International Workshop on High Energy Circular Electron Positron Collider
IHEP, Beijing
Nov 8-10 2017

CERN roadmap and FCC

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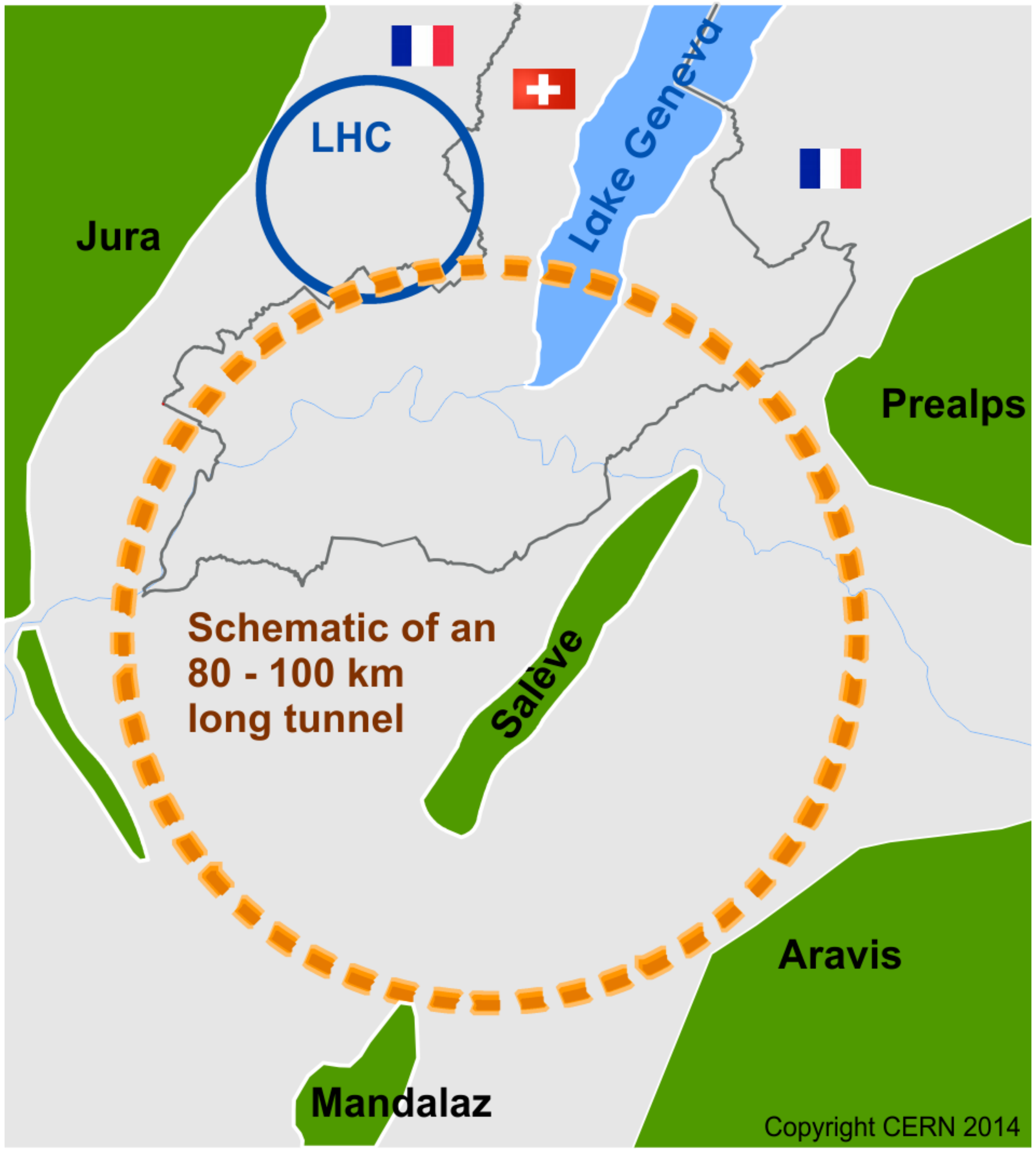
CERN’s Future Circular Colliders (FCC) study

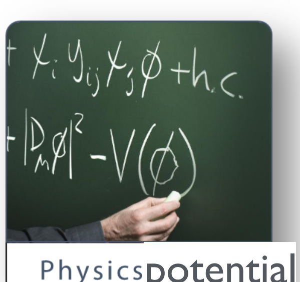


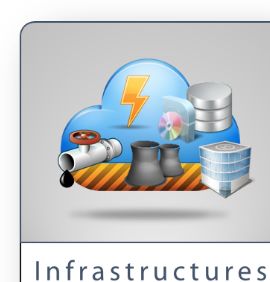
International FCC collaboration (CERN as host lab) to study:

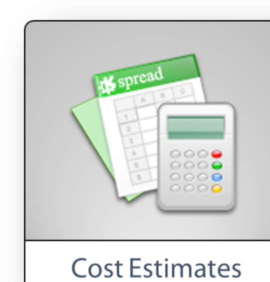
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

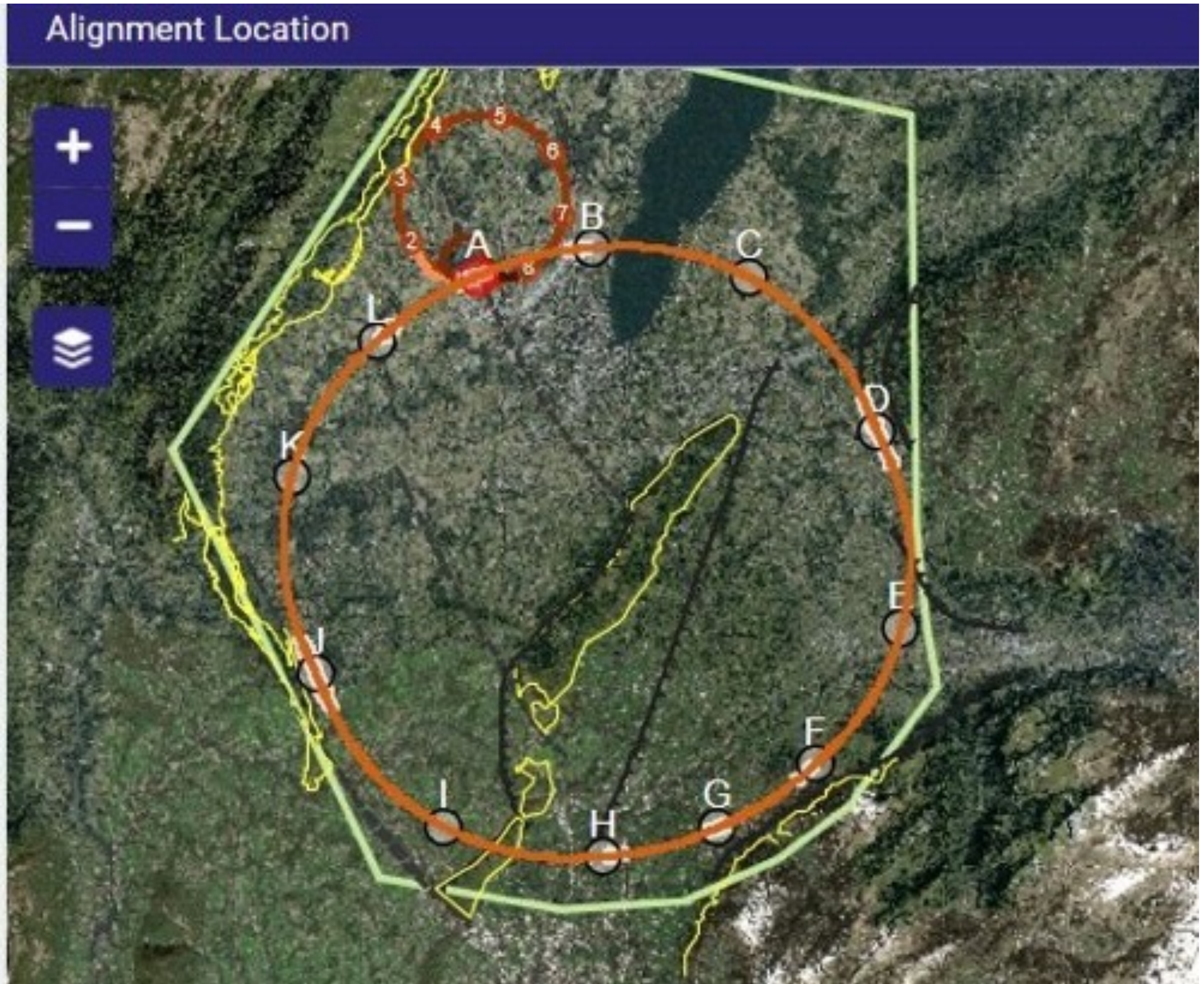
- **~100 km tunnel infrastructure**
  in Geneva area, site specific
- ***e*$^+$*e*$^-$ collider (*FCC-ee*),**
  as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,**
  integration of one IP, e from ERL
- **CDR for end 2018**



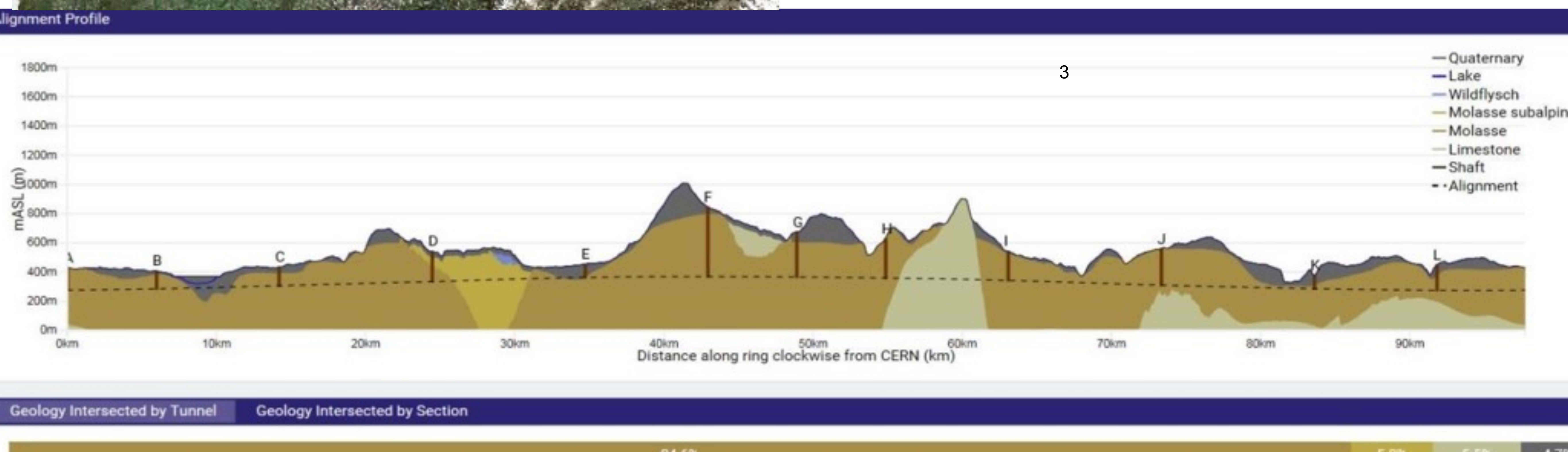




Overall layout optimization

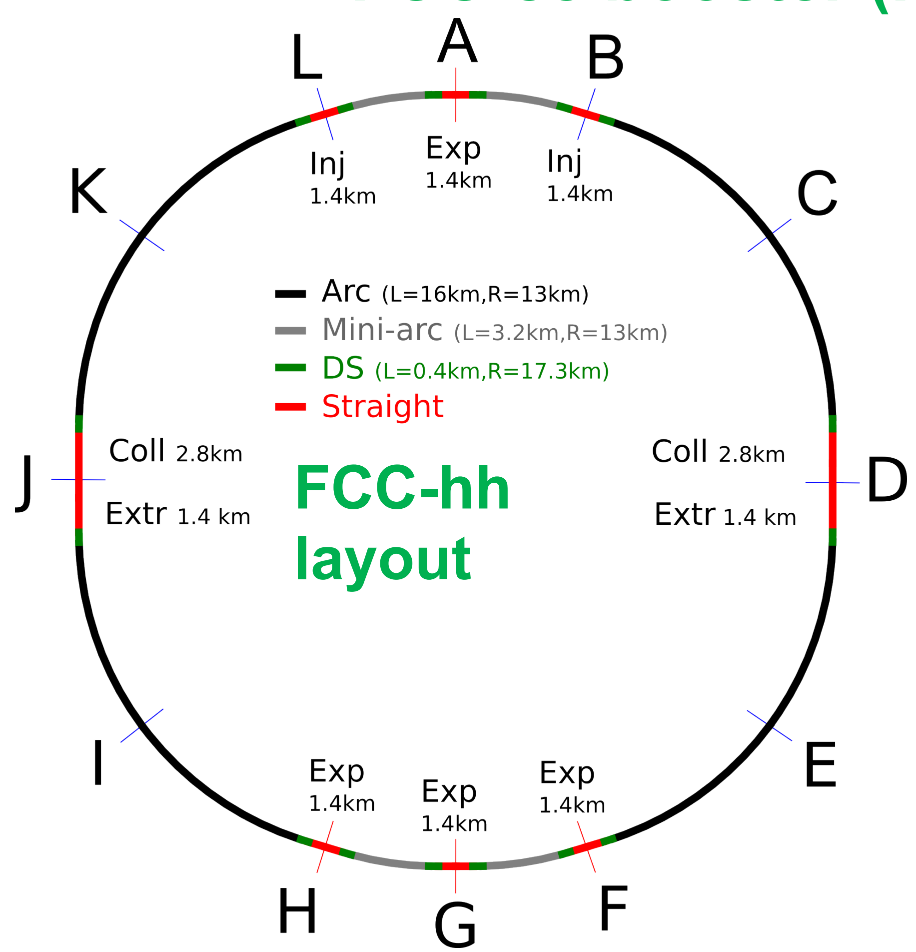


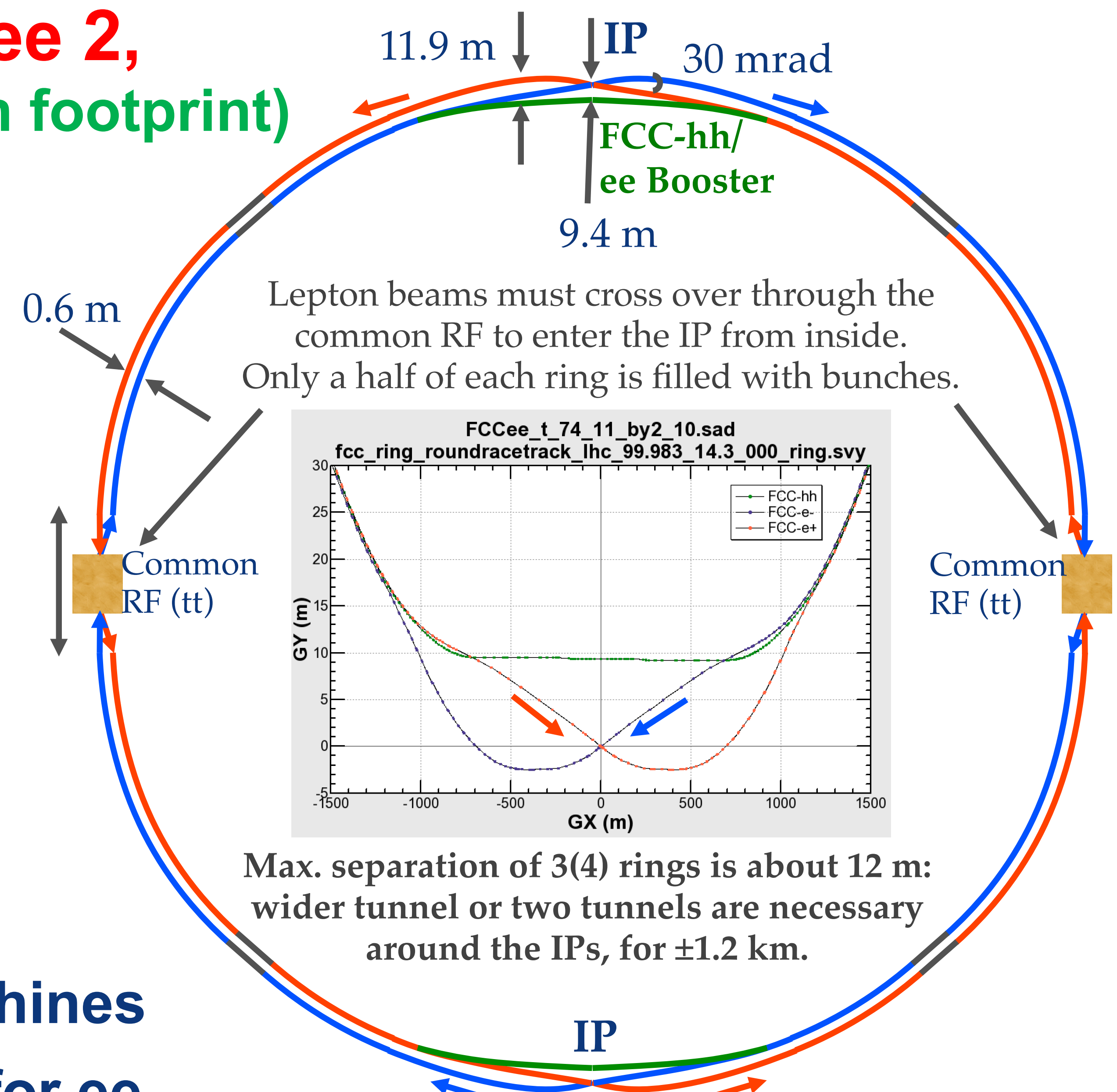
- Optimized length: 97.5 km
  - Accessibility, rock type, shaft depth, etc.
  - Tried different options from 80 to 100 km
- Tunneling
  - Molasse 90% (easy to dig)
  - Limestone 5%, Moraines 5% (tougher)
- Shallow implementation
  - 30m below Leman lakebed
  - Only one very deep shaft (F, 476m)
    - Alternatives studied (e.g. inclined access)



Common layouts for hh & ee

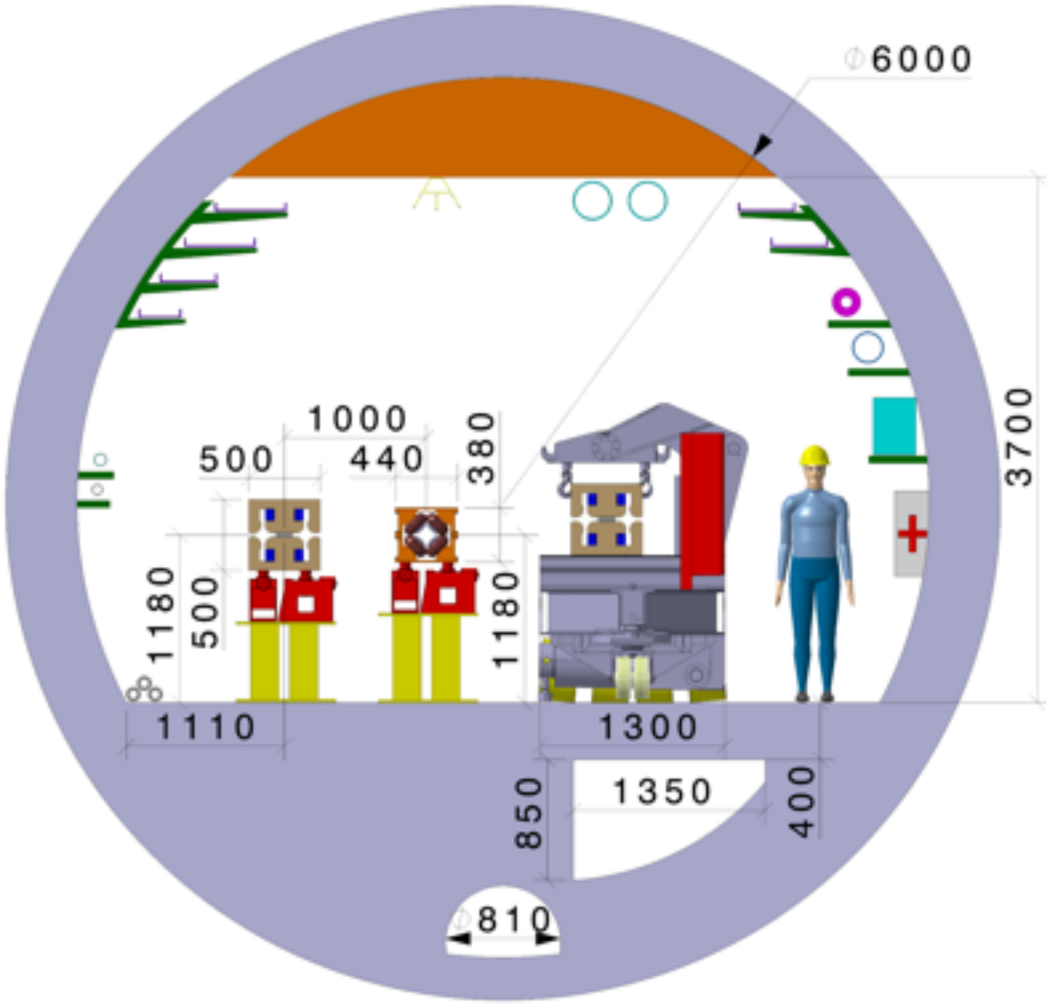
FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)





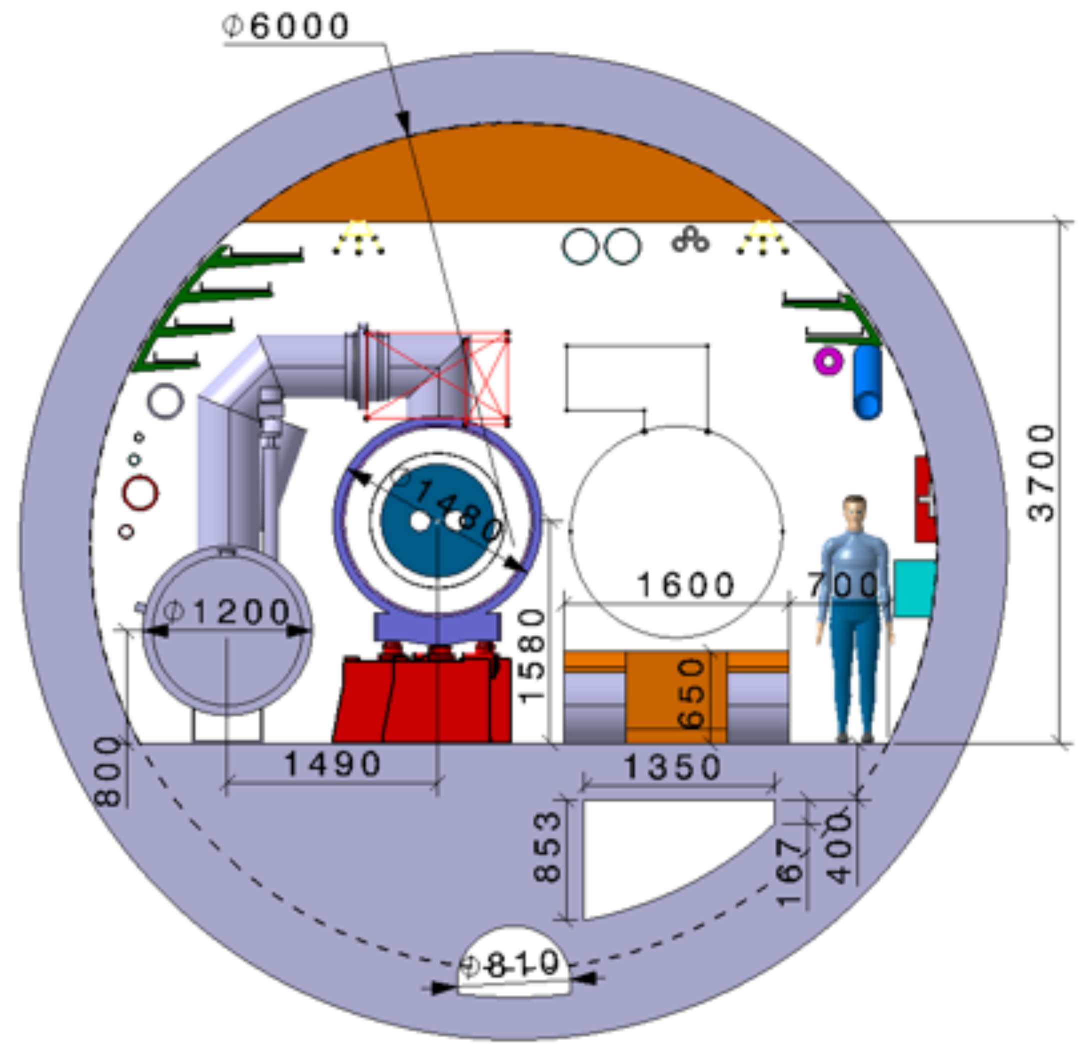
- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

ee



Φ6000
1000
500
440
380
3700
1180
500
1180
1110
1300
1350
850
400
Φ810

hh

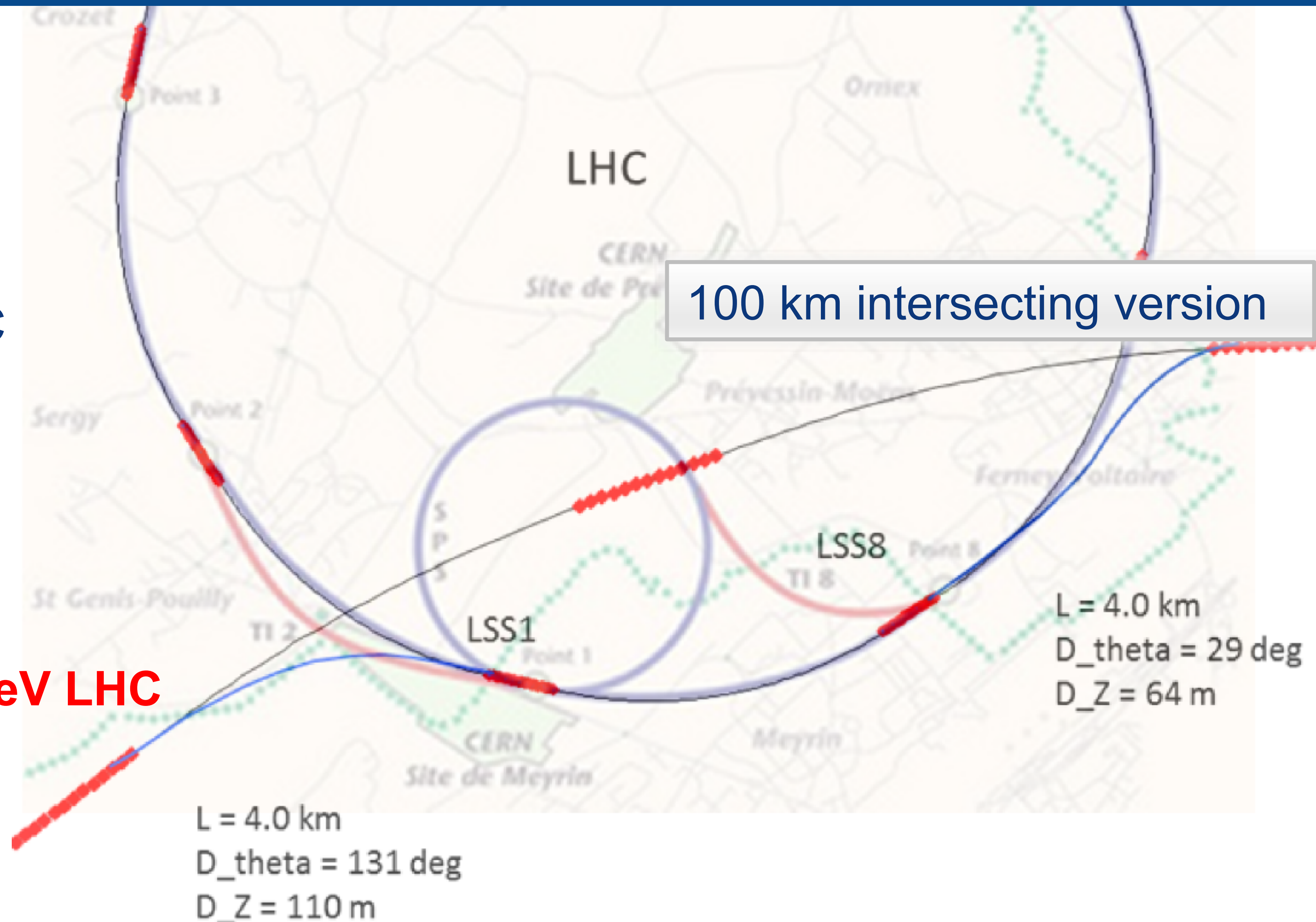


Φ6000
1480
Φ1200
1600
700
3700
1580
650
800
1490
1350
853
167
400
Φ810

FCC-hh injector studies

Injector options:

- SPS → LHC → FCC
- SPS/SPS$_{upgrade}$ → FCC



Current baseline:

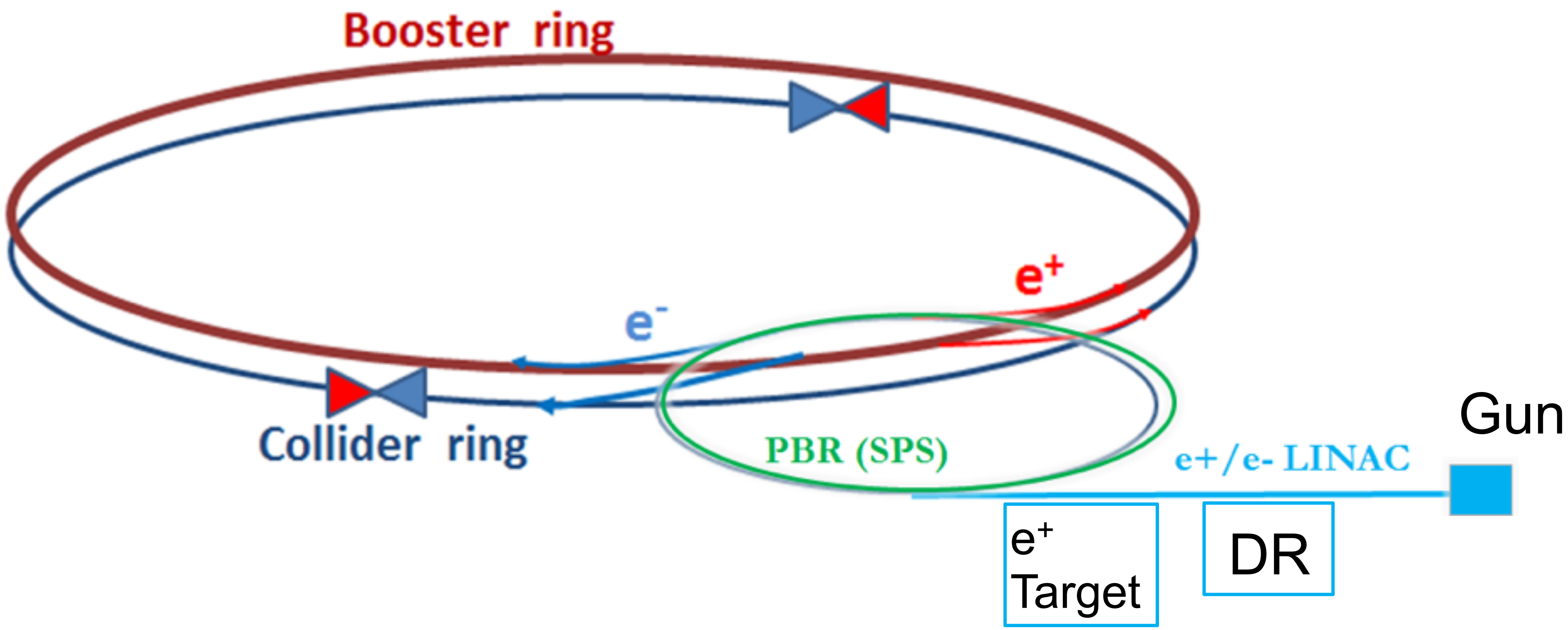
- Injection energy 3.3 TeV LHC

Alternative option:

- Injection around 1.5 TeV
- SPS$_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp

FCC-ee injector complex

- **Baseline is comprised of:**
  - An e^- and e^+ LINAC (length 250 m @ 25 MV/m) from ~0 to 6 GeV
  - An e^+ production target and an $e^\pm$ damping ring (circumference 250 m)
  - A pre-booster ring (from 6 to 20 GeV) – probably in the SPS tunnel
  - A booster ring (from 20 GeV to the full FCC-ee energy), for continuous top-up injection



FCC-ee collider parameters

	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
arc cell optics	60/60	90/90	90/90	90/90
emittance hor/vert [nm]/[pm]	0.27/1.0	0.28/1.0	0.63/1.3	1.45/2.7
β* horiz/vertical [m]/[mm]	0.15/.8	0.2/1	0.3/1	1/2
SR energy loss / turn (GeV)	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.44	2.0	10.9
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
no. of bunches / beam	16640	2000	393	39
beam current [mA]	1390	147	29	5.4
SR total power [MW]	100	100	100	100
luminosity [10^{34} cm^{-2}s^{-1}]	230	32	7.8	1.5
luminosity lifetime [min]	70	50	42	44
allowable asymmetry [%]	±5	±3	±3	±3

Luminosity goals and operation model

- The FCC-ee physics goals require at least
  - 150 ab^{-1} at and around the Z pole ($\sqrt{s}$~91.2 GeV)
  - 10 ab^{-1} at the WW threshold ($\sqrt{s}$~161 GeV)
  - 5 ab^{-1} at the HZ cross section maximum ($\sqrt{s}$~240 GeV)
  - 0.2 ab^{-1} at the top threshold ($\sqrt{s}$~350 GeV) and 1.5 ab^{-1} above ($\sqrt{s}$~365 GeV)

5×10^{12} Z
10^8 WW
10^6 HZ
10^6 $t\bar{t}$

- Operation model (with 10% safety margin) with two IPs
  - 200 scheduled physics days per year (7 months – 13 days of MD / stops)
  - Hübner factor ~ 0.75 (lower than achieved with KEKB top-up injection, ~0.8)
  - Half the design luminosity in the first two years of Z operation (~LEP1)
  - Machine configuration between WPs changed during Winter shutdowns (3 months/year)

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold	365 GeV
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	13	7	1.6	1.3
Lumi/year (2 IP)	26 ab^{-1}	52 ab^{-1}	7.8 ab^{-1}	1.8 ab^{-1}	0.4 ab^{-1}	0.35 ab^{-1}
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	0.5	4

- Total running time : 12-13 years (~ LEP)

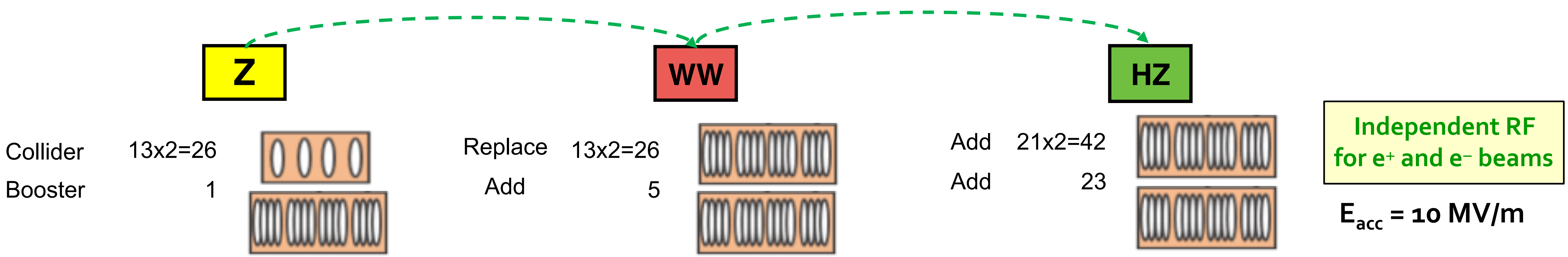
Longer shutdown: install 74 RF CMs
LEP Record: 32 in one shutdown !

The SCRF system: optimization and staging

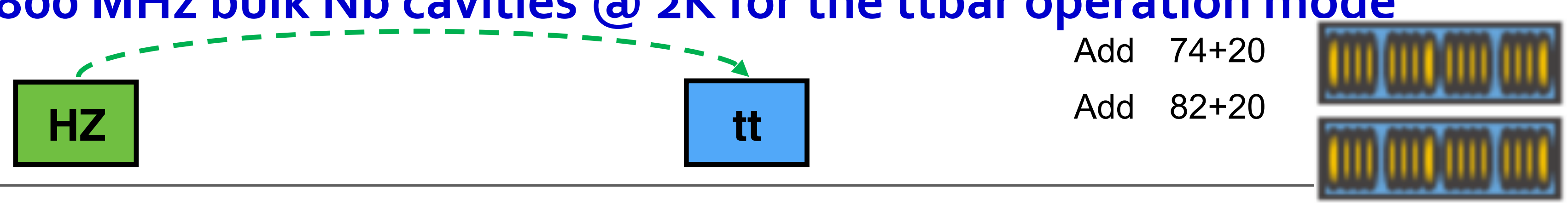
- **Very broad range of operation parameters**
  - SR energy loss from 36 MeV to 9.21 GeV
  - Total voltage from 0.1 (Z) to 11 GV (tt)
  - Total current from 5.4 mA (tt) to 3.9 A (Z)
    - Aim at acceleration efficiency and cost reduction at high energy
    - Aim at cell shape and impedance optimization against HOMs at high current
  - Fast acceleration from 20 to 45 – 182.5 GeV in the booster
- **Solution : Operation staging**

(single cells) (multi cells) (multi cells)

  - Start with 400 MHz Nb/Cu cavities @ 4.5K for the Z, WW, and Higgs operation modes



  - Realign all cavities to make RF common to both beams
  - Add 800 MHz bulk Nb cavities @ 2K for the ttbar operation mode



Total length ~1.8km

Power consumption

- The RF system needs to compensate for 100 MW SR losses
  - Corresponds to 200 MW electric power with 50% RF power sources (klystrons)
    - Klystron efficiency was ~55% at LEP2
  - Recent (2015) breakthroughs in klystron design promise 90% efficiency
    - Assume 85% will be achieved and take 10 – 20% margins

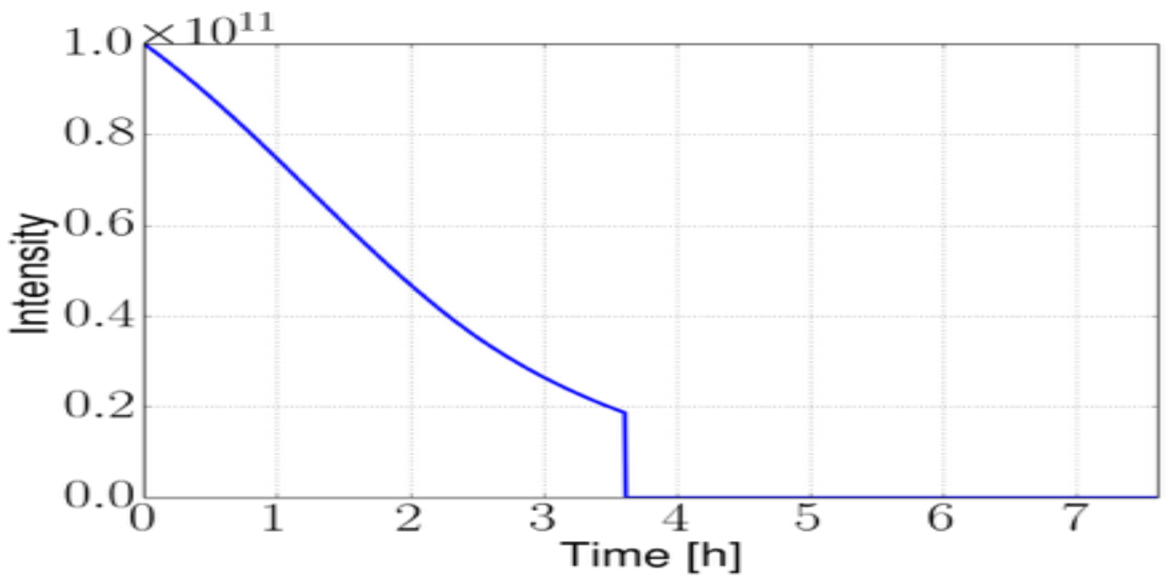
lepton collider	Z		W	ZH	$t\bar{t}$	LEP2
luminosity / interaction point [10^{34} cm^{-2}s^{-1}]	207	90	19	5	1.3	0.012
total RF power [MW]	163		163	145	145	42
collider cryogenics [MW]	3	2	5	23	39	18
collider magnets [MW]	3		10	24	50	16
booster RF & cryogenics [MW]	4		4	6	7	N/A
booster magnets [MW]	0		1	2	5	N/A
pre-injector complex [MW]	10		10	10	10	10
physics detectors (2) [MW]	10		10	10	10	9
cooling & ventilation [MW]	47		49	52	62	16
general services [MW]	36		36	36	36	9
total electrical power [MW]	276	~275	~288	~308	~364	~120

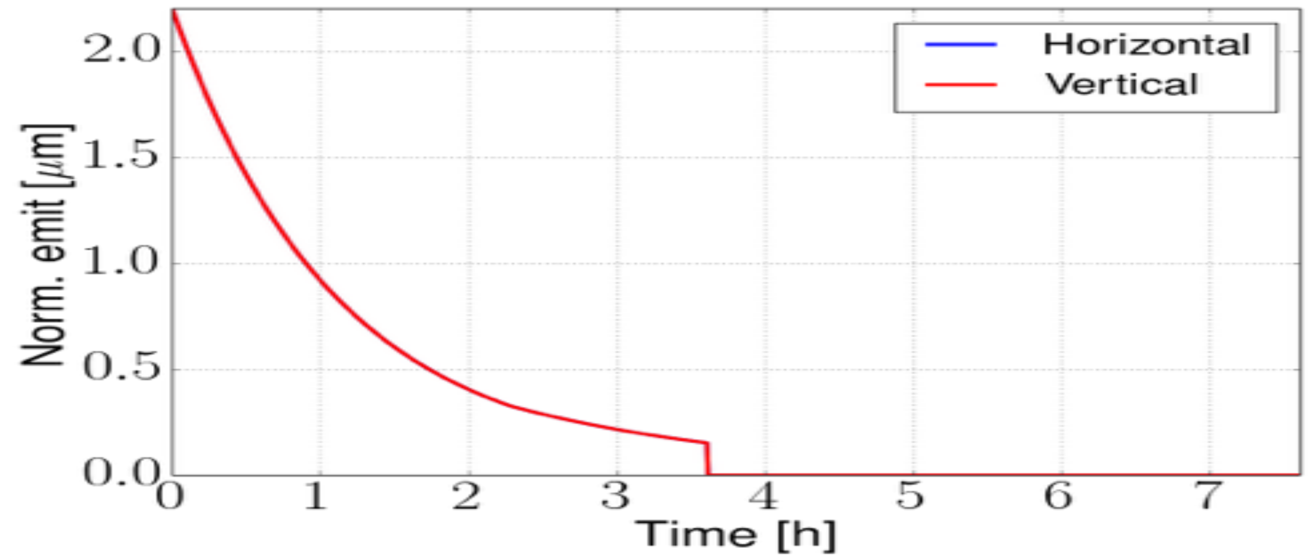
  - For comparison
    - LHC Run1: 210 MW, HL-LHC: 260 MW, FCC-hh: ~500 MW
    - CLIC: 250 MW (at 380 GeV) to 580 MW (at 3 TeV)

FCC-pp collider parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

pp Luminosity evolution during a fill





Developed model including most relevant effects

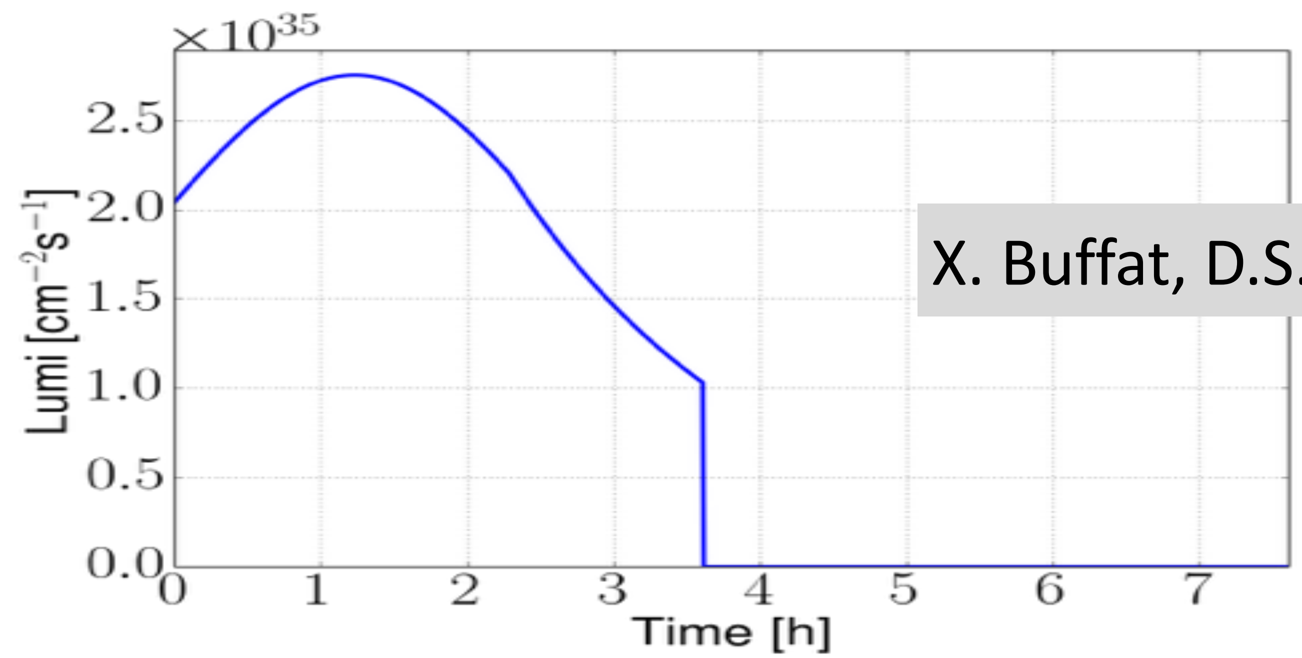
- Improvement with more detail planned

$\Rightarrow$ Reach 8fb^{-1}/day with ultimate for 25ns spacing

$\Rightarrow$ 5ab^{-1} per 5 year run

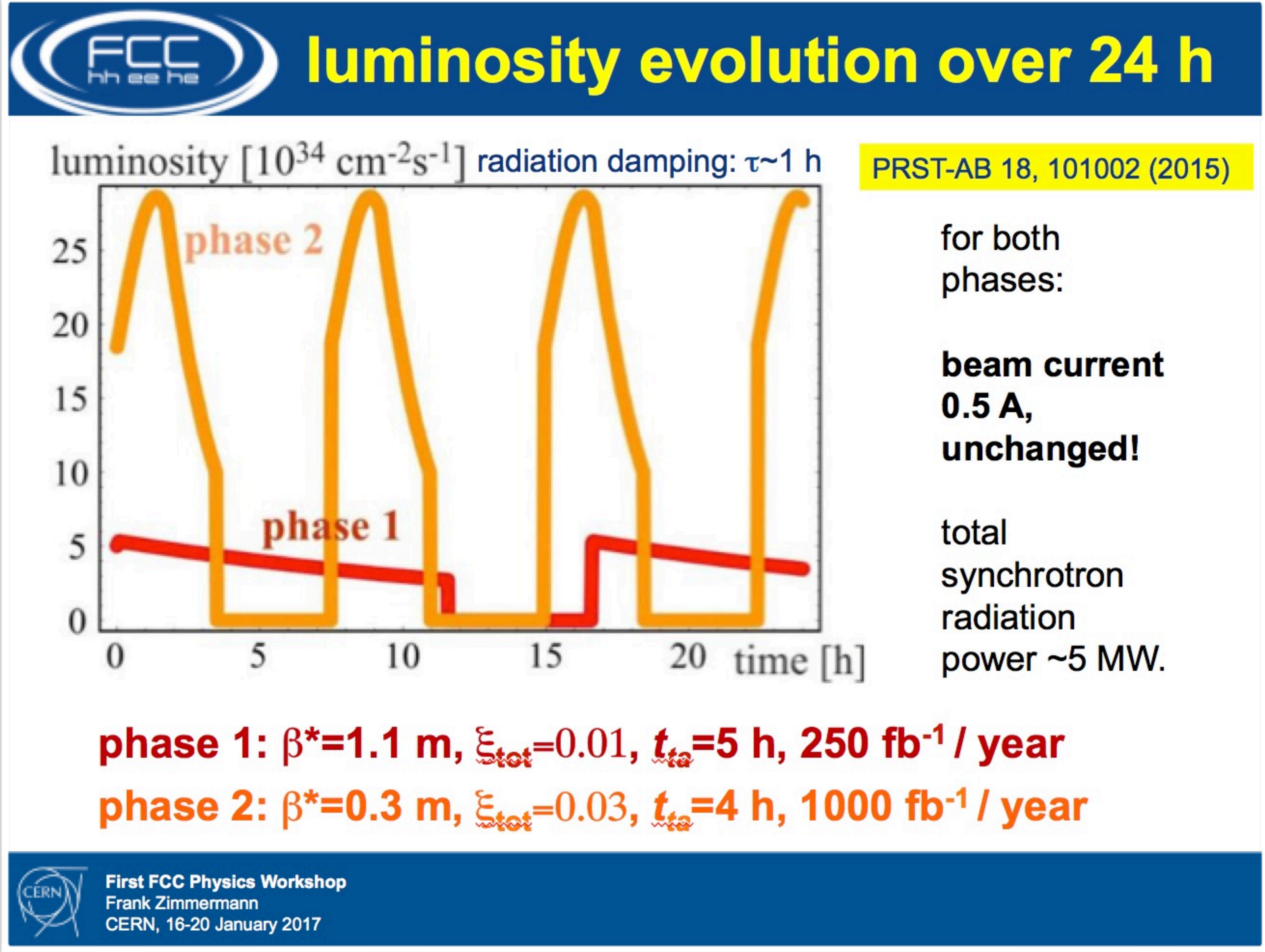
$\Rightarrow$ Beam is burned quickly

$\Rightarrow$ A reason to have enough charge stored



Turn-around time

Ultimate example, 25ns, no luminosity levelling 8fb^{-1}/day



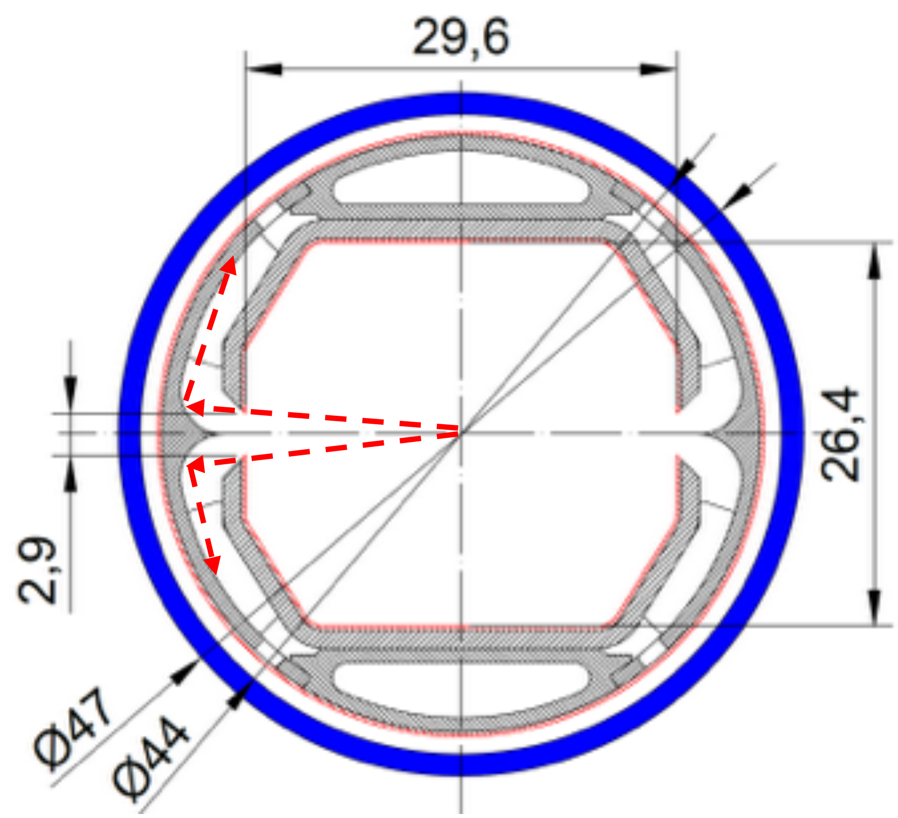
look @ Zimmermann's slides for many more details, 25ns vs 5ns, etc

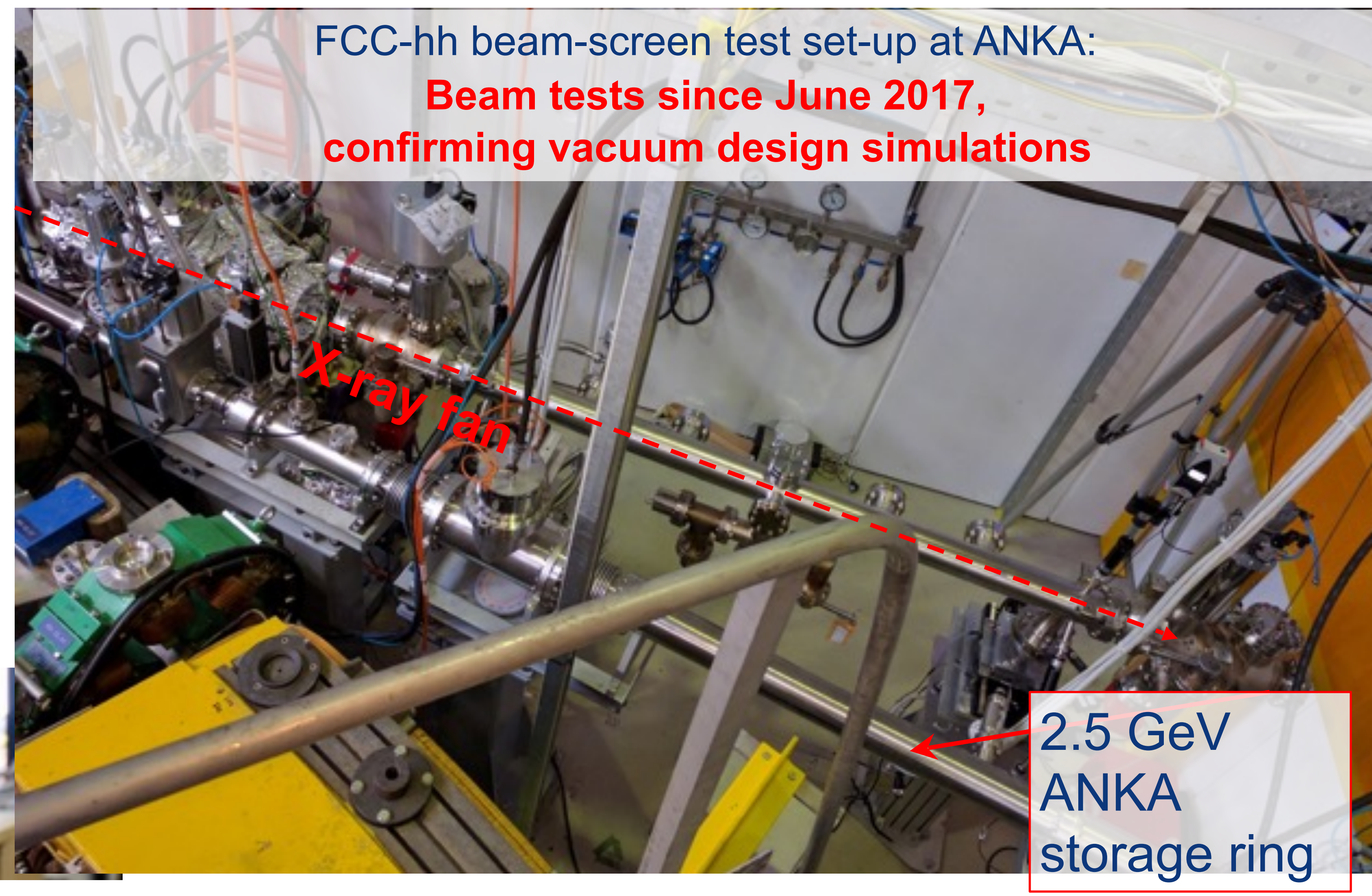
=> total of O(20) ab-1 over 25 years of operation.

FCC-hh cryogenic beam vacuum system

Synchrotron radiation **(~ 30 W/m/beam (@16 T field)** (LHC <0.2W/m) **~ 5 MW total load in arcs**

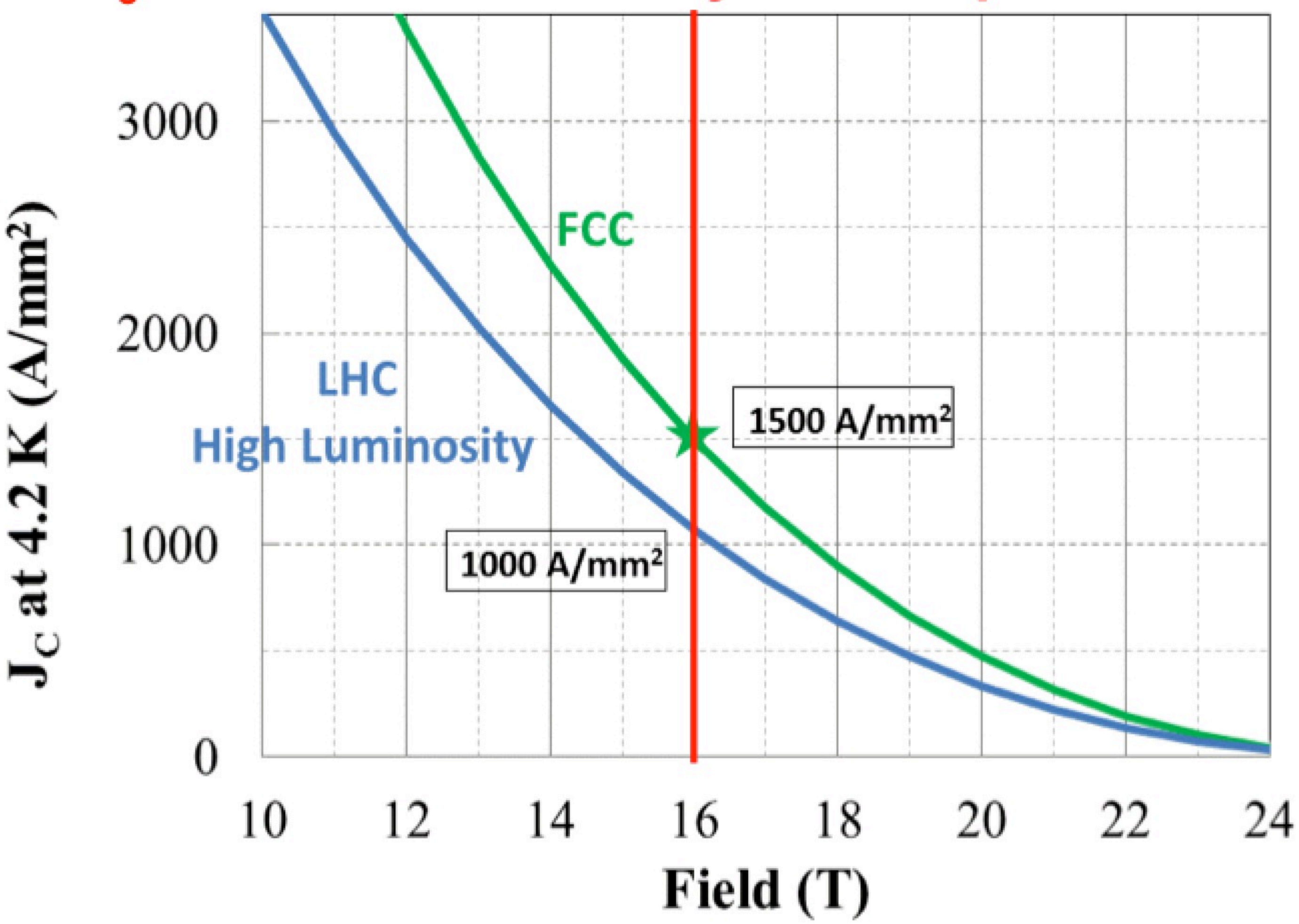
- **Absorption of synchrotron radiation at ~50 K** for cryogenic efficiency (**5 MW →100 MW cryoplant**)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.





Nb_3Sn conductor development program

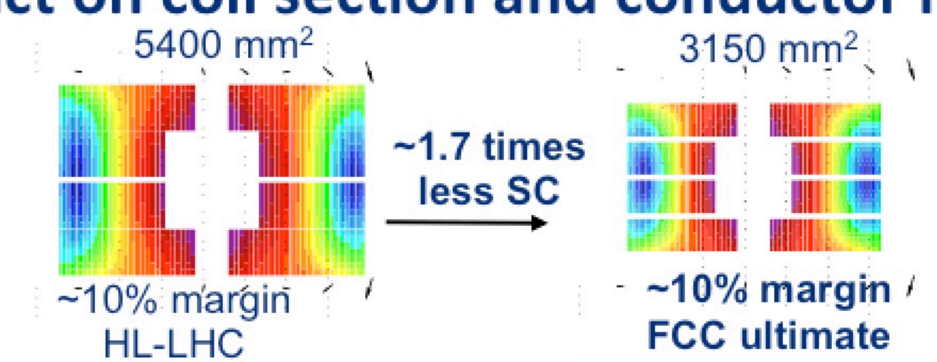
Nb_3Sn is one of the key cost & performance factors for FCC-hh / HE-LHC



Main development goals:

- J_c increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire
- Reference wire diameter 1 mm
- Potentials for large-scale production and cost reduction

Impact on coil section and conductor mass



collaborations FCC Nb_3Sn program

procurement of state-of-the-art conductor for protoyping:

- **Bruker/OST**– **European/US**

stimulation of conductor development with regional industry:

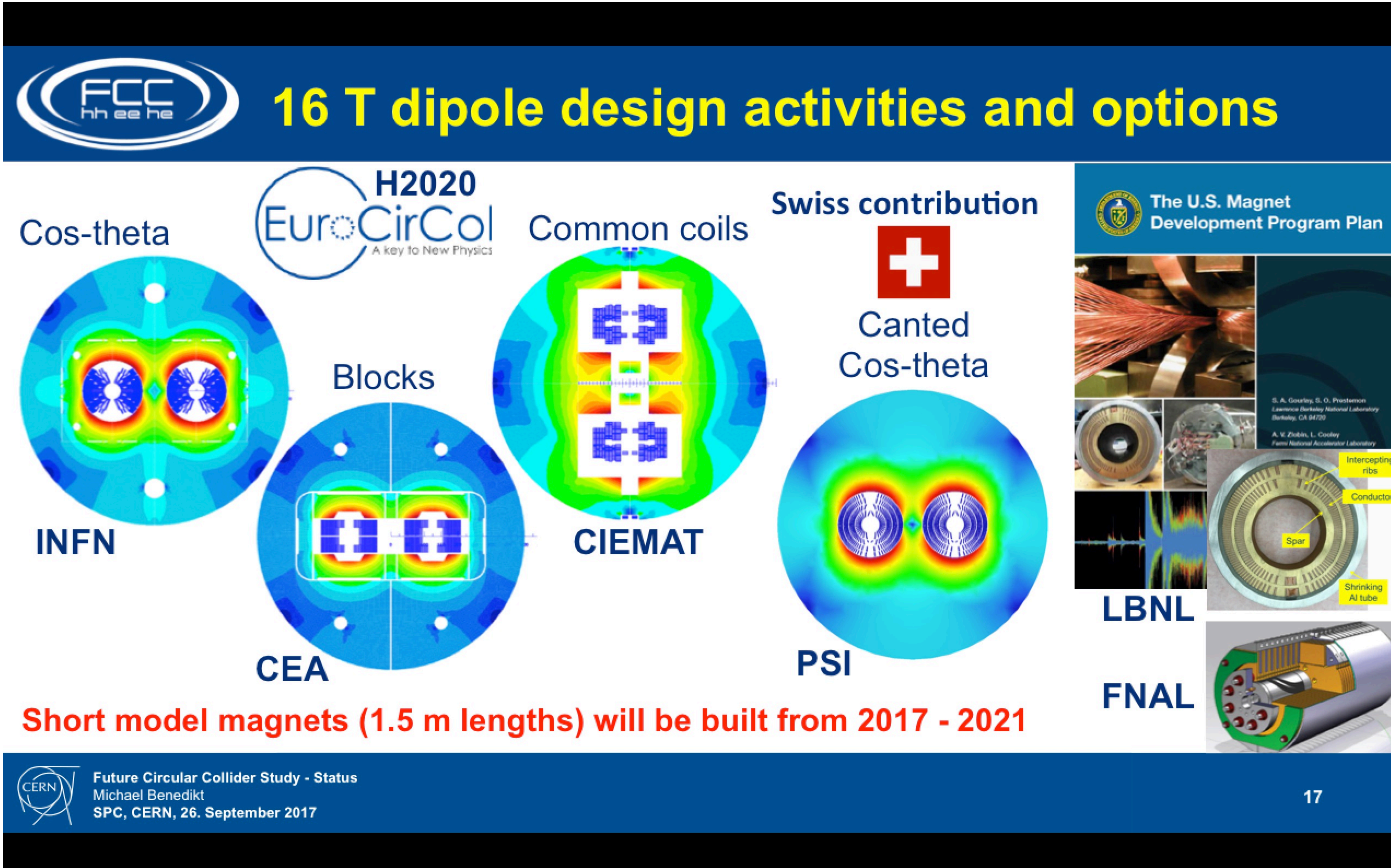
- **CERN/KEK** – **Japanese** contribution. Japanese **industry** (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
- **CERN/Bochvar High-technology Research Inst.** – **Russian** contribution. Russian **industry** (TVEL) and laboratories
- **CERN/KAT** – **Korean** **industrial** contribution
- **CERN/Bruker**– **European** **industrial** contribution

characterization of conductor & research with universities:

- **Europe: Technical Univ. Vienna, Geneva University, University of Twente**
- **Applied Superconductivity Centre** at Florida State University

new US DOE MDP effort – **US** activity with **industry** (OST) and labs

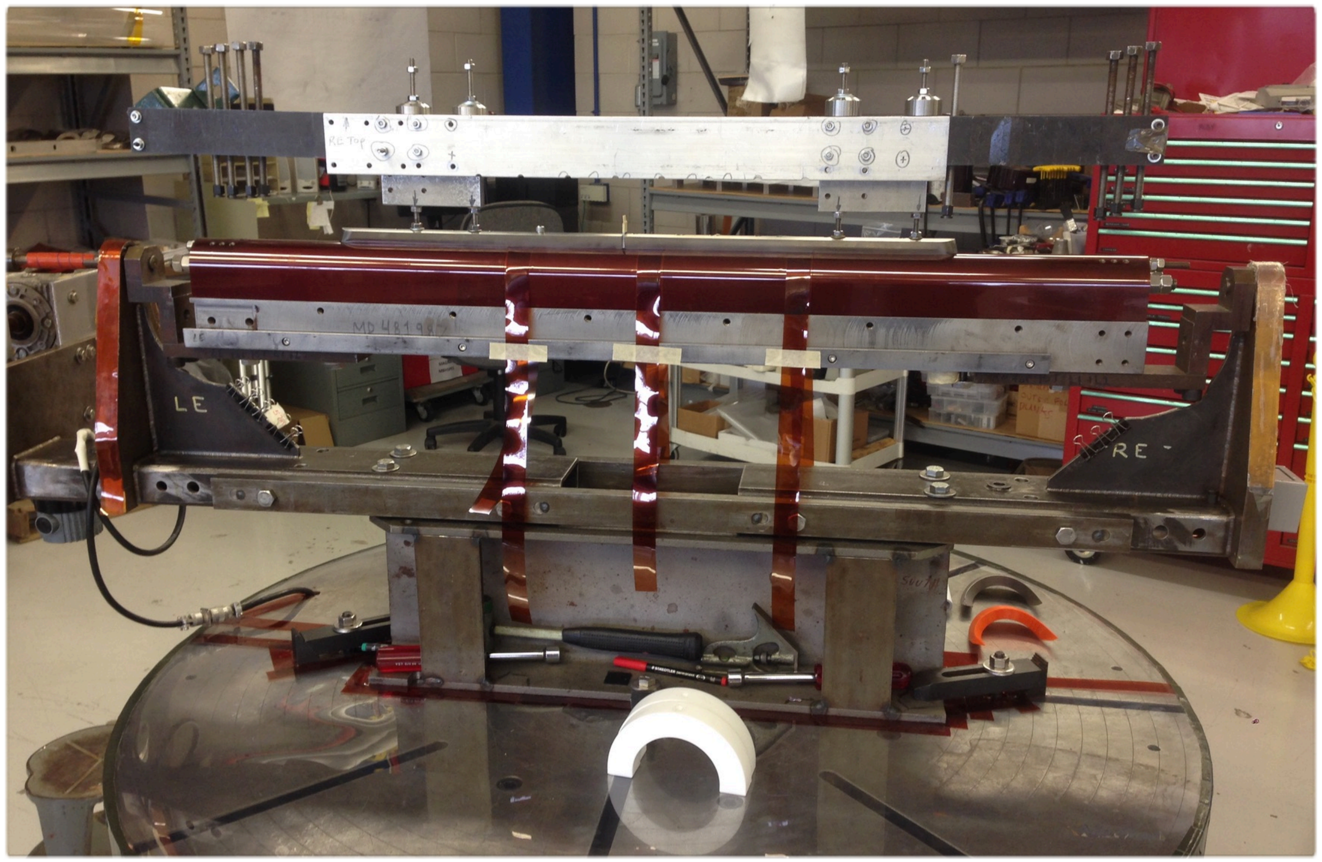
see S.Prestemon talk

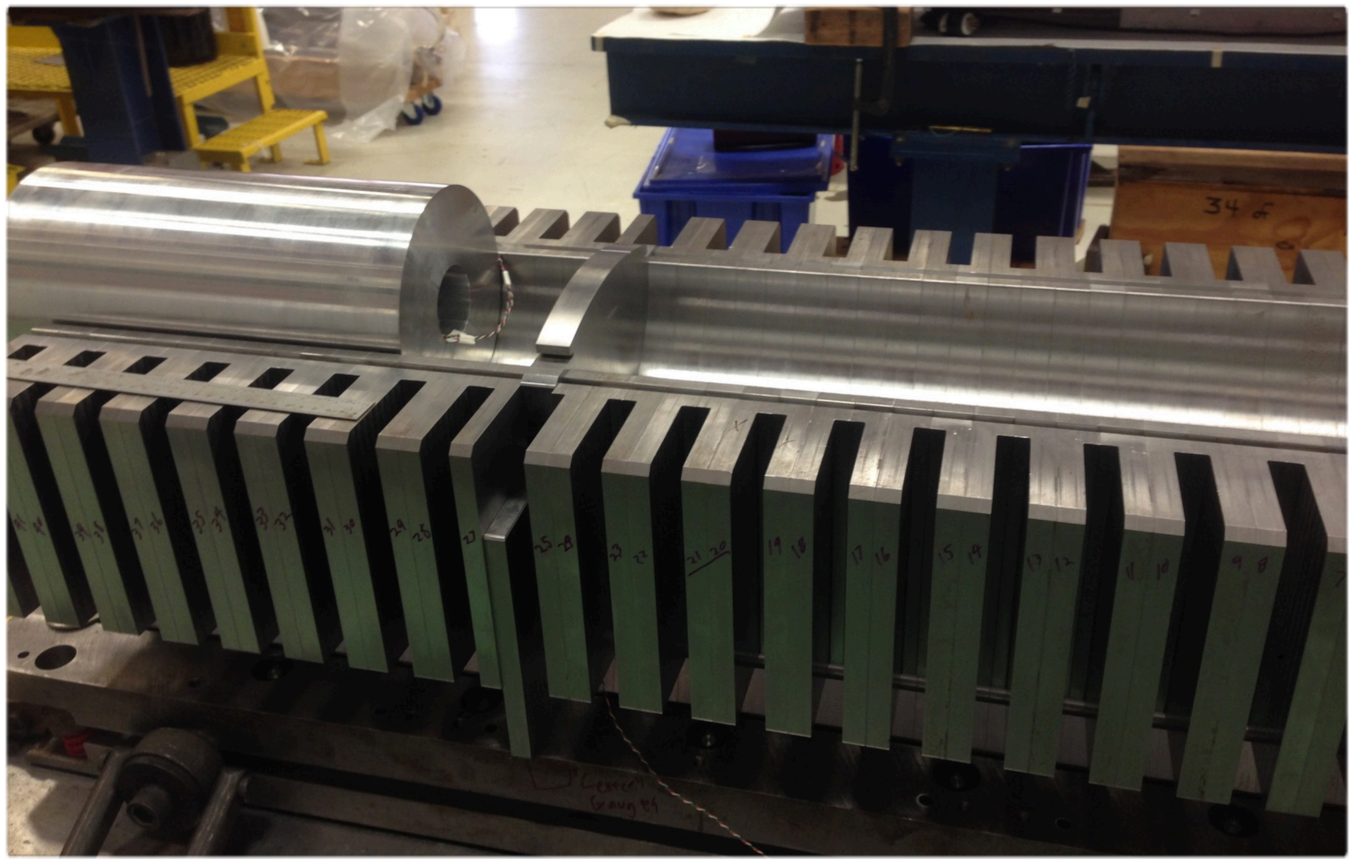


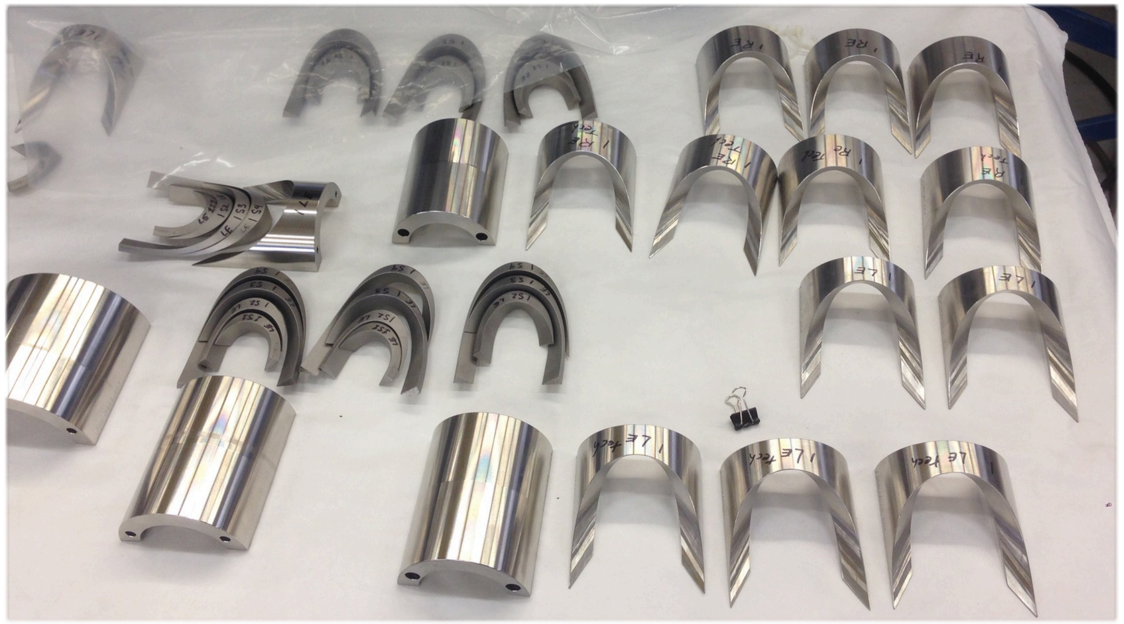
see D.Tommasini talk

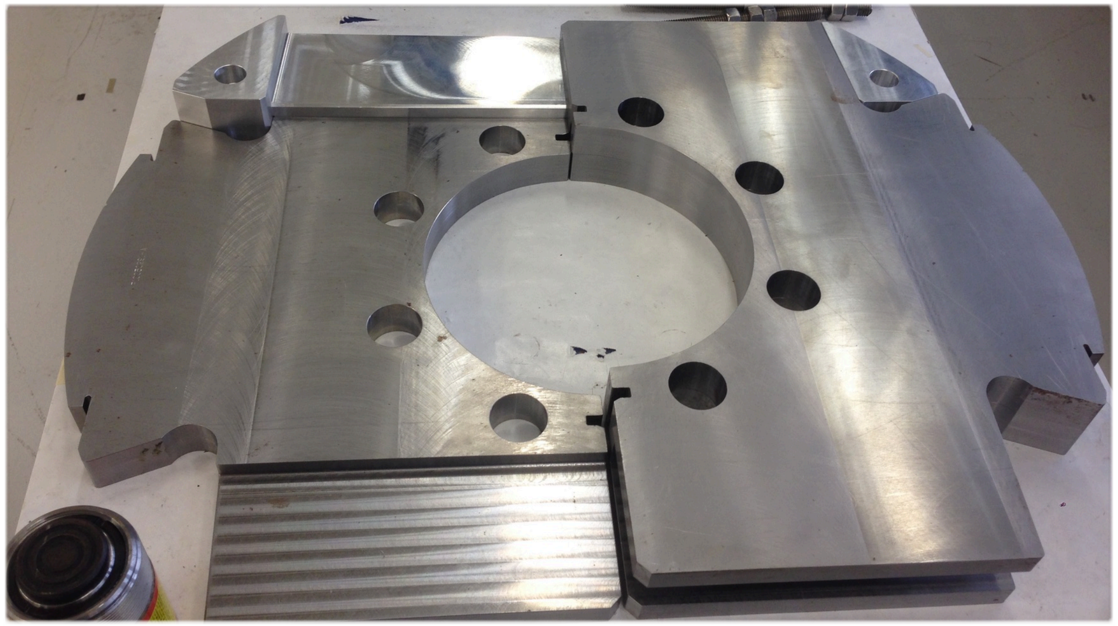
15T dipole prototyping at FNAL (60mm aperture, L=1m)

ready for testing by mid-2018

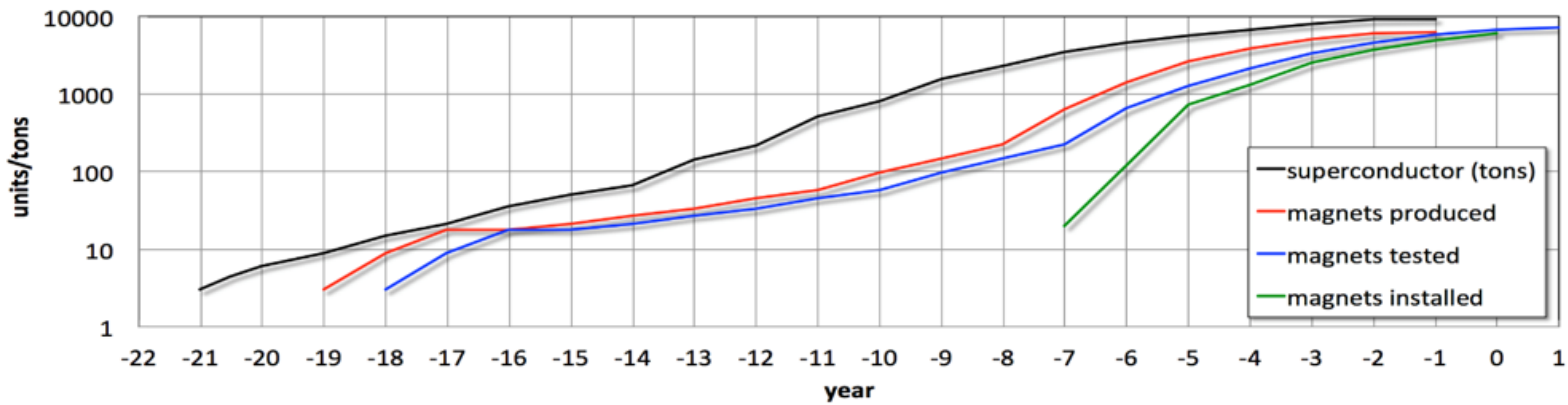


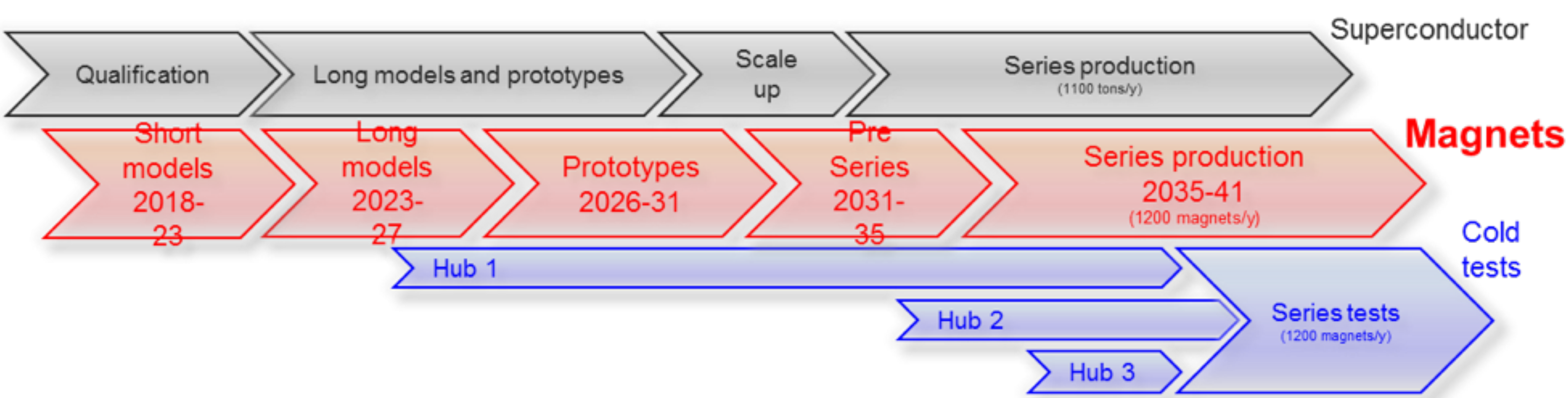






FCC 16 T magnet R&D schedule

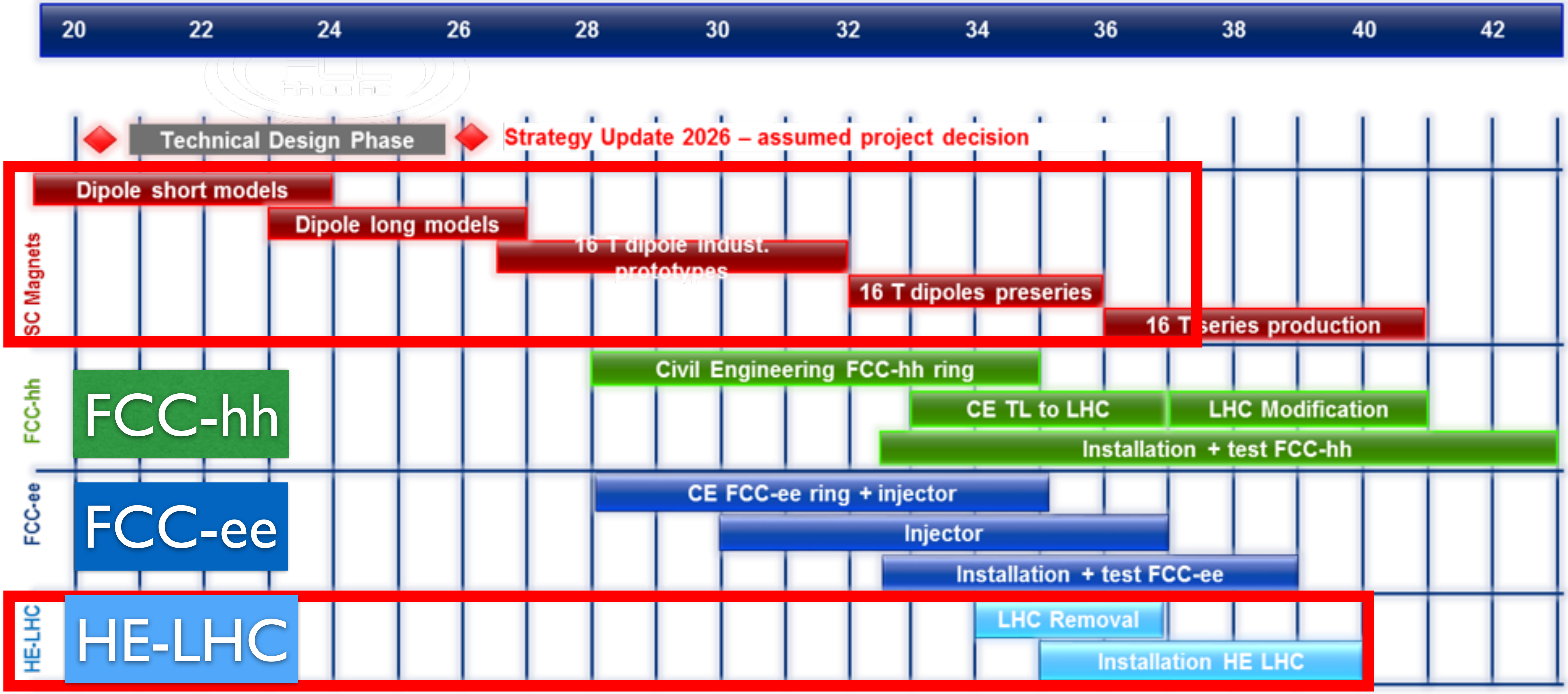




total duration of magnet program: ~20 years

would follow HL-LHC *Nb_3Sn* program with long models w industry from 2023/24

Fastest Possible Technical Schedules



technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

M. Benedikt

Detector studies

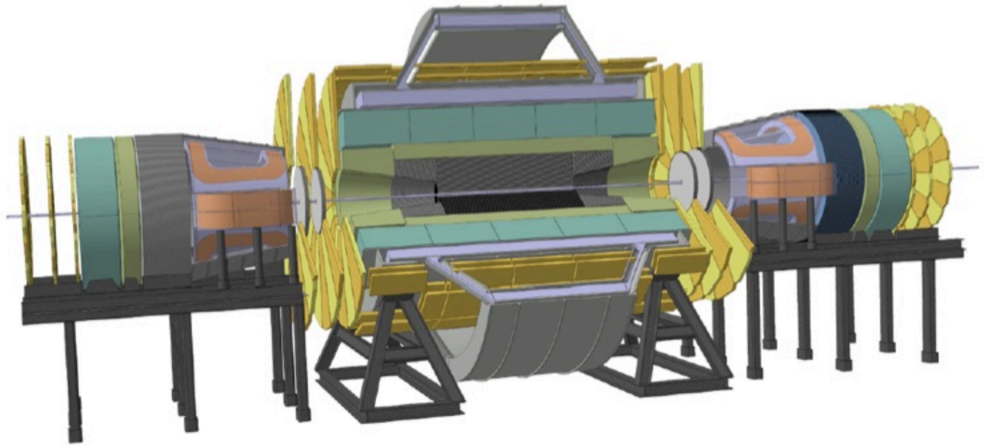
- **Detector design** group leader: Werner Riegler
  - Indico site of mtgs: http://indico.cern.ch/category/8920/
  - join the mailing list
- **Physics Simulation** subgroup leaders: Heather Gray & Filip Moortgat
  - Indico site of mtgs: http://indico.cern.ch/category/6067/
  - join the mailing list
- Monthly mtgs of each group, if interested register to the mailing lists

Reference detector

earlier design

6 T, 12 m bore solenoid, 10 Tm dipoles, shielding coil

- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project

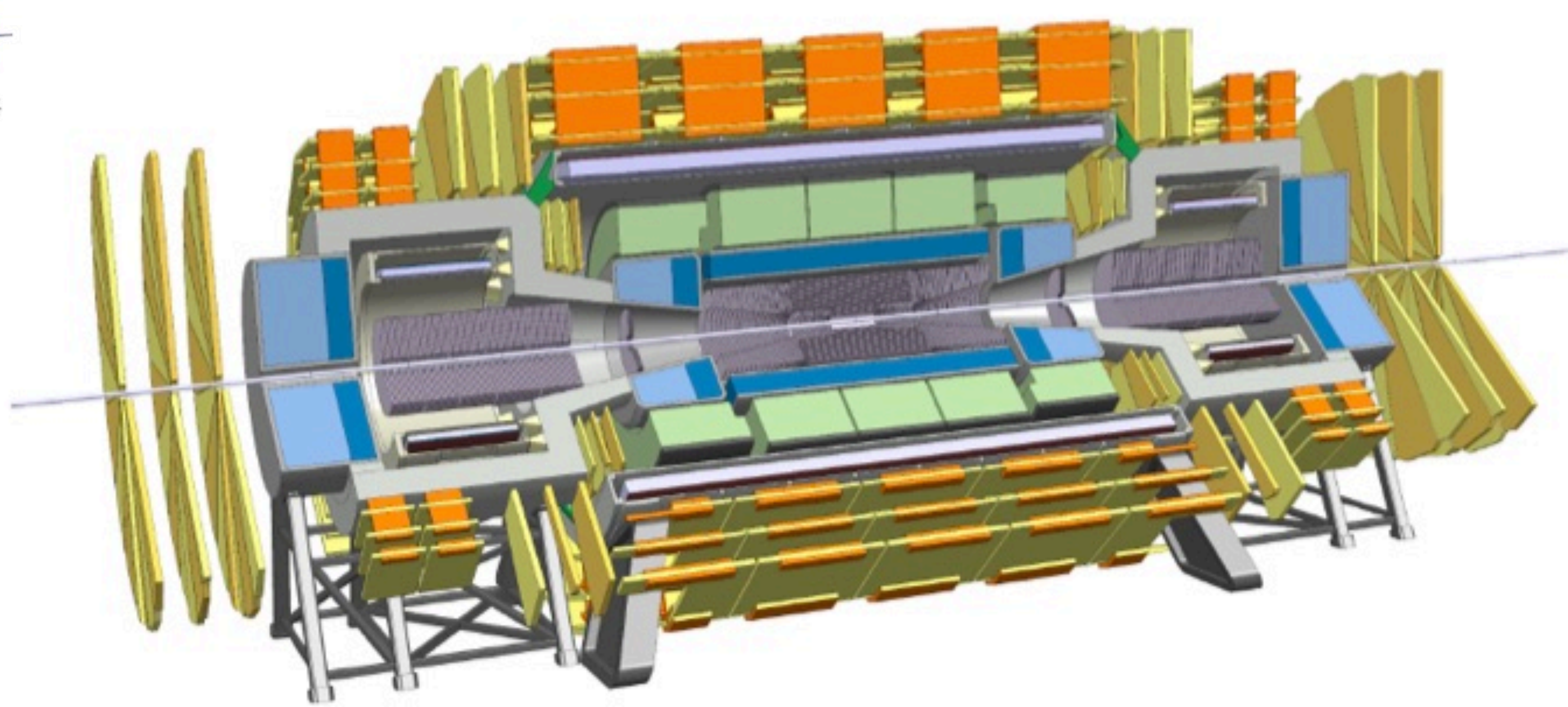


→

current design

4 T, 10 m bore solenoid, 4 T forward solenoids, no shielding coil

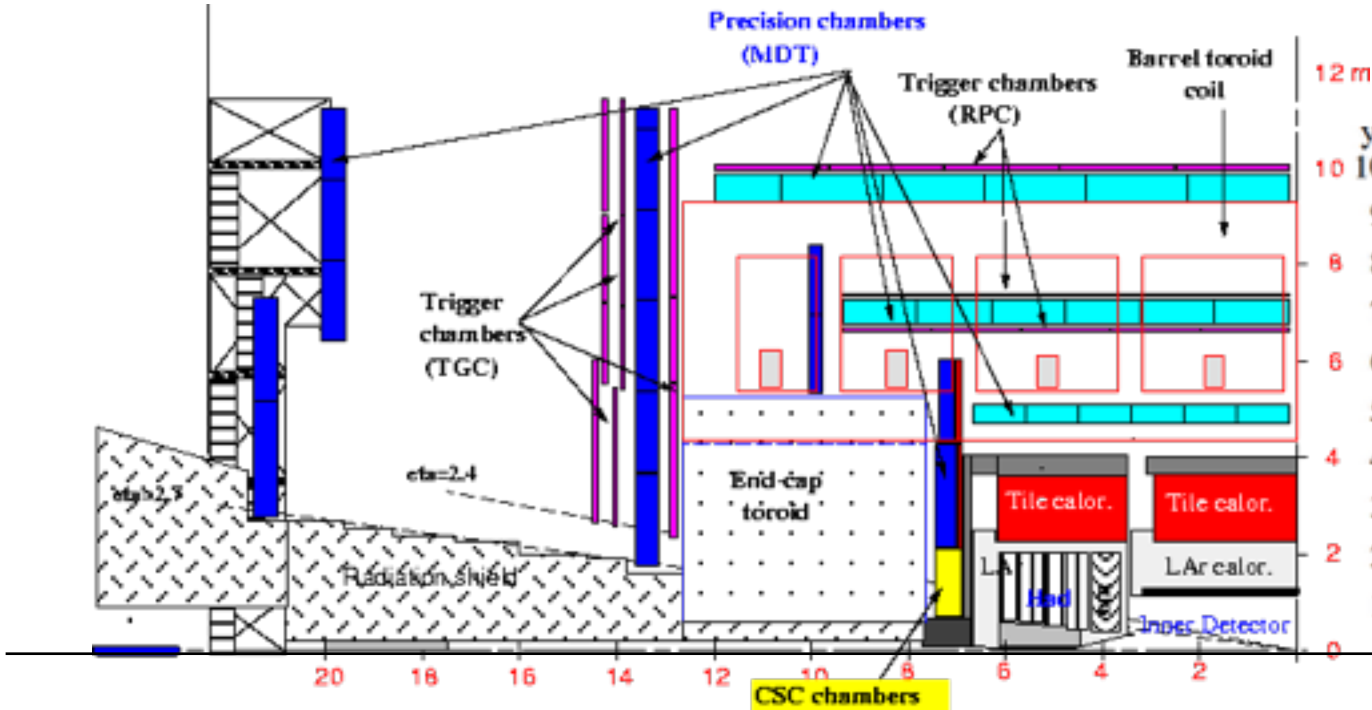
- 14 GJ stored energy
- rotational symmetry for tracking!
- 20 m diameter (~ ATLAS)
- 15 m shaft
- ~1 billion project

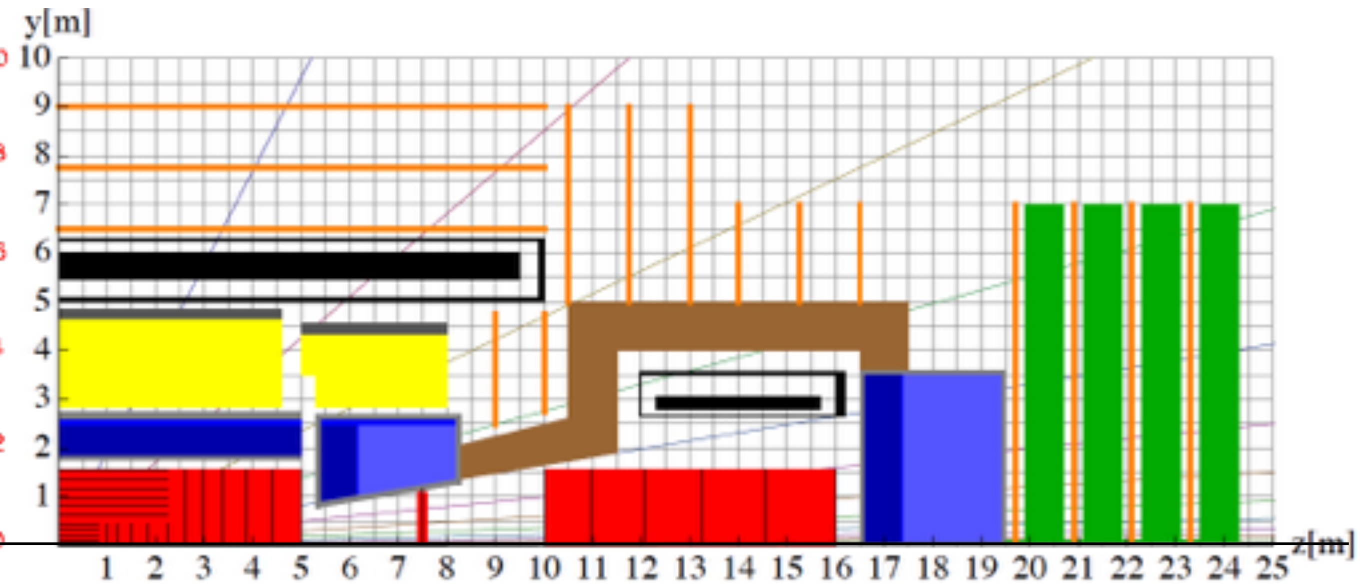


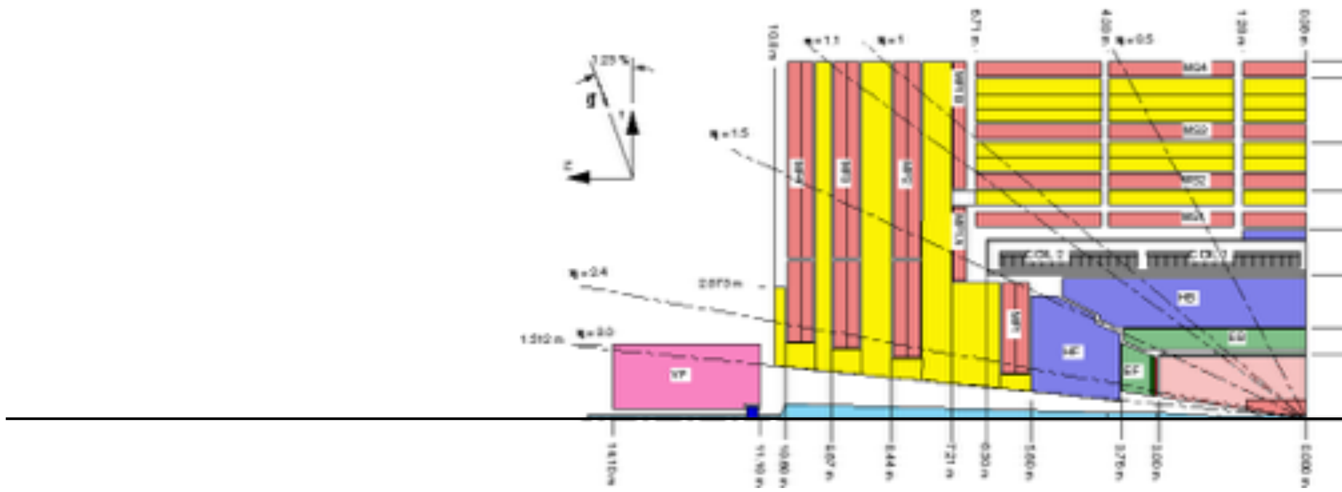
latest l^* = 40 m

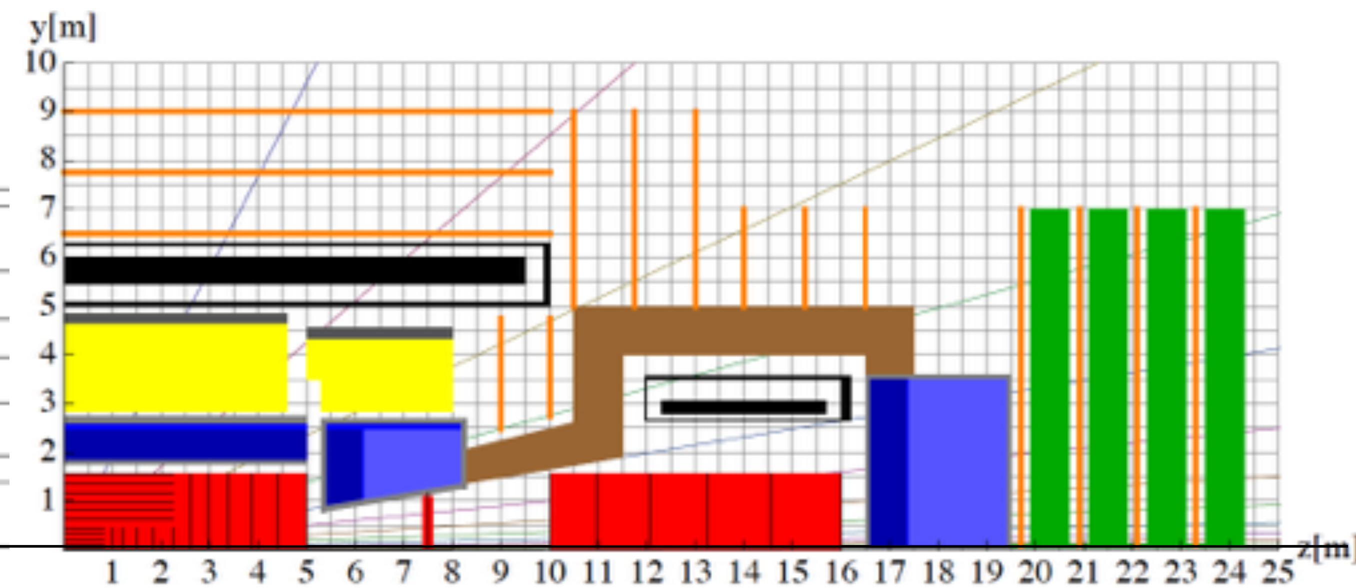
W. Riegler et al.

Comparison to ATLAS & CMS





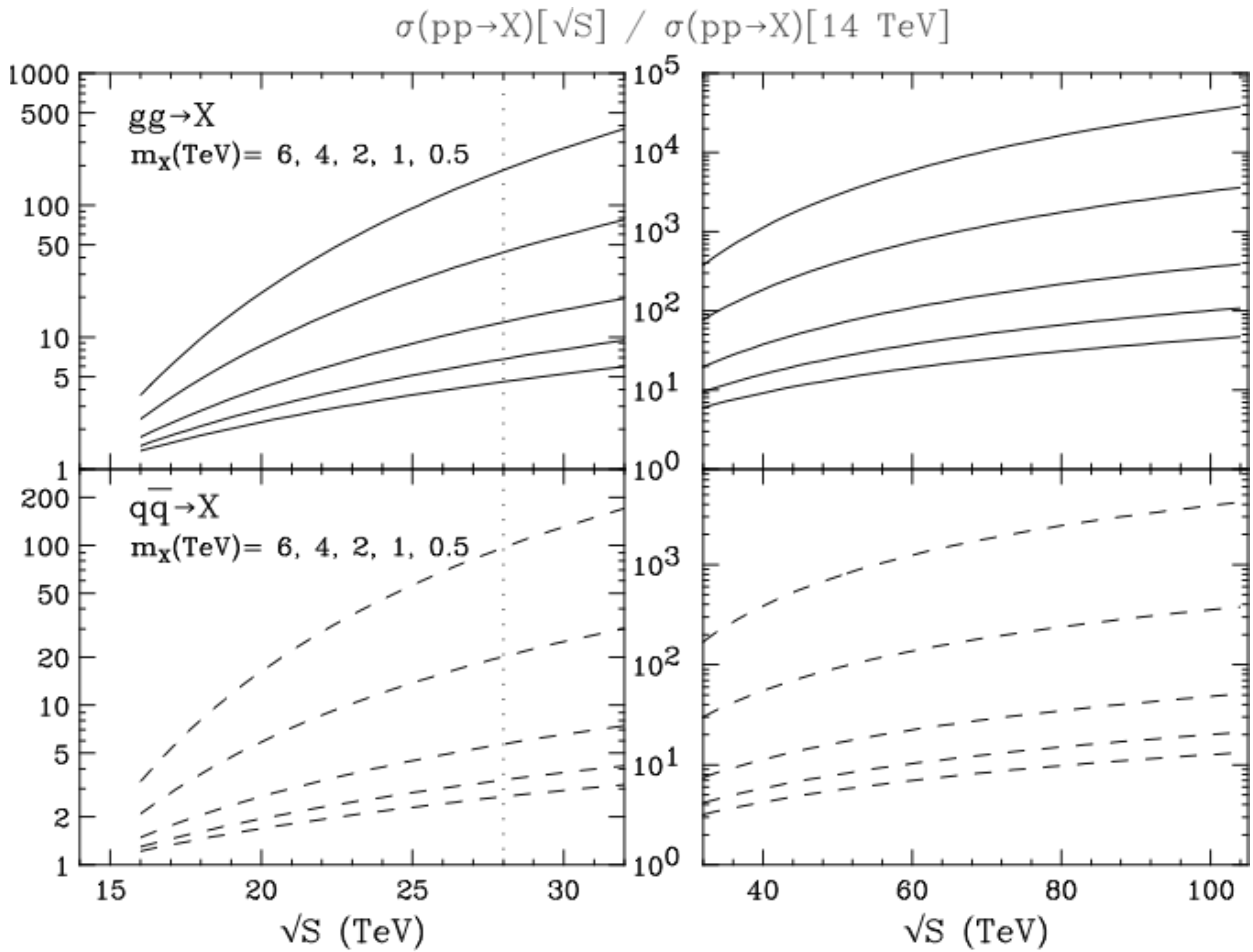




HE-LHC:

27 TeV pp in the LHC tunnel

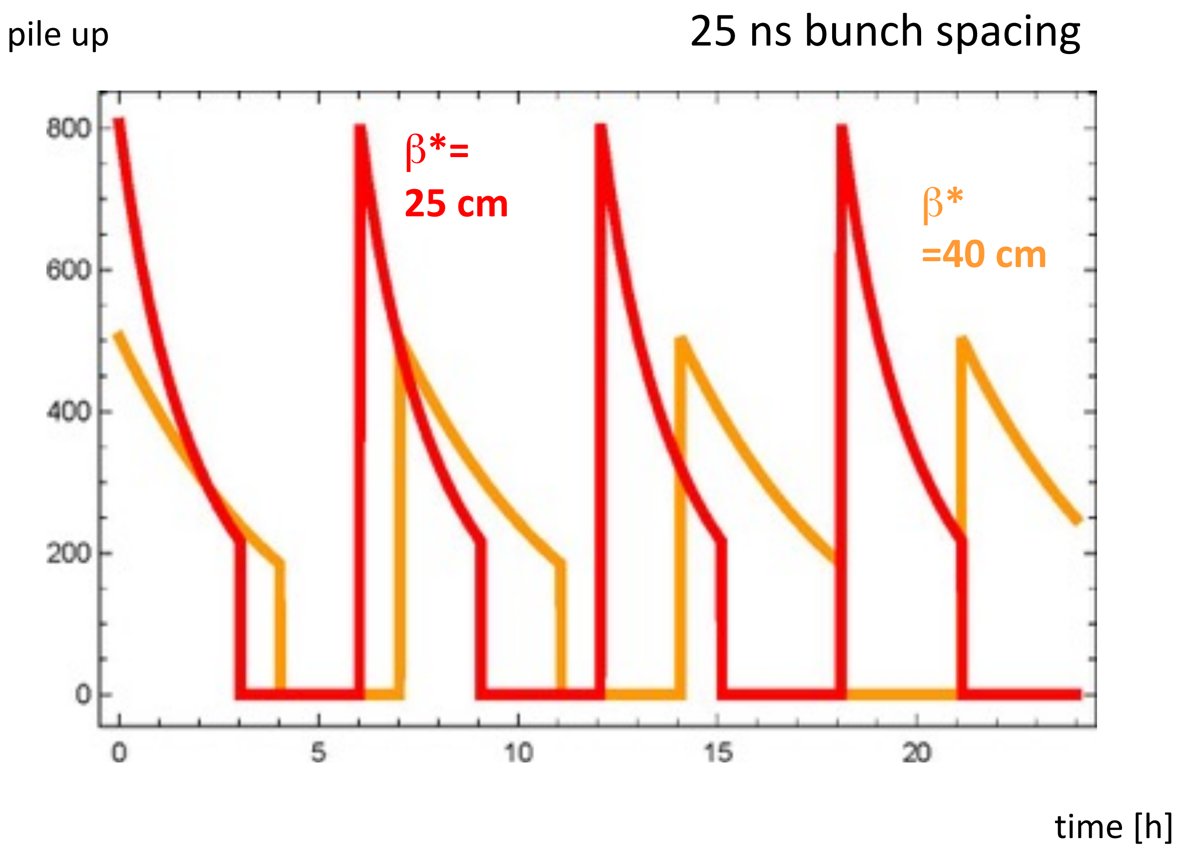
Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC

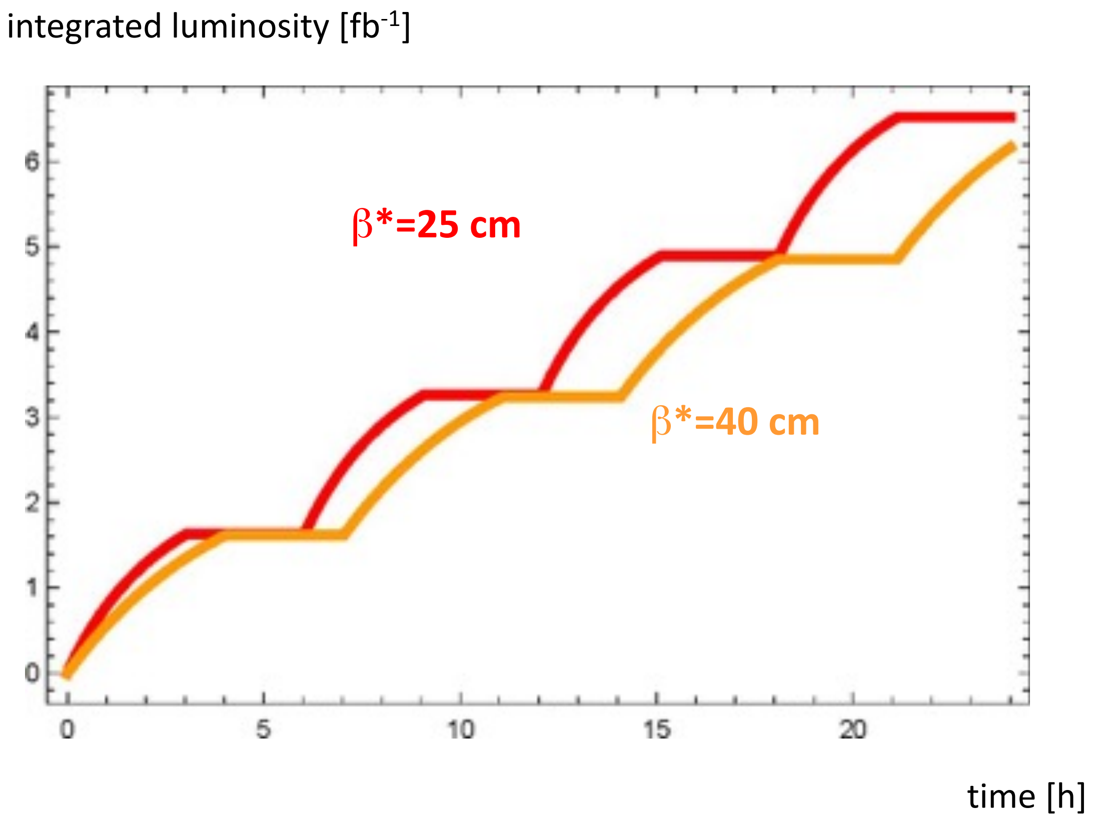


Possible questions/options

- If $m_X \sim 6$ TeV in the gg channel, rate grows x 200 @27 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 27 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses $\gtrsim 2m_X$ ($\Rightarrow$ *27 TeV would be insufficient ....*)
- If $m_X \sim 0.5$ TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 $\int L$ at LHC?
  - Do we build CLIC?
- etc.etc.

HE-LHC pile up & performance





with 160 days of physics, 70% availability, 3 h turnaround time

β^*=25 cm: 820 fb^{-1}/year
β^*=40 cm: 700 fb^{-1}/year

not quite 4x HL-LHC, but close

~15% reduction with 2x lower peak pile up

=> O(15 ab^{-1}) over 20-25 years

What does the HE-LHC entail?

- **Necessary:**
  - empty the tunnel (more time & $s than removing LEP)
  - full replacement of the magnets (today's cost ~4xLHC. First prototypes in ~2026)
  - upgrade of RF, cryogenics, collimation, beam dumps, …
- **Very likely:**
  - major upgrade of SPS, to inject at O(1 TeV) (magnets, RF, transfer lines, cryo if SC, …)
  - major overhaul of detectors (radiation damage after HL-LHC, use of new technologies)

=> it's like building the LHC ex-novo

- very unlikely to be cheaper …
- … but not incompatible with a ~constant CERN budget
- nevertheless feasibility to be proven (eg magnets bigger than LHC's: will they fit in the tunnel ??)

HE-LHC tunnel integration

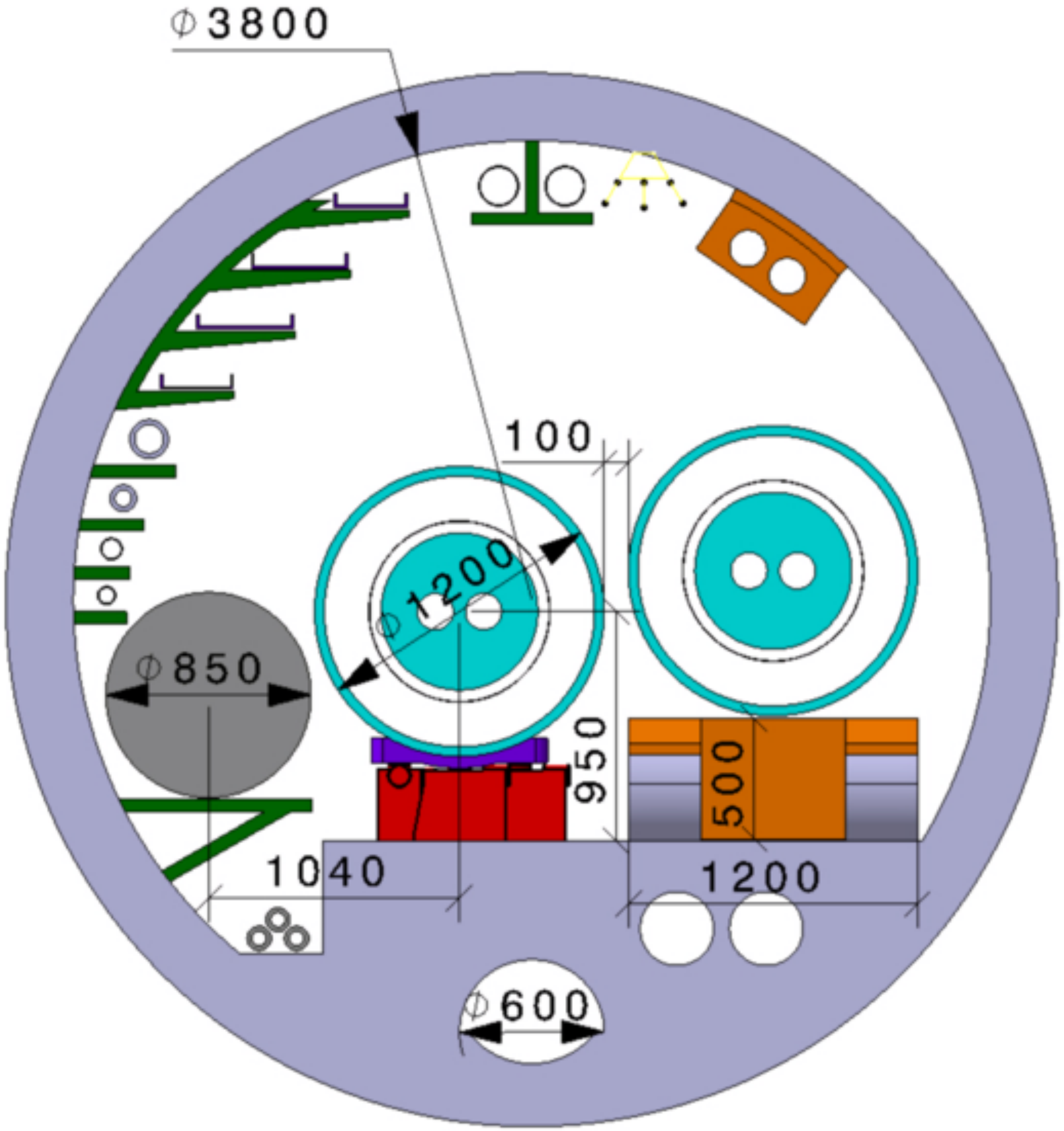
requirement: no major CE tunnel modifications

- challenges for tunnel integration
- **maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**

strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

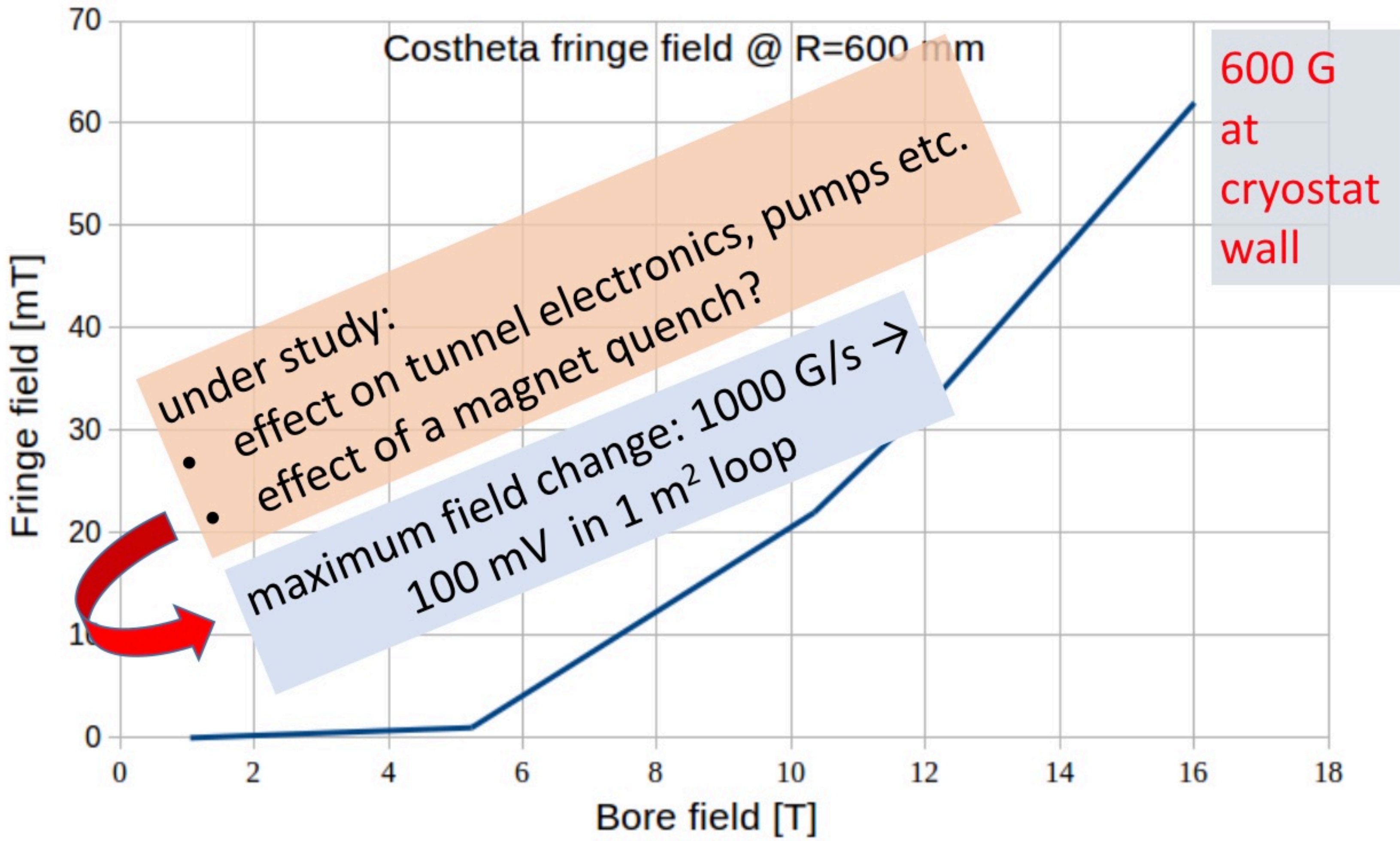
- options und consideration:
  - **allow stray-field and/or cryostat as return-yoke**
  - active compensation with (simple) shielding coils
  - **optimization of inter-beam distance (compactness)**
  - *(QRL integrated in magnets, → reduced integral field because of longitudinal space required for service module (5%))*

→ smaller diameter, also relevant for FCC-hh cost optimization



Challenges of compact (1.2m⦰)16T dipoles

- Dipole bend for HE-LHC (5mm over 14m)
- Field errors ⇒ reduced dynamic aperture at 100 TeV
- Physical aperture loss due to beam screen
- Impact of stray fields on tunnel electronics, esp. during quench



For more details on the challenges of HE-LHC (optics, injection, collimation/ extraction, IR and triplet protection, …) see Zimmermann at https://indico.cern.ch/event/647676

Conceptual Design Report

1 – PHYSICS

Physics opportunities across all scenarios

2 Hadron Collider Summary

3 – Hadron Collider Comprehensive

- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment
- eh

4 Lepton Collider Summary

5 – Lepton Collider Comprehensive

- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment

6 High Energy LHC Summary

7 – High Energy LHC Comprehensive

- Accelerator
- Injectors
- Infrastructure

Refs to FCC-hh, HL-LHC, LHeC

Physics landscape

Summary volumes

Detailed volumes

⇒ to be completed by end 2018

European Strategy for Particle Physics

- Sept 2017: Council establishes the Strategy Secretariat:
  - Halina Abramovicz Scientific Secretary, with Chairs of SPC (R.K.Ellis), ECFA (tba, November), european laboratory directors group (L.Rivkin)
- Sept 2018: Council nominates Preparatory Group and Strategy Group
- Dec 2018: deadline for submission of input from the community
- 2019: Community discussions
  - Open Symposium (~Sept '19, and possibly one in early '19)
  - Preparatory group summarizes community feedback in Briefing Books
- Early 2020: Strategy Group discussion and preparation of the draft Strategy (1-week mtg, inspired by briefing books)
- May 2020: adoption of the Strategy by Council

remarks

- Input welcome from the full international community, addressing also other global, regional or national plans
- Strategy group includes 1 voting rep / member state, as well as observers from associate/observer states, other regions, astro and nuclear communities, EU, …
- Final Strategy statements endorsed and signed by Council.
  - However, the Strategy is a collection of resolutions and statements, not an implementation plan. Implementation of the Strategy, and consideration/approval of specific initiatives/facilities emerging from it, is a subsequent process, in the hands of Council and CERN's management.
- Timeline of Strategy releases so far:
  - 2006, 2013, 2020 ⇒ ~7 year timeframe

FCC Collaboration & Industry Relations


FCCWEEK2018
Future Circular Collider Conference
AMSTERDAM, Netherlands
9 - 13 APRIL
fccw2018.web.cern.ch
also 2018 FCC Physics Workshop, 15-19 January 2018, CERN
https://indico.cern.ch/event/618254/

Resources

Talks at HL/HE-LHC workshop:

HE-LHC: F.Zimmermann, https://indico.cern.ch/event/647676/contributions/2721141/
HL-LHC: L.Rossi, https://indico.cern.ch/event/647676/contributions/2721132/

FCC academic training lectures:

FCC-ee: P.Janot, https://indico.cern.ch/event/666889/
FCC-hh (detectors): W.Riegler, https://indico.cern.ch/event/666890/
FCC-hh/eh (physics): MLM, https://indico.cern.ch/event/666891/

thanks to all of them and M.Benedikt for sharing slides