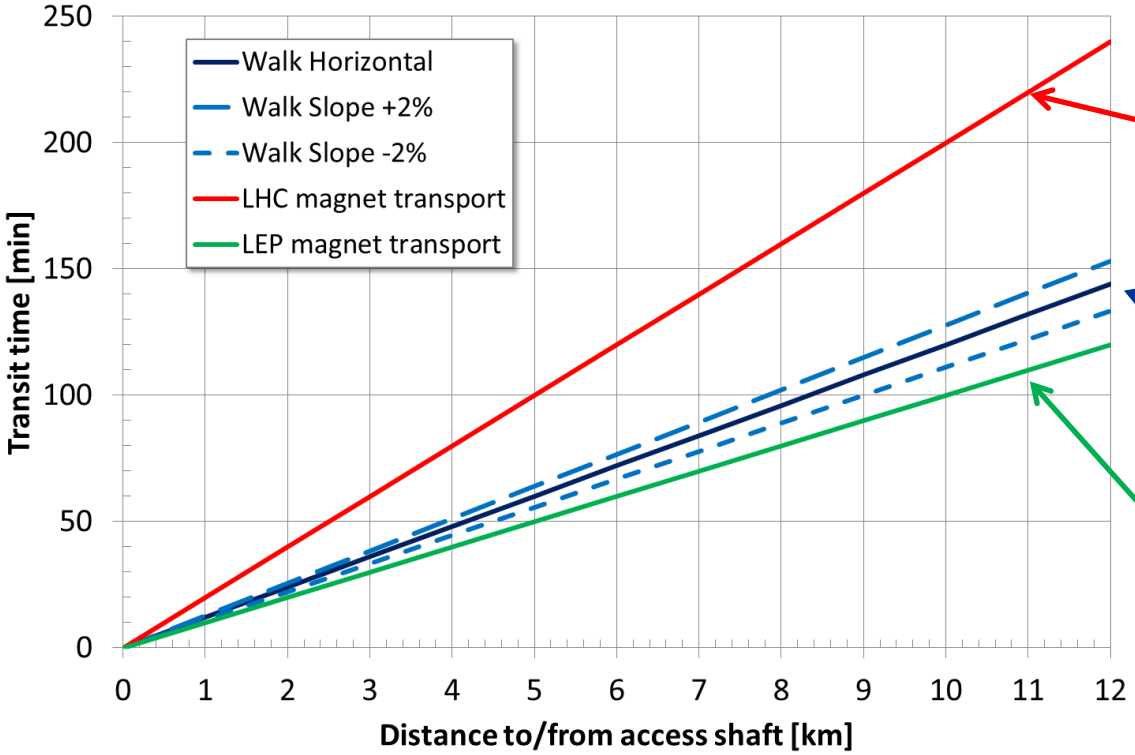


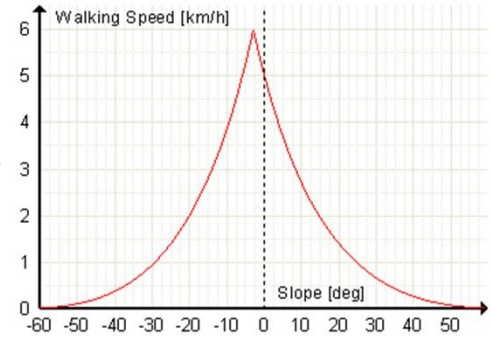
Need for a technical service tunnel?
Need for a safety tunnel?

Sector length
A multi-criteria discussion

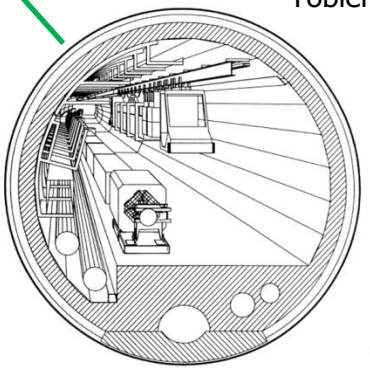
- Access, egress and personnel safety
- Equipment transport
- Installation rates
- Ventilation
- Electrical distribution
- Cryogenics *See forthcoming presentation by L. Tavian*
  - Cryoplant unit size
  - Distribution lines
- Stored energy in magnets
- Inductance of magnet chains and maximum voltage to ground

Sector length
Access, egress and transport

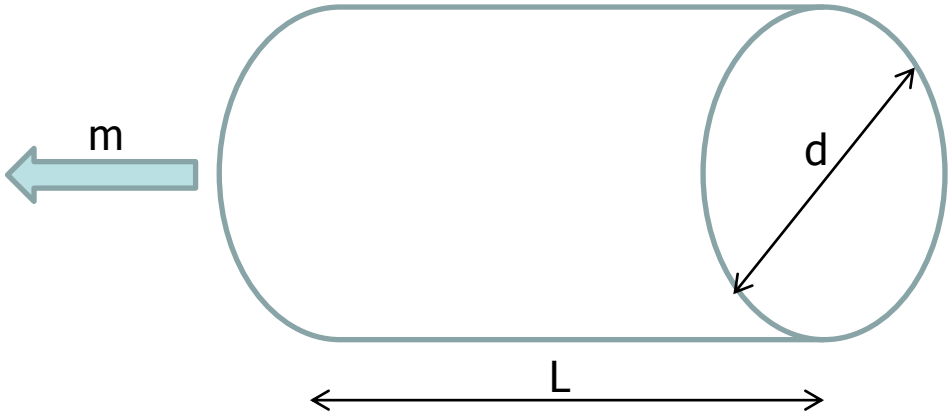




Tobler's hiking function



Sector length
Piped utilities



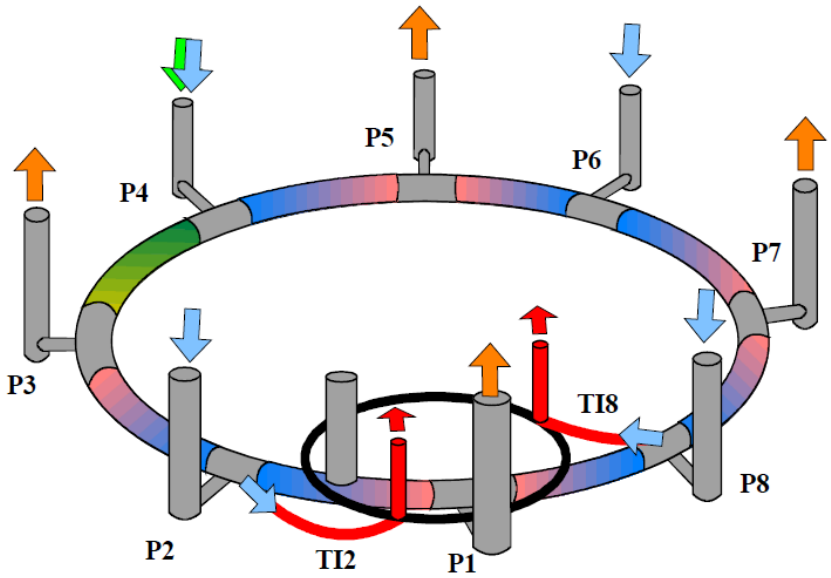
- Mass flow-rate m for feeding a sector of length L
  - At constant linear load, $m \sim L$
- Pressure drop
  - At given fluid density, $\Delta P \sim m^2 L/d^5 \sim L^3/d^5$
  - For fixed ΔP, $d \sim L^{3/5}$
- Mechanical power for circulation
  - $W \sim m \Delta P \sim L^4/d^5$

$\Rightarrow$ *Strong dependence on sector length, unless larger pipe diameters are used*

A case in tunnel safety: the ventilation scheme

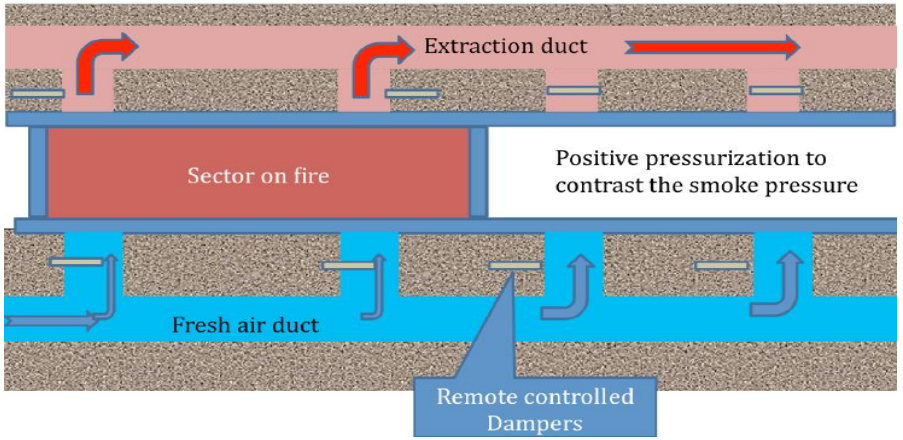
Longitudinal

- Tunnel is the air duct
- Safety not guaranteed downstream of danger area

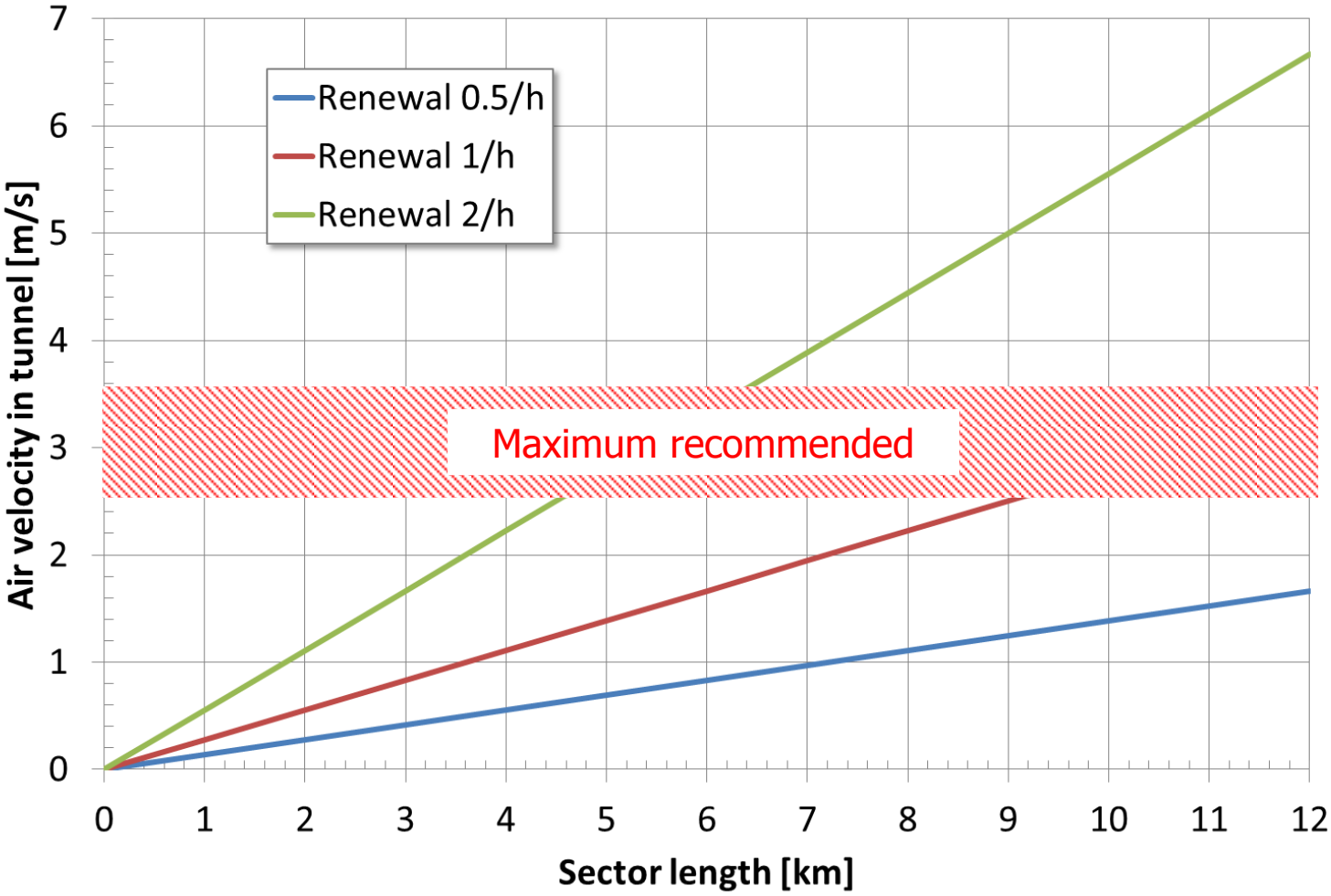


Transverse

- Need fresh-air & extraction ducts in tunnel (larger X-section)
- Danger area can be segmented



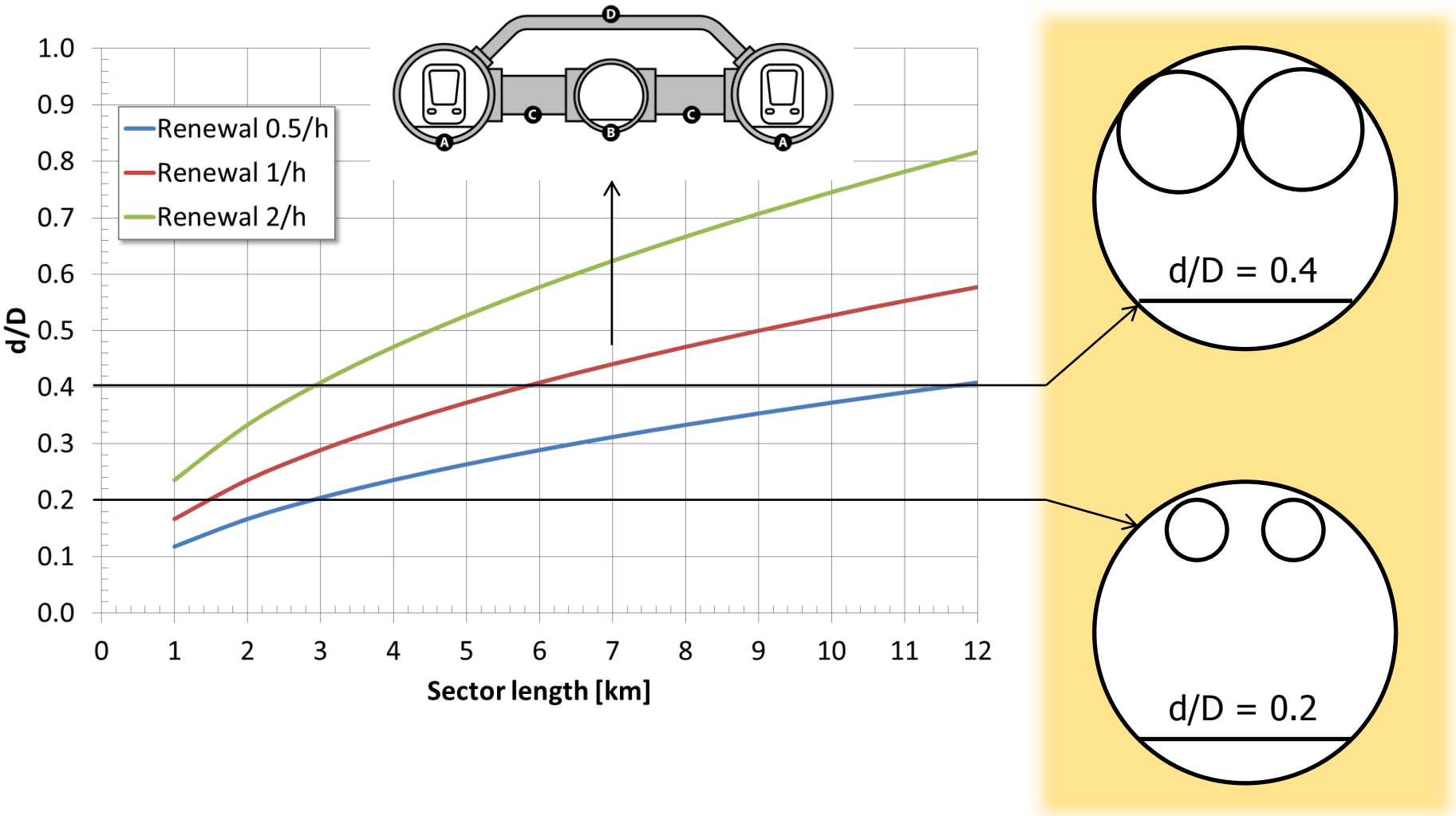
Sector length
Air velocity in longitudinal ventilation



Longitudinal ventilation of long sectors requires excessive air velocities

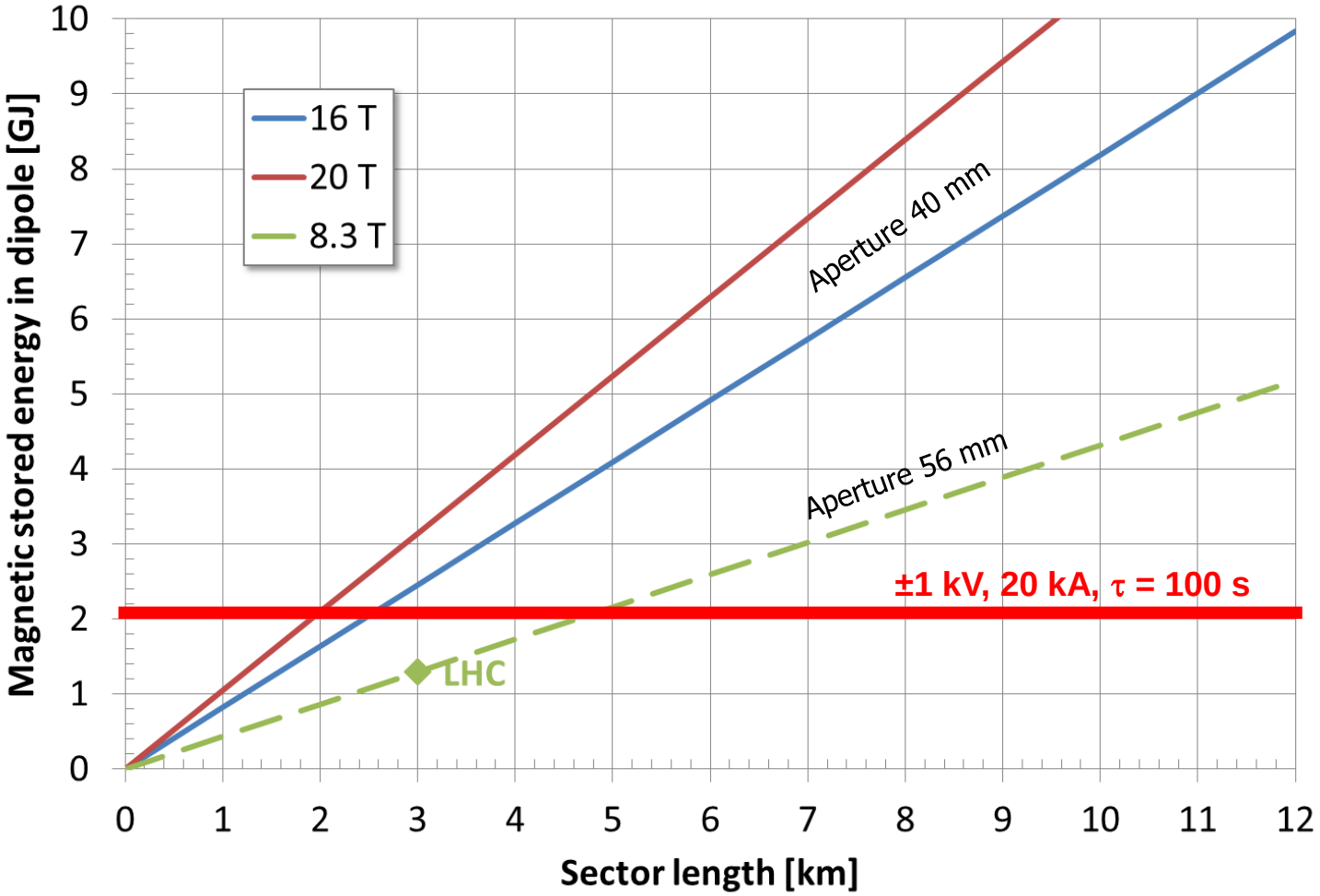
Sector length

Ratio of ventilation duct to tunnel diameter in transverse ventilation (v_{duct} = 10 m/s)



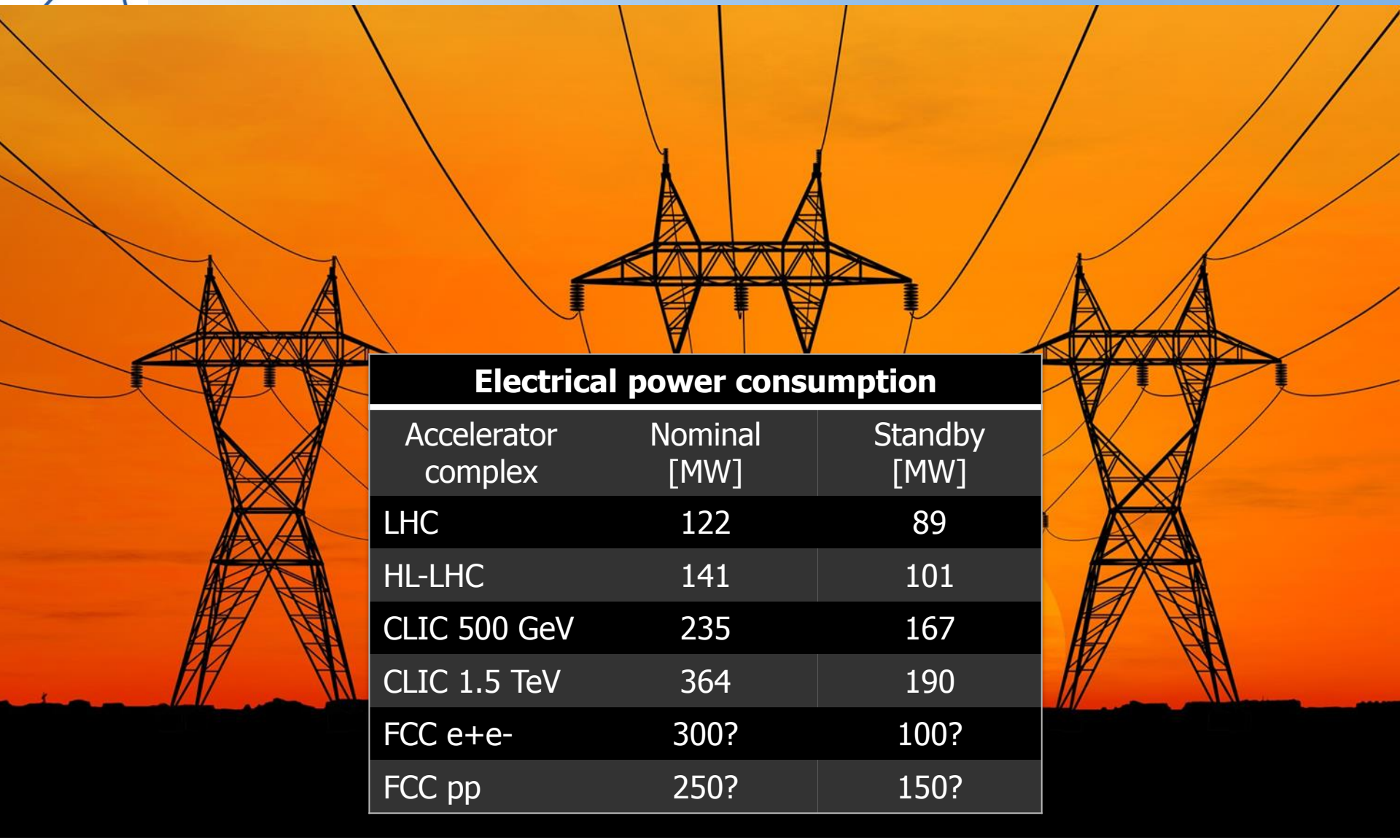
Transverse ventilation of long sectors requires very large ducts → separate ventilation tunnel

Sector length
Stored energy in twin-aperture dipole chain



Stored energy limited by magnet current, voltage withstand and emergency discharge time

Large machines consume electricity…

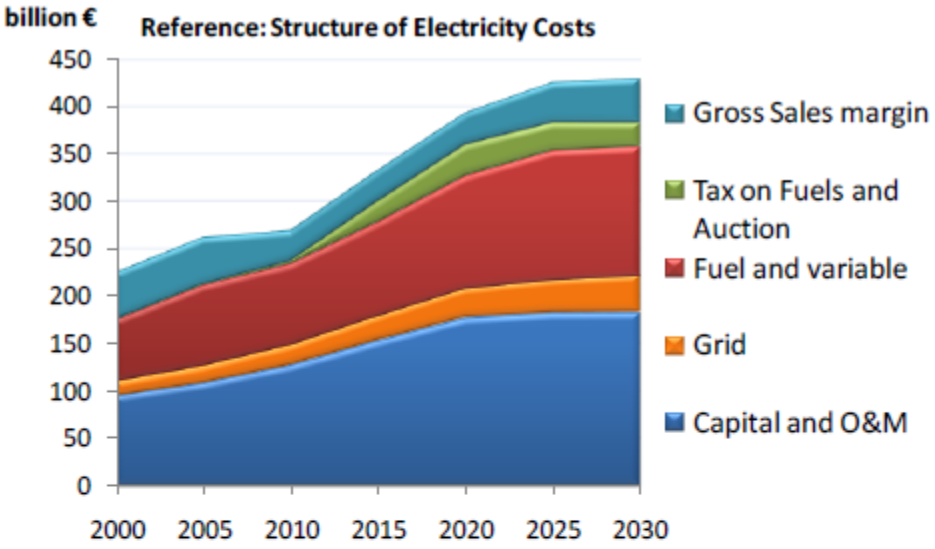


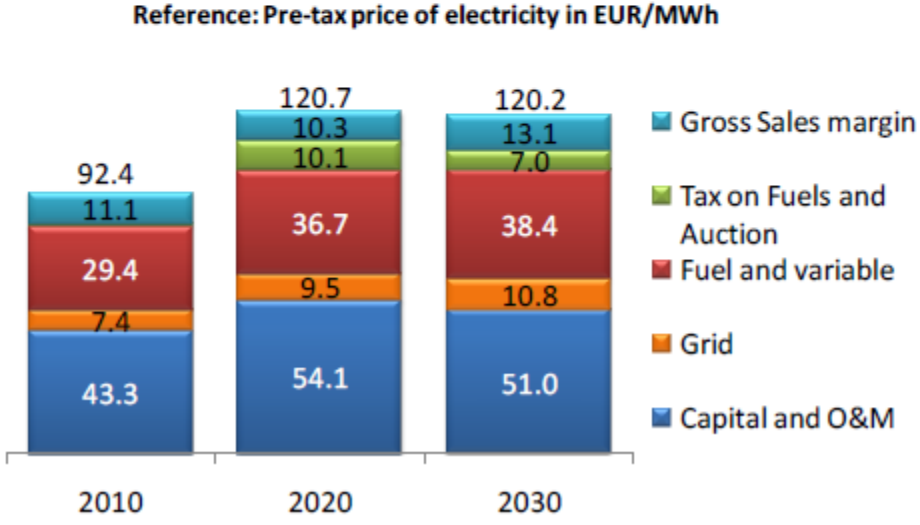
Electrical power consumption		
Accelerator complex	Nominal [MW]	Standby [MW]
LHC	122	89
HL-LHC	141	101
CLIC 500 GeV	235	167
CLIC 1.5 TeV	364	190
FCC e+e-	300?	100?
FCC pp	250?	150?

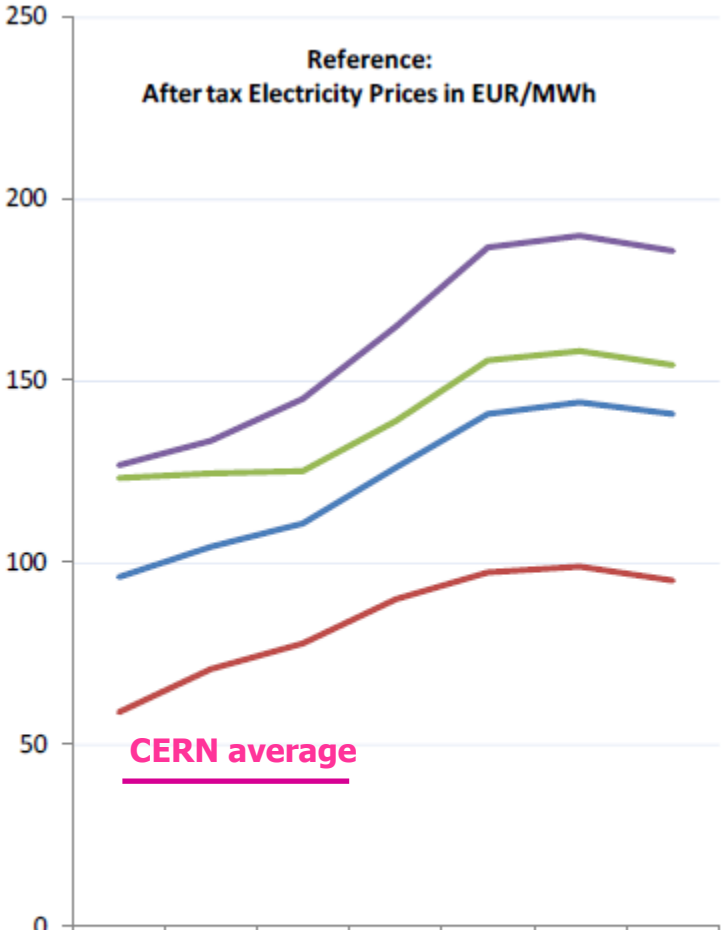
… the price of which will increase

European Commission, Directorate-General for Energy

EU energy trends to 2030, Reference Scenario 2010

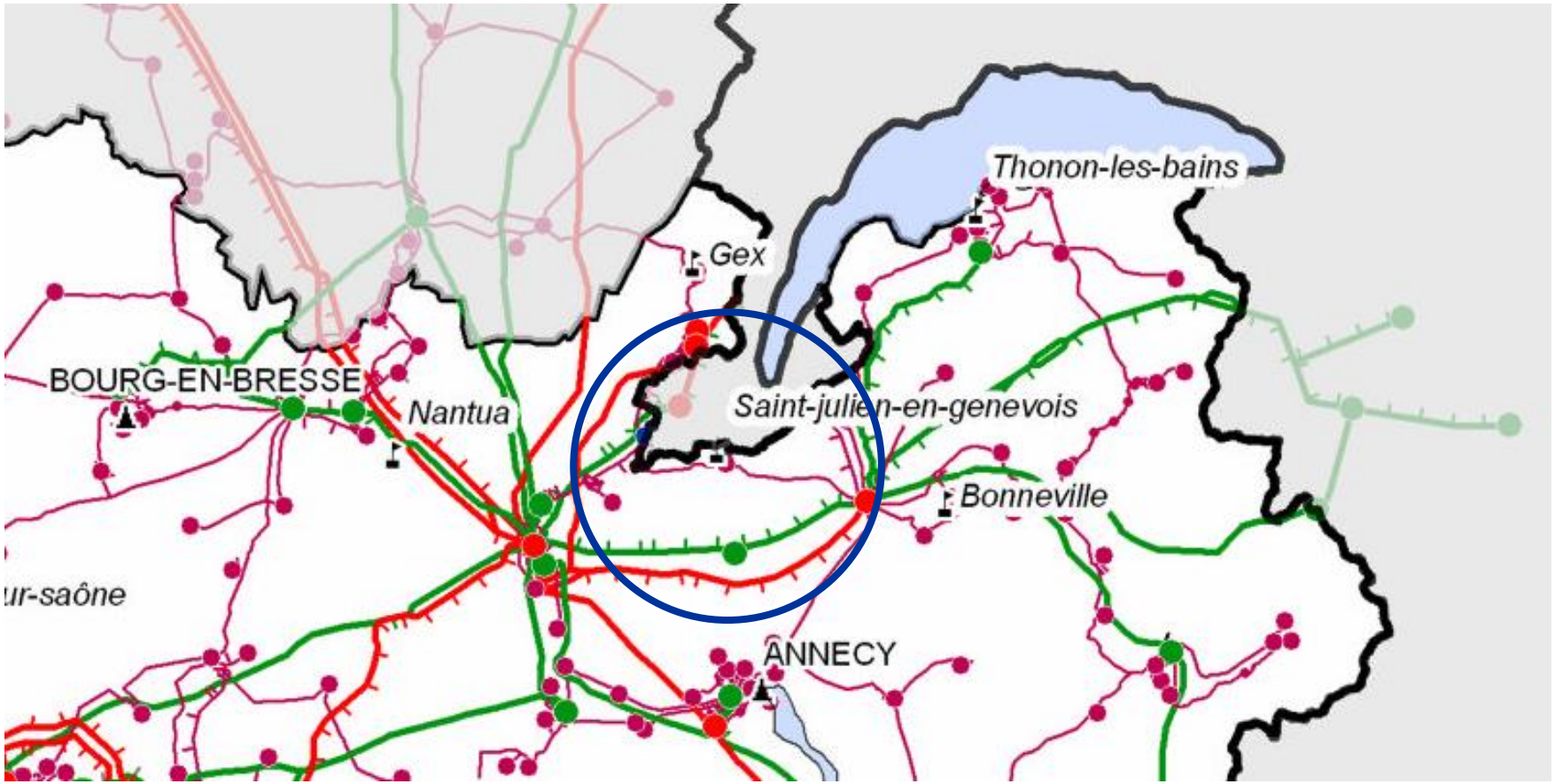






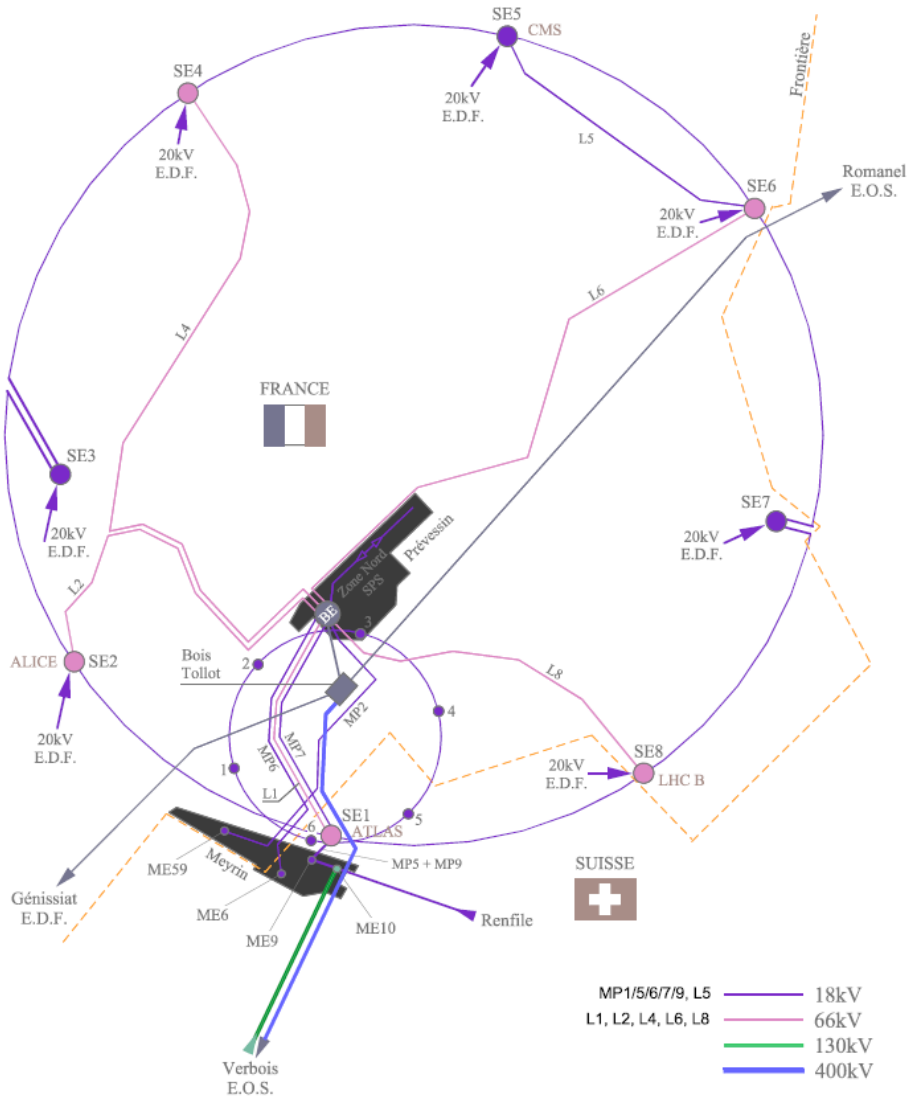
	2000	2005	2010	2015	2020	2025	2030
Average	96	104	110	126	141	144	141
Industry	59	71	78	90	97	99	95
Services	123	124	125	139	155	158	154
Households	127	133	145	165	186	190	186

Transport and distribution of electricity
HV lines (Source: RTE)



Transport and distribution of electricity
Cornier substation with 400 kV line

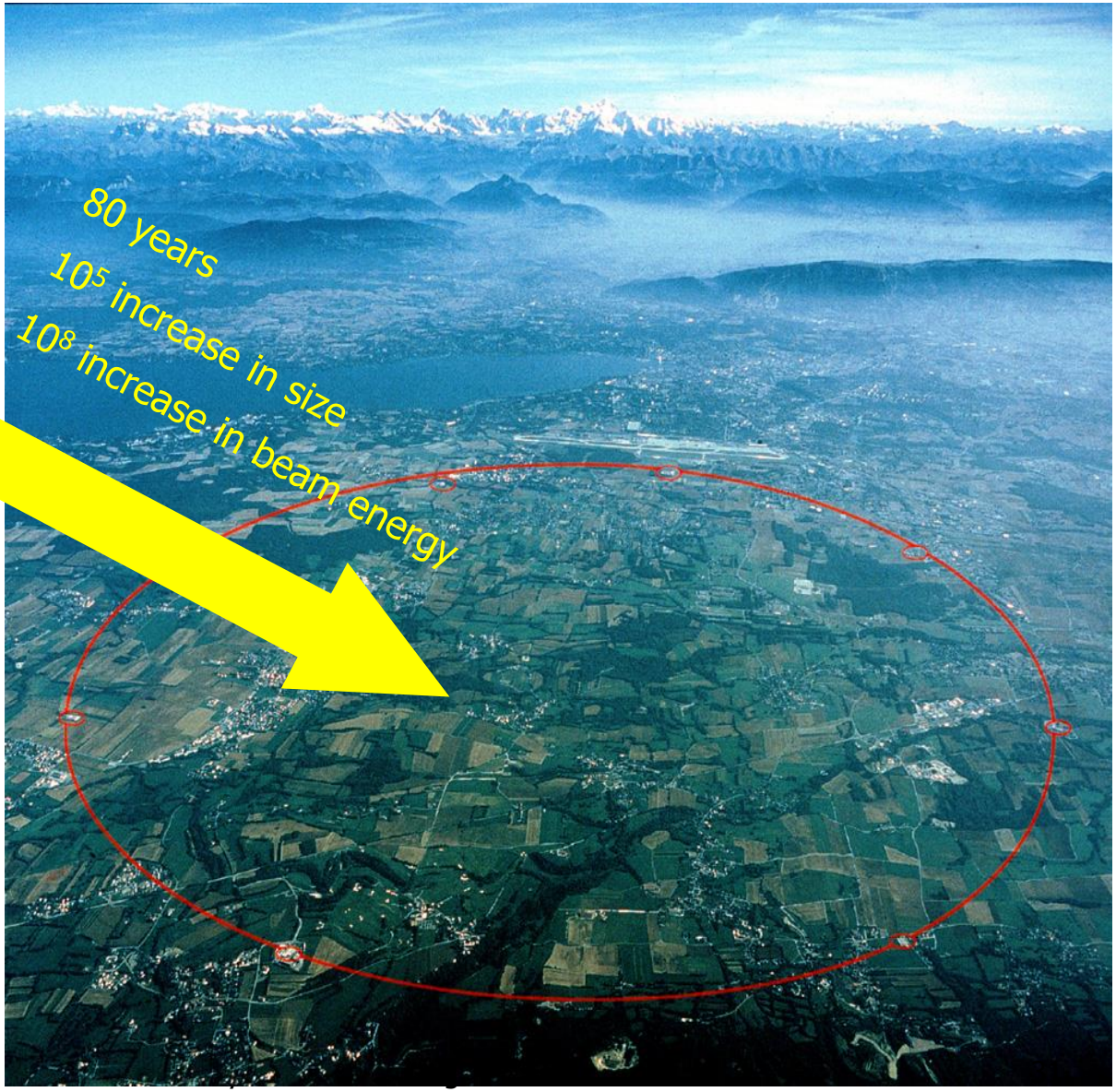
Transport and distribution of electricity
Local networks



- Choice of distribution voltages
- Connection to main substations
- Above ground vs in tunnel
- Network independence & redundancy
- No-break supply

Development of circular accelerators
Growth in performance >> growth in size

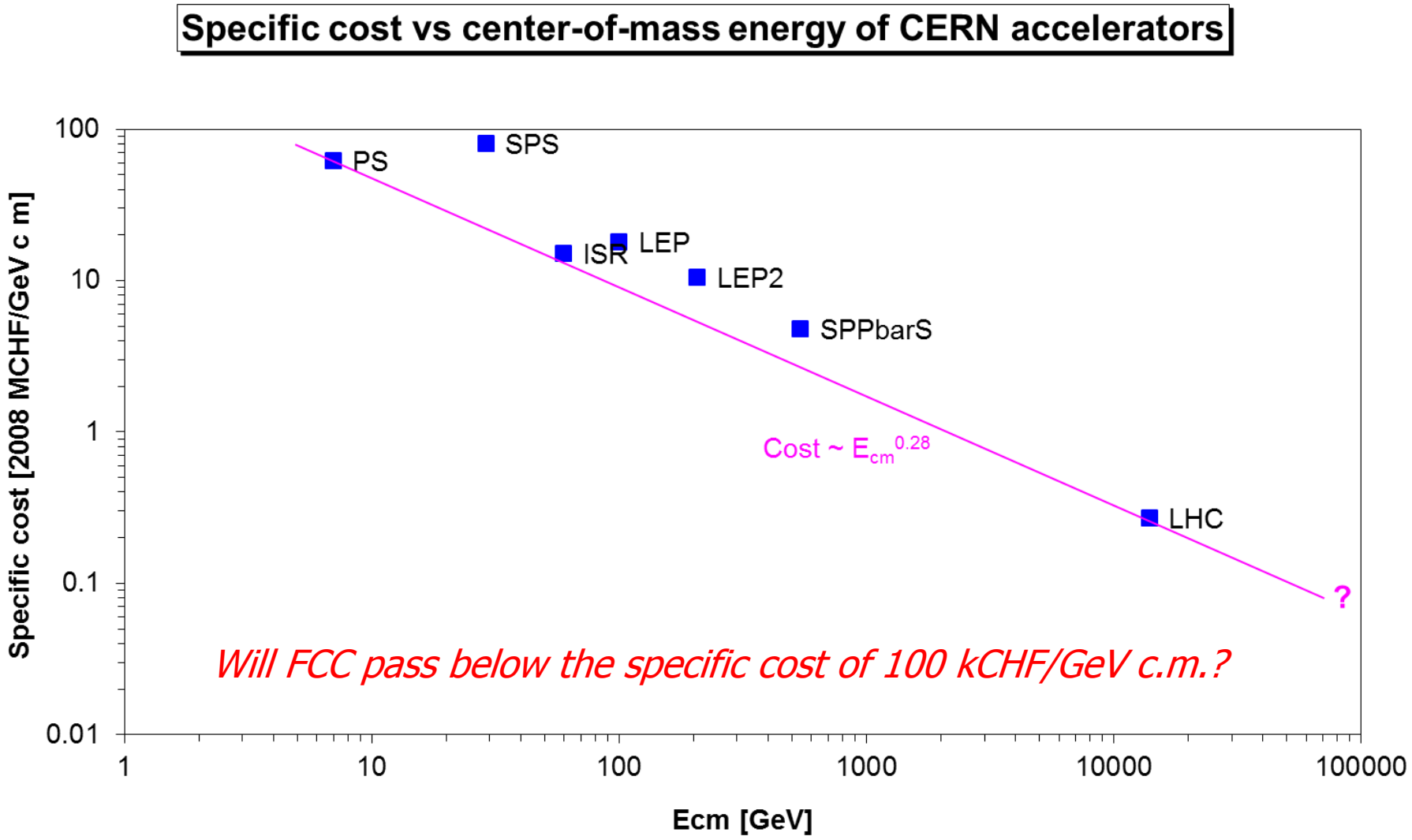
Lawrence's first cyclotron (1930)



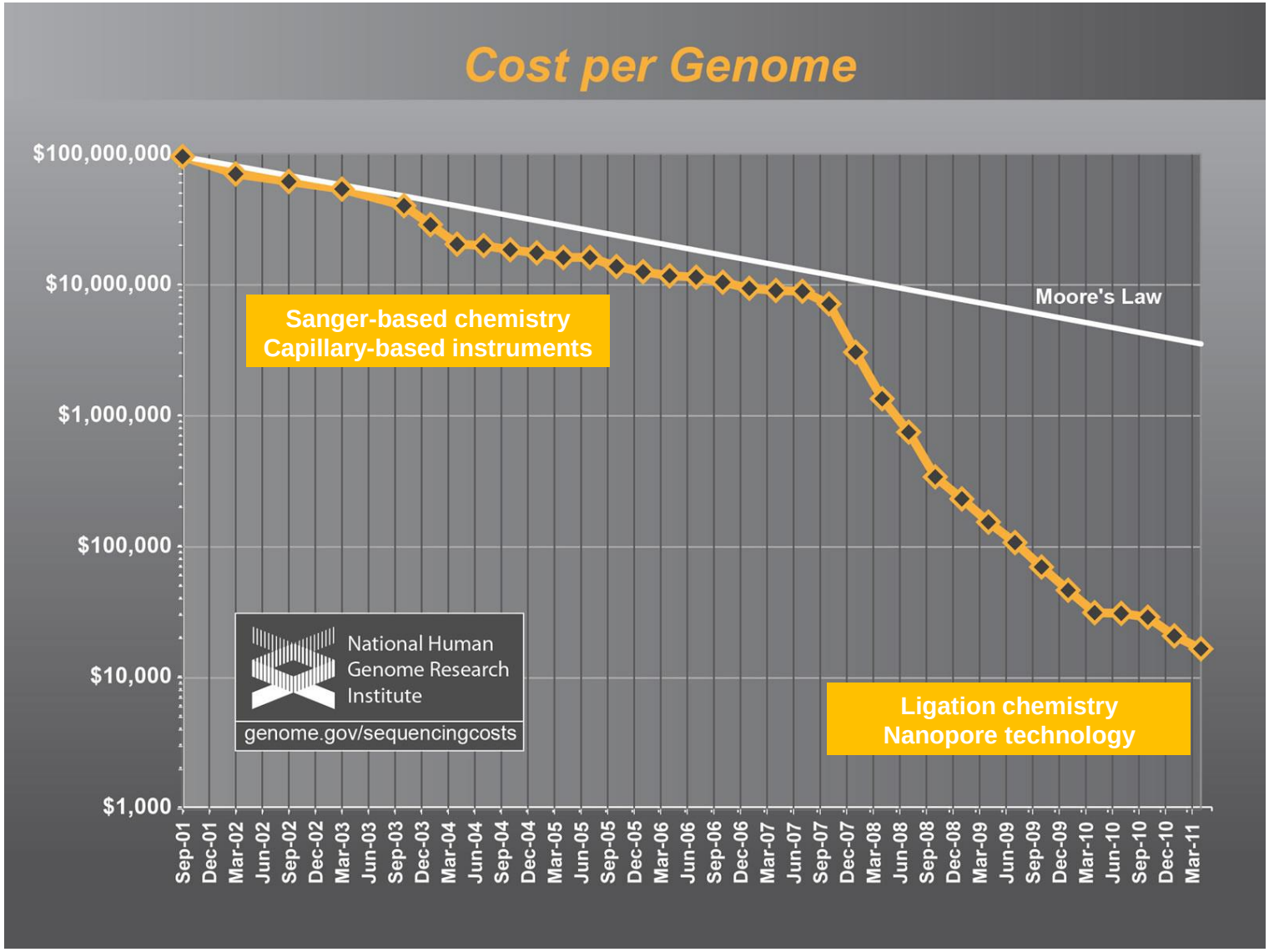
Large Hadron Collider (2009)

Ph. Lebrun

A sustained decrease in specific cost

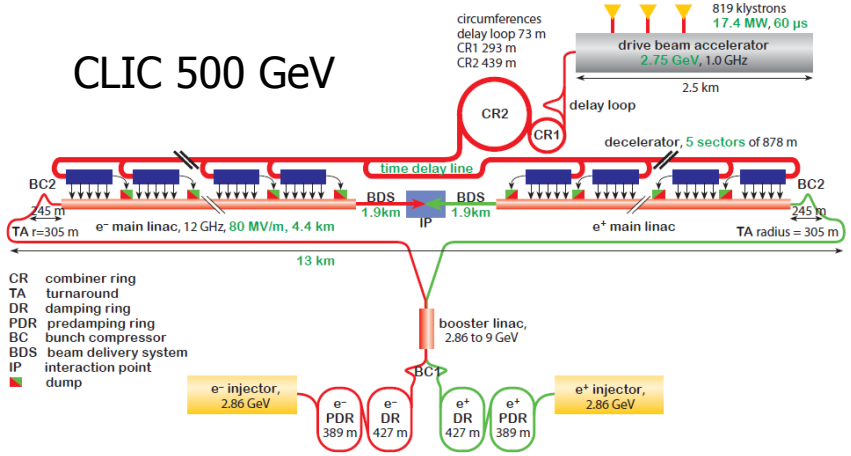


Cost breakthrough vs gradual progress
The case of human genome sequencing

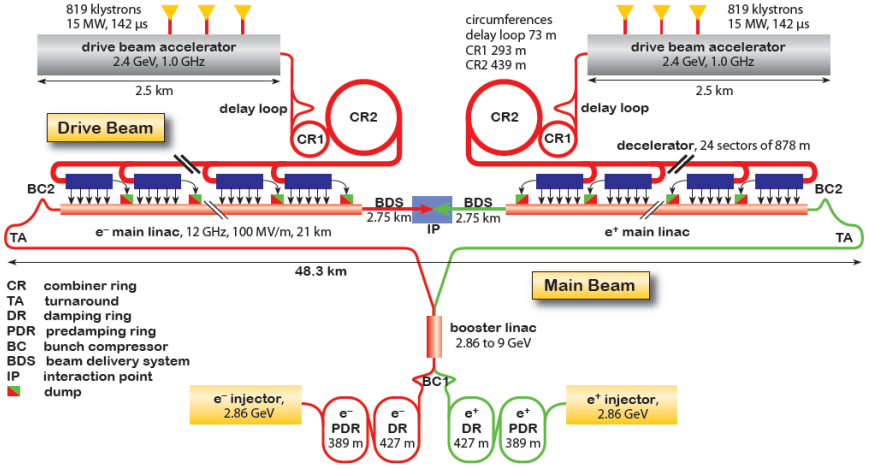


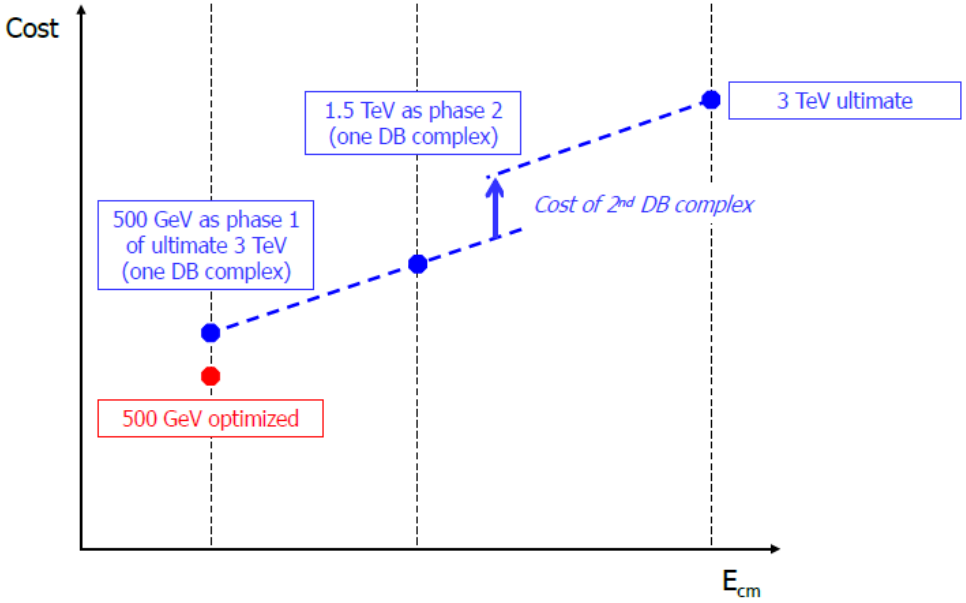
First-order phase transition in cost: CLIC energy stages

CLIC 500 GeV

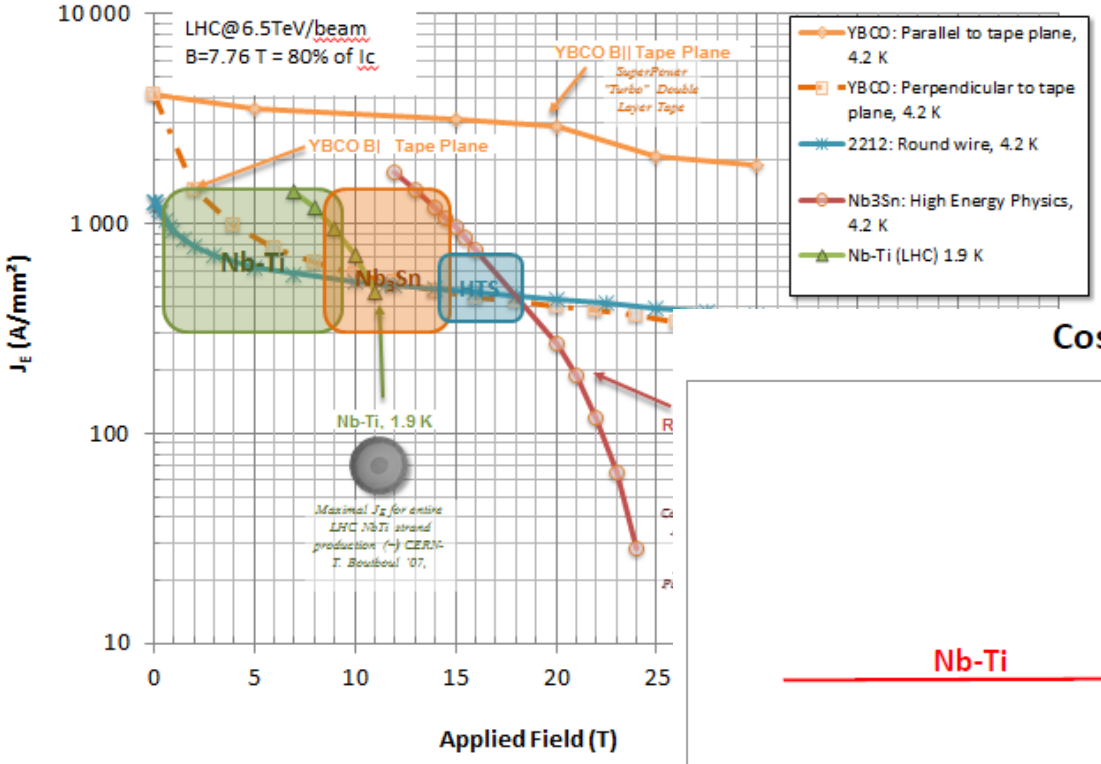


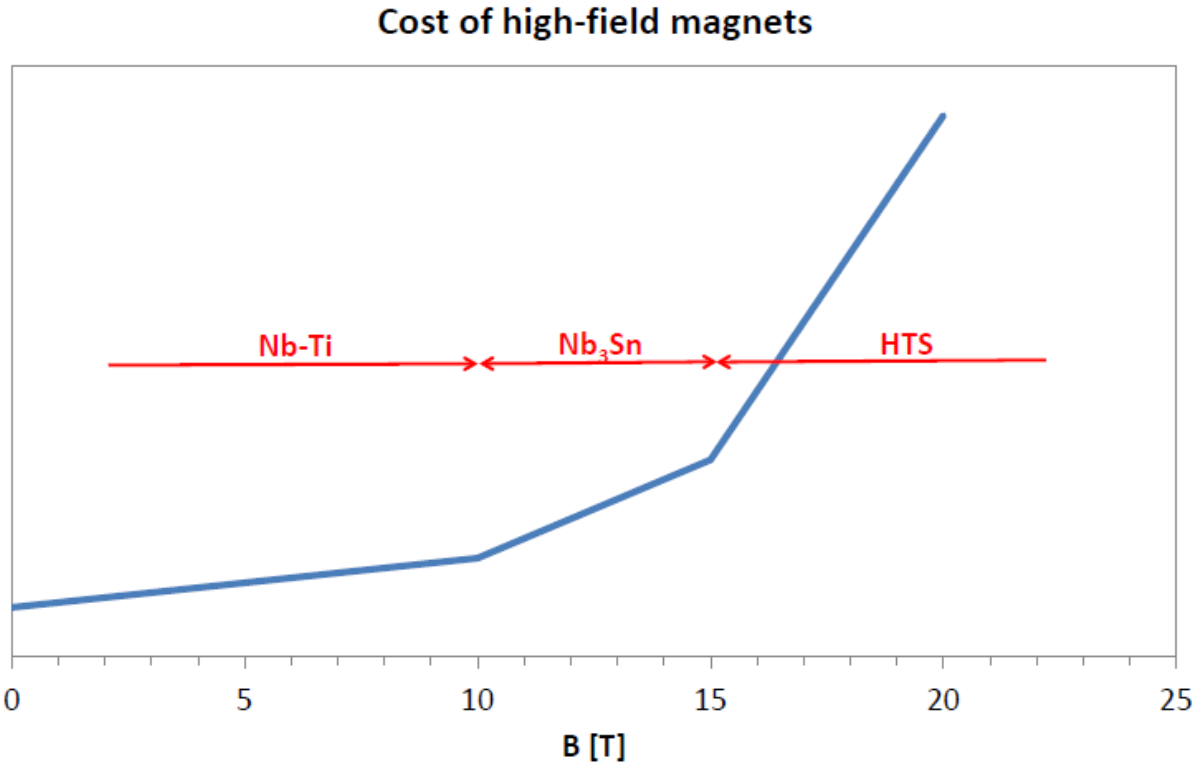
CLIC 3 TeV





Second-order phase transitions in cost: high-field superconducting magnets





Some phase transitions presented in this meeting

- In the FCC-hh injector complex
  - Is the HE injector in the FCC-hh main ring a LHC-like (26.7 km) or a SPS-like (6.9 km) synchrotron?
  - The "latent" cost is $\mathcal{O}$ (BCHF) for capital expenditure, $\mathcal{O}$ (tens of MW) for power consumption
  - What is the field swing acceptable in the HE injector? In the main ring?
  - Conversely, with only the 6.3 km high-energy injector, what is the maximum energy achieveable in the main ring?
- In the FCC-ee main ring
  - Transition from single magnetic channel to twin magnetic channel machine: number of bunches (electrostatic separation, beamstrahlung)
  - Minimum number of RF straight sections to stay within allowed energy sawtoothing: important for staging
    - Equip fewer points with RF and cryo at lower energy
    - Operate cryoplants closer to nominal capacity, i.e. better efficiency

Summary and outlook

- Civil engineering and infrastructure represent an important fraction of the capital expenditure of large high-energy accelerator complexes
- Conventional facilities also contribute substantially to electricity consumption and thus to operational expenditure of these machines
- CERN's experience in building machines of increasing size and performance can be applied to the study of 80-100 km circular accelerators in the Geneva basin
- Still, the step from LEP/LHC to FCC represents major challenges which will require inventive solutions in accelerator science & technology as well as in conventional facilities
- We also welcome collaborations with interested partner institutes in the latter domain

⇒ *Breakout session this afternoon at 14h00, Room M1 130*

"La difficulté de réussir ne fait qu'ajouter à la nécessité d'entreprendre"
Beaumarchais

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Tunnel geology
Exploratory study of 113 km tunnel in Geneva basin (2001)