FUTURE COLLIDERS PROJECTS

2^{ND} PART

BARBARA DALENA Paris-Saclay University and CEA Paris-Saclay

OUTLINE 2ND PART

- Futures Circular Colliders Projects
  - HL-LHC
  - FCC-ee/FCC-hh
  - Novel techniques

High Luminosity-LHC

$$L = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon}\cdot F$$

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing an integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established use of **engineering margins:**

$L_{peak\ ult}$ ≅ 7.5 10^{34} cm^{-2}s^{-1} and

Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}

LHC should not be the limit, would Physics programs require more…

Parameter	Nominal LHC	HL-LHC (standard)	HL-LHC (BCMS)	HL-LHC (8b+4e)
Beam energy in collision [TeV]	7	7	7	7
Particles per bunch, N [10^{11}]	1.15	2.2	2.2	2.2
Number of bunches per beam	2808	2760	2748	1968
Number of collisions in IP1 and IP5*	2808	2748	2736	1960
Half-crossing angle in IP1 and IP5 [μrad]	142.5	250	250	250
Minimum β^* [m]	0.55	0.15	0.15	0.15
e_n [μm]	3.75	2.50	2.50	2.50
Total reduction factor R_0 without crab cavities at min. β^*	0.836	0.342	0.342	0.342
Total reduction factor R_1 with crab cavities at min. β^*	-	0.716	0.716	0.716
Beam–beam tune shift/IP [10^{-3}]	3.1	8.6	8.6	8.6
Peak luminosity without crab cavities L_{peak} [10^{34} cm^{-2} s^{-1}]	1.00	8.11	8.07	5.78
Peak luminosity with crab cavities $L_{peak}\times R_1/R_0$ [10^{34} cm^{-2} s^{-1}]	-	17.0	16.9	12.1
Levelled luminosity [10^{34} cm^{-2} s^{-1}]	-	5.0	5.0	3.6
Events/crossing m (with levelling and crab cavities)	27	131	132	131

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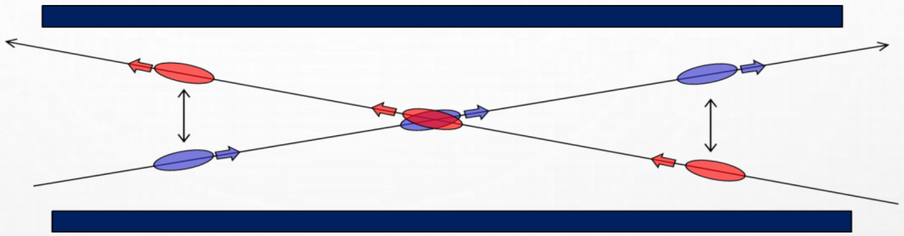
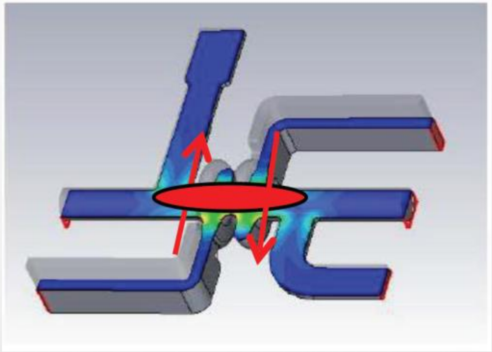
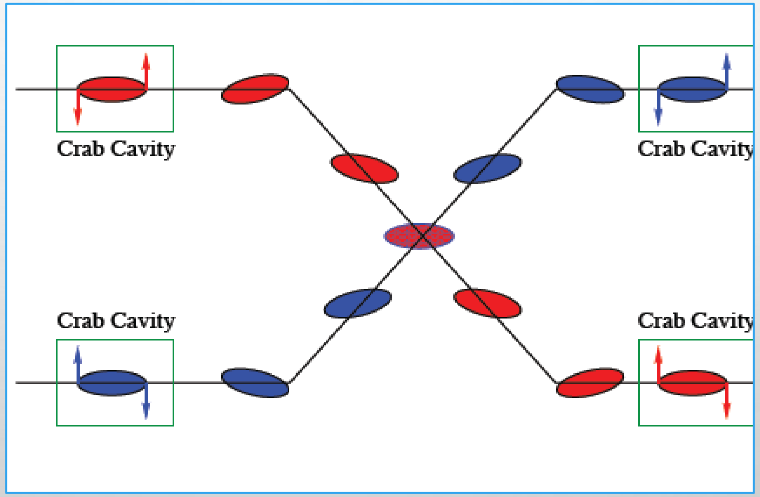
COMPENSATION OF GEOMETRIC REDUCTION FACTOR

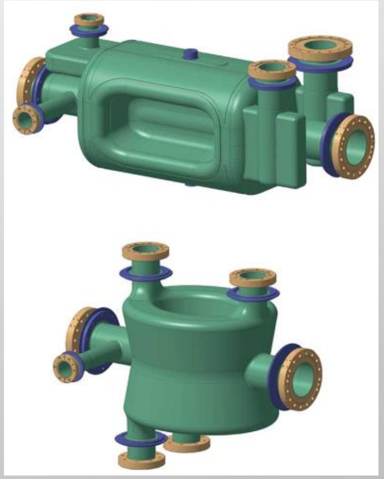
$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} \cdot \boxed{F} \qquad \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$





- Crossing angle at HL-LHC must be larger than at LHC, due to higher intensity and higher beam divergence
  - Would cause very large loss in luminosity: F≈0.35
- To compensate: use “crab cavities” that tilt the bunches longitudinally and ensure overlap at the collision point
- Prototypes tests in the SPS!

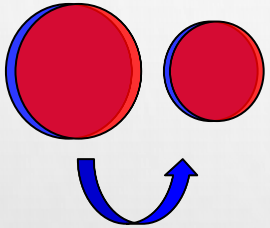




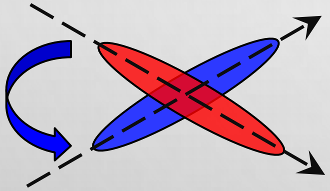
Schematic view of RFD (top) and DQW (bottom) crab cavity. Image credit: R Leuxe/CERN

LEVELLING MECHANISMS

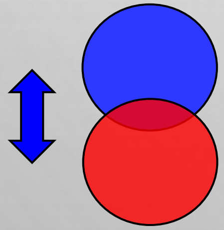
- Levelling techniques will be a vital ingredient for HL-LHC operation and have been used successfully in operation:



β*: Main levelling mechanism during the fill. Operational in 2018

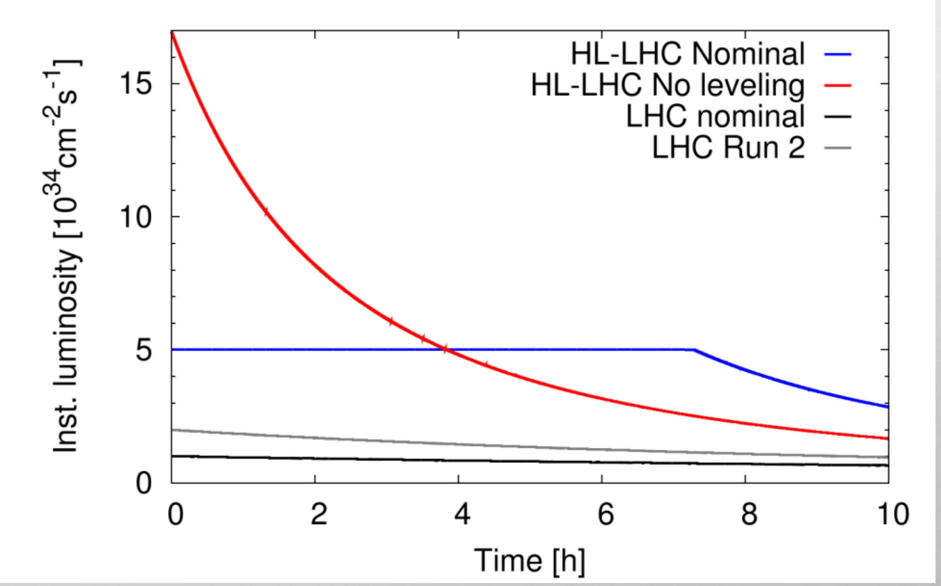


Crossing angle: Might be needed to optimize beam lifetime and as mean to reduce pile-up density given the reduced crabbing angle. Operational in 2017



Separation: Will be used in ALICE and LHCb and for fine adjustments (separations < 1 σ) in ATLAS and CMS ➔ Operational since Run 1

Reducing heat load on the IT triplet (quench and cooling limits)
Limiting pile up in the detectors



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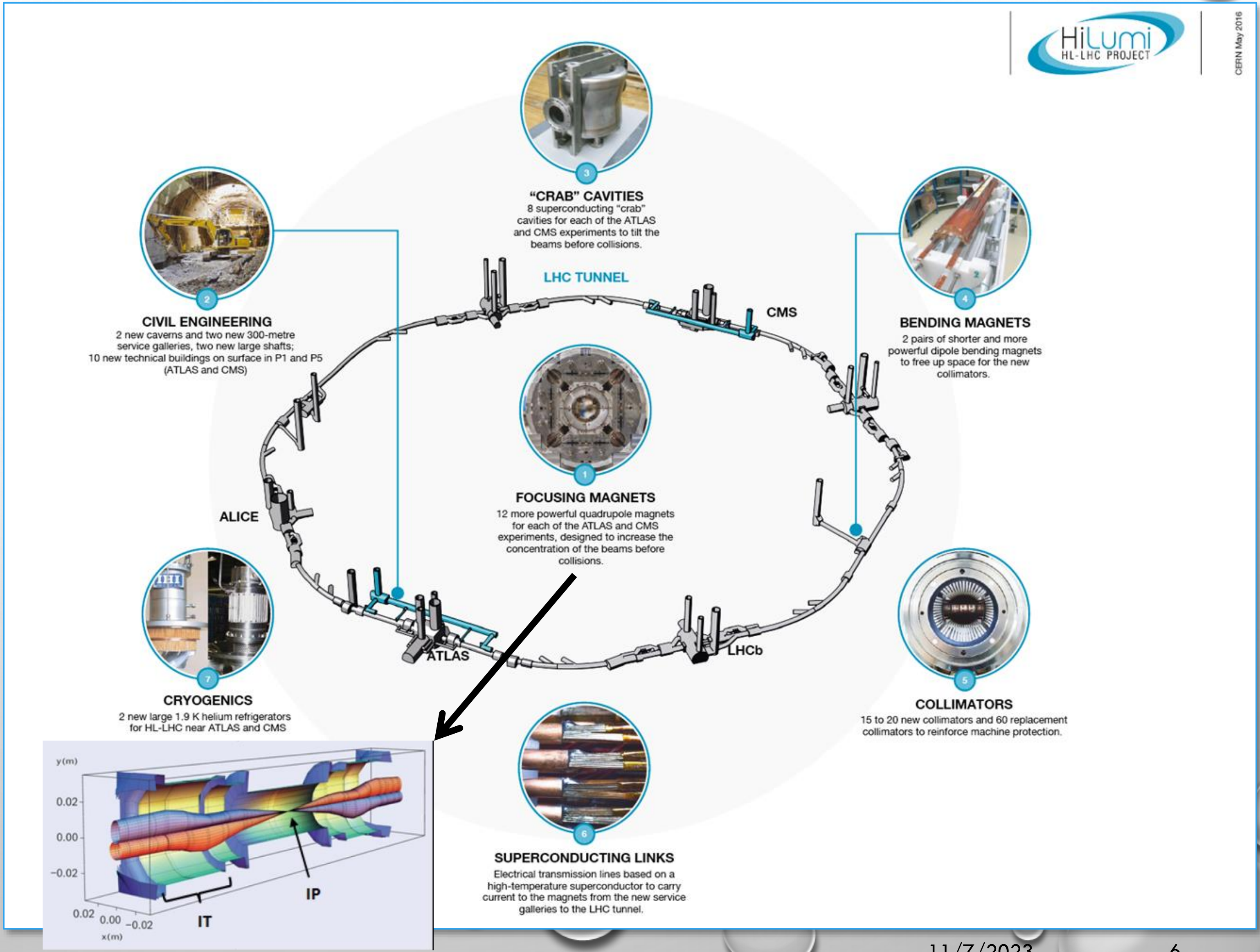
~1.2 KM OF NEW HARDWARE IN LHC

- New final focus quadrupoles around ATLAS and CMS:

  Ni_3Sn technology (See S. I. Bermudez's lecture) for more aperture

  Radiation damage
- Matching section: separation dipoles, first double aperture magnet and correctors (See S. I. Bermudez's Lecture)
- Crab Cavities
- Cryogenics plants
- SC links and rad. Mitigation
- 11 T Nb3Sn dipole for collimation



"CRAB" CAVITIES
8 superconducting "crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

CIVIL ENGINEERING
2 new caverns and two new 300-metre service galleries, two new large shafts; 10 new technical buildings on surface in P1 and P5 (ATLAS and CMS)

BENDING MAGNETS
2 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

CRYOGENICS
2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.

FUTURE CIRCULAR COLLIDERS

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

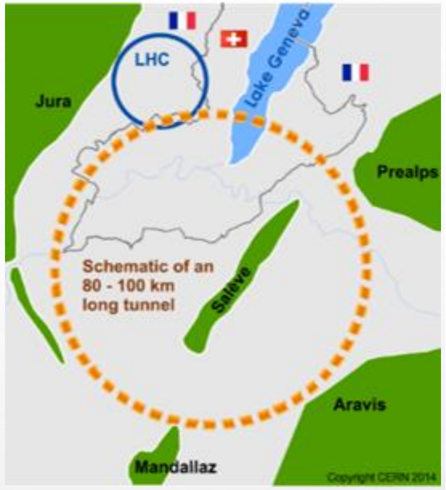
- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements
- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC*-ee),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from ERL

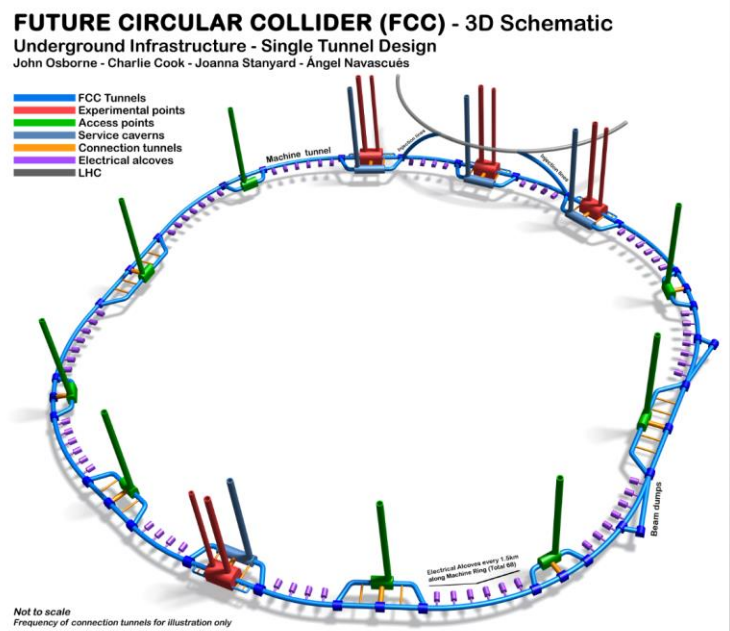
CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

Summary documents provided to EPPSU SG

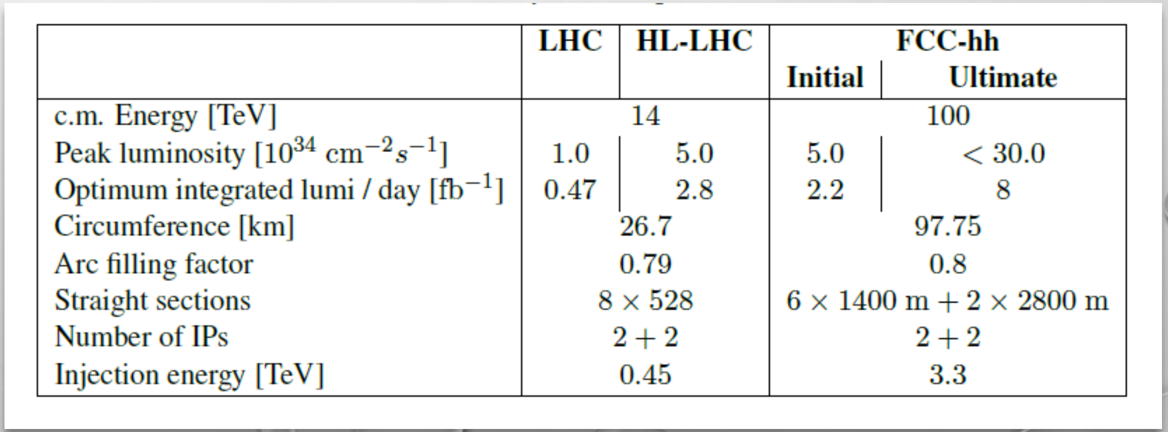
- **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
- Accessible on http://fcc-cdr.web.cern.ch/

Cost: ~28.6 BCHF




FUTURE CIRCULAR COLLIDER (FCC) - 3D Schematic
Underground Infrastructure - Single Tunnel Design
John Osborne - Charlie Cook - Joanna Stanyard - Ángel Navascués

Not to scale
Frequency of connection tunnels for illustration only

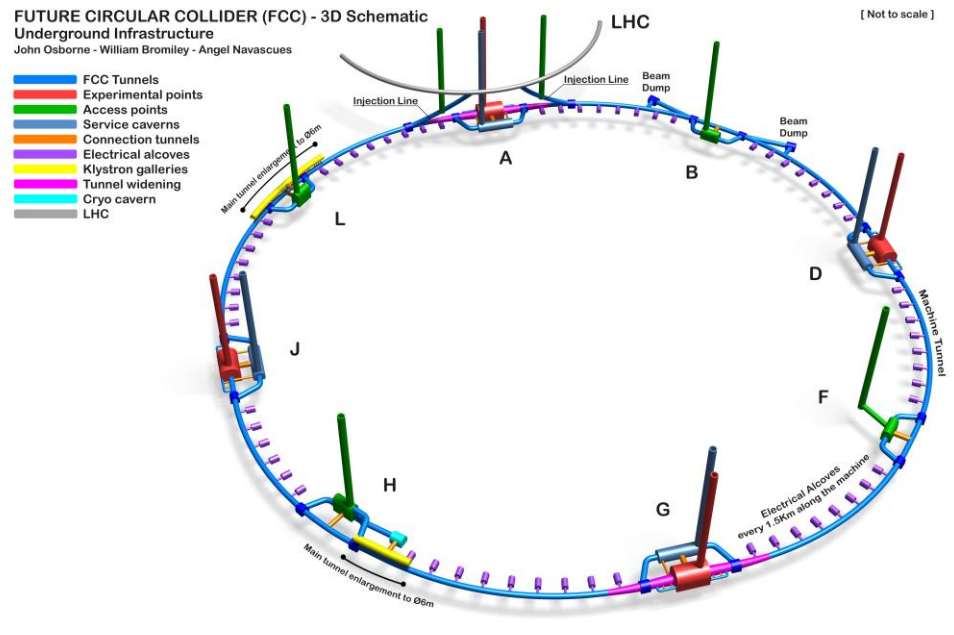


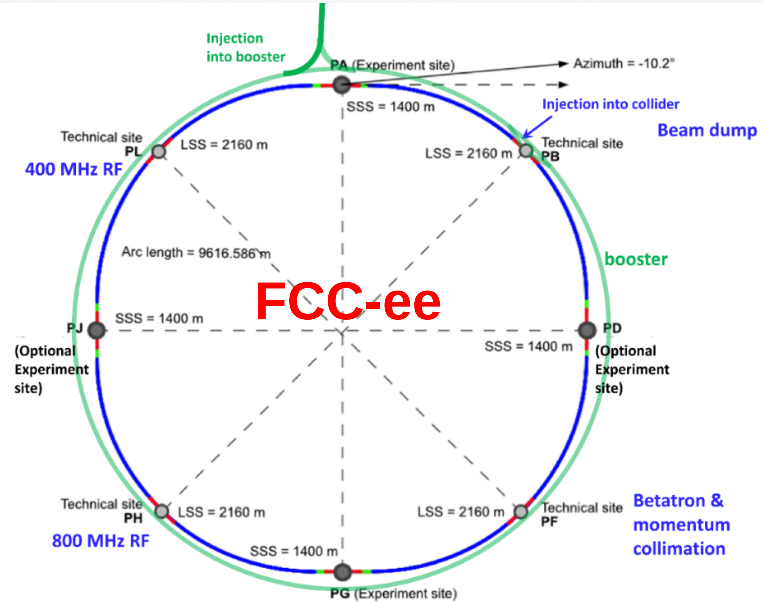
	LHC	HL-LHC	FCC-hh Initial	FCC-hh Ultimate
c.m. Energy [TeV]	14		100	
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	< 30.0
Optimum integrated lumi / day [fb^{-1}]	0.47	2.8	2.2	8
Circumference [km]	26.7		97.75	
Arc filling factor	0.79		0.8	
Straight sections	8×528		6×1400 m + 2×2800 m	
Number of IPs	2 + 2		2 + 2	
Injection energy [TeV]	0.45		3.3	

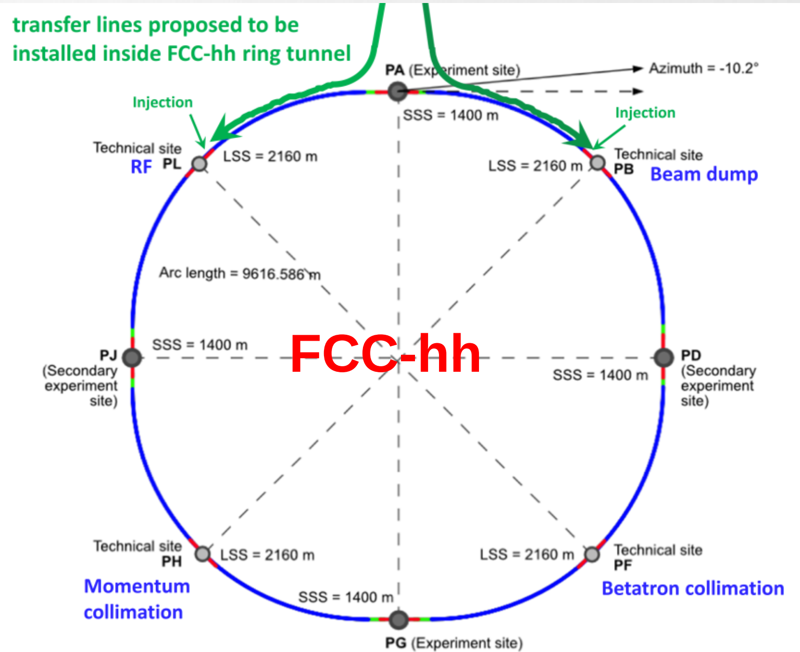
PREPARING FOR NEXT STRATEGY

Comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, reusing CERN's existing infrastructure
- FCC integrated program allows continuation of HEP after completion of the HL-LHC program







M. Giovannozzi ICHEP 2022

FEASIBILITY STUDY GOALS AND ROADMAP

Highest priority goals:

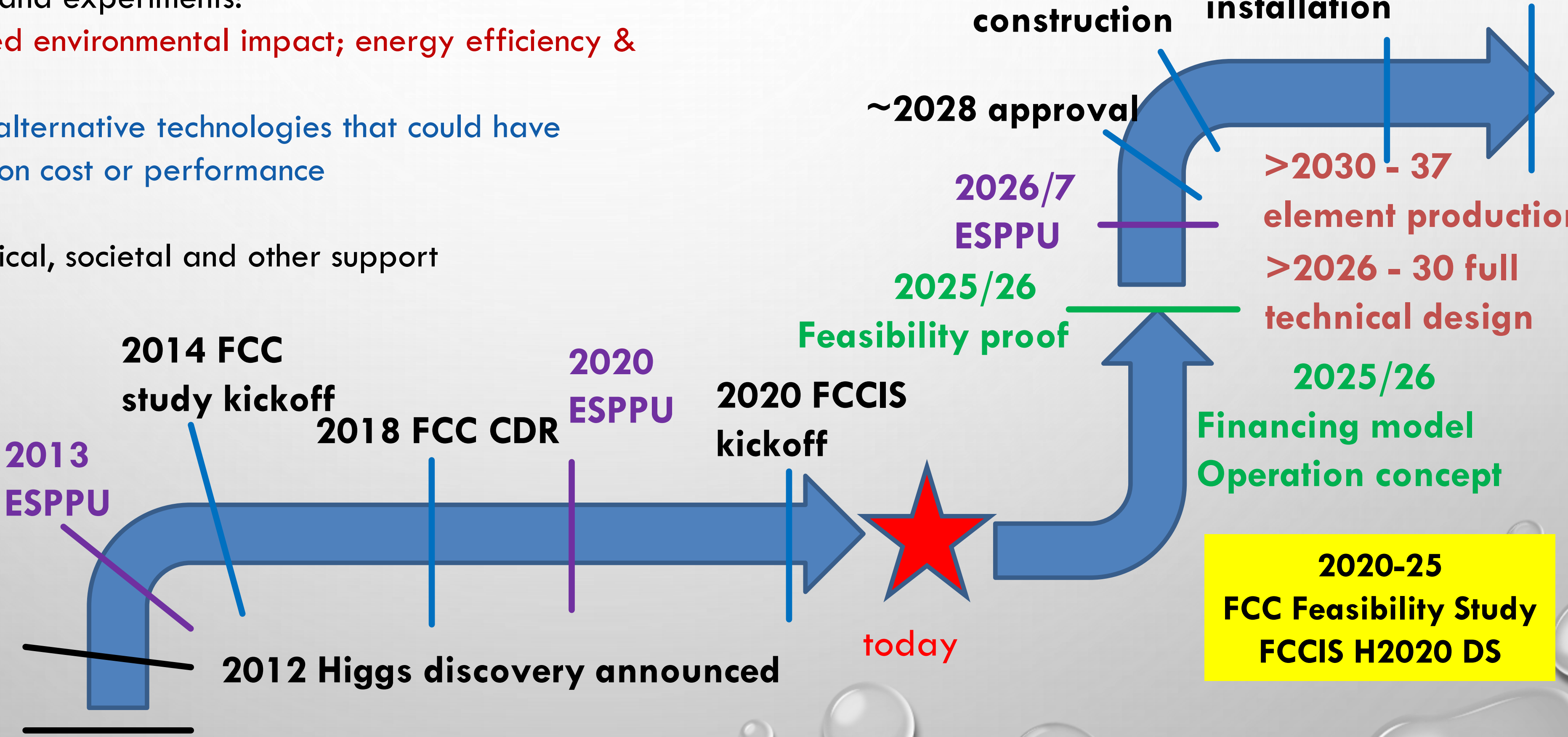
Financial feasibility

Technical and administrative feasibility of tunnel: no show-stopper for ~100 km tunnel

Technologies of machine and experiments:

- magnets; minimized environmental impact; energy efficiency & recovery
- Establish a list of alternative technologies that could have significant impact on cost or performance

Gathering scientific, political, societal and other support



2012 Higgs discovery announced

2013
ESPPU

2014 FCC
study kickoff

2018 FCC CDR

2020
ESPPU

2020 FCCIS
kickoff

today

2025/26
Feasibility proof

2025/26
Financing model
Operation concept

2026/7
ESPPU

~2028 approval

>2026 - 30 full
technical design

>2030 - 37
element production

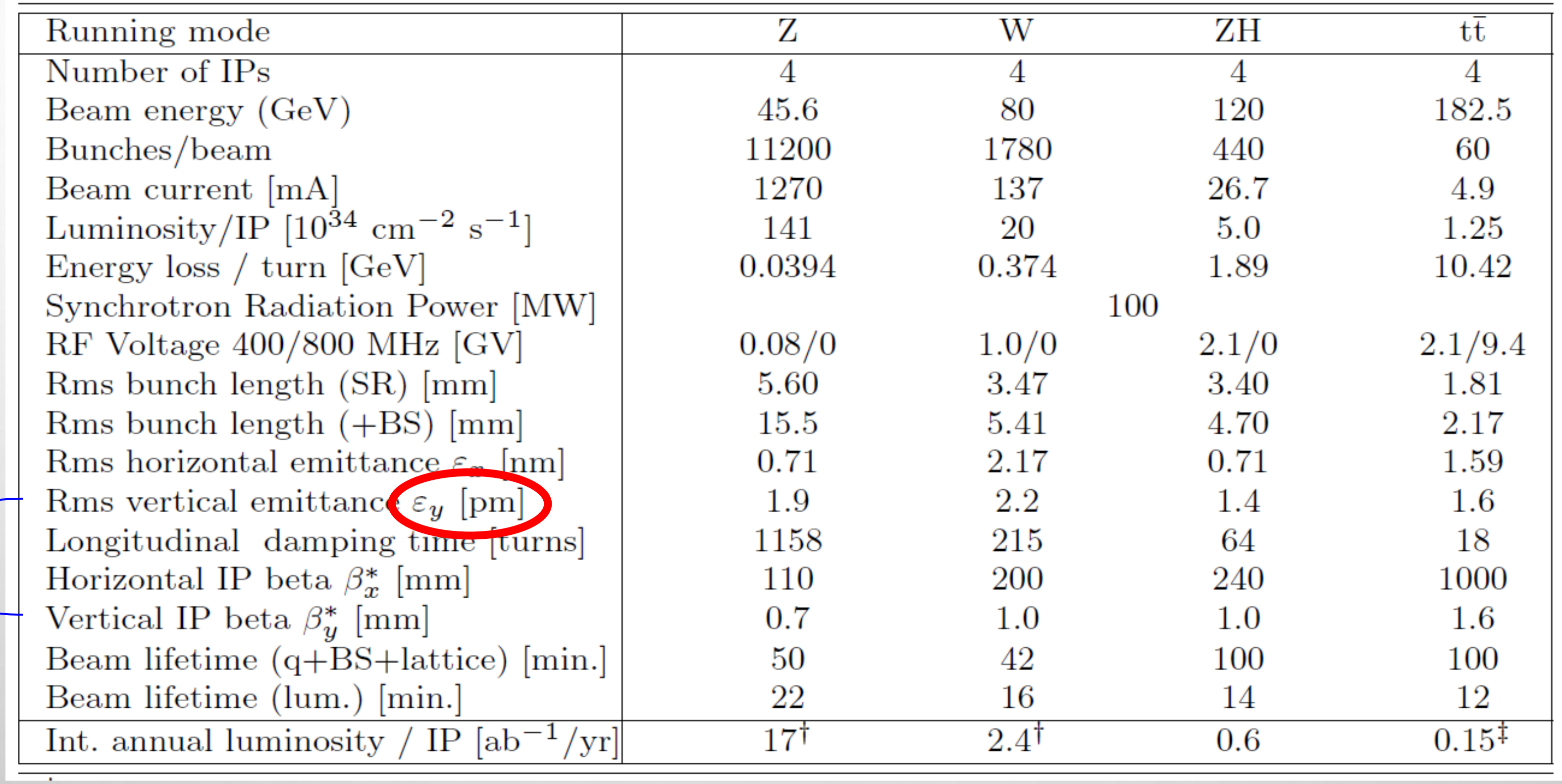
>2030
start tunnel
construction

>2038
machine
installation

>2045 first
ee collisions

2020-25
FCC Feasibility Study
FCCIS H2020 DS

FCC-ee PARAMETERS

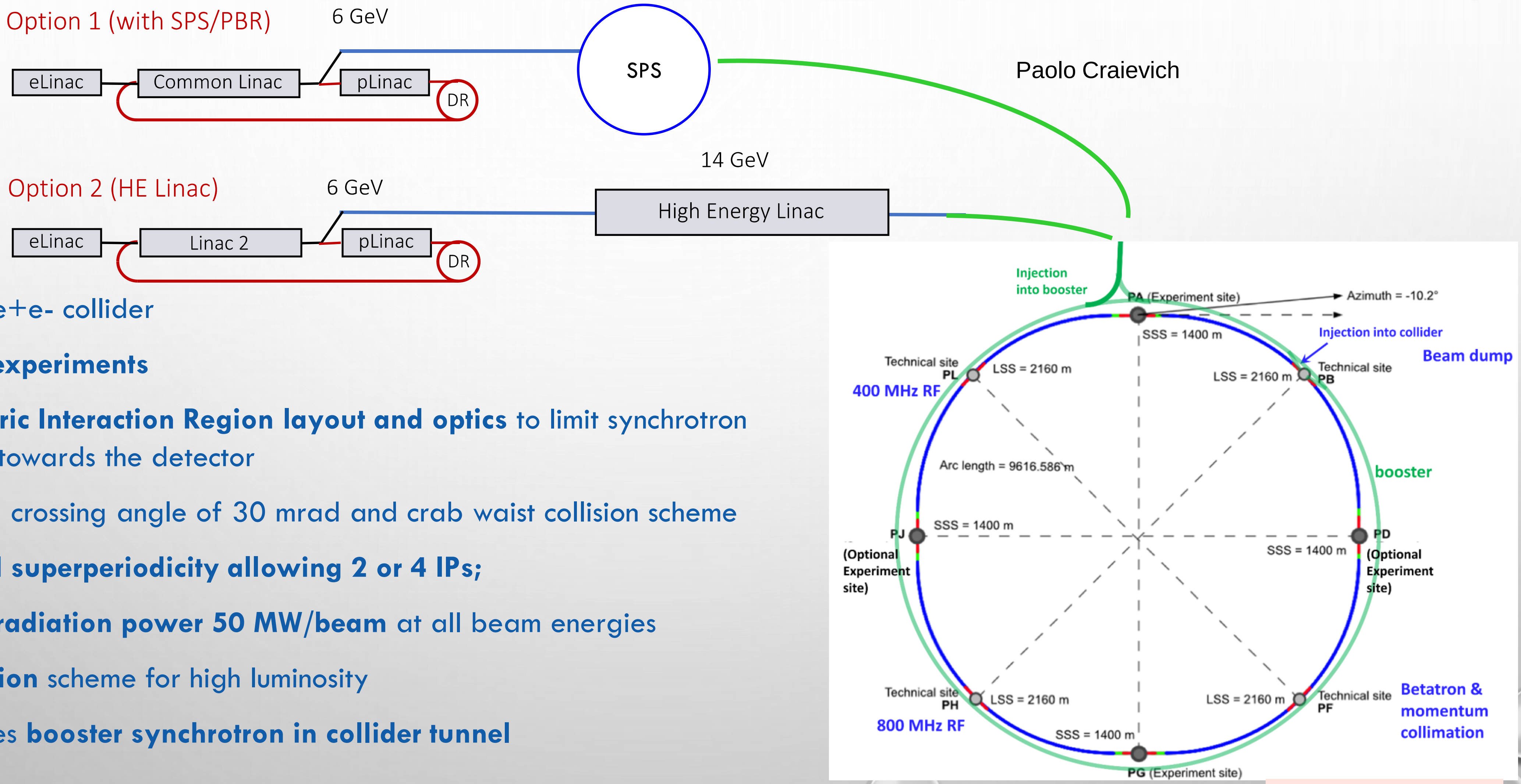


Running mode	Z	W	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1270	137	26.7	4.9
Luminosity/IP $[10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}]$	141	20	5.0	1.25
Energy loss / turn [GeV]	0.0394	0.374	1.89	10.42
Synchrotron Radiation Power [MW]	100			
RF Voltage 400/800 MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	3.47	3.40	1.81
Rms bunch length (+BS) [mm]	15.5	5.41	4.70	2.17
Rms horizontal emittance ε_x [nm]	0.71	2.17	0.71	1.59
Rms vertical emittance ε_y [pm]	1.9	2.2	1.4	1.6
Longitudinal damping time [turns]	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	200	240	1000
Vertical IP beta β_y^* [mm]	0.7	1.0	1.0	1.6
Beam lifetime (q+BS+lattice) [min.]	50	42	100	100
Beam lifetime (lum.) [min.]	22	16	14	12
Int. annual luminosity / IP $[\text{ab}^{-1}/\text{yr}]$	$17^{\dagger}$	$2.4^{\dagger}$	0.6	$0.15^{\ddagger}$

σ_y ~[36-51] nm

⇒ **High efficient RF system, small emittance and short lifetime beam**

BASIC DESIGN CHOICES



Paolo Craievich

Double ring e+e- collider

Two or four experiments

- **Asymmetric Interaction Region layout and optics** to limit synchrotron radiation towards the detector
- Horizontal crossing angle of 30 mrad and crab waist collision scheme

Perfect 4-fold superperiodicity allowing 2 or 4 IPs;

Synchrotron radiation power 50 MW/beam at all beam energies

Top-up injection scheme for high luminosity

Implies **booster synchrotron in collider tunnel**

M. Hofer ICHEP 2022

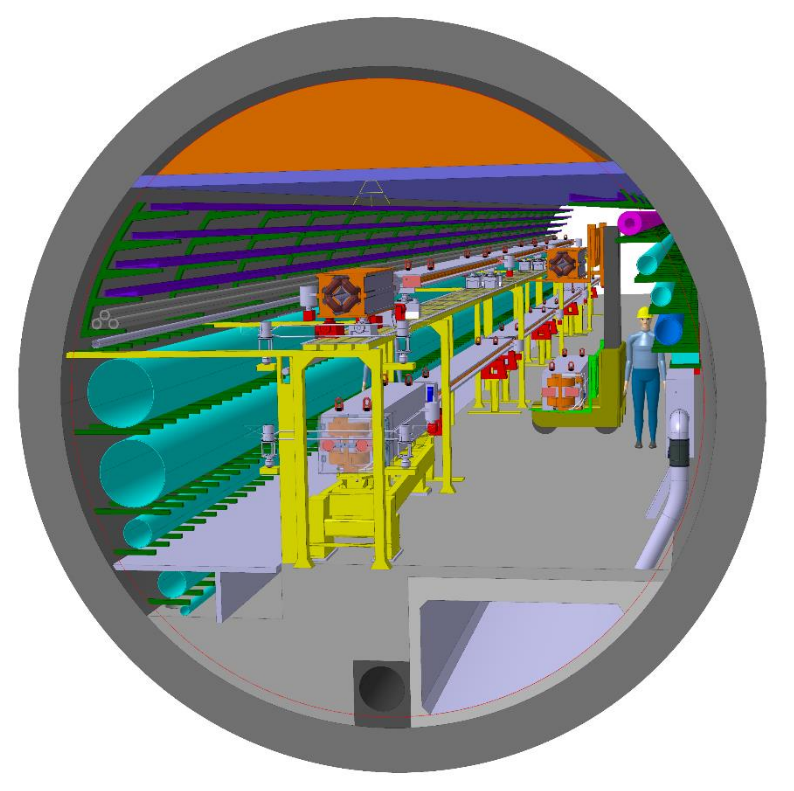
K. Oide, J. Gutleber

FCC-ee KEY TECHNOLOGIES: ARCS

Aim of the project

- **Arc half-cell**: most recurrent assembly of mechanical hardware in the accelerator (~1500 similar FODO cells in the FCC-ee)
- **Mock-up** → Functional prototype(s) → Pre-series → Series
- Building a mock-up allows optimizing and testing **fabrication, integration, installation, assembly, transport, maintenance**
- Working with demonstrators of the different equipment, and/or structures with equivalent volumes, weights, stiffness

F. Carra et al



Arc perspective view, F. Valchkova-Georgieva

OPTICS CORRECTIONS STRATEGY (FCC-EE BOOSTER)

Motivation

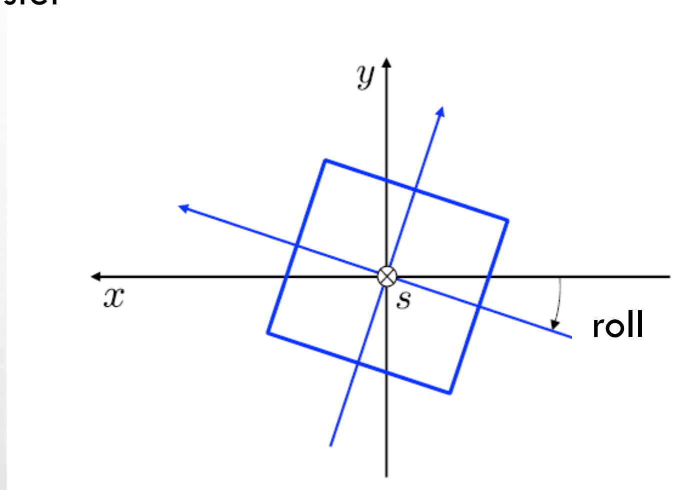
- Evaluate specifications of the main **magnets misalignment** of the High Energy Booster arcs cells **and of magnets field error**
- Definition of the **orbit correction strategy and of correctors specifications** for the booster

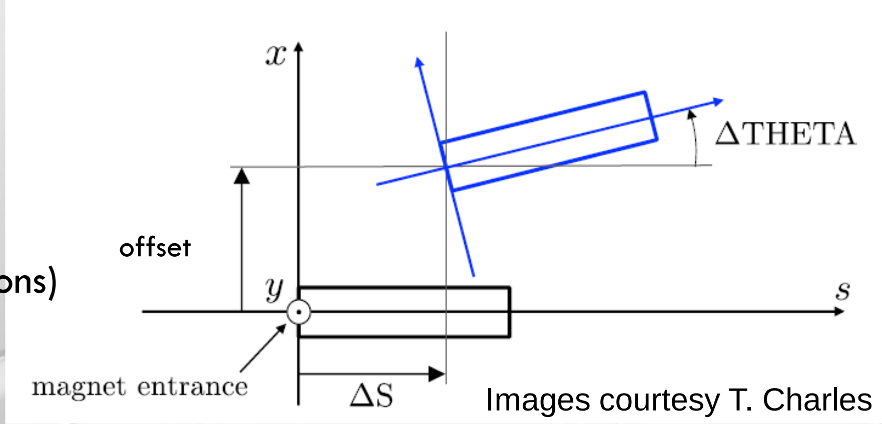
Orbit correction using beam position monitors reading

errors	Case	Plane	3 x Analytical RMS	3 x Mean RMS/seeds
MQ offset = 150 µm MB field err = 10^{-3} MB roll = 300 µrad BPM offset = 150 µm MS offset = 150 µm BPM resolution = 50 µm	Residual orbit [µm]	x	188	174
		y	192	188
	Correctors stengths [mTm]	x	16	17
		y	16	17

Improvements and related work to do:

- Other methods than SVD - AI ?
- Demonstrate full emittance **tuning**
- Study the impact of booster support vibrations on emittance (dynamic imperfections)
- Study the impact of energy ramp during the booster cycle





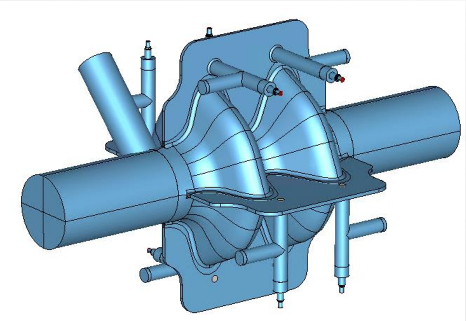
Images courtesy T. Charles

FCC-ee KEY TECHNOLOGIES: SRF-CAVITIES

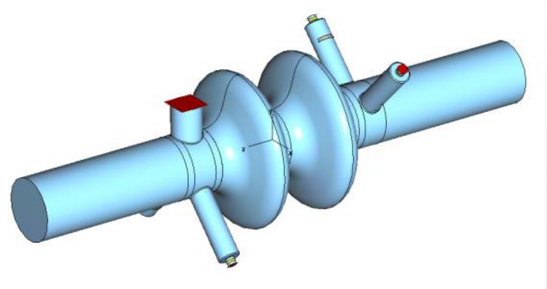
We need to replenish energy loss by synchrotron radiation:
Superconductive RF most efficient way

see W. Venturini Lectures on RF superconductivity

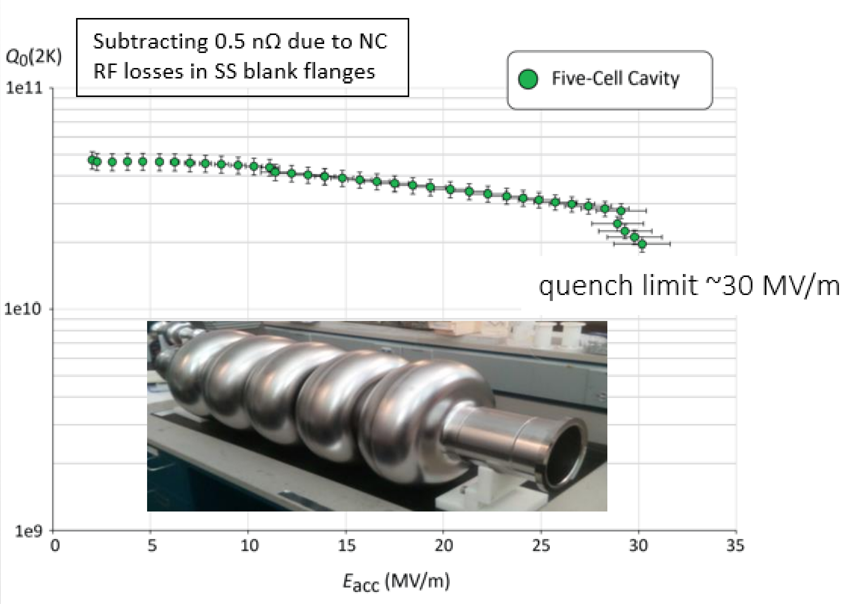
- **SRF technology building on LHC studies and collaborative R&D** (F. Peauger et al.)
  - 5-cell 800 MHz cavity without damping built and tested at 2K by Jefferson lab with excellent results
  - 400 MHz cavities based on LHC studies of Cu-coated Nb cavities at 4.5K
  - Alternative slotted waveguide elliptical cavity with f=600 MHz



SWELL 2-cell 600 MHz cavity for Z, W, H



Model for 2-cell 400 MHz for WW and ZH

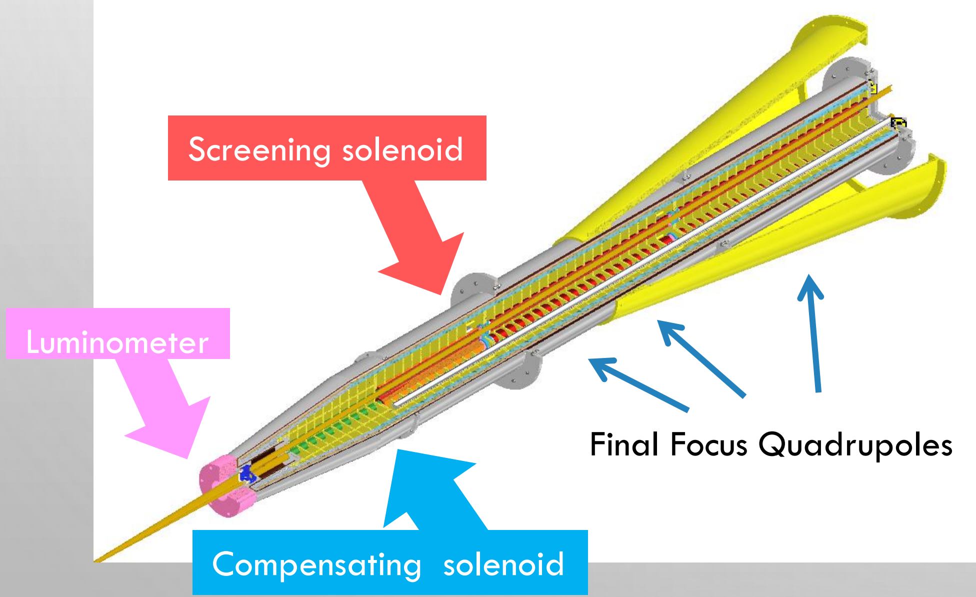


quench limit ~30 MV/m

- **RF placement optimized for infrastructure requirements** (F. Valchkova-Georgieva et al)

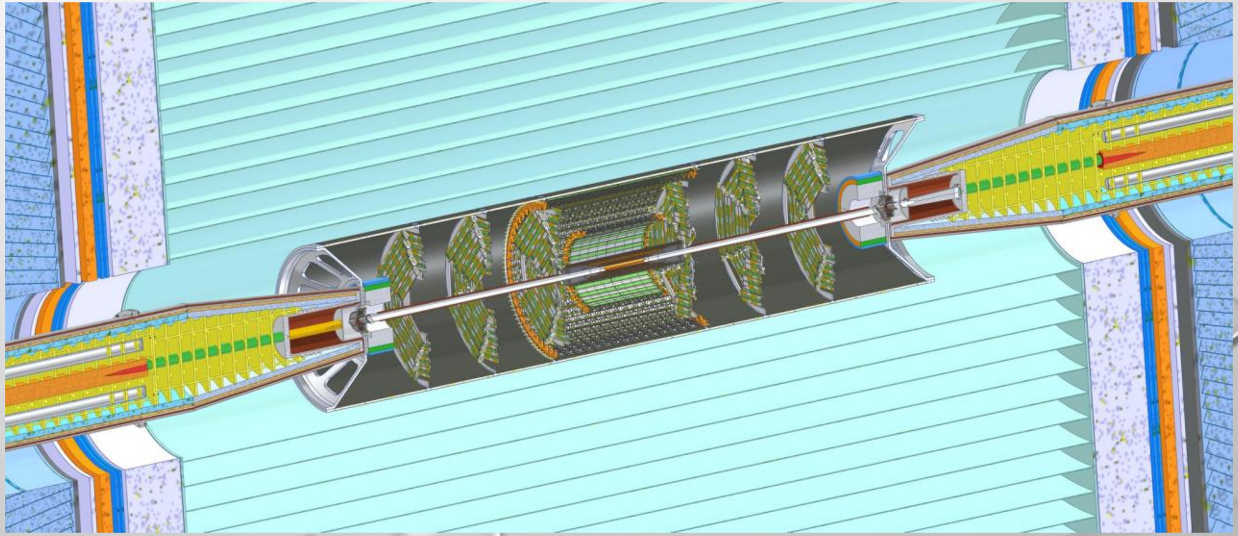
FCC-ee KEY TECHNOLOGIES: INTERACTION REGION

- **Canted-Cosine-Theta magnets**
  - Elegant 2-layer design for inner quadrupoles
  - Working to fit within 100 mrad stay-clear cone
  - Prototype built and warm-tested
  - Complex integration of SC quadrupoles, LumiCal, shielding, diagnostics…
  - Mock-up under discussion

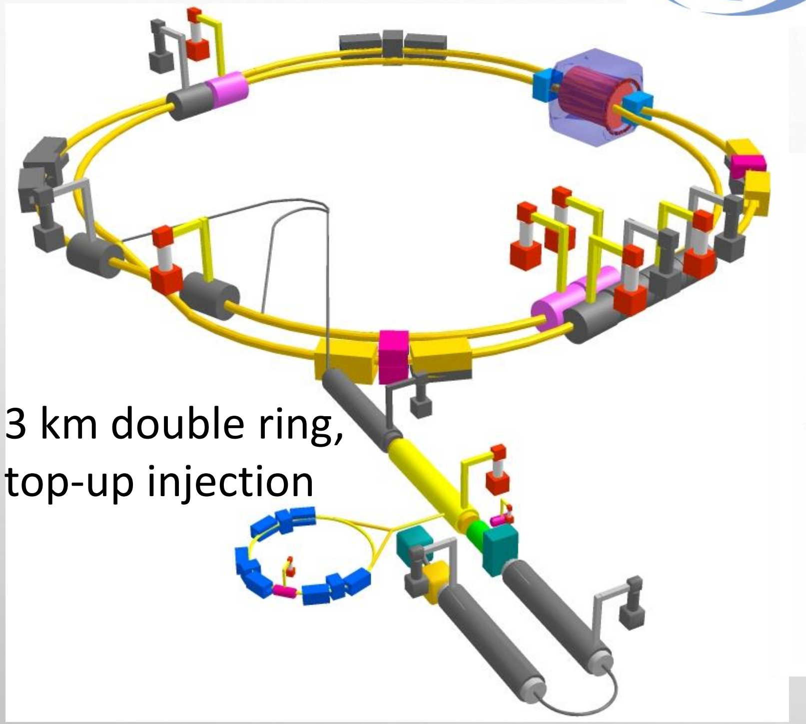


- **FCC-ee interaction region**
  - **L*** is **2.2 m.**
  - The 10 mm central radius is for ± 9 cm from the IP.
  - The two symmetric beam pipes with radius of 15 mm are merged at 1.2 m from the IP
  - Low impedance vacuum chamber
  - Synchrotron Radiation Background and photon dumps

Integration within the detector

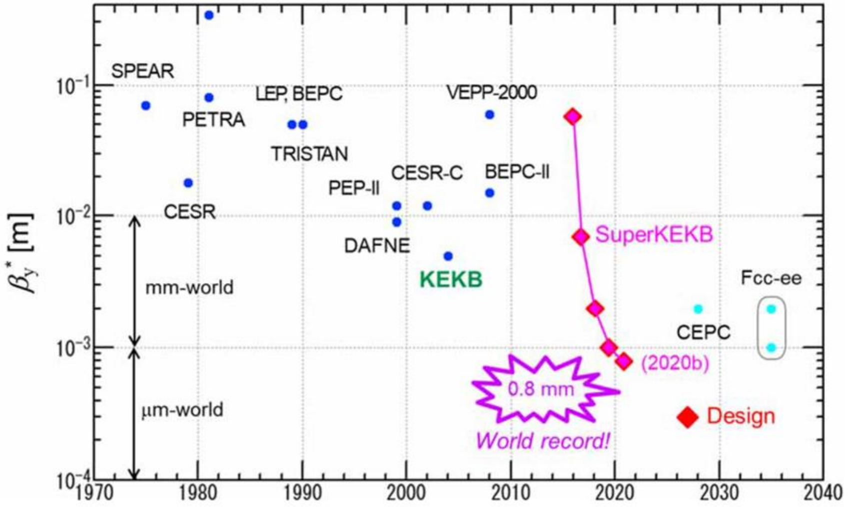


SUPERKEKB AS FCC-EE TEST FACILITY

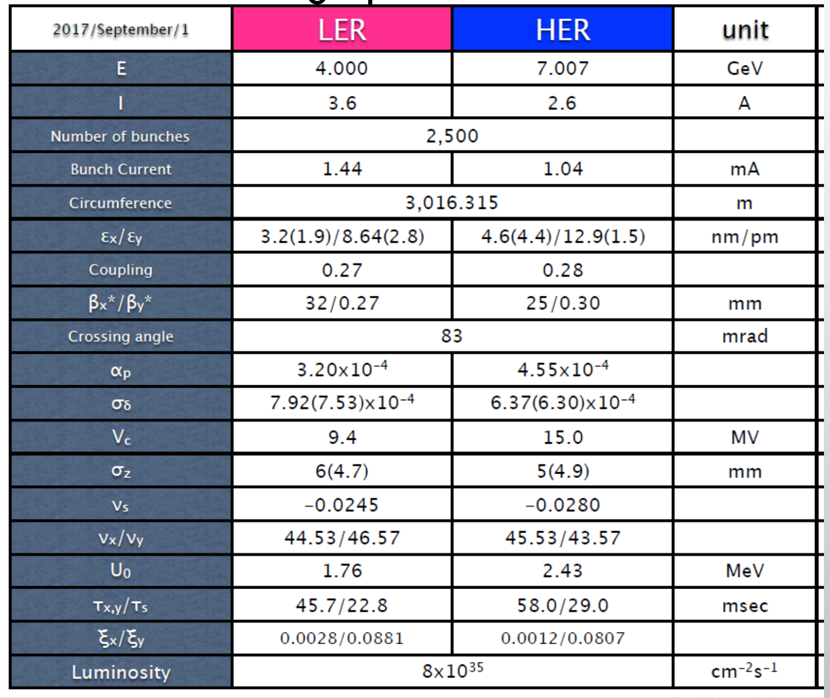


3 km double ring,
top-up injection

world's highest luminosity
4.7×10^{34} cm^{-2}s^{-1} & lowest β^*



Design parameters



2017/September/1	LER	HER	unit
E	4.000	7.007	GeV
I	3.6	2.6	A
Number of bunches	2,500		
Bunch Current	1.44	1.04	mA
Circumference	3,016.315		m
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm
Coupling	0.27	0.28	
β_x^*/β_y^*	32/0.27	25/0.30	mm
Crossing angle	83		mrad
α_p	3.20×10^{-4}	4.55×10^{-4}	
σ_δ	$7.92(7.53) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$	
V_c	9.4	15.0	MV
σ_z	6(4.7)	5(4.9)	mm
ν_s	-0.0245	-0.0280	
ν_x/ν_y	44.53/46.57	45.53/43.57	
U_0	1.76	2.43	MeV
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807	
Luminosity	8×10^{35}		cm^{-2}s^{-1}

- β_y^* = 0.8 mm demonstrated
- Collision with large crossing angle compensated by sextupoles schemes (as in DAFNE and as foreseen in FCC-ee)
- Design luminosity not reached so far due to intensity limitation (fast beam losses) in Super KEKB

FCC-hh parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	96		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	91		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity $[10^{11}]$	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [mm]	2.2		2.5	3.75
peak luminosity $[10^{34}\ cm^{-2}s^{-1}]$	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

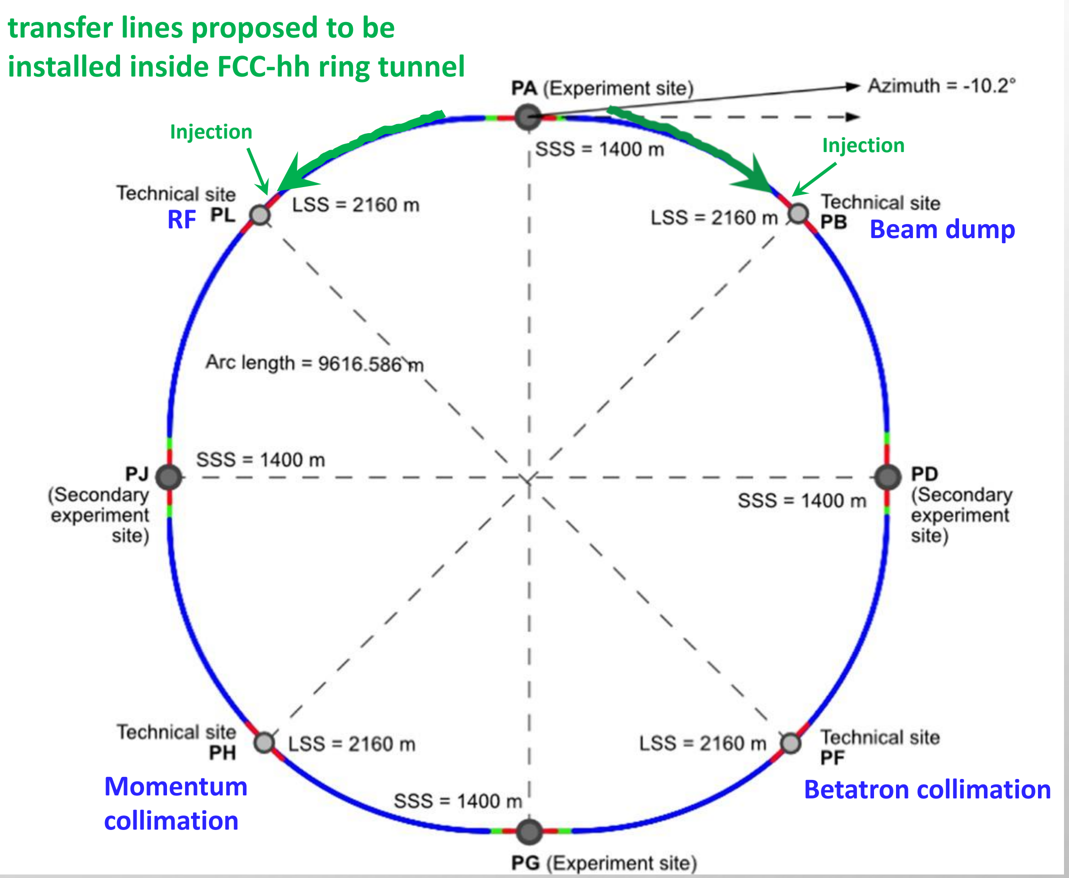
⇒ SR comparable to light sources, beam losses, high field magnets

BASIC DESIGN CHOICES

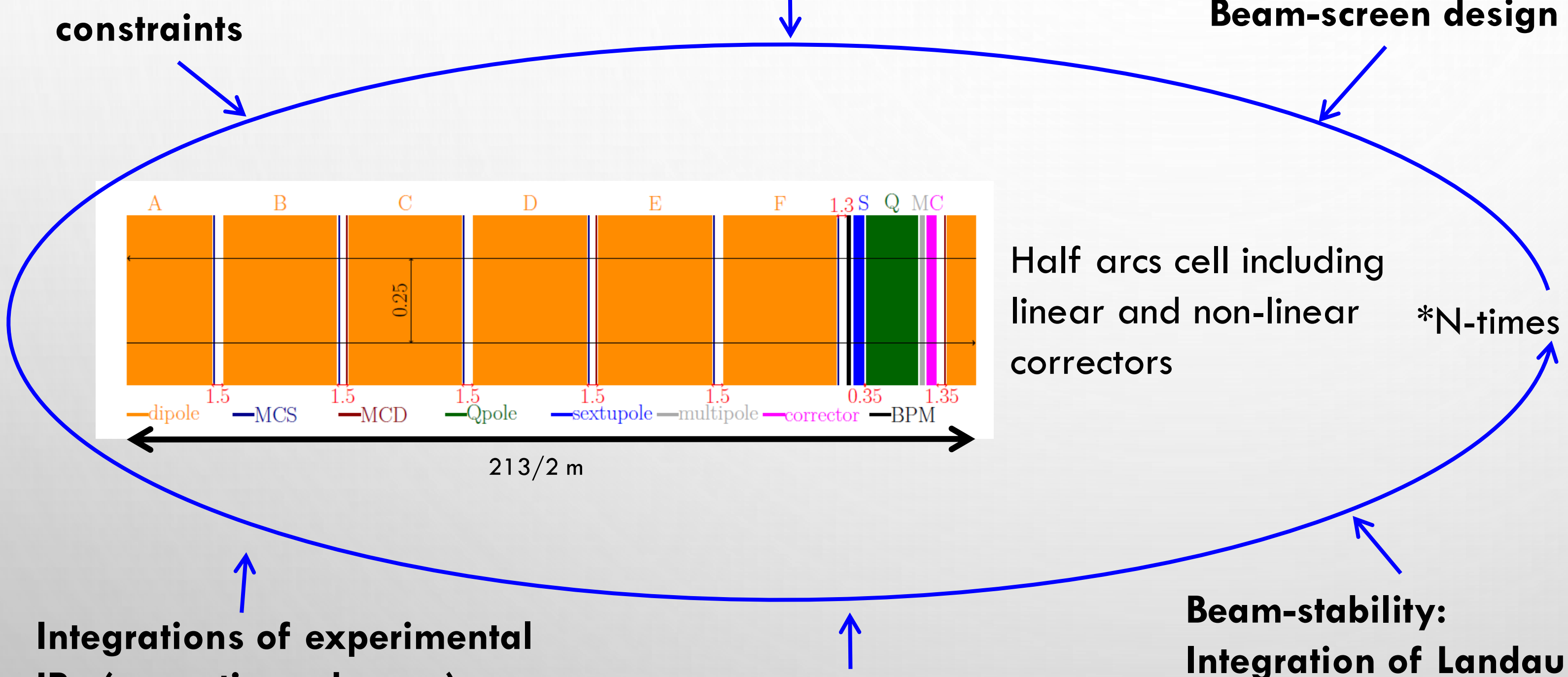
The main drivers

- Placement studies

- **Exact four-fold symmetry (FCC-ee layout)**
- Four experiments (A, D, G, & J)
- Two collimation insertions
  - betatron cleaning (F)
  - momentum cleaning (H)
- Extraction insertion + injection (B)
- RF insertion + injection (L)
- **Last part of transfer lines in the ring tunnel, using normal-conducting magnets**
- Compatible with LHC or SPS as injector



ARC CONCEPT (CDR)



Civil engineer constraints

Magnets max gradient and Field Quality

Beam-screen design

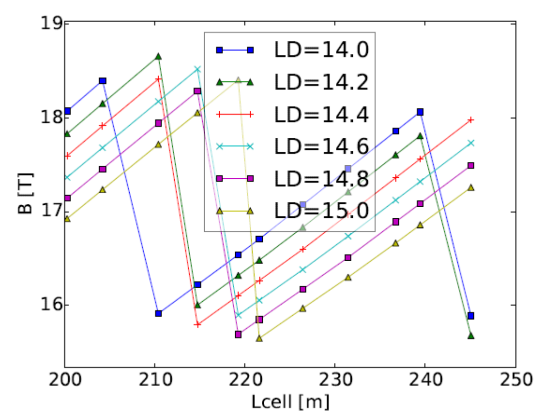
Half arcs cell including linear and non-linear correctors

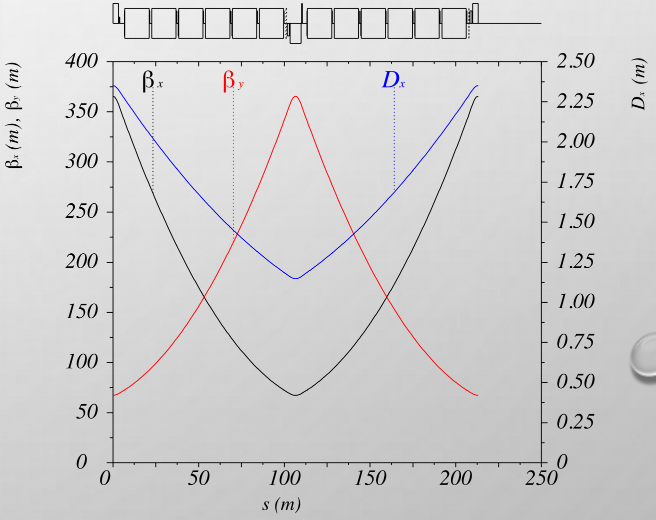
*N-times

Integrations of experimental IRs (correction schemes)

Collimation requirements

Beam-stability: Integration of Landau Damping octupoles





FODO cell

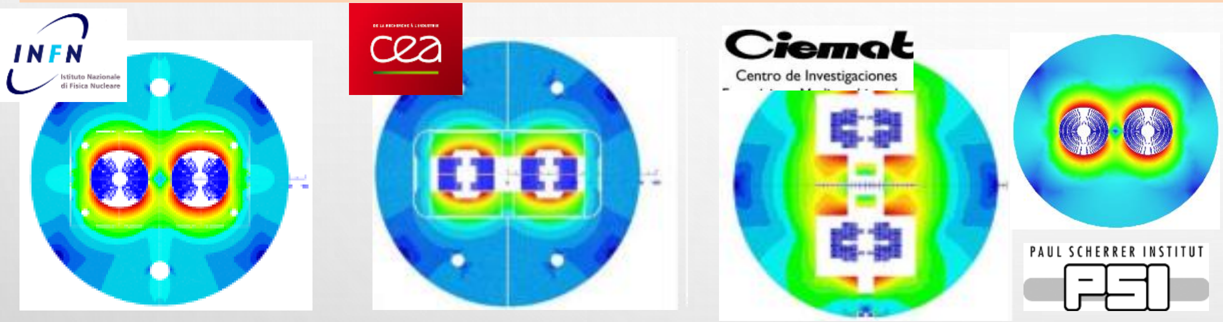
FCC-hh KEY TECHNOLOGIES: HIGH FIELD MAGNETS

Need 16 T to reach 48 TeV /beam

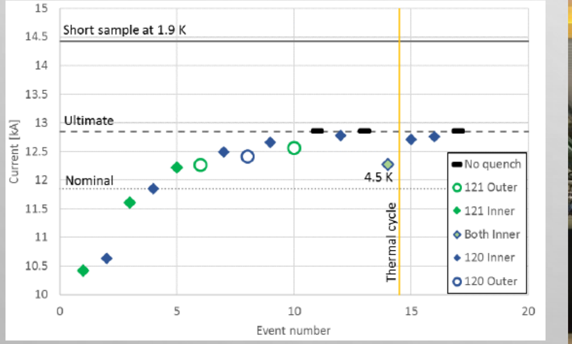
⇒ Move from NbTi (LHC technology) to Nb_3Sn 14.3 m long dipoles

⇒ **HL-LHC** experience is fundamental, but further step are needed to reduce the cost

⇒ Exploring HTS superconductors (See S. I. Bermudez Lecture)



HL-LHC **11T First Nb_3Sn magnet, FRESCA2 dipole**



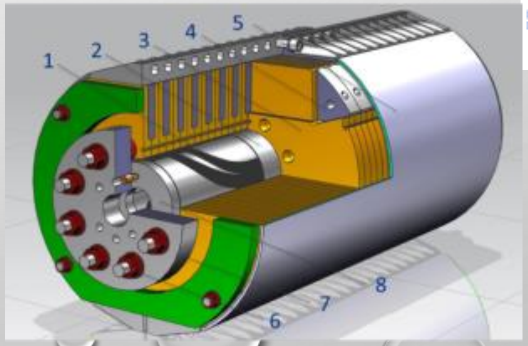
Magnet is key cost driver

- Improve cable performance
- Reduce cable cost
- Improve fabrication of magnet
- Minimize amount of cables
- Push lattice filling factor
- Field Quality

Short models in 2018 – 2023

Prototypes 2026 – 2032

Synergies with other fields



15 T dipole demonstrator

60-mm aperture

4-layer graded coil

FCC-hh KEY TECHNOLOGY: MACHINE PROTECTION

~30 W/M SYNCHROTRON RADIATION (LHC: 1 W/M)

Small to make magnet cheap (aperture 50 mm)

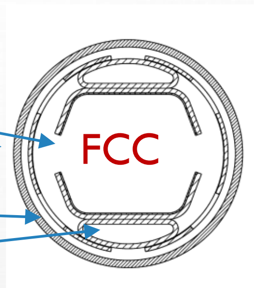
Extract photons for good vacuum

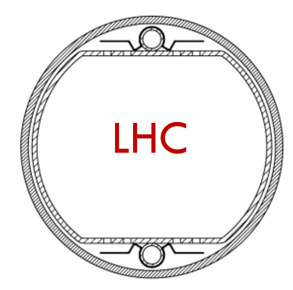
Strong to withstand quench

Hide pumping holes from beam and

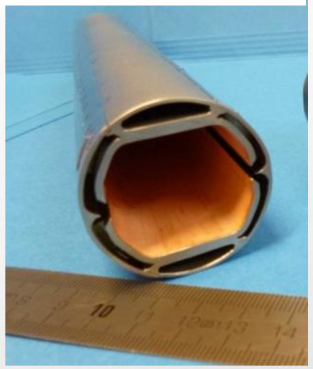
REBCO-Cu longitudinal coating for low impedance

Laser treatment / carbon coating against e-cloud





Tests at KARA/KIT

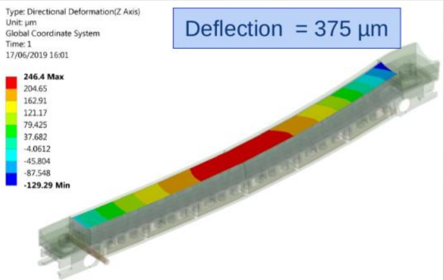


- The loss of even a tiny fraction of the beam could cause a magnet quench or even damage

~8 GJ kinetic energy per beam in FCC-hh O(20) times LHC

- Boing 747 at cruising speed or 400 kg of chocolate (Run 25,000 km to spent calories)

- Use carbon-based materials for highest robustness
- **Very challenging engineering task** to design these collimators



Designed shielding to cope with the 500 kW collision debris per experiment

Collimation system design

- Designed system that can cope with the losses
- Detailed studies and optimization of performance

Beam dump design

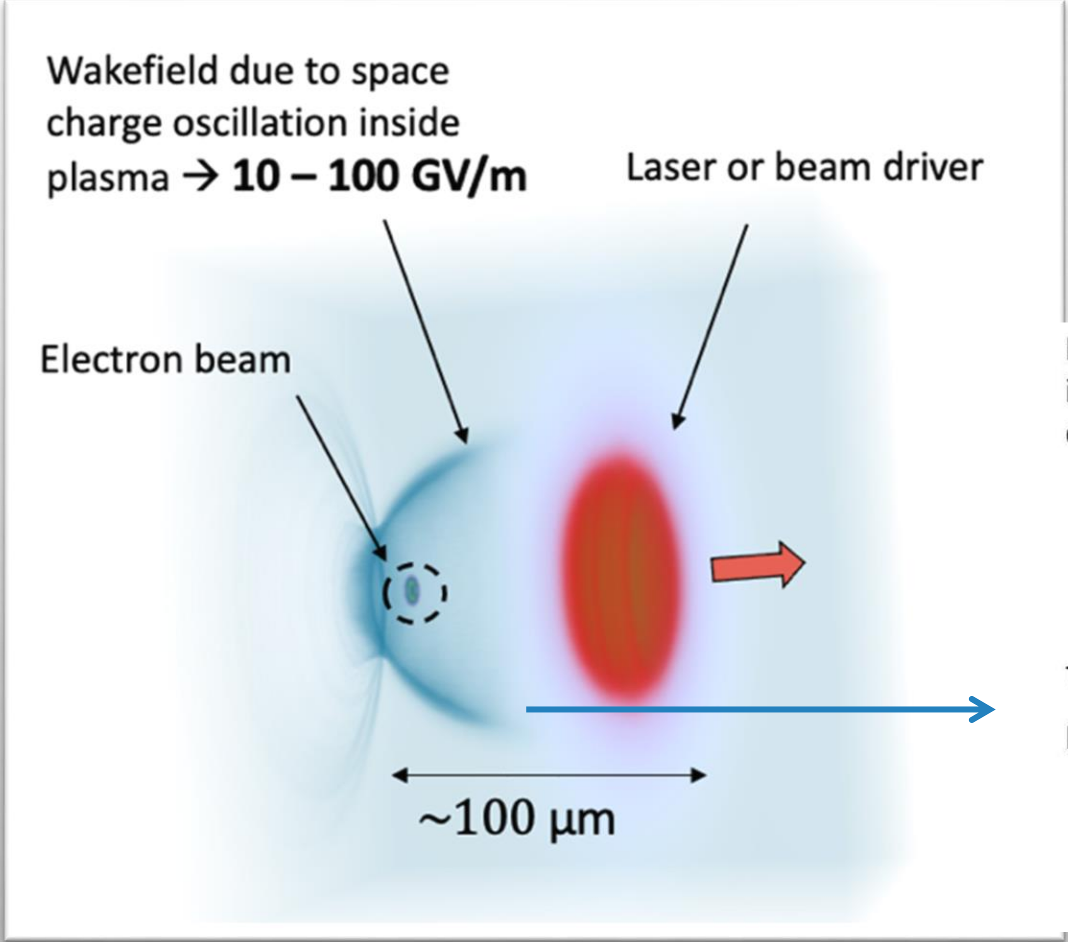
Machine protection (See F. Salvat Lecture)

NOVEL TECHNIQUES

"The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies"

- High Field Magnets
- Super conductive cavities
- Plasma accelerations and other techniques
- Energy Recovery Linacs (ERL)
- Muons Colliders

PLASMA WAKE ACCELERATORS PRINCIPLE

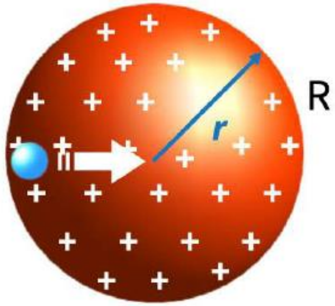


$$E_{cm} \approx L_{linac} G_{acc}$$

They have the potential to overcome the length and the accelerating gradient limitations of the linear colliders

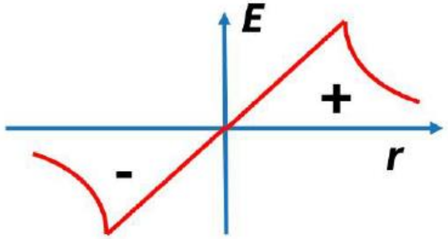
M. Ferrario et al.

From Maxwell's equations, the electric field in a (positively) charged sphere with uniform density n_i at location r is



$$\vec{E}(r) = \frac{q_i n_i}{3\epsilon_0} r$$

The field is **increasing** inside the sphere



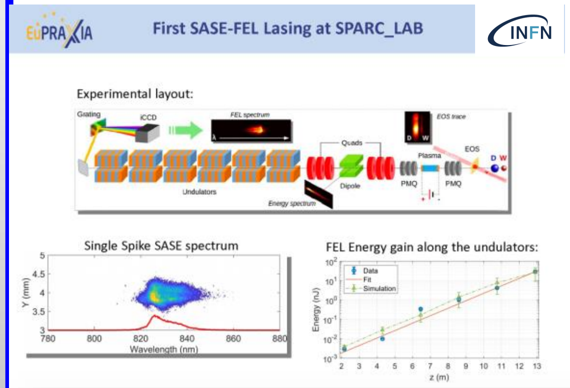
Let's put some numbers

$n_i = 10^{16}\ cm^{-3}$

$R = 0.5\ \lambda_p = 150\ \mu m$ $\Rightarrow$ $E \approx 10 \frac{GV}{m}$

PLASMA WAKEFIELD R&D

- Specific topics to be addressed:
  - Positron acceleration
  - Technological issue (efficiency, cooling, polarization,…)
- The world wide R&D focus on beam quality, beam stability, staging and continuous operation

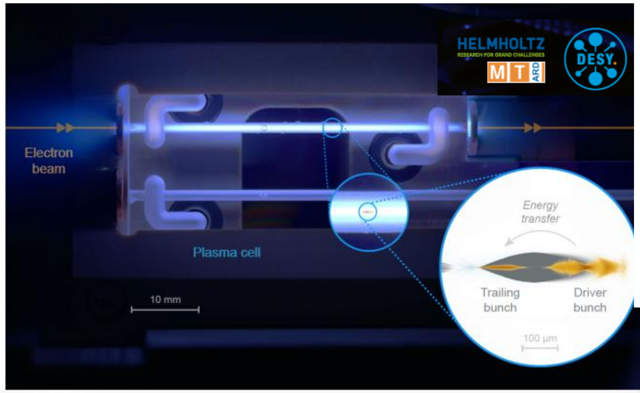


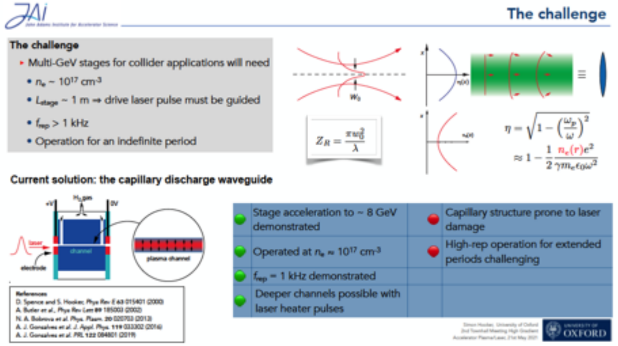
First SASE-FEL Lasing at SPARC_LAB

Experimental layout:

Single Spike SASE spectrum

FEL Energy gain along the undulators:





The challenge

The challenge
- Multi-GeV stages for collider applications will need
  - $n_e \sim 10^{17}$ cm^{-3}
  - $L_{stage} \sim 1$ m → drive laser pulse must be guided
  - $f_{rep} > 1$ kHz
  - Operation for an indefinite period

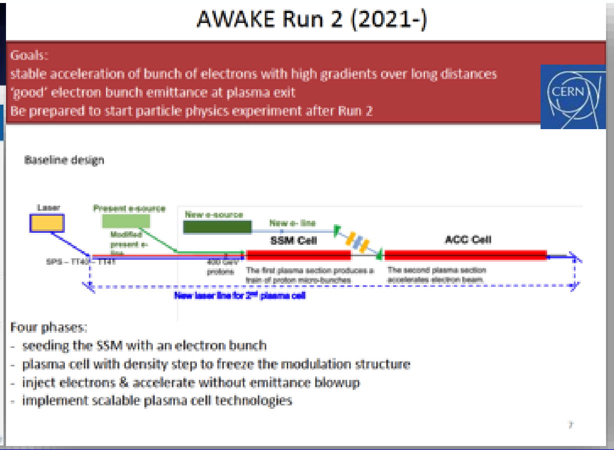
$$Z_R = \frac{\pi w_0^2}{\lambda}$$

$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

Current solution: the capillary discharge waveguide

🟢	Stage acceleration to ~ 8 GeV demonstrated	🔴	Capillary structure prone to laser damage
🟢	Operated at $n_e \approx 10^{17}$ cm^{-3}	🔴	High-rep operation for extended periods challenging
🟢	f_{rep} = 1 kHz demonstrated		
🟢	Deeper channels possible with laser heater pulses		

References
D. Spence and S. Hooker, Phys Rev E 63 015401 (2000)
A. Butler et al., Phys Rev Lett 89 185003 (2002)
N. A. Bobrova et al. Phys. Plasm. 20 020703 (2013)
A. J. Gonsalves et al. J. Appl. Phys. 119 033302 (2016)
A. J. Gonsalves et al. PRL 122 084801 (2019)

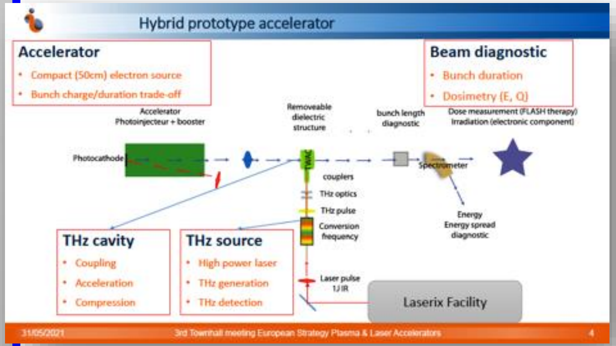


AWAKE Run 2 (2021-)

Goals:
stable acceleration of bunch of electrons with high gradients over long distances
'good' electron bunch emittance at plasma exit
Be prepared to start particle physics experiment after Run 2

Baseline design

Four phases:
- seeding the SSM with an electron bunch
- plasma cell with density step to freeze the modulation structure
- inject electrons & accelerate without emittance blowup
- implement scalable plasma cell technologies



Hybrid prototype accelerator

Accelerator
- Compact (50cm) electron source
- Bunch charge/duration trade-off

Beam diagnostic
- Bunch duration
- Dosimetry (E, Q)

THz cavity
- Coupling
- Acceleration
- Compression

THz source
- High power laser
- THz generation
- THz detection

Challenges & Opportunities leading up to 2030

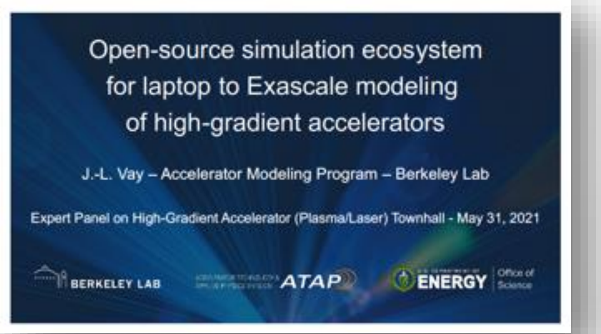
Over the next 10 years simulation tools for plasma based accelerators will need to address additional challenges and opportunities:
- Extended acceleration distances
- Ultra-high field intensities
- Provide detailed quantitative predictions that include additional models relevant for HEP

Full scale modelling of the AWAKE* experiment

Strategies being followed in the framework of the OSIRIS kinetic plasma simulation code
- Leverage the power of present and future Tier-0 HPC systems for addressing these challenges
- Improvement of core algorithms in terms of accuracy, stability, and additional physics to cope with longer accelerating distances and ion motion/hydrodynamic scales, and increased laser intensities and address HEP relevant parameters
- Improvements on parameter input and output, for both quantitative simulations with one-to-one comparison with experimental setups and use in integrated modeling toolchains

* E. Adli et al. **Nature** 561, 363-366 (2018)

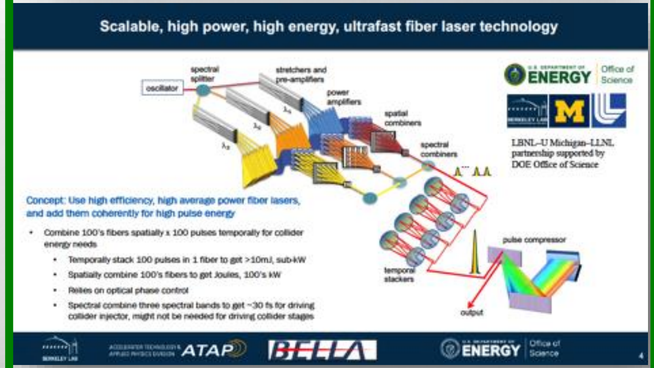
Ricardo Fonseca | 2021 CERN Expert Panel on High-Gradient Accelerator (Plasma/Laser)



Open-source simulation ecosystem
for laptop to Exascale modeling
of high-gradient accelerators

J.-L. Vay – Accelerator Modeling Program – Berkeley Lab

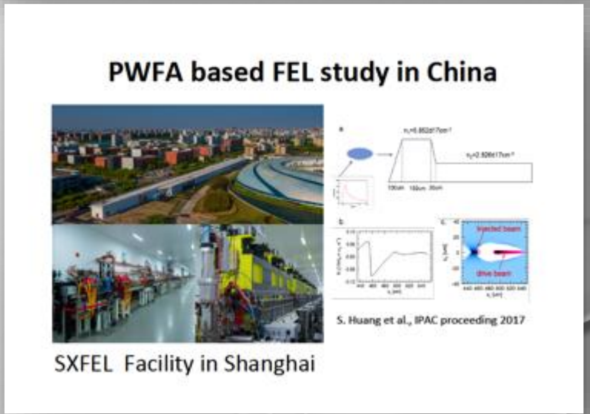
Expert Panel on High-Gradient Accelerator (Plasma/Laser) Townhall - May 31, 2021



Scalable, high power, high energy, ultrafast fiber laser technology

Concept: Use high efficiency, high average power fiber lasers, and add them coherently for high pulse energy
- Combine 100's fibers spatially x 100 pulses temporally for collider energy needs
  - Temporally stack 100 pulses in 1 fiber to get >10mJ, sub-kW
  - Spatially combine 100's fibers to get Joules, 100's kW
  - Relies on optical phase control
  - Spectral combine three spectral bands to get ~30 fs for driving collider injector, might not be needed for driving collider stages

LBNL–U Michigan–LLNL partnership supported by DOE Office of Science



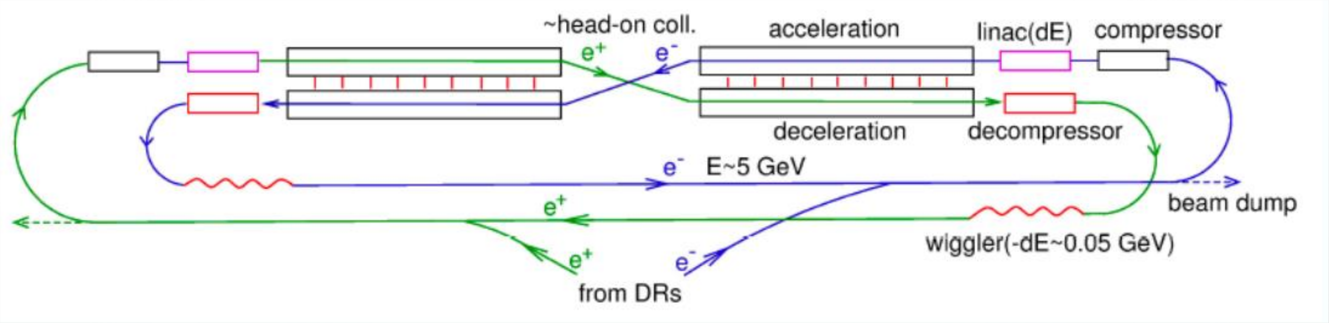
PWFA based FEL study in China

SXFEL Facility in Shanghai

S. Huang et al., IPAC proceeding 2017

LINEAR COLLIDER WITH ERL

Multi-pass linac



The concept become really viable with recent advances in SRF technology: reach high cavity quality factors ($Q_0 \geq 10^{10}$) enabling high average current operation

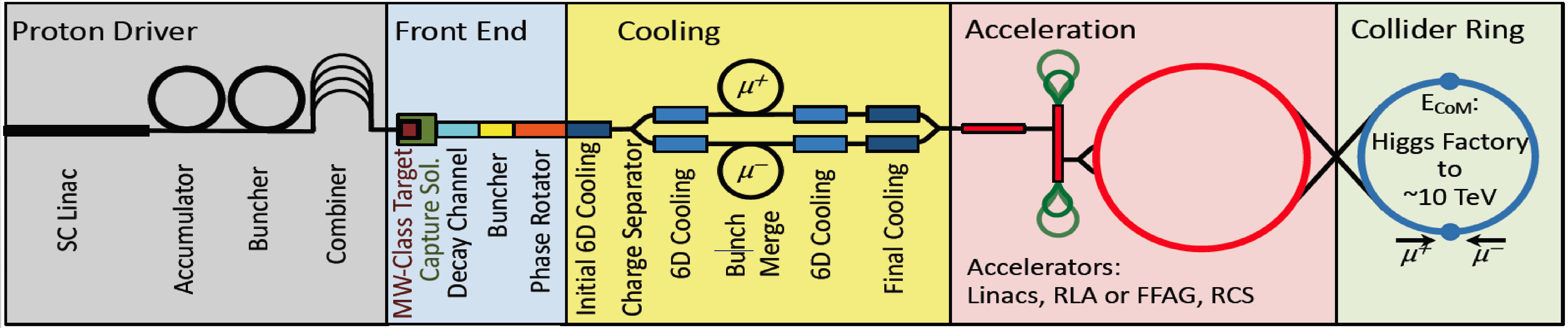
Demonstration facilities around the world are pursuing to gain experimental experience of this technique

MUONS COLLIDERS

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Muons are heavier than electrons ⇒ they loose less energy because of synchrotron radiation can reach ~ 10 TeV energy in the center of mass with leptons!

Would be easy if the muons did not decay: lifetime is τ = γ x 2.2 μs



Short, intense proton bunch (Drives the **beam quality**)

Ionisation cooling of muon in matter (requires both **high fields magnets** and **high gradient cavities**)

Acceleration to collision energy (**cost** and **power consumption** limited, cycle of the order of ~10 ms)

Collision
Dense neutrino flux, beam induced backgrounds

Protons produce pions which decay into muons muons are captured

CONCLUSIONS

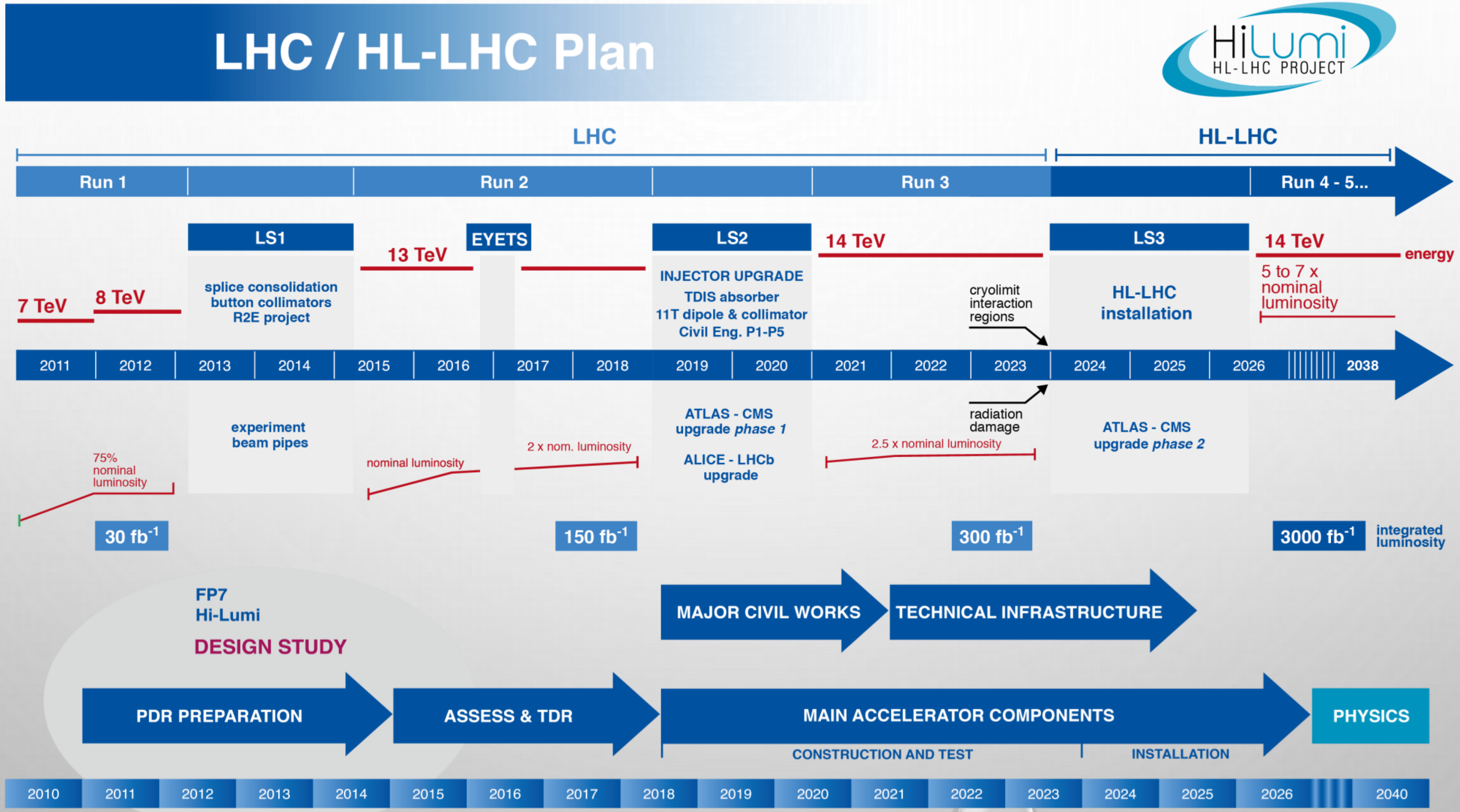
- High Energy Accelerator Field is very active !
  - Plenty of different projects are under study to be ready to address different and complementary physics questions
  - Many beam dynamics challenges to be addressed
  - Key technology R&D roadmaps have been created:
    - A lot of synergies with other fields (energy, medicine, etc...)

- There is always room for new ideas!

You are very welcome to join us!

THANK YOU!

TIMELINE



LHC / HL-LHC Plan

HiLumi HL-LHC PROJECT

LHC

HL-LHC

Run 1 | Run 2 | Run 3 | Run 4 - 5...

7 TeV

8 TeV

LS1

splice consolidation
button collimators
R2E project

13 TeV

EYETS

LS2

INJECTOR UPGRADE
TDIS absorber
11T dipole & collimator
Civil Eng. P1-P5

14 TeV

cryolimit
interaction
regions

LS3

HL-LHC
installation

14 TeV

energy

5 to 7 x
nominal
luminosity

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2038

75%
nominal
luminosity

experiment
beam pipes

nominal luminosity

2 x nom. luminosity

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

radiation
damage

2.5 x nominal luminosity

ATLAS - CMS
upgrade *phase 2*

30 fb^{-1}

150 fb^{-1}

300 fb^{-1}

3000 fb^{-1}

integrated
luminosity

FP7
Hi-Lumi

DESIGN STUDY

MAJOR CIVIL WORKS

TECHNICAL INFRASTRUCTURE

PDR PREPARATION

ASSESS & TDR

MAIN ACCELERATOR COMPONENTS

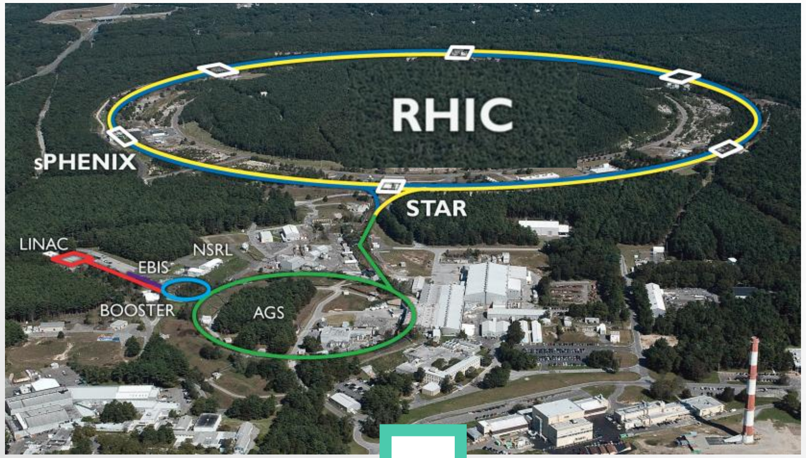
CONSTRUCTION AND TEST

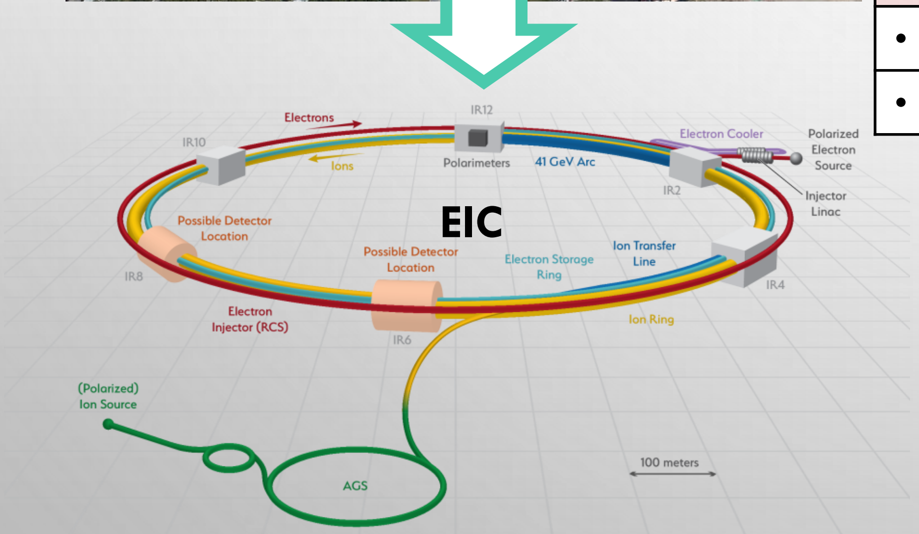
INSTALLATION

PHYSICS

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2040

EIC





Hadron Storage Ring: 40 - 275 GeV

- RHIC Yellow+Blue Ring and Injector Complex
- Many Bunches, 1160 @ 1A Beam Current
- Bright Vertical Beam Emittance εxp= 1.5 nm
- Requires Strong Cooling (CeC)

Electron Storage Ring: 2.5 - 18 GeV (new)

- Many Bunches, Large Beam Current - 2.5 A
- 9 MW Synchrotron Radiation, SRF Cavities
- Needs injection of polarized bunches

Electron Rapid Cycling Synchrotron: (new) **0.4-18 GeV**

- Spin Transparent Due to High Periodicity
- 1-2 Hz cycle for On-Energy Injection into ESR

High Luminosity Interaction Region(s) (new)

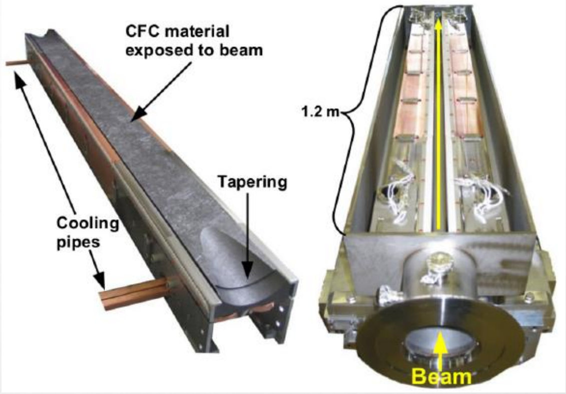
- 25 mrad Crossing Angle with Crab Cavities
- Superconducting Magnets
- Spin Rotators for Longitudinal Spin at IP
- Forward Hadron Instrumentation

Double-ring design based on existing RHIC complex

COLLIMATORS AND ALIGNMENT

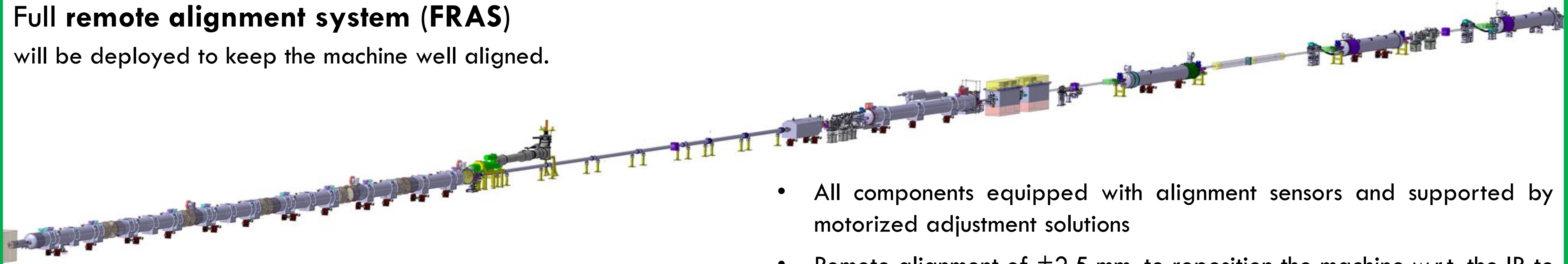
- Losses from the beam are inevitable, and could cause magnet quenches or even damage
- With higher intensity in the HL-LHC, need to enforce machine protection
- New collimators to be installed to better protect the machine. LS2 **upgrade:**
  - — Dispersion suppressor cleaning for ALICE
  - — Low-impedance primary and secondary (coated) collimators in IR7
  - — Passive absorbers for IR7

Collimation upgrade



Full **remote alignment system** (**FRAS**)

will be deployed to keep the machine well aligned.

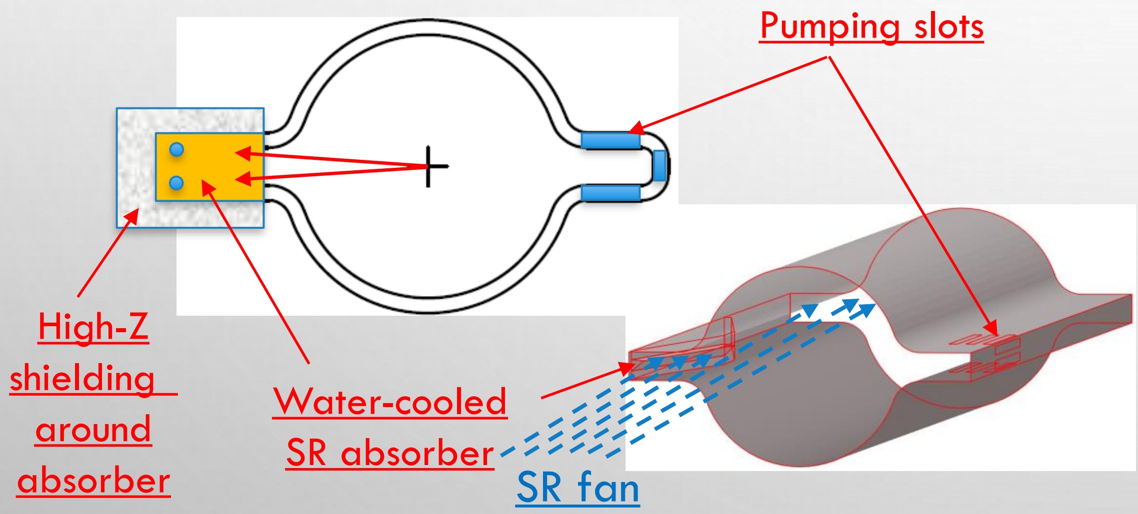


- All components equipped with alignment sensors and supported by motorized adjustment solutions
- Remote alignment of ±2.5 mm, to reposition the machine w.r.t. the IP, to correct ground motion.

R. De Maria ICHEP 2022

FCC-ee KEY TECHNOLOGIES: VACUUM SYSTEM

- **Specifying vacuum system**
  - Consider discrete absorbers space every <6 m or continuous absorbers along chamber wall
  - NEG coated Cu vacuum chamber
  - Need shielding to minimize tunnel radiation levels

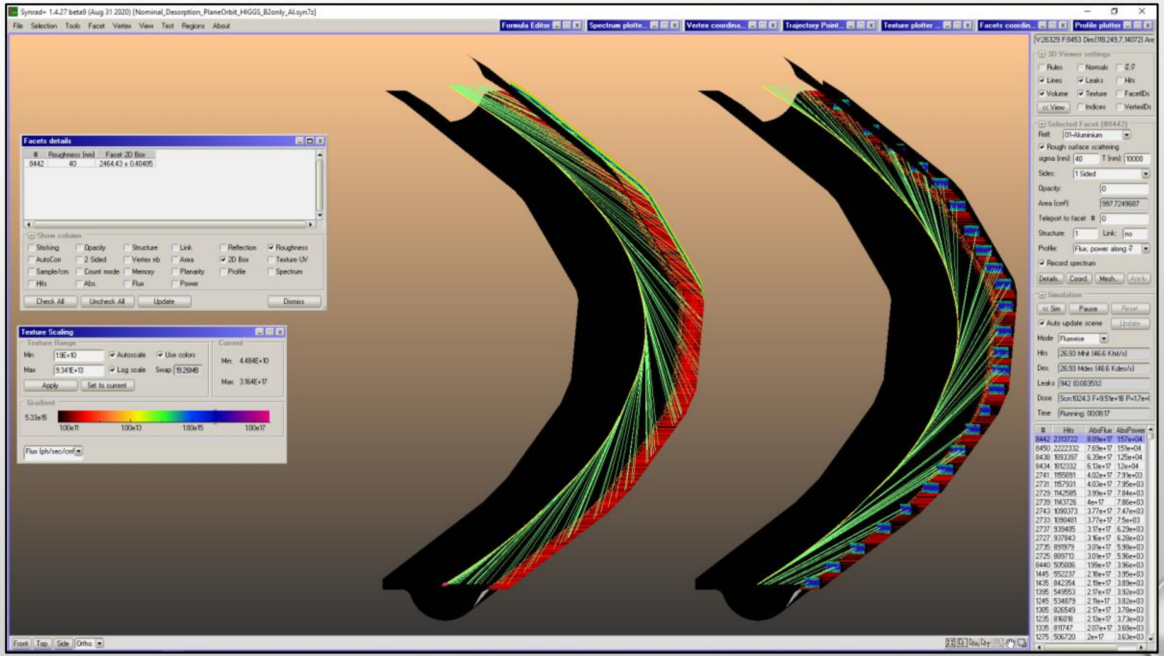


Pumping slots

High-Z shielding around absorber

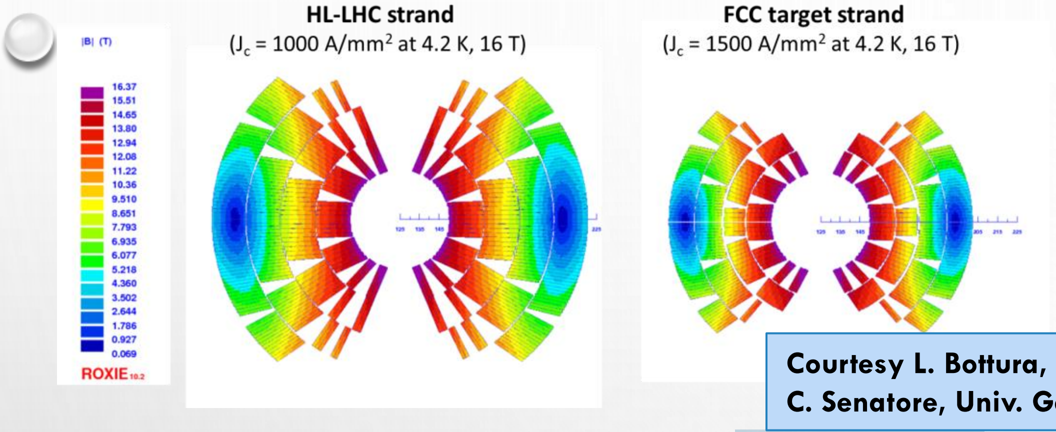
Water-cooled SR absorber

SR fan



R. Kersevan FCCIS workhop 2021

FCC-hh KEY TECHNOLOGIES: HIGH FIELD MAGNETS



HL-LHC strand
(J_c = 1000 A/mm^2 at 4.2 K, 16 T)

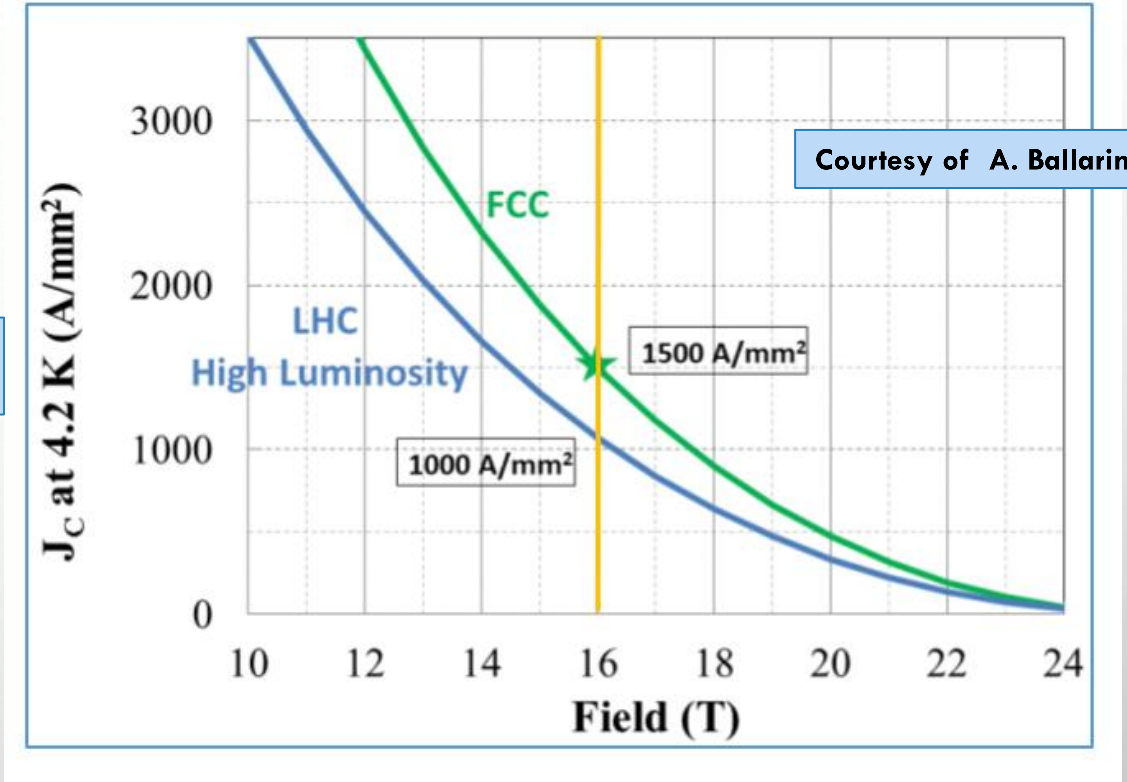
FCC target strand
(J_c = 1500 A/mm^2 at 4.2 K, 16 T)

Courtesy L. Bottura, CERN
C. Senatore, Univ. Geneva

B [T]	16		16
J_{op} [A/mm^2]	300	2x	600
w [mm]	76		38
A_{coil} [mm^2]	20'000		7'000

Doubling the operating current density brings a reduction of the superconductor area to one third

$A_{coil} \propto SC\ mass \propto$



Courtesy of A. Ballarino, CERN

The most promising route to fill the performance gap is the Internal Oxidation

Parrell et al., AIP Conf. Proc. 711 (2004) 369
Boutboul et al., IEEE TASC 19 (2009) 2564
Xu et al., APL 104 (2014) 082602

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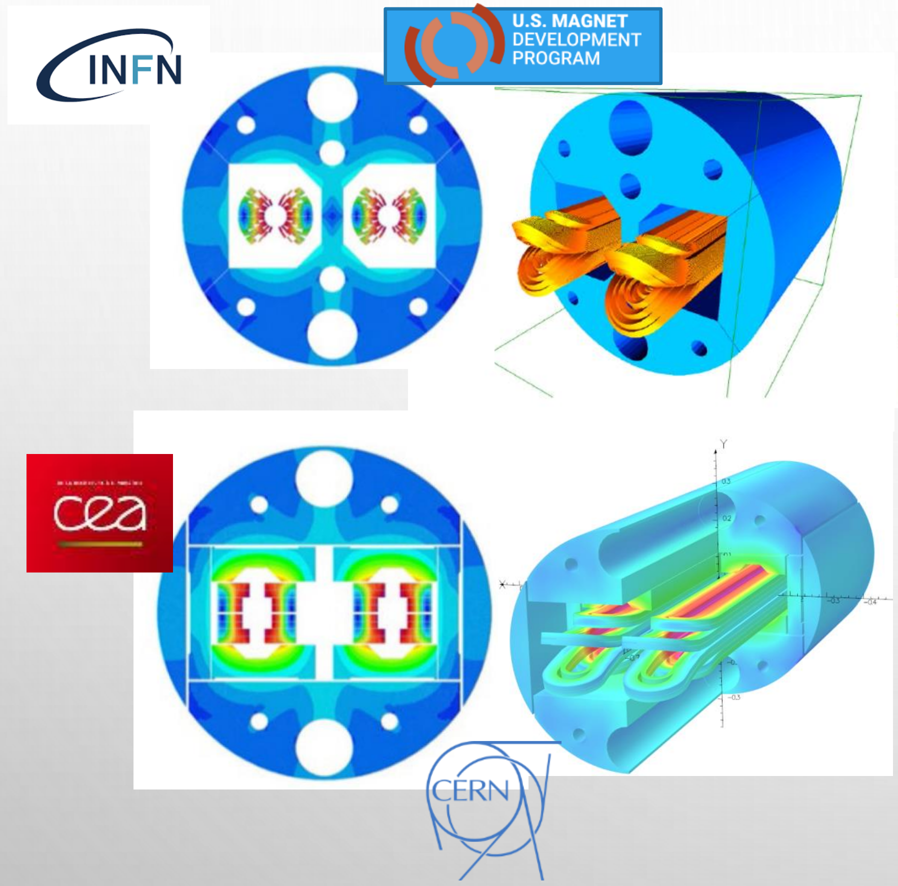
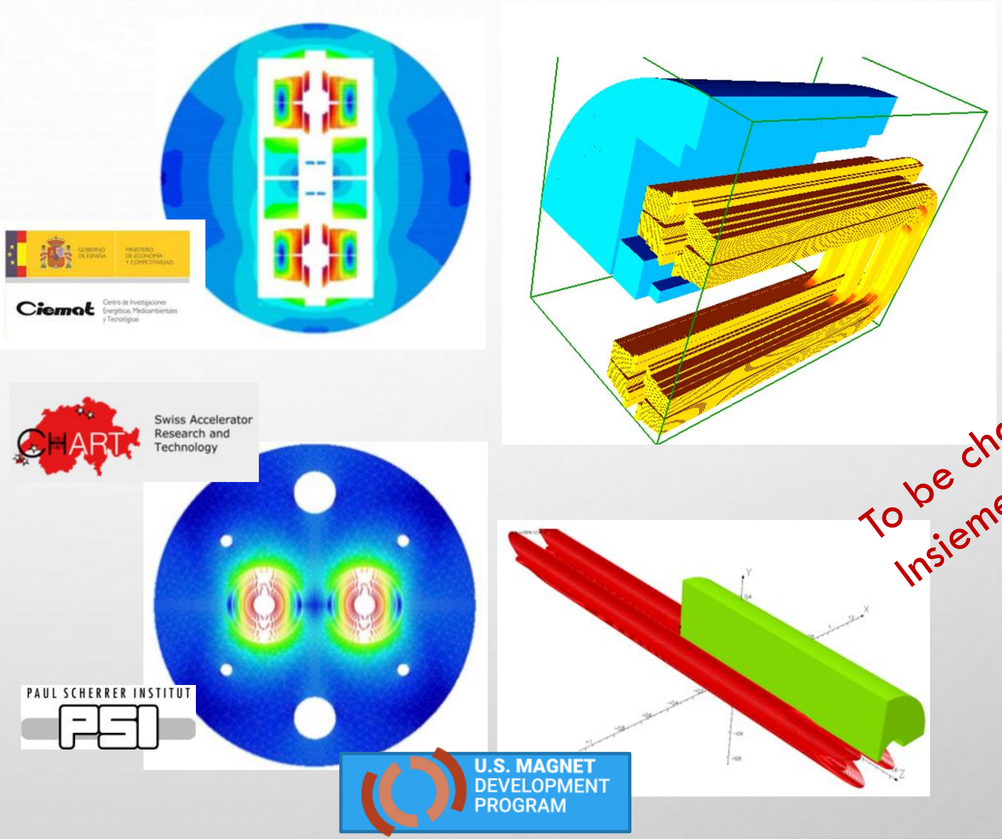
FCC-hh KEY TECHNOLOGIES: MAGNETS R&D





To be changed
Insieme a quella di prima

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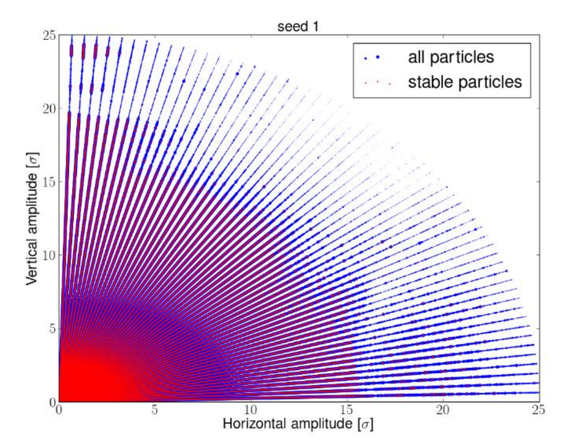
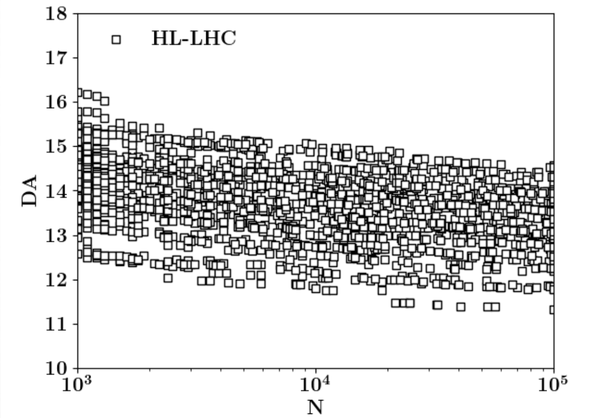
High Field Magnet technolgy can always serve for a HE-LHC

MAGNETS FIELD QUALITY AND PARTICLES PHASE SPACE STABILITY REGION



$$DA(N) = \frac{2}{\pi}\int_0^{\pi/2} r_s(\theta; N)\,d\theta$$



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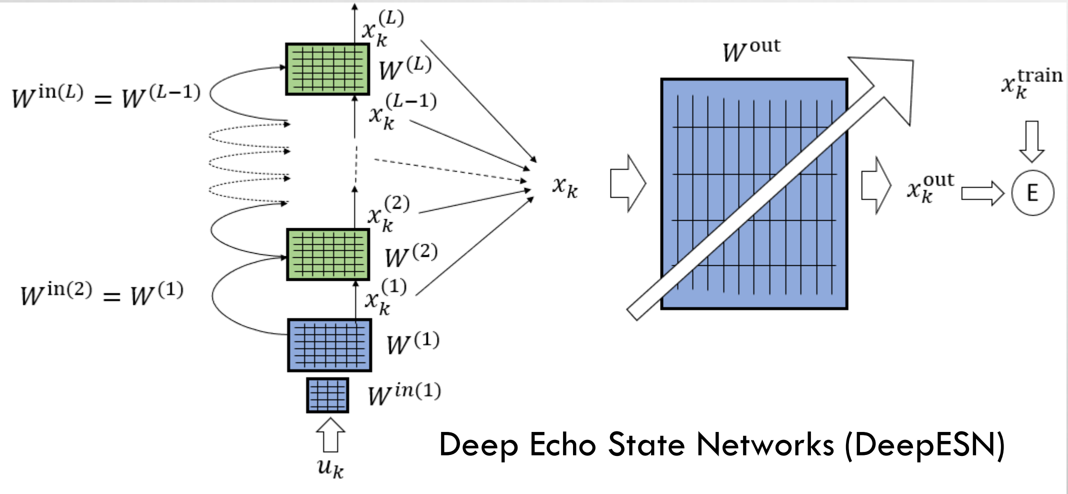
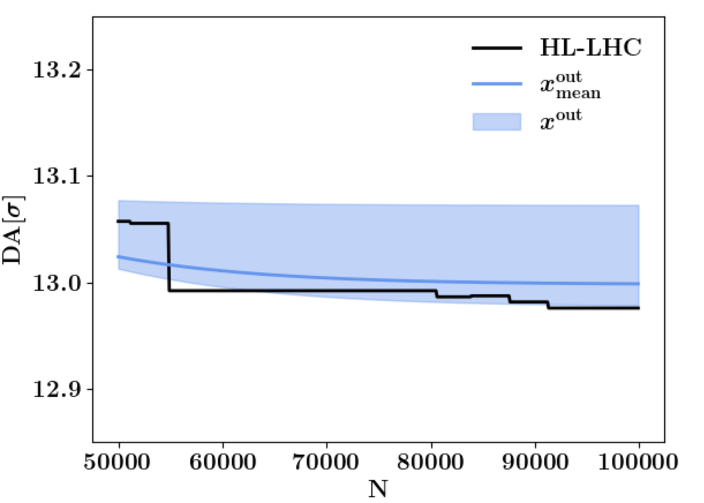
?

Replace CPU costly tracking simulations with fast surrogate model of the time evolution of Dynamic Aperture



Deep Echo State Networks (DeepESN)



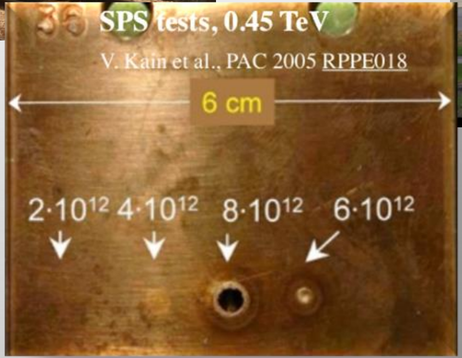
FCC-hh KEY TECHNOLOGY: MACHINE PROTECTION

HL-LHC: 680 MJ - kinetic energy of

TGV train cruising at 215 km/h

FCC-hh: 8.3 GJ – kinetic energy of

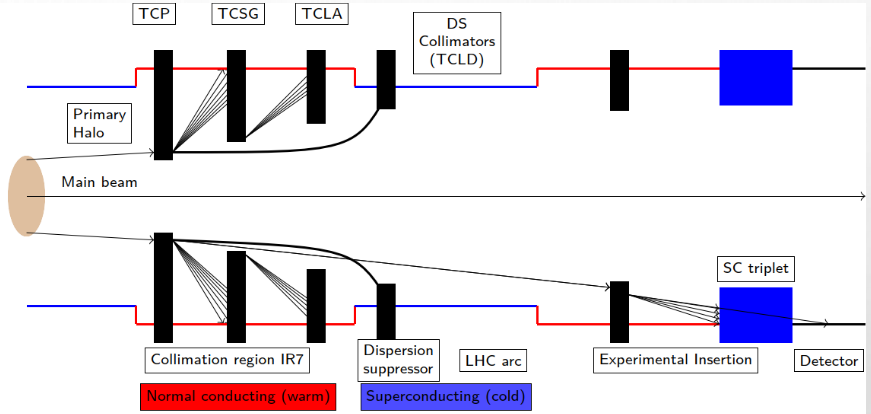
Airbus A380 (empty) cruising at 880 km/h



FCC-hh COLLIMATION

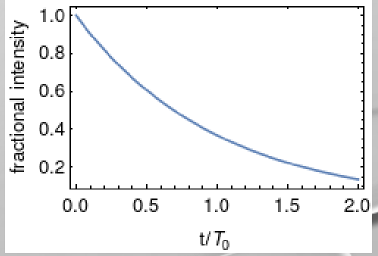
- The loss of even a tiny fraction of the beam could cause a magnet quench or even damage
- To safely intercept any losses and protect the machine: use collimation system (see lecture a. Lechner)
    - Should be the smallest aperture limitation in the ring
- 500 kw of continuous losses from collisions, downstream of experiments
- Design requirement: safely handle beam lifetime of 12-minute during ~10 s from instabilities, operational mistakes, orbit jitters….
    - Corresponds to power load of about 11.6 MW from the beam losses
    - Collimators must digest these losses without breaking, while protecting the superconducting magnets

Deploying multi-stage collimation system inspired by LHC



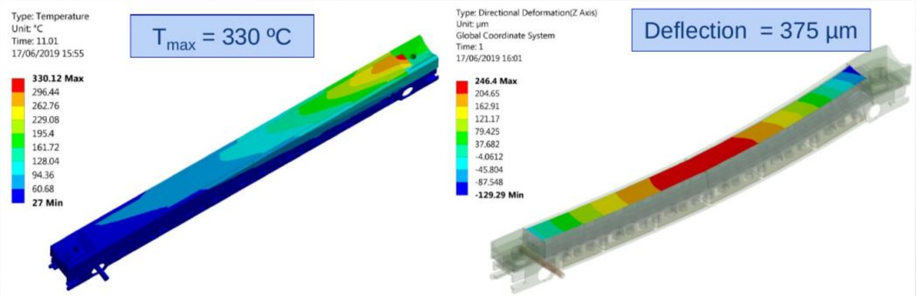
Beam lifetime:
usually defined as time needed for reduction of intensity by factor 1/e assuming losses proportional to intensity (often true, but not always)

$$-\frac{dN}{dt} \propto N(t) \Rightarrow N(t) = N_0 e^{-t/T_0}$$

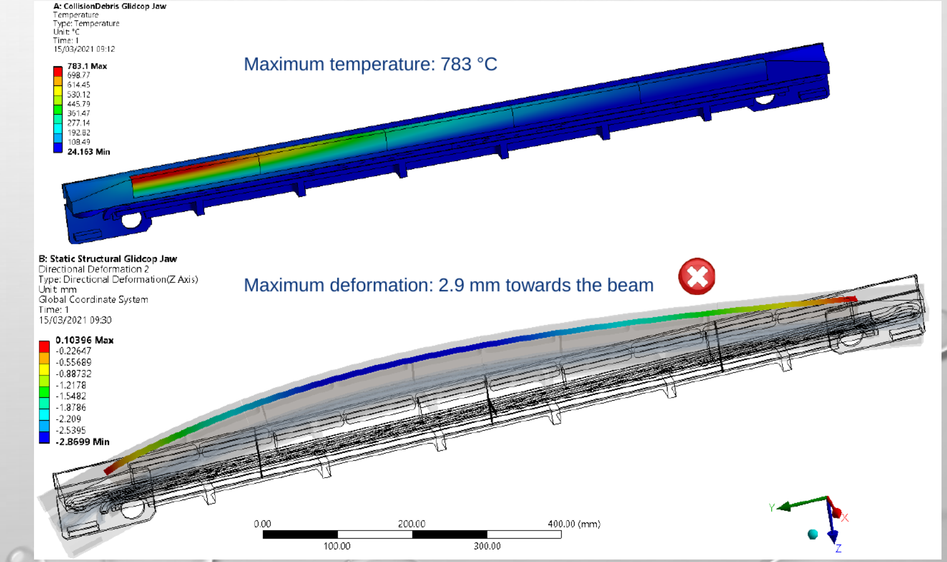


FCC-hh COLLIMATORS ROBUSTNESS

- Use carbon-based materials for highest robustness, with hardware design based on LHC but developed further
- Very important to study material response to the high loads
- Typically 3-stage simulations:
  - Generation of impact coordinates of lost particles
  - Energy deposition studies (e.G. FLUKA, see lecture A. Lechner)
  - Thermo-mechanical study using e.G. ANSYS of dynamic material response
    - Study peak temperatures, deformations, melting, detachment of material
- Very challenging engineering task to design these collimators


T_{max} = 330 °C

Deflection = 375 µm


Maximum temperature: 783 °C

Maximum deformation: 2.9 mm towards the beam

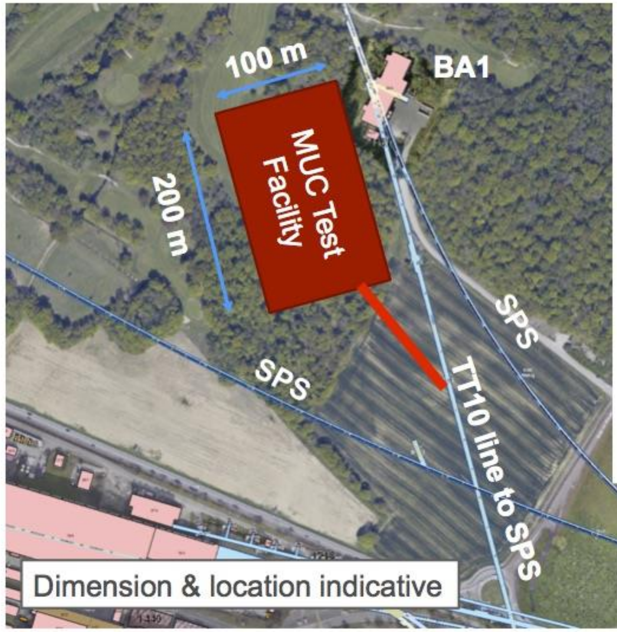
MUONS DEMOSTRATOR FACILITY

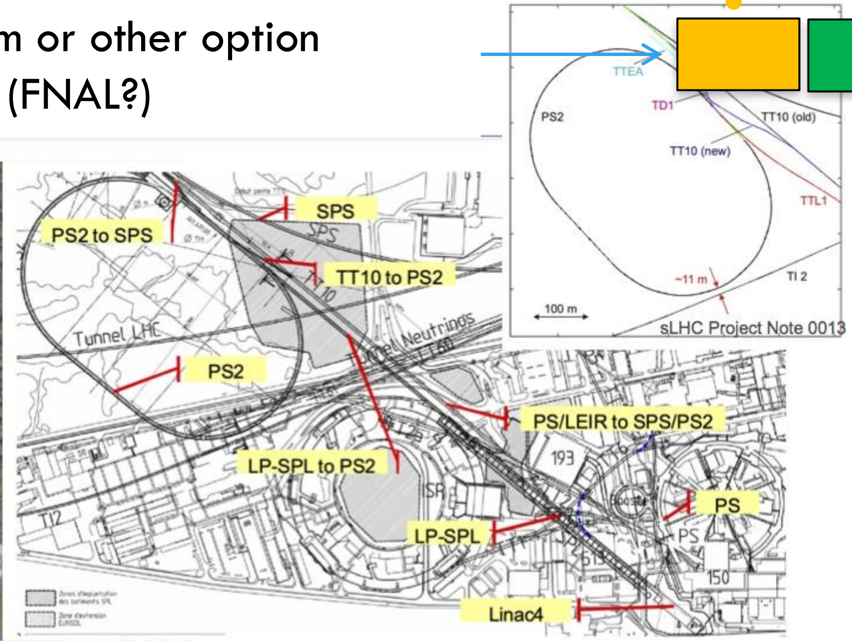
Planning demonstrator facility with muon production target and cooling stations

Suitable site on CERN land exists that can use PS proton beam

- could combine with NuStorm or other option

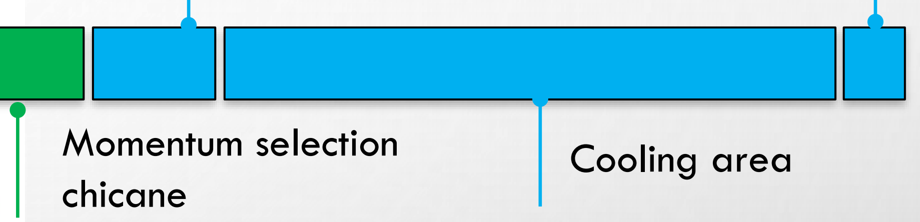
Other sites should be explored (FNAL?)





M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061



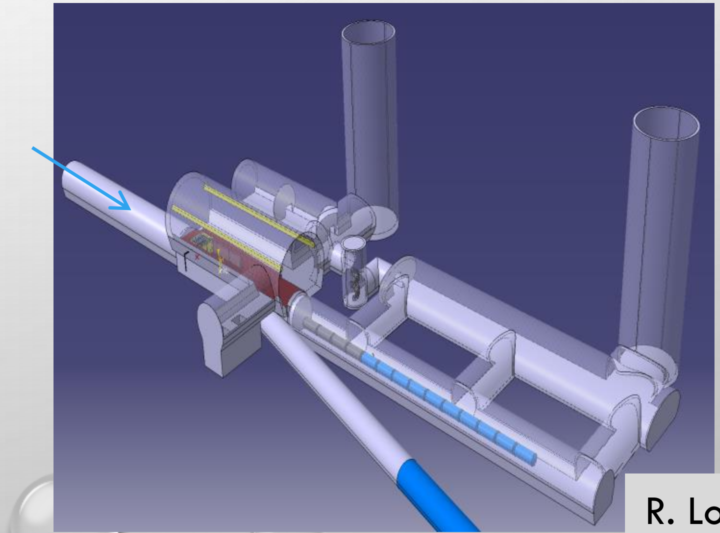
Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

Collimation and upstream diagnostics area

Downstream diagnostics area

Momentum selection chicane

Cooling area

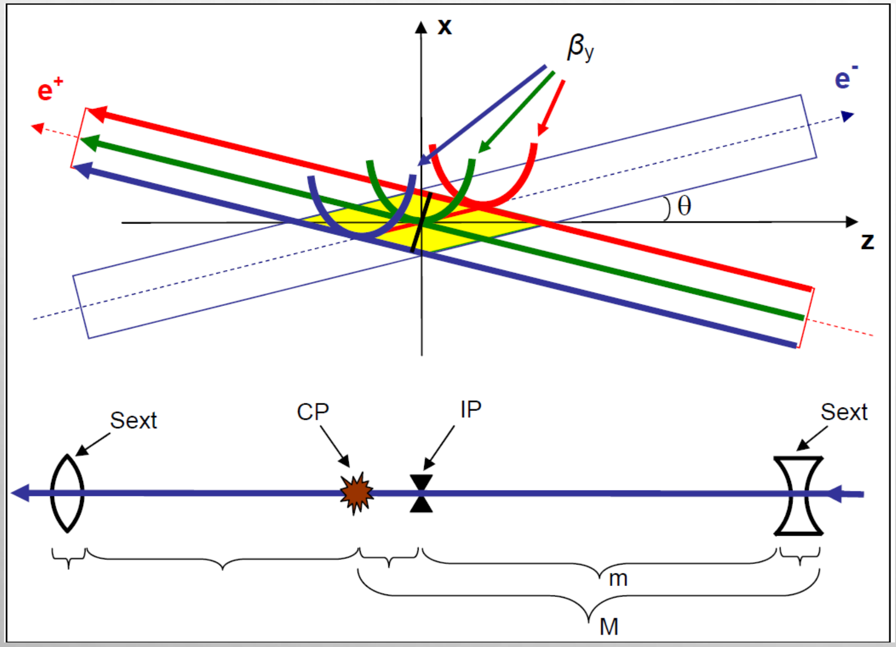


R. Losito et al.

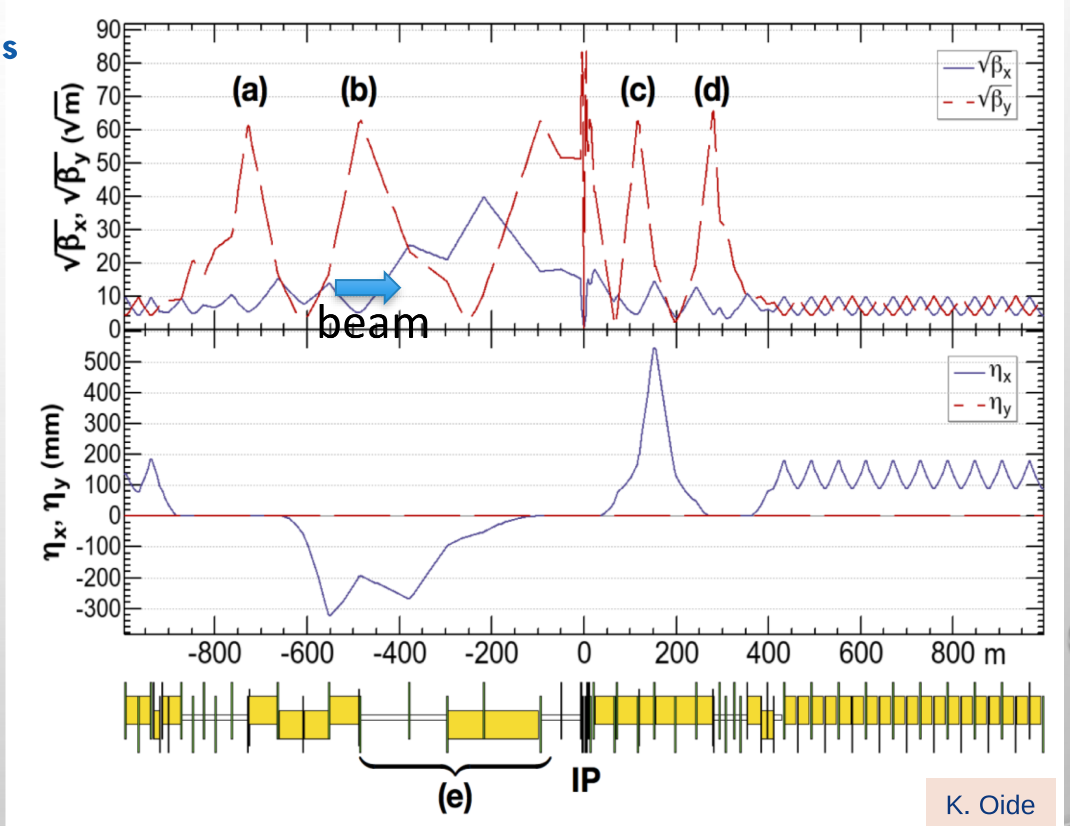
FCC-ee COLLIDER OPTICS AND BEAM-BEAM

- **Novel ‘virtual’ crab waist combining local vertical chromaticity correction**
  - ○ Crab waist was demonstrated at DAFNE
  - ○ Crab waist is also being used at SuperKEKB
- **Optimized optics configurations for each of the 4 working points**

Crab waist scheme https://arxiv.org/abs/physics/0702033



CDR optics, ttbar 182.5 GeV

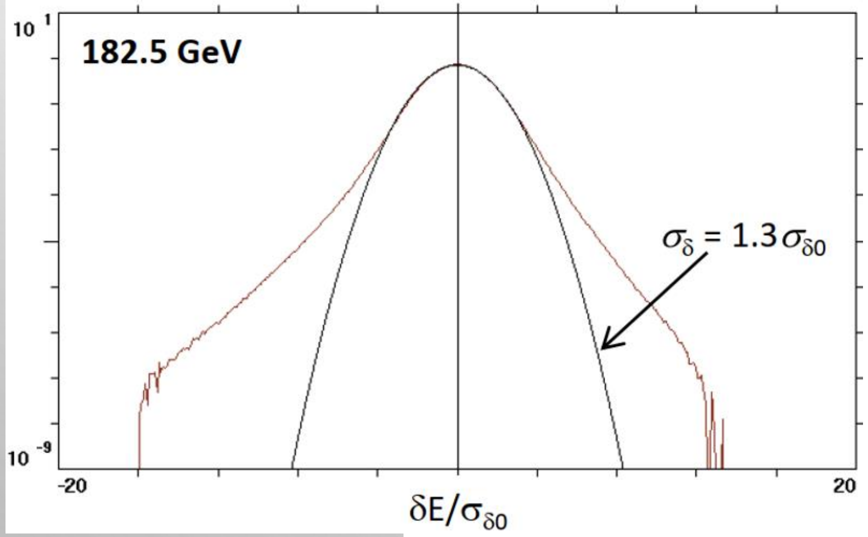


K. Oide

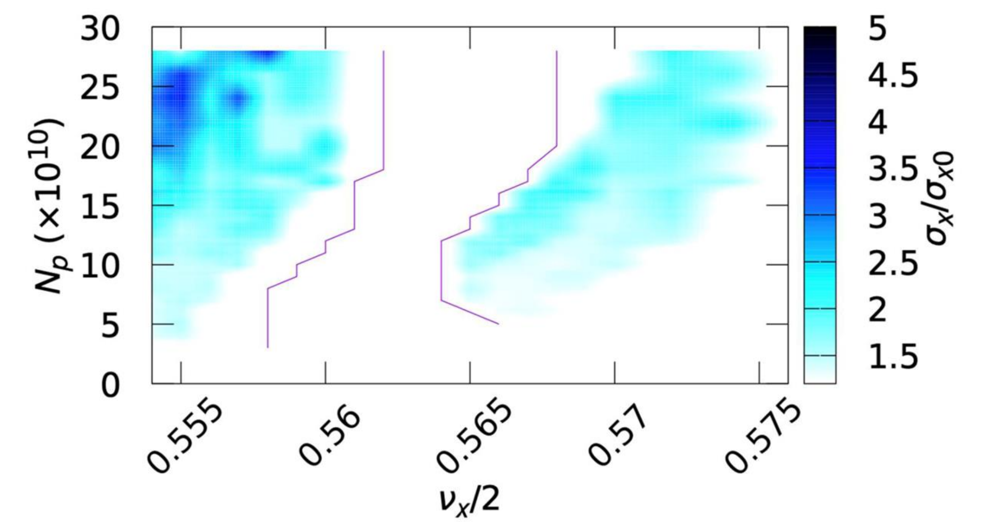
BEAM-BEAM AND COLLECTIVE EFFECTS

- **Beam-beam at high luminosity drives the ring parameters (limits Luminosity)**
- **Developing impedance model for the ring based on vacuum components**
- **Single bunch instabilities can be calculated based on impedance, beam-beam, and ring optics but there is complicated interplay**
- **Multibunch instabilities constrain bunch spacing**
- **Large ring circumference limits feedback gain**
    - **Developing integrated simulations for collective effects with feedback**

Beamstrahlung → Dynamic aperture



BB and impedance → Tunes and α_c



Y. Zhang, M. Zobov

F. Zimmermann, T. Raubenheimer FCC week 2022

FCC-ee COLLIDER OPTICS AND COLLECTIVE EFFECTS

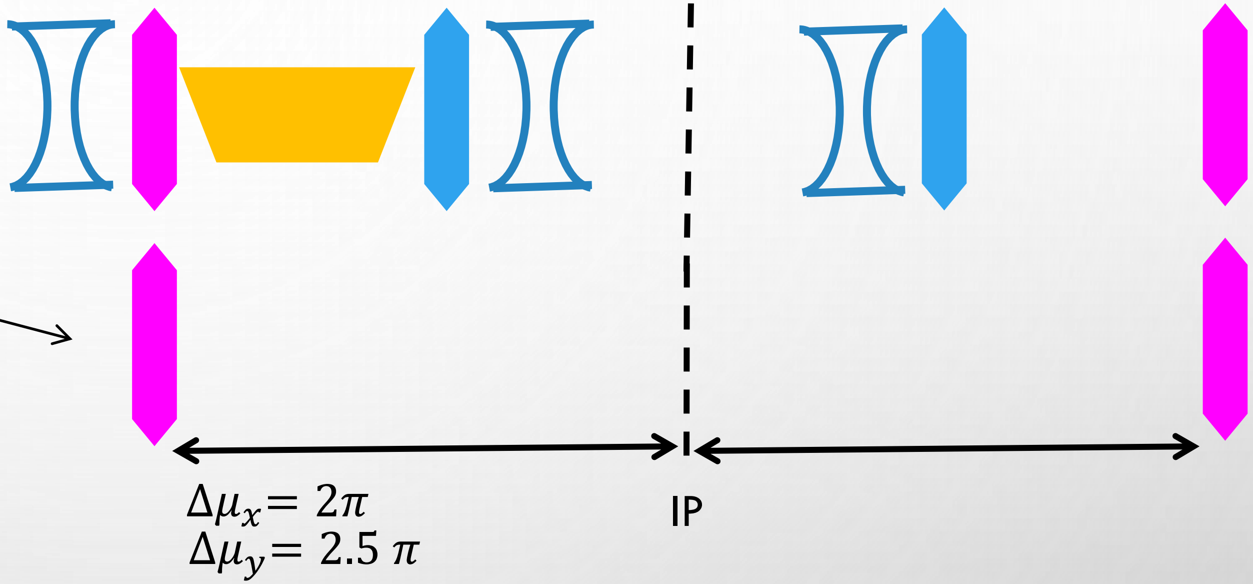
- **Novel 'virtual' crab waist**

combines local vertical chromaticity correction with crab waist of lepton factories

$$\beta_y^* \approx \frac{2\sigma_x}{\theta} \ll \sigma_z \qquad (\theta = \text{half crossing angle})$$

- Sextupoles settings are chosen to control vertical beam size chromatic aberrations at the IP
- Two external sextupoles control also the beam divergence at the IP (crab waist)

$\Rightarrow$ Luminosity is enhanced and beam beam resonances suppressed

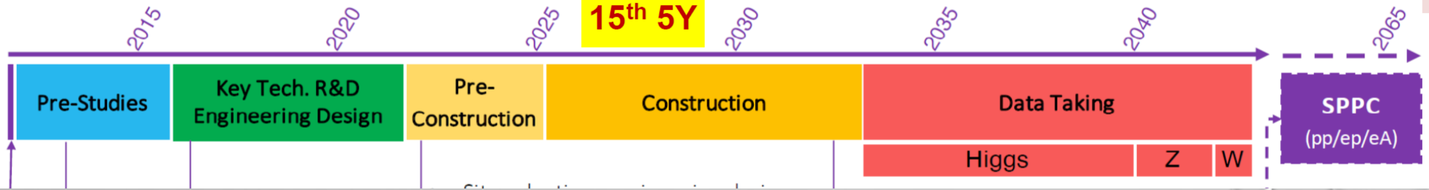


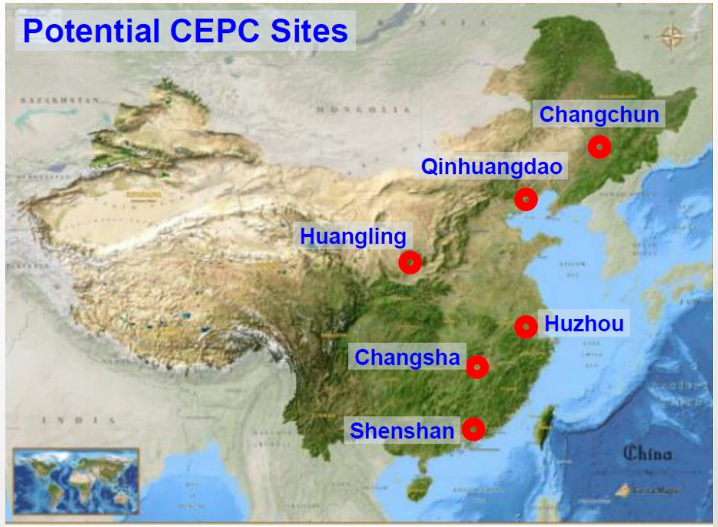
- Crab waist was demonstrated at DAFNE
- Crab waist is also being used at SuperKEKB

- Single bunch instabilities can be calculated based on impedance, beam-beam, and ring optics but there is complicated interplay
- Developing impedance model for the ring based on vacuum components and integrated simulations for collective effects with feedback

CEPC/SPPC

- ☐ 2013-2025: Key technology R&D, from CDR to TDR, site selection, international collaboration etc.
- ☐ Ideal case: Approval in the 15th Five-Year Plan, and start construction (~8 years)





Technically very similar project to FCC The start with lepton collider followed then by Hadron Collider **has been always the plan of China since 2013.**

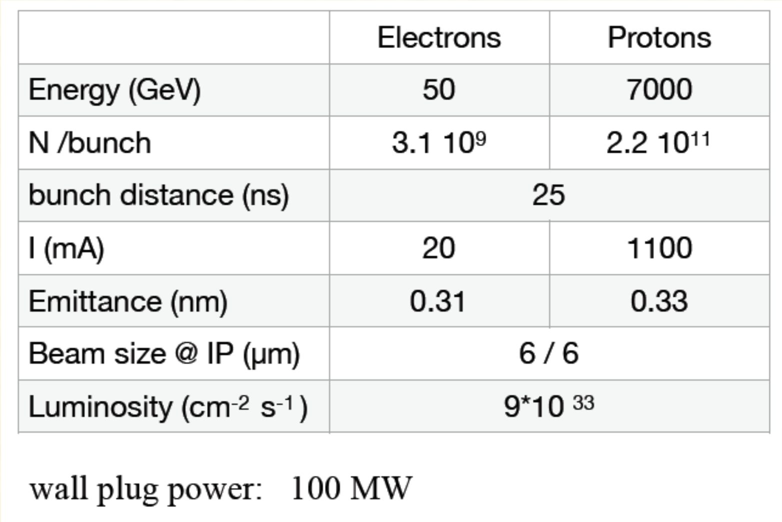
The choice for SC Magnet R&D is unique: IBS –iron based SC an HTS potentially **much lower cost,** but lower performance than REBCO.

LHeC

Design of a ERL based 50 GeV electron beam in collision with the 7 TeV LHC protons.

Fully Modular Concept

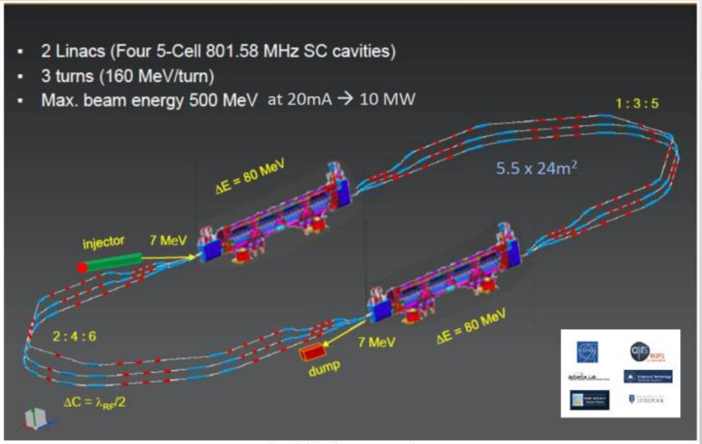
- Imbedded in a LHC Interaction Region
- Influence on optics & orbit compensated
- Flexibility of the LHC rings checked
- Asymmetric beam optics for ultimate e-p luminosity
- Non-colliding p-beam well separated
- Negligible beam-beam force on both proton beams



	Electrons	Protons
Energy (GeV)	50	7000
N /bunch	$3.1\ 10^{9}$	$2.2\ 10^{11}$
bunch distance (ns)	25	
I (mA)	20	1100
Emittance (nm)	0.31	0.33
Beam size @ IP (µm)	6 / 6	
Luminosity ($cm^{-2}\ s^{-1}$)	$9*10^{33}$	

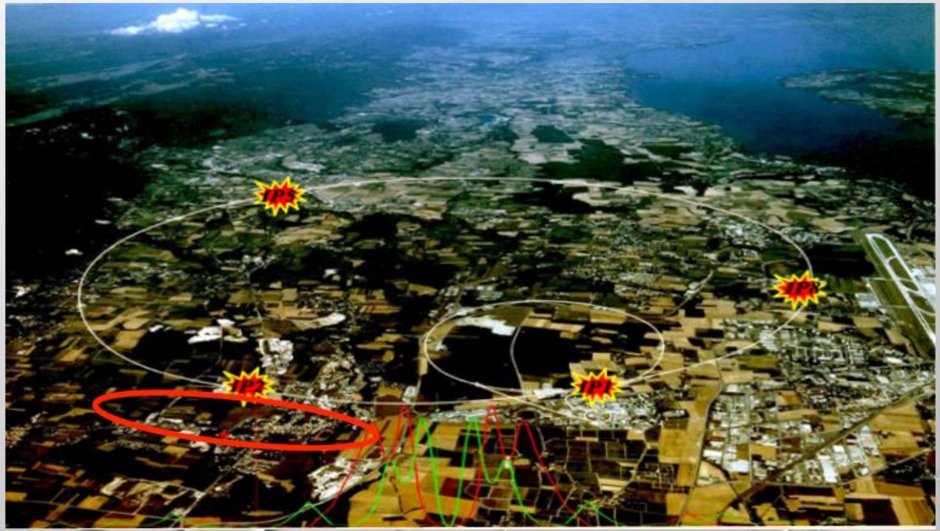
wall plug power: 100 MW

Low energy test facility PERLE



- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW

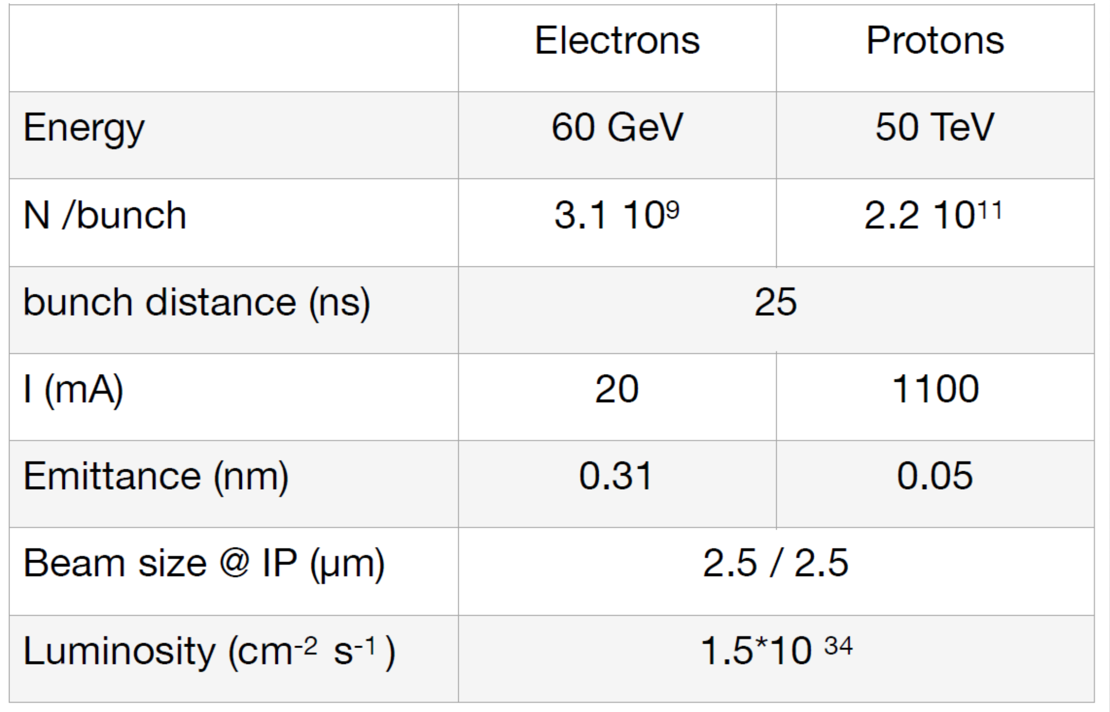
B. Holzer ICHEP 2022



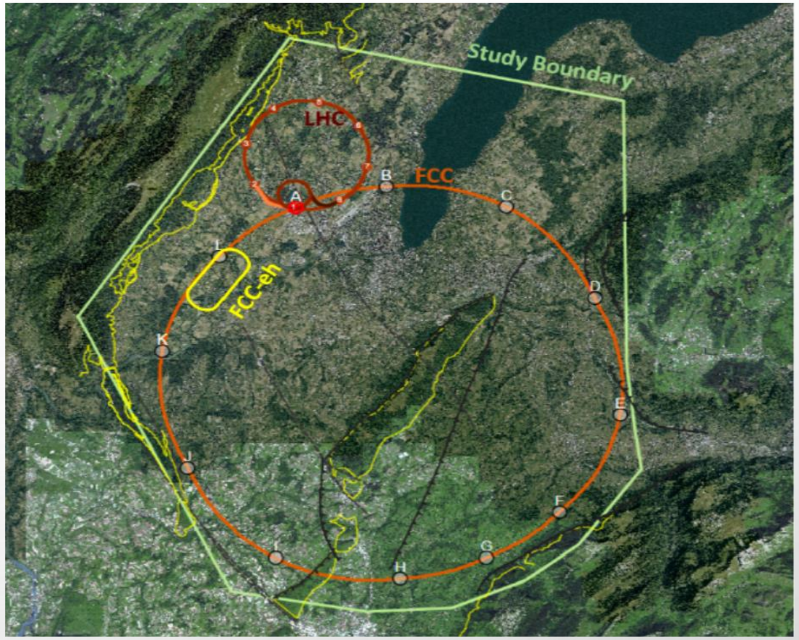
FCC-eh

ERL & IR can be imbedded at any straight section

60 GeV (electron) x 50 TeV (proton) → 1.5 TeV collider



	Electrons	Protons
Energy	60 GeV	50 TeV
N /bunch	3.1 10^9	2.2 10^{11}
bunch distance (ns)	25	
I (mA)	20	1100
Emittance (nm)	0.31	0.05
Beam size @ IP (μm)	2.5 / 2.5	
Luminosity (cm^{-2} s^{-1})	1.5*10^{34}	

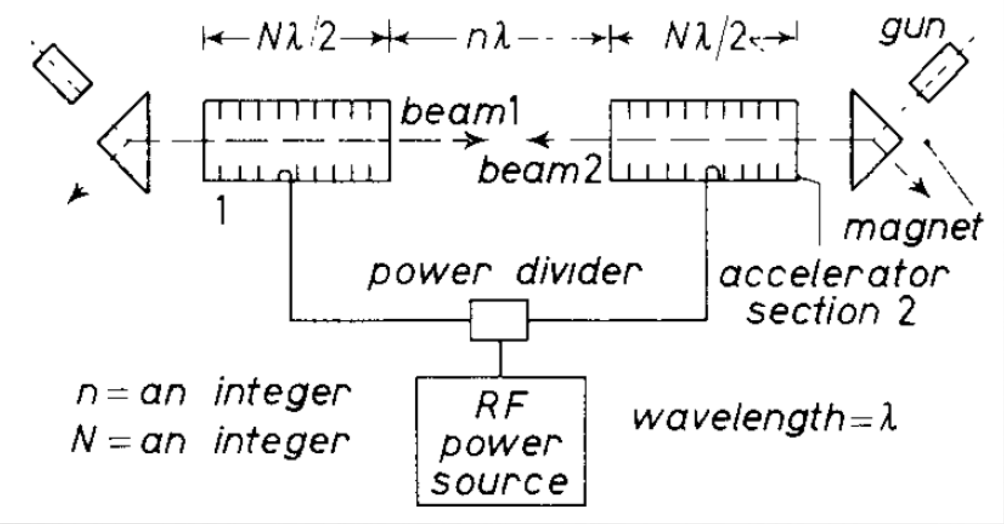


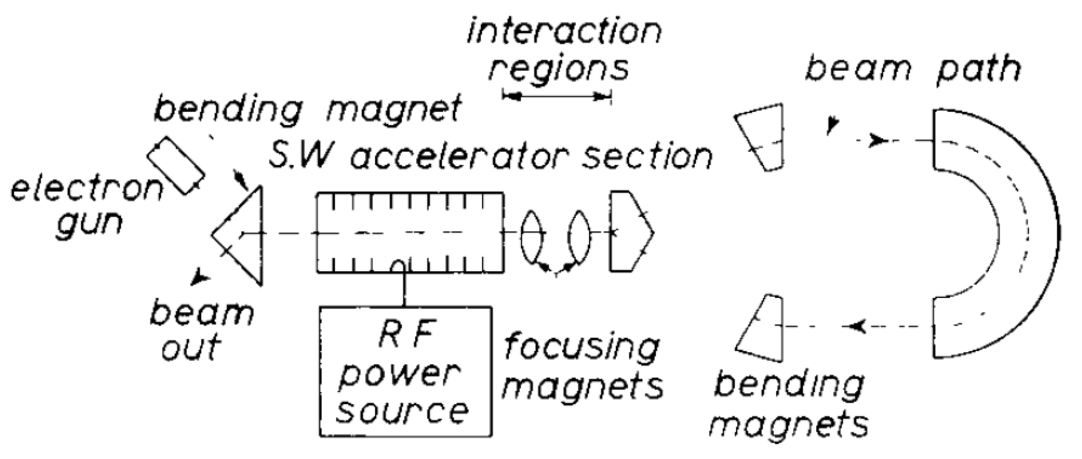
FCC-CDR: Eur. Phys. J. ST 228 (2019, 4.775)

B. Holzer ICHEP 2022

ERL PRINCIPLE

W. KAABI ICHEP 2022



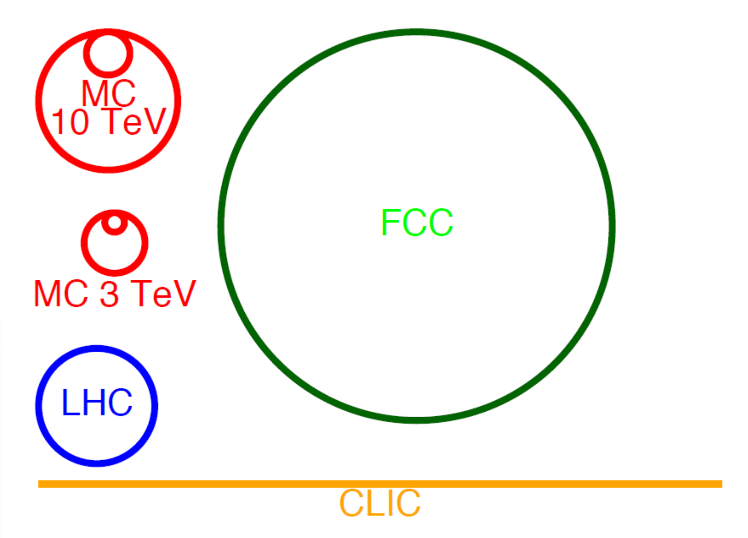


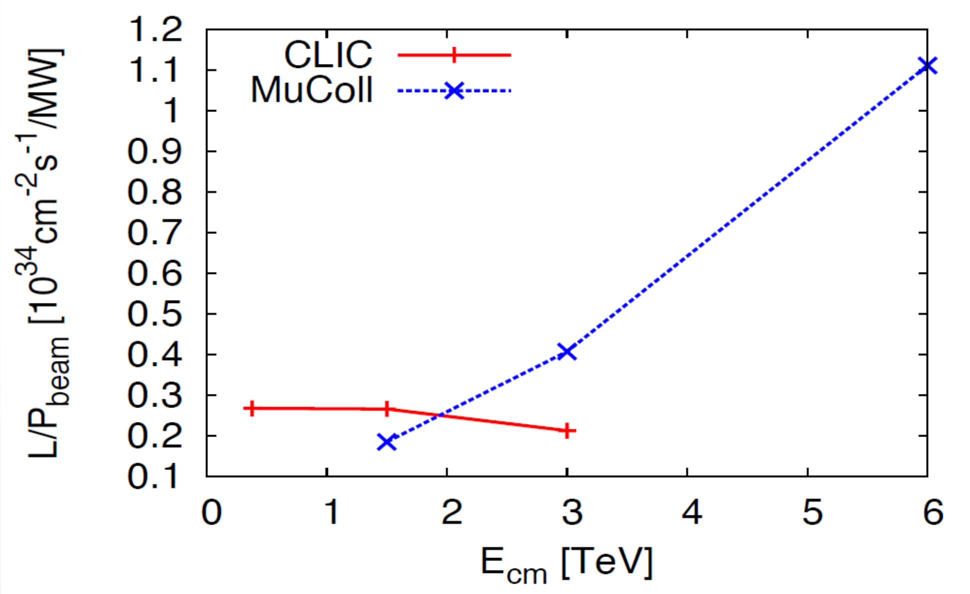
- ERL concept was proposed first in **1965 by Maury Tigner** [1] (Cornell University) for colliders…

[1] *M. Tigner: "A Possible Apparatus for Electron Clashing-Beam Experiments", Il Nuovo Cimento Series 10, Vol. 37, issue 3, pp 1228-1231,1 Giugno 1965*

- The concept was experimented first in 1986 at SCA/FEL in Stanford, accelerating beams at rather low power.
- The concept become really viable with recent advances in SRF technology in the last decades, quantified by reaching high cavity quality factors ($Q_0 \geq 10^{10}$) enabling high average current operation.

MUON COLLIDER SUSTAINABILITY





Muon Collider:

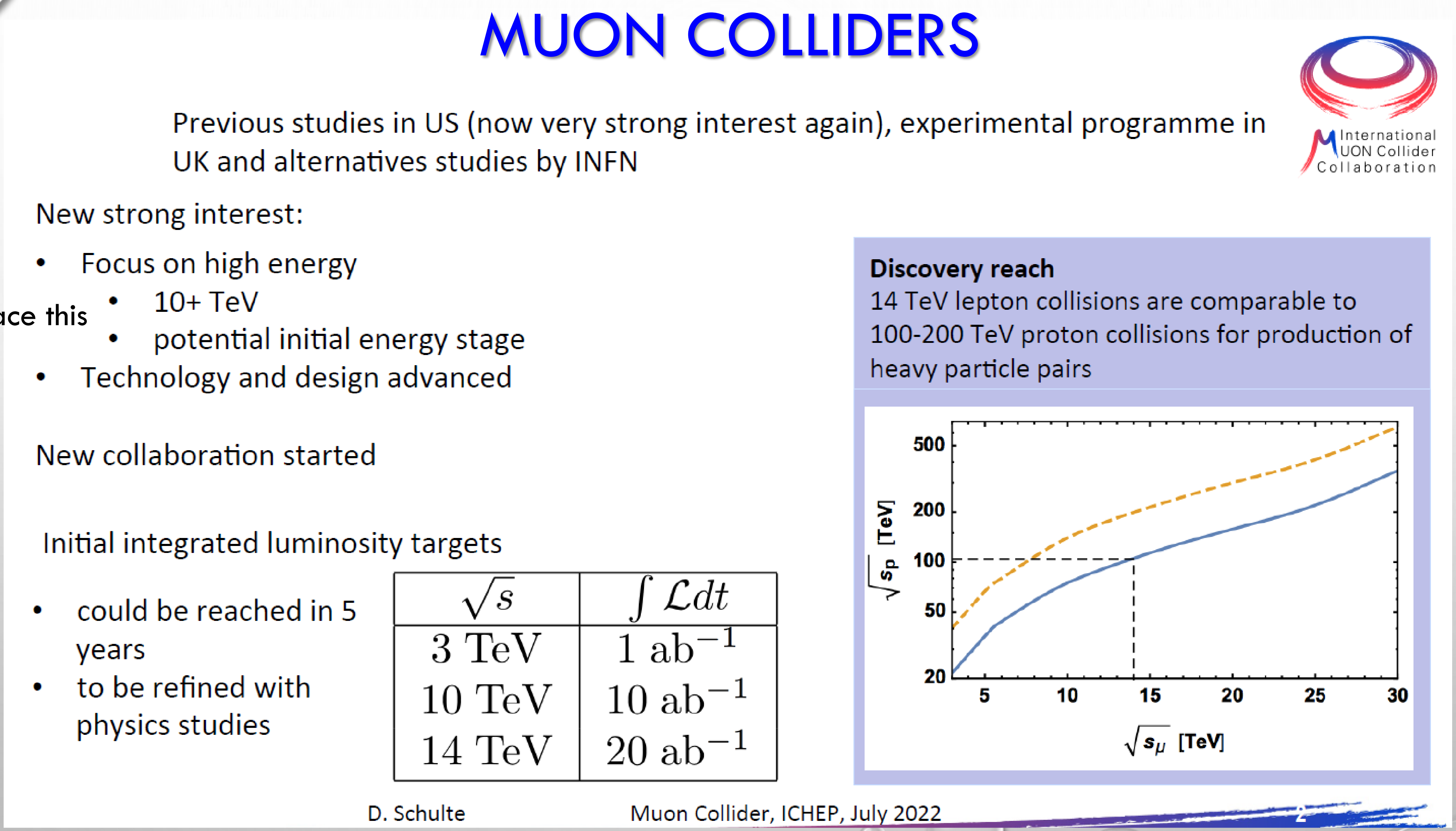
Acceleration and collision in multiple turns in rings promises

- **Power efficiency**
- **Compact tunnels,** 10 TeV similar to 3 TeV CLIC
- **Cost effectiveness**
- **Natural staging** is natural

Synergies exist (neutrino/higgs)

Unique opportunity for a **high-energy, high-luminosity lepton collider**

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}



MUON COLLIDERS

International
MUON Collider
Collaboration

Previous studies in US (now very strong interest again), experimental programme in UK and alternatives studies by INFN

New strong interest:

- Focus on high energy
  - 10+ TeV
  - potential initial energy stage
- Technology and design advanced

Replace this

New collaboration started

Initial integrated luminosity targets

- could be reached in 5 years
- to be refined with physics studies

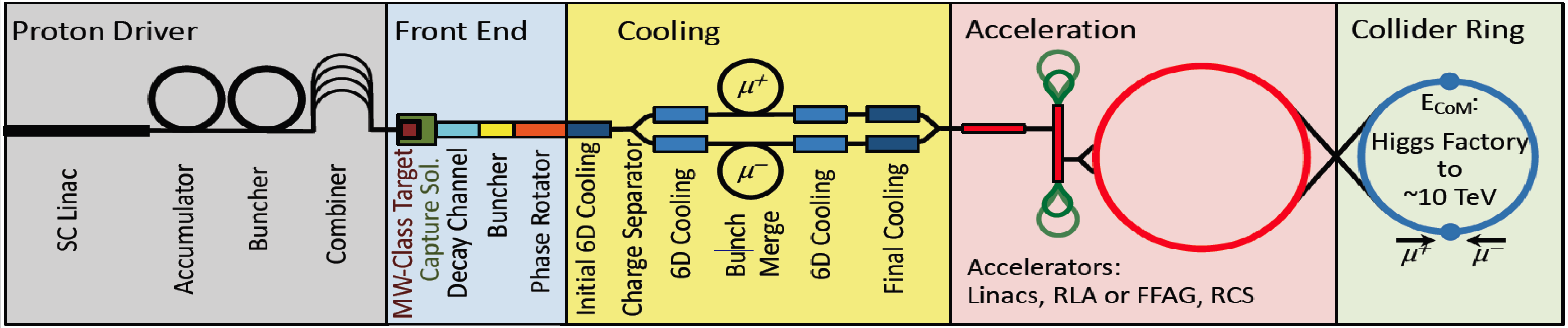
$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	$1\ \mathrm{ab}^{-1}$
10 TeV	$10\ \mathrm{ab}^{-1}$
14 TeV	$20\ \mathrm{ab}^{-1}$

Discovery reach
14 TeV lepton collisions are comparable to 100-200 TeV proton collisions for production of heavy particle pairs

D. Schulte Muon Collider, ICHEP, July 2022

MOUNS COLLIDER SCHEME

Would be easy if the muons did not decay: lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short, intense proton bunch

Ionisation cooling of muon in matter

Acceleration to collision energy

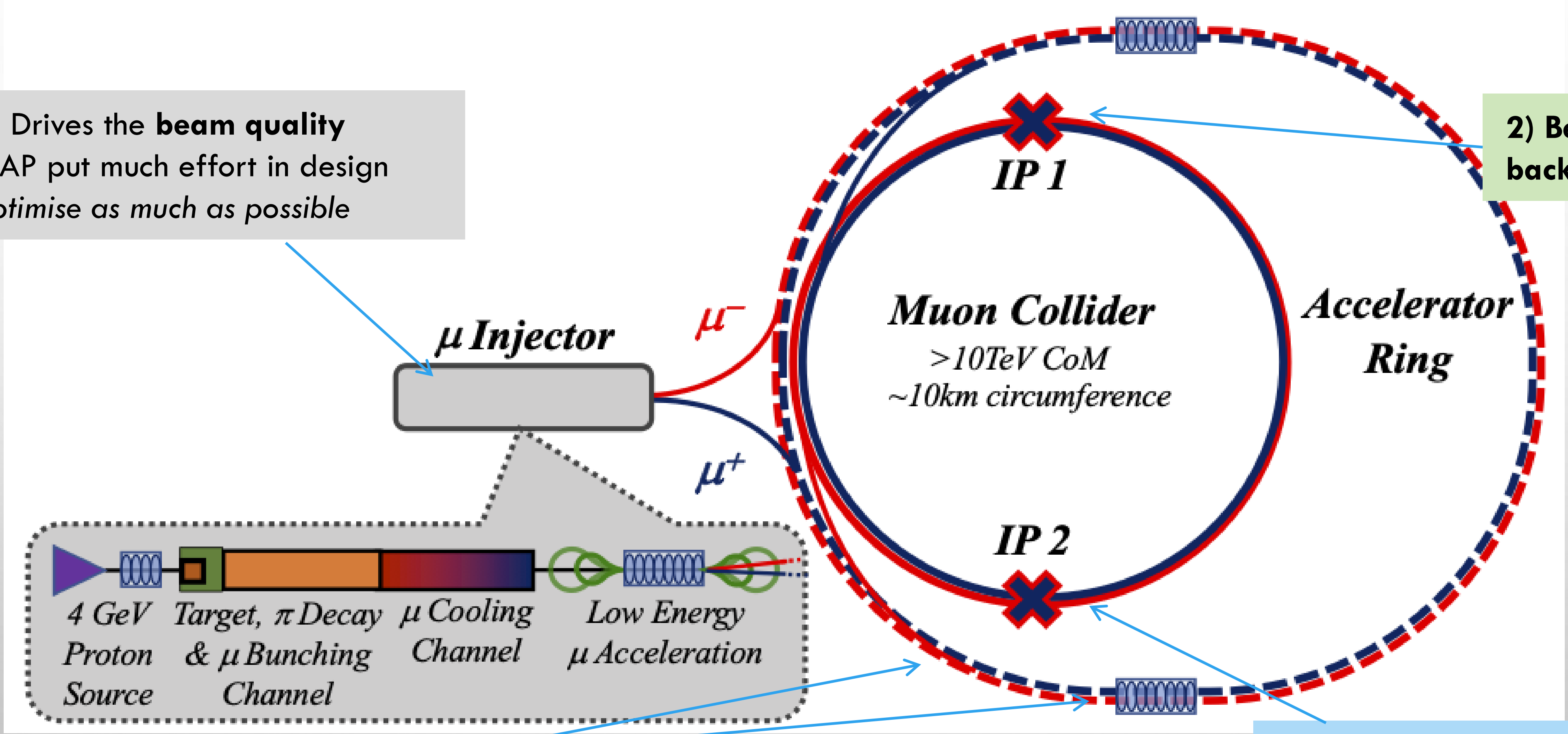
Collision

Protons produce pions which decay into muons
muons are captured

KEY CHALLENGES

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible

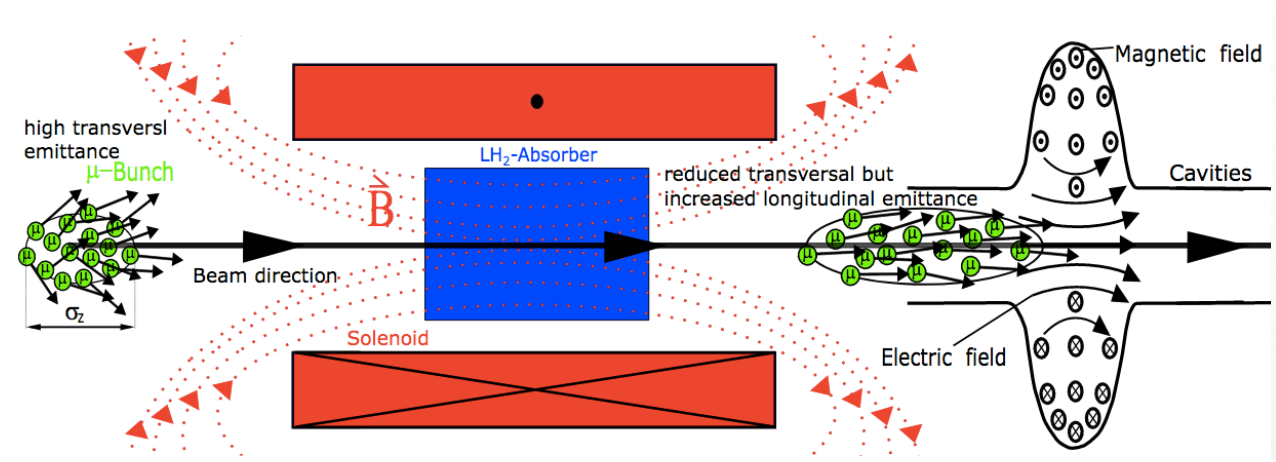
2) Beam-induced background

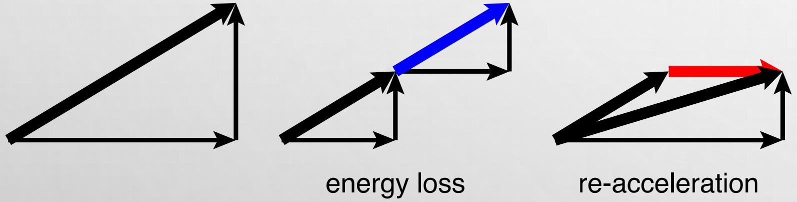


3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

1) Dense neutrino flux
mitigated by mover system
and site selection

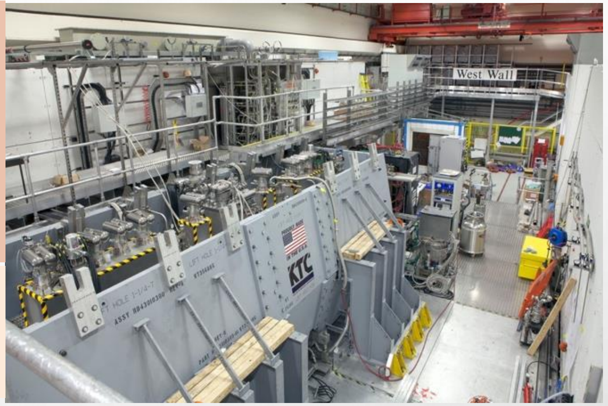
COOLING PRINCIPLE AND R&D



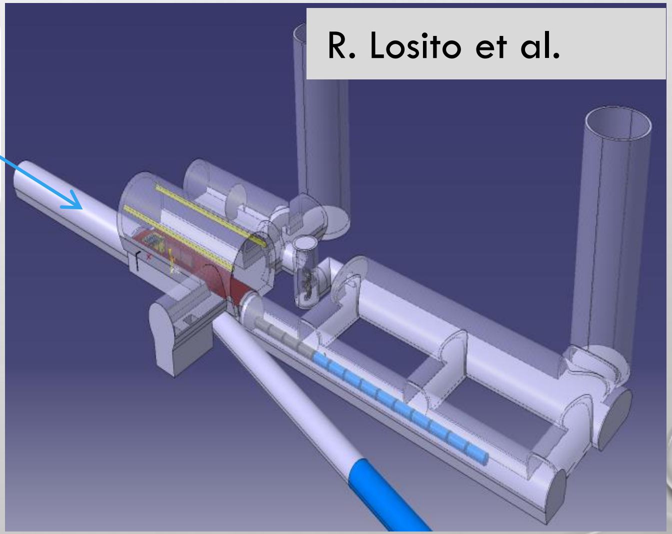


Principle of ionization cooling with no RF has been demonstrated in **MICE at RAL**

Nature vol. 578, p. 53-59 (2020)



Needs cooling of orders of magnitude in 6D
Demonstrated 10% ε reduction in 2D (consistent with prediction)



R. Losito et al.

Planning **demonstrator facility** with muon production target and cooling stations

Suitable site on CERN land exists that can use PS proton beam

- could combine with NuStorm or other option

Other sites should be explored (FNAL?)