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
  - CepC/SppC
  - LHeC/FCC-eh
  - Muons colliders

High Luminosity-LHC

A peak luminosity of $L_{peak} = 5\times10^{34}$ **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:**

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

Ultimate Integrated $L_{int\ ult} \sim 4000$ 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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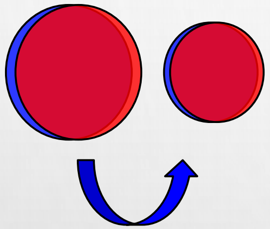
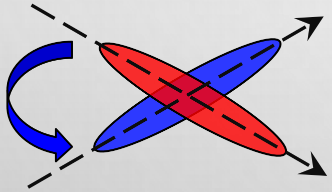
LEVELLING MECHANISMS

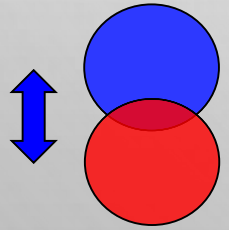
- Levelling techniques will be a vital ingredient for HL-LHC operation and have been used successfully in operation:



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

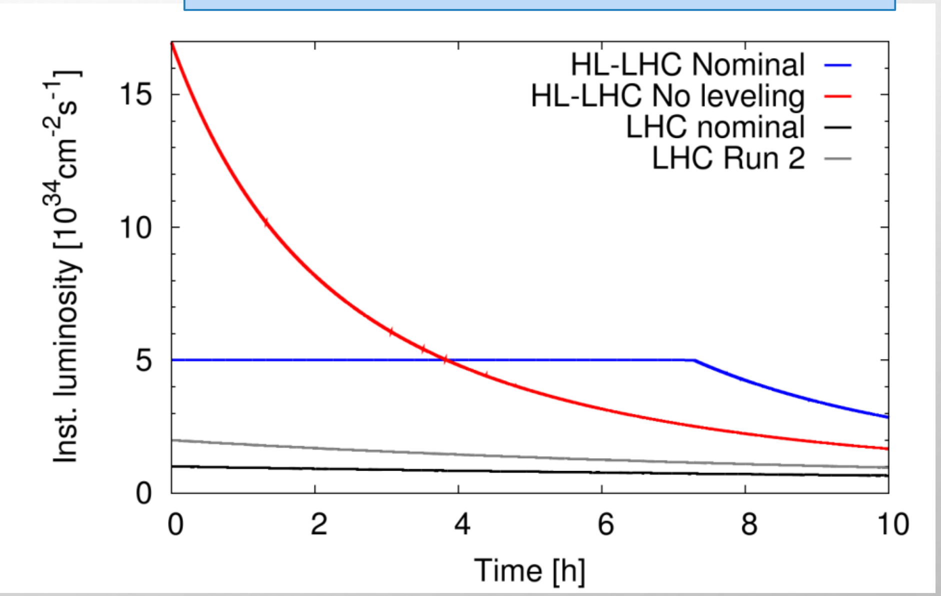


Crossing angle: Might be needed to optimize beam lifetime and as mean to reduce pile-up density given the reduced crabbing angle. Operational in 2017



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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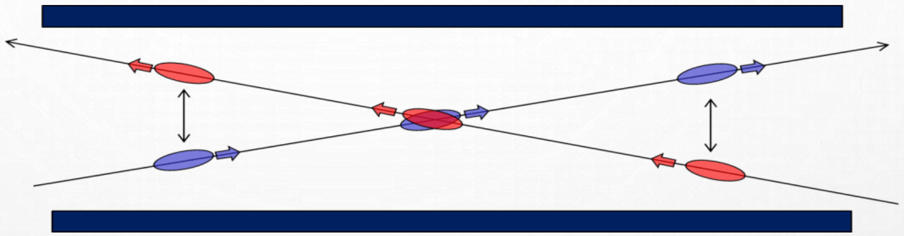
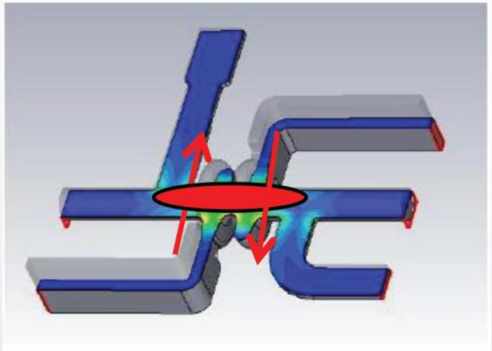
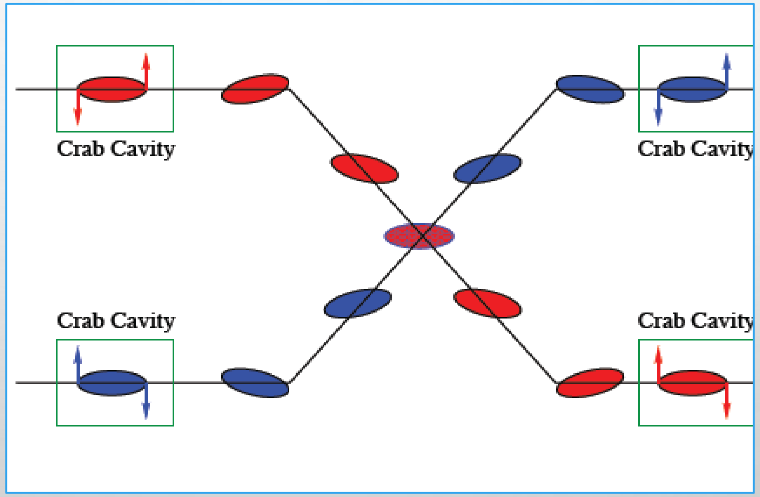
COMPENSATION OF GEOMETRIC REDUCTION FACTOR

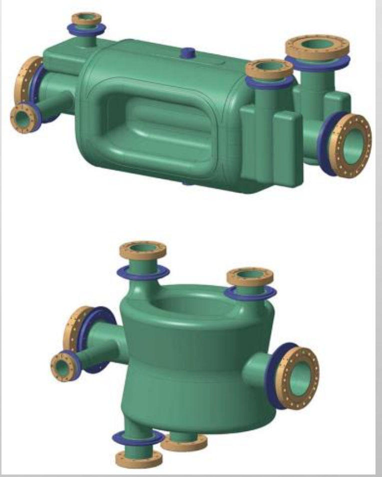
$$L = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon}\cdot F \qquad \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$





- 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

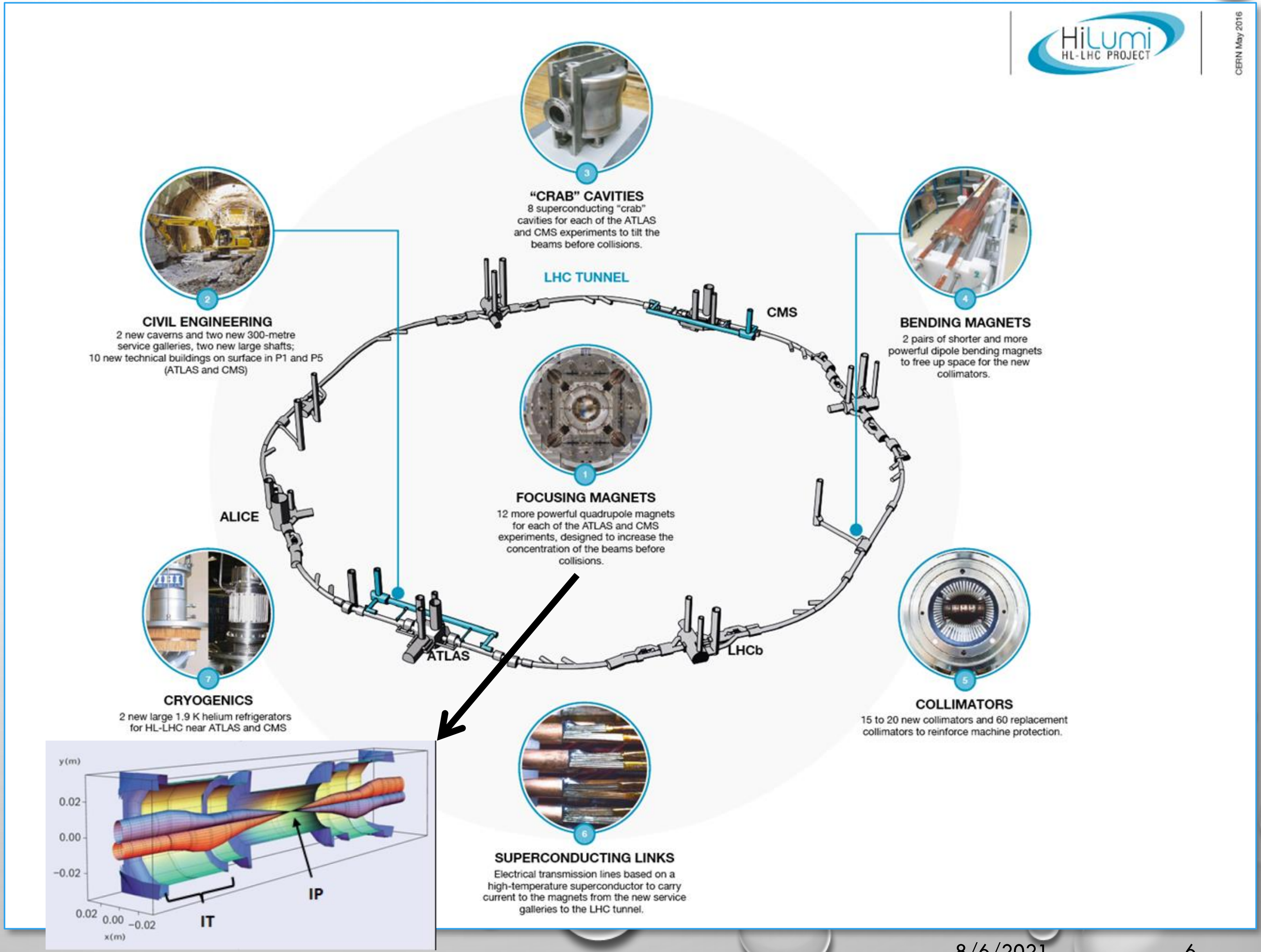
~1.2 KM OF NEW HARDWARE IN LHC

- New final focus quadrupoles around ATLAS and CMS:

  Ni_3Sn technology (See H. Felice lecture) for more aperture

  Radiation damage
- Matching section: separation dipoles, first double aperture magnet and correctors (See H. Felice Lecture)
- Crab Cavities

- 11 T Nb3Sn dipole in DS for collimation
- Cryogenics plants
- SC links and rad. Mitigation



FUTURE CIRCULAR COLLIDERS

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

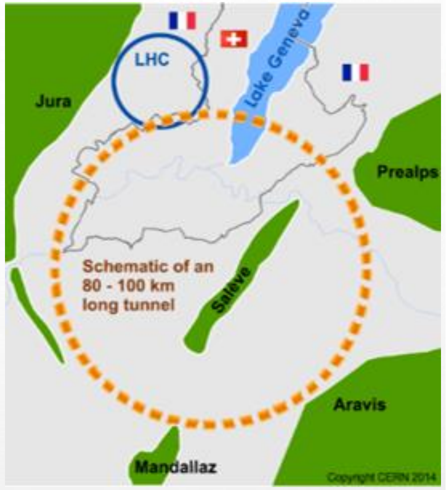
- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements
- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC*-ee),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from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

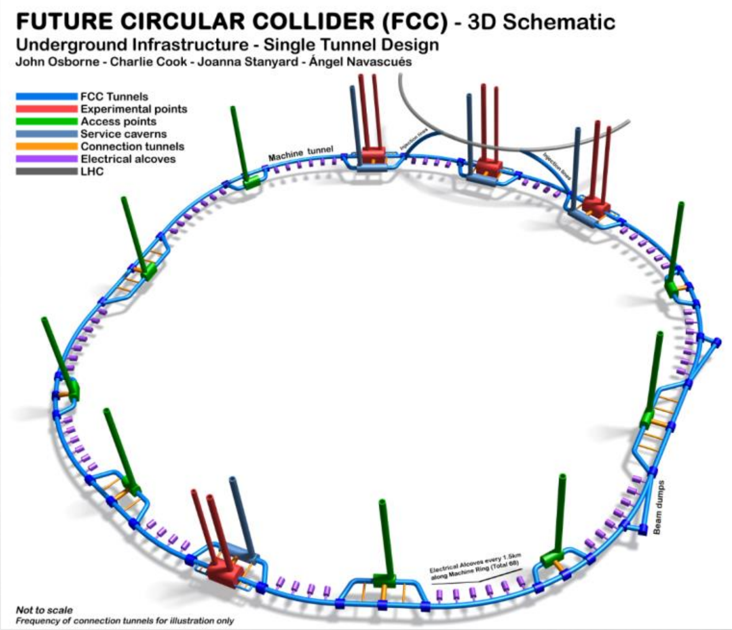
CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

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
Power: ~580 MW (hh) ≤ 340 MW (ee)



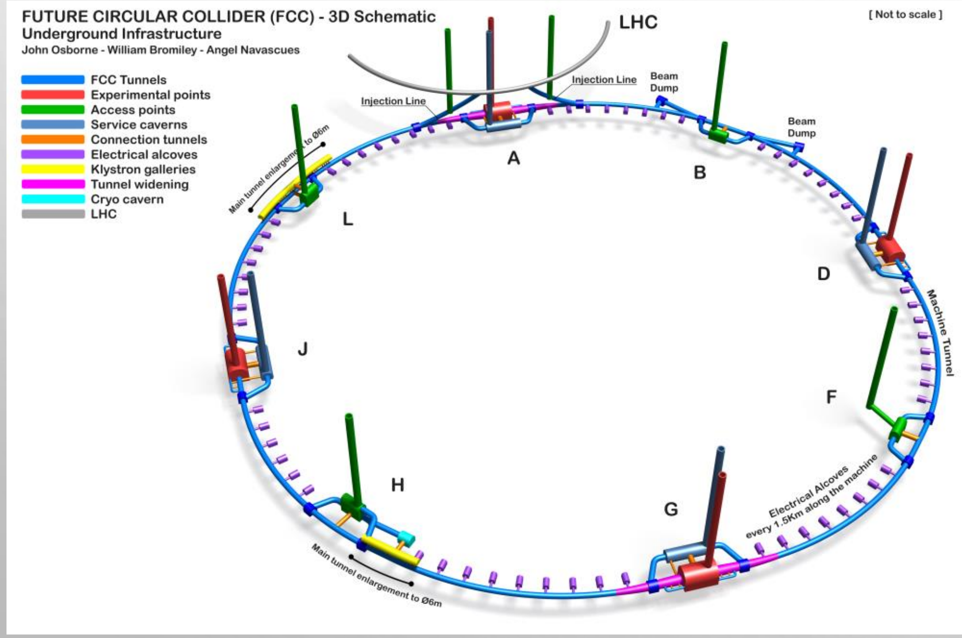


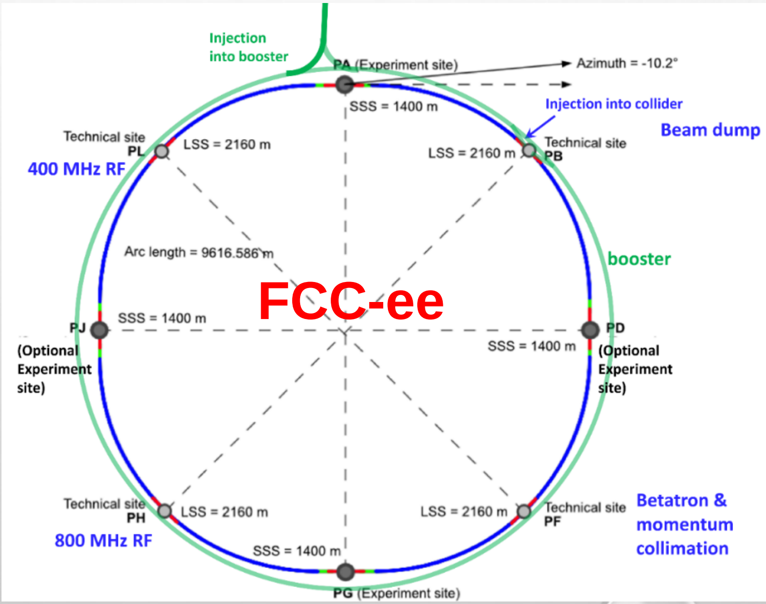
	LHC	HL-LHC	FCC-hh Initial	FCC-hh Ultimate
c.m. Energy [TeV]	14		100	
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0	< 30.0
Optimum integrated lumi / day [fb^{-1}]	0.47	2.8	2.2	8
Circumference [km]	26.7		97.75	
Arc filling factor	0.79		0.8	
Straight sections	8×528		6×1400 m $+ 2 \times 2800$ m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

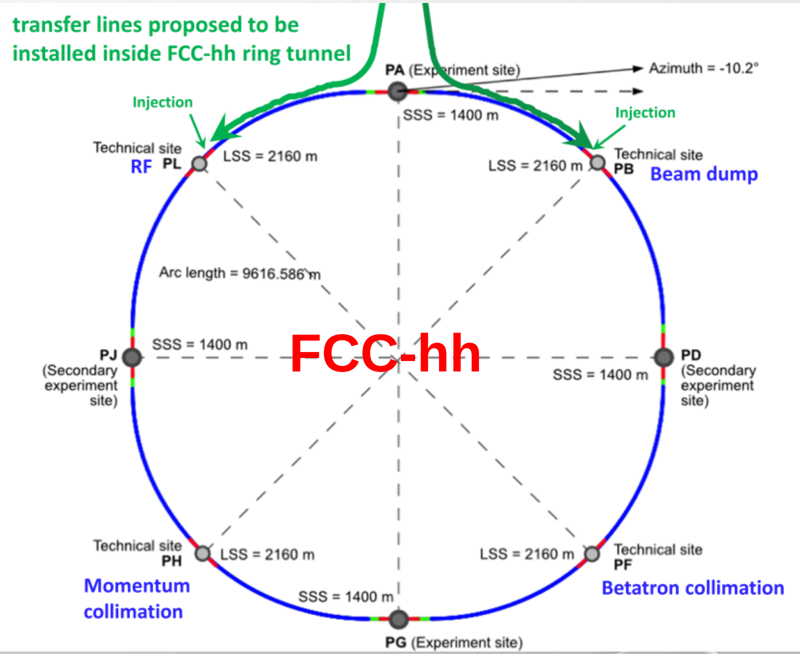
PREPARING FOR NEXT STRATEGY

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







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FEASIBILITY STUDY GOALS AND ROADMAP

Highest priority goals:

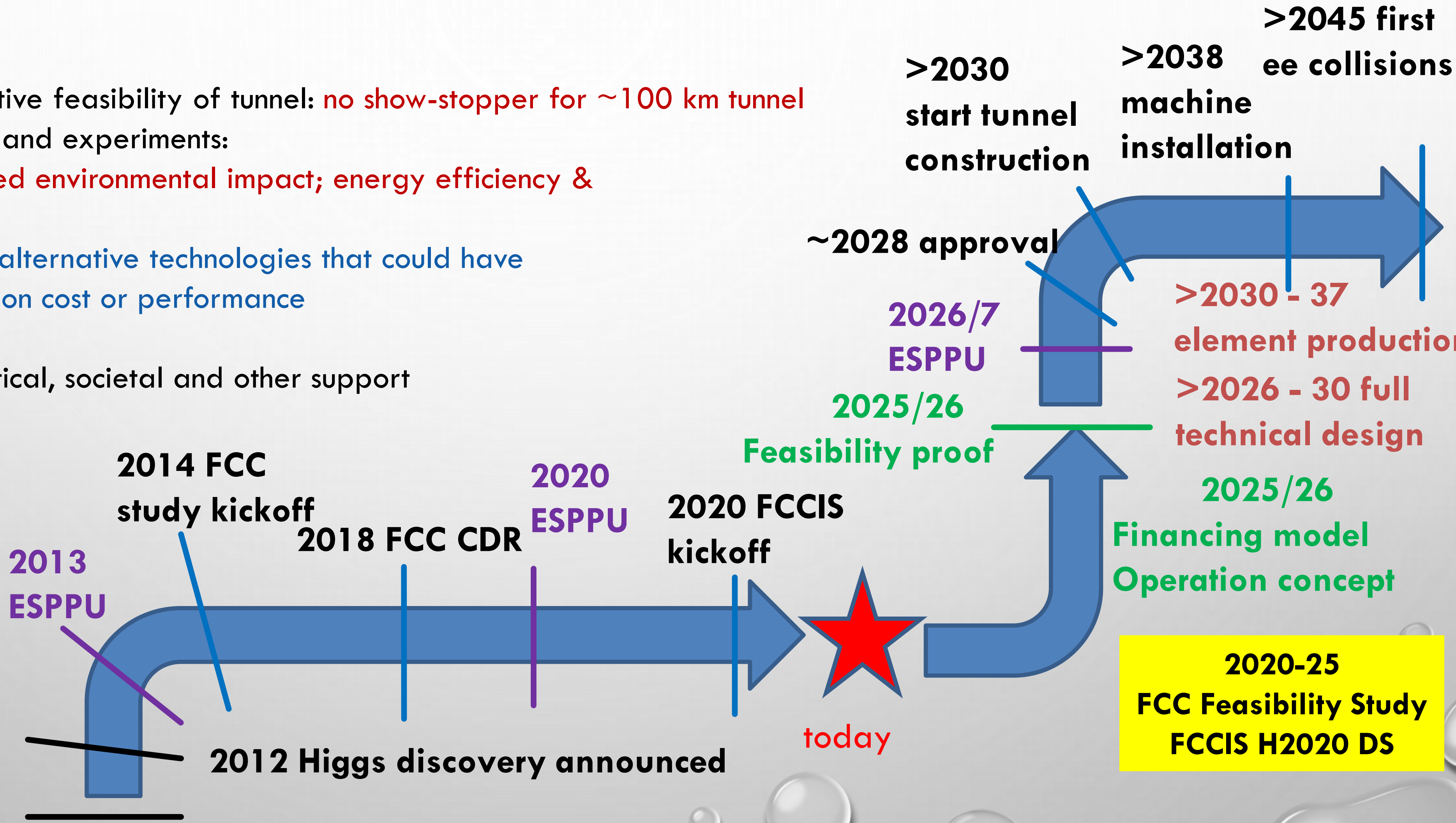
Financial feasibility

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

Technologies of machine and experiments:

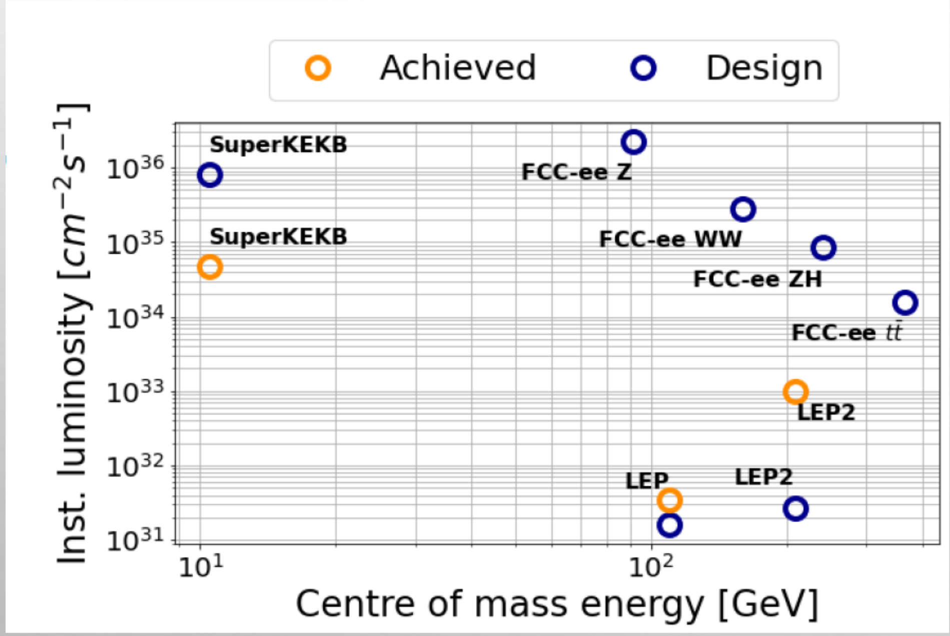
- magnets; minimized environmental impact; energy efficiency & recovery
- Establish a list of alternative technologies that could have significant impact on cost or performance

Gathering scientific, political, societal and other support

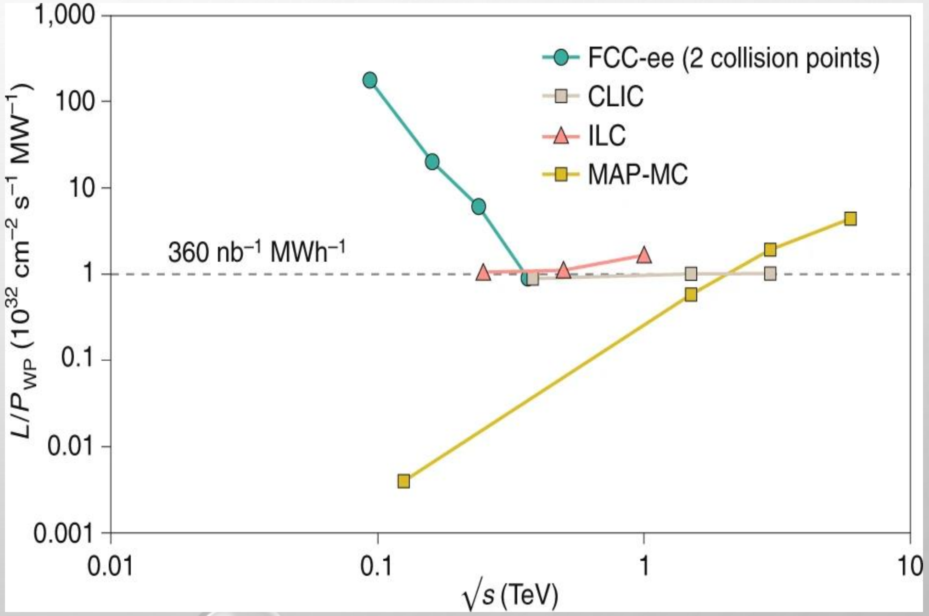


FCC-ee LUMINOSITY

- **FCC-ee efficient L from Z to $t\bar{t}$**
  - Thanks to twin-aperture magnets, SRF, efficient RF power, top-up injection
- **Accumulate >2.5 ab^{-1} with ~0.5×10^{6} H produced per IP**
- **Accumulate >75 ab^{-1} with ~2×10^{12} Z produced per IP**
- **Run plan naturally starts at Z but is under discussion**



Luminosity vs. electricity consumption



FCC-ee PARAMETERS

Parameter [4 IPs, 91.1 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	40
bunch intensity [10^{11}]	2.43	2.91	2.04	2.37
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400 / 800 MHz [GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004 / 0.159	0.011 / 0.111	0.0187 / 0.129	0.093 / 0.140
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	1.95 / 2.75
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.26	1.25
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

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

BASIC DESIGN CHOICES

Double ring e+e- collider with circumference of 91 km

Two or four experiments

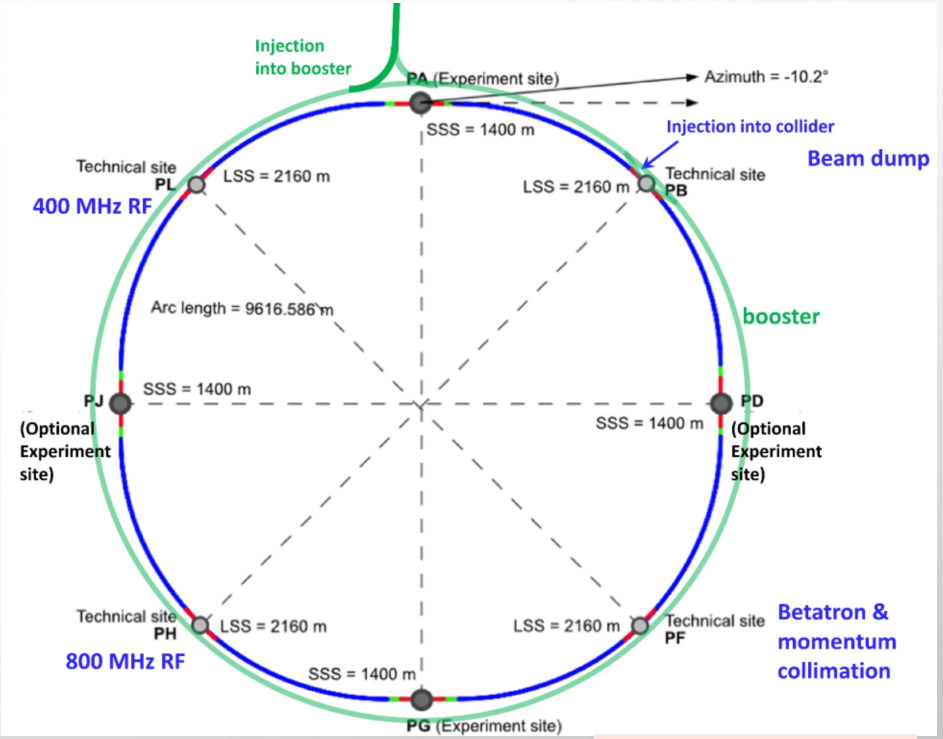
- **Asymmetric IR layout and optics** to limit synchrotron radiation towards the detector
- Horizontal crossing angle of 30 mrad and crab waist collision scheme

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**



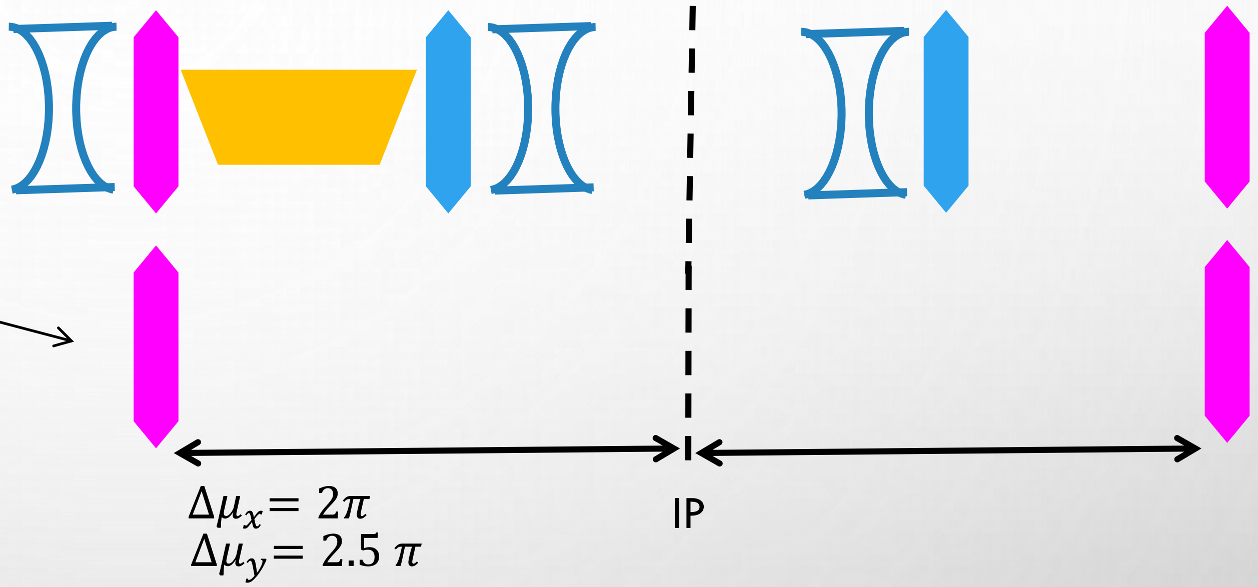
K. Oide, J. Gutleber

M. Hofer ICHEP 2022

FCC-ee COLLIDER OPTICS AND COLLECTIVE EFFECTS

- **Novel 'virtual' crab waist**

combines local vertical chromaticity correction with crab waist of lepton factories



$$\beta_y^* \approx \frac{2\sigma_x}{\theta} \ll \sigma_z$$ ($\theta =$ 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)

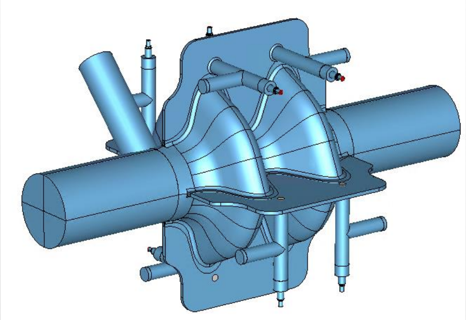
$\Rightarrow$ Luminosity is enhanced and beam beam resonances suppressed

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

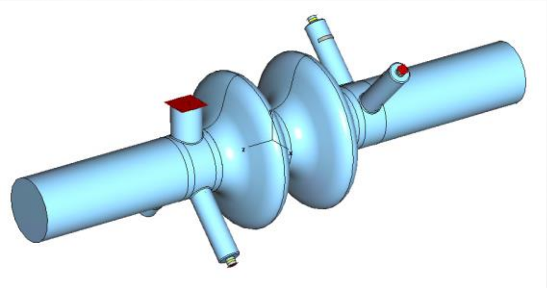
- Single bunch instabilities can be calculated based on impedance, beam-beam, and ring optics but there is complicated interplay
- Developing impedance model for the ring based on vacuum components and integrated simulations for collective effects with feedback

FCC-ee KEY TECHNOLOGIES: SRF-CAVITIES

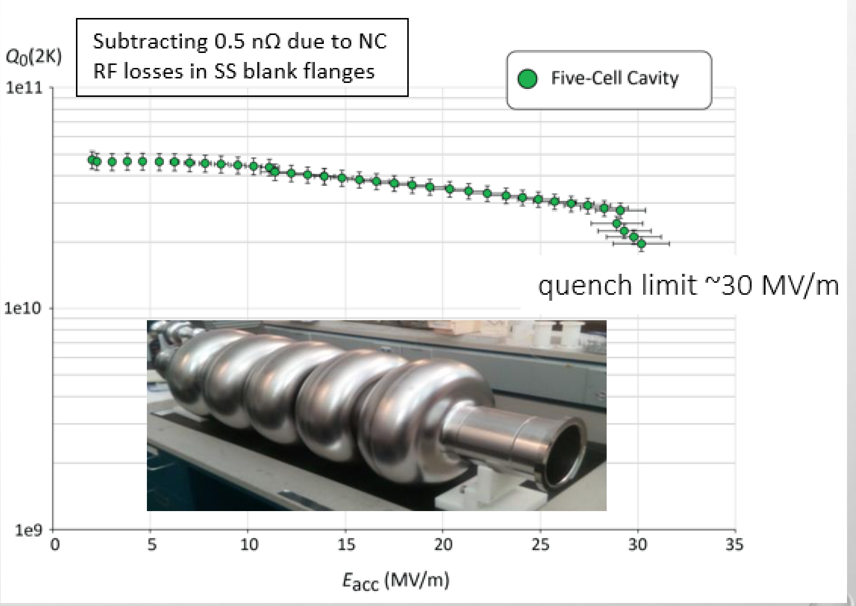
- **SRF technology building on LHC studies and collaborative R&D** (F. Peauger et al.)
  - 5-cell 800 MHz cavity without damping built and tested at 2K by Jefferson lab with excellent results
  - 400 MHz cavities based on LHC studies of Cu-coated Nb cavities at 4.5K
  - Alternative slotted waveguide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



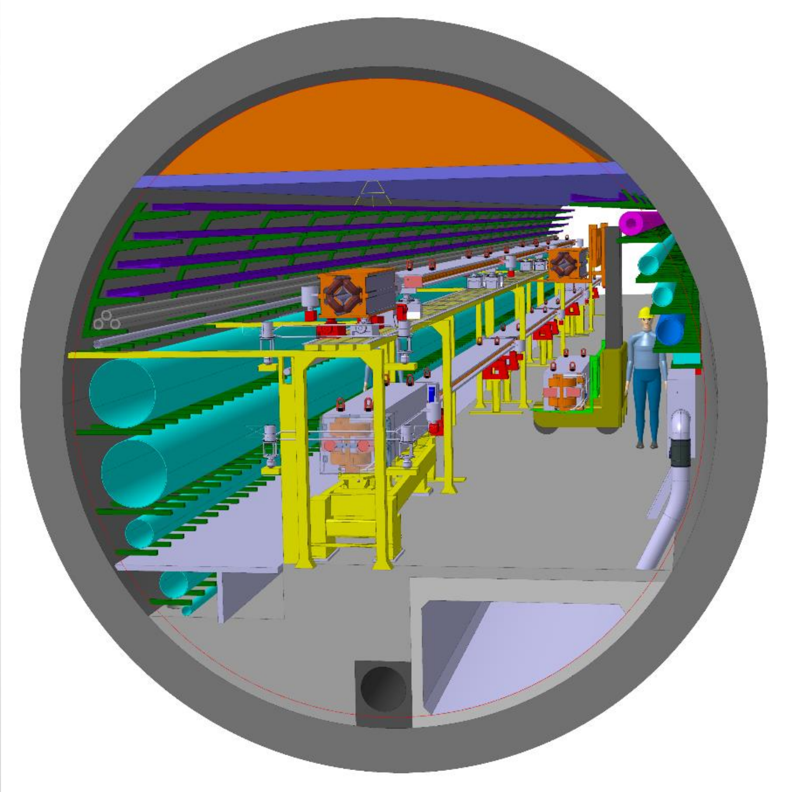
- **RF placement optimized for infrastructure requirements** (F. Valchkova-Georgieva et al)
- **Single RF region for Z and WW operation to reduce uncertainty on centre-of-mass energy** (J. Keintzel et al.)

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

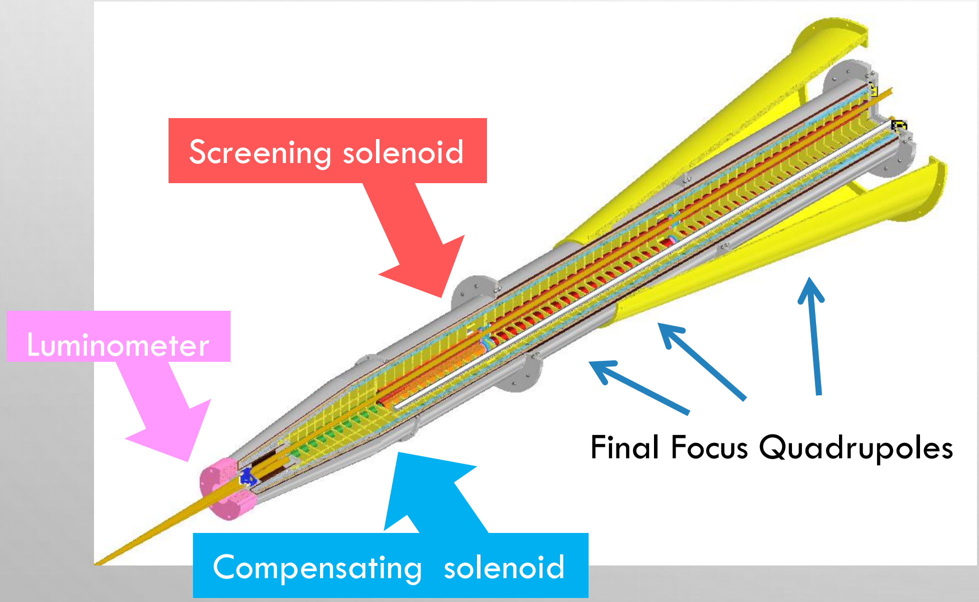
F. Carra et al

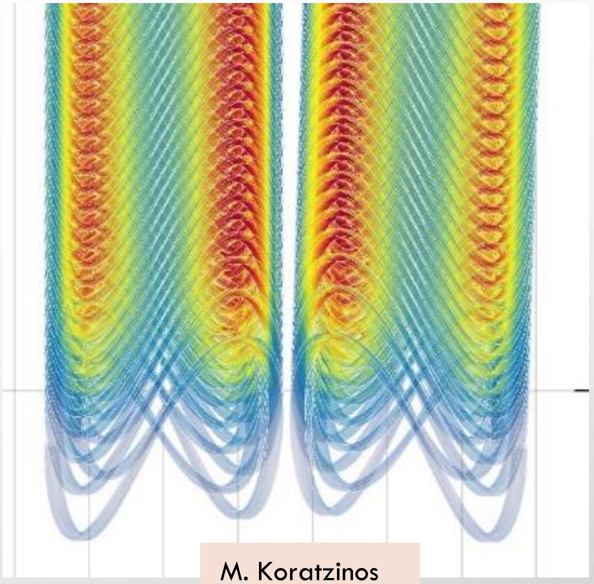


Arc perspective view, F. Valchkova-Georgieva

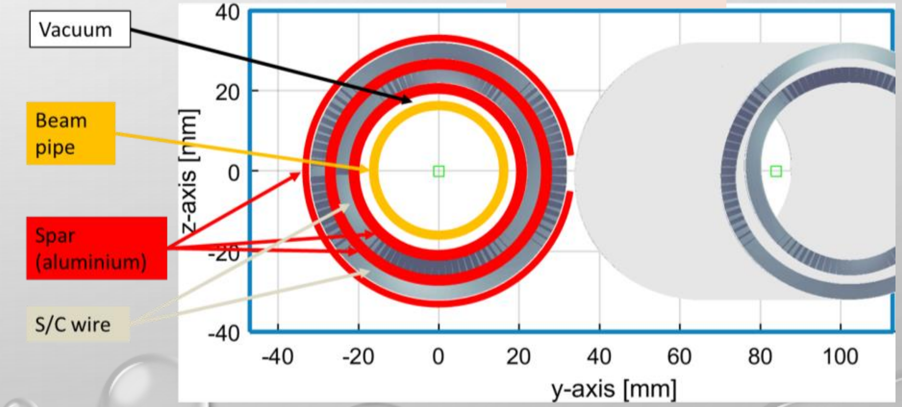
FCC-ee KEY TECHNOLOGIES: INTERACTION REGION

- **Canted-Cosine-Theta magnets w/ fringe fields fully compensated**
  - 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, diagnostic…
  - Mock-up under discussion





M. Koratzinos



FCC-hh parameters

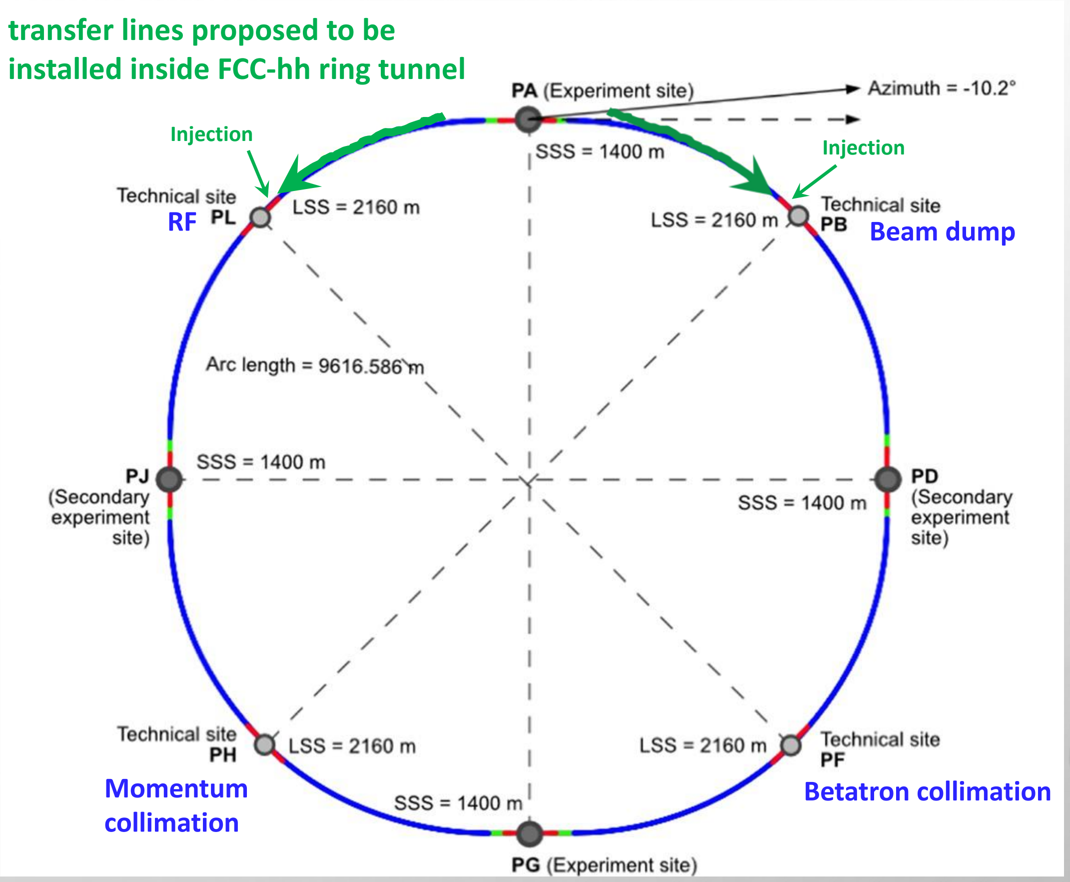
parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	91		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	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

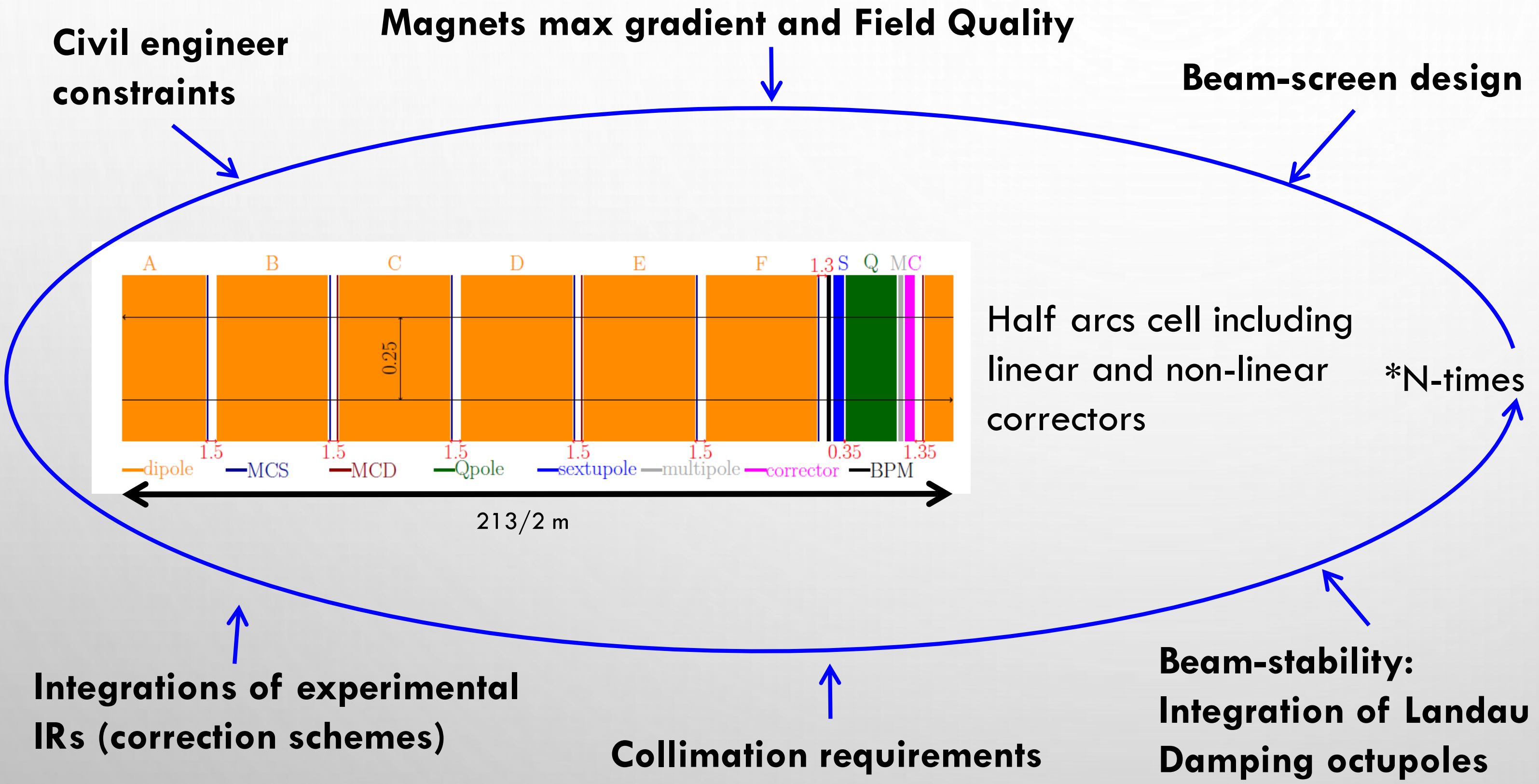
BASIC DESIGN CHOICES

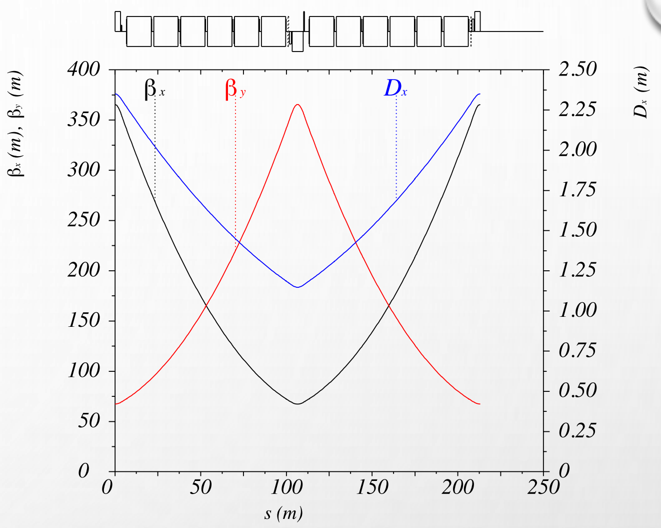
- **Exact four-fold symmetry**
- Four experiments (A, D, G, & J)
- Two collimation insertions
  - betatron cleaning (F)
  - momentum cleaning (H)
- Extraction insertion + injection (B)
- RF insertion + injection (L)
- **Last part of transfer lines in the ring tunnel, using normal-conducting magnets**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

- **Number of arc cells: 42**
- **Cell length: 215.3 m**
- **Length of experimental straight sections: 1400 m**
- **Length of technical straight sections: 2160 m**
- **Length of circumference: 91.1 km**

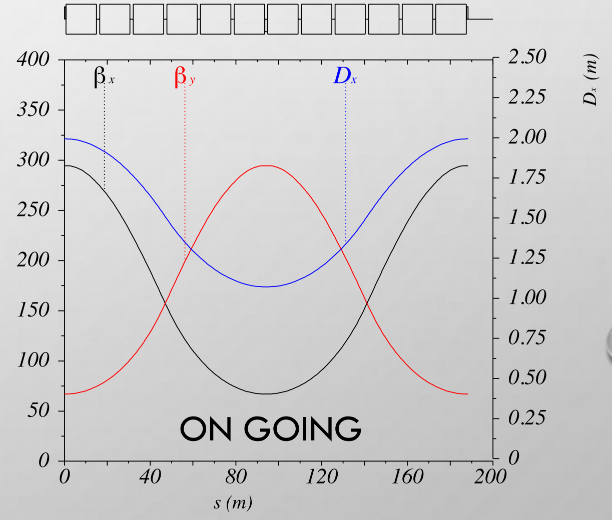


ARC CONCEPT





Nominal FCC-hh FODO cell



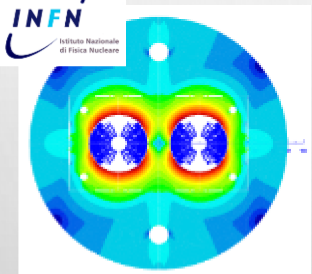
FCC-hh combined-function cell

FCC-hh KEY TECHNOLOGIES: HIGH FIELD MAGNETS

Need 16 T to reach 50 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 H. Felice Lecture)

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

INFN Istituto Nazionale di Fisica Nucleare



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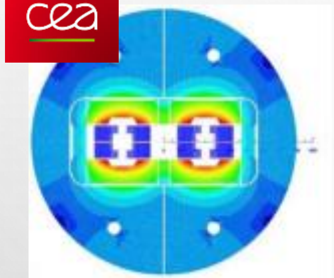
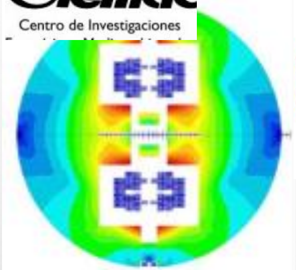
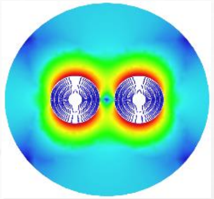


Ciemat Centro de Investigaciones



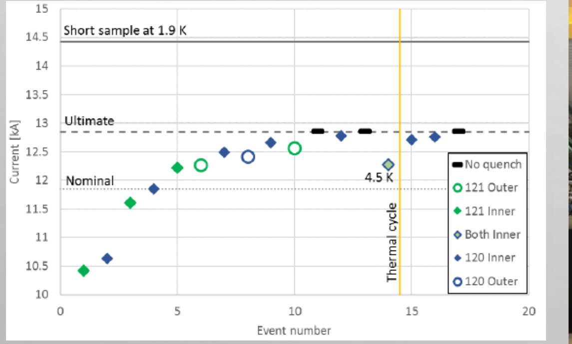


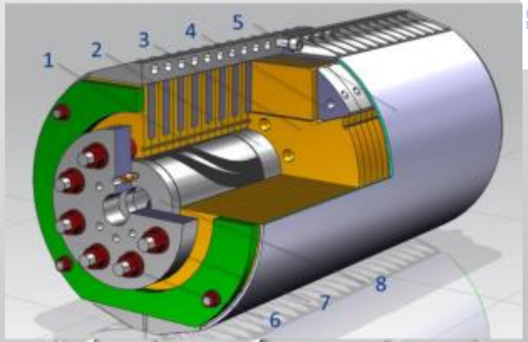
PAUL SCHERRER INSTITUT PSI

Short models in 2018 – 2023
Prototypes 2026 – 2032

HL-LHC **11T First Nb_3Sn magnet, FRESCA2 dipole** Can be used for HE-LHC

Synergies with other fields





Fermilab 50 Years of Discovery
15 T dipole demonstrator
60-mm aperture
4-layer graded coil

U.S. MAGNET DEVELOPMENT PROGRAM

FCC-hh KEY TECHNOLOGY: MACHINE PROTECTION

- 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 F. Salvat)

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

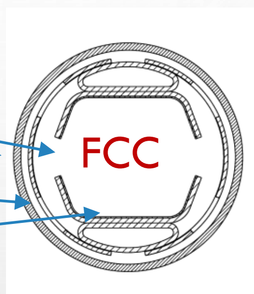
Small to make magnet cheap (aperture 50 mm)

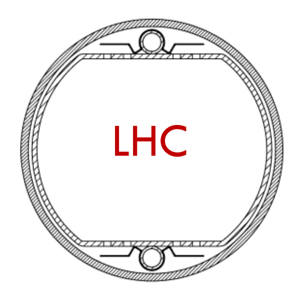
Extract photons for good vacuum

Strong to withstand quench

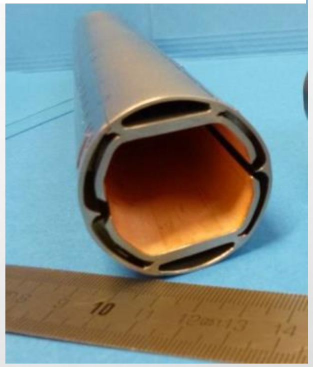
Hide pumping holes from beam for low impedance

Laser treatment / carbon coating against e-cloud





Tests at KARA/KIT



~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

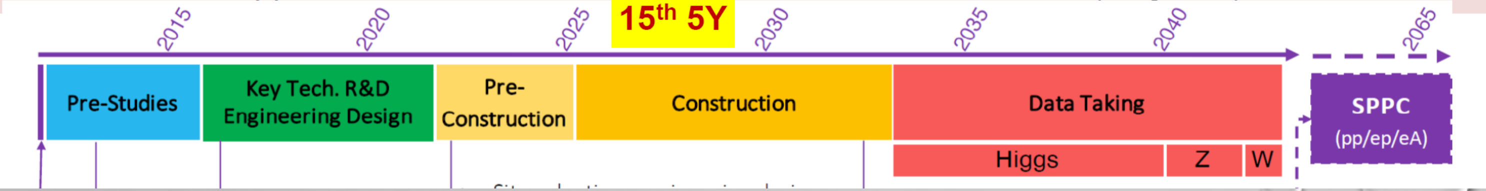
Collimation system design
- Designed system that can cope with the losses
- Detailed studies and optimization of performance

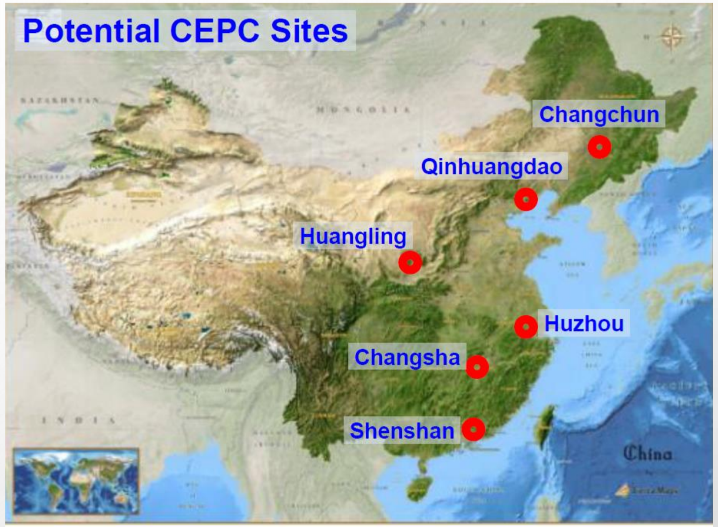
Beam dump design

Machine protection (See F. Salvat Lecture)

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.

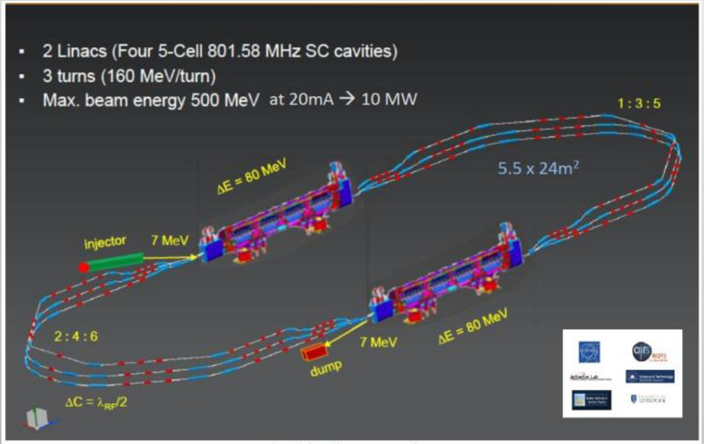
Fully Modular Concept

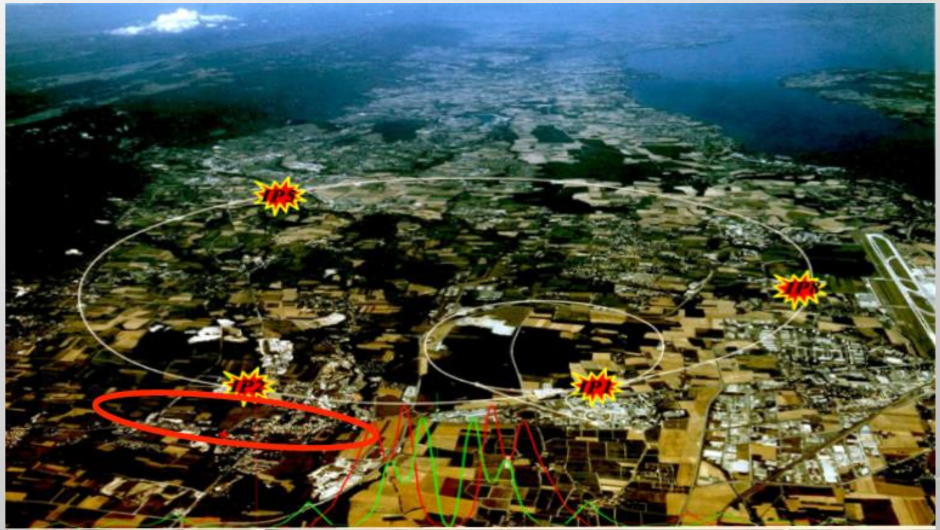
- Imbedded in a LHC Interaction Region
- Influence on optics & orbit compensated
- Flexibility of the LHC rings checked
- Asymmetric beam optics for ultimate e-p luminosity
- Non-colliding p-beam well separated
- Negligible beam-beam force on both proton beams

	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





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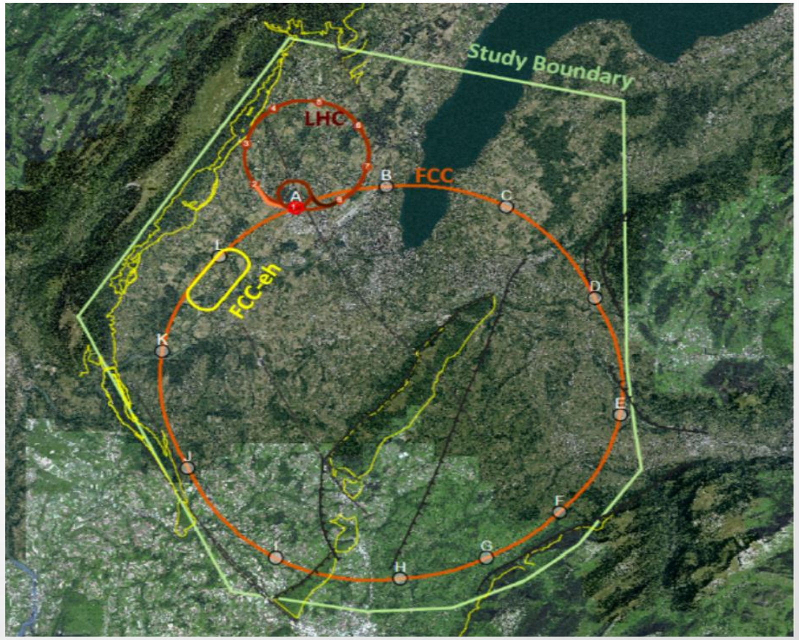
FCC-eh

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 ($cm^{-2}\ s^{-1}$)	$1.5*10^{34}$	

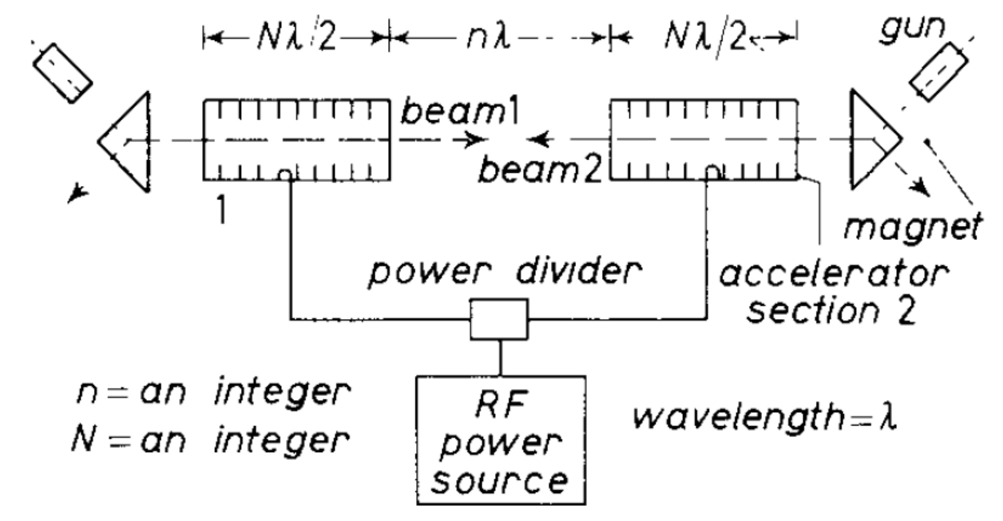


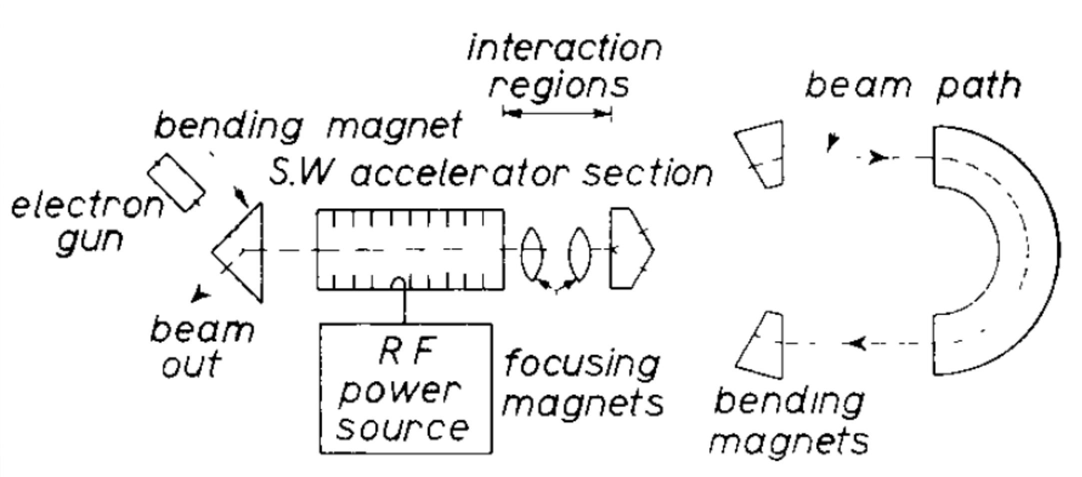
FCC-CDR: Eur. Phys. J. ST 228 (2019, 4.775)

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 COLLIDERS

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

International MUON Collider Collaboration

New strong interest:

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

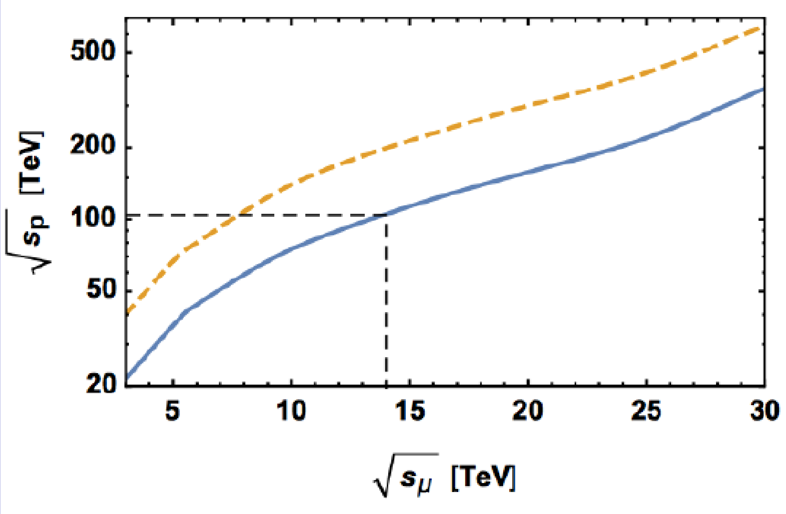
New collaboration started

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 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

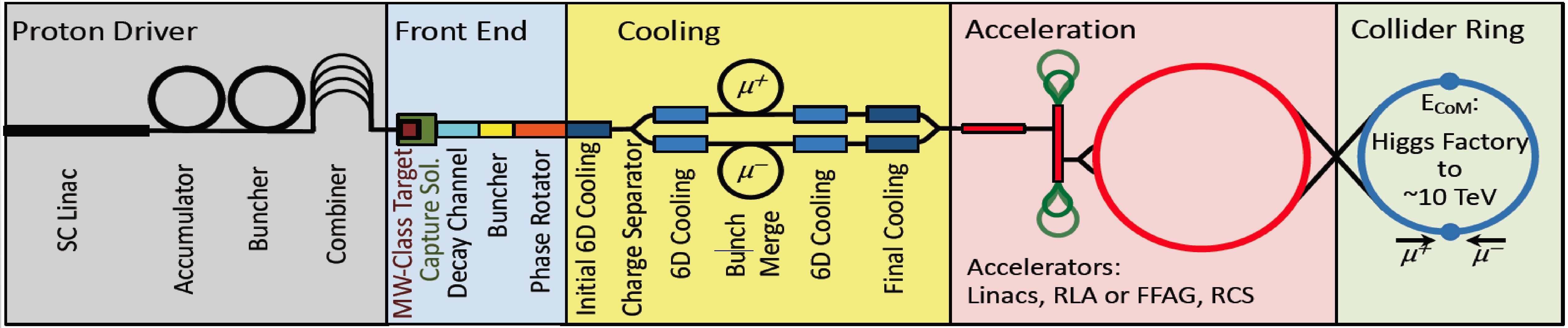
Discovery reach
14 TeV lepton collisions are comparable to 100-200 TeV proton collisions for production of heavy particle pairs



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

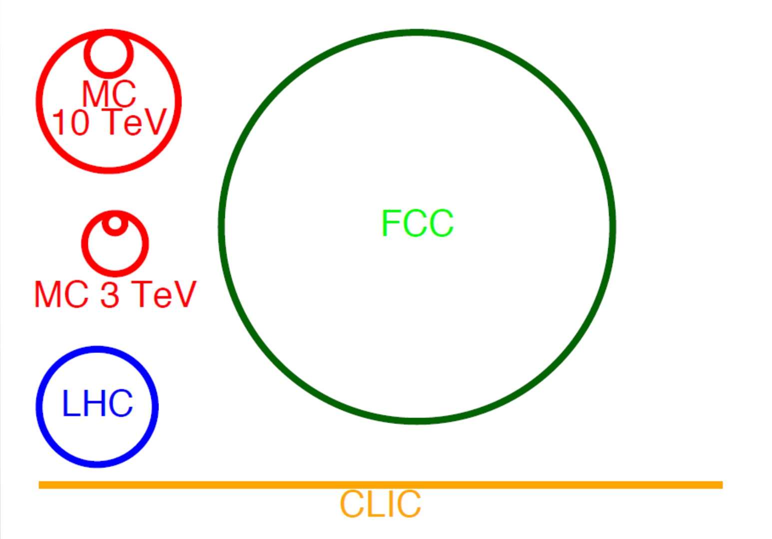
Ionisation cooling of muon in matter

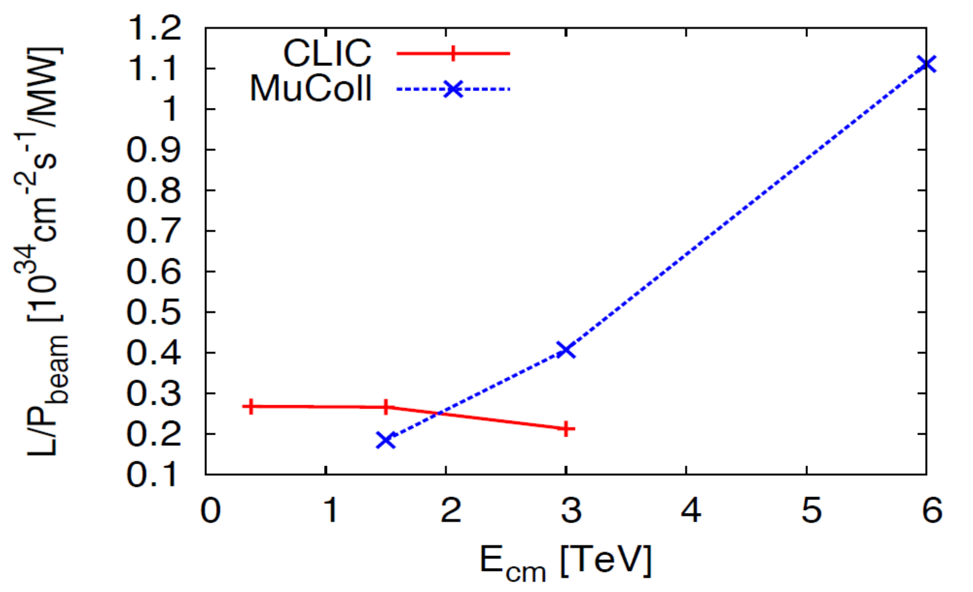
Acceleration to collision energy

Collision

Protons produce pions which decay into muons
muons are captured

MUON COLLIDER SUSTAINABILITY





Muon Collider:

Acceleration and collision in multiple turns in rings promises

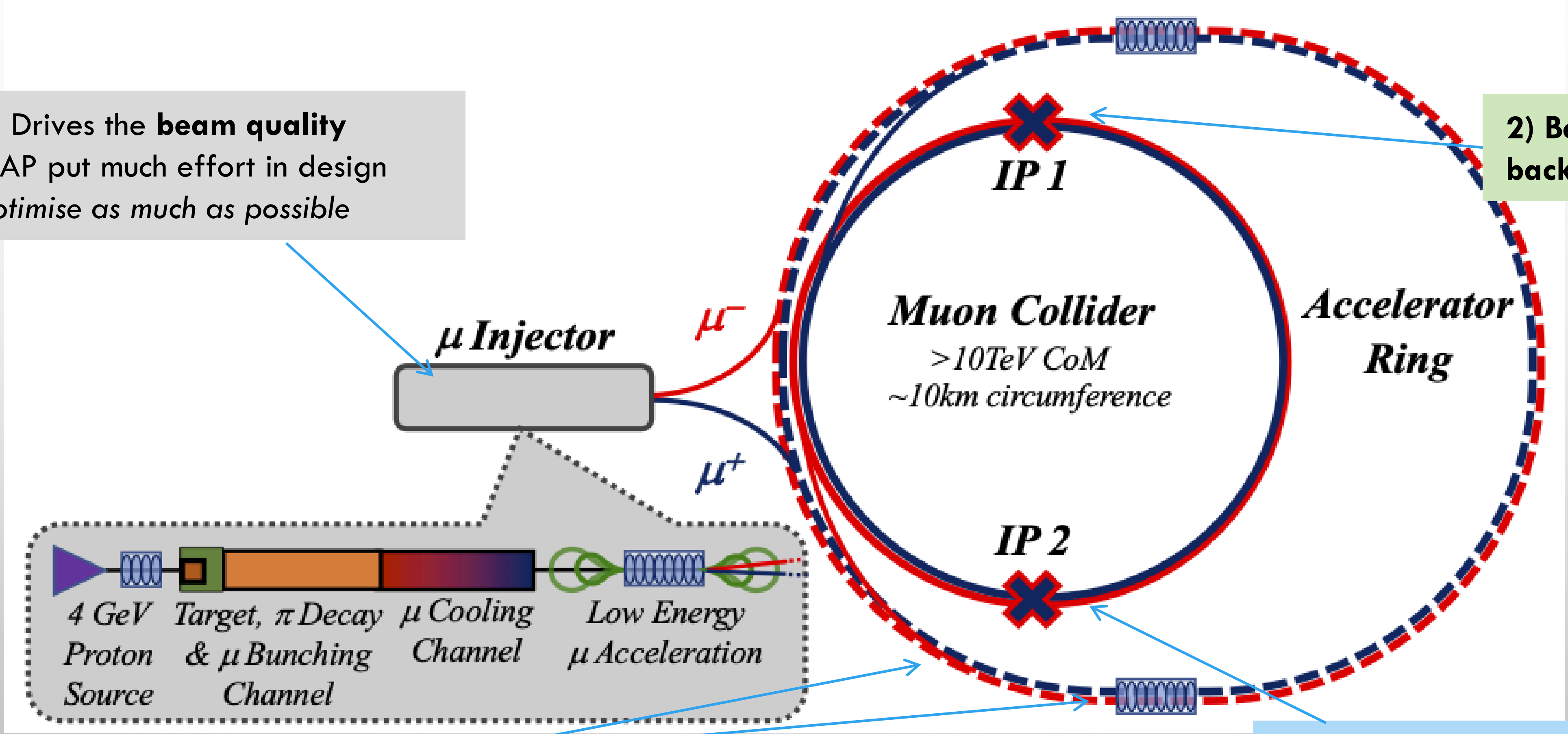
- **Power efficiency**
- **Compact tunnels,** 10 TeV similar to 3 TeV CLIC
- **Cost effectiveness**
- **Natural staging** is natural

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}

KEY CHALLENGES



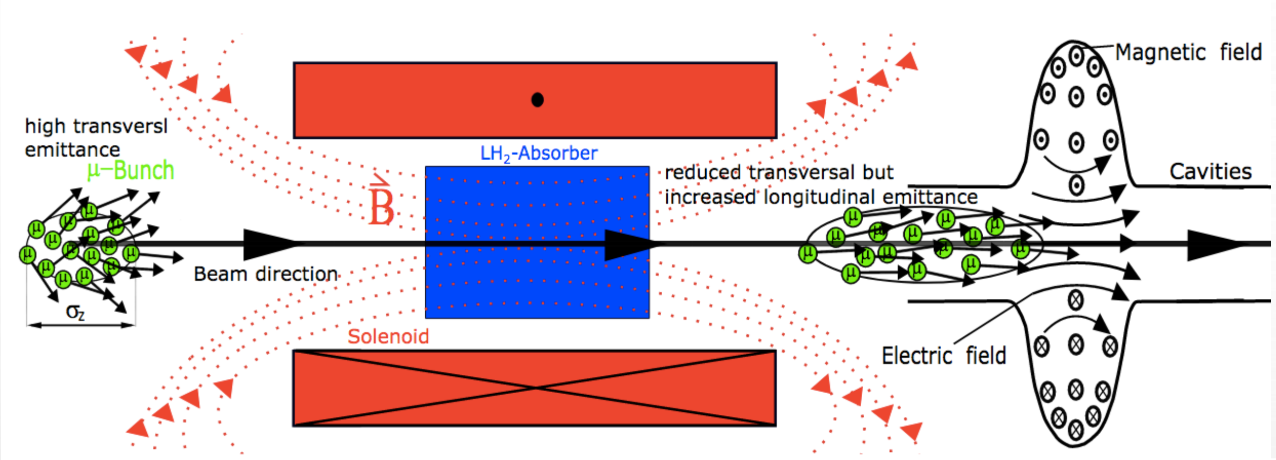
4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible

2) Beam-induced background

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

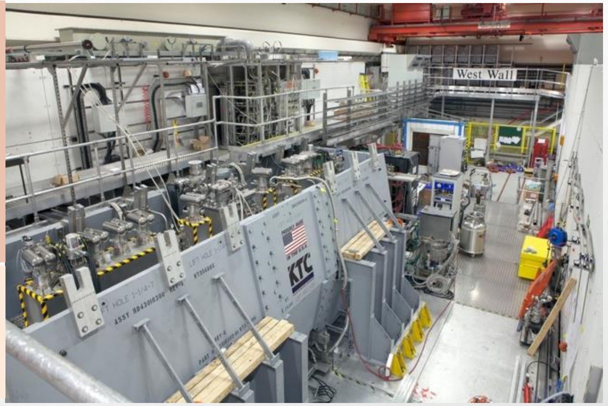
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

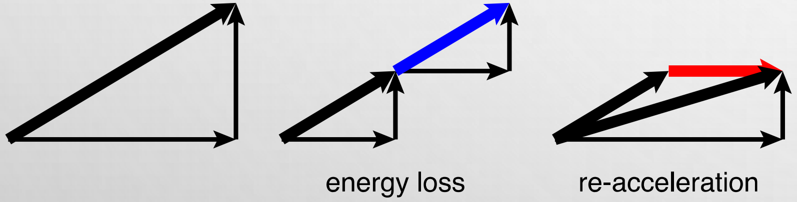
COOLING PRINCIPLE AND R&D



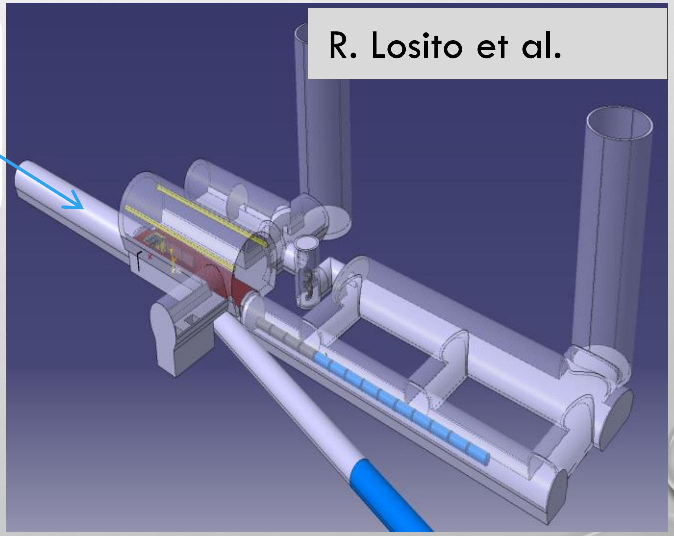
Principle of ionization cooling with no RF has been demonstrated in **MICE at RAL**

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





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



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?)

CONCLUSIONS

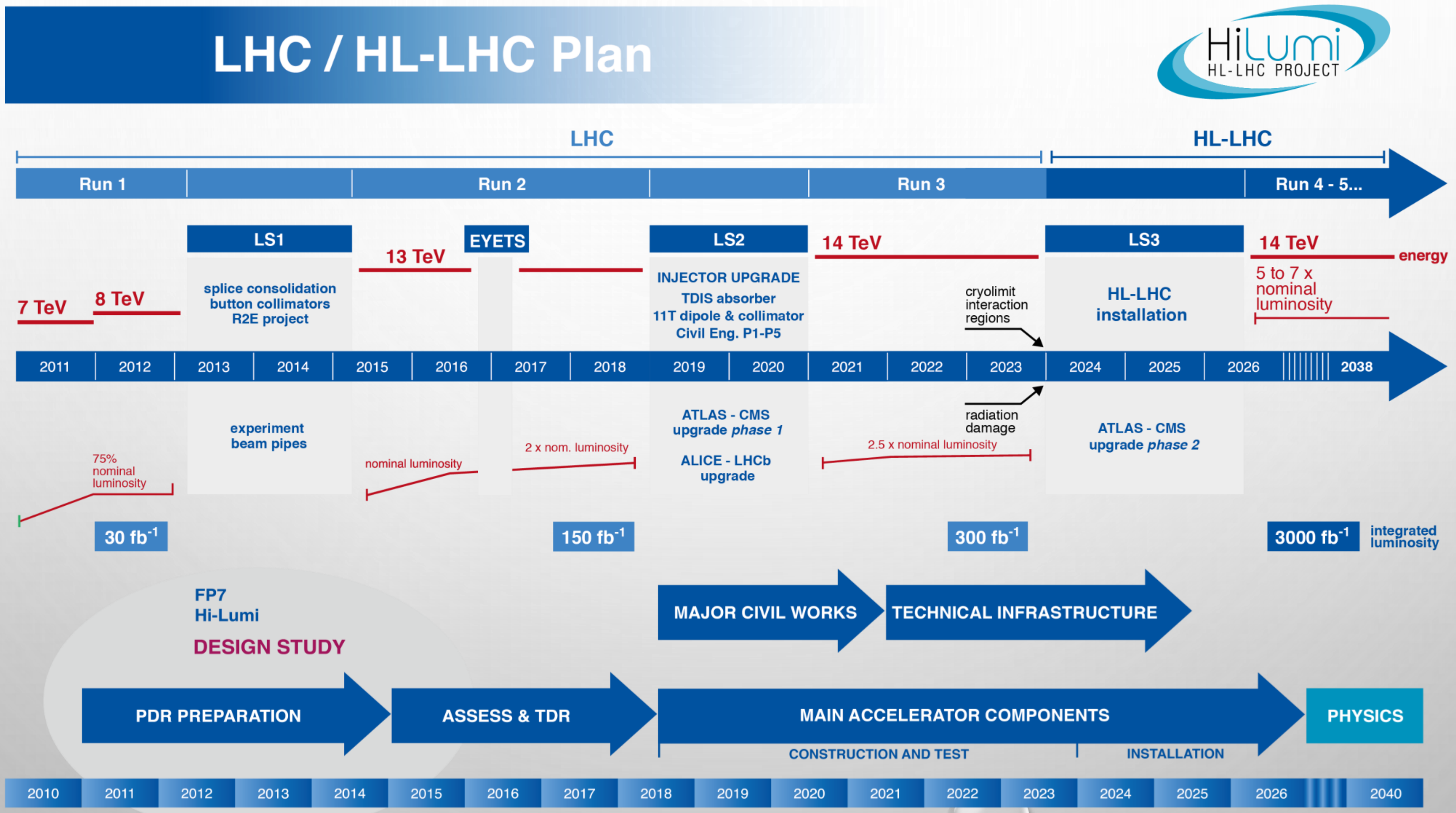
- High Energy Accelerator Field is very active !
  - Plenty of different projects are under study to be ready to address different and complementary physics questions
  - Many beam dynamics challenges to be addressed
  - Key technology R&D roadmaps have been created:
    - A lot of synergies with other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

- There is always room for new ideas!

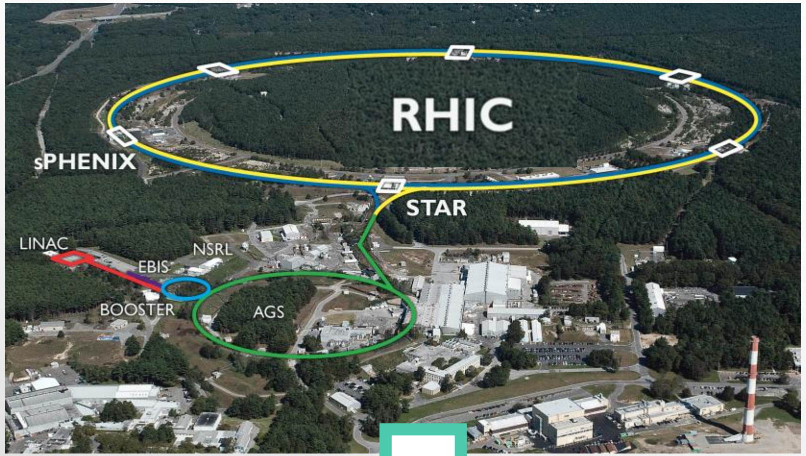
You are very welcome to join us!

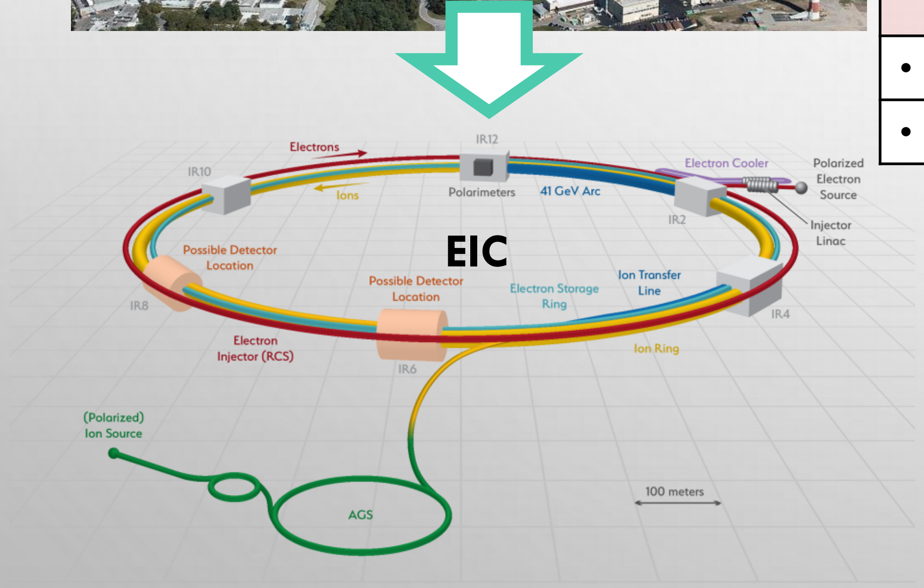
THANK YOU!

TIMELINE


LHC / HL-LHC Plan
HiLumi HL-LHC PROJECT
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
INJECTOR UPGRADE
TDIS absorber
11T dipole & collimator
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2038
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
upgrade phase 2
75%
nominal
luminosity
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
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
PHYSICS
CONSTRUCTION AND TEST
INSTALLATION
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)

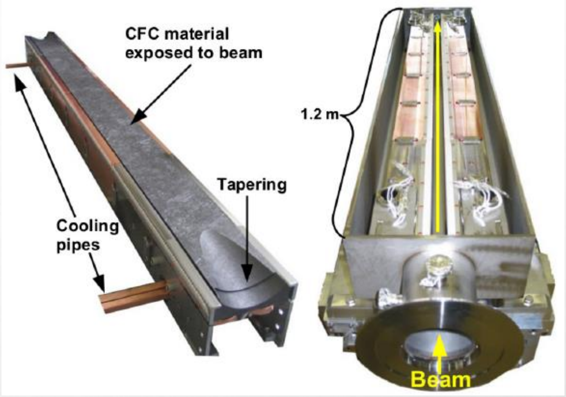
- 25 mrad Crossing Angle with Crab Cavities
- Superconducting Magnets
- Spin Rotators for Longitudinal Spin at IP
- Forward Hadron Instrumentation

Double-ring design based on existing RHIC complex

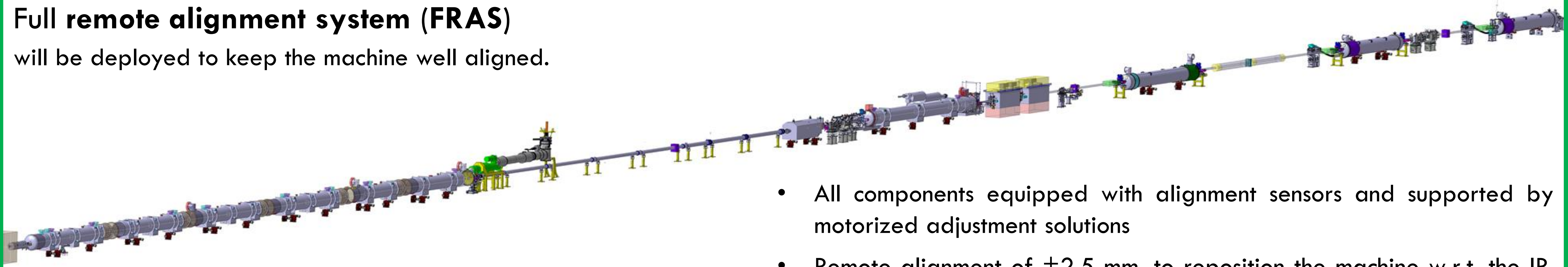
COLLIMATORS AND ALIGNMENT

- 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.

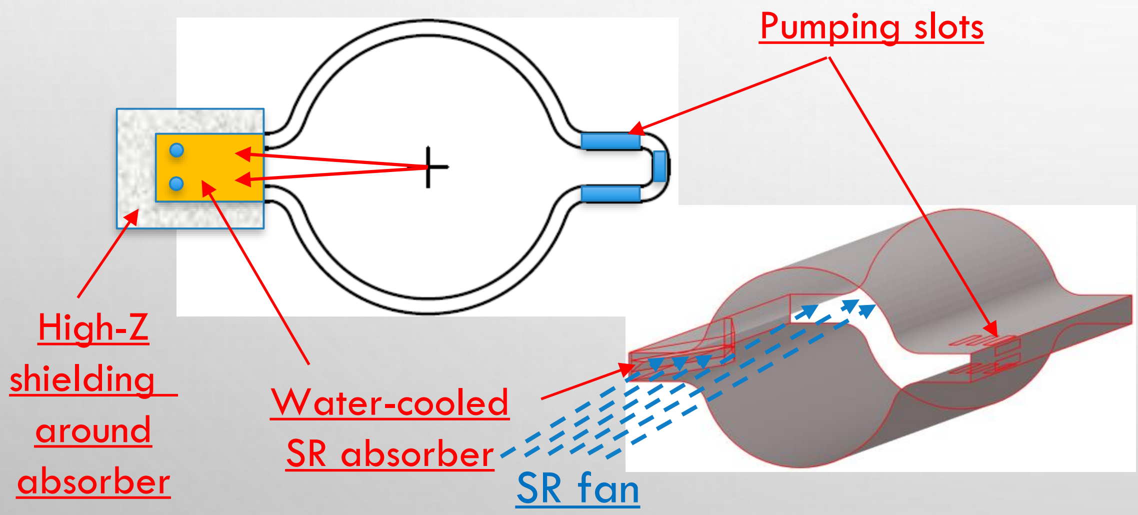


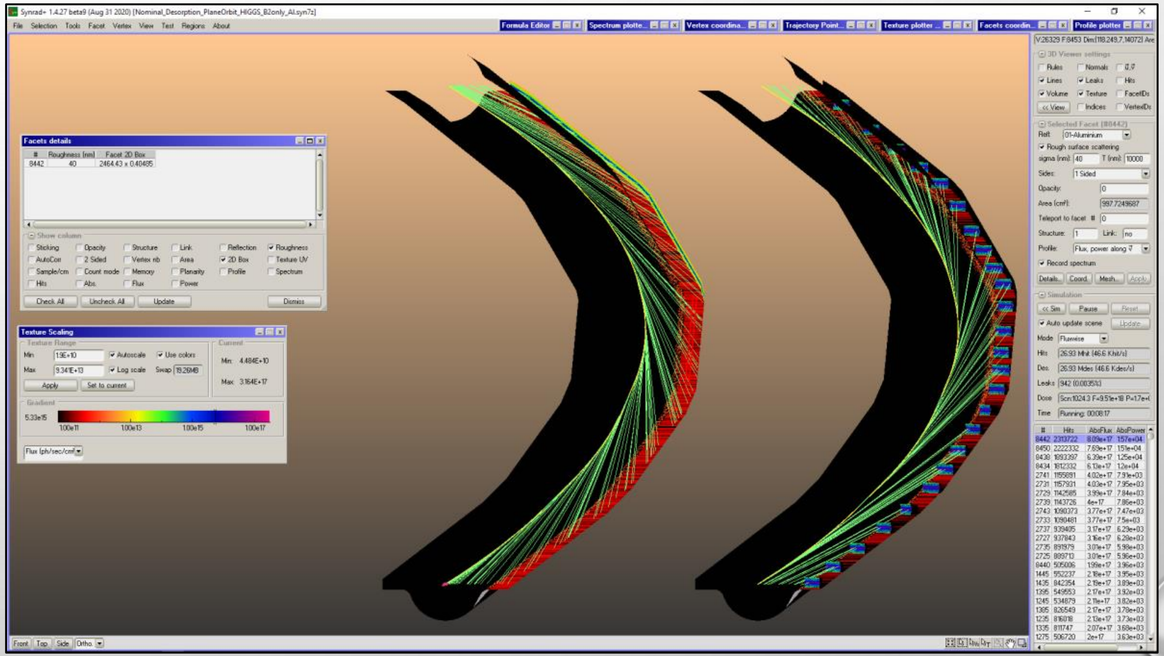
- All components equipped with alignment sensors and supported by motorized adjustment solutions
- Remote alignment of ±2.5 mm, to reposition the machine w.r.t. the IP, to correct ground motion.

R. De Maria ICHEP 2022

FCC-ee KEY TECHNOLOGIES: VACUUM SYSTEM

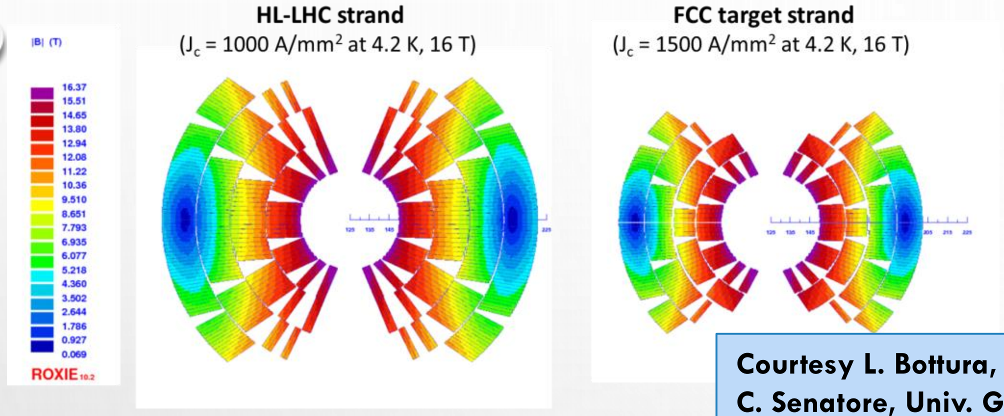
- **Specifying vacuum system**
  - Consider discrete absorbers space every <6 m or continuous absorbers along chamber wall
  - NEG coated Cu vacuum chamber
  - Need shielding to minimize tunnel radiation levels





R. Kersevan FCCIS workhop 2021

FCC-hh KEY TECHNOLOGIES: HIGH FIELD MAGNETS

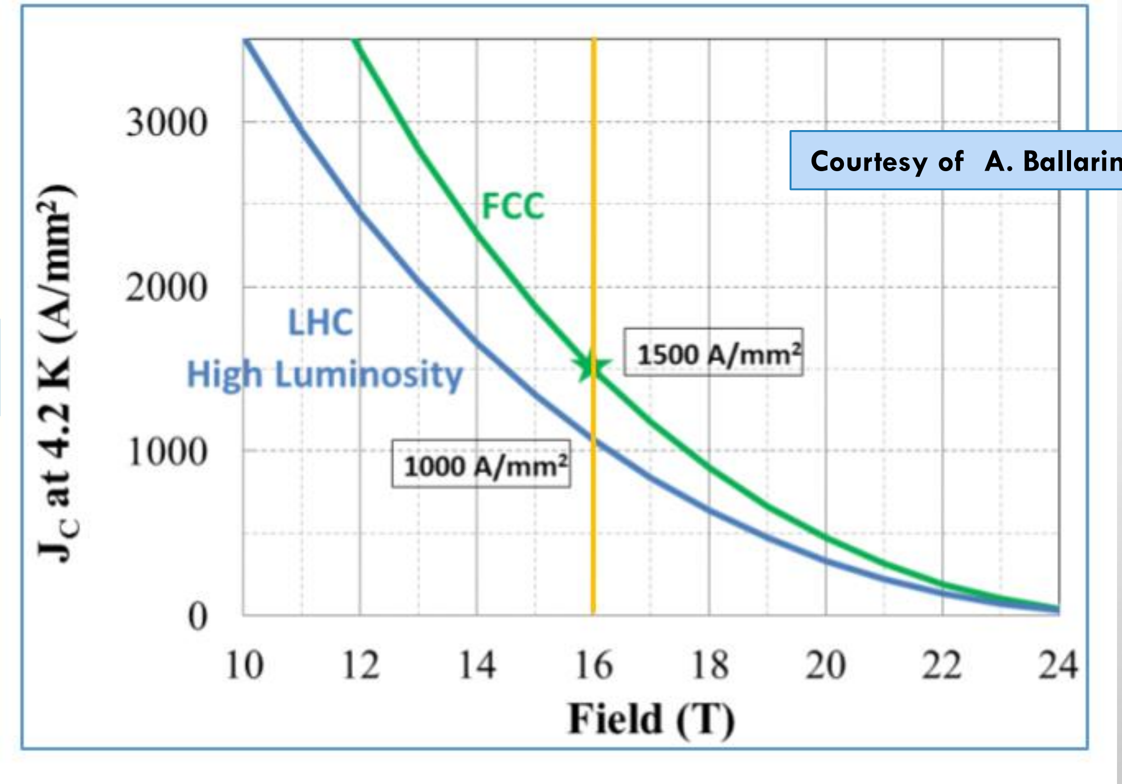


Courtesy L. Bottura, CERN
C. Senatore, Univ. Geneva

	HL-LHC		FCC
B [T]	16		16
J_{op} [A/mm²]	300	2x →	600
w [mm]	76		38
A_{coil} [mm²]	20'000		7'000

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

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



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

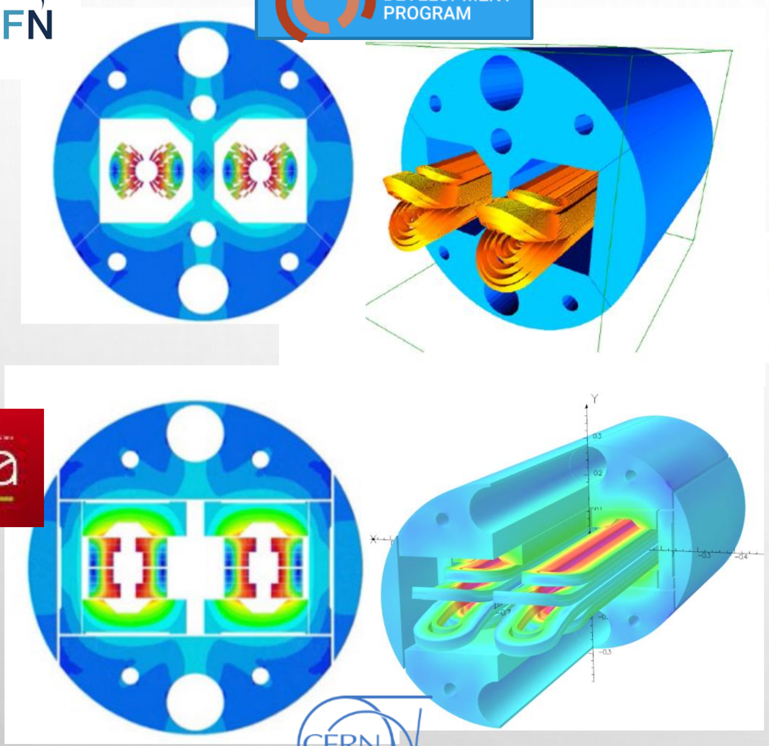
Parrell et al., AIP Conf. Proc. 711 (2004) 369
Boutboul et al., IEEE TASC 19 (2009) 2564
Xu et al., APL 104 (2014) 082602

L. Rossi ICHEP 2022

FCC-hh KEY TECHNOLOGIES: MAGNETS R&D

INFN

U.S. MAGNET DEVELOPMENT PROGRAM



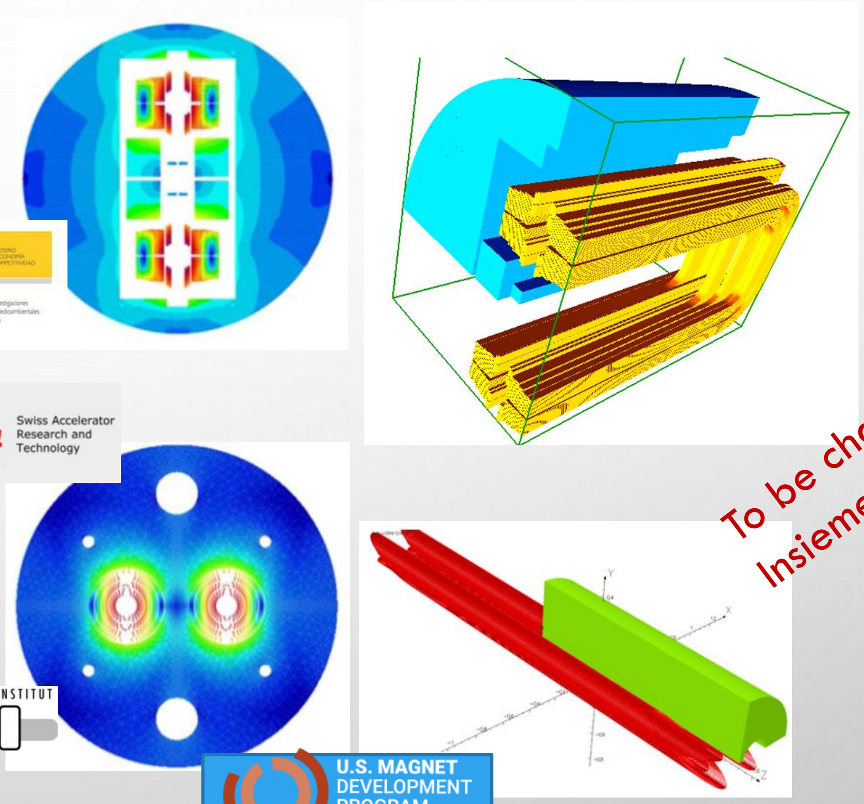
cea

CERN

Ciemat

CHART Swiss Accelerator Research and Technology

PAUL SCHERRER INSTITUT PSI



U.S. MAGNET DEVELOPMENT PROGRAM

To be changed
Insieme a quella di prima

L. Rossi ICHEP 2022

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

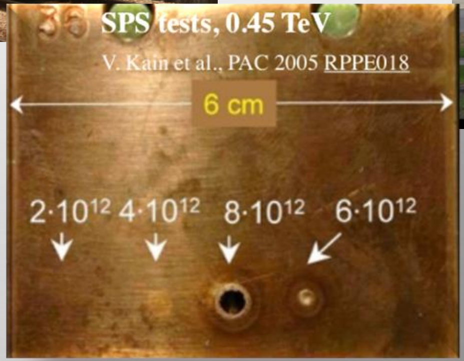
FCC-hh KEY TECHNOLOGY: MACHINE PROTECTION

HL-LHC: 680 MJ - kinetic energy of

TGV train cruising at 215 km/h

FCC-hh: 8.3 GJ – kinetic energy of

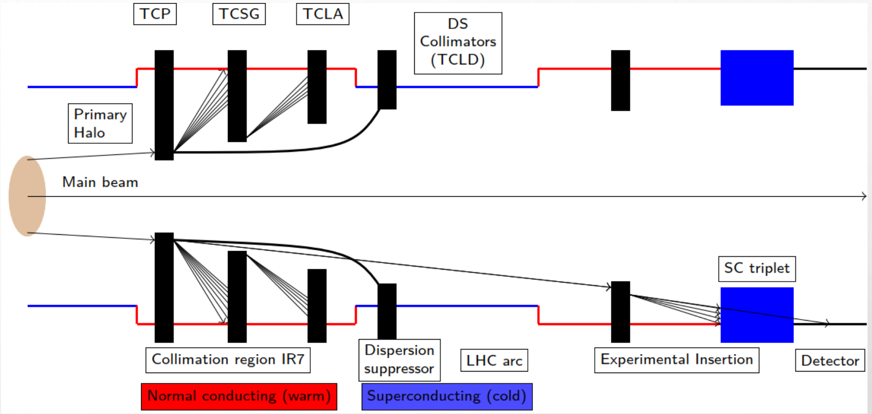
Airbus A380 (empty) cruising at 880 km/h



FCC-hh COLLIMATION

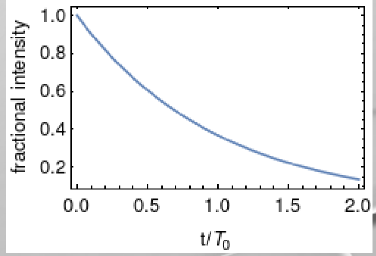
- The loss of even a tiny fraction of the beam could cause a magnet quench or even damage
- To safely intercept any losses and protect the machine: use collimation system (see lecture a. Lechner)
  - Should be the smallest aperture limitation in the ring
- 500 kw of continuous losses from collisions, 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



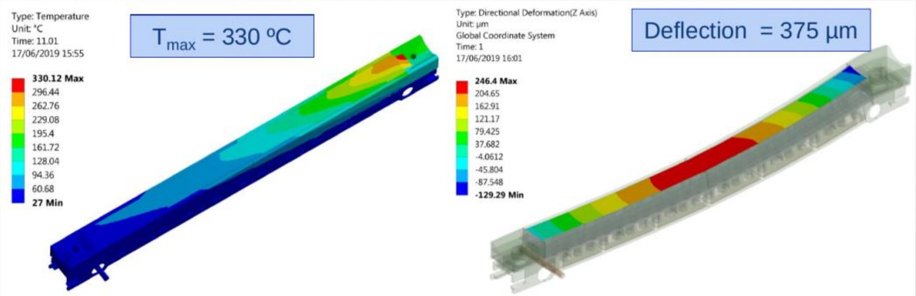
Beam lifetime:
usually defined as time needed for reduction of intensity by factor 1/e
assuming losses proportional to intensity (often true, but not always)

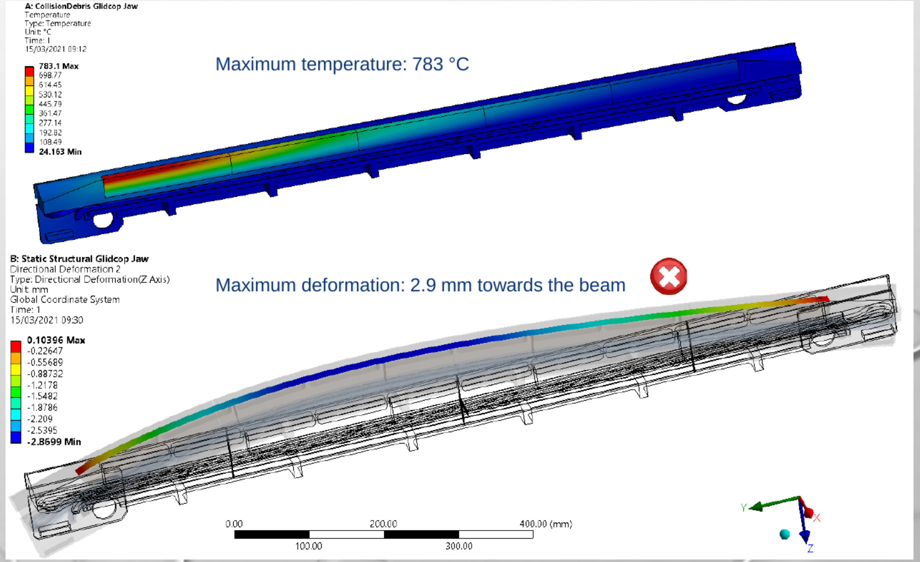
$$-\frac{dN}{dt} \propto N(t) \Rightarrow N(t) = N_0 e^{-t/T_0}$$



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





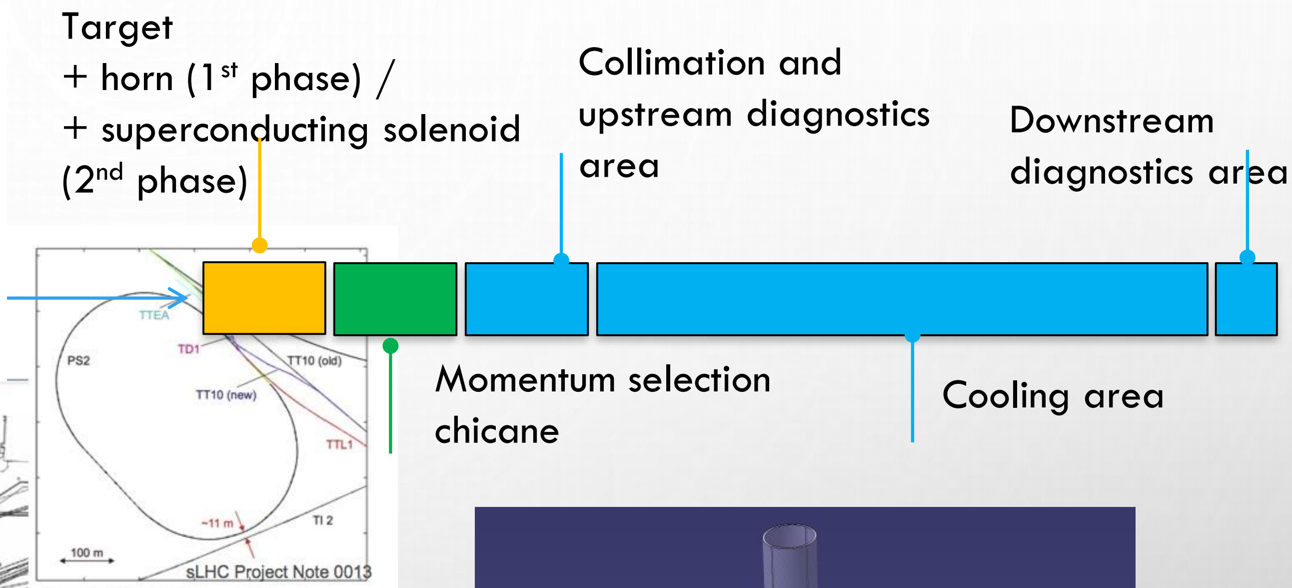
MUONS DEMONSTRATOR FACILITY

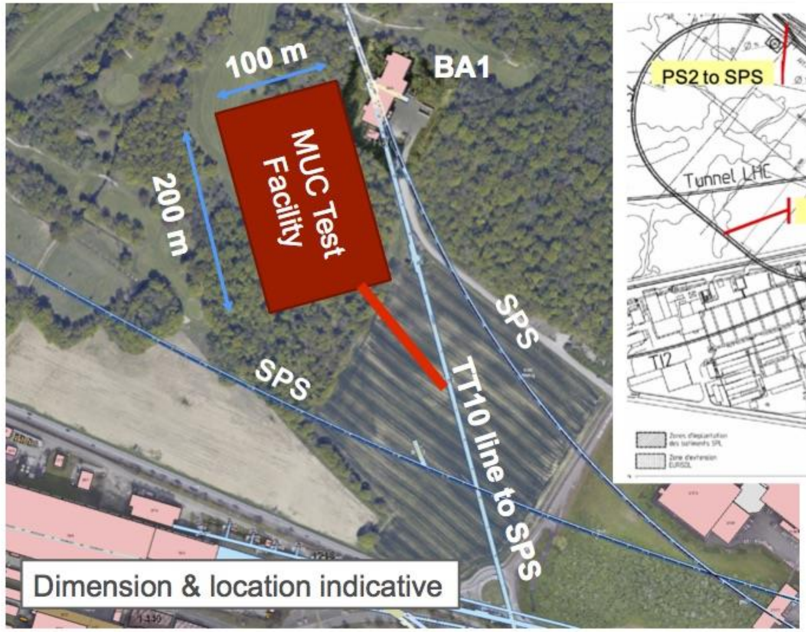
Planning demonstrator facility with muon production target and cooling stations

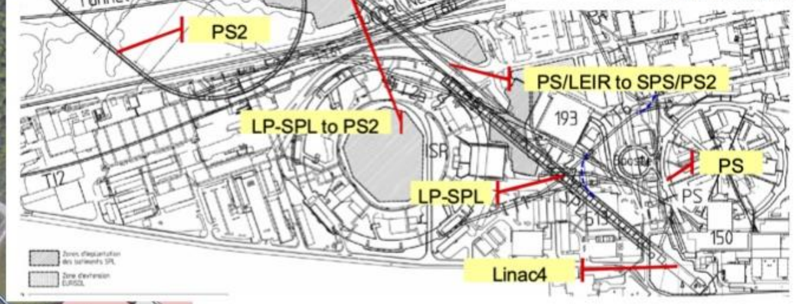
Suitable site on CERN land exists that can use PS proton beam

- could combine with NuStorm or other option

Other sites should be explored (FNAL?)

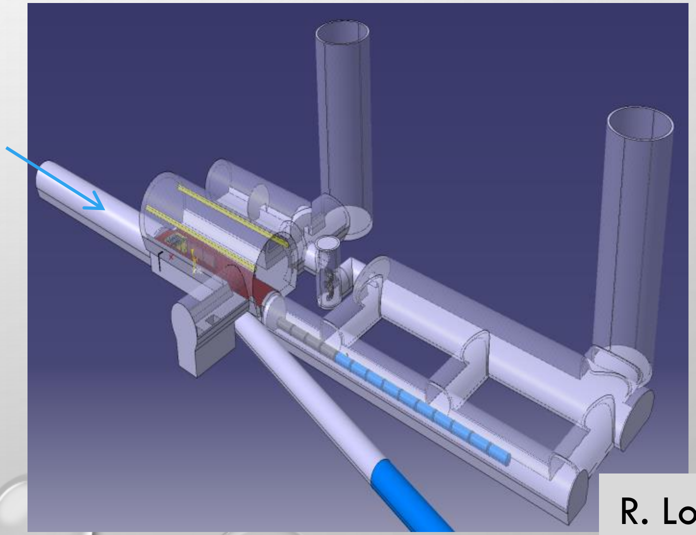






M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061

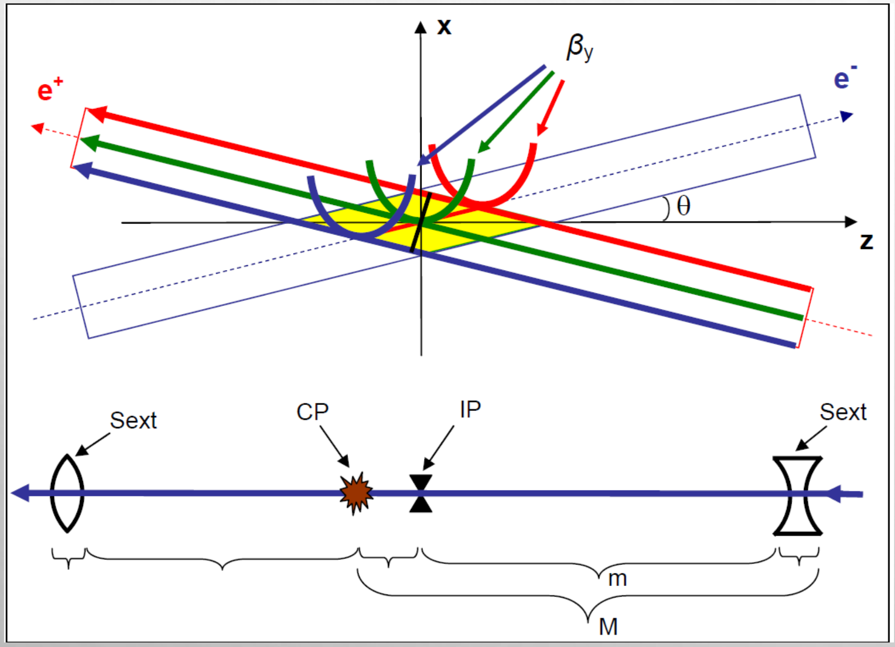


R. Losito et al.

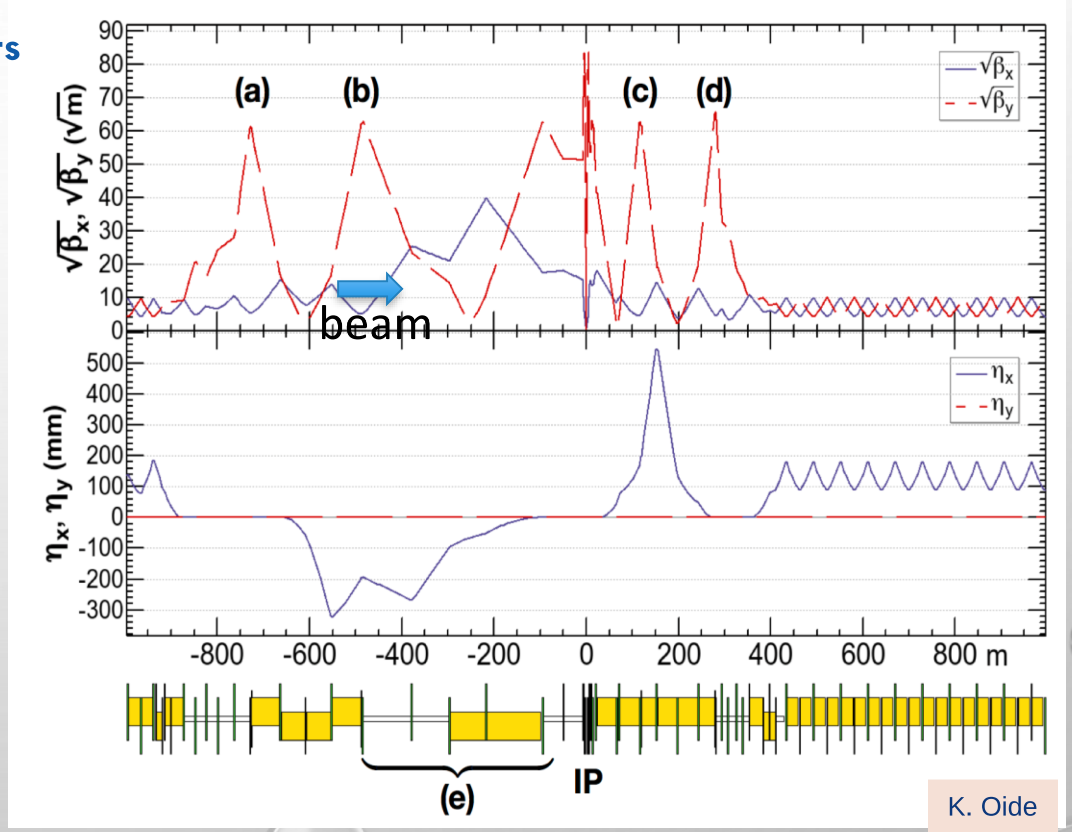
FCC-ee COLLIDER OPTICS AND BEAM-BEAM

- **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



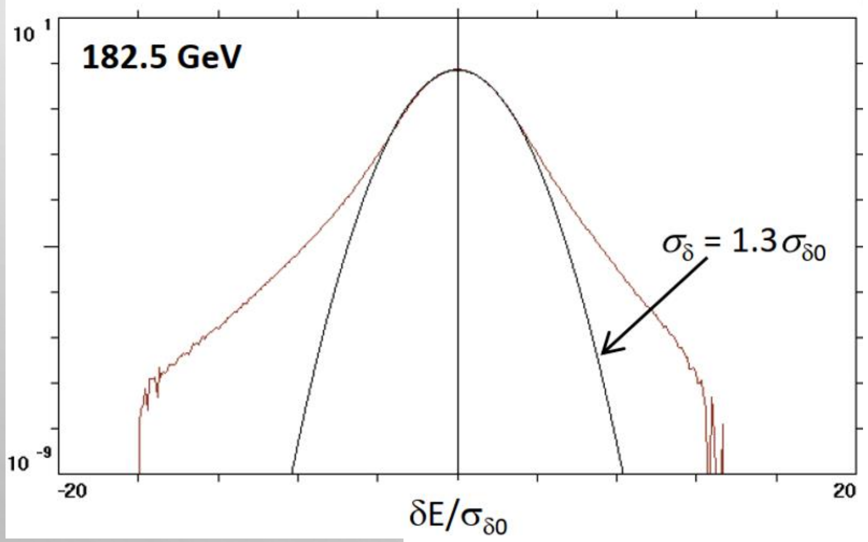
CDR optics, ttbar 182.5 GeV



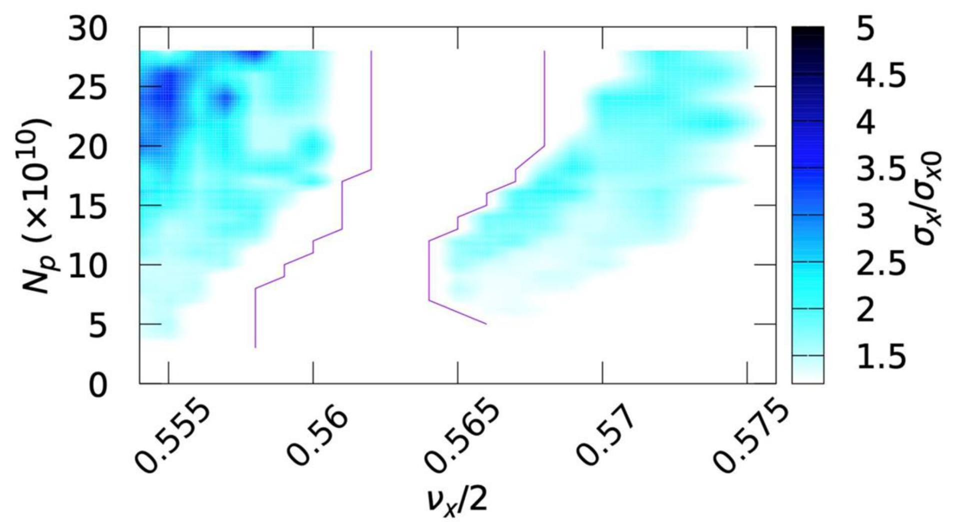
BEAM-BEAM AND COLLECTIVE EFFECTS

- **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



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