Future Circular Collider: the next BIG accelerator challenge

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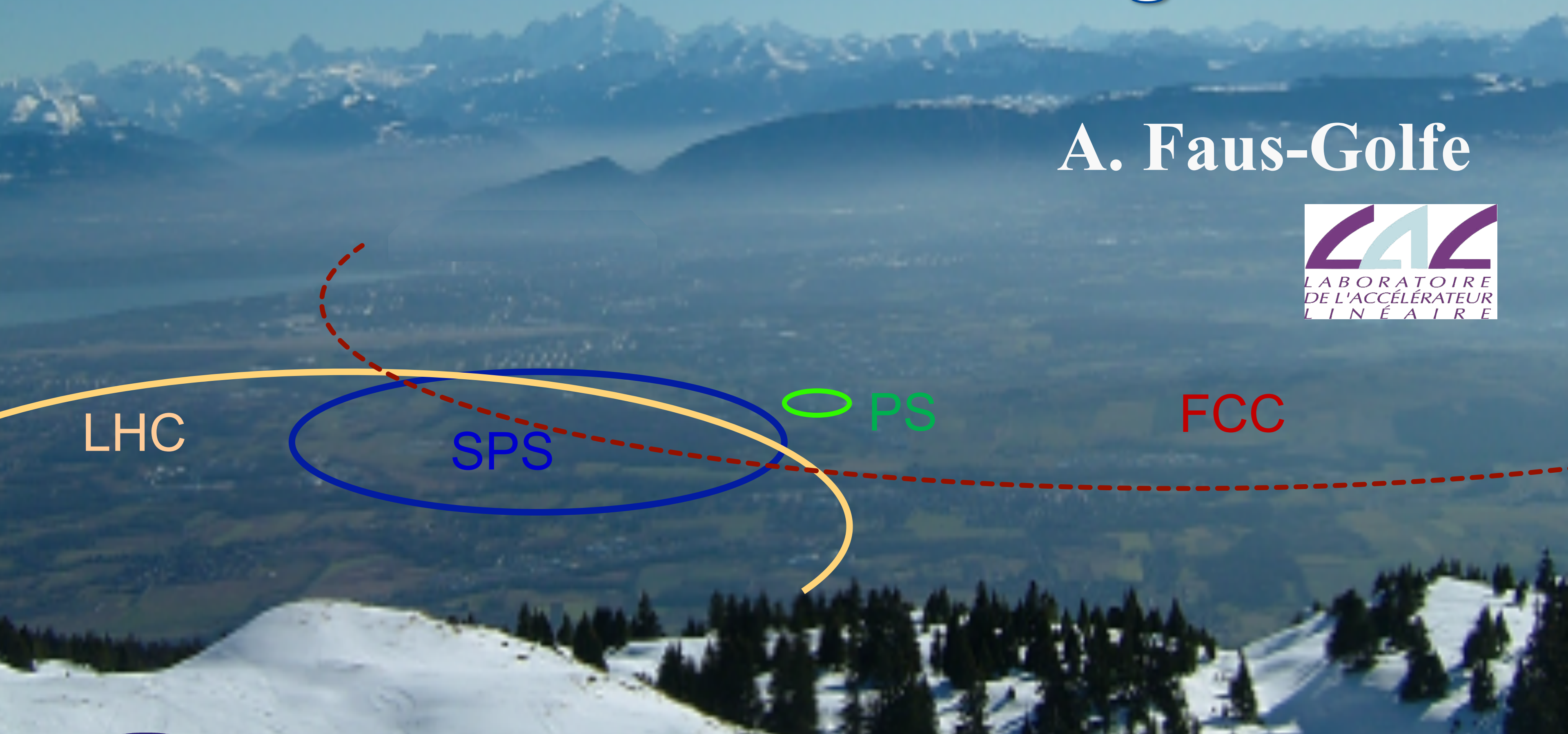


FCC hh ee he

EuroCirCol

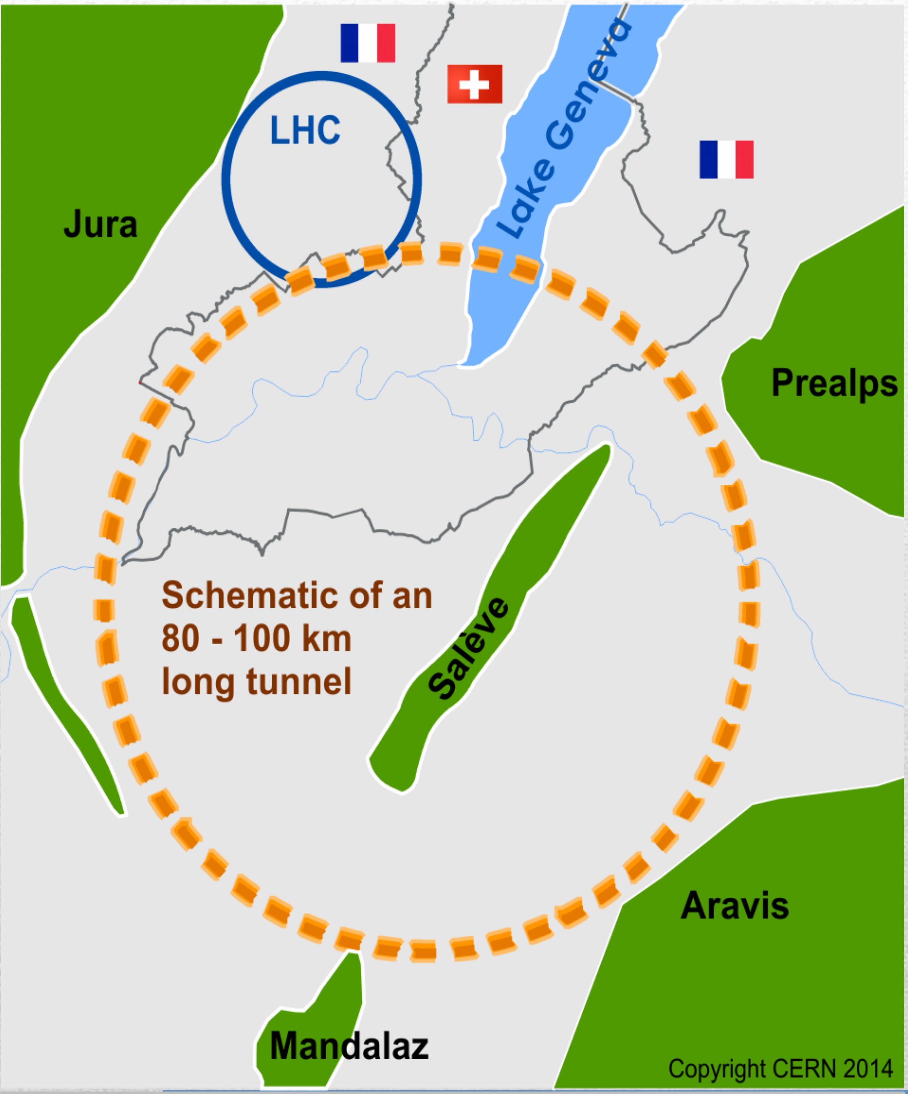
http://cern.ch/fcc

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*

Outline

- The FCC project: FCC-hh, FCC-ee, HE-LHC, FCC-eh
- Parameters and layout of FCC-hh
- FCC-hh Superconducting Magnets and SRF
- FCC-hh special technologies
- FCC civil engineering and infrastructure
- FCC and other future projects

Scope of FCC Study



~16 T ⇒ 100 TeV *pp* in 100 km

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

- ***FCC-hh: pp*-collider**

main emphasis, defining infrastructure requirements

- ***FCC-ee:* e^+e^- collider**

as potential first step

- ***FCC-he: p-e* collider**

integration one IP, e^- from ERL

- ***HE-LHC***

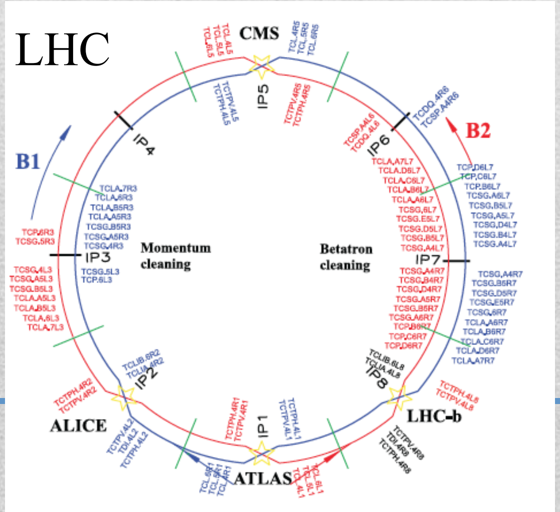
with *FCC-hh magnet* technology

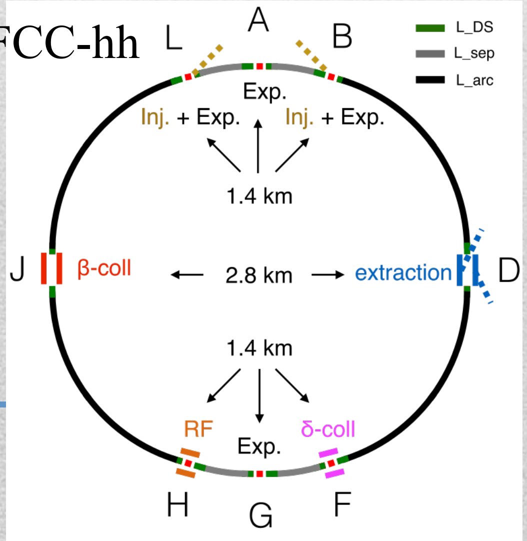
FCC-hh collider parameters

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

FCC-hh / LHC / HL-LHC parameters comparison

Parameters	LHC	HL-LHC	FCC-hh	Scale LHC
Length [m]	26658	26658	97749	x3.67
Top beam energy [GeV]	7000	7000	50000	x7.14
Bunch count [25 ns]	2808	2808	10600	x3.77
Bunch particle count [10^{11}]	1.15	2.2	1	x0.87
Stored beam energy [GJ]	0.362	0.693	8.4	x23.2
Normalized emittance [mmrad]	3.75	2.5	2.2	x0.59
Luminosity [10^{34} cm^{-2} s^{-1}]	1	5	5	x5
Beam-collimator interaction [GeV]	114.62	114.62	306.32	x2.67

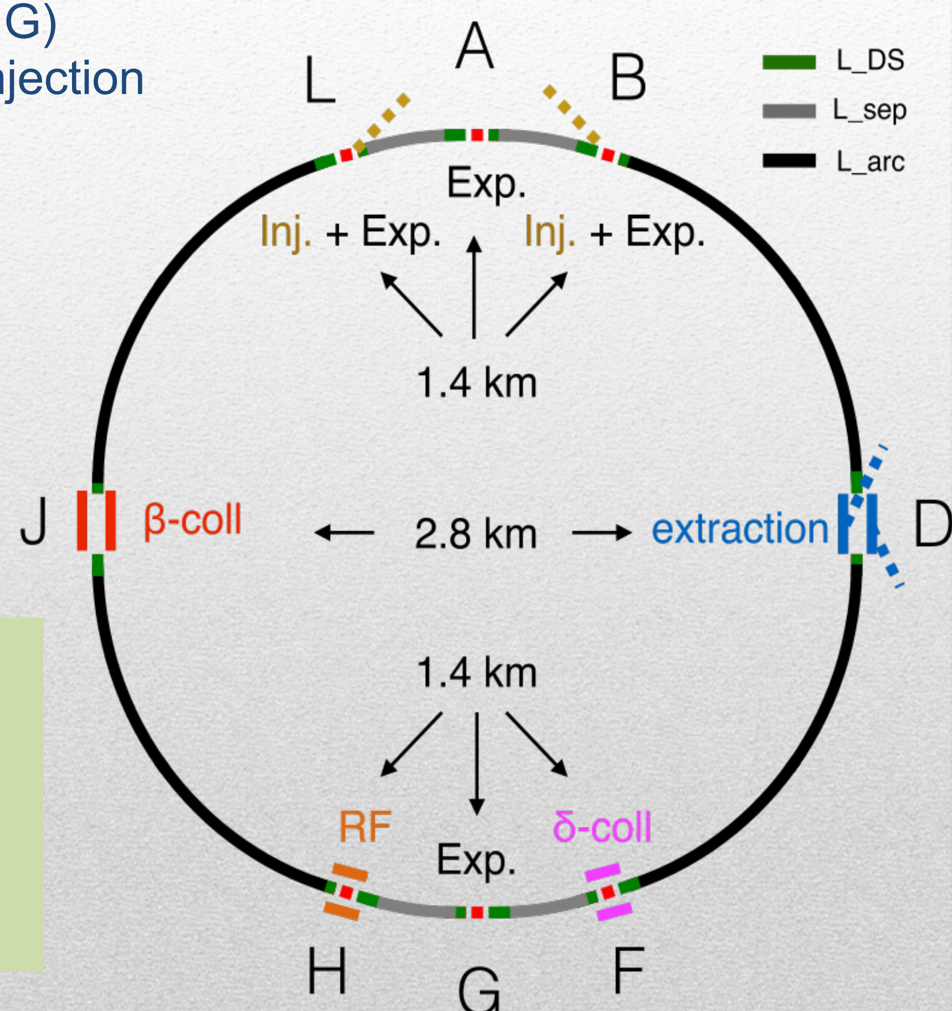




FCC-hh "new" layout

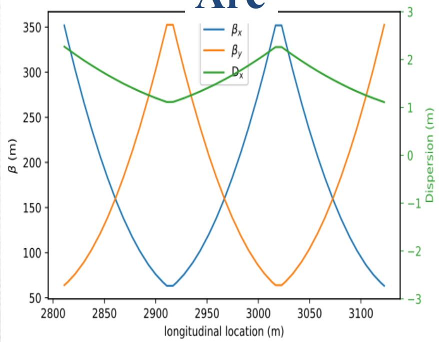
- **Two high-luminosity experiments** (A & G)
- **Two other experi**ments combined with injection (L & B)
- **Two collimation insertions**
  - Betatron cleaning (J)
  - Momentum cleaning (F)
- **Extraction insertion** (D)
- **Clean insertion with RF** (H)
- Compatible with LHC or SPS as injector

New features:
- **Overall length 97.75 km**
- **Economy length 2.25 km**
- Injections upstream side of experiments
- **Avoids mixing of extraction region and high-radiation collimation areas**

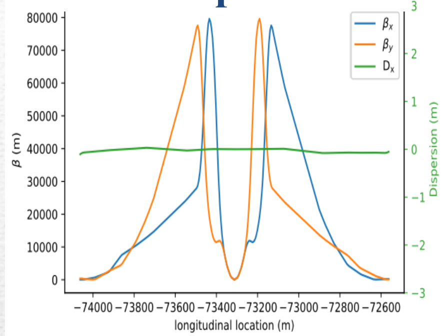


Integrated FCC-hh lattice design

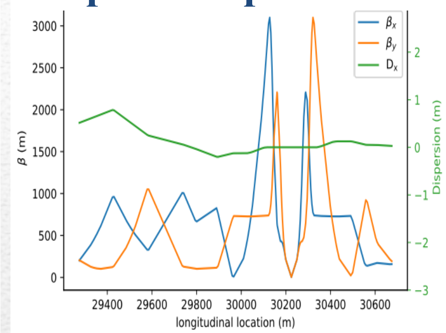
Arc



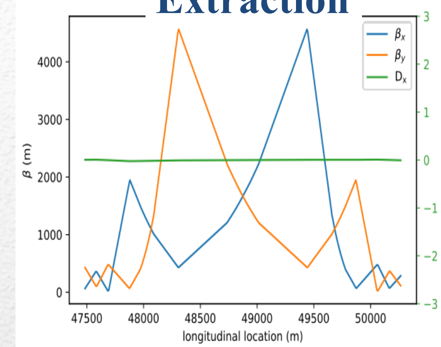
Main experiments



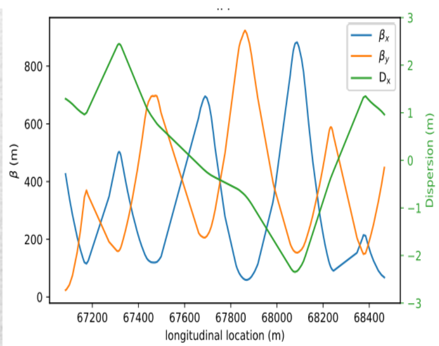
Special experiments



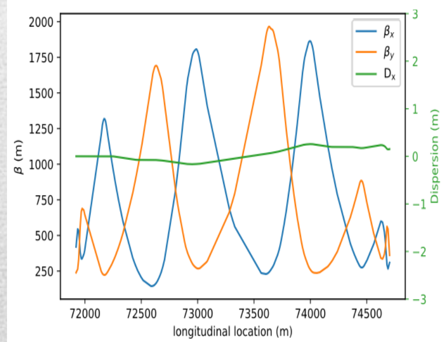
Extraction



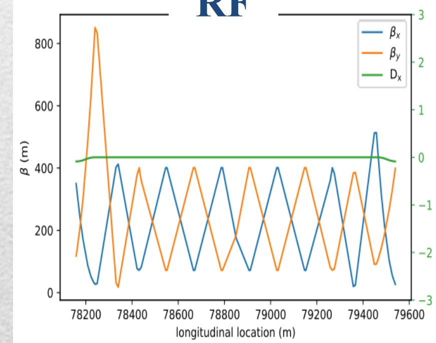
Momentum collimation



Betatron collimation



RF



Full integrated lattice exists:

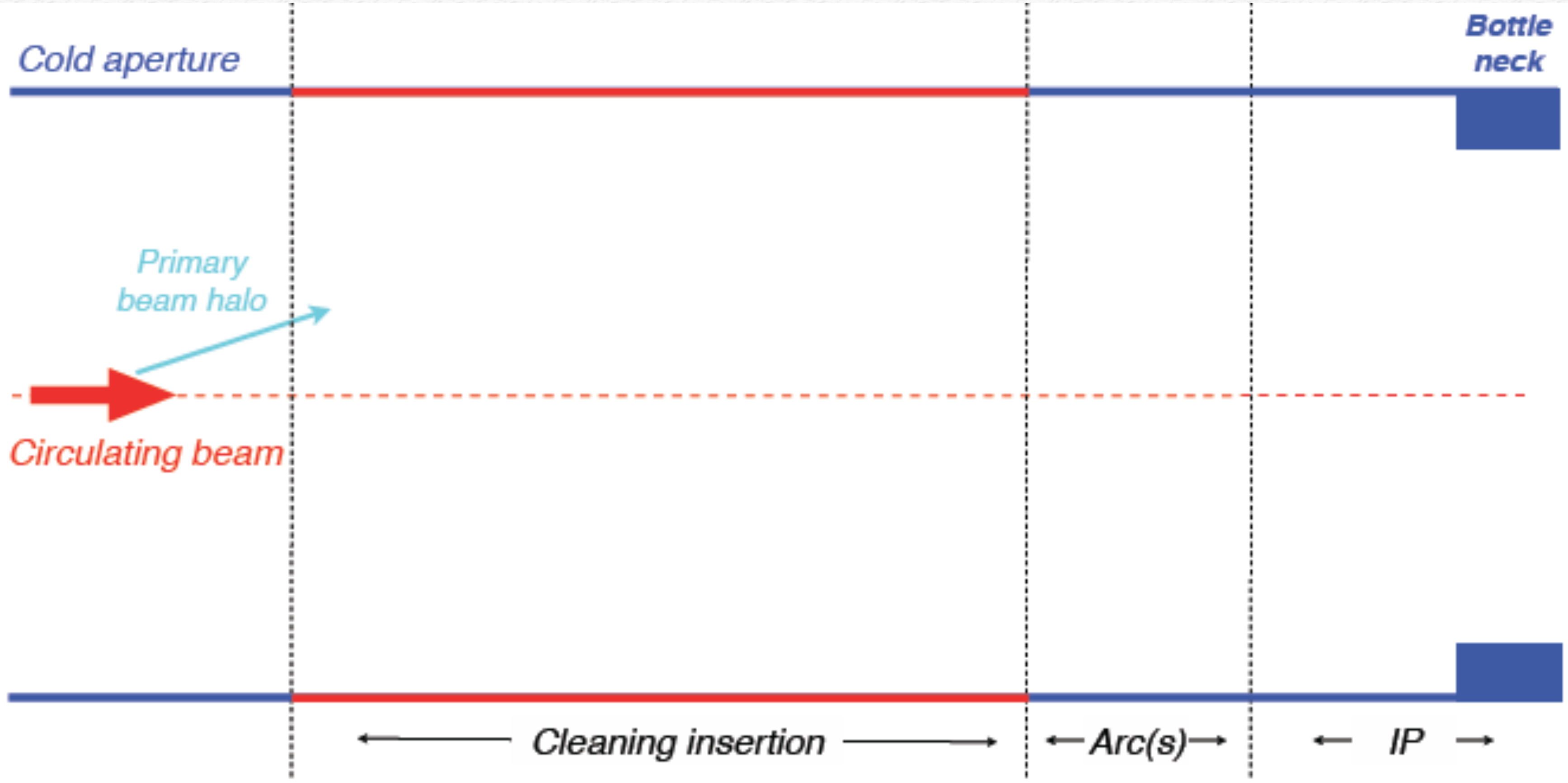
- Lattice studies with imperfection, Dynamic Aperture at injection and collision
- DA optimization in iteration with magnet design (balancing errors at injection/ collision)
- Tentative specifications for magnets correctors and alignment tolerance

The collimation system

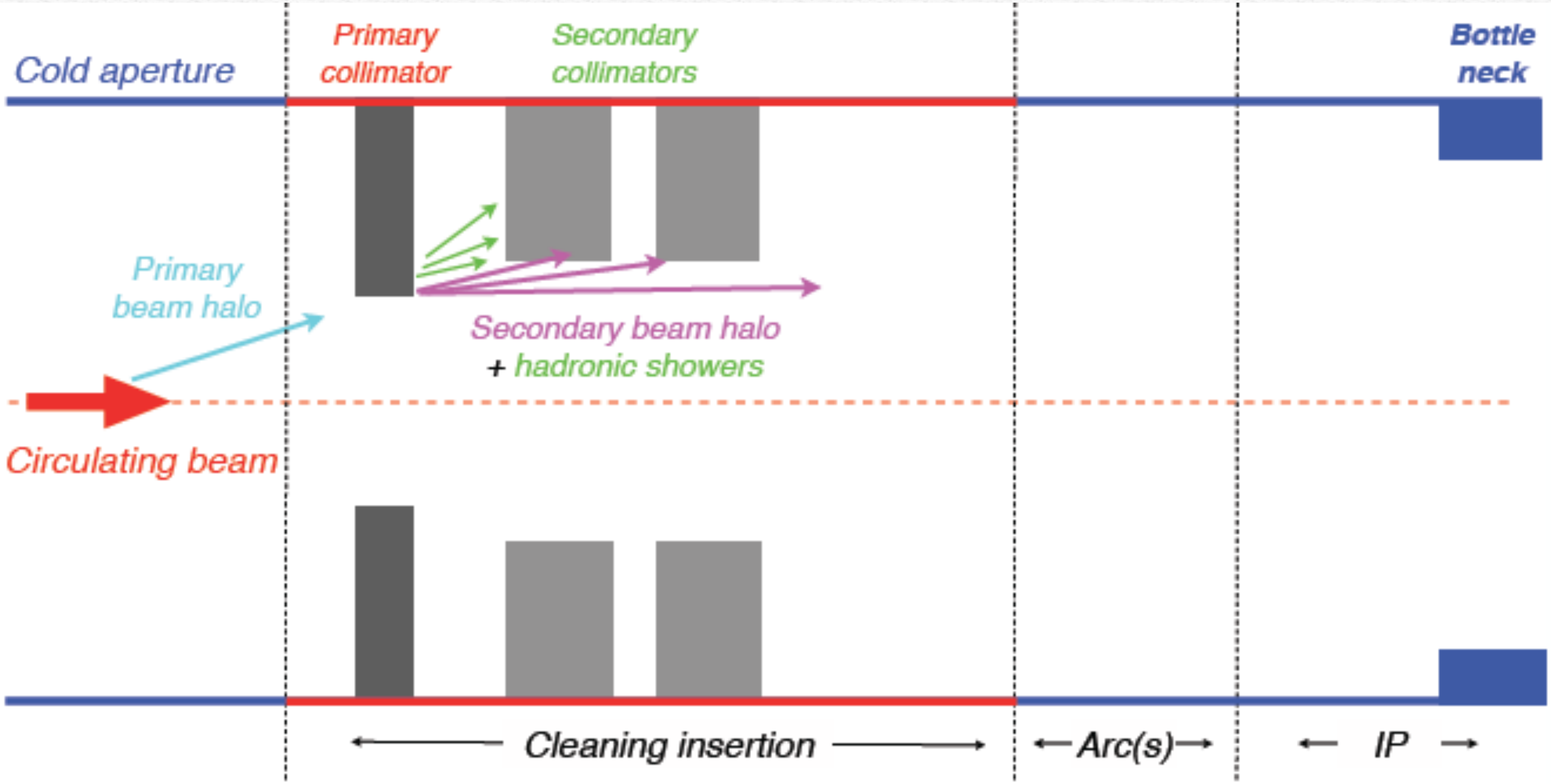
- **Halo cleaning** versus quench limits (for SC machines)
- Passive **machine protection**
  First line of defense in case of accidental failures
- **Reduction of total doses** on accelerator equipment
  Provide local protection to equipment exposed to high doses
- **Cleaning of physics debris** (collision products)
  Avoid SC magnet quenches close to the high-lumi experiments
- **Concentration of losses/activation** in controlled areas
  Avoid many loss locations around the 100-km tunnel
- **Optimize background** in the experiments
  Minimize impact of halo losses on quality of experimental data

The collimation system

Multi-stage collimation system

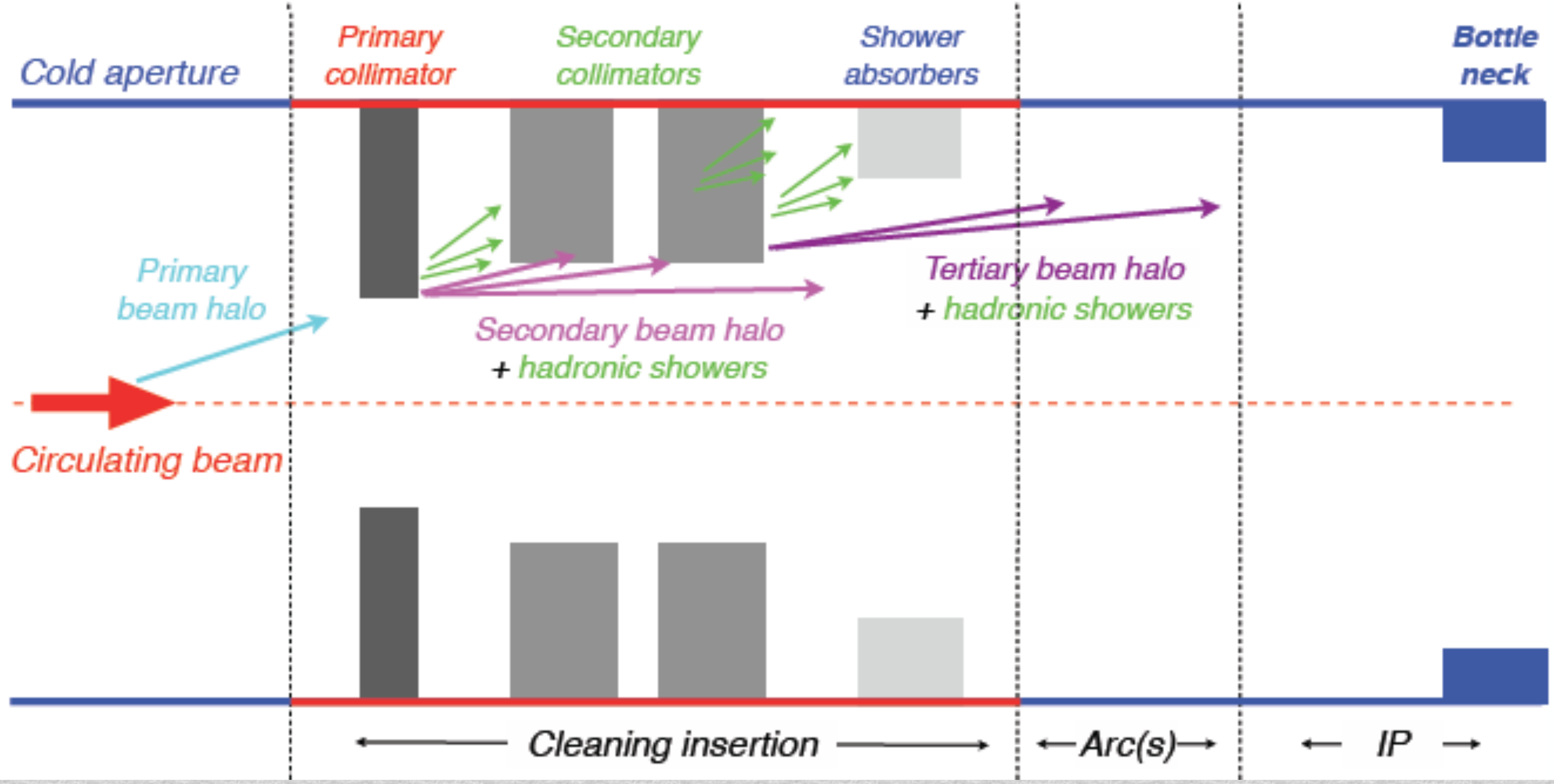


Multi-stage collimation system



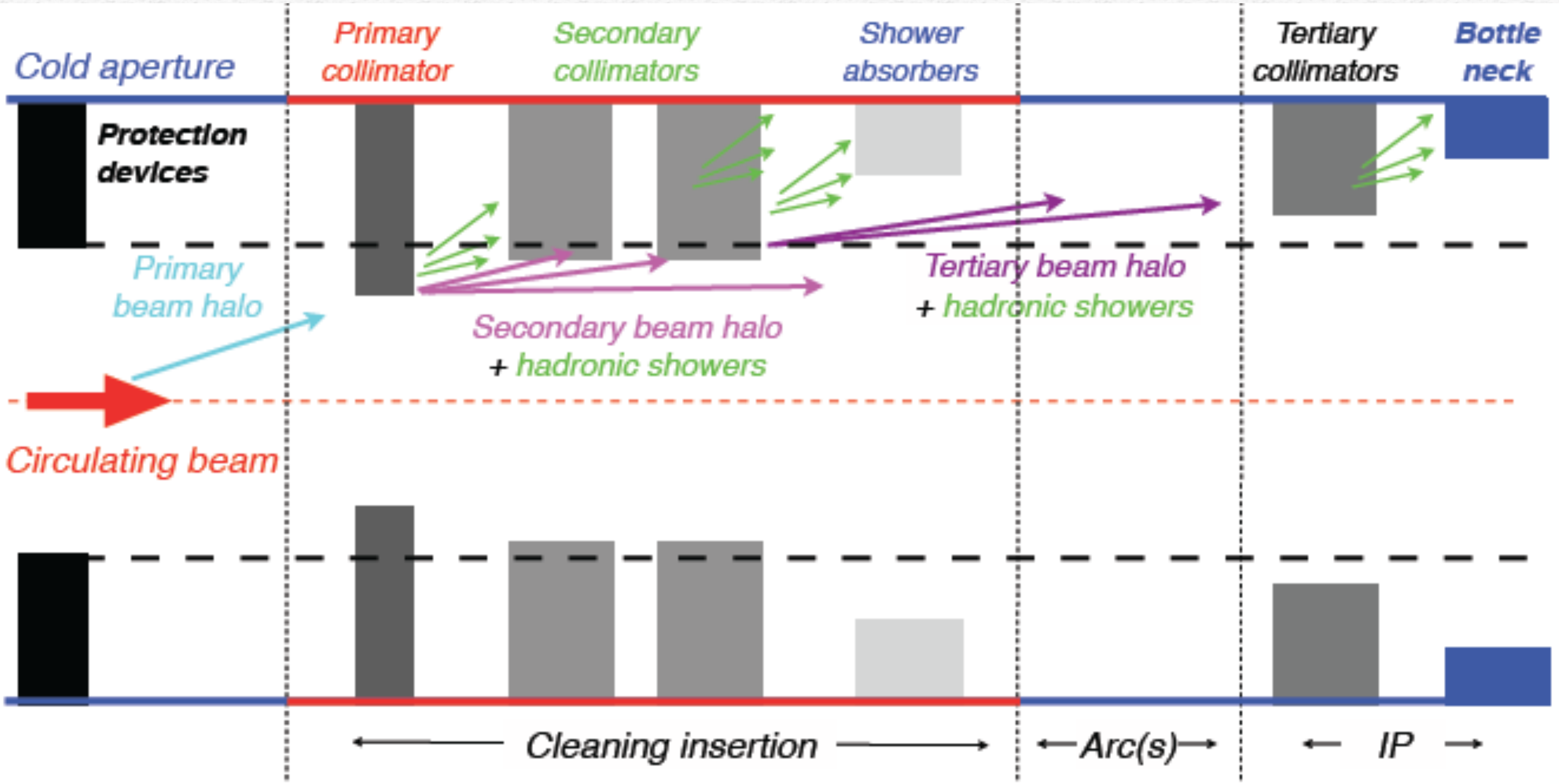
The collimation system

Multi-stage collimation system



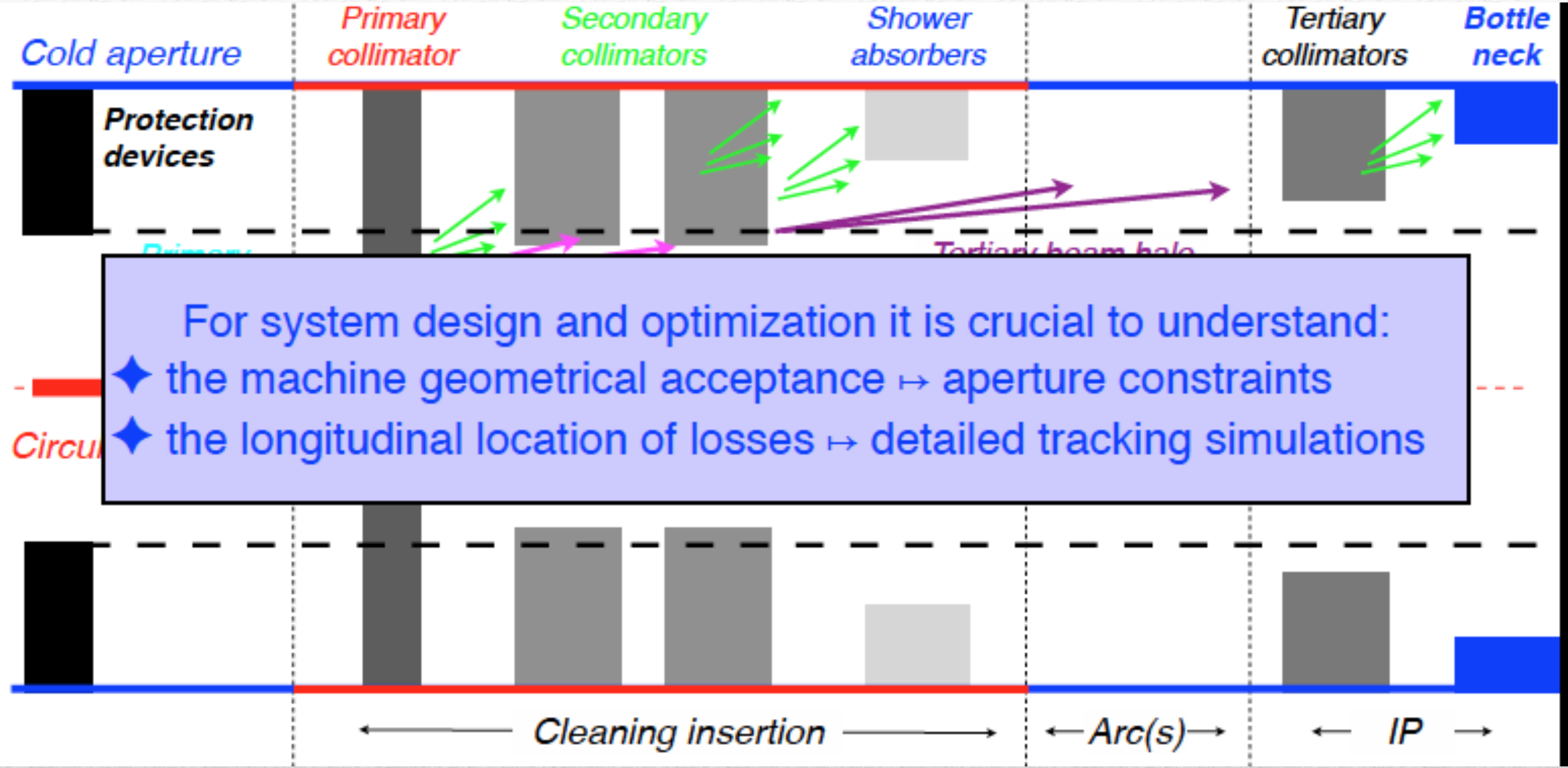
The collimation system

Multi-stage collimation system



The collimation system

Multi-stage collimation system



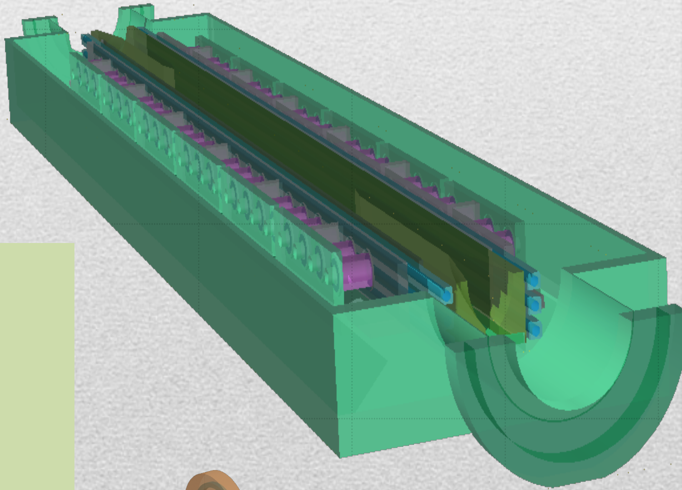
For system design and optimization it is crucial to understand:

- the machine geometrical acceptance ↦ aperture constraints
- the longitudinal location of losses ↦ detailed tracking simulations

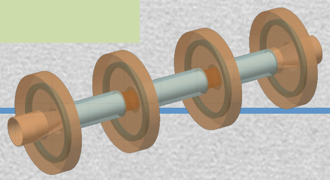
The collimation system

Same collimators and absorbers as in LHC:

- **Primary collimators**: 7.6 σ, 0.6 m long carbon based collimators
- **Secondary collimators**: 8.8 σ, 1 m long carbon based collimators
- **Active absorbers**: 12.6 σ, 1 m long, tungsten based collimators
- **Passive absorbers:** in front of the magnets, 0.4m to 1.5m long



- CFC collimators consume significant portion of the impedance budget
- Investigate alternative materials, e.g. Molybdenum Graphite (MoGr) which is foreseen for HL-LHC

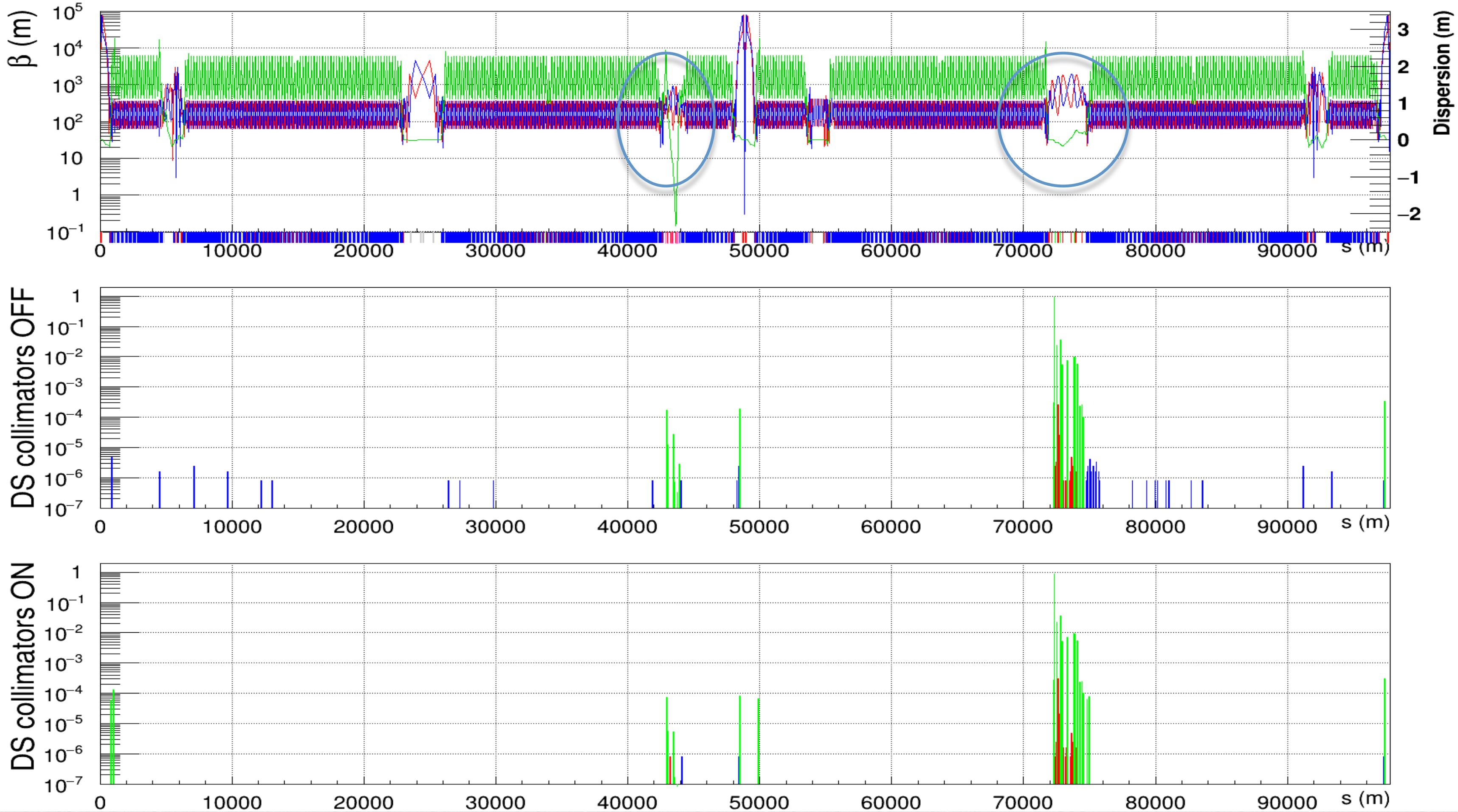


The collimation system

Full ring loss map V8 on-momentum

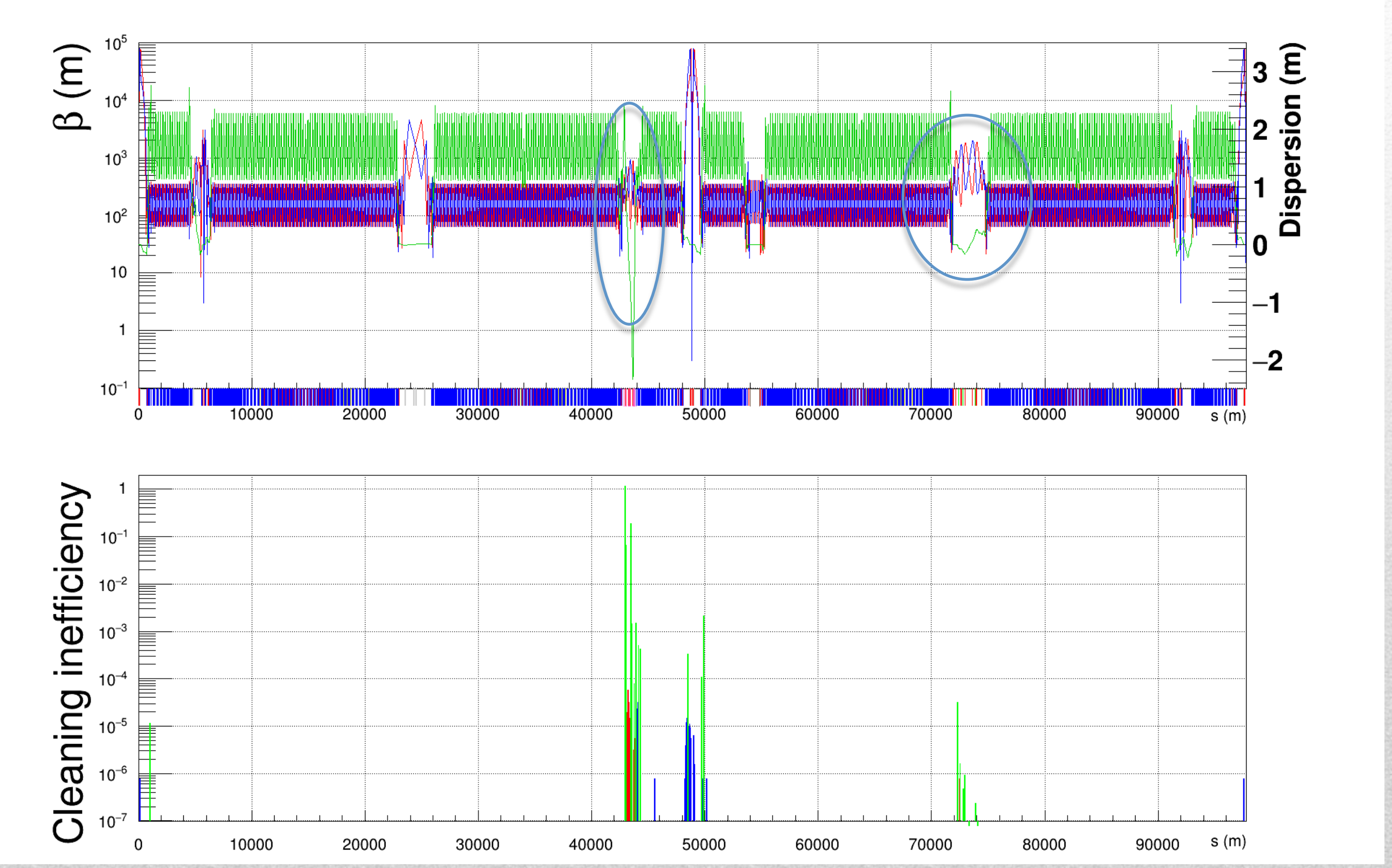
The collimation system

Full ring loss map V8 on-momentum wo/w DS collimators



The collimation system

Full ring loss map V8 off-momentum



The SC Magnets and SRF

16 T magnets target:

- **a reference design** for the 16 T dipoles, including integration in **cryostat**;
- a **concept** for the magnet and **circuit protection**;
- an estimate of the **cost** for the series production;

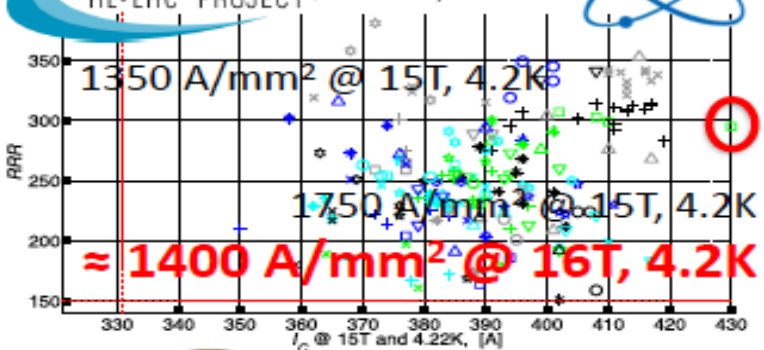
But many unknowns:

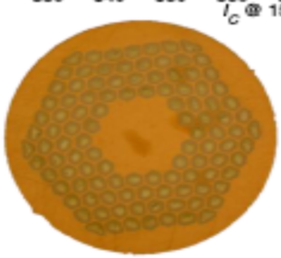
- **conductor cost**
- achievable **conductor performance**, no enhancements expected within 2018
- **electromechanical performance** of conductor and cable not yet fully characterized
- achievable **magnet performance** (required margin) has a major impact on cost
- **No** Nb_3Sn **magnet operating** in a particle accelerator in 2018

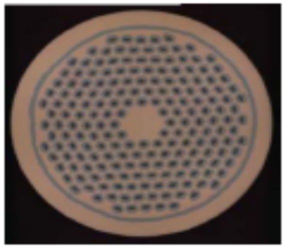
The Conductor (Nb_3Sn) Development Program:

HiLumi HL-LHC PROJECT

BRUKER



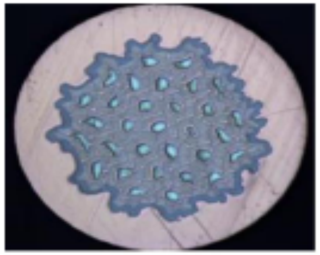


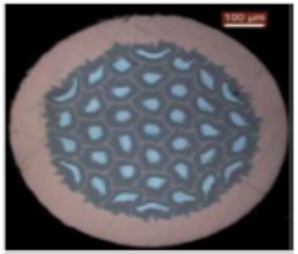


1274 A/mm² @ 15T, 4.2K

≈ 1000 A/mm² @ 16T, 4.2K

ROSATOM TVEL BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM

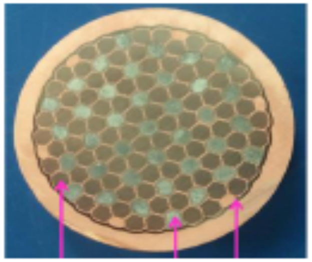


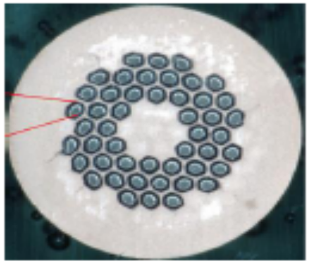


2850 A/mm² @ 12T, 4.2K

≈ 1250 A/mm² @ 16T, 4.2K

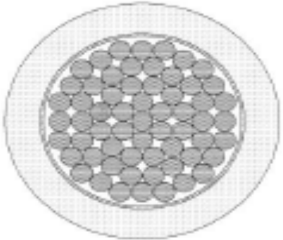
≈ 950 A/mm² @ 16T, 4.2K





JASTEC SUPERCONDUCTOR

FURUKAWA ELECTRIC



NFRI National Fusion Research Institute

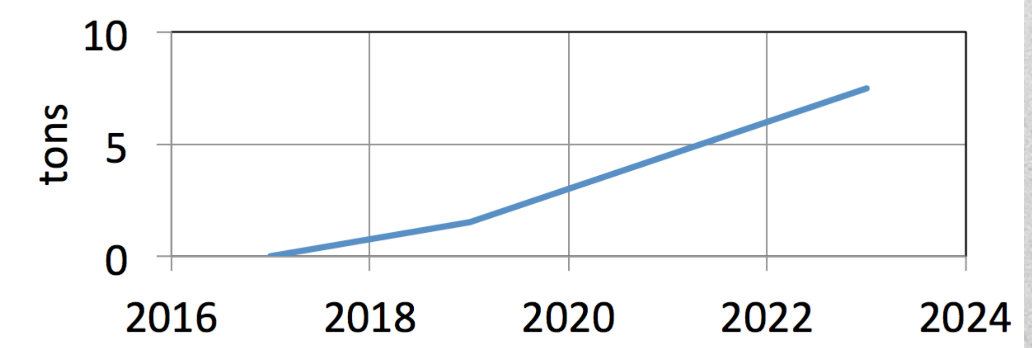
KISWIRE KAT

Western Superconducting Technologies Co., Ltd.

Global effort

What do we expect next ?

- Understand limits of Nb_3Sn while moving towards the first performance targets (Jc current density, RRR residual resistance ratio)
    - Allowable engineering limits (stress, strain)
    - Grain formation and grain refinement physics
- Evaluate the potential and opportunity for alternative superconductors (MgB_2, Bi-2212, REBCO, Fe-based)
- Procure the first large lengths of superconducting wire to feed the technology and model program
    - 1.5 tons by 2019
    - 6 tons by 2023

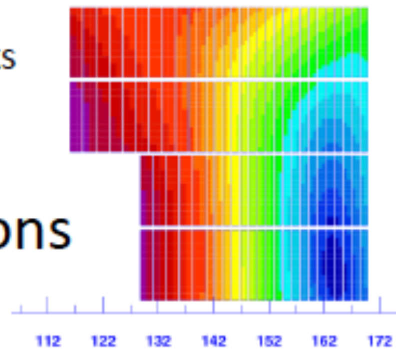


The SC Magnets and SRF

The evolution of the dipole designs:

Blocks

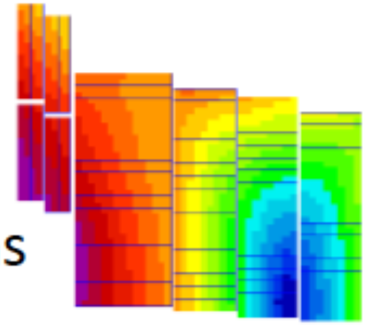
7.4 ktons



C. Lorin, CEA

Common coils

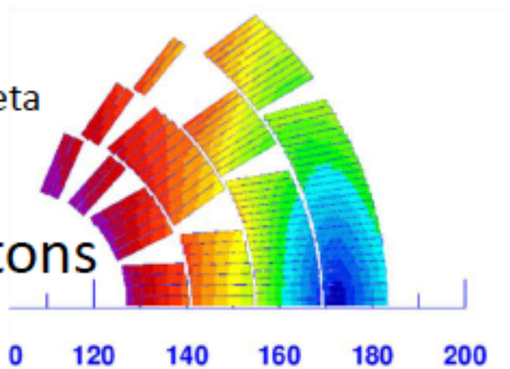
9.2 ktons



F. Toral, CIEMAT

Cos-theta

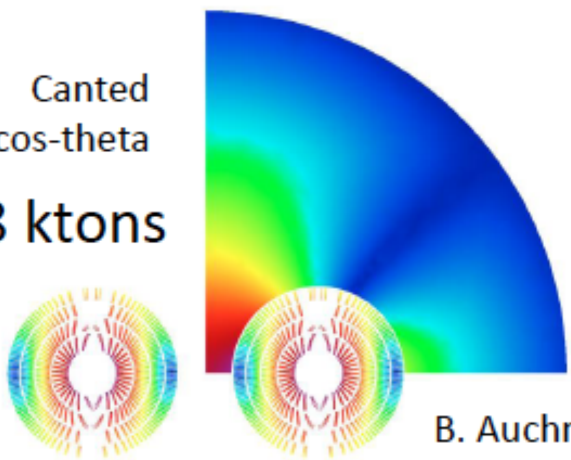
7.4 ktons



V. Marinozzi, INFN

Canted cos-theta

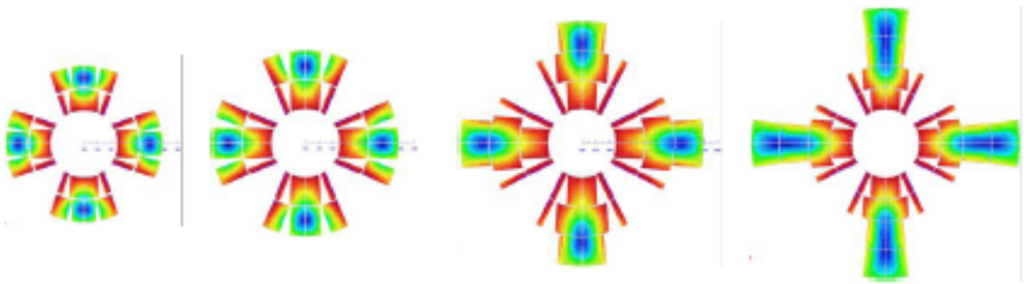
9.8 ktons



B. Auchmann, PSI

All designs stable and optimized (recall initial estimate of 9000 tons)

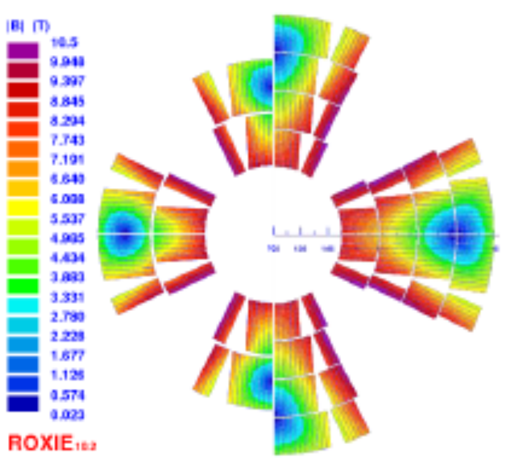
The main Quadrupole design:

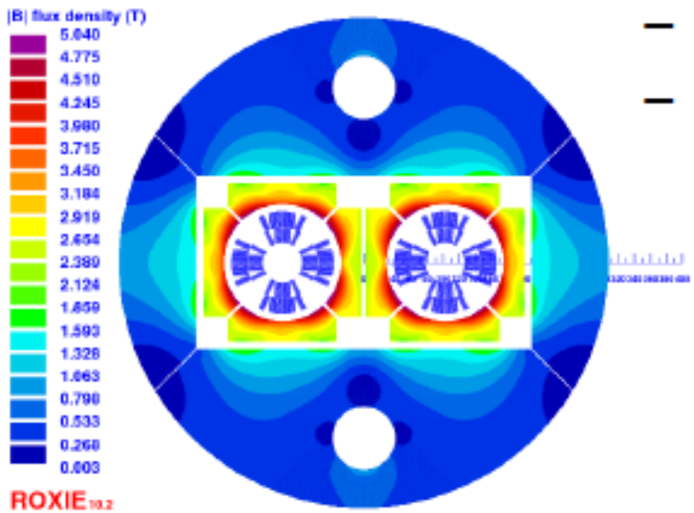


365 T/m 390 T/m 413 T/m 392 T/m

It seems that to reach

- $G > 400$ T/m
  - 4 layers → complexity
- 370 T/m < G < 390 T/m
  - 2 layers → $I_{op} > 25$ kA
- $G < 360$ T/m
  - 2 layers, I_{op} ~ 20 kA
  - More room for support in case of inter-aperture reduction





360 T/m 400 T/m

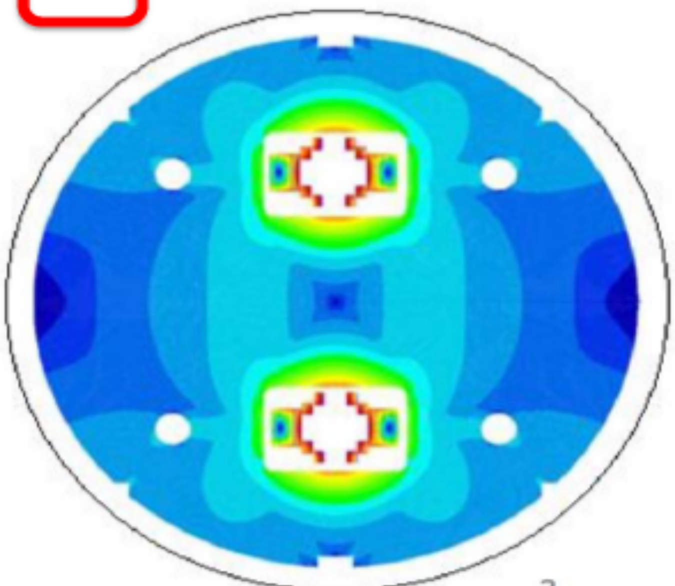
The SC Magnets and SRF

The companions in this effort:

The SC Magnets and SRF

The companions in this effort: CN

Conceptual design of the SPPC 12-T magnet with IBS and common coil configuration



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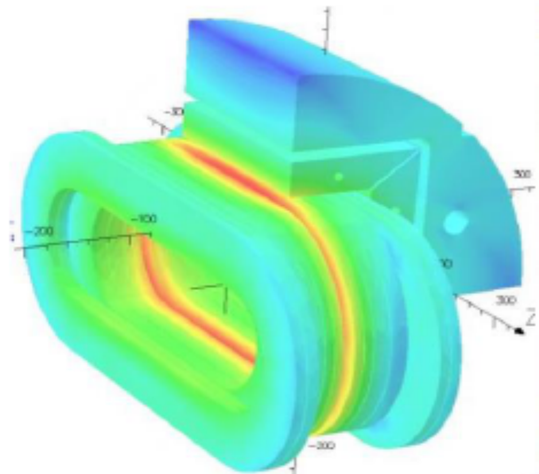
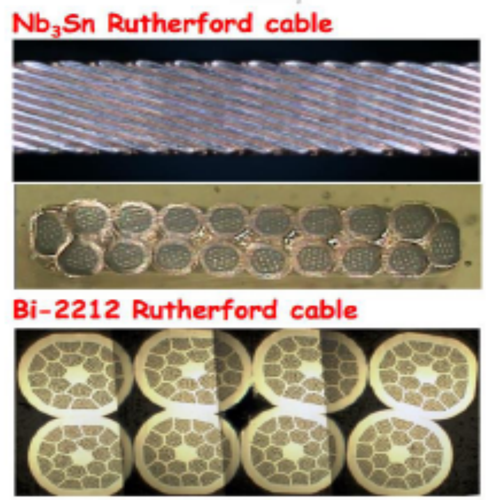
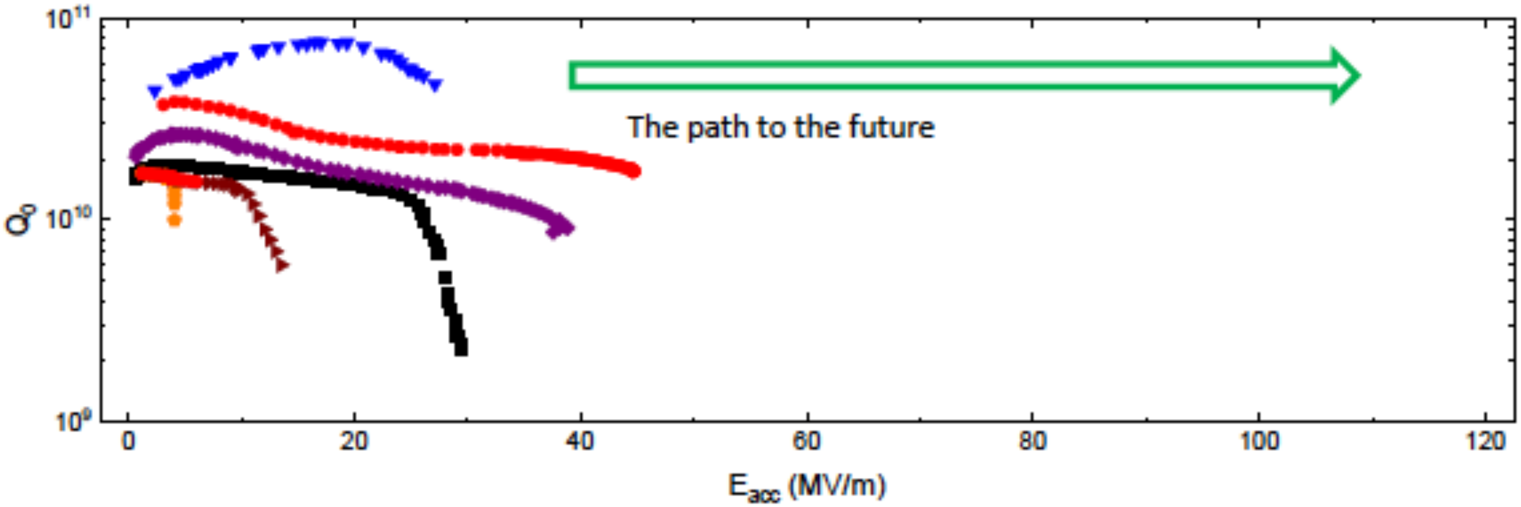


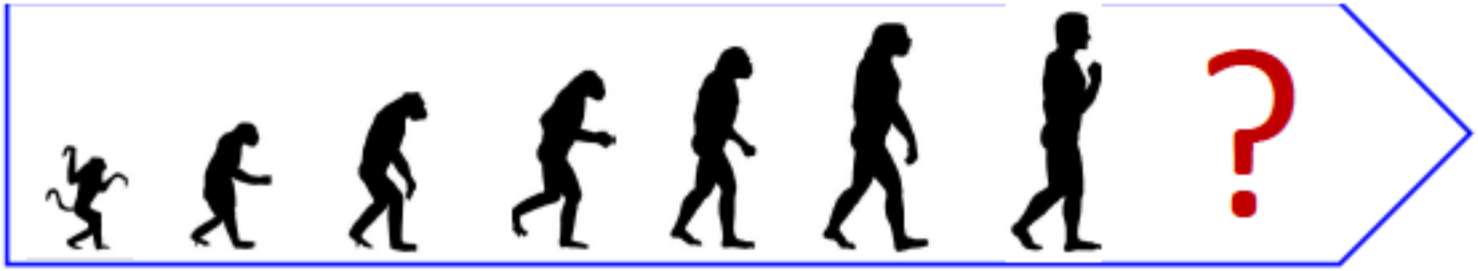


Significant engagement in HFM technology

Q. Xu, IHEP

The SRF Roadmap "evolution":





The SRF High-Q Roadmap:

2018 | 2020 | 2022 | 2024 | 2026 | 2028

Physics of RF Surface Resistance

- Understand the field dependence of BCS surface resistance and effect of different impurities
- Apply gained knowledge and develop new understanding for alternative materials
- Understand origin of residual resistance and its field dependence
- Understand trapped magnetic flux losses and flux trapping

Doping

- Continue exploration with nitrogen in Nb at different temperatures
- Doping for new materials
- Probing the ultimate limits of Nb RF surface resistance by doping with different impurities
- Study Nb doping at different frequencies and temperatures

Potential of Nb material: Q(2 K) ~ 1x10^{11} @ 1.3 GHz

Nb_3Sn or other new materials

- Pursue current promising path forward for material in bulk form (Nb_3Sn) – explore and optimize coating techniques and treatments for single cell / multi-cell cavities
- Nb_3Sn studies for cryomodule operation
- Explore SIS for Nb_3Sn
- Evaluate alternative materials, bulk or film (NbN, NbTiN, MgB_2) first on samples, then on cavities

Potential of Nb_3Sn material: Q(4 K) ~ 1x10^{11} @ 1.3 GHz

Magnetic Flux Losses

- Drastically reduce sensitivity to magnetic flux for Nb and new materials
- In situ removal of trapped magnetic field (in cryomodule)
- Develop Materials Specs to ensure maximum flux detrapping

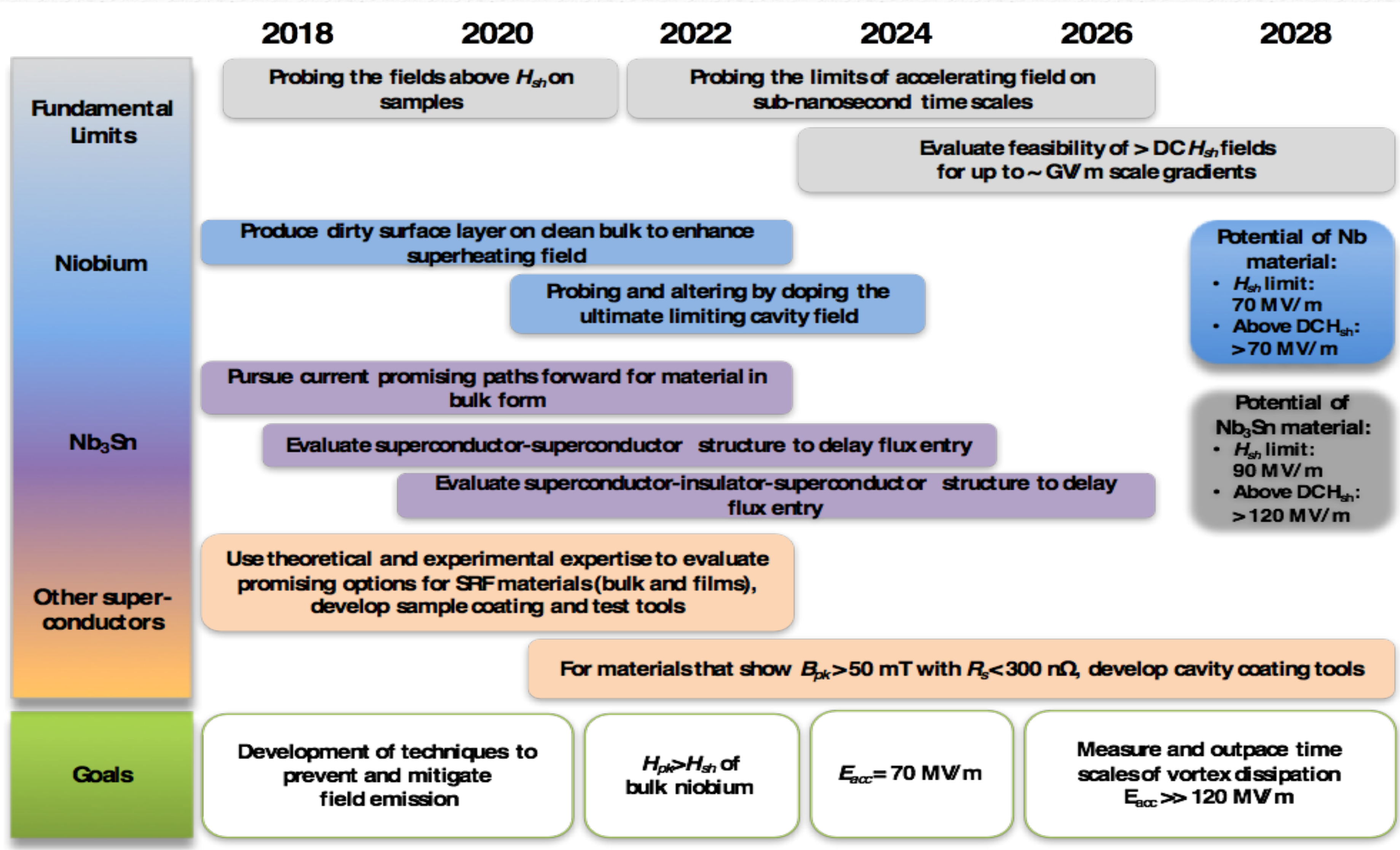
Impact:
- Retain 1x10^{11}
- Sustain very high gradients

Goals

- Q > 4x10^{10} at 2 K, 1.3 GHz and E_{acc} > 35 MV/m
- Nb_3Sn: E_{acc} > 20 MV/m with Q_0 > 1x10^{10} at 1.3 GHz, 4.2 K
- *Residual resistance < 1 nΩ in cryomodule*
- *Nb_3Sn cryomodule ready technology*

The SC Magnets and SRF

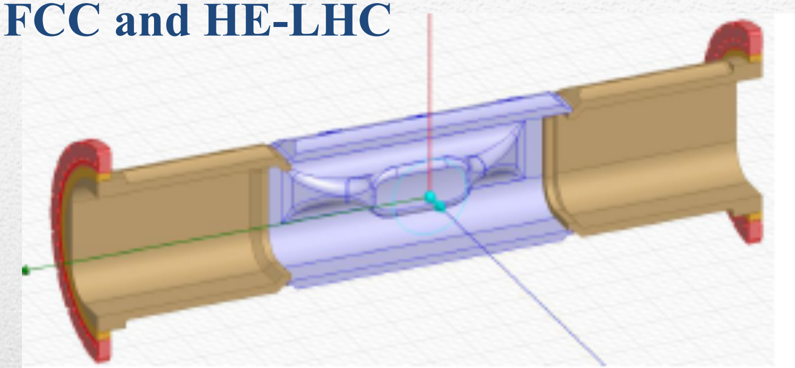
The SRF High-Gradient Roadmap:



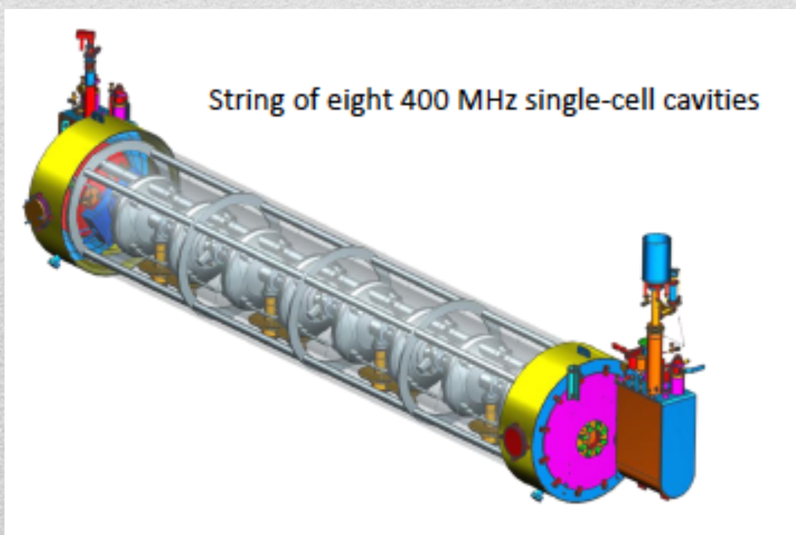
The SC Magnets and SRF

Many others :

Innovative CRAB cavities for FCC and HE-LHC

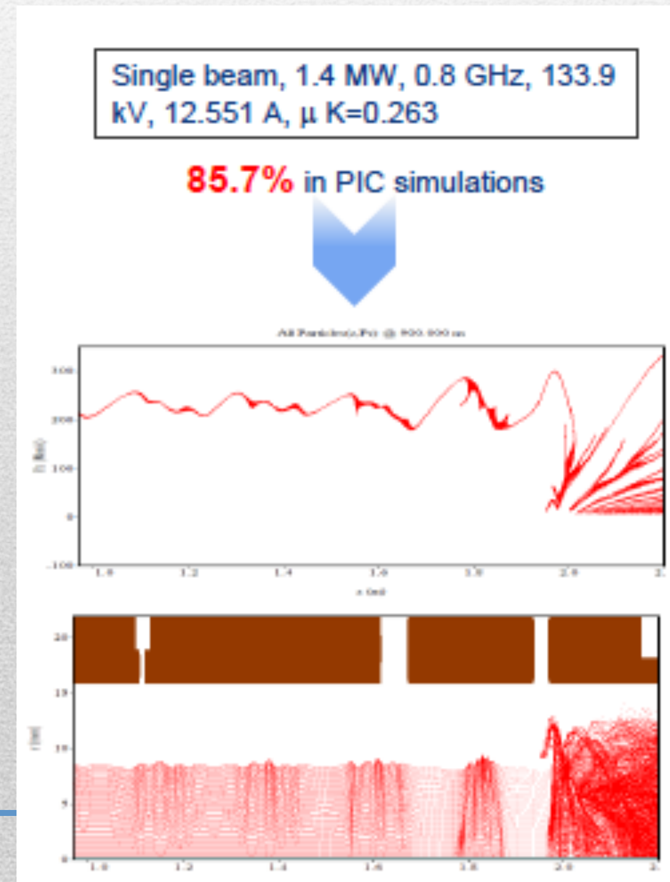


Cryomodules design

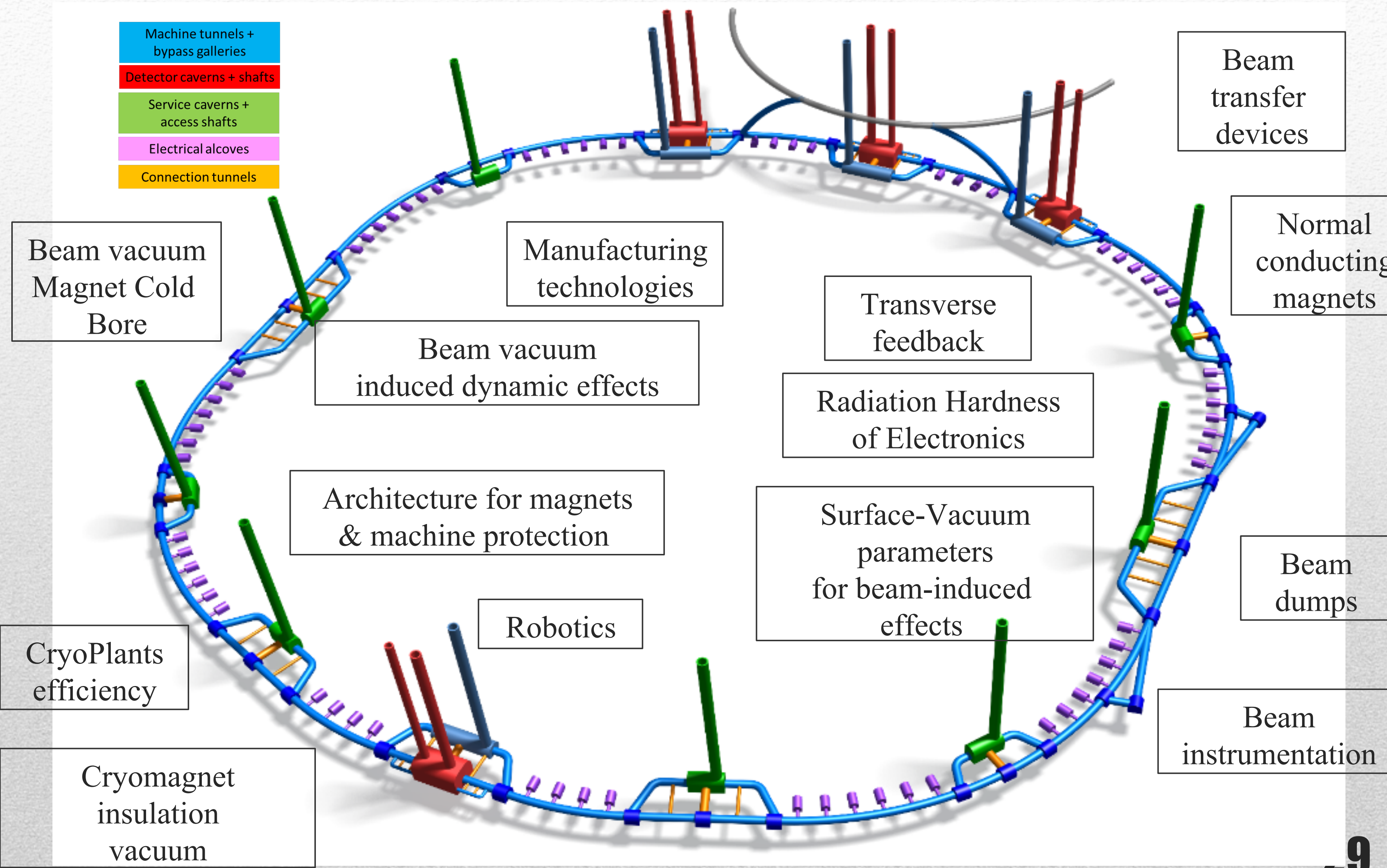


High-Efficiency Klystros

FCC: 100MW beam power ≈ 165 MW grid power => every 1 % gain in efficiency ≈ 10 GWh/year (≈ 0.4M€/year)



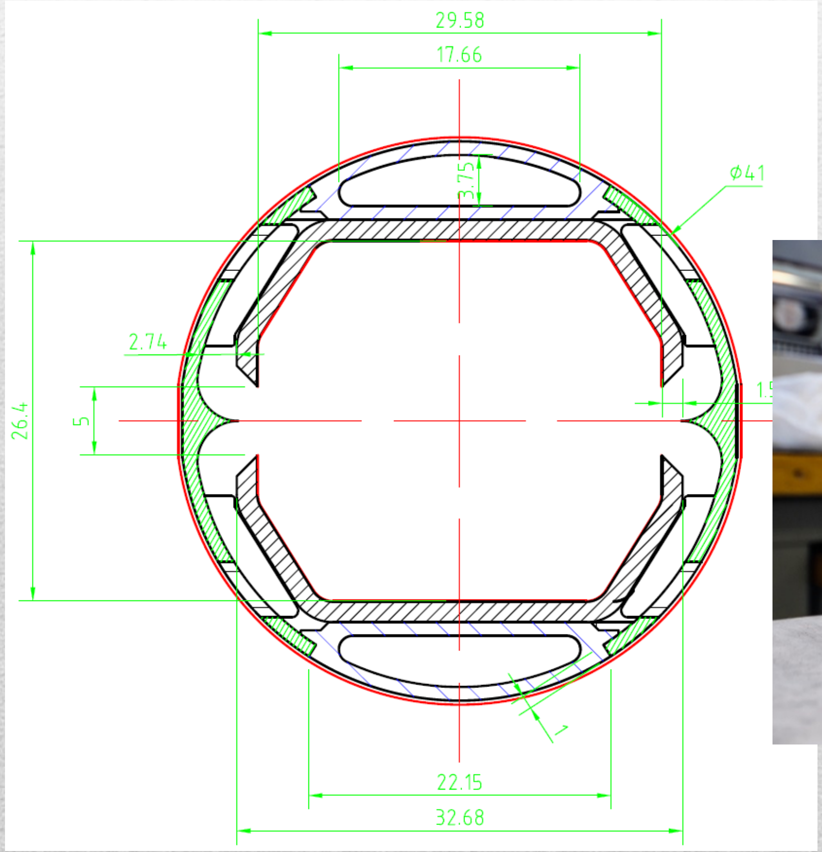
The special technologies



The special technologies

Beam Vacuum:

- One of the most critical elements for FCC-hh
- Absorption of synchrotron radiation at ~50 K for cryogenic efficiency (5 MW total power)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.



FCC Beamscreen prototype for test at ANKA:

External copper rings for heat transfer to cooling tubes

The special technologies

Beam Instrumentation:

- **BPMs:**

Electronics prototype in order to measure the **resolution for turn by turn** measurements (single bunch) for signals levels corresponding to $5 * 10^8$ protons measured with a 30 mm button.

Paper study for a BPM with 4+N sensors for interlocked BPMs.

- **Transverse profiles:**

Development from a gasjet sheet monitor to a **gasjet scanner**. Simulations and construction of a prototype.

Theoretical & experimental studies to improve halo diagnostics from a contrast ratio 10^{-4} to 10^{-6} including apodization and a semitransparent cover for the central beam. Studies of parasitic light sources and their mitigation.

X-ray interferometry for proton profile evaluations

- **Versatile communication link (rad-hard) based on HEP chips and fibre optics**

Civil engineering and Infrastructure

Alignment | Shafts | Query

Choose alignment option

V4variation_v2017-2

Tunnel elevation at centre:322mASL

Grad. Params

Azimuth (°): -23.5

Slope Angle x-x(%): 0.3

Slope Angle y-y(%): 0.08

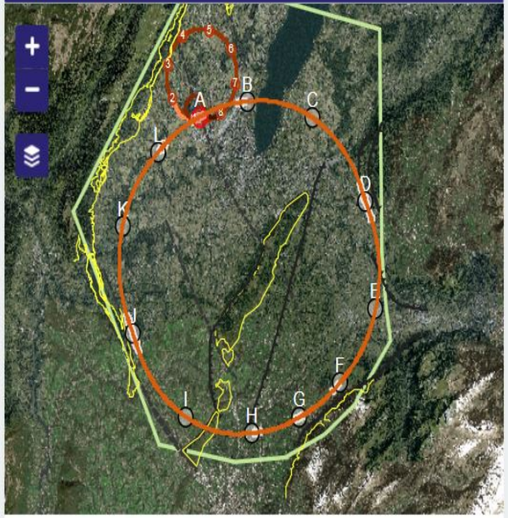
LOAD | SAVE | CALCULATE

Alignment centre

X: 2499941 Y: 1107760

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	37°	49m	-40°	83m
SPS		121m		126m
TI2		121m		126m
TI8		51m		118m

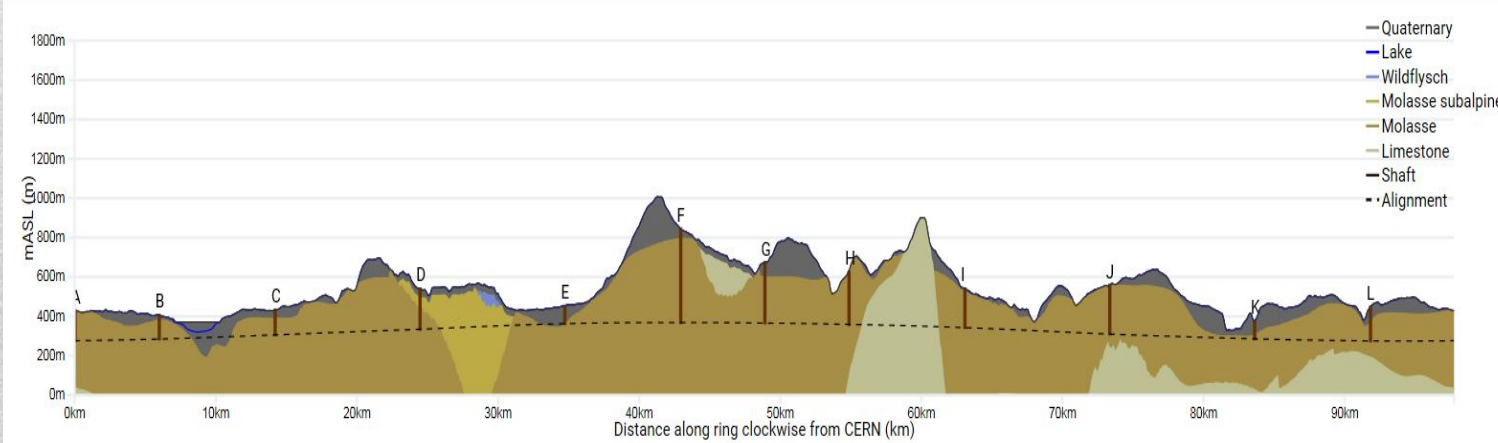
Alignment Location



Geology Intersected by Shafts | Shaft Depths

	Shaft Depth (m)			Geology (m)			
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Limestone
A	152	0	0	0	152	0	0
B	121	0	0	26	95	0	0
C	127	0	0	44	83	0	0
D	205	66	0	40	100	0	0
E	89	0	0	89	0	0	0
F	476	0	0	49	427	0	0
G	307	0	0	73	234	0	0
H	266	0	0	0	266	0	0
I	198	0	0	11	187	0	0
J	248	0	0	1	247	0	0
K	88	0	0	70	18	0	0
L	172	0	0	89	83	0	0
Total	2449	66	0	492	1892	0	0

Alignment Profile



Geology Intersected by Tunnel | Geology Intersected by Section

84.6% | 5.2% | 5.5% | 4.7%

Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc.

Tunneling

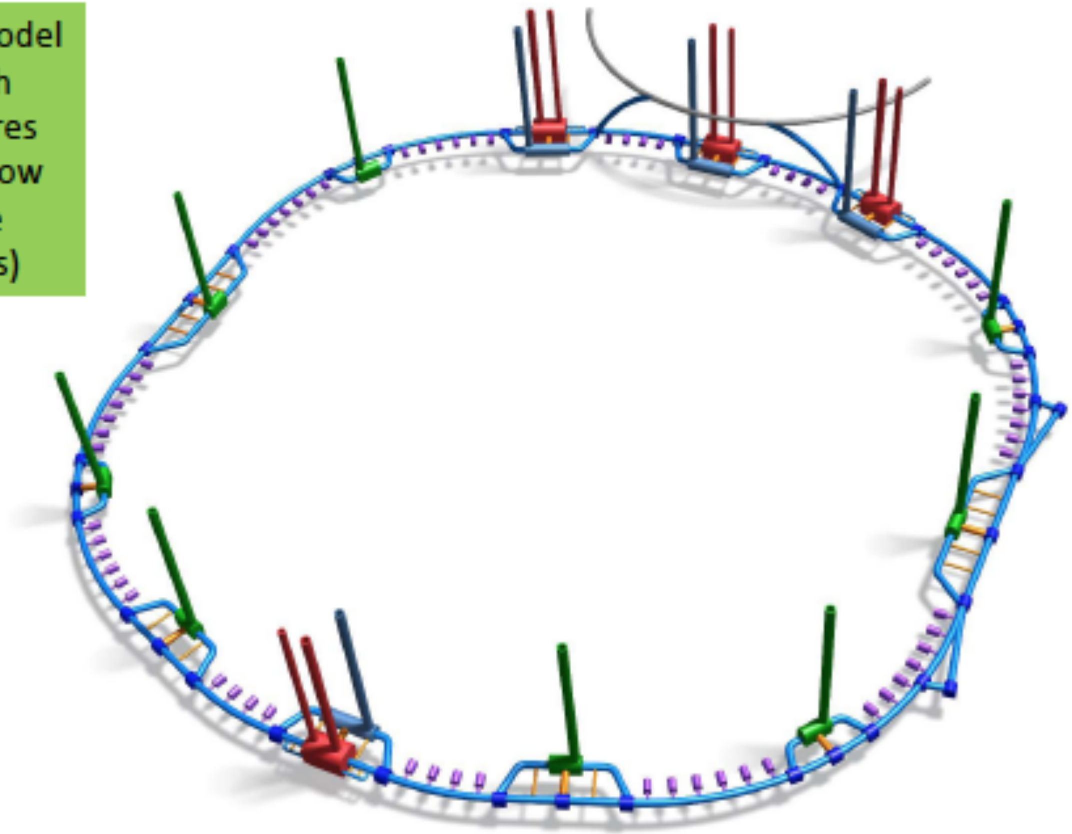
- Molasse 90%, Limestone 5%, Moraines 5%

Shallow implementation

- ~ 30 m below lakebed
- Reduction of shaft length and technical installations
- One very deep shaft **F** (RF or collimation), alternatives being studied, e.g. inclined access

Overall Schematic 3D view:

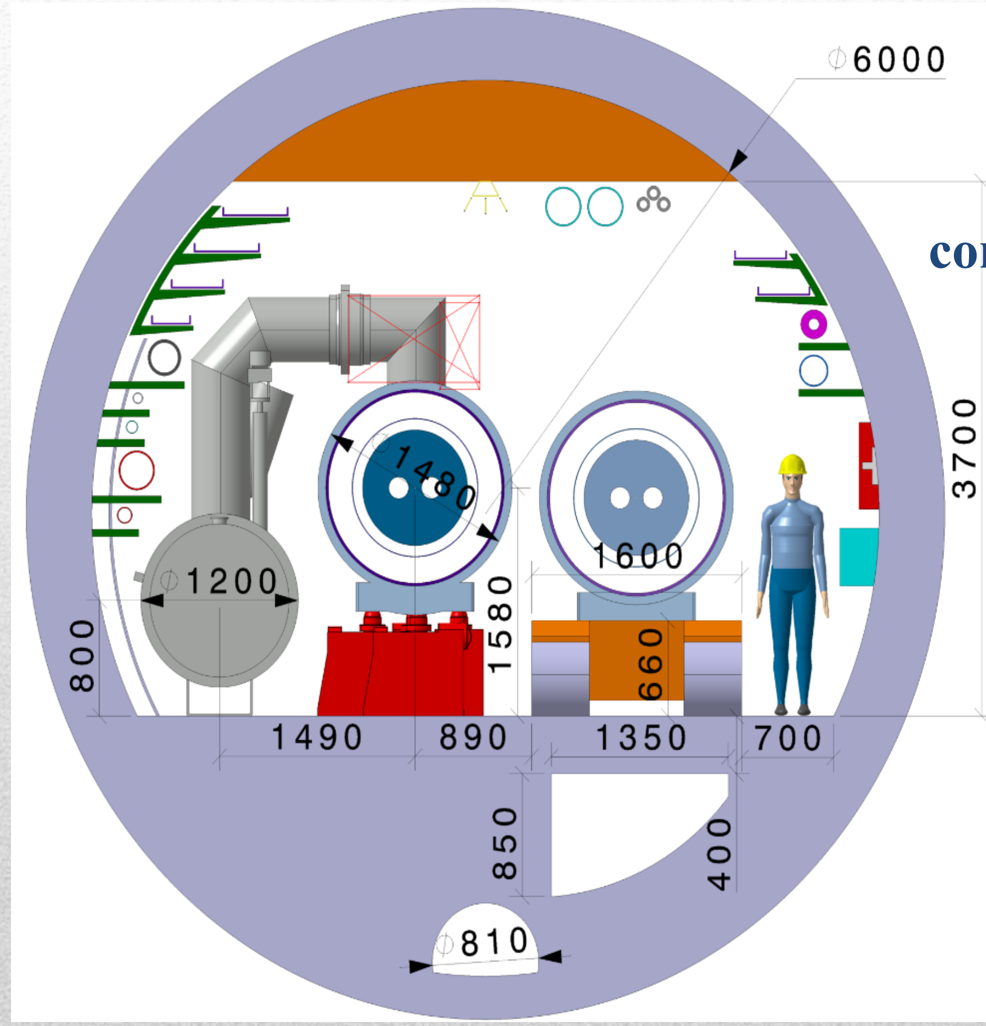
Single tunnel model updated with all main features known up to now (w/o FCC-ee enlargements)



Colour code:

- Machine tunnels + bypass galleries
- Detector caverns + shafts
- Service caverns + access shafts
- Electrical alcoves
- Connection tunnels

Civil engineering and Infrastructure

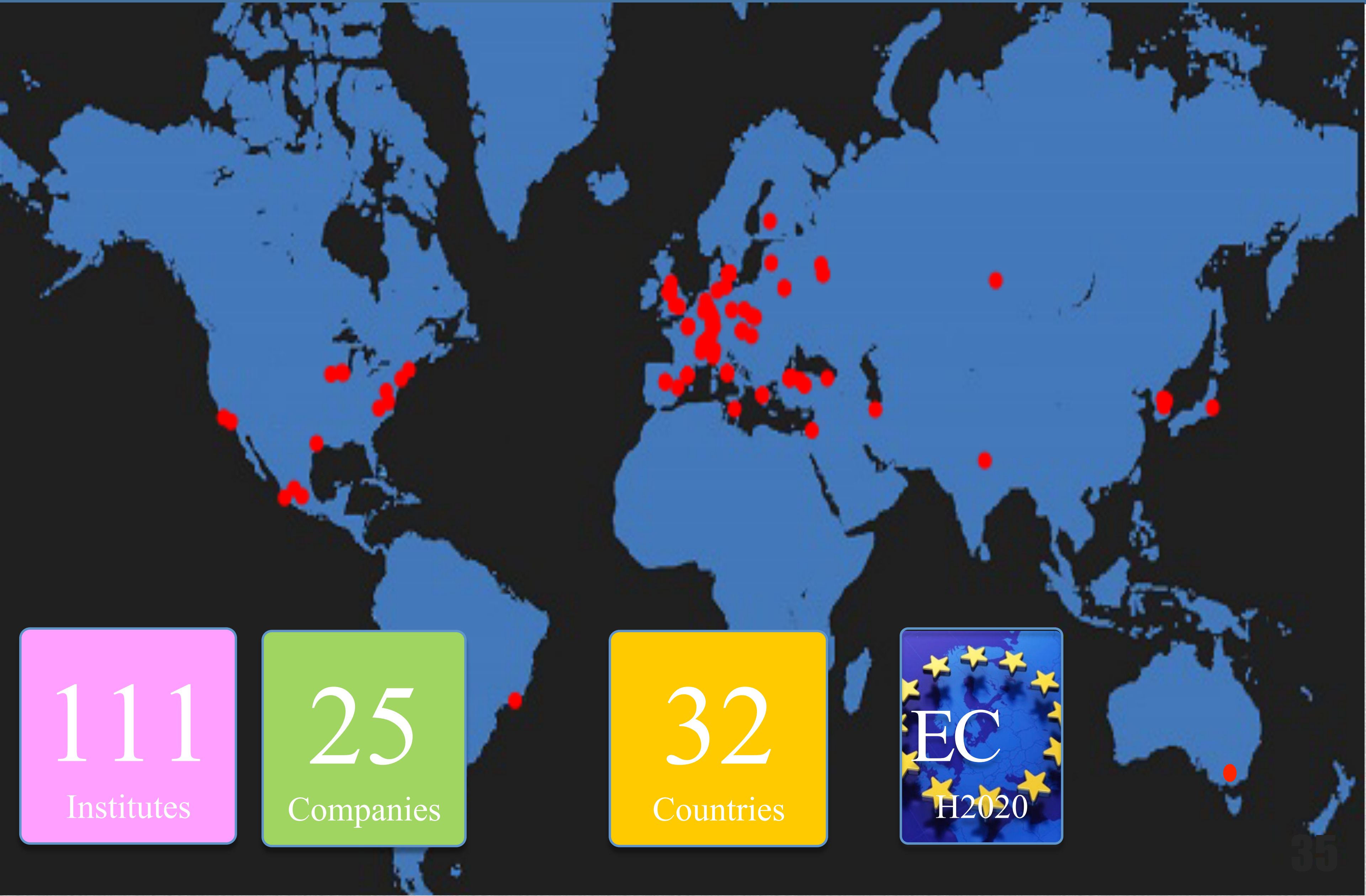


FCC-hh integration

Basic layout following LHC concept

- **6 m inner tunnel diameter**
- Main space allocation:
  - 1200 mm cryo distribution line (QRL)
  - 1480 mm installed cryomagnet
  - 1600 cryomagnet magnet transport
  - >700 mm free passage.

Collaboration & Industry Relations



111
Institutes

25
Companies

32
Countries

EC
H2020

FCC and other Future projects

Accelerators Present and Future perspectives

Local Accelerator Projects P2I

An uncompleted view ...

2017 2018 2020 2025

ALTO
PHIL
IPHI
SUPRATECH
ANDROMEDE
COXINEL-Xfive

ThomX
Compton-ring
APOLLON
mutipeta-watt laser

PRAE
HG-RF high-perf.

LUNEX5
FEL 5eme generation

C-PERLE
ERL Multipass
High-Intensity

In operation
In construction
Under study

International Large Scale Projects

2017 2019 2020 2025 2026 2028 2040

LHC
ATF2
Super B
XFEL
...

ESS
HP-SC linac

EU Strategy:
FCC/CLIC, ILC
LBNF...

HL-LHC
11T Nb_3Tn

FAIR

LBNF

ILC
1.3GHz SC
nano-beam/
stabilization

CepC

PLC

CLIC
12 GHz two-beam
nano-beam/
stabilization

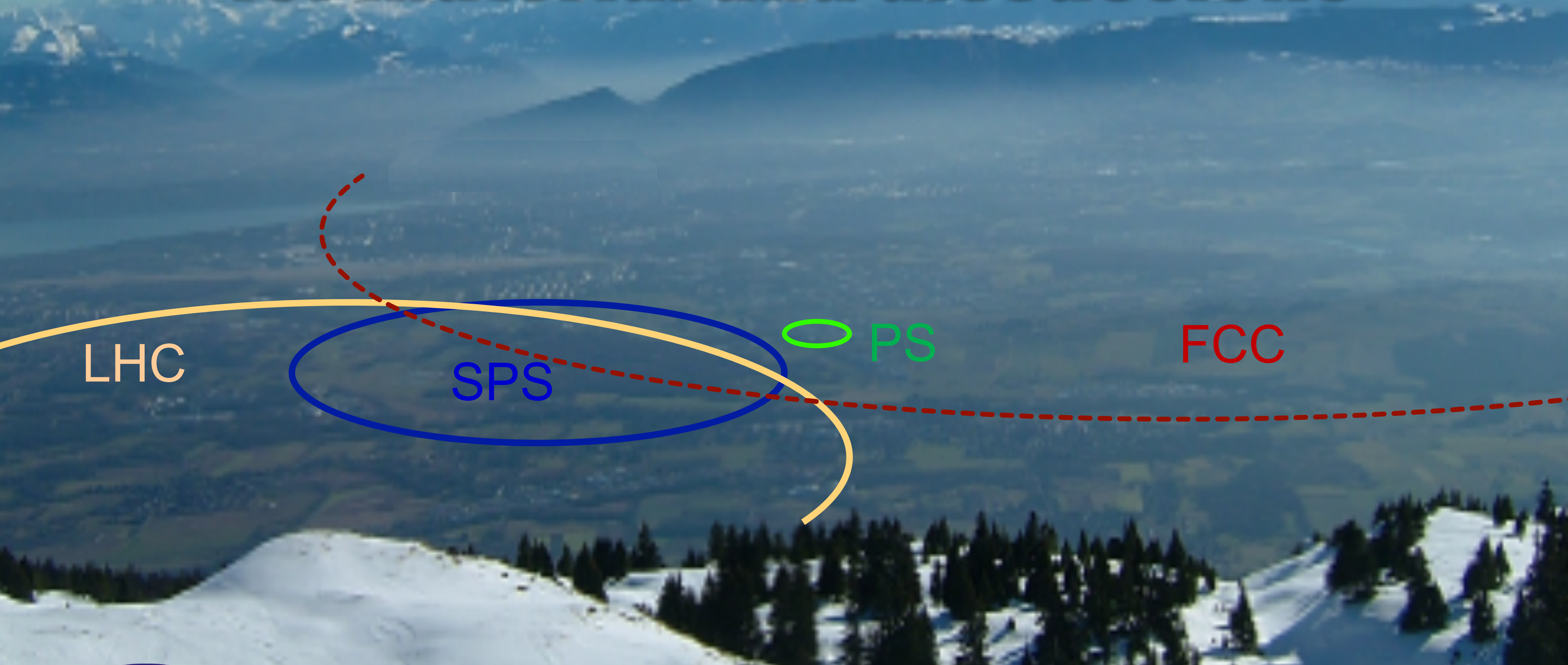
HE-LHC
16T Nb_3Tn/NbTn

FCC pp
16T Nb_3Tn/NbTn

FCC ee
High current Z-pole

CppC

Thank you to the all the collaborators for material and discussions



http://cern.ch/fcc

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Civil engineering and Infrastructure

Present working hypothesis for HE LHC esign:

No major CE modification on machine unnel and caverns

- Similar geometry and layout as LHC machine and experiments
- Due to 16 T dipole field and increased cryogenic load, magnet cryostat and cryo distribution line (QRL) larger than for LHC.
- Challenges for tunnel integration and QRL & 16 T cryostat design.
- **Maximum magnet cryostat external diameter compatible with LHC tunnel: 1200 -1250 mm**
- **Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**