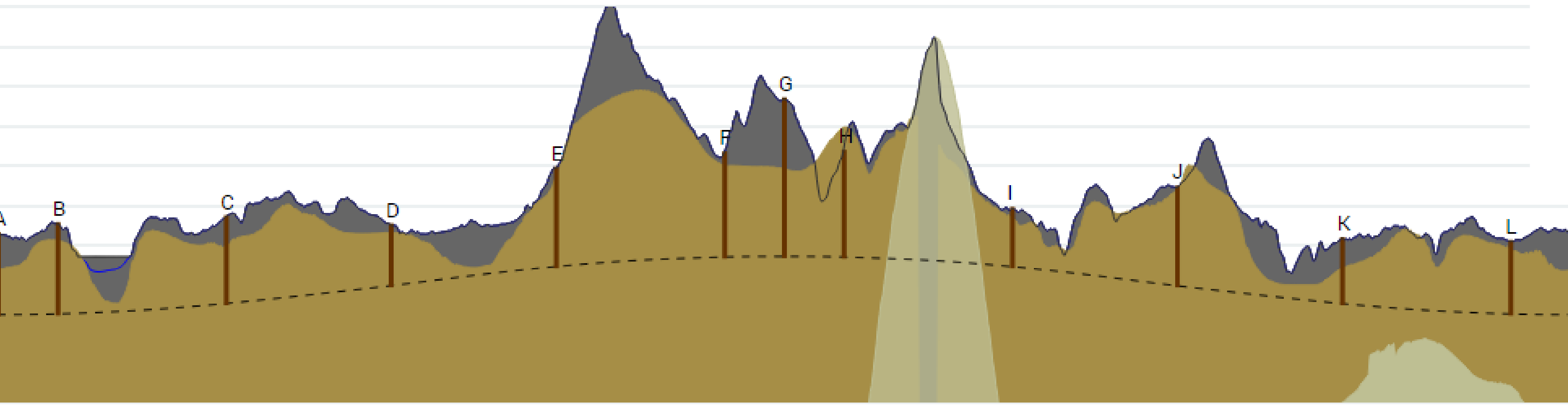


TOT-FCC: Tunnel Optimisation Tool for the Future Circular Collider

Introduction and lessons learnt

C. Cook, J. Osborne, P. Lebrun, Y. Robert, M. Jones, Y. Loo, C. Sturzaker, M. Sykes,

on behalf of the Civil Engineering & Geology working group

27-07-2015

Contents

- Introduction to TOT-FCC
- Progression of options
- How to compare options?
- Lessons learnt
- Future plans

Introduction to TOT-FCC: Data

Data in the tool :

- Study area boundary
- General tunnel geometry
- 3D Geological model (Digital Elevation Model (DEM), Molasses rockhead, Limestone rockhead)
- Lake Geneva bathymetry
- Hydrology
- Environmentally sensitive and protected areas
- Urban areas
- Geothermal Activity

Introduction to TOT-FCC: Data

Data in the tool :

Study area boundary

- Confined by natural formations on all sides (Jura, Vuache, Pre-alpes, Lake Geneva)
- Dimensioned with early FCC machine shapes in mind:

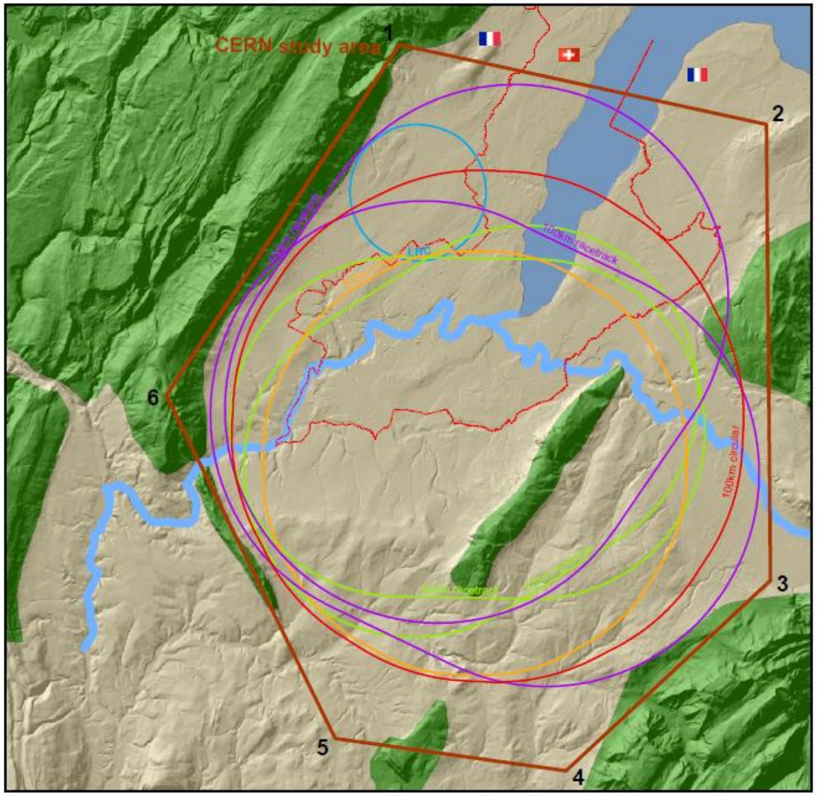
ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

Laboratoire Européen pour la Physique de Particules
European Laboratory for Particle Physics

GS/SE-DOP CH-1211 GENEVE 23 -Tel: central: +41 (22) 767 6111 - direct 41 (22) 767 3414

FCC
Determination of the geological survey area

Created from CERN Geographic Information System



Legend

Machine Scenarios :
- 100km circular
- 100km racetrack
- 83km circular
- 83km racetrack
- LHC
- CERN

CERN study area

Points	Long	Lat
1	6.040043	46.354002
2	6.348873	46.313785
3	6.355130	46.060480
4	6.193496	45.952406
5	6.008318	45.968384
6	5.866667	46.198026

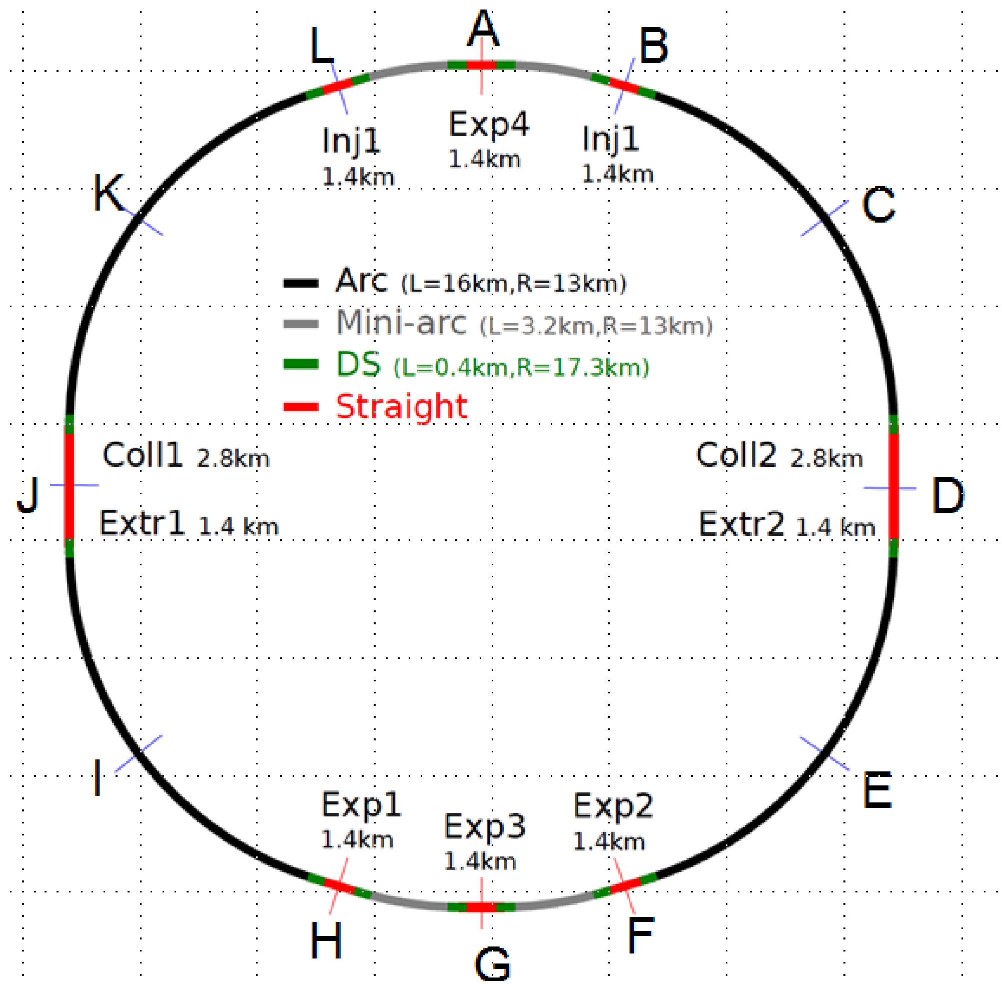
Drawn by : ETL | Date: 27/10/2014 | 0 5,000 10,000 20,000 Meters

Introduction to TOT-FCC: Data

Data in the tool :

General tunnel geometry

- Settled on 'quasi-circle' design after also looking at 'circular' and 'racetrack' designs.
- FCC circumference is a multiple of LHC :
  - 80 km (3.0x LHC)
  - 87 km (3.25x LHC)
  - 93 km (3.50x LHC)
  - 100 km (3.75x LHC)
- 12 shafts, one shaft at each point (A-L)



Introduction to TOT-FCC: Data

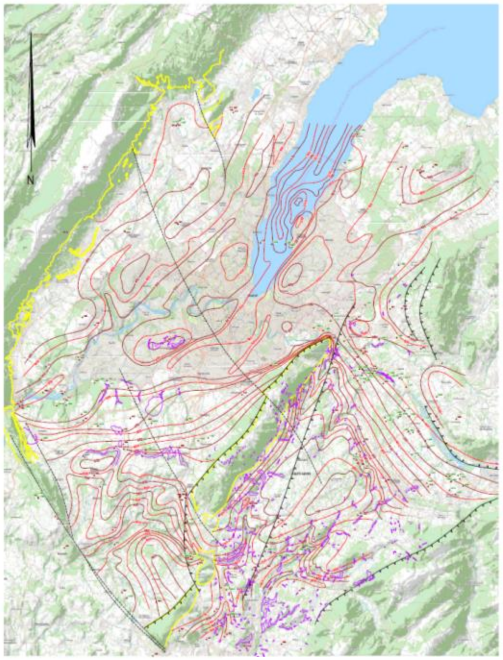
Data in the tool :

3D geological model: Geological rockheads & Digital Elevation Model (DEM)

Digital Elevation Model (DEM)

1) The DEM has been sourced from the EU Copernicus programme and has a quoted vertical accuracy of +/- 2.9m

2) Molasse rockhead contours developed by Geotechnique Appliquee Deriaz (GADZ)



GEOTECHNIQUE APPLIQUEE DERIAZ S.A.
GADZ

More information on the DEM:
http://ec.europa.eu/eurostat/c/portal/layout?p_l_id=4311198&p_v_l_s_g_id=0

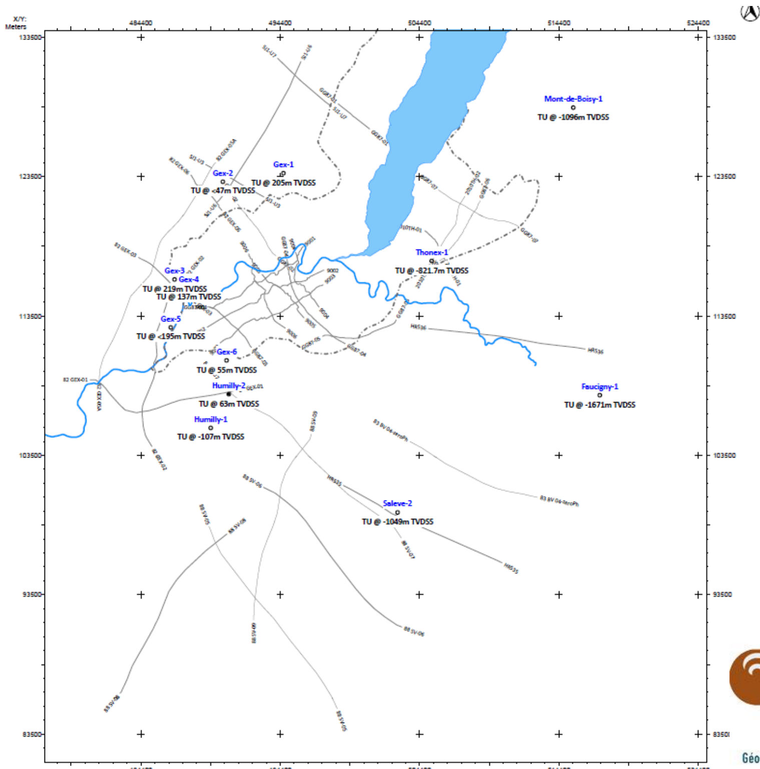
Introduction to TOT-FCC: Data

Data in the tool :

3D geological model: Geological rockheads & Digital Elevation Model (DEM)

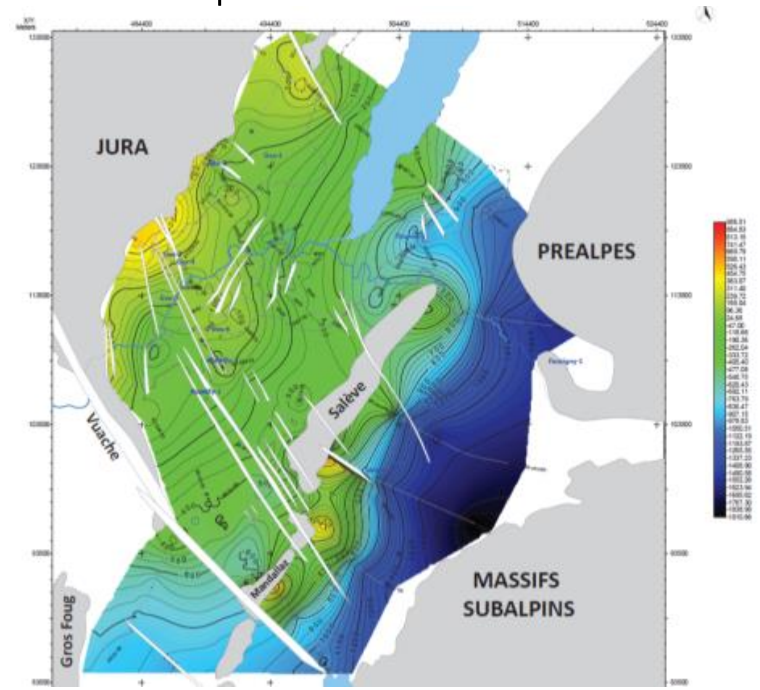
Development of geological rockheads (surfaces):

3) Seismic and geotechnical borehole data purchased from Bureau de Recherches Géologiques et Minières (BRGM)



brgm
Géosciences pour une Terre durable

4) This data was then processed by Geneva Geo Energy to create a Limestone rockhead depth map covering the FCC study area. GGE cautioned that due to interpolotion over large distances, local inaccuracies of up to +-50m are possible



(Geneva Geo Energy, 2014)

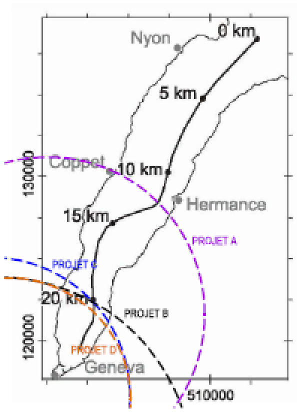
GENEVA GEO ENERGY

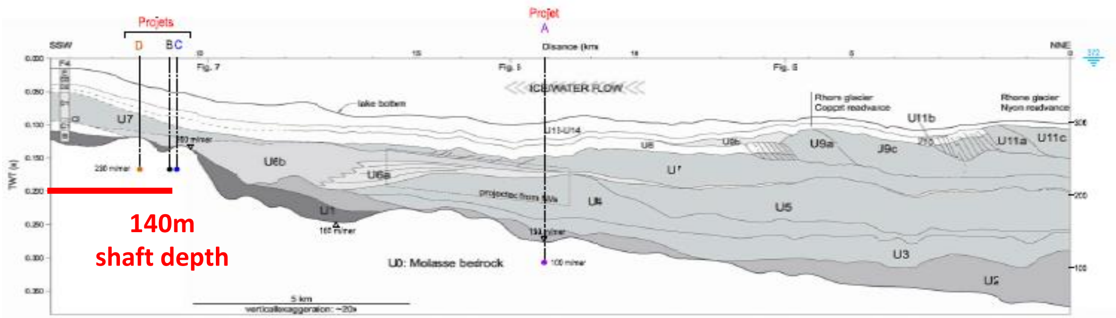
Introduction to TOT-FCC: Data

Data in the tool :

Lake Geneva Bathymetry

- Geology underneath Lake Geneva 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





Profil synthétique longitudinal du Petit-lac

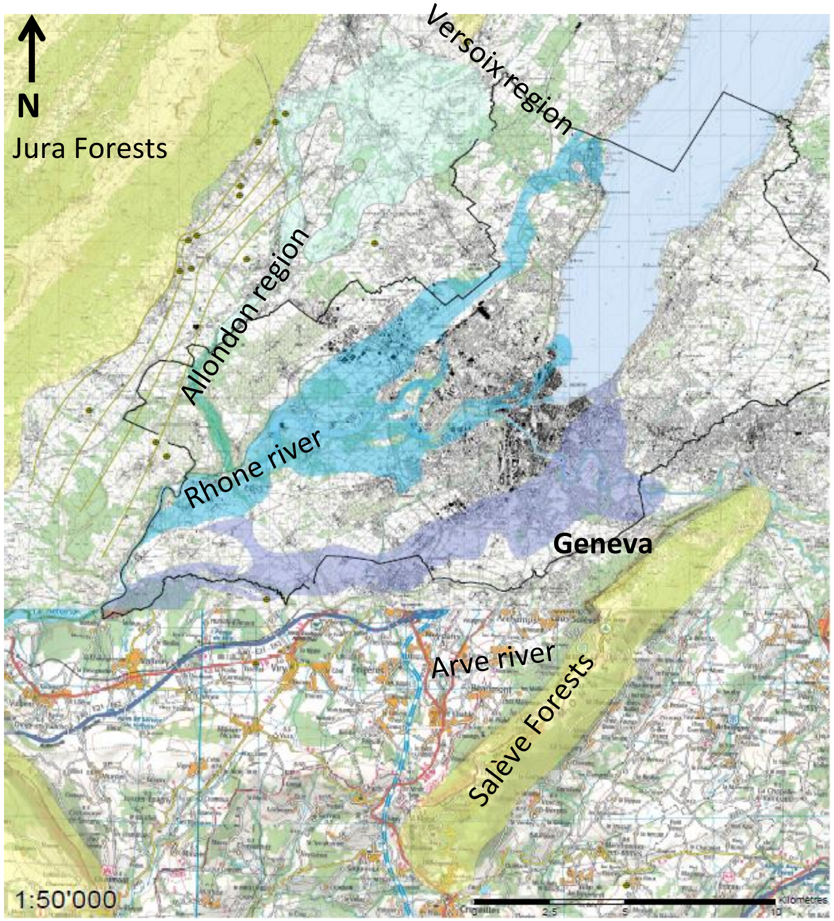
d'après Fiore-Giraclos et all. (2010)

Introduction to TOT-FCC: Data

Data in the tool :

Environmentally sensitive areas

- Natural parks
- Areas of biological significance and wetlands
- Protected water sources
- Groundwater (aquifers)



Introduction to TOT-FCC: Data

Data in the tool :

Buildings

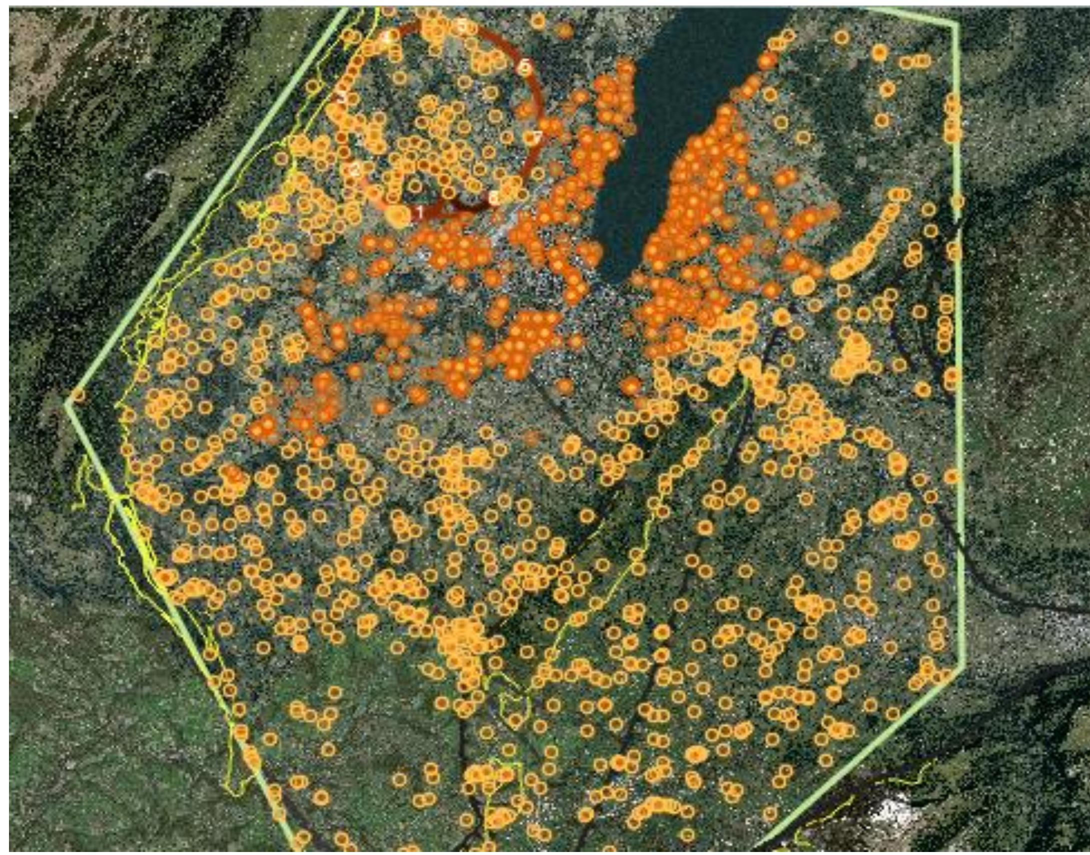
- Buildings data covers both the Swiss and French sides of the FCC study area.
- In Switzerland, the data includes buildings with planning permission (shown in light blue)

Introduction to TOT-FCC: Data

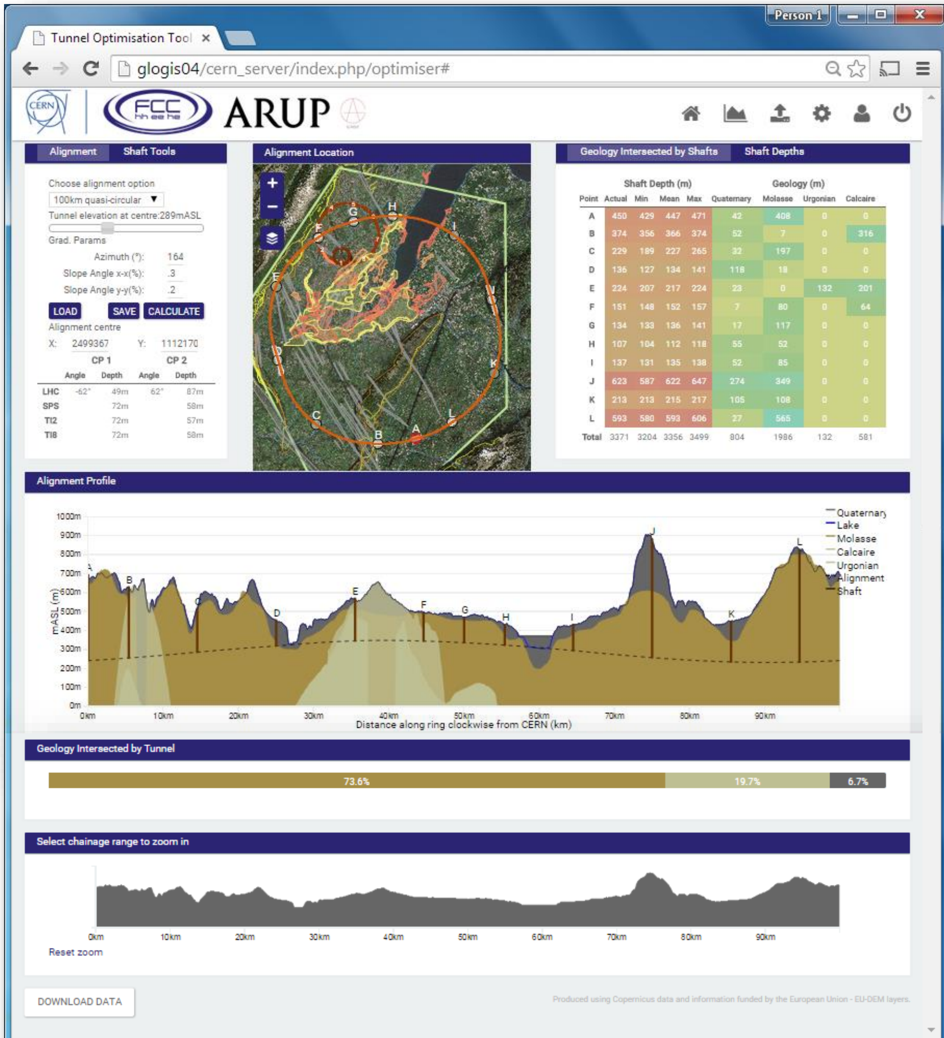
Data in the tool :

Geothermal boreholes

- Over 1800 boreholes in the FCC study area ranging from 20m – 400m in depth.
- Only 10 to 20 boreholes are usually within a 50m radius of a given FCC tunnel option under study

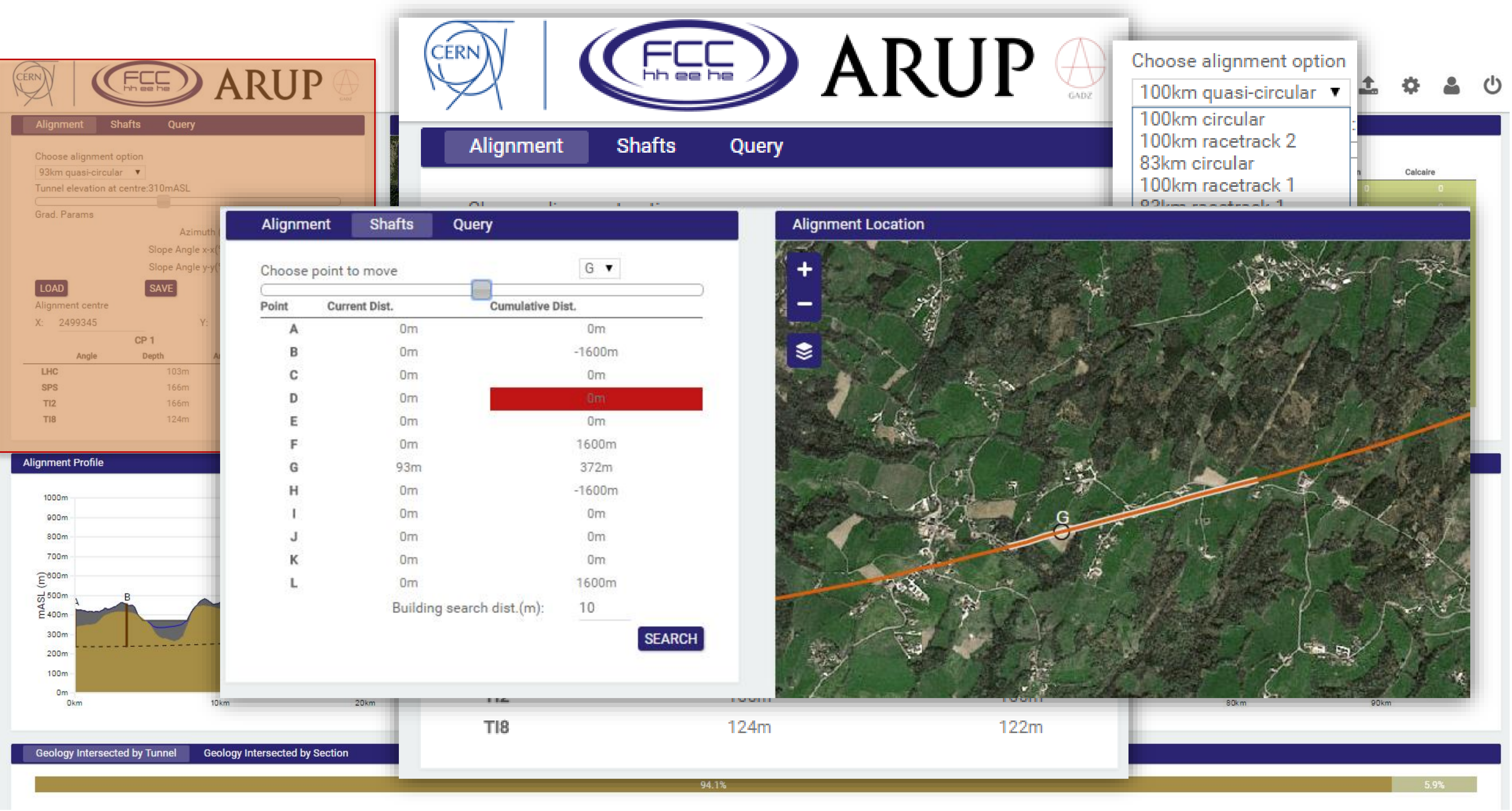


Introduction to TOT: Interface

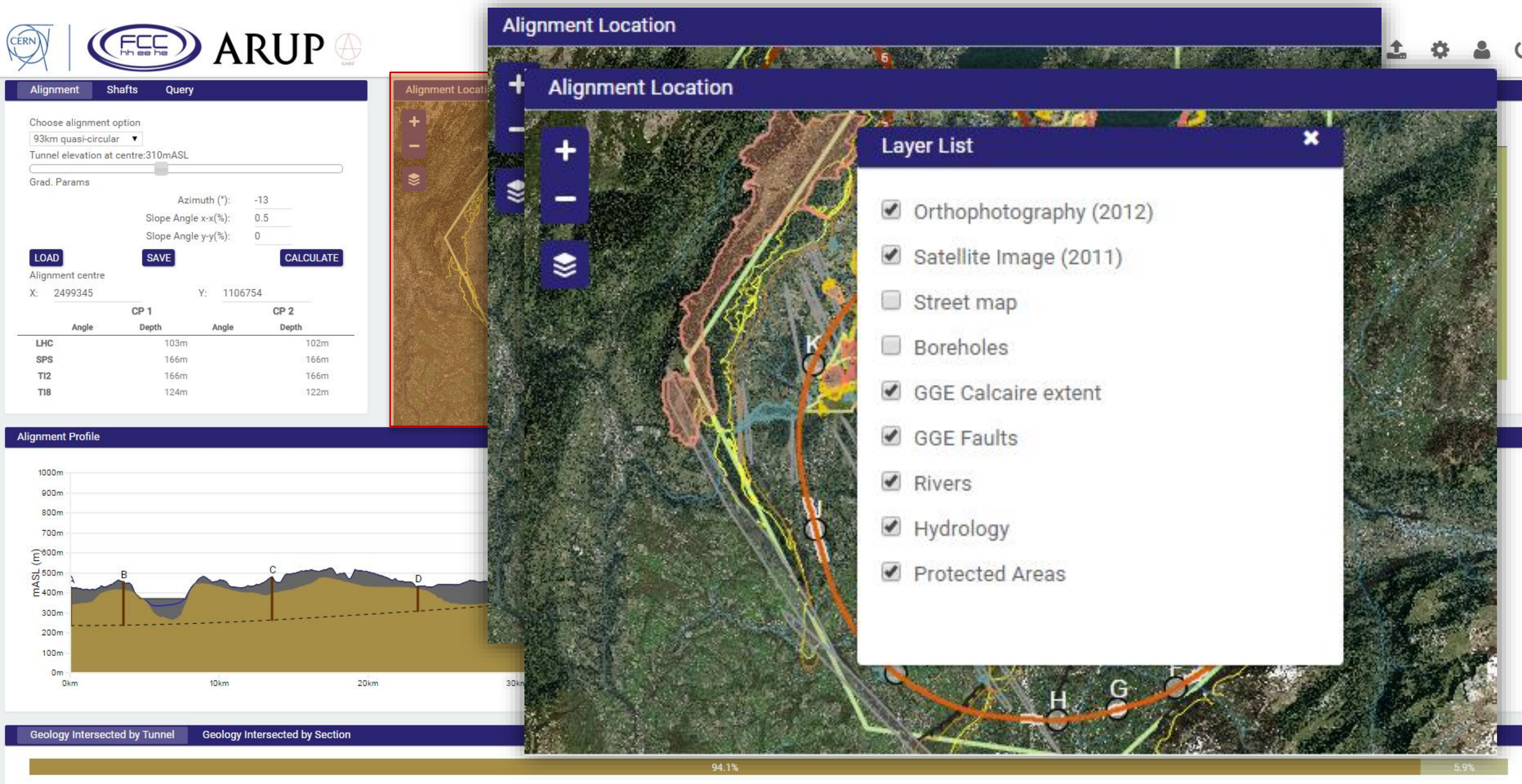


- Max value extracted from early project data
- Iterative process and comparison of options - data & knowledge increases and assumptions change
- Development began in Feb 2014, first results in September 2014
- TOT-ILC currently under development - collaboration between CERN, KEK and ARUP

User interface - Input parameters

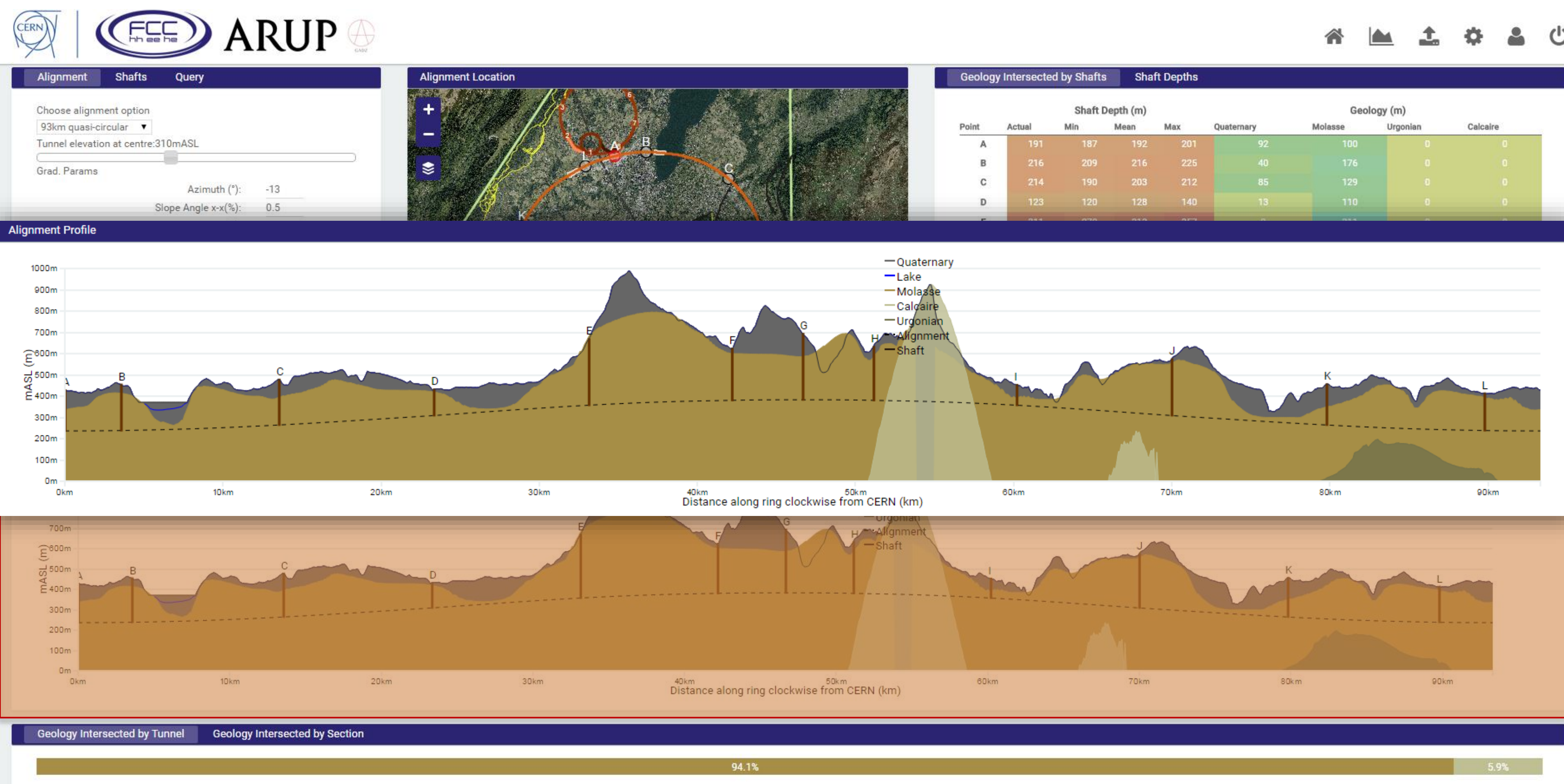


User interface - Input parameters



Introduction to TOT: Interface

User interface – Alignment profile



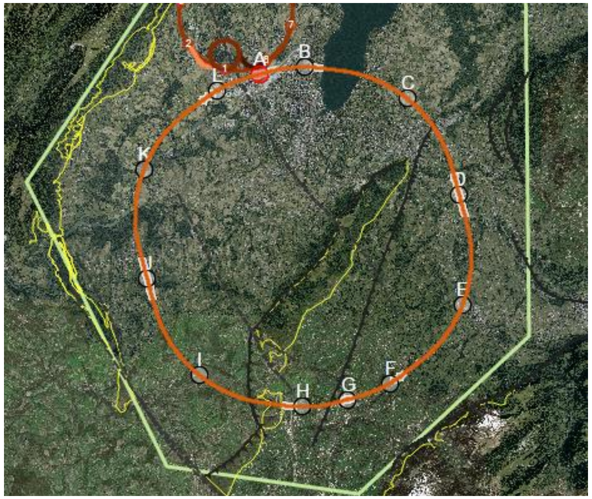
John Osborne (CERN-GS)

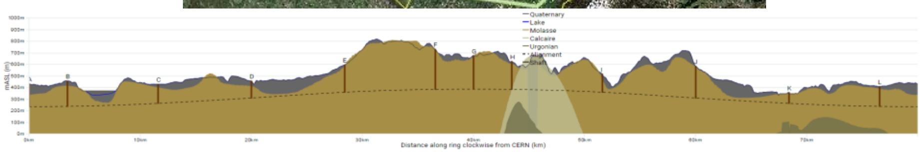
User interface – Outputs

Point	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Quaternary	Molasse	Urgonian	Calcaire
A	191	187	192	201	92	100	0	0
B	216	209	216	225	40	176	0	0
C	214	190	203	212	85	129	0	0
D	123	120	128	140	13	110	0	0
E	311	270	313	357	0	311	0	0
F	243	243	259	286	23	220	0	0
G	311	290	314	341	108	203	0	0
H	252	226	254	277	47	205	0	0
I	96	88	96	106	59	37	0	0
J	265	252	267	283	18	247	0	0
K	192	174	184	192	106	86	0	0
L	175	173	175	179	18	157	0	0
Total	2589	2422	2601	2799	609	1980	0	0

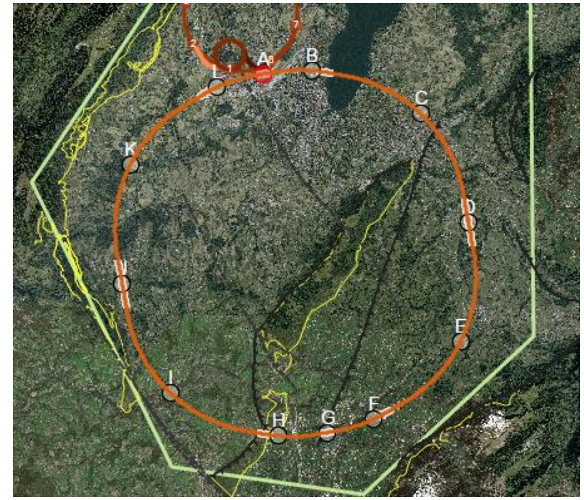
Positioning Process

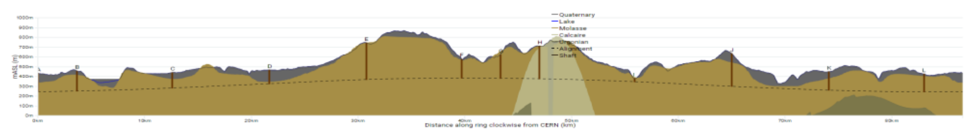
80km



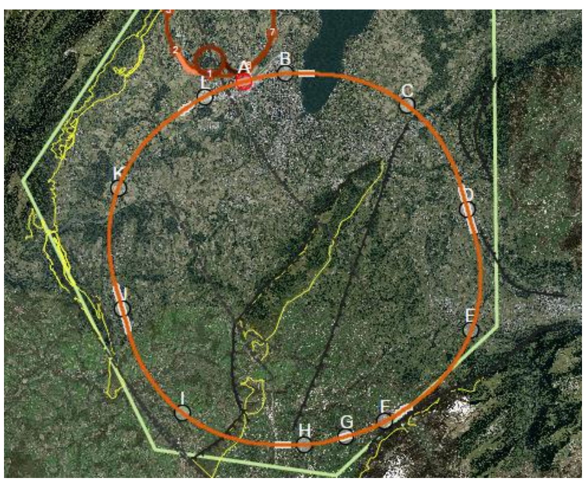


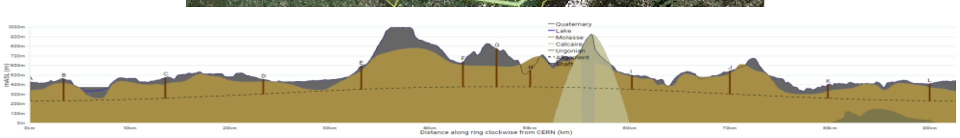
87km



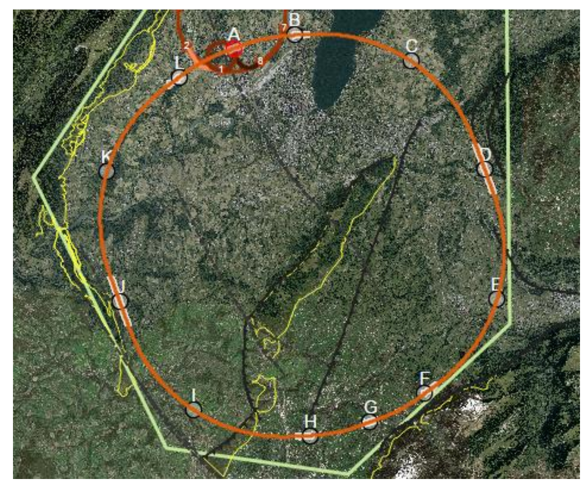


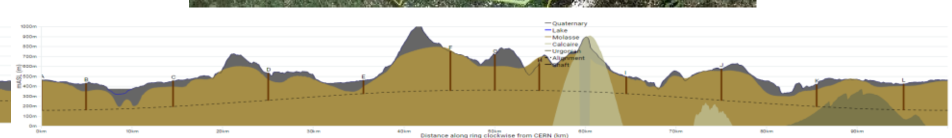
93km
(option 1a)





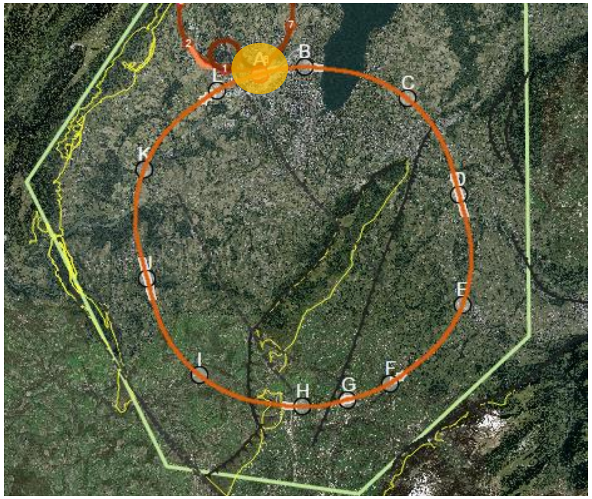
100km
(option 2a)

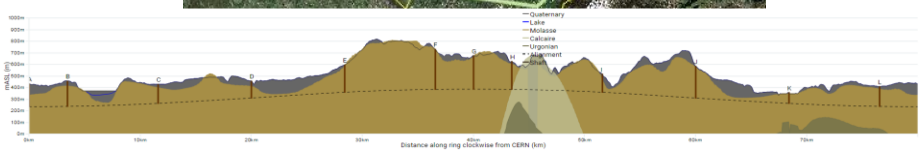




Positioning Process

80km

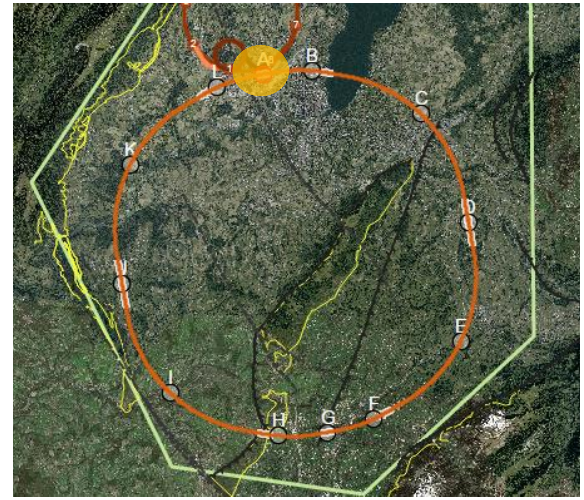


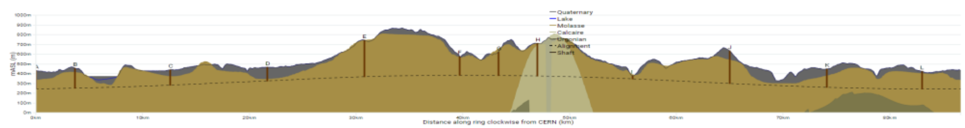


General Positioning

- 80km, 87km & 93km share the same location for point A in Meyrin area

87km





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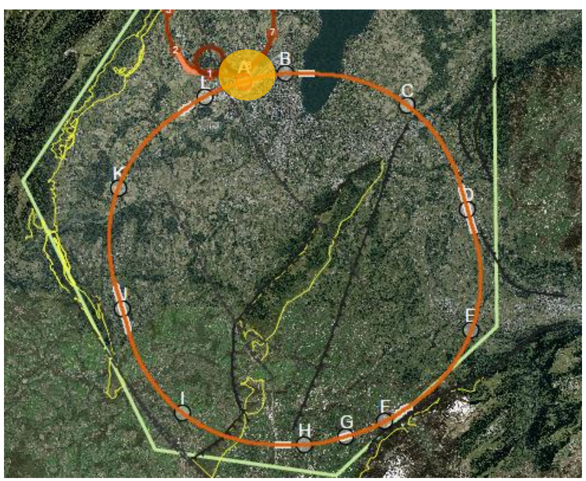

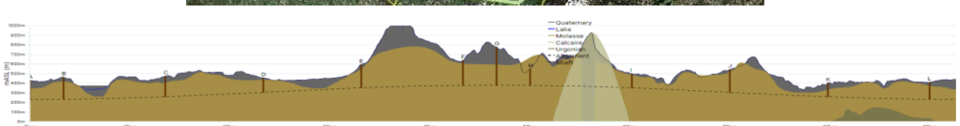

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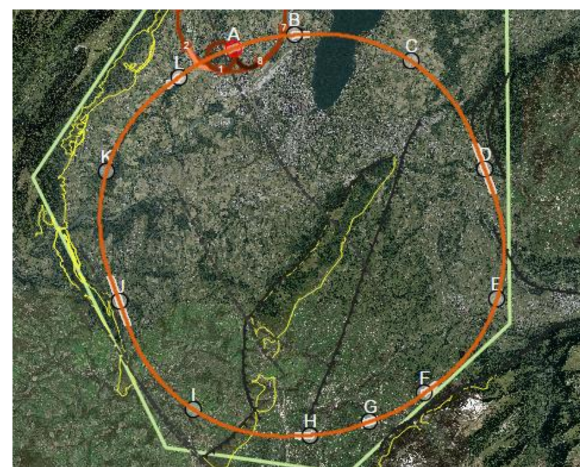
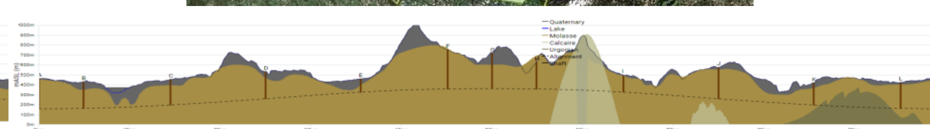
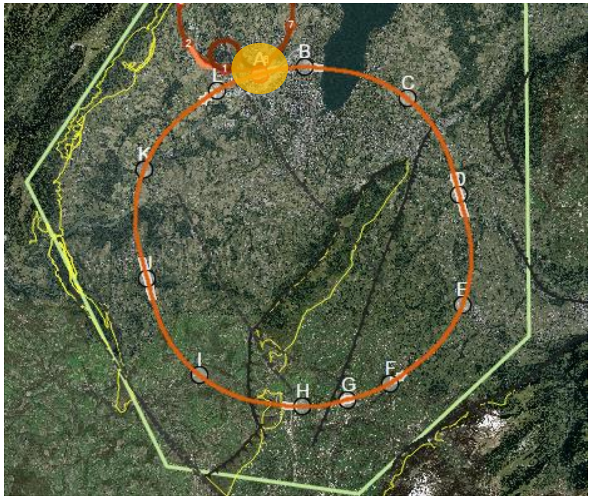




Positioning Process

80km



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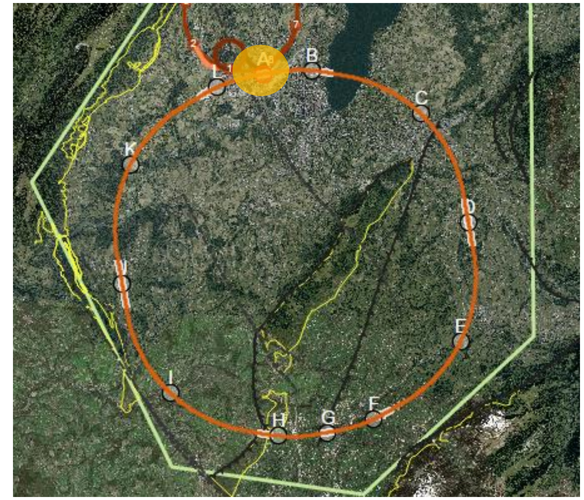
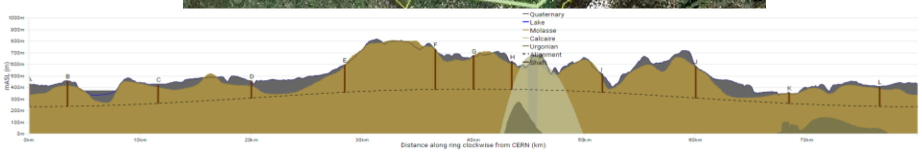
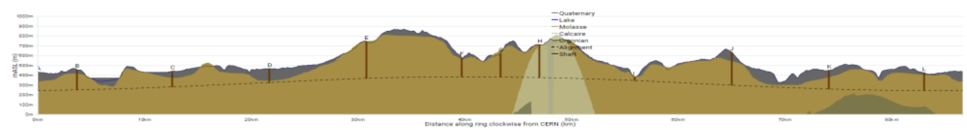
87km

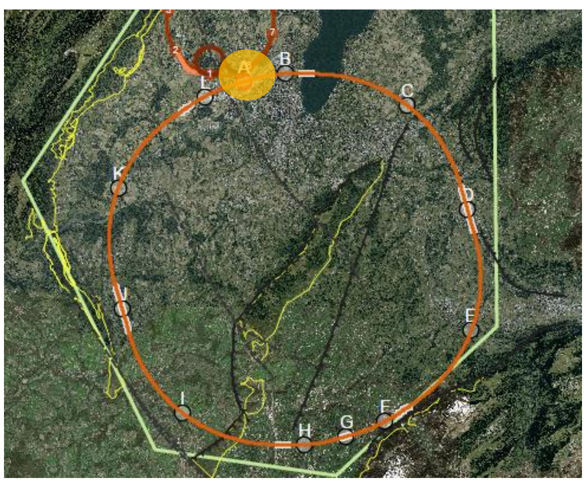






93km

(option 1a)



100km

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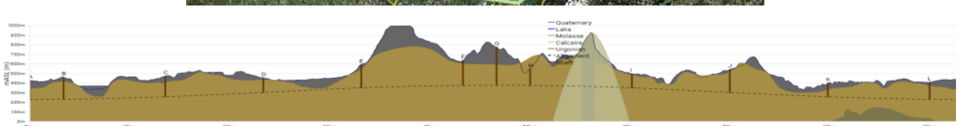
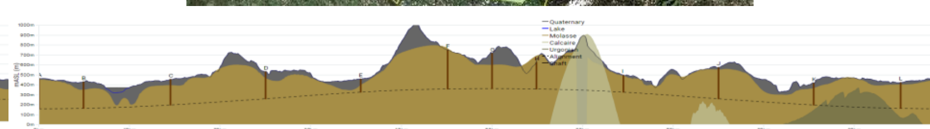
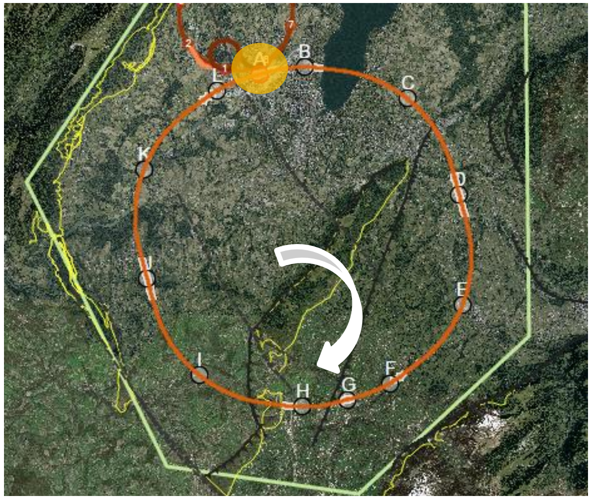




Positioning Process

80km



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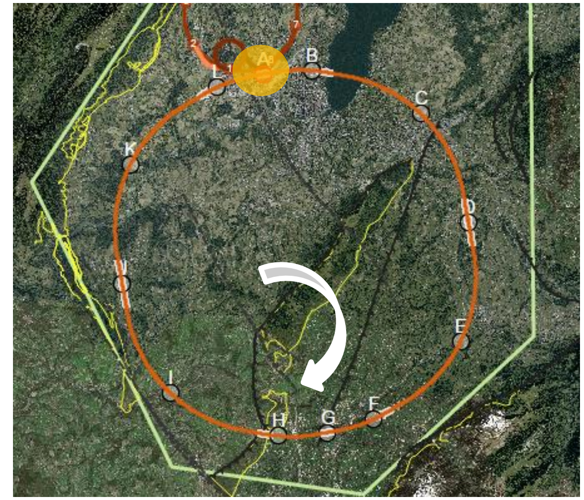
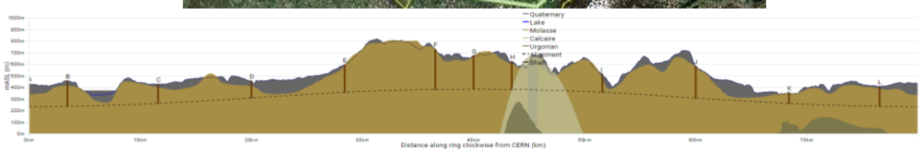
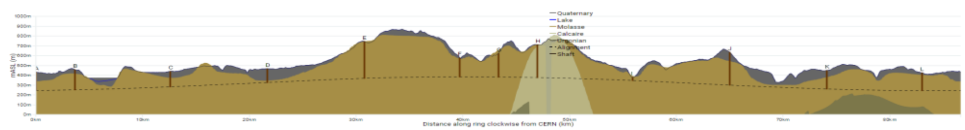


87km





93km
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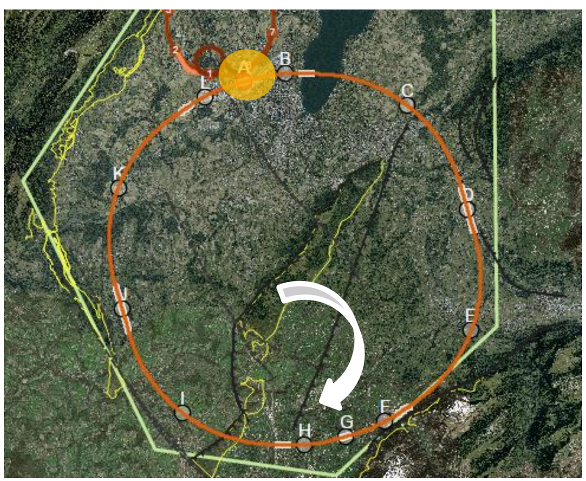

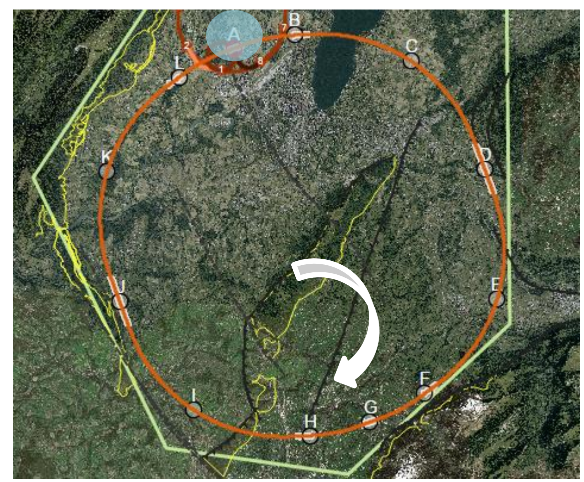

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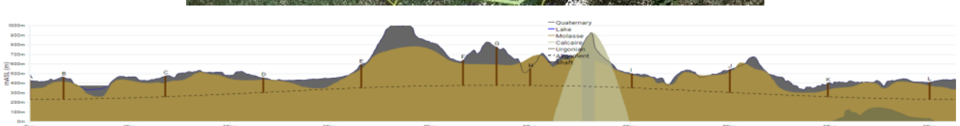
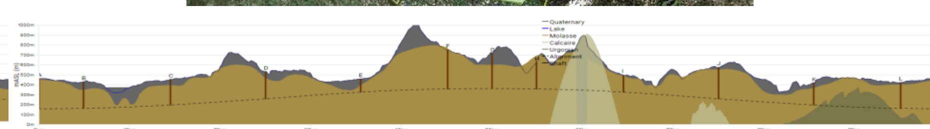
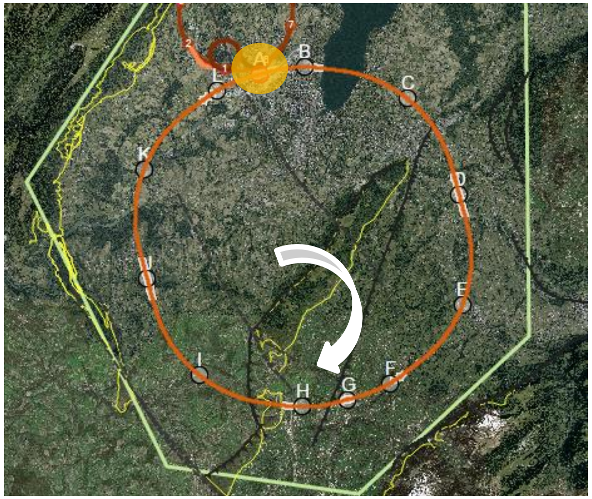
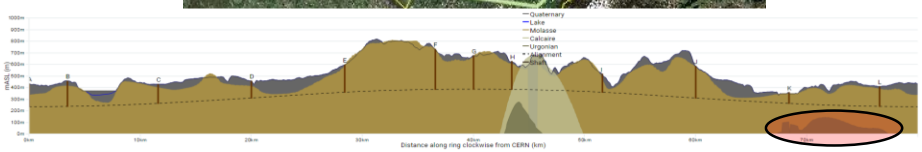




Positioning Process

80km





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- Point A for 100km is in Prevessin area
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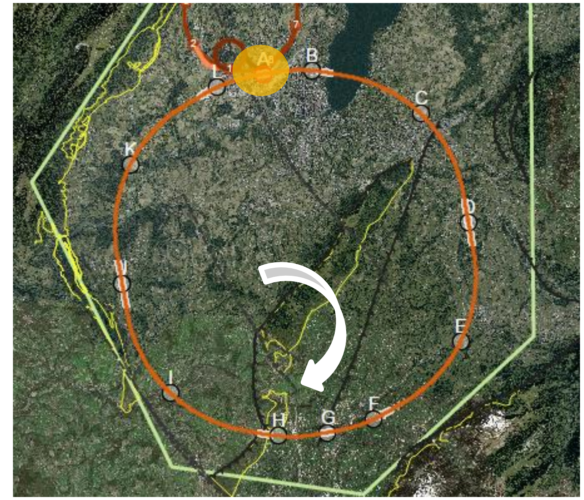
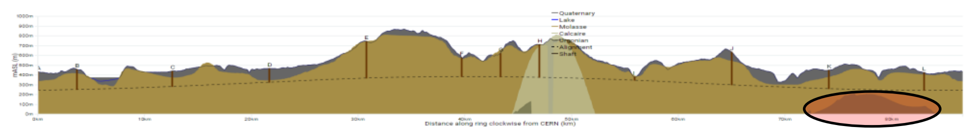
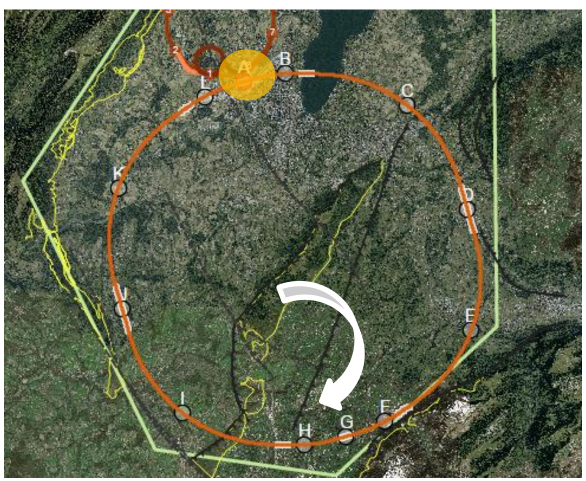
- Rotation limited by Jura (80km, 87km & 93km) or Vuache (100km)

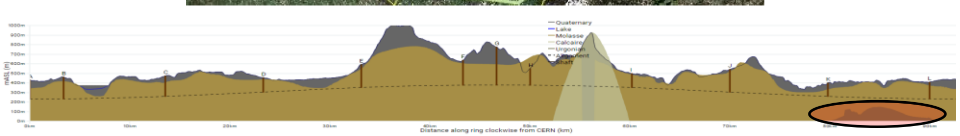
87km



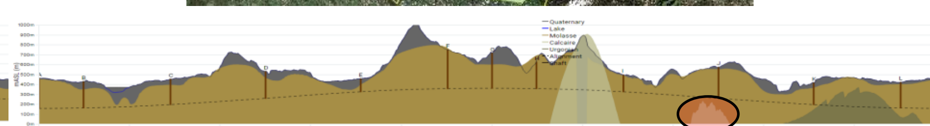


93km
(option 1a)



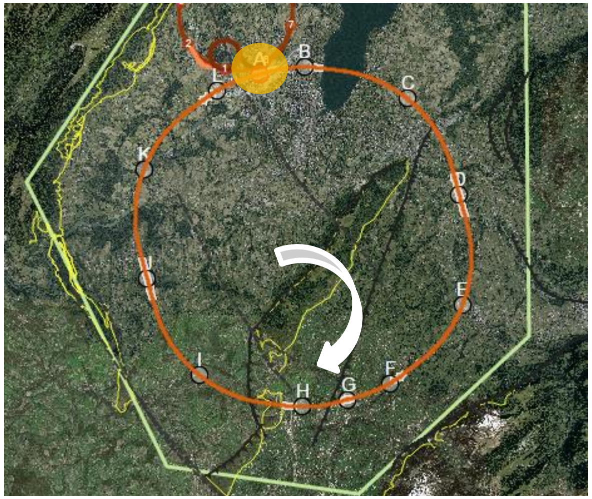


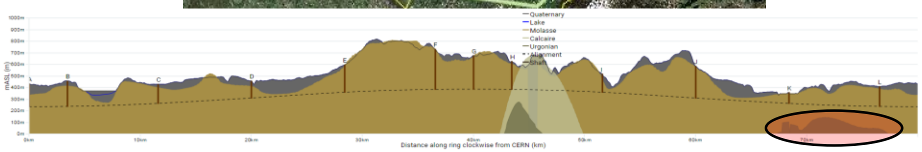
100km
(option 2a)



Positioning Process

80km





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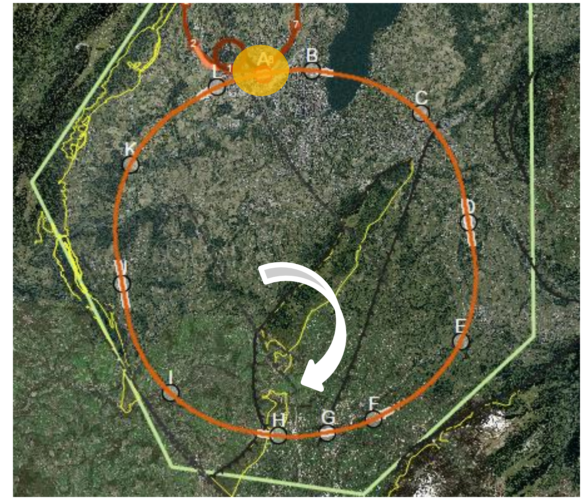
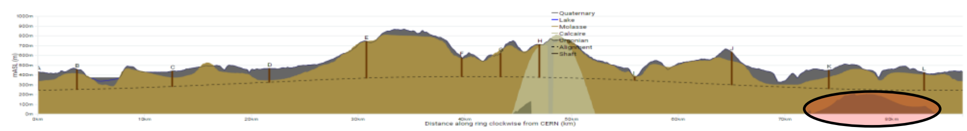
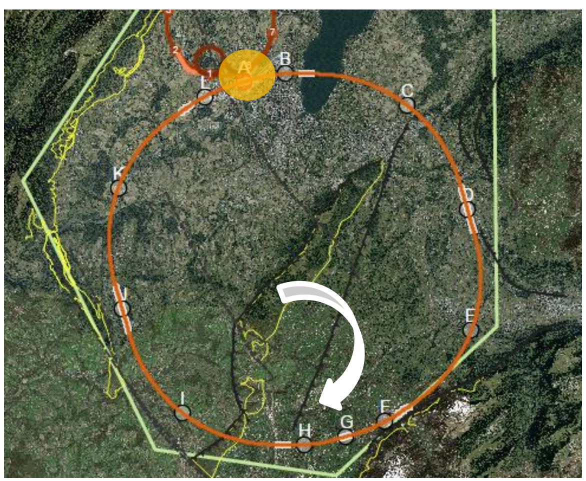
- 80km, 87km & 93km share the same location for point A in Meyrin area
- Point A for 100km is in Prevessin area
- All options rotated clockwise as far as possible to minimise depth under lake
- Rotation limited by Jura (80km, 87km & 93km) or Vuache (100km)
- Tunnel inclined about x-x & y-y to follow contours of the surface as much as possible

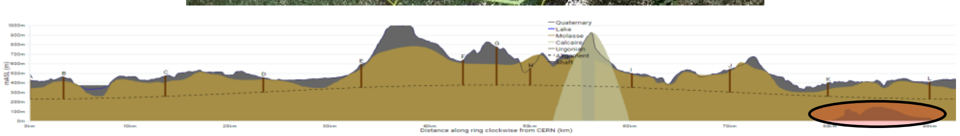
87km



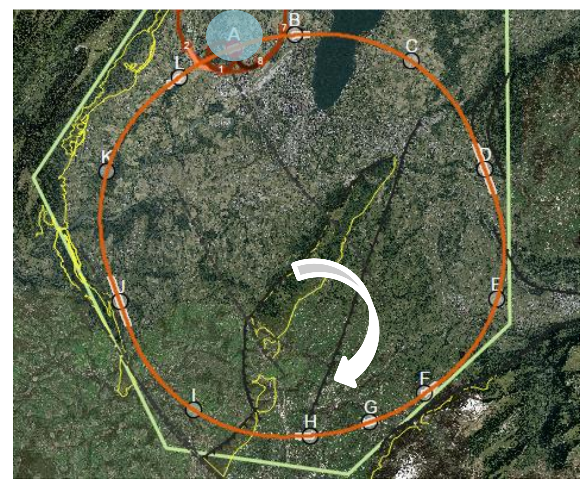


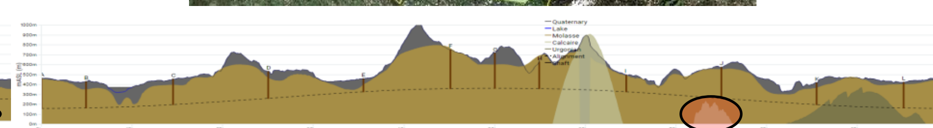
93km
(option 1a)





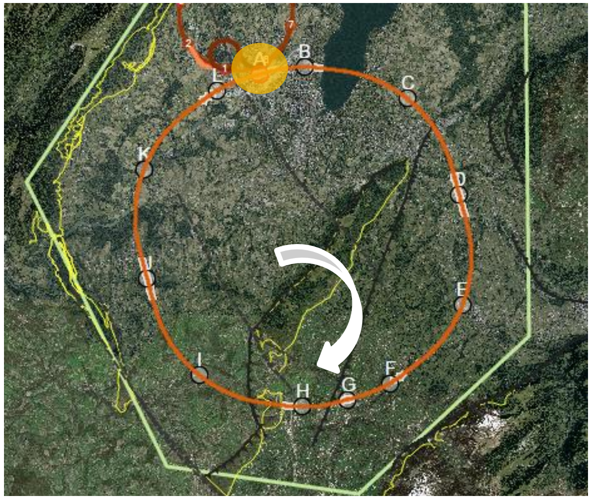
100km
(option 2a)





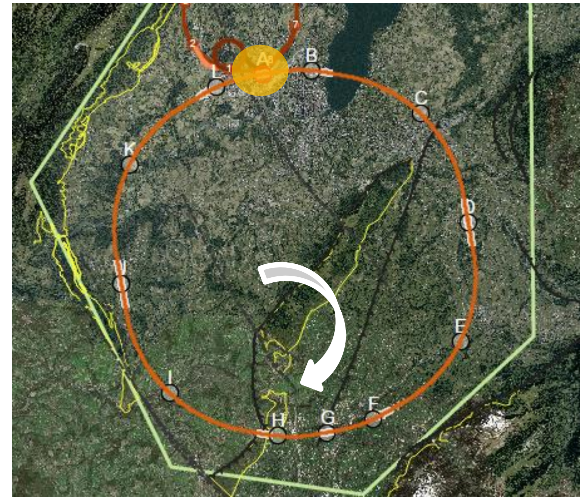
Positioning Process

80km

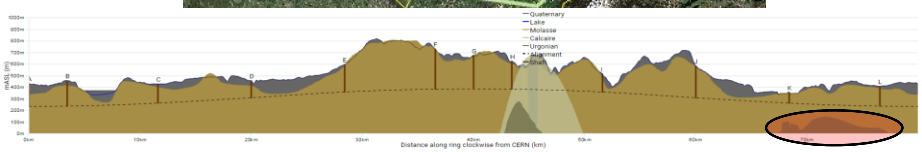


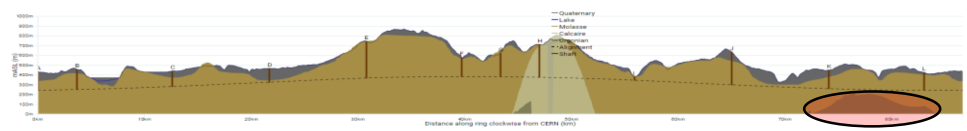
General Positioning

- 80km, 87km & 93km share the same location for point A in Meyrin area
- Point A for 100km is in Prevessin area
- All options rotated clockwise as far as possible to minimise depth under lake
- Rotation limited by Jura (80km, 87km & 93km) or Vuache (100km)
- Tunnel inclined about x-x & y-y to follow contours of the surface as much as possible

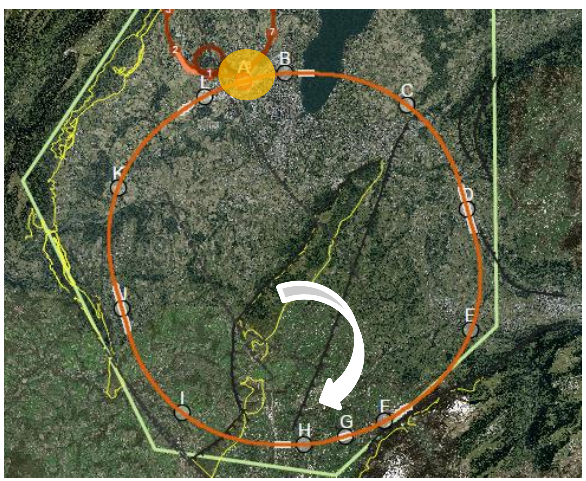


87km





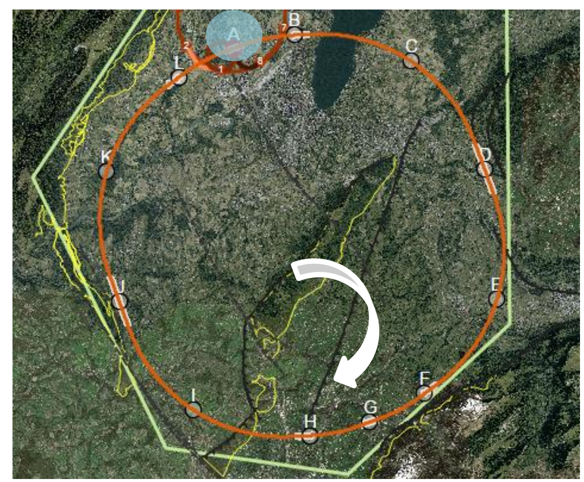
93km
(option 1a)



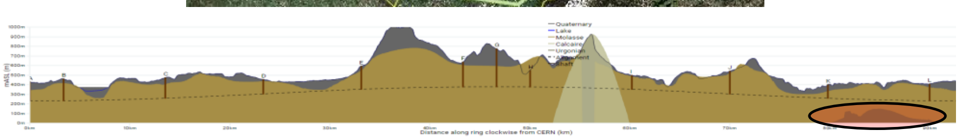
Small alignment and shaft movements

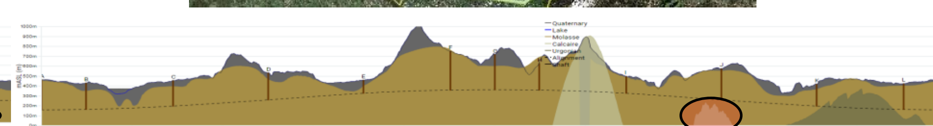
Positioned so that:

- All surface sites are in potentially feasible locations i.e. avoid environmentally protected areas and the built-environment
- Shaft depths are minimised (F,G,H in particular)



100km
(option 2a)





Intersecting Option (100km)

Alignment | Shafts | Query

Choose alignment option: 100km quasi-circular

Tunnel elevation at centre:261mASL

Grad. Params

Azimuth (°): -20

Slope Angle x-x(%): 0.65

Slope Angle y-y(%): 0

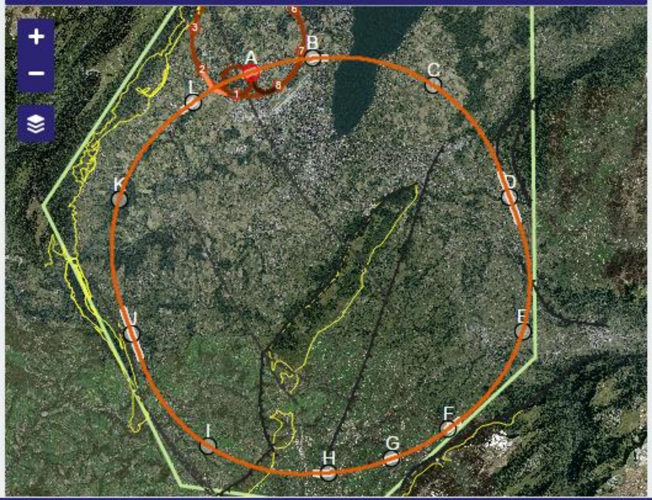
LOAD | SAVE | CALCULATE

Alignment centre

X: 2499731 Y: 1108403

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	-64°	220m	64°	172m
SPS		242m		241m
TI2		235m		241m
TI8		242m		170m

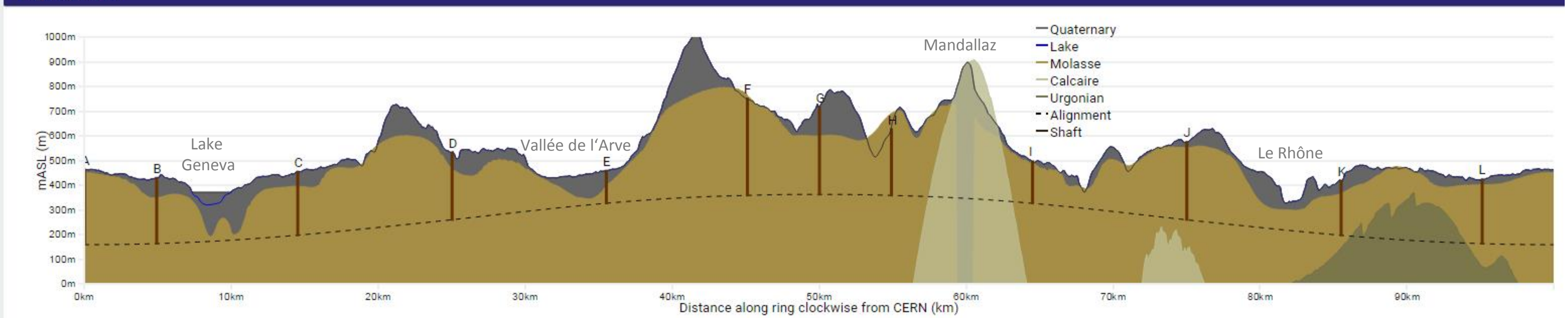
Alignment Location



Geology Intersected by Shafts | Shaft Depths

Shaft Depth (m)		Geology (m)			
Point	Actual	Quaternary	Molasse	Urgonian	Calcaire
A	304	12	292	0	0
B	266	80	186	0	0
C	257	58	199	0	0
D	272	64	208	0	0
E	132	64	68	0	0
F	392	0	392	0	0
G	354	116	237	0	0
H	268	0	268	0	0
I	170	12	158	0	0
J	315	22	293	0	0
K	221	52	169	0	0
L	260	21	239	0	0
Total	3211	501	2710	0	0

Alignment Profile



Geology Intersected by Tunnel | Geology Intersected by Section

86.5% | 7.8% | 5.7%

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

Challenges:

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

Non-intersecting Option (100km)

Alignment | Shafts | Query

Choose alignment option

100km quasi-circular ▾

Tunnel elevation at centre:291mASL

Grad. Params

Azimuth (°): -17

Slope Angle x-x(%): 0.48

Slope Angle y-y(%): 0

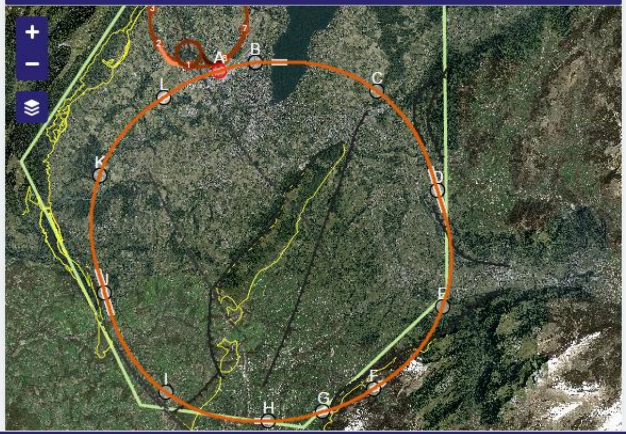
LOAD | SAVE | CALCULATE

Alignment centre

X: 2500583 Y: 1105970

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC		122m		122m
SPS		187m		187m
TI2		187m		187m
TI8		139m		137m

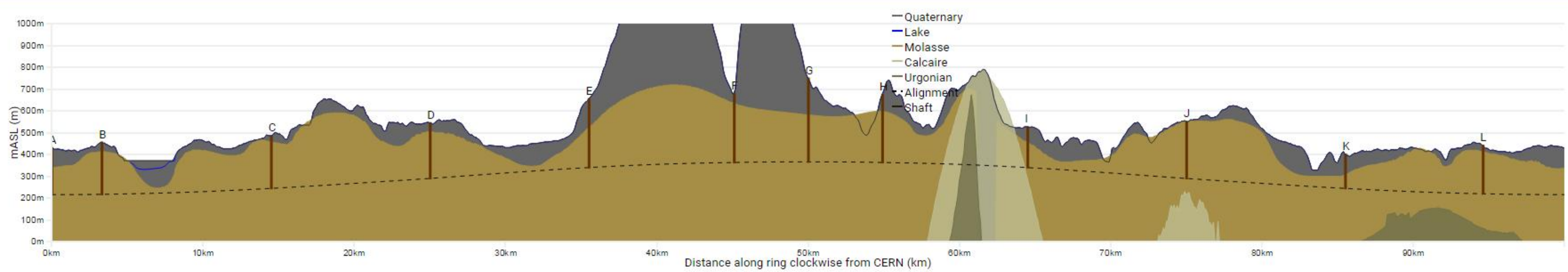
Alignment Location



Geology Intersected by Shafts | Shaft Depths

	Shaft Depth (m)	Geology (m)			
Point	Actual	Quaternary	Molasse	Urgonian	Calcaire
A	214	93	122	0	0
B	238	42	196	0	0
C	241	26	215	0	0
D	254	42	212	0	0
E	315	131	184	0	0
F	316	44	273	0	0
G	383	166	216	0	0
H	311	77	235	0	0
I	186	70	116	0	0
J	260	0	260	0	0
K	156	93	63	0	0
L	221	28	193	0	0
Total	3095	812	2282	0	0

Alignment Profile



Geology Intersected by Tunnel | Geology Intersected by Section

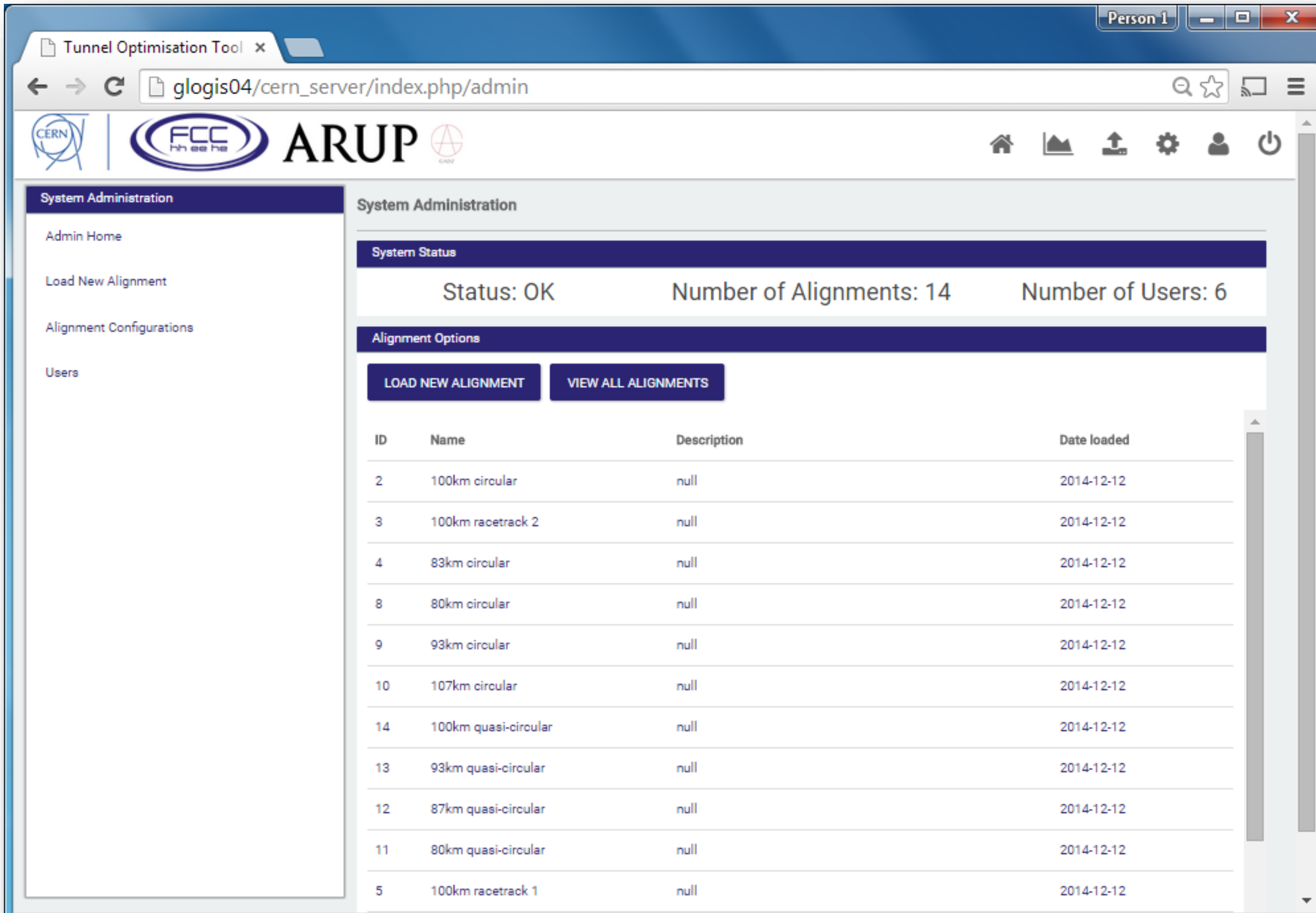
94.6% | 1.0 | 4.4%

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

Challenges:

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

Back-end functionality



How to compare options?

Applying Amberg Metrics

2. Each element of construction (1 meter of shaft, 1 meter of tunnel, 1 cavern) is multiplied by its respective **unit multiplication factor** which are dependant on the geological conditions and relative to the cost/risk of tunnelling 1m in molasse

Example (arbitrary alignment)

Tunnel unit multiplication factors

Tunnel	Geological conditions	Unit multiplication factors	Installation of TBM (52.85) or Dual mode TBM (70.46)	Mode change
tunnel	Moraine < 12 bar	1.38	52.85	26.42
tunnel	Molasse	1.00		
tunnel + injections	Molasse flowing water	1.53	70.46	
tunnel	Urgonian	1.23		
tunnel + injections	Urgonian flowing water	1.76	70.46	
tunnel	Calcaire	1.09		
tunnel + injections	Calcaire flowing water	1.62	70.46	
tunnel + injections	Calcaire & Karst	1.91		

Shaft unit multiplication factors

shaft (conv.)	Geological conditions	Unit multiplication factor	Installation and ground freezing
			125.00
shaft (conv.)	stiff clay < 50 m	3.66	
shaft (conv.)	sandy-silty < 50 m	6.60	
shaft (conv.) 1	soil with ground water < 50 m	8.64	
shaft (conv.)	Molasse	3.66	
shaft (conv.) + injections	Molasse flowing water	4.54	70.46
shaft (conv.)	Urgonian	2.48	
shaft (conv.) + injections	Urgonian flowing water	3.36	70.46
shaft (conv.)	Calcaire	3.01	
shaft (conv.) + injections	Calcaire flowing water	3.89	70.46
shaft (conv.) + injections	Calcaire & Karst	4.38	

Cavern unit multiplication factors

Cavern type	Geological conditions	Unit multiplication factor
shaft bottom cavern 2 x 70 m / 200 m2	soil below GWL	17.72
shaft bottom cavern 2 x 70 m / 200 m2 1	soil above GWL stiff clay	9.23
shaft bottom cavern 2 x 70 m / 200 m2	Molasse	6.76
shaft bottom cavern 2 x 70 m / 200 m2 + injections	Molasse flowing water	7.64
shaft bottom cavern 2 x 70 m / 200 m2	Urgonian	5.11
shaft bottom cavern 2 x 70 m / 200 m2 + injections	Urgonian flowing water	5.99
shaft bottom cavern 2 x 70 m / 200 m2	Calcaire	5.75
shaft bottom cavern 2 x 70 m / 200 m2 + injections	Calcaire flowing water	6.63
shaft bottom cavern 2 x 70 m / 200 m2 + injections	Calcaire & Karst	7.12

How to compare options?

Applying Amberg Metrics

1. This gives a total cost risk for the tunnelling, each shaft and each cavern and a grand total for the alignment

Example (arbitrary alignment)

Total shafts and bottom caverns	33,591.30

+

Total tunnels	122,207.60

=

Total FCC	155,798.90

How to compare options?

Applying Amberg Metrics

Amberg metrics include the cost/risk of:

Tunnels

- Tunnel Boring Machine (TBM) excavation in moraines, molasse, calcaire & urgonian with or without water pressure
- Installation of a typical TBM or 'dual mode' TBM

Shafts

- Construction of 12 shafts (conventional and mechanical) in moraines, molasse, calcaire & urgonian with or without water pressure

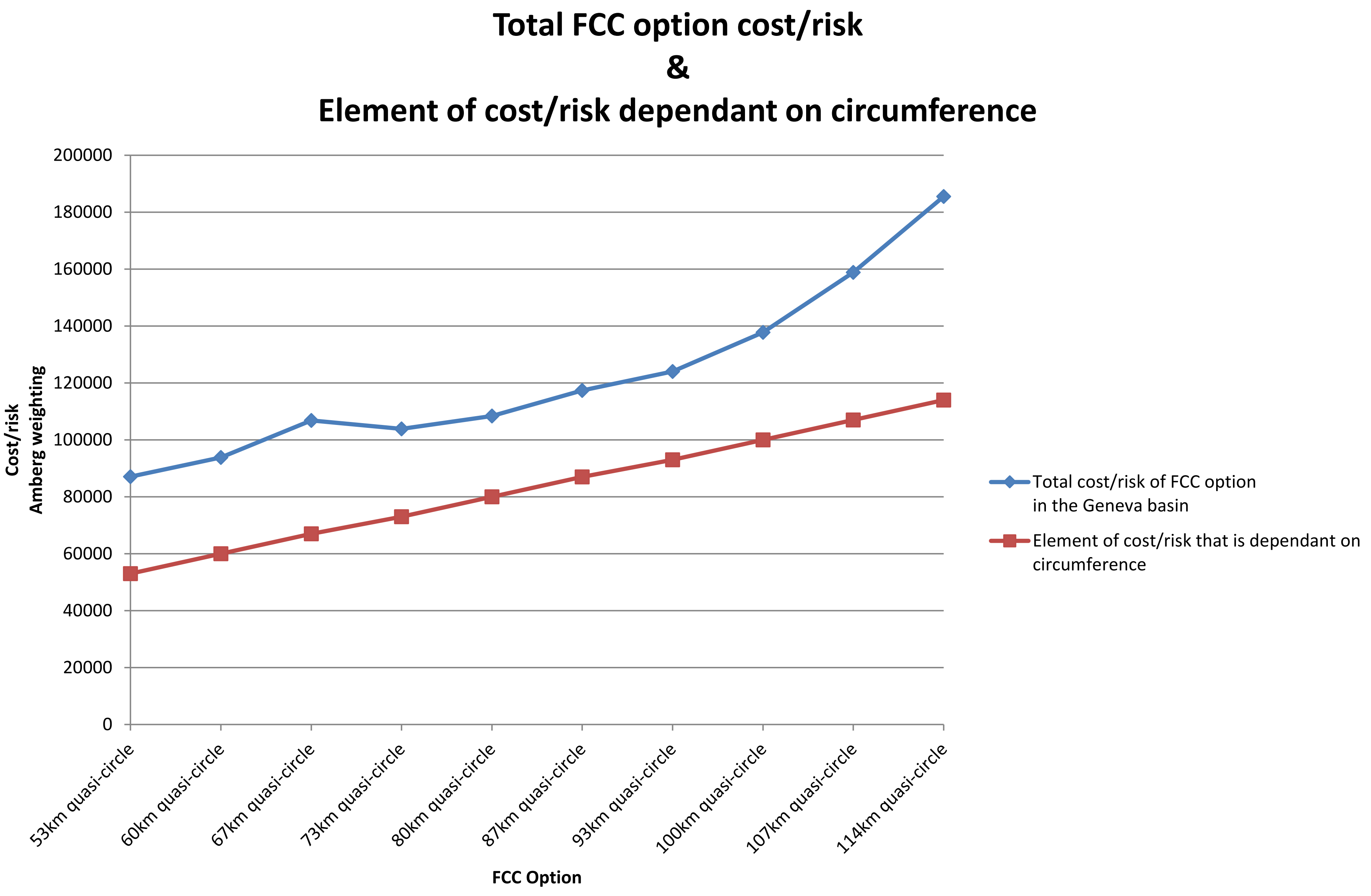
TBM Caverns

- Construction of 24 70mx200m^2 shaft bottom caverns for TBM assembly

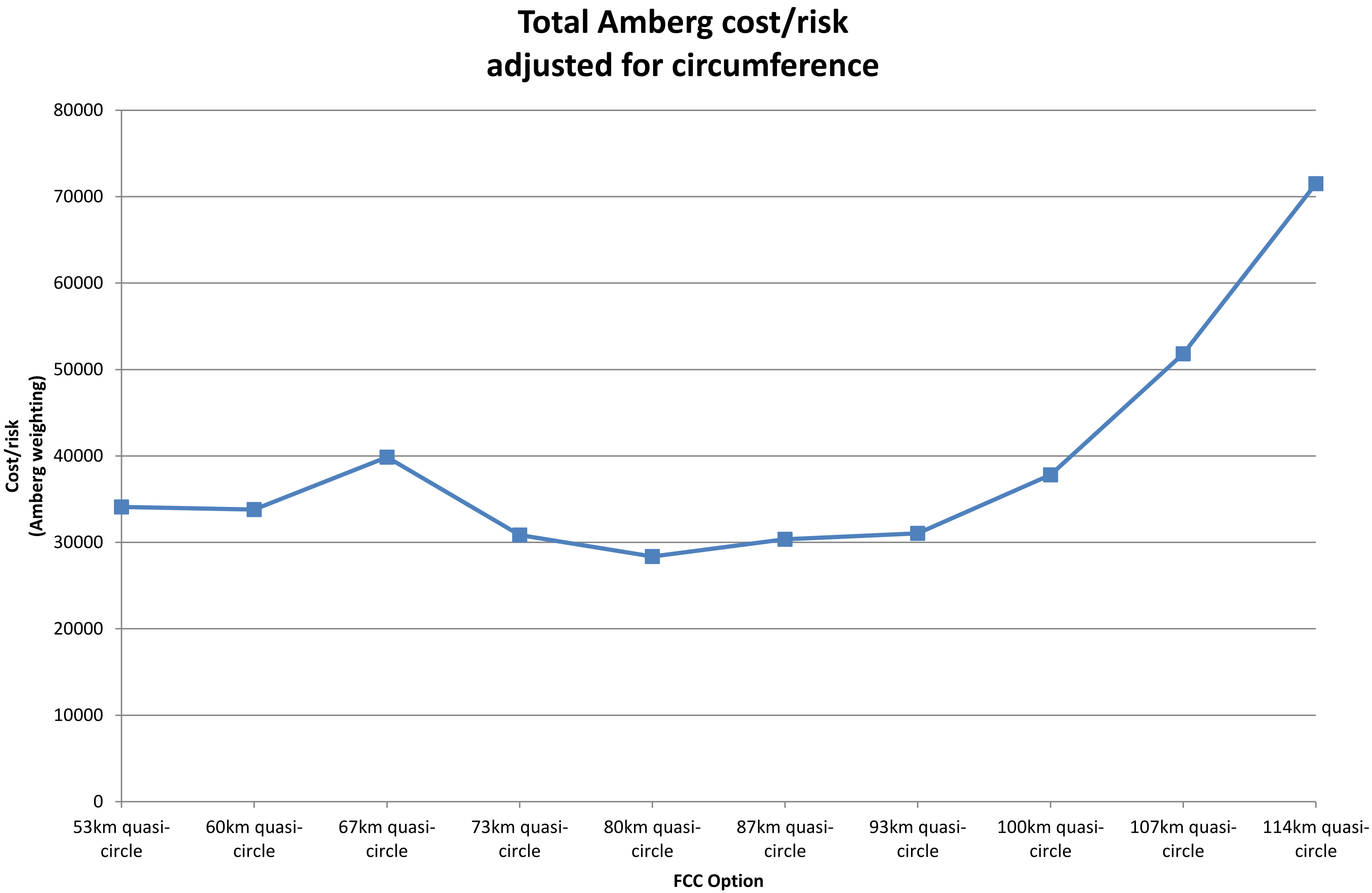
Not yet included:

- Connection to the LHC
- Feasibility of over ground site locations
- Environmental considerations (other than shafts avoiding protected areas)
- Risk of severe tunnel squeezing at depths up to 650m in molasse
- Experimental and service caverns
- Cost/risk for cavern construction at large depths
- Etc.

Latest results - Comparison between options of different circumference



Latest results - Comparison between options of different circumference



Lessons learnt

Lesson 1(a) : Software continues to progress - TOT evolves as the FCC study evolves

- Evolution of options, changing focus of study, changing assumptions

  → New data sets, increased data maturity, new functionalities within TOT

Importance for TOT-ILC: Consideration may need to be given to the future strategy, resources and budget for TOT-ILC development

Lessons learnt

Lesson 1(b): It is the user's responsibility to suggest TOT upgrades to ARUP based on their own experience and knowledge of the project requirements

- Developments to TOT-FCC sometimes on a month to month basis

→ Phase 2 of TOT-FCC development is now planned for the upcoming year

Importance to TOT-ILC: The user (KEK) has the responsibility of both using TOT-ILC as a decision aiding tool and making recommendations to ARUP for future development of TOT-ILC

Lessons learnt

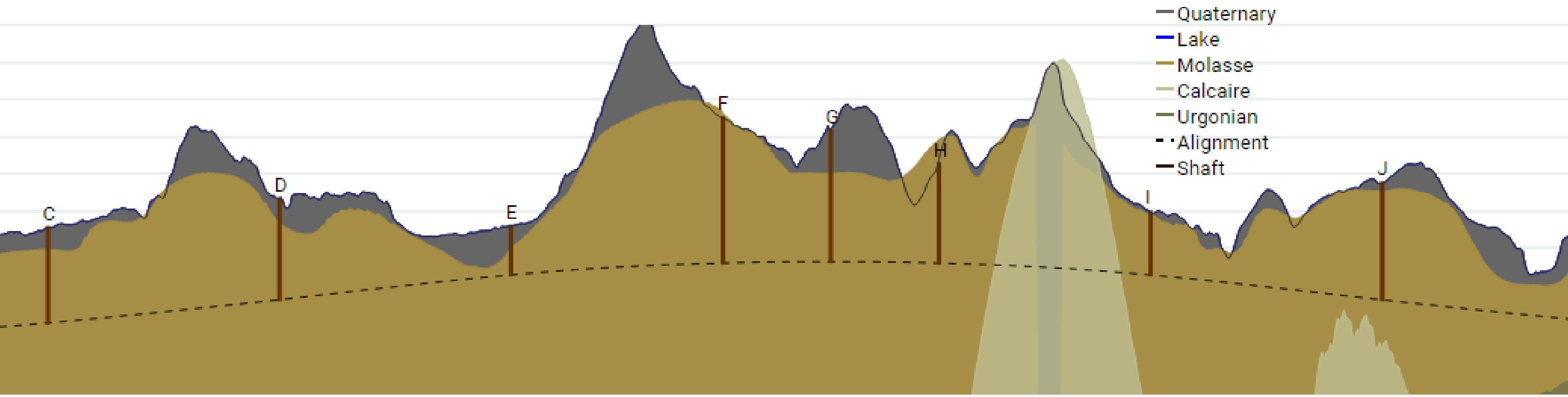
Lesson 2: Comparison between options – not everything can be compared like for like

- Early project stage, many variables (CE + physics demands), many unknowns (geology, future development etc.)

  → Estimated what we can (Amberg metrics) but, some variables cannot be compared like for like without subjective weighting

Importance to TOT-ILC: Optimisation of shaft locations (shaft length vs. surface constraints)

Lessons learnt



Lesson 3: Communication of results has been one of the most useful applications of TOT

- Regular updates for interested groups at CERN and external engineering consultants. Also, external showcasing of the study (IPAC15 [USA], BTSYM [UK])

  → Graphics & data from TOT for every iteration
  → For FCC, a great deal of positive outisde interest has been generated, thanks to TOT communication (press releases, conferences etc.)

Importance to TOT-ILC: The main purpose of TOT-ILC will be a decision aiding tool. However, a major benefit will also be for communication throughout the study

Demonstration

http://cerngis05/cern_server/index.php

CERN

www.cern.ch