Reliability of a Future Circular Collider

Peter Sollander, CERN

ARW Knoxville, April 28, 2015

Thanks for input: A. Apollonio, M. Benedikt, F. Bordry, L. Bottura, P. Collier, J. Gutleber, P. Lebrun, J. Osborne, R. Steerenberg, B. Todd, S. Virtanen

Outline

- Future Circular Collider study
  - Motivation, goal and scope
  - Parameters and technology
  - The reliability work package
  - Collaboration with Tampere University of Technology
- Will not say much about
  - Geological study
  - Tunnel cross section options
  - Dipole magnets
  - Power consumption
  - *Unless asked…*

Motivation, goal and scope

Motivation

- **European Strategy for Particle Physics 2013:**

  "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines.….”

- **US P5 recommendation 2014:**

  ”….A very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window….”

M. Benedikt, FCC week, Washington D.C. March 2015

Goal of FCC Study

- **Conceptual Design Report**
- **By end 2018**
- **In time for next European Strategy Update**

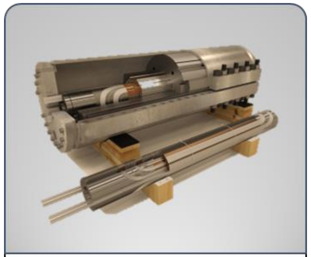
Scope: Accelerator & Infrastructure

Collider Designs

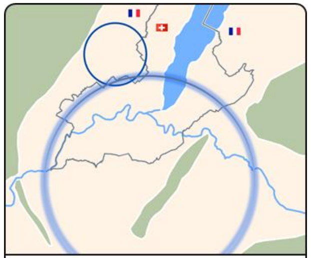
FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs

FCC-ee: **e^+e^- collider**, potential intermediate step

FCC-he: **integration aspects** of pe collisions

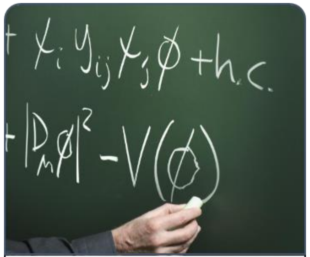

R&D Programs

Push key technologies
in dedicated R&D programmes e.g.
16 Tesla magnets for **100 TeV** pp in **100 km**
SRF technologies and RF power sources

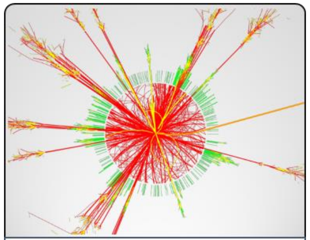

Infrastructures

Tunnel infrastructure in Geneva area, linked to CERN accelerator complex
Site-specific, requested by European strategy

Scope: Physics & Experiments


Physics Cases

Elaborate and document
- Physics opportunities
- Discovery potentials

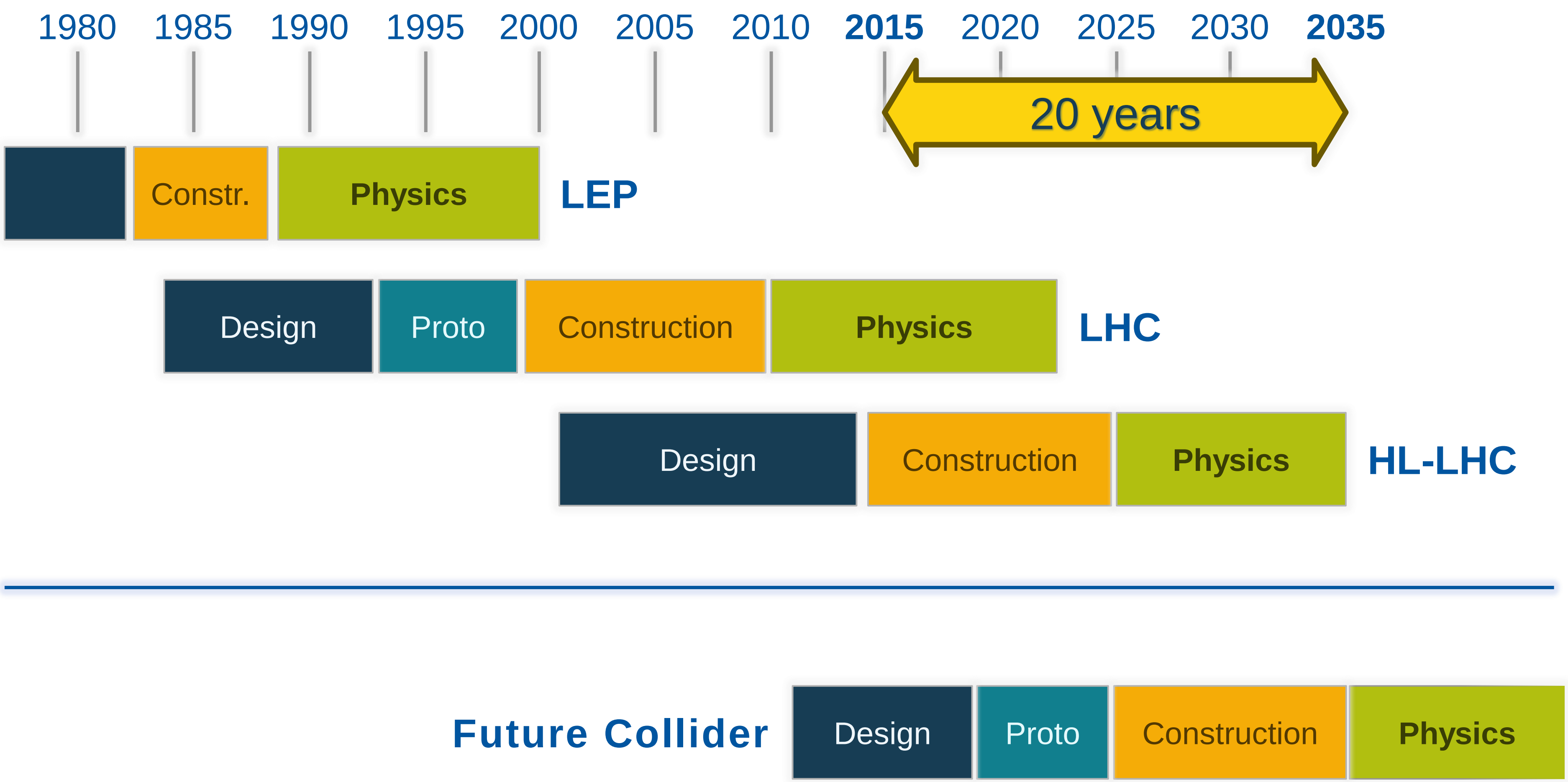

Experiments

Experiment concepts for hh, ee and he
Machine Detector Interface studies
Concepts for worldwide data services

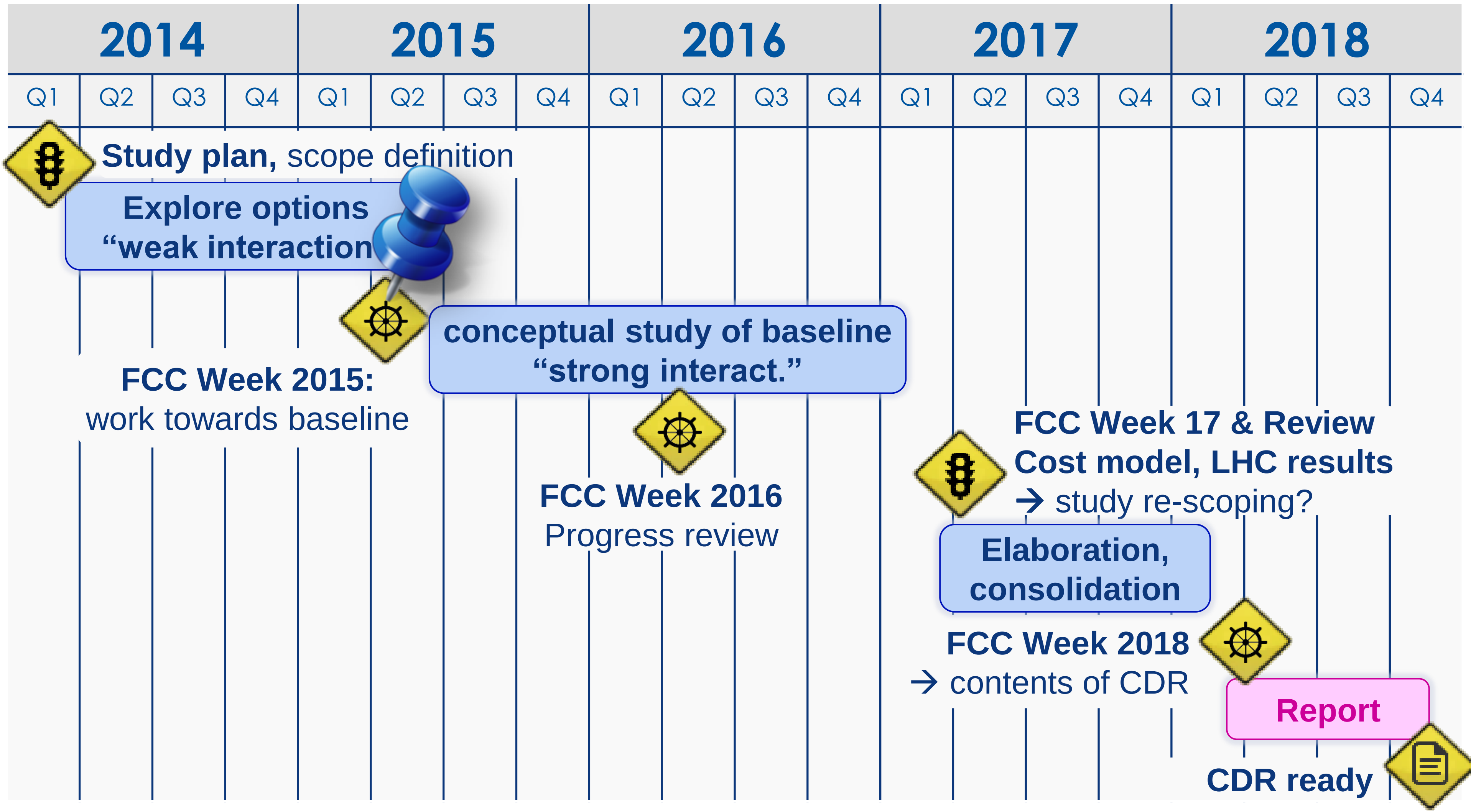
Cost Estimates

Overall cost model
Cost scenarios for collider options
Including infrastructure and injectors
Implementation and governance models

CERN Circular Colliders + FCC



Study time line towards CDR



Parameters and organization

Key Parameters FCC-hh

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

FCC-hh Luminosity Goals

- **Two parameter sets for two operation phases:**
  - **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
    250 fb^{-1}/year (averaged)
    2500 fb^{-1} within 10 years (~HL LHC total luminosity)
  - **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
    1000 fb^{-1}/year (averaged)
    ➔ 15,000 fb^{-1} within 15 years
  - **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

Collaboration Status

- 51 institutes
- 19 countries
- EC participation

FCC Study Organization

Study Lead	M. Benedikt, F. Zimmermann
Hadron Collider **Physics & Experiments**	A. Ball, F. Gianotti, M. Mangano
Lepton Collider **Physics & Experiments**	A. Blondel, J. Ellis, C. Grojean, P. Janot
ep **Physics**, **Experiment**, IP Integration	M. Klein, O. Bruning
Hadron **Injectors**	B. Goddard
Hadron Collider	D. Schulte, M. Syphers
Lepton **Injectors**	Y. Papaphilippou
Lepton Collider	F. Zimmermann, J. Wenninger, U. Wienands
Accelerator Technologies **R&D**	L. Bottura, E. Jensen, L. Tavian
Special Technologies	JM. Jimenez
Infrastructures & Operation	P. Lebrun, P. Collier
Costing & Planning	P. Lebrun, F. Sonnemann

Infrastructures & Operation topics

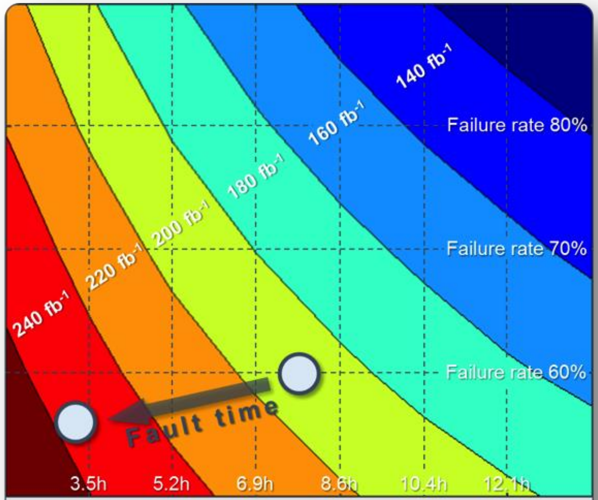
- Geology & civil engineering
- Integration
- Electrical distribution
- Cryogenics
- Cooling & ventilation
- Transport & handling
- Installation
- Survey & alignment
- Controls
- Power/energy consumption
- Availability & reliability
- General safety
- Radiation protection

P. Lebrun, FCC week, Washington D.C. March 2015

Reliability

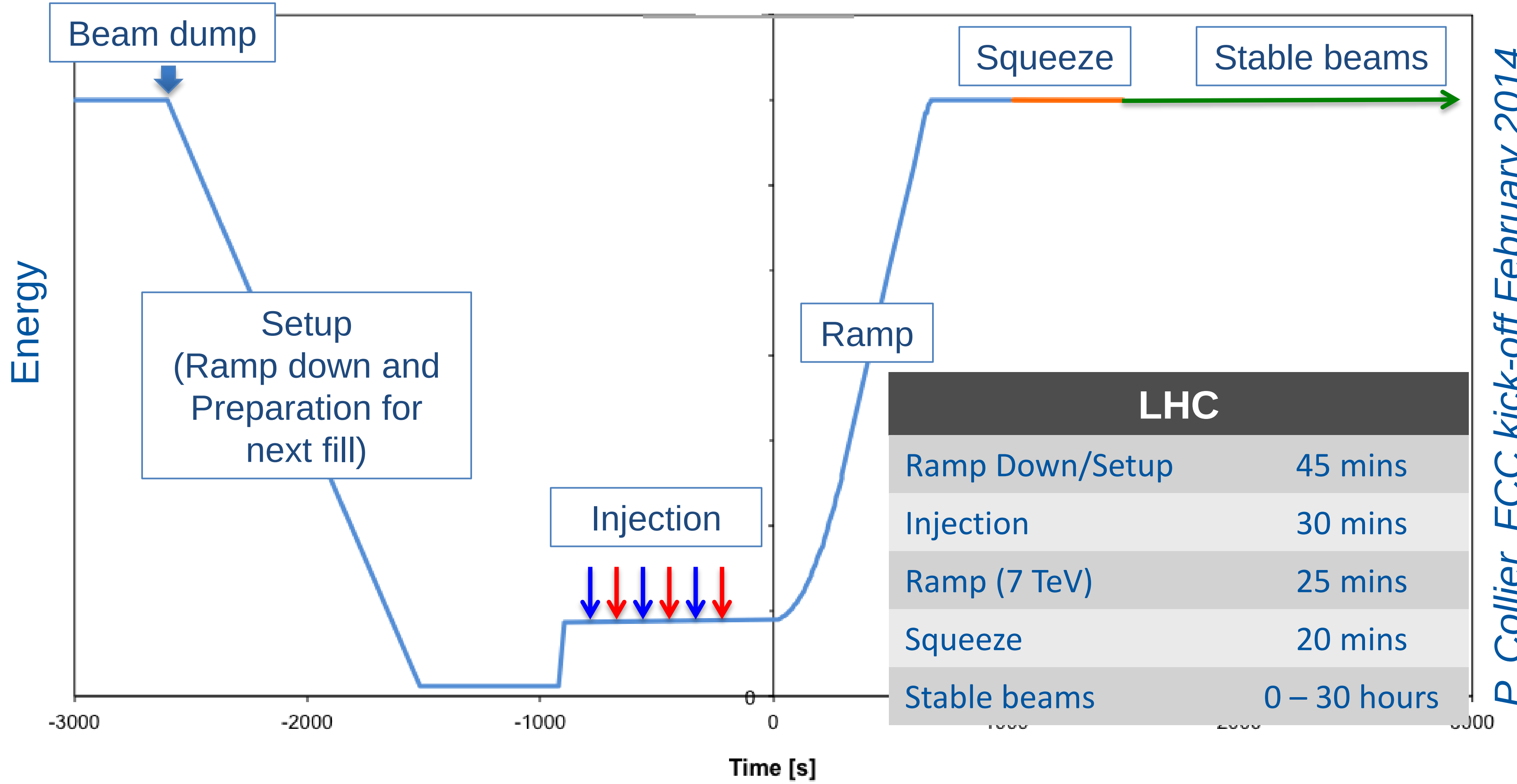
Reliability is key for performance

- Improving component reliability soon reaches limits. Cost no longer justifies efforts
- Road to improve physics performance (integrated luminosity) is to increase duration of fills and to reduce turnaround times
- Studies to identify key potentials and to tune investment / effectiveness at global level: LHC as basis, HL-LHC as test-bed



Reach luminosity goal by reducing turnaround time

Operational Cycle



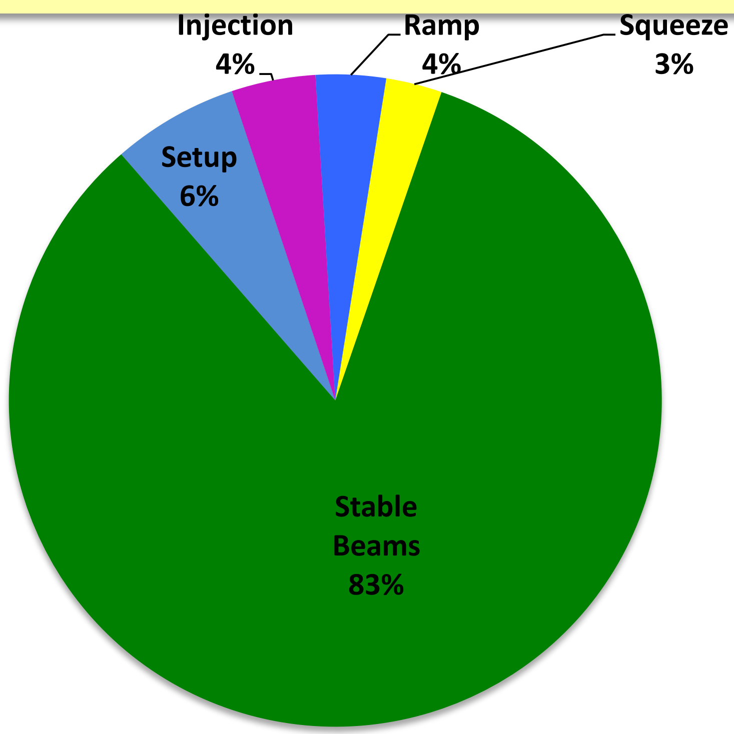
LHC	
Ramp Down/Setup	45 mins
Injection	30 mins
Ramp (7 TeV)	25 mins
Squeeze	20 mins
Stable beams	0 – 30 hours

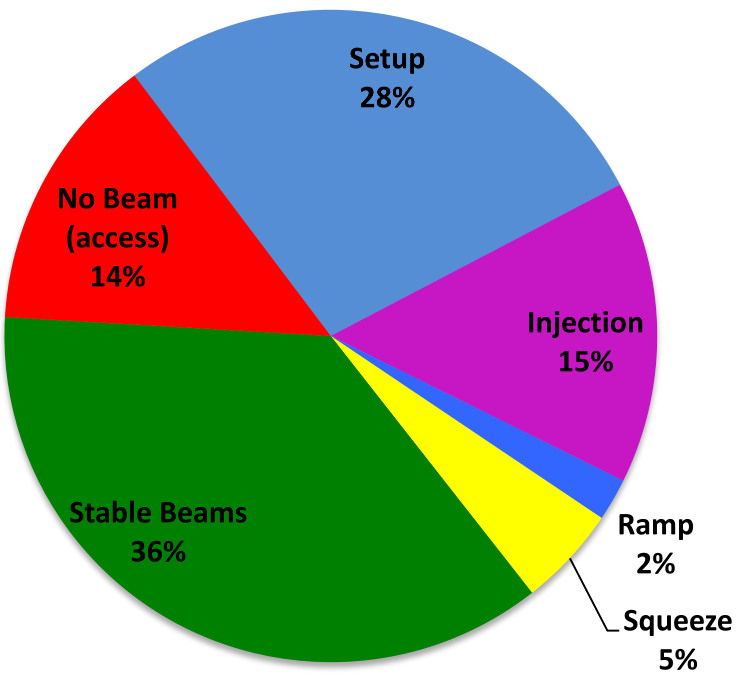
P. Collier, FCC kick-off February 2014

Should take this as a basis for FCC-hh as well and see the impact

Gross scaling : FCC-hh = 4xLHC in terms of equipment

If we assume fault time scales in the same way then, based on 2012 LHC statistics, FCC will never do any Physics!

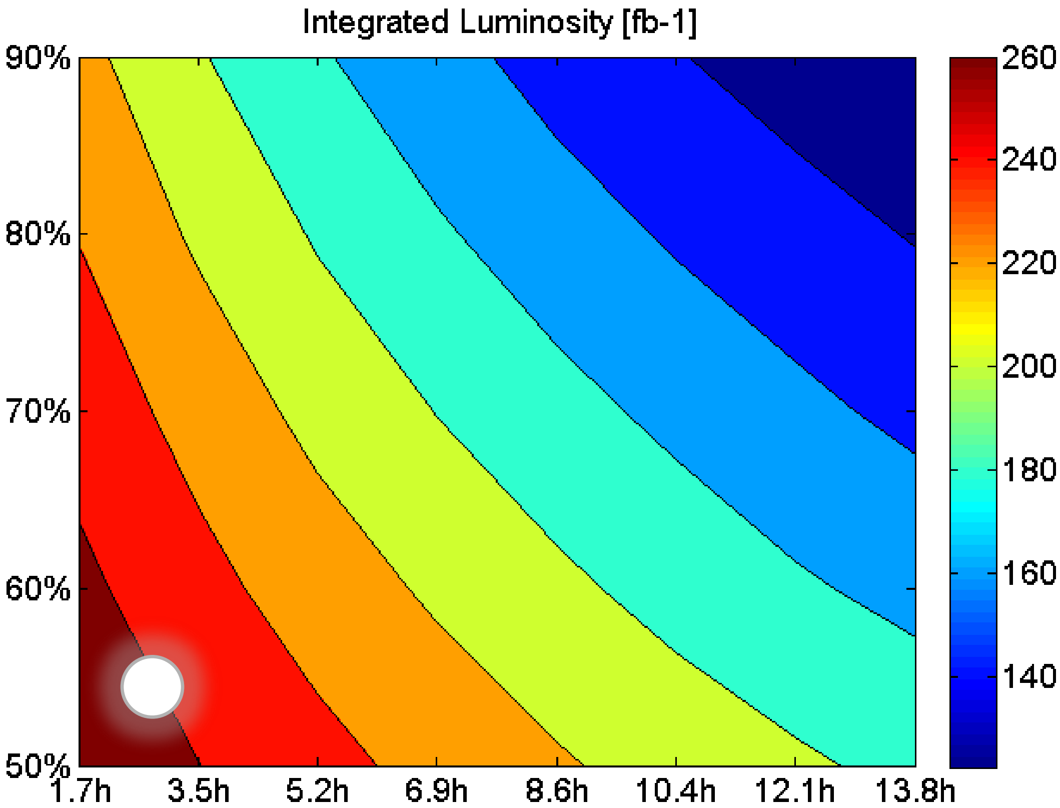




In spite of how it looks LHC operation in 2012 was very good !!

Luminosity → Reliability → Design requirements

Failure tendency (Reliability)



Unavailability (hours)

Localization + Diagnostics + Logistics + Repair

The Reliability work package

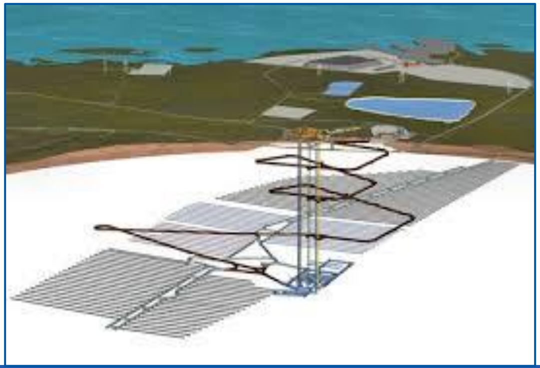
Assess if and how industrial RAMS methods can be used for the FCC

1. Evaluate the suitability of industrially applied RAMS methods and tools for use in particle accelerator projects
2. Assess benefits for the design of future accelerators
3. Formulate high level recommendations
4. Train system experts to use selected methods and tools

Tampere University of Technology knows RAMS

- Big industries
  - Statoil, Procter & Gamble, Wartsila, Kone, …
  - Integrated operations
- Military
  - F18 Hornet reliability
- Nuclear industry
  - Posiva nuclear waste management (encapsulation plant)
- … and more

- 3.5 people strong team for FCC study



TUT made RAMS design for Finnish encapsulation plant

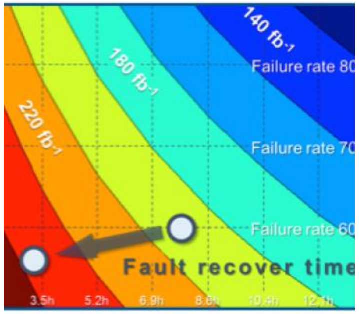
- 3 minutes film
- Challenges
  - First of its kind
  - Application of new and unknown technologies
  - Very high reliability required for certain operations
  - Remote handling
  - Long operation period (100+ years)

Modeling an existing accelerator will tell if the methods are applicable

- Model LHC with injectors and sub-systems
  - Collaborate with existing groups and efforts
    - Availability Working Group, Machine Protection, etc.
  - Model top-down
- Identify key contributors to downtime
- Example areas that may be interesting to study
  - Impact of injectors
  - Optimizing turn-around time (fast ramps, injection strategy)
  - Large scale technical systems (cryogenics)
  - Machine protection
  - Maintainability (100km ring)
  - …
- Feed back results to LHC, HL-LHC, other machines..

Summary

- The FCC study considers availability key to achieve requested performance
- A work package is defined for RAMS
- Tampere University of Technology has RAMS expertise and will work for the FCC study
- Work units are defined and about to start
- Findings should be useful to LHC and HL-LHC as well
- More collaborators are welcome…



Availability

Additional slides

Potential locations : European Strategy : Krakow 2012

- Location 1:

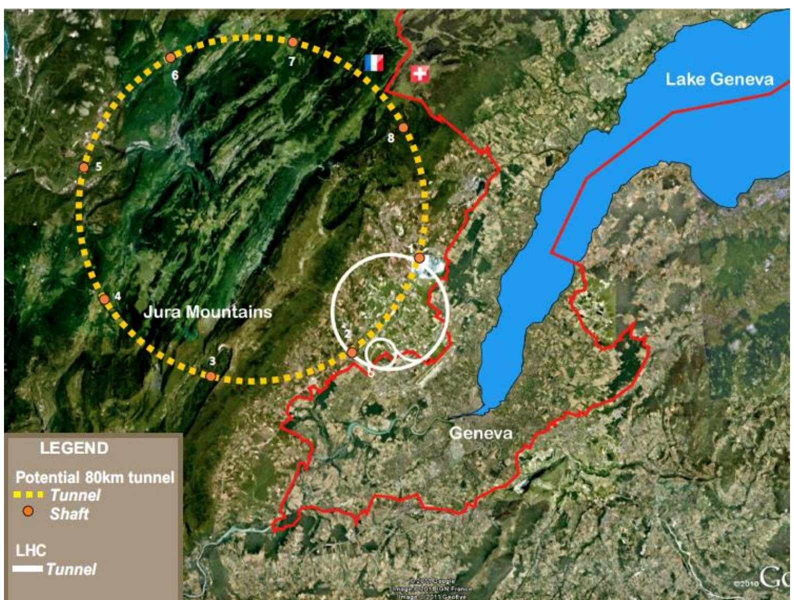
80km Jura option

- Fully housed in France
- 90% in Jura Limestones
- 10% in Molasse
- Connected to LHC
- Shafts every 10km

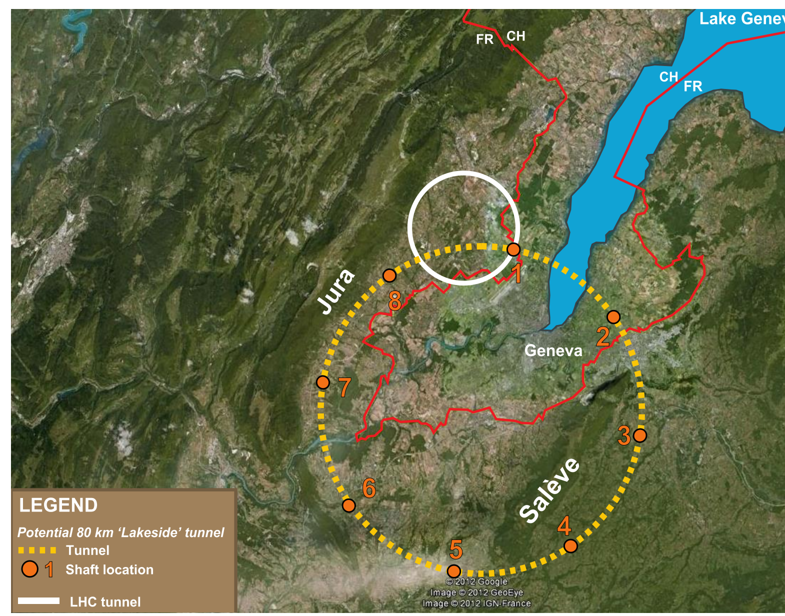
- Location 2:

80km Lakeside option

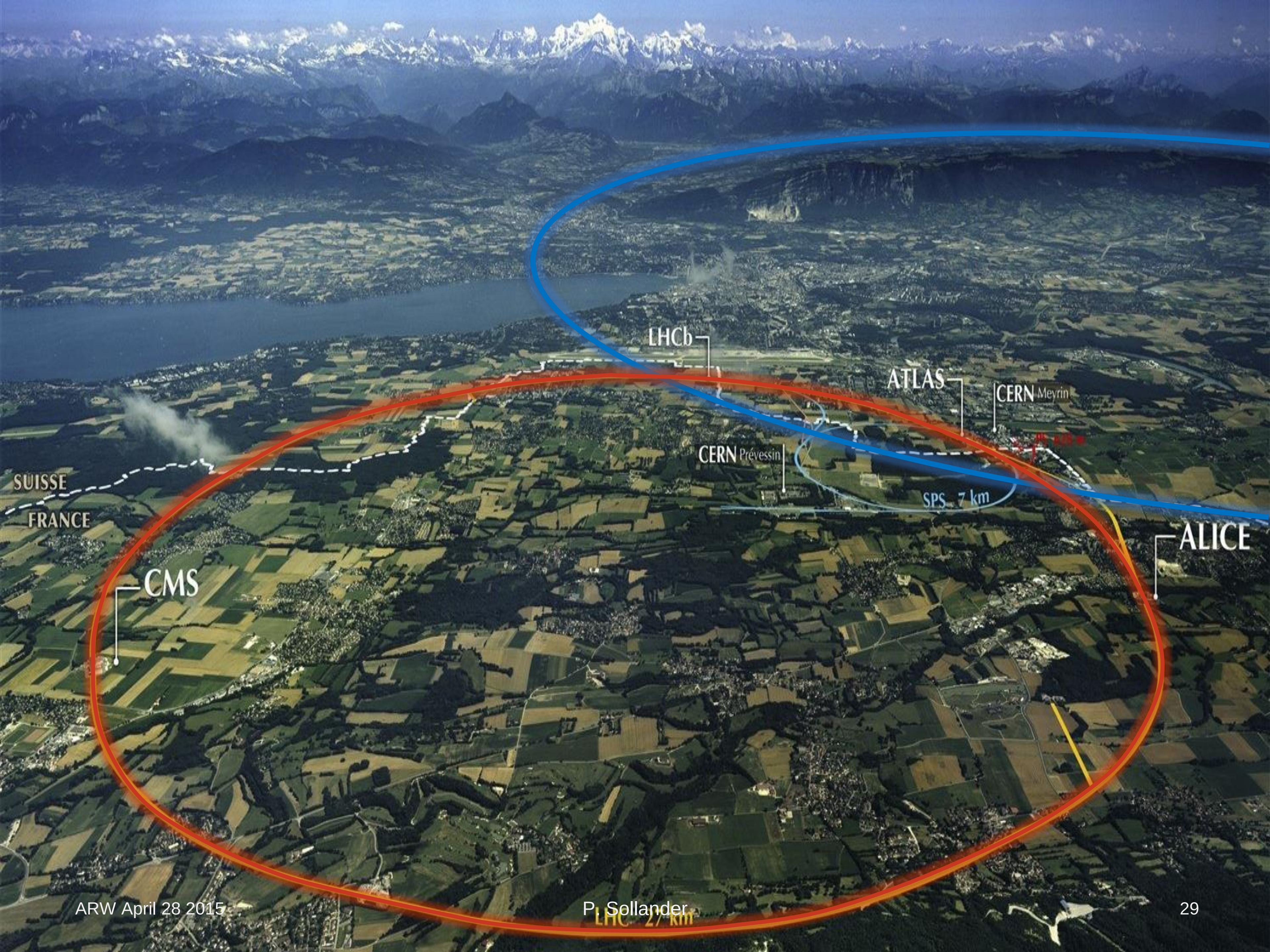
- Housed in France and Switzerland
- 10% in Limestones (Jura, Salève)
- 90% in Molasse
- Passes under Lake Geneva
- Around the back of the Salève
- Connected to LHC
- Shafts every 10km



Option 1: 80km Jura

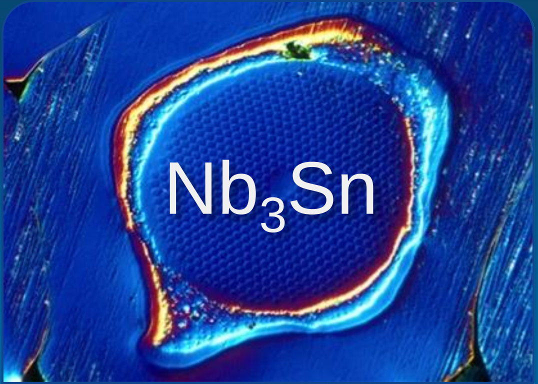


Option 2: 80km Lakeside


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

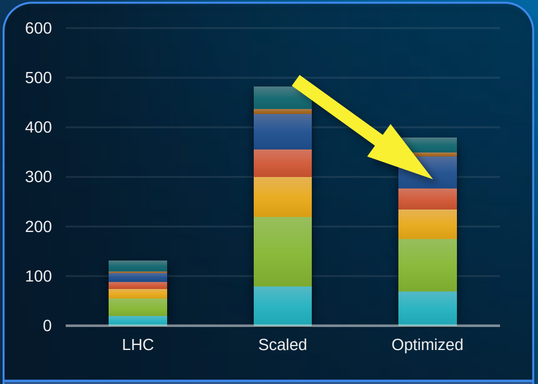
Push technologies to reach goals

High-field Magnets



Novel Materials and Processes

Large-scale Cryogenics

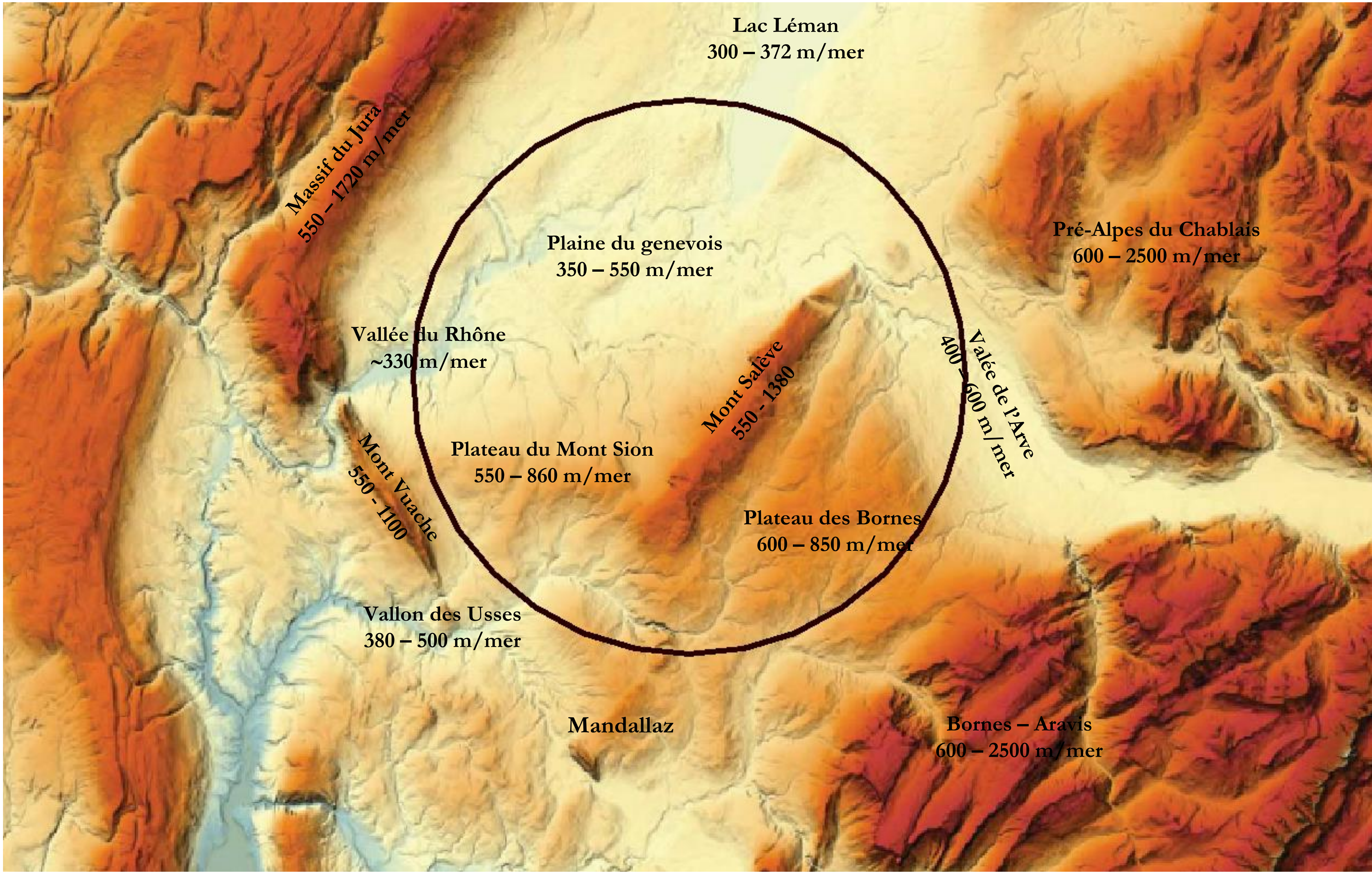


Power Efficiency

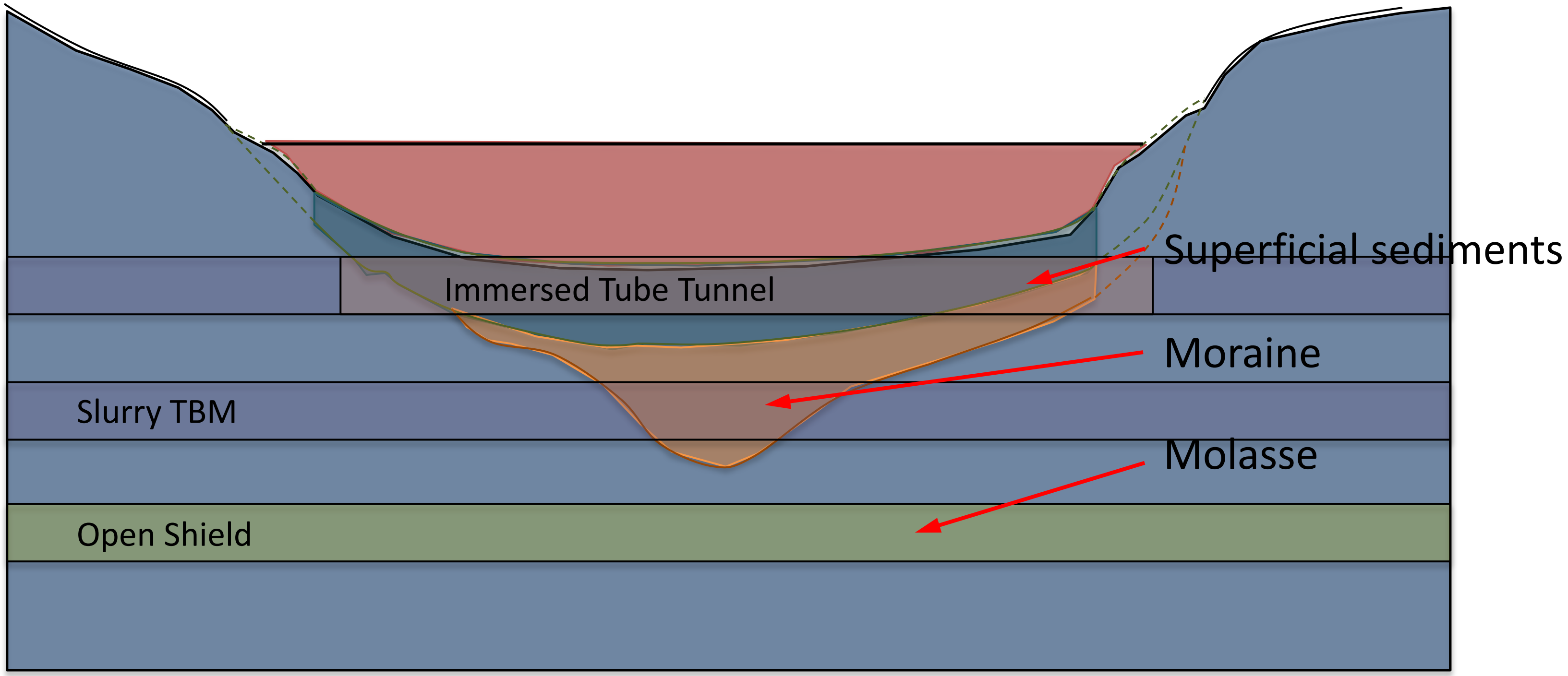
Global Scale Computing

Reliability & Availability

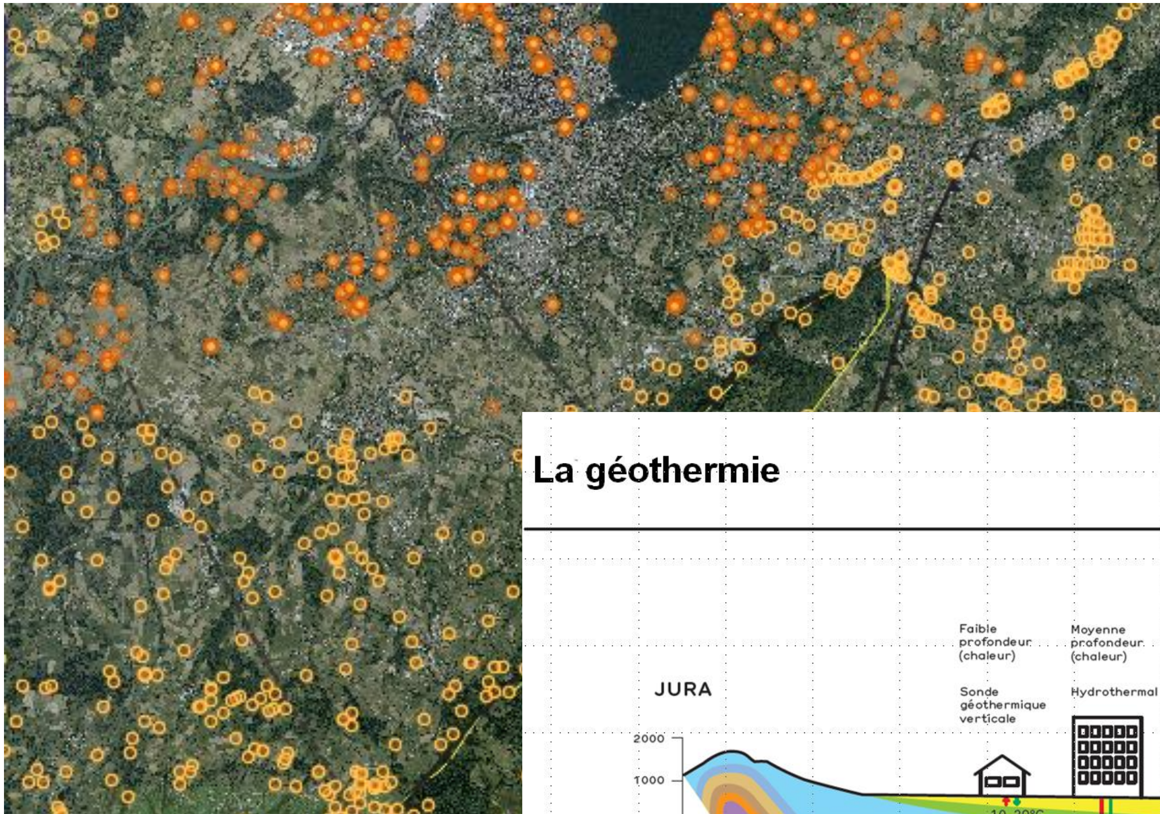
CE considerations for input into the tool : *topography*



Lake Crossing: Tunnelling Considerations

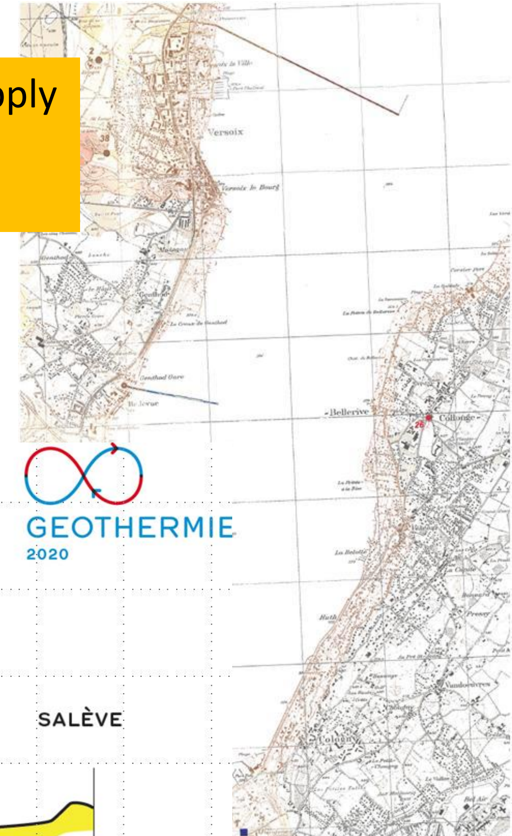


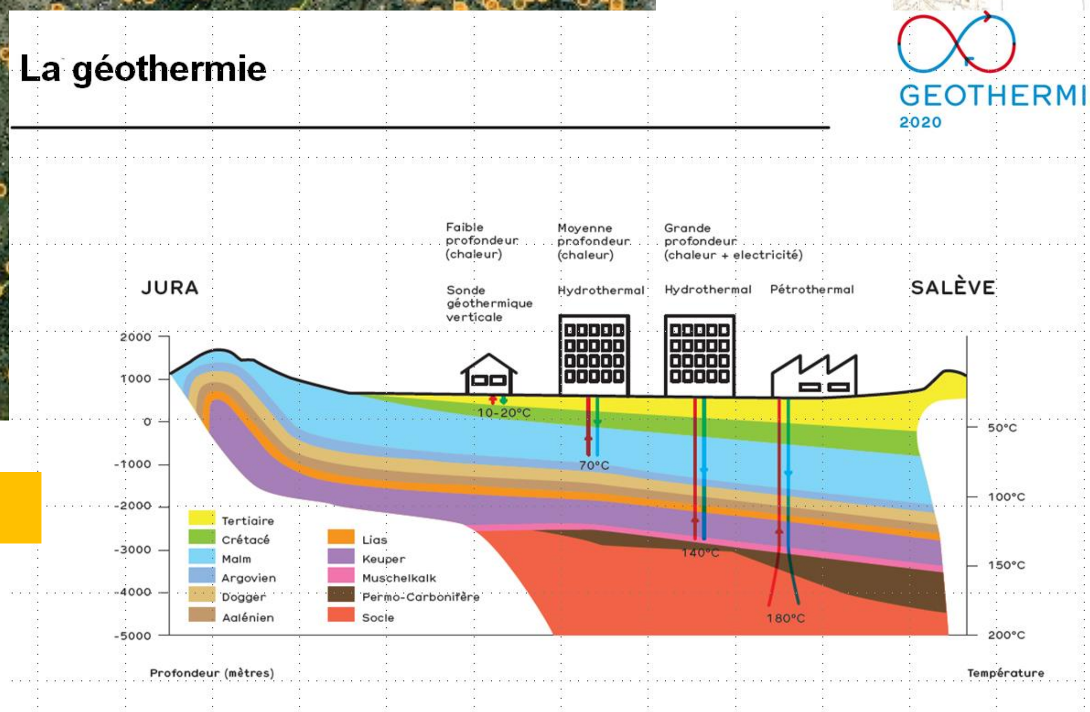
CE considerations for input into the tool : *Man-made hazards*



Geothermal drillings

Water supply pipelines





Geological data in the model

Data in the tool :

- Study area boundary
- Molasse-quaternary boundary (top of Molasse rockhead)
- Limestone-molasse boundary (molasse rockbottom)
- Limestone roof level refined with additional seismic data from BRGM, analysed by Geneva Geo Energy
- Hydrology
- Geothermal Boreholes
- Environmentally sensitive and protected areas
- Urban areas

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

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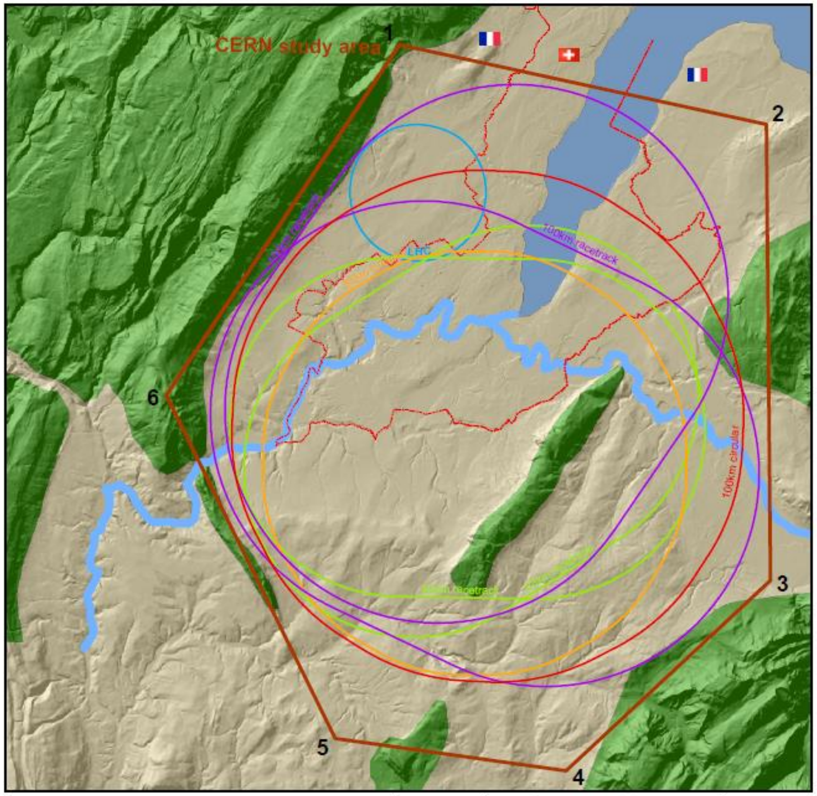
FCC
Determination of the geological survey area

Created from CERN Geographic Information System



Legend

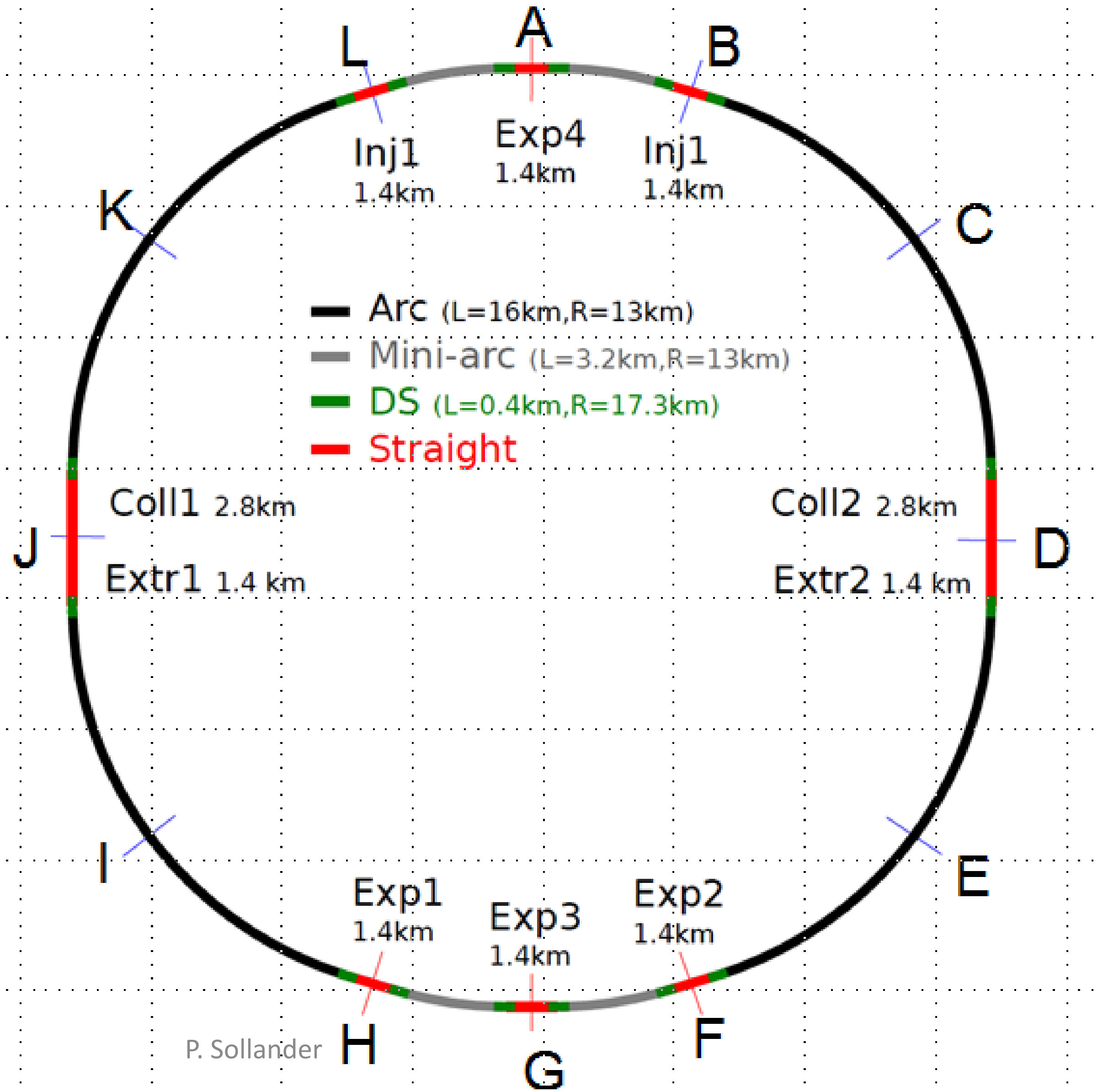
Machine Scenarios :
100km circular — 83km circular — LHC — CERN
100km racetrack — 83km racetrack

CERN study area		
Points	Long	Lat
1	6.040043	46.354092
2	6.349873	46.313785
3	6.355130	46.060480
4	6.193486	45.952405
5	6.008318	45.968384
6	5.866667	46.158026

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

General tunnel configuration

- FCC circumference is a multiple of LHC :
  - 80 km (3.0x LHC)
  - 87 km (3.25x LHC)
  - 93 km (3.75x LHC)
  - 100 km (4x LHC)



P. Sollander

(1a) 93km Quasi-circle

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

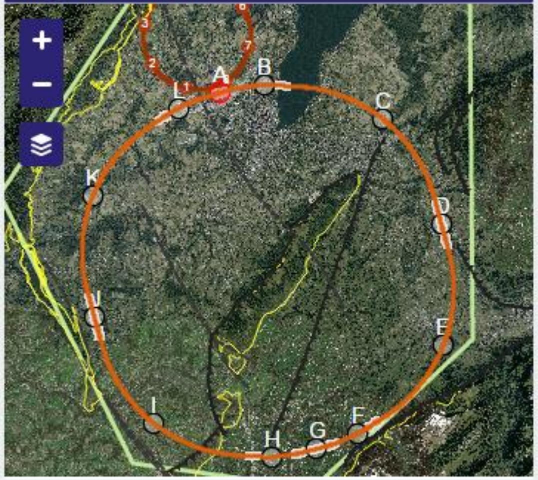
CALCULATE

Alignment centre

X: 2499812 Y: 1106889

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

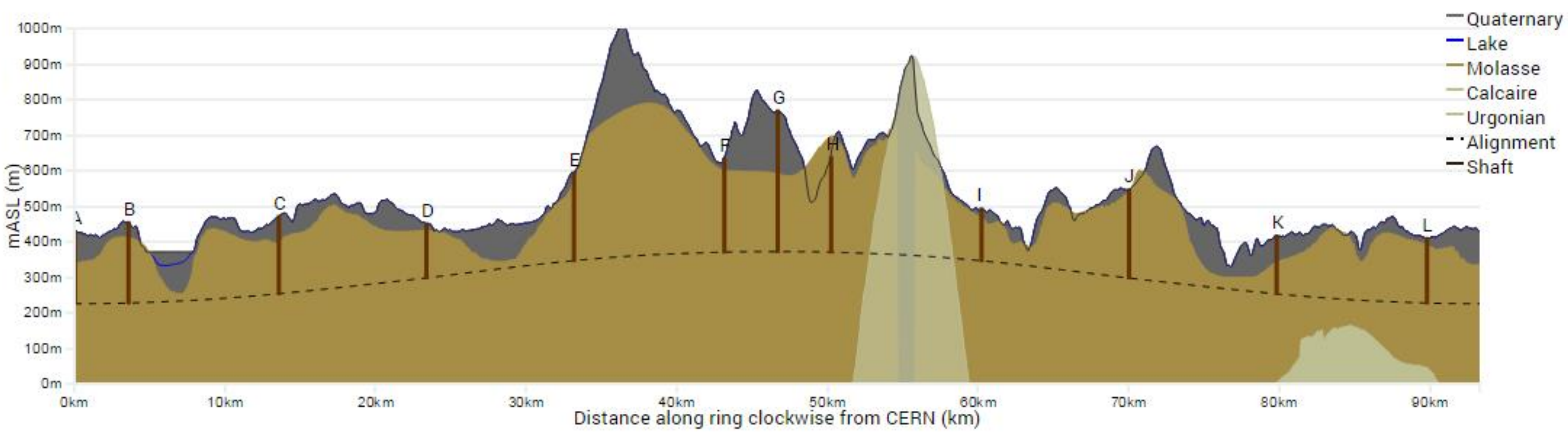
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)			
Point	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

Alignment Profile



Geology Intersected by Tunnel

94.1%	5.9%

(2a) 100km Quasi-circle

Alignment | Shaft Tools

Choose alignment option

100km quasi-circular ▼

Tunnel depth at centre: 263mASL

Gradient Parameters

Azimuth (°): -20

Slope Angle x-x(%): .65

Slope Angle y-y(%): 0

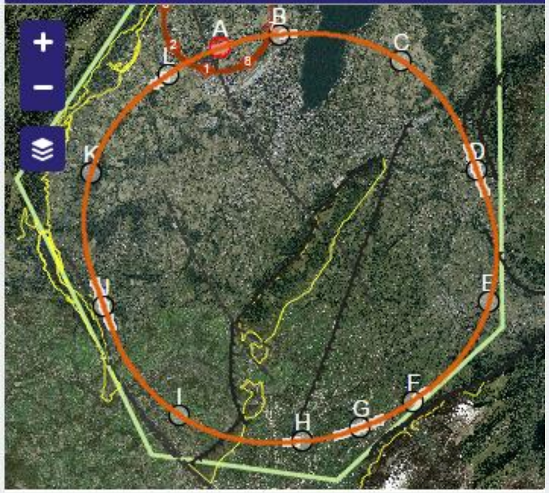
CALCULATE

Alignment centre

X: 2499731 Y: 1108403

LHC Intersection	CP 1	CP 2
Angle	-64°	64°
Depth	218m	170m

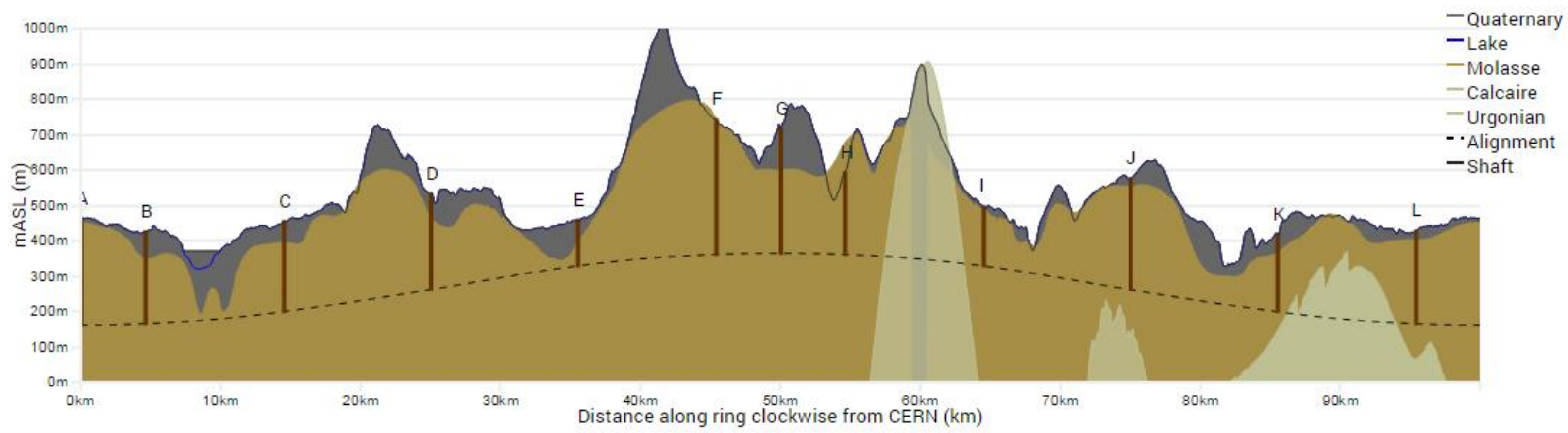
Alignment Location



Geology Intersected by Shafts | Shaft Depths

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	302	301	302	303	12	290	0	0
B	261	255	260	265	76	184	0	0
C	255	246	252	257	58	197	0	0
D	270	246	268	278	64	206	0	0
E	130	128	130	133	64	66	0	0
F	381	367	379	389	0	385	0	0
G	352	339	359	374	116	235	0	0
H	232	194	230	265	0	313	0	0
I	168	163	171	180	12	156	0	0
J	313	311	317	323	22	291	0	0
K	219	209	223	249	52	167	0	0
L	262	258	263	271	25	237	0	0
Total	3145	3017	3154	3287	501	2729	0	0

Alignment Profile



Geology Intersected by Tunnel

86.7% | 13.3%

(1b) 93km Quasi-circle

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular ▾

Tunnel elevation at centre:328mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .45

Slope Angle y-y(%): .25

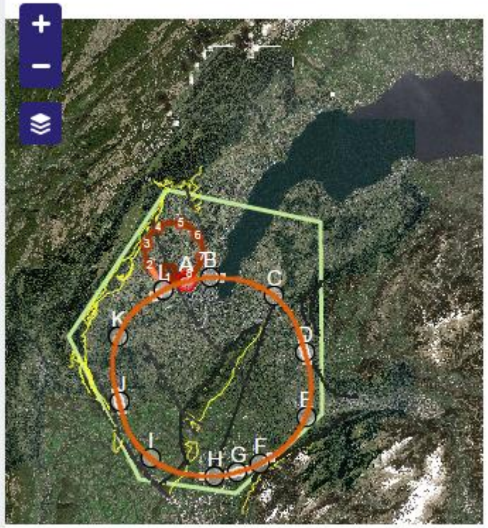
CALCULATE

Alignment centre

X: 2499812 Y: 1106889

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC		114m		115m
SPS		140m		140m
TI2		140m		140m
TI8		95m		97m

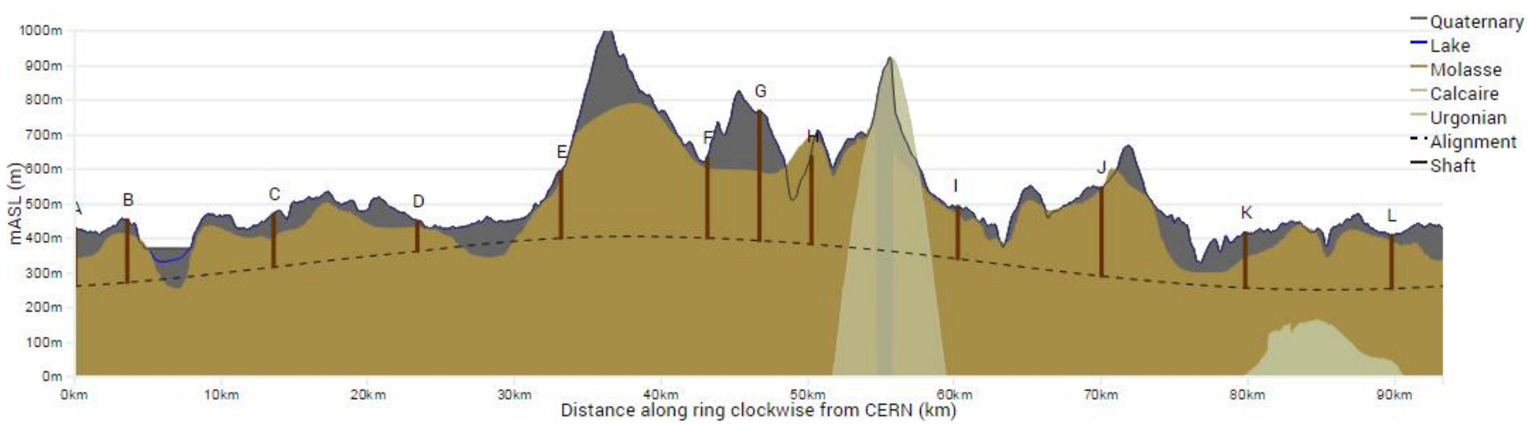
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	167	164	168	176	93	74	0	0
B	182	168	179	186	42	140	0	0
C	154	144	153	162	75	80	0	0
D	88	85	89	93	19	69	0	0
E	193	179	195	207	24	169	0	0
F	231	220	238	274	32	199	0	0
G	375	370	371	375	177	198	0	0
H	253	218	261	309	0	312	0	0
I	152	146	149	154	26	125	0	0
J	254	253	257	264	6	249	0	0
K	159	149	156	160	76	83	0	0
L	155	155	157	159	17	138	0	0
Total	2363	2251	2373	2519	586	1836	0	0

Alignment Profile



Geology Intersected by Tunnel

88.3% | 5.9% | 5.8%

(2b) 100km Quasi-circle

Alignment | **Shaft Tools**

Choose alignment option

100km quasi-circular ▼

Tunnel elevation at centre:327mASL

Gradient Parameters

Azimuth (°): -20

Slope Angle x-x(%): .5

Slope Angle y-y(%): .15

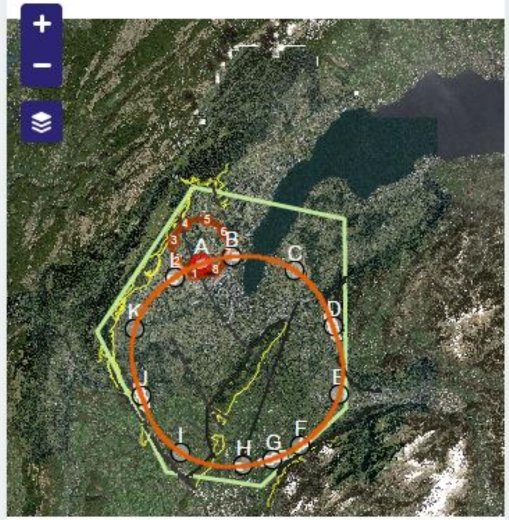
CALCULATE

Alignment centre

X: 2499731 Y: 1108403

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	-64°	169m	64°	112m
SPS		154m		154m
TI2		147m		154m
TI8		154m		84m

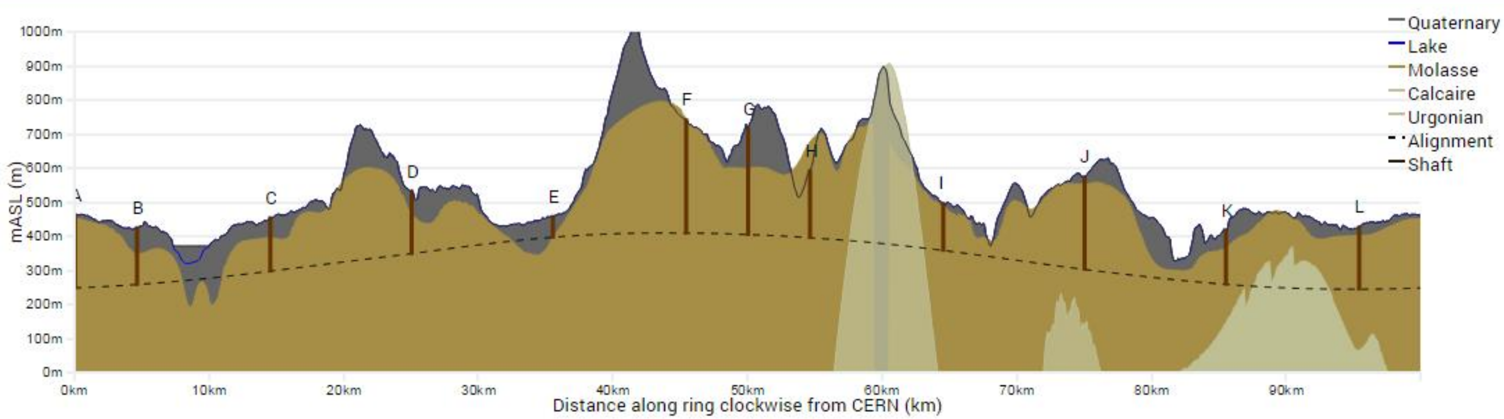
Alignment Location



Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	214	213	215	215	12	202	0	0
B	167	162	166	171	76	91	0	0
C	157	148	154	159	58	99	0	0
D	183	159	181	191	64	120	0	0
E	62	59	62	65	62	0	0	0
F	333	319	331	341	0	337	0	0
G	311	299	319	333	116	195	0	0
H	197	159	195	231	0	278	0	0
I	138	133	141	150	12	126	0	0
J	272	270	276	282	22	250	0	0
K	159	149	163	189	52	107	0	0
L	183	178	183	192	25	158	0	0
Total	2377	2248	2386	2519	499	1963	0	0

Alignment Profile

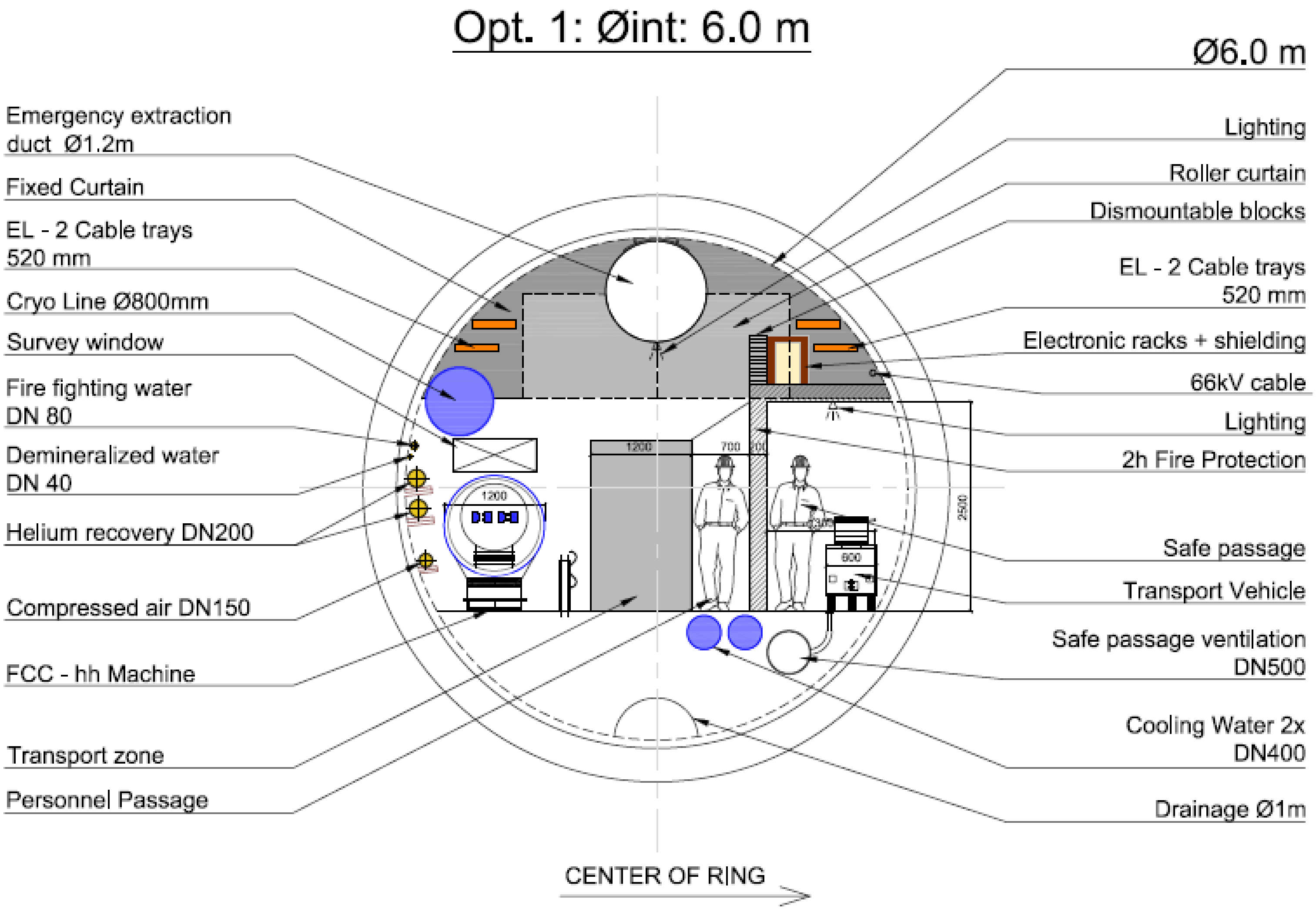


Geology Intersected by Tunnel

83.0% | 10.9% | 6.1%

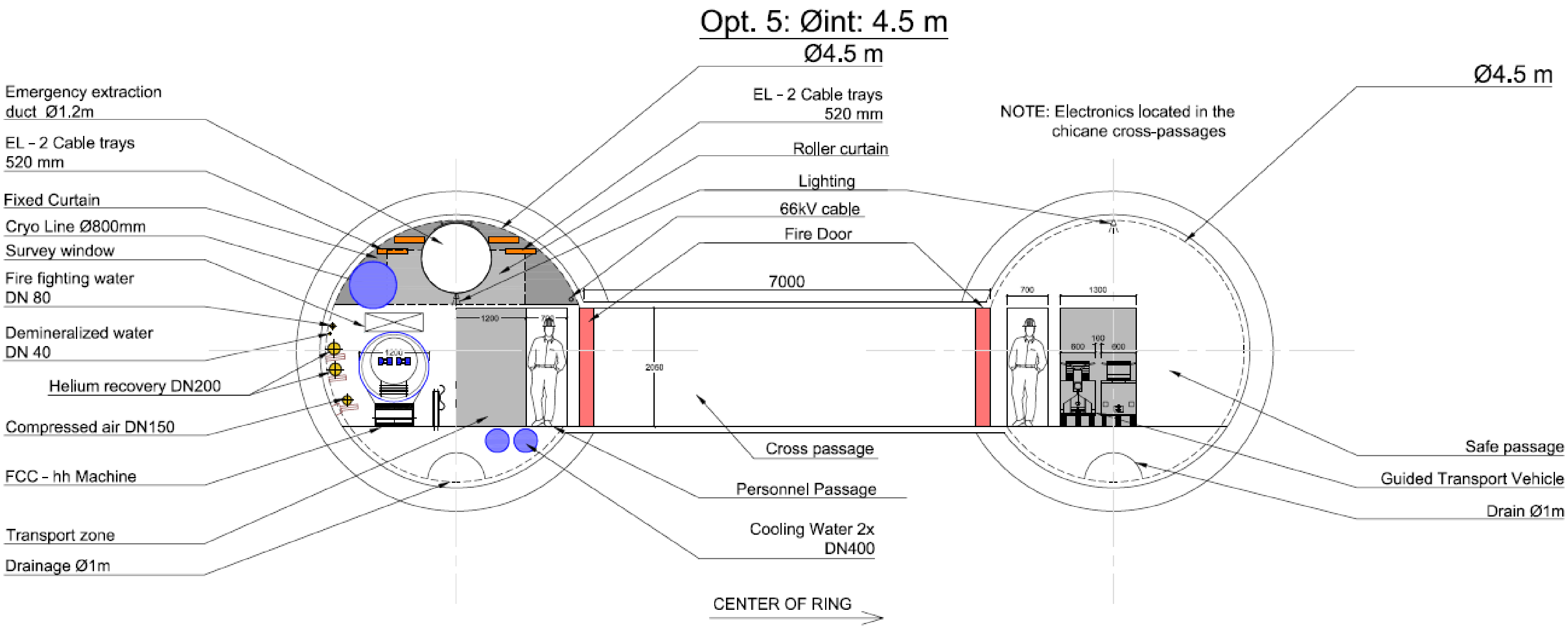
Feasibility Study – Early cross sections

hh machine



Feasibility Study – Early cross sections

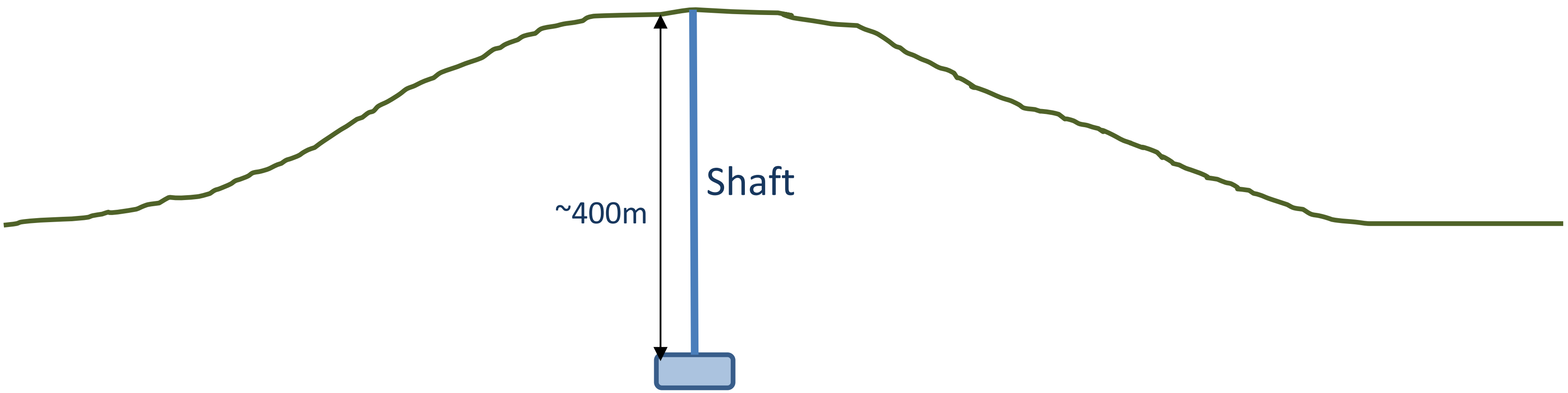
hh machine



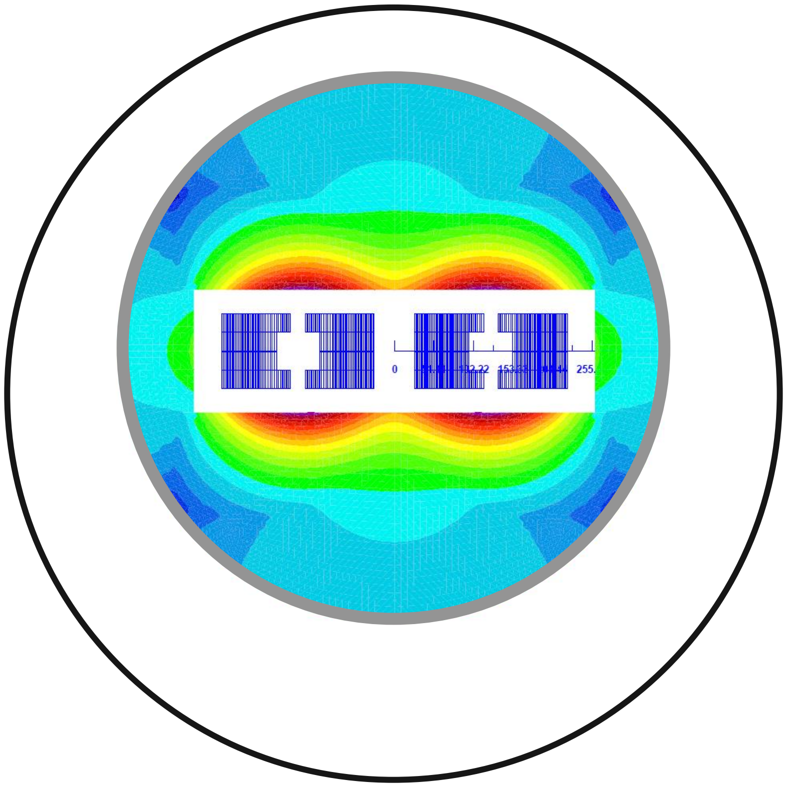
John Osborne (CERN-GS)

Detector cavern access

Shaft (vertical) vs. Inclined tunnel?



MB – block @ 1.9 K



Number of apertures	(-)	2
Aperture	(mm)	50
Inter-aperture spacing	(mm)	250
Operating current	(kA)	16.4
Operating temperature	(K)	1.9
Nominal field	(T)	16
b_2 @ 2/3 Aperture	10^{-4}	40.5
b_3 @ 2/3 Aperture	10^{-4}	2.8
Peak field	(T)	16.3
Margin along the load line	(%)	~20
Stored magnetic energy	(MJ/m)	3.2
Fx (per ½ coil)	(kN/m)	7600
Fy (per ½ coil)	(kN/m)	-3800
Inductance (magnet)	(mH/m)	22.8
Yoke ID	(mm)	-
Yoke OD	(mm)	700
Weight per unit length	(kg/m)	2500
Area of SC	(mm^2)	6650
Area of cable low-Jc Nb_3Sn	(mm^2)	7180
Area of cable high-Jc Nb_3Sn	(mm^2)	10900
Area of cable Nb-Ti	(mm^2)	4000
Turns Low-J Nb_3Sn per pole	-	19
Turns High J Nb_3Sn per pole	-	41
Turns Nb-Ti per pole	-	15

1 m diameter "cryostat" envelope
Mechanical concept: Collared coils

Design by D. Schoerling, J. van Nugteren

Power consumption summary

Items	LHC Steady State Power [MW]	FCC-hh Steady State Power [MW]	Comment
Magnet Circuits	20	86.4	Wall-plug, worked out estimate
RF	18	32	Rough estimate
Cryogenics	32	190	To be revisited/refined
Cooling	20	71	Power in cooling water
Ventilation	14	56	Rough, 4 x LHC
Other Machine	2.5	10	Rough, 4 x LHC
General services	13	52	Rough, 4 x LHC
Experiments	22	30	(10 + 10 + 5 + 5)
Total	**147.5**	**527.4**	