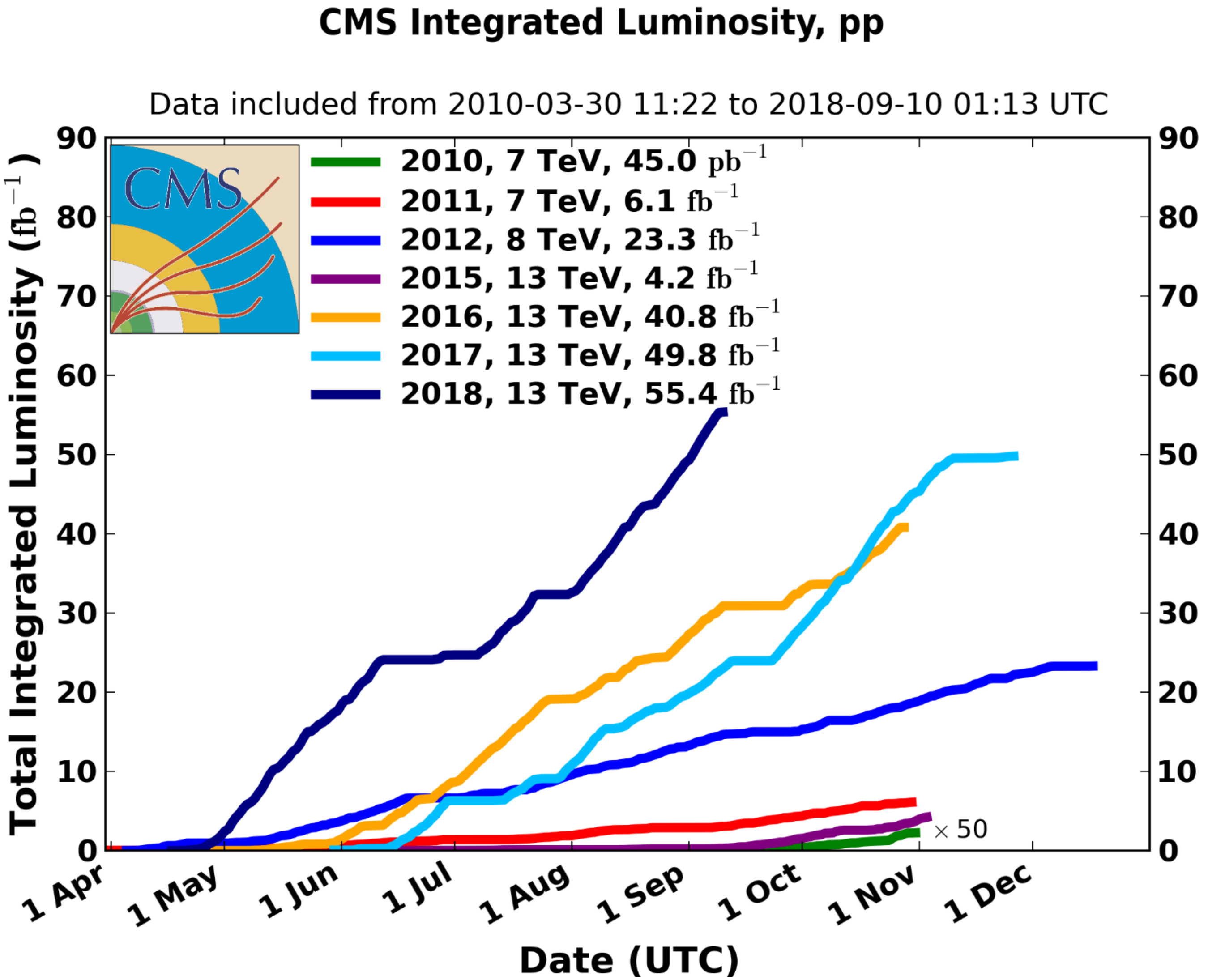
Machine Aspects of Future pp Colliders

Frank Zimmermann

CERN, Pisa School on Future Colliders

*Work supported by the **European Commission** under the **HORIZON 2020 project ARIES**, grant agreement 730871*

LHC: today's frontier collider



excellent performance at E_{cms}=13 TeV

energy frontier in ~25 years

- very large circular hadron collider - only feasible approach to reach 100 TeV c.m. collision energy in coming decades
- access to new particles (direct production) in few-TeV to 30 TeV mass range, far beyond LHC reach
- much-increased rates for phenomena in sub-TeV mass range → much increased precision w.r.t. LHC

M. Mangano

circular hadron collider energy reach

$$E \propto B_{dipole} \times \rho_{bending}$$

cf. LHC: factor ~4 in radius, factor ~2 in field → O(10) in E_{cms}

why not build a linear hadron collider?

ILC real-estate gradient:

250 GeV/11 km ~23 MeV/m

length of a 100 TeV linear collider
based on ILC technology:

100 TeV/(23 MeV/m) > 4000 km !

for me it is clear, we need a circular tunnel

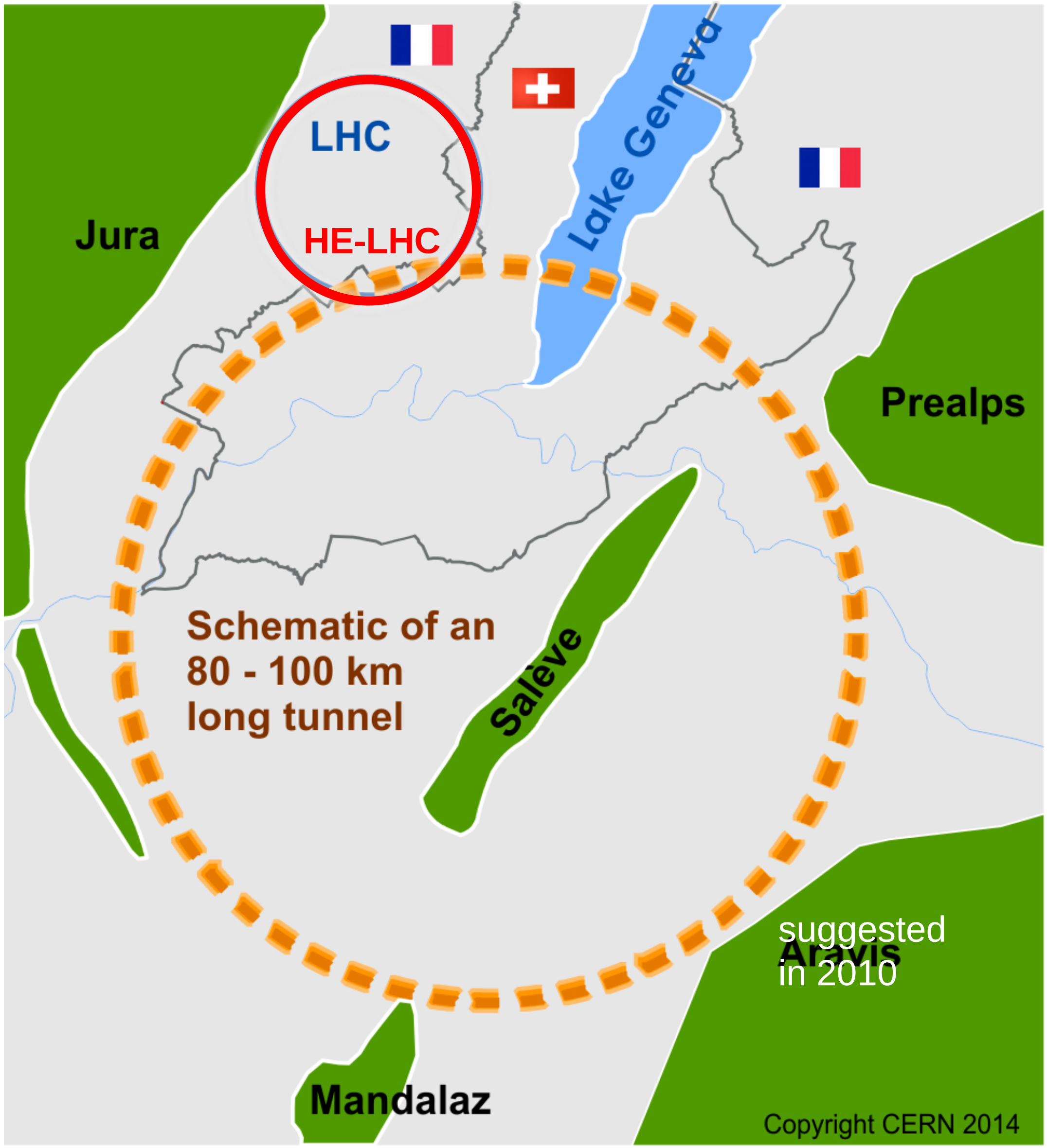
Future Circular Collider Study
Goal: CDR for European Strategy Update 2019/20

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

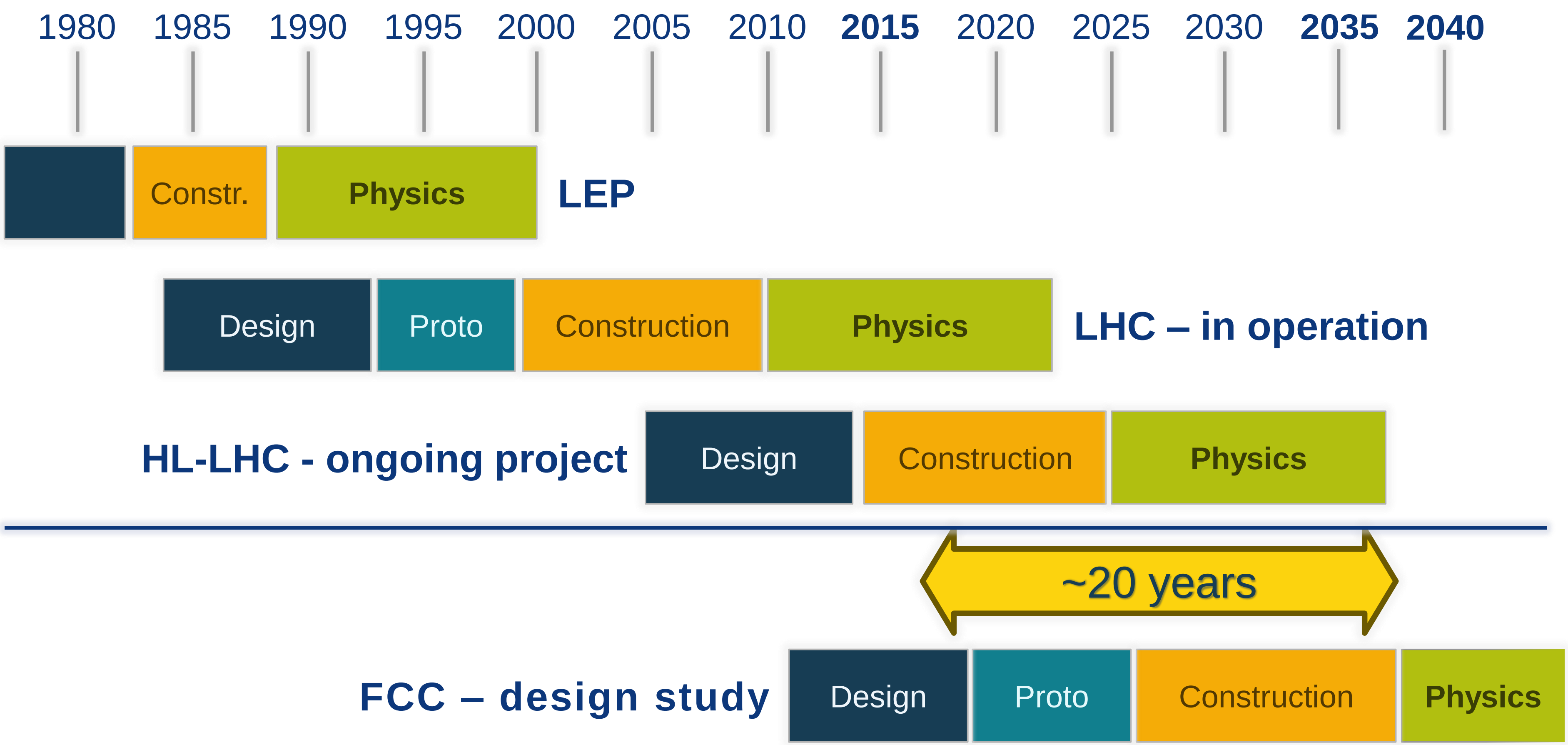
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

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



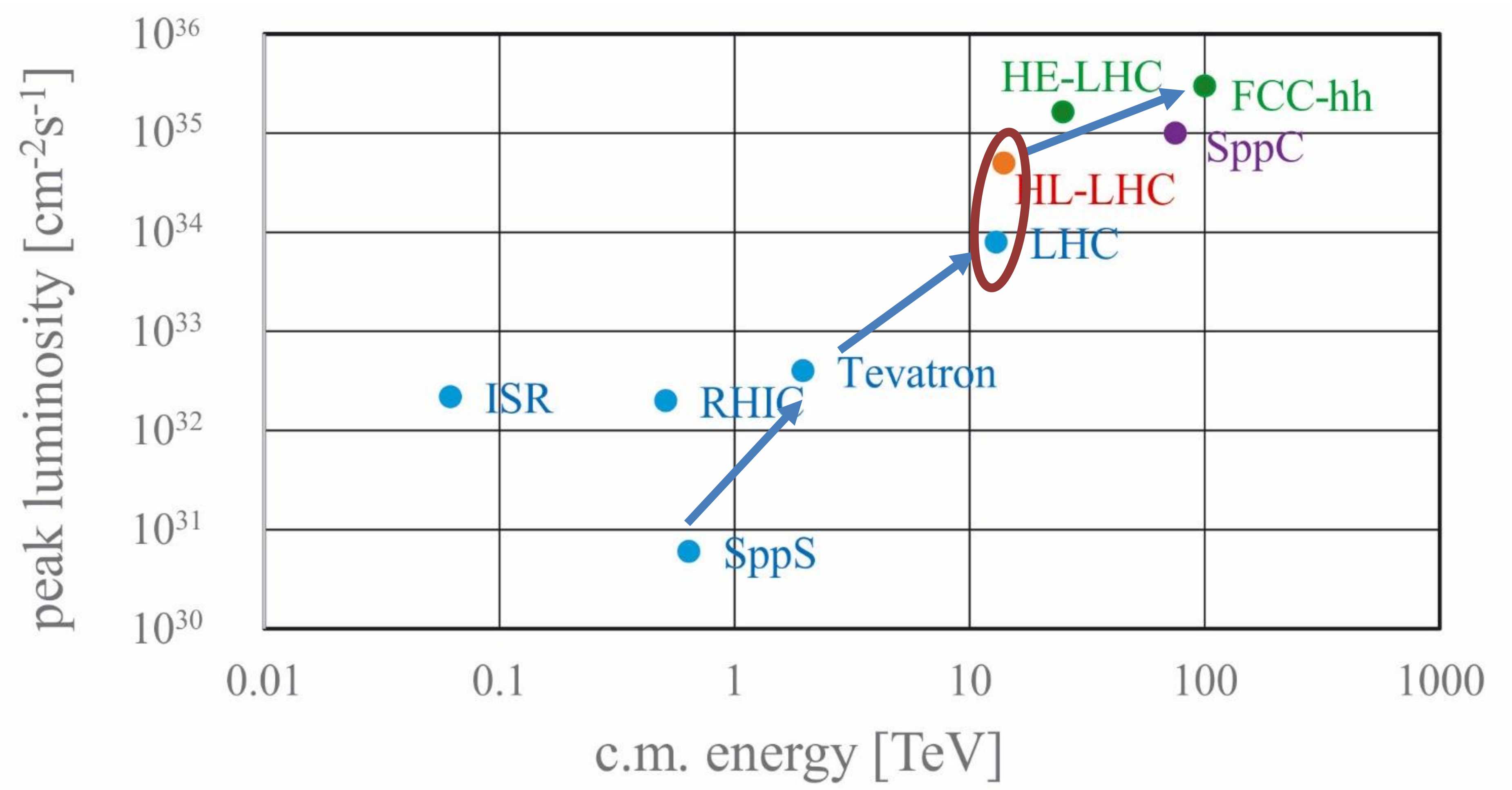
CERN Circular Colliders & FCC



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

milestone: CDR by end 2018 for next update of European Strategy

past, present & proposed hadron colliders



peak luminosity limited by SR power & beam-beam

synchrotron radiation power / beam:

$$P_{SR} = n_b N_b \frac{c C_{\gamma p} E^4}{\rho C}$$

limited

$$C_{\gamma p} \equiv \frac{4\pi}{3} \frac{r_p}{\left(m_p c^2\right)^3}$$

total beam-beam tune shift

$$\xi = \frac{n_{IP} r_p N_b}{4\pi \varepsilon_N}$$

maximum acceptable

- ρ: bending radius
- C: circumference
- n_b: #bunches/beam
- N_b: #p/bunch
- E: beam energy
- r_p: class. proton radius

luminosity

$$L = \frac{c}{C} \frac{\gamma n_b N_b^2}{4\pi \beta^* \varepsilon_N}$$

luminosity formula for SR-power and tune-shift limited hadron collider

$$L = C_{lum} \frac{P_{SR} \rho \xi}{\beta^* E^3 n_{IP}}$$

with

$$C_{lum} \equiv \frac{3\left(m_p c^2\right)^2}{4\pi r_p^2} \approx 10^{29} \frac{\mathrm{TeV}^2}{\mathrm{m}^2}$$

peak luminosity limited by pile up

event pile up / Xing

$$\mu = \sigma_{\text{inel}} \frac{\gamma N_b^2}{4\pi\beta^* \varepsilon_N}$$

maximum acceptable

σ_{tot} [mbarn] ≈ 42.1$s^{-0.467}$-32.19 $s^{-0.540}$ +35.83 +0.315 $\ln^2(s/34)$; s in units of GeV^2

~112 mbarn at 14 TeV, ~156 mbarn at 100 TeV

σ_{inel} [mbarn] ≈ σ_{tot}-11.7 +1.59 $\ln s$ - 0.134 $\ln^2 s$

~83 mbarn at 14 TeV, ~110 mbarn at 100 TeV

luminosity $$L = \frac{c}{C} \frac{\gamma n_b N_b^2}{4\pi\beta^* \varepsilon_N}$$

luminosity formula for pile-up limited hadron collider

$$L = f_{rev} \frac{n_b \mu}{\sigma_{\text{inel}}}$$

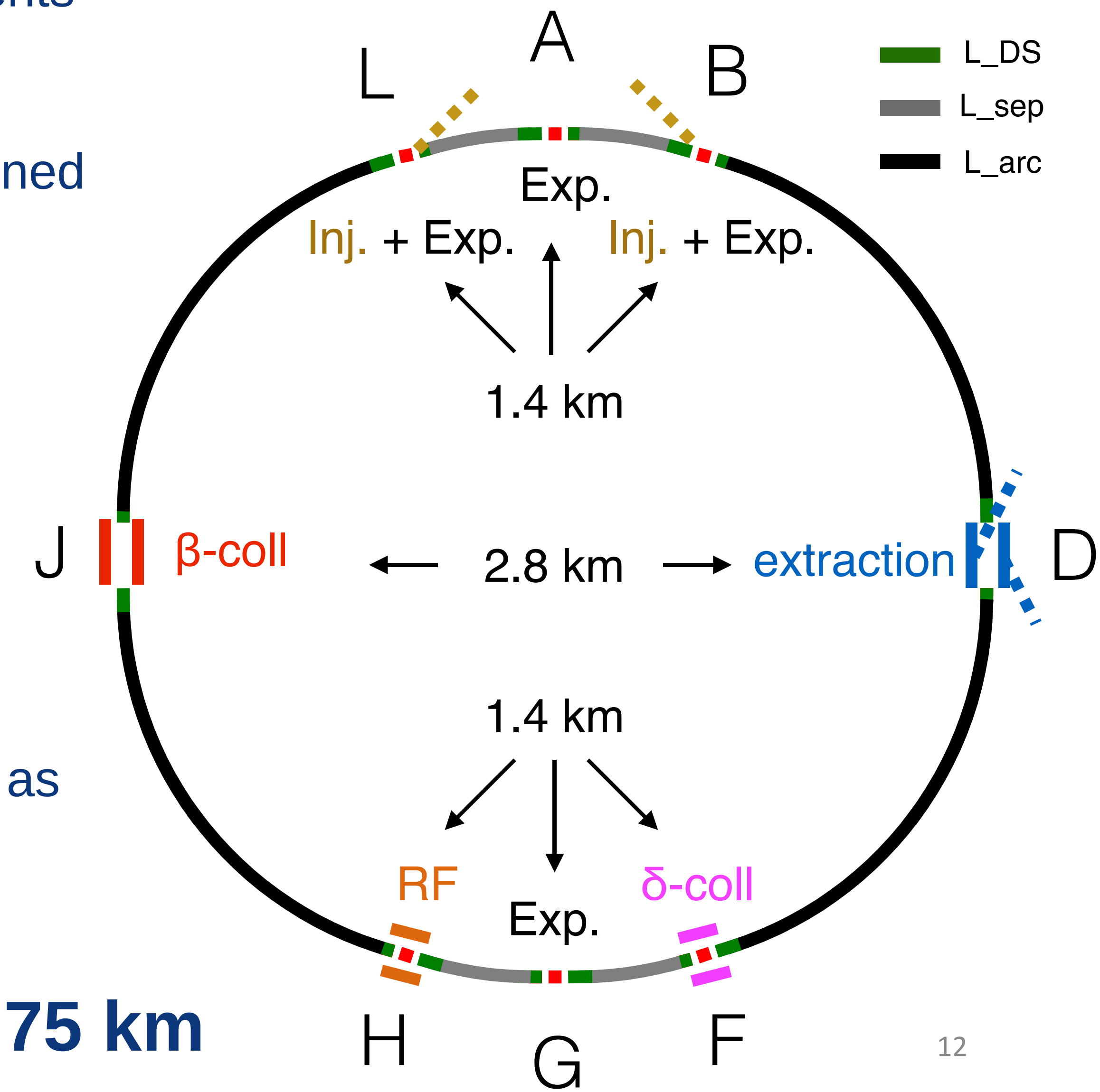
shorter bunch spacing could help?!
(e.g. 25→ 5 ns would increase n_b 5x!)

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

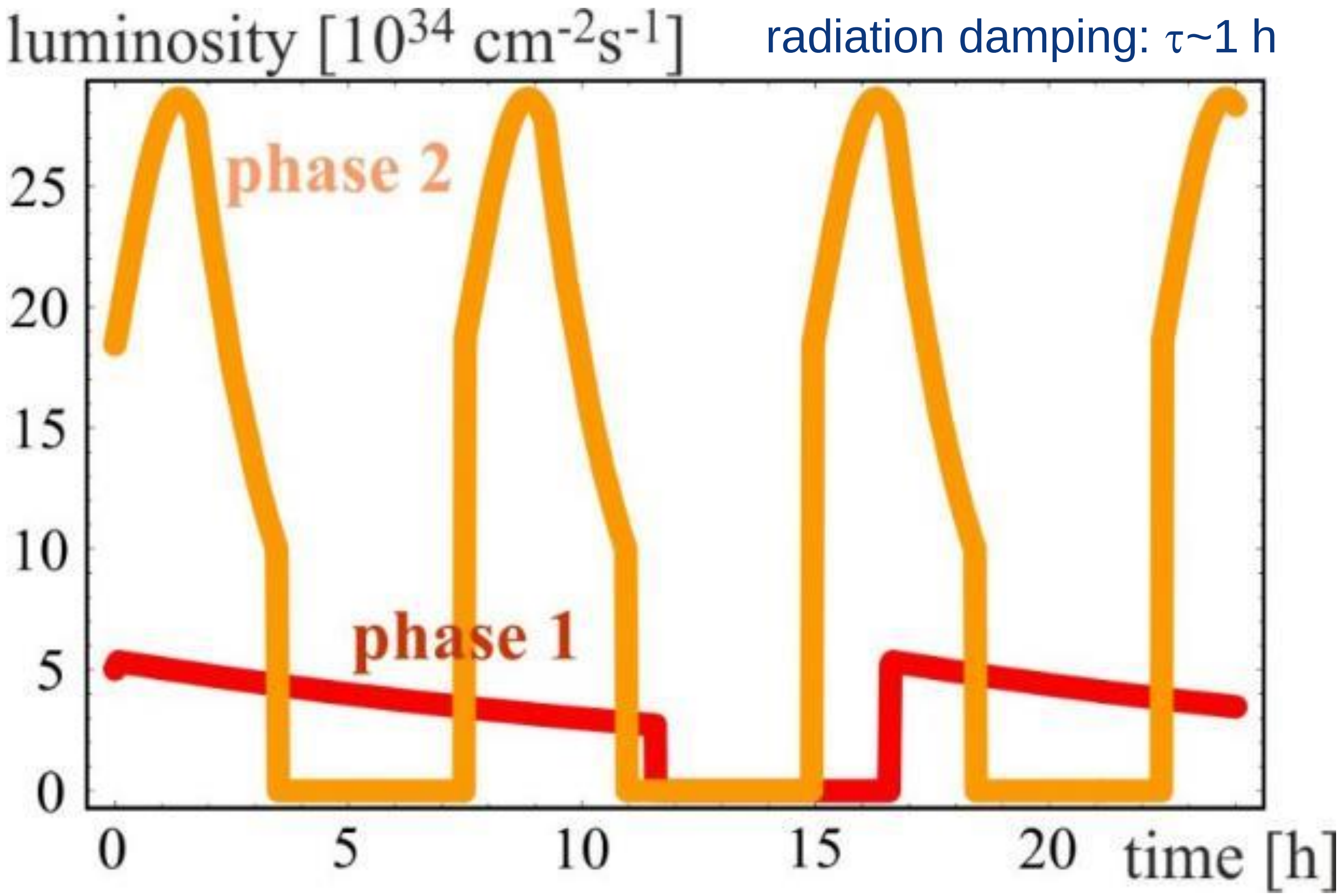
FCC-hh layout 2017

- two high-luminosity experiments (A & G)
- two other experiments combined with injection (L & B)
- two collimation insertions
  - betatron cleaning (J)
  - momentum cleaning (F)
- extraction insertion (D)
- clean insertion with RF (H)
- compatible with LHC or SPS as injector



circumference: 97.75 km

FCC-hh luminosity over 24 h



PRST-AB 18, 101002 (2015)

for both phases:

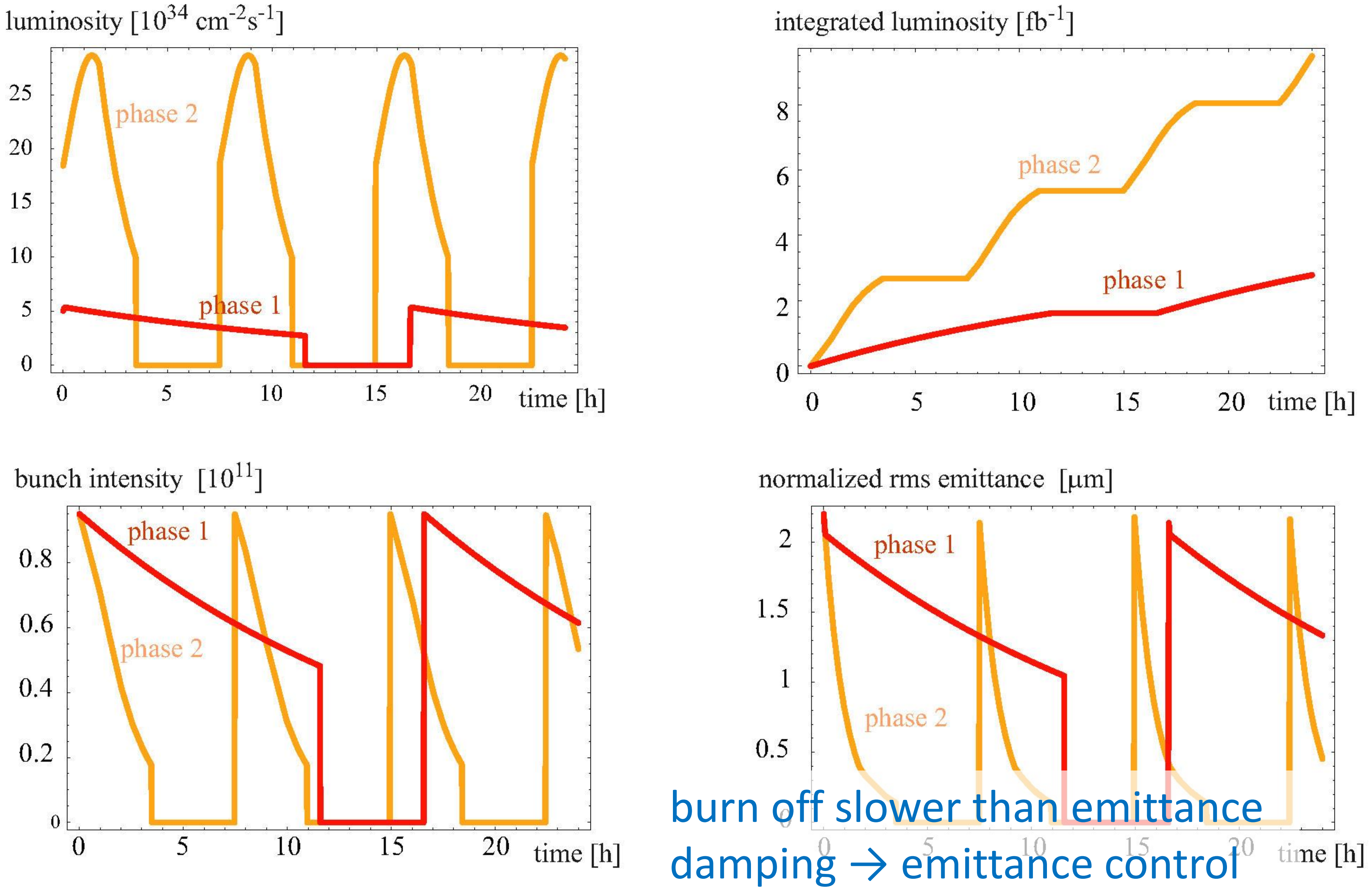
beam current 0.5 A, unchanged!

total synchrotron radiation power ~5 MW.

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

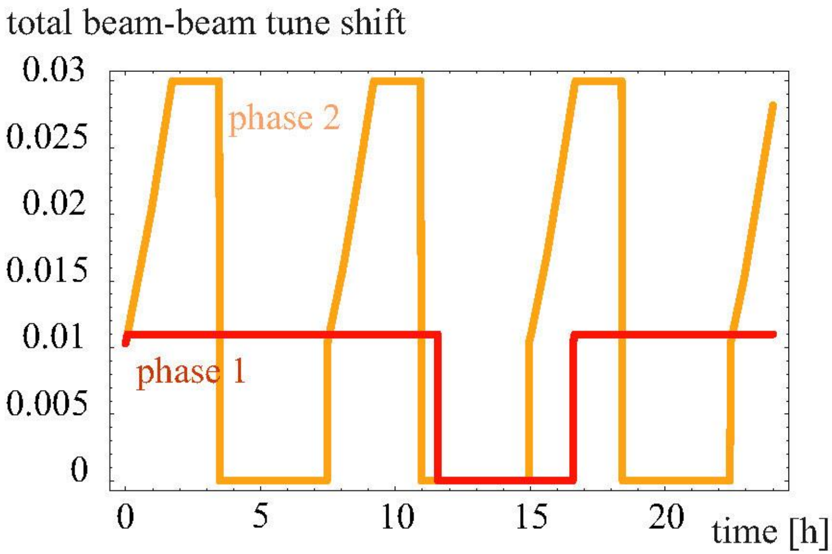
phase 2: β^*=0.3 m, $\xi_{tot}=0.03$, t_{ta}=4 h, 1000 fb^{-1} / year

FCC-hh - 100 TeV c.m., 25 ns

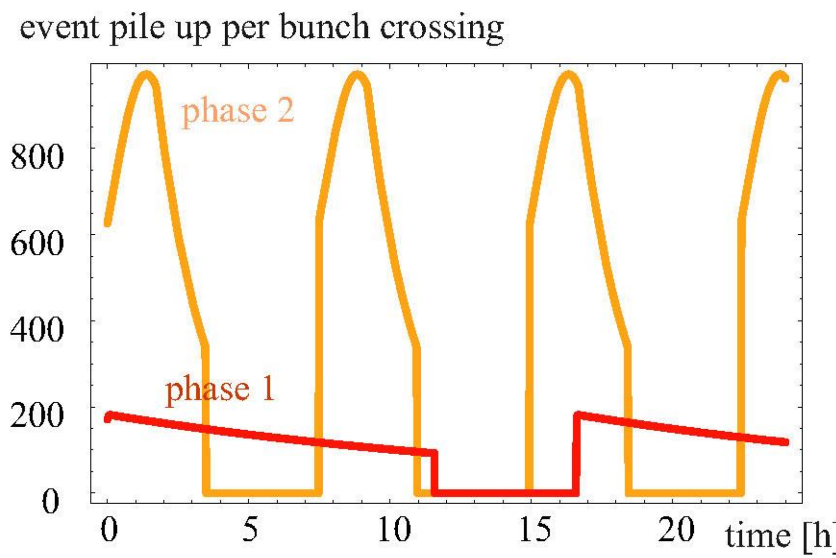


burn off slower than emittance damping → emittance control

FCC-hh - 100 TeV c.m., 25 ns



in phase 2, β^* 1.1→0.3 m, without (or with less) emittance control: tune shift increases during fill until reaching maximum of 0.03



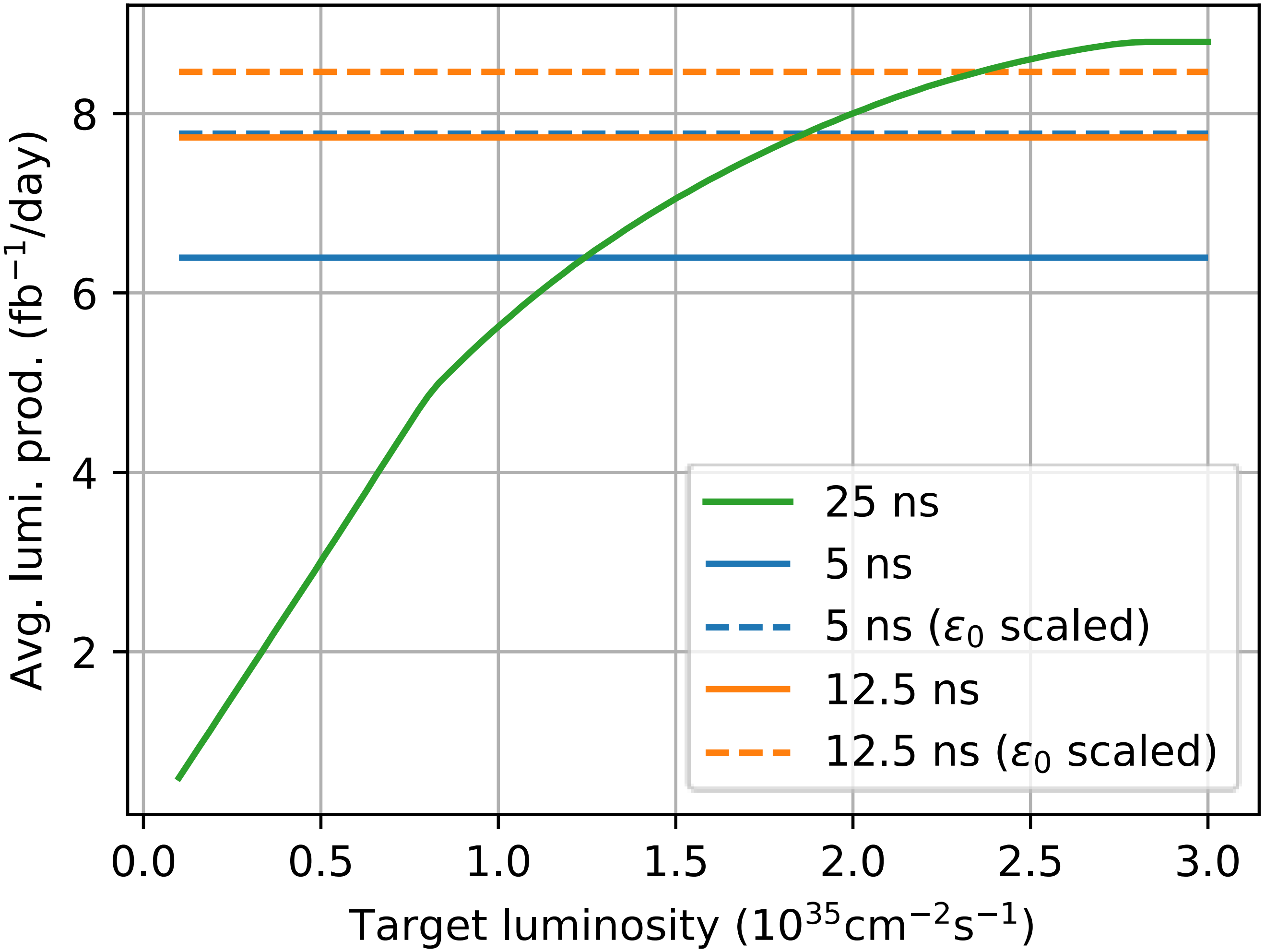
pile up mitigations: 25 ns w luminosity levelling or closer bunch spacing

luminosity levelling with 25 ns beam is an option (green curve)

limited luminosity loss for 500 events per bunch crossing

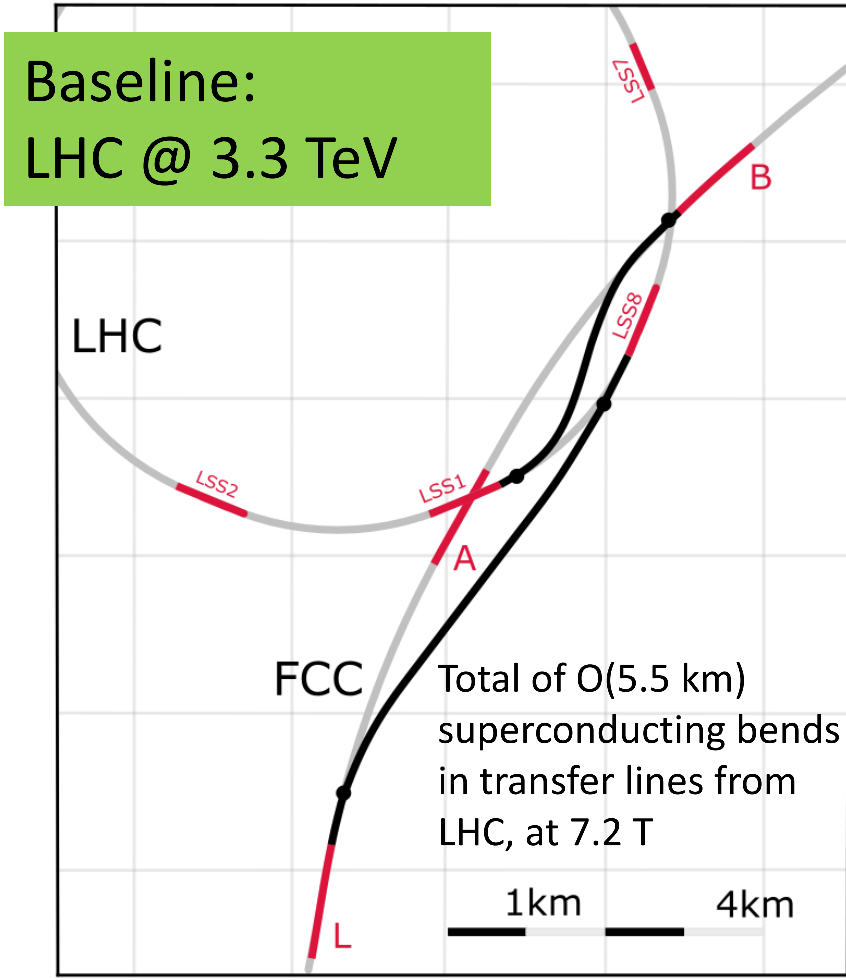
maybe still acceptable at 330 events

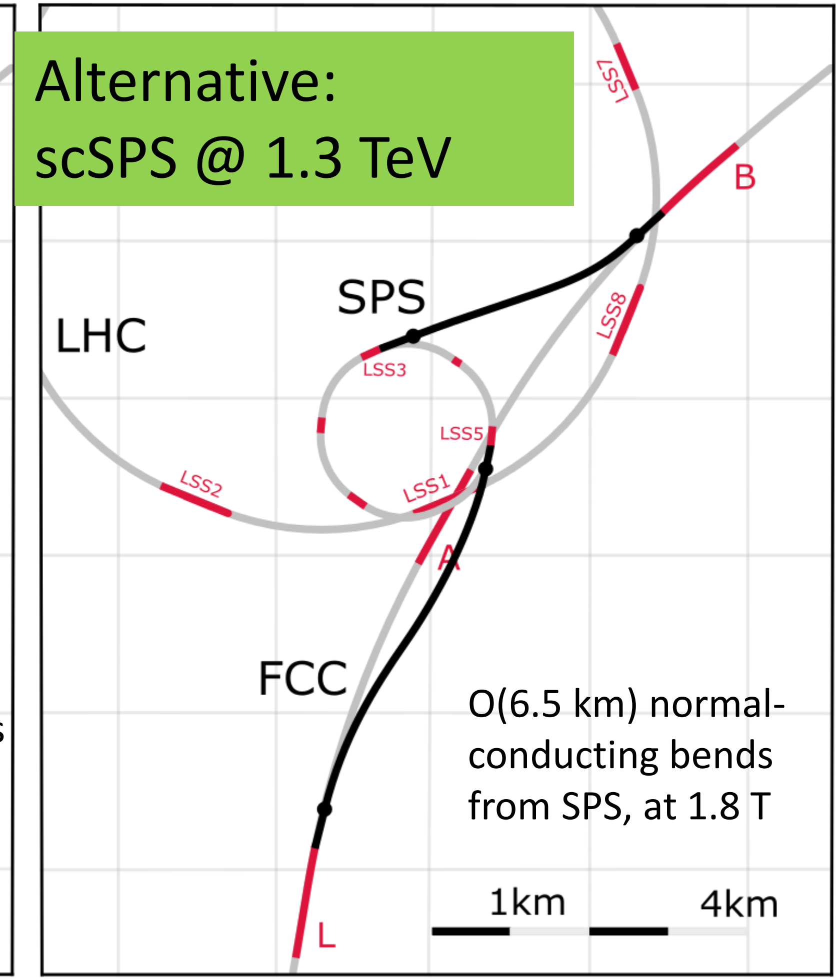
lines show average luminosities
for closer bunch spacing



A. Langner, D. Schulte

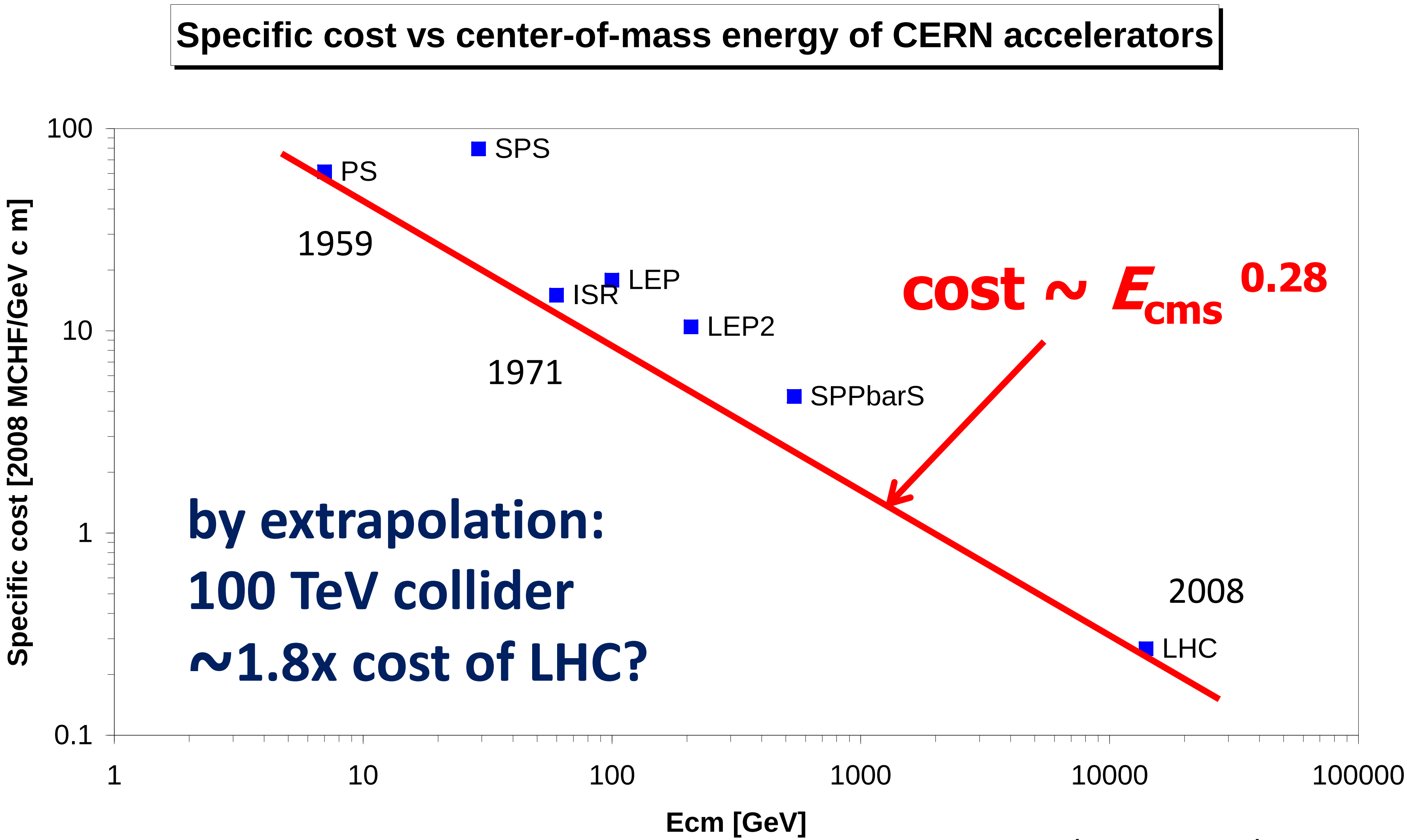
FCC-hh injector options





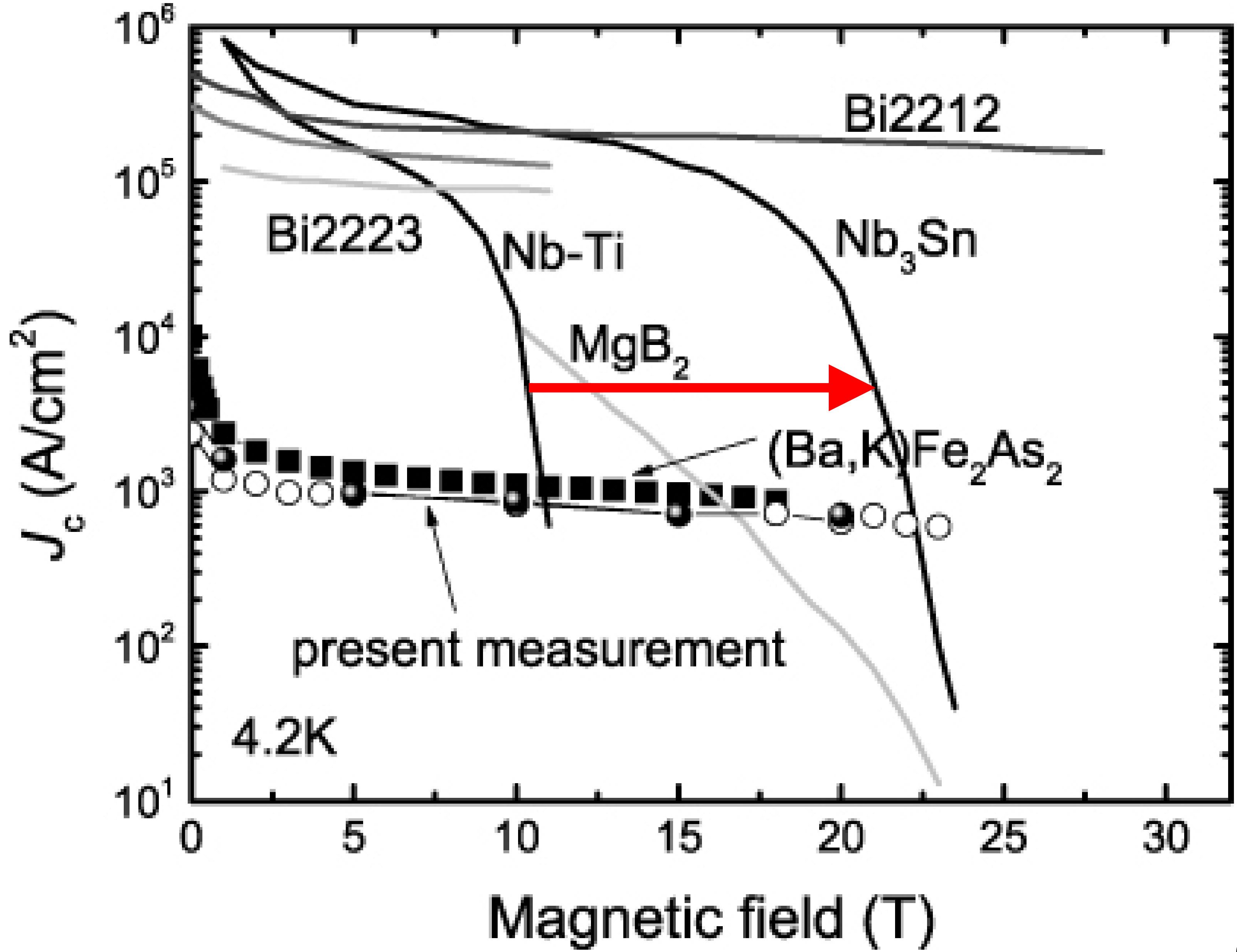
Current baseline: Injection energy 3.3 TeV LHC → Field-swing FCC-hh like LHC
Alternative options: Injection from $SPS_{upgrade}$ around 1.3 TeV
$SPS_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp, cf. SIS 300 design
$SPS_{upgrade}$ would also be an ideal injector for HE LHC (as alternative to the 450 GeV SPS)

cost of future accelerators



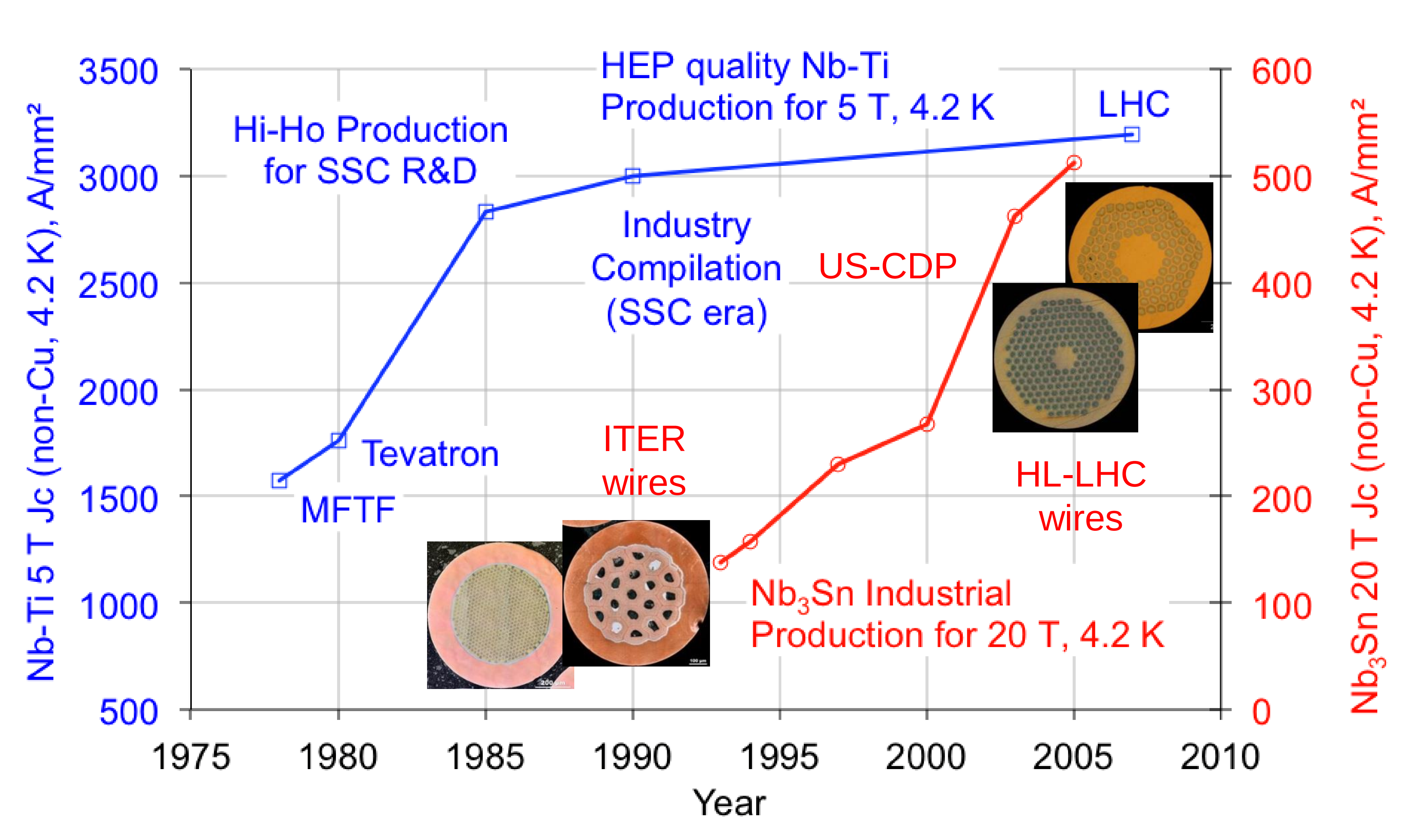
P. Lebrun, RFTech 2013

HL-LHC/FCC technology change: *Nb-Ti* → *Nb_3Sn*



O. Bruning

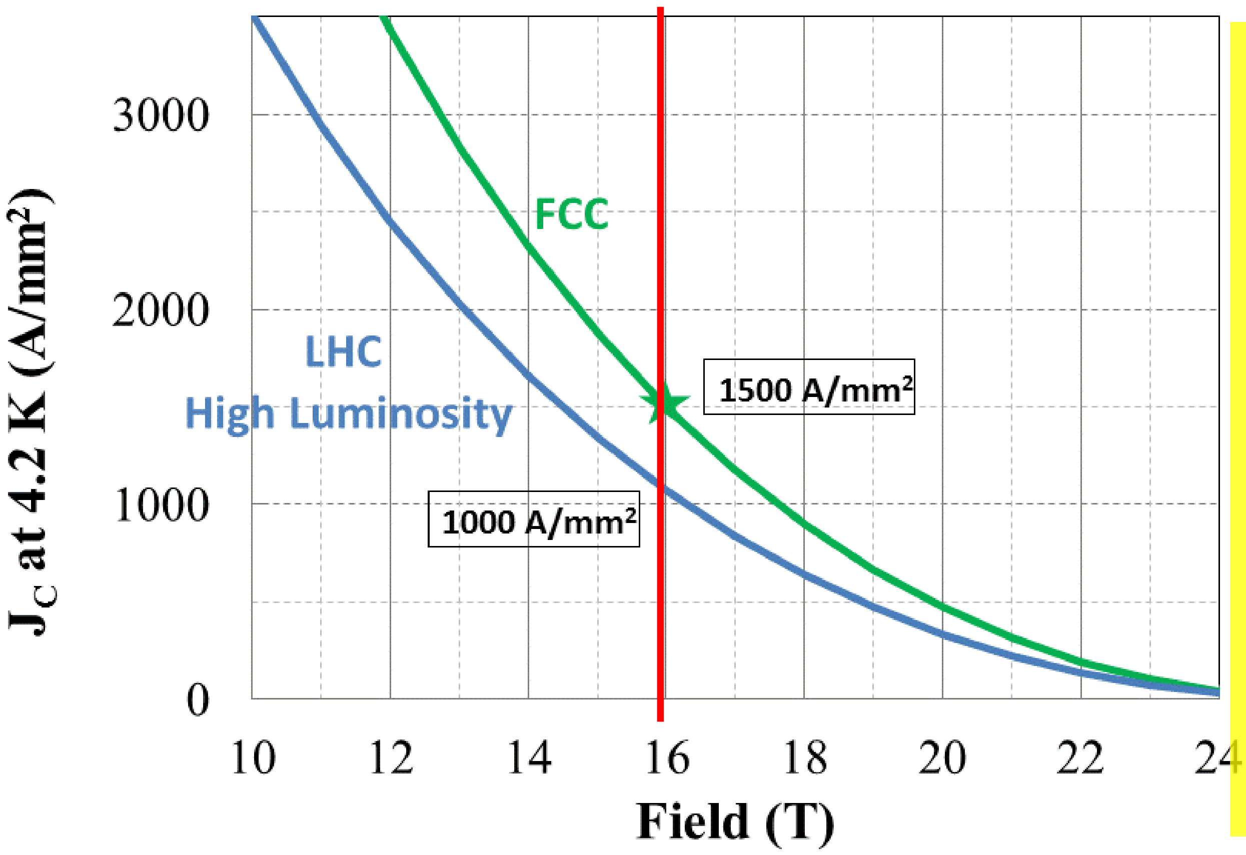
SC wire production: *Nb-Ti* and *Nb_3Sn*



B. Strauss, data by courtesy of J. Parrell (US DOE OST)

FCC Nb_3Sn conductor program

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



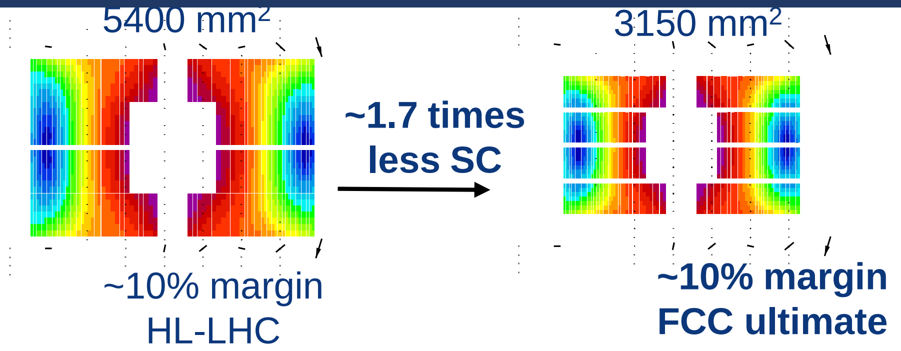
main development goals until 2020:

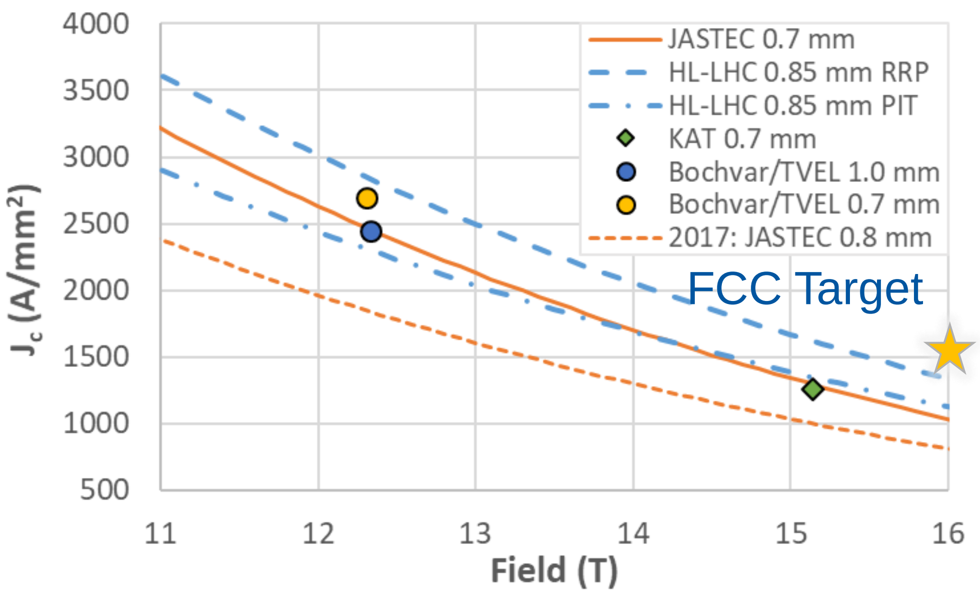
- J_c increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire
- reference wire diameter 1 mm
- potentials for large scale production and cost reduction

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**

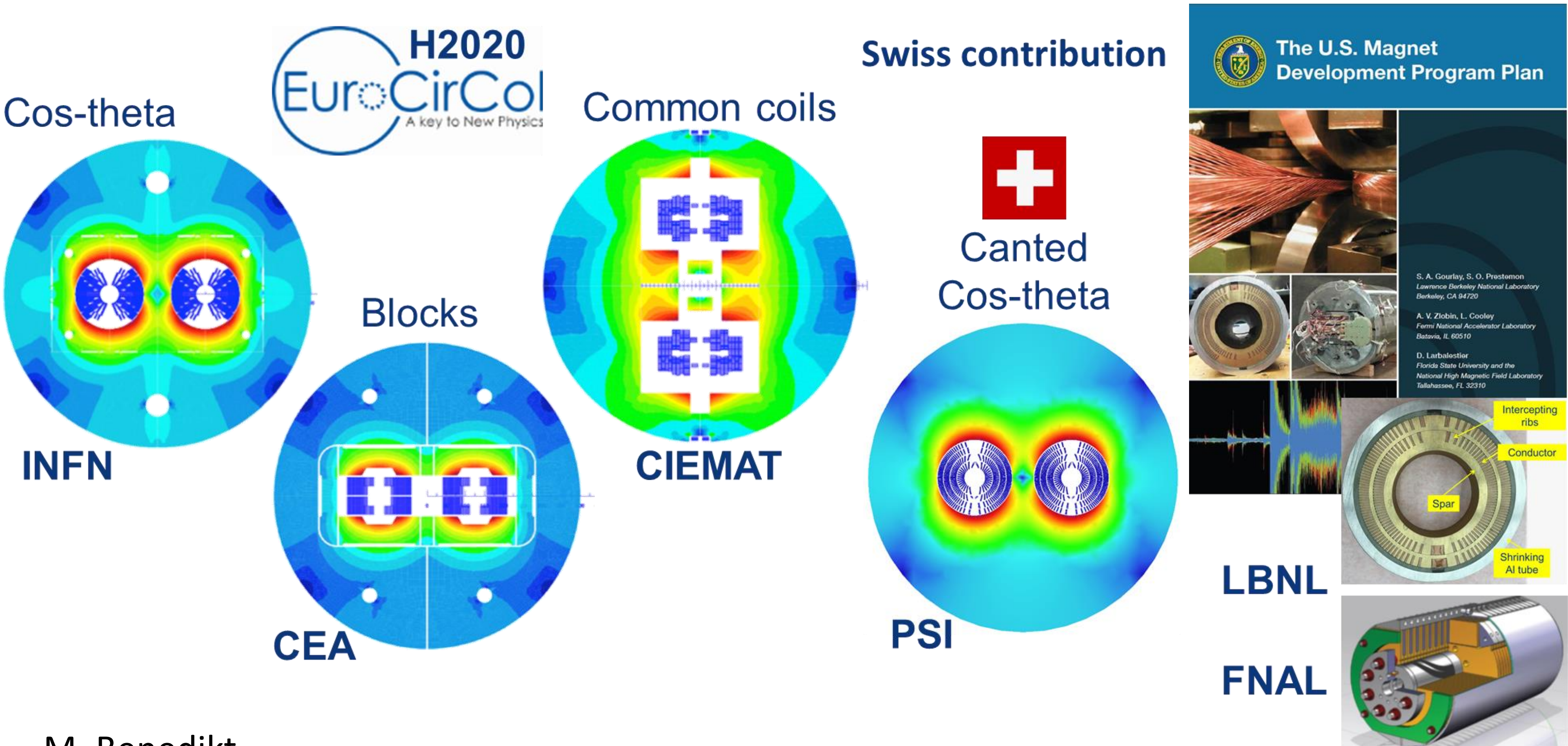
Conductor activities for FCC started in 2017:

- **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

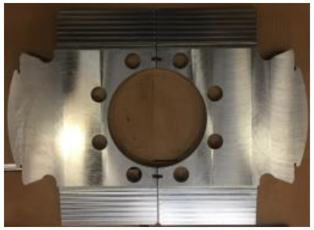


M. Benedikt

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

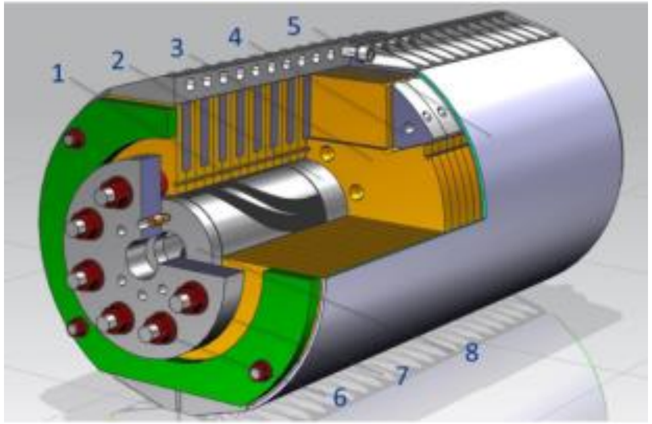
Russian 16 T magnet program launched by BINP recently

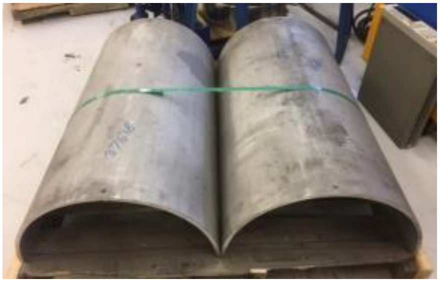
15 T dipole demonstrator (US MDP)



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

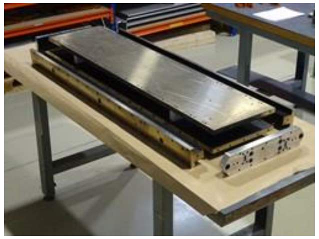
16 T ERMC construction at CERN

First ERMC coil winding

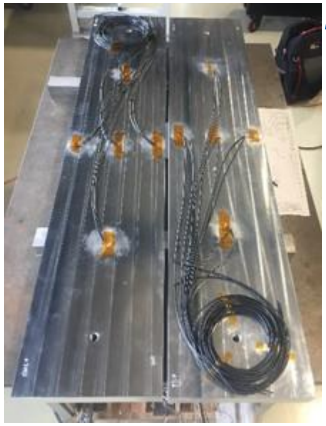
Aluminum shell

Magnet yoke

Coil Reaction Tool



Coil Impregnation Tool



Dummy coils

Axial rods

D. Tommasini

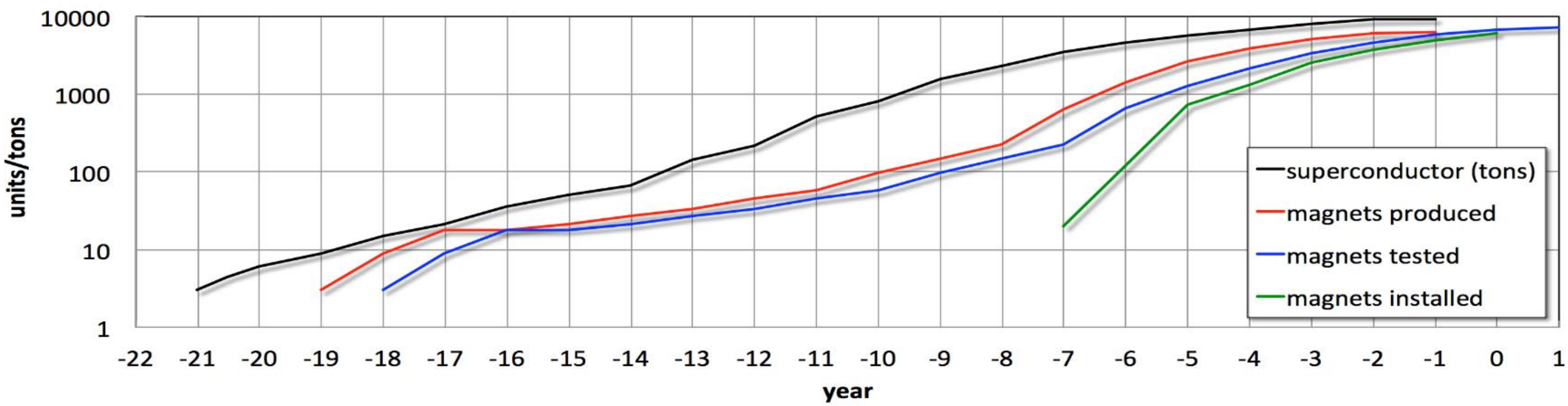
Coil fabrication

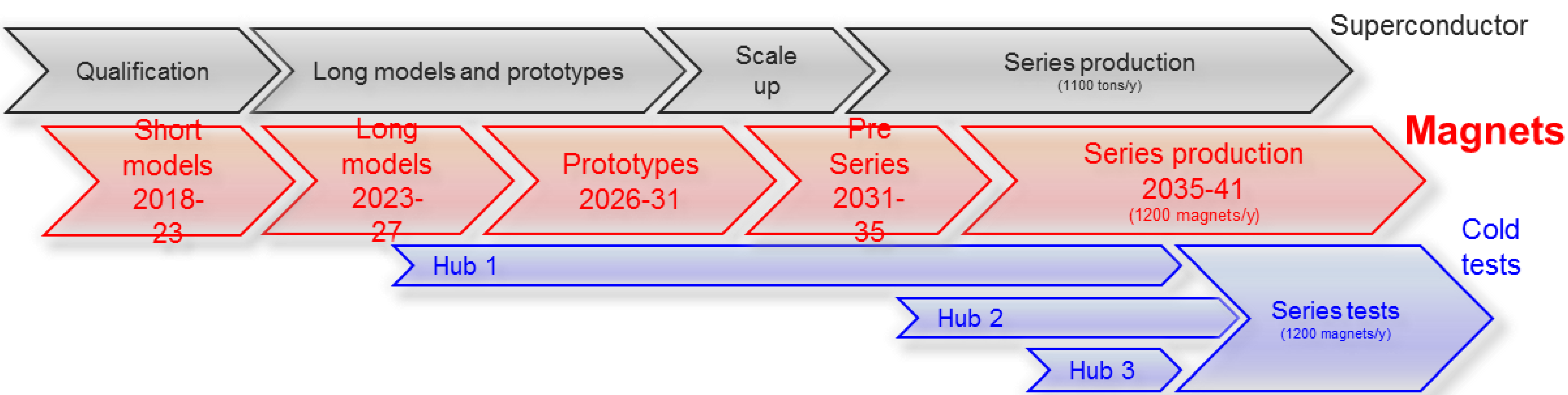
Winding of the first coil has been completed. Preparation for reaction on-going. All tooling for coil production ready

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 is not an easy machine

push for "cheap" injection from SPS at 450 GeV

- **poor field quality and much larger beam** than for FCC-hh
- **less physical aperture** than for LHC,
  complicating collimation and protection at injection

limited length of straight section (LEP tunnel)

- cannot apply length scaling with energy used for FCC-hh design,
  complicating collimation at top energy

magnets must be bent, while FCC-hh magnets are straight

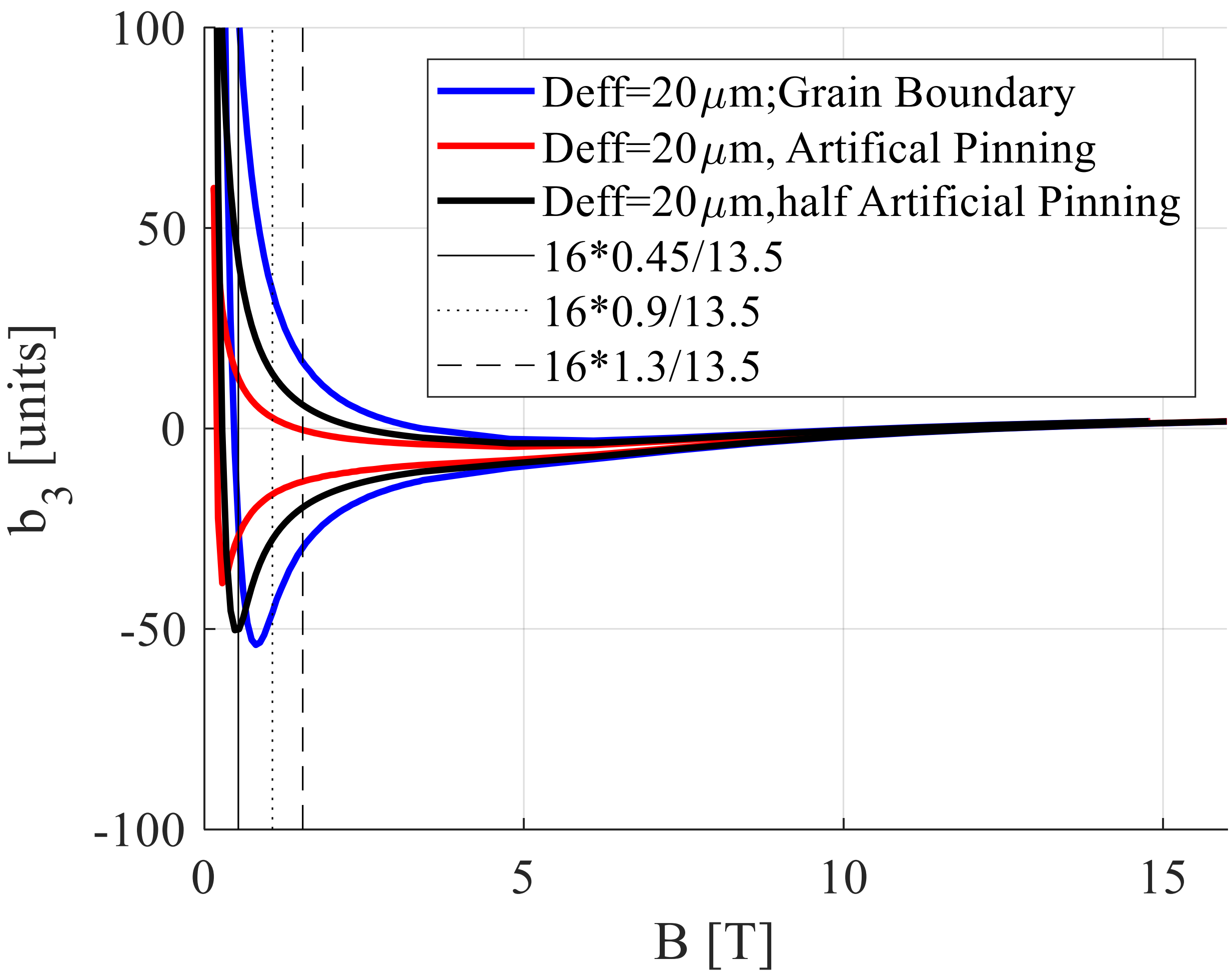
- can magnets made from Nb_3Sn (brittle) be bent mechanically?
  additional complication

limited tunnel cross section

- restricted transverse size of magnet cryostats

field errors limit dynamic aperture

- Nb_3Sn wire with 20 μm instead of 50 μm filaments
- in addition must introduce *artificial pinning centres*



sextupole field errors in $N_{b3}Sn$ dipole as a function of dipole field

3 injection energies (450, 900 and 1300 GeV) are indicated

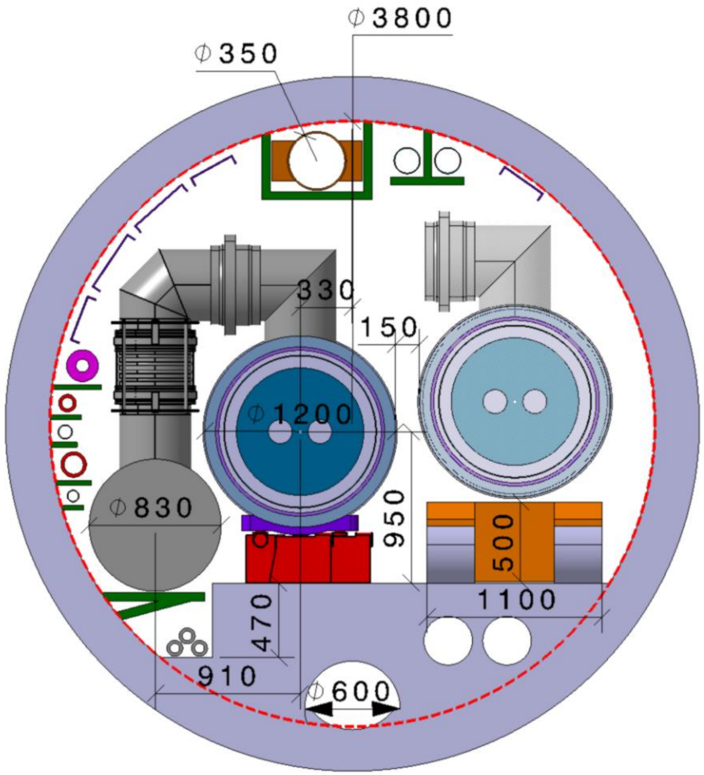
S. Izquierdo Bermudez

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**



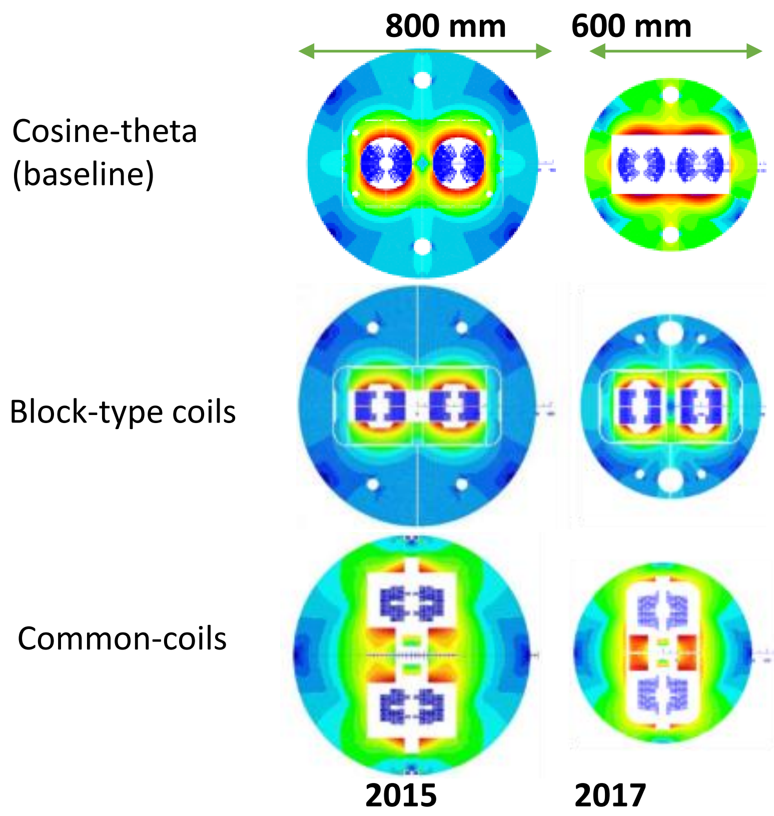
integration and design strategy:

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

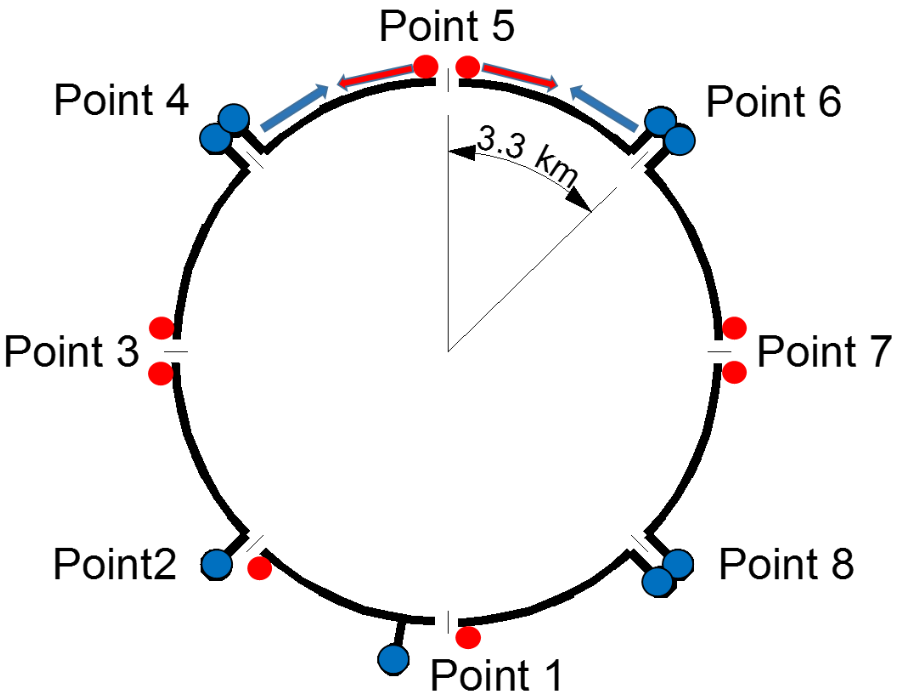
V. Mertens, M. Benedikt

16 T dipole evolution & HE-LHC cryogenics

- Coil optimization and margin 18 → 14%
- Stray-field < 0.1 T at cryostat



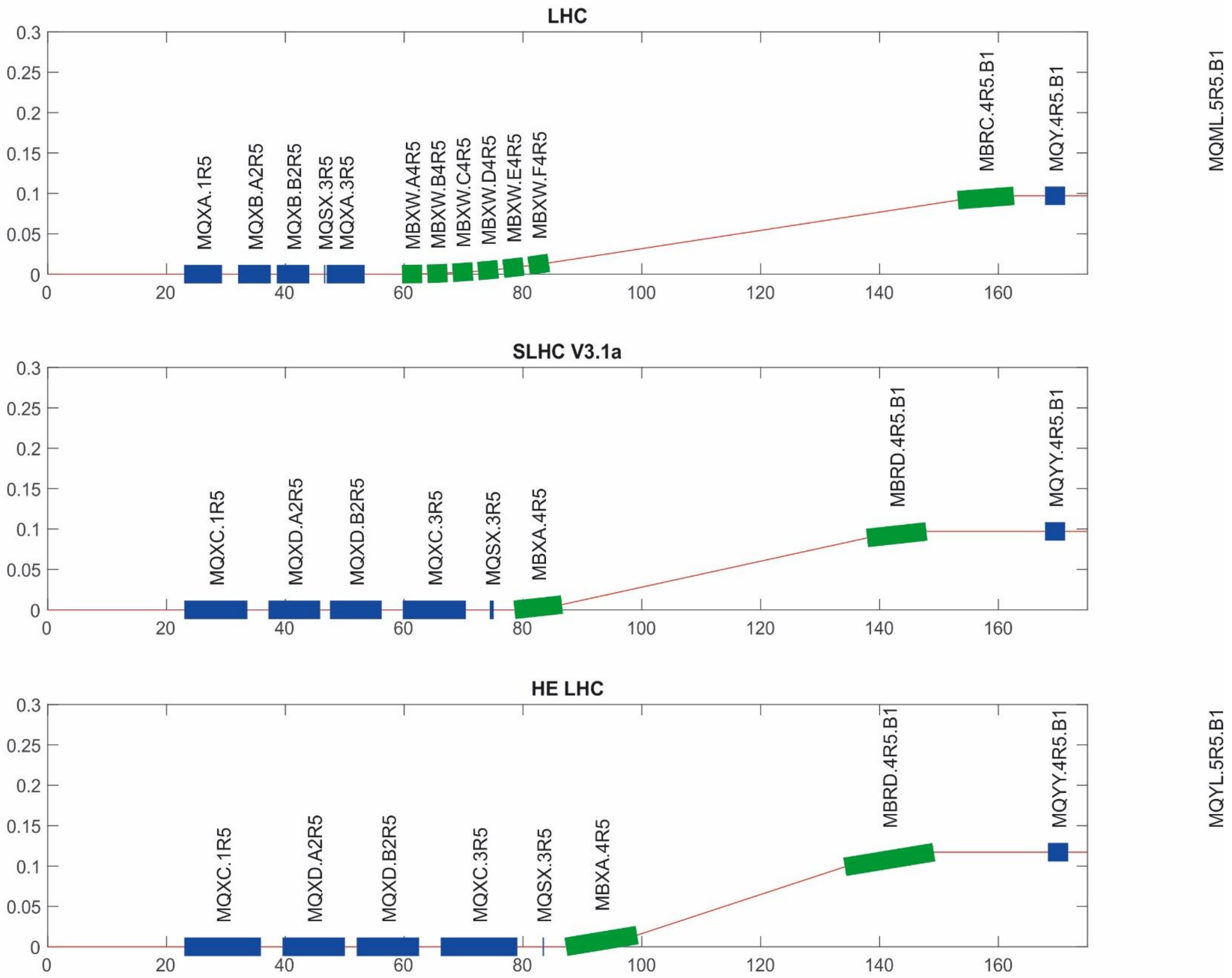
Half-sector cooling instead of full sector (as for LHC) to limit cross section of cryogenic distribution line



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);

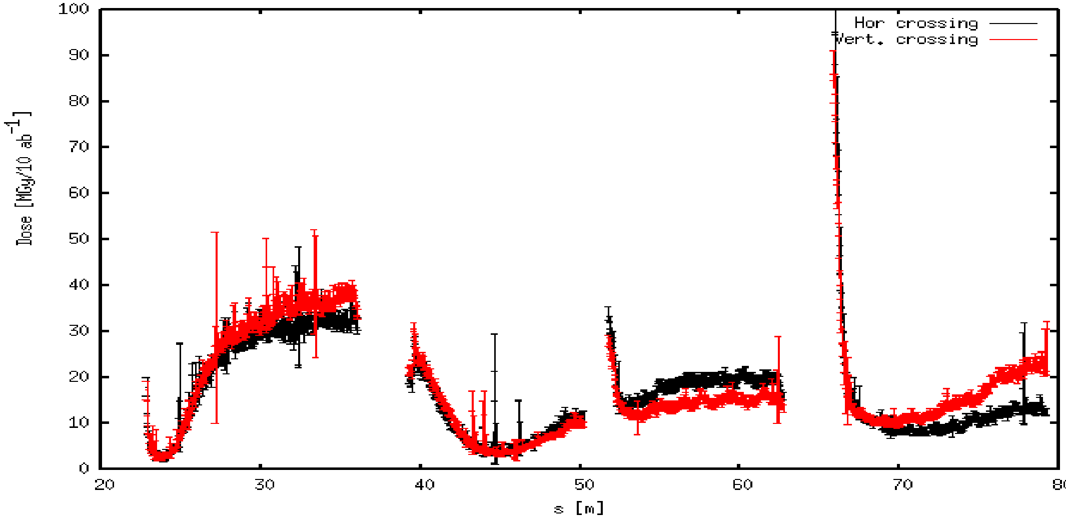
ca. 11 m
for crab cavities

L. van Riesen Haupt

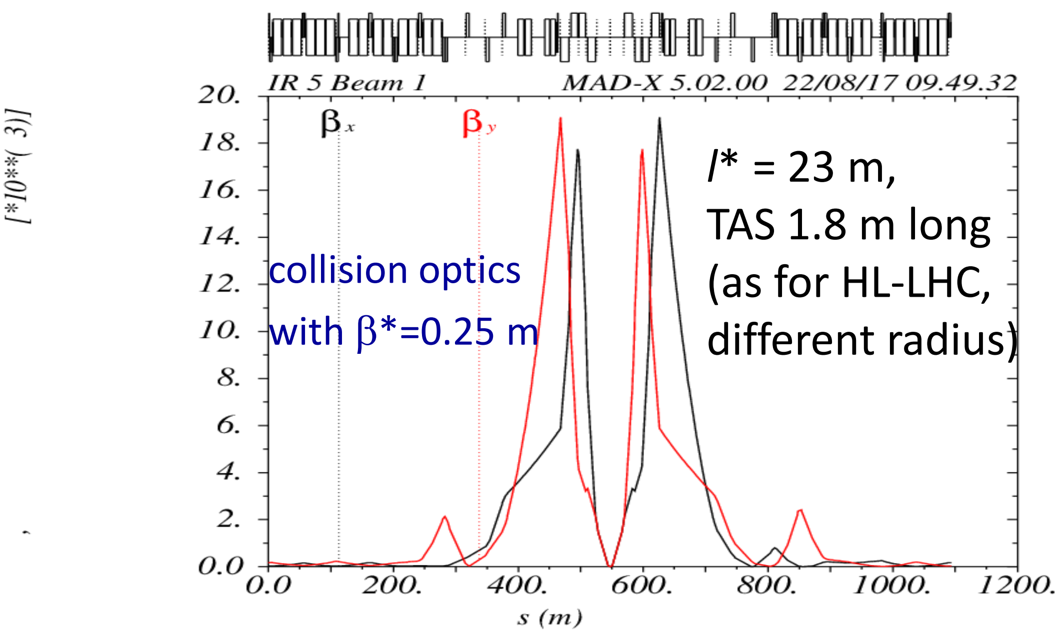
HE-LHC IR optics & triplet shielding

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

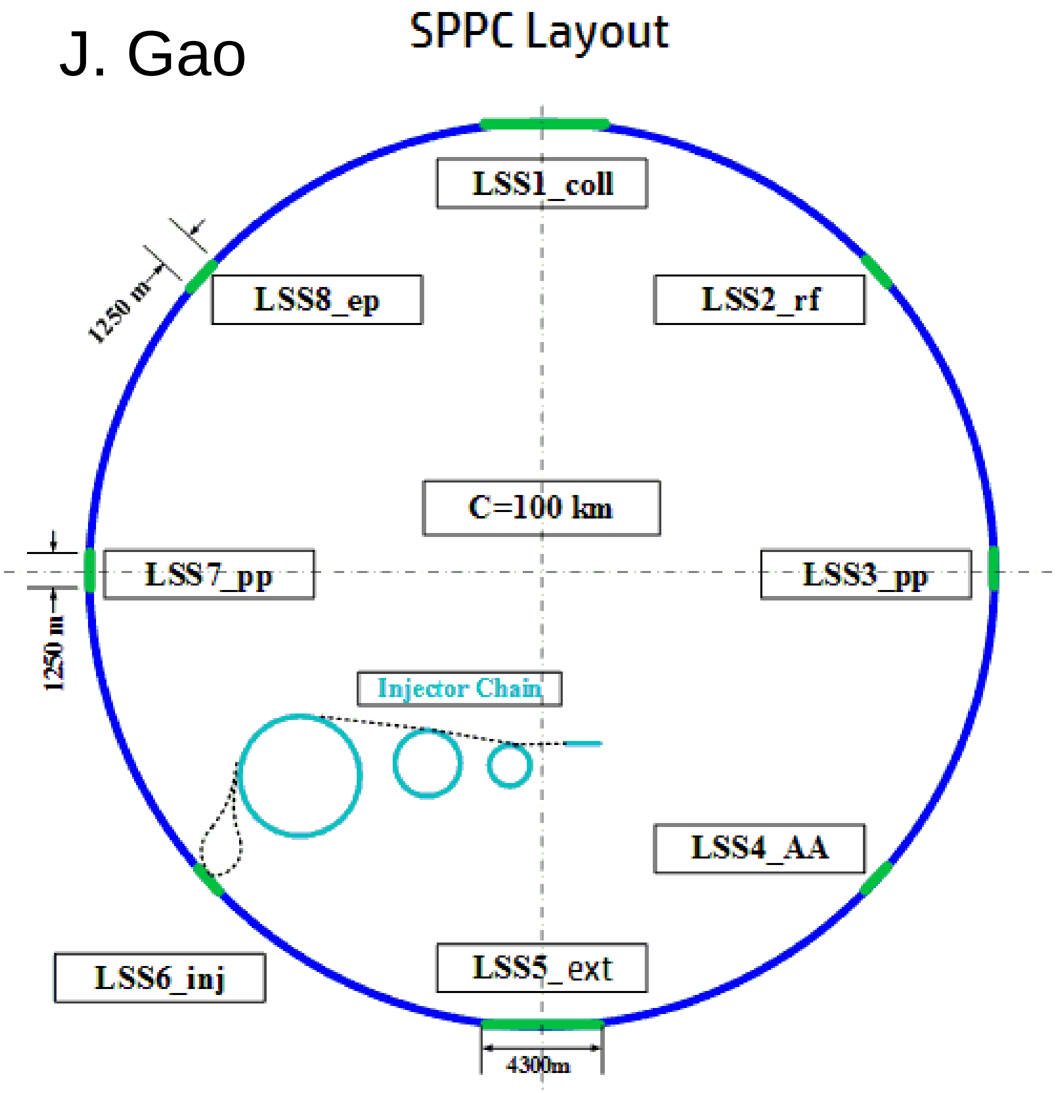
SPPC main parameters

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



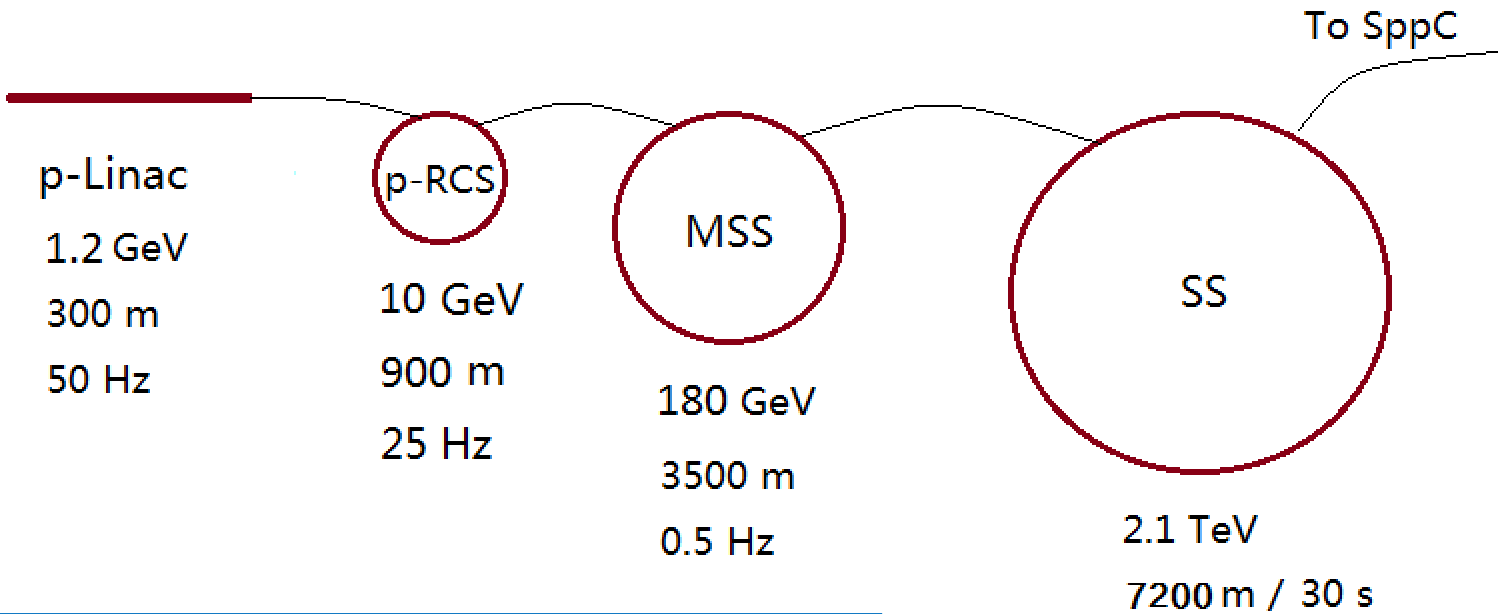
circumference: 100 km

- 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

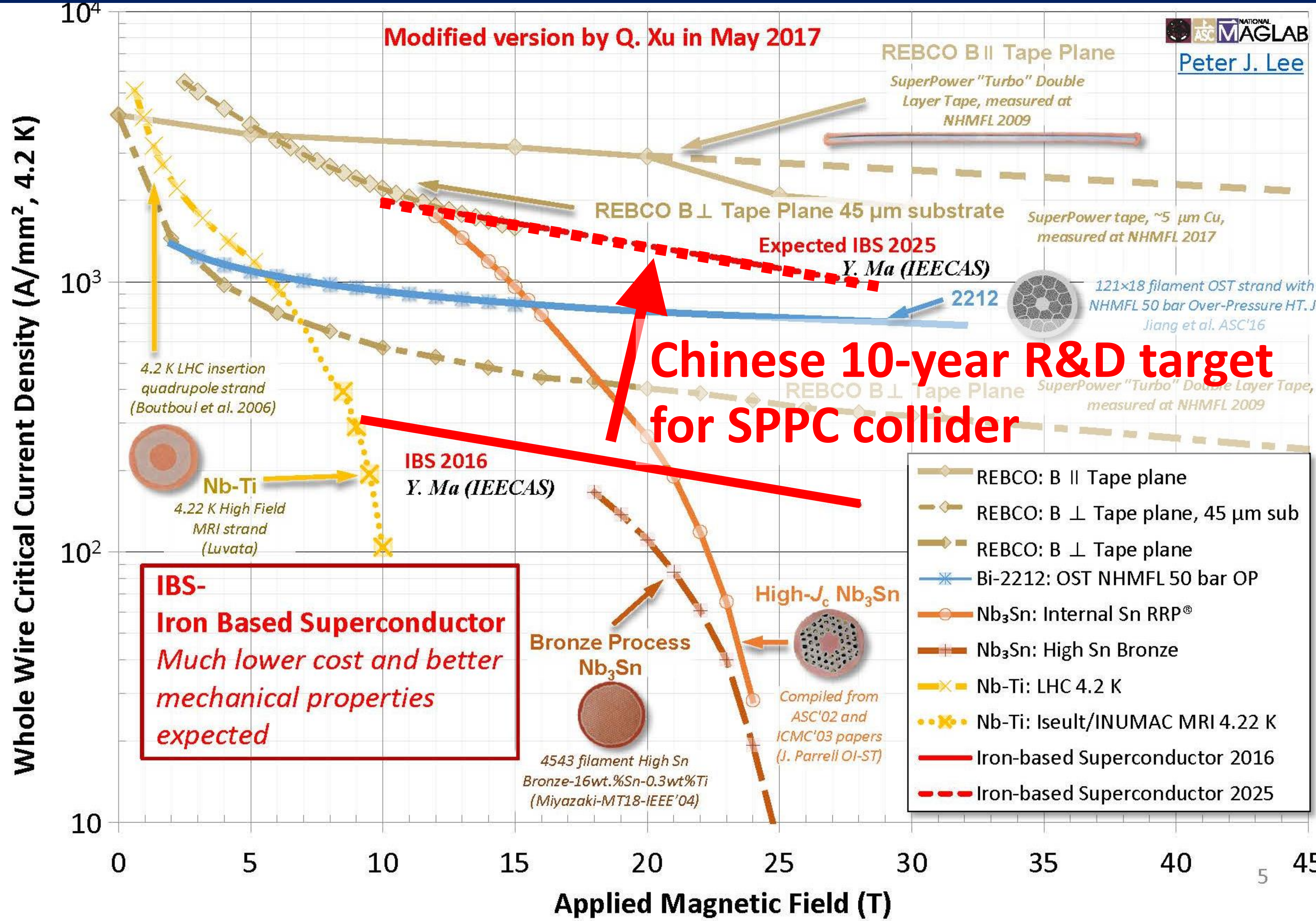
MSS: Medium-Stage Synchrotron

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

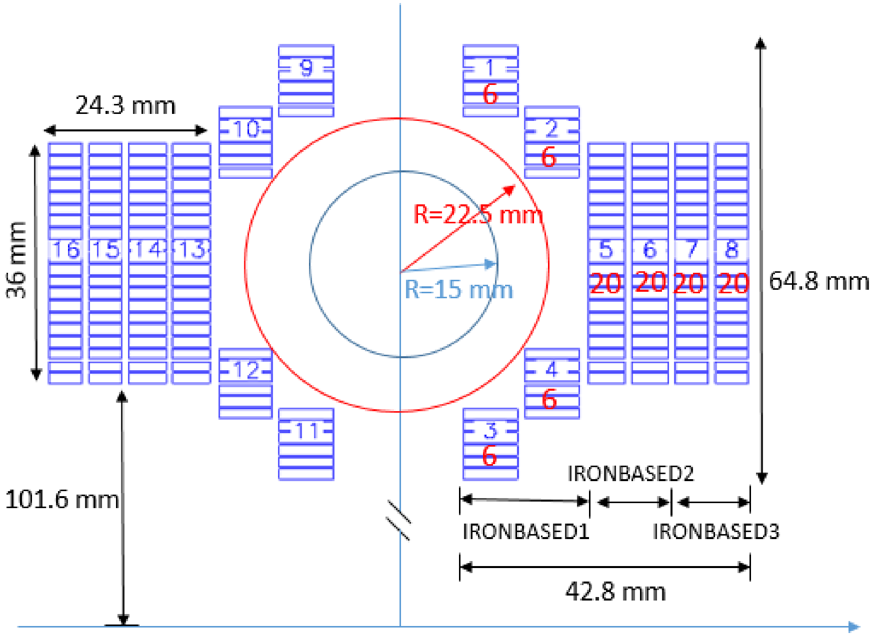
In October 2016, A consortium for High-temperature superconducting materials, industrialization and applications was formed in China, with participation of major research and production institutions on HTS.

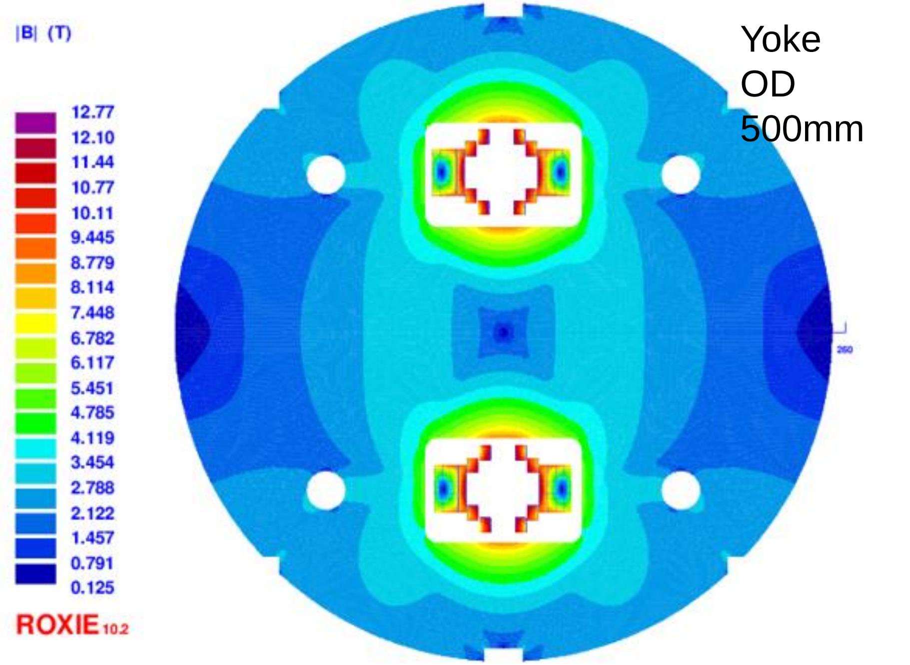
China is actually leading the development of Fe-HTS technology in the world; world-first 100-m Fe-HTS wire was made by CAS-Institute of Electrical Engineering in the last year .

J. Gao,
J. Tang,
Q. Xu

SppC Design of 12-T Fe-based Dipole Magnet

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





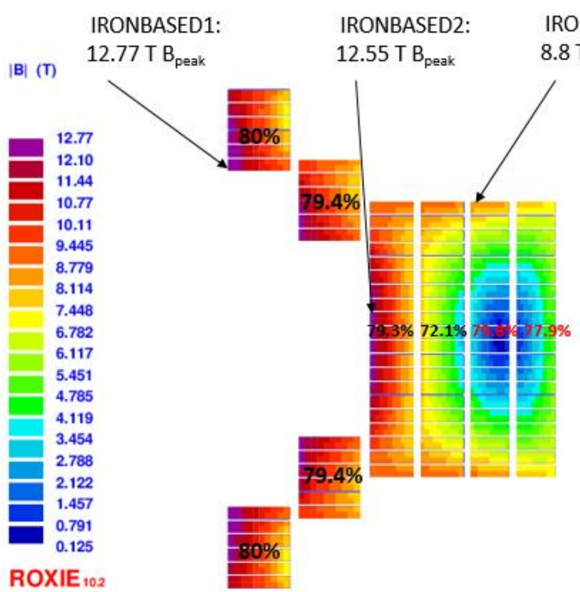


Table 1: Main parameters of the cables

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

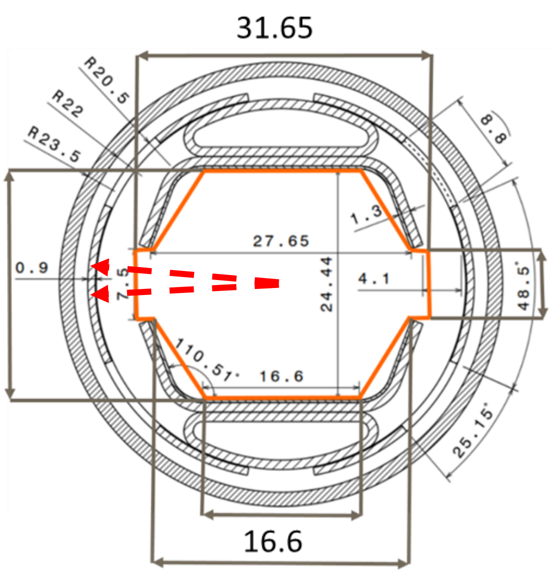
Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IRON-BASED	0. 802	1	200	4. 2	10	4000	111

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

FCC-hh cryogenic beam vacuum system

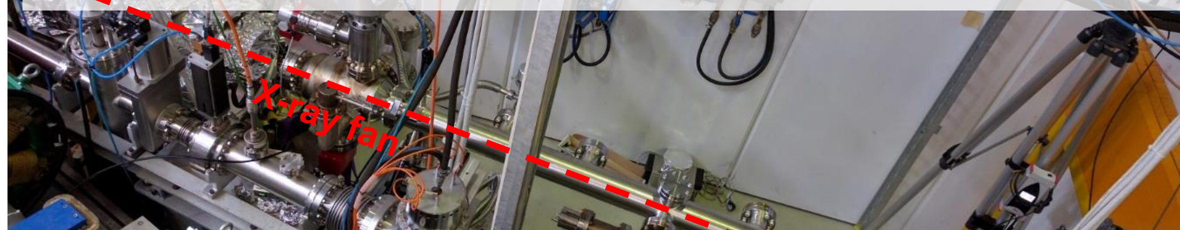
synchrotron radiation **(~ 30 W/m/beam (@16 T field)** (cf. LHC <0.2W/m) **~ 5 MW total load in arcs**

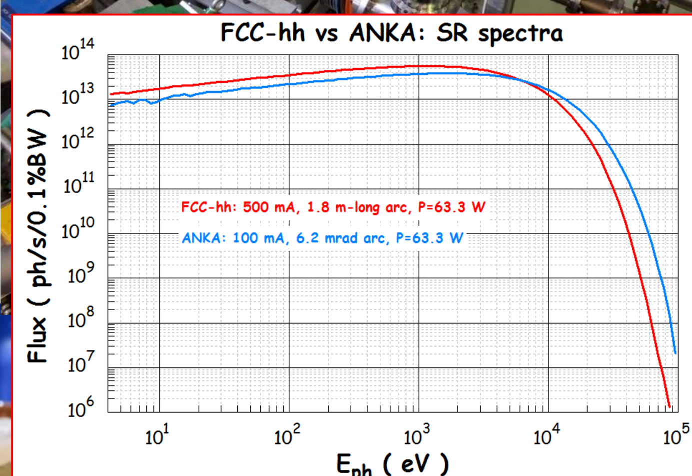
- **absorption of synchrotron radiation at higher temperature (> 1.8 K)** for cryogenic efficiency
- provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.



FCC-hh beam-screen test set-up at ANKA/Germany:

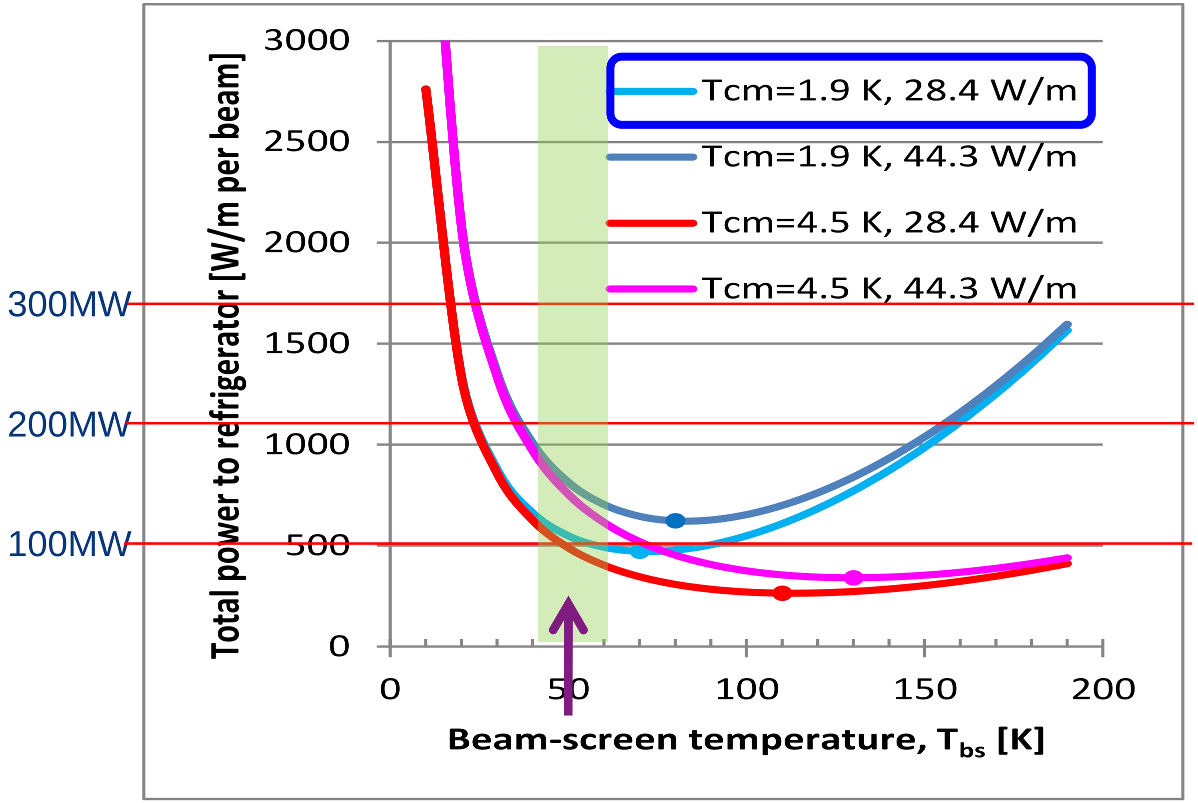
beam tests since June 2017, for prototypes, confirming vacuum design simulations





ANKA e^- photon spectrum = FCC –hh spectrum

FCC-hh cryoplants – energy efficiency



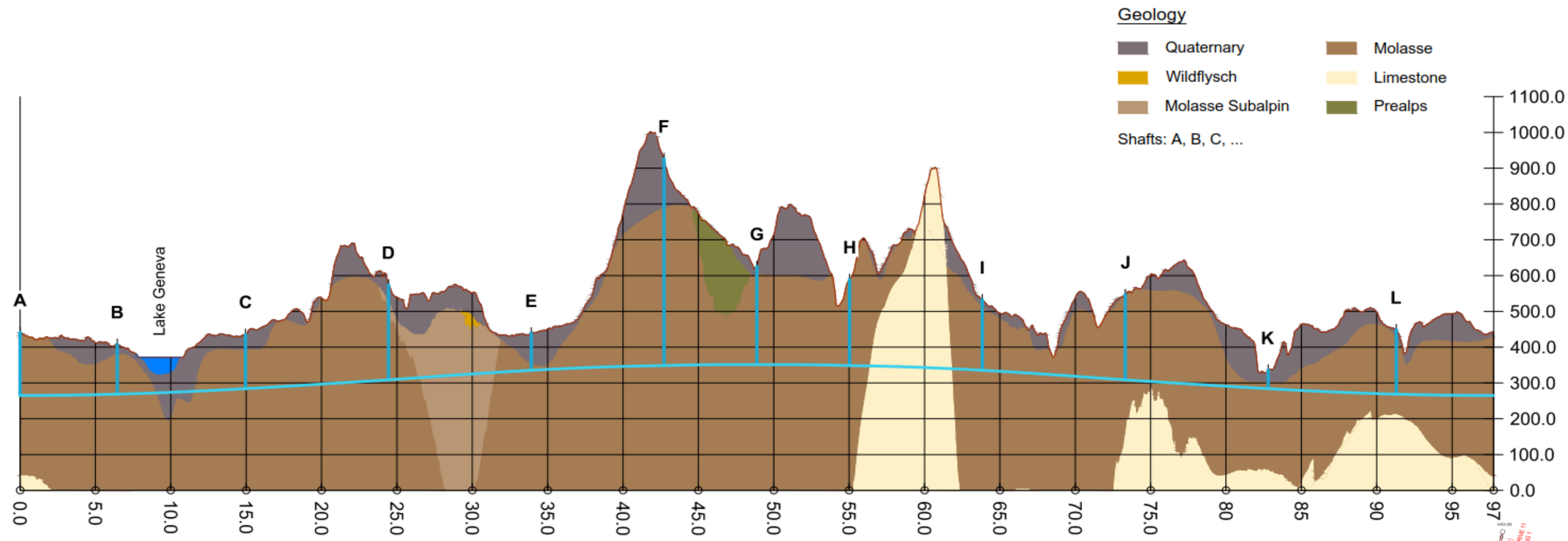
BS temperature choice through overall optimisation:

- **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 .**

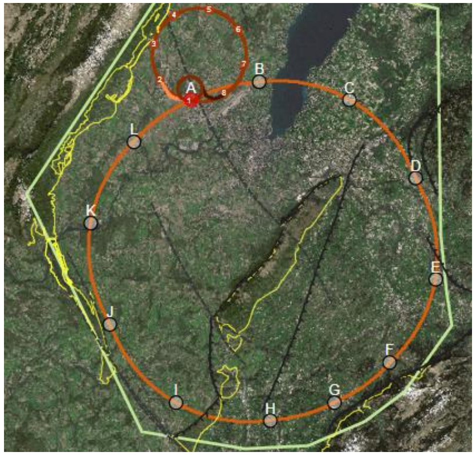
FCC implementation - footprint baseline

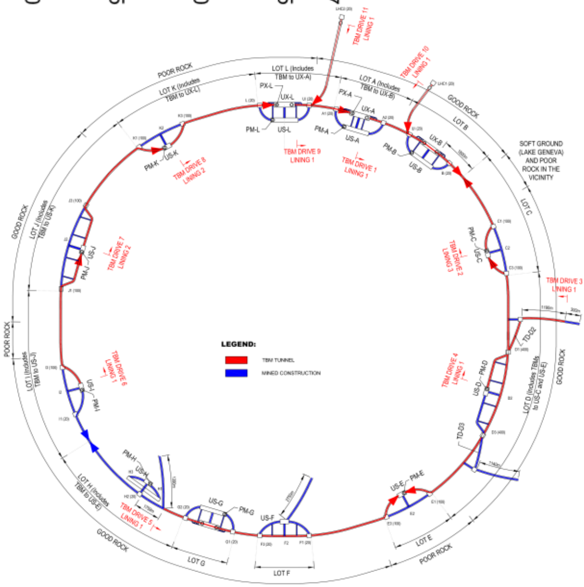


present baseline position established considering:

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

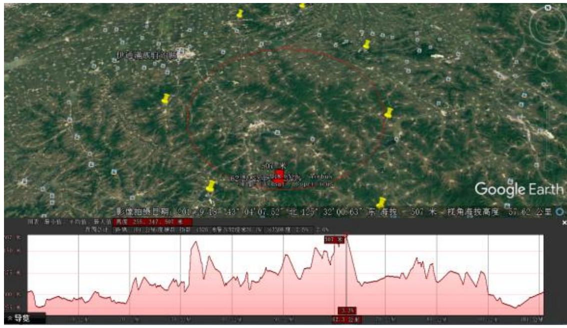
next step: review of surface site locations and machine layout



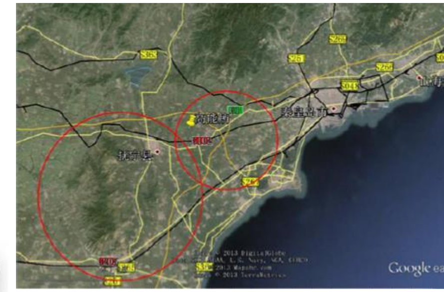


J. Osborne, J. Stanyard

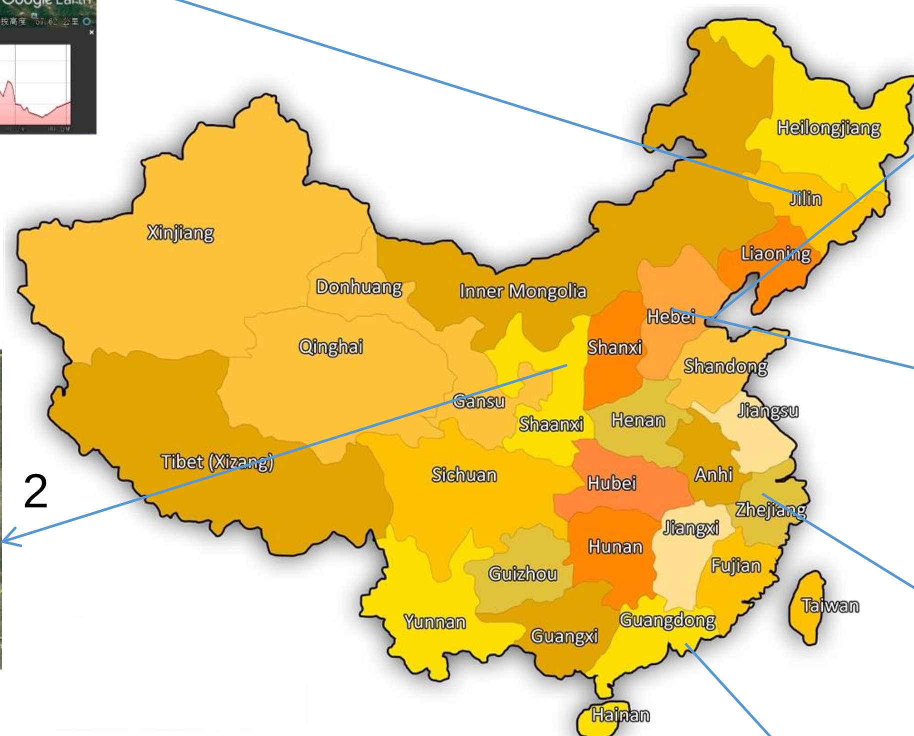
CEPC Site Selections

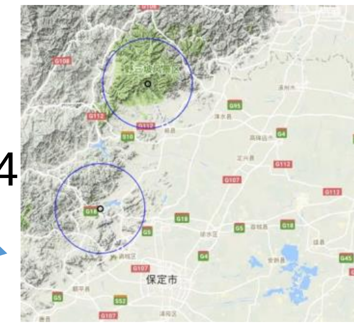


6

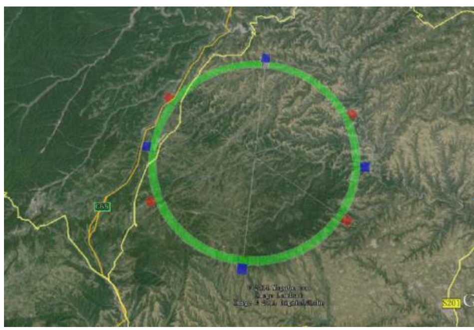


1

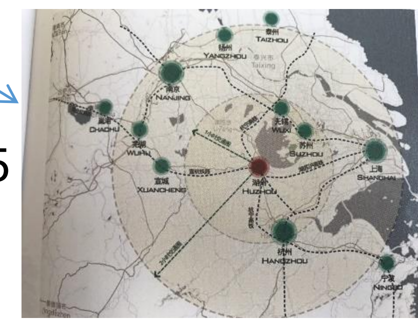




4



2



5

1) Qinhuangdao, Hebei Province（Completed in 2014）

2) Huangling, Shanxi Province（Completed in 2017)

3) Shenshan, Guangdong Province(Completed in 2016)

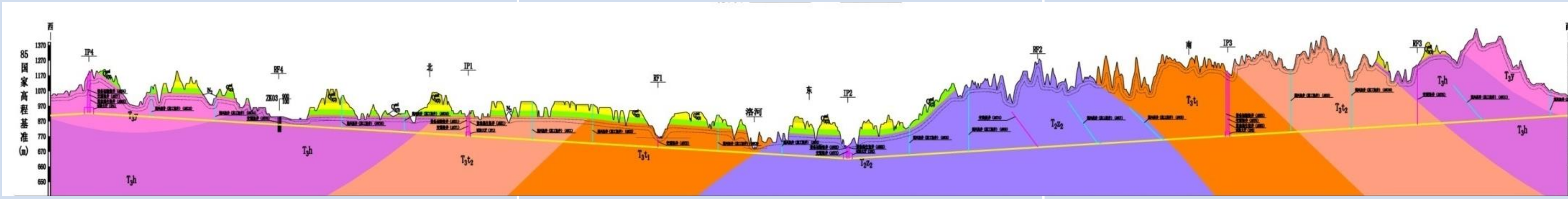
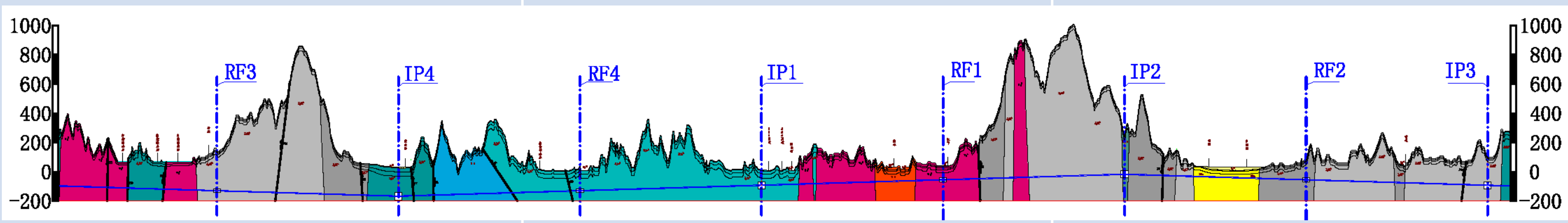
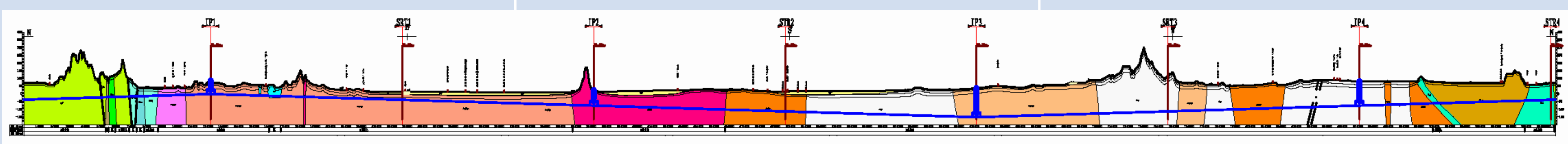
4) Baoding (Xiong an), Hebei Province (Started in August 2017)

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

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

3

J. Gao

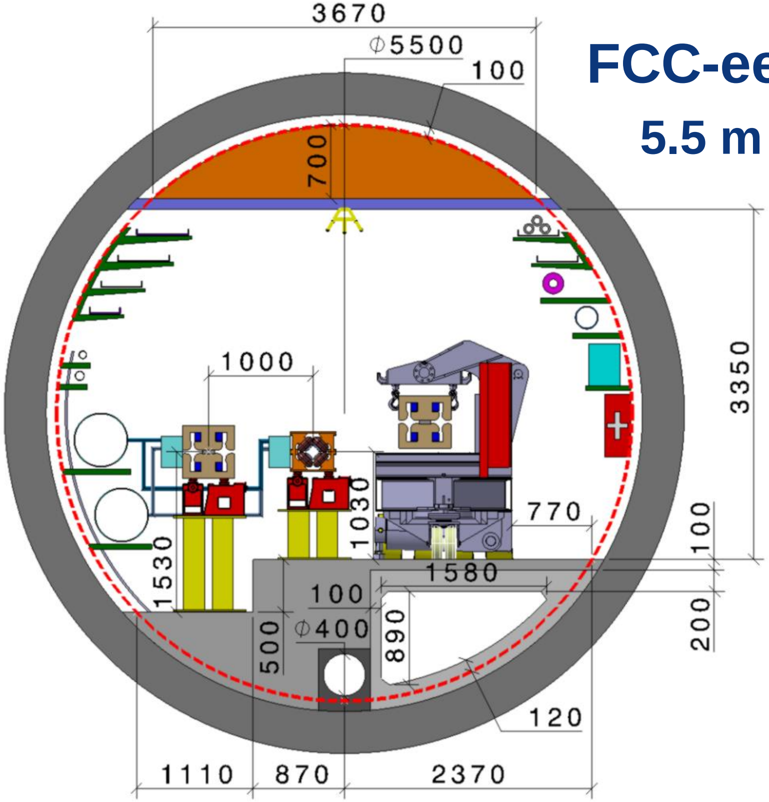
<table>
<tr><th>Item</th><th>Huangling</th><th>Shenshan</th><th>Funing</th></tr>
<tr><td rowspan="6">Project layout</td><td colspan="3">Huangling (100 km)</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Shenshan (100 km)</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">Funing (100 km)</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Construction difficulty</td><td>Moderate</td><td>Relatively difficult</td><td>Relatively easy</td></tr>
</table>

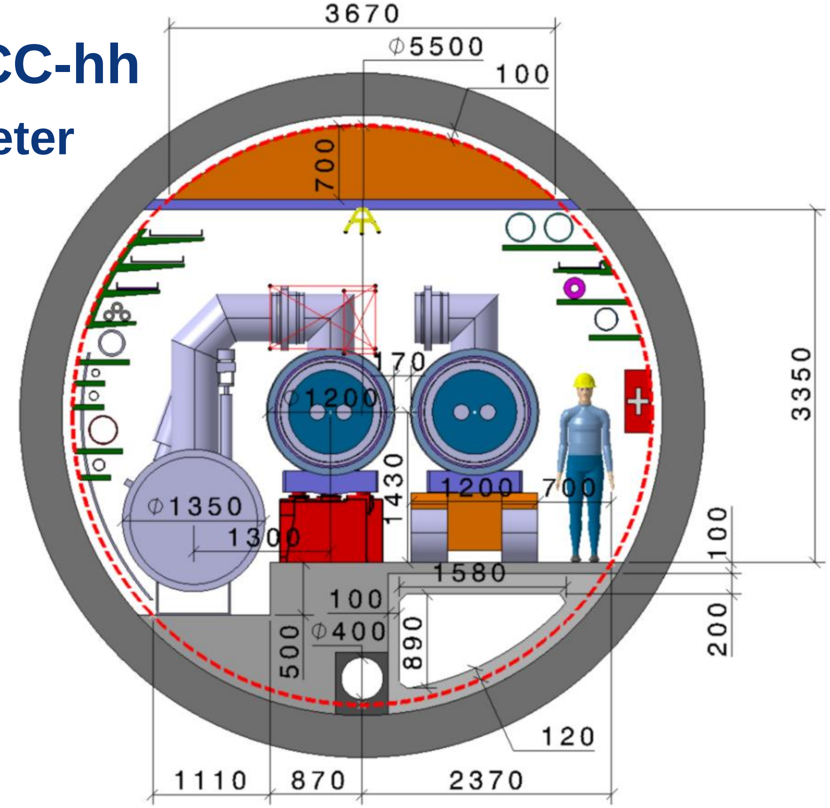
X. Lou

FCC – tunnel integration in arcs

FCC-ee **FCC-hh**

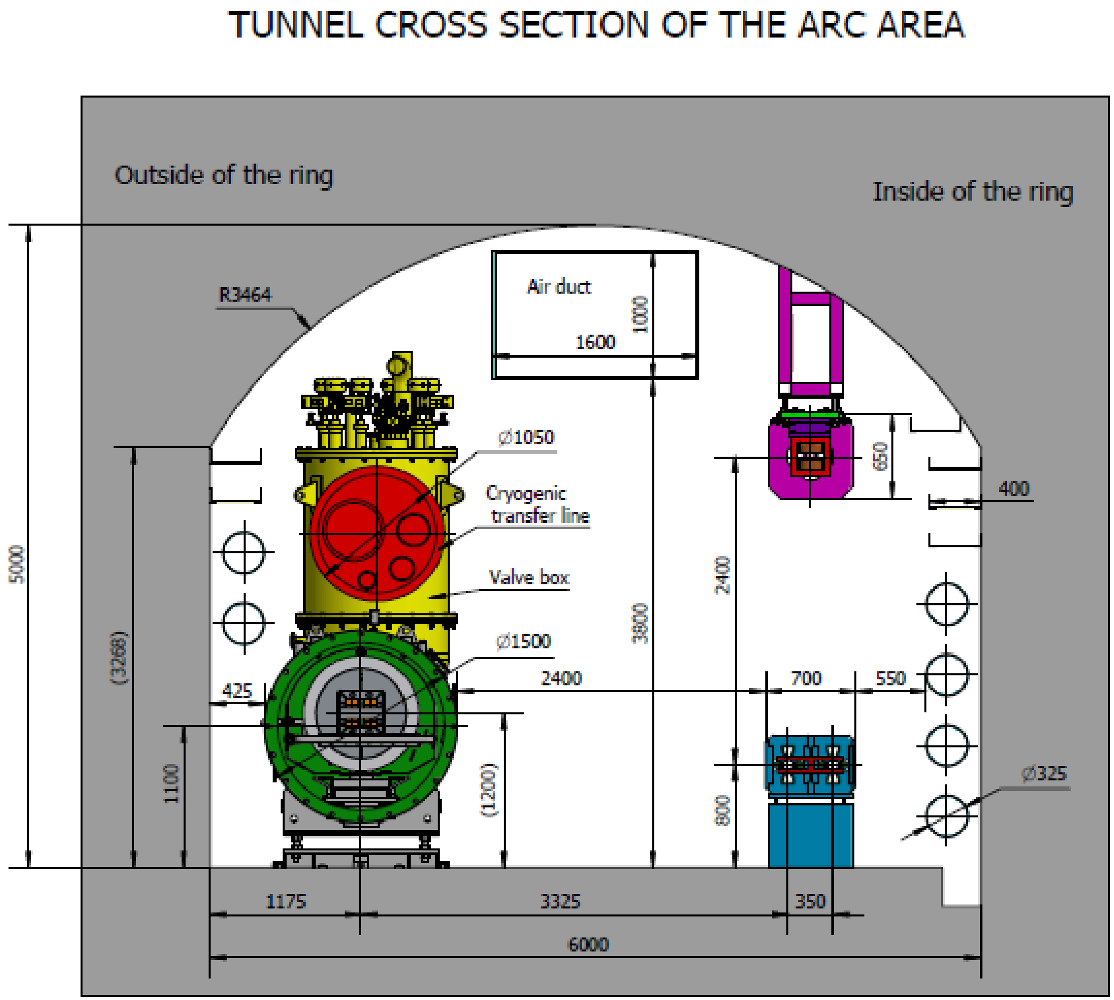
5.5 m inner diameter





V. Mertens

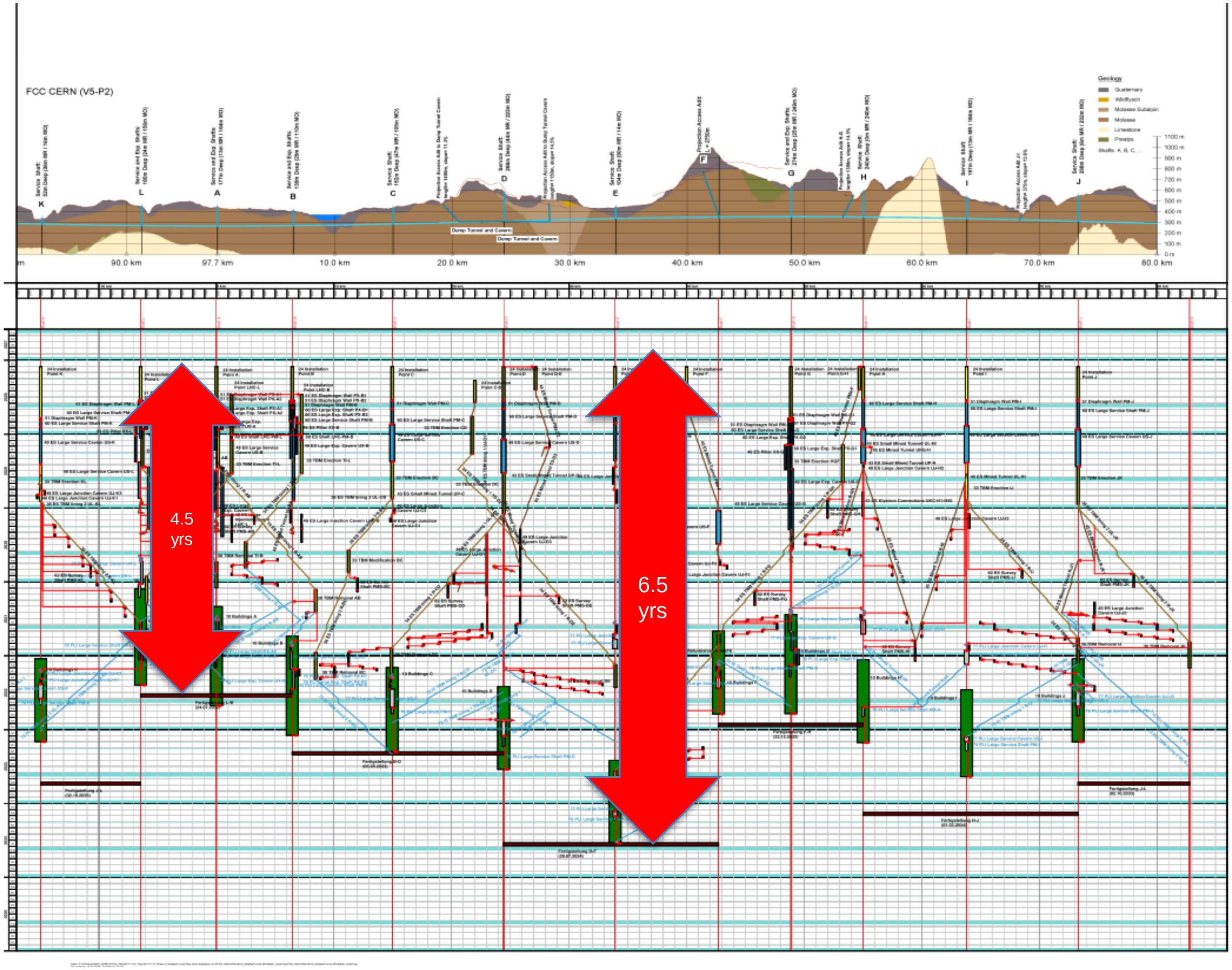
CEPC/SppC – tunnel integration in arcs



6.0 m width, hosting 5 rings simulatenously

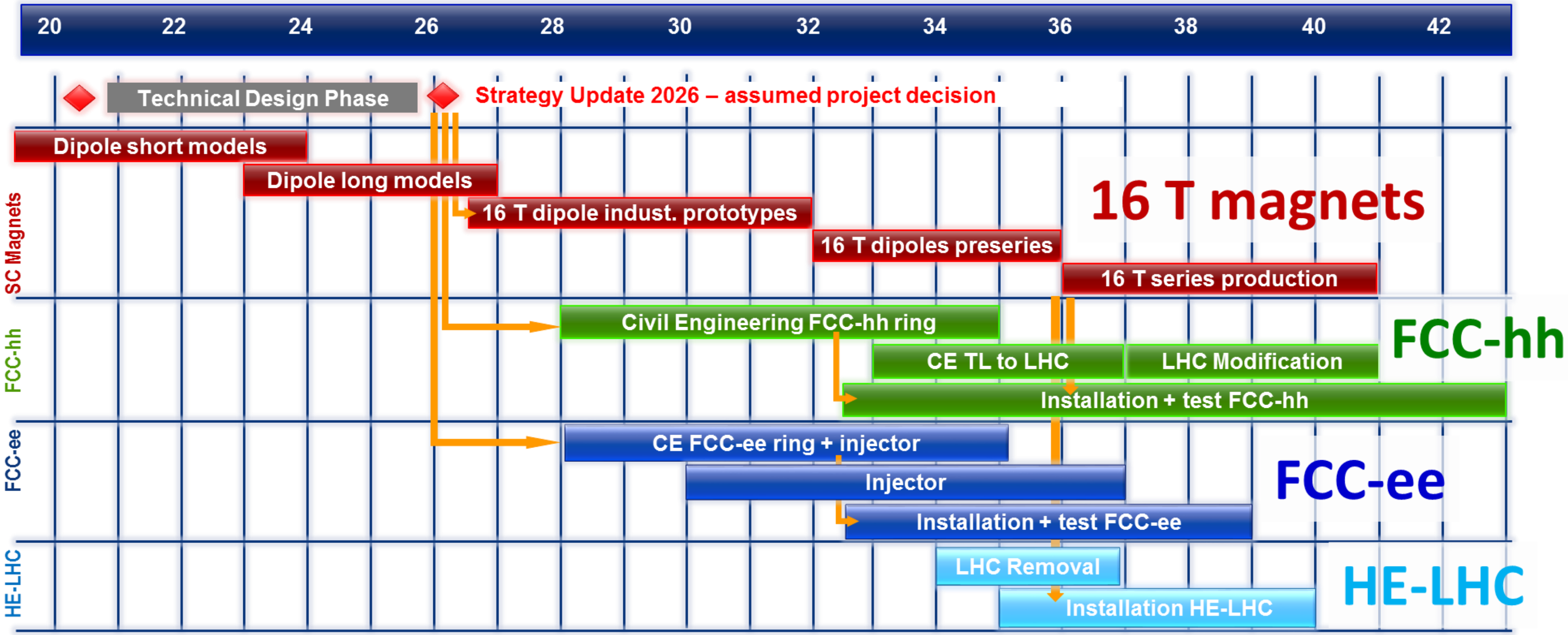
J. Gao

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)**

Global FCC Collaboration

from Italy
- *CNR-SPIN*, Genoa
- *CSIL*, Milan
- *INFN*, Frascati (Roma)
- *Sapienza*, Rome
- *UNICAL*, Arcavacata di Rende
- *UNIGEOA*, Genova
- *UNIMI*, Milan
- *UNIROMA3*, Roma

124 Institutes

30 Companies

32 Countries

EC H2020

EU H2020 Design Study EuroCirCol

UNIVERSITY OF TWENTE.

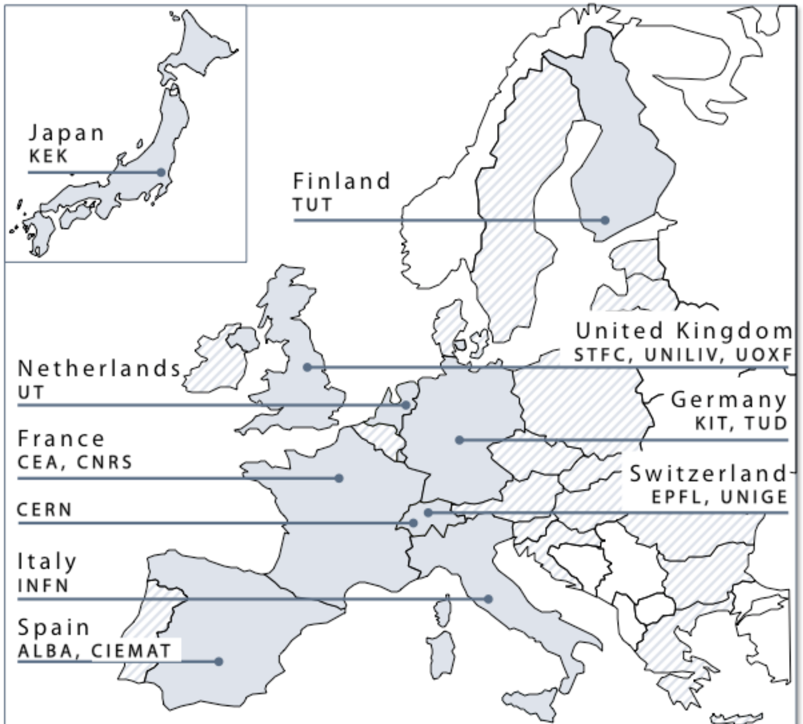
INFN

TAMPERE UNIVERSITY OF TECHNOLOGY

EuroCirCol

cea

cnrs dépasser les frontières



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

CERN

UNIVERSITY OF LIVERPOOL

UNIVERSITY OF OXFORD

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

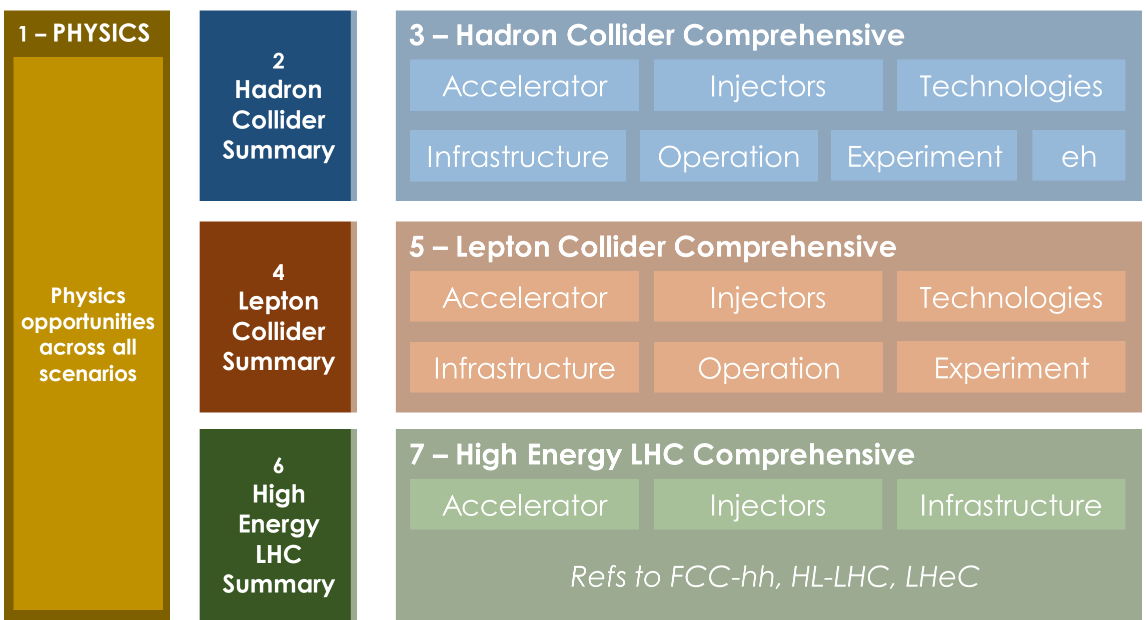
CDR Concise summary volumes 1 (PH), 2 (hh), 4 (ee), 6 (HE):

- 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



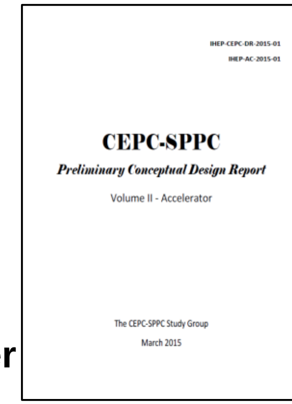
M. Benedikt

CEPC Accelerator from Pre-CDR to CDR

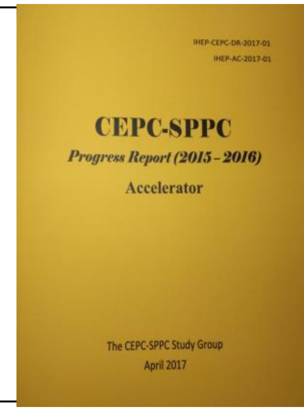
J. Gao

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

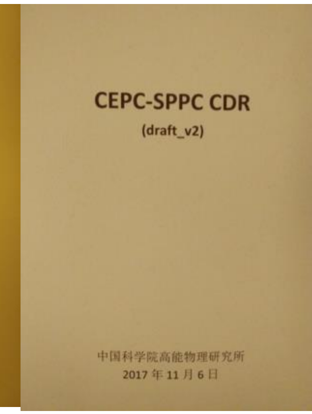
- **Executive Summary**
  1. **Introduction**
  2. **Machine Layout and Performance**
  3. **Operation Scenarios**
  4. **CEPC Collider**
  5. **CEPC Booster**
  6. **CEPC Linac**
  7. **Systems Common to the CEPC Linac, Booster and Collider**
  8. **Super Proton Proton Collider**
  9. **Conventional 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



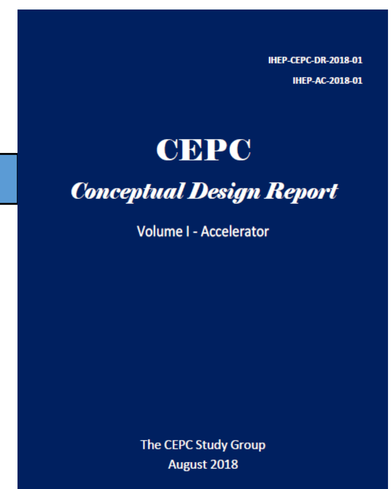
March 2015



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

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-$\mu\mu$

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

EuroCirCol Final Meeting & FCC Week 2019

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

appendix: path to FCC-$\mu\mu$

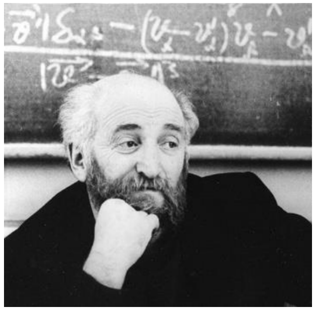
how to go further – beyond FCC-hh?

muon collider* is back !

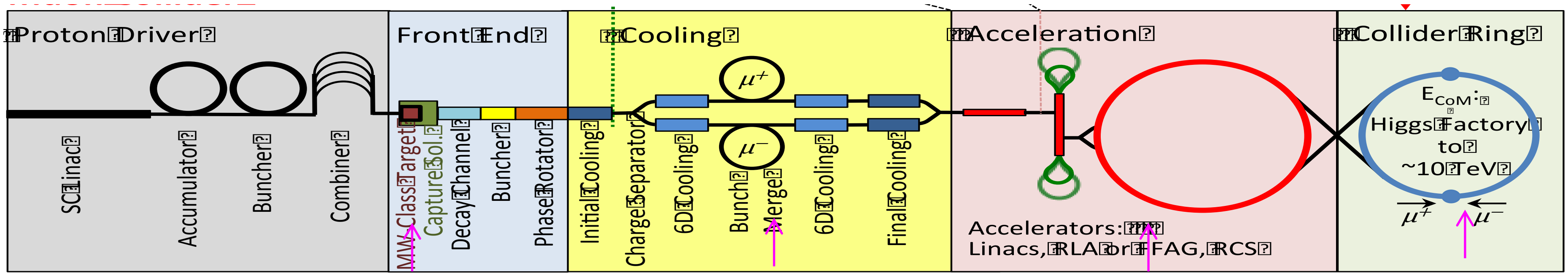
3 recent new ideas :

- 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)



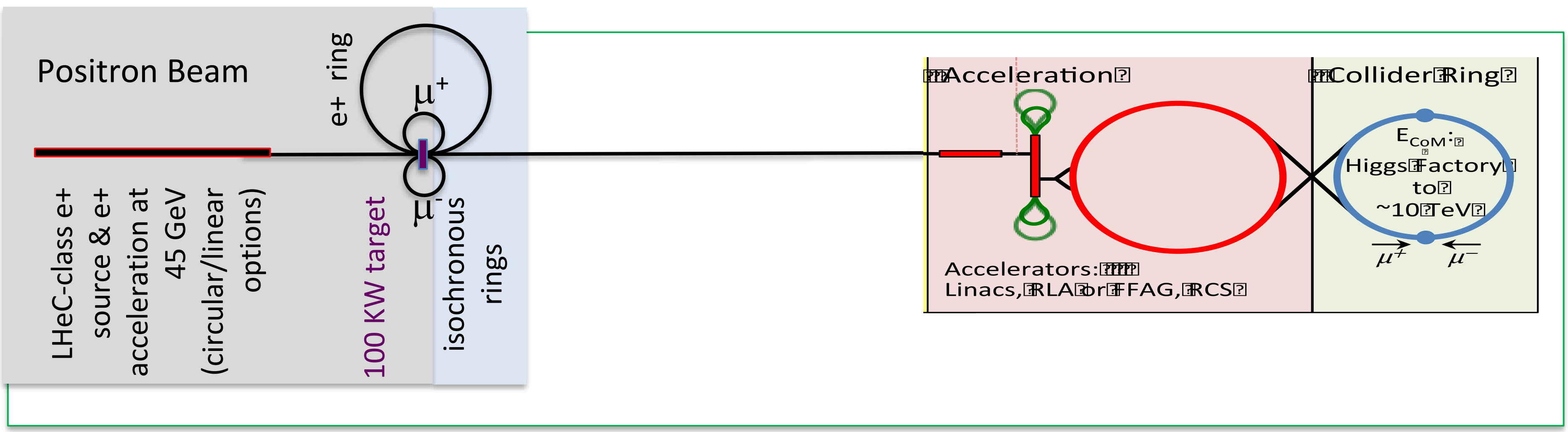
key challenges

~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 $e^+e^- \rightarrow \mu+\mu-$

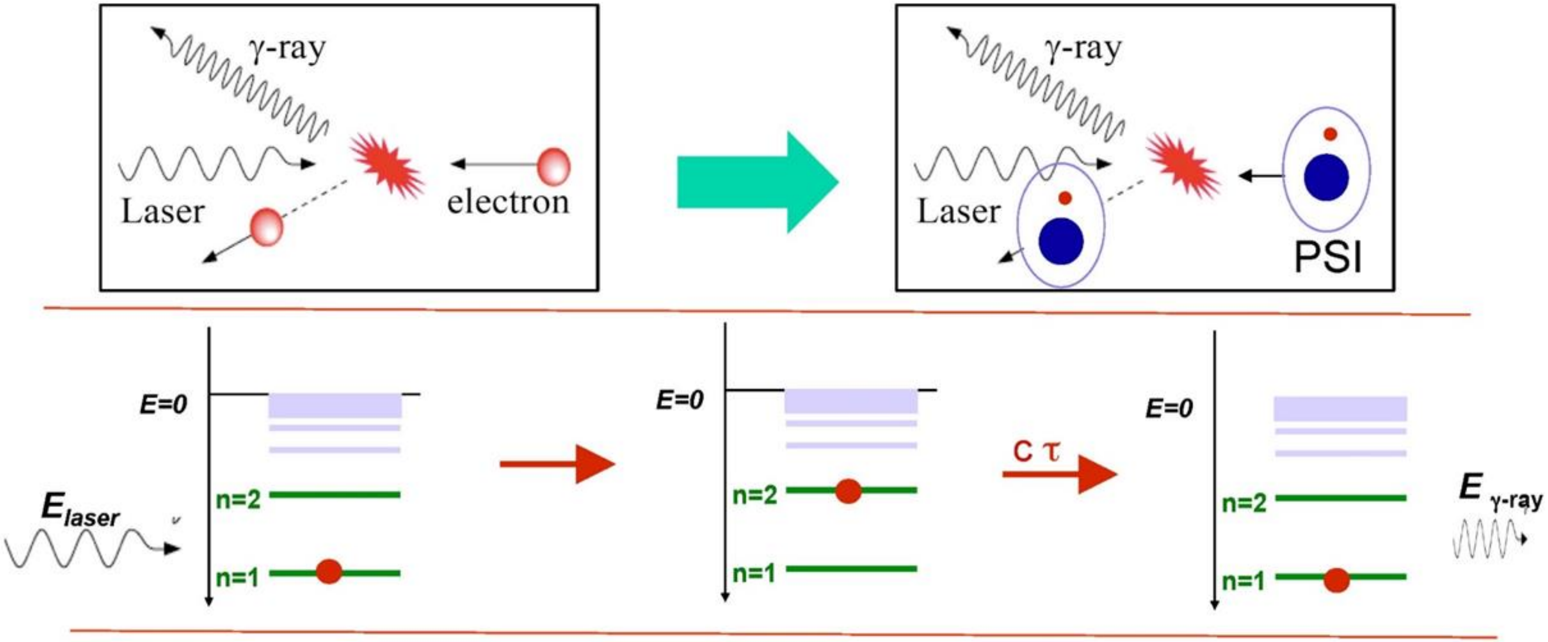
key R&D

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



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

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

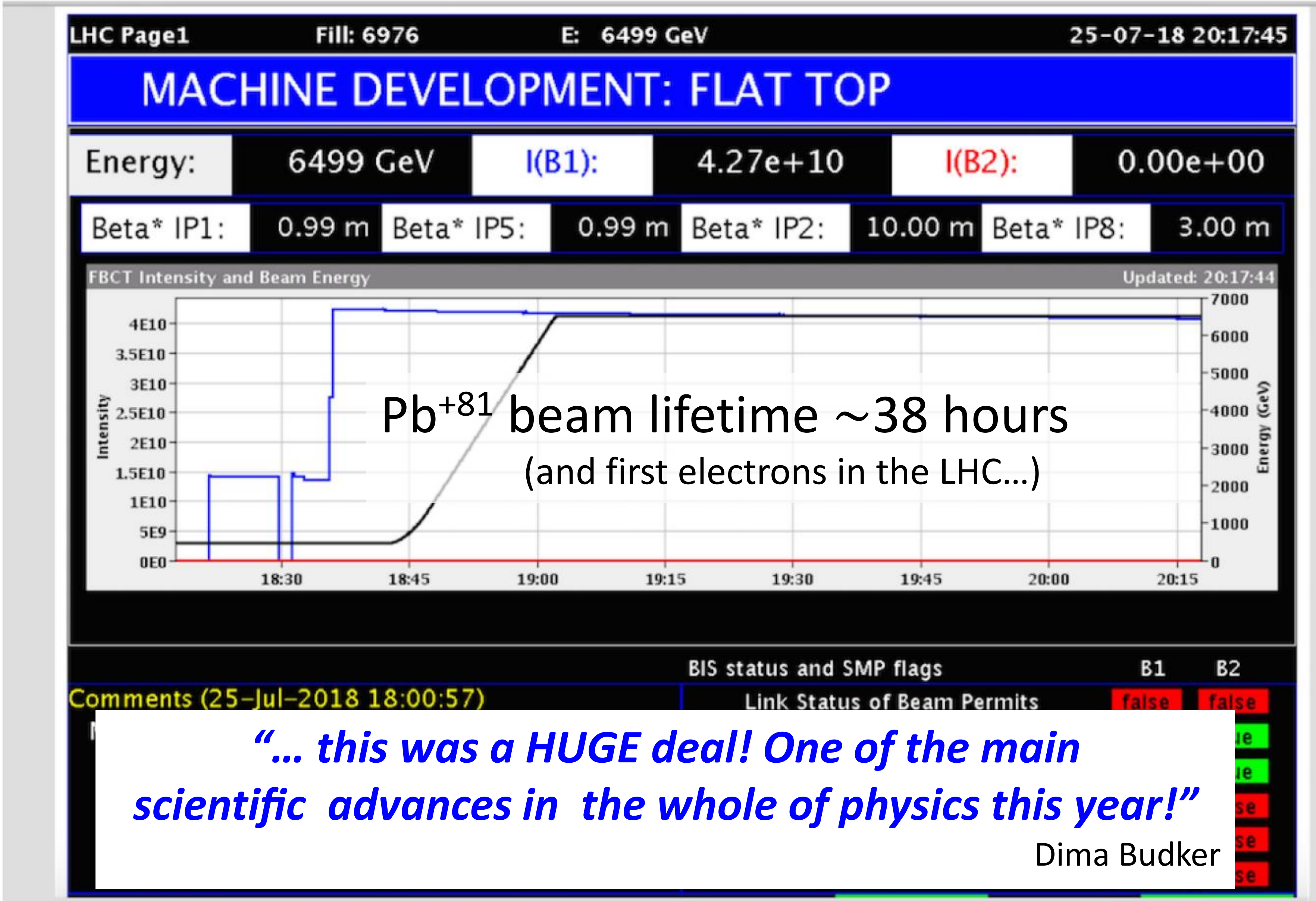
Note: $(E_{laser}/m_{beam}) \times 4\gamma_L \ll 1$

high photon energies,
high cross section

W. Krasny

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

γ factory proof-of-principle experiment in the LHC



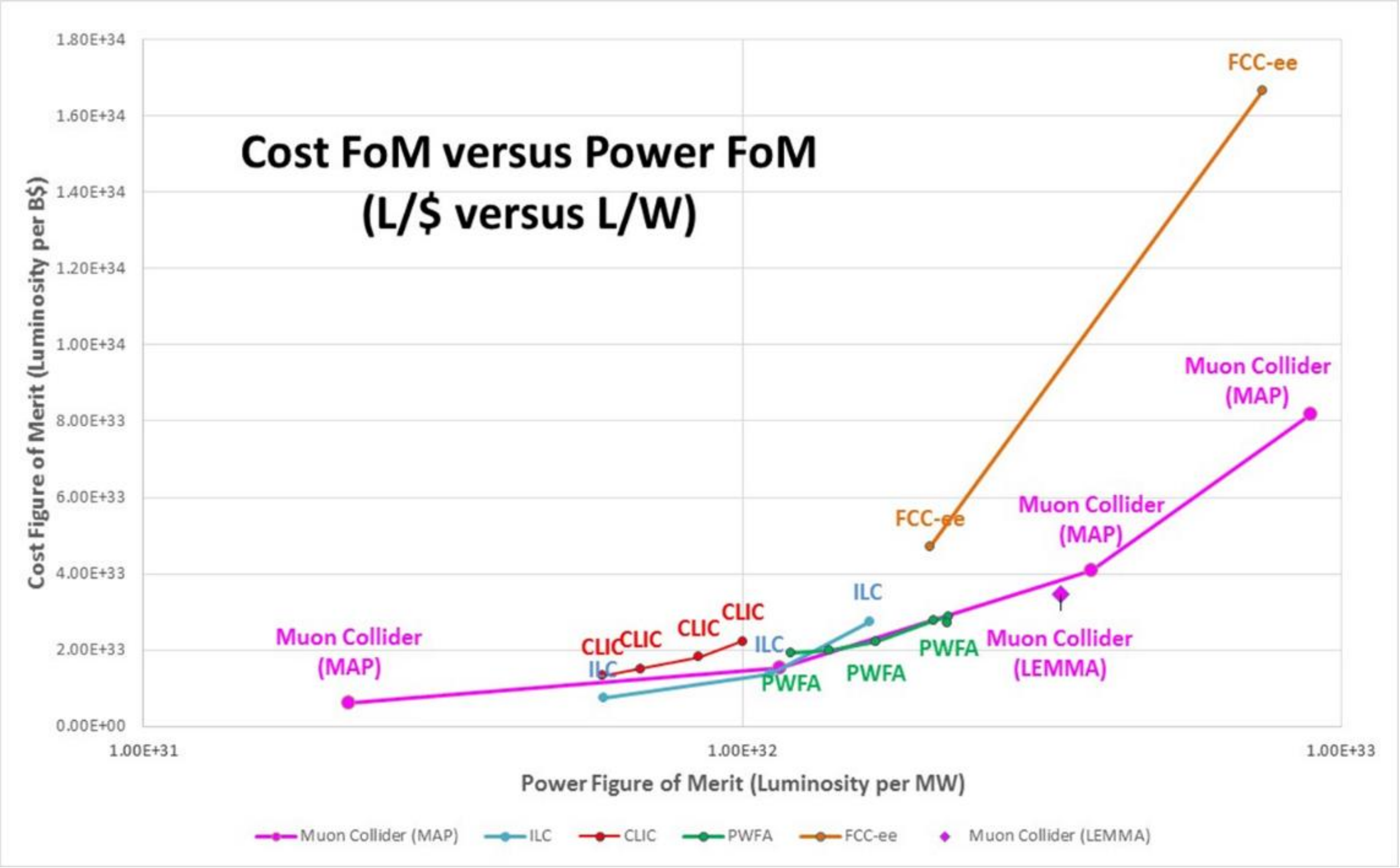
Pb^{+81} beam lifetime ~38 hours

(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

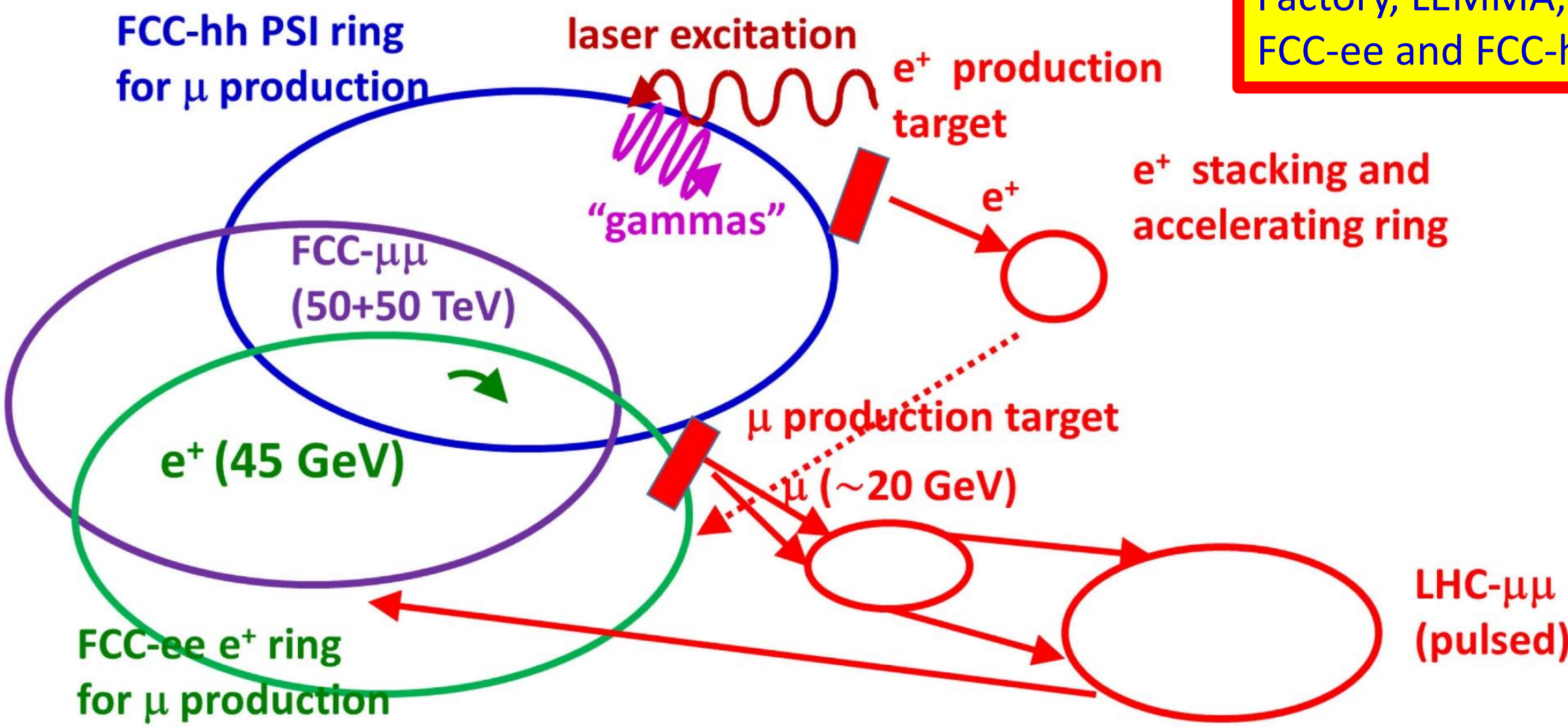
cost & power efficiency of future lepton colliders



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



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

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