



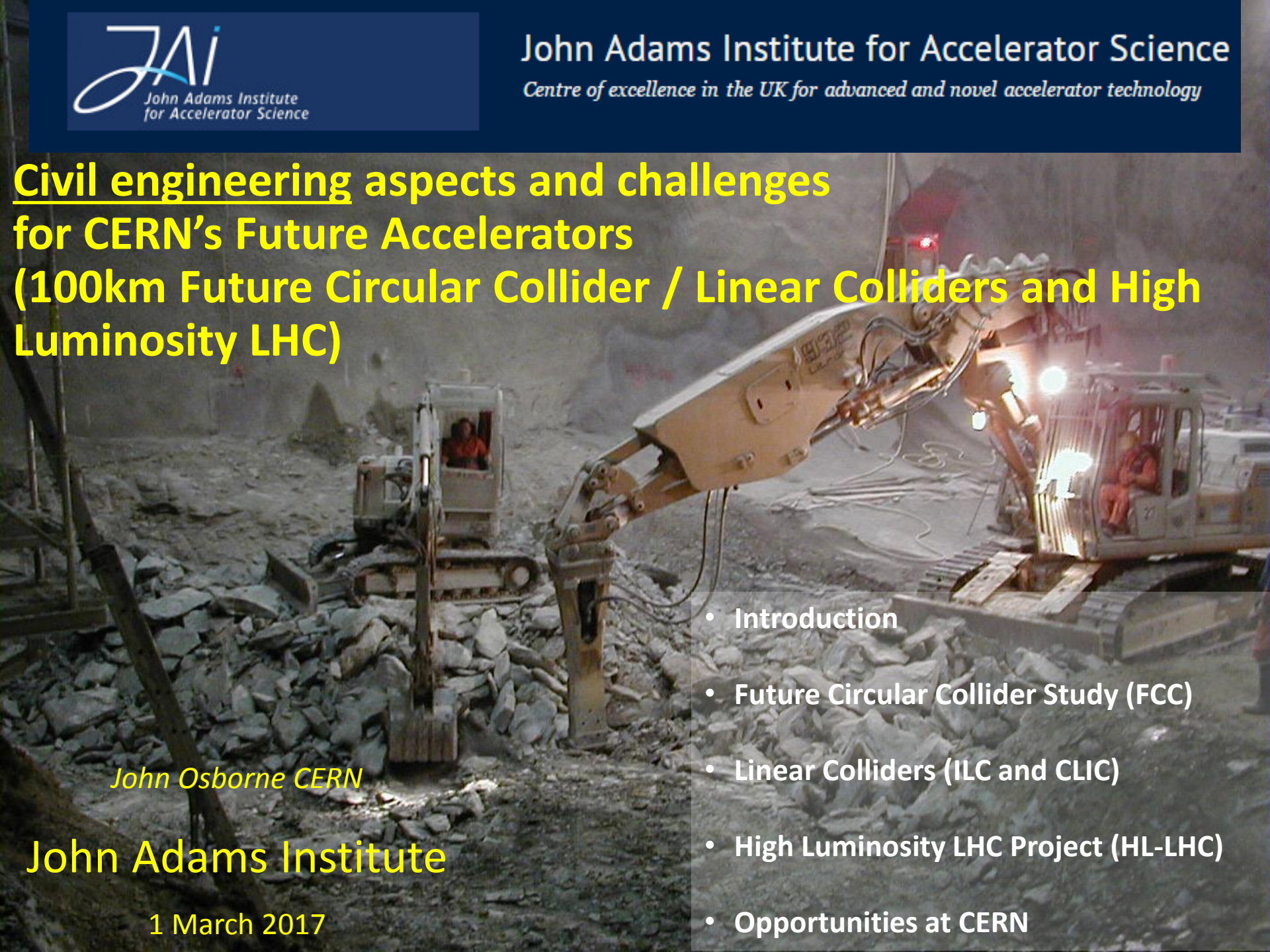
<https://edms.cern.ch/document/1761678/1>

# Civil engineering aspects and challenges for CERN's Future Accelerators (100km Future Circular Collider / Linear Colliders and High Luminosity LHC)

*John Osborne CERN*

John Adams Institute

1 March 2017

- 
- Introduction
  - Future Circular Collider Study (FCC)
  - Linear Colliders (ILC and CLIC)
  - High Luminosity LHC Project (HL-LHC)
  - Opportunities at CERN



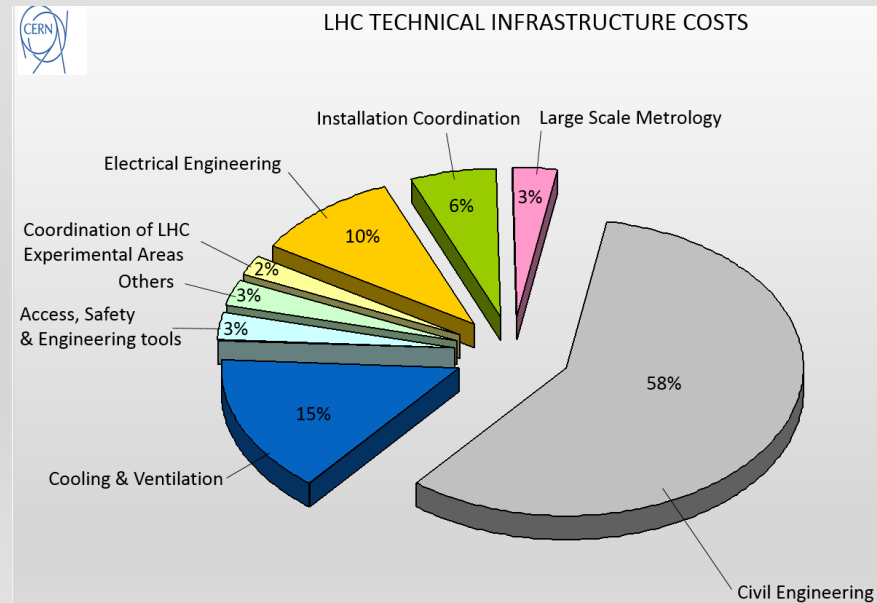
# My Background



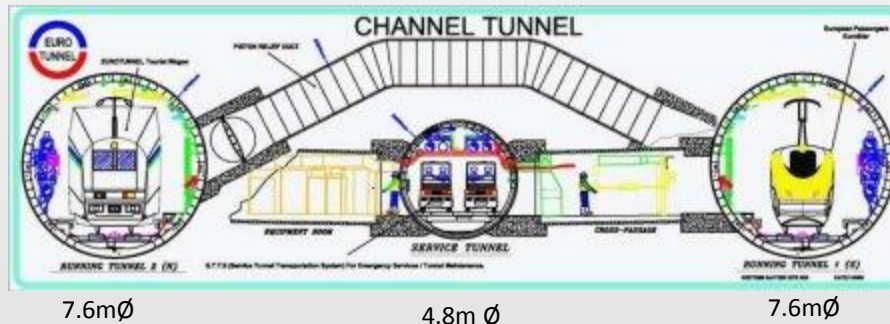
- Graduated from Liverpool University 1988 with Civil Engineering Degree
- Worked for 10 years for UK Contractor, Carillion (formally Tarmac) on :
  - Conwy tunnel
  - Design Secondment in Glasgow with Sir Alexander Gibb & Partners (now Jacobs)
  - Medway tunnel
  - Jubilee Line Extension, Canary Wharf Station
  - A13 extension, Dagenham, Precast Segmental Bridge over Ford's factory
- Joined CERN in 1998 for Large Hadron Collider Works (CMS)
- Now working on CERN's Future Accelerator Projects

# Introduction

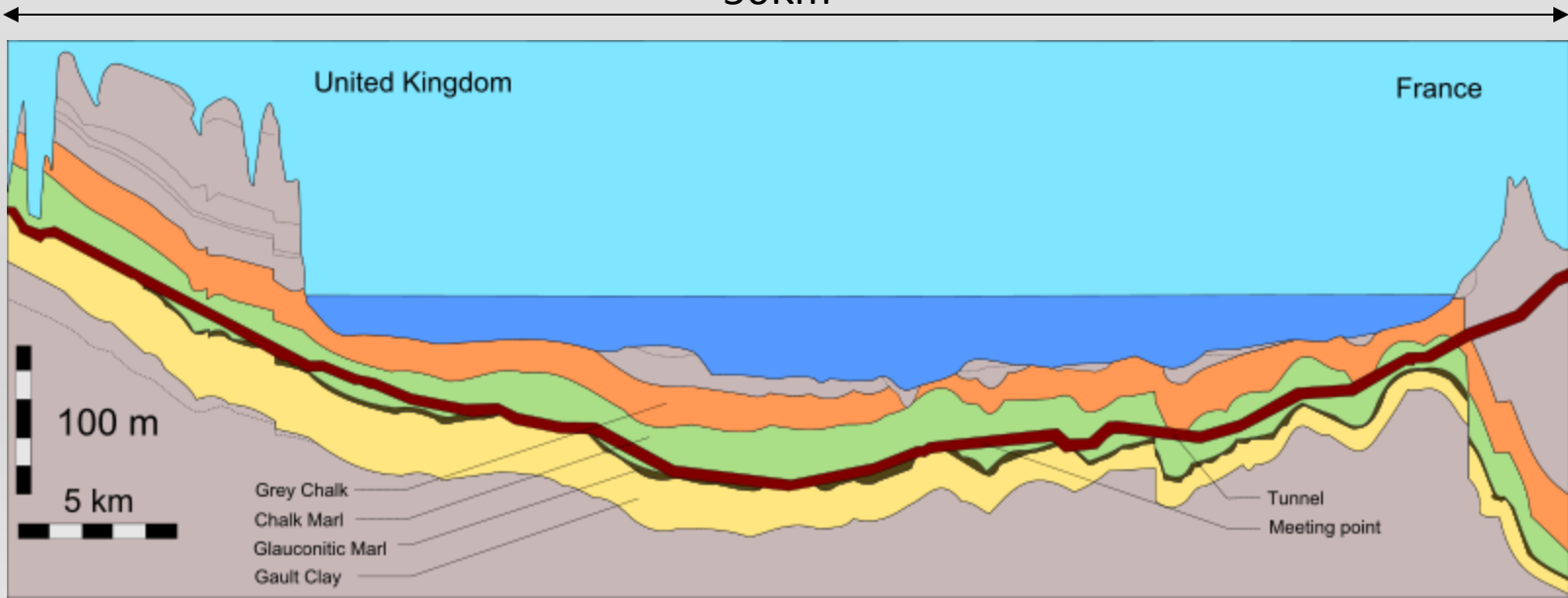
- Why should civil and infrastructure costs be considered at such an early stage :
  - Approximately 30-40% of budget for large scale physics projects
  - Infrastructure works can make or break projects
- What are the key challenges ?
  - 90% of Infrastructure costs are for Civil Engineering, HVAC and Electricity
  - Safety, Environmental....



# For FCC, CLIC & ILC, similar World Projects: eg Channel Tunnel



50Km



# Channel Tunnel Construction (2)

## 1987 - 15th December

Boring of the service tunnel starts on the UK side.

## 1988 - 28th February

Start of service tunnel boring on the French side.

## 1990 - 1st December

British and French teams achieved the first historic breakthrough under the Channel, in the service tunnel, 22.3 km from the UK and 15.6 km from France.

## 1991 - 22nd May

Breakthrough in the North rail tunnel.

## 1991 - 28th June

Breakthrough in the South rail tunnel.

## 1993 - 10th December

Handover from TML to Eurotunnel.

## 1993 - 1994

Equipment installation and testing.



- 7 years from first excavation to operation
- At peak 15,000 workers
- 6 TBM's used for tunnelling
- Very approximate cost = \$9.1 billion (1985 prices)
- Difficulties :
  - Financing
  - Political
  - Water ingress
  - Safety (10 workers died), fire..
  - Cost overruns....

Feasibility studies started 200 years ago with in **Napoleonic** times !!!



# Main civil engineering risks (1)

*A full risk assessment must be carried out for both the **pre-construction phase** and **execution phase** of the works.*

*The **Pre-construction phase** must assess risks such as :*

- Delay during the planning permission approval process
- Objections raised from the public on environmental grounds
- Problems with the project management team
- Project financing uncertainties
- Tenders submissions not reaching minimum bidding standards
- Non appropriate sharing of risk in tender documents



# Main civil engineering risks (2)

***The execution phase of the works must assess risks such as :***

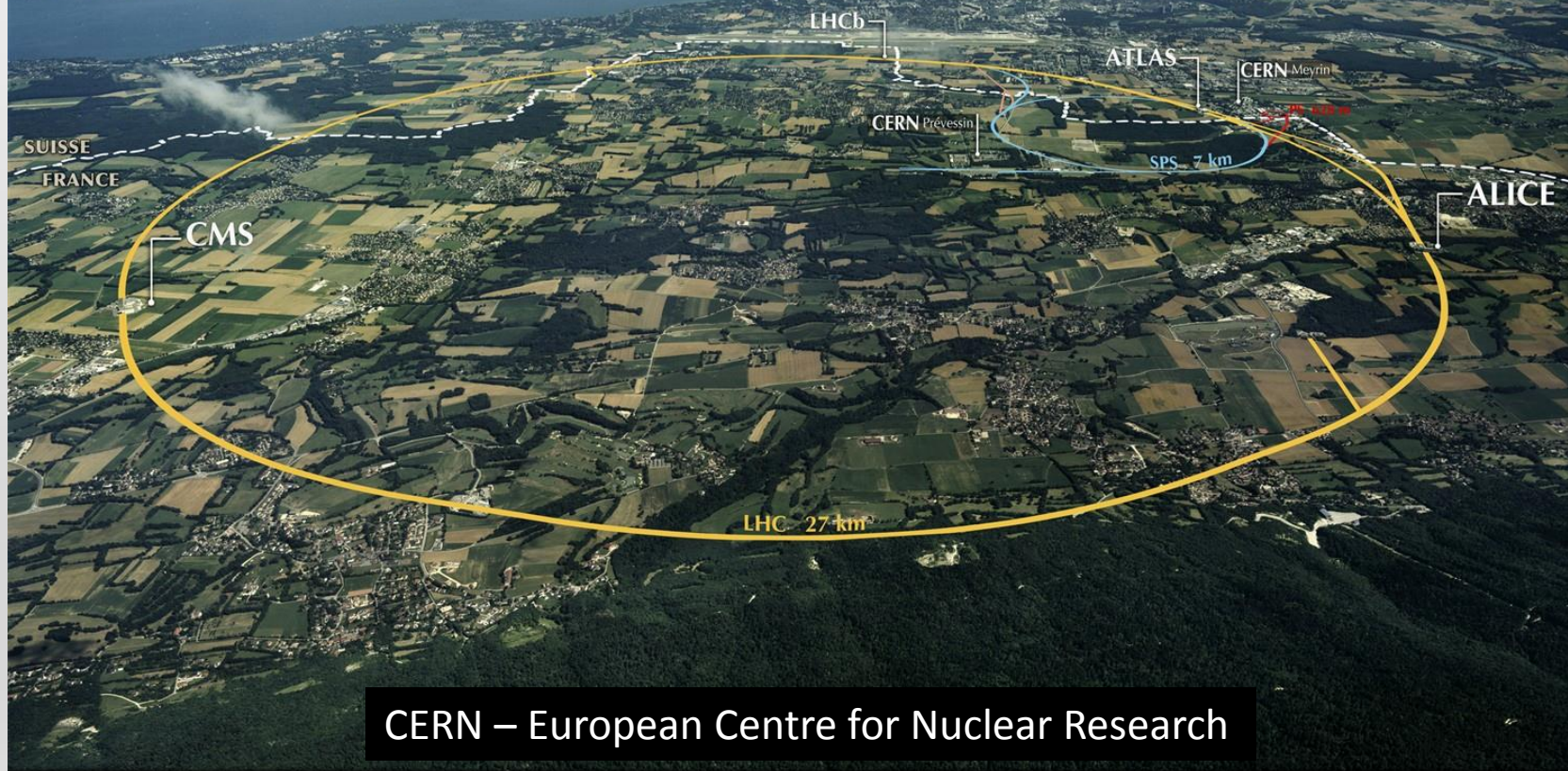
- Uncertainties with geological, hydrological and climate conditions, including:
  - Unstable tunnel excavation face
  - Fault zones
  - Large amounts of water inflow
  - Unexpected ground movements (especially in large caverns)
- Anomalies in contract documents (e.g. large quantity inaccuracies)
- Interference from outside sources
- Delayed submission of approved execution drawings
- Design changes from the consultants and/or owner
- Lack of thorough safety and/or environmental control
- Changes in legislation
- Labour relations
- etc



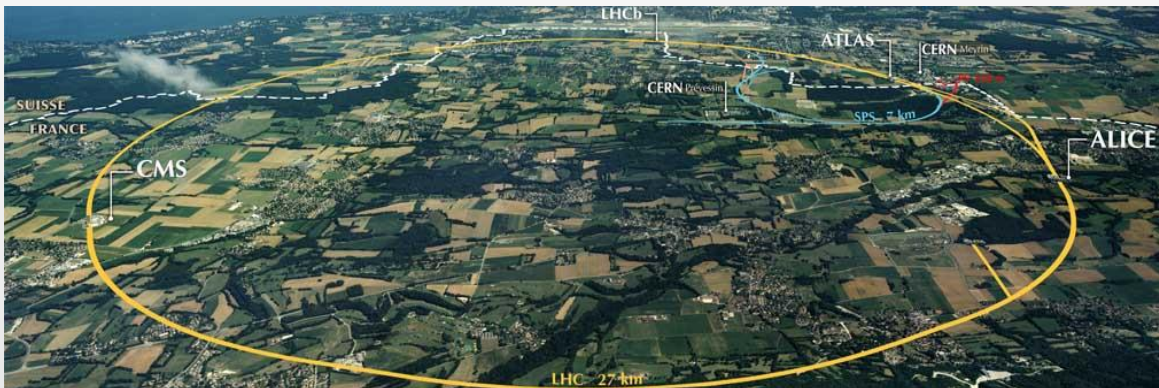
# Civil Engineering : Geology & Site Investigation

- Thorough site investigation is essential in order to avoid surprises during tendering/construction
- For LHC studies, all LEP geotechnical investigative reports were collated and new specific borings executed 3-4 years before the start of the worksite.
- As an example, for the CMS worksite, 11 new boreholes were drilled and tested. Information collated included :
  - Detailed cross sections of ground geology
  - Any known faults in the underlying rock identified
  - Ground permeability
  - Existence of underground water tables
  - Rock strengths etc etc
- Separate contracts were awarded for these site investigations prior to Tender design studies starting.
- Even with all this very detailed knowledge of the local geology some unforeseen ground conditions were encountered during the works

# CERN – The World's Largest Particle Physics Laboratory



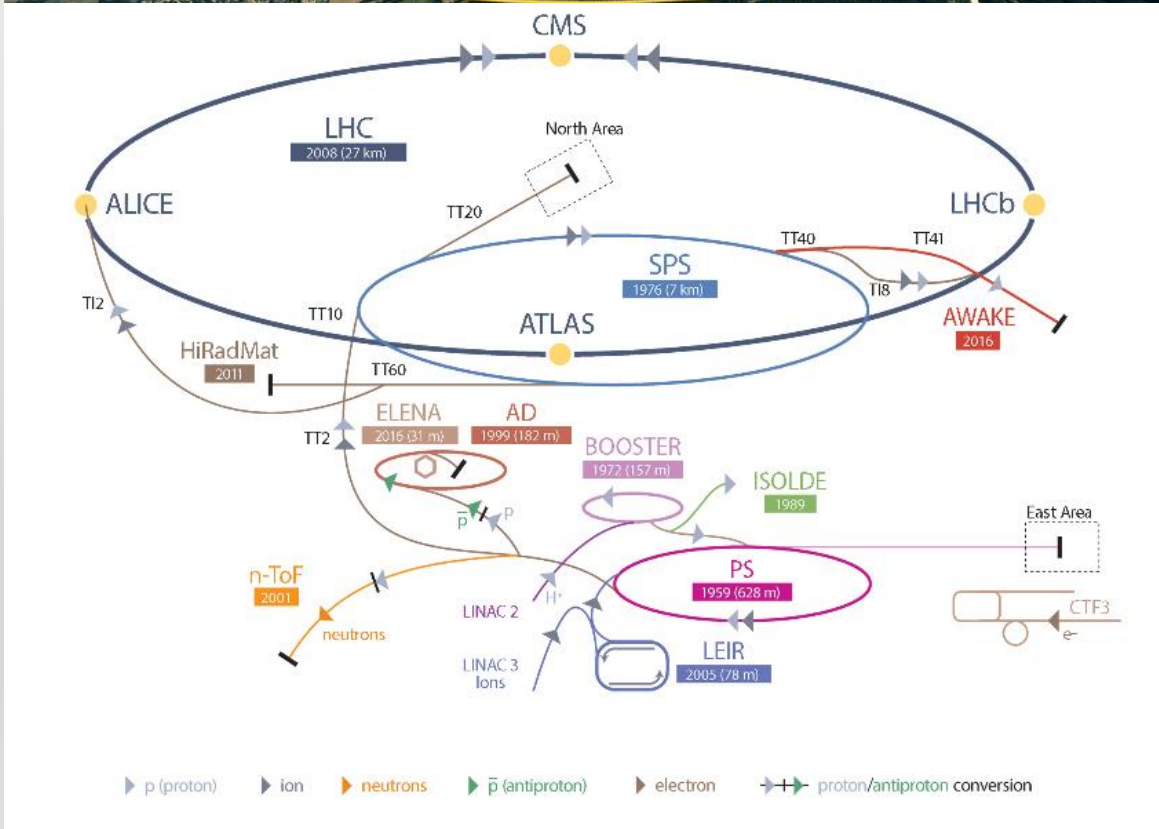
CERN – European Centre for Nuclear Research



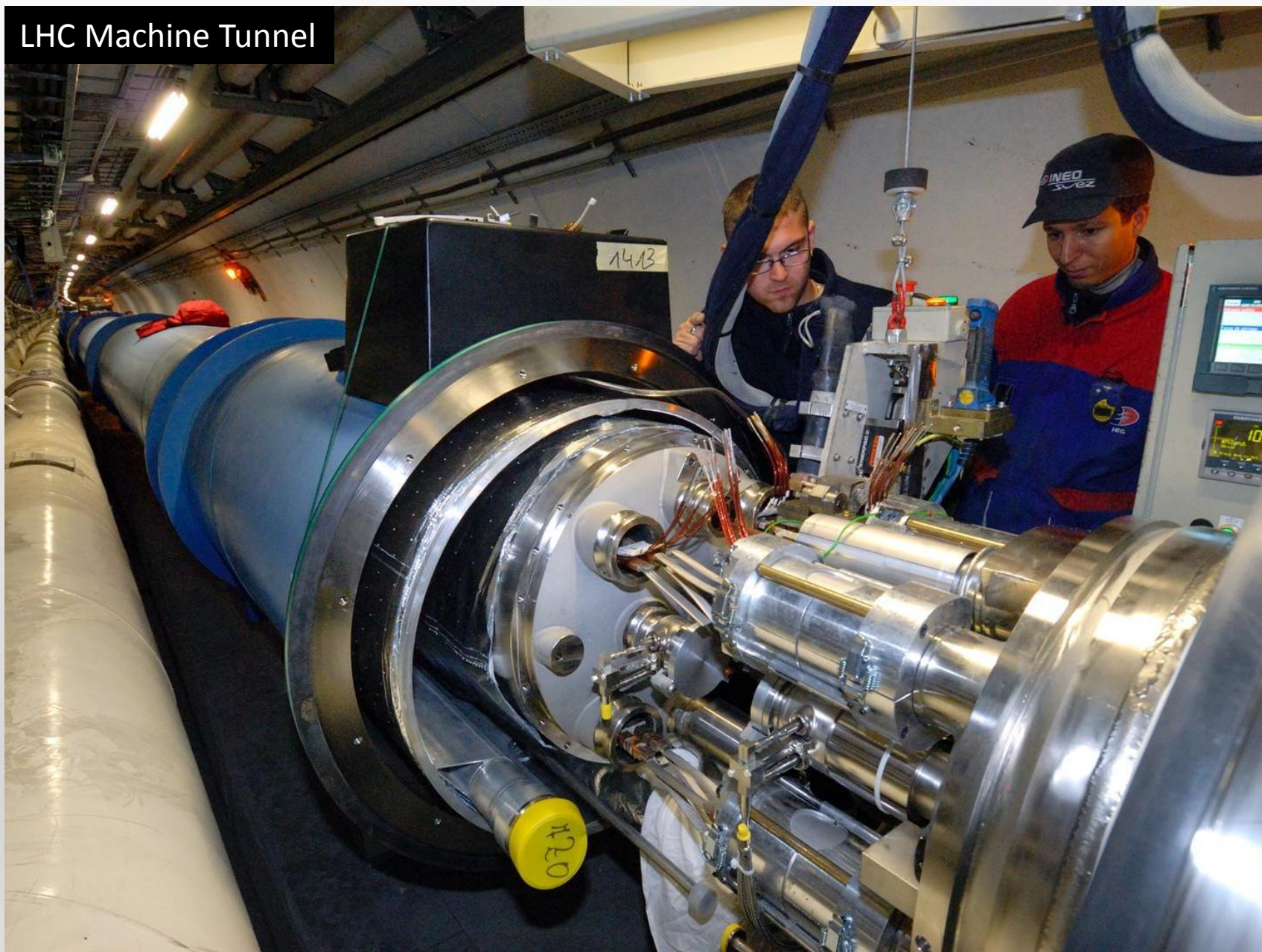
- Large Hadron Collider :

- 27km long
- 50-175m depth
- 4.5m  $\varnothing$  TBM tunnels
- Molasse and limestone

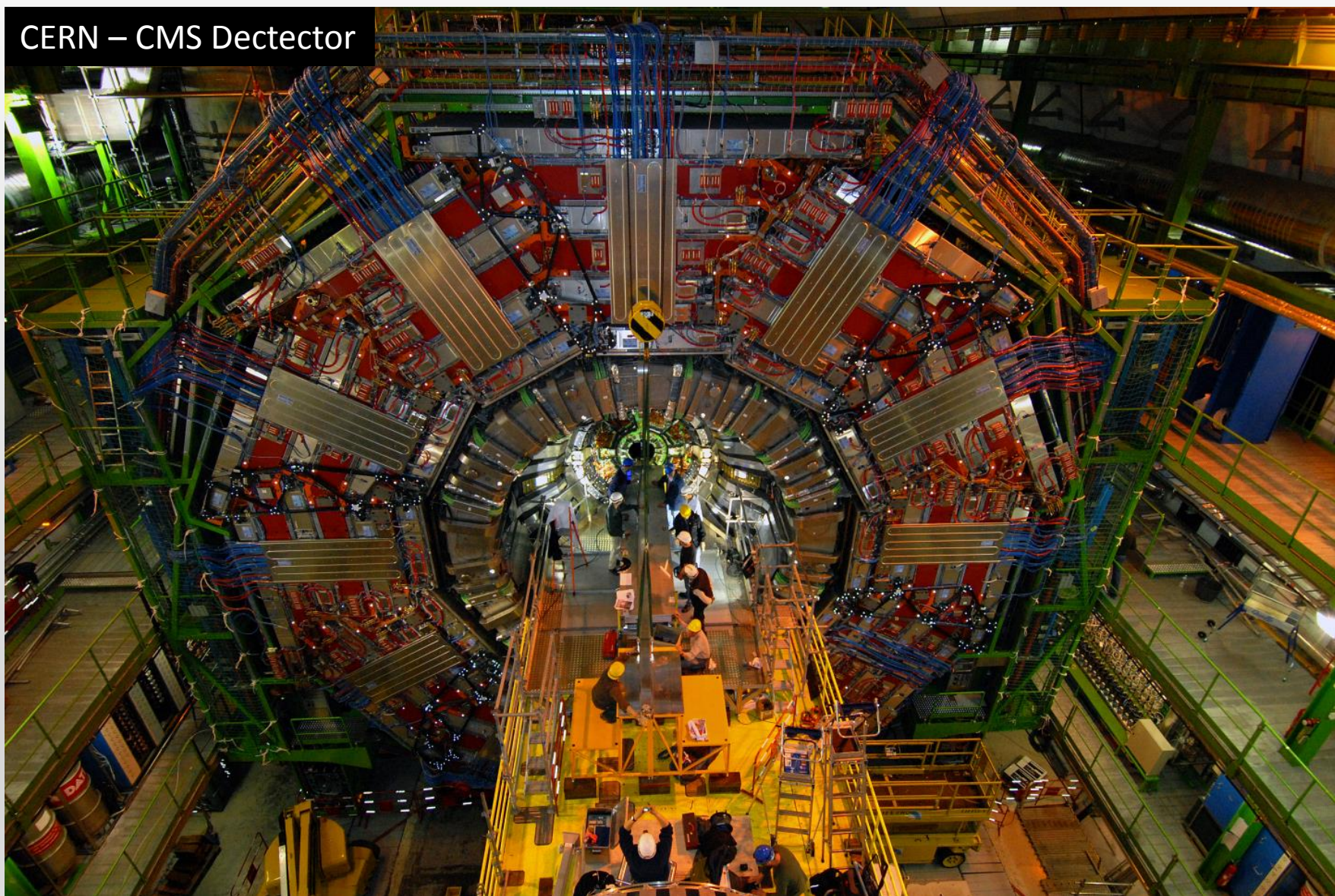
Total underground tunnels >70km  
More than 80 Caverns



# LHC Machine Tunnel



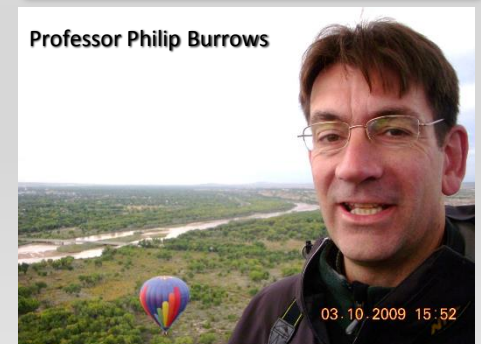
## CERN – CMS Dectector





# The United Kingdom and CERN

- ❑ Founding member of CERN (1954)
- ❑ Top level management:
  - Past: Two DGs (J. Adams, C. Llewellyn-Smith)
  - LHC Project Leader (Lyn Evans)
  - Director for Accelerators and Technology (Steve Myers)
  - Present : Beams Department Head (Paul Collier)
- ❑ Leading theoretical role in setting experimental agenda (Peter Higgs)
- ❑ Leading role in IT@CERN
  - WWW (Tim Berners-Lee)
  - Grid (e-science)
- ❑ Participates in all four LHC experiments with major management responsibilities
- ❑ Leading role in public outreach
- ❑ Oxford Visiting Professor in Particle and Accelerator Physics
- Emmanuel Tsismelis (CERN International Relations)





# The Future Circular Collider Study (FCC)

**Collision energy:**

100TeV

**Circumference:**

80km-100km

**Physics considerations:**

Enable connection to the LHC (or SPS)

**Construction:**

c.2025-35

**Cost:**

TBC

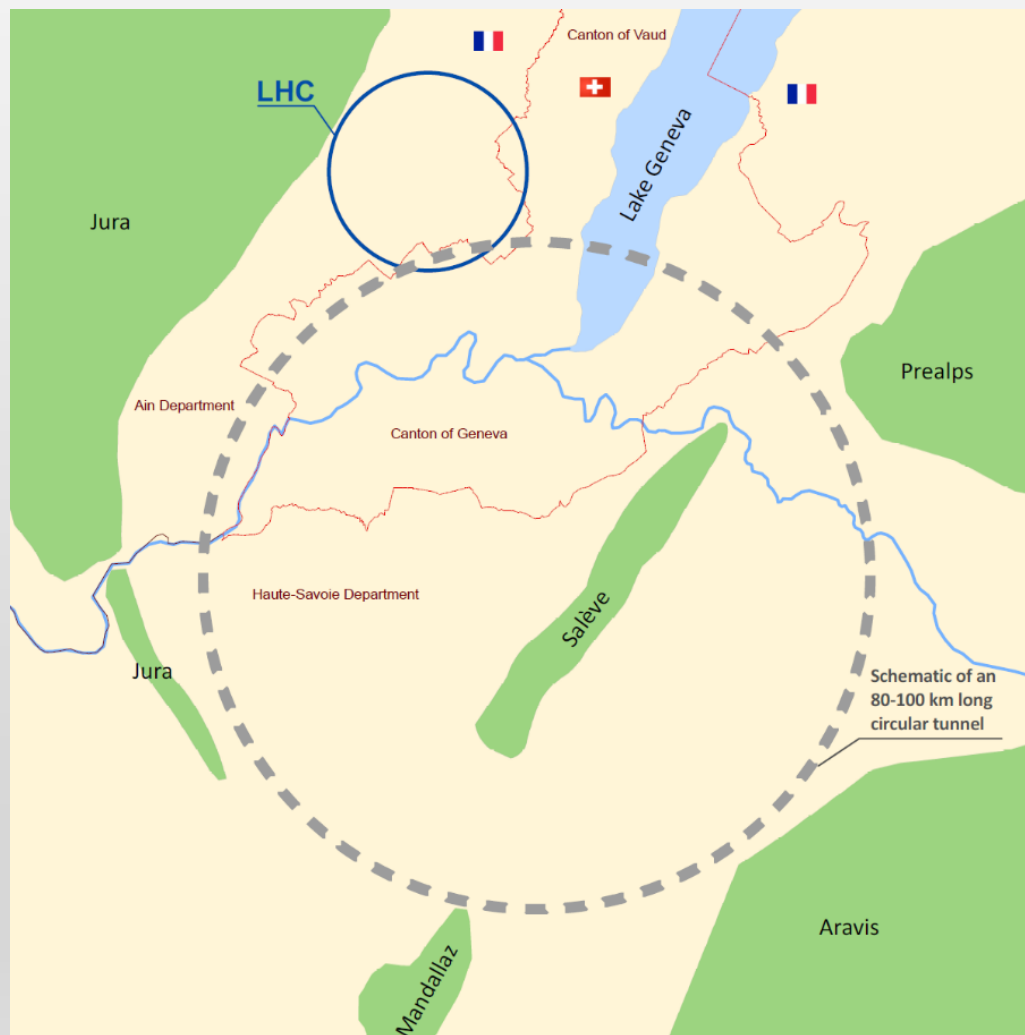
**Aims of the civil engineering feasibility study:**

Is 80km-100km feasible in the Geneva basin?

Can we go bigger?

What is the 'optimal' size?

What is the optimal position?



## Jura

High overburden  
Karstic limestone

## Vuache

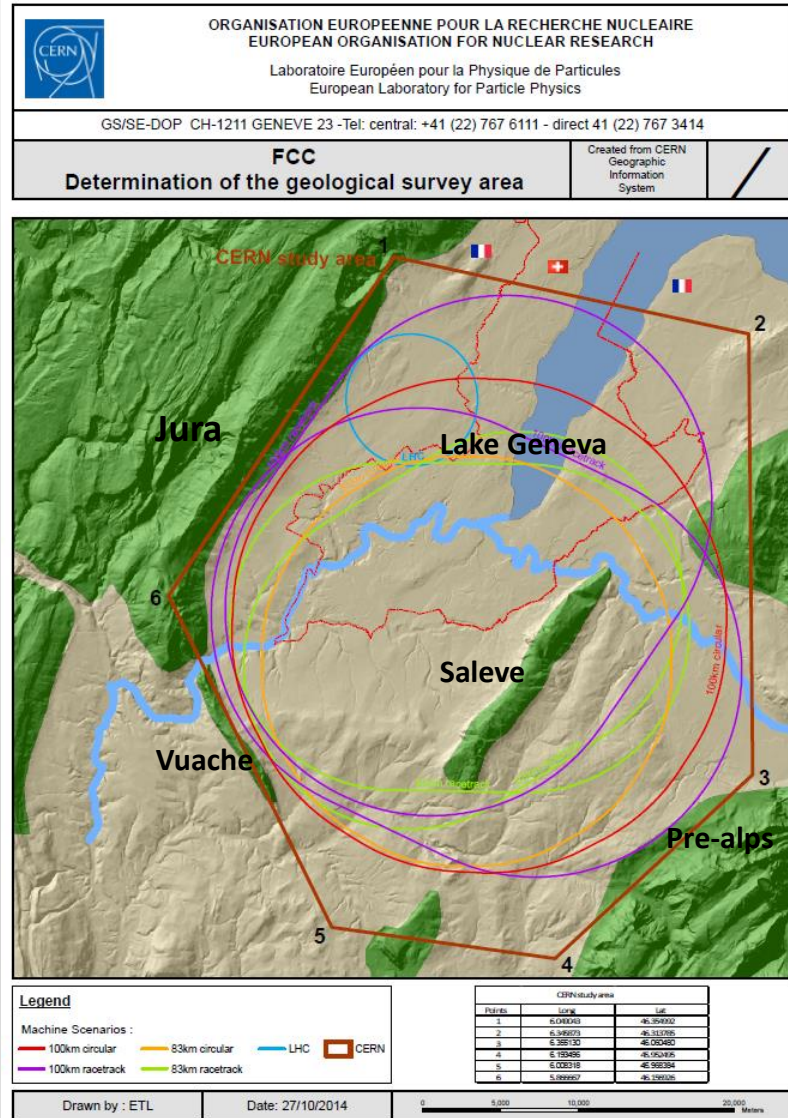
Highly fractured limestone with karst

## Pre-alps

Rapidly increasing tunnel depth  
Less well-known limestone

## Lake Geneva

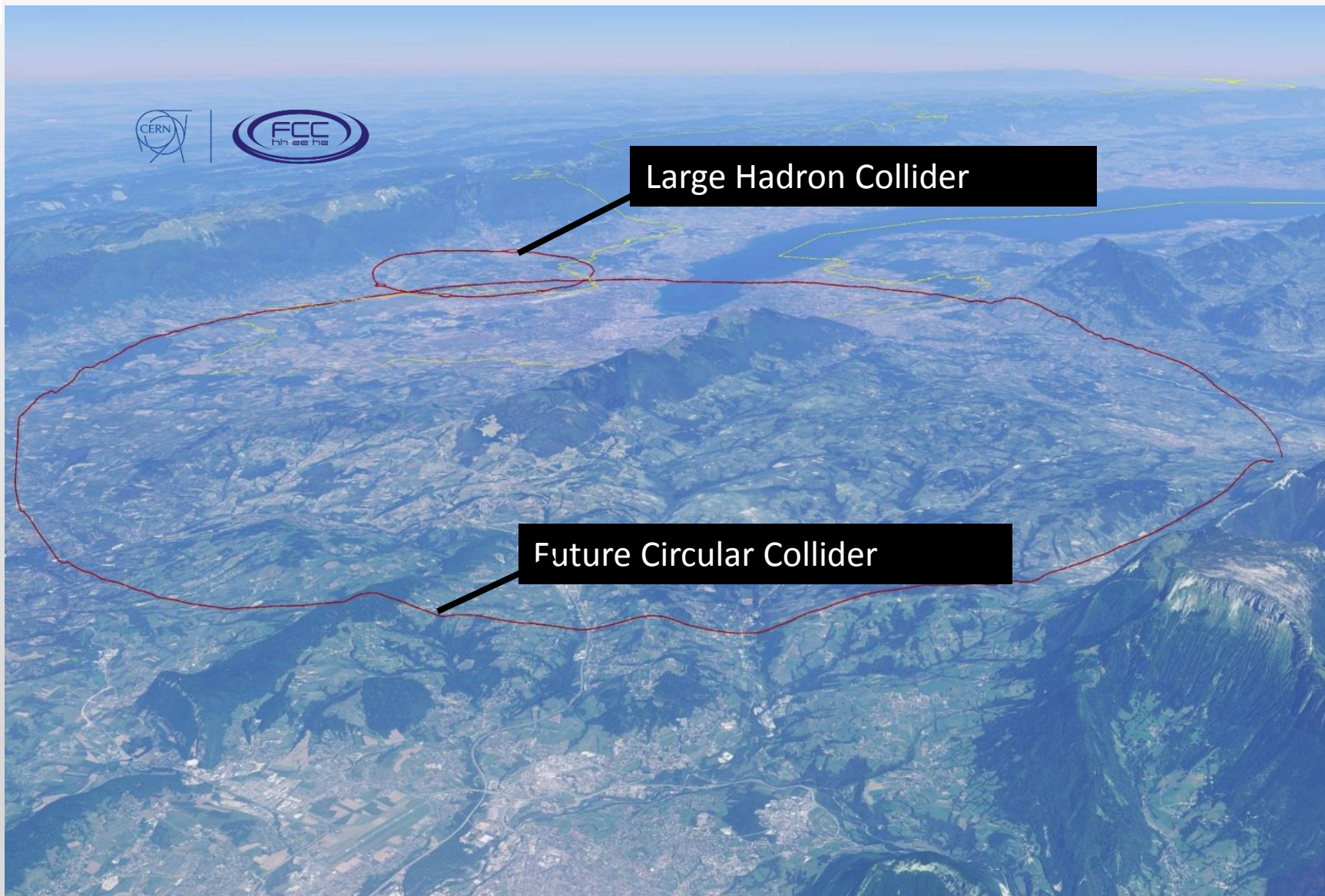
Lake depth increases quickly in NE direction





Large Hadron Collider

Future Circular Collider



## Rock properties

### Moraines

- Glacial deposits comprising gravel, sands silt and clay
- Water bearing unit
- Low strength

### Molasse

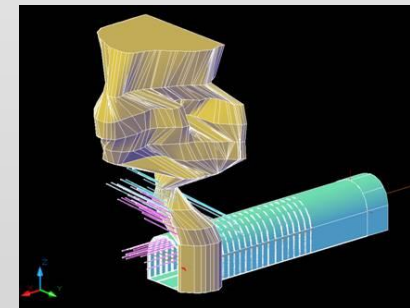
- Mixture of sandstones, marls and formations of intermediate composition
- Considered good excavation rock
- Relatively dry and stable
- Relatively soft rock
- However, some risk involved
- Structural instability (swelling, creep, squeezing)

### Limestone

- Hard rock
- Normally considered as sound tunneling rock
- In this region fractures and karsts encountered
- High inflow rates measured during LEP construction (600L/sec)
- Clay-silt sediments in water

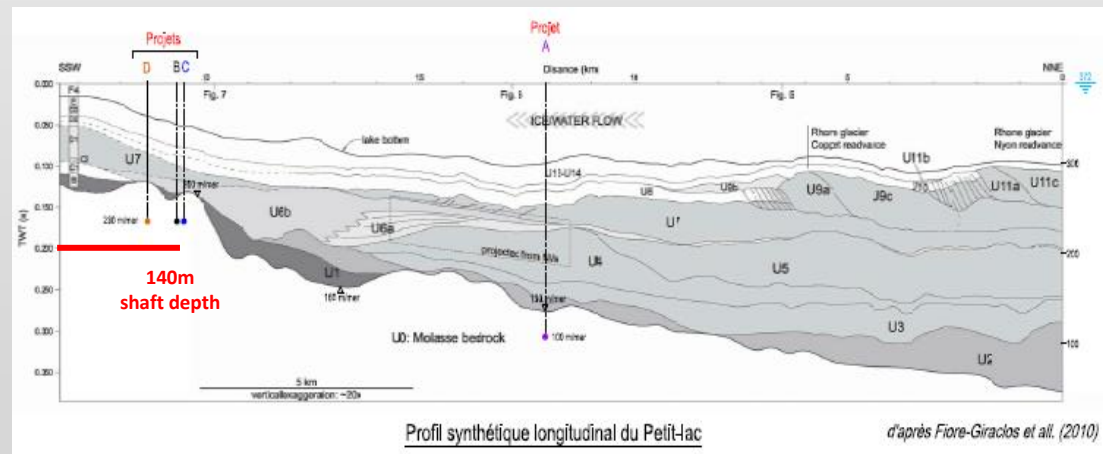
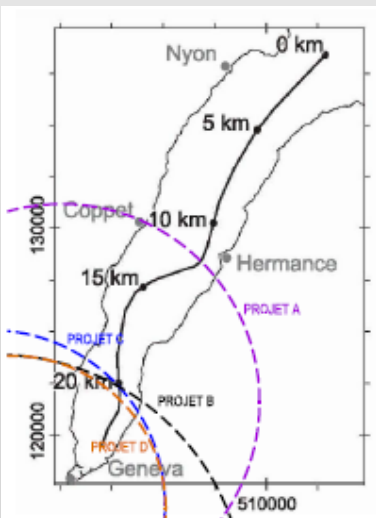
Rock type	Average $\sigma_c$ (Mpa)
<b>Sandstone</b> <i>weak</i>	10.6
<i>strong</i>	22.8
<i>Very strong</i>	48.4
<b>Sandy marl</b>	13.4
<b>Marl</b>	5.7

*Molasse Compression strengths*



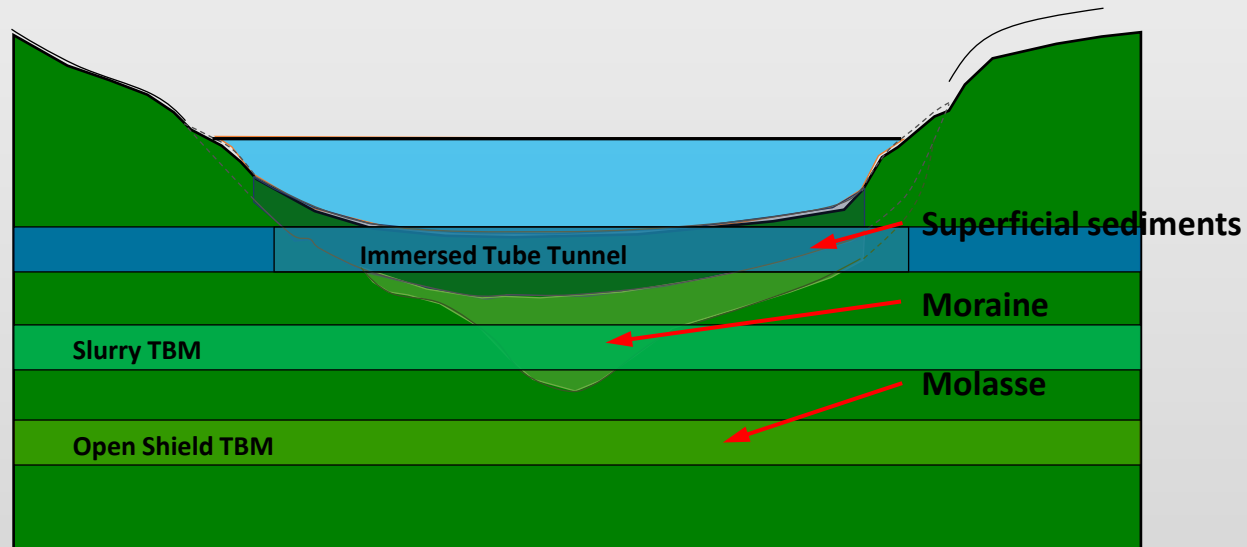
*Model of tunnel collapse caused by Karsts*

- Geology is not yet well understood
- Some seismic soundings performed for the possible construction of a road tunnel
- Molasse bedrock covered by a deep layer of moraines



# Feasibility Study – Geology

## Lake Crossing: Tunnelling Considerations



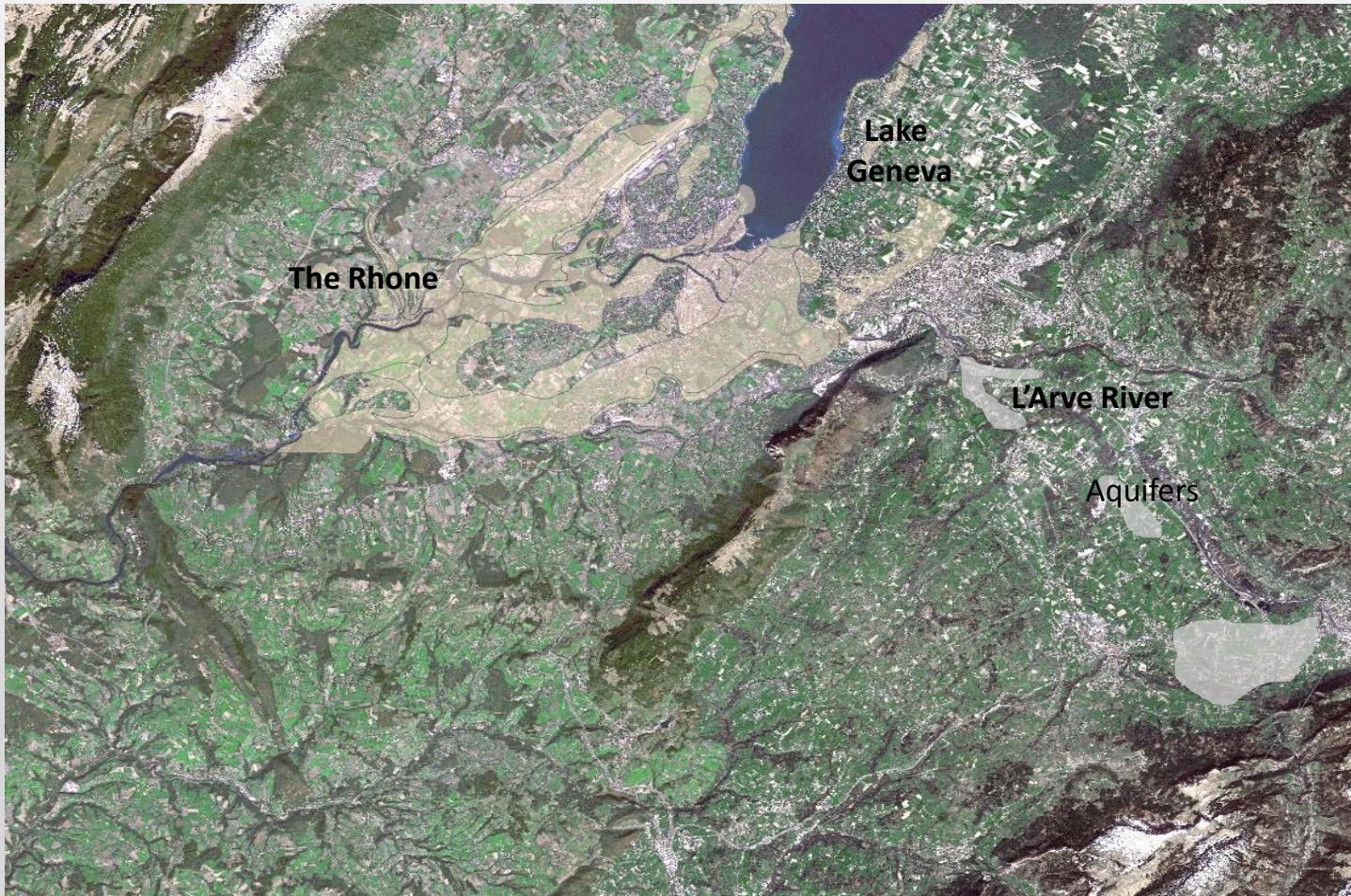
Medway  
Tunnel  
Immersed  
Tube Tunnel

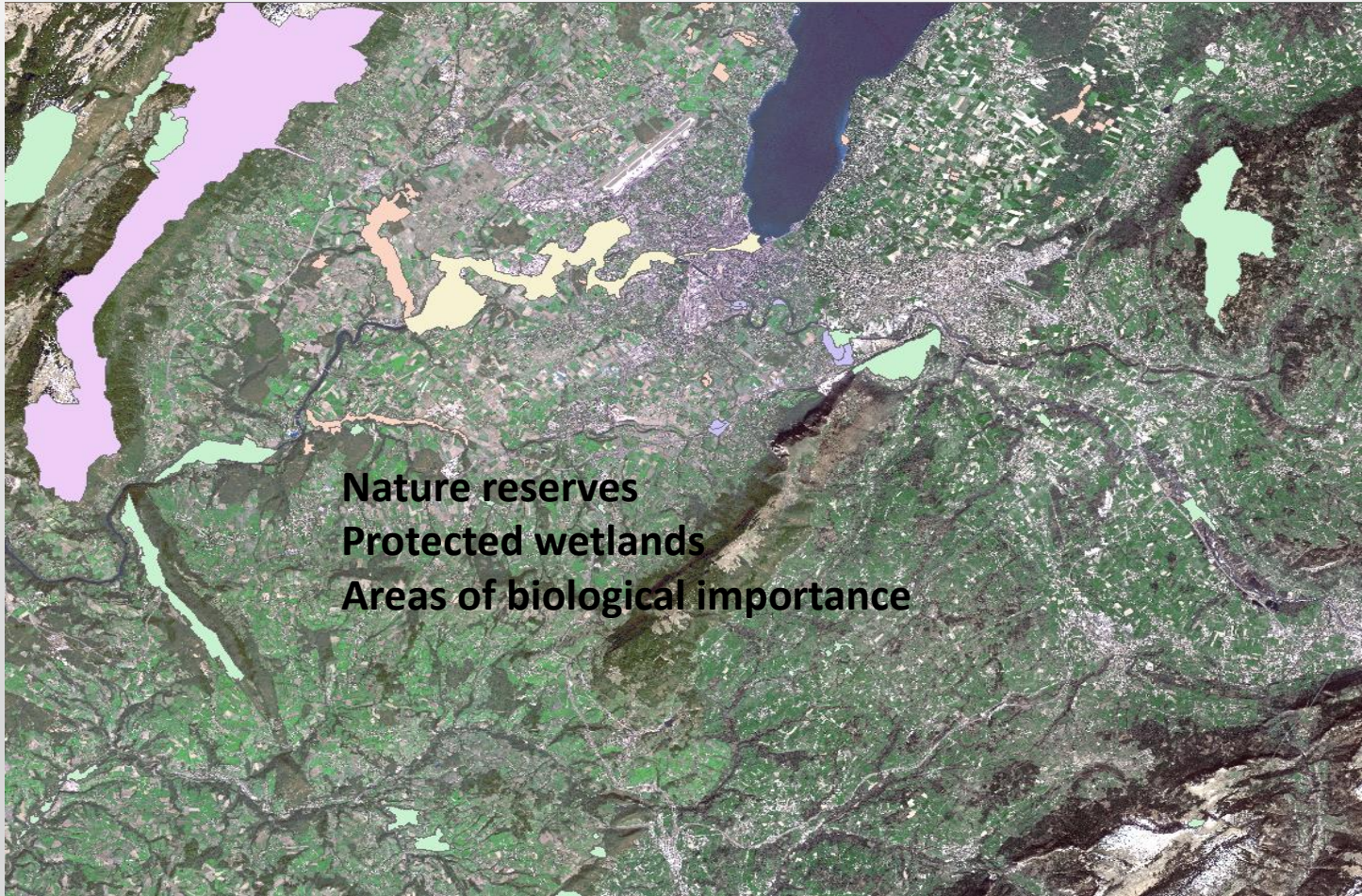




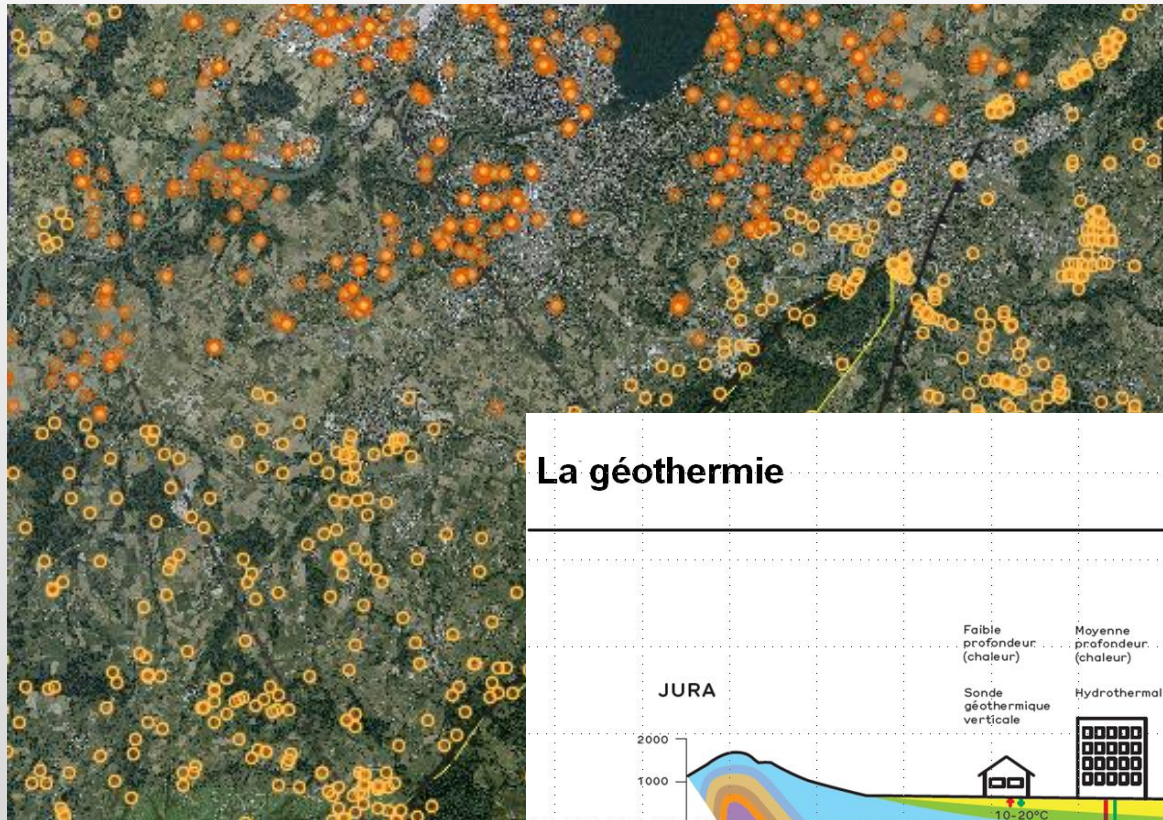
- Streamlines the conventional approach which is broadly linear and manual
- Max value extracted from early project data
- Single Source of Data
- Visual decision aid
- Clash detection – Regional Scale
- Iterative process and comparison of options

## Feasibility Study – Hydrology

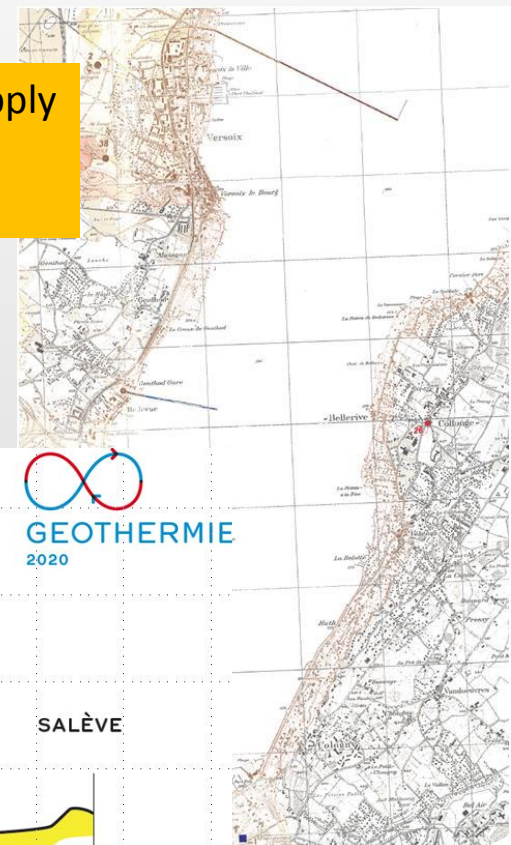




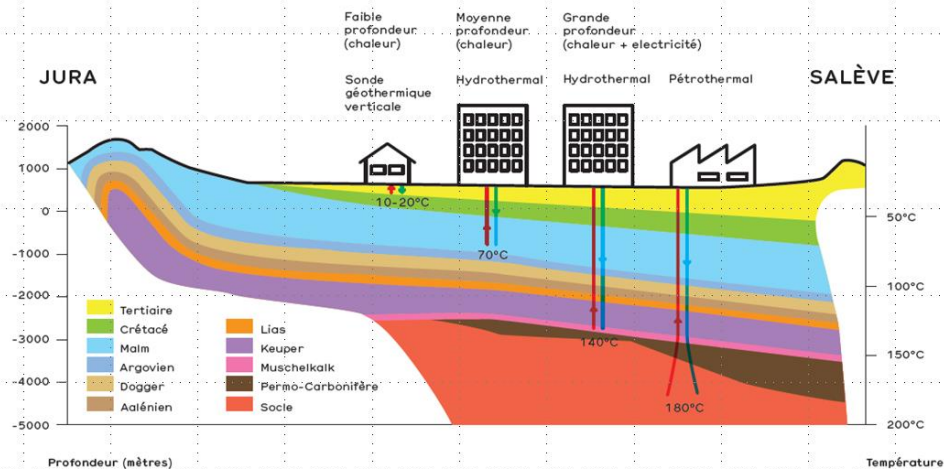




Water supply  
pipelines

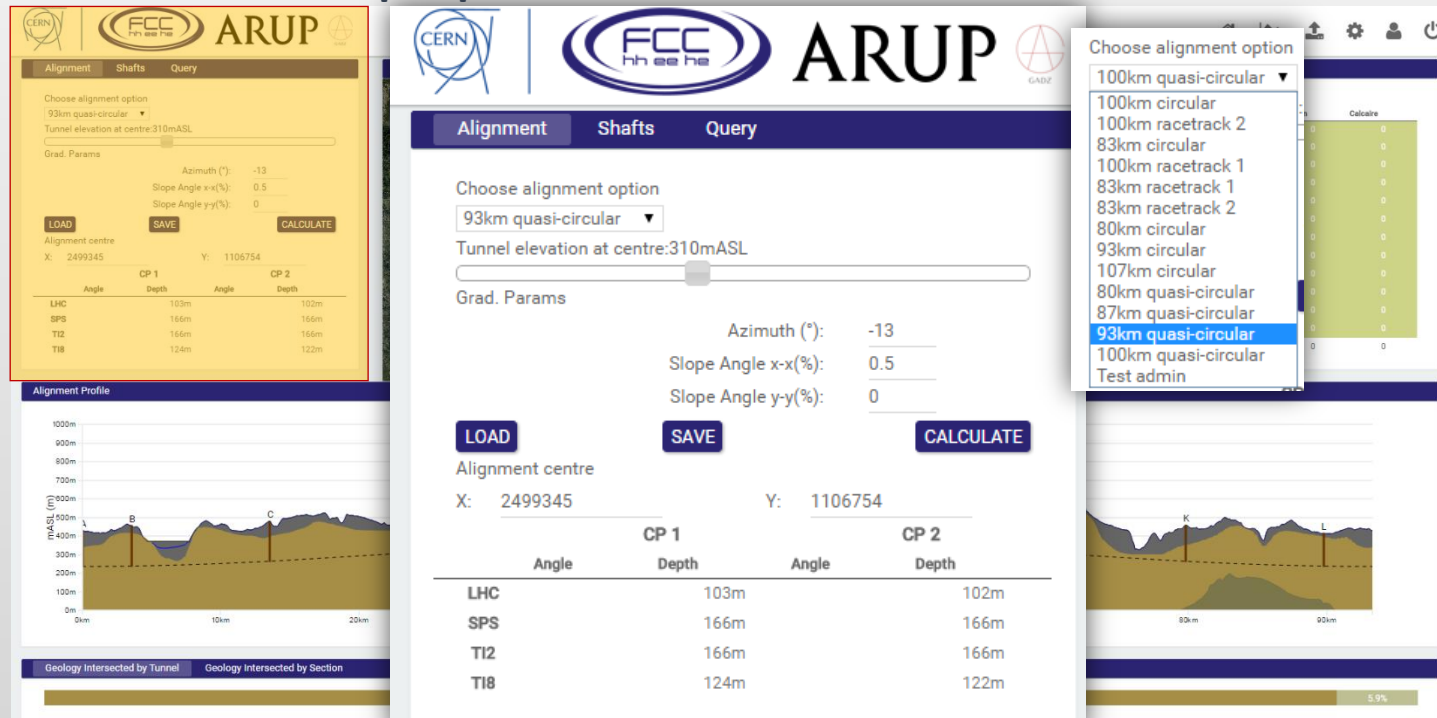


## La géothermie



Geothermal drillings

## User interface - Input parameters



The screenshot displays the user interface of the BIM Tunnel Optimisation Tool, featuring the CERN, FCC, and ARUP logos. The interface is divided into three main sections: Alignment, Shafts, and Query.

**Alignment Section:**

- Choose alignment option:** A dropdown menu showing "93km quasi-circular".
- Tunnel elevation at centre:** A slider set to 310mASL.
- Grad. Params:**
  - Azimuth (\*): -13
  - Slope Angle x-x(%): 0.5
  - Slope Angle y-y(%): 0
- Buttons:** LOAD, SAVE, CALCULATE.
- Alignment centre:** X: 2499345, Y: 1106754.
- Table:**

	Angle	Depth	Angle	Depth
LHC		103m		102m
SPS		166m		166m
T12		166m		166m
T18		124m		122m

**Alignment Profile:** A graph showing the tunnel profile with points A, B, C, and D. The y-axis is labeled "mASL (m)" and ranges from 0 to 1000. The x-axis is labeled "km" and ranges from 0 to 20.

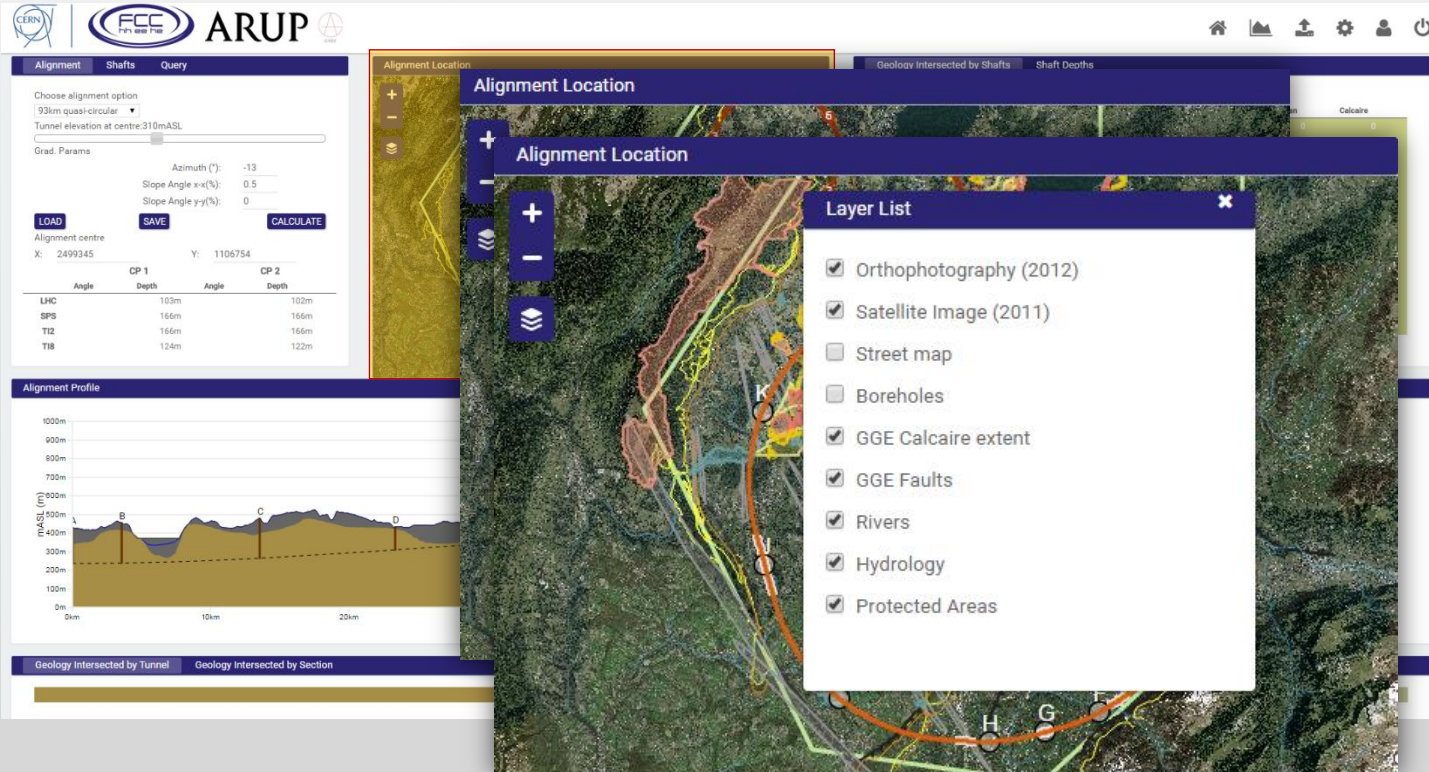
**Geology Intersected by Tunnel / Geology Intersected by Section:** A section at the bottom showing geological data.

**Choose alignment option dropdown:**

- 100km quasi-circular
- 100km circular
- 100km racetrack 2
- 83km circular
- 100km racetrack 1
- 83km racetrack 1
- 83km racetrack 2
- 80km circular
- 93km circular
- 107km circular
- 80km quasi-circular
- 87km quasi-circular
- 93km quasi-circular (selected)
- 100km quasi-circular
- Test admin

# BIM – Tunnel Optimisation Tool

## User interface - Input parameters



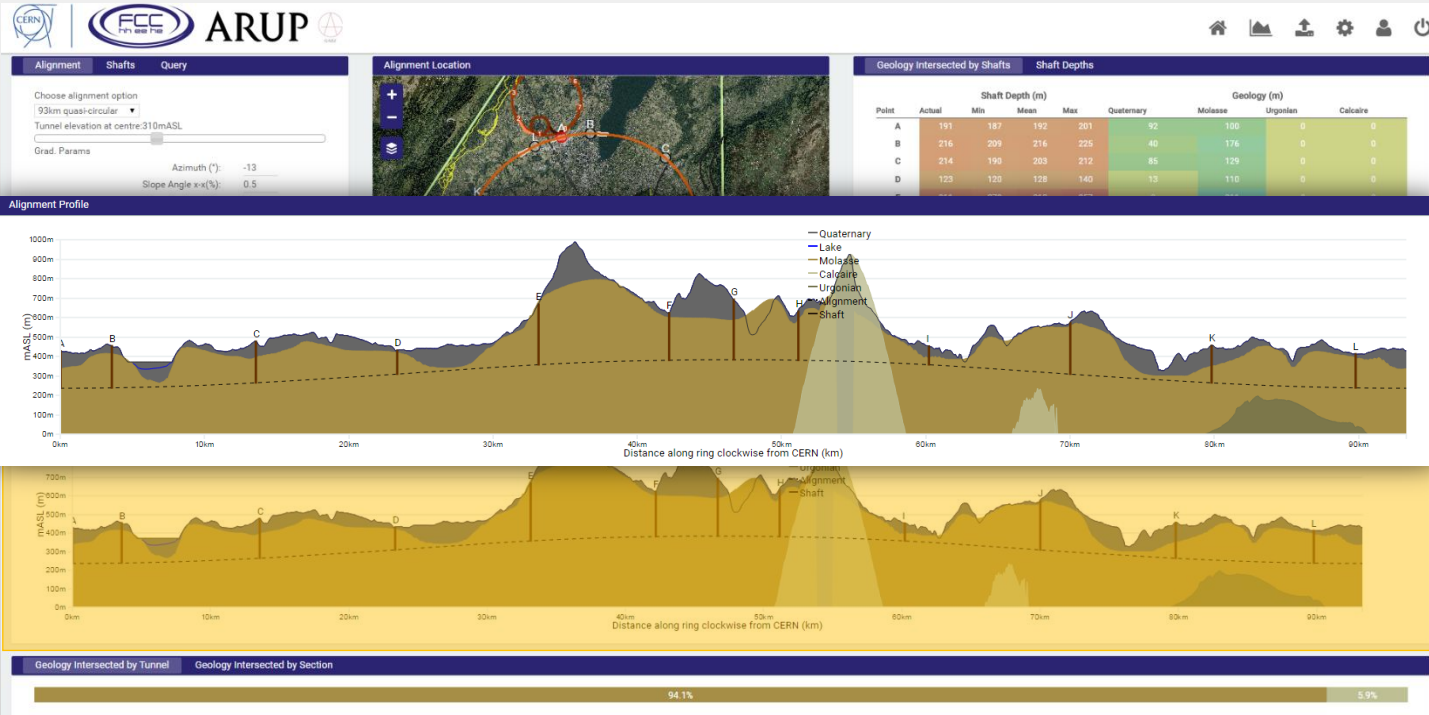
The screenshot displays the user interface of the BIM – Tunnel Optimisation Tool. The interface is divided into several panels and sections:

- Top Bar:** Contains logos for CERN, FCC, and ARUP, along with navigation icons (home, map, upload, settings, user, power).
- Alignment Location Panel:**
  - Choose alignment option:** 93km quasi-circular.
  - Tunnel elevation at centre:** 310mASL.
  - Grad. Params:**
    - Alignment centre: X: 2499345, Y: 1106754.
    - CP 1: Angle 103m, Depth 166m.
    - CP 2: Angle 102m, Depth 166m.
  - Buttons:** LOAD, SAVE, CALCULATE.
- Alignment Profile Panel:**
  - Graph:** A cross-section profile showing the tunnel alignment (dashed line) and ground surface (solid line) with points A, B, C, and D marked.
  - Y-axis:** Elevation (m) from 0 to 1000m.
  - X-axis:** Distance (km) from 0 to 20km.
- Map View:**
  - Alignment Location:** A map showing the tunnel alignment (orange line) overlaid on a satellite image.
  - Layer List:**
    - ☒ Orthophotography (2012)
    - ☒ Satellite Image (2011)
    - ☐ Street map
    - ☐ Boreholes
    - ☒ GGE Calcaire extent
    - ☒ GGE Faults
    - ☒ Rivers
    - ☒ Hydrology
    - ☒ Protected Areas

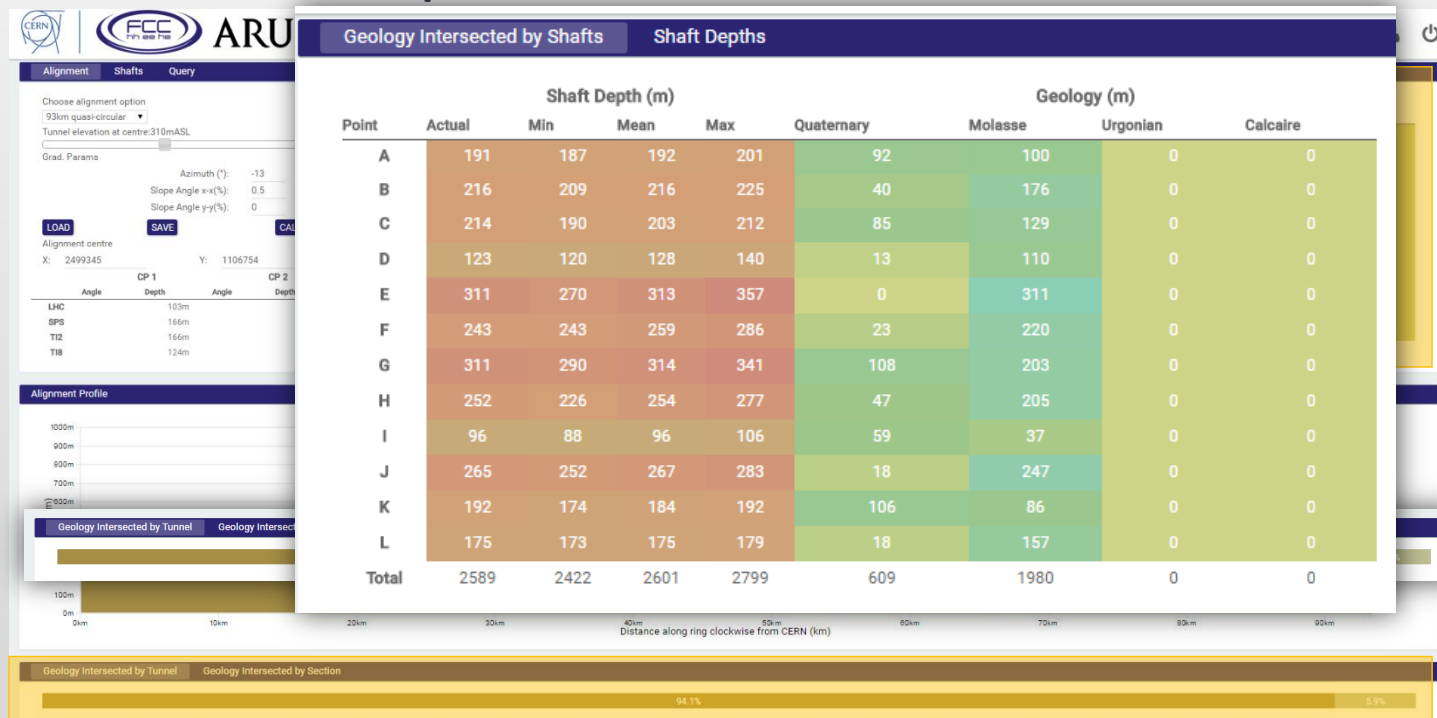
# BIM – Tunnel Optimisation Tool



## User interface – Alignment profile



## User interface – Outputs



Alignment

Shaft Tools

Choose alignment option

93km quasi-circular ▾

Tunnel depth at centre: 299mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .5

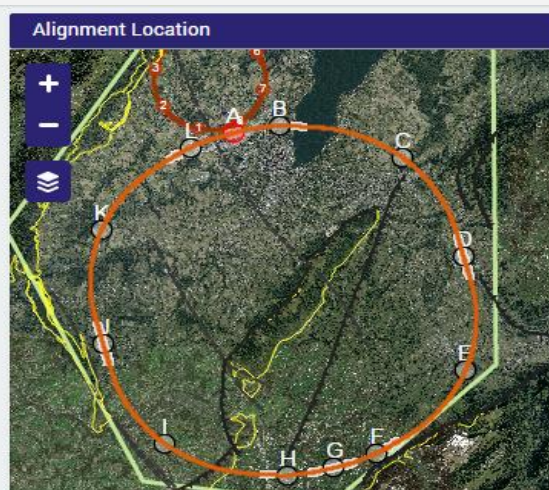
Slope Angle y-y(%): 0

**CALCULATE**

Alignment centre

X: 2499812 Y: 1106889

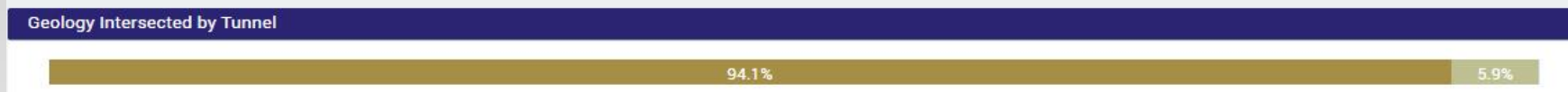
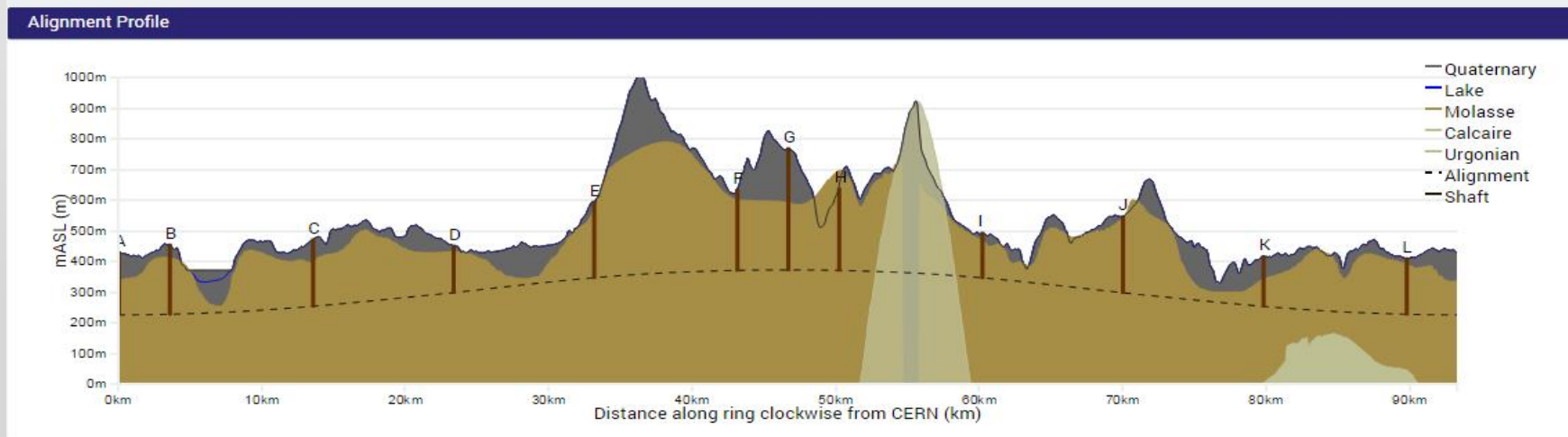
LHC Intersection	CP 1	CP 2
Angle		
Depth	586m	587m



Geology Intersected by Shafts

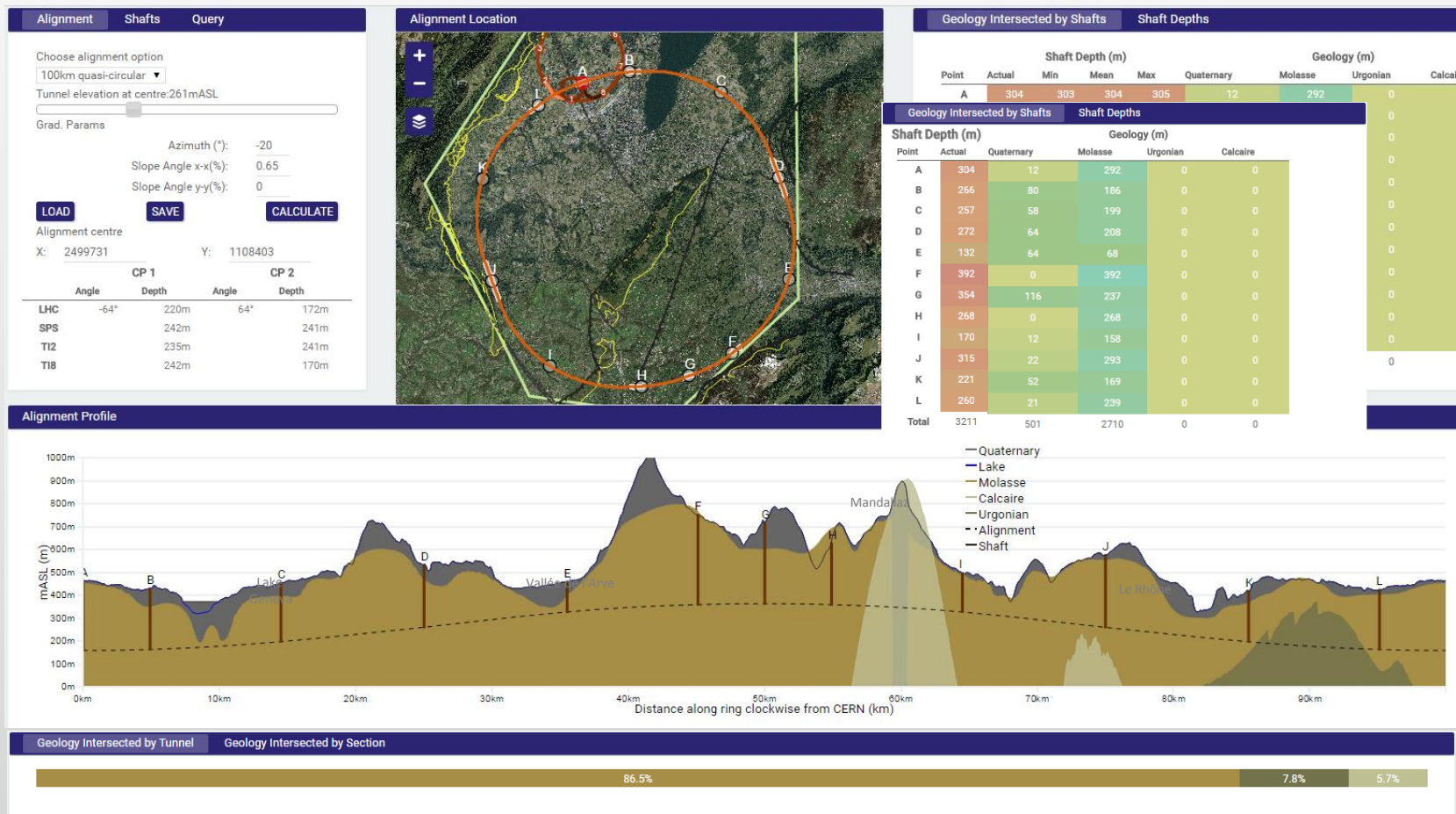
Shaft Depths

Point	Shaft Depth (m)				Geology (m)			
	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	203	200	204	212	93	111	0	0
B	226	213	224	231	42	185	0	0
C	218	208	217	225	75	143	0	0
D	153	150	154	158	19	134	0	0
E	247	233	249	261	24	223	0	0
F	262	251	269	304	32	230	0	0
G	396	392	393	396	177	220	0	0
H	266	231	274	322	0	325	0	0
I	146	141	144	149	26	120	0	0
J	248	247	251	258	6	242	0	0
K	163	153	159	164	76	87	0	0
L	182	182	184	187	17	165	0	0
Total	2711	2601	2722	2867	586	2184	0	0



# Feasibility Study – Early results

## 100km circumference : “LHC Intersecting option”



- Avoids Jura limestone: **No**
- Max overburden: **650m**
- Deepest shaft: **392m**
- % of tunnel in limestone: **13.5%**
- Total shaft depths: 3211m

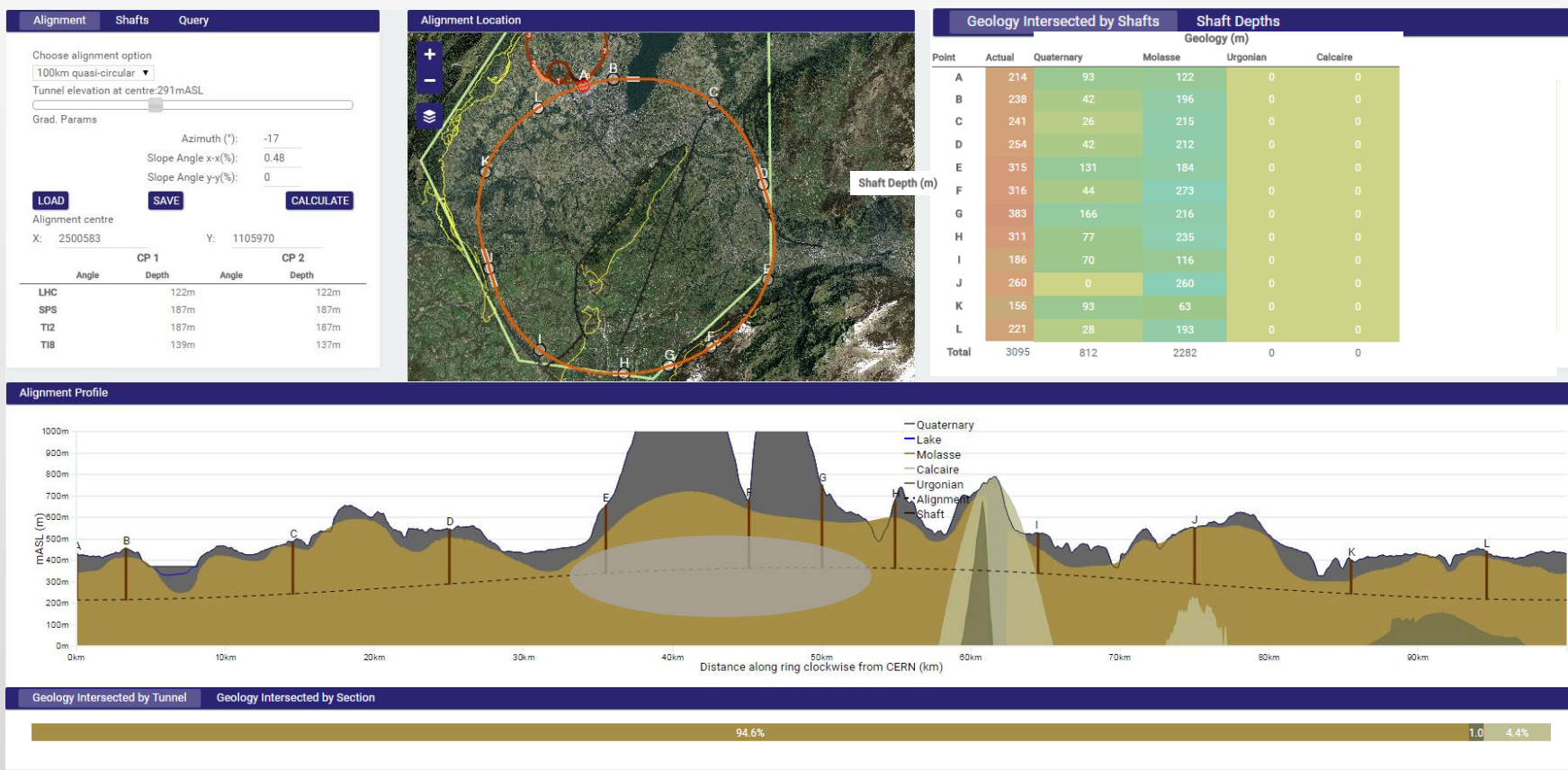
Point A Campus: Prevessin (large potential area)

Challenges:

- 7.8km tunnelling through Jura limestone
- 300m-400m deep shafts and caverns in molasse

# Feasibility Study – Early results

## 100km circumference : “Non-intersecting option”



- Avoids Jura limestone: **Yes**
- Max overburden: **1350m**
- Deepest shaft: **383m**
- % of tunnel in limestone: **4.4%**
- Total shaft depths: **3095m**

Point A Campus: Meyrin (small potential area, next to airport)

Challenges:

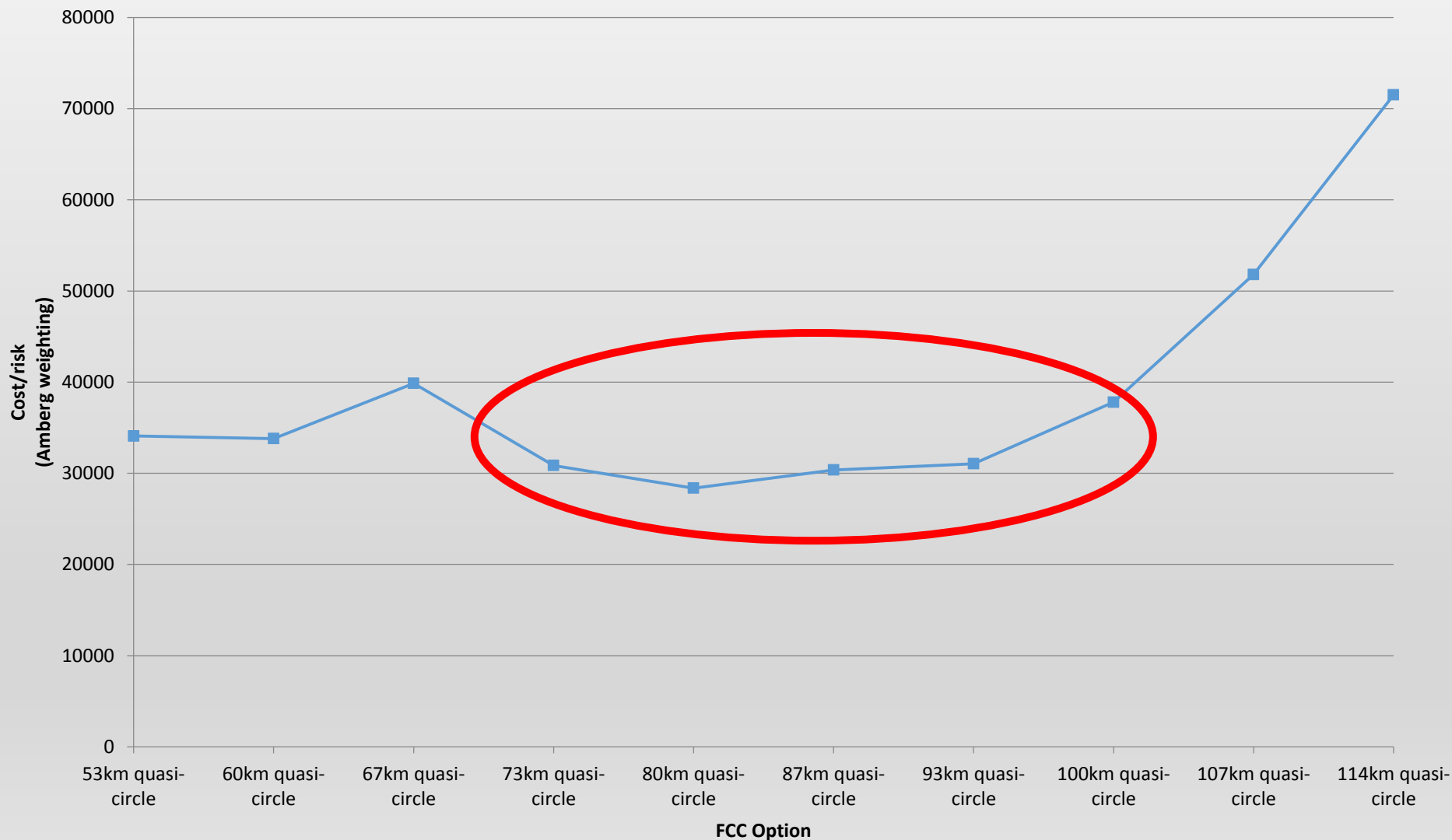
- 1.35km tunnel overburden
- 300m-400m deep shafts and caverns in molasse



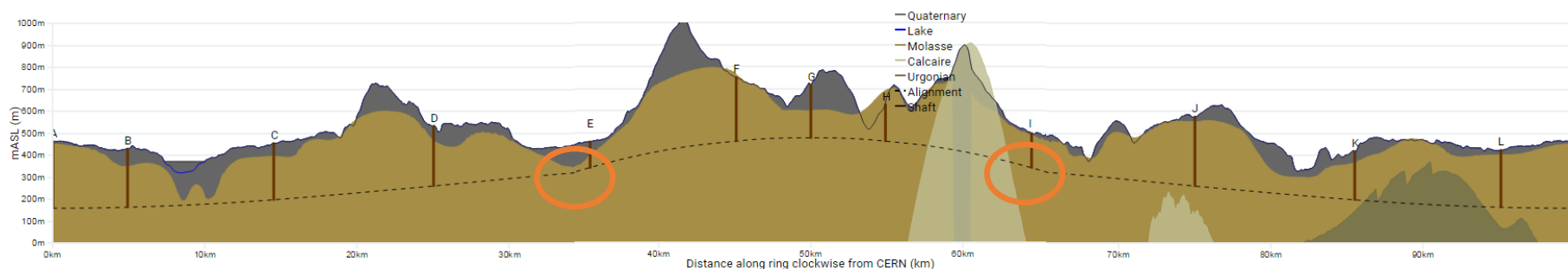
# Siting Review June 2015

## Comparison between options of different circumference

### Total Amberg cost/risk adjusted for circumference



## 100km Single Kink Example



### 100km Example

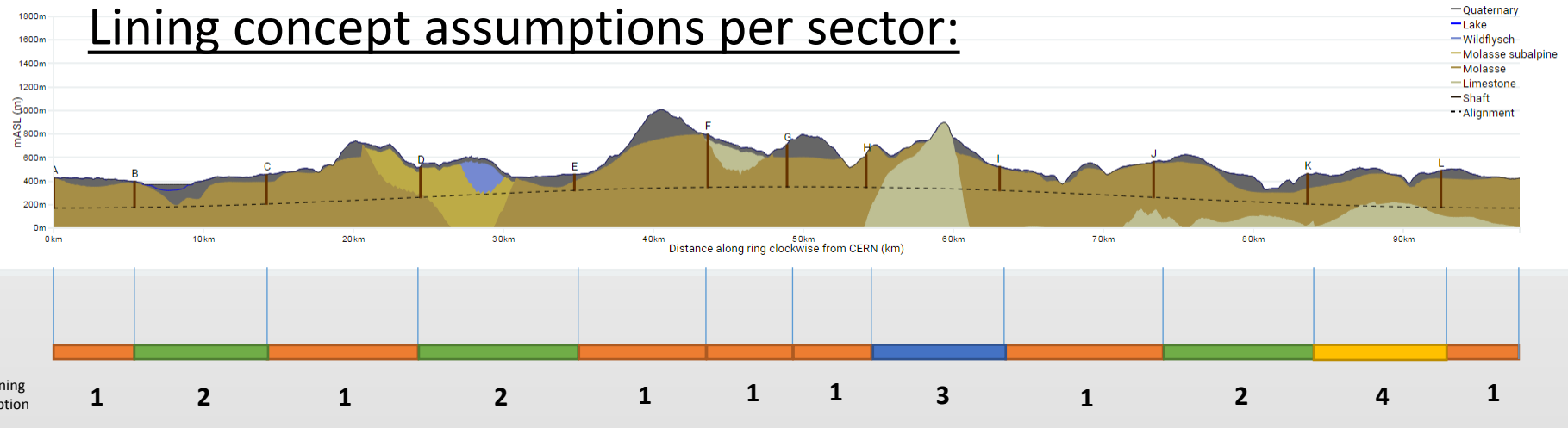
Slope after kink [%]	Change in slope [%]	Shaft Depths					Total depth (of all 12 shafts)	Shaft depths % Reduction
		E	F	G	H	I		
0.5	0.0	132	392	354	268	170	3211	0%
0.9	0.25	131	378	339	254	169	3166	1%
1.4	0.75	128	350	307	226	166	3072	4%
2.4	1.75	110	290	241	166	157	2859	11%

### Benefits to CE:

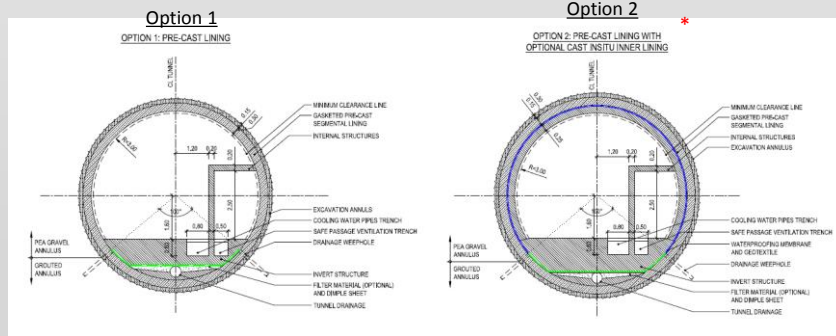
- 50m-100m reduction in depth of the deepest shafts is possible
- Overall shaft construction reduced by 140m – 352m (equivalent to removing 1 shaft)

# FCC Tunnel Lining Concepts

Alignment Profile

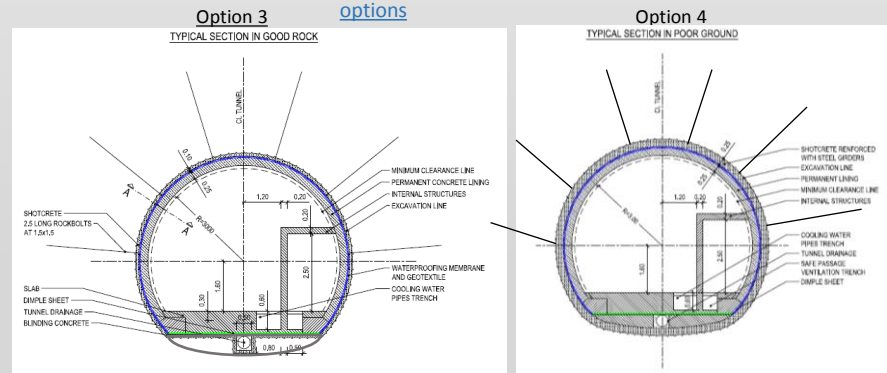


TBM Tunnel options



\*It is assumed 50% will have optional inner lining

Mined Tunnel options

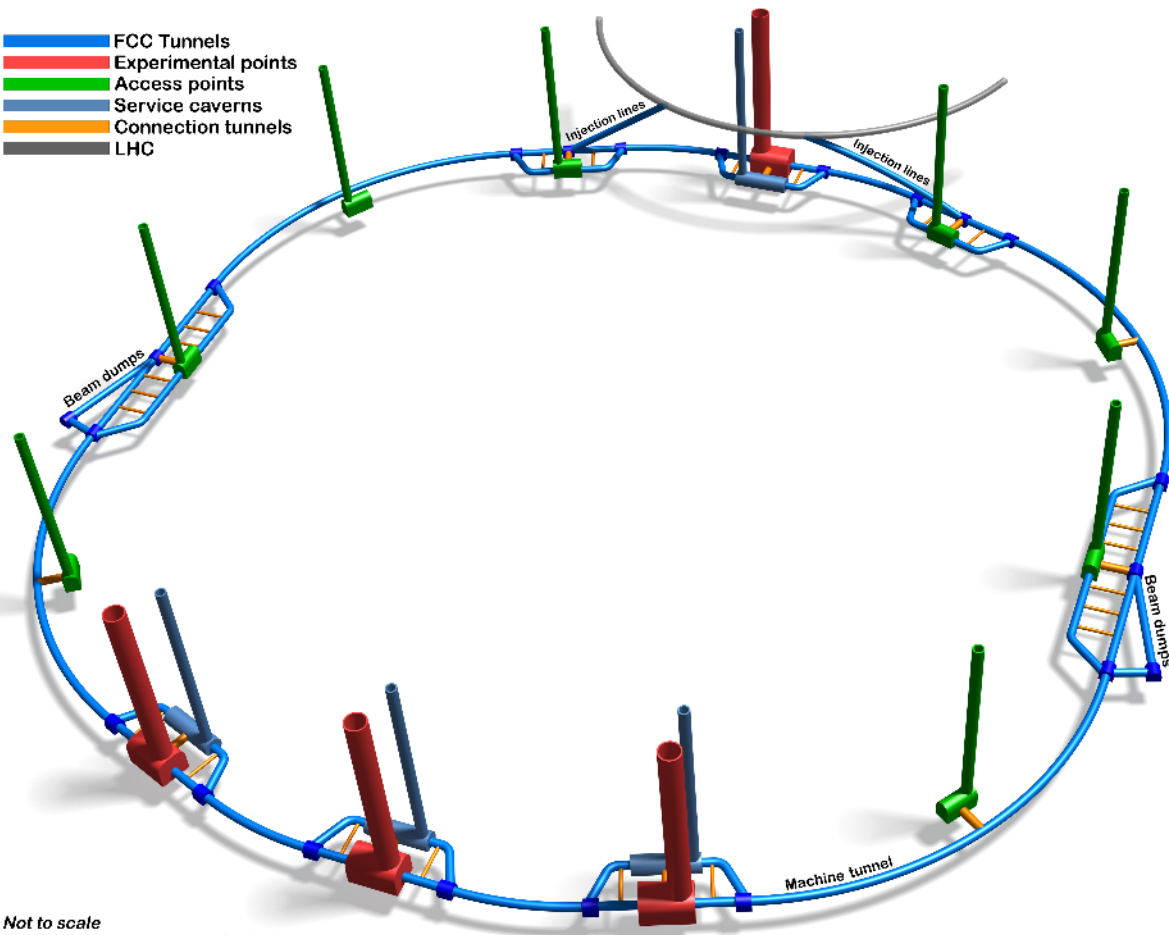


## FUTURE CIRCULAR COLLIDER (FCC) - 3D Schematic

### Underground Infrastructure - Single Tunnel Design

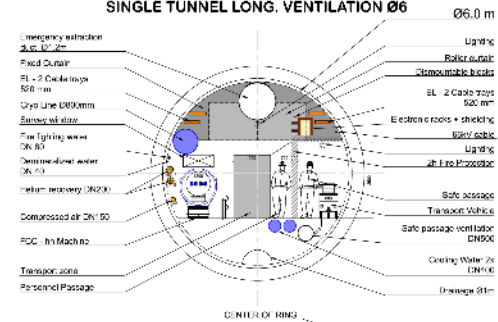
John Osborne - Charlie Cook - Ángel Navascués

- FCC Tunnels
- Experimental points
- Access points
- Service caverns
- Connection tunnels
- LHC

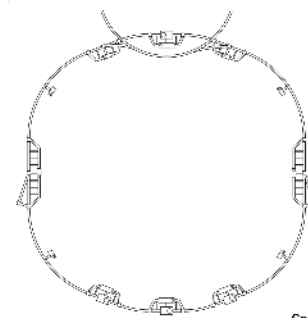
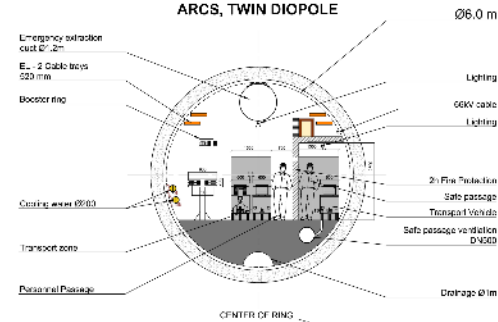


Not to scale  
Frequency of cross-passages for illustration only

### FCC-HH POSSIBLE TUNNEL CROSS SECTION: SINGLE TUNNEL LONG. VENTILATION Ø6



### FCC-ee POSSIBLE TUNNEL CROSS SECTION: ARCS, TWIN DIPOLE

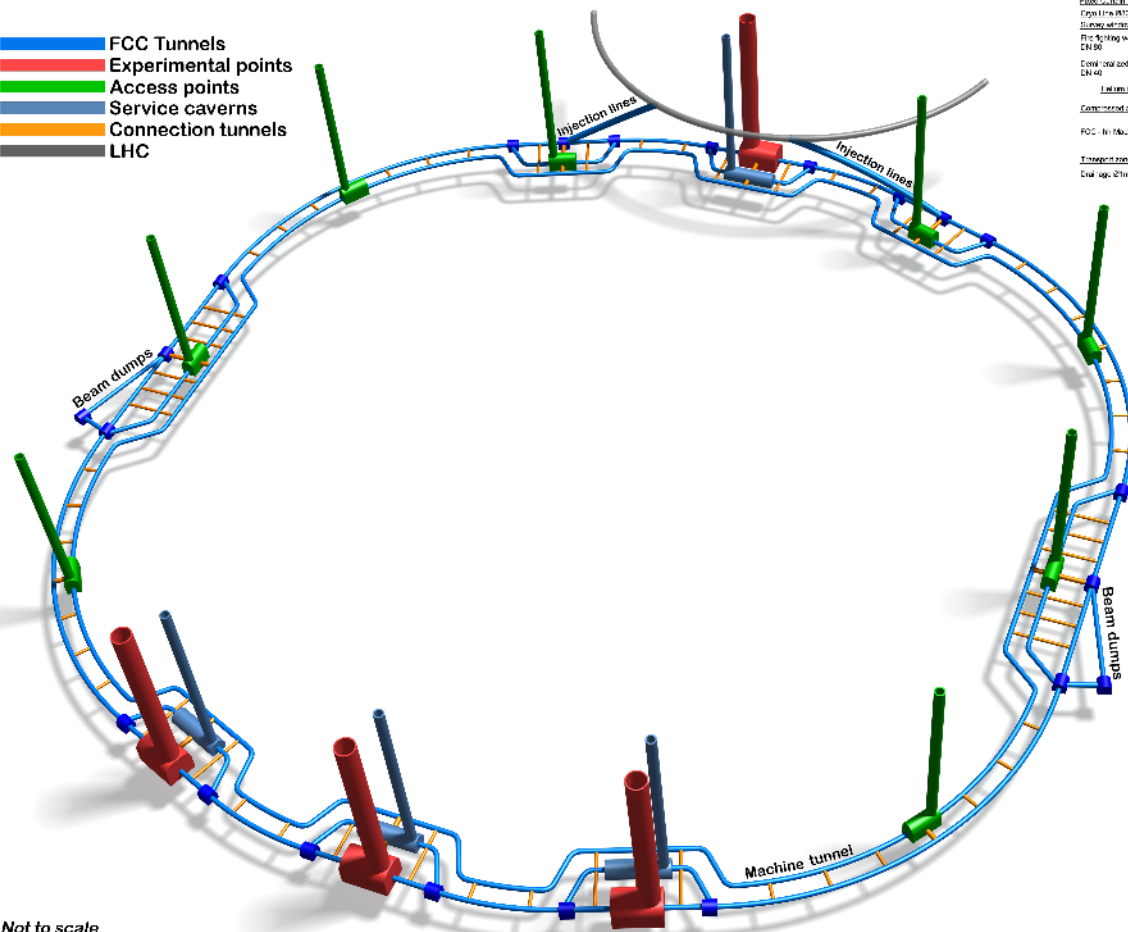


## FUTURE CIRCULAR COLLIDER (FCC) - 3D Schematic

### Underground Infrastructure - Twin Tunnel Design

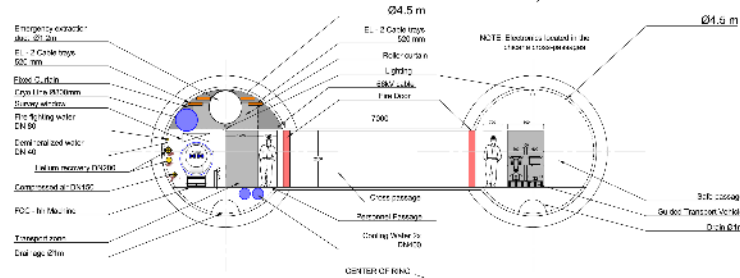
John Osborne - Charlie Cook - Ángel Navascués

- FCC Tunnels
- Experimental points
- Access points
- Service caverns
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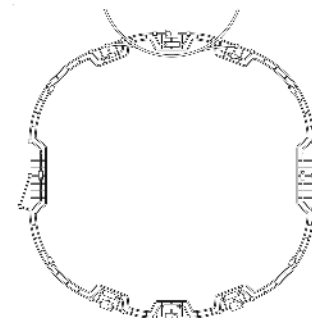
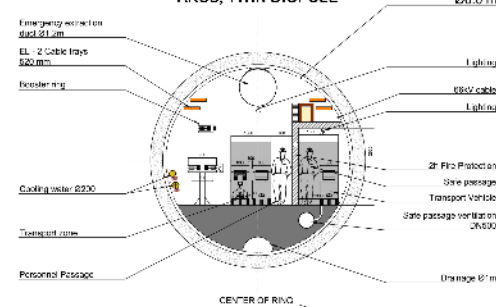


Not to scale  
Frequency of cross-passages for illustration only

FCC-HH POSSIBLE TUNNEL CROSS SECTION:  
DOUBLE TUNNEL LONG. VENTILATION Ø4,5

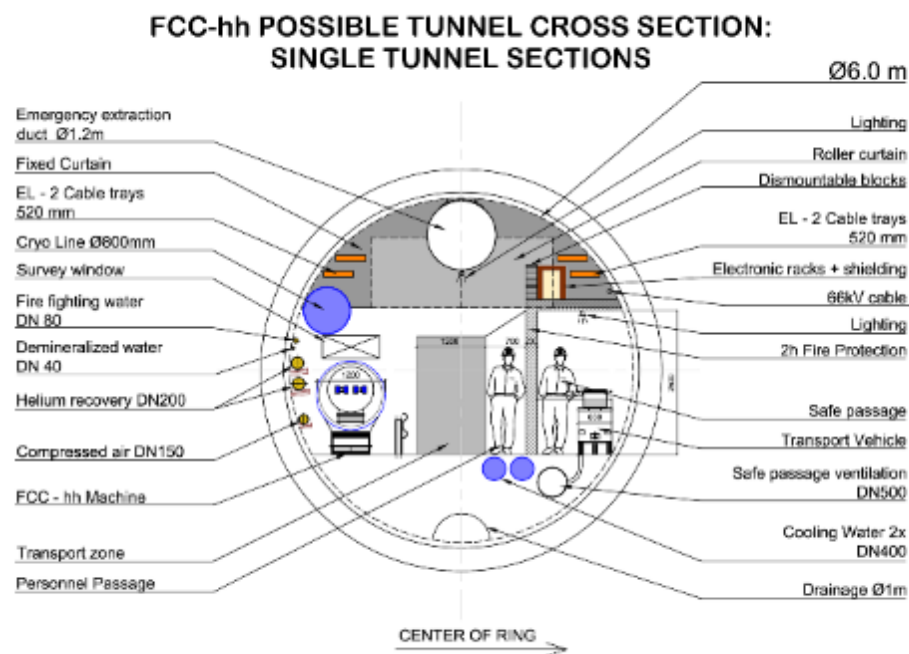


FCC-ee POSSIBLE TUNNEL CROSS SECTION:  
ARCS, TWIN DIPOLE

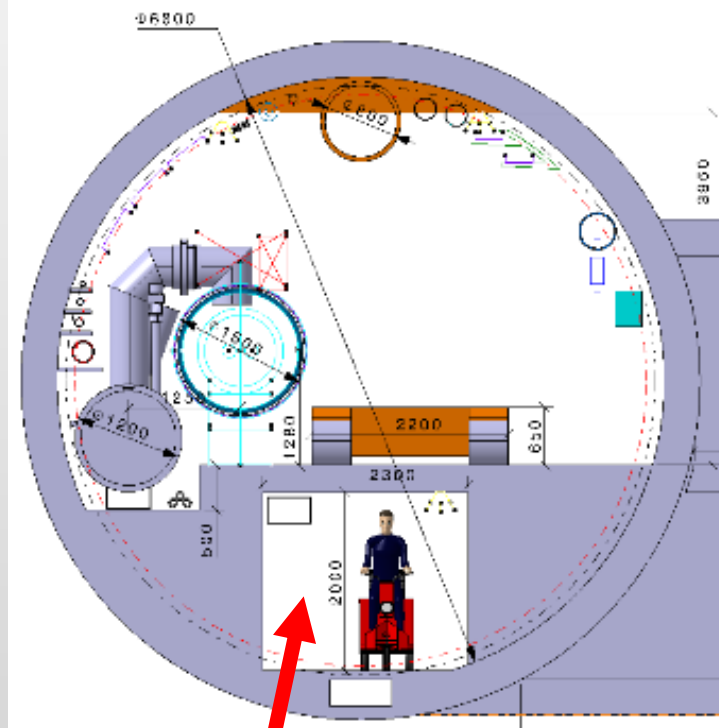


# FCC Single tunnel cross-sections

6.0m tunnel

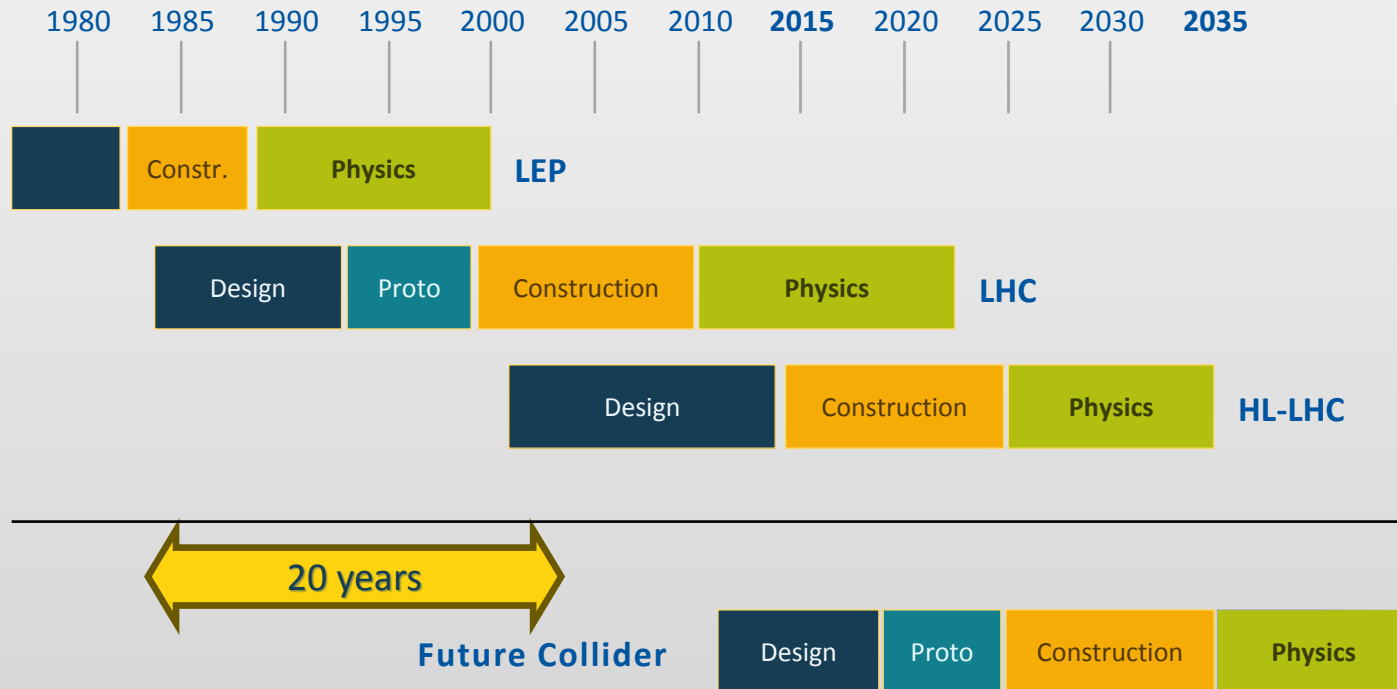


6.8m tunnel



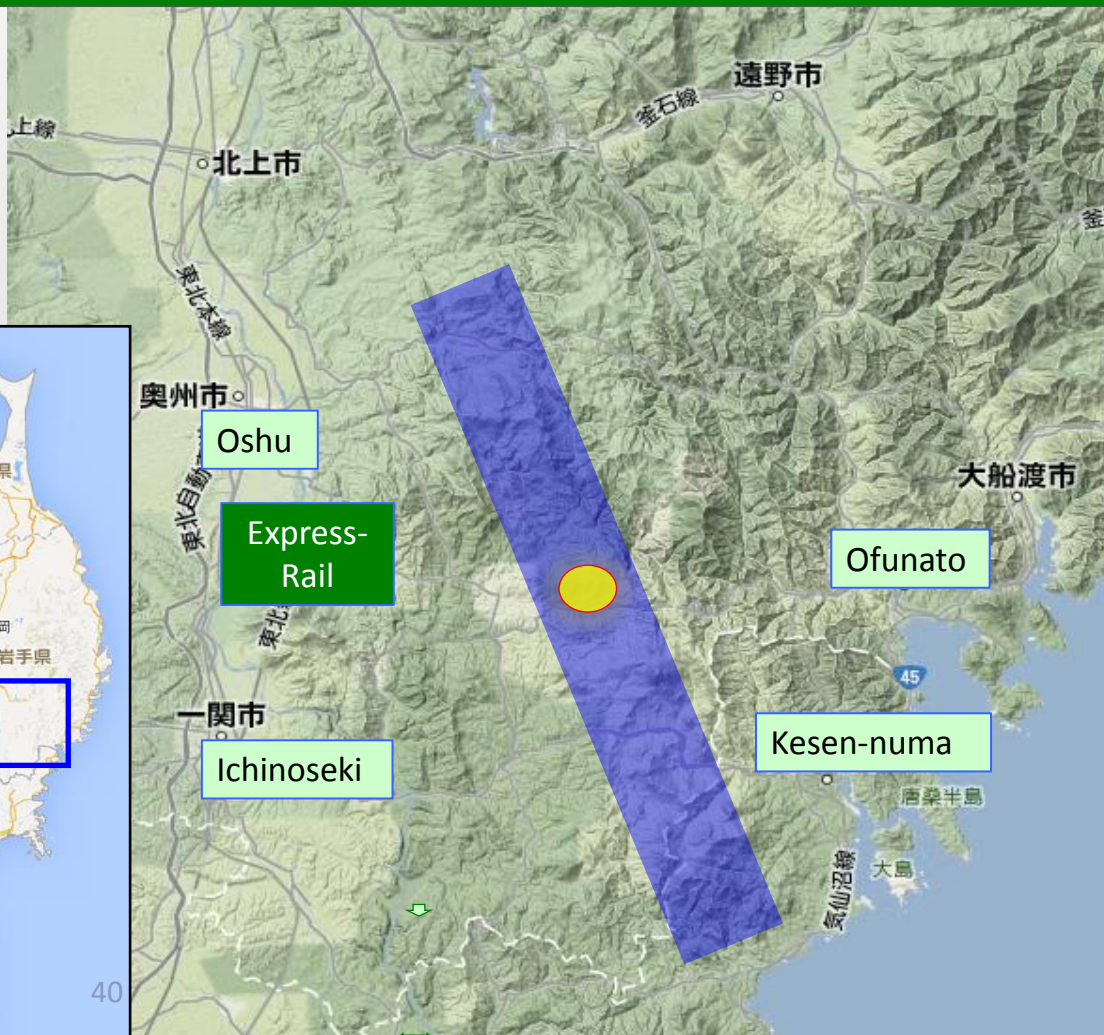


# CERN Circular Colliders + FCC



## ILC Site Candidate Location in Japan: Kitakami

4



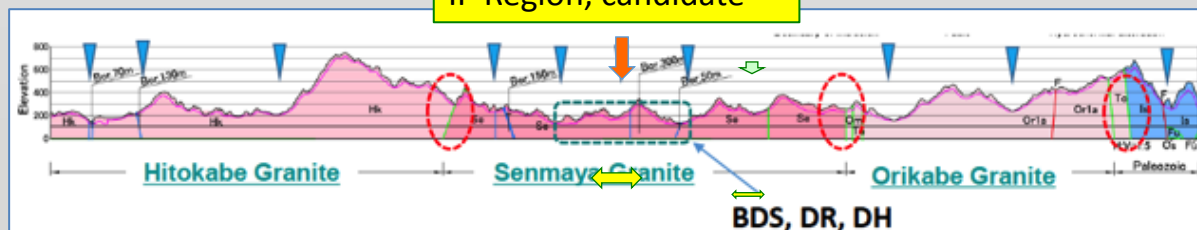
# A New Borehole at a Candidate Interaction Point



A new boring test progressed to demonstrate the “vertical access feasibility” for detector hall at IP



IP Region, candidate

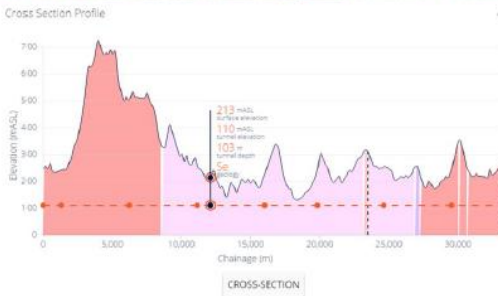


# CERN/KEK Collaboration to develop TOT for ILC Optimisation

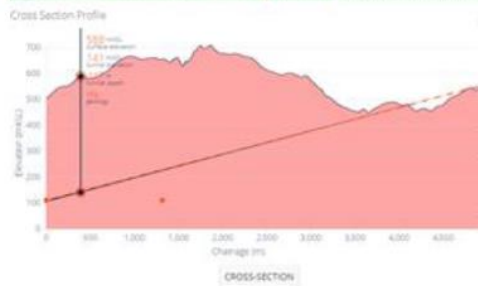
Many new features added to the tool, such as :

- IP position can be changed
- LINAC Rotation/Flip
- Access tunnels

**New 250GeV  
Layouts/costing in 2017**



- Surface elevation: 305mASL
- Tunnel elevation: 110mASL
- Tunnel depth: 195mASL
- Geology: Se

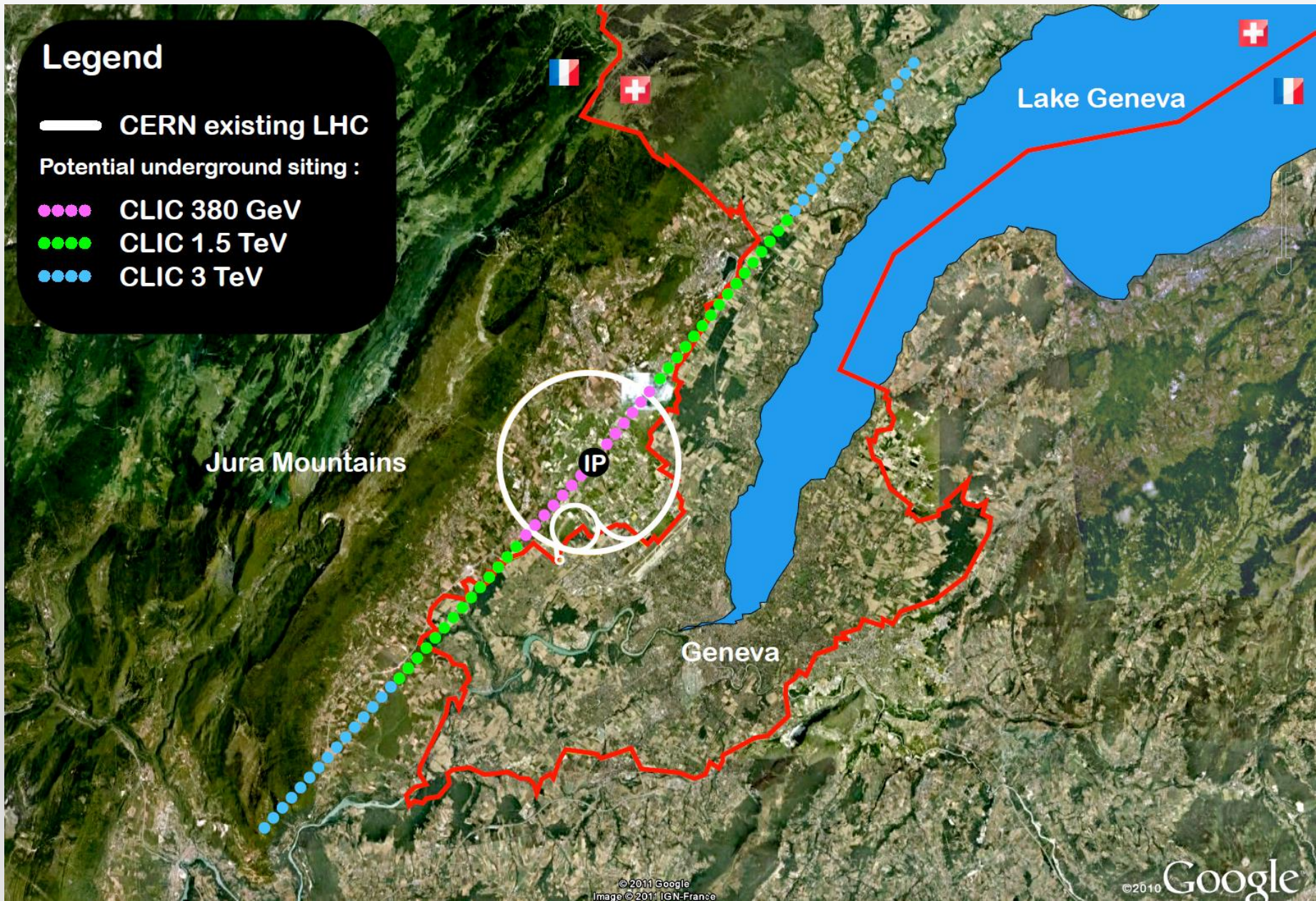


- Surface elevation: 588mASL
- Tunnel elevation: 141mASL
- Tunnel depth: 430mASL
- Geology: Hk

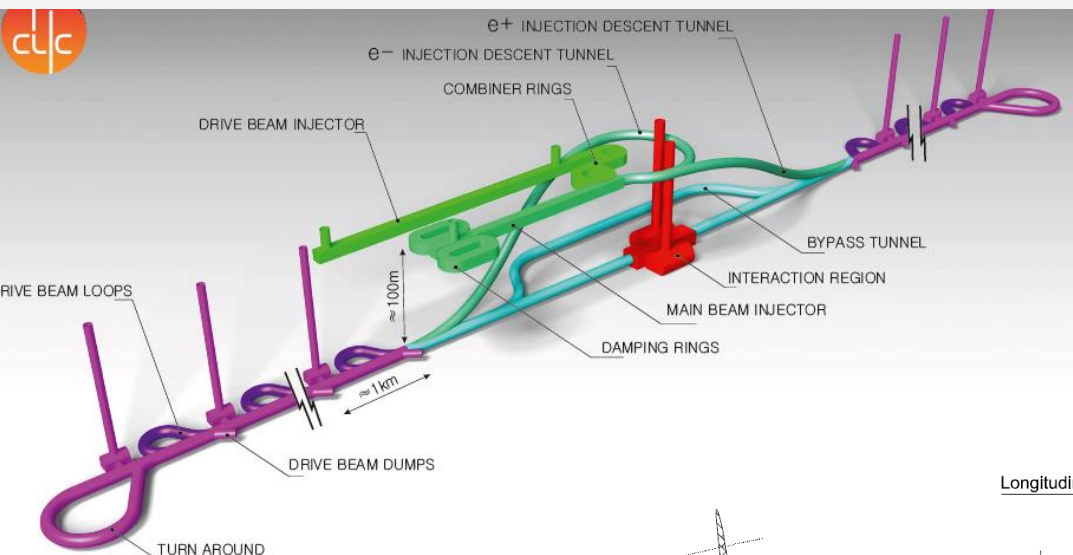


TOT now being developed for ILC Japan Site and road tunnel under Stonehenge

# Compact Linear Collider (CLIC) Studies at CERN



# CLIC Studies at CERN



CLIC SCHEMATIC  
(not to scale)

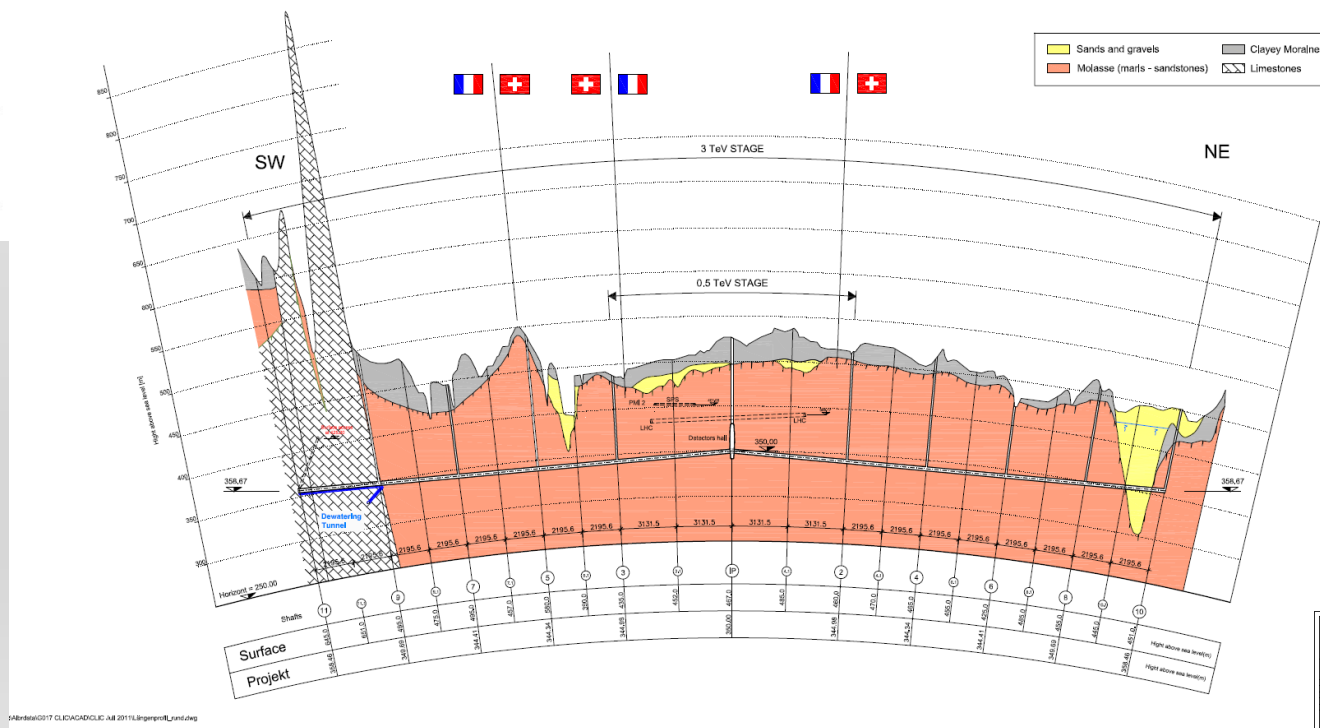
New 380GeV, 1.5TeV and 3.0TeV accelerator layouts to be developed in 2017 ready for next European Strategy update.

Klystron option also being studied.

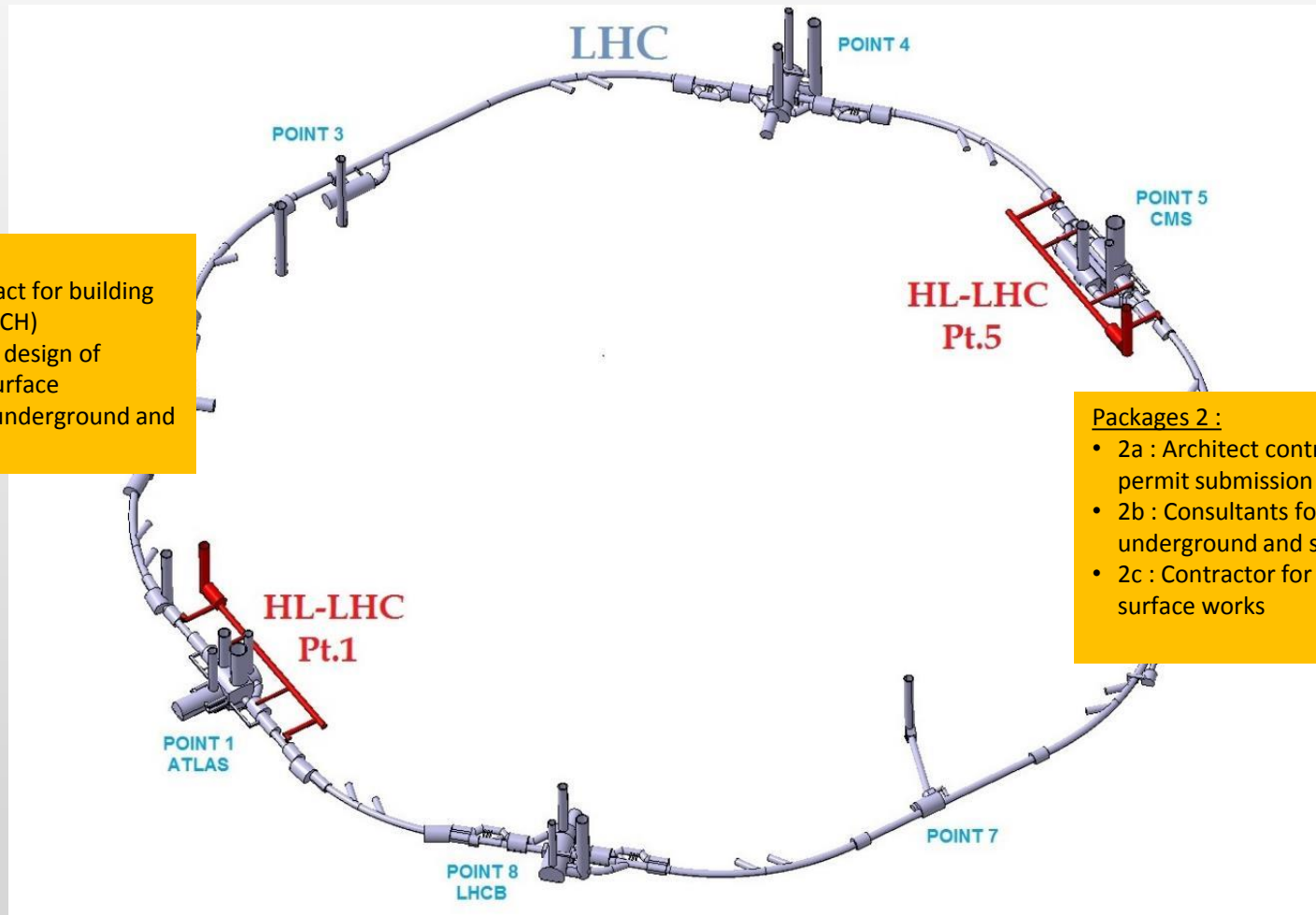
CLIC TOT ?

New Infrastructure WG being set-up (CE, EL, CV etc).

Longitudinal section 1:100'000 / 2000



# • High Luminosity LHC Project (HL-LHC)



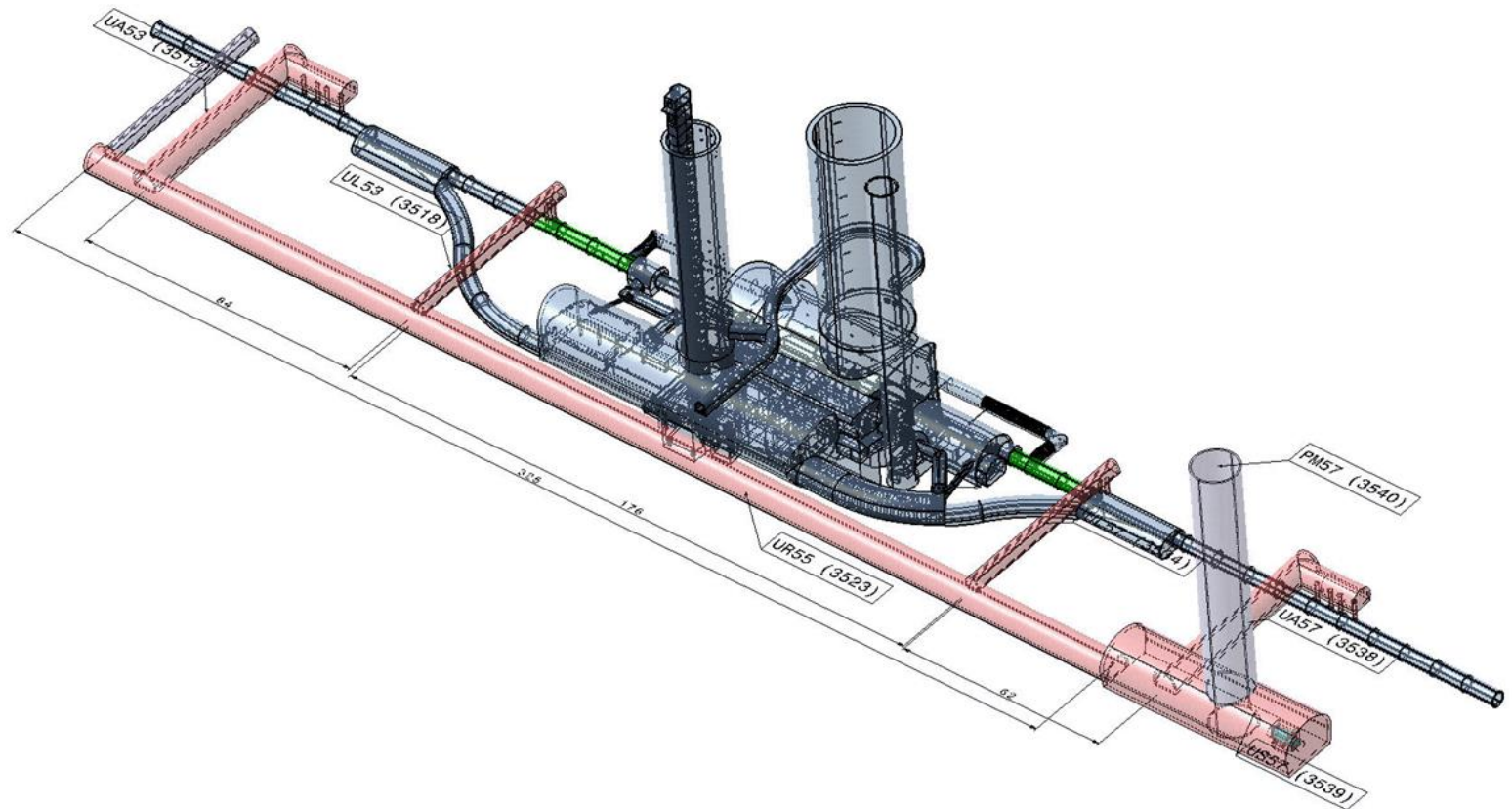
## Packages 1 :

- 1a : Architect contract for building permit submission (CH)
- 1b : Consultants for design of underground and surface
- 1c : Contractor for underground and surface works

## Packages 2 :

- 2a : Architect contract for building permit submission (F)
- 2b : Consultants for design of underground and surface
- 2c : Contractor for underground and surface works

# HL Underground Civil Works at LHC Point 5 (CMS)



# Site boundary enlargement for HL civil works : Point 5 CMS



# Surface Works at Point 5 CMS



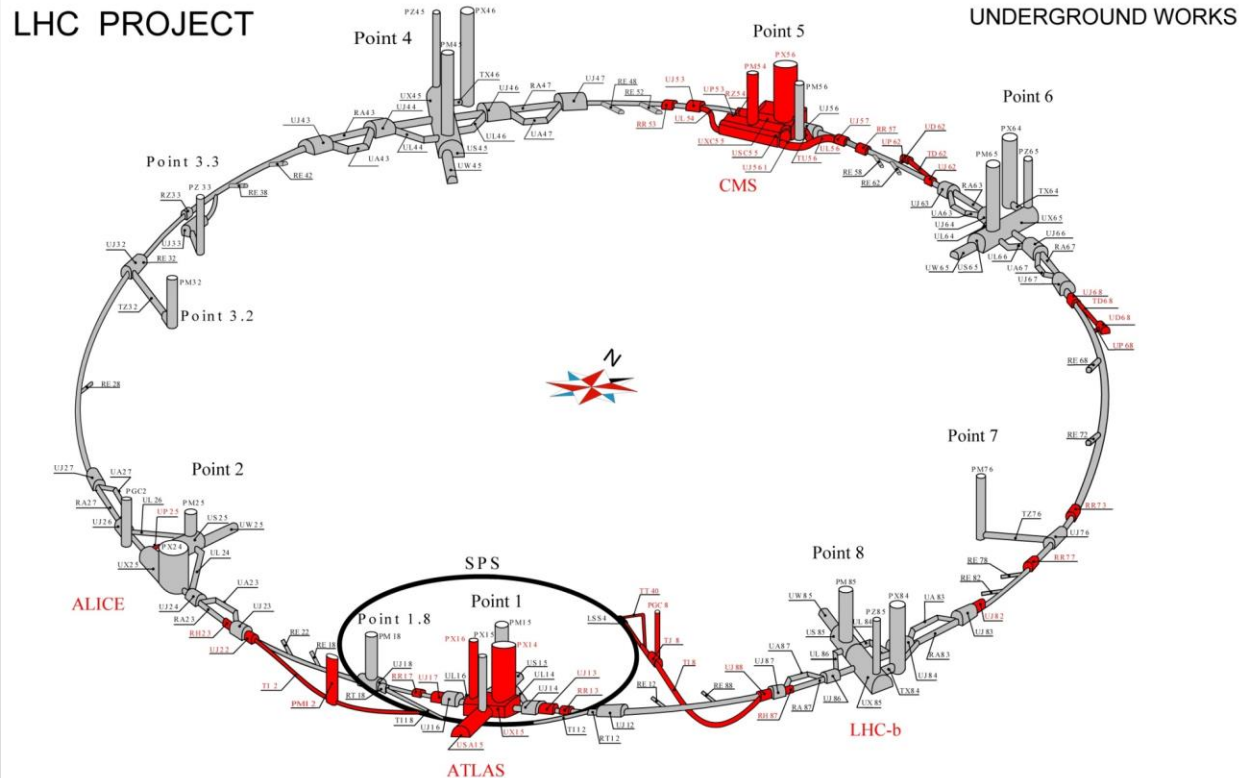


## ***Key challenges for High Luminosity and lessons learnt from LHC civil works :***

- Technical (e.g. unforeseen ground conditions, vibration impact on LHC, water ingress)
- Environmental (e.g. rock disposal, noise)
- Planning (Delay in Bld permit, vibration, revised LS2 schedule, installation windows for other CERN contractors)

# LHC Civil works very similar 1998-2005 (but on a larger scale)

## LHC PROJECT



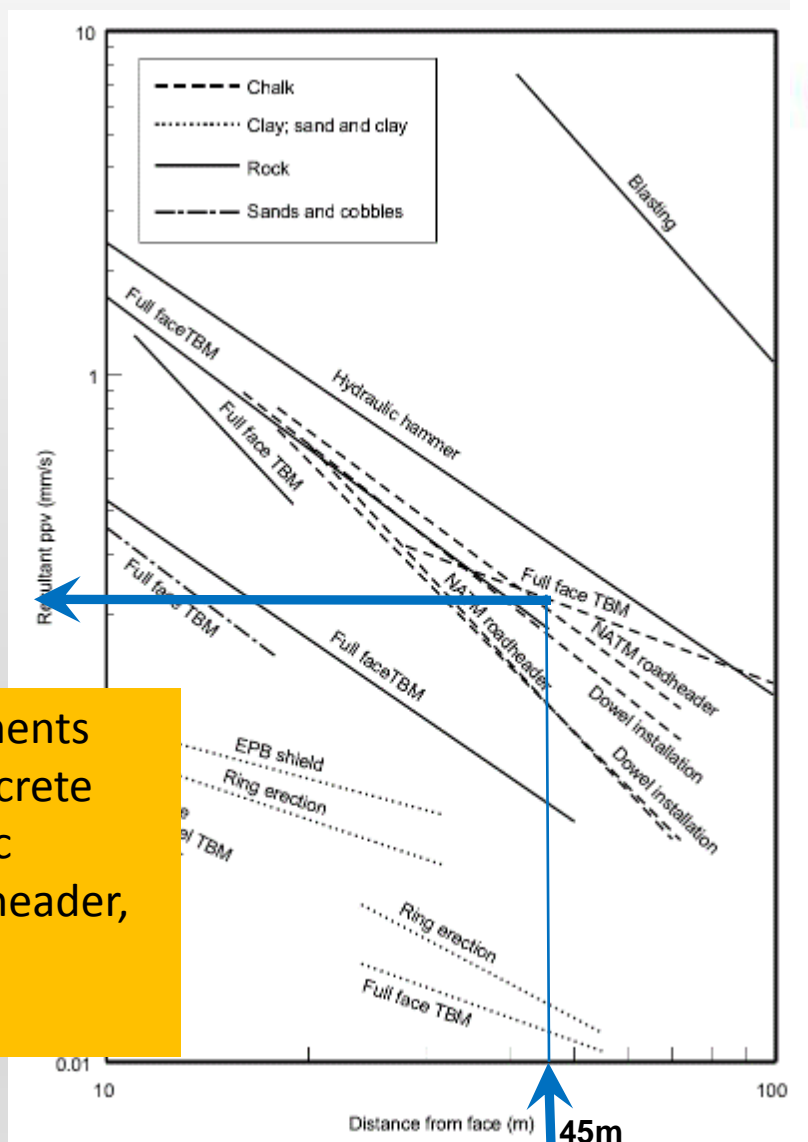
Package	Place		Consultants	Contractors
1	POINT 1	ATLAS	- EDF (F) - KNIGHT & PIESOLD (GB)	- TEERAG-ASDAG (A) - BARESEL (D) - LOCHER (CH)
2	POINT 5	CMS	- GIBB (GB) - GEOCONSULT (A) - SGI(CH)	- DRAGADOS (E) - SELI (I)
3A	Other Points	All other points except TI8 (including ALICE and LHC-b)	- BROWN & ROOT (GB) - INTECSA (E) - HYDROTECHNICA (P)	- TAYLOR-WOODROW (GB) - AMEC (GB) - SPIE-BATIGNOLLES (F)
3B	TI 8	TI 8 tunnel	DITO	- LOSINGER (CH)

# The main 'vibration' activities are driving the civil engineering planning

Results from Dr Hiller's (Arup) studies - Vibration from tunnelling

0.2 mm/s  
 $2 \times 10^{-4}$  m/s  
 200  $\mu$ m/s

New measurements needed for concrete pump, hydraulic hammer, roadheader, Jumbo



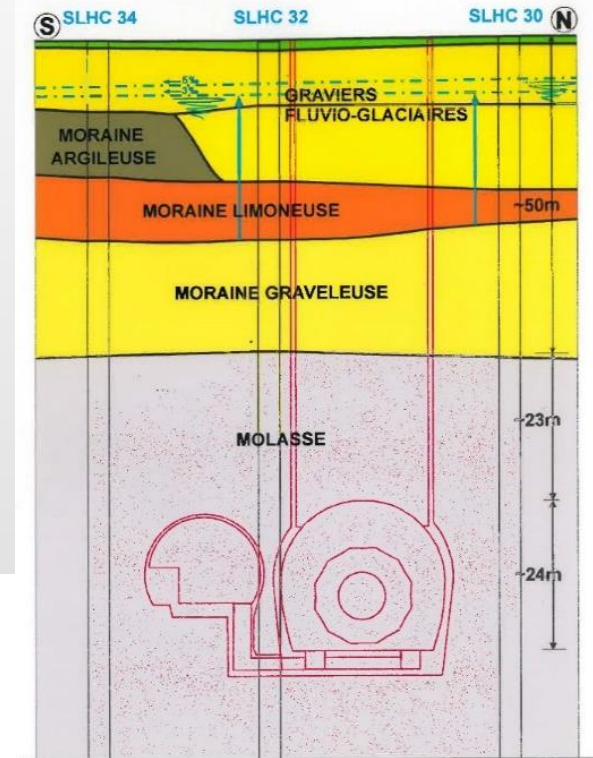
Roadheaders will be used for excavation



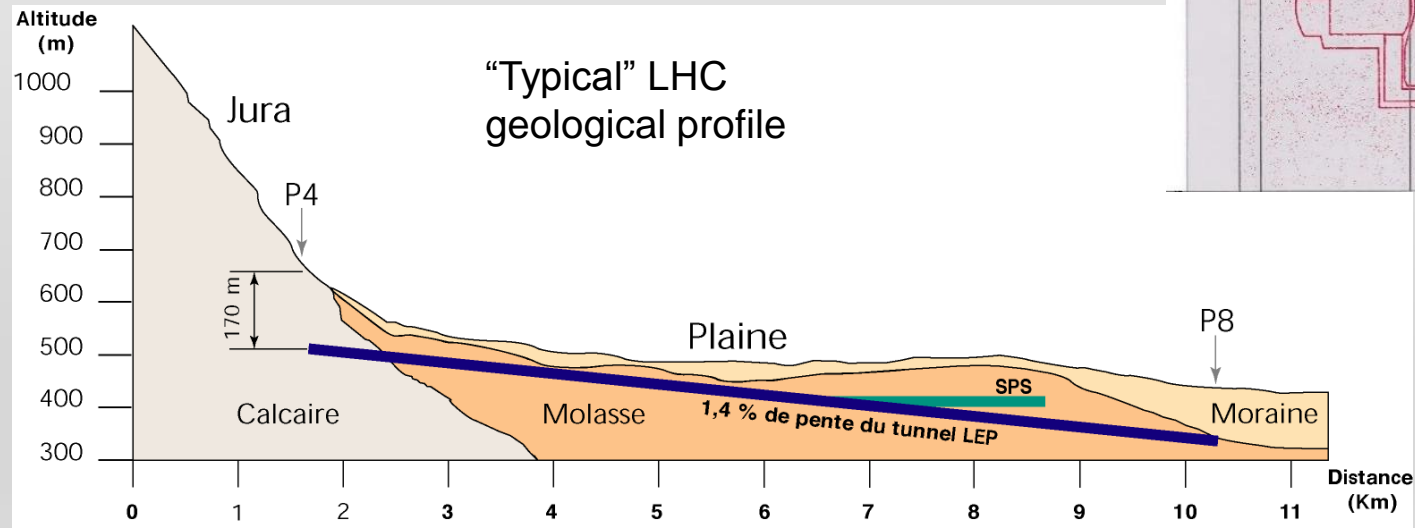
**At 45m, tunnelling vibration would give ~200  $\mu$ m/s peak**

# Technical Challenges : Unexpected ground conditions

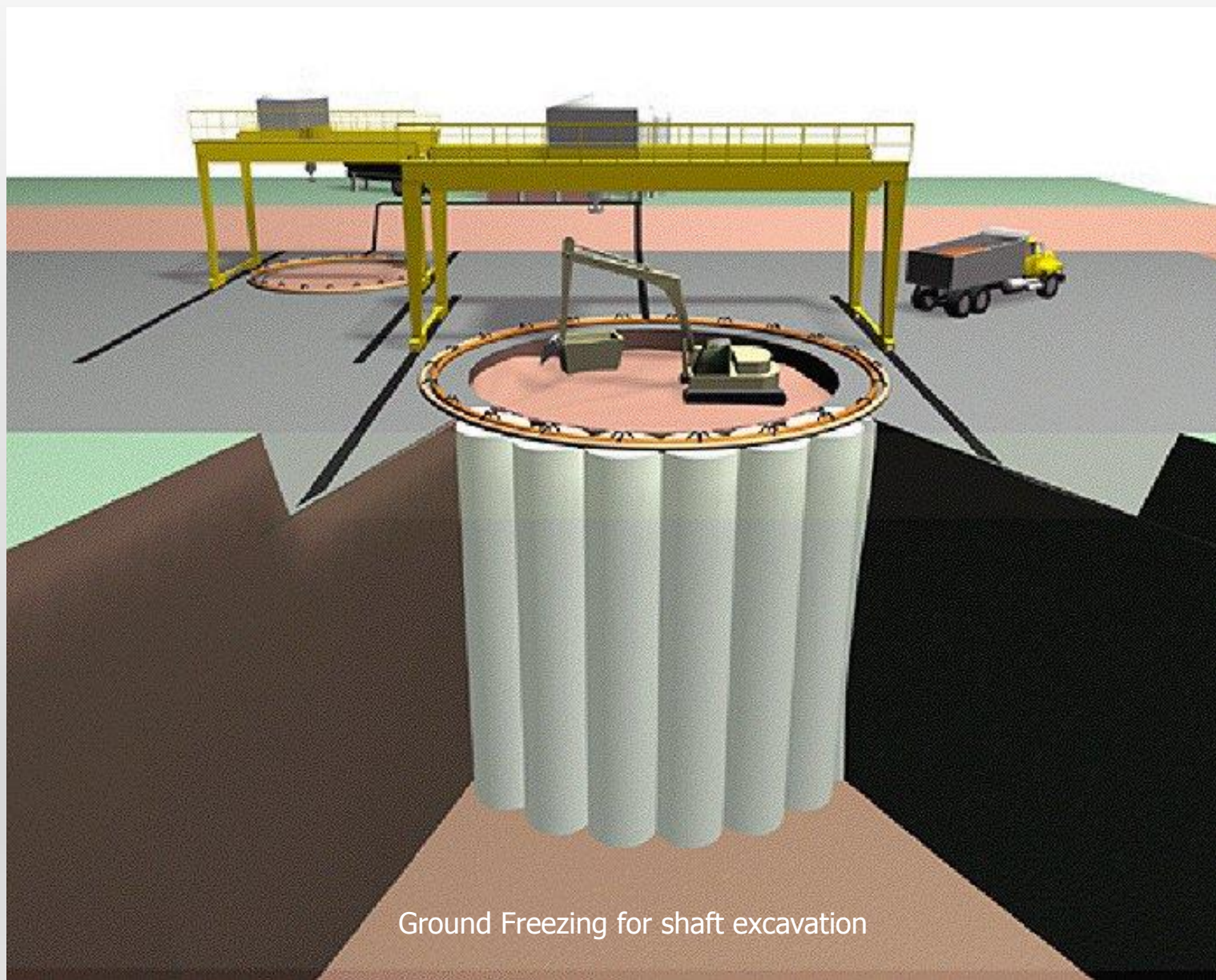
Point 5 CMS  
geological profile  
is fairly complex



“Typical” LHC  
geological profile



# Technical Challenges : CMS shaft ground freezing : 1998-2000



Ground Freezing for shaft excavation



1999

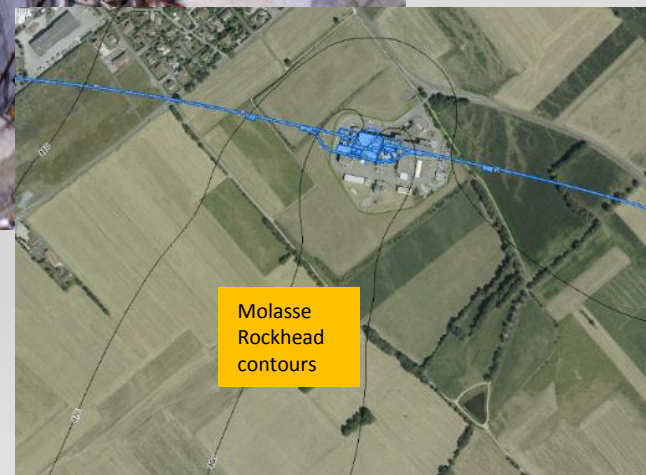


**Point 5 -Excavation commencement of PM54 shaft - July 09, 1999 - CERN ST-CE**







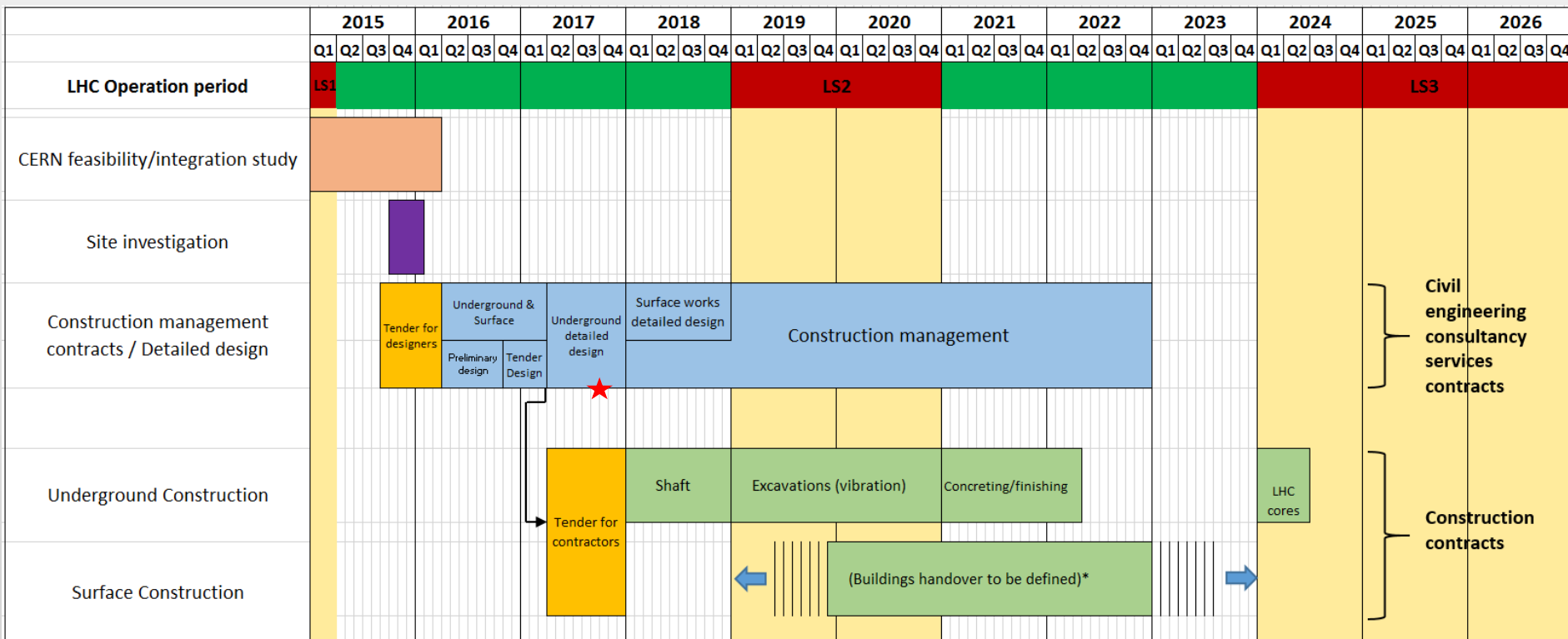


# Environmental Challenges : Rock disposal





# Civil Engineering HL-LHC Simplified Schedule





# Opportunities for engineers at CERN

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## CERN's GET Fellowship scheme

In 2009, CERN introduced a new 'Graduate Engineering Training (GET)' scheme.

CERN offers outstanding possibilities for training and work experience in engineering fields.

The aim of this scheme is to encourage Fellowship applications from talented engineers. CERN is not only an exciting place to work for physicists, but is also a leading employer in engineering fields.

## Are you?

- A national of a CERN [Member State](#).
- Graduated or are about to graduate with a university degree (BSc level or above) or a technical engineer qualification.
- Either, have a **MEng/MSc** level diploma or above with no more than **10 years** relevant experience;
- Or have a **BEng/BSc** or a technical engineer diploma with no more than **4 years** relevant experience.

<https://jobs.web.cern.ch/join-us/fellowship-programme>

<https://tenderopportunities.stfc.ac.uk/>



THANK YOU and Questions ?

<https://edms.cern.ch/document/1761678/1>