Geneva site

Beyond LHC: Future Circular Colliders

Studies in Europe and China

F. Zimmermann, 20th RDMS CMS Meeting, Tashkent

incl. slides from M. Benedikt (CERN) and J. Gao, X. Lou (IHEP) gratefully acknowledging input from FCC coordination group, global FCC design study team, CEPC/SPPC design study, and all other contributors

Qinhuangdao site

http://cern.ch/fcc

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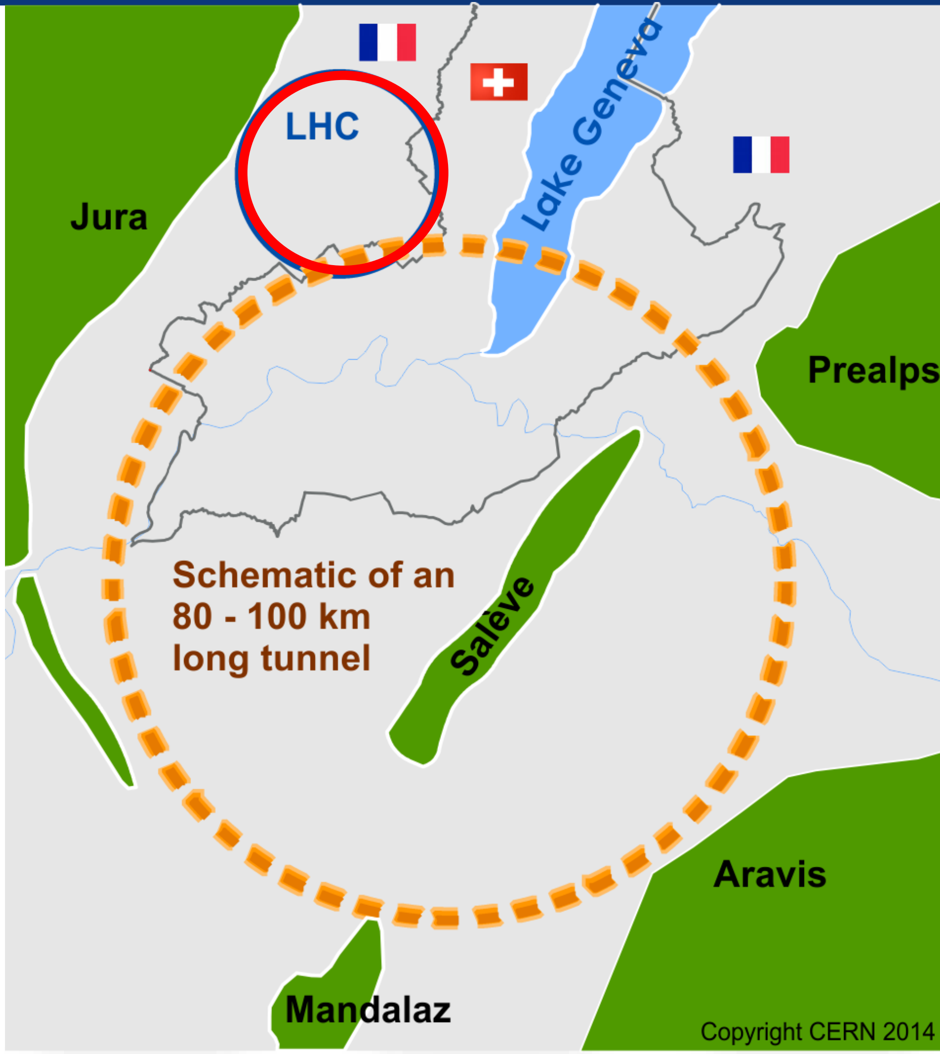
Future Circular Collider study - scope

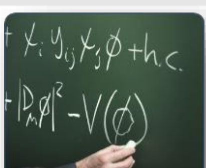


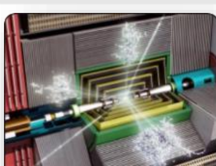
international FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → long-term goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

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


Physics Cases


Experiments

Collider Designs


R&D Programs


Infrastructures


Cost Estimates

FCC study: physics and performance targets

FCC-ee:

- **exploration of 10 to 100 TeV energy scale via couplings with precision measurements , ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)** ($m_{Z,}$ m_{W}, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings)

➢ **machine design for highest luminosities at Z, WW, ZH and ttbar working points**

FCC-hh:

- **highest center of mass energy for direct production up to 20 - 30 TeV**
- **huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks**

➢ **machine design for 100 TeV c.m. energy & int. luminosity $\sim$ 20ab^{-1} within 25 years**

HE-LHC:

- **doubling LHC collision energy with FCC-hh 16 T magnet technology**
- **c.m. energy $\sim$ 27 TeV $=$ 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC**

➢ **machine design within constraints from LHC CE and based on HL-LHC and FCC technologies**

FCC-ee basic design choices

double ring e+ e- collider ~100 km

follows footprint of FCC-hh, except around IPs

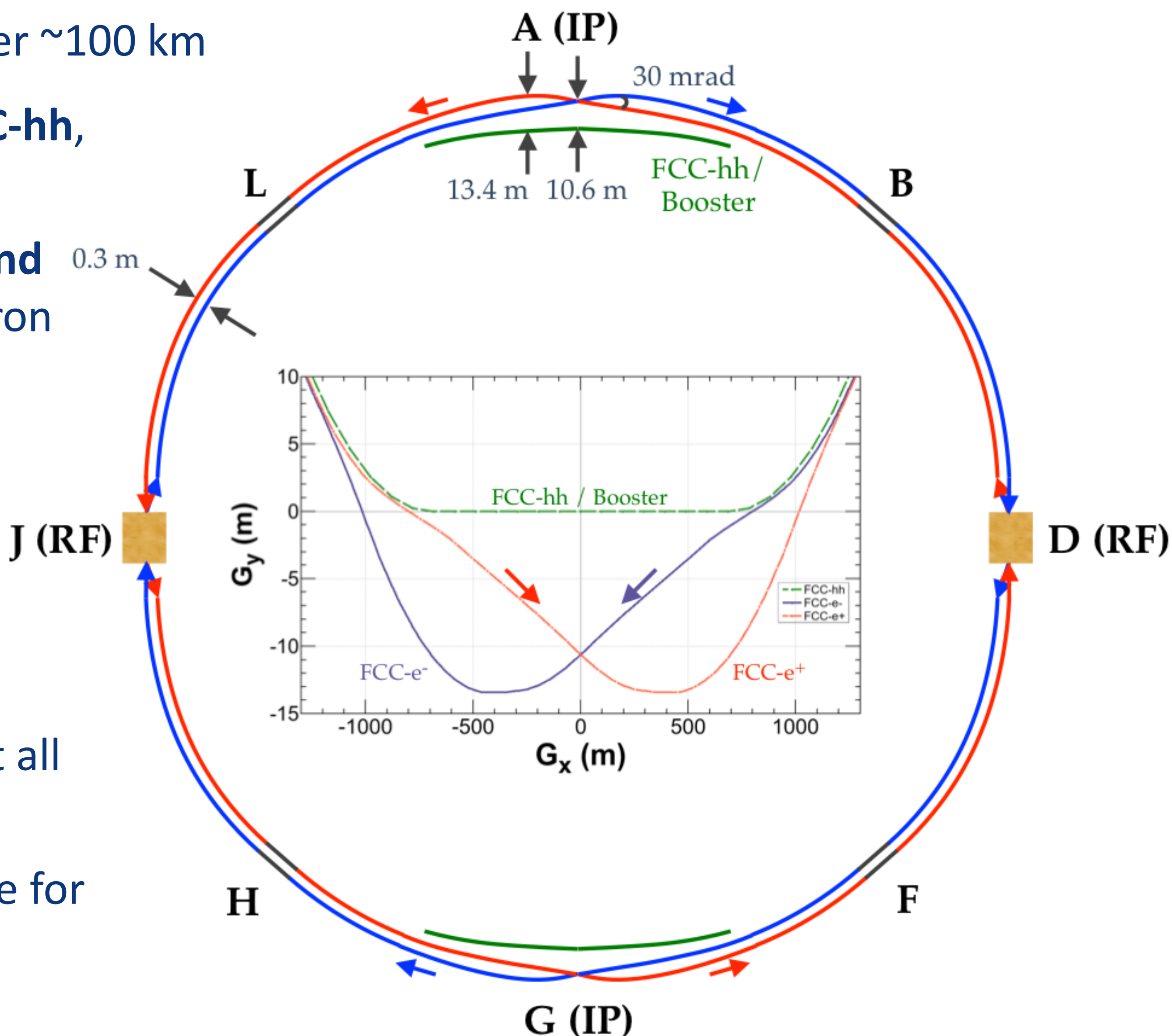
asymmetric IR layout and optics to limit synchrotron radiation towards the detector

2 IPs, large horizontal crossing angle **30 mrad, crab-waist optics**

synchrotron radiation power 50 MW/beam at all beam energies

top-up injection scheme for high luminosity

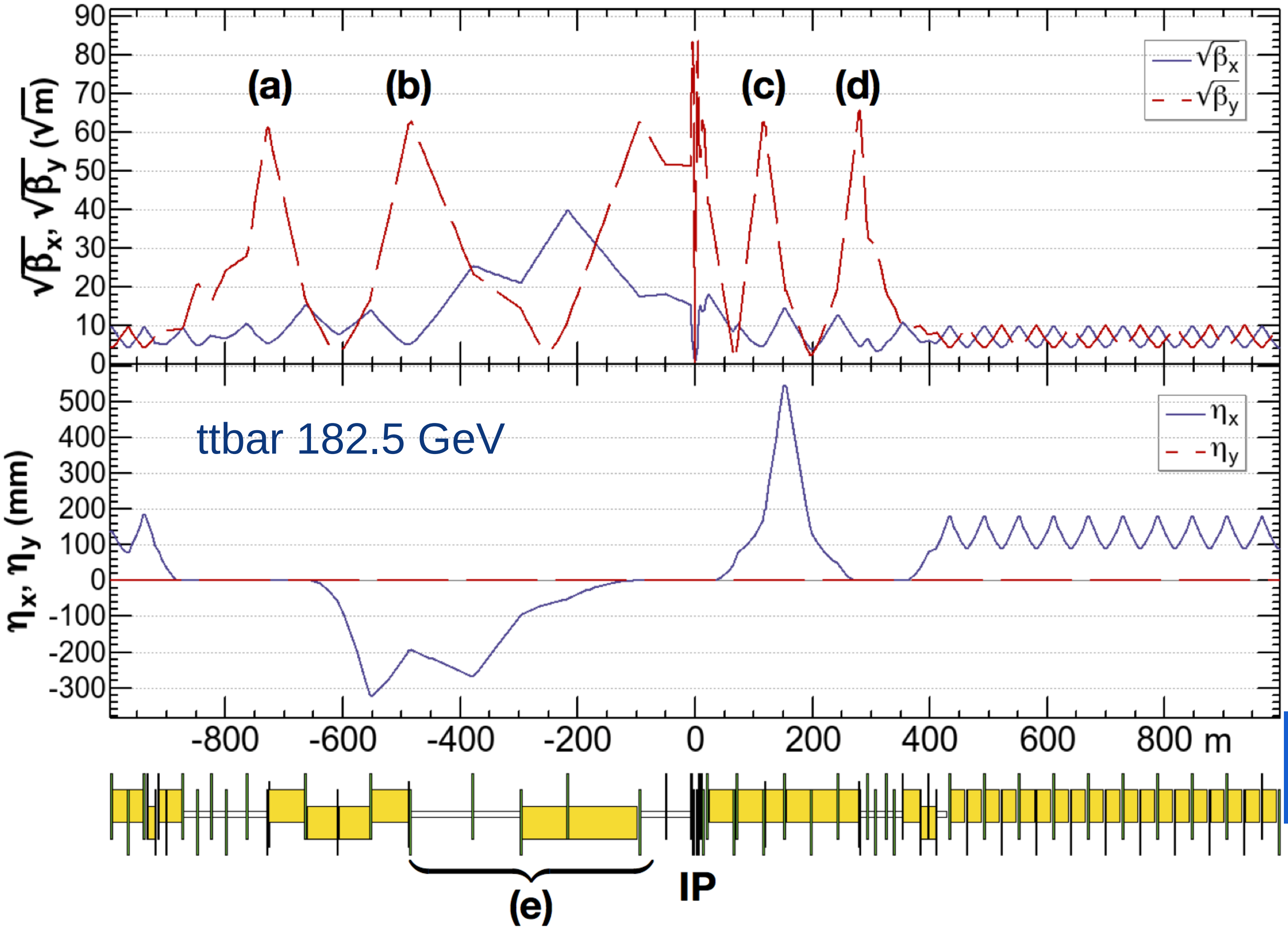
requires **booster synchrotron in collider tunnel**



FCC-ee collider parameters: 4 modes

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee asymmetric crab waist IR optics



asymmetric IR optics to suppress synchrotron radiation toward the IP, **$E_{critical}$ <100 keV from 450 m from IP (e)**

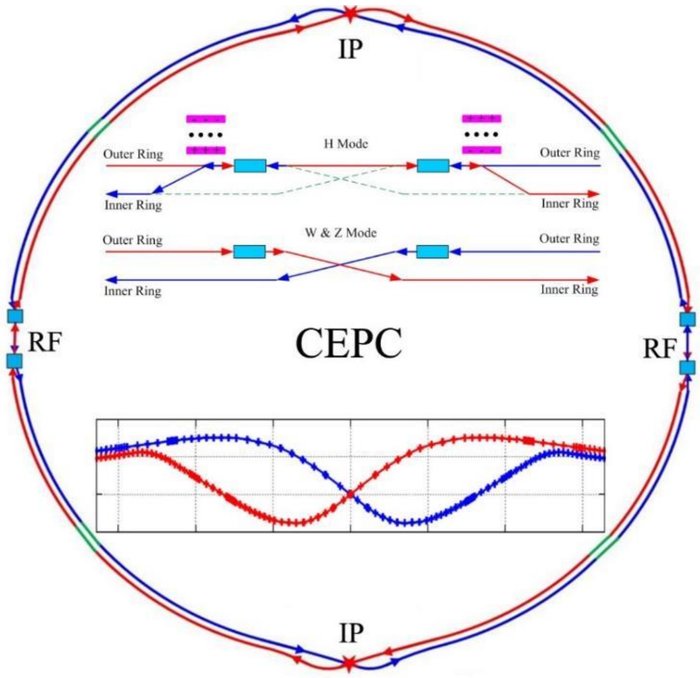
yellow boxes: dipole magnets

K. Oide

4 sextupoles (a – d) for local vertical chromaticity correction and crab waist, optimized for each working point.

Common arc lattice for all energies, **60 deg for Z, W and 90 deg for ZH, tt** for maximum stability and luminosity

CEPC CDR Baseline: 3 operation modes (no top running)



- **Higgs factory as first piority** (fully partial double ring, with common SRF system for e+ and e- beams)
- W and Z factories are incorporated by beam swithyard (W and Z factories are double ring, with independent SRF system for e+ and e- beams)
- Higgs factory baseline SR per beam 30 MW to Minimize AC power

economic CEPC baseline design as Higgs factory:

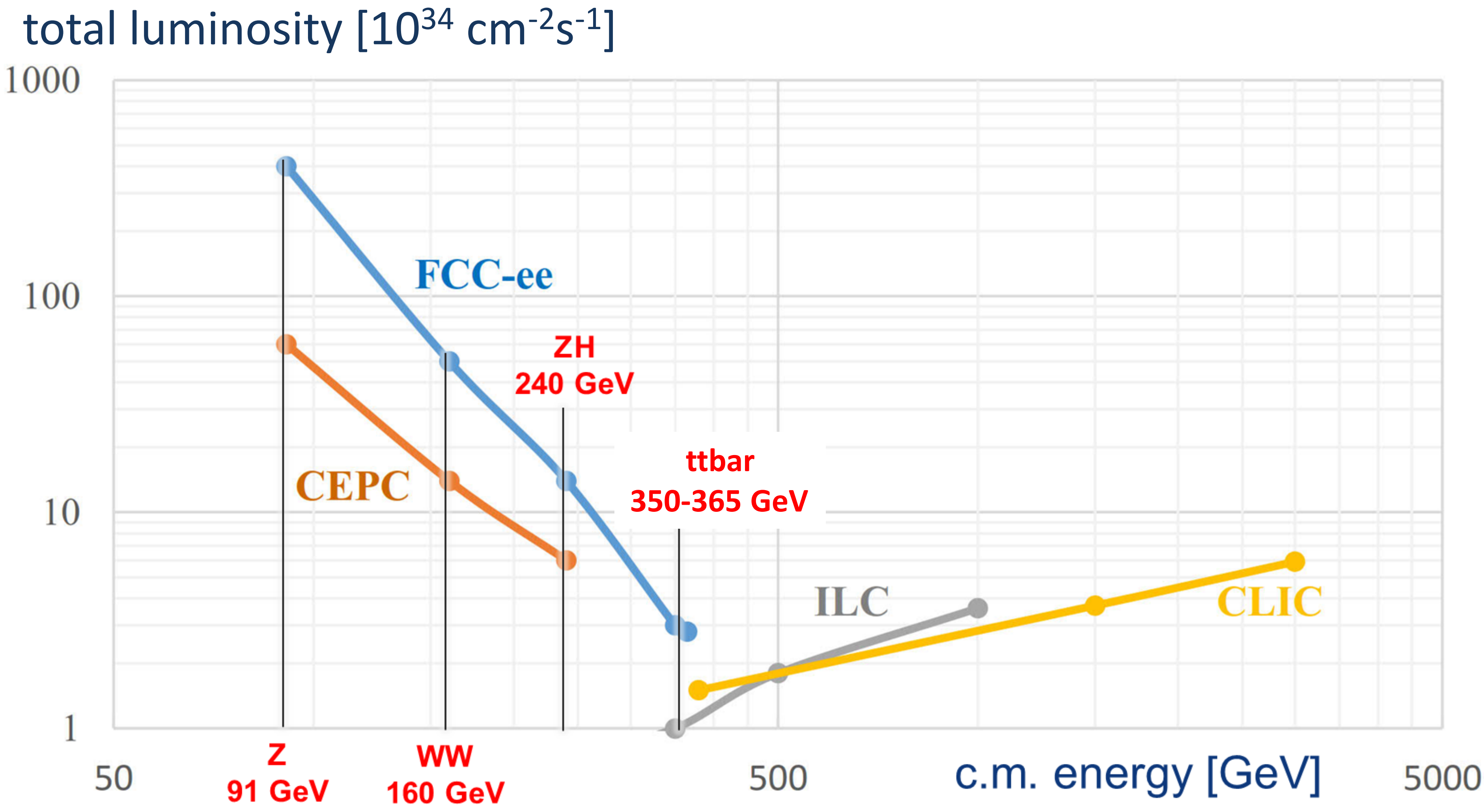
- **W, Z factories incorporated with the same SRF system** hardware by using beam switchyard to change from Higgs factory and W, Z factories
- synchrotron radiation power per beam at Higgs energy is set to 30MW to minimize AC power consumption

J. Gao

CEPC CDR Parameters (September 2018)

	Higgs	*W*	*Z*（*3T*）	*Z*（*2T*）
Number of IPs	2			
Beam energy (GeV)	**120**	**80**	**45.5**	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	**30**	**30**	**16.5**	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	**0.36/0.0015**	**0.36/0.0015**	**0.2/0.0015**	**0.2/0.001**
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	**1.94**	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	**1.35**	**0.4**	**0.23**	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.1	0.05	0.023	
Lifetime _simulation (min)	100			
Lifetime (hour)	**0.67**	**1.4**	**4.0**	**2.1**
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP L ($10^{34}cm^{-2}s^{-1}$)	**2.93**	**10.1**	**16.6**	**32.1**

lepton collider luminosities

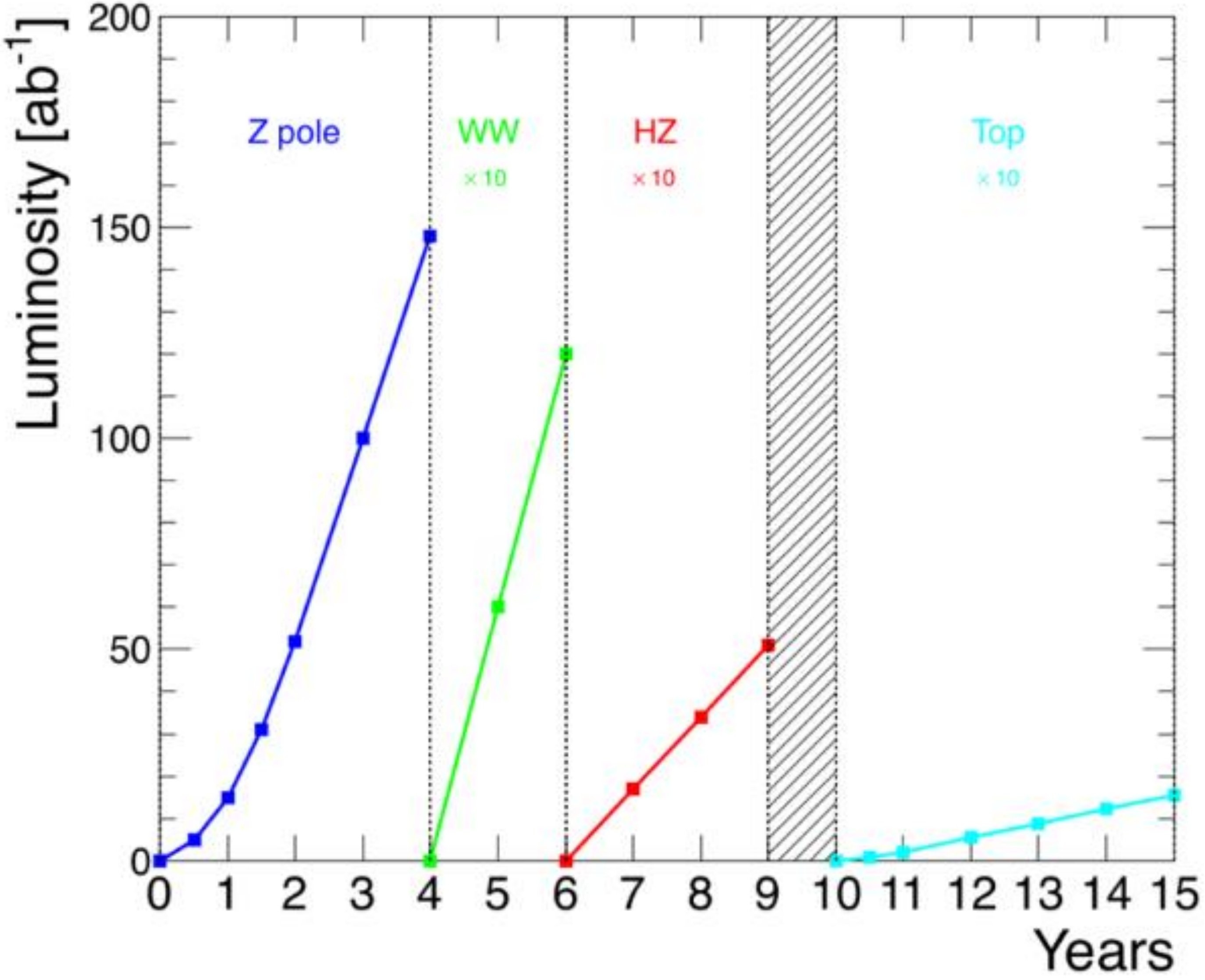


FCC-ee physics operation model

working point	nominal luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr half luminosity in first two years (Z) and first year (ttbar) to account for initial operation	physics goal	run time [years]
***Z* first 2 years**	100	**26 ab^{-1}/year**	**150 ab^{-1}**	**4**
***Z* later**	200	**48 ab^{-1}/year**		
W	25	**6 ab^{-1}/year**	**10 ab^{-1}**	**1 - 2**
H	7.0	**1.7 ab^{-1}/year**	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	**0.2 ab^{-1}/year**	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	**0.34 ab^{-1}/year**	**1.5 ab^{-1}**	**4**

total program duration: 14 – 15 years - *including machine modifications*
phase 1 (*Z, W, H*): 8 – 9 years,   phase 2 (top): 6 years

FCC-ee luminosity projection



FCC-ee RF staging scenario

"Ampere-class" machine

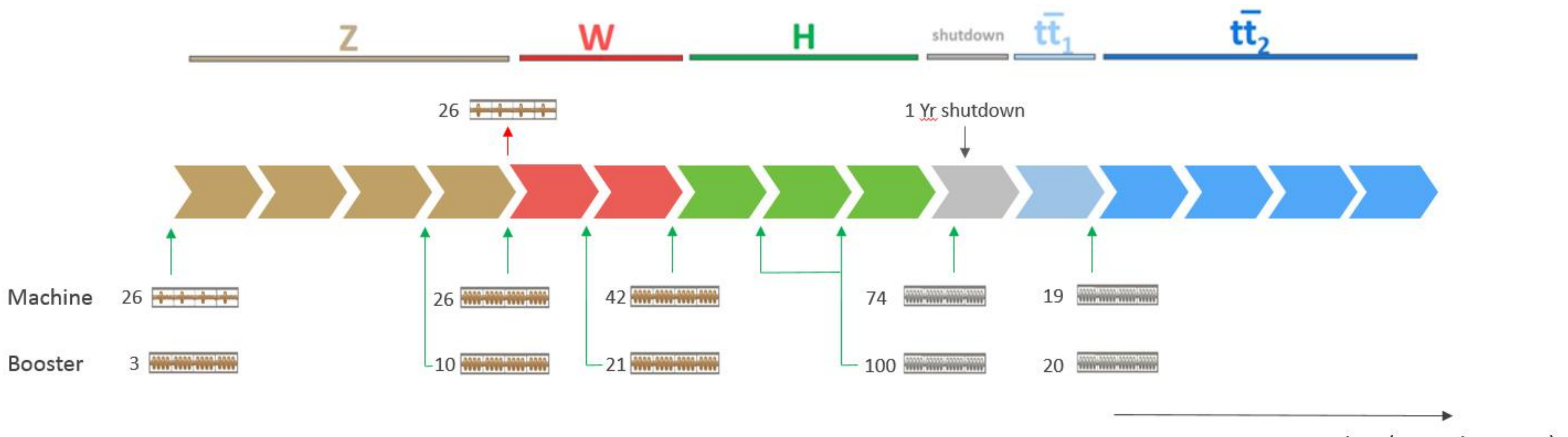
WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

"high-gradient" machine

O. Brunner

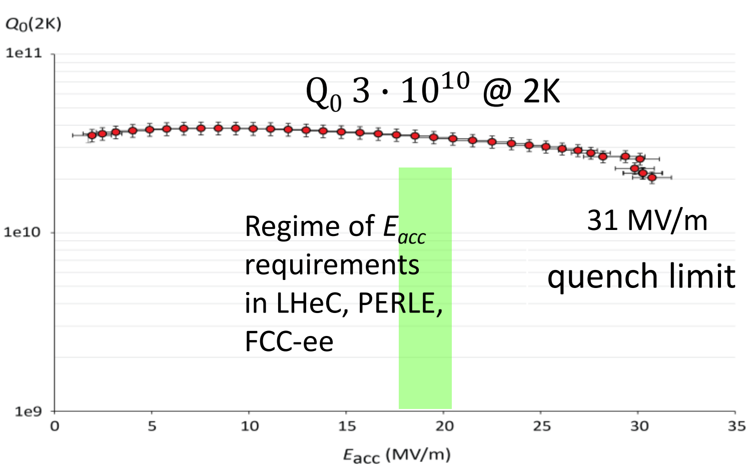
three sets of RF cavities to cover all options for FCC-ee & booster:

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

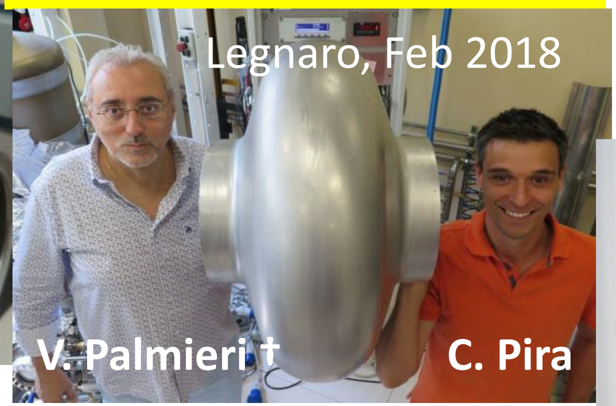


FCC SRF cavity development (examples)

5-cell 800 MHz cavity, JLAB prototype for both FCC-ee (t-tbar) & FCC-eh



seamless 400 MHz single-cell cavity formed by spinning at INFN-LNL



tooling fabricated and successfully tested with an aluminium cavity

† We're saddened by the sudden death of Vincenzo Palmieri this year

CERN half-cells produced by Electro-Hydro-Forming (EHF) at B_{max}

EASITrain

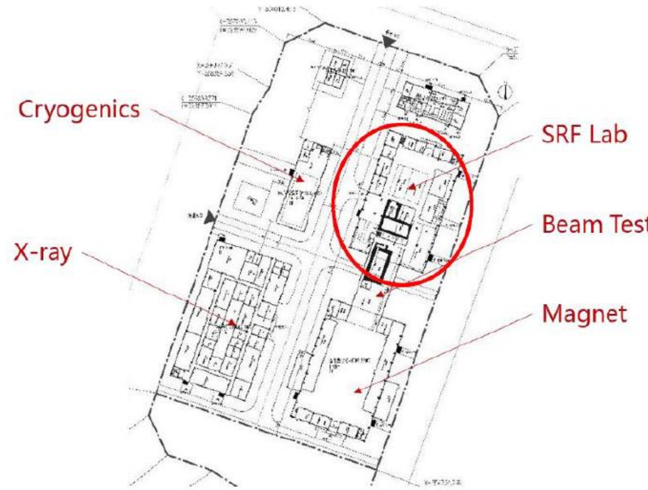
high strain rate technology using shockwaves in water from HV discharge.
EHF investigated for half-cells and seamless Nb&Cu cavities

O. Brunner, E. Jensen

CEPC SRF cavities - production at PAPS

Platform of **A**dvanced **P**hoton **S**ource Technology R&D, Huairou Science Park, Huairou, Beijing

Construction: 2017 - 2019
Ground Breaking: May 31, 2017

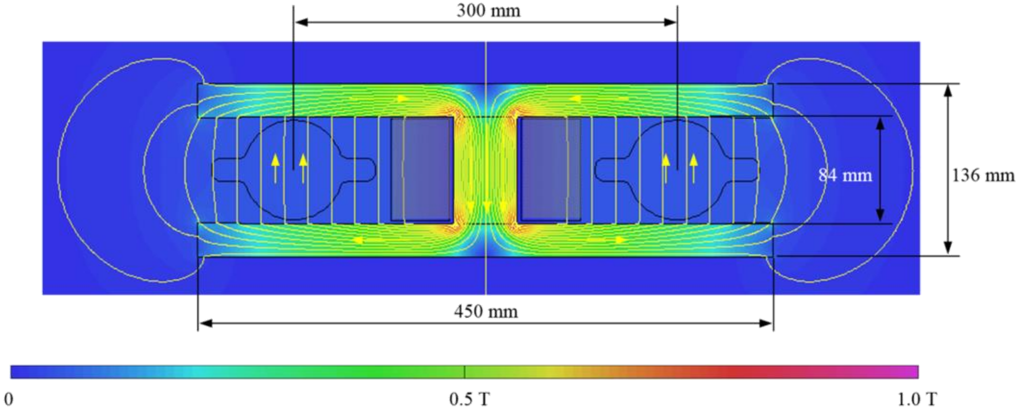


4500 m^2 SRF lab

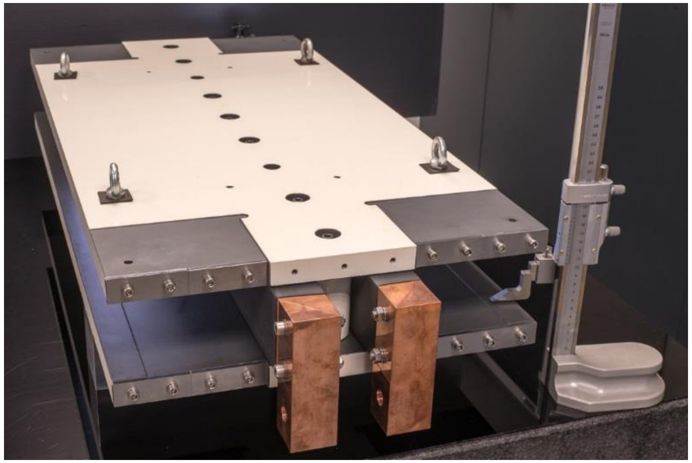
- 500M RMB funded by city of Beijing
- Construction: May 2017 – June 2020
- Include RF system & cryogenic systems magnet technology, beam test, etc.

low-power low-cost design for FCC-ee magnets

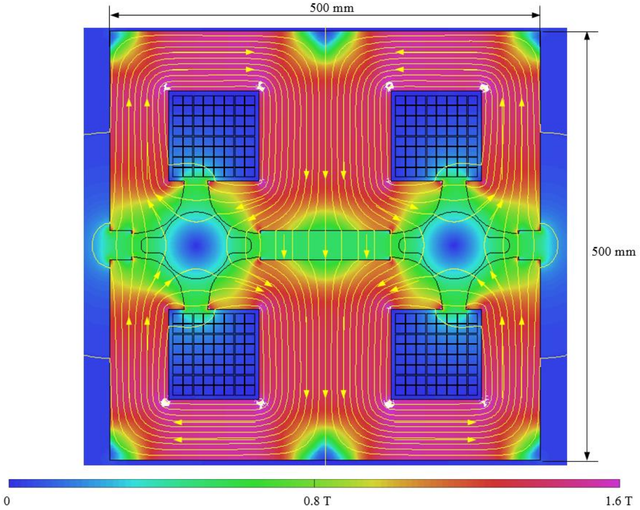
twin-dipole design with 2× power saving 16 MW (at 175 GeV), with Al busbars



first 1 m prototype



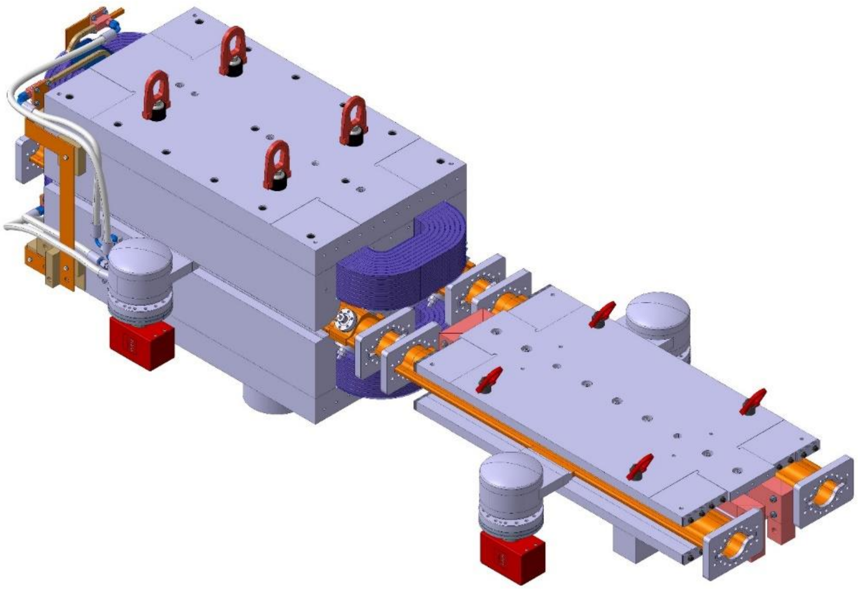
twin F/D quad design with 2× power saving; 25 MW (at 175 GeV), with Cu conductor



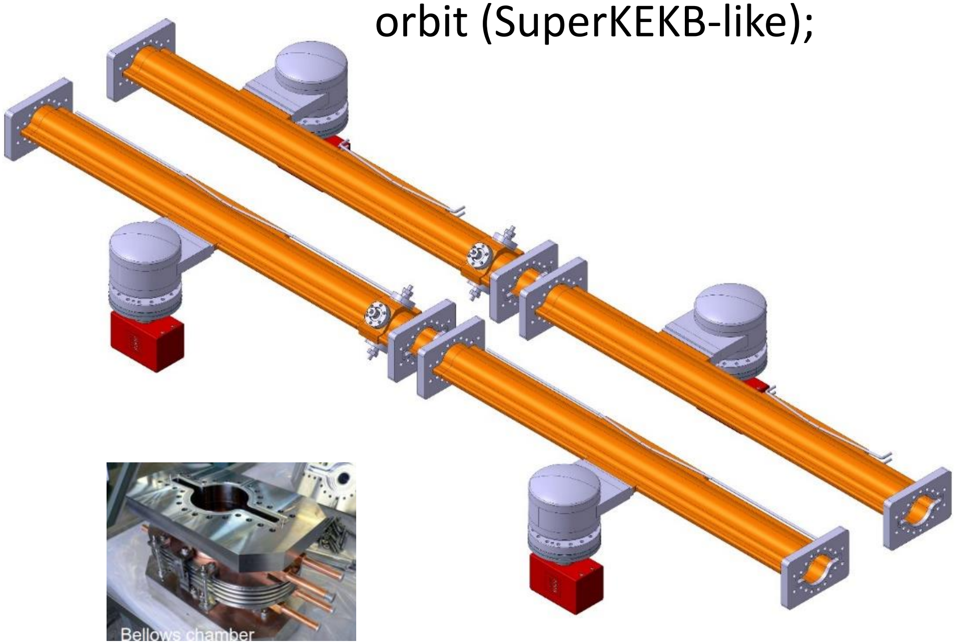
first 1 m prototype

A. Milanese

FCC-ee arc vacuum prototyping and integration



Vacuum chamber cross section: 70 mm ID with ”winglets” in the plane of the orbit (SuperKEKB-like);

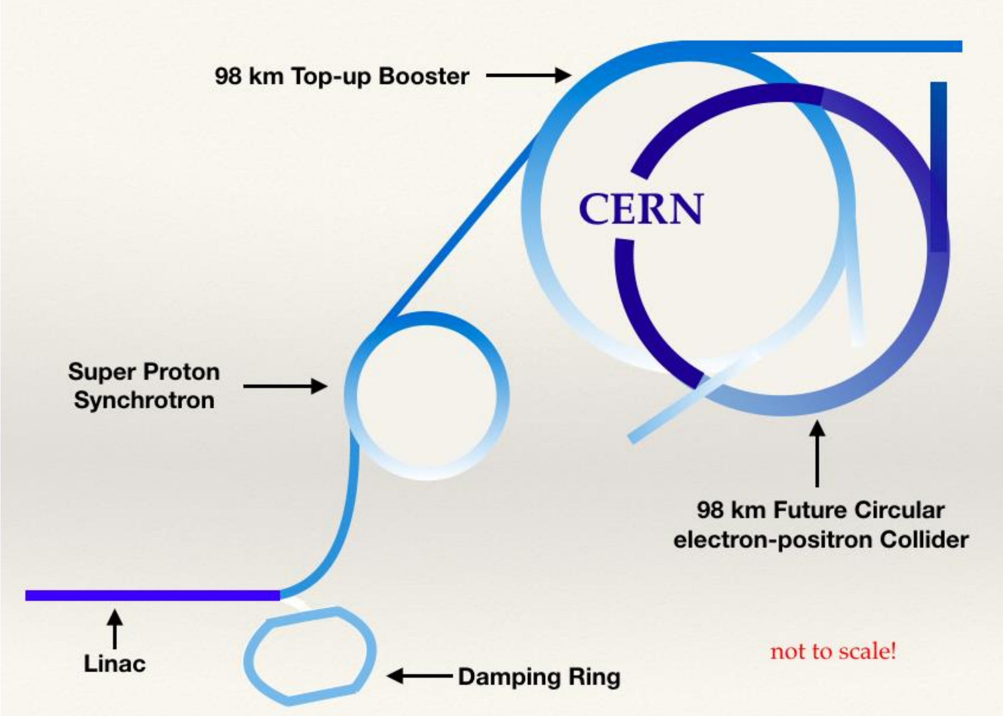


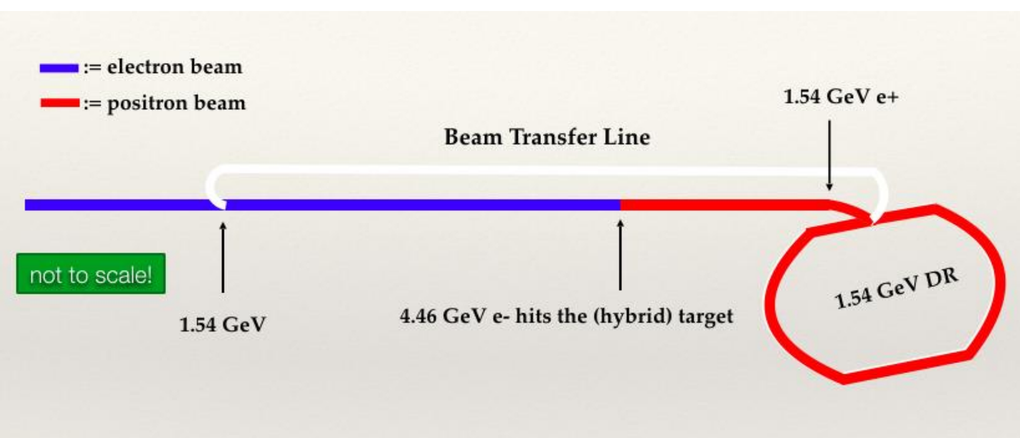
- chambers feature **lumped SR absorbers with NEG-pumps** placed next to them.
- **construction of chamber prototypes in coming months and integration with twin magnets**

R. Kersevan, C. Garion

FCC-ee injector layout

S. Ogur, K. Oide, Y. Papaphilippou





SLC/SuperKEKB-like 6 GeV linac accelerating; **1** or **2** bunches with repetition rate of **100-200 Hz**

same linac used for e+ production @ **4.46 GeV** e+ beam emittances reduced in DR @ **1.54 GeV**

injection @ **6 GeV** into of Pre-Booster Ring (SPS or new ring) and acceleration to 20 GeV

injection to main Booster @ **20 GeV and interleaved** filling of e+/e- (below **20 min** for full filling) and continuous top-up

CEPC: 10 GeV linac, no prebooster

FCC-ee el. power consumption [MW]

Beam energy (GeV)	45.6 Z	80 W	120 ZH	182.5 ttbar
RF (SR = 100)	163	163	145	145
Collider cryo	1	9	14	46
Collider magnets	4	12	26	60
Booster RF & cryo	3	4	6	8
Booster magnets	0	1	2	5
Pre injector	10	10	10	10
Physics detector	8	8	8	8
Data center	4	4	4	4
Cooling & ventilation	30	31	31	37
General services	36	36	36	36
Total	259	278	282	359

CEPC power & comparing efficiency

CEPC Power for Higgs and Z

	System for Higgs (30MW)	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	103.8	0.15	5.8				109.75
2	Cryogenic System	11.62	0.68			1.72		14.02
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	47.21	11.62	1.75	1.06	0.26		61.9
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	31.79	3.53	1.38	0.63	1.2		38.53
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	213.554	20.972	10.276	1.845	7.385	12	266.032

266MW

2.5x less luminosity than FCC-ee at ~equal power

	System for Z	Location and electrical demand(MW)						Total (MW)
		Ring	Booster	LINAC	BTL	IR	Surface building	
1	RF Power Source	57.1	0.15	5.8				63.05
2	Cryogenic System	2.91	0.31			1.72		4.94
3	Vacuum System	9.784	3.792	0.646				14.222
4	Magnet Power Supplies	9.52	2.14	1.75	0.19	0.05		13.65
5	Instrumentation	0.9	0.6	0.2				1.7
6	Radiation Protection	0.25		0.1				0.35
7	Control System	1	0.6	0.2	0.005	0.005		1.81
8	Experimental devices					4		4
9	Utilities	19.95	2.22	1.38	0.55	1.2		25.3
10	General services	7.2		0.2	0.15	0.2	12	19.75
	Total	108.614	9.812	10.276	0.895	7.175	12	148.772

149MW

8x less luminosity than FCC-ee at ~60% the power

J. Gao

sketch of FCC-ee physics

EXPLORE **10-100 TeV energy scale** (and beyond) with Precision Measurements

DISCOVER a **violation of flavour conservation or universality & unitarity**

DISCOVER **dark matter as «invisible decay» of H or Z** (or in LHC loopholes)

DISCOVER **very weakly coupled particle in 5-100 GeV energy scale** such as: Right-Handed neutrinos, Dark Photons

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164;

ZH cross-section receives a E_{cm} -dependent correction from λ_H

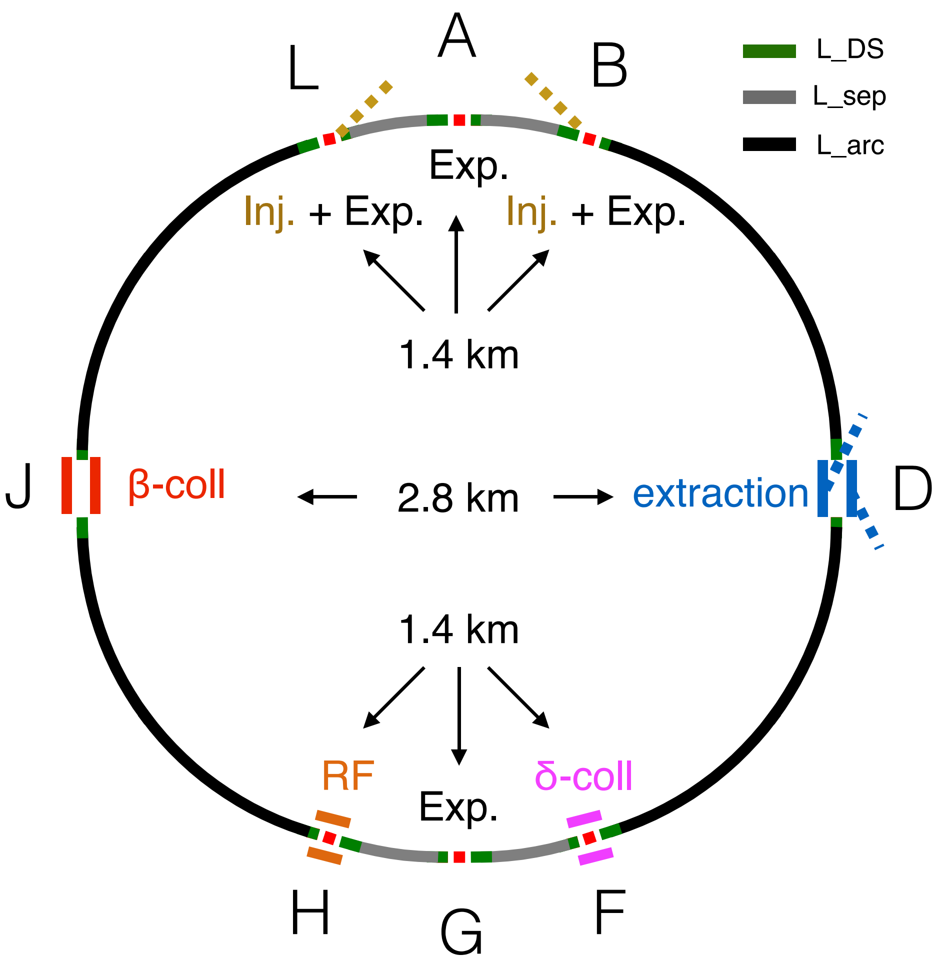
investigating now : **the possibility of reaching 5σ observation of Higgs self coupling at FCC-ee:**
4 detectors + recast of running scenario

A. Blondel, ICHEP 2018

FCC-hh collider parameters

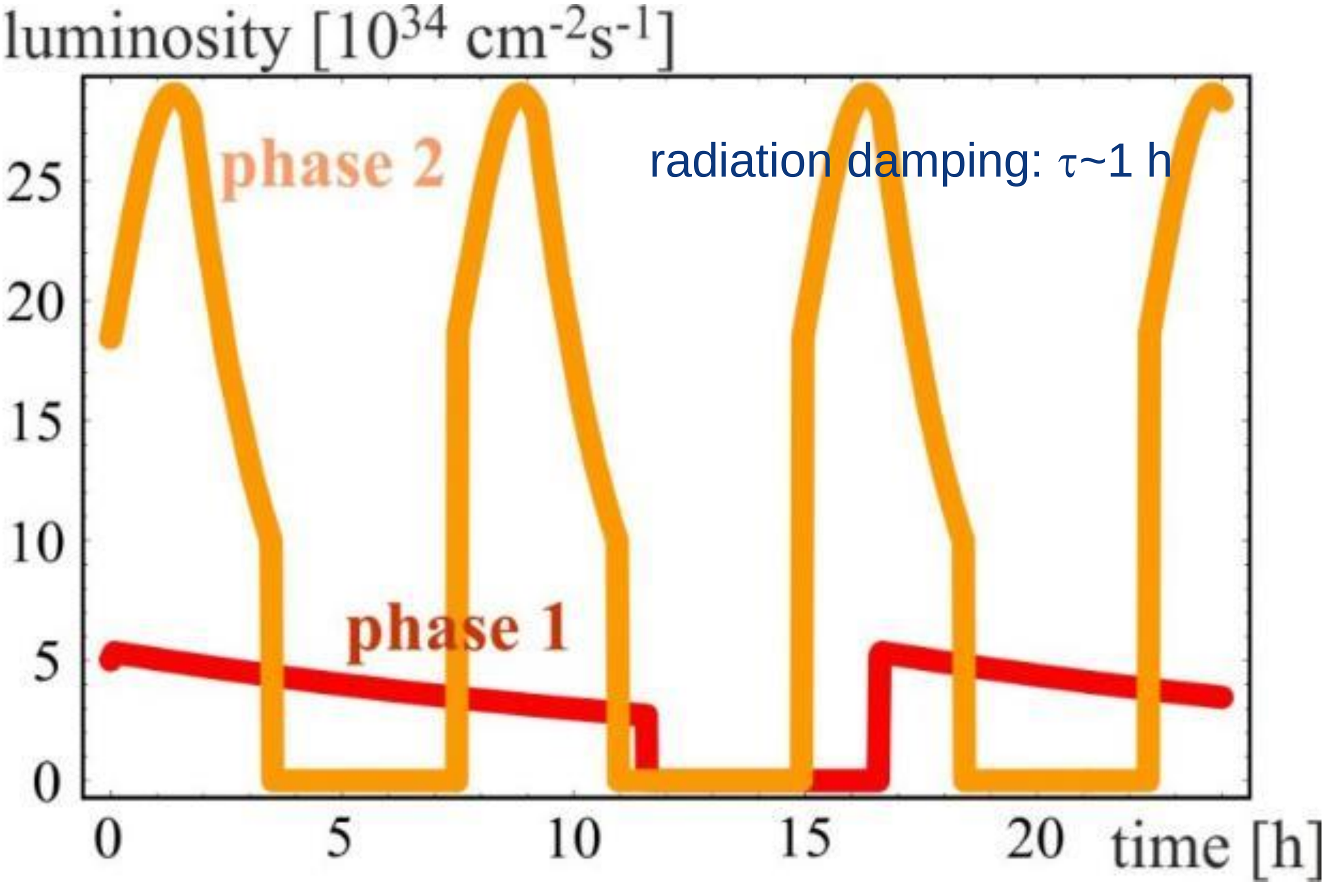
parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.1	1.1	0.58
bunch intensity [10^{11}]	1		2.2	2.2	1.15
bunch spacing [ns]	25		25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.45	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	16	5 (lev.)	1
events/bunch crossing	170	1000	460	132	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

FCC-hh layout and optics



- **circumference 97.8 km**
- **two high-luminosity experiments (A & G)**
- **two other experiments (L & B)** combined with **injection upstream** of experiments
- **two collimation insertions**
  - betatron cleaning (J)
  - momentum cleaning (F)
- **Extraction/dump insertion (D)**
- **RF insertion (H)**
- **integrated optics for full ring established**, beam dynamics studies confirm design goals

FCC-hh operation phases



phase 2: Interplay of radiation damping, luminosity burn-off, controlled transverse blow-up

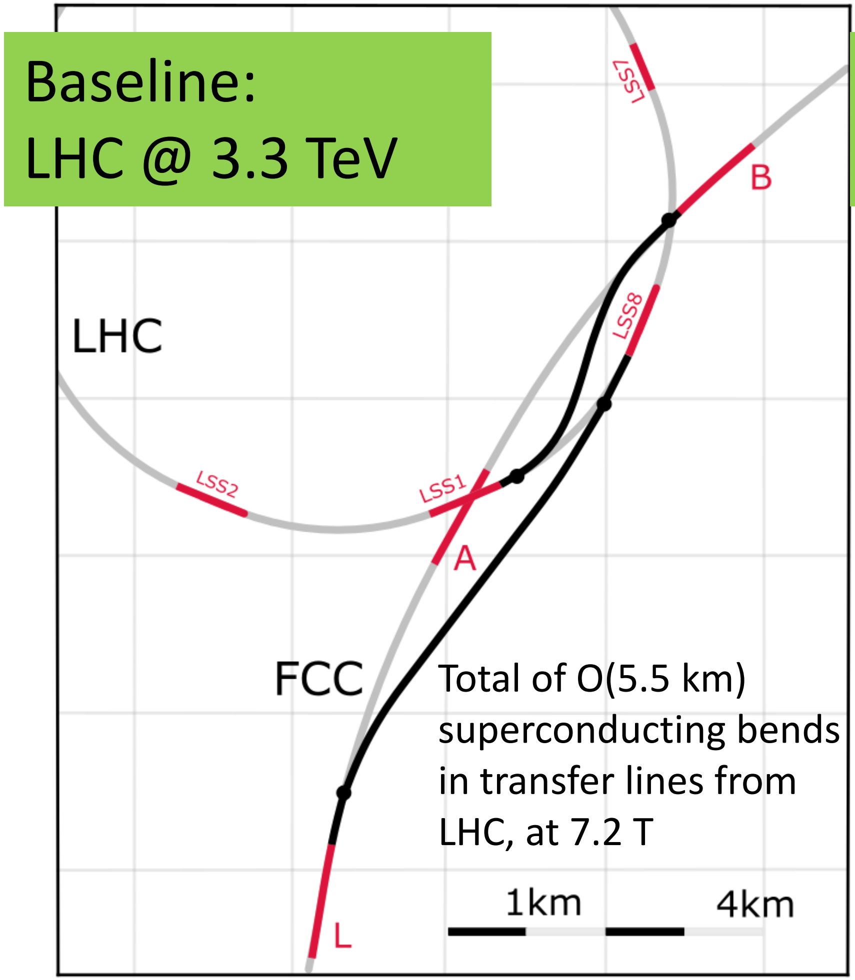
phase 1 (initial):
β^*=1.1 m,
ΔQ_{tot}=0.01, t_{ta}=5 h
250 fb^{-1} / year

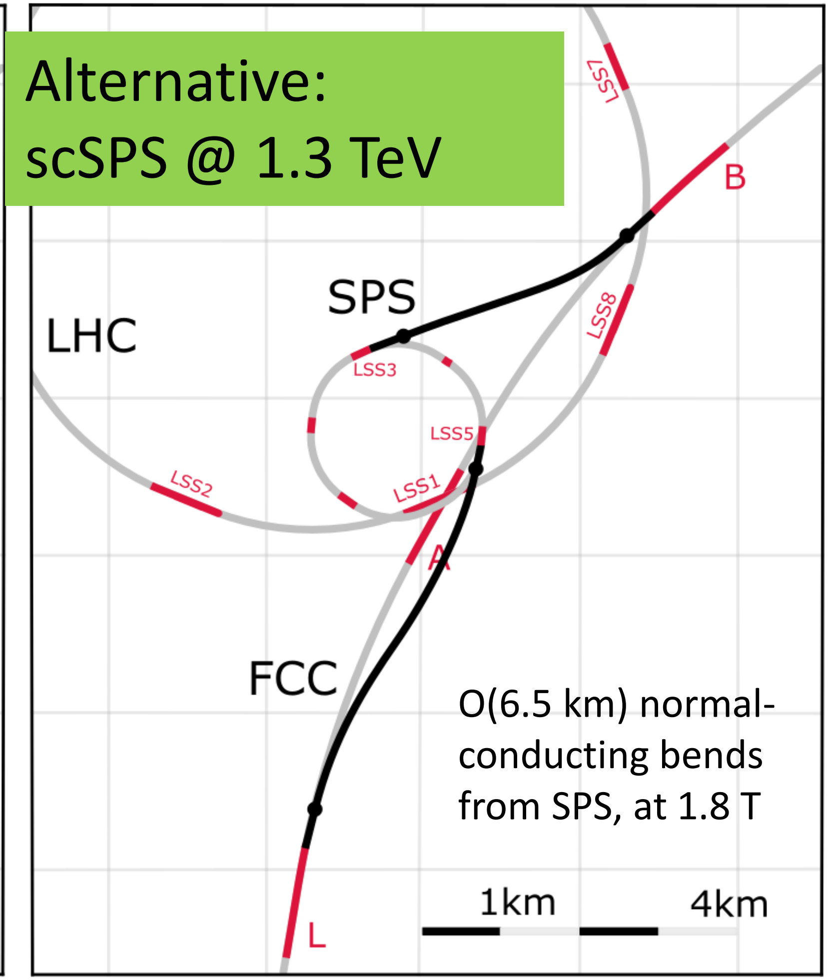
phase 2 (nominal):
β^*=0.3 m, ΔQ_{tot}=0.03,
t_{ta}=4 h
1 ab^{-1} / year

transition via operation experience, no HW modification

total integrated luminosity over 25 years of operation
O(20) ab^{-1}/experiment - consistent with physics goals

FCC-hh injector options





Current baseline: **Injection energy 3.3 TeV LHC → Field-swing FCC-hh like LHC**

Alternative options: Injection from $SPS_{upgrade}$ around 1.3 TeV

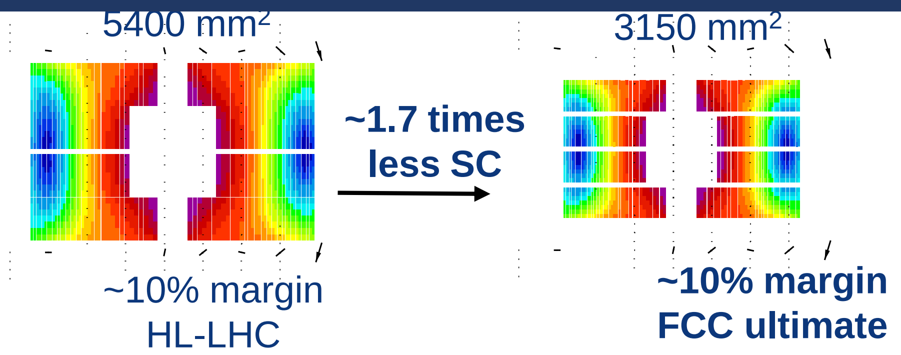
$SPS_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp, cf. SIS 300 design

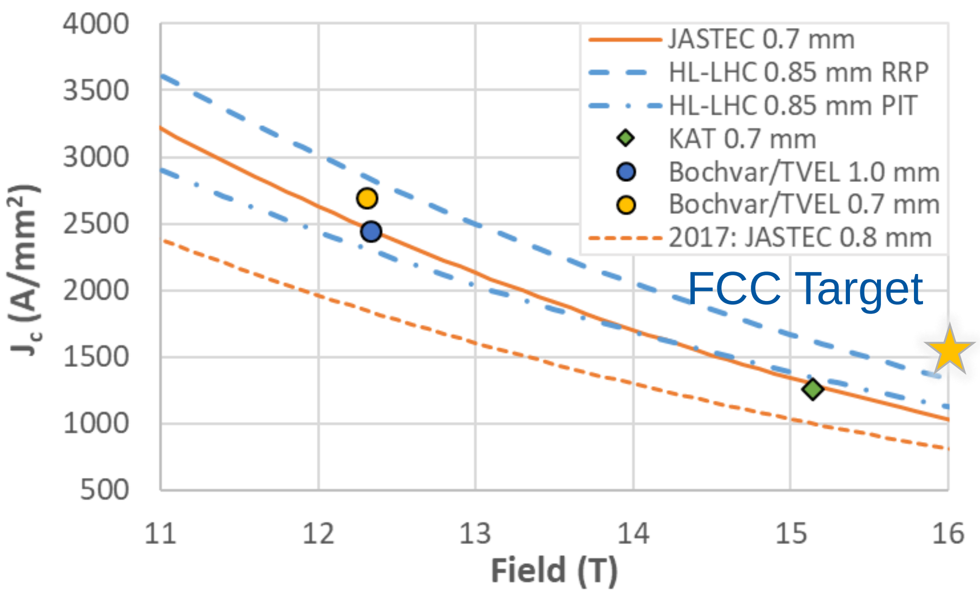
$SPS_{upgrade}$ would also be an ideal injector for HE LHC (as alternative to the 450 GeV SPS)

worldwide FCC Nb_3Sn program

Main development goal is wire performance increase:

- **J_c (16T, 4.2K) > 1500 A/mm² →50% increase wrt HL-LHC wire**
- **Reduced coil & magnet cross-section**





after only one year development, **prototype Nb_3Sn wires from several new industrial FCC partners** (Japan, Korea, Russia) **already achieve HL-LHC performance**

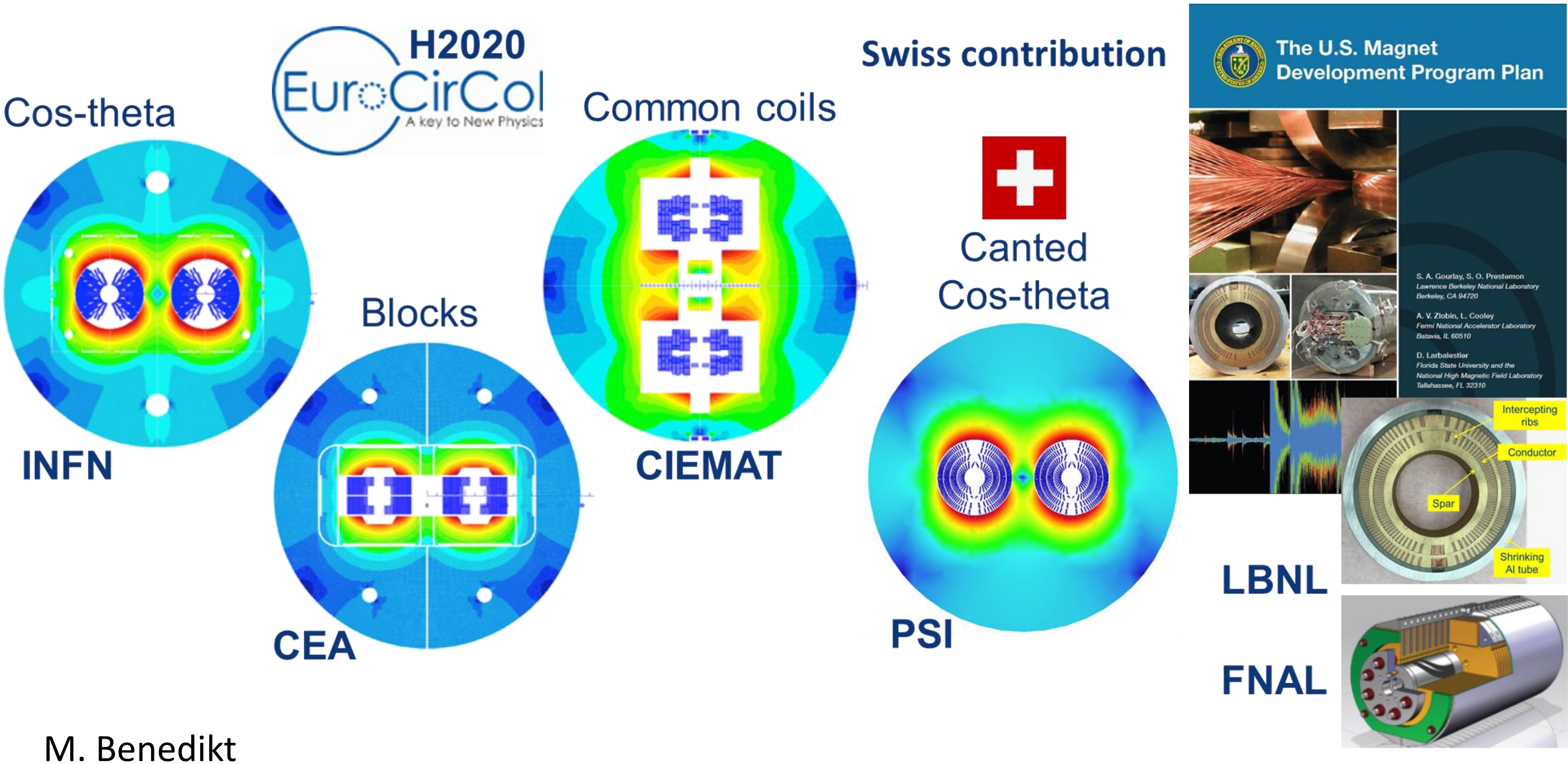
Conductor activities for FCC started in 2017:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT**, **Korea**
- **Columbus**, **Italy**
- **University of Geneva**, **Switzerland**
- **Technical University of Vienna**, **Austria**
- **SPIN**, **Italy**
- **University of Freiberg**, **Germany**

In addition, agreements under preparation:

- **Bruker**, **Germany**
- **Luvata Pori**, **Finland**

16 T dipole design activities & options

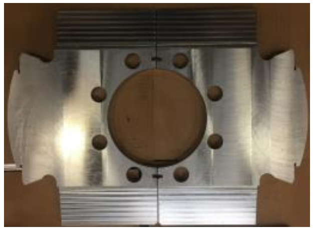


M. Benedikt

short model magnets (1.5 m lengths) built from 2018 – 2022

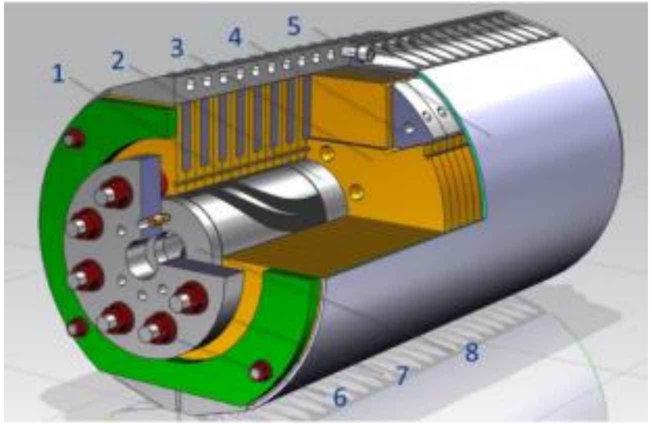
Russian 16 T magnet program launched by BINP recently

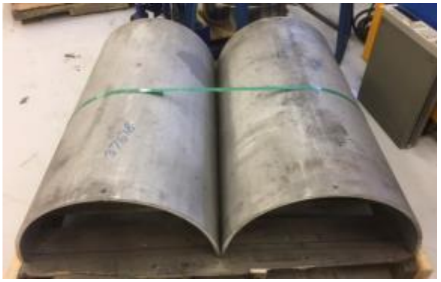
15 T dipole demonstrator (US MDP)



Iron Laminations

AL I-Clamps





StSt Skin

Fillers

End Plates

Axial Rods

- **All coil parts, structural components and tooling are available at FNAL**
- **Coil fabrication and the work with mechanical structure are in progress**
- **First magnet test in September 2018**

A. Zlobin

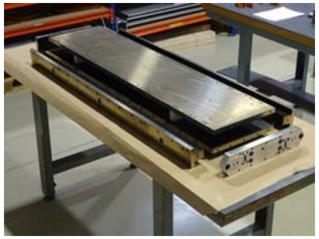
16 T ERMC construction at CERN

First ERMC coil winding

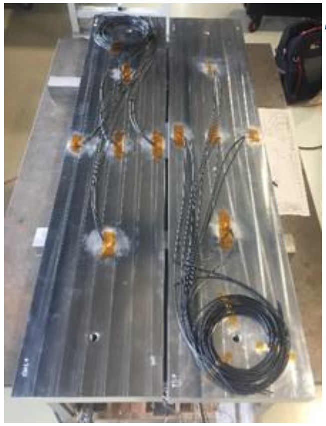
Aluminum shell

Magnet yoke

Coil Reaction Tool



Coil Impregnation Tool



Dummy coils

Axial rods

D. Tommasini

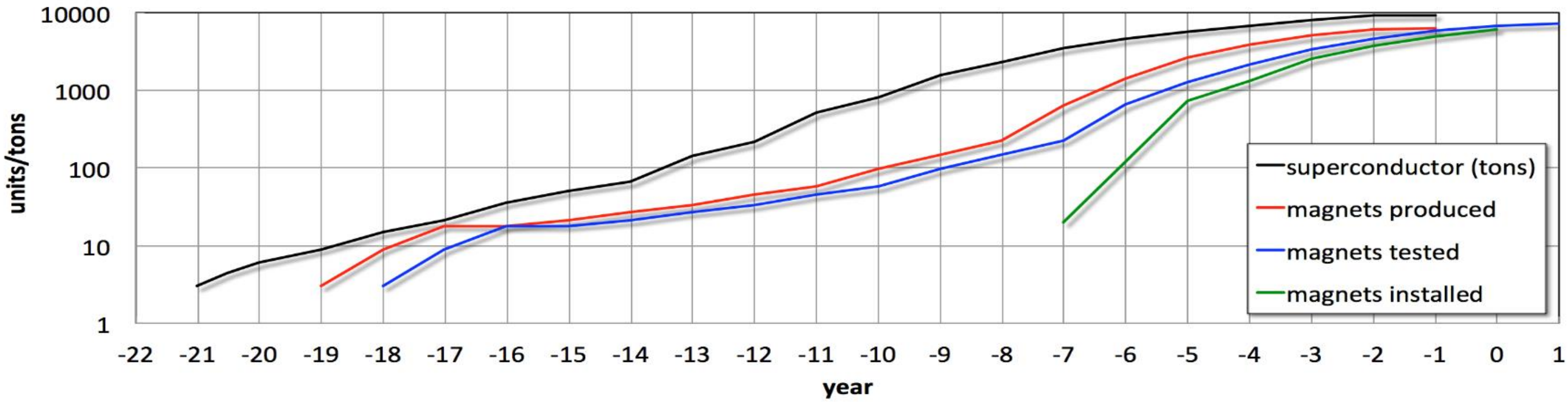
Coil fabrication

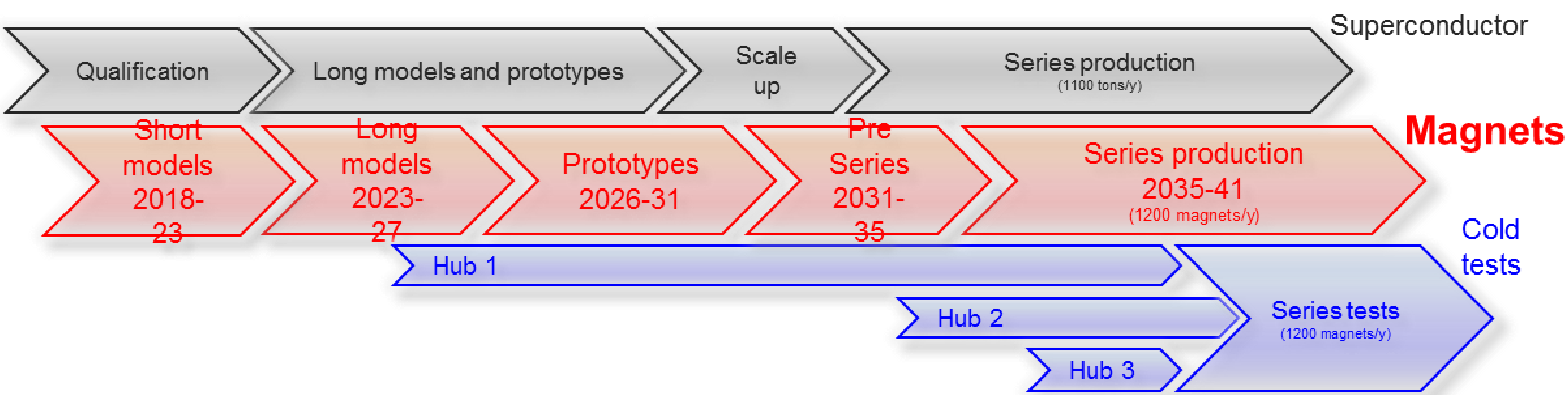
Winding of the first coil has been completed. Preparation for reaction on-going. All tooling for coil production ready

Magnet assembly

Components and tooling ready. Dummy assembly to characterize the structure behavior on-going.

FCC 16 T magnet R&D schedule





total duration of magnet program: ~20 years

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

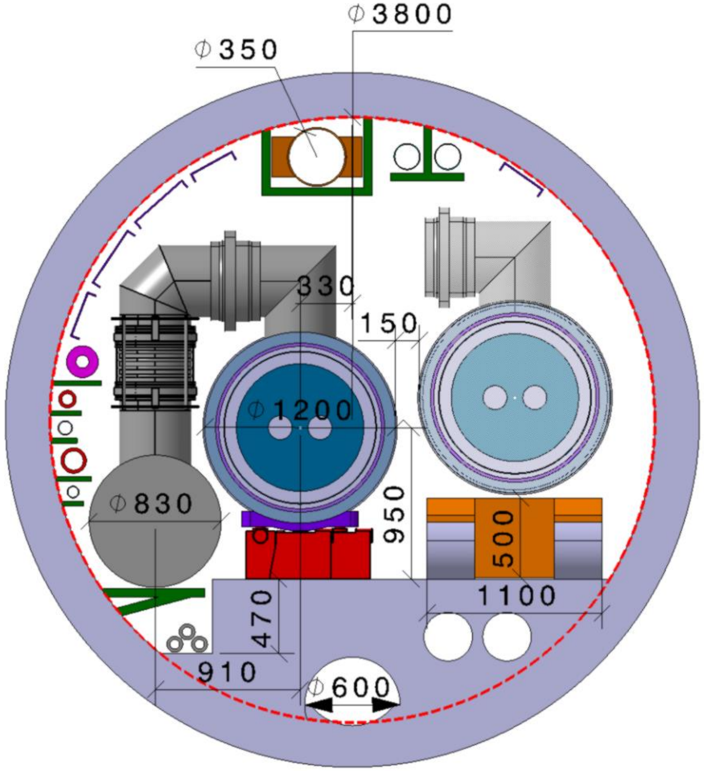
M. Benedikt, L. Bottura

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 & experiments
- **maximum magnet cryostat diameter ~1200 mm**
- **maximum QRL diameter ~830 mm**



integration and design strategy:

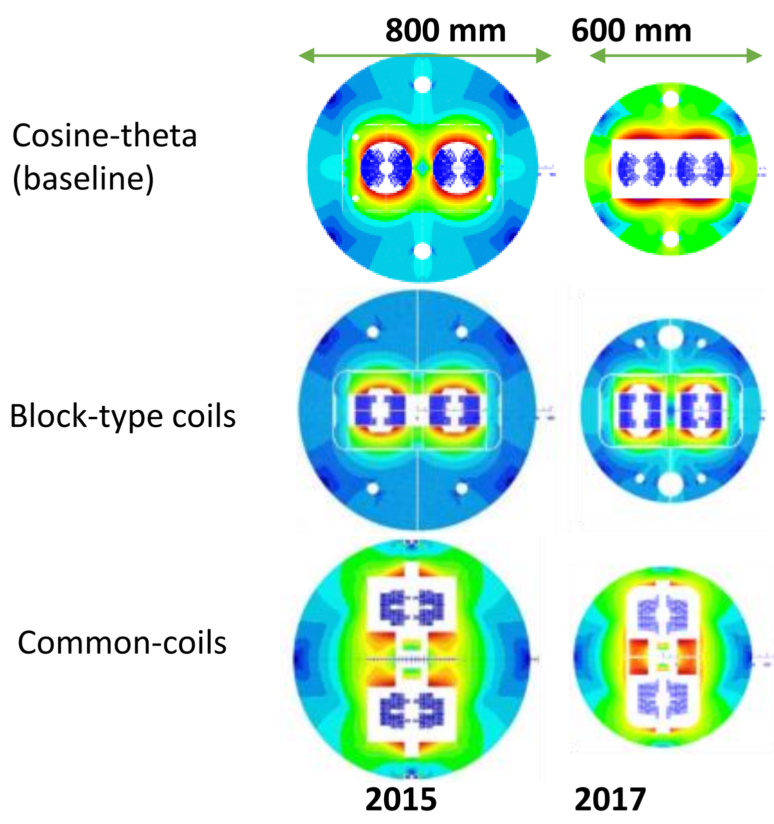
- development of optimized 16 T magnet, compatible with HE LHC requirements
- new cryogenic layout to limit QRL dimension

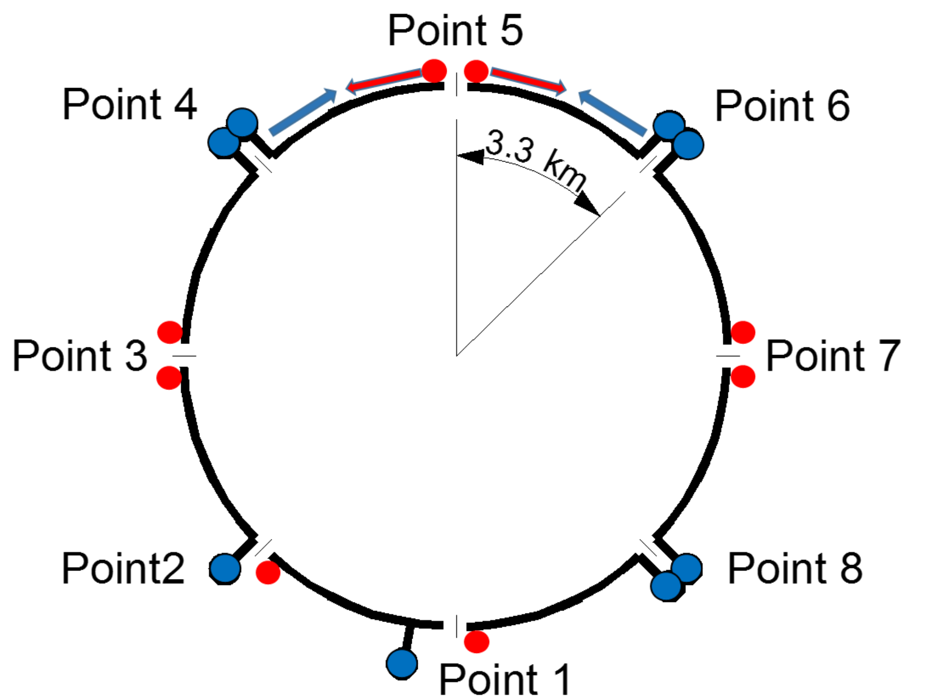
V. Mertens, M. Benedikt

16 T dipole design evolution

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

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

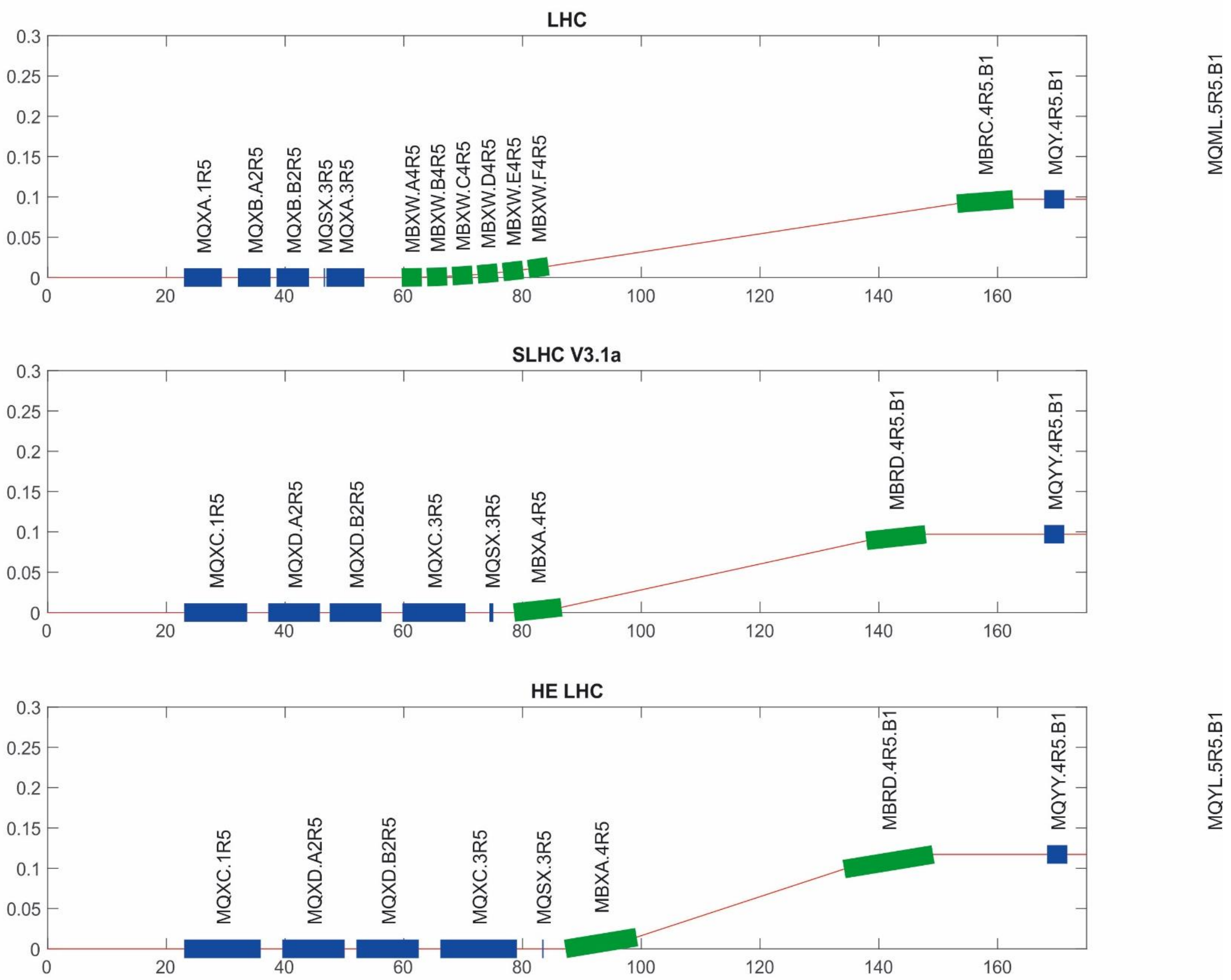




higher heat load and integration limitations:

- 8 additional 1.8 K refrigeration units wrt. LHC
- 8 new higher-power 4.5 K cryoplants

HE-LHC IR layout



triplet lengths:

LHC: 30.4 m

HL-LHC: 41. 8 m

HE-LHC: 56 m (13.5 TeV);

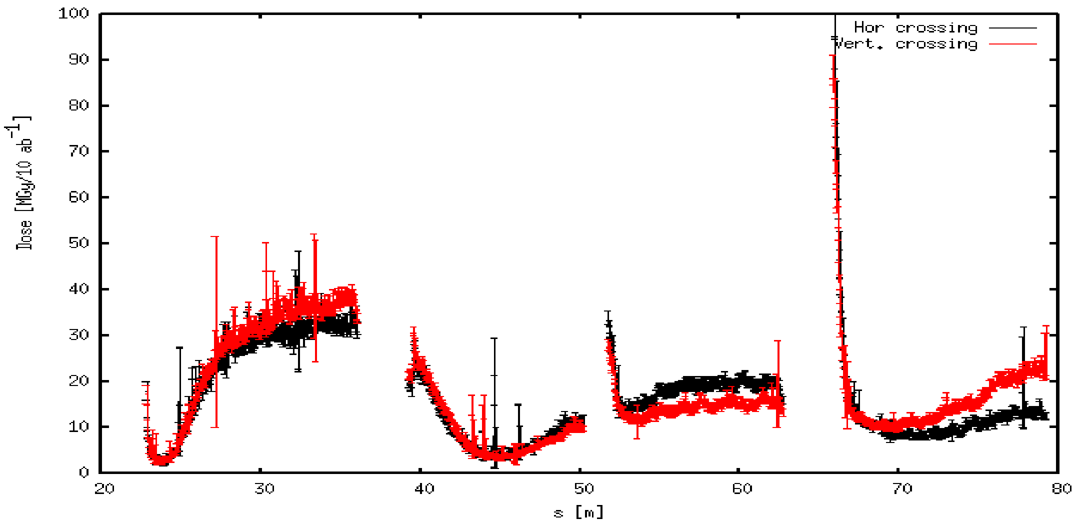
ca. 11 m for crab cavities

L. van Riesen Haupt

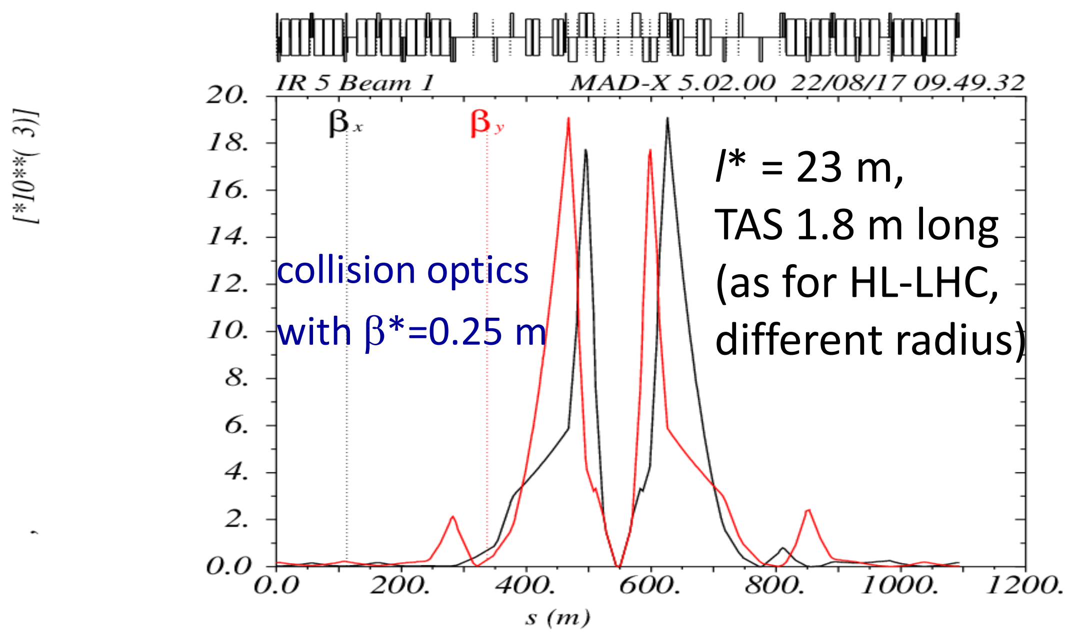
HE-LHC IR optics & triplet shielding

rriplet quadrupole design with 2 cm inner tungsten shielding

for 10 ab^{-1} integral luminosity: ~40 MGy peak dose (peak at Q3 can be reduced w addt'l shielding)



J. Abelleira



L. van Riesen Haupt

General optics design work ongoing for HE LHC with focus on: injection (energy), field quality, physical & dynamic aperture, protection

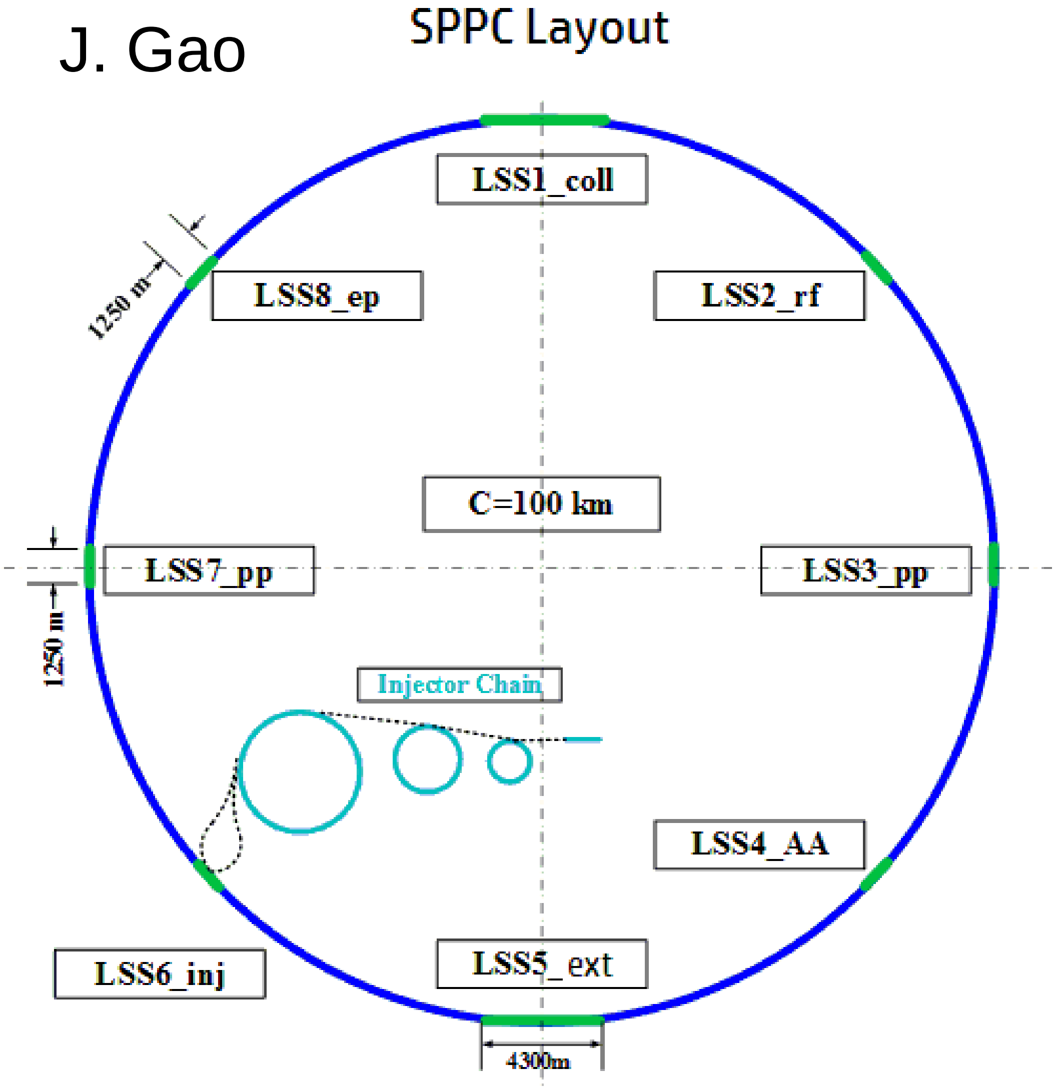
SPPC main parameters

Parameter	Unit	SPPC			FCC	
		PreCDR	"CDR"	"Ultimate"		
Circumference	km	54.4	100	100	100	
c.m. energy	TeV	70.6	75	125-150	100	
dipole field	T	20	12	20-24	16	
injection energy	TeV	2.1	2.1	4.2	3.3	
#IPs		2	2	2	2	
luminosity per IP	10^{35} cm^{-2}s^{-1}	1.2	1.0	-	0.5	3.0
norm. emittance	μm	4.1	2.4	?	2.2 (0.44)	
IP beta function	m	0.75	0.75	-	1.1	0.3
beam current	A	1.0	0.7	-	0.5	
bunch separation	ns	25	25	-	25 (5)	25 (5)
bunch population	10^{11}	2.0	1.5	-	1.0 (0.2)	1.0 (0.2
SR power /beam	MW	2.1	1.1	-	2.5	
SR heat load/ap	W/m	45	13	-	30	

J. Tang

SppC layout 2017

J. Gao



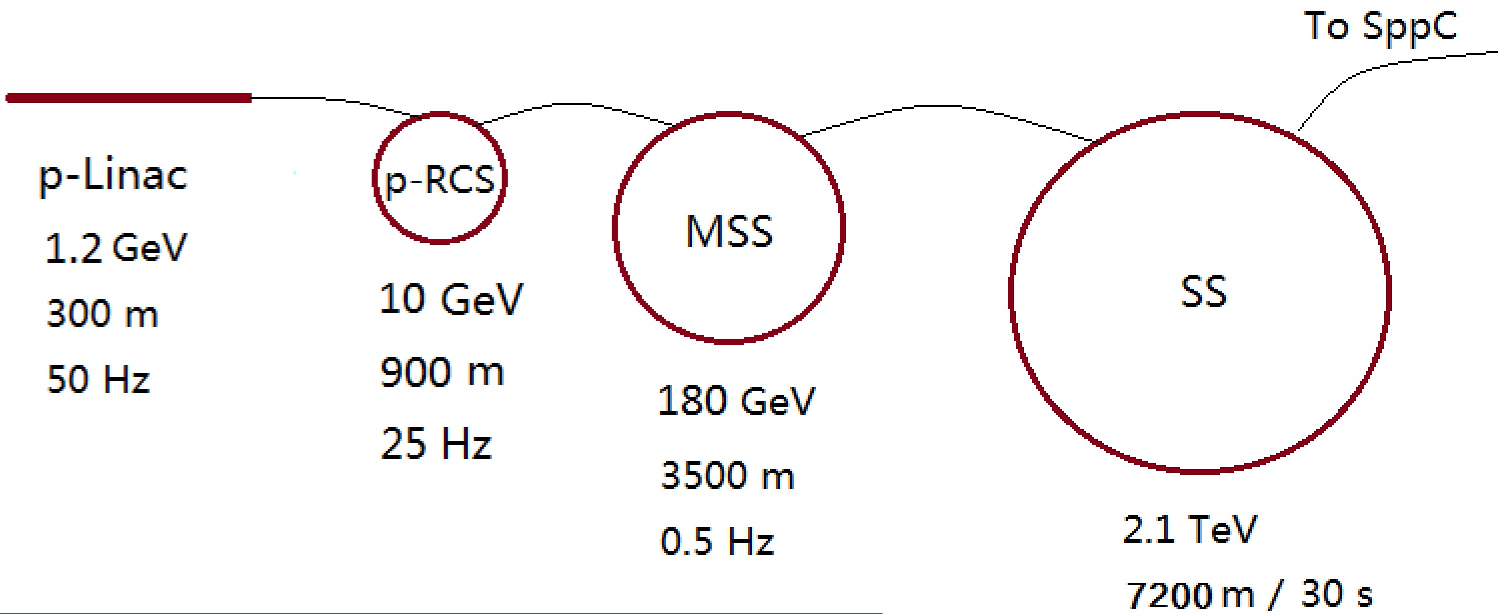
circumference: 100 km

- coexistence ee, pp, ep
- two high-luminosity pp experiments
- two other experiments for AA & ep
- one (combined) collimation insertion
- one RF insertion
- extraction insertion
- injection insertion
- greenfield injector chain

J. Gao, X. Lou, J. Tang

SppC injector chain

J. Gao



p-Linac: proton superconducting linac

p-RCS: proton rapid cycling synchrotron

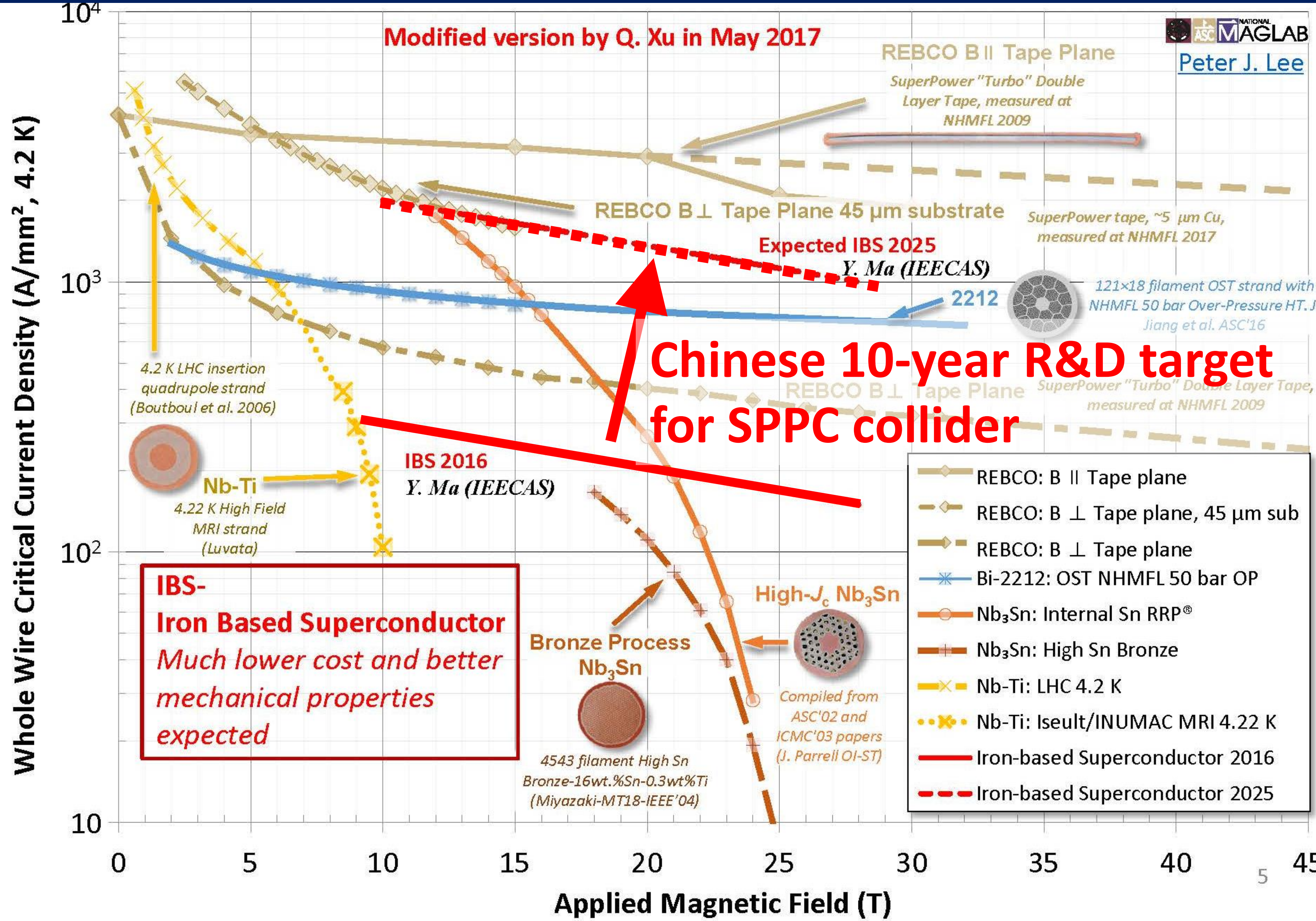
MSS: Medium-Stage Synchrotron

SS: Super Synchrotron

ion beams: dedicated linac (I-Linac) and RCS (I-RCS)

SppC: wire from Fe-based HTS*

*discovered at TIT/Japan in 2008



SppC: China-Domestic Collaboration on HTS

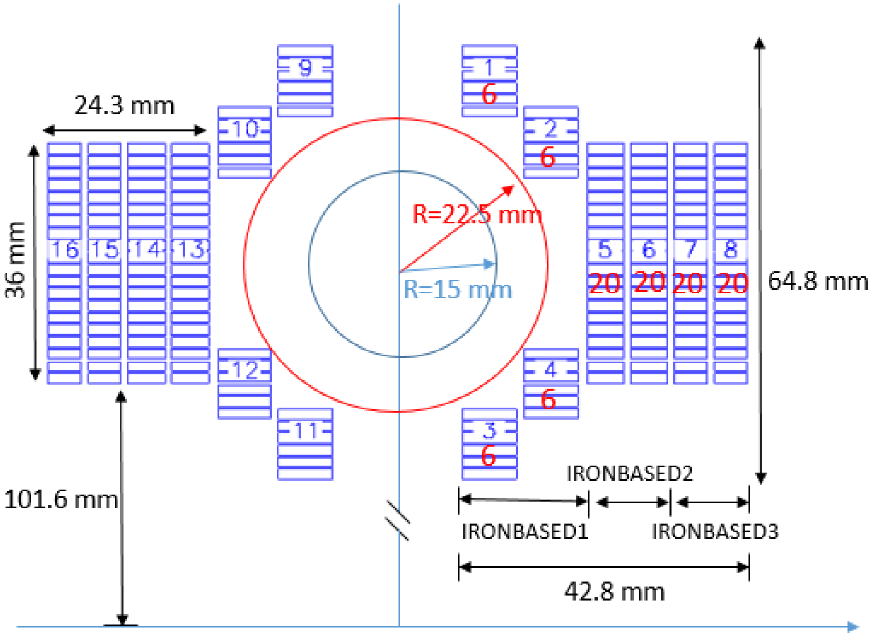
In October 2016, A consortium for High-temperature superconducting materials, industrialization and applications was formed in China, with participation of major research and production institutions on HTS.

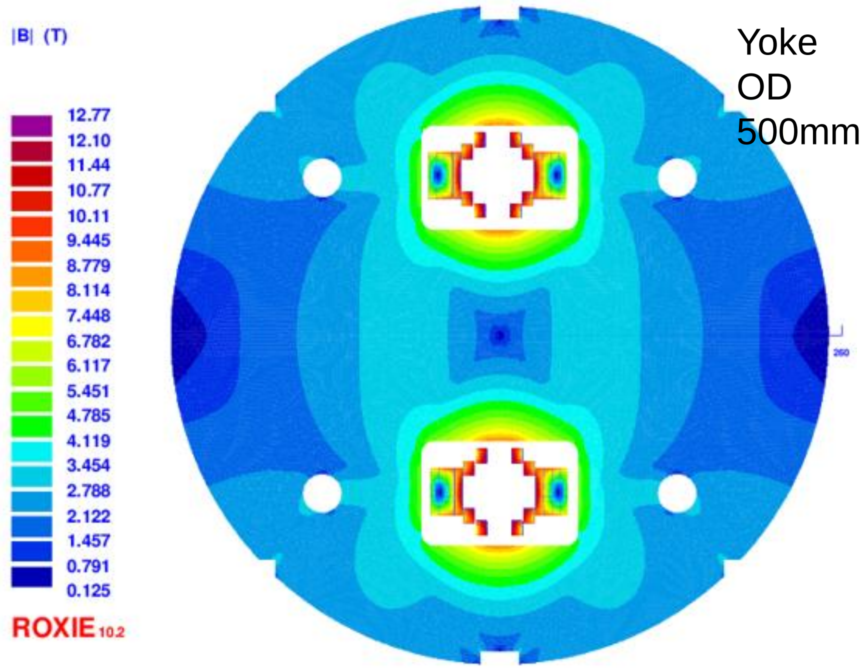
China is actually leading the development of Fe-HTS technology in the world; world-first 100-m Fe-HTS wire was made by CAS-Institute of Electrical Engineering in the last year .

J. Gao,
J. Tang,
Q. Xu

SppC Design of 12-T Fe-based Dipole Magnet

C. Wang, E. Kong (USTC), Q. Xu et al.





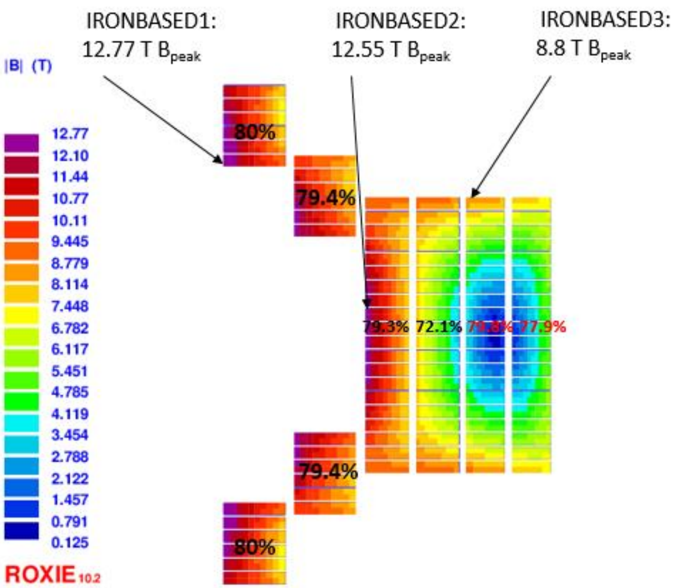


Table 1: Main parameters of the cables

Cable	Hight	Width-i	Width-o	Ns	Strand	Filament	Insulation
IRONBASED 1	8	1.5	1.5	20	IRON-BASED	FE-BASED	0.15
IRONBASED 2	5.6	1.5	1.5	14	IRON-BASED	FE-BASED	0.15
IRONBASED 3	5	1.5	1.5	12	IRON-BASED	FE-BASED	0.15

Table 2: Main parameters of the strand

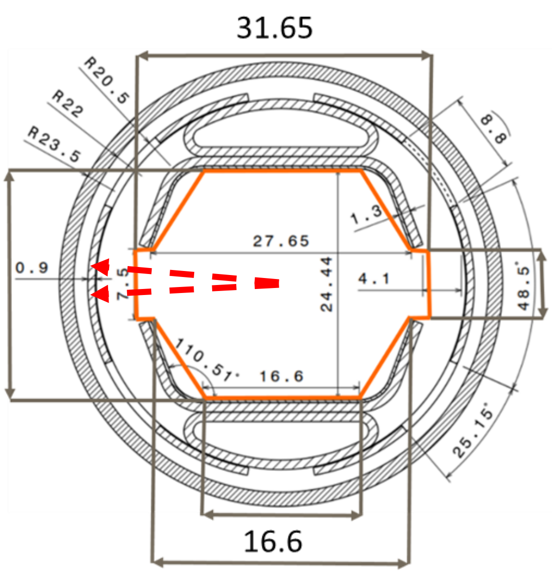
Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IRON-BASED	0. 802	1	200	4. 2	10	4000	111

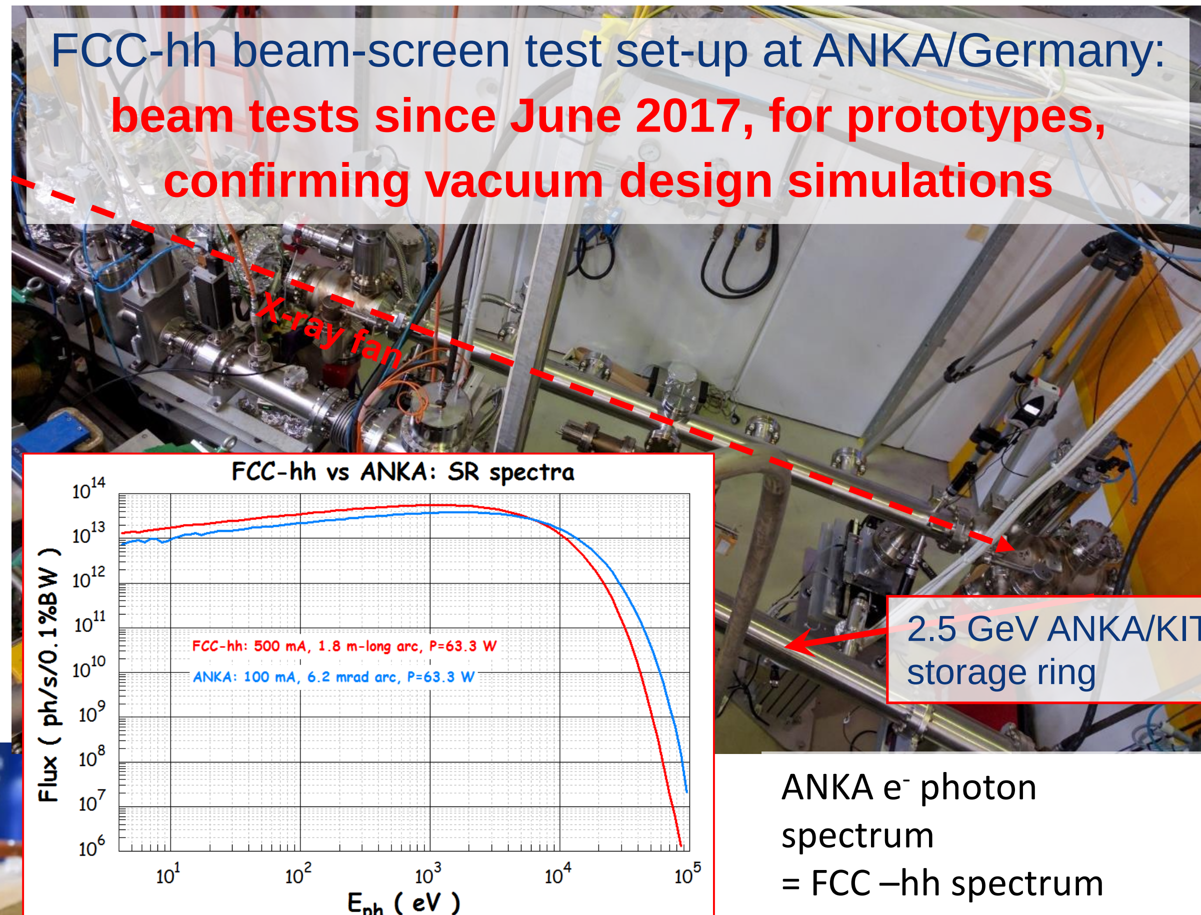
One meter of such magnet requires iron-based HTS strand length of 6.08 km

FCC-hh cryogenic beam vacuum system

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

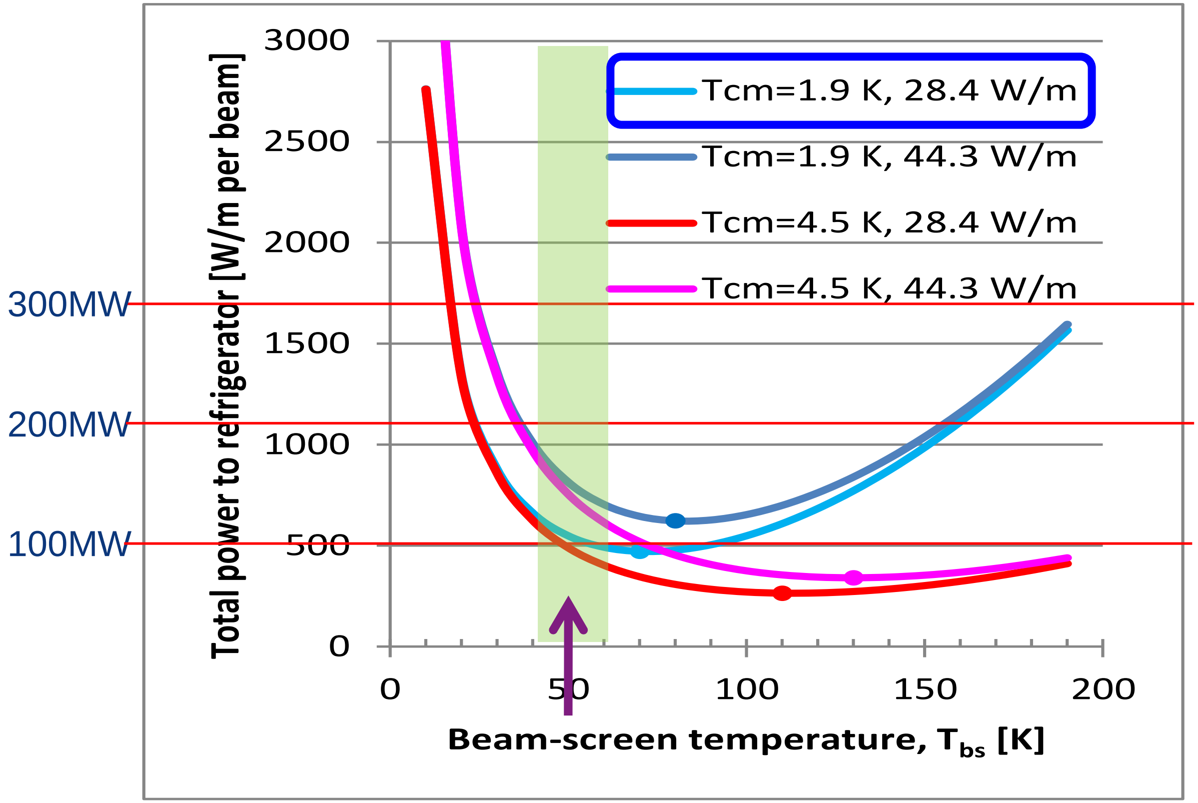
- **absorption of synchrotron radiation at higher temperature (> 1.8 K)** for cryogenic efficiency
- provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.





ANKA e⁻ photon spectrum
= FCC –hh spectrum

FCC-hh cryoplants – energy efficiency



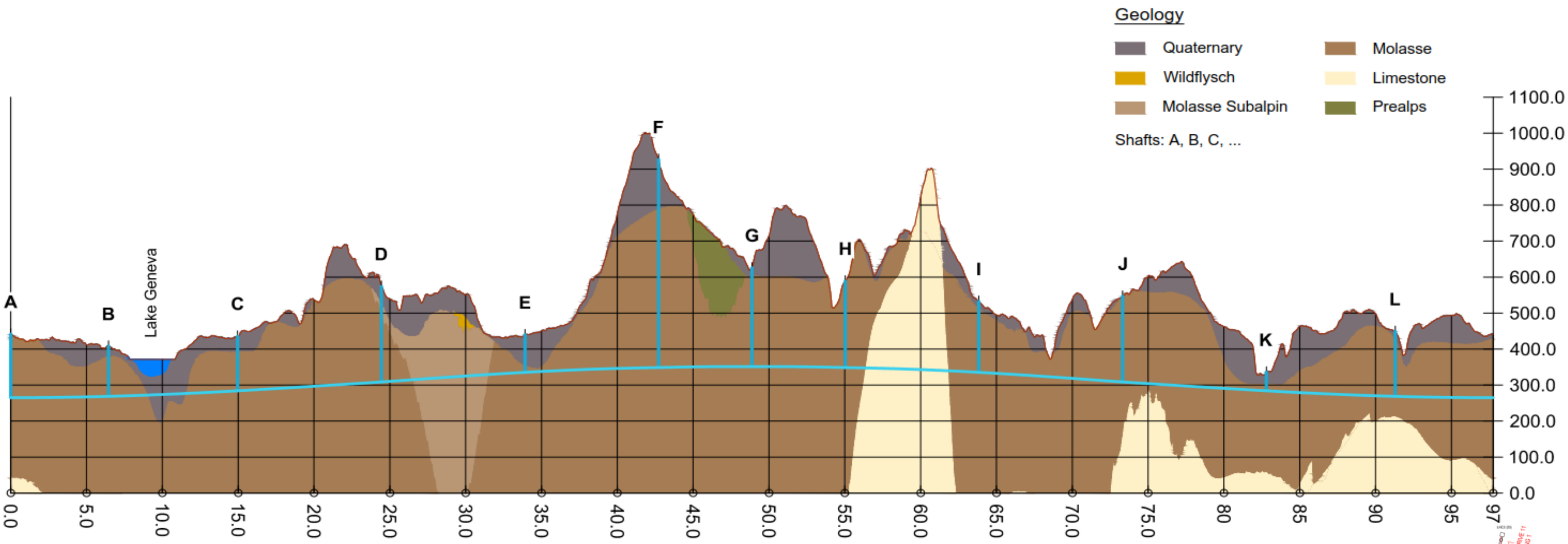
BS temperature choice through overall optimisation:

- cryoplant power consumption
- vacuum system performance
- impedance and beam stability

L. Tavian, P. Lebrun

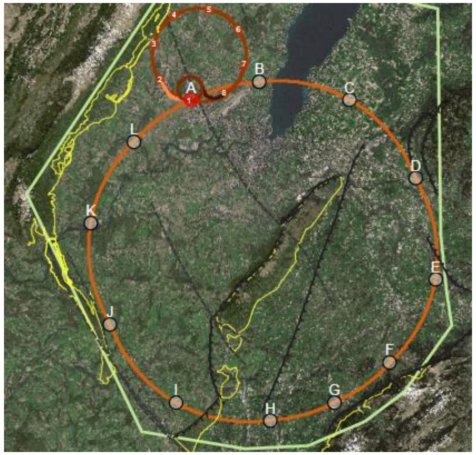
- **optimum beam screen operation temperature 40 - 60 K**
- **electrical power for beam screen cooling ~100 MW .**

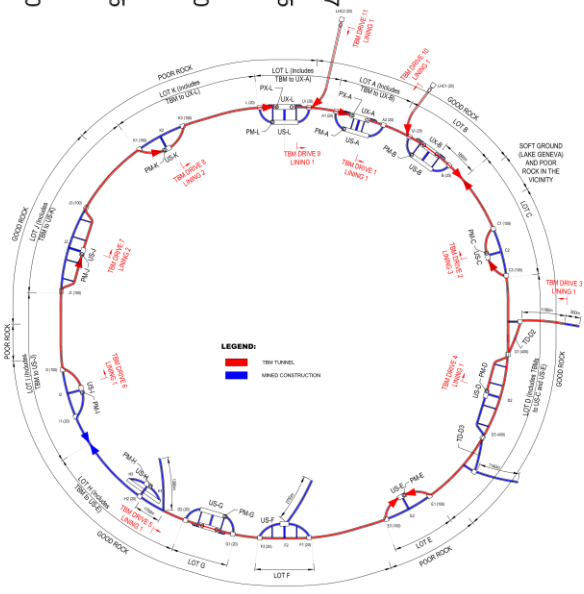
FCC implementation - footprint baseline



present baseline position established considering:

- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

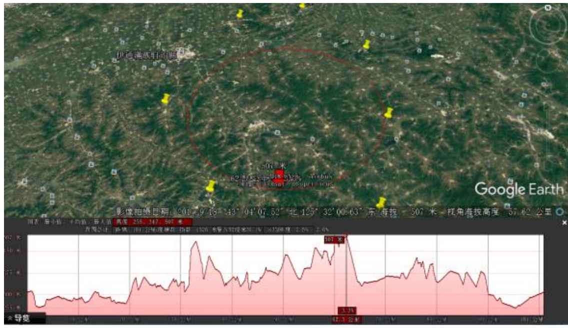




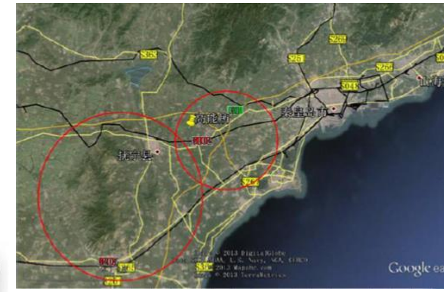
next step: review of surface site locations and machine layout

J. Osborne, J. Stanyard

CEPC Site Selections



6



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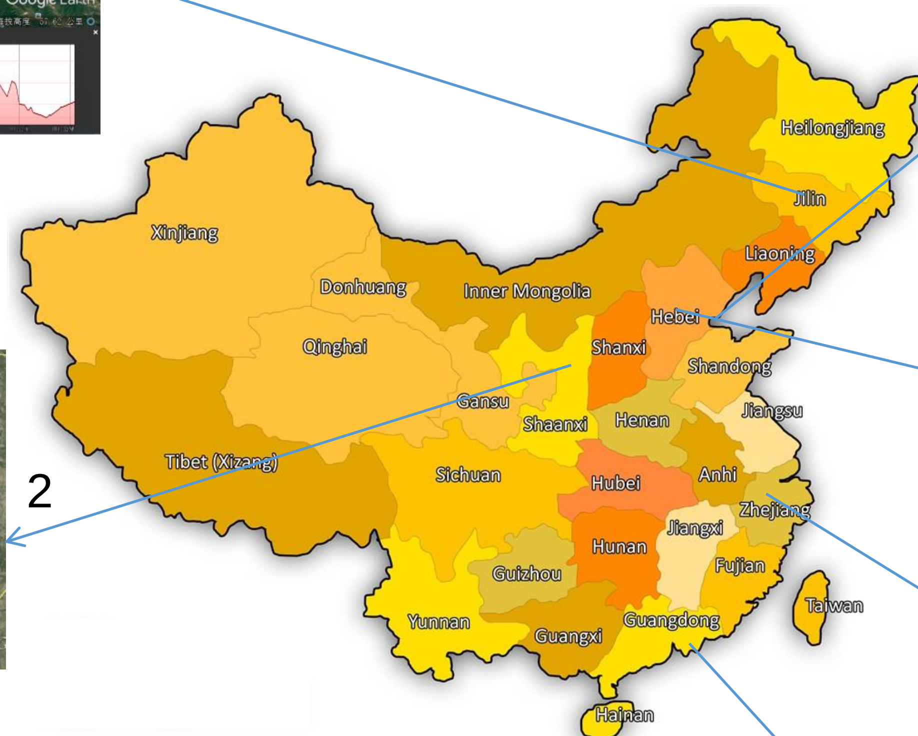

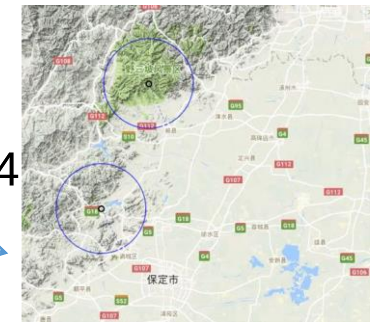

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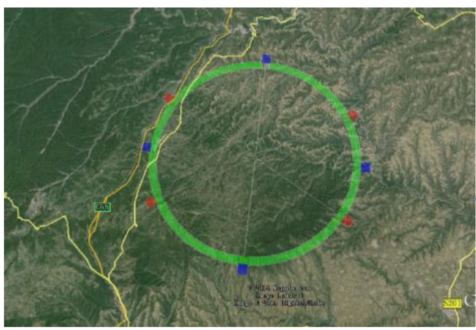

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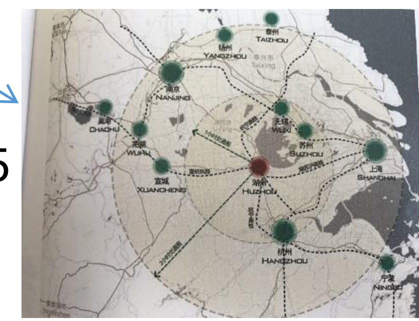


5

3

1) Qinhuangdao, Hebei Province（Completed in 2014）

2) Huangling, Shanxi Province（Completed in 2017)

3) Shenshan, Guangdong Province(Completed in 2016)

4) Baoding (Xiong an), Hebei Province (Started in August 2017)

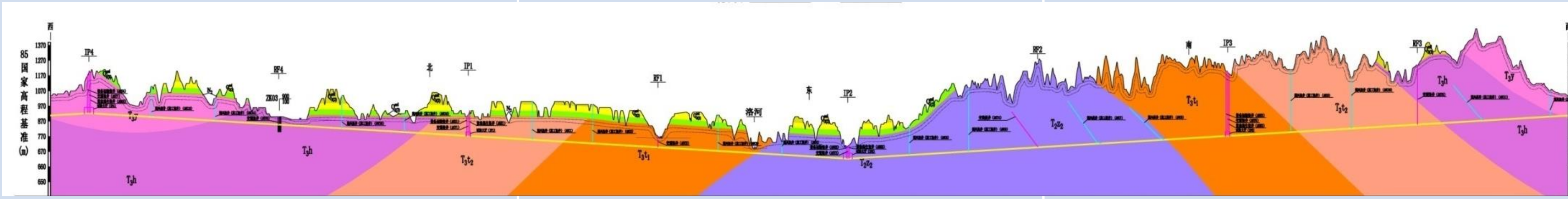
5) Huzhou, Zhejiang Province (Started in March 2018)

6) Chuangchun, Jilin Province (Started in May 2018)

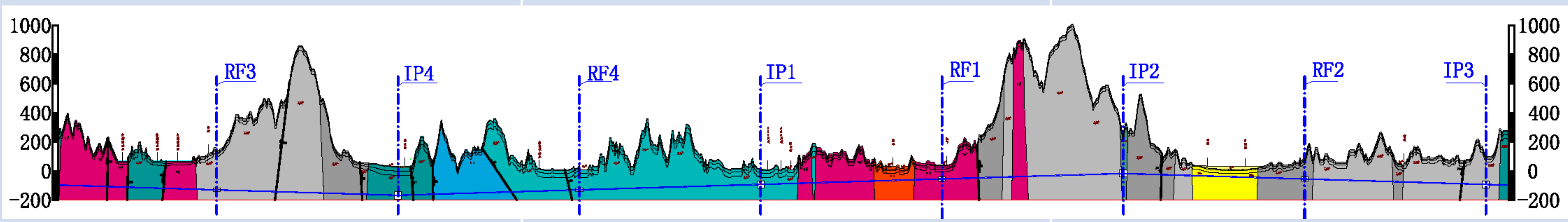
J. Gao

<table>
<tr><th>Item</th><th>Huangling</th><th>Shenshan</th><th>Funing</th></tr>
<tr><td>Project layout</td><td colspan="3">

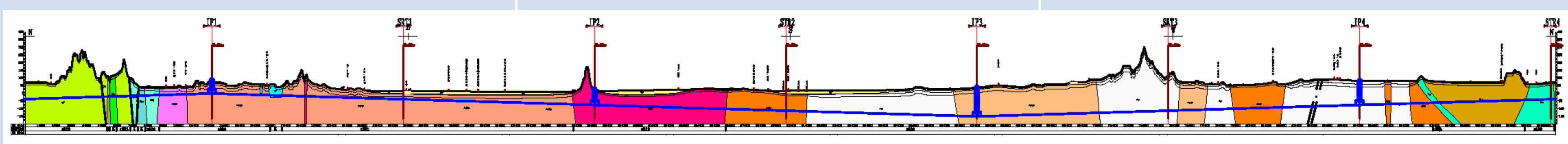
Huangling (100 km)



Shenshan (100 km)



Funing (100 km)



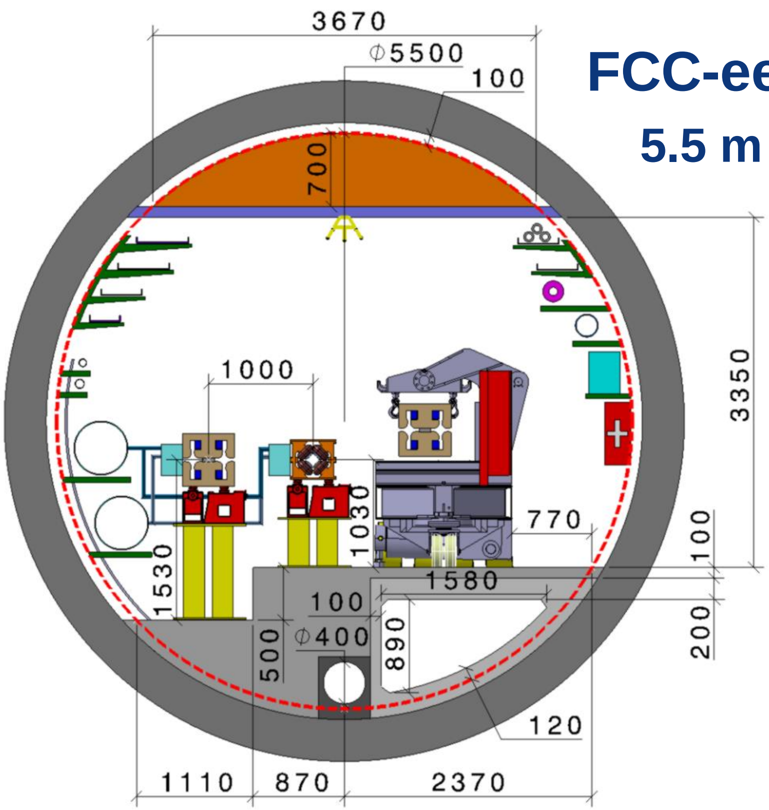
</td></tr>
<tr><td>Construction difficulty</td><td>Moderate</td><td>Relatively difficult</td><td>Relatively easy</td></tr>
</table>

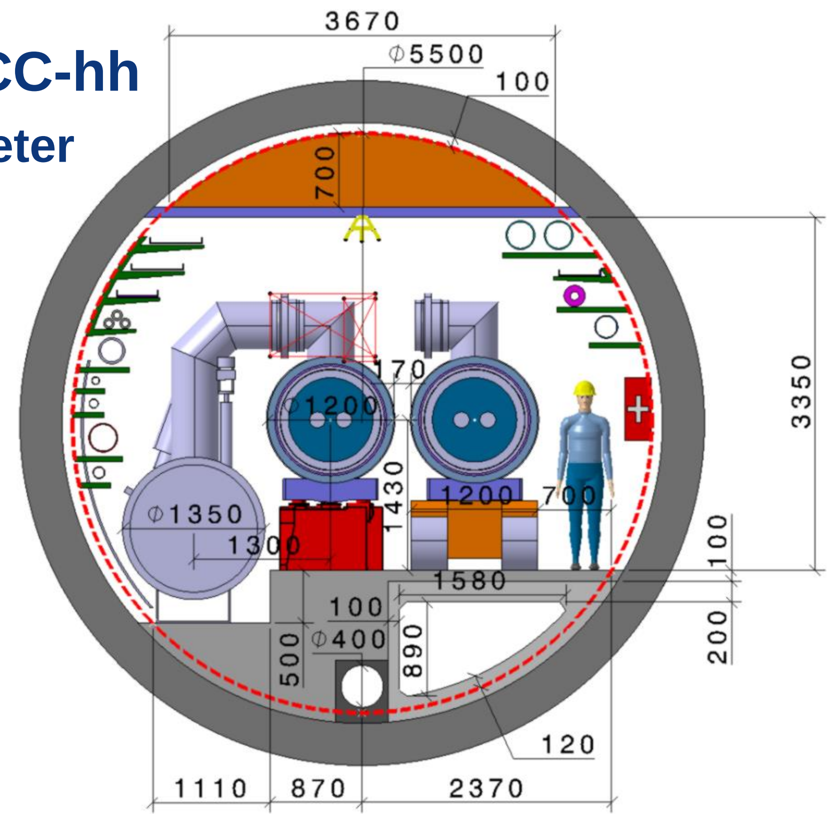
X. Lou

FCC – tunnel integration in arcs

FCC-ee **FCC-hh**

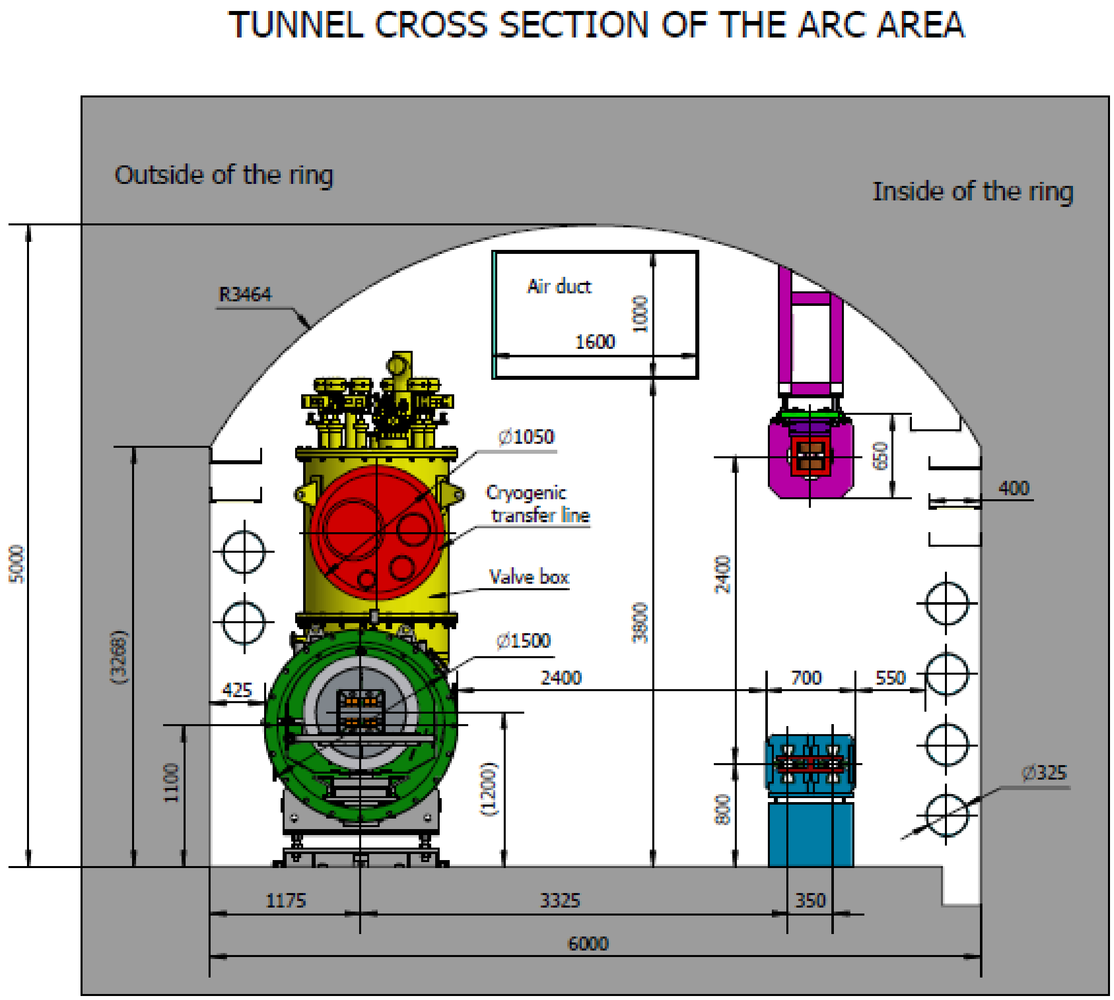
5.5 m inner diameter





V. Mertens

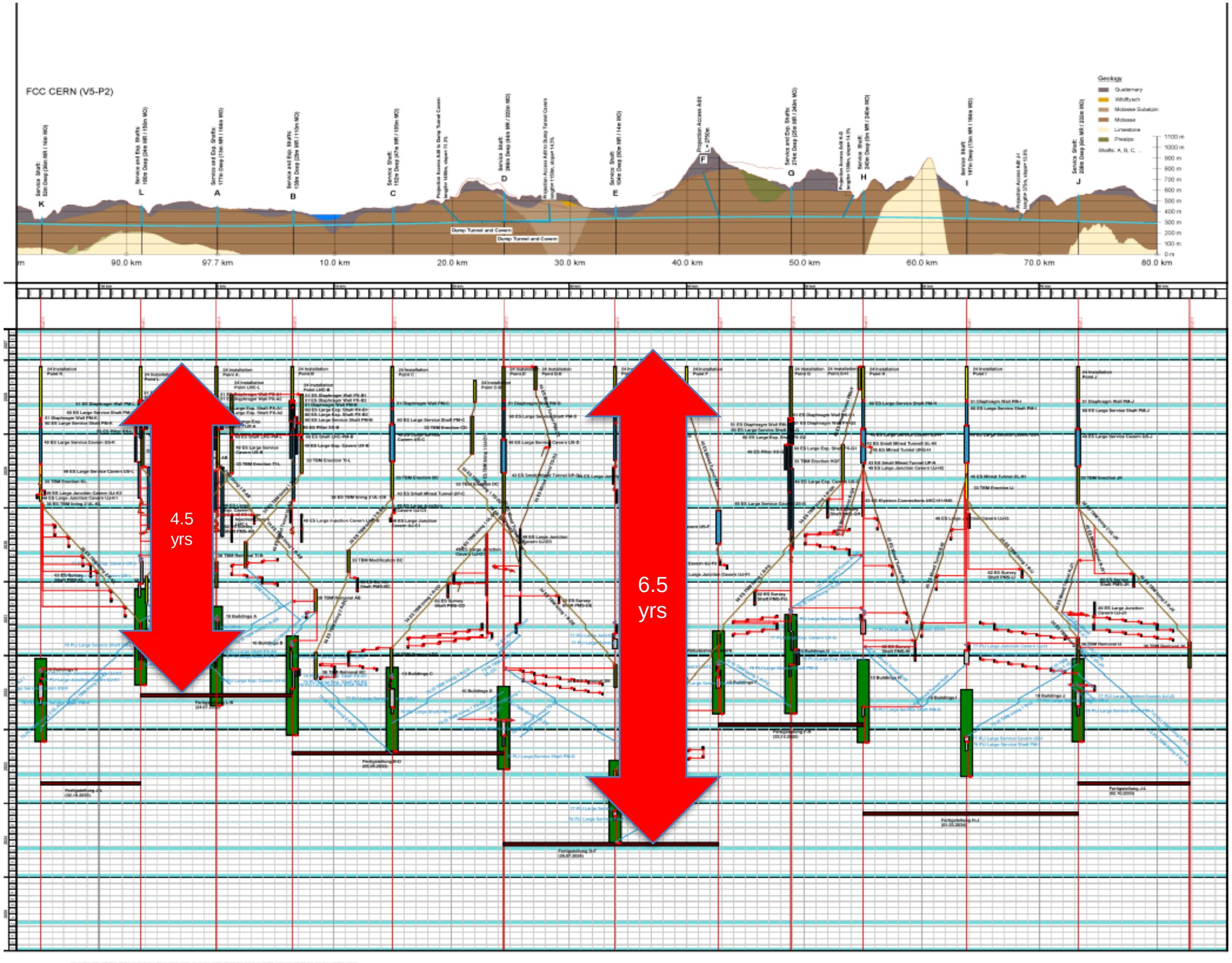
CEPC/SppC – tunnel integration in arcs



6.0 m width, hosting 5 rings simulatenously

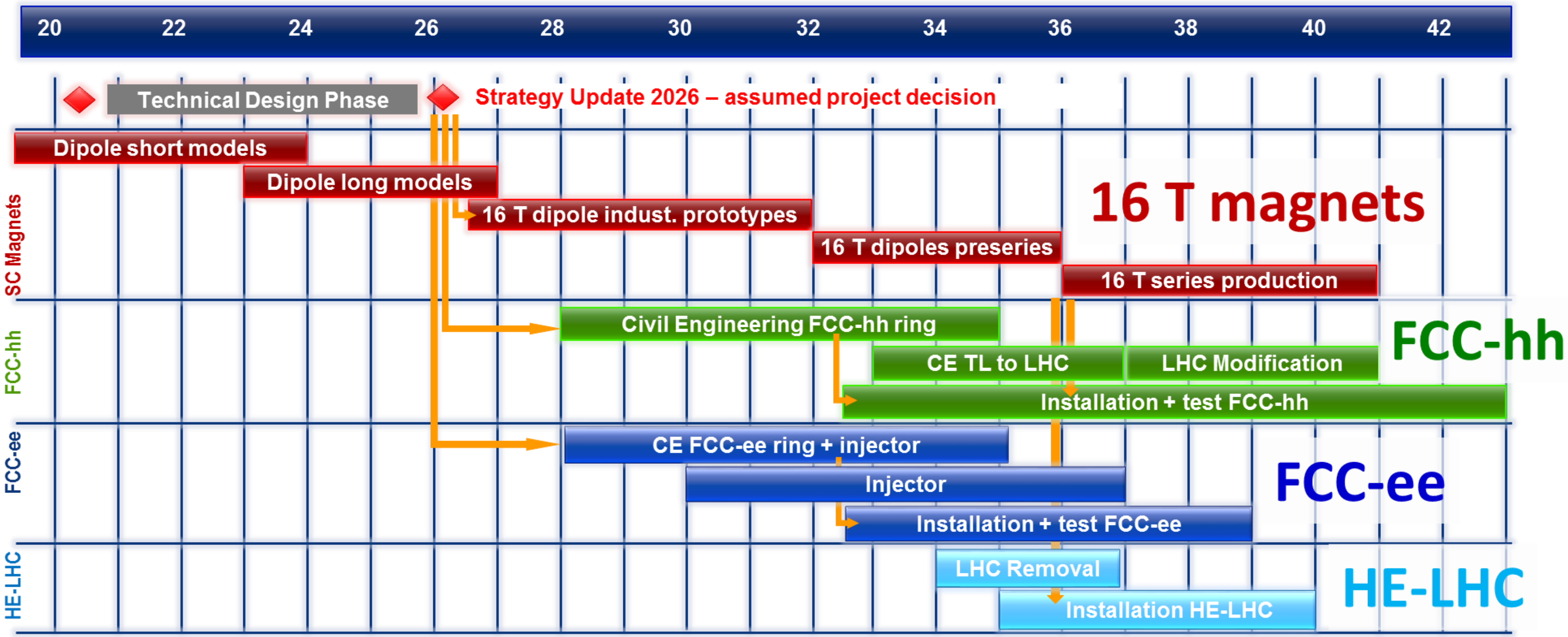
J. Gao

CE schedule studies



- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

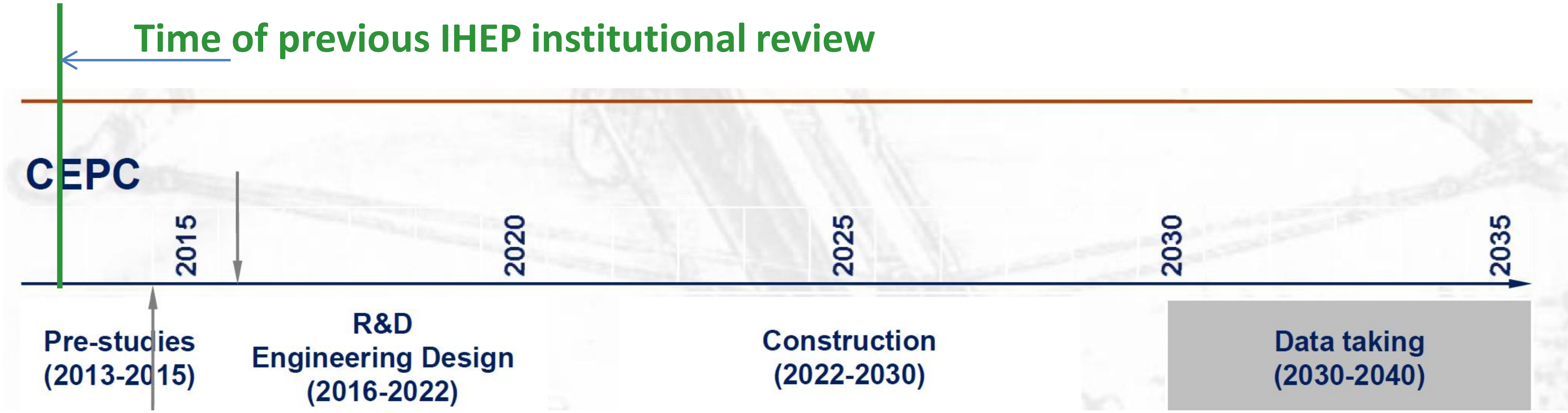
technical schedule for each of three options



schedule constrained by 16 T magnets & CE
→ earliest possible beam operation dates

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

CEPC Schedule (ideal)



design issues
R&D items
Pre-CDR

design, funding
R&D program
intl. collaboration
site study

seek approval, site decision
construction during 14th 5-year plan
commissioning

- CEPC data-taking starts before the LHC program ends around 2035
- earlier than the FCC(hh, ee)
- possibly concurrent, but advantageous and complementary to ILC

X. Lou

Global FCC Collaboration

124 Institutes

30 Companies

32 Countries

FCC Collaboration Status

123 collaboration members & CERN as host institute, April 2018

AIBU, Bolu,Turkey
Ankara U., Turkey
Aristode U Thessaloniki, Greece
Athens U., Greece
Austrian Inst. of Tech., Vienna, Austria
Basel U., Switzerland
Belgrade U., Serbia
Bern U., Switzerland
BINP, Novosibirsk, Russia
Birmingham U., UK
BUAP Universidad, Puebla, Mexico
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CELLS/ALBA, Cerdanyola del Vallès, Spain
CIEMAT, Madrid,Spain
CINVESTAV, Mexico
CSIC, Madrid, Spain
CSIL, Milan, Italy
CNRS, Paris, France
CNR-SPIN, Genova, Italy
Cockcroft Institute, Daresbury, UK
Colima U., Mexico
UCPH Copenhagen, Denmark
CUNI, Prague, Czech Republic
TU Darmstadt, Germany
TU Delft, Netherlands
TU Dortmund, Germany
DOE, Washington, USA
TU Dresden, Germany
Duke U, Durham, USA
EPFL, Lausanne, Switzerland
UT Enschede, Netherlands
ESS, Lund, Sweden
ETHZ, Switzerland
FNAL, Batavia, USA
Fraunhofer, Dortmund, Germany
Genoa U., Genoa, Italy
Geneva U., Switzerland
Giresun U., Turkey
Goethe U. Frankfurt, Germany
GSI, Darmstadt, Germany
GWNU, Gangneung, South Korea
Guanajuato U., Mexico
Hellenic Open U., Patra, Greece
HEPHY, Vienna, Austria
Houston U., USA
ICMAB-CSIC, Bellatera, Spain
IFIC-CSIC, Paterna, Spain
IIT Kanpur, India
IFAE, Bellaterra, Spain
IFJ PAN Krakow, Poland
INFN, Frascati/Rome, Italy
INP Minsk, Belarus
DESY, Hamburg, Germany
Iowa U., USA
IPM Tehran, Iran
Irvine UC, USA
Isik U., Sile, Turkey
Istanbul U., Turkey
Istanbul Aydin U., Turkey
JAI, Oxford, UK
JINR Dubna, Russia
Jefferson LAB, Newport News, USA
FZ Jülich, Germany
KAIST, Yuseong gu, South Korea
KEK, Ibaraki, Japan
KIAS, Seoul, South Korea
King's College London, UK
KIT Karlsruhe, Germany
KU Leuven, Belgium
KU, Seoul, South Korea
Korea U. Sejong, South Korea
Lancaster U., UK
LAPP, Annecy, France
Liverpool U., UK
Lund U., Sweden
Malta U, Malta
MAX IV, Lund, Sweden

FCC Collaboration Status

123 collaboration members & CERN as host institute, April 2018

Melbourne U, Australia
MEPhI, Moscow, Russia
Michigan U, Ann Arbor, USA
MINES ParisTech, Paris, France
MISiS, Moscow, Russia
MIT, Cambridge, USA
Naturhistorisches Museum, Vienna, Austria
NIKHEF, Netherlands
Northern Illinois U., Dekalb, USA
NC PHEP Minsk, Belarus
Okan U., Istanbul, Turkey
Oxford U., UK
Patras U, Greece
Piri Reis, Istanbul, Turkey
PSI, Villigen, Switzerland
Rostock U., Germany
RTU, Riga, Latvia
Santa Barbara UC, USA
Sapienza/Rome, Italy
SFTC, Daresbury, UK
Siegen U., Germany
Silesia U., Katowice, Poland
SINP MSU, Moscow, Russia
Stanford U., USA
Stuttgart U., Germany

Tel Aviv U., Israel
TOBB ETU, Ankara, Turkey
TU Bergakademie Freiberg, Germany
TU Tampere, Finland
TU Vienna, Austria
UAS TW, Austria
ULUDAG, Turkey
UNICAL, Cosenza, Italy
UNIMAN, Manchester, UK
UNIMI, Milan, Italy
UNIROMA3, Rome, Italy
UPC, Barcelona, Spain
URJC, Spain
USASK & CLS, Canada
UTOKYO, Tokyo, Japan
Wigner RCP, Budapest, Hungary
Wroclaw UT, Poland
Wirtschaftsuniversität Wien, Austria

Uzbekistan missing !?

EU H2020 Design Study EuroCirCol

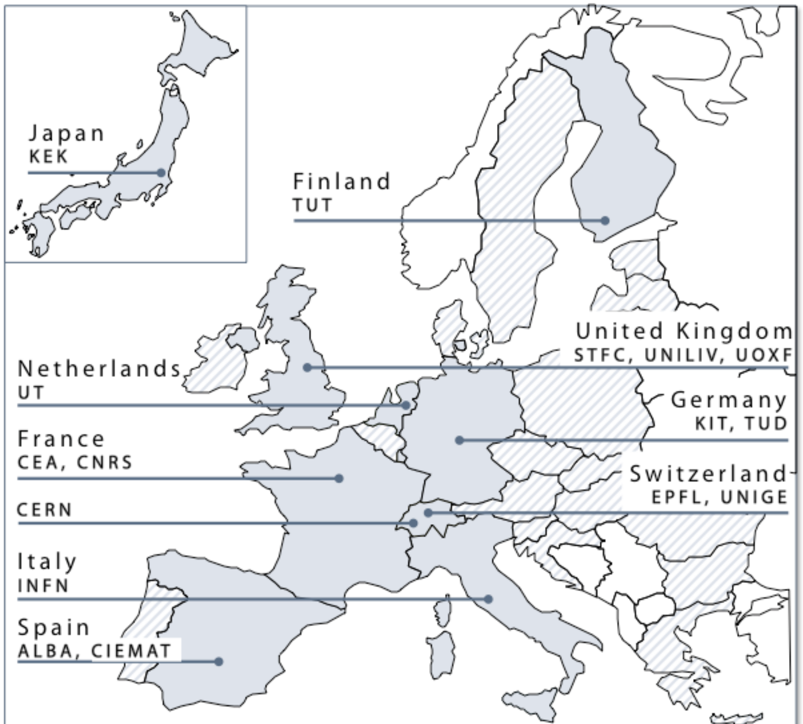
UNIVERSITY OF TWENTE. INFN TAMPERE UNIVERSITY OF TECHNOLOGY EuroCirCol

cea

cnrs dépasser les frontières

CERN

UNIVERSITY OF OXFORD



EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

TECHNISCHE UNIVERSITÄT DARMSTADT

KIT Karlsruher Institut für Technologie

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

UNIVERSITÉ DE GENÈVE

ALBA

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

MANCHESTER 1824

European Union Horizon 2020 program

- Support for FCC-hh study
- 3 MEURO co-funding
- Started June 2015, ends in May 2019

Scope:

FCC-hh collider

- Optics Design (arc and IR)
- Cryogenic beam vacuum system design including beam tests at ANKA
- 16 T dipole design, construction folder for demonstrator magnets

EASITrain Marie Curie Training Network

European Advanced Superconductivity Innovation and Training Network

➢ **selected for funding by EC in May 2017, started 1 October 2017**

- SC wires at low temperatures for magnets (Nb_3Sn, MgB_2, HTS)
- Superconducting thin films for RF and beam screen (Nb_3Sn, Tl)
- Electrohydraulic forming for RF structures
- Turbocompressor for Nelium refrigeration
- Magnet cooling architectures

Horizon 2020 program

Funding for 15 Early Stage Researchers over 3 years & training

13 Beneficiaries

BRUKER, cea, Columbus Superconductors, HZB Helmholtz Zentrum Berlin, SPIN, Universität Stuttgart, INFN, Technische Universität Dresden, TU Wien Technische Universität Wien, Universität Siegen, WU, I-CUBE, CERN

12 Partners

Bmax, ASG Superconductors, Bilfinger Babcock Noell GmbH, CemeCon The Tool Coating, IEEE Advancing Technology for Humanity, Criotec Impianti S.r.l., MAN Diesel & Turbo, Terra Mater Factual Studios, Red Bull Media House, research instruments, Sigmaphi, Università degli Studi di Genova, Air Liquide

J. Gutleber

FCC Planning – CDR Production

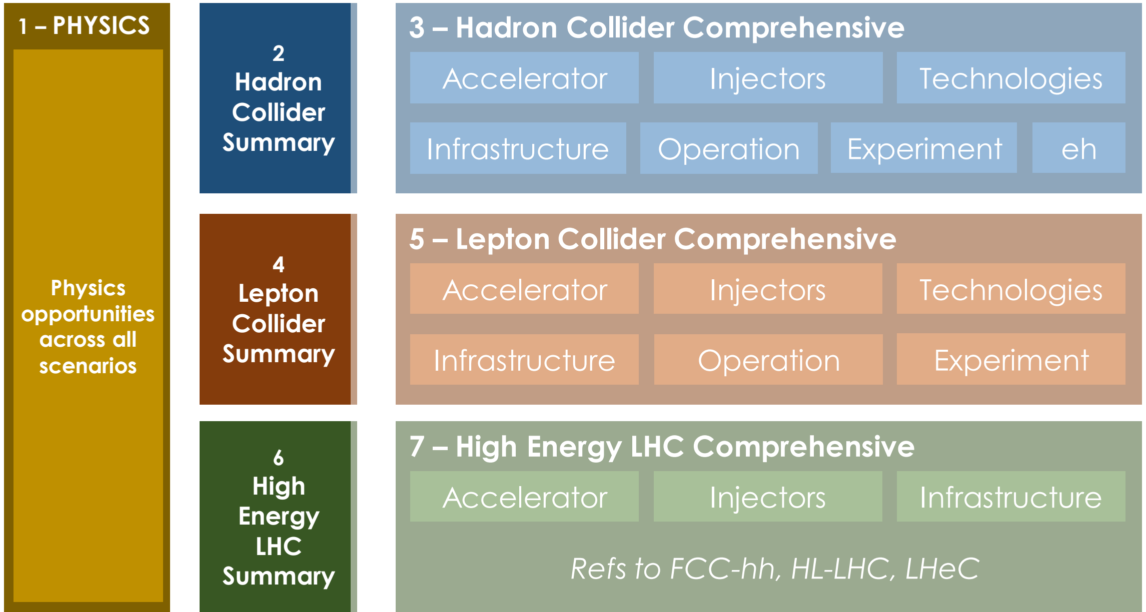
CDR Concise summary volumes 1 (PH), 2 (hh), 4 (ee), 6 (HE):

- **Completion of design work, coherent and consistent; contents for concise volumes by end June 2018**
- **Overall final editing July – August 2018; Proof reading and approval September – October**
- **“Print-ready” versions by November 2018**

CDR long technical volumes 3, 5, 7:

- **Collection of input (from status June 2018) during July – October 2018.**
- **Overall volume editing November 2018 – January 2019; Proof reading and approval February – March 201**

Cost study based on CDR status (June 2018), other documents for ESU, June - November 2018



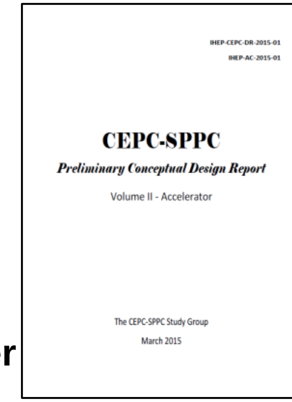
M. Benedikt

CEPC Accelerator from Pre-CDR to CDR

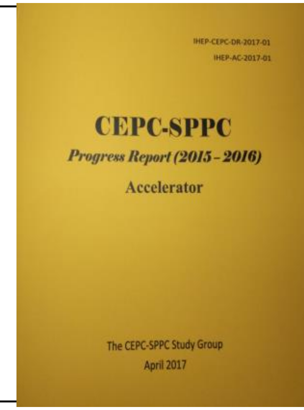
J. Gao

CEPC accelerator CDR completed in June 2018 (released on Spet. 2 2018)

- **Executive Summary**
  1. **Introduction**
  2. **Machine Layout and Performance**
  3. **Operation Scenarios**
  4. **CEPC Collider**
  5. **CEPC Booster**
  6. **CEPC Linac**
  7. **Systems Common to the CEPC Linac, Booster and Collider**
  8. **Super Proton Proton Collider**
  9. **Conventional Facilities**
  10. **Environment, Health and Safety**
  11. **R&D Program**
  12. **Project Plan, Cost and Schedule**
- Appendix 1: CEPC Parameter List
- Appendix 2: CEPC Technical Component List
- Appendix 3: CEPC Electric Power Requirement
- Appendix 4: Advanced Partial Double Ring
- Appendix 5: CEPC Injector Based on Plasma Wakefield Accelerator
- Appendix 6: Operation as a High Intensity γ-ray Source
- Appendix 7: Operation for e-p, e-A and Heavy Ion Collision
- Appendix 8: Opportunities for Polarization in the CEPC
- Appendix 9: International Review Report

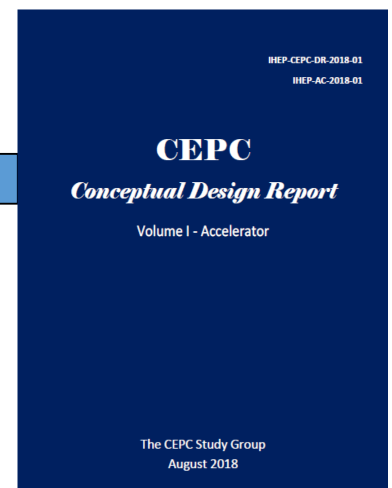


March 2015



April 2017

Draft CDR for Mini International Review in Nov. 2017



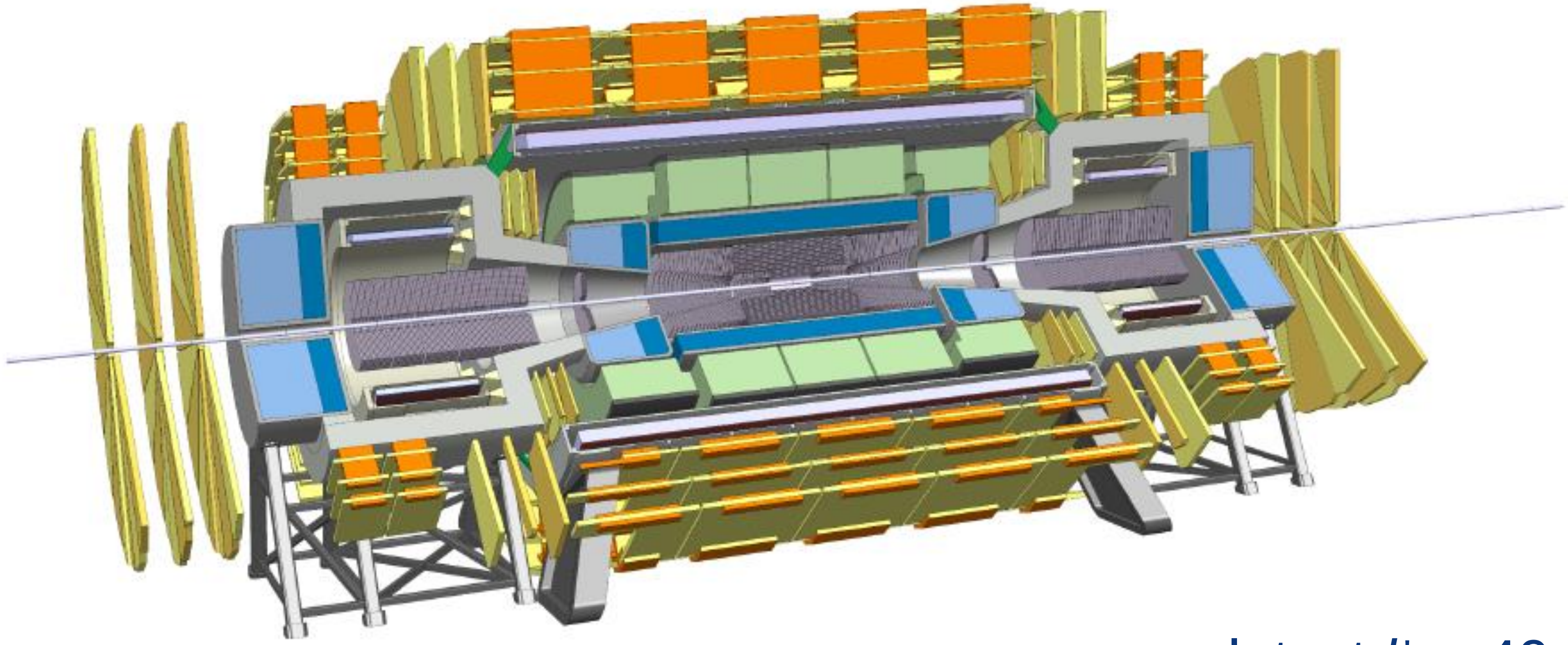
CDR International Reviewed June 28-30, 2018, final CDR (accelerator) released on Sept. 2, 2018

CEPC Path to Realization

- **Science & Technology is strongly supported** by the present central government ➔ it also is a "requirement" for local governments (difference seen in Beijing & Shanghai since 2016)
- not difficult to find **local support for the site**
- **in March 2018** State Council announced "**Implementation method to support China-initiated large international science projects and plans**"
  - science of matter, evolution of the universe, life science, earth, energy, …
  - goal:
    - **up to 2020, 3-5 preparatory projects; 1-2 construction projects**
    - **up to 2035, 6-10 preparatory projects; ? construction projects**
  - Ppossible competitors: ~ 50 ideas collected, fusion reactor, space program, brain program, investigation of the Qinghai-Tibet Plateau, CEPC, …
- CEPC/IHEP are working with MOST to be included in the roadmap planning, project selection, etc.

X. Lou

FCC-hh detector – reference design



latest l^* = 40 m

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

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

W. Riegler et al.

sketch of FCC-hh physics

FCC-hh is a HUGE discovery machine (if nature …), but not only

- Highest center of mass energy → a big step in high mass reach!
  ex: strongly coupled new particles up to >30 TeV
  Excited quarks, Z', W', up to ~tens of TeV
  Final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV ; Sensitivity to high energy phenomena in e.g. WW scattering

- HUGE production rates for single & multiple production of H,W,Z & quarks
  -- Higgs precision tests using ratios to e.g. γγ/μμ/ ττ/ZZ, ttH/ttZ @<% level
  -- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling λ_H at the few percent level
  -- detection of rare decays H→ Vγ (V= ρ,φ,J/ψ,ϒ,Z…)
  -- search for invisibles (DM searches, RH neutrinos in W decays)
  -- renewed interest for long lived (very weakly coupled) particles.
  -- rich top and HF physics program

- Cleaner signals for high Pt physics
  -- allows clean signals for channels presently difficult at LHC (e.g. H→ bb)

M. Magano et al., Physics at a 100 TeV pp collider: CERN Yellow Report (2017) no.3

example synergy of FCC-ee/hh/eh

HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume
SM or ee measurements
Ffor FCC-hh : H→ ZZ to serve as cross-normalization (well measured at FCC-ee)

for ttH, combination of ±4% (model dependent)HL-LHC with FCC-ee will lead to ttH coupling to ± 3%...
model independent!

for g_{HHH} investigating now : the possibility of reaching 5σ observation at FCC-ee:
4 detectors
+ recast of running scenario

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.22 %**	**< 1%** *	
WW	**0.47%**		
Γ_H	**1.6%**		
γγ	4.2%	**<1%**	
Zγ	--	**1%**	
ttH	13%	**1%**	
bb	**0.7%**		0.5%
ττ	**0.8%**		
cc	**0.7%**		1.8%
gg	**1.0%**		
μμ	8.6%	**1-2%**	
uu,dd	H→ ργ?	H→ ργ?	
ss	H→ φγ ?	H→ φγ ?	
ee	**ee → H**		
HH	40%	**~3-5%**	20%
inv, exo	<0.55%	**10^{-3}**	5%

A. Blondel, ICHEP2018

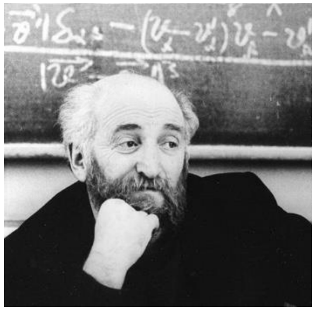
how to go further – beyond FCC-hh?

muon collider* is back !

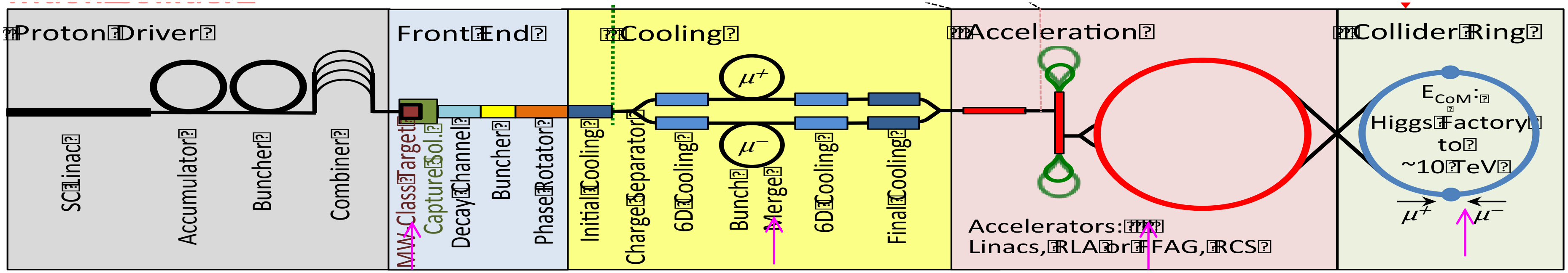
3 recent new ideas :

- LEMMA μ production by e^+ annihilation
- Gamma factory for e^+ generation
- full exploitation of FCC complex

*first proposed by
Gersh Budker in 1969



from US-MAP (2015) to LEMMA scheme (2017)



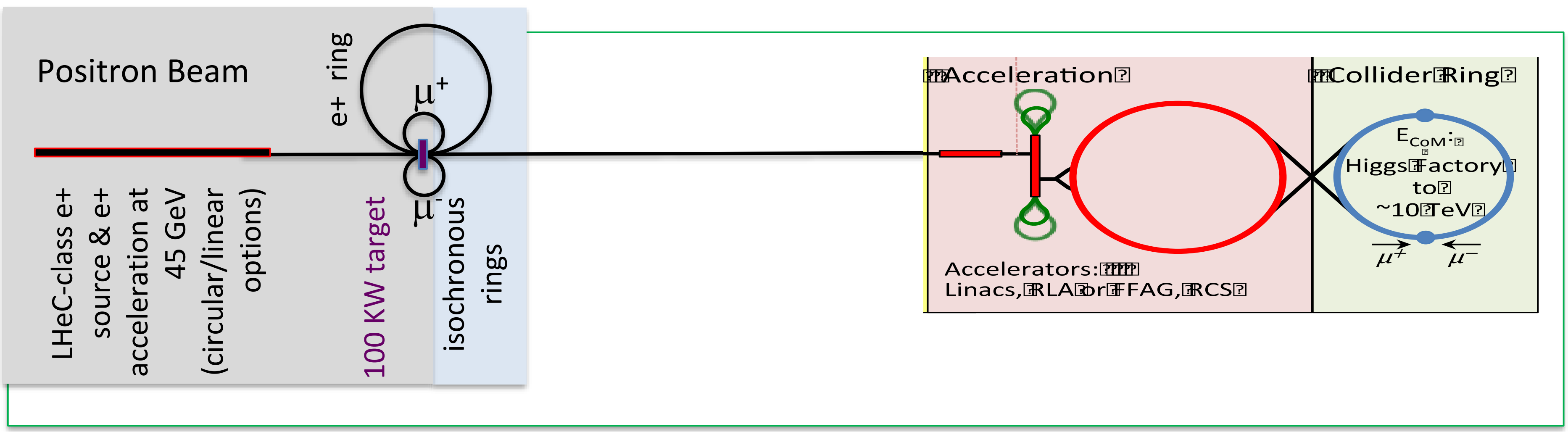
key challenges

~10^{13}-10^{14} μ / sec tertiary particle $p \rightarrow \pi \rightarrow \mu$:

fast cooling (τ=2μs) by 10^6 (6D)

fast acceleration mitigating μ decay

background from μ decay



key challenges

~10^{11} μ / sec from $e^+e^- \rightarrow \mu+\mu-$

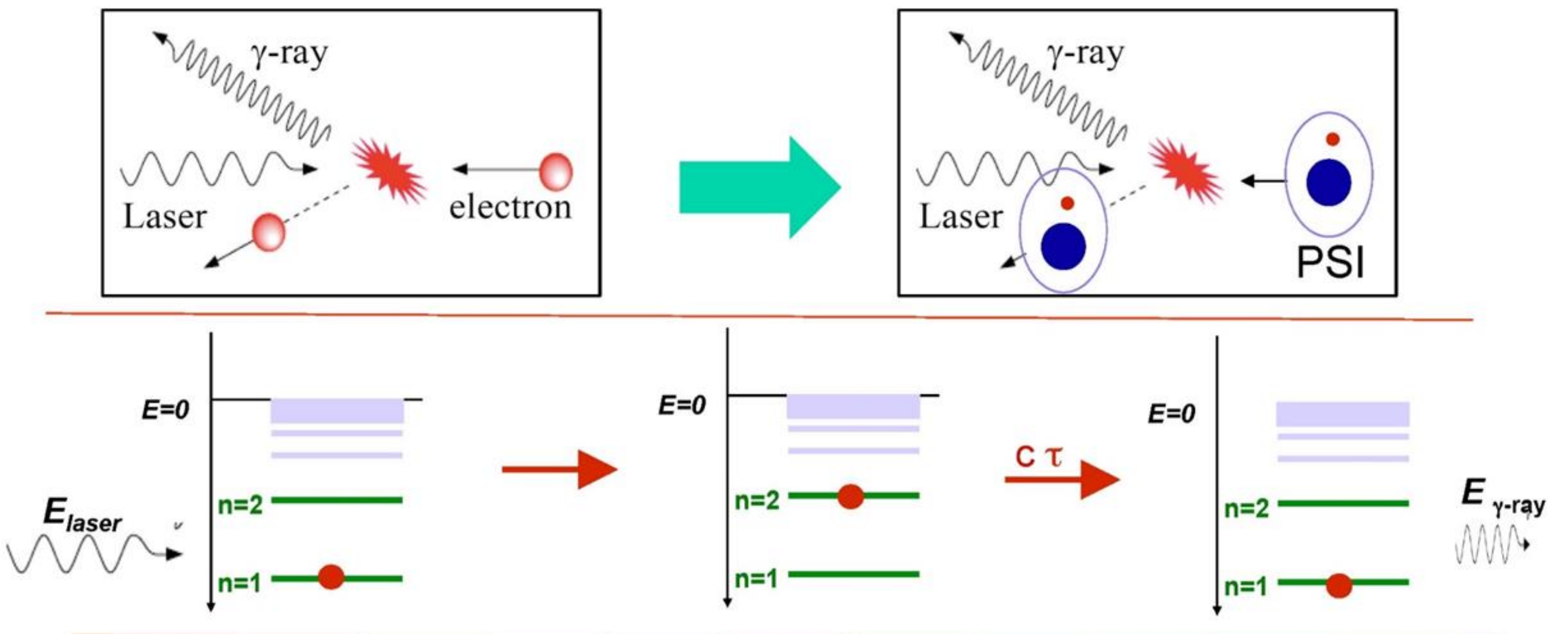
key R&D

10^{15} e^+/sec, 100 kW class target, NON destructive process in e+ ring

M. Antonelli, M. Boscolo, P. Raimondi et al.

"Gamma Factory" based on "PSI"
Compton back scattering at LHC or FCC

Simple Idea: replace an Electron beam by a Partially Stripped Ion (PSI) beam



$E_{laser} = 1Ry\,(Z^2 - Z^2/n^2)/2\gamma_L$

$E_{\gamma\text{-ray}} = E_{laser} \times 4\gamma_L^{\,2}/(1+(\gamma_L\theta)^2)$

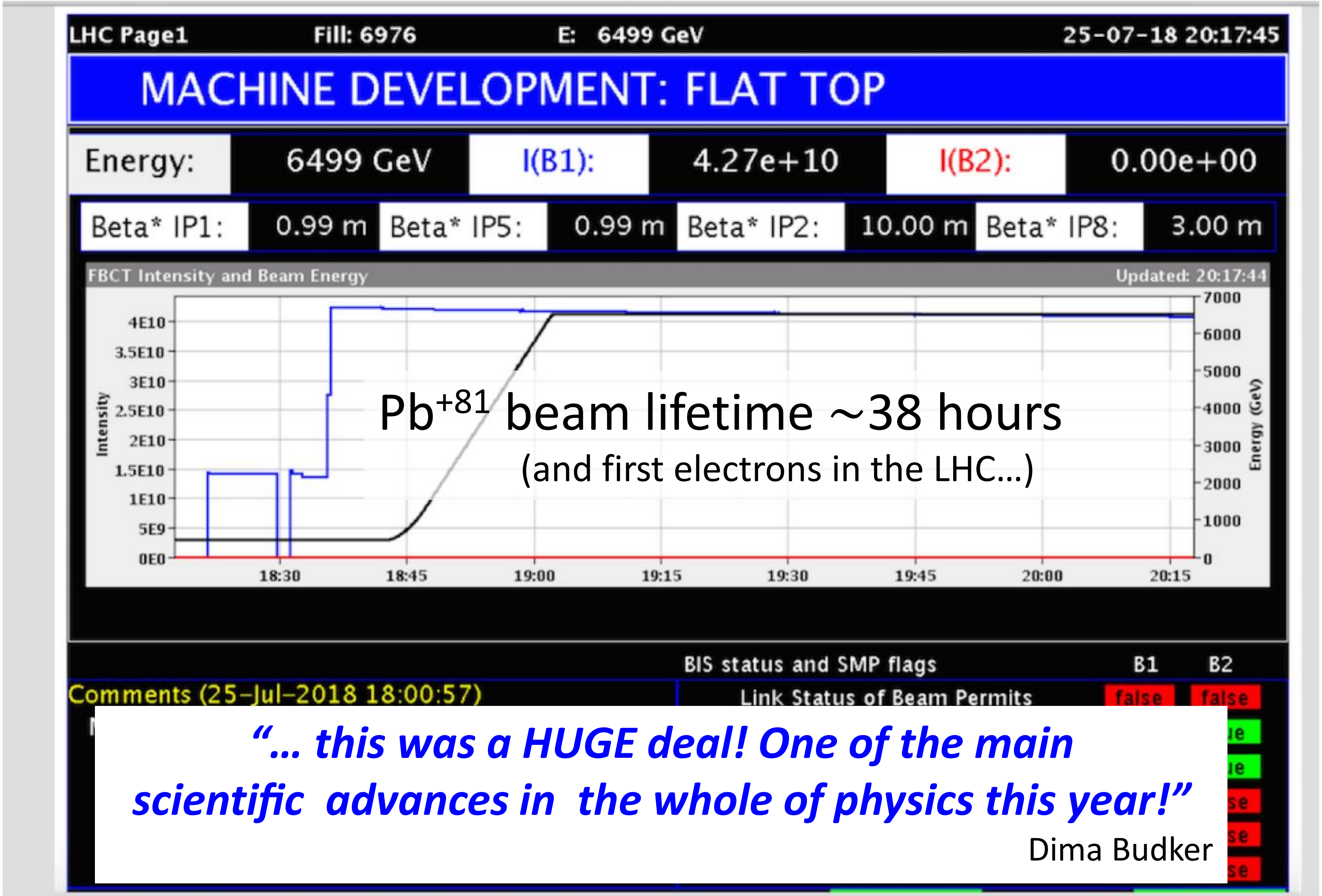
Note: $(E_{laser}/m_{beam}) \times 4\gamma_L \ll 1$

W. Krasny

FCC based Gamma Factory could provide >10^{17} e^+/s

high photon energies,
high cross section

γ factory proof-of-principle experiment in the LHC



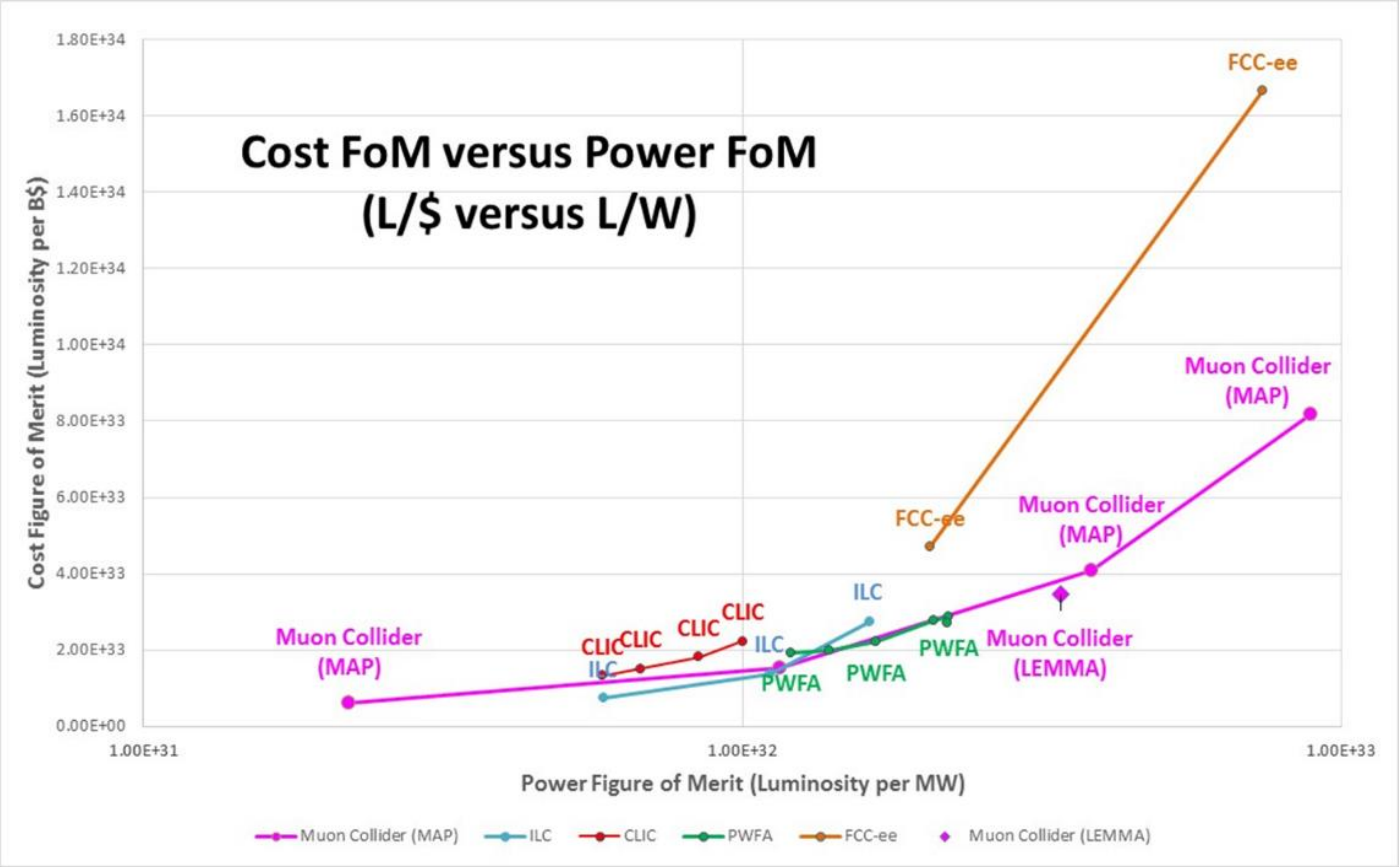
Pb^{+81} beam lifetime ~38 hours

(and first electrons in the LHC…)

"… this was a HUGE deal! One of the main scientific advances in the whole of physics this year!"

Dima Budker

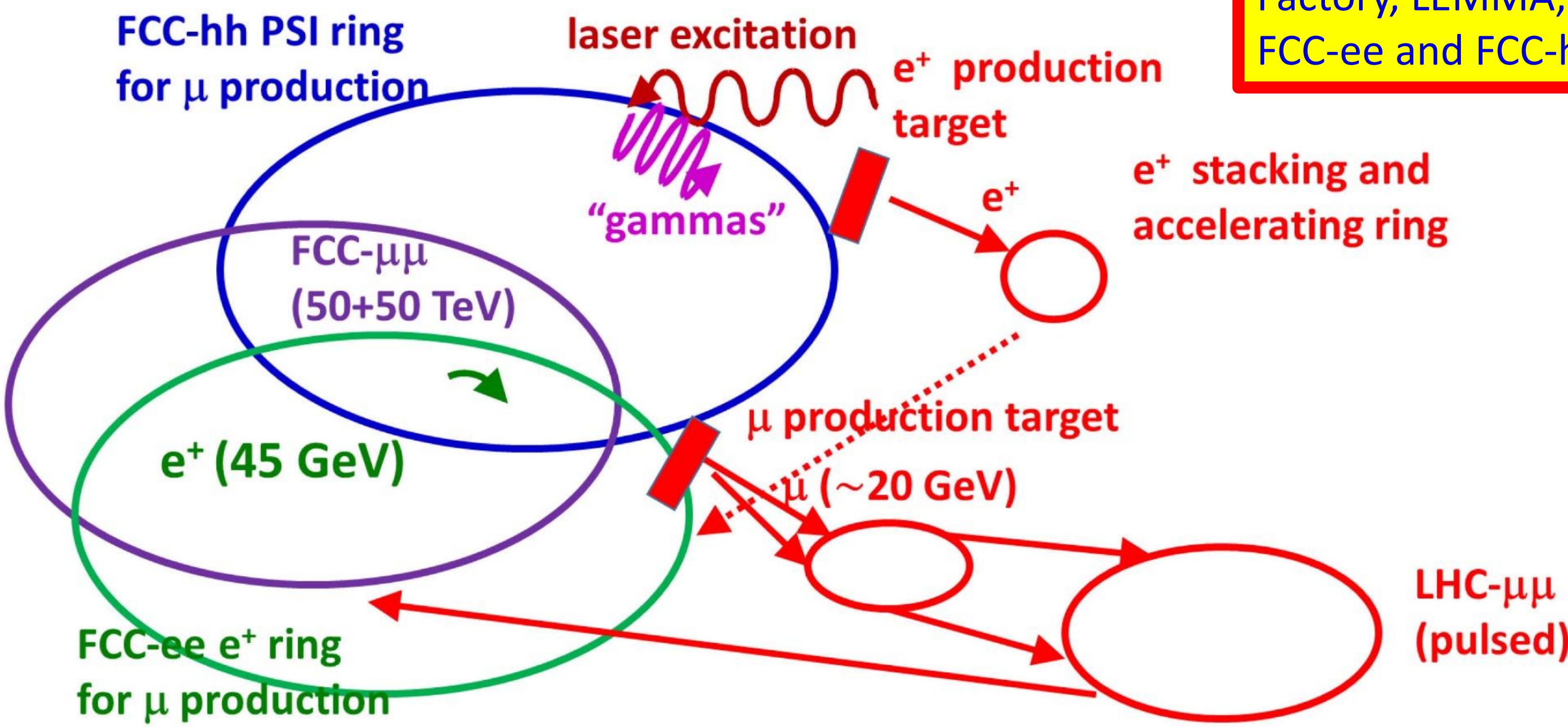
cost & power efficiency of future lepton colliders



Cost-figure-of-merit versus power-figure-of-merit for future lepton colliders (Jean-Pierre Delahaye)

100 TeV μ collider FCC-μμ with FCC-hh PSI e⁺ & FCC-ee μ± production

Combining Gamma Factory, LEMMA, FCC-ee and FCC-hh



$$L \approx f_{rev}\dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N}\frac{1}{3^6}\gamma\tau^2\frac{1}{4\pi\beta^*} = \frac{1}{3^6}\left\{\left(\frac{eF_{dip}}{2\pi m_\mu}\right)^3\frac{\tau_0^2}{4\pi c^2}\right\}\left[B^3C^2\right]\left[\dot{N}_\mu\frac{\dot{N}_\mu}{\varepsilon_N}\right]\frac{1}{\beta^*}$$

100 TeV μ collider in C=100 km FCC tunnel with B=16 T → $L>10^{34}$ cm^{-2}s^{-1}

a few conclusions

- FCC study develops high-performance energy frontier circular colliders for post-LHC era – input to ESU'19/20
- parallel effort in China (CEPC/SppC) – Chinese decision could come within 2 to 5 years
- worldwide R&D programs on key technologies: Nb_3Sn superconductor, high-field magnets, highly-efficient SC RF
- international FCC collaboration growing steadily, many R&D opportunities; all of the community invited to join
- FCC concept supports attractive staged long-term strategy for particle physics: FCC-ee → FCC-hh → FCC-μμ

    highest-luminosity collisions up to very high energies; collider program extending well into the 22^{nd} century

FCC CDR Presentation Event

PARIS

29 / 30 January, 2019

EuroCirCol Final Meeting FCCWeek 2019

https://indico.cern.ch/event/727555