Large Circular Collider Studies Overview

CAS – Future Colliders - Zuerich

M. Benedikt, 22 February 2018

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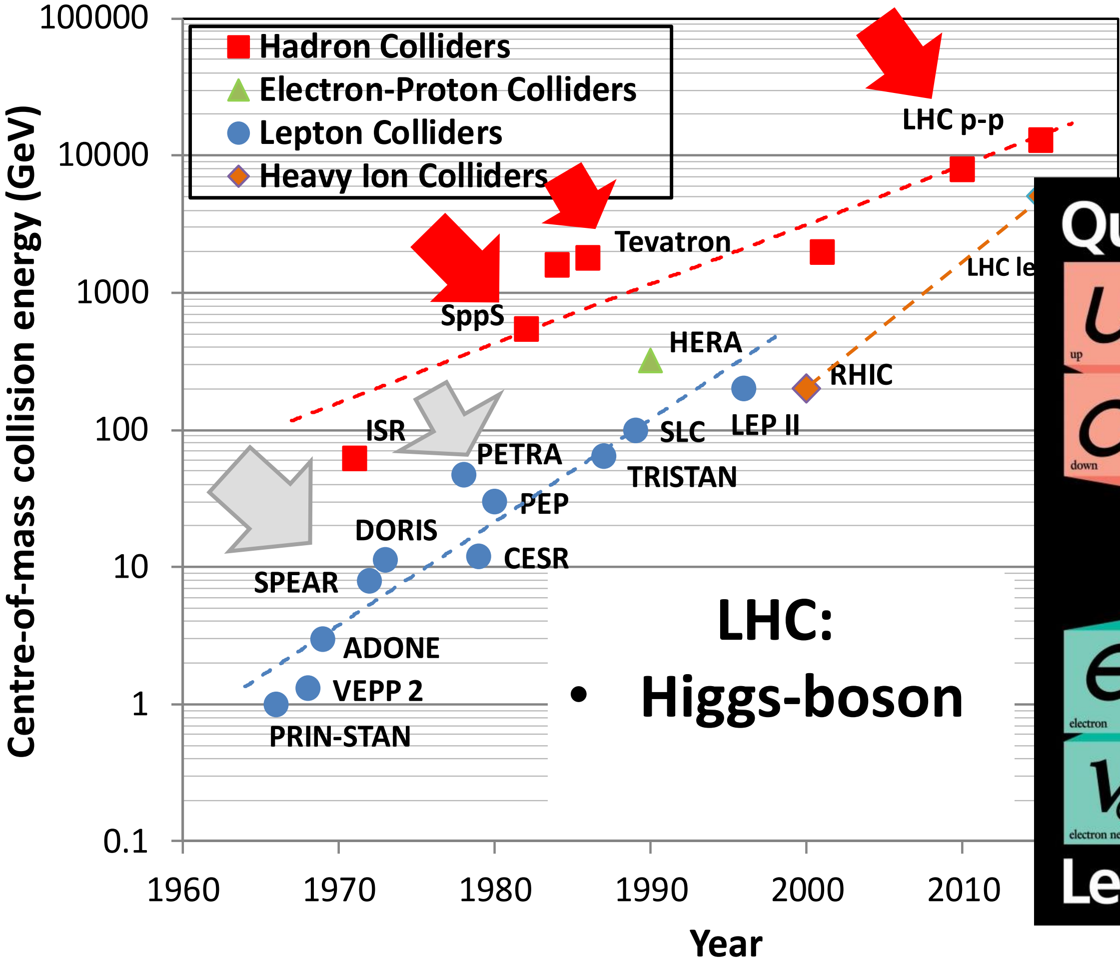
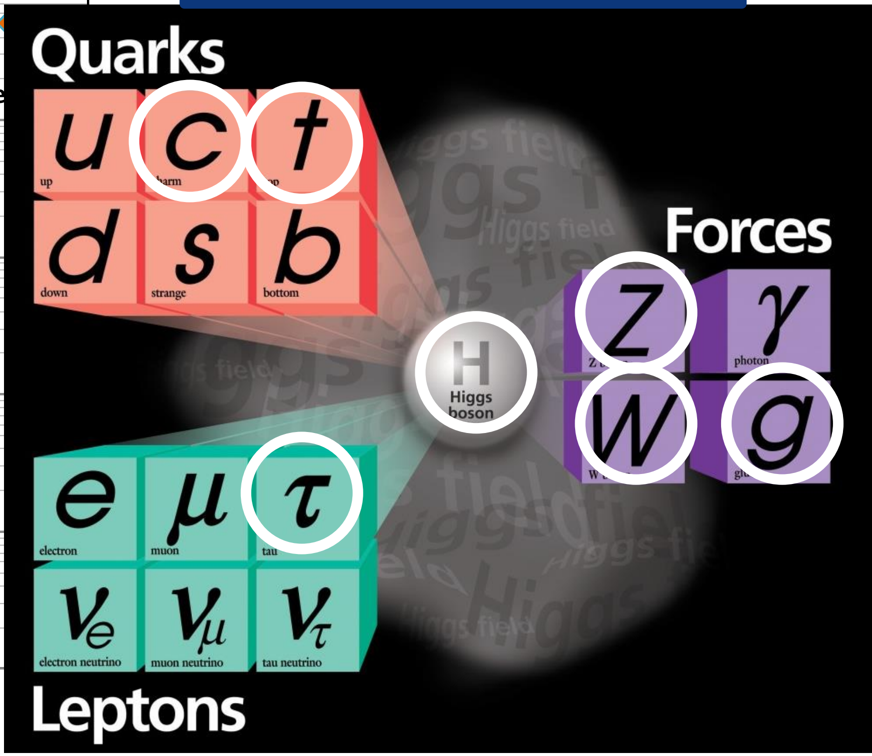
Discoveries by colliders



LHC:

- **Higgs-boson**

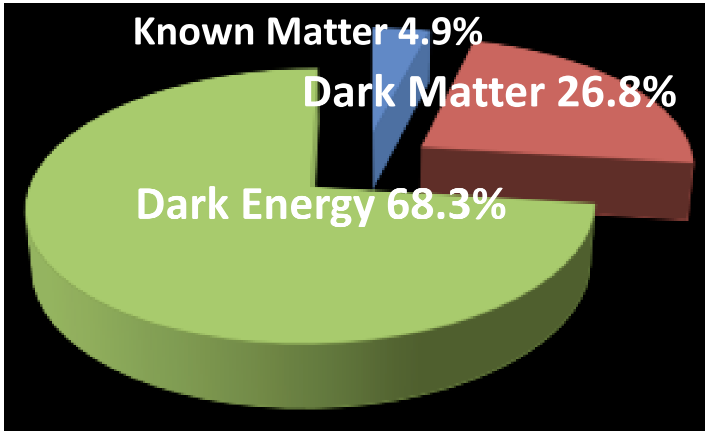
Standard Model Particles and forces

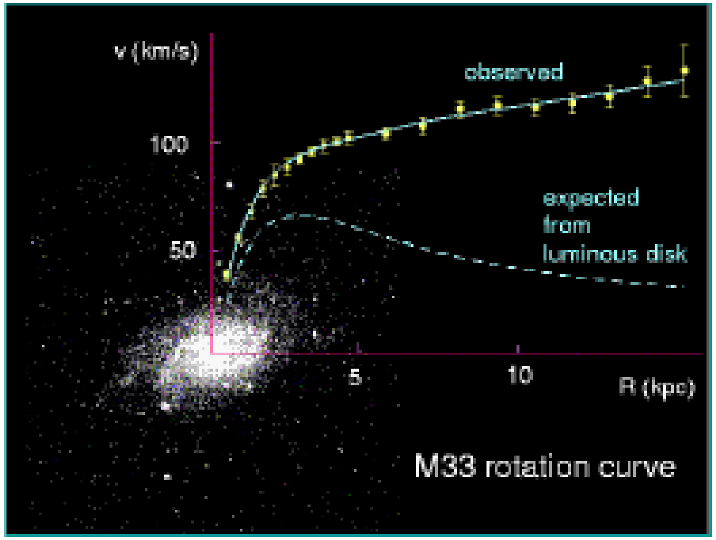


Colliders are powerful instruments in High Energy physics for particle discoveries and precision measurements

Many open questions remaining

- Standard model describes known matter, i.e. 5% of the universe!



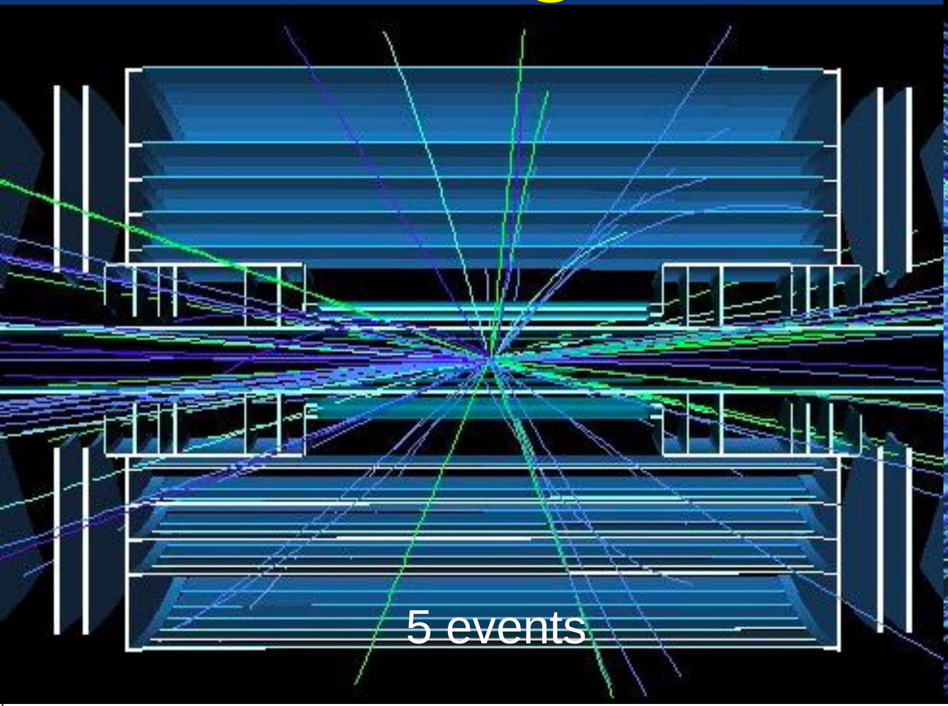


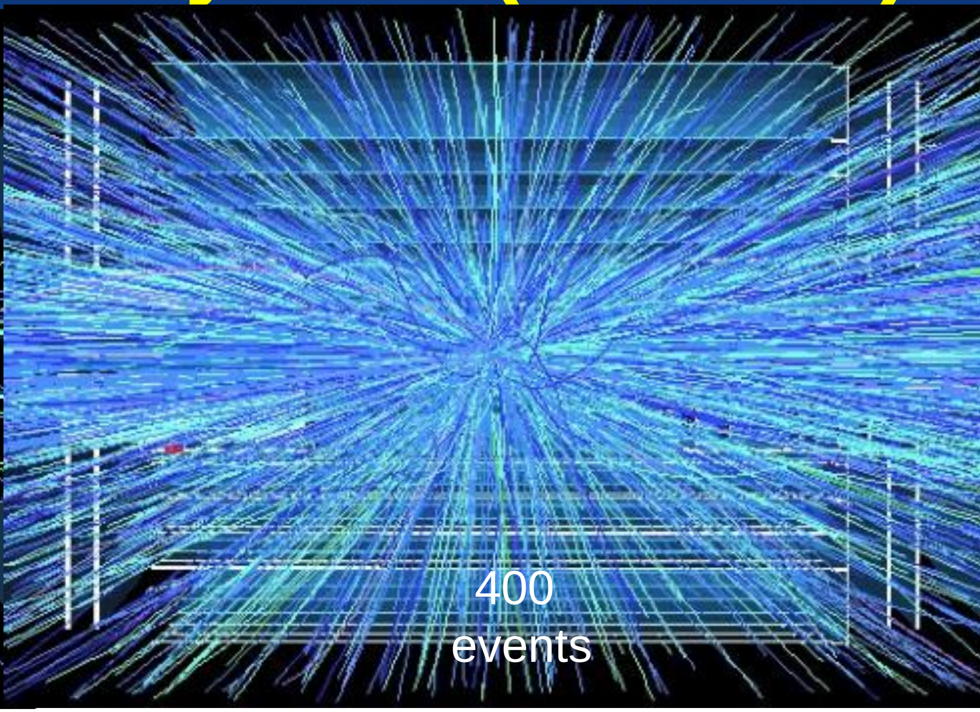
galaxy rotation curves, 1933 - Zwicky

- what is dark matter?
- what is dark energy?
- why is there more matter than antimatter?
- why do the masses differ by more than 13 orders of magnitude?
- do fundamental forces unify in single field theory?
- what about gravity?
- Is there a “world equation – theory of everything”? …

K. Borras

Goal of High Luminosity LHC (HL-LHC)





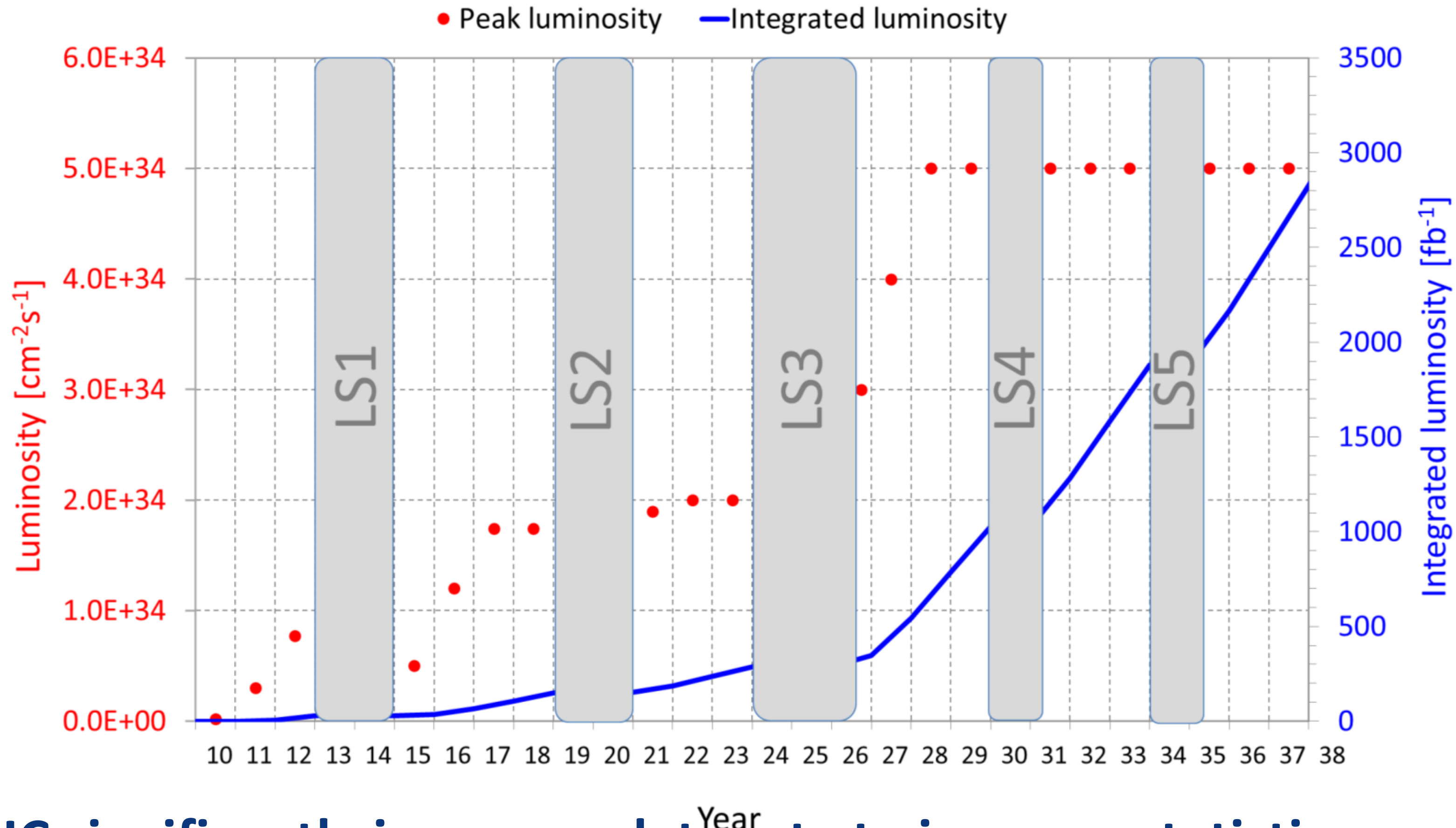
implying an integrated luminosity of **250 fb^{-1} per year**,

design oper. for $\mu = $ **140** (➔ peak luminosity **5 10^{34} cm^{-2} s^{-1}**)

➔ Operation with levelled luminosity! (beta*, crossing angle & crab cavity)

➔10x the luminosity reach of first 10 years of LHC operation!!

HL-LHC upgrade – full LHC exploitation

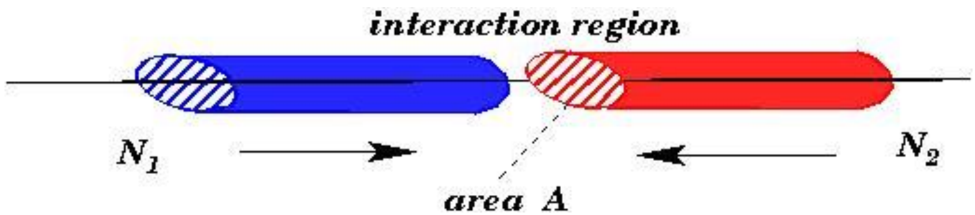


HL-LHC significantly increases data rate to improve statistics, measurement precision, and energy reach in search of new physics

Gain of a factor 5 in rate, factor 10 in integral data wrt initial design

LHC upgrade goals: performance optimization

- Luminosity recipe (round beams):



$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

→ maximize bunch intensities (1.1 → $2.2\text{x}10^{11}$) → Injector complex

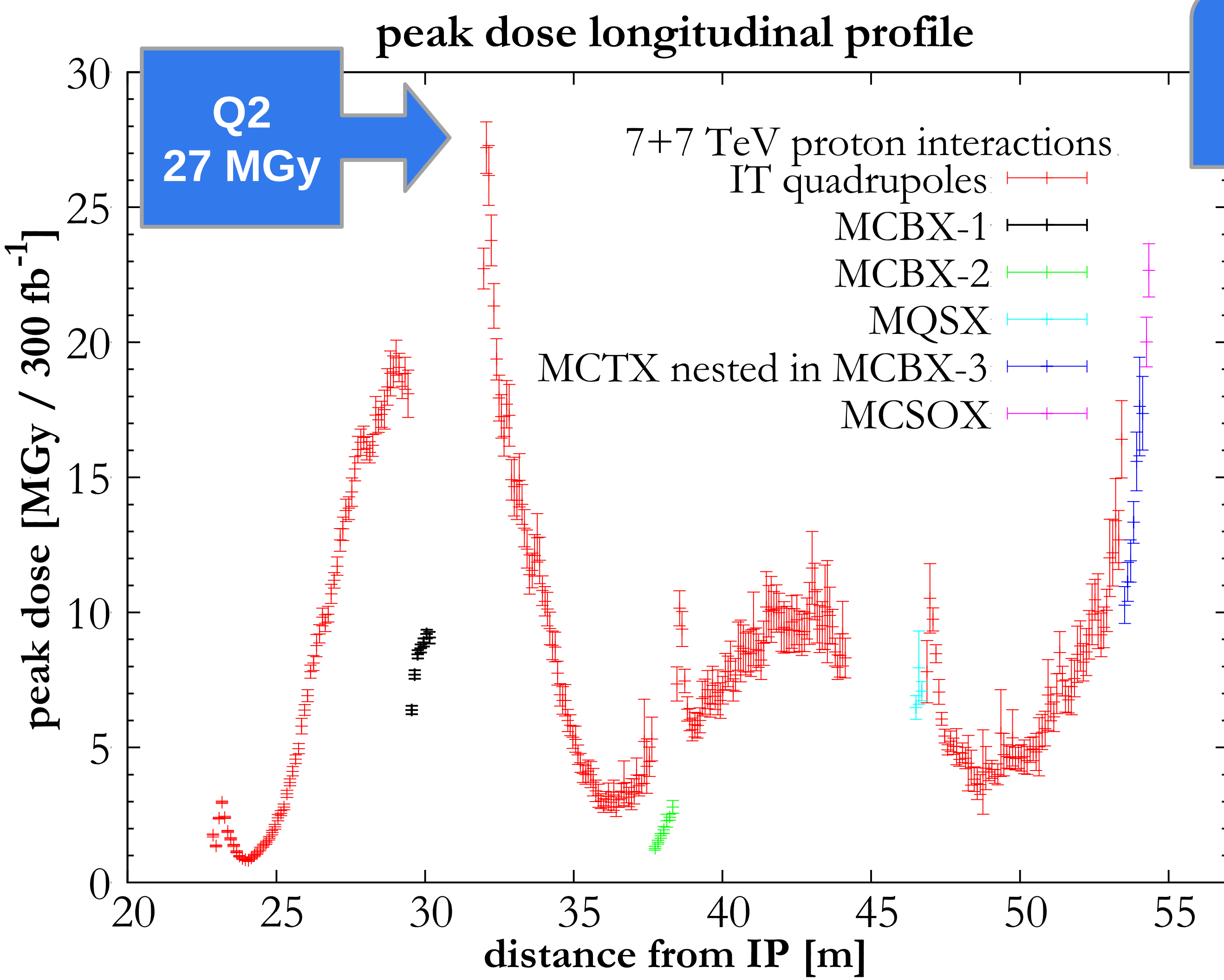
→ minimize the beam emittance (3.75→ 2.5 μm) Upgrade LIU

→ minimize beam size (β* 0.55 → 0.15 m); → New triplet quadrupoles

→ compensate for 'F' geometry crossing; → Crab Cavities

→ improve machine 'Efficiency' → minimize number of unscheduled beam aborts

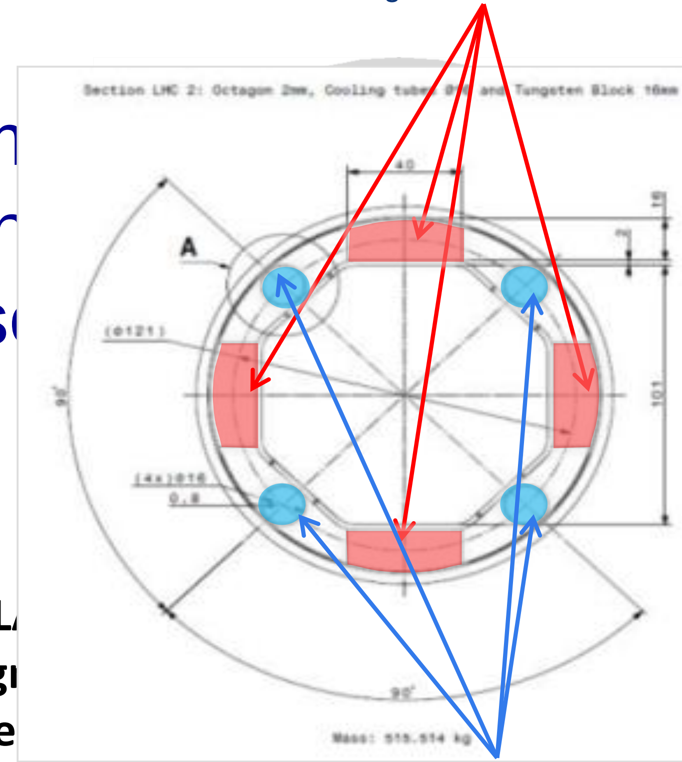
LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb-1



Cold bore insulation ≈ 35 MGy

HL-LHC technical bottleneck: Radiation damage to triplet magnets

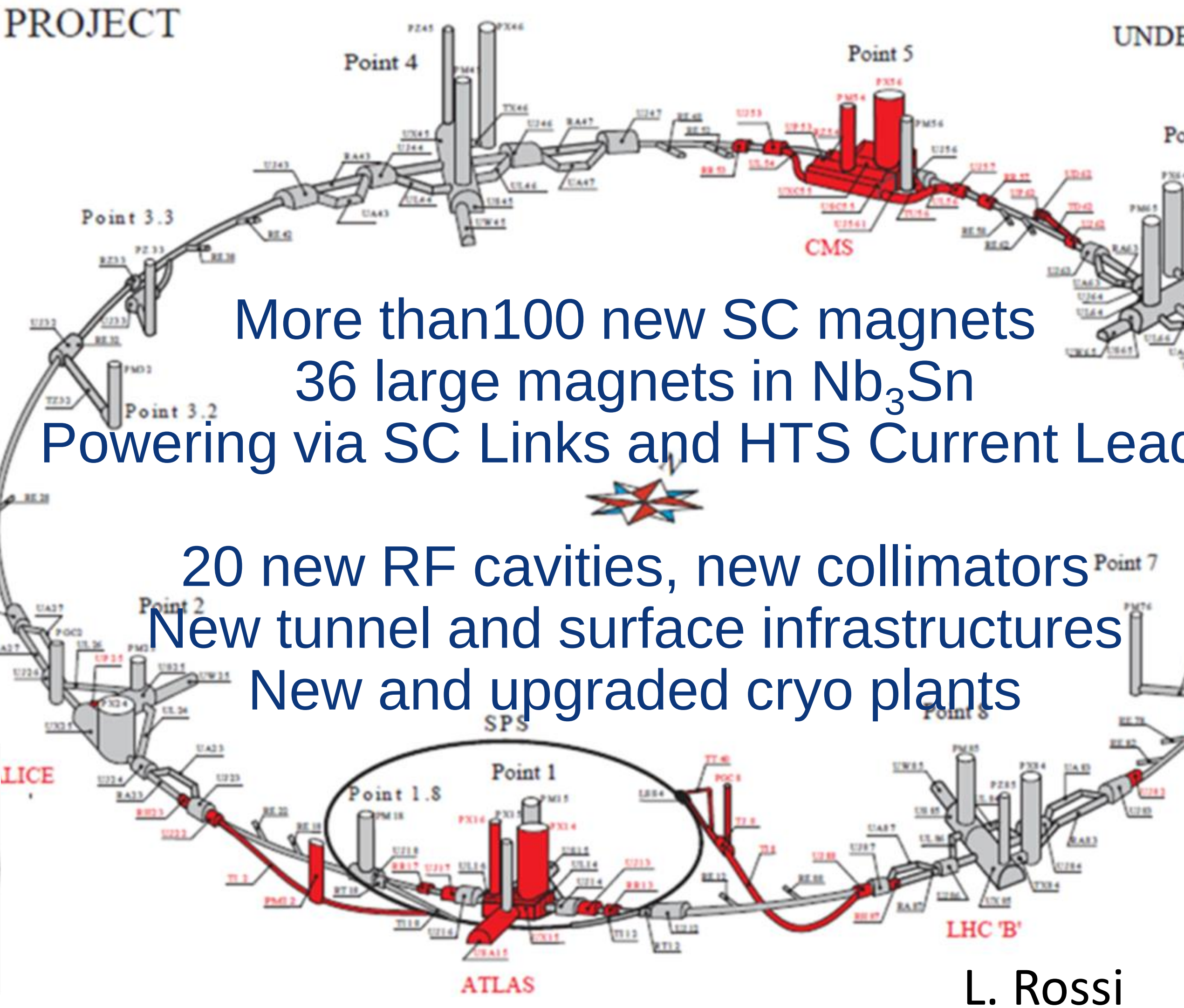
Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magn coils receive a similar radiation dose @ 10 times higher integrated luminosity 3000 fb^{-1}! ➔ Shielding!



US-L
magn
Base
technology

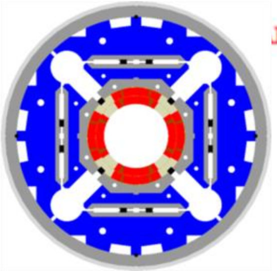
- ➔ Requires larger aperture!
- ➔ New magnet technology
- ➔ LHC: 70mm at 210 T/m ➔HL@ 150mm diameter 140 T/m
- ➔ LHC: 8T peak field at coils ➔ HL> 12T field at coils (Nb_3Sn)!

High Luminosity LHC project scope



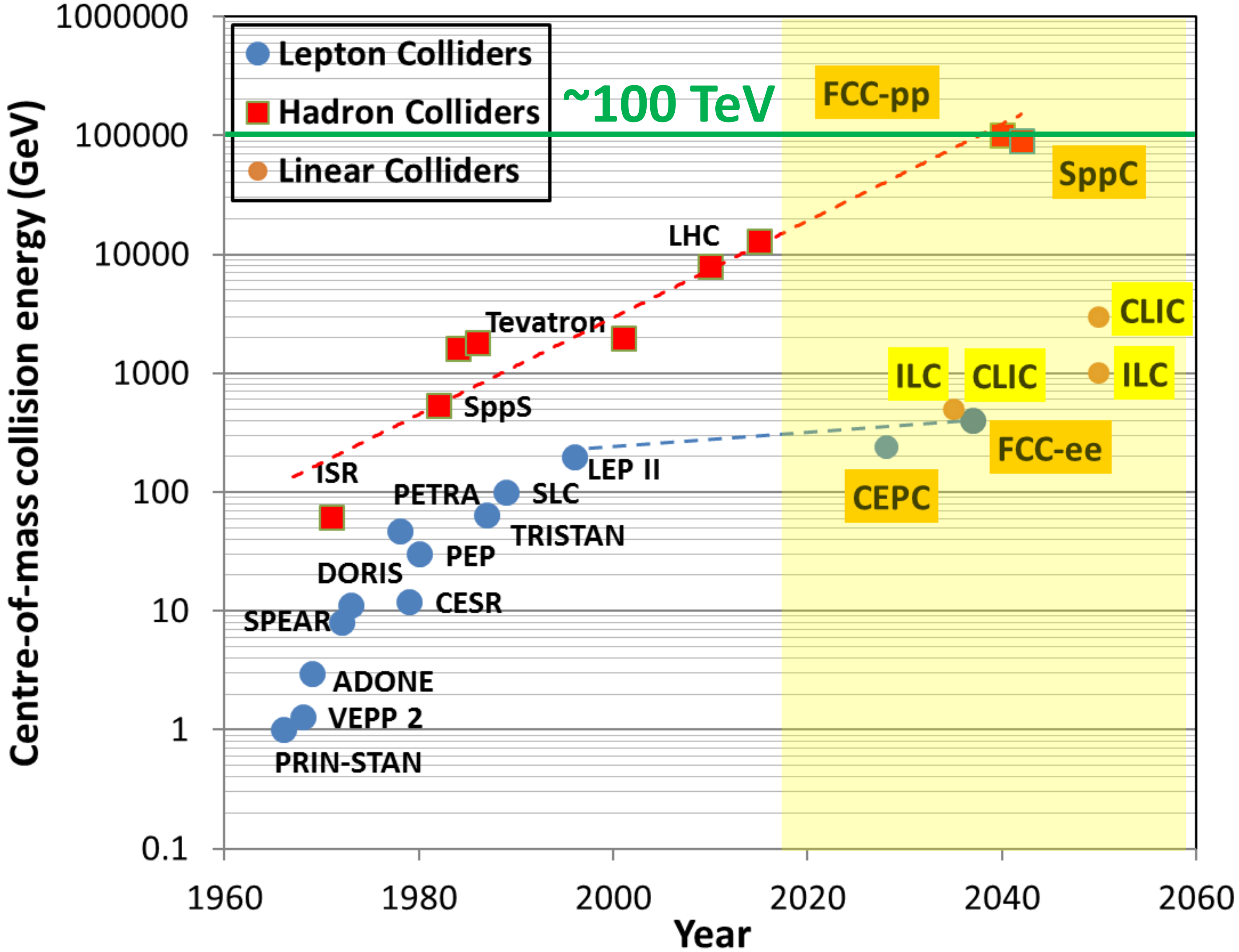
More than100 new SC magnets
36 large magnets in Nb_3Sn
Powering via SC Links and HTS Current Leads

20 new RF cavities, new collimators
New tunnel and surface infrastructures
New and upgraded cryo plants



L. Rossi

High Energy Colliders under study



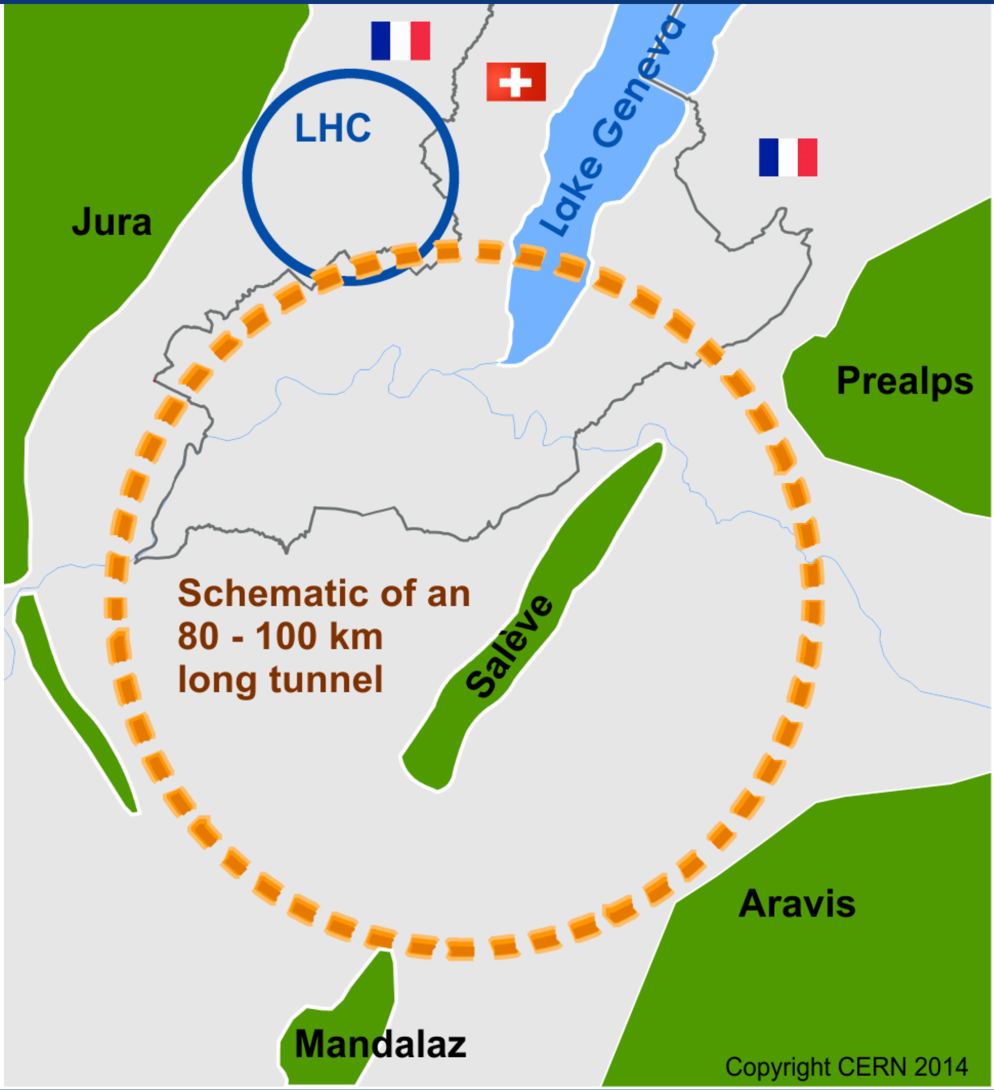
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

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

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

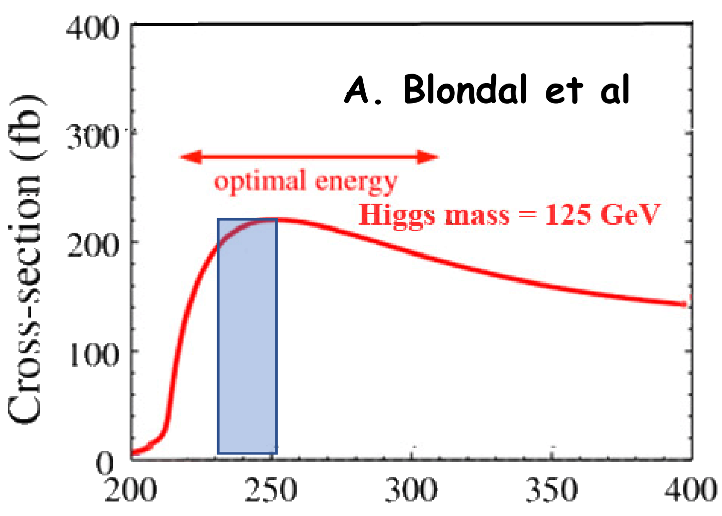
~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



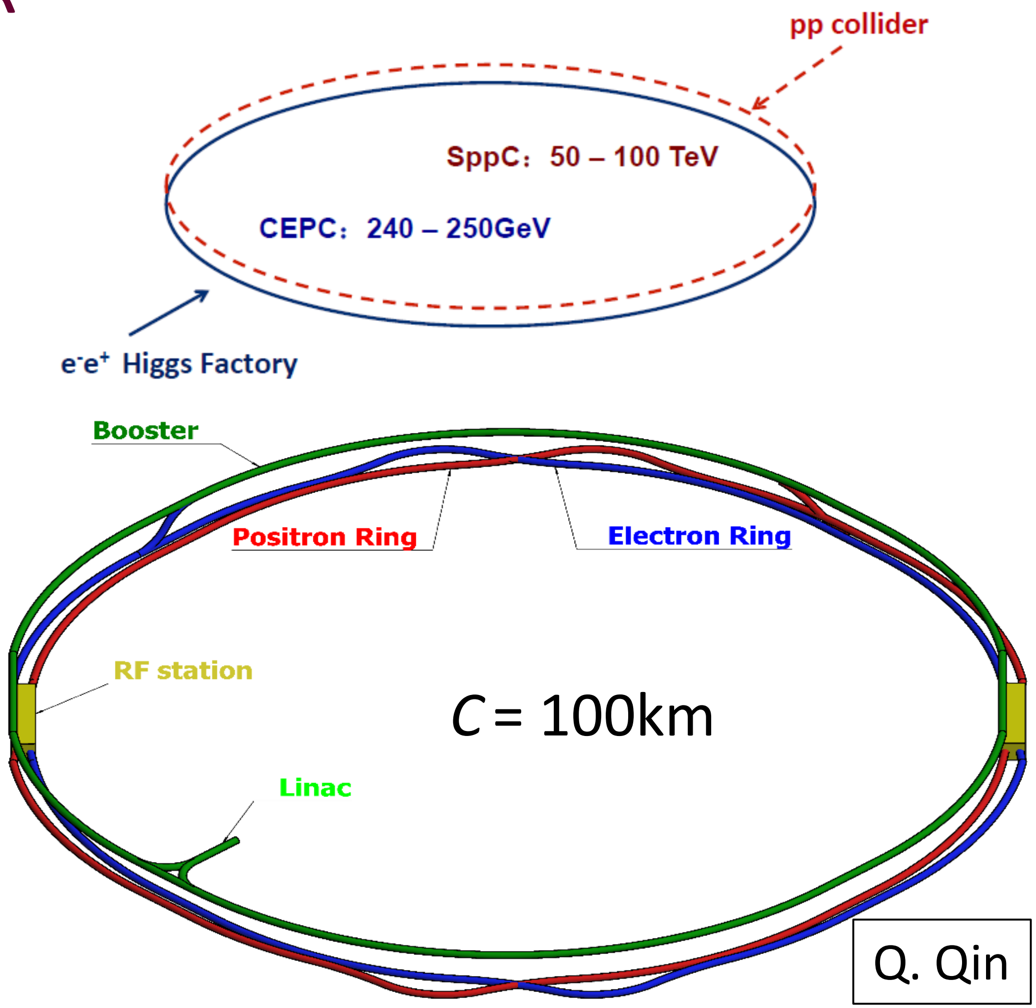
CEPC-SppC outline

- E_b=120GeV for CEPC
  - Limited by beamstrahlung & SR (~125GeV)



- $E_{b,max}$=100TeV for SppC
  - Limited by dipole field & C

- A CEPC (phase I) + SppC (phase II) was proposed in IHEP, Sept. 2012



Lepton collider studies

- FCC-ee and CEPC
  - Both designs based on separate vacuum chambers and magnetic channels for electrons and positrons
  - Much higher number of bunches and beam current compared with LEP machine (single chamber, only few bunches)
  - Overall limiting parameter is synchrotron radiation:
    - 100 MW for FCC-ee
    - 60 MW for CEPC
    - Determines maximum luminosities

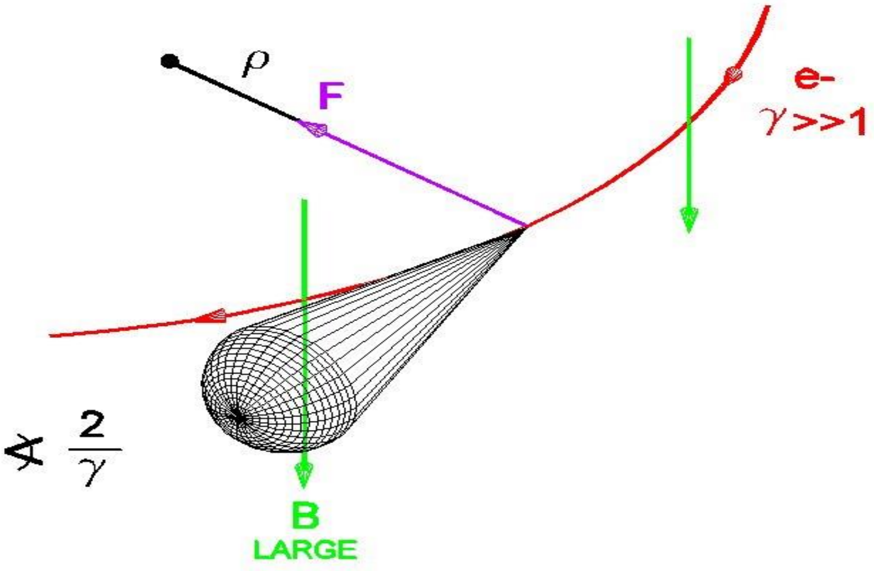
Synchrotron radiation

- Lepton colliders: name of the game here - **luminosity: as many collisions as possible → high beam current, small beam size.**
- Energy reach of circular e^+e^- colliders is limited due to synchrotron radiation of charged particles on curved trajectory:

$$\Delta E \propto (E_{kin}/m_0)^4/\rho$$

$$m_{prot} = 2000\ m_{electr}$$

$$\Delta E_{electron} \sim 10^{13}\ \Delta E_{proton}$$



FCC-ee parameters

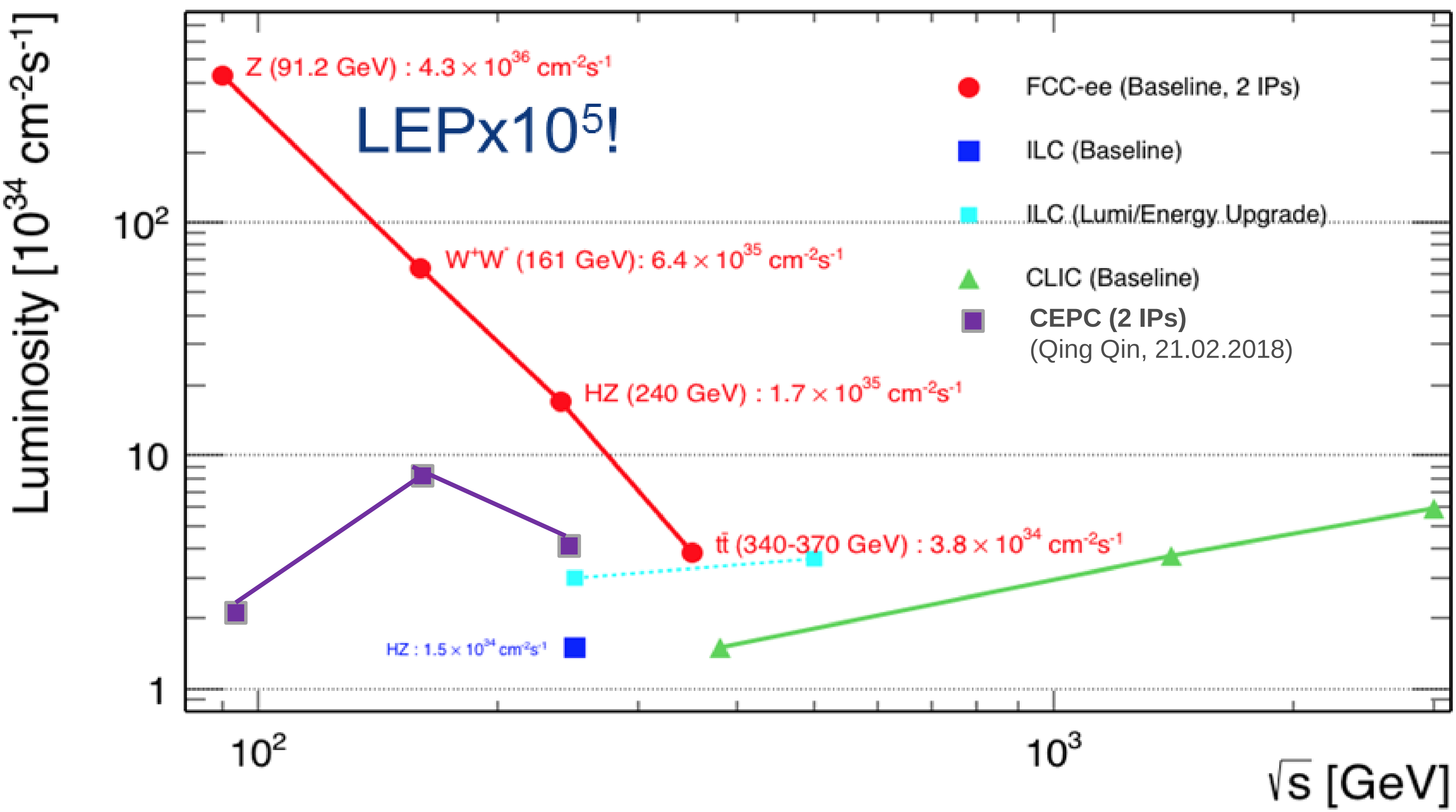
parameter	Z	WW	H (ZH)	ttbar	
beam energy [GeV]	45	80	120	175	182.5
beam current [mA]	1390	147	29	6.4	5.4
no. bunches/beam	16640	2000	393	48	39
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7	2.8
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.21
total RF voltage [GV]	0.1	0.44	2.0	9.5	10.9
SR power [MW]	100				
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	2	2
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.34	1.45
vert. geom. emittance [pm]	1.0	1.0	1.3	2.7	2.7
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>30	>7	>1.5	>1.3

Parameters of CEPC double ring

	Higgs	*W*	*Z*
Number of IPs	2		
Energy (GeV)	**120**	**80**	**45.5**
Circumference (km)	**100**		
SR loss/turn (GeV)	1.68	0.33	0.035
Half crossing angle (mrad)	16.5		
Piwinski angle	2.75	4.39	10.8
N_e/bunch (10^{10})	12.9	3.6	1.6
Bunch number	286	5220	10900
Beam current (mA)	17.7	90.3	83.8
SR power /beam (MW)	**30**	**30**	**2.9**
Bending radius (km)	10.9		
Momentum compaction (10^{-5})	1.14		
β_{IP} x/y (m)	0.36/0.002		
Emittance x/y (nm)	1.21/0.0036	0.54/0.0018	0.17/0.0029
Transverse σ_{IP} (um)	20.9/0.086	13.9/0.060	7.91/0.076
ξ_x/ξ_y/IP	0.024/0.094	0.009/0.055	0.005/0.0165
V_{RF} (GV)	2.14	0.465	0.053
f_{RF} (MHz) (harmonic)	650 (217500)		
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.48	3.7	5.18
HOM power/cavity (kw)	0.46 (2cell)	0.32(2cell)	0.11(2cell)
Energy spread (%)	0.098	0.066	0.037
Energy acceptance requirement (%)	1.21		
Energy acceptance by RF (%)	2.06	1.48	0.75
Photon number due to beamstrahlung	0.25	0.11	0.08
Lifetime due to beamstrahlung (hour)	1.0		
Lifetime (hour)	0.33 (20 min)	3.5	7.4
F (hour glass)	0.93	0.96	0.986
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	**2.0**	**4.1**	**1.0**

Q. Qin

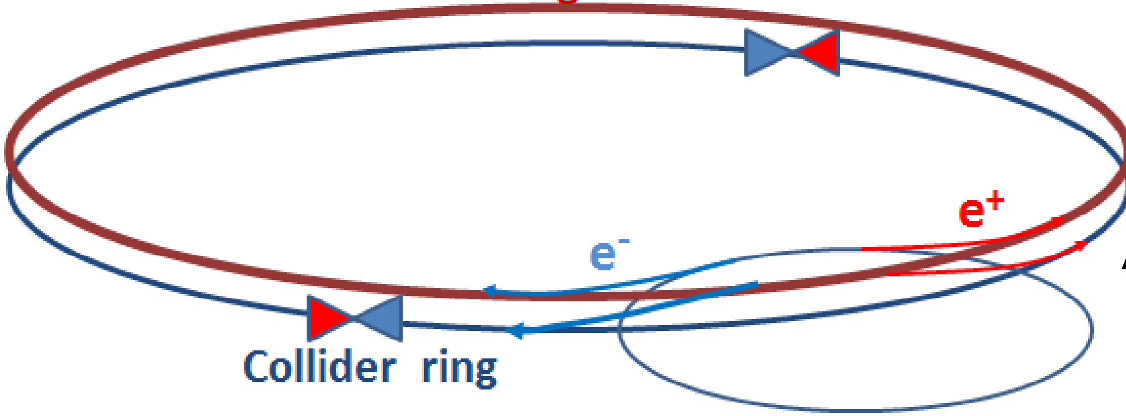
Lepton collider luminosities



Top-up injection concept

Beside the collider ring(s), a booster of the same size (same tunnel) must permanently provide beams for top-up injection

- **same RF voltage, but low power (~ MW)**
- **top up frequency ~0.1 Hz**
- **booster injection energy ~10-20 GeV**
- **bypass around the experiments**



A. Blondel

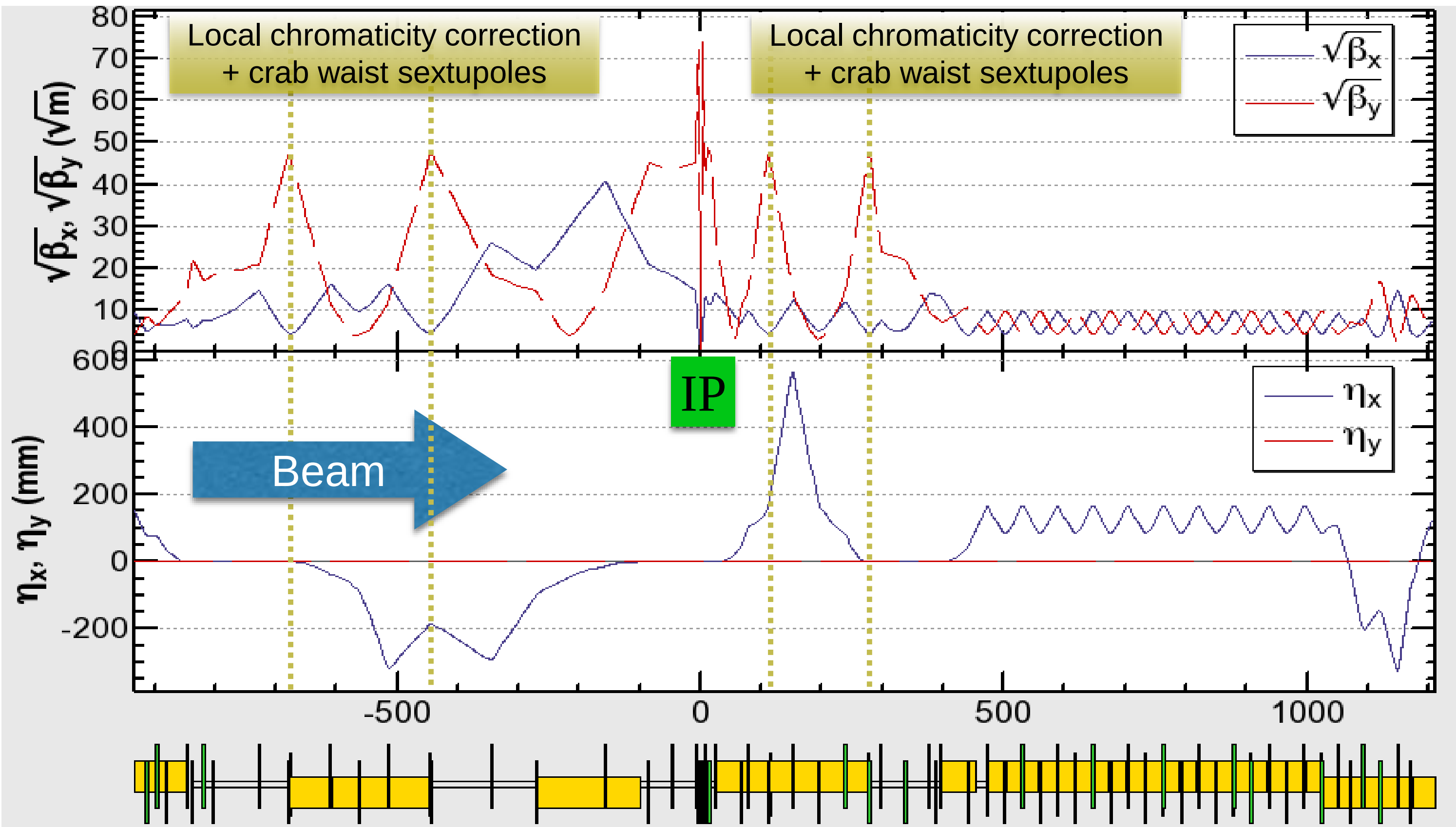
Injector complex for e^+ and e^- beams of 10-20 GeV

- **Injector similar to Super-KEKB injector is suitable**

FCC-ee optics design

Interaction region: asymmetric optics design

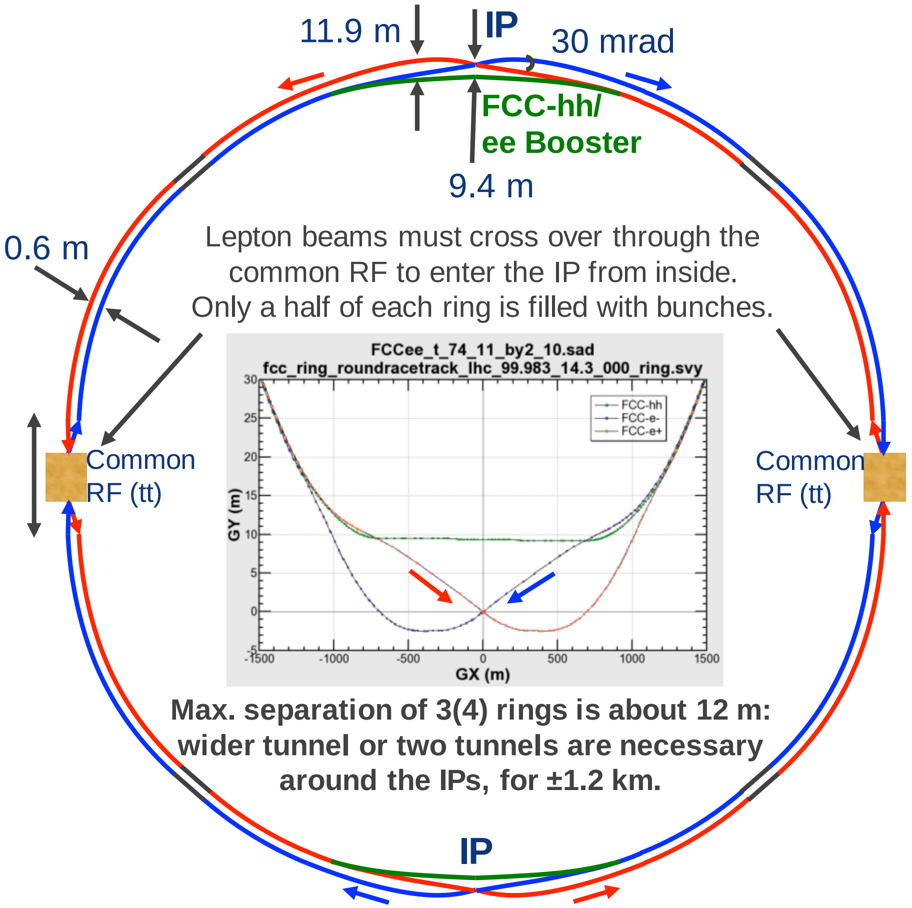
- To limit (MeV) synchrotron radiation from upstream dipoles to detector
- <100 keV up to ~500 m from interaction point



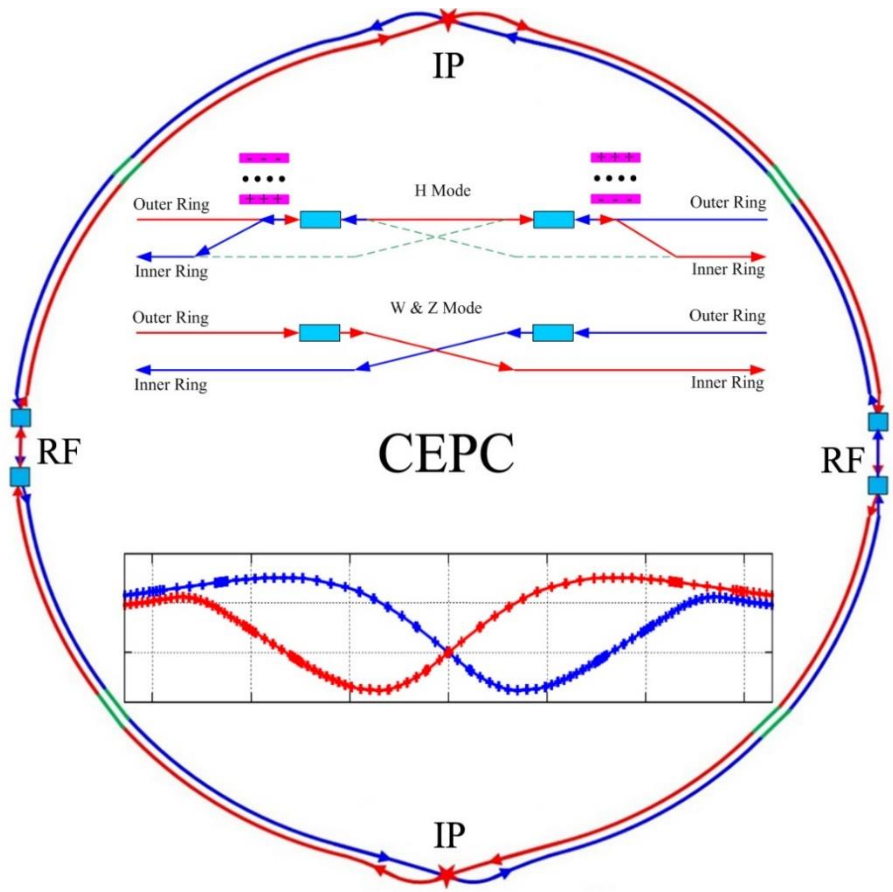
K. Oide

Lepton collider layouts

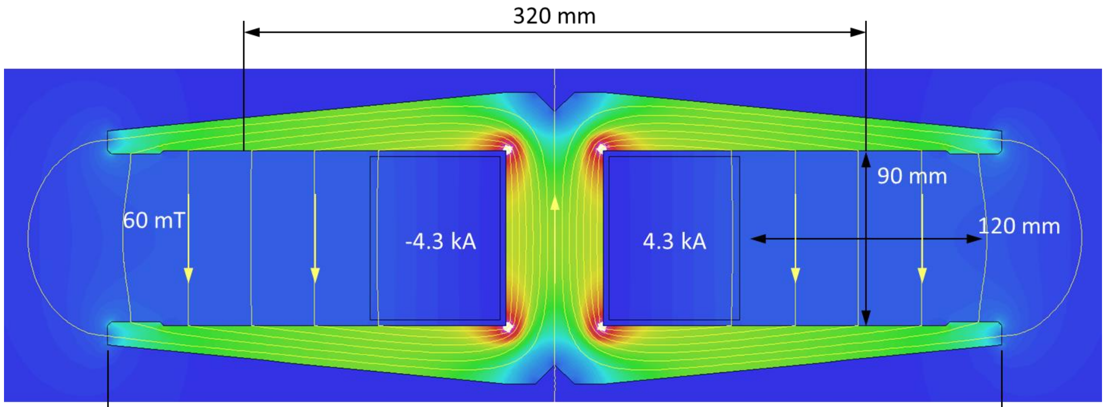
FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

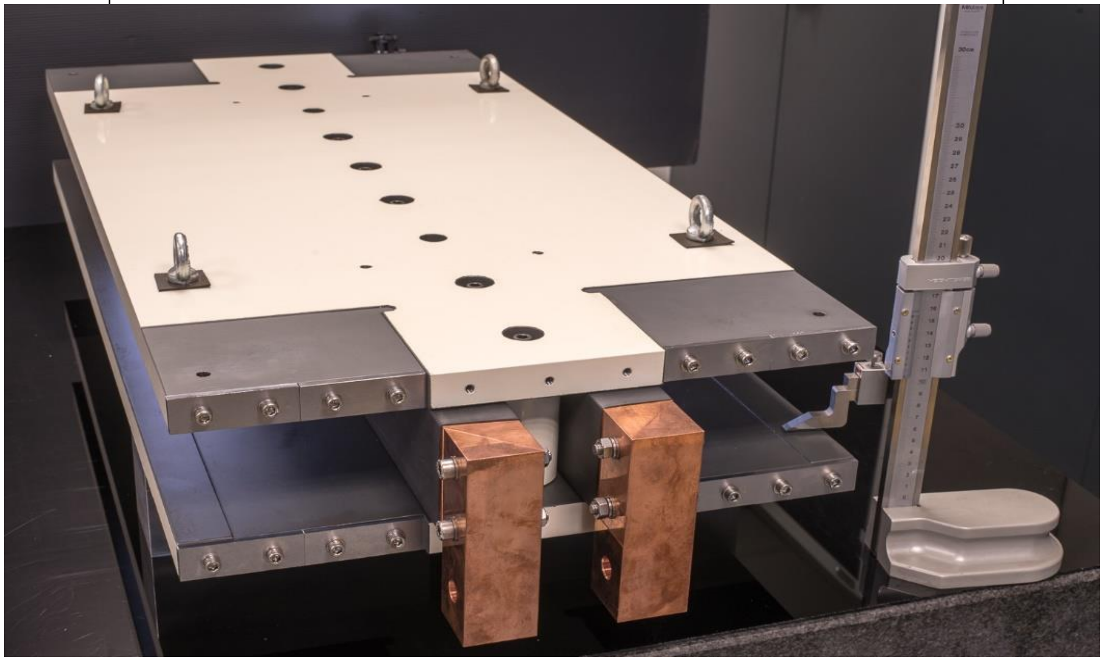


CEPC Layout



Efficient 2-in-1 FCC-ee arc magnets





A. Milanese

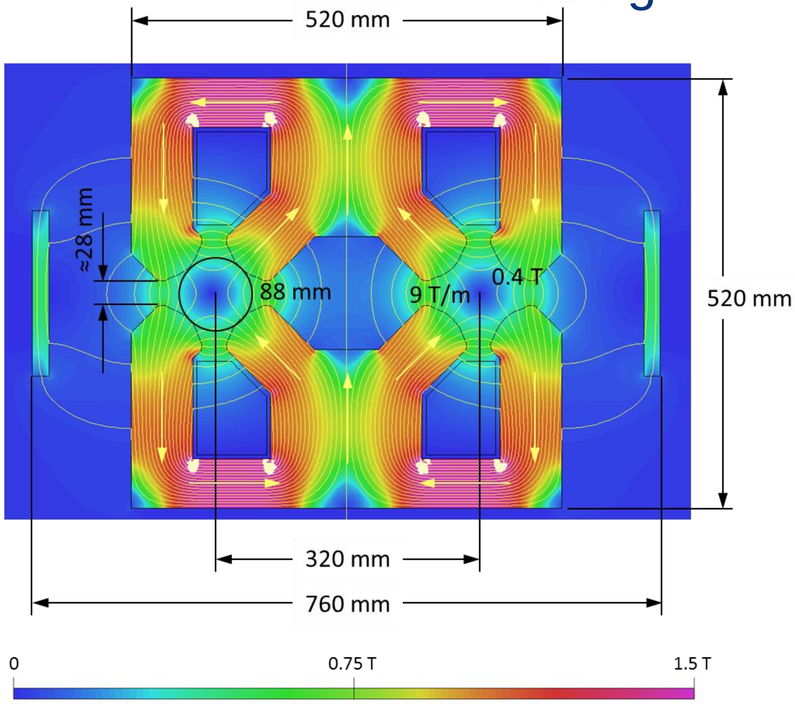
Dipole:

twin aperture yoke

single busbars as coils

Quadrupole:

twin 2-in-1 design



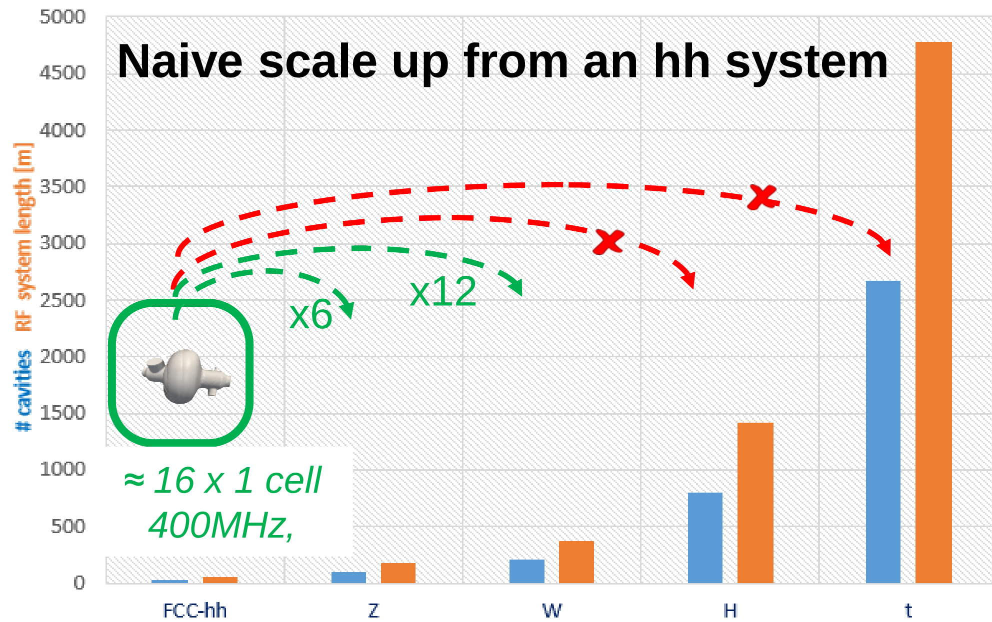
FCC-ee RF system requirements

Very large range of operation parameters

"Ampere-class" machines

	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
hh	0.032		500	
Z	0.4/0.2	30000/90000	1450	0.034
W	0.8	5162	152	0.33
H	5.5	770	30	1.67
t	11	78	6.6	7.55

"high gradient" machines



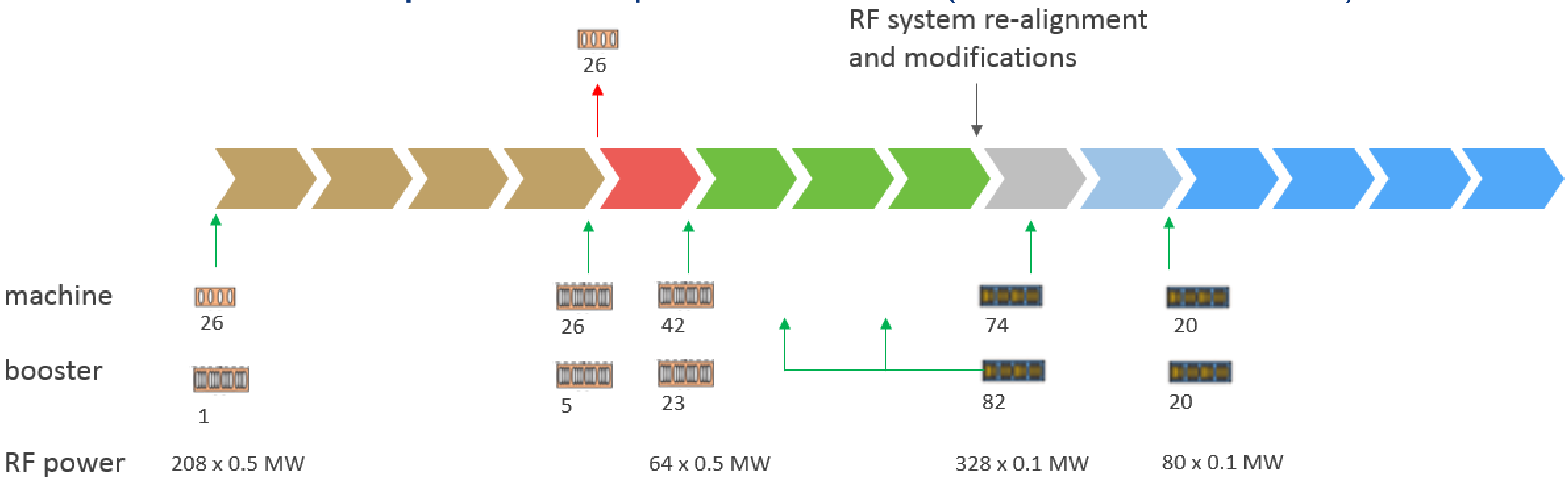
- Voltage and beam current ranges span more than factor > 10^2
- No single RF system solution satisfying requirements

FCC-ee operation concept & RF staging

Integral luminosities for physics define running time, total ~14 years.

Three sets of RF cavities to cover all options for FCC-ee & booster:

- **high intensity (Z, FCC-hh): 400 MHz mono-cell cav (4/cryomodule)**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (5/c.m.)**
- Installation sequence comparable to LEP (≈ 30 CM/shutdown)



Hadron collider studies

- **FCC-hh, SppC and HE-LHC**

  - **All based on higher magnetic fields and new SC materials for accelerator magnets**
    - **FCC-hh and HE LHC use Nb_3Sn,**
    - **SppC uses Fe-based SC**

  - **FCC-hh and SppC based on larger bending radius and tunnel circumference of ~100 km**

  - **HE LHC uses existing LHC tunnel infrastructure**

hadron collider parameters (*pp*)

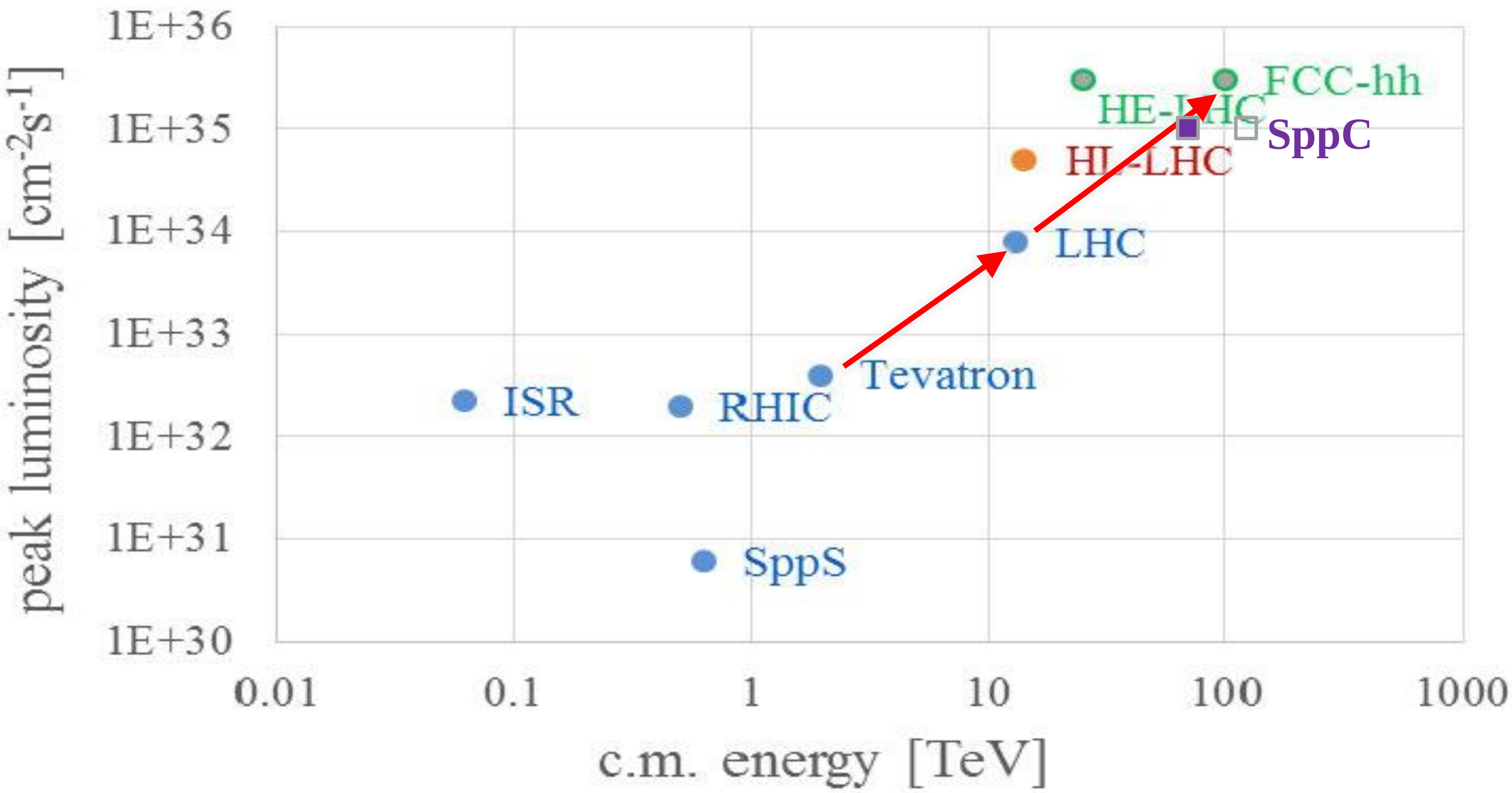
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	**100**		**25**	14
dipole field [T]	**16**		**16**	8.3
circumference [km]	**100**		**27**	27
# IP	**2 main & 2**		**2 & 2**	2 & 2
beam current [A]	**0.5**		**1.27**	(1.12) 0.58
bunch intensity [10^{11}]	**1 (0.2)**	**1 (0.2)**	**2.5**	(2.2) 1.15
bunch spacing [ns]	**25 (5)**	**25 (5)**	**25 (5)**	25
IP $\beta^*_{x,y}$ [m]	**1.1**	**0.3**	**0.25**	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	**30**	**34**	(5) 1
peak #events/bunch crossing	170	**1020** (204)	**1070** (214)	(135) 27
stored energy/beam [GJ]	**8.4**		**1.4**	(0.7) 0.36
synchrotron rad. [W/m/beam]	**30**		**4.1**	(0.35) 0.18

SPPC main parameters (updated)

Parameter	Unit	Value		
		PreCDR	**CDR**	Ultimate
Circumference	km	54.4	**100**	100
C.M. energy	TeV	70.6	**75**	125-150
Dipole field	T	20	**12**	20-24
Injection energy	TeV	2.1	**2.1**	4.2
Number of IPs		2	**2**	2
Nominal luminosity per IP	$cm^{-2}s^{-1}$	$1.2x10^{35}$	**$1.0x10^{35}$**	-
Beta function at collision	m	0.75	**0.75**	-
Circulating beam current	A	1.0	**0.7**	-
Bunch separation	ns	25	**25**	-
Bunch population		$2.0x10^{11}$	**$1.5x10^{11}$**	-
SR power per beam	MW	2.1	**1.1**	-
SR heat load per aperture @arc	W/m	45	**13**	-

Q. Qin

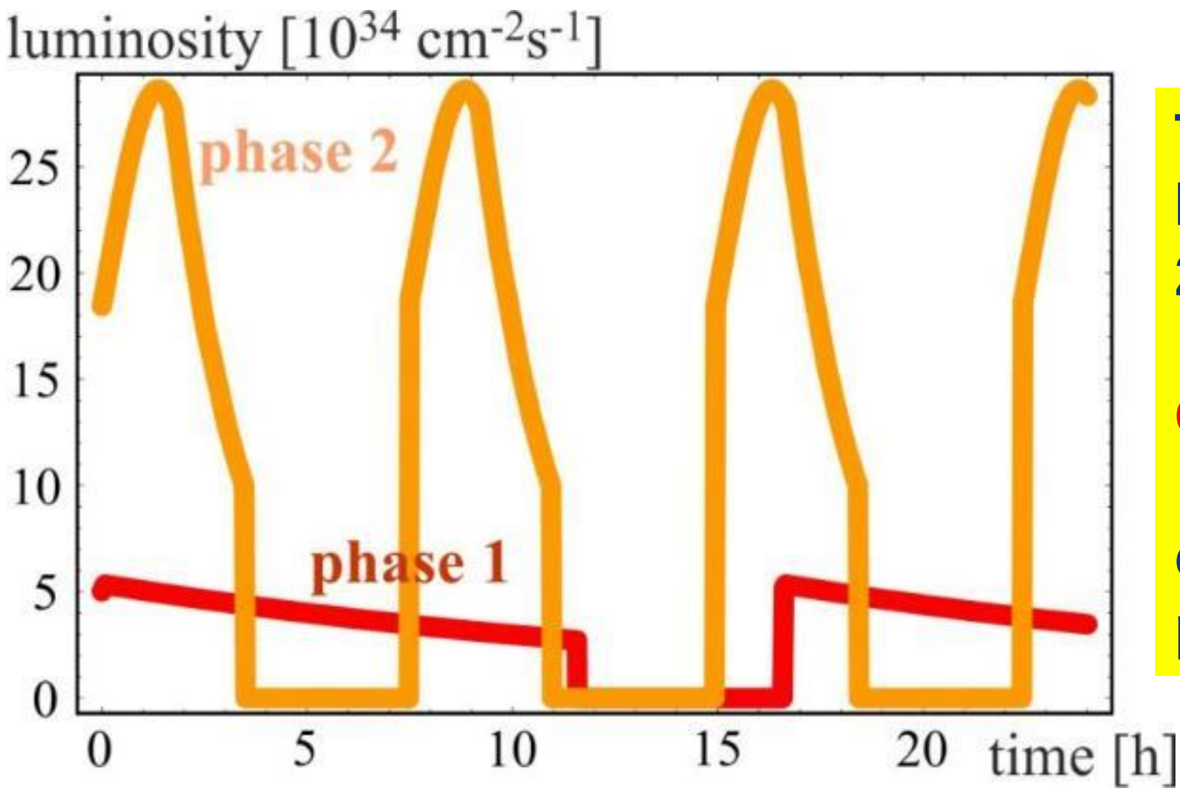
pp/p-pbar in the *L-E* plane



FCC-hh luminosity evolution

phase 1: β*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h, 1 ab^{-1} / year



Total integrated luminosity over 25 years operation:

O(20) ab^{-1}/experiment

consistent with physics goals

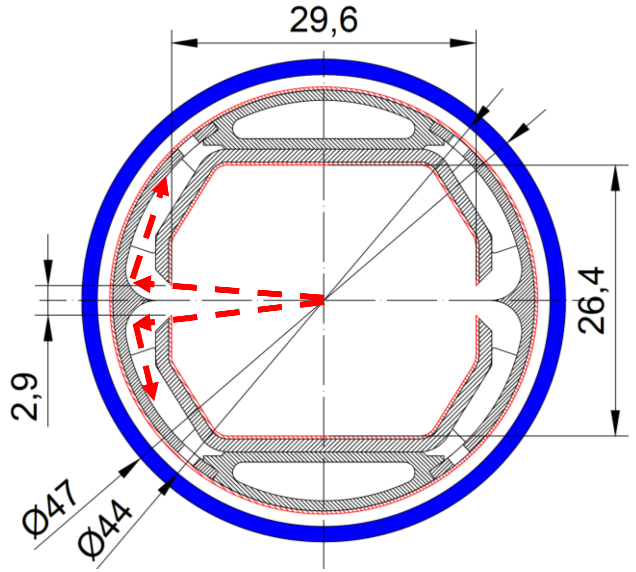
PRST-AB 18, 101002 (2015)

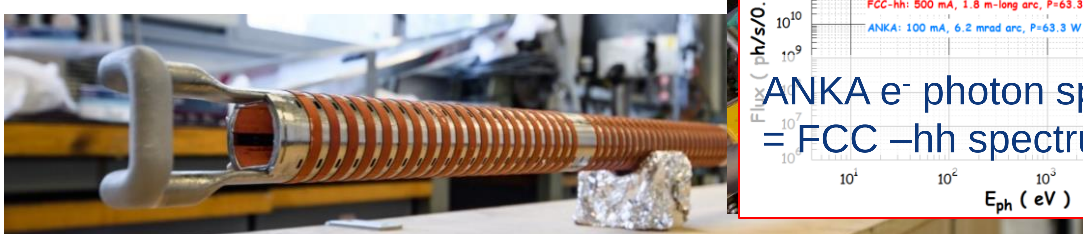
Interplay of radiation damping, luminosity burn-off, controlled transvers blow-up

FCC-hh beam screen prototype

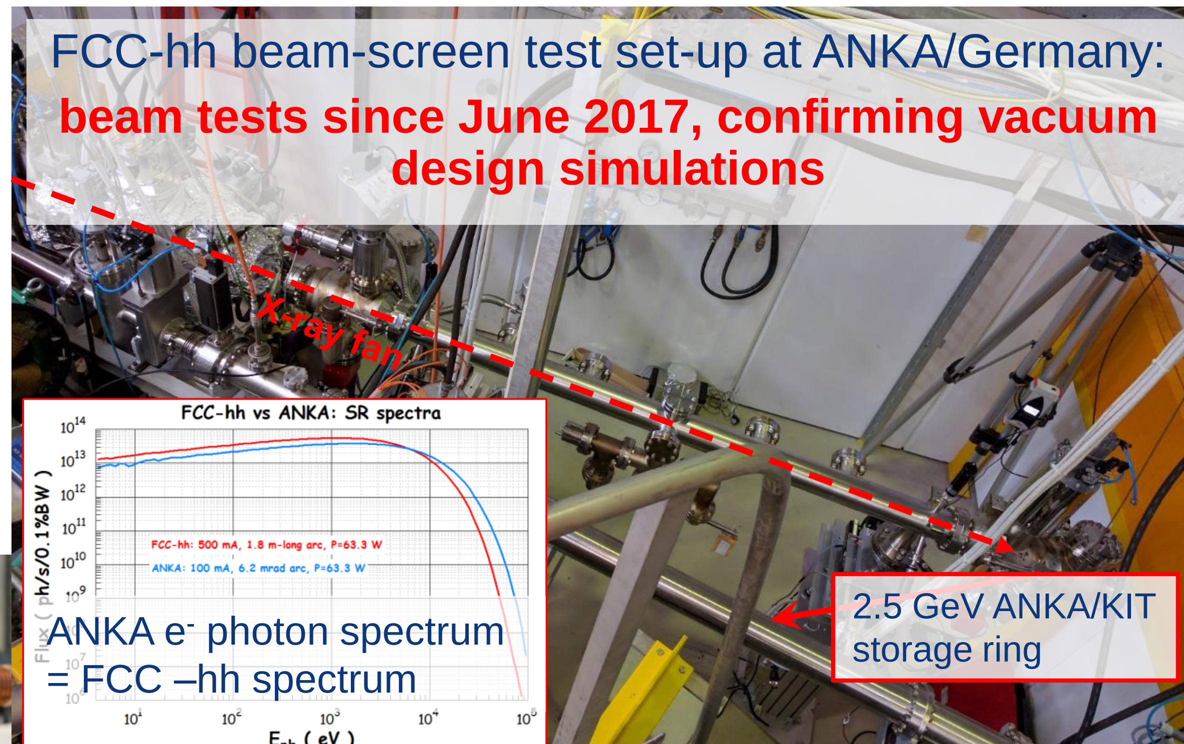
Synchrotron radiation (~ 30 W/m/beam (@16 T) (cf. LHC <0.2W/m) **~ 5 MW total load in arcs**

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

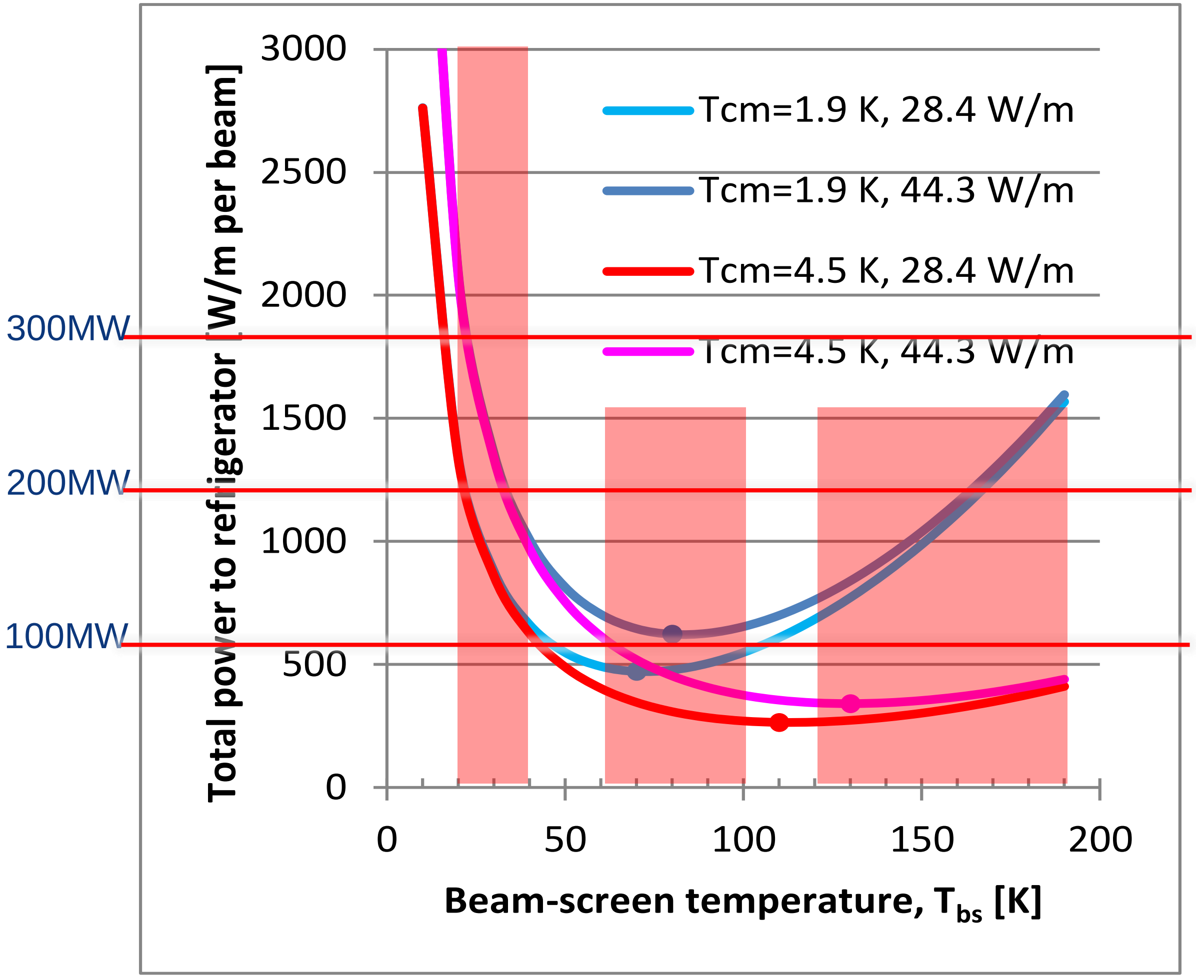




FCC-hh beam-screen test set-up at ANKA/Germany:
beam tests since June 2017, confirming vacuum design simulations



FCC-hh cryosystem – efficiency



Overall optimisation of

- **Cryoplant power consumption**
- **Vacuum system**
- **Impedance and beam stability**

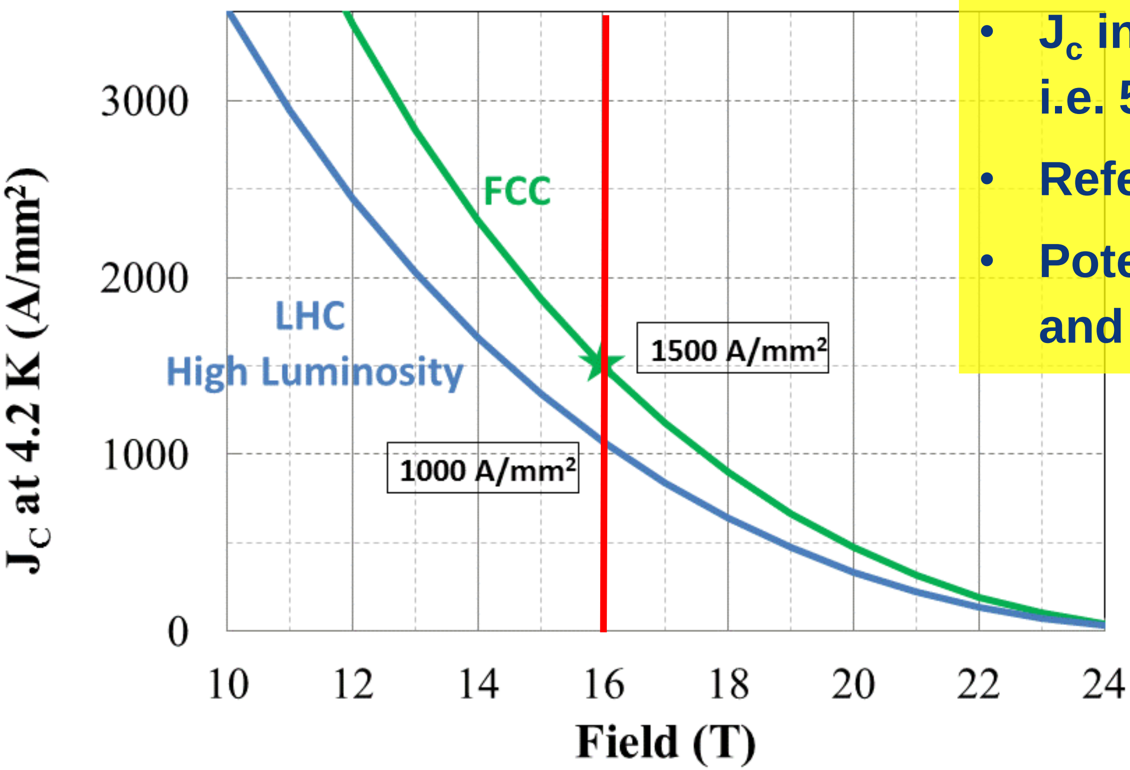
- **Optimum beam screen operation temperature 40 - 60 K**
- **Electrical power for beam screen cooling ~100 MW .**
- **Total electrical power for cryoplants ~ 200 MW.**

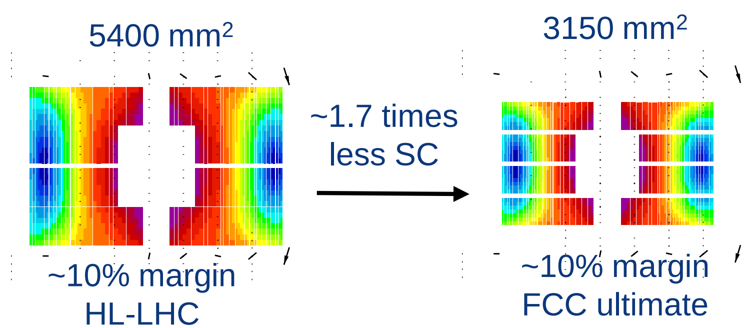
Nb_3Sn conductor program

Nb_3Sn is one of the major cost & performance factors for FCC-hh and is given highest attention

Main development goals until 2020:

- J_c increase (16T, 4.2K) > 1500 A/mm^2 i.e. 50% increase wrt HL-LHC wire
- Reference wire diameter 1 mm
- Potentials for large scale production and cost reduction

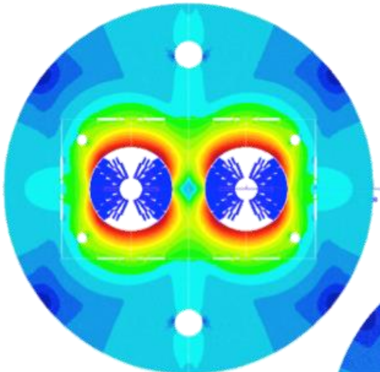




16 T dipole options and plans

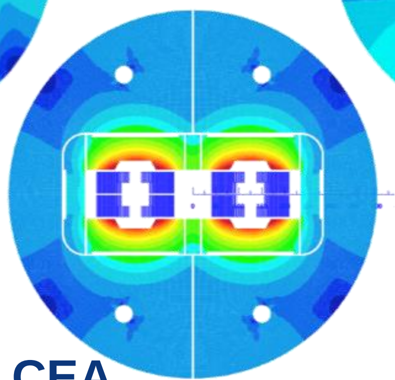
H2020

Cos-theta



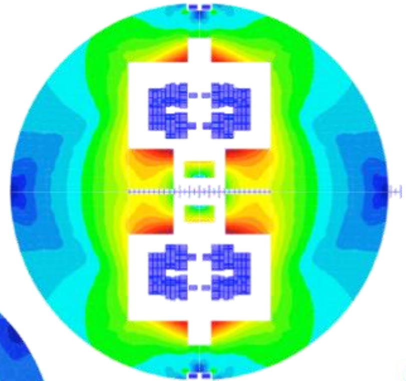
INFN

Blocks



CEA

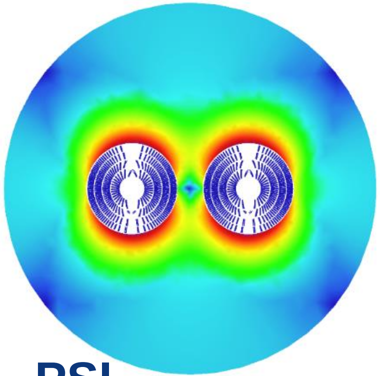
Common coils



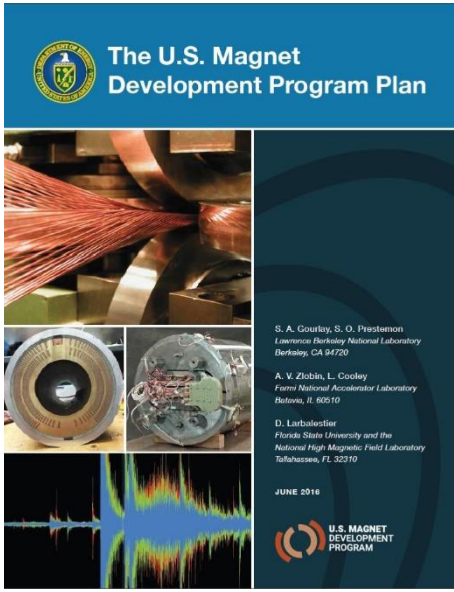
CIEMAT

Swiss contribution

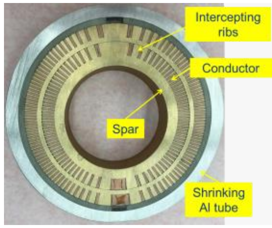
Canted Cos-theta



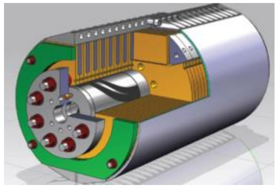
PSI



LBNL



FNAL



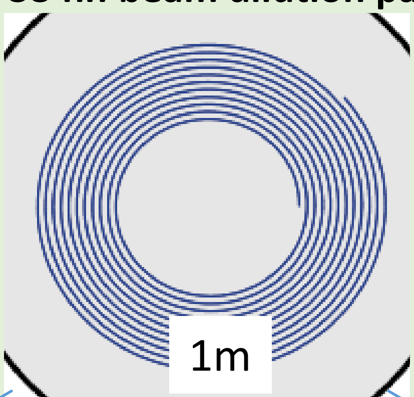
Short model magnets (1.5 m lengths) will be built 2017 – 2022
Long model production with industry 2023 - 2026

Beam power & machine protection

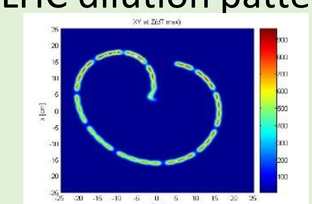
8 GJ kinetic energy per beam

- O(20) times LHC (3 x bunches, 7 x energy)
- Airbus A380 at 720 km/h
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories

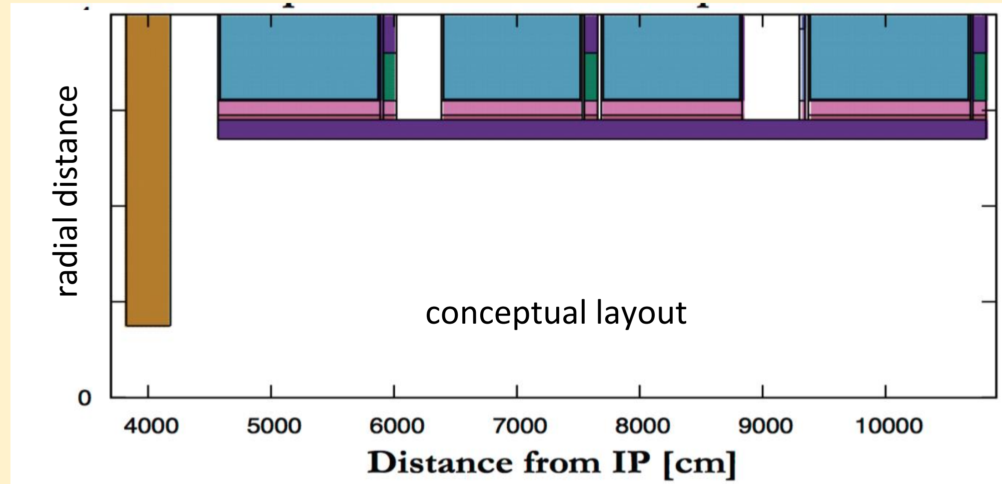
FCC-hh beam dilution pattern at dump



LHC dilution pattern



Up to **500 kW collision debris per experiment**
Mainly lost in triplets, challenge for lifetime and quench



Triplet design allows **thick shielding, tungsten ≤ 55 mm**

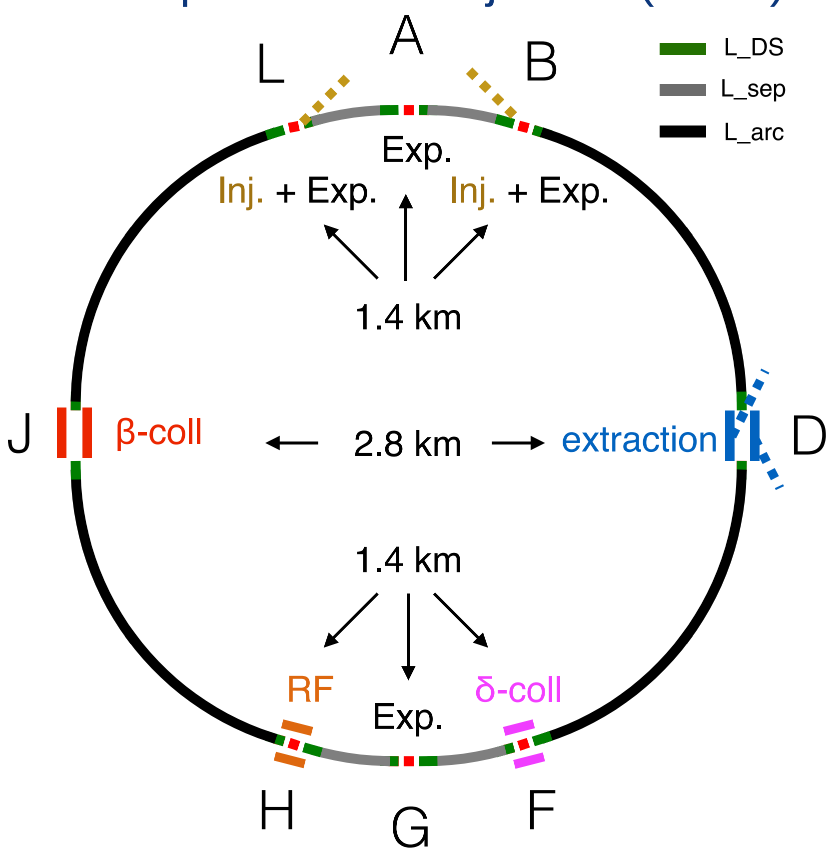
- Dose ≤ 30 MGy → **survives project lifetime (20 ab^{-1})**

Collimation system design ongoing (optics & HW)

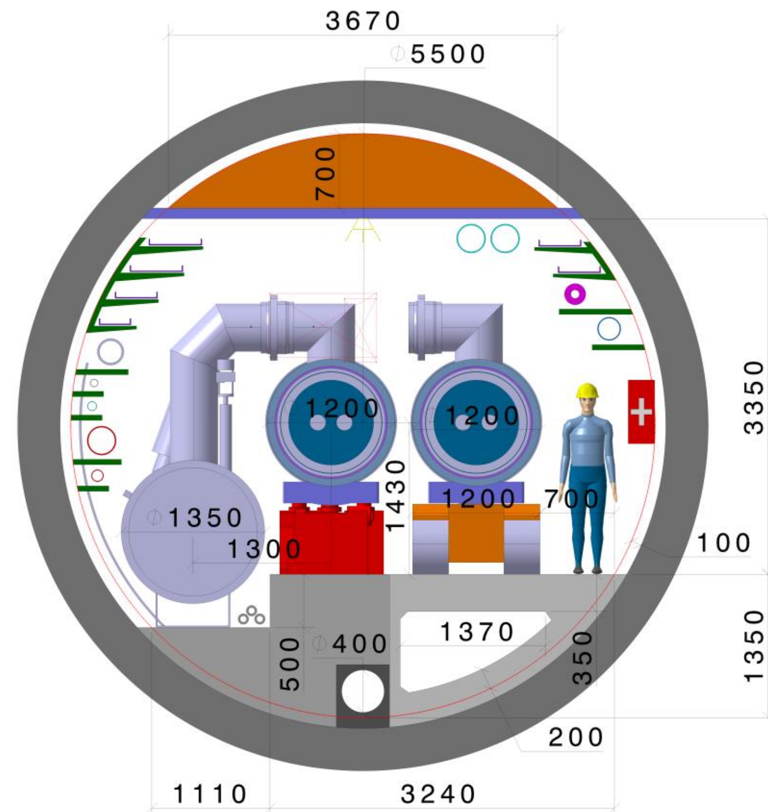
- Goal is sustain beam lifetimes **down to 12 minutes** (11MW losses) → **Looks achievable**

FCC layout and integration concept

- Two high-luminosity experiments (A & G)
- Two experiments & injection (L & B)



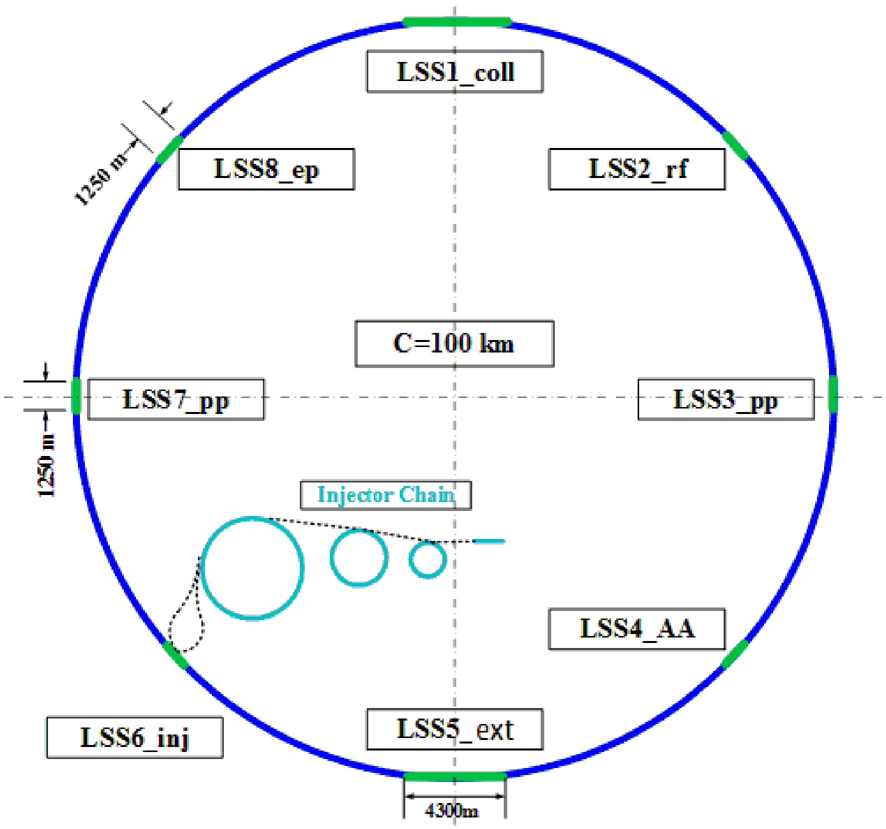
- FCC-hh integration concept
- 5.5 m diameter tunnel



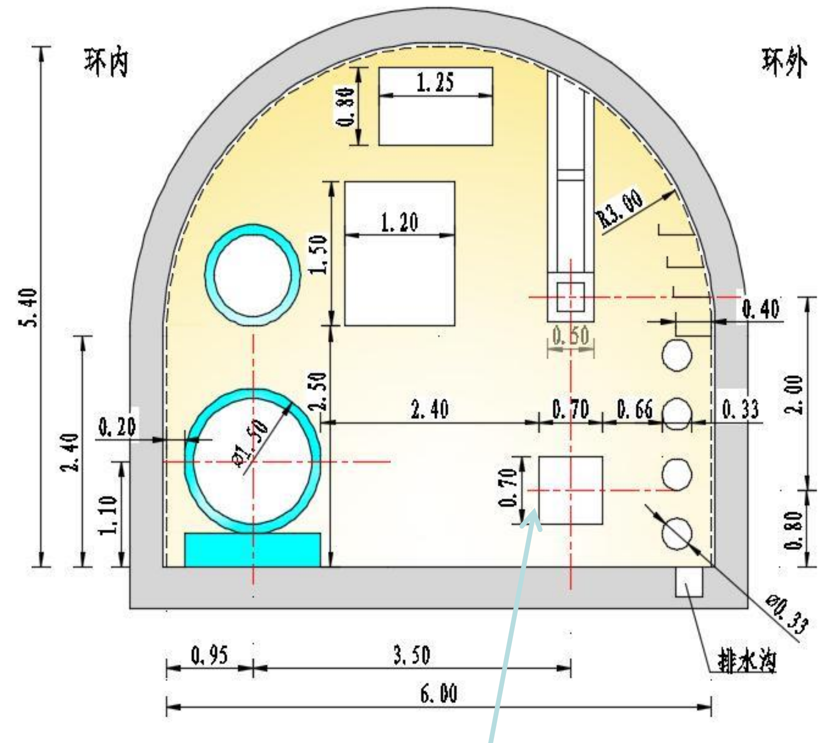
- Betatron cleaning (J), momentum cleaning (F)
- Extraction insertion (D), RF insertion (H)

SPPC Layout and tunnel cross-section

SPPC Layout



Tunnel cross-section



More space required for CEPC double-ring scheme

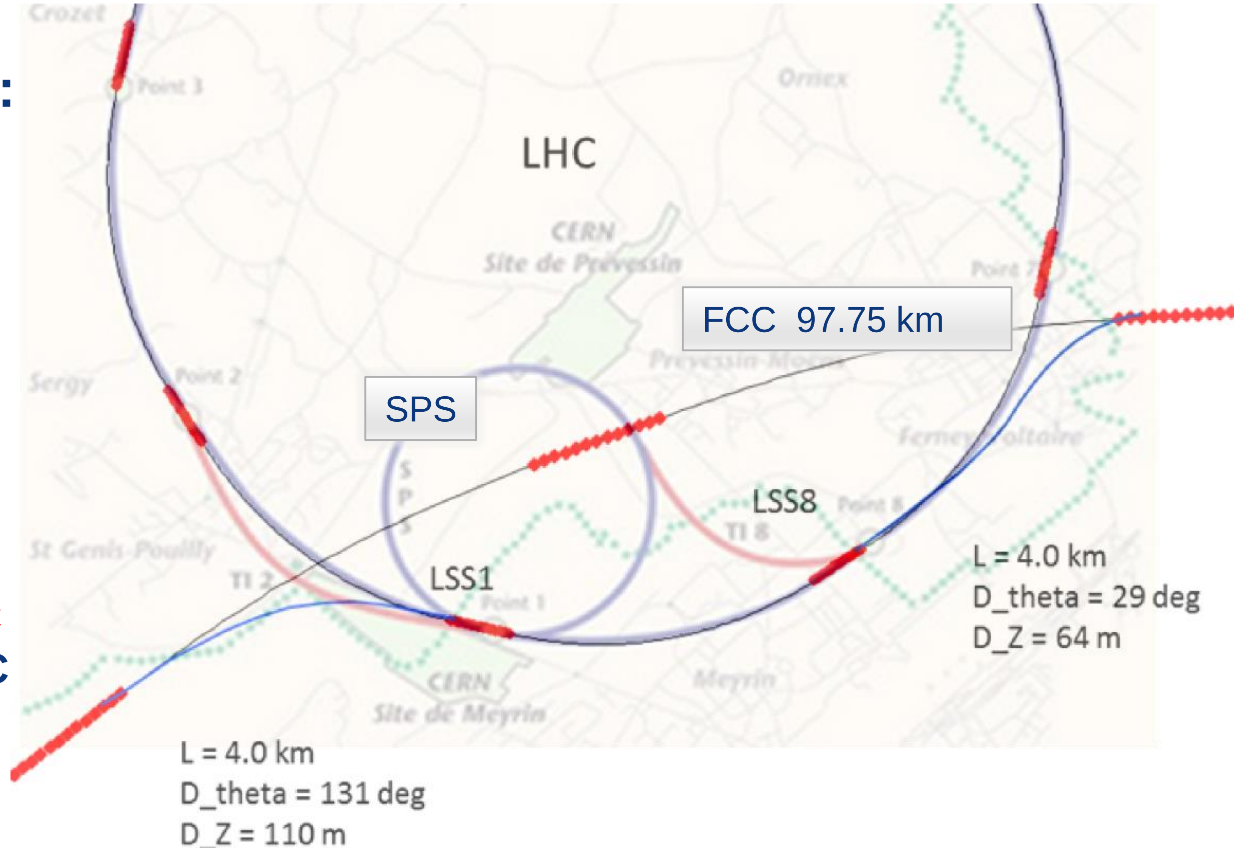
中国科学院高能物理研究所
Institute of High Energy Physics

Q. Qin

FCC-hh injector complex

Injector options FCC-hh:

- SPS → LHC → FCC
- $SPS_{upgrade}$ → FCC



Current baseline:
- **Injection energy 3.3 TeV LHC**

→ **Field-swing FCC-hh like LHC**

Alternative options:
- **Injection from $SPS_{upgrade}$ around 1.3 TeV**
- **$SPS_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp, cf. SIS 300**
- **$SPS_{upgrade}$ would also be an ideal injector for HE LHC (alternative to 450 GeV SPS)**

Progress on site investigations

Alignment | Shafts | Query

Choose alignment option

V4variation_v2017-2

Tunnel elevation at centre:322mASL

Grad. Params

Azimuth (°): -23.5

Slope Angle x-x(%): 0.3

Slope Angle y-y(%): 0.08

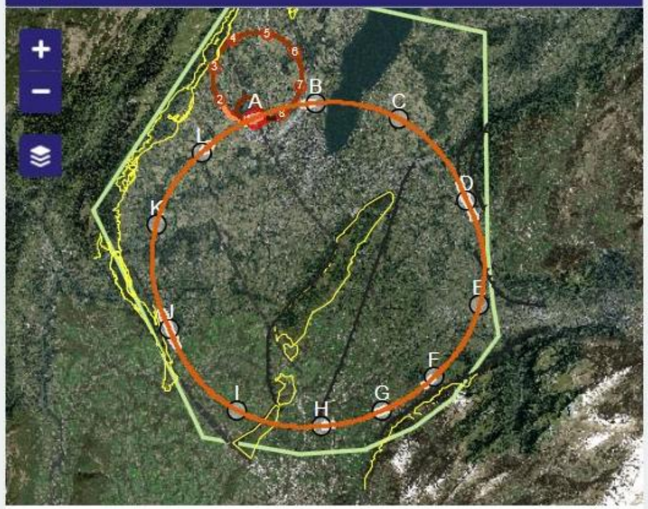
LOAD | SAVE | CALCULATE

Alignment centre

X: 2499941 Y: 1107760

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

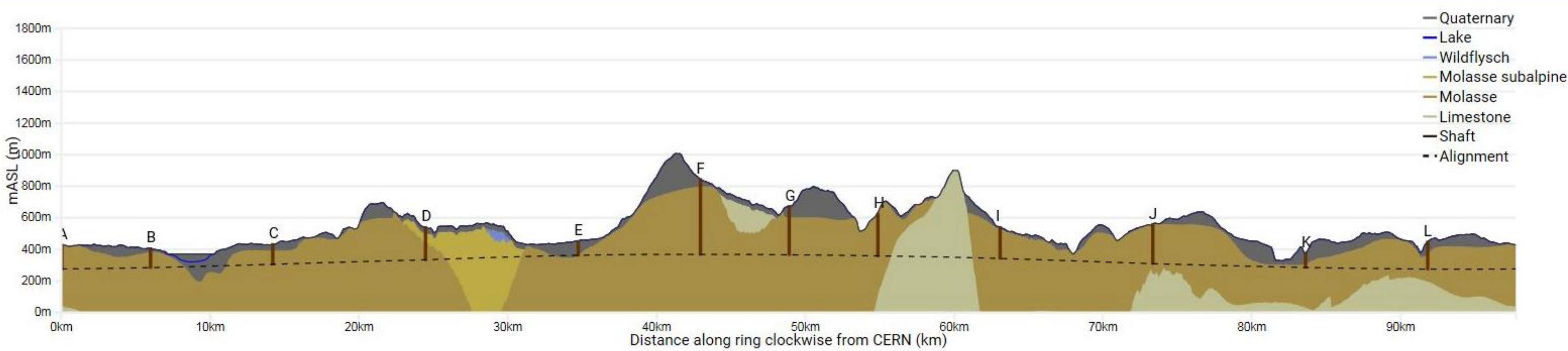
Alignment Location



Geology Intersected by Shafts | Shaft Depths

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

Alignment Profile



Geology Intersected by Tunnel | Geology Intersected by Section

84.6% | 5.2% | 5.5% | 4.7%

Progress on site investigations

Alignment | Shafts | Query

Choose alignment option

V4variation_v2017-2

Tunnel elevation at centre:322mASL

Grad. Params

Azimuth (°): -23.5

Slope Angle x-x(%): 0.3

Slope Angle y-y(%): 0.08

LOAD | SAVE | CALCULATE

Alignment centre

X: 2499941 Y: 1107760

	CP 1		CP 2	
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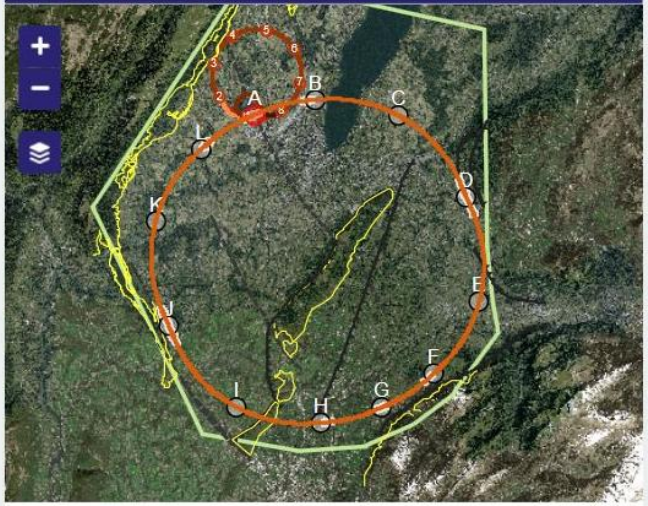
Alignment Location



Geology Intersected by Shafts | Shaft Depths

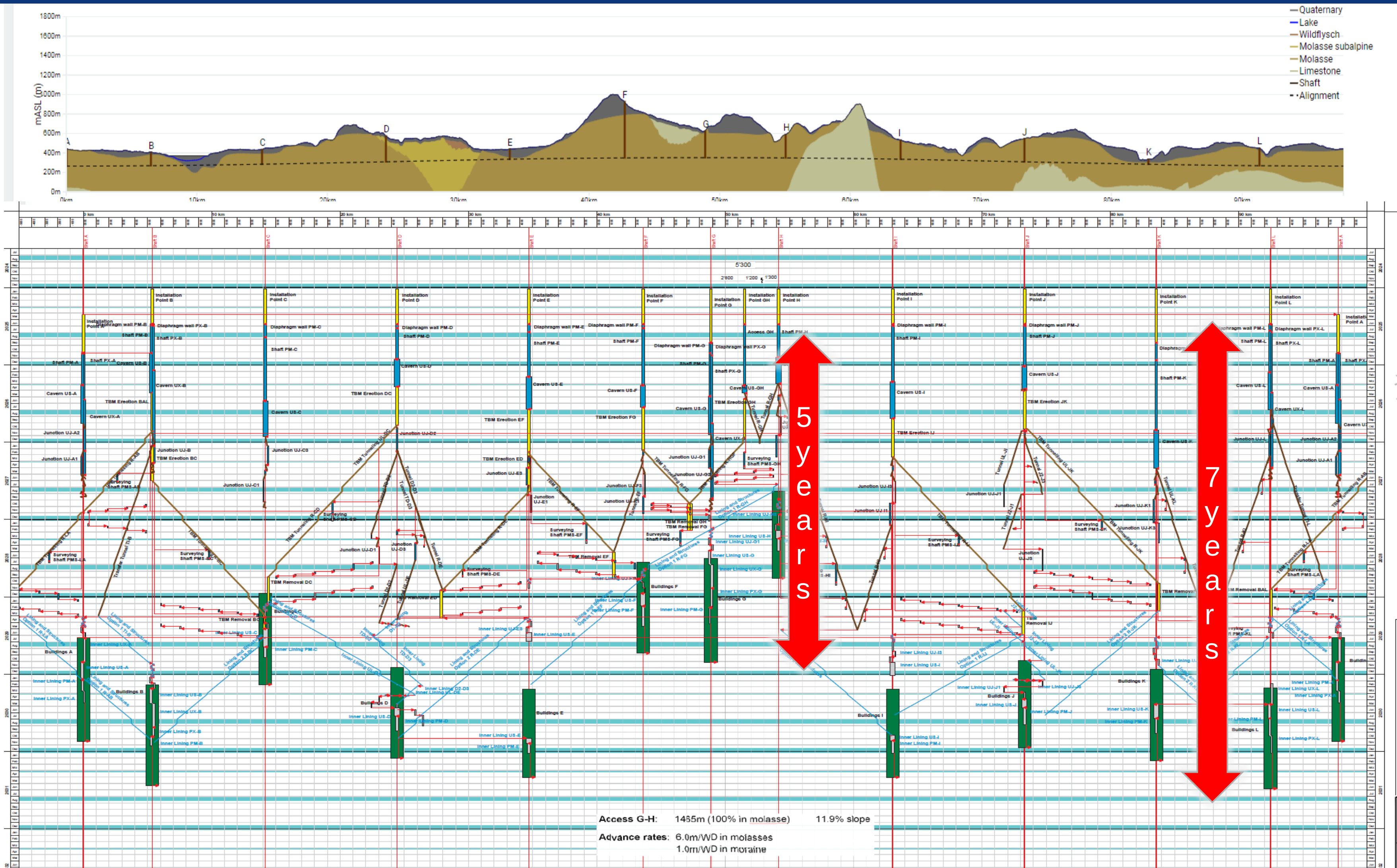
	Shaft Depth (m)	Geology (m)					
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Limestone
A	152	0	0	0	152	0	0
B	121	0	0	26	95	0	0
C	127	0	0	44	83	0	0
D	205	66	0	40	100	0	0
E	89	0	0	89	0	0	0
F	476	0	0	49	427	0	0
G	307	0	0	73	234	0	0
H	266	0	0	0	266	0	0
I	198	0	0	11	187	0	0
J	248	0	0	1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

Alignment Profile

- 90 – 100 km fits geological situation well
- Connected to LHC as potential injector
- Detailed investigations on implementation of the preferred 97.75 km variant

84.6% 5.2% 5.5% 4.7%

CE schedule study



HE-LHC: Topics requiring special attention

Many aspects extrapolated/copied from HL-LHC/FCC-hh. Important exceptions:

Tunnel integration and magnet technology

- **compact 16 T** magnets (stray field, etc..) (LHC tunnel 3.8 m vs. FCC-hh 5.5 m)
- **HE-LHC Nb_3Sn magnets must be bent** - 9 mm horizontal orbit shift (vs. 2 FCC-hh)

Straights

- low-beta insertions, **longer triplet than HL-LHC, β^* reach**
- collimation insertions, **LHC optics scaling not applicable**, warm dipole length increase
- extraction straights – **length of kicker & septum sections**

Injector and injection energy

- **physical & dynamic aperture and beam size at injection**
- **impedance and beam stability,**
- **field swing of 16 T magnets…**

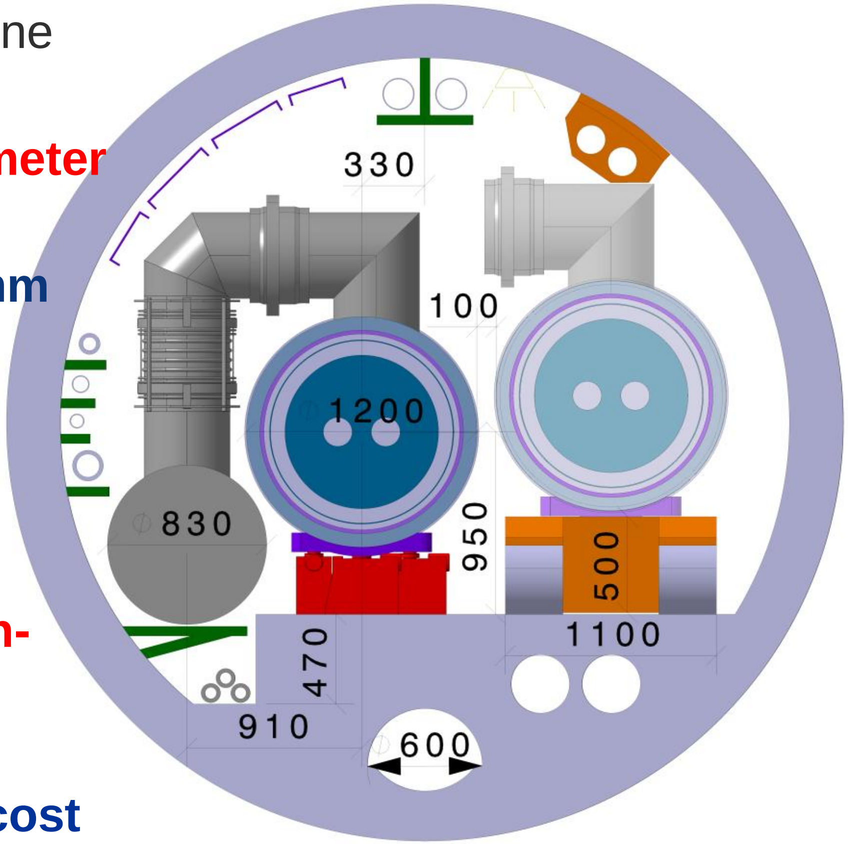
HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical cryostat design gives ~1500 mm diameter!**

LHC tunnel diameter 3.8 m



Strategy: optimize 16 T magnet, compatible with HE LHC and FCC-hh :

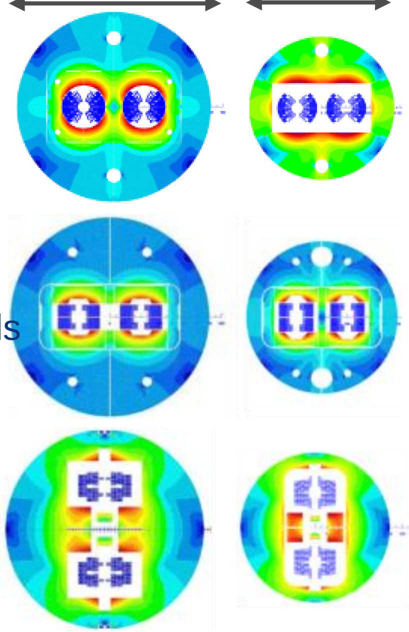
- **Allow stray-field and/or cryostat as return-yoke**
- **Optimization of inter-beam distance**
  → Smaller diameter relevant for FCC-hh cost

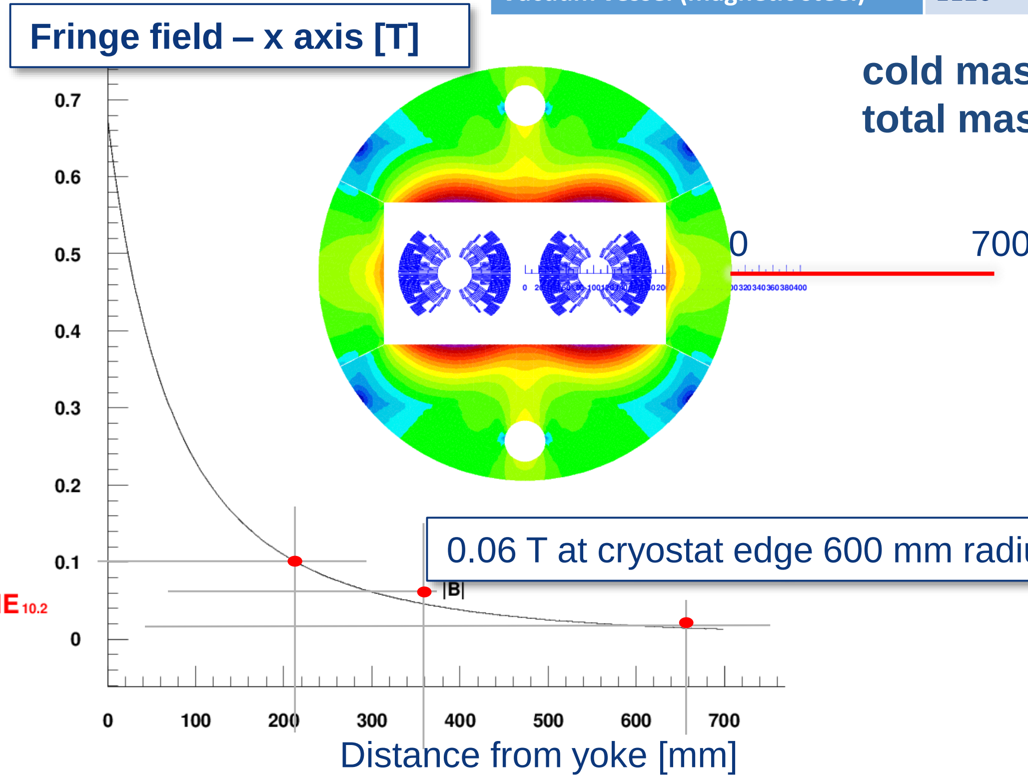
16 T dipole integration approach

Design evolution

- Coil optimization and margin 18 → 14%
- Inter-beam distance 250 → 204 mm
- Stray-field < 0.1 T at cryostat

Description	ID in mm	OD in mm
Iron yoke	-	600
Aluminium shrinking cylinder	600	740
Stainless steel He tight shell	740	760
Al radiation shield	934	940
Vacuum vessel (magnetic steel)	1120	1220





cold mass 40t
total mass 62t

e-h colliders – LHeC

<u>CDR Study assumptions:</u>

-Assume parallel operation to HL-LHC

-Limit power consumption to 100 MW

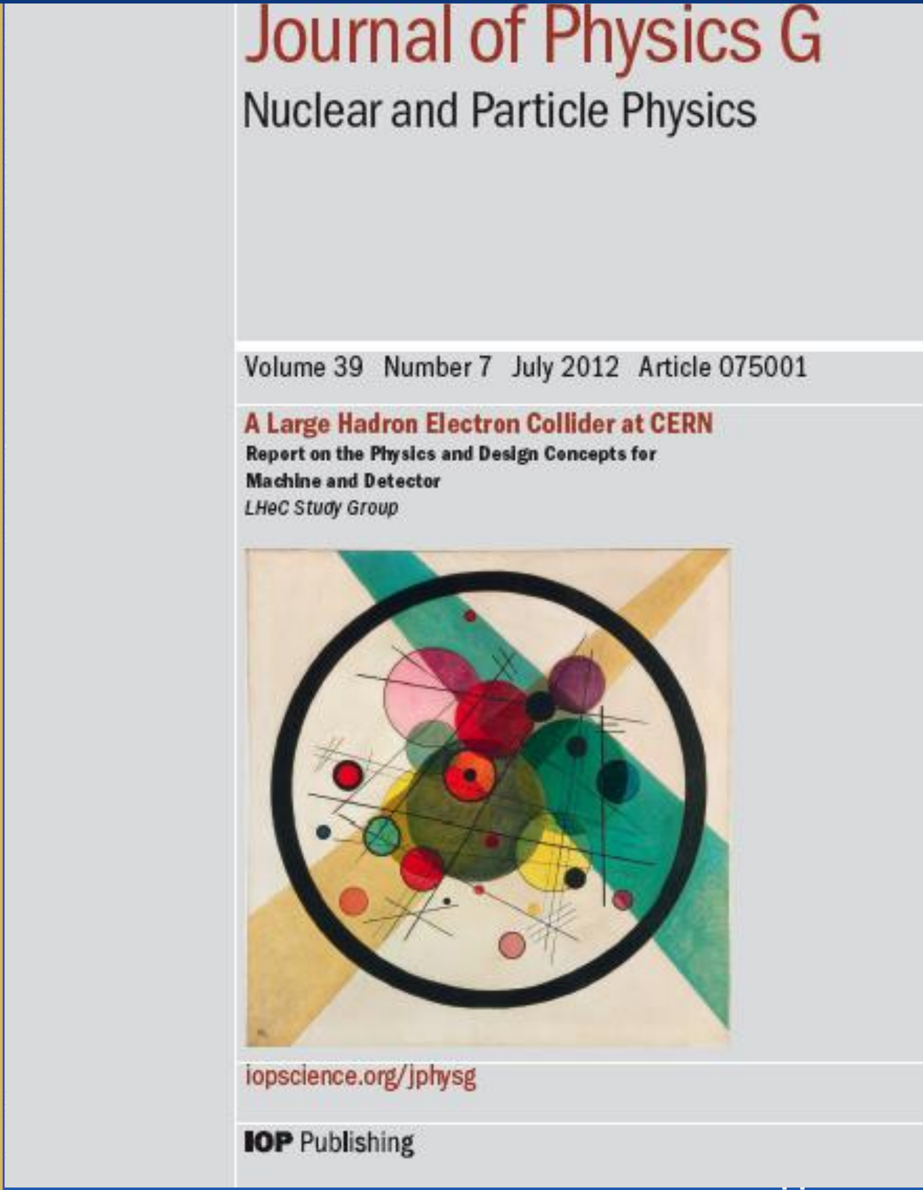
➔ (beam & SR power < 70 MW)

➔ 60 GeV beam energy

-Int. Luminosity > 100 * HERA

-Peak Luminosity > 10^{33} $cm^{-2}s^{-1}$

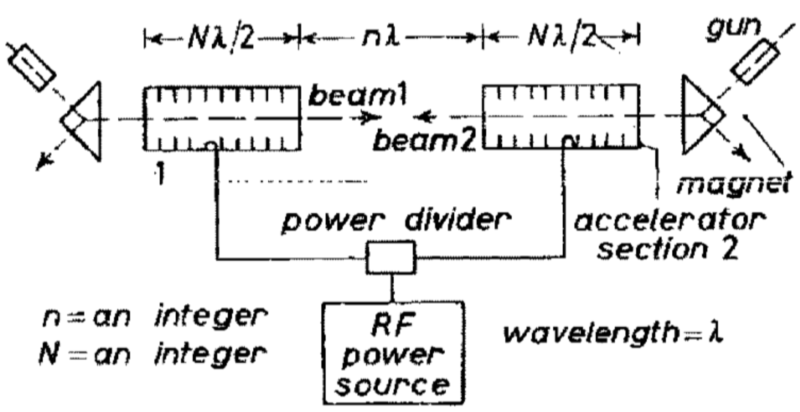
-ERL identified as baseline option



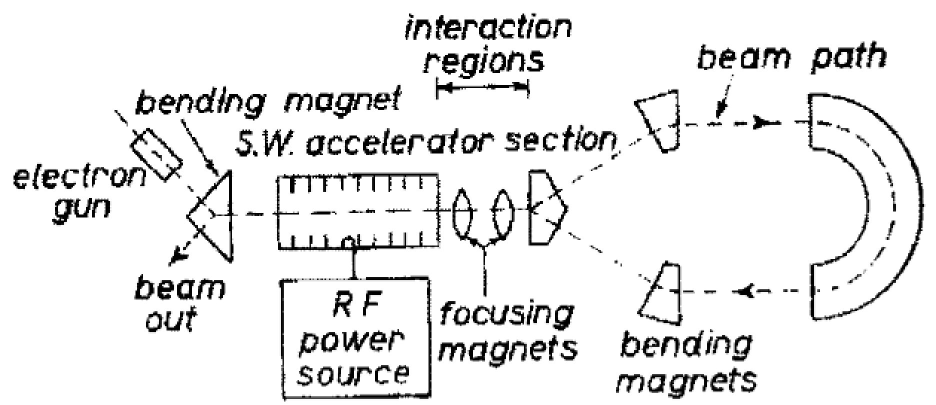
Motivation: Accelerator Technology Development

- Energy Recovery Linac concept: First proposal 50 years ago

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



or

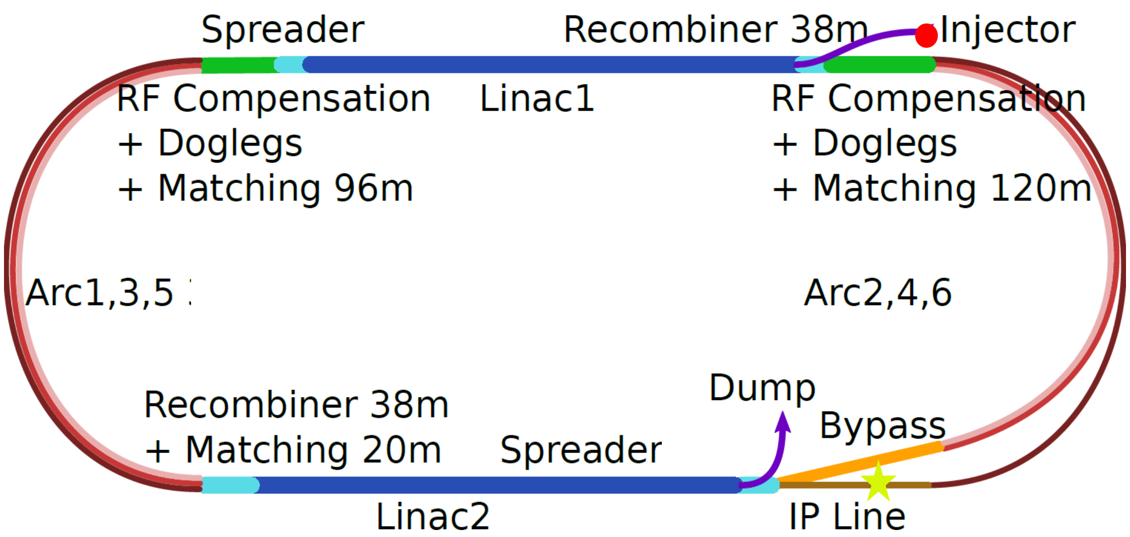


- First Tests: Done at SCA @ Stanford in 1986

Recirculating Linac with Energy Recovery

60 GeV acceleration with Recirculating Linacs:

Animation from A. Bogacz (JLab) @ ERL'15



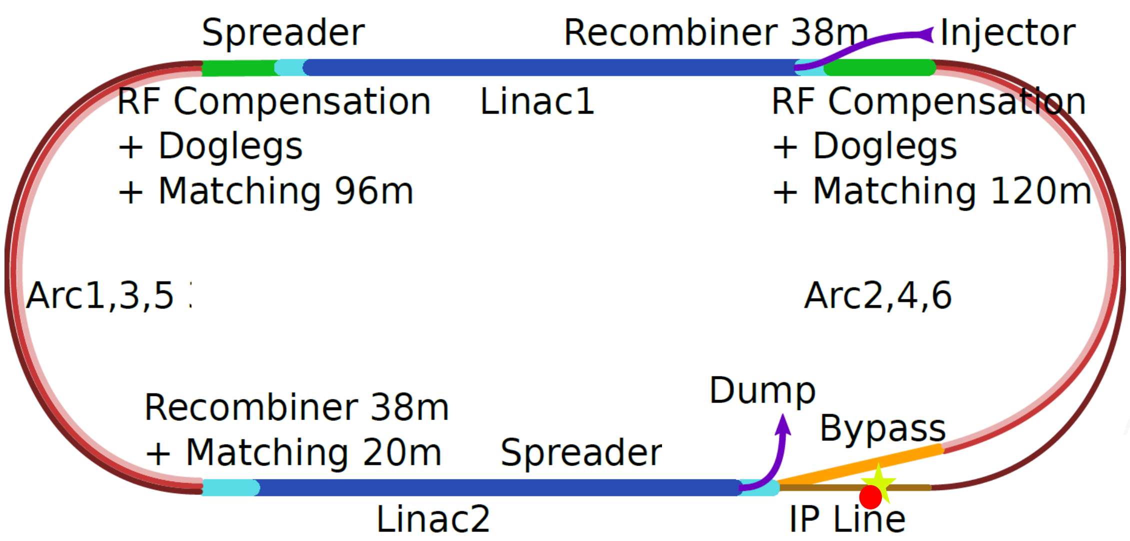
➔ Three accelerating passes through each of the two 10 GeV linacs (efficient use of LINAC installation!)

➔ 60 GeV beam energy

Recirculating Linac with Energy Recovery

Collisions with one HL-LHC Beam:

Animation from A. Bogacz (JLab) @ ERL'15



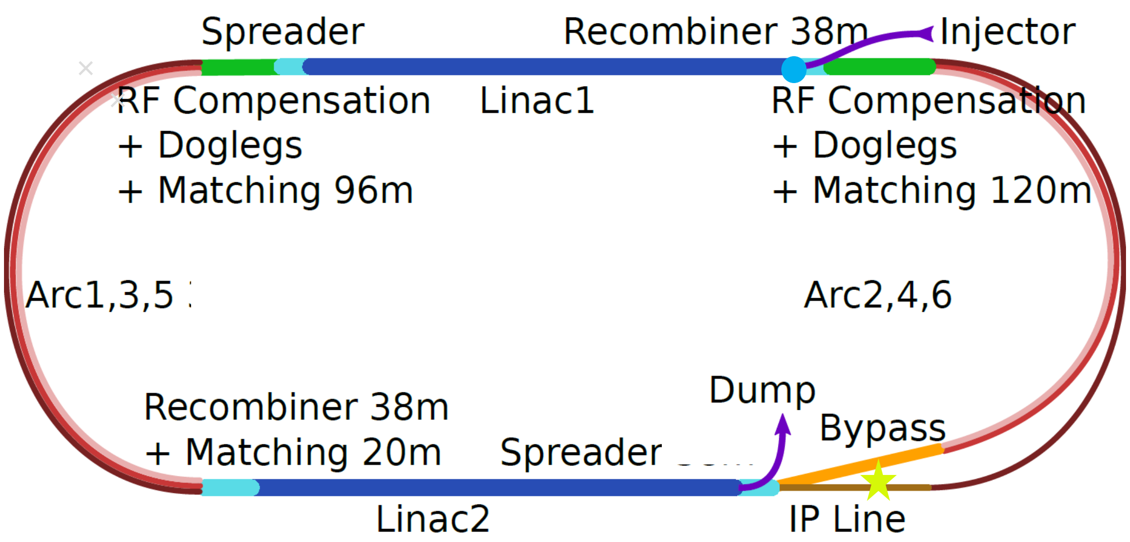
➔ Collisions with one of the LHC proton beams

➔ l/2 RF wave length shift on return arc following the collision

Recirculating Linac with Energy Recovery

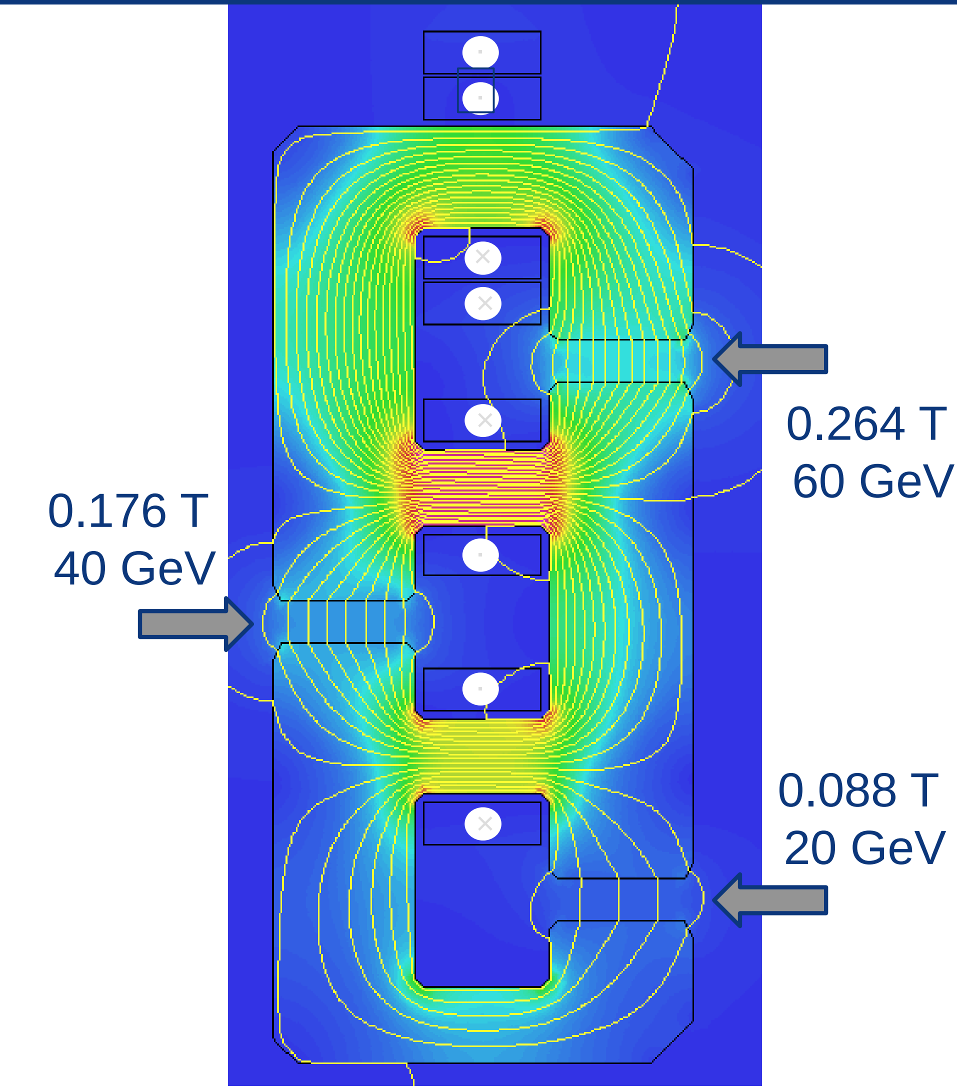
60 GeV deceleration with Recirculating Linacs:

Animation from A. Bogacz (JLab) @ ERL’15



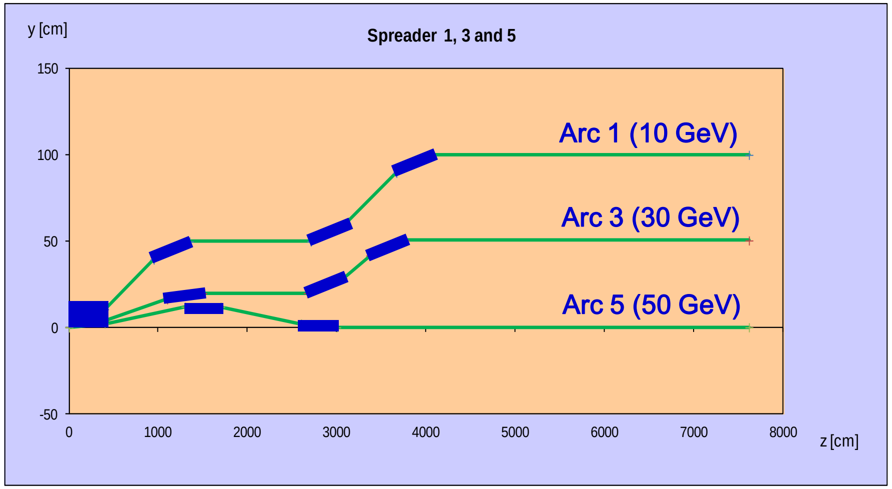
- ➔ Three decelerating passes through each of the two 10 GeV linacs
- ➔ Beam dump at injection energy (e.g. 500 MeV)

Return Arc Dipoles optimization



Vertical Separation

A. Bogacz (JLab) @ ERL2015, Stony Brook University



Magnet design

- keep idea of recycling Ampere-turns
- stack the apertures vertically but offset them also transversally
- same vertical gap, 25 mm
- simple coils, same powering circuit
- as before, trim coils can be added for two apertures, to give some tuning

LHeC ring-linac with ERL parameters

Super Conducting Recirculating Linac with Energy Recovery

Choose ⅓ of LHC circumference ➔

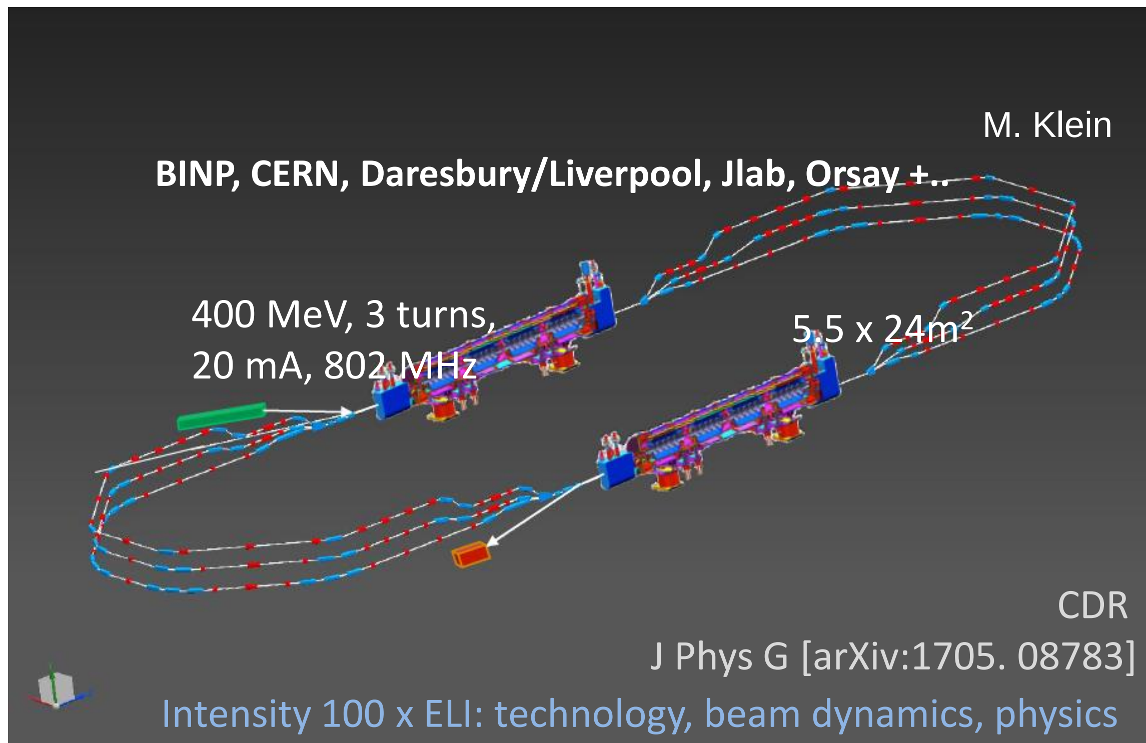
Two 1 km long, 10 GeV SC LINACs with 3 accelerating and

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	16	16	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20	3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10	0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4	7	7
rms Beam divergence σ□$^*_{x,y}$ [μrad]	80	40	70	58
Beam Current @ IP[mA]	1112	25	430 (860)	6.6
Bunch Spacing [ns]	25	25	25 (50)	25 (50)
Bunch Population	$2.2*10^{11}$	$4*10^{9}$	$1.7*10^{11}$	$(1*10^{9})$ $2*10^{9}$
Bunch charge [nC]	35	0.64	27	(0.16) 0.32

SRF cavity development & ERL test facility

5-cell 800 MHz cavity, JLAB prototype for FCC-ee (top mode) & FCC-eh;
also single-cell cavities for all FCC's

optimized for high current operation



PERLE@Orsay
ERL test facility

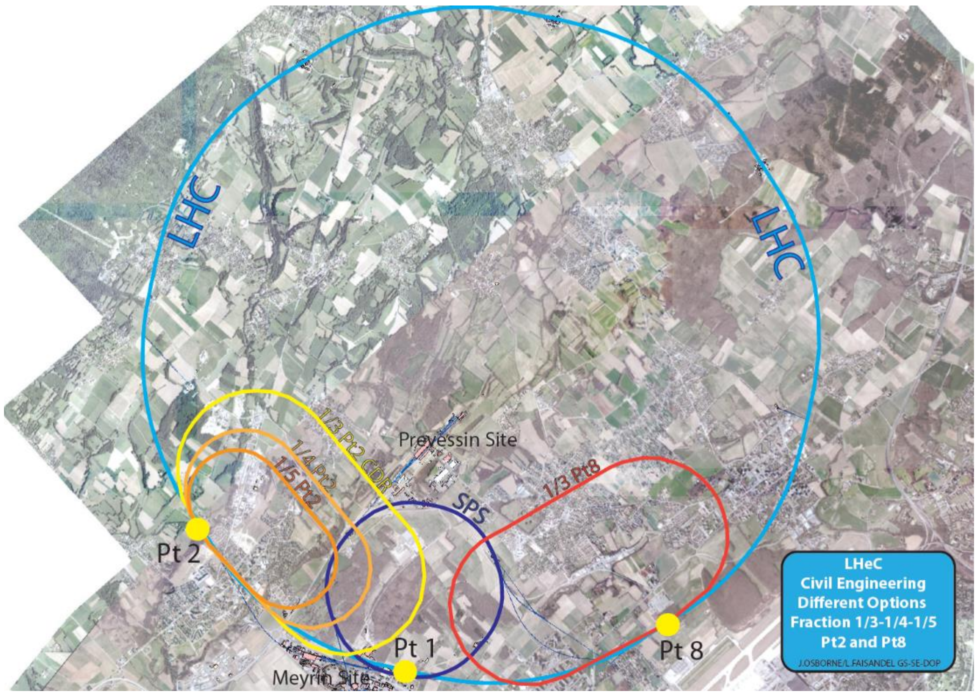
FCC-eh: 60 GeV e^- from Energy Recovery Linac (ERL)

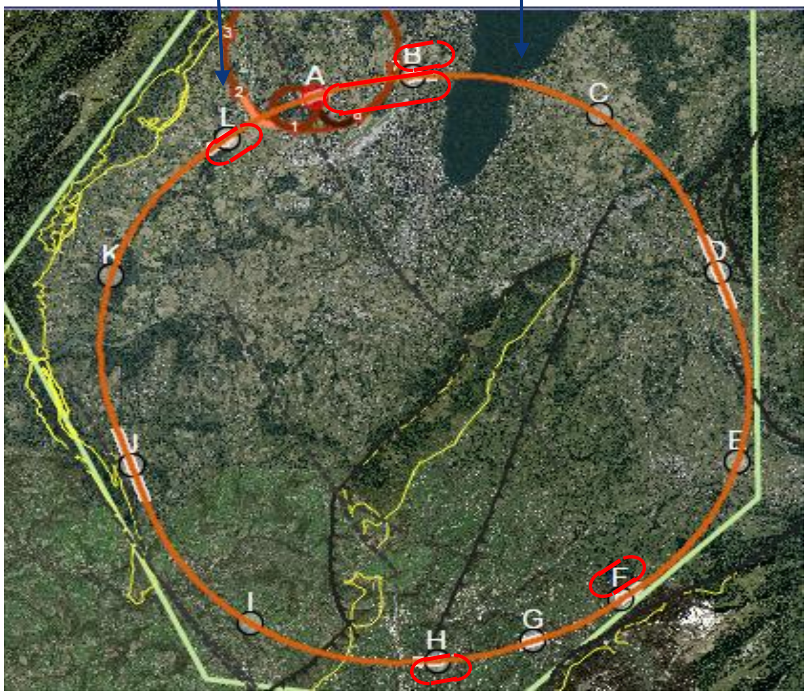
LHeC, HE-LHeC, FCC-eh configuration

C. Cook @ FCC week in Rome

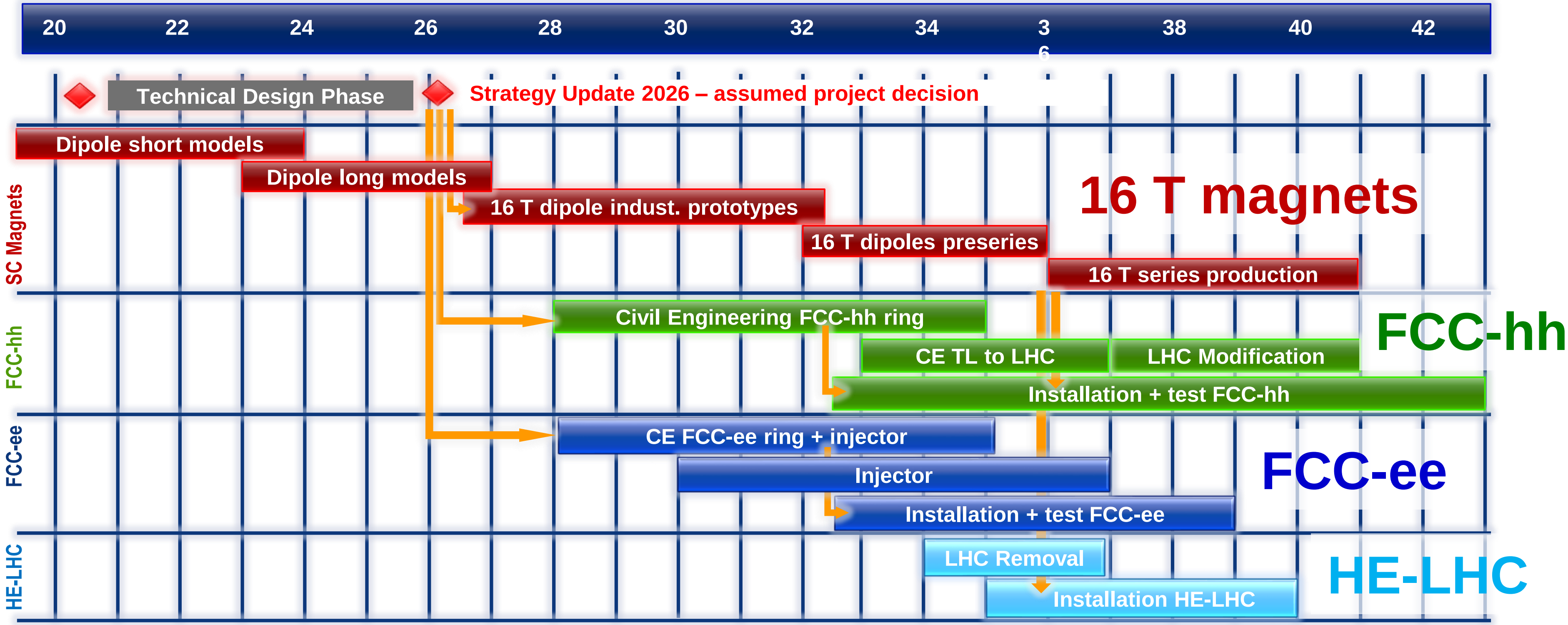
Independent FCC-he
Point L, F, H or B
➔ Point L best option

LHeC / FCC-he
LHC P8 & FCC PB





FCC-Technical schedules



schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates

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

Conclusion & Acknowledgements

- Strong worldwide activities on studies for large circular colliders centered around FCC and CEPC/SppC.

- Many challenging topics and areas for R&D, requiring strong international collaboration to develop optimized designs and the technologies needed for construction.

- We depend and rely on young enthusiastic participants (with a long breath!) to push our field forward and you are warmly invited to join/enforce the ongoing efforts!

- Many thanks to colleagues in FCC collaboration and CEPC/SppC for valuable input, in particular to A. Ballarino, O. Bruning, K. Oide, Q. Qin, L. Rossi, D. Schulte, D. Tommasini and F. Zimmermann for provision of slides and detailed discussions.

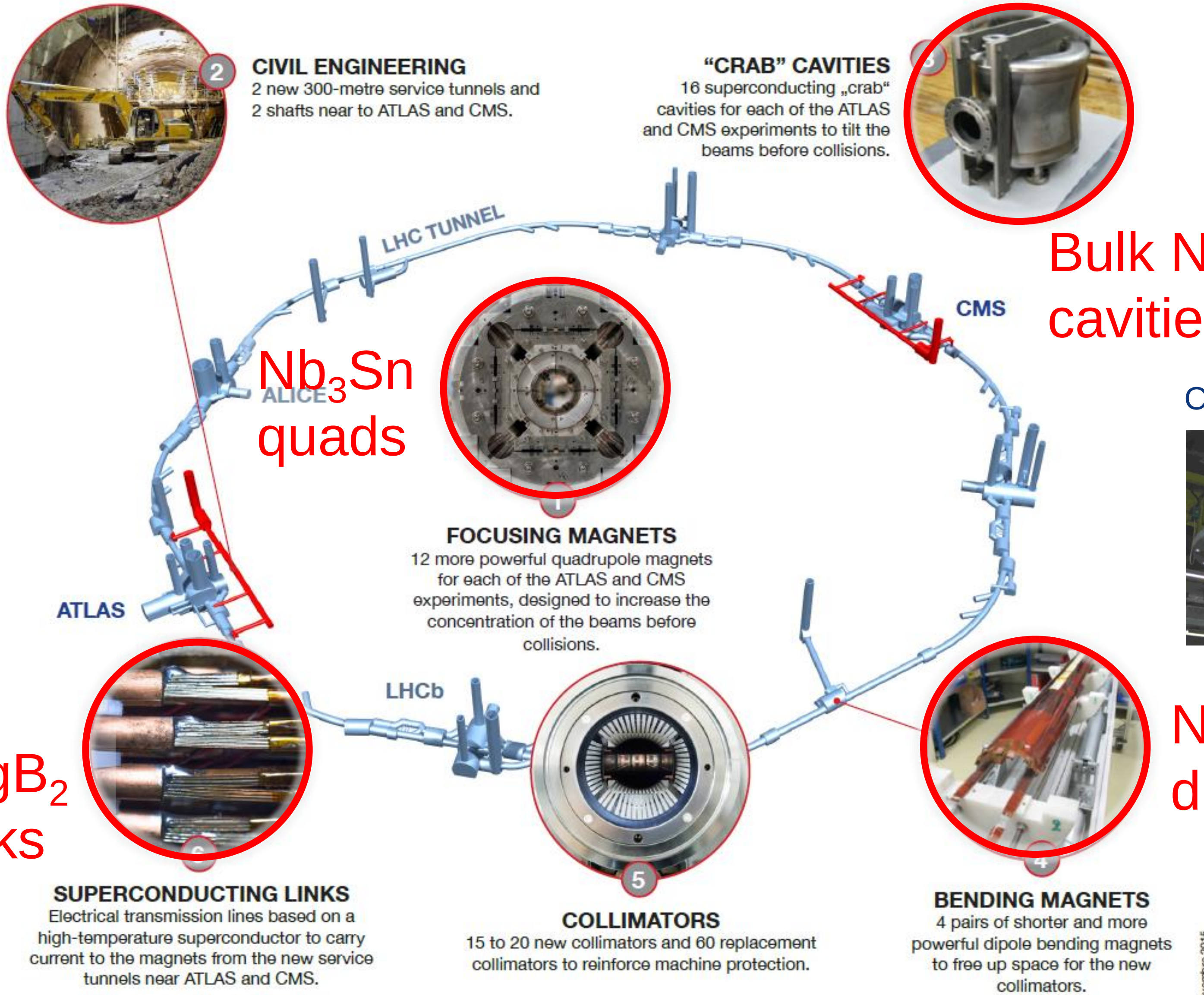
Reserve slides

LHC Limitations and HL-LHC challenges

- **Insertion quadrupole magnets lifetime and aperture:**
  ➔ New stronger insertion magnets with increased aperture
- **Geometric Reduction Factor:** ➔ SC Crab Cavities
  ➔ New technology and first application for a hadron storage ring!
- **Performance Optimization: Pileup density** ➔ Lumi levelling
  ➔ requires virtual luminosity >> target levelled luminosity
- **Beam power & losses** ➔ addt'l collimators in dispersion suppressors
- **Machine effciency and availability:**
  # R2E ➔ removal of all electronics from tunnel region
  # e-cloud ➔ beam scrubbing (conditioning of surface), etc
- **Technical bottle necks (e.g. cryogenics)**
- **Civil Engineering (underground)**

HL LHC project landmarks

Cryo@P4



Bulk Nb cavities

Nb_3Sn quads

Cryo@P1-P5

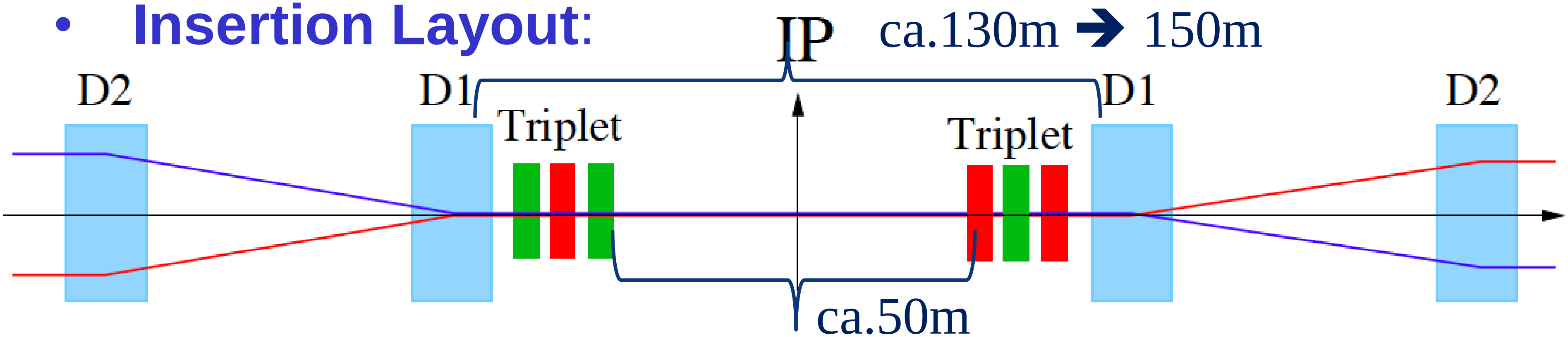
MgB_2 links

Nb_3Sn dipoles

Nb_3Sn for the first time in an operating accelerator (~ 30 tons)

HL-LHC Challenges: Crossing Angle

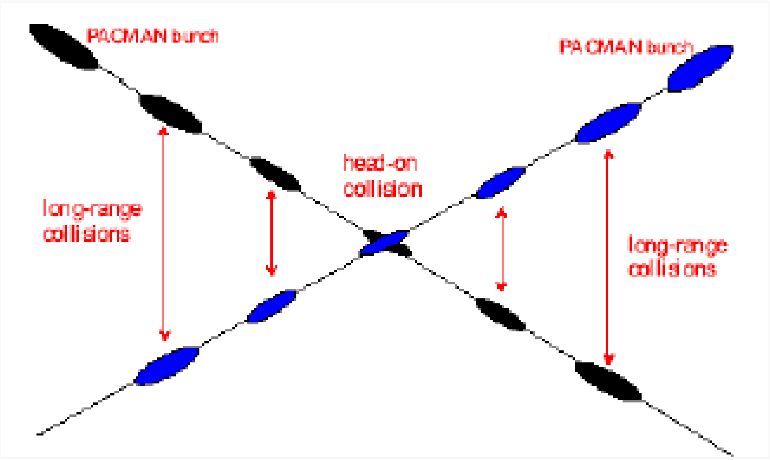
- **Insertion Layout:**



- **Parasitic bunch encounters:**

Operation with ca. 2800 bunches @ 25ns spacing
➔ approximately 30 unwanted collisions per Interaction Region (IR).

Operation requires crossing angle prop. 1/√β*.
➔ Factor 2 increase, 2 x 150 to 2 x 300 μrad)



- **Perturbations from long-range beam-beam interaction:**

efficient operation requires large beam separation at unwanted collision points
➔ Separation of 10 -12 σ ➔ **larger triplet apertures for HL-LHC!**

HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

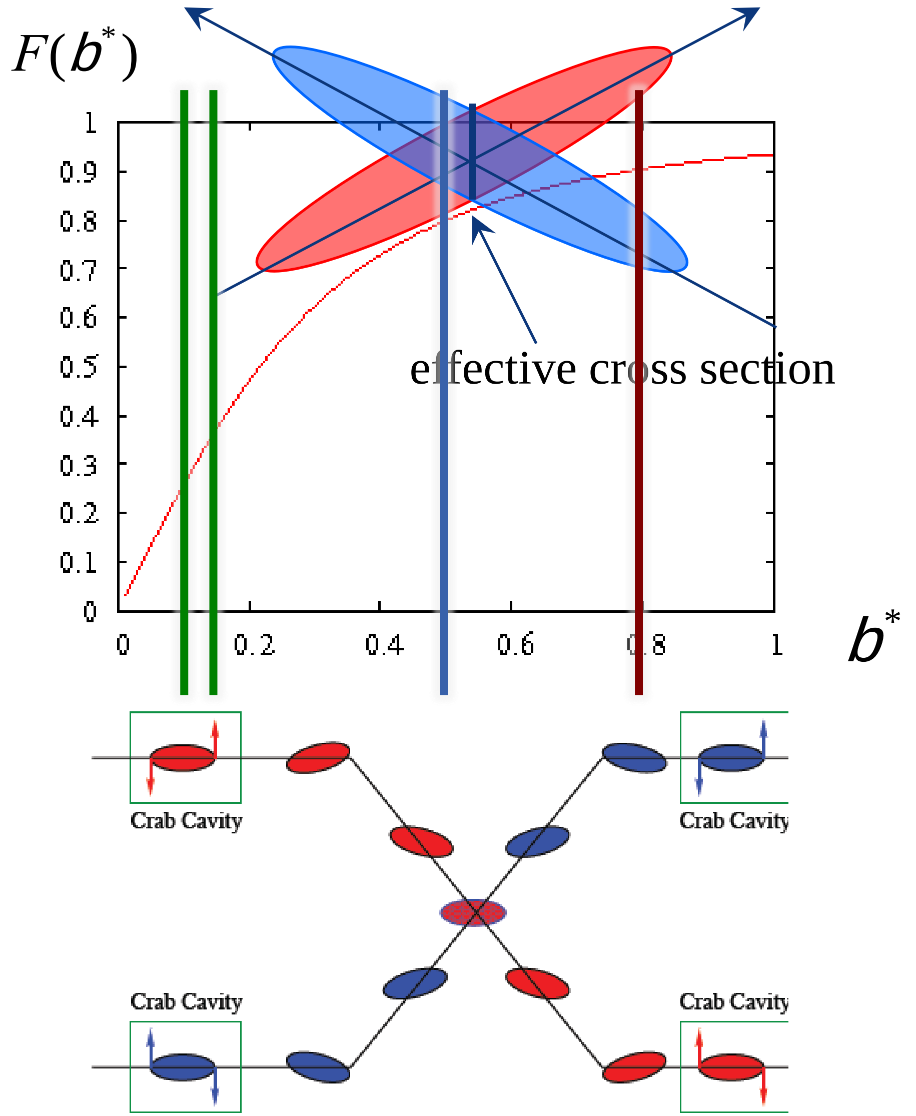
Crab Cavities:

- Reduces the effect of geometrical reduction factor
- Independent for each IP

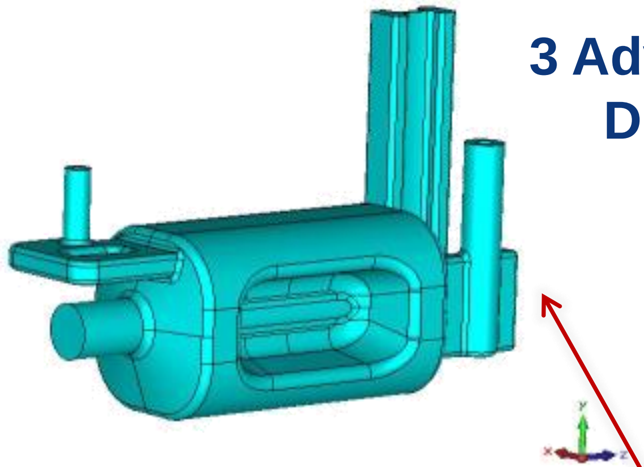
$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

- Challenging space constraints:

  ➔ requires novel compact cavity design

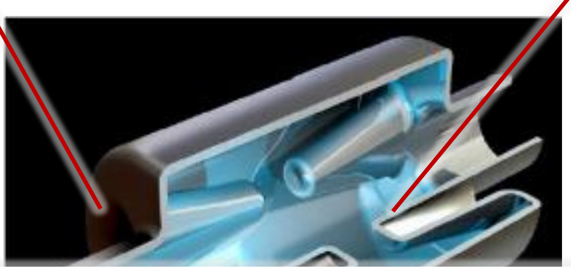


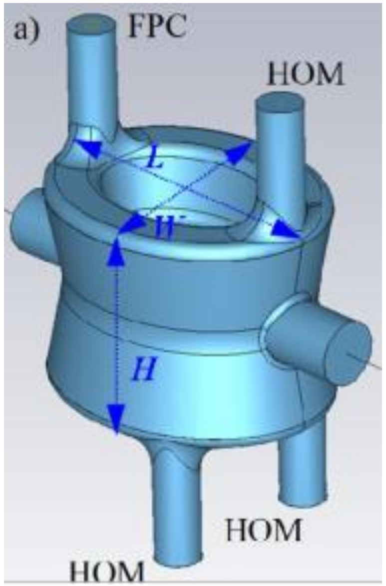
HL-LHC crab cavity designs



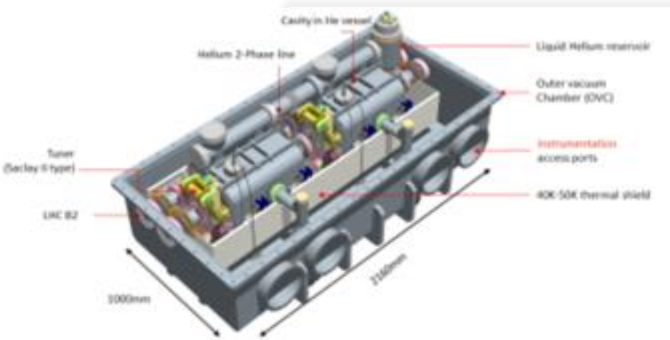
3 Advanced Design Studies with Different Coupler concepts

RF Dipole: Waveguide or waveguide-coax couplers





Double ¼-wave: Coaxial couplers with



on Double ¼-wave in order to be ready
lation in SPS in 2017/2018 TS

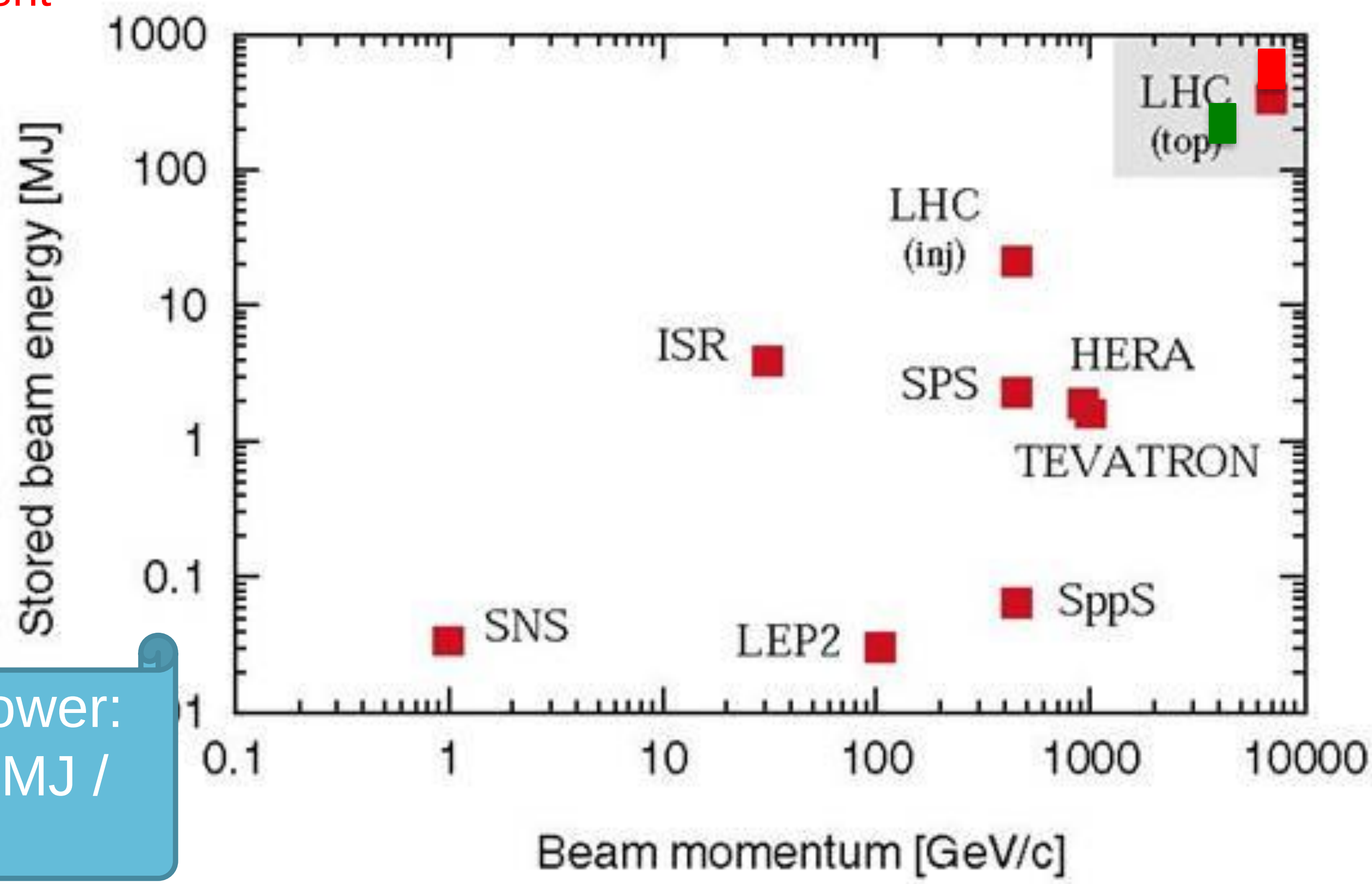
4-rod: (
differen

Present baseline: 4 cavity/cryomod
TEST in SPS prepared for run2018

LHC Challenges: Beam Power

Unprecedented beam power:

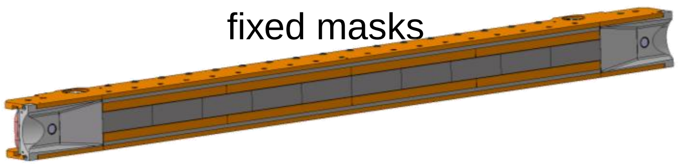
- ➔ potential equipment damage in case of failures during operation
- ➔ In case of failure the beam must never reach sensitive equipment!



Stored Beam power:
HL-LHC > 500 MJ / beam

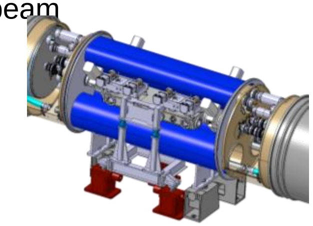
Collimation system upgrades

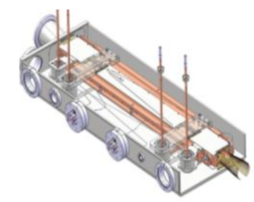
Completely new layouts
Novel materials.
IR1+IR5, <u>per beam</u>:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

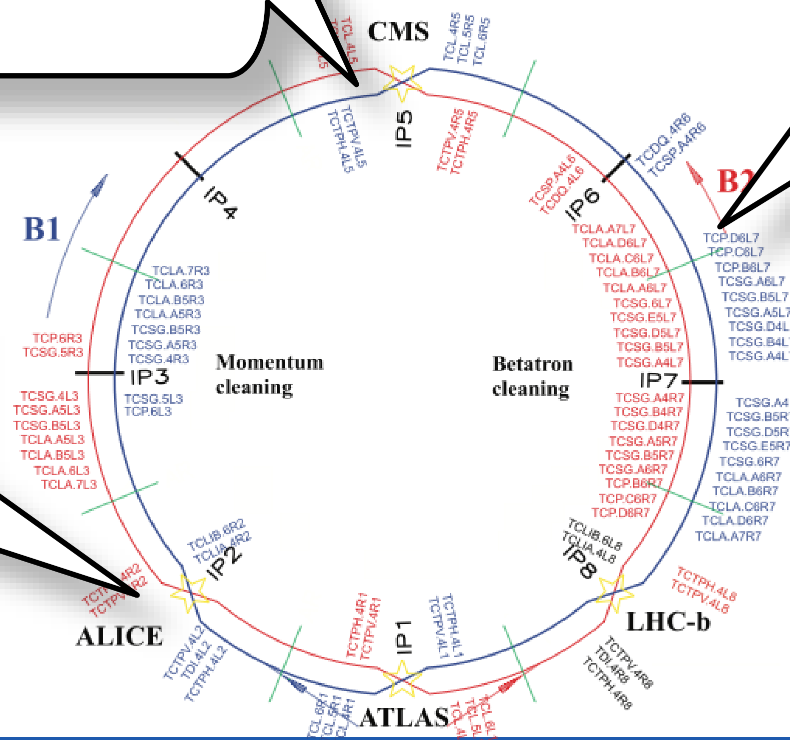


40 new collimators to be produced by LS3 in the present baseline!

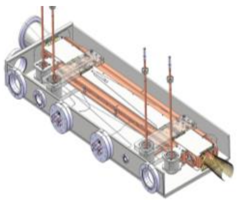
Cleaning: DS coll. + 11T dipoles, 2 units per beam



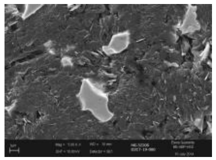


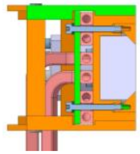


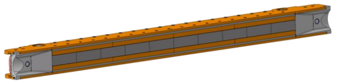
Ion physics debris:
DS collimation



Low-impedance, high robustness secondary collimators

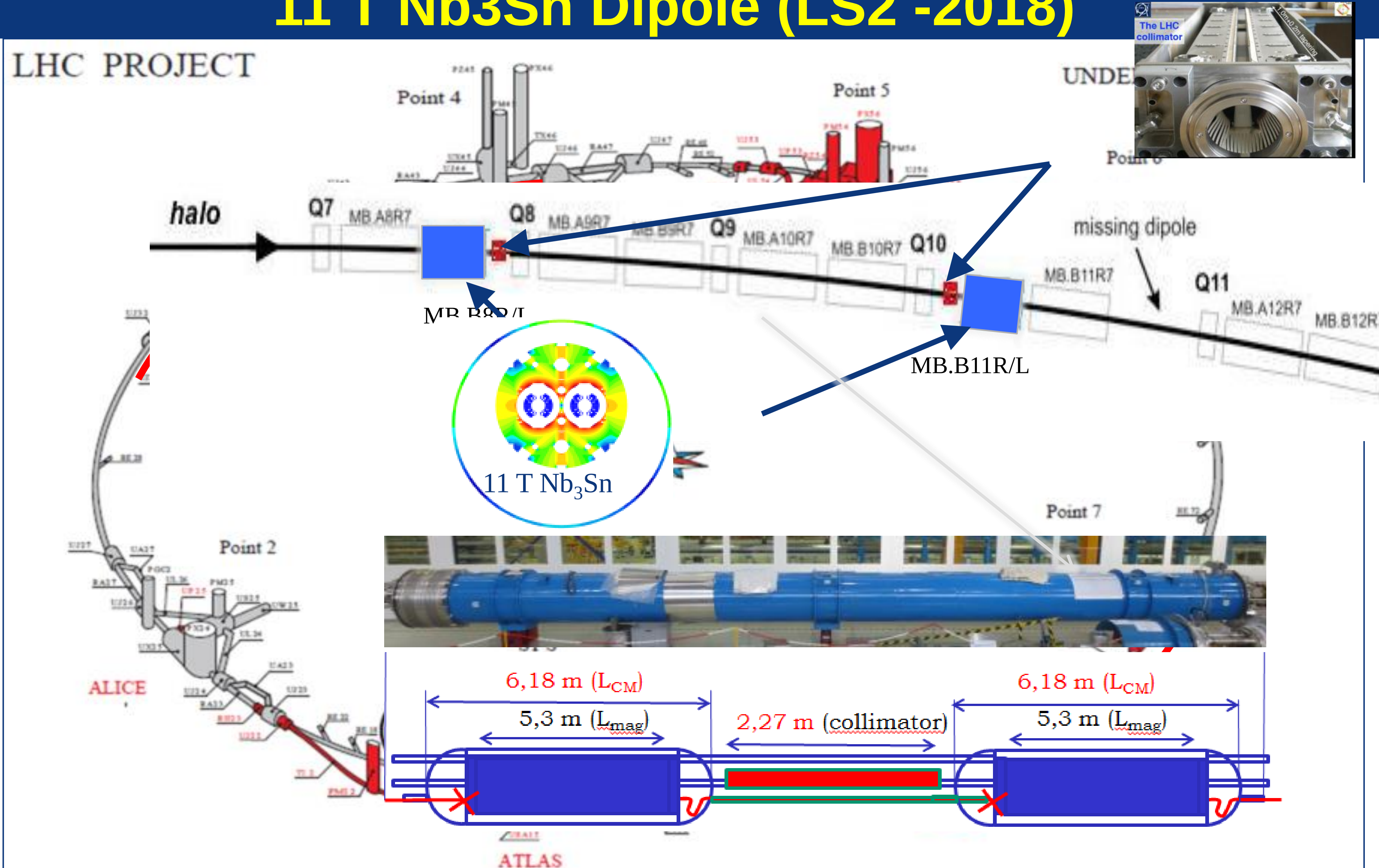




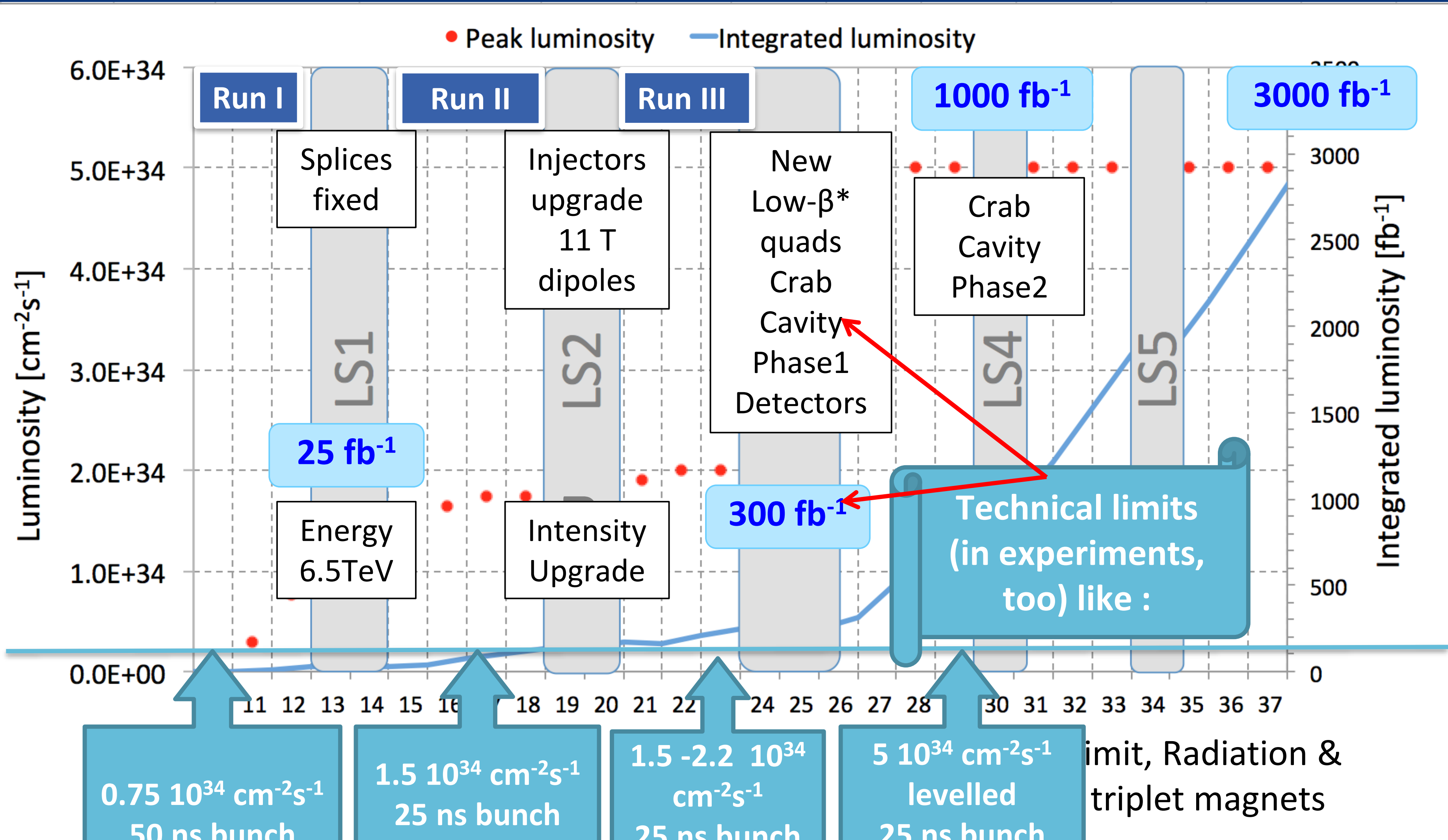


S. Redaelli,
Chamonix 2016, 28-01-2016

Dispersion Suppressor collimators – 11 T Nb3Sn Dipole (LS2 -2018)



Implementation & Performance Projection:



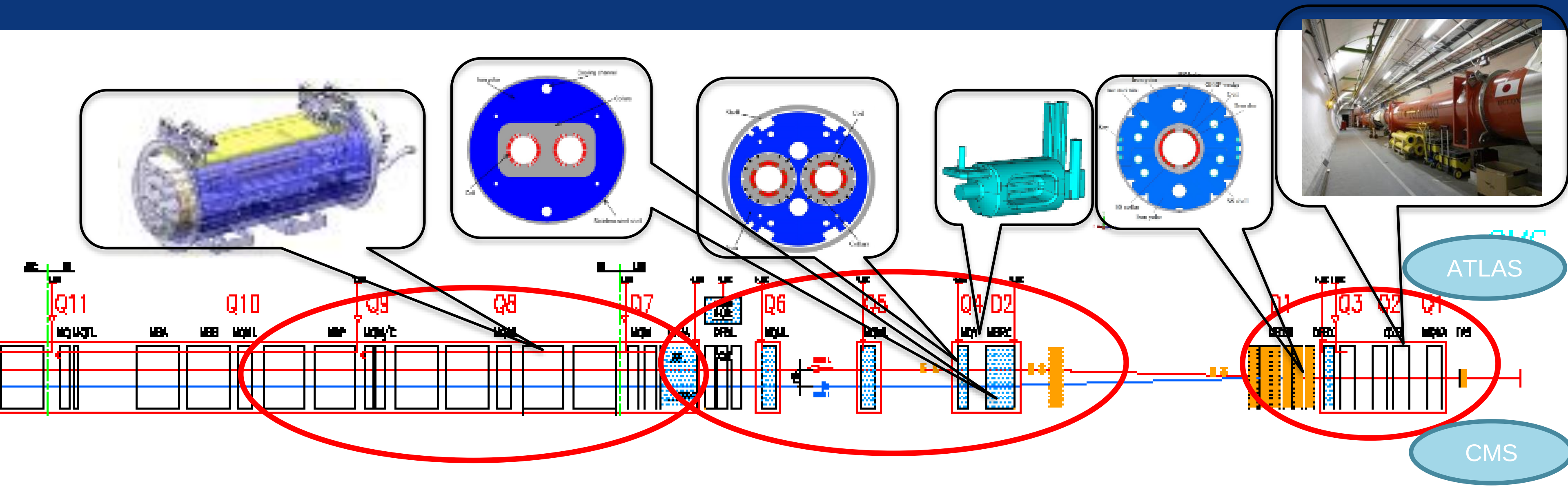
0.75 10^{34} cm^{-2}s^{-1}
50 ns bunch
high pile up ~40

1.5 10^{34} cm^{-2}s^{-1}
25 ns bunch
high pile up ~40

1.5 -2.2 10^{34} cm^{-2}s^{-1}
25 ns bunch
very high pile up > 60

5 10^{34} cm^{-2}s^{-1}
levelled
25 ns bunch
very high pile up ~140

The critical zones around IP1 and IP5



3. For collimation we also need to change the DS in the continuous cryostat: 11T Nb_3Sn dipole

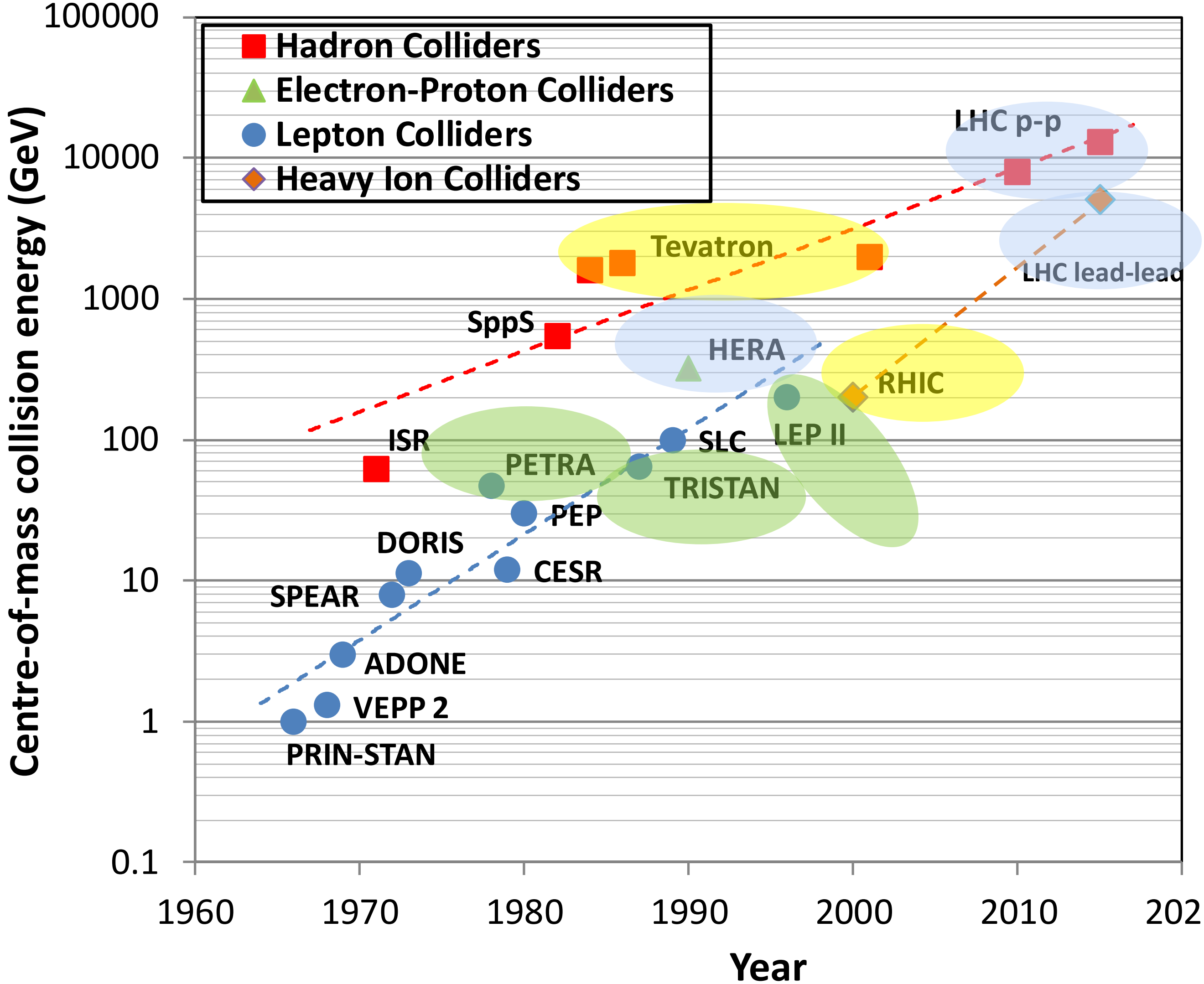
2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

1. New triplet Nb_3Sn required due to:
-Radiation damage
-Need for more aperture

Changing the triplet region is not enough for reaching the HL-LHC goal!

➔ More than 1.2 km of LHC !!
➔ Plus technical infrastructure (e.g. Cryo and Powering)!!

Colliders constructed and operated



Colliders with superconducting RF system

Colliders with superconducting arc magnet system

Colliders with superconducting magnet & RF

Main SC Magnet system FCC (16 T) vs LHC (8.3 T)

FCC

Bore diameter: 50 mm

Dipoles: $4578\ units, 14.3\ m\ long, 16\ T \Leftrightarrow \int Bdl{\sim}1\ MTm$

$\text{Stored energy} \sim 200\ \text{GJ (GigaJoule)} \sim 44\ \text{MJ/unit}$

Quads: $762\ magnets,\ \ 6.6\ m\ long, 375\ T/m$

LHC

Bore diameter: 56 mm

Dipoles: $1232\ units, 14.3\ m\ long, 8.3\ T \Leftrightarrow \int Bdl{\sim}0.15\ MTm$

$\text{Stored energy} \sim 9\ \text{GJ (GigaJoule)} \sim 7\ \text{MJ/unit}$

Quads: $392\ units,\ \ 3.15\ m\ long, 233\ T/m$

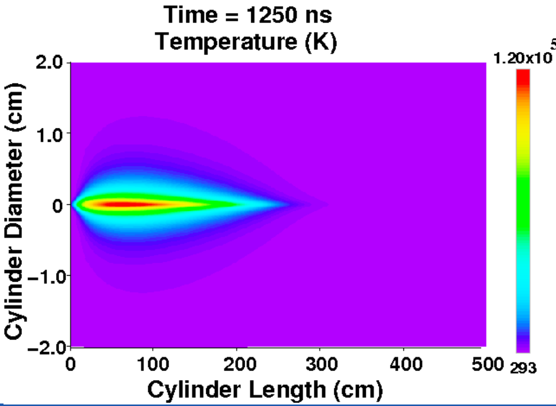
Beam power & machine protection

Stored energy 8.4 GJ per beam

– Factor 25 higher than for LHC, equivalent to A380 (560 t) at nominal speed (850 km/h). Can melt 12t of copper.

Damage of a beam with an energy of 2 MJ

Hydrodynamic tunneling: beam penetrates ~**300 m** in Cu



– **Collimation, control of beam losses and radiation effects (shielding) are of prime importance.**

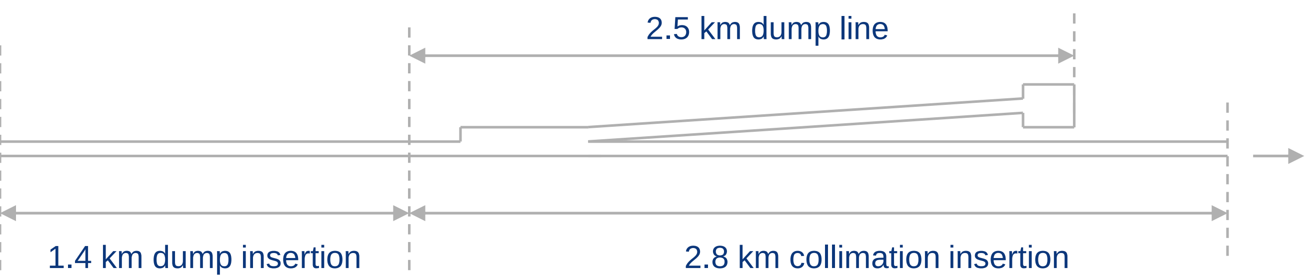
– **Injection, beam transfer and beam dump all critical.**

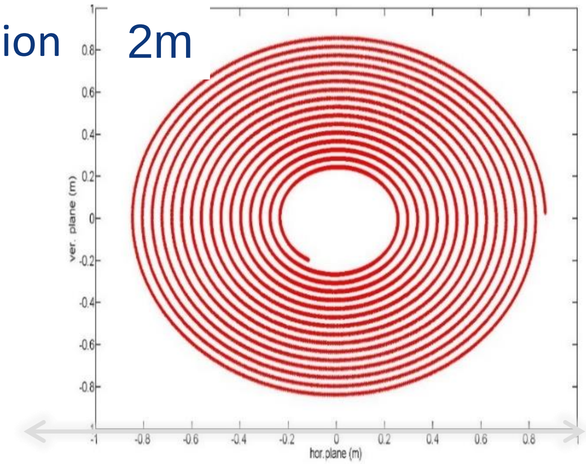
Machine protection issues to be addressed early on!

FCC-hh beam dilution system

Huge energy to be extracted and dumped => need large dump section

Beam rigidity: 167 T.km => need long way to dilute beam ~2.5km!



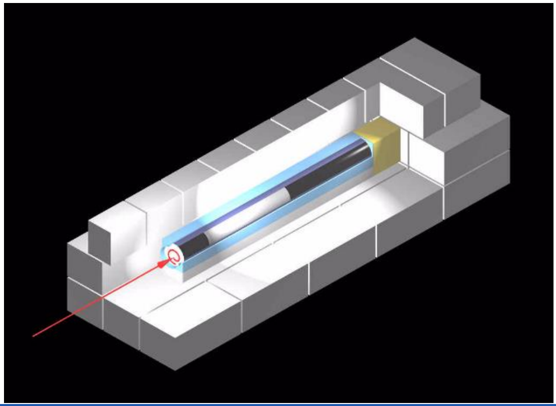


FLUKA studies:

- Bunch separation >1.8 mm
- Branch separation: 4 cm
- Keeps T<1500°C

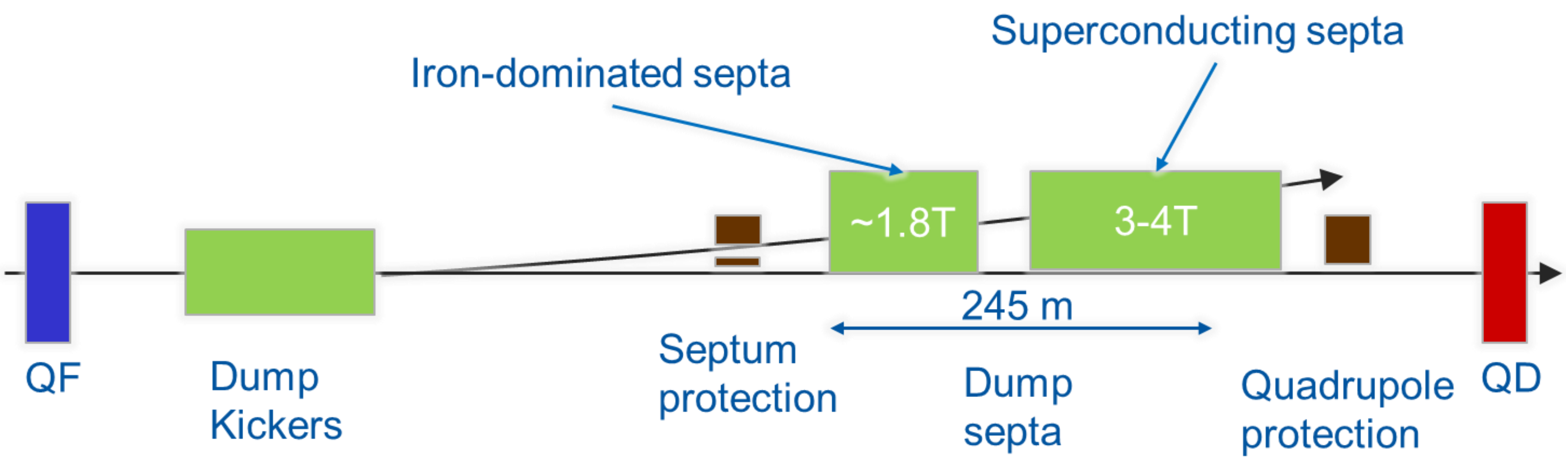
Very reliable kickers, high segementation, new methods for triggering (laser)

SC septum

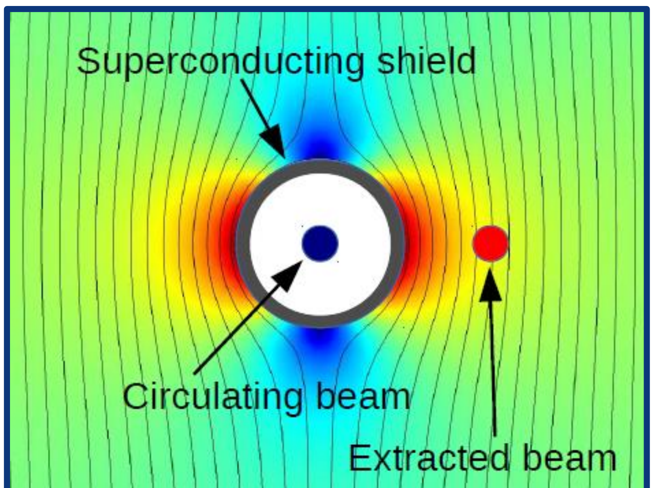


R&D on Superconducting Septa

Need an extraction system for safely removing the beam from the collider hybrid system: short overall length with high robustness & availability



SuShi concept: SC shield creates field-free region inside strong dipole field



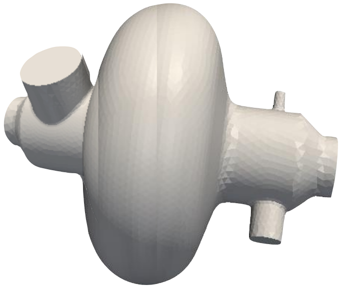
3 candidate technologies:

(1) NbTi/Nb/Cu multilayer sheet
(2) HTS tape/coating
(3) Bulk MgB_2

RF system R&D lines

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)

- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)



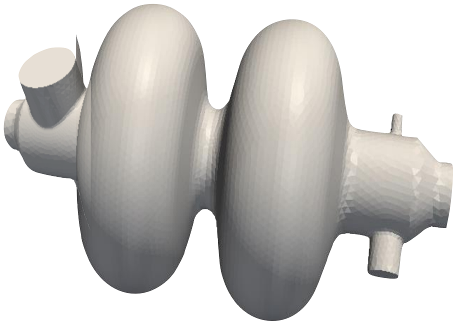
hh
≈ 16 cells per beam

Z
≈ 100 per beam
(+ 100 for booster ring)

W
≈ 210 per beam
(+ 210 for booster ring)

400 or 800 MHz multi-cell cavities preferred for ee-ZH, ee-tt and ee-WW

- Baseline options 400 MHz Nb/Cu @4.5 K, ◄—► 800 MHz bulk Nb system @2K
- R&D: High Q_0 cavities, coating, long-term: Nb_3Sn like components



W
≈ 200 per beam
(+ 200 for booster)

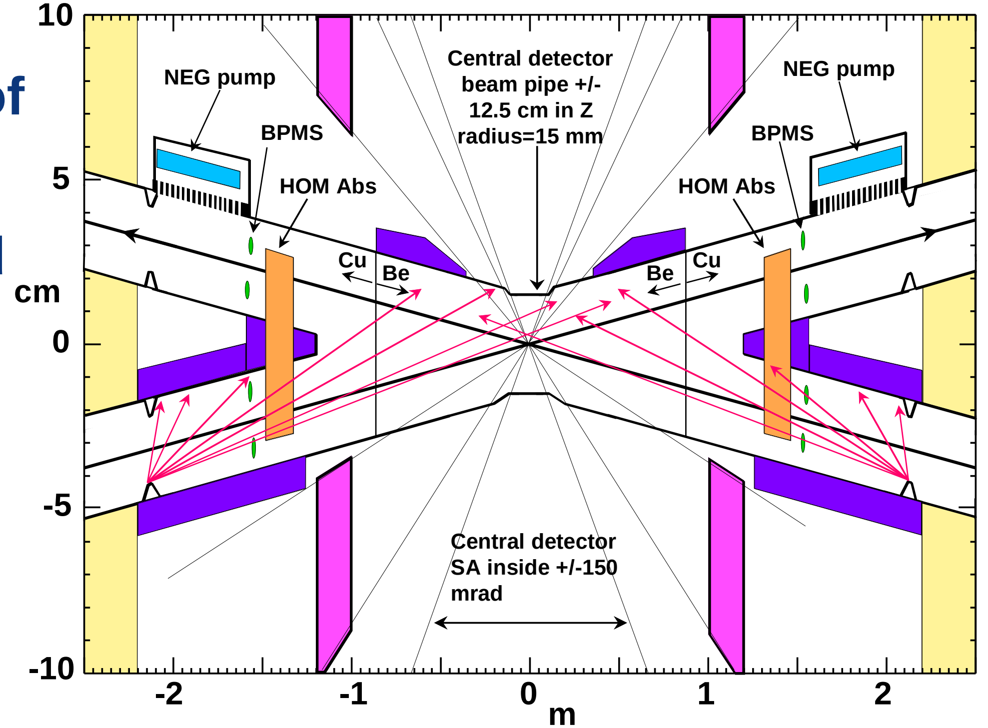
H
≈ 800 per beam
(+ 800 for booster)

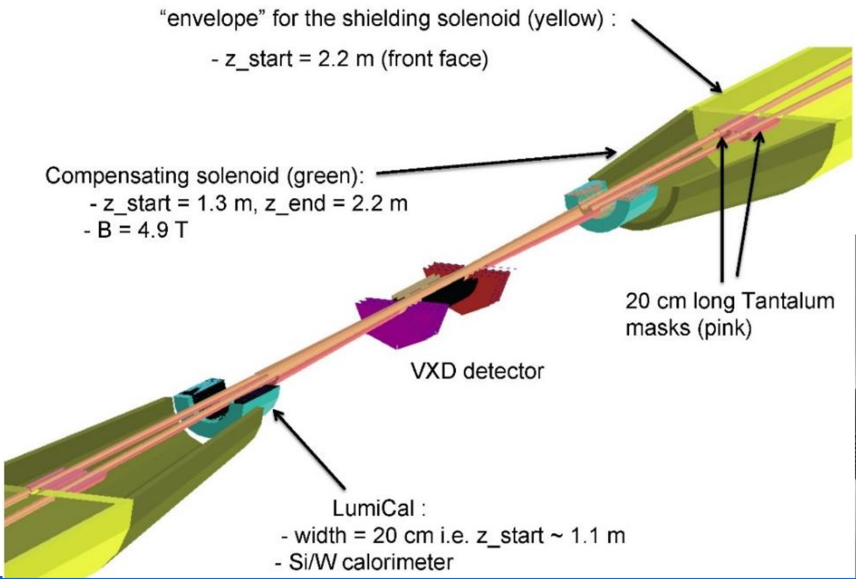
t
≈ common 2600 cells for both beams
(+ 2600 for booster)

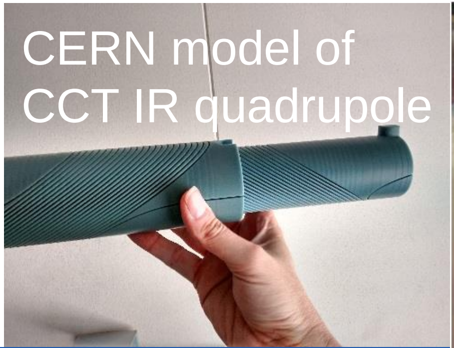
FCC-ee MDI optimisation

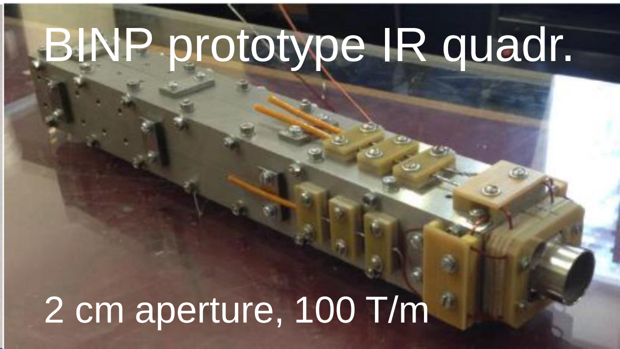
MDI work focused on optimization of

- *l**, IR quadrupole design
- Detector, compensation solenoid
- SR masking and chamber layout







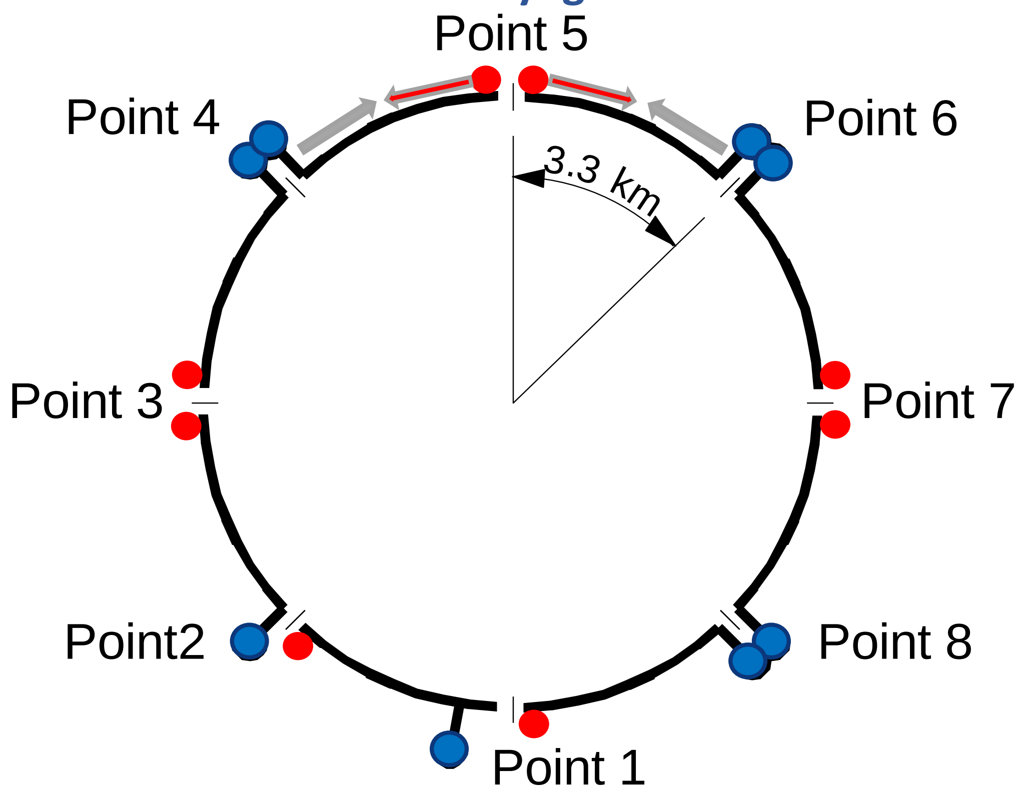


HE-LHC cryogenic layout

Higher heat load and integration limitations (Cryo-line diameter) requires installation of
8 additional 1.8 K refrigeration units wrt. LHC
- 2.3 kW @ 1.8 K (~ LHC size)
- P elect: ~500 kW per unit

8
- 28 kW @ 4.5 K (including 2.3 kW @ 1.8 K)
- P elect: ~6500 kW per cryoplant
  (cf. 4200 kW for LHC cryoplant)

Half-sector cooling instead of full sector (as for LHC) to limit cross section of cryogenic distribution line



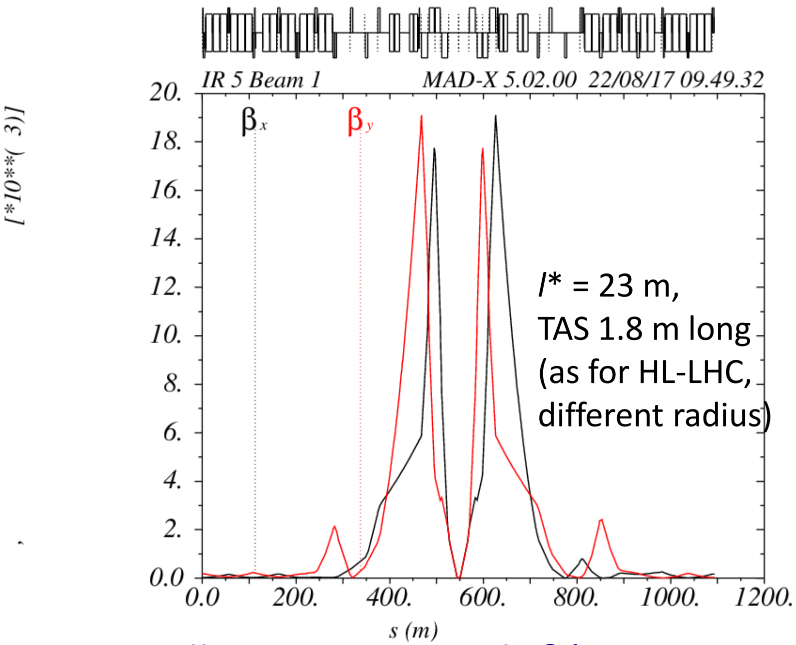
HE-LHC IR optics & triplet shielding

triplet lengths:

HE-LHC: 56 m (13.5 TeV)

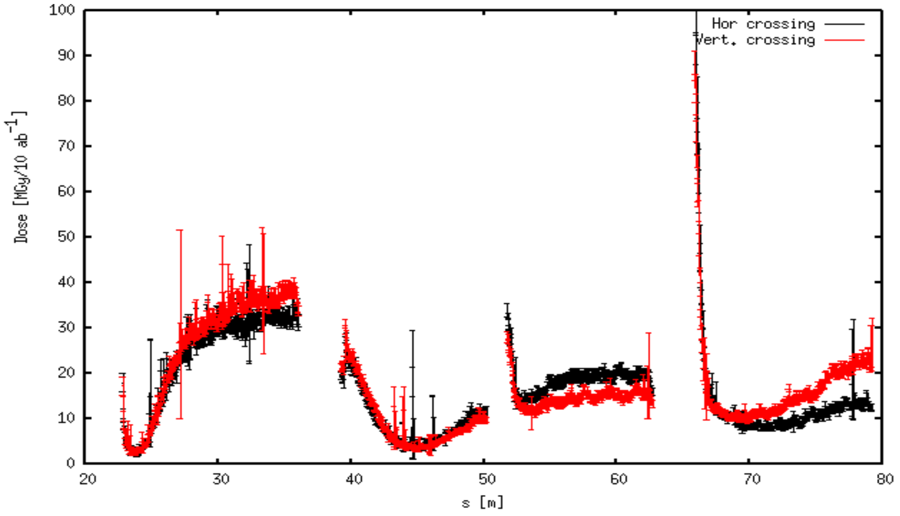
HL-LHC: 41. 8m, LHC: 30.4 m

ca. 11 m space for crab cavities



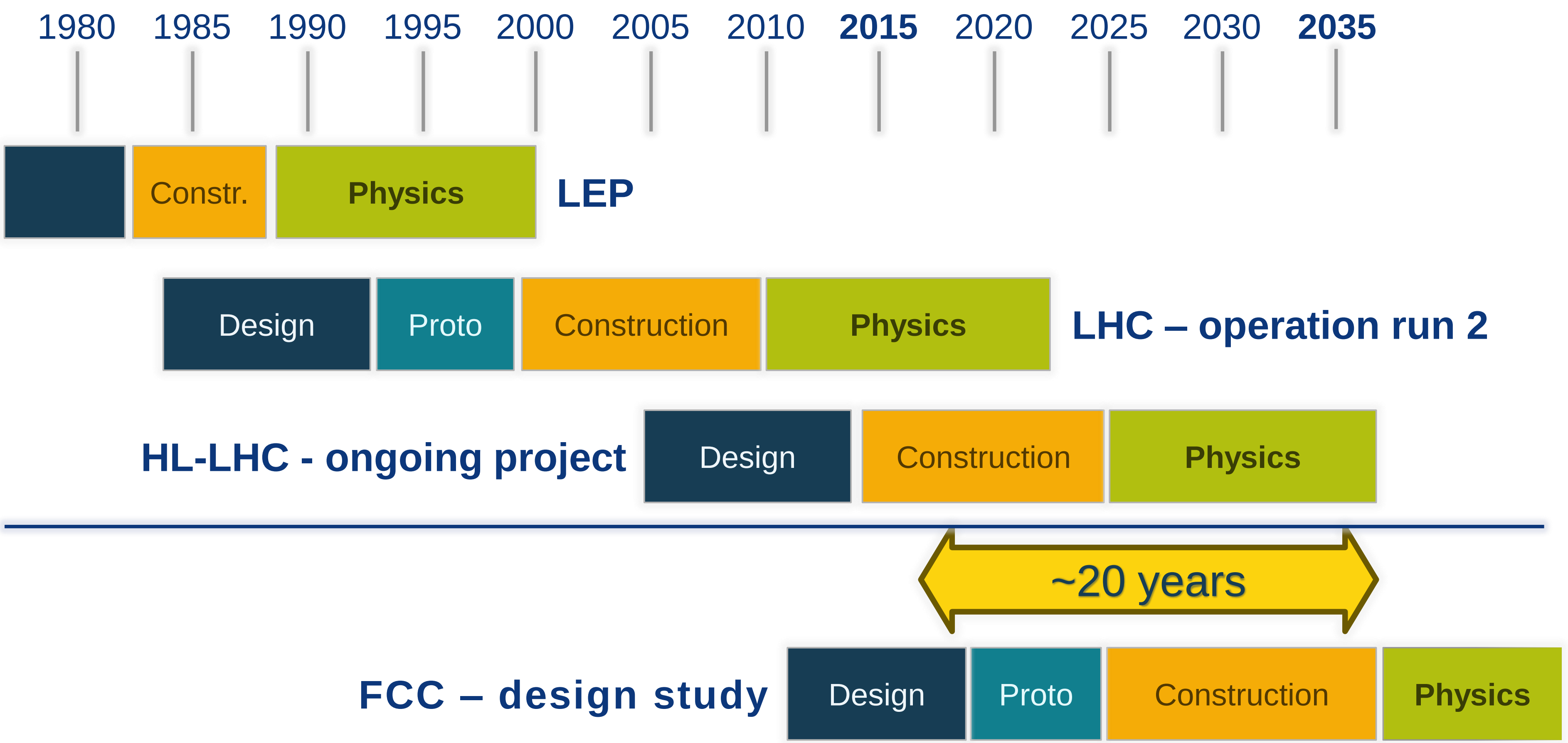
collision optics with β*=0.25 m

- **Triplet quadrupoles with 2 cm inside tungsten shielding**
- **For 10 ab^{-1} total luminosity: 30-40 MGy peak radiation (peak at Q3 can be reduced with shielding)**



Work on collimation insertions ongoing

CERN Circular Colliders & FCC



Must advance fast now to be ready for the period 2035 – 2040

Goal of phase 1: CDR by end 2018 for next update of European Strategy