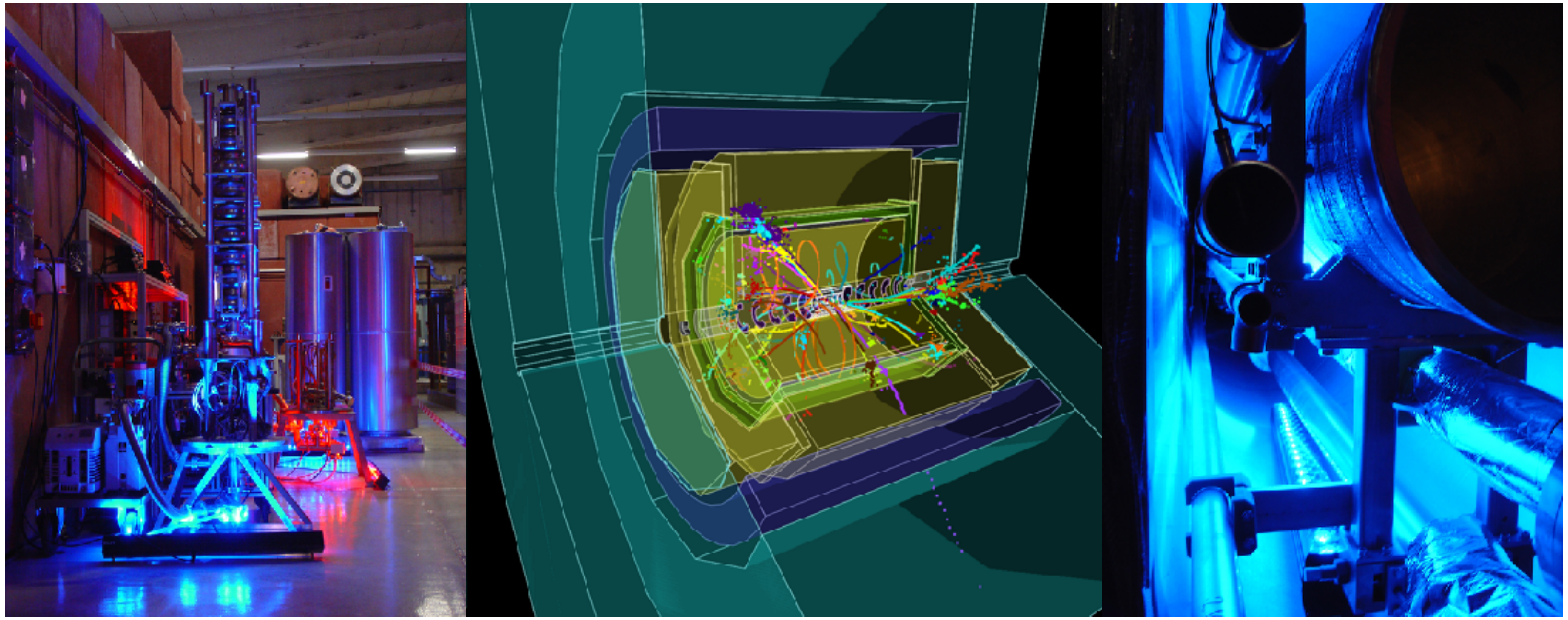
Future Colliders for the Energy Frontier



Karsten Buesser
DESY, 19.08.2019

Outline

A little bit of history: how the rush for high energy accelerators came on (and why)

Which particles to collide? And how?

The Circular Path:

- The Present: LHC
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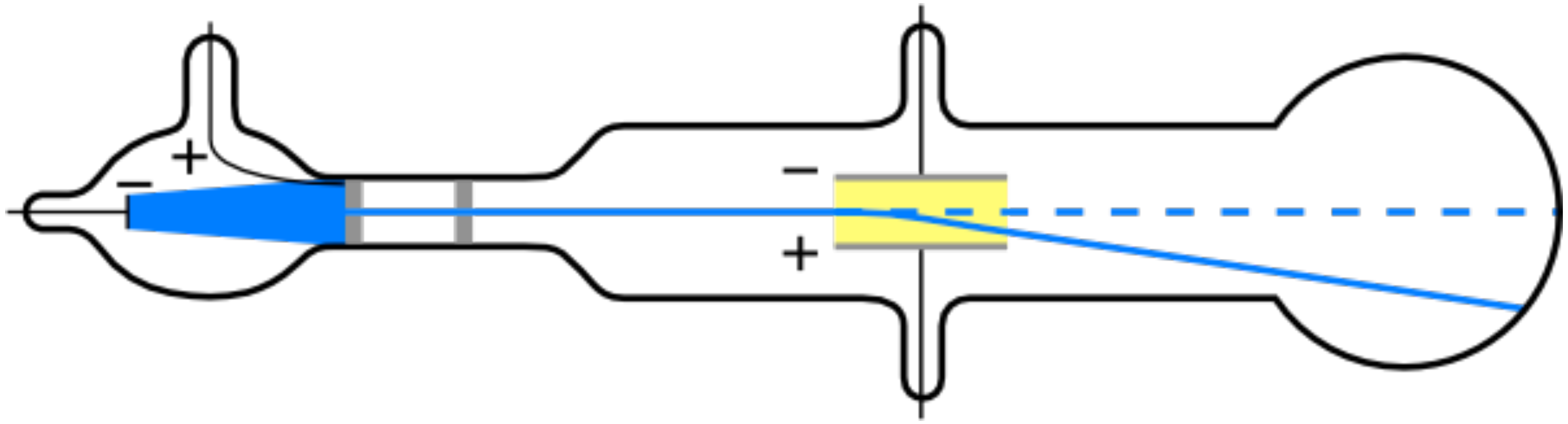
The Real Axis - the Real Frontier…

History

One of The First Linear Accelerators

J.J. Thomson (1897)

- Measurement of q/m ratio of cathode ray particles with electric bending fields
- New particle: 1800 times lighter than the hydrogen atom
- The electron was found!

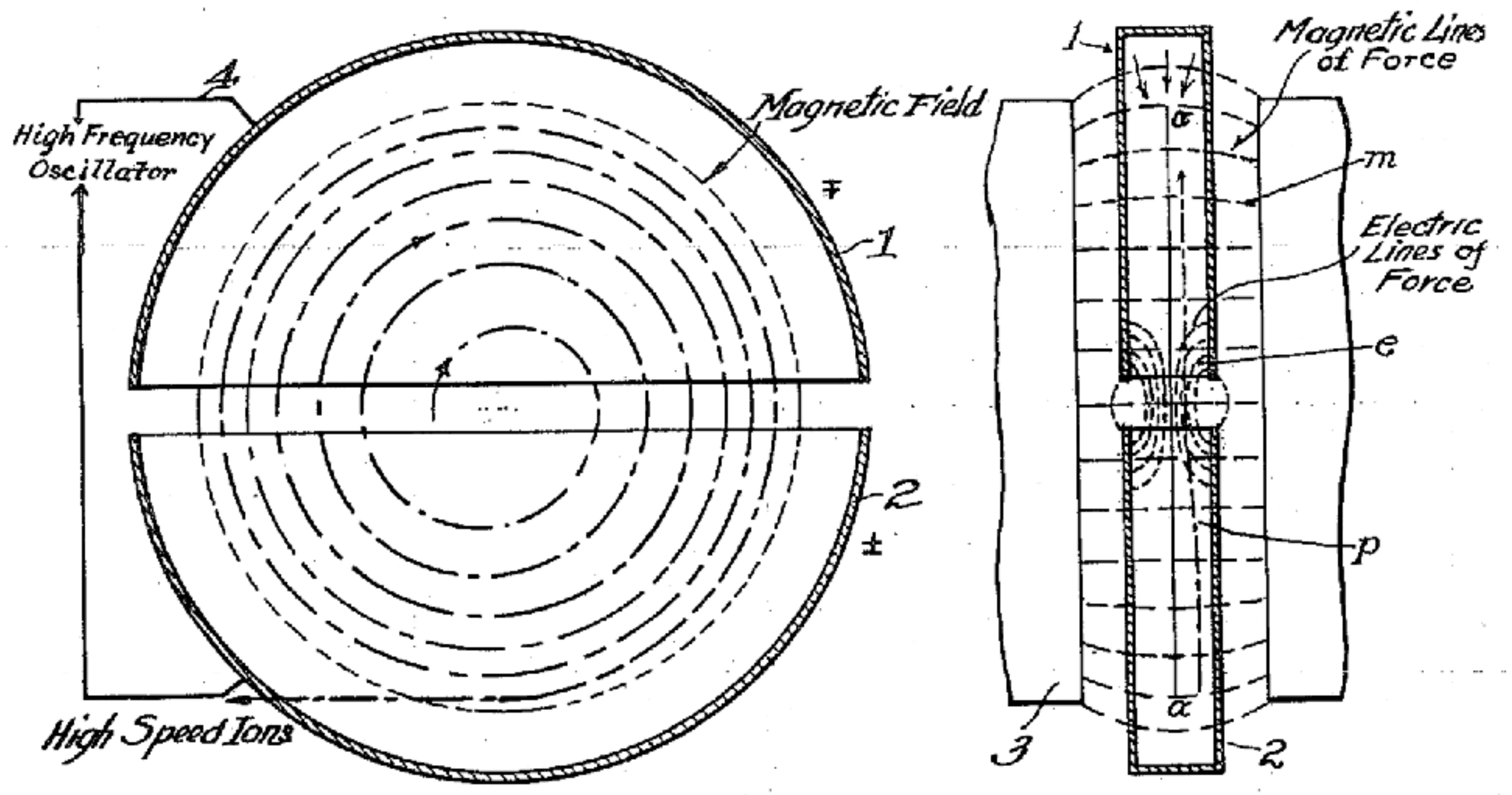


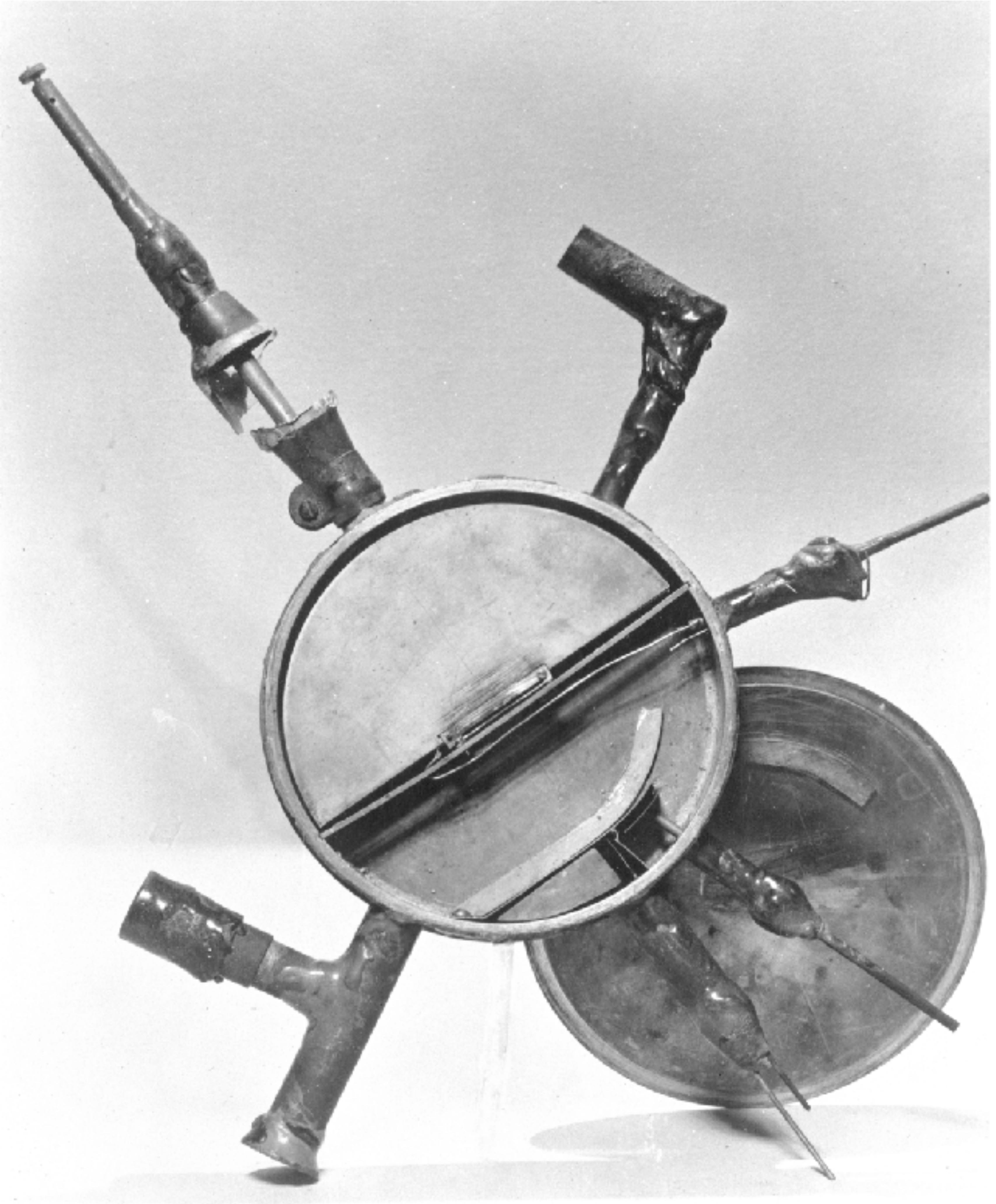
Electrons accelerated with 1 V gain energy of 1 electron volt (eV):
Electrons in cathode ray tubes: ~10.000 eV

The First Circular Accelerator

E.O. Lawrence (1931)

- 5-inch-cyclotron (12,7cm)
- Accelerating voltage: 2 kV
- Particle energies: 80 keV
- Hadron machine!





Big Science (1939): 60-inch-Cyclotron

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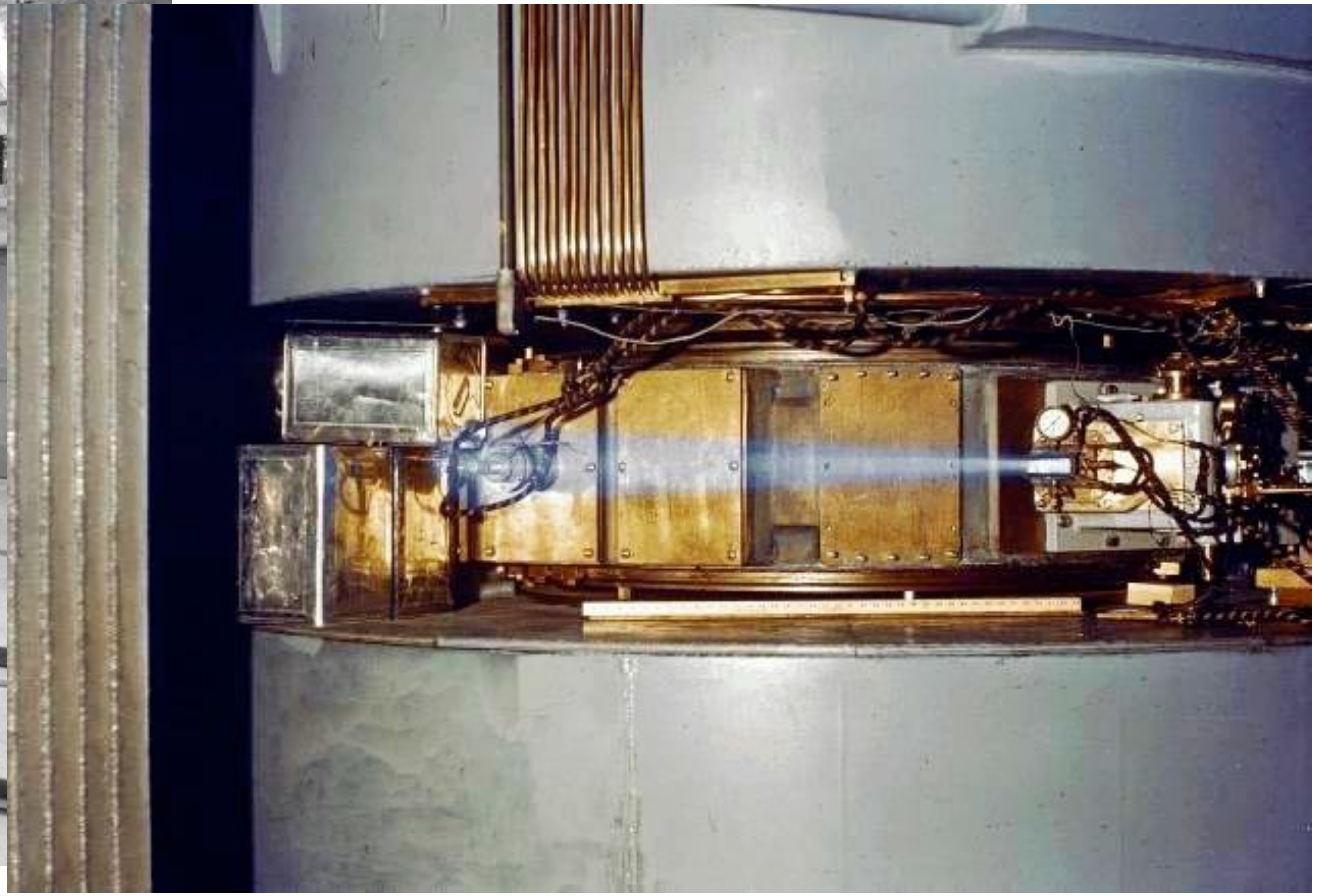
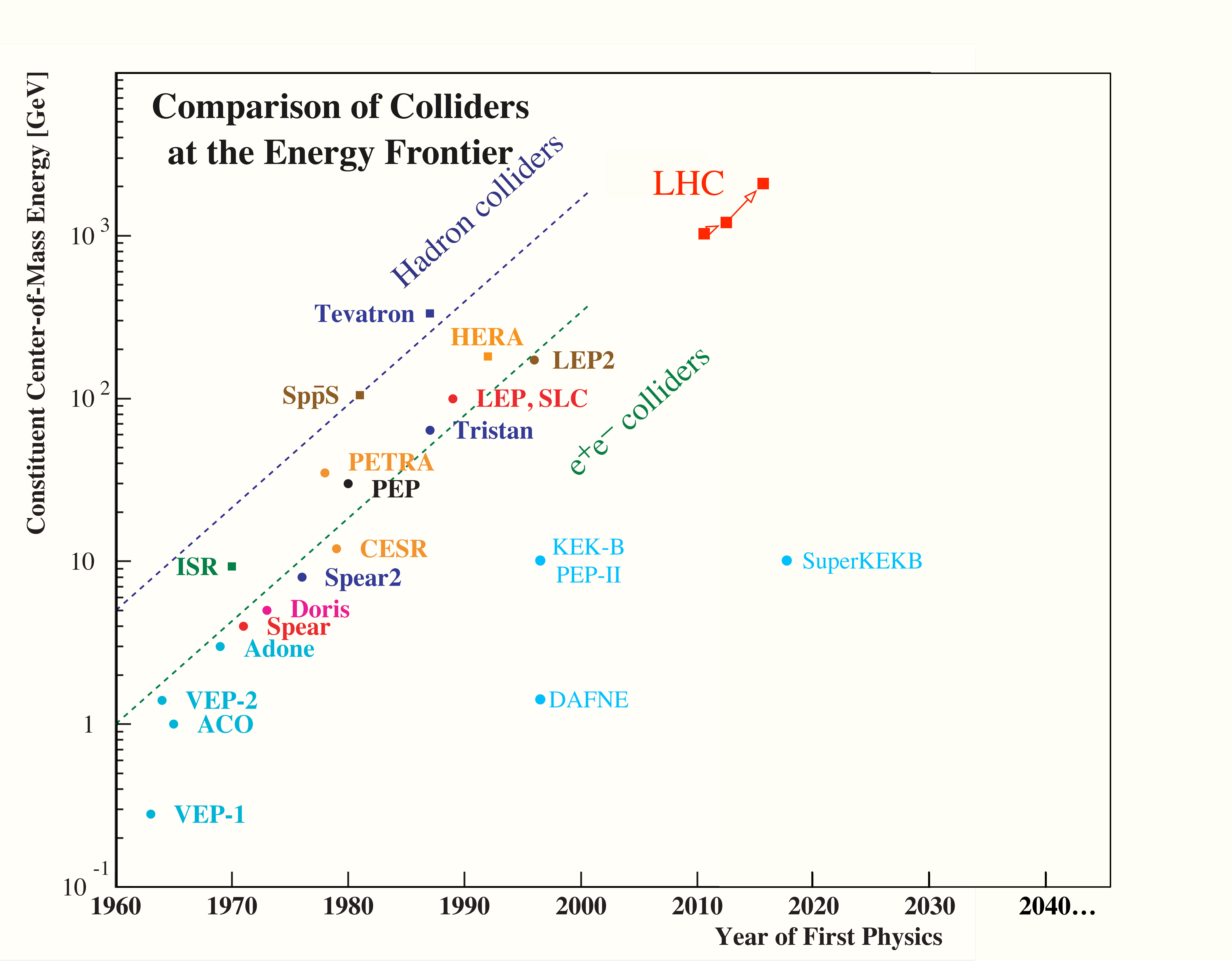


Even Bigger Science (1946): 184-inch-Cylcotron

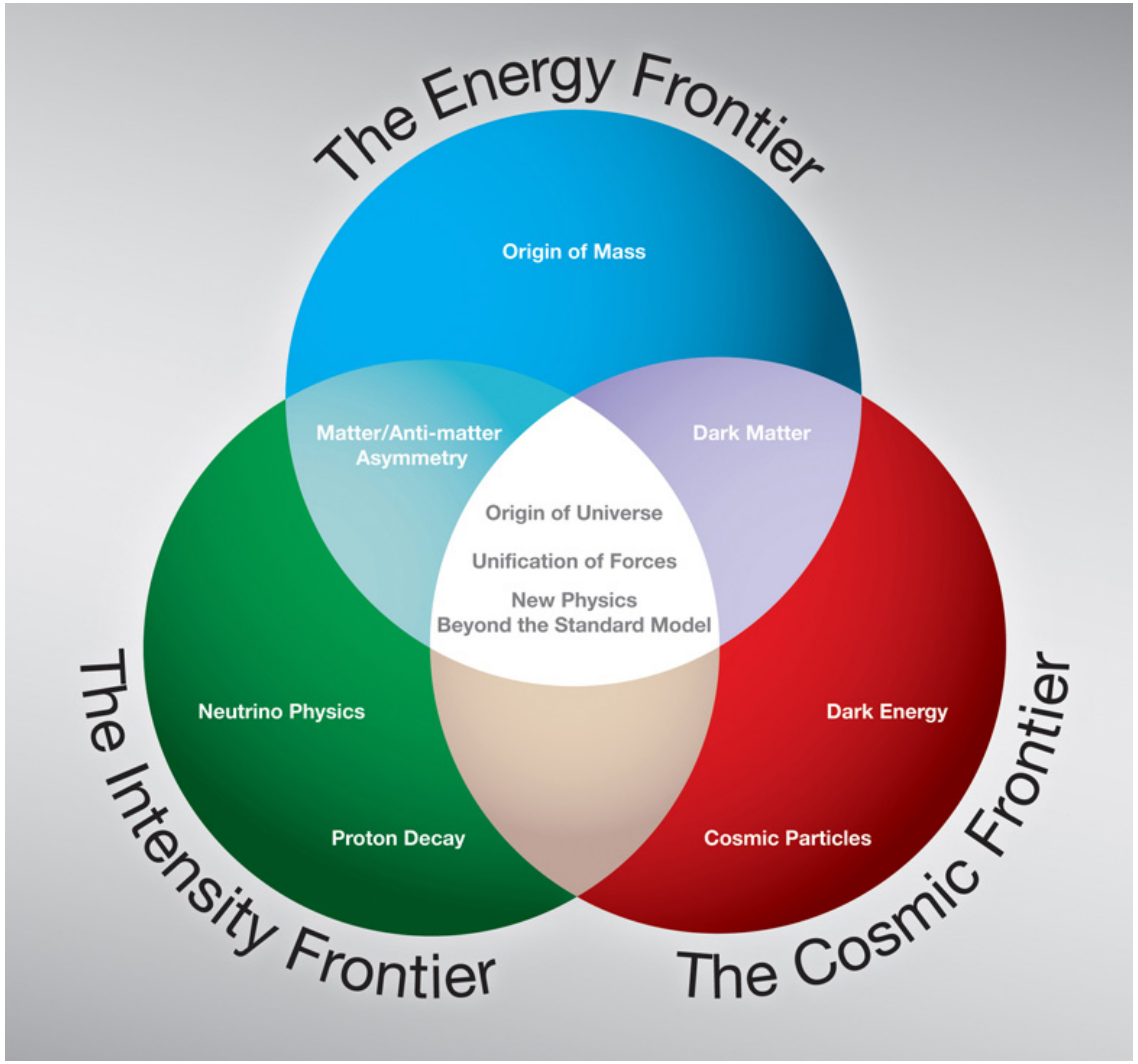
Even Bigger Science (1946): 184-inch-Cylcotron

Energy: 100 MeV

Evolution of Colliders - the Historv

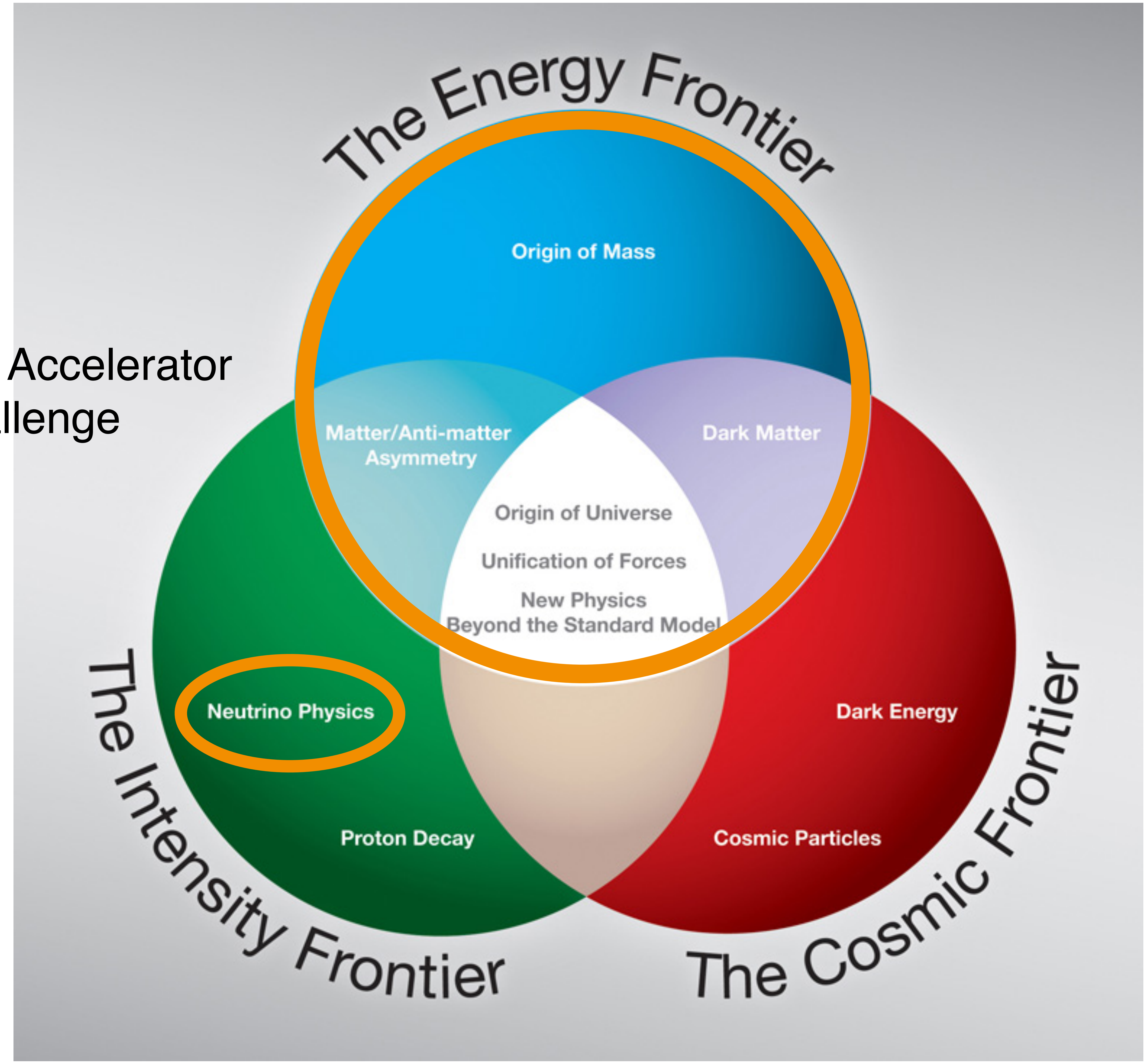


Frontiers in Particle Physics



Frontiers in Particle Physics

The Accelerator Challenge



Why High Energies?

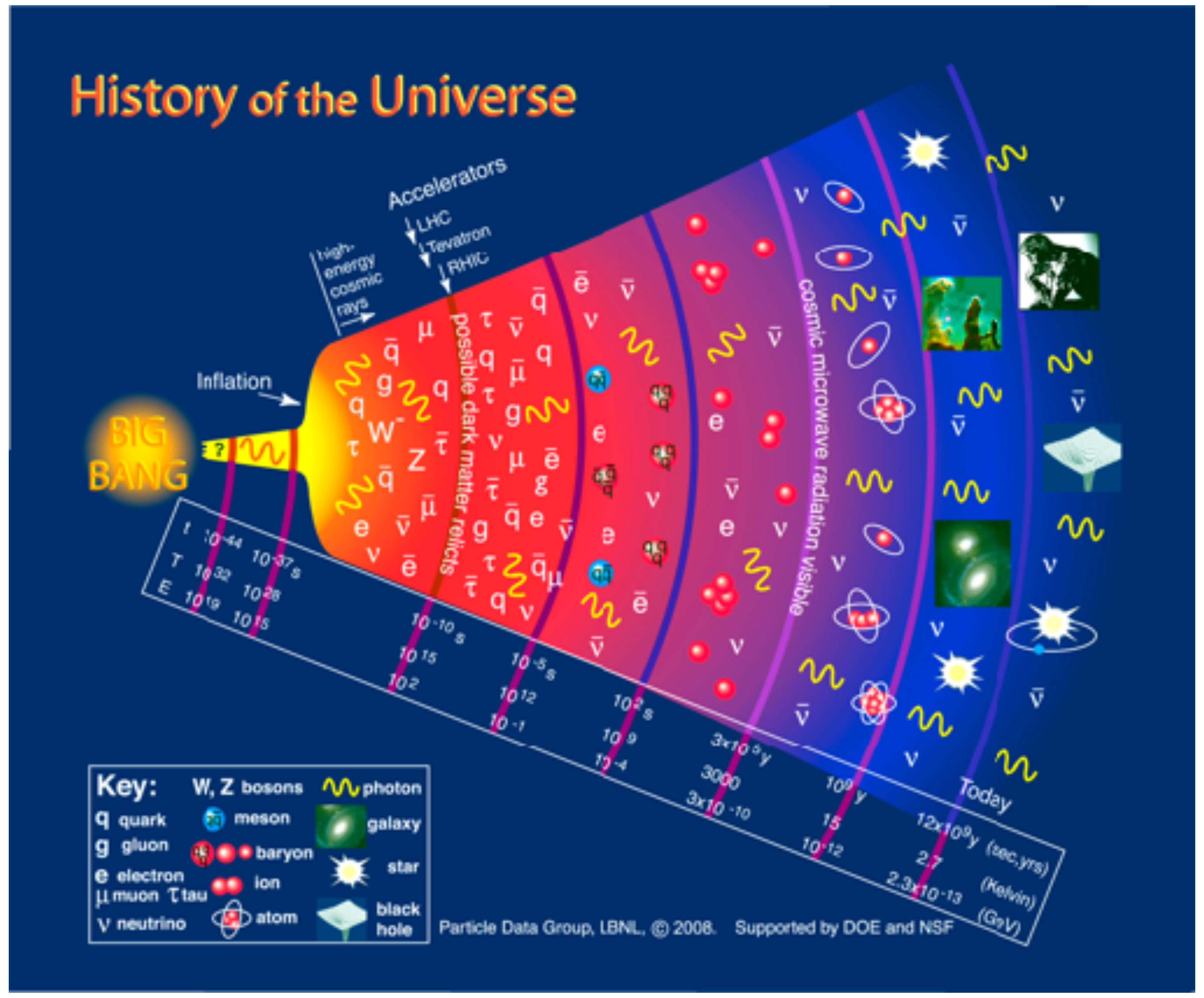
de Broglie wavelength of matter particles: $$\lambda = \frac{h}{p}$$

- the higher the momentum, the lower the wavelength, the better the resolution

the higher the collision energy, the larger the masses of potential newly produced particles:

$$E = mc^2$$

the higher the energy, the further back in history of the universe



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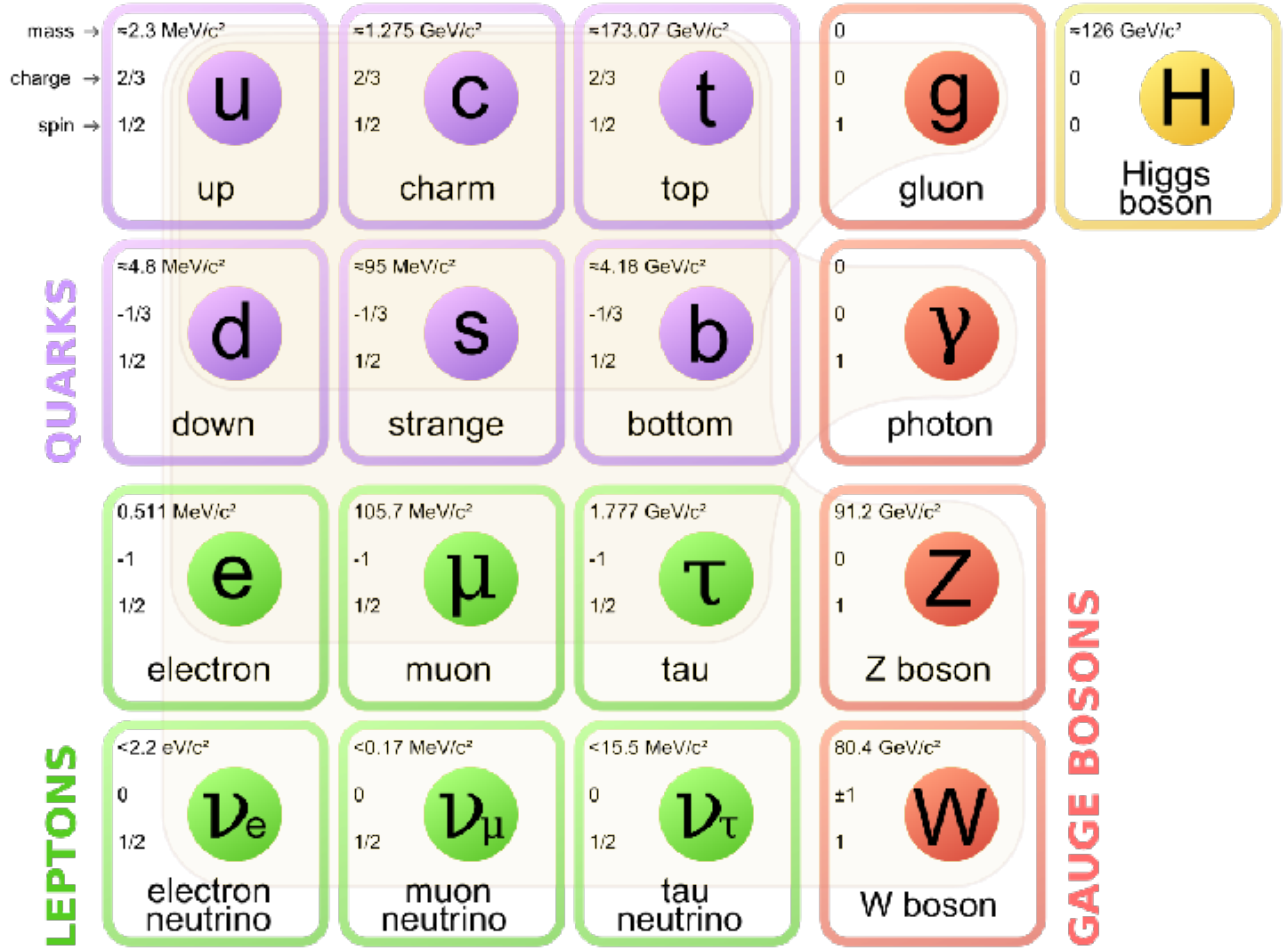
The Real Axis - the Real Frontier…

Which Particles to Collide?

Ideally:

- elementary particle with well defined quantum numbers
- charged
- mostly stable
- easy to get
- large collision cross sections



Have a look at the standard model particles:

- quarks:
- charged leptons:
- neutrinos:
- Z:
- W:
- gluons:
- photons:
- Higgs:

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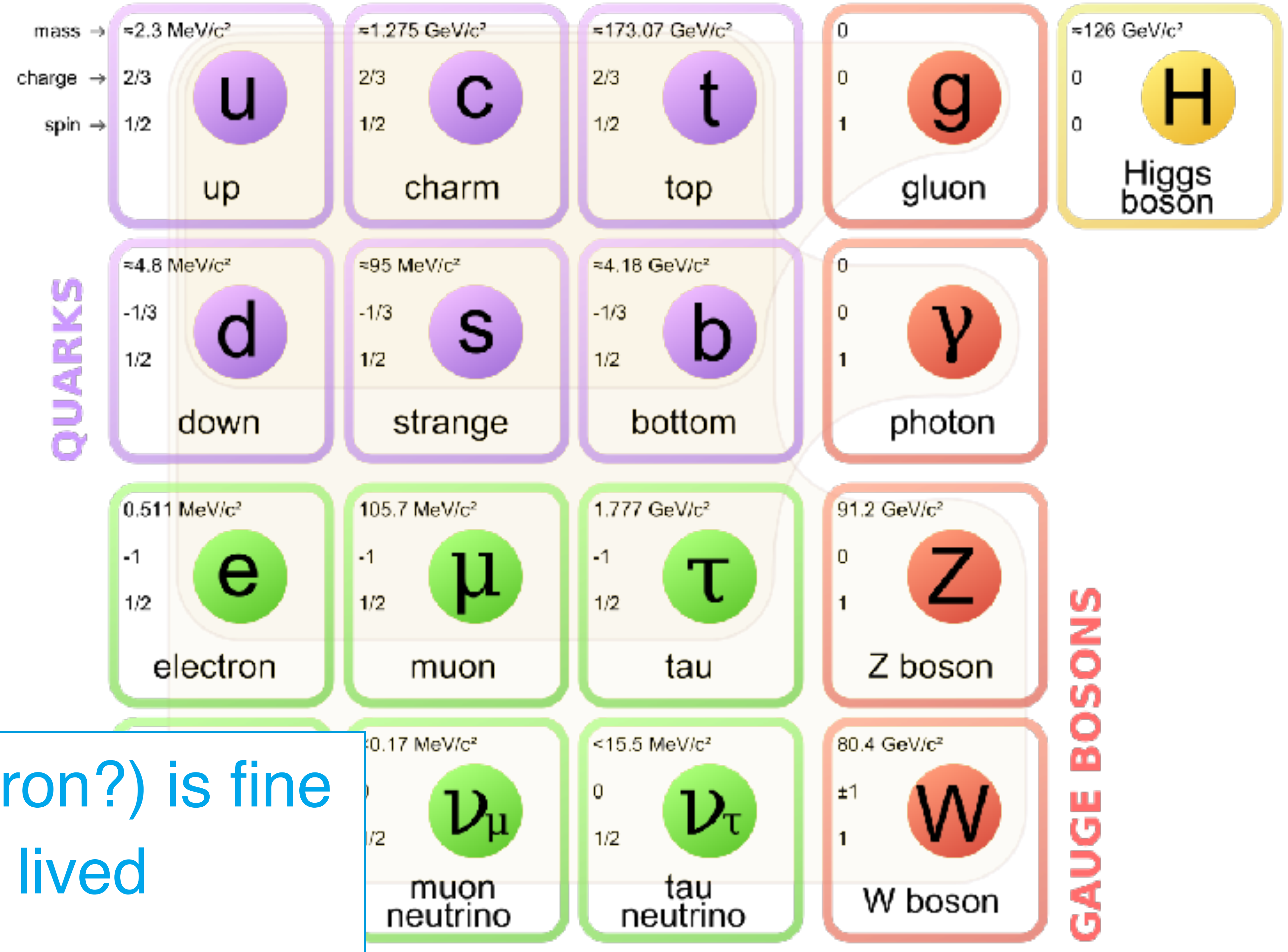
Ideally:

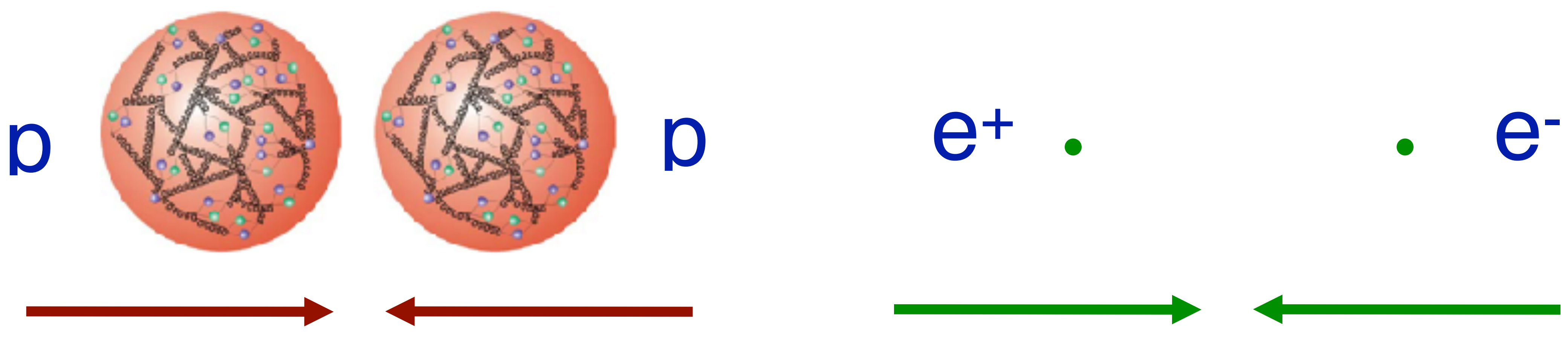
- elementary particle with well defined quantum numbers
- charged
- mostly stable
- easy to get
- large collision cross sections

Have a look at the standard model particles:

- quarks: do not come in singles, but proton (and neutron?) is fine
- charged leptons: electron is good, muon maybe, tau too short lived
- neutrinos: theoretically surely beautiful, but …
- Z: neutral, too short lived
- W: charged, but also way too short life time
- gluons: come only in bound states
- photons: neutral, but maybe…
- Higgs: ;-)



Hadron and Lepton Colliders



Proton (Anti-)Proton Collider	Electron Positron Collider
Energy range high (limited by bending magnets power)	Energy range limited (by RF power)
Composite particles, different initial state constituents and energies in each collision	Pointlike particles, well defined initial state quantum numbers and energies
Difficult hadronic final states	Easier final states
Discovery Machines (with some precision potential)	Precision Machines (with some discovery potential)

The Storage Ring Challenge

Magnets hold particles on circular trajectories

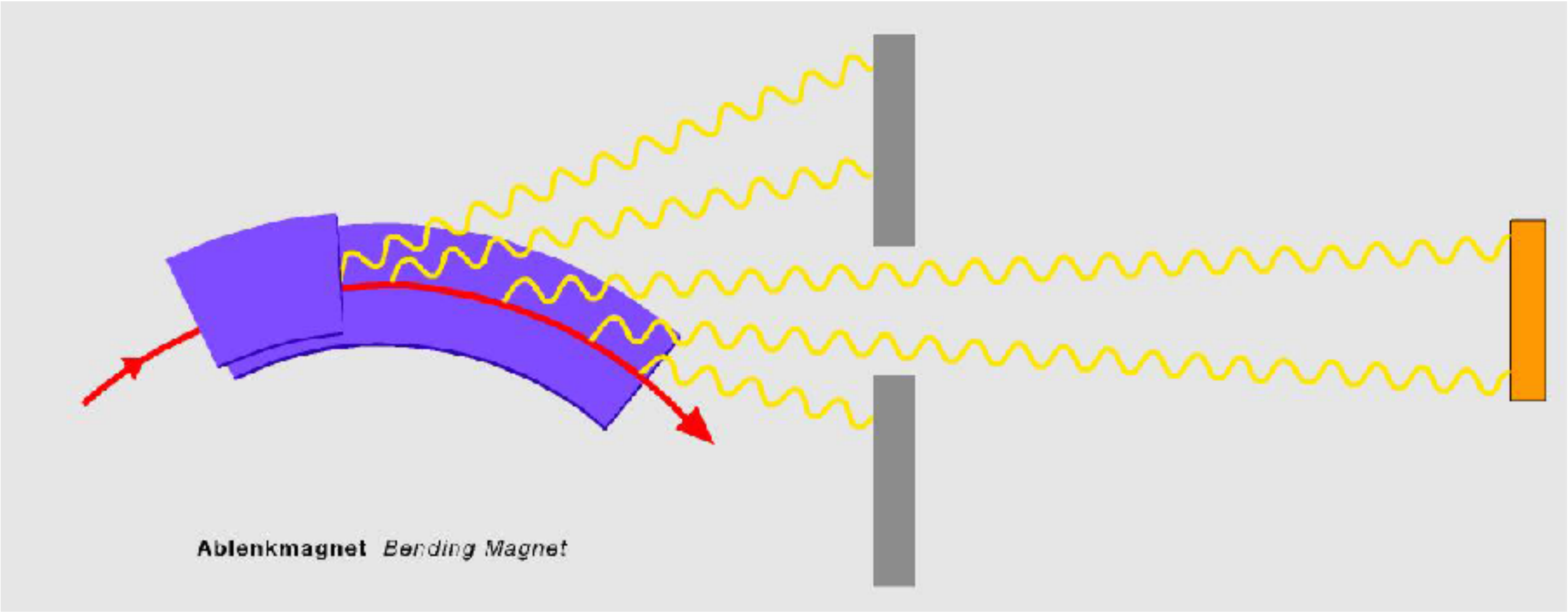
- dipole fields: ~E/r

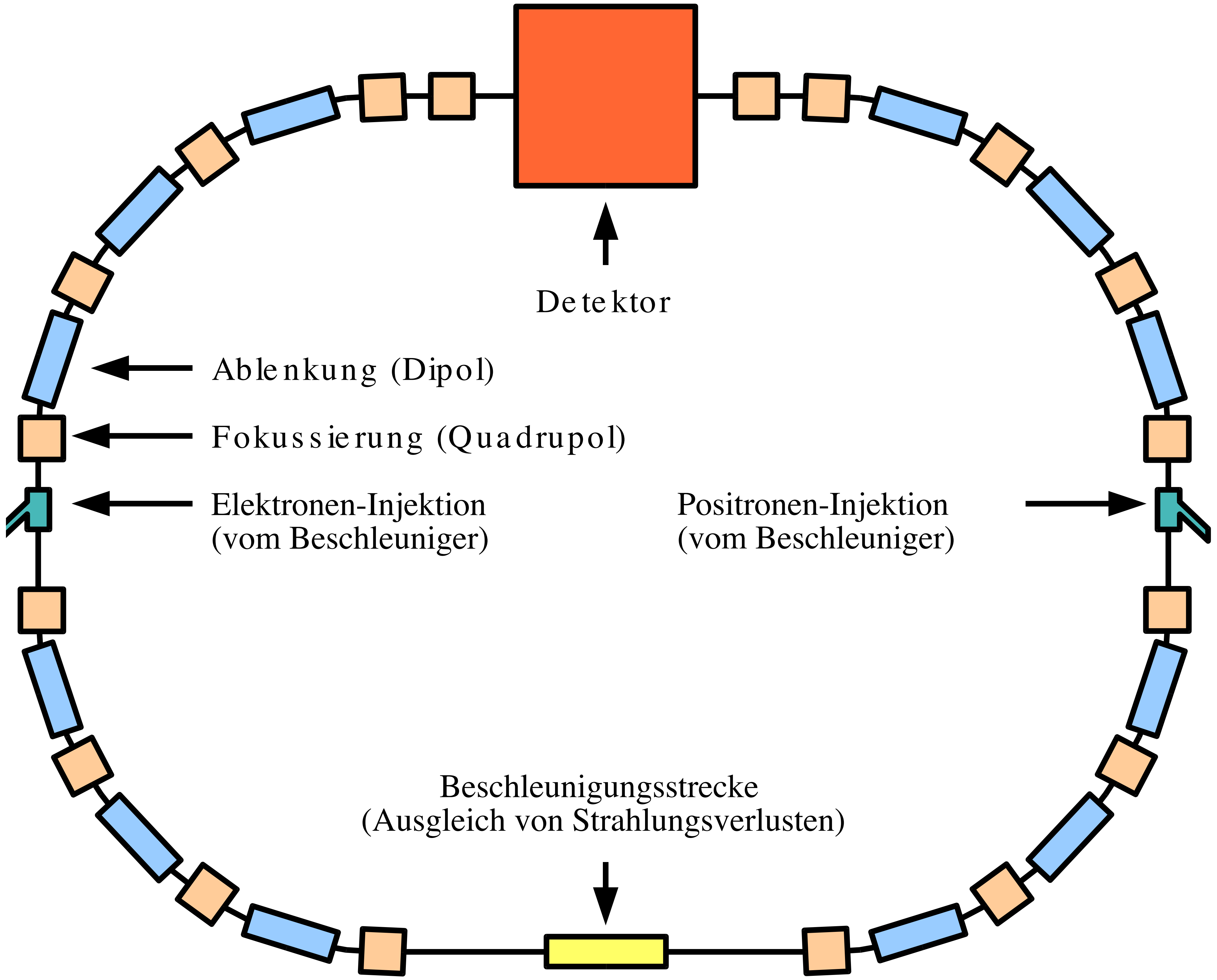
Light particles (leptons) lose energy via synchrotron radiation:

- radiation loss (power): $\sim E^4/r$
- radiation loss (power): $\sim 1/m^4$

Rules of thumb:

- Hadron machines are limited by dipole magnet strengths
- Electron machines are limited by acceleration power





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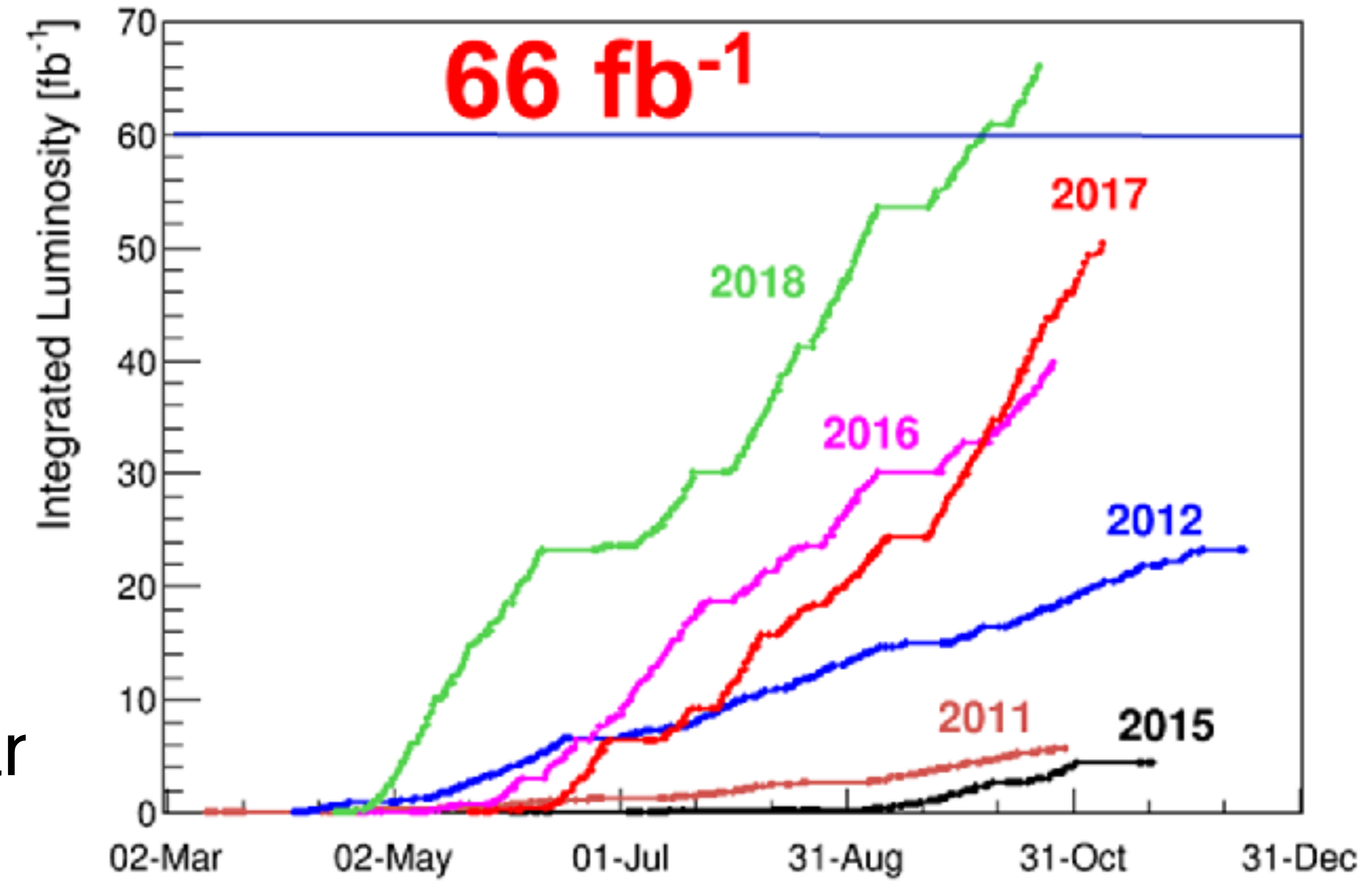
LHC

The Current Energy Frontier: LHC

LHC Integrated Luminosity

LHC has reached its design luminosity of $10^{34} cm^{-2}s^{-1}$ in July 2016

- The discovery of the W boson by UA1 at the SppS collider was published with an integrated luminosity of 18 nb^{-1}
  - Phys. Lett. 122B (1983) 103pp
- LHC delivers this in a good week within less than 5 seconds…
- In 2018 routinely well above design luminosity!

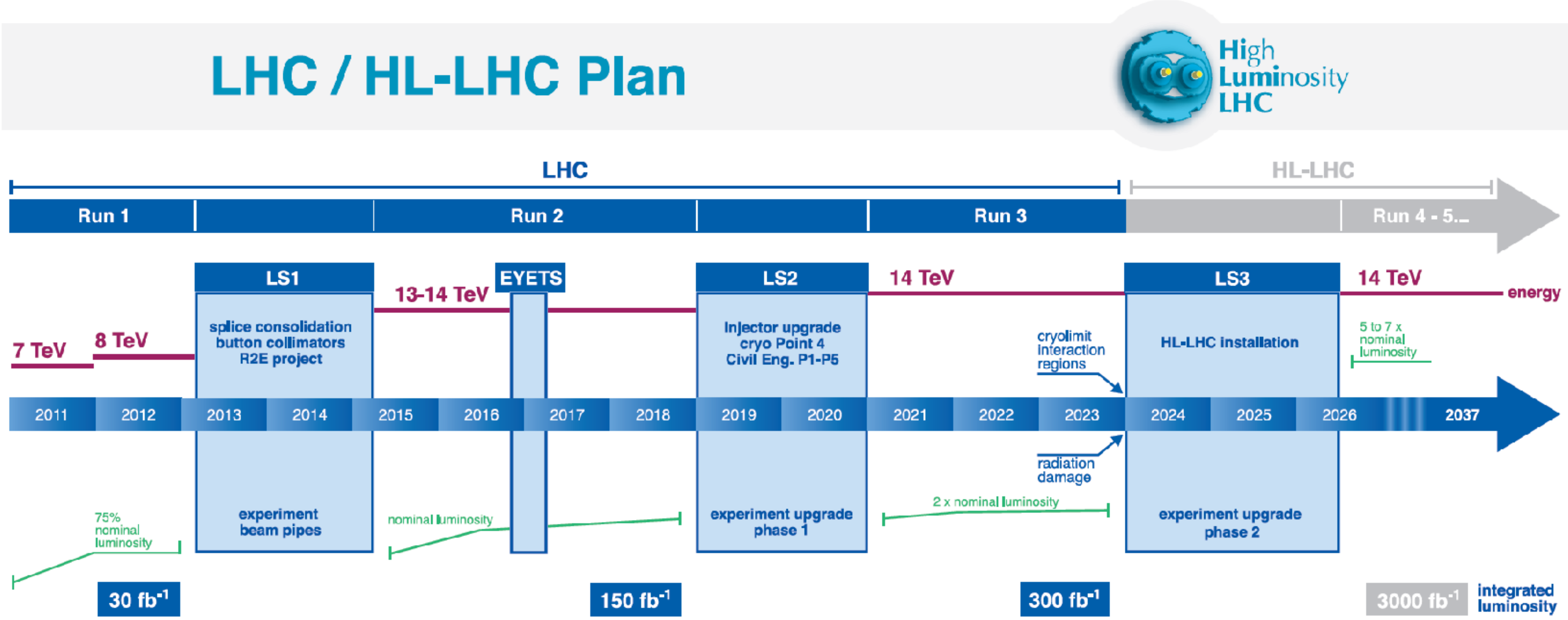


F. Bordry

Period	Int. Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66.0
Total Run1 + Run 2	189.3

LHC Roadmap (as in CERN Medium Term Plan)

- Phase 1: 300 fb^{-1}
  - High-Lumi LHC starts mid 2026
- Phase 2: 3000 fb^{-1} until mid 2030s



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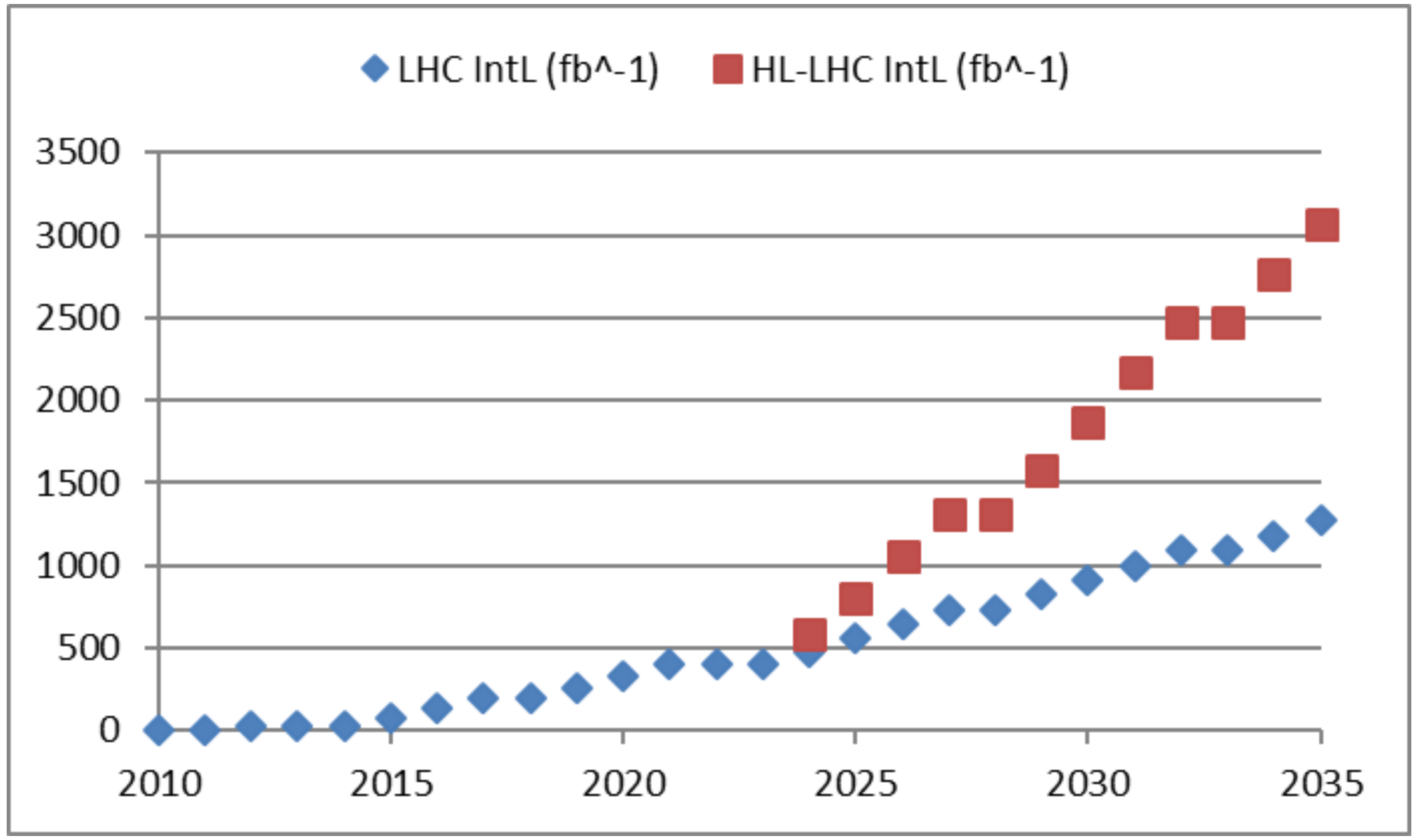
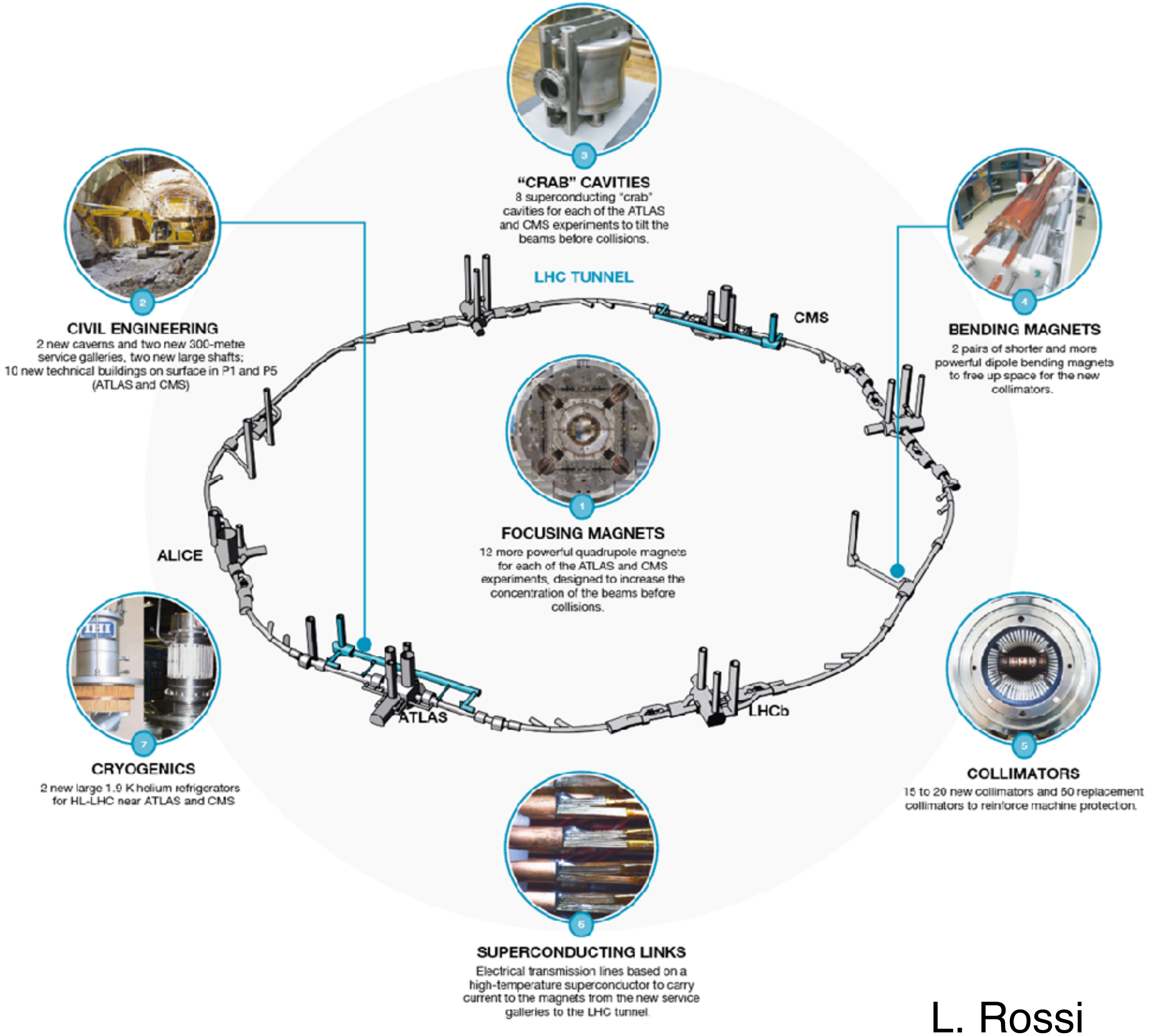
LHC Luminosity Upgrade

High Luminosity Upgrade to the LHC

Increase luminosity to $L=5\times10^{34}cm^{-2}s^{-1}$

- Factor of ~5 above current design
- Full exploitation of LHC is highest priority on global HEP strategies
- Major intervention at ~1.2 km of the LHC





L. Rossi

High Field SC Magnets

Squeezing the beams: High Field SC Magnets

F. Bordry

Quads for the inner triplet

Decision 2012 for low-β quads

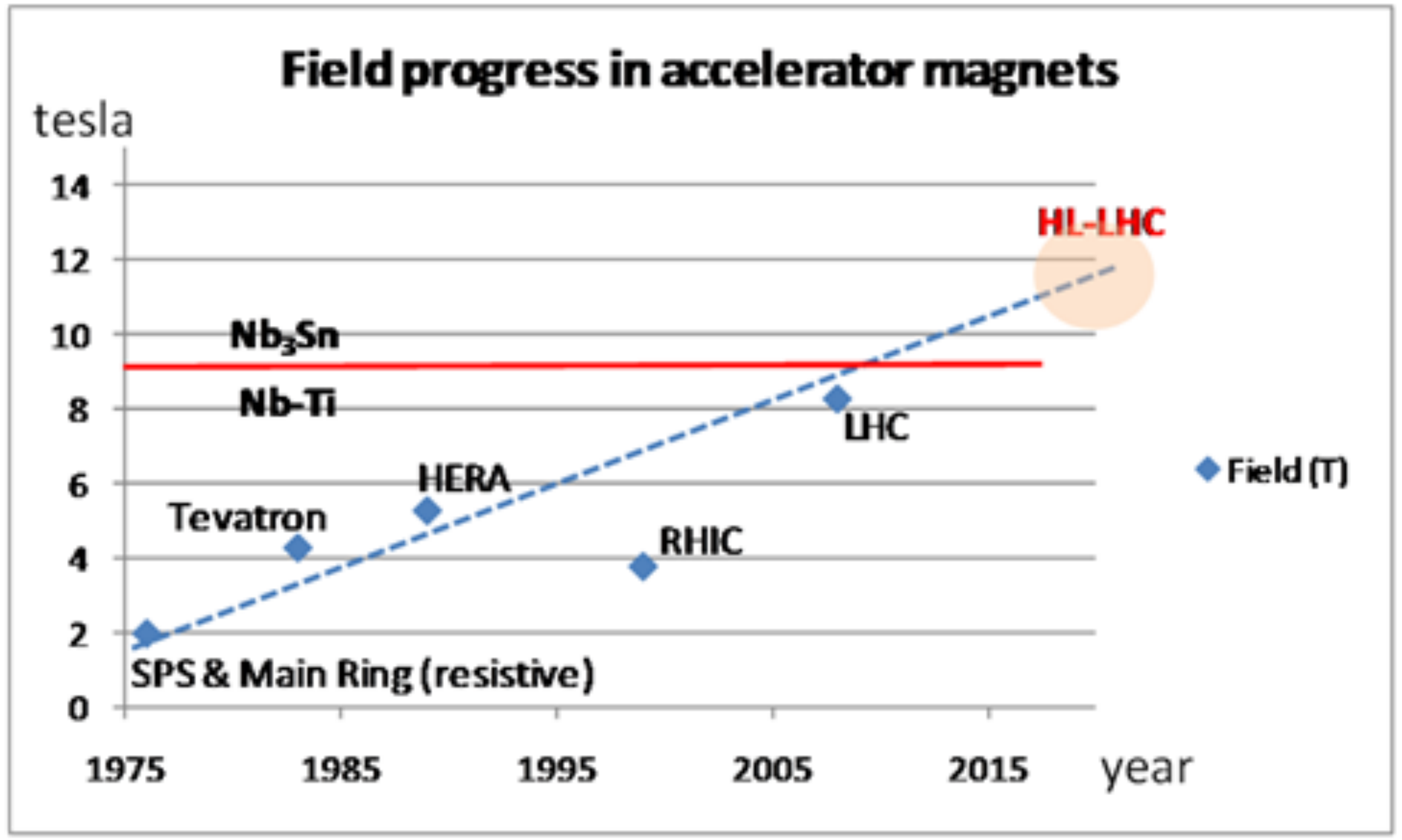
Aperture ∅ 150 mm – 140 T/m

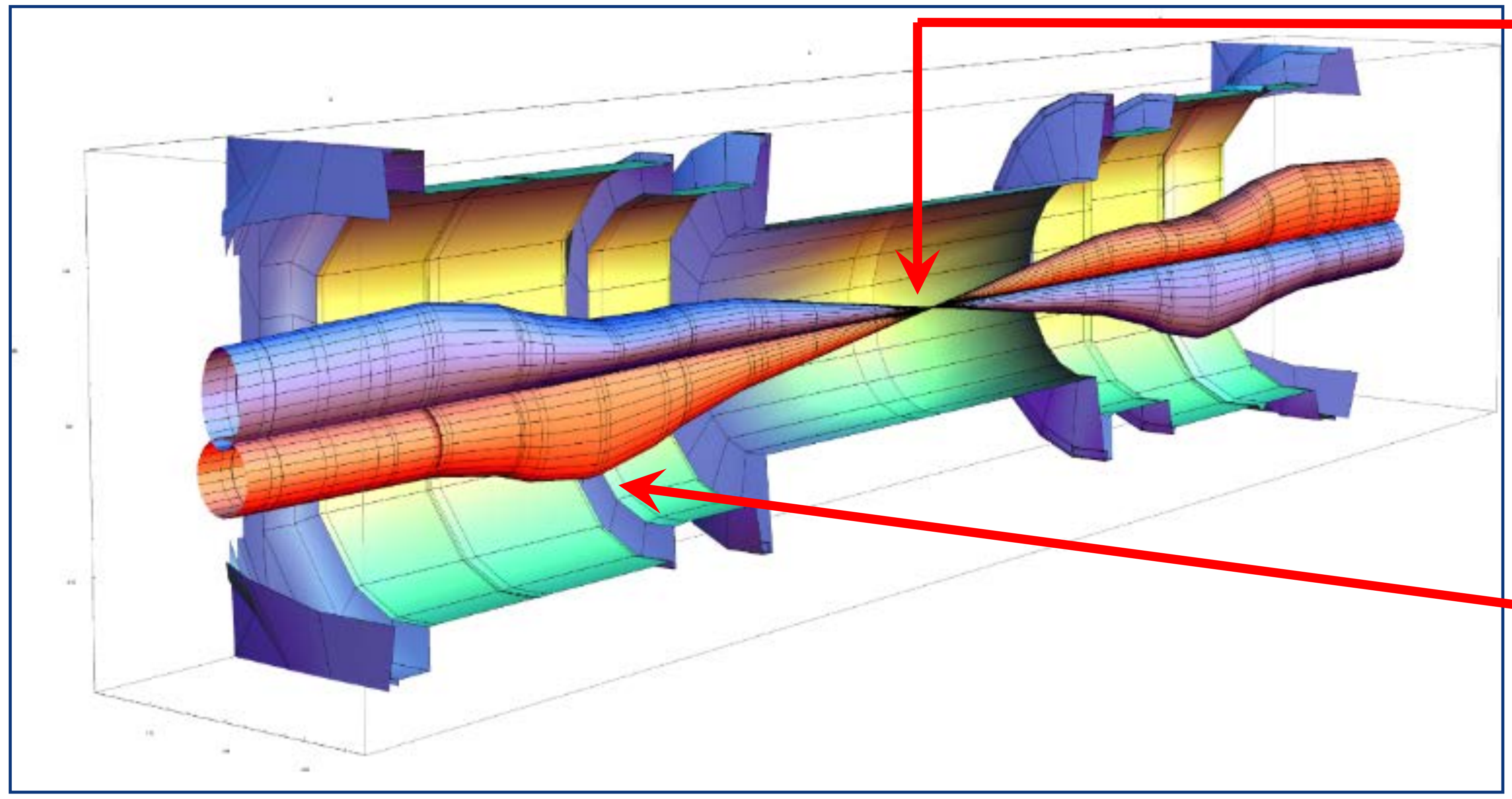
(B_{peak} ≈12.3 T)

operational field, designed for 13.5 T

=> Nb_3Sn technology

(LHC: 8 T, 70 mm)

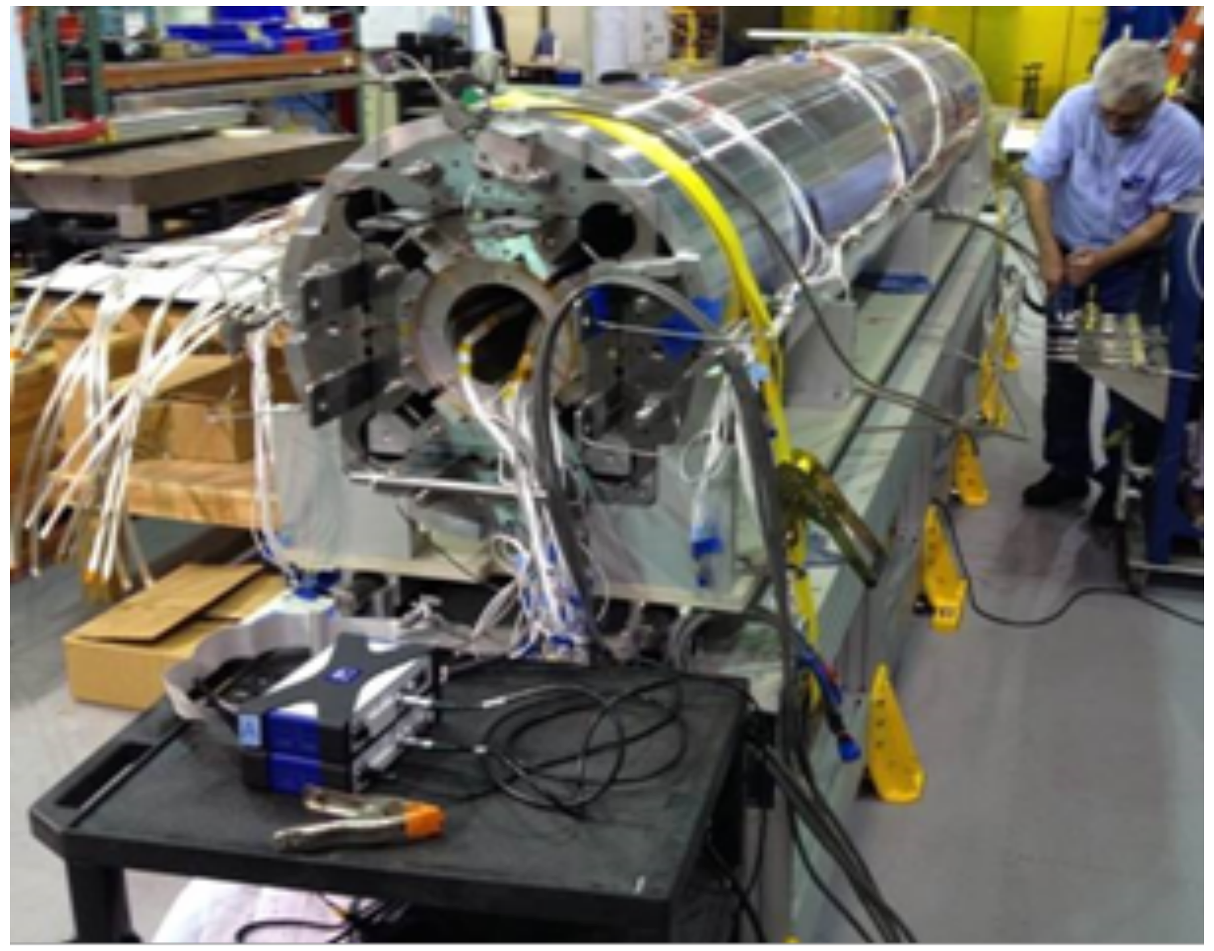




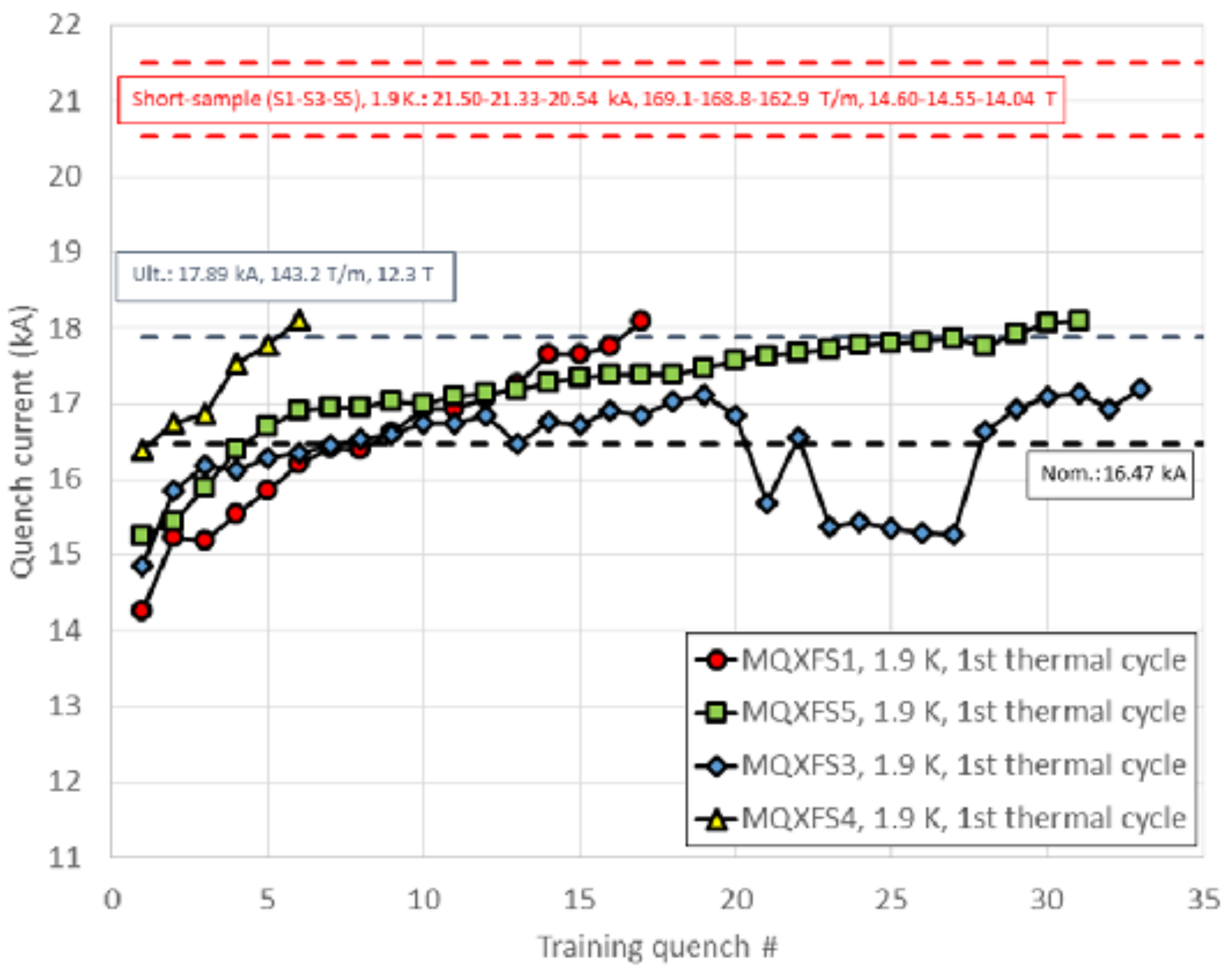
	$β_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

High Field Magnet R&D

SC Quadrupoles for Inner Triplet (Nb3Sn Technology)
Production of first long (7.5m) magnets has been started (US)





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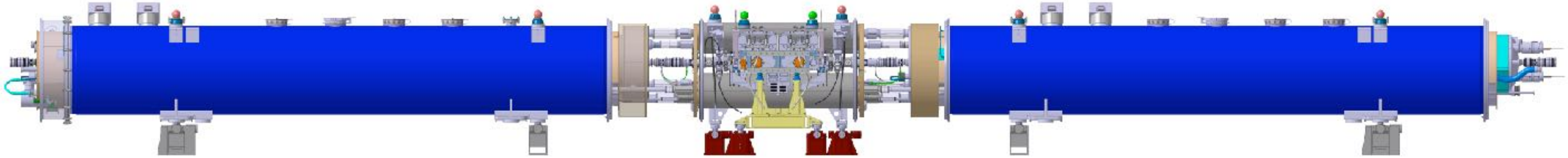
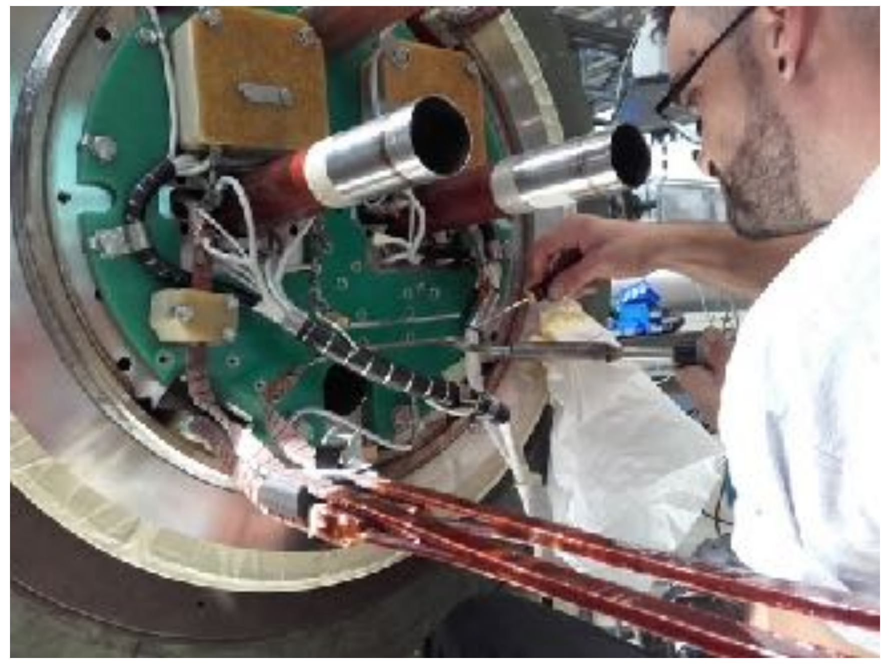
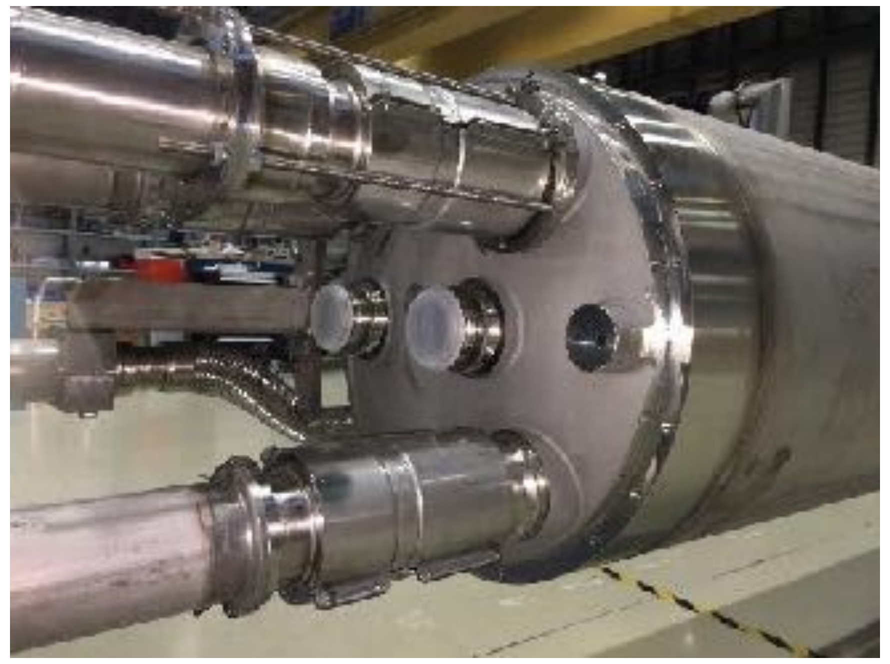
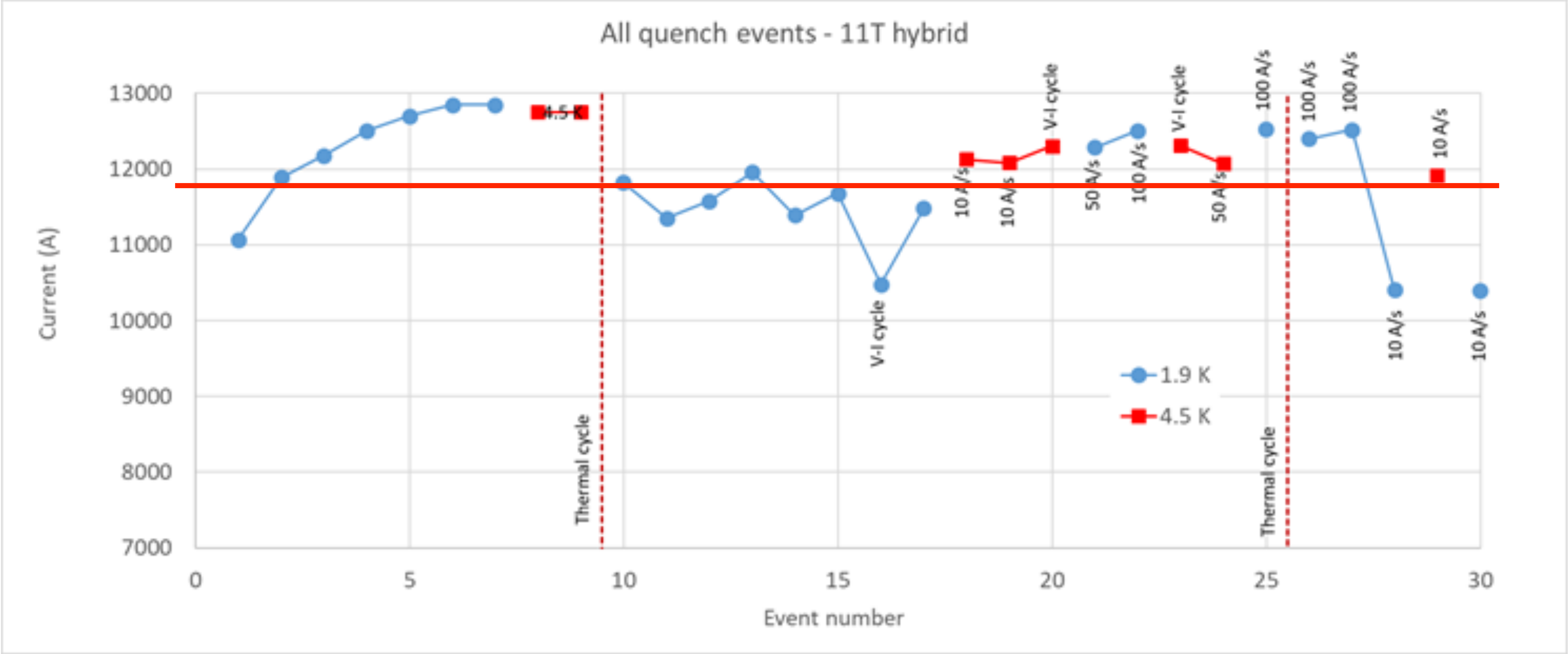
High Field Magnet R&D

11T bending magnets for collimator section (Nb3Sn Technology)









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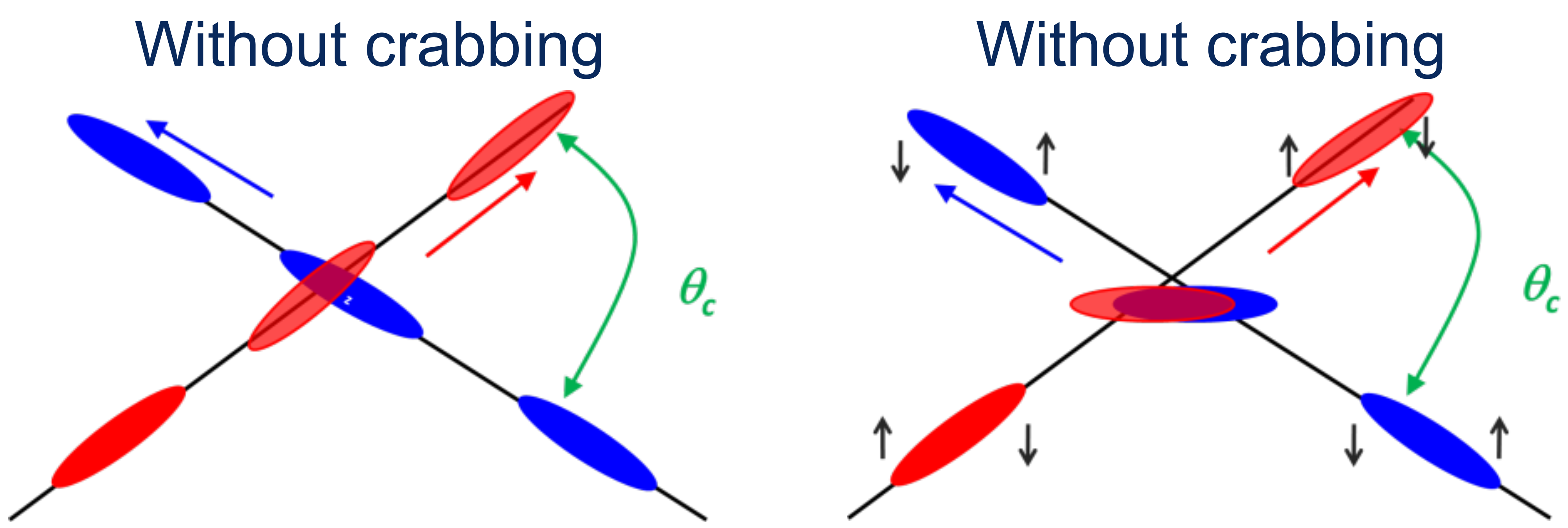
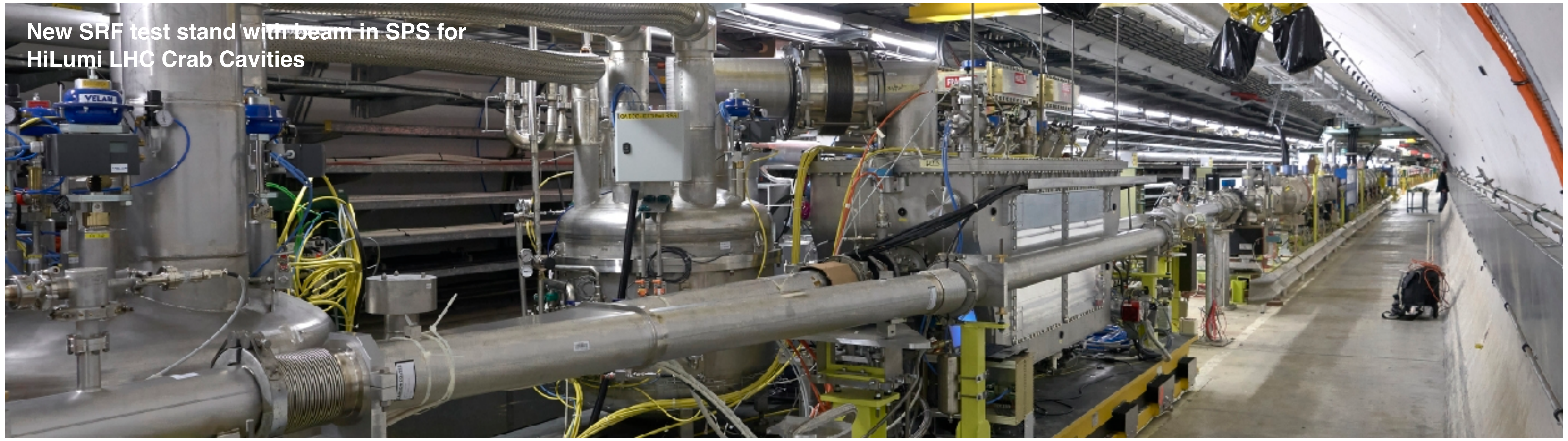
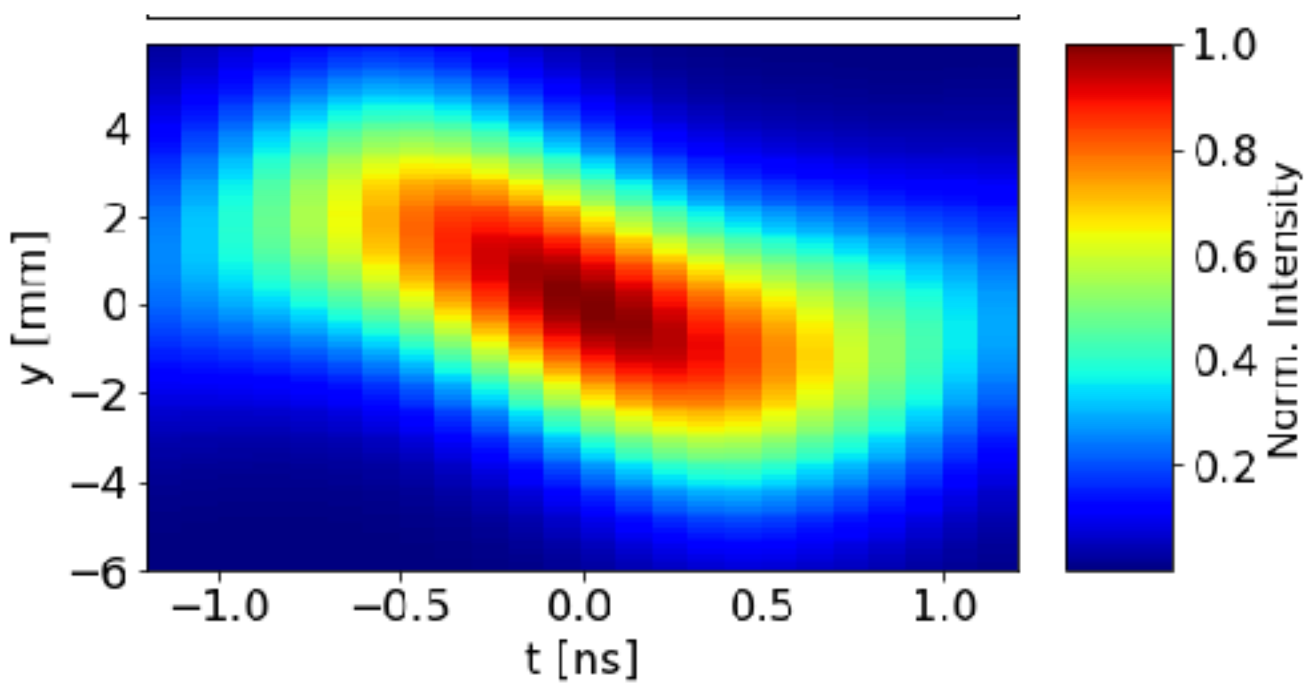
Crab Cavities

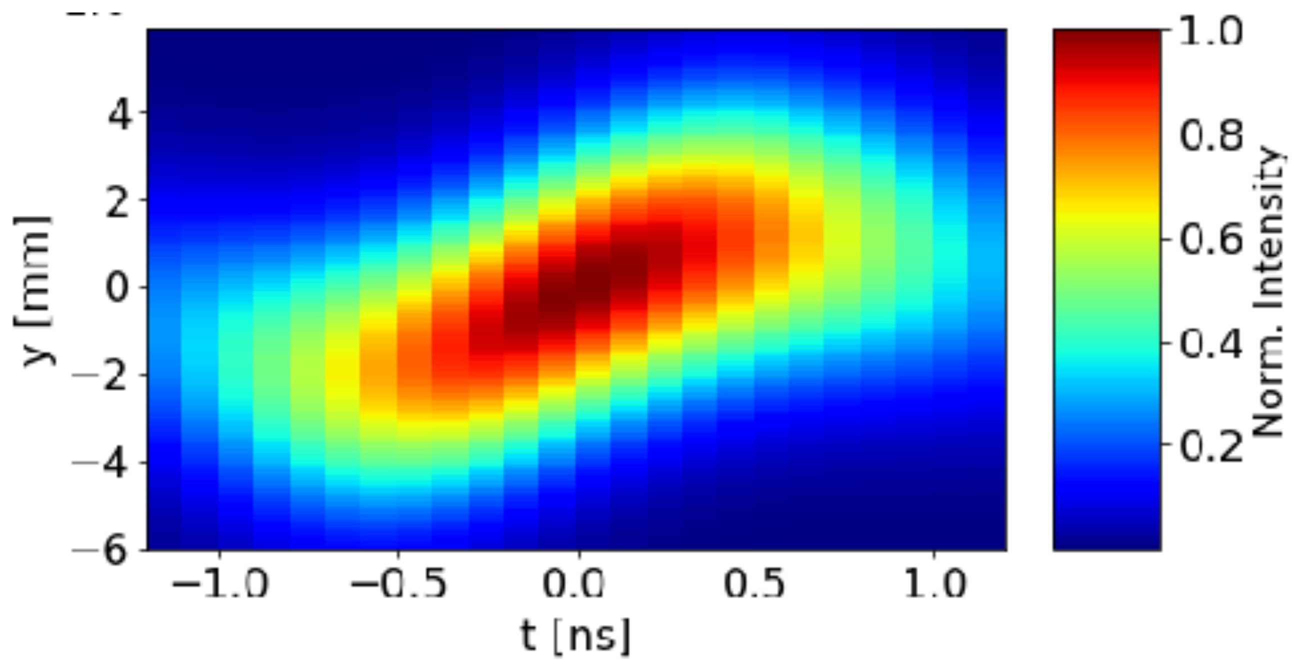
Aim: reduce the effect of the crossing angle



RF phase scan w.r.t the beam phase with cavity 1: principle validated! Transparency of CC to beam demonstrated! MDs very successful (with voltage limitation).







L. Rossi

HL-LHC Detector Upgrades

ATLAS and CMS need to undergo major upgrade programmes to be ready for HL-LHC:

- Central tracking detectors have reached the end of their lifetime after Phase-I (radiation damage)
- Much higher pile-up (factor 10) of events in one picture
- Trigger, Muon systems, Calorimeters need upgrades

This keeps most of the worldwide HEP physics and detector community busy until >2025!

- R&D is in full swing, sub-detector TDRs have been written
- Funding is mostly secured
- Production will start within the next years

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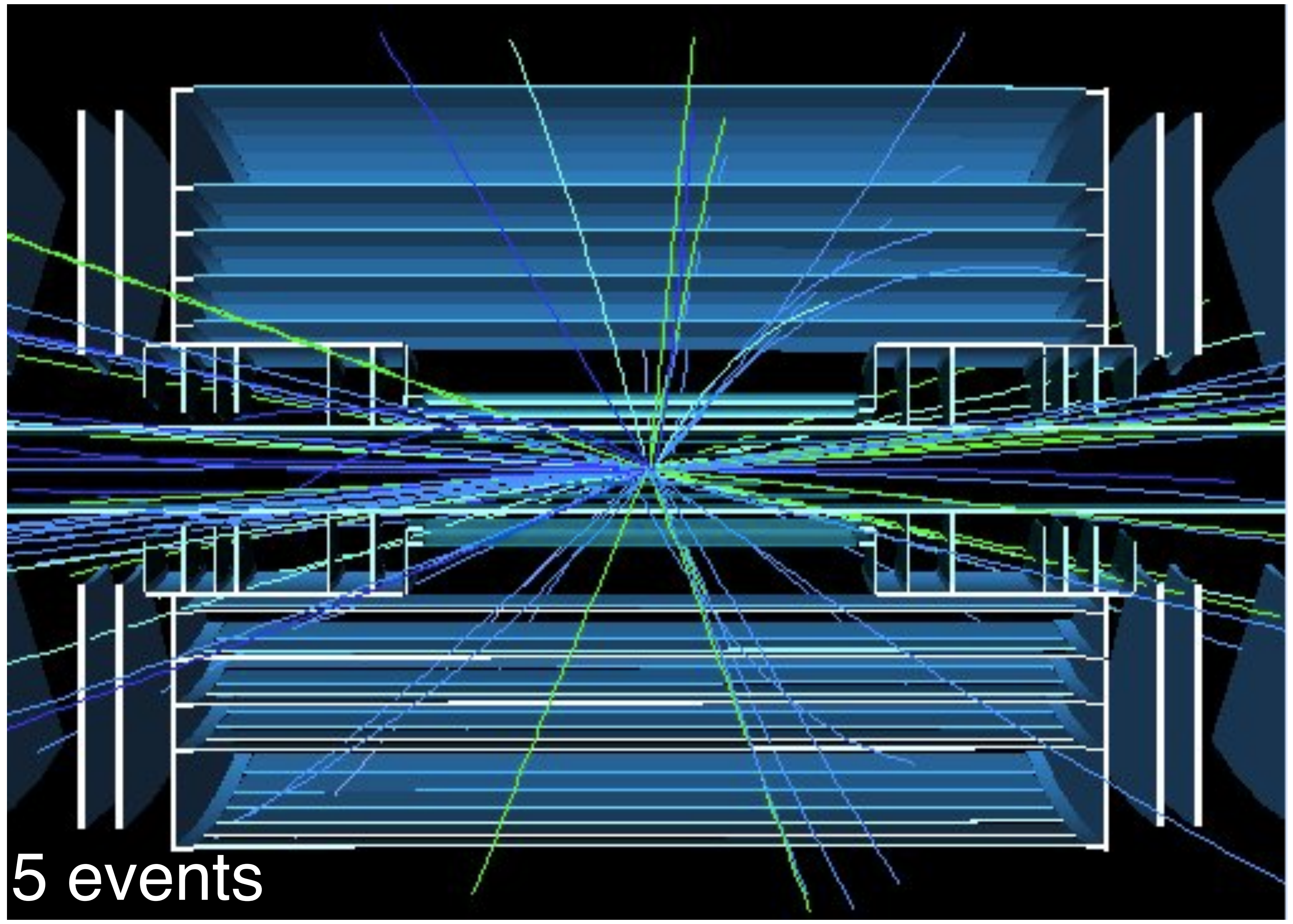

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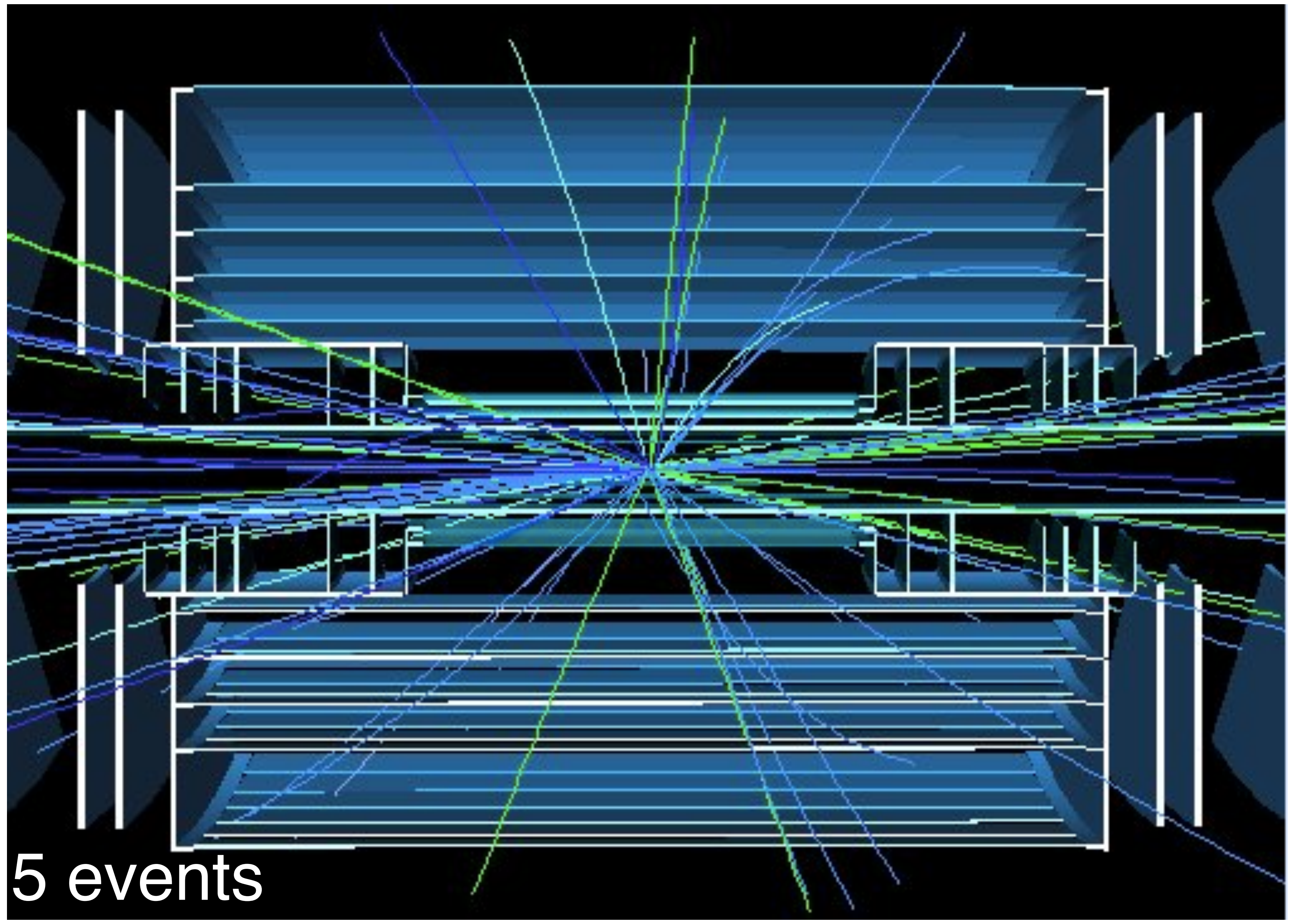

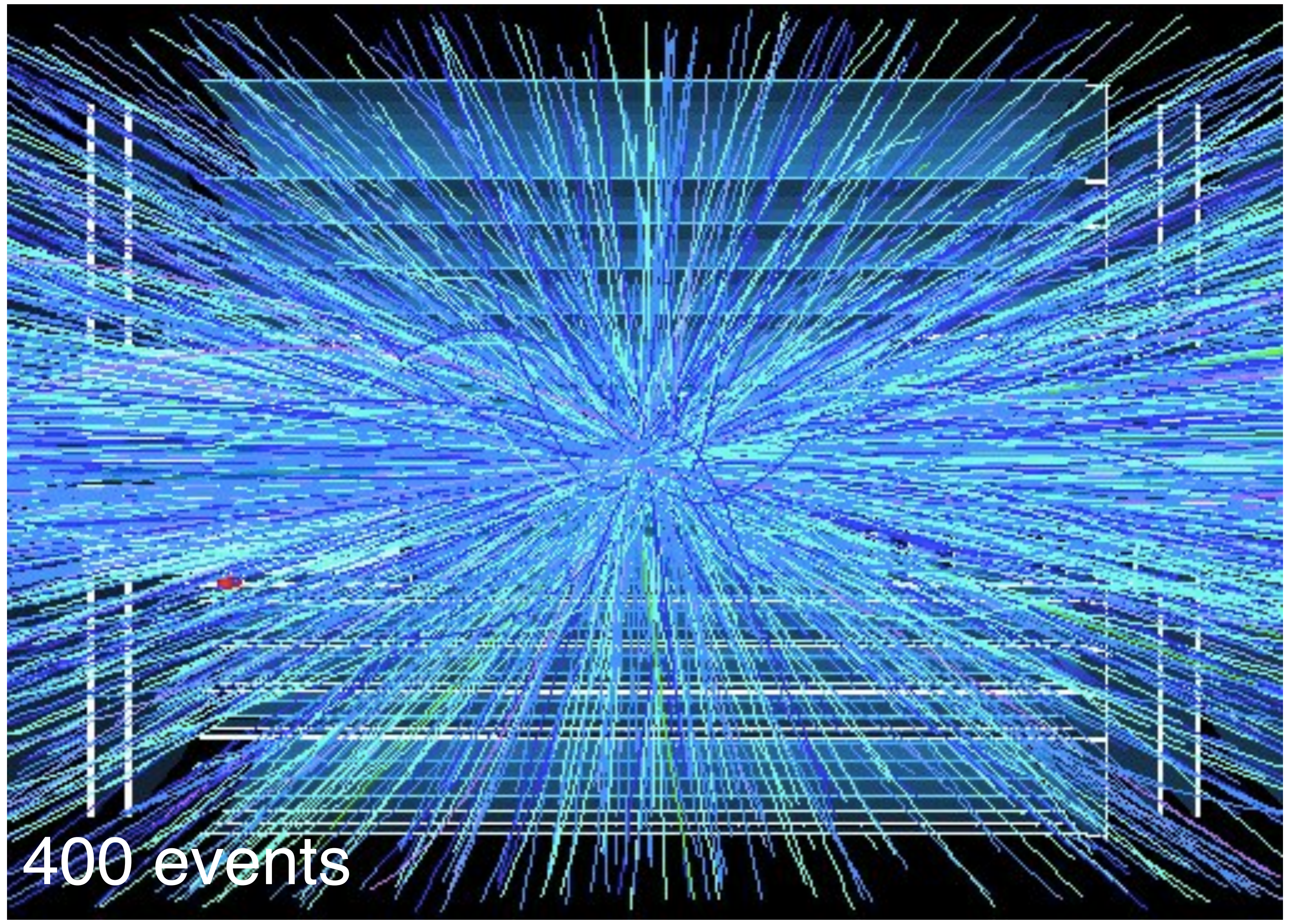

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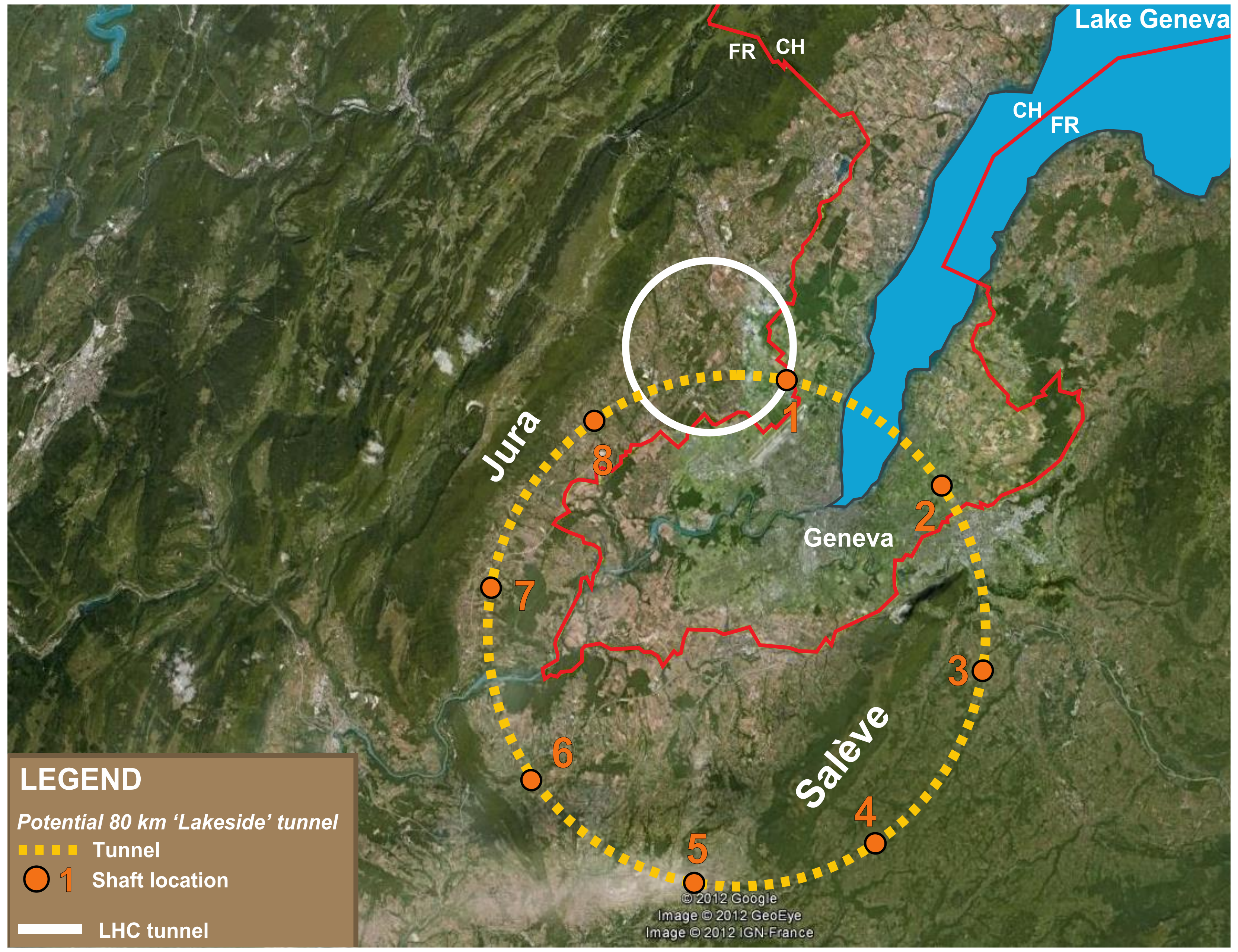
FCC-hh

FCC: Future Circular Collider at CERN



100 km circular collider at CERN

pp (hh) collisions at 100 TeV

- need high field magnets: 16-20T

e+e- collider as possible first stage

- „magnet developments for FCC-hh will anyhow take time"…
- high luminosity (benefits of the storage ring)
- limited in energy to ~ <350 GeV
- Higgs-Top factory

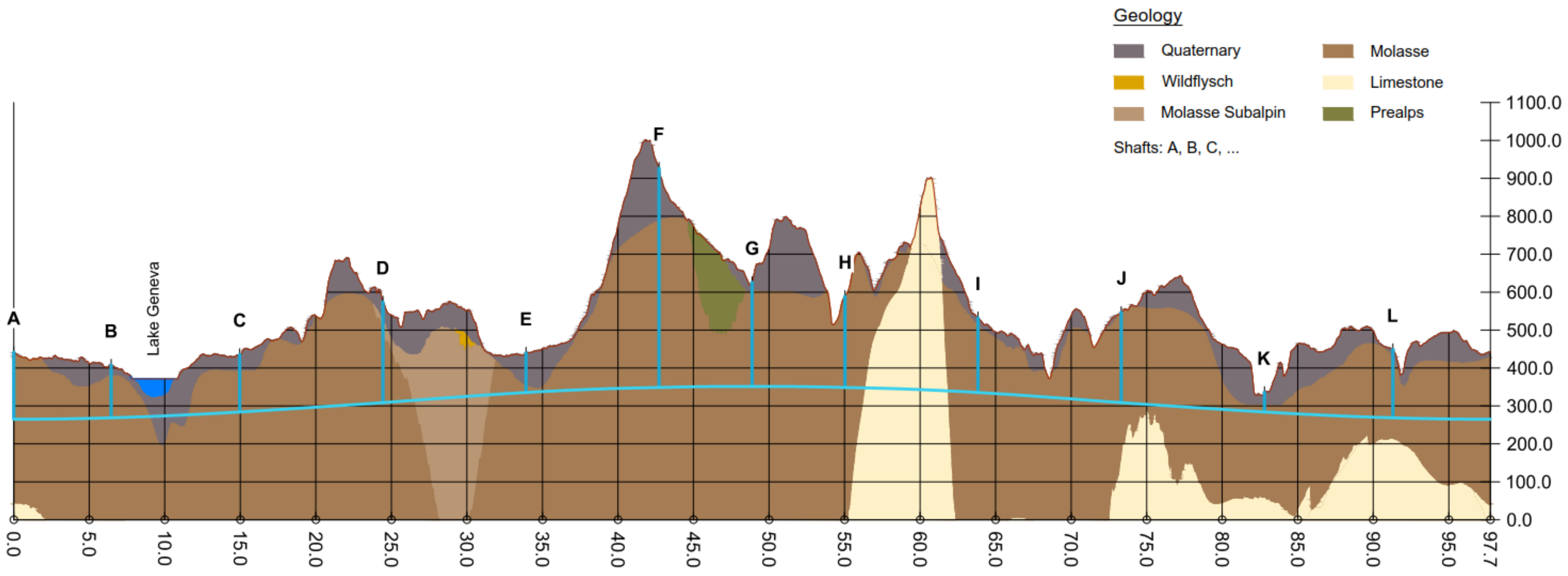
eh Collider („Super-HERA")?

Design study started at CERN

- Conceptual Design Report published

The „next big thing" at CERN?

Realisation after 2035



FCC in Geneva Area

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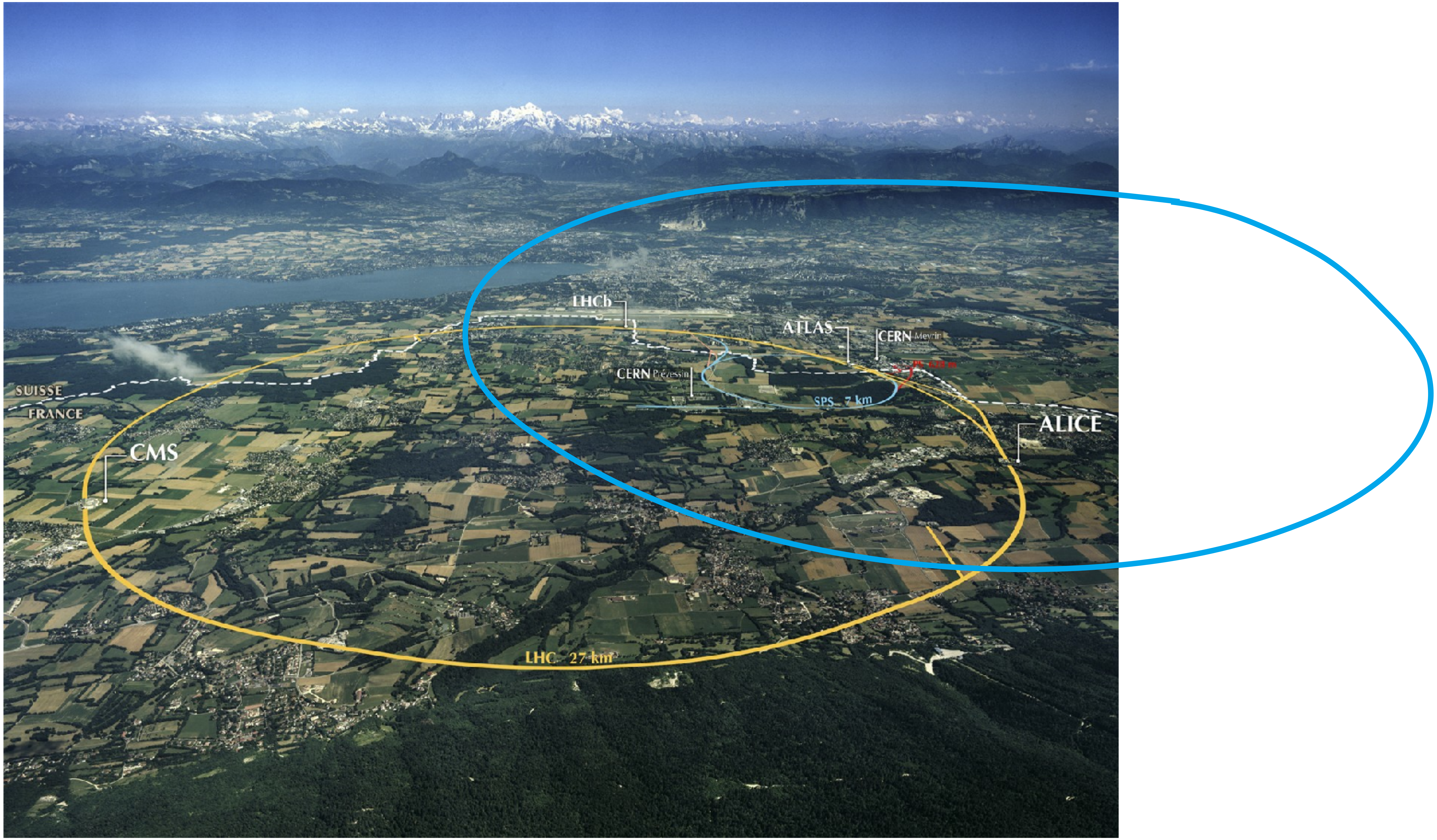
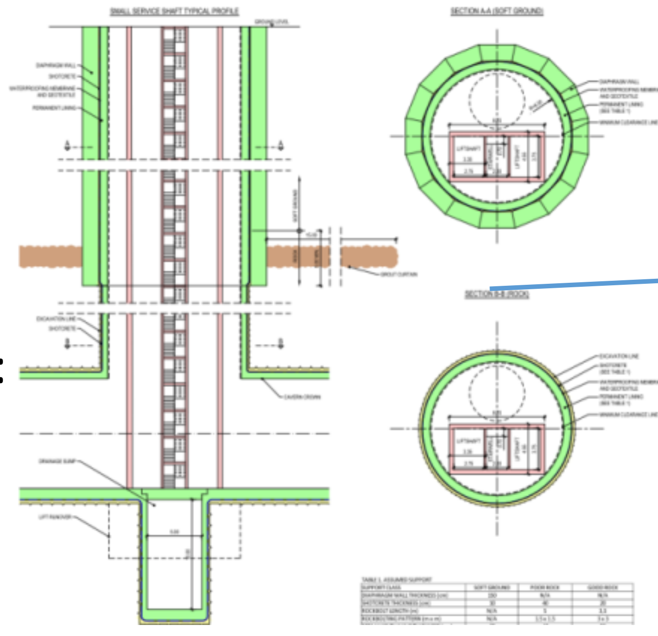
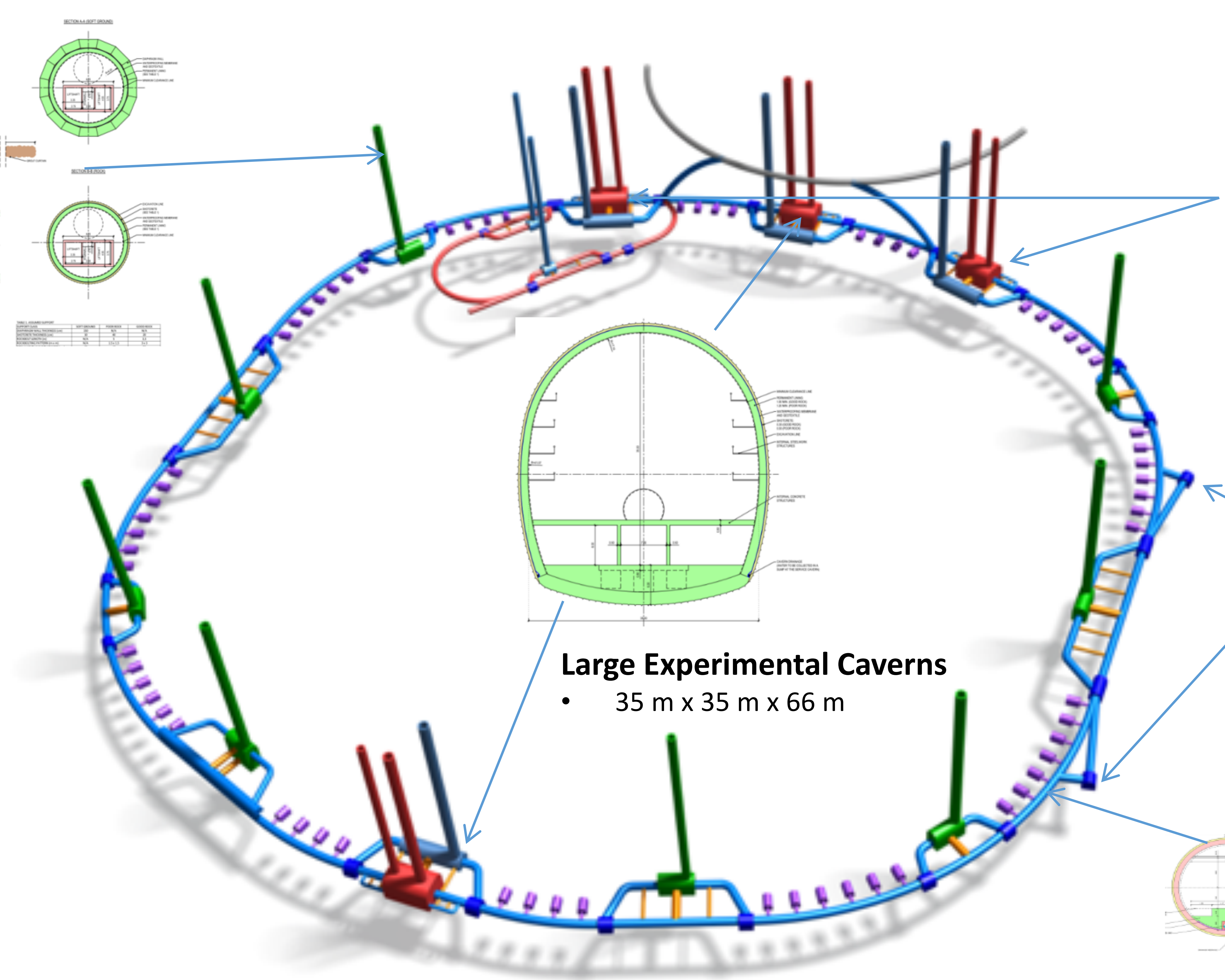
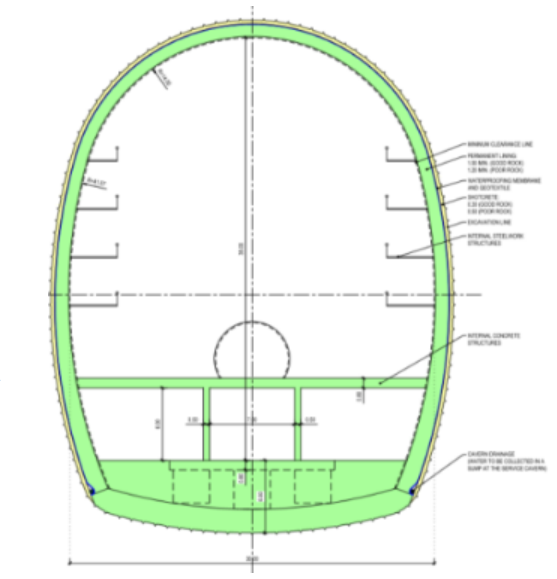


FCC-hh Layout

Shafts:
Experimental Shafts:
15 m dia. + 10 m dia.
Service shafts:
12 m dia.
Magnet delivery shaft:
18 m

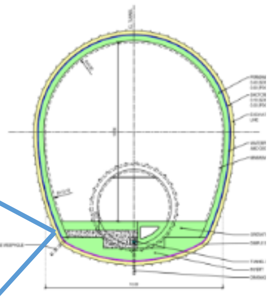




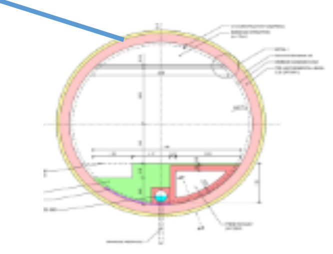


Small Experimental Caverns
- 30 m x 35 m x 66m

Large Experimental Caverns
- 35 m x 35 m x 66 m



Dump Caverns
- 10 m x 10 m x 50 m



Tunnels:
- 97.75 km of 5.5 dia. machine tunnel
- Approx. 8 km 5.5 dia by-pass tunnels

J. Osborne

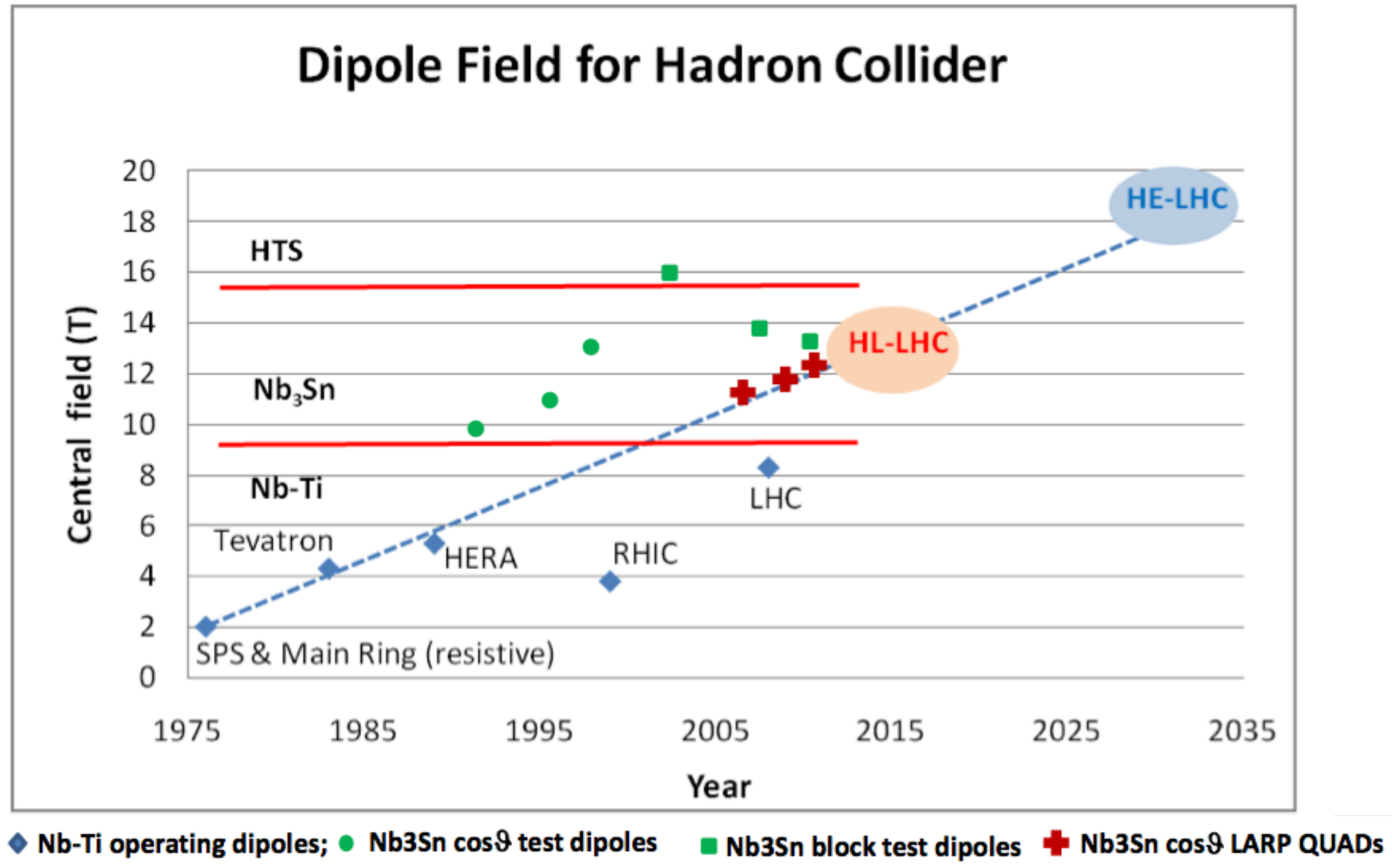
FCC-hh Parameters

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	1	2.2	2.2	1.15
bunch spacing [ns]	25	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	0.25	0.15 (min.)	0.55
normalized emittance [mm]	2.2		2.5	2.5	3.75
peak luminosity $[10^{34}\ cm^{-2}s^{-1}]$	5	30	28	5 (lev.)	1
events/bunch crossing	170	1000	800	132	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

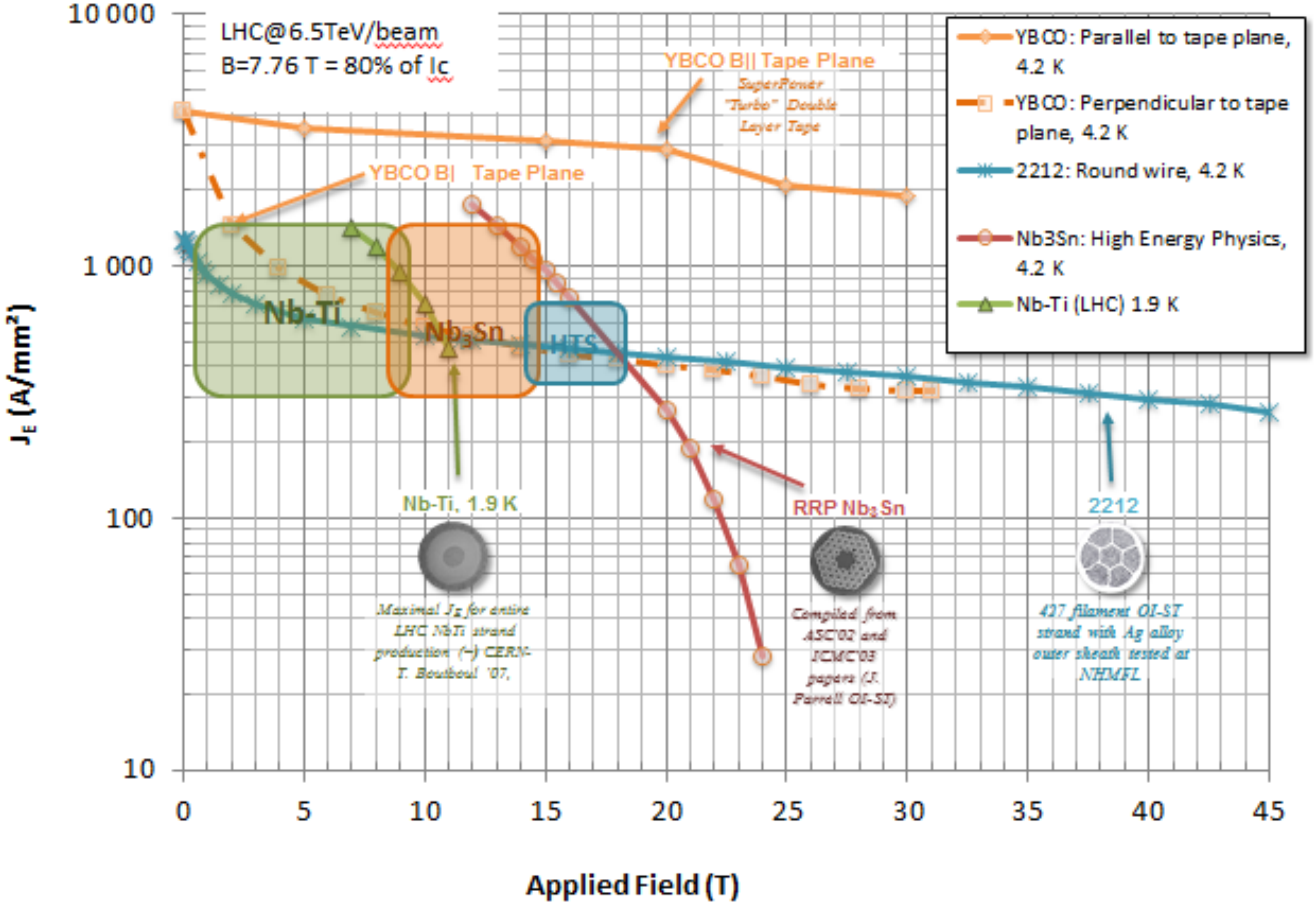
FCC-hh: The Magnet Challenge

Nb3Sn dipole magnets would reach 16T field

- need to go to high temperature superconductors for even higher fields
- R&D needed to bring the cost down
- Hybrid coils under discussion



HFM – FCC-hh



N. Walker, D. Schulte

FCC-hh: The Magnet Challenge

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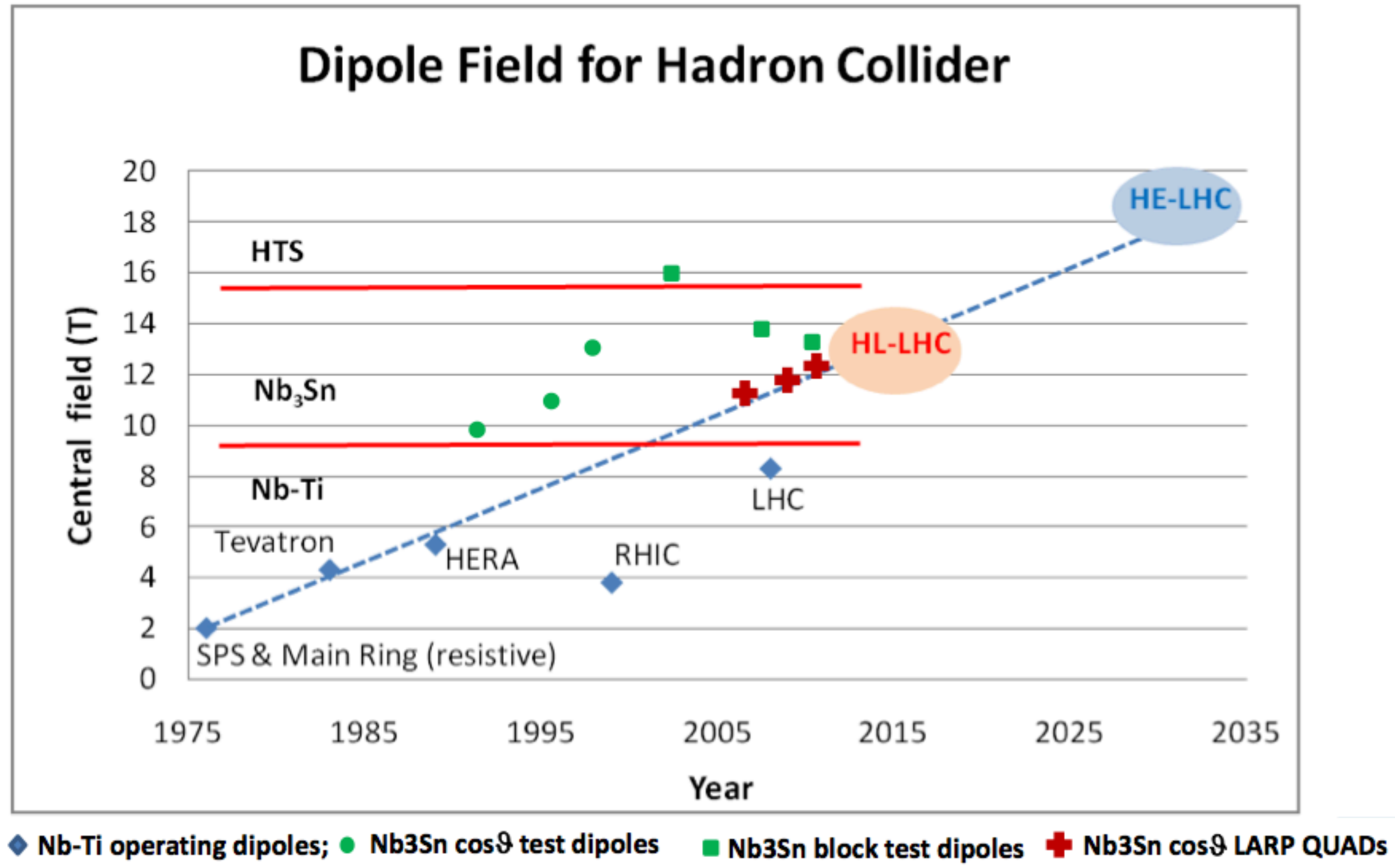
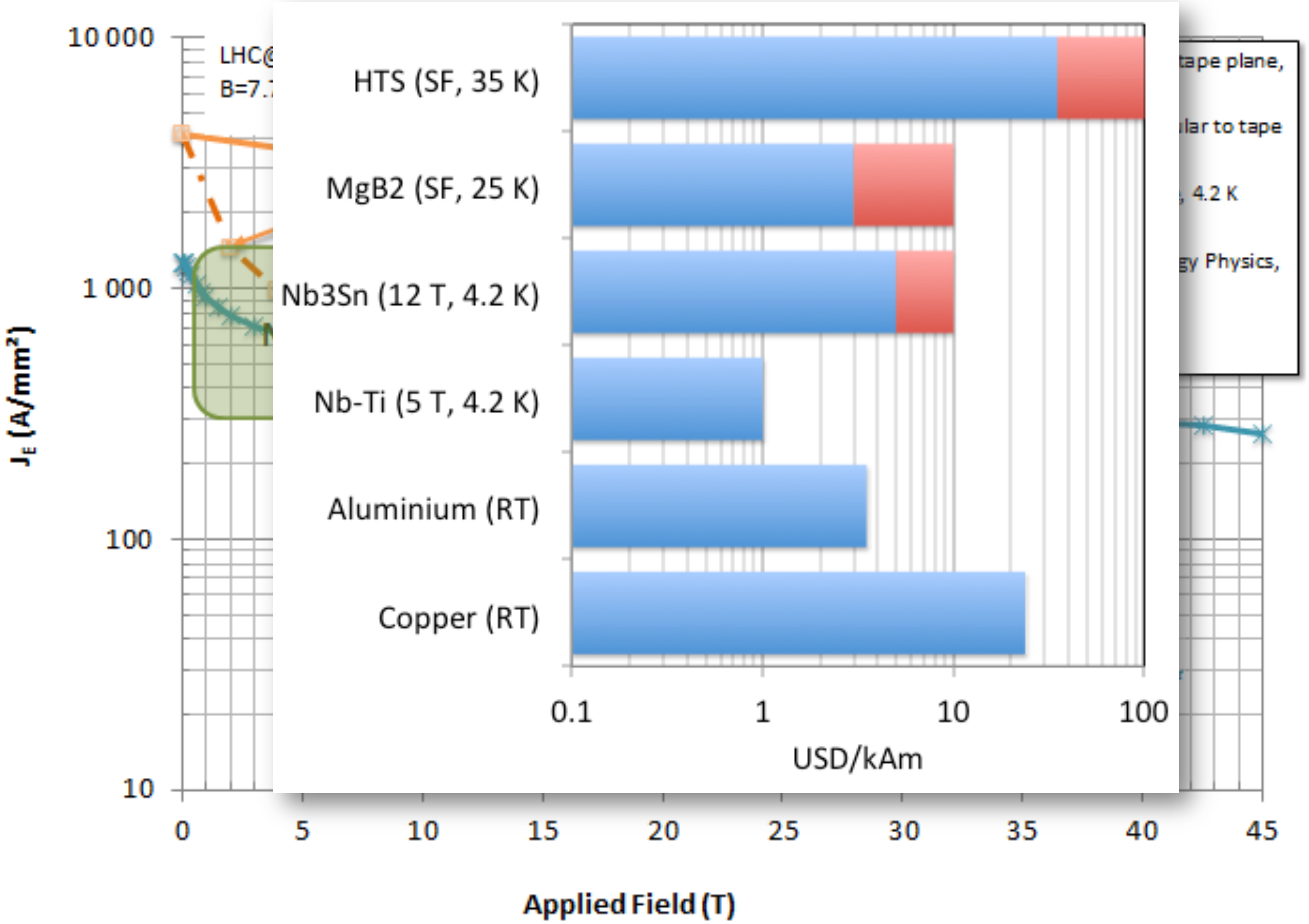
- need to go to high temperature superconductors for even higher fields
- R&D needed to bring the cost down
- Hybrid coils under discussion

HFM – FCC-hh





N. Walker, D. Schulte

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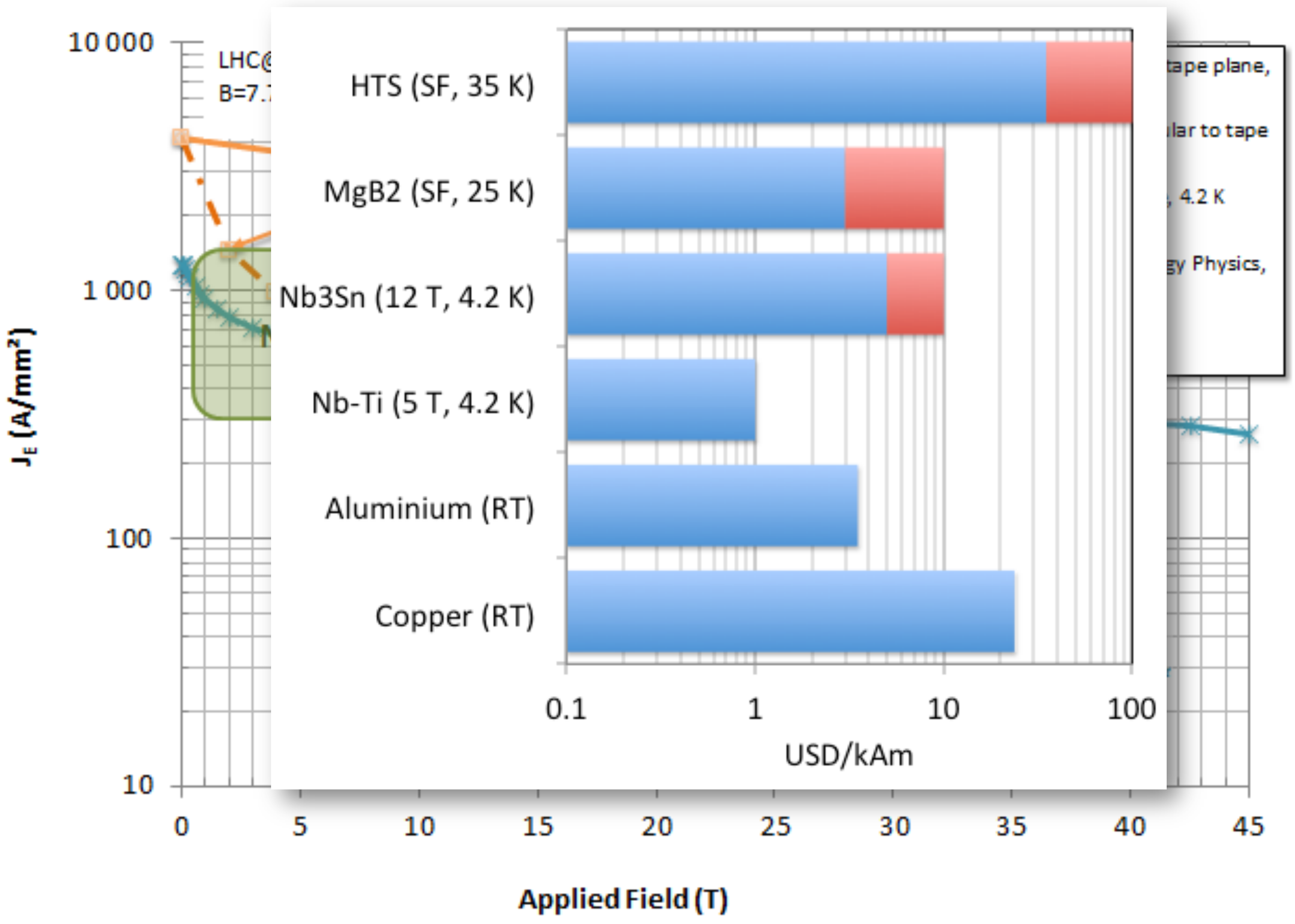

N. Walker, D. Schulte

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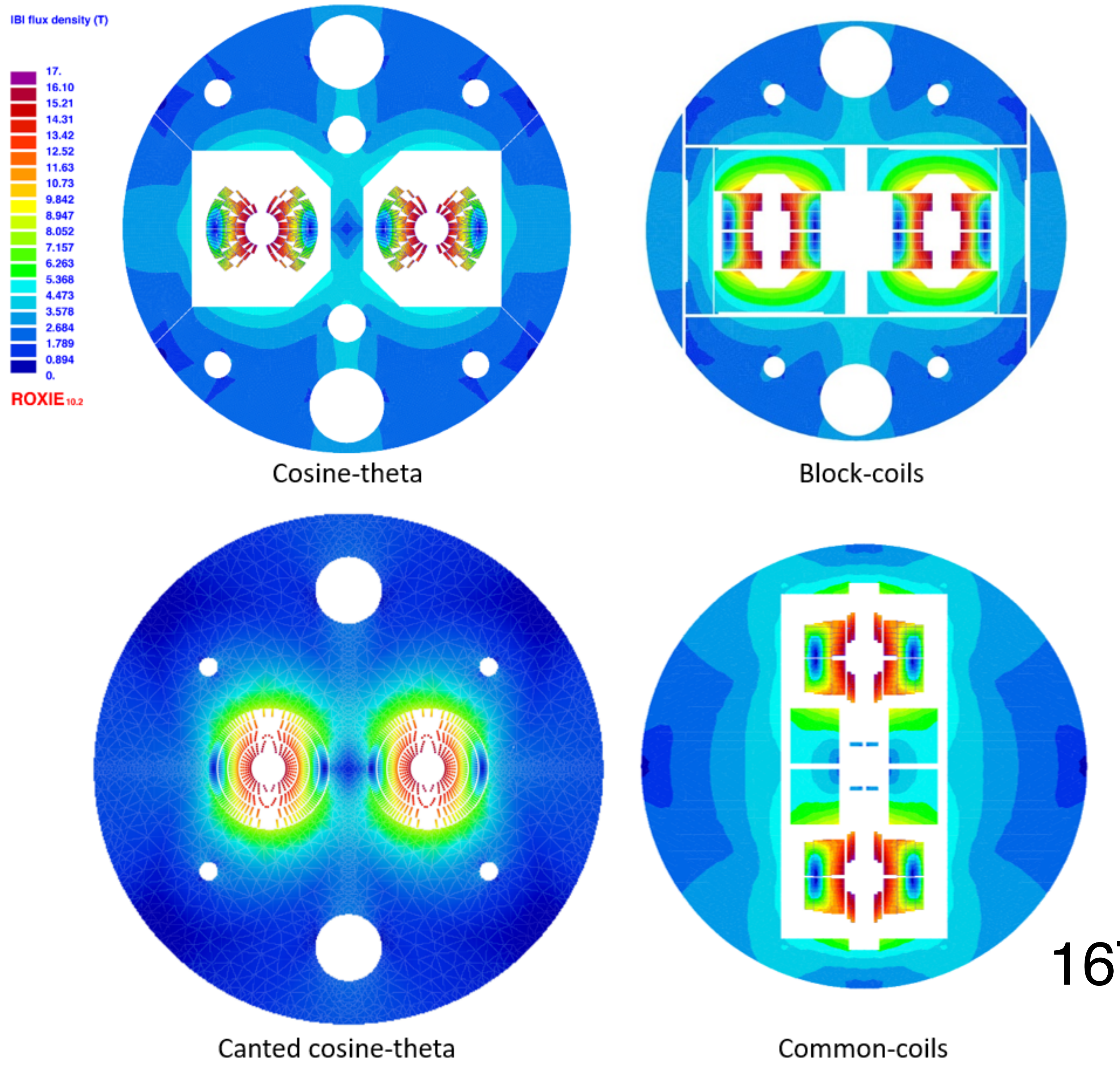
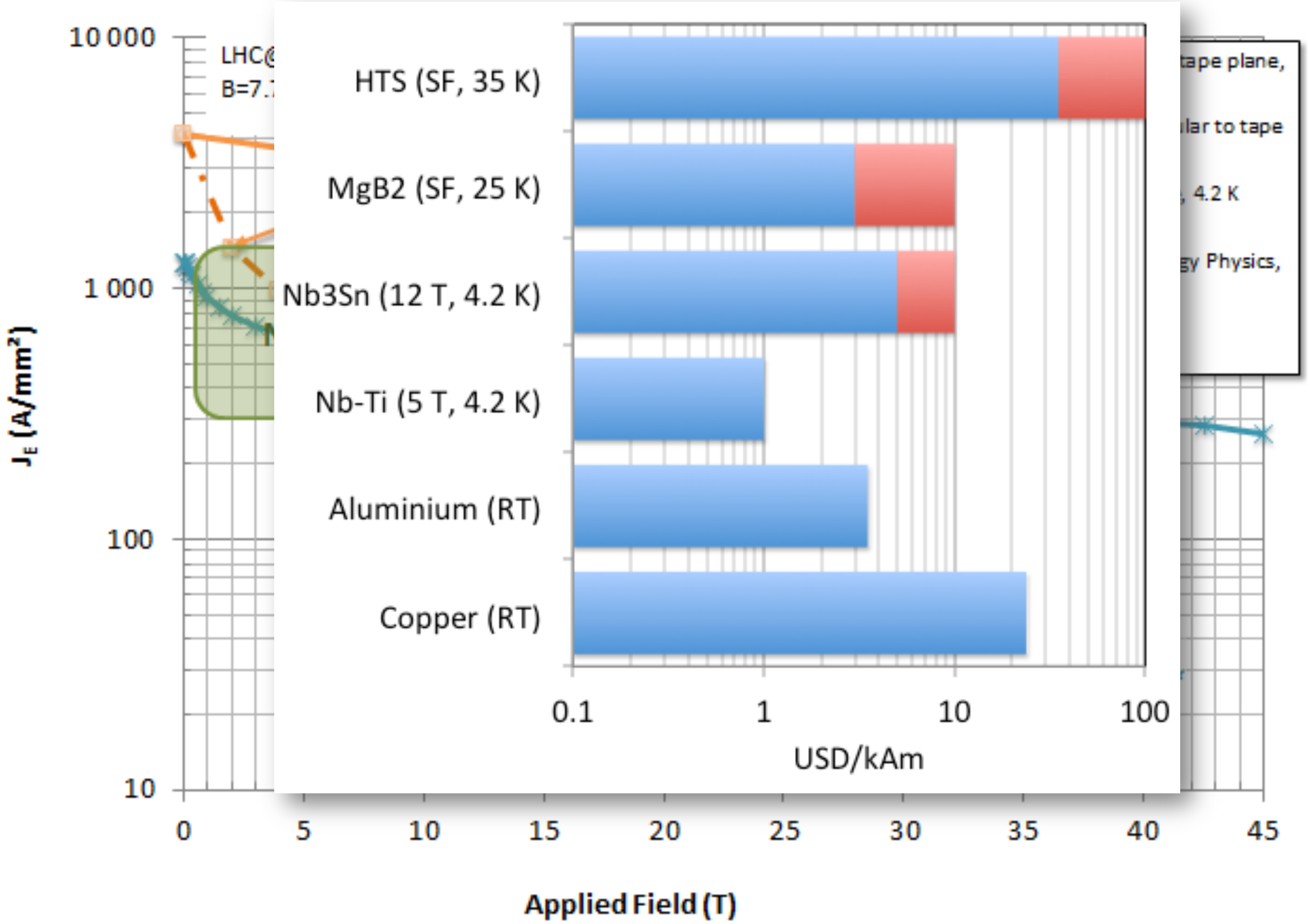


16T Coils

HFM – FCC-hh



N. Walker, D. Schulte

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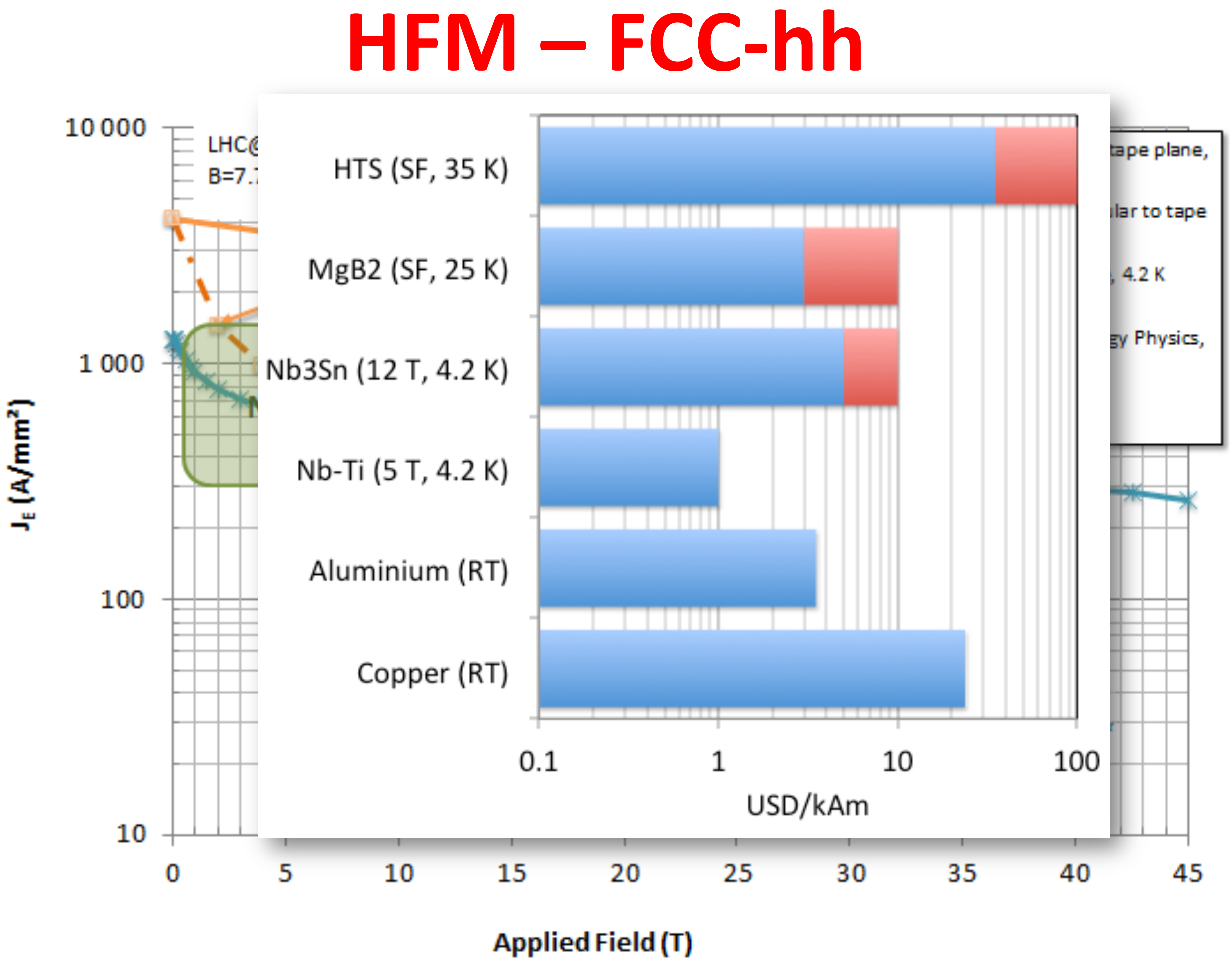

N. Walker, D. Schulte

FCC-hh: The Magnet Challenge

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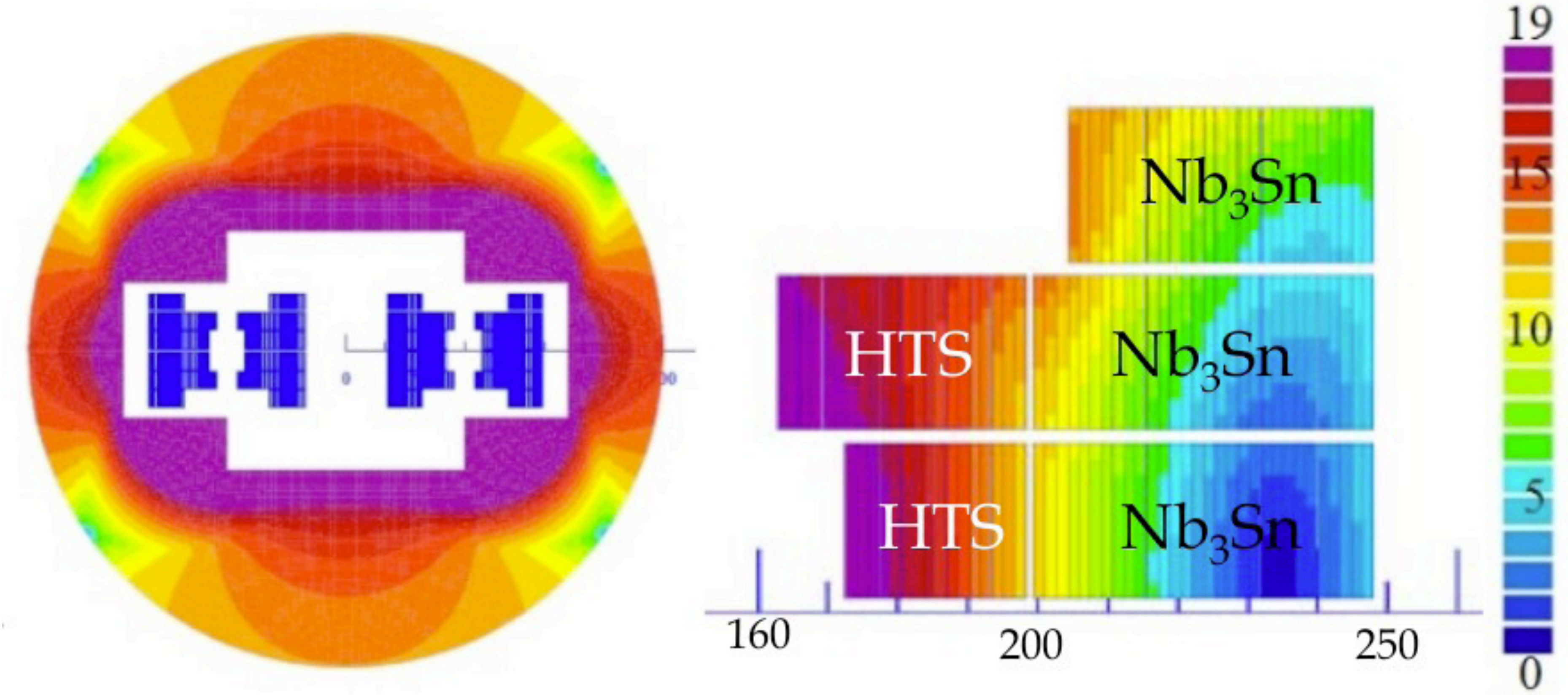
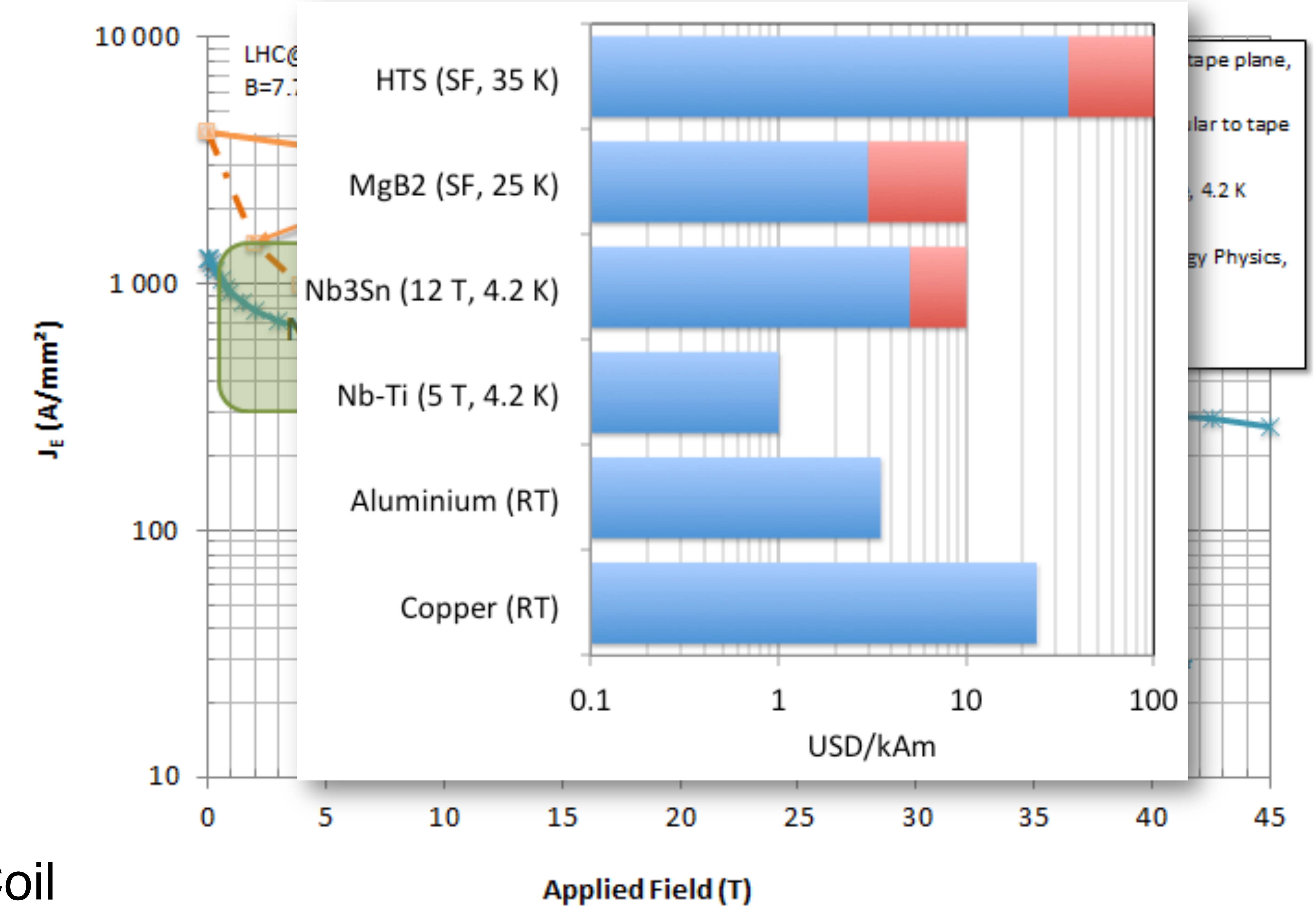


20 T Coil

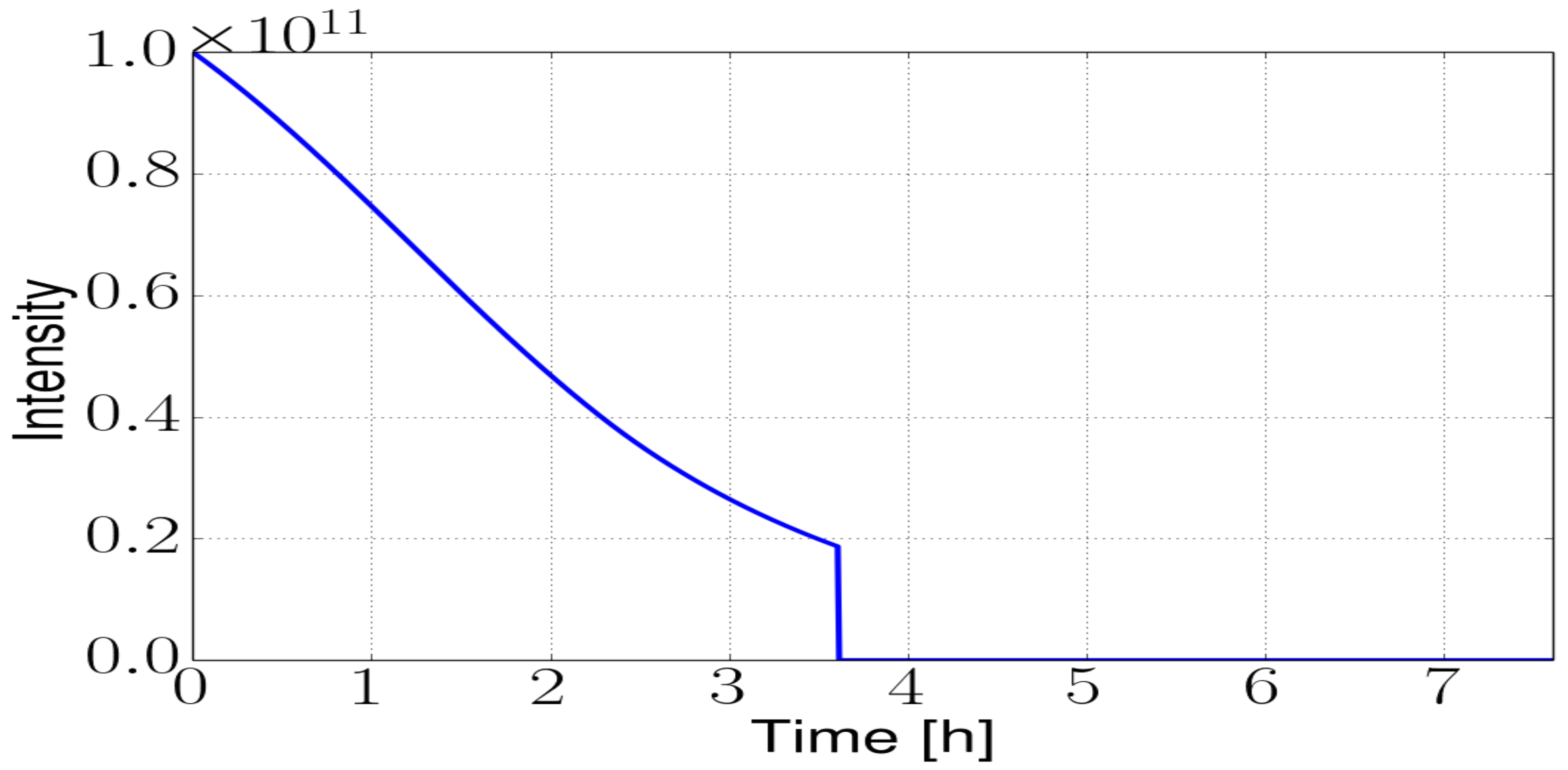
HFM – FCC-hh

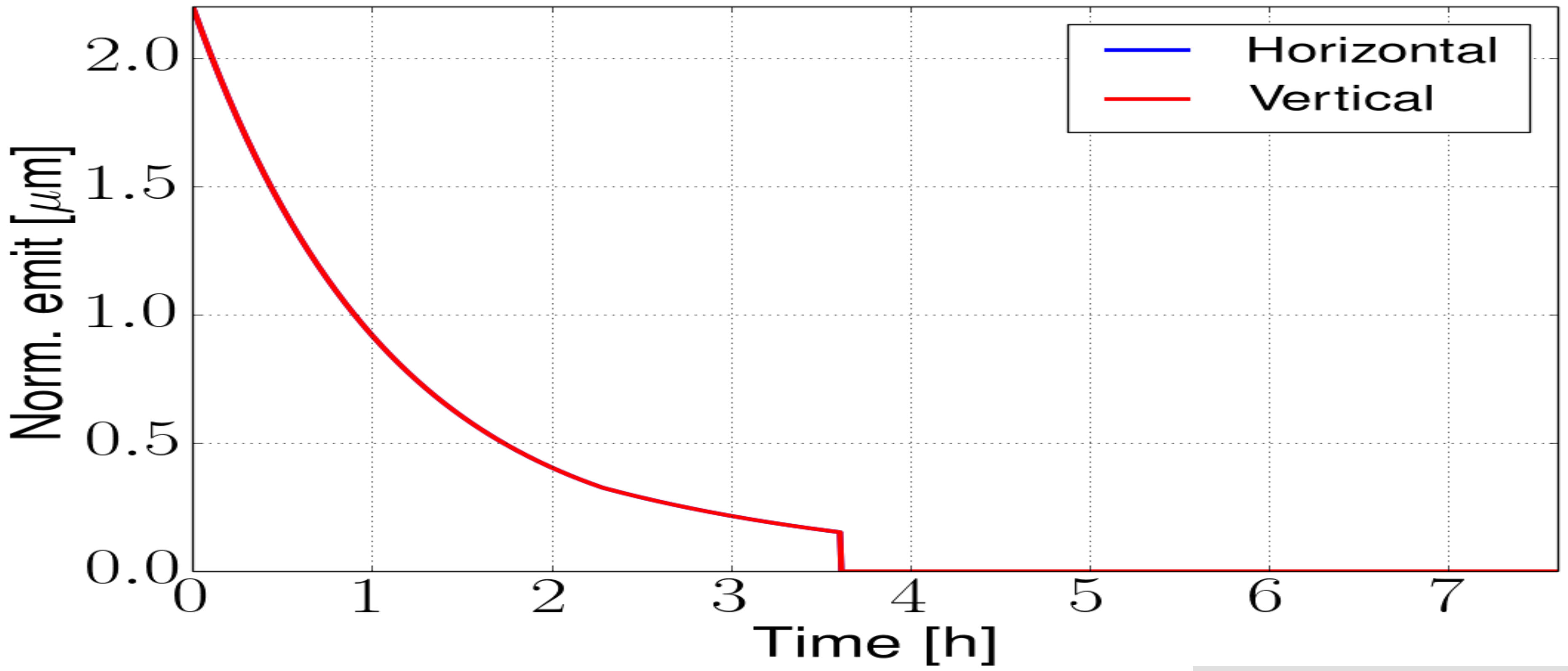


N. Walker, D. Schulte

Projected Beam Lifetimes

Luminosity During a Run



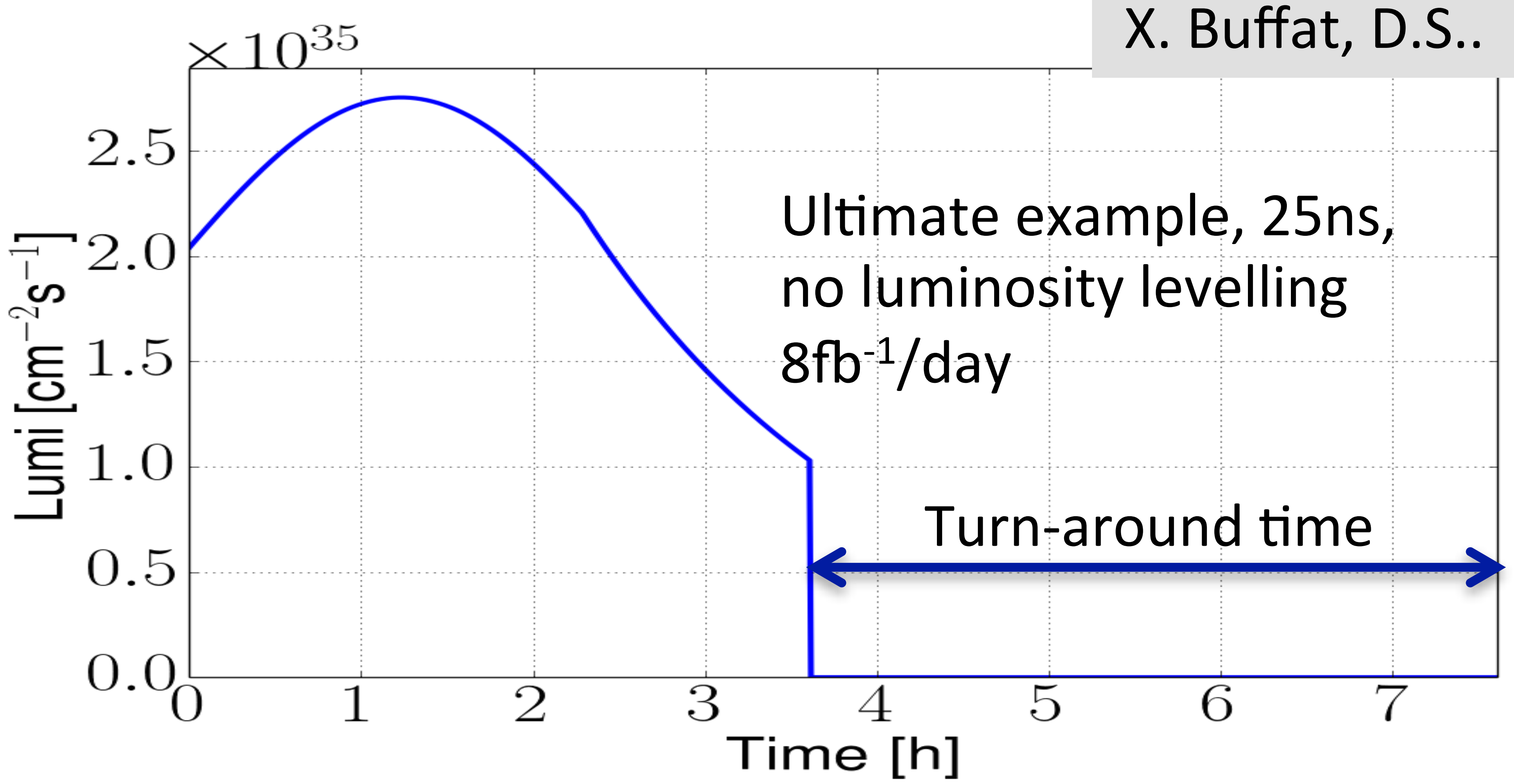


X. Buffat, D.S..

Developed model including most relevant effects
- Improvement with more detail planned

⇒ Reach 8fb^{-1}/day with ultimate for 25ns spacing
⇒ 5ab^{-1} per 5 year run

⇒ Beam is burned quickly
⇒ A reason to have enough charge stored



D. Schulte FCC-hh, Berlin, May 2017 5

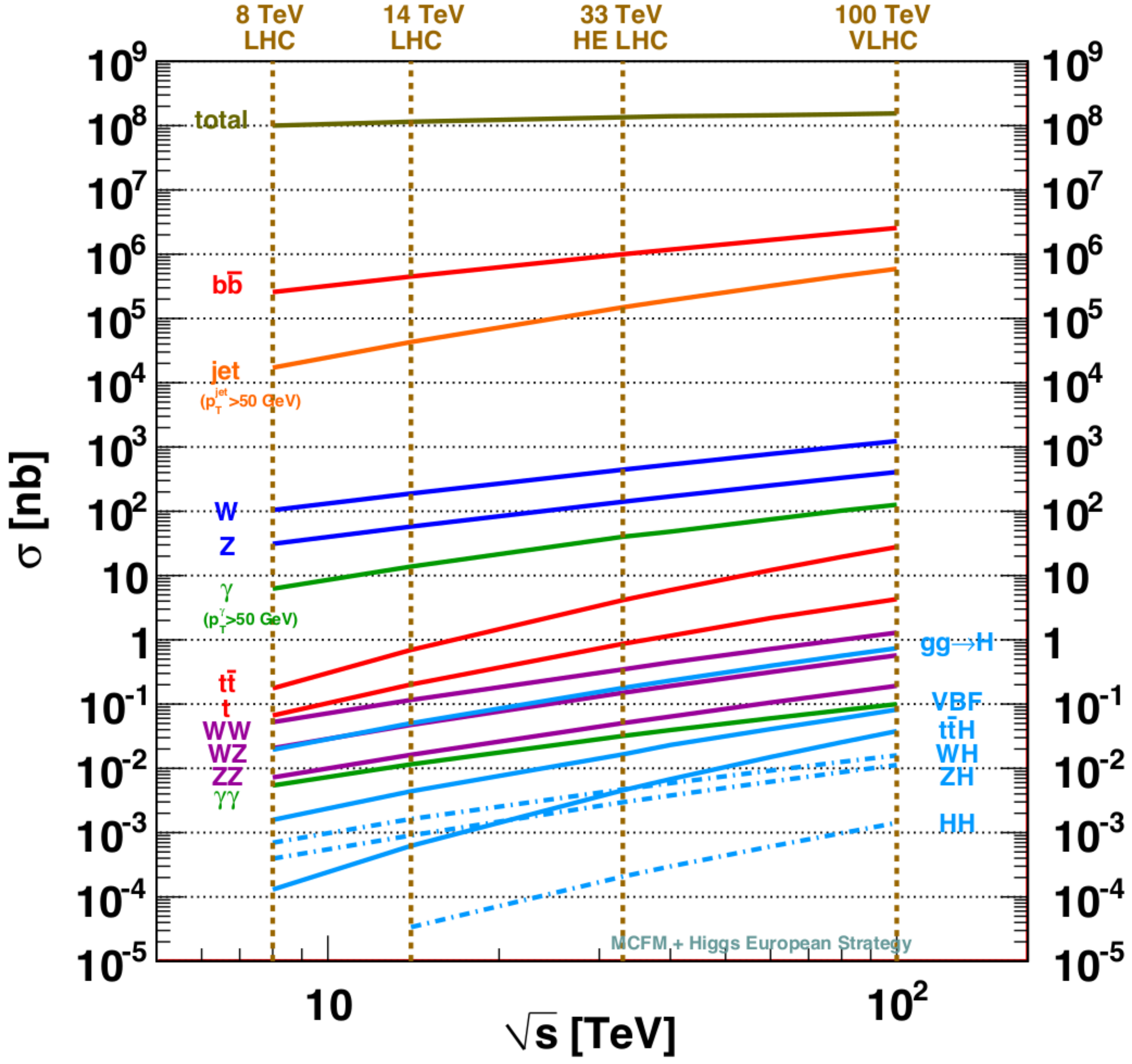
D. Schulte

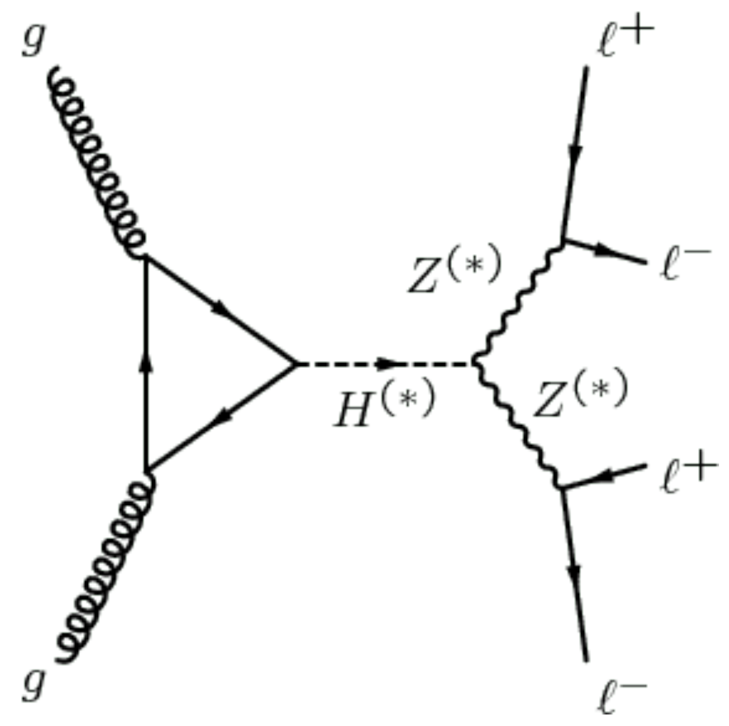
Detector Requirements

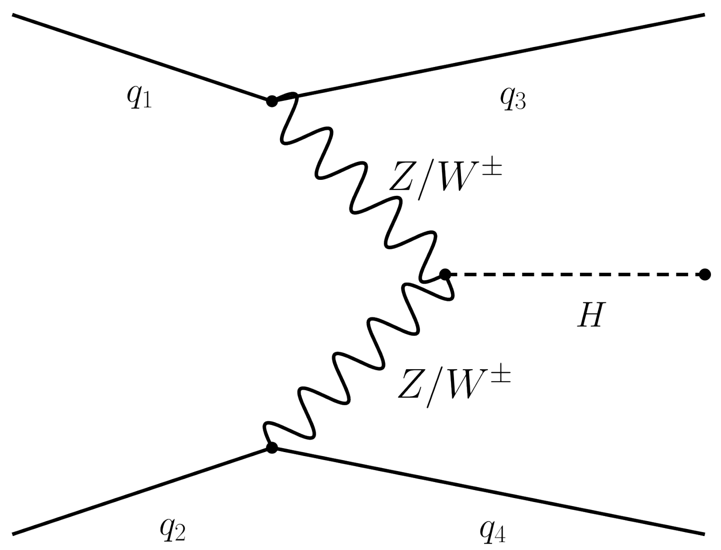
Physics requirements

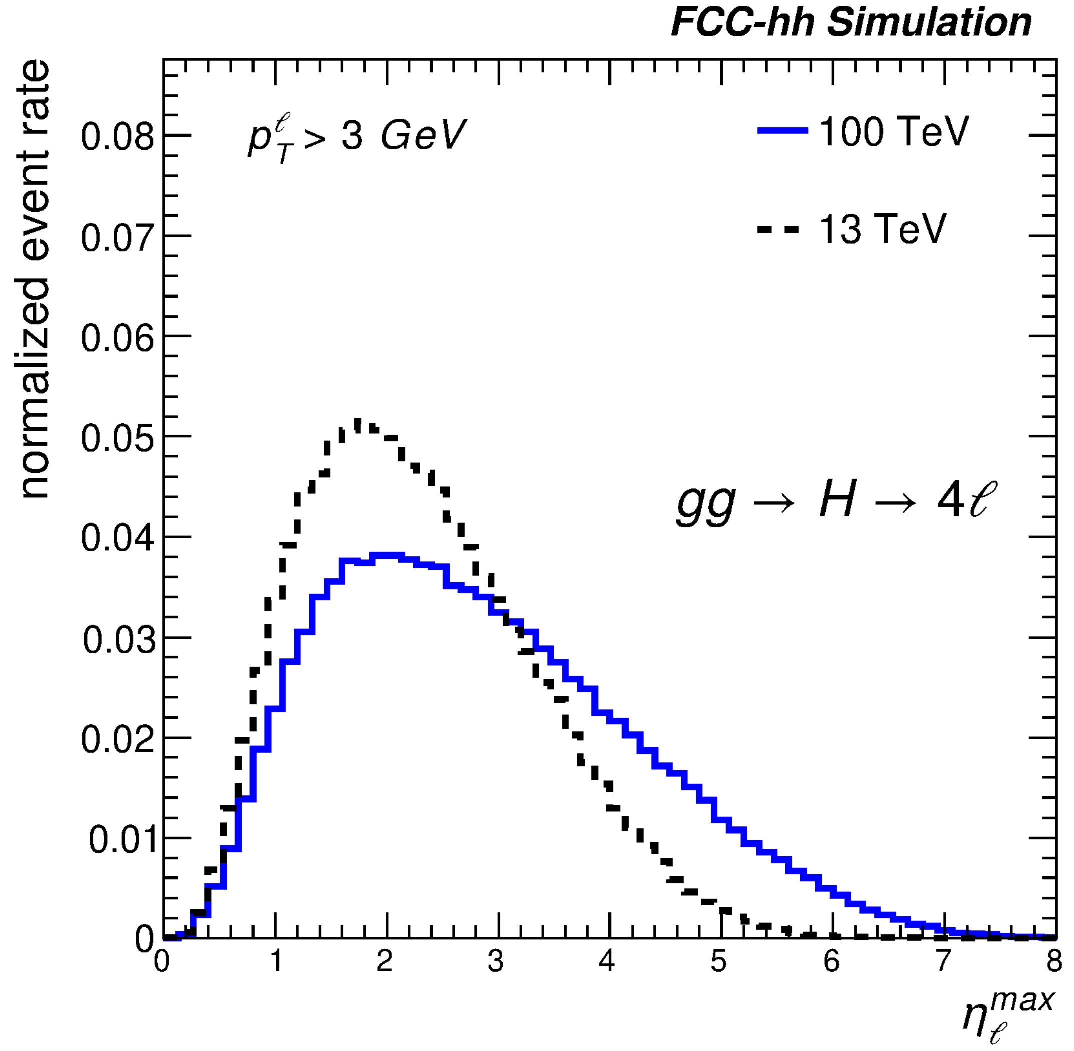
More forward physics → large acceptance

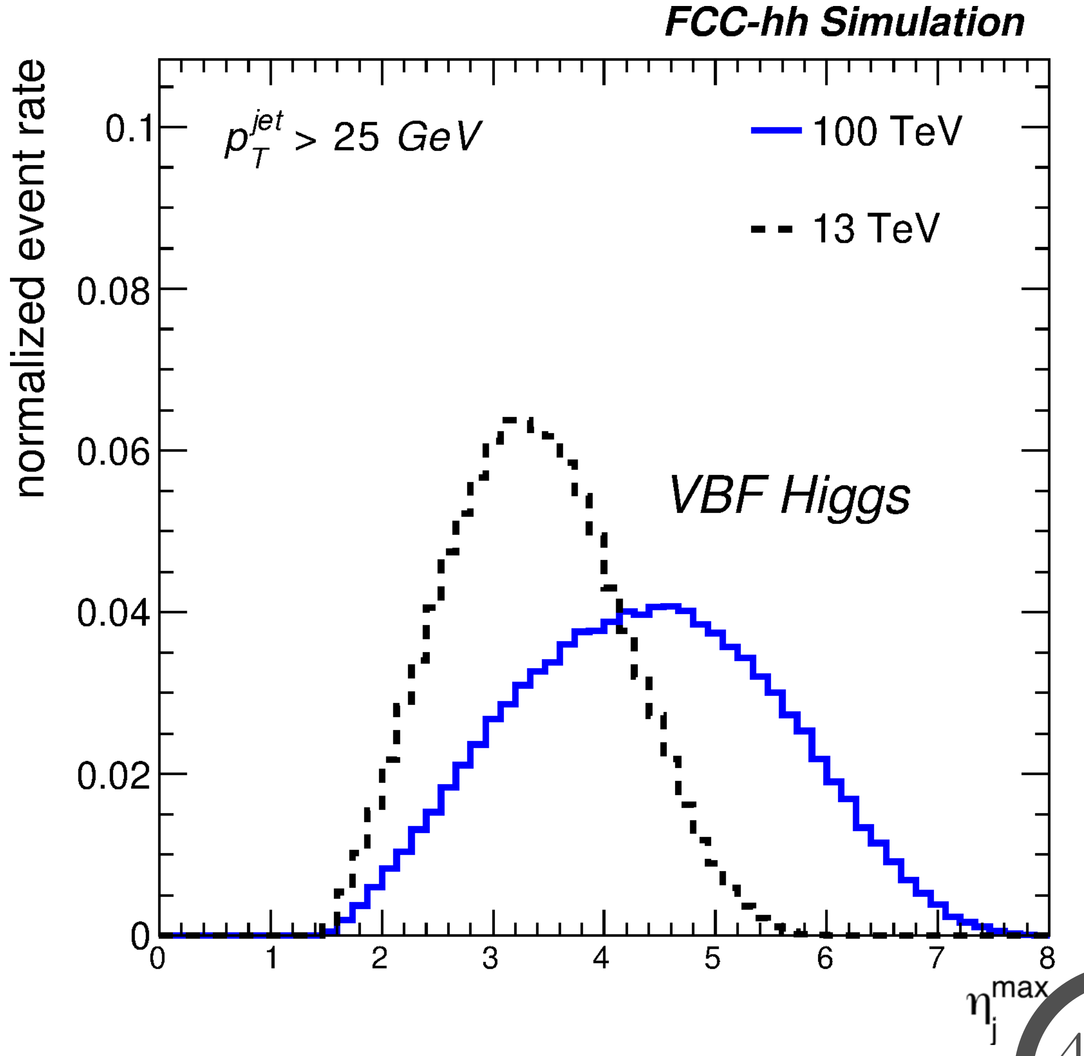
- precision momentum spectroscopy and energy measurements up to $|\eta| < 4$
- tracking and calorimetry up to $|\eta| < 6$





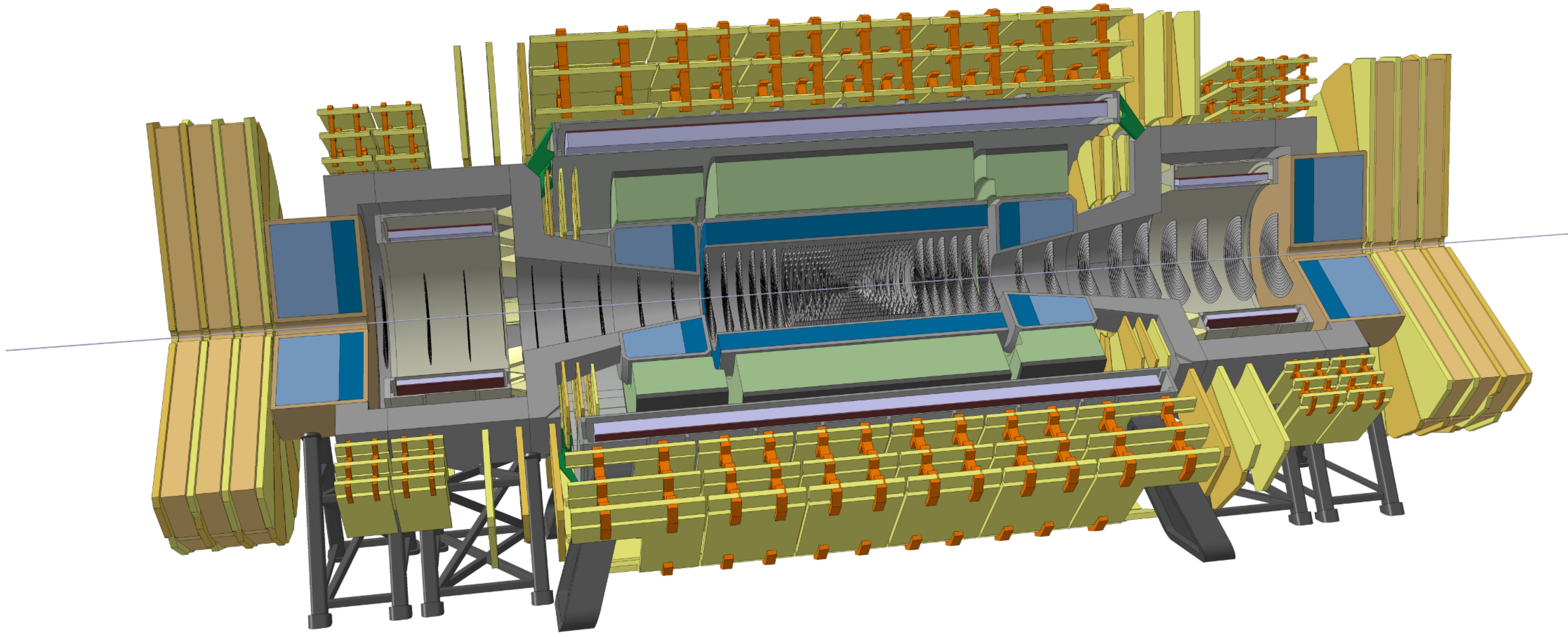


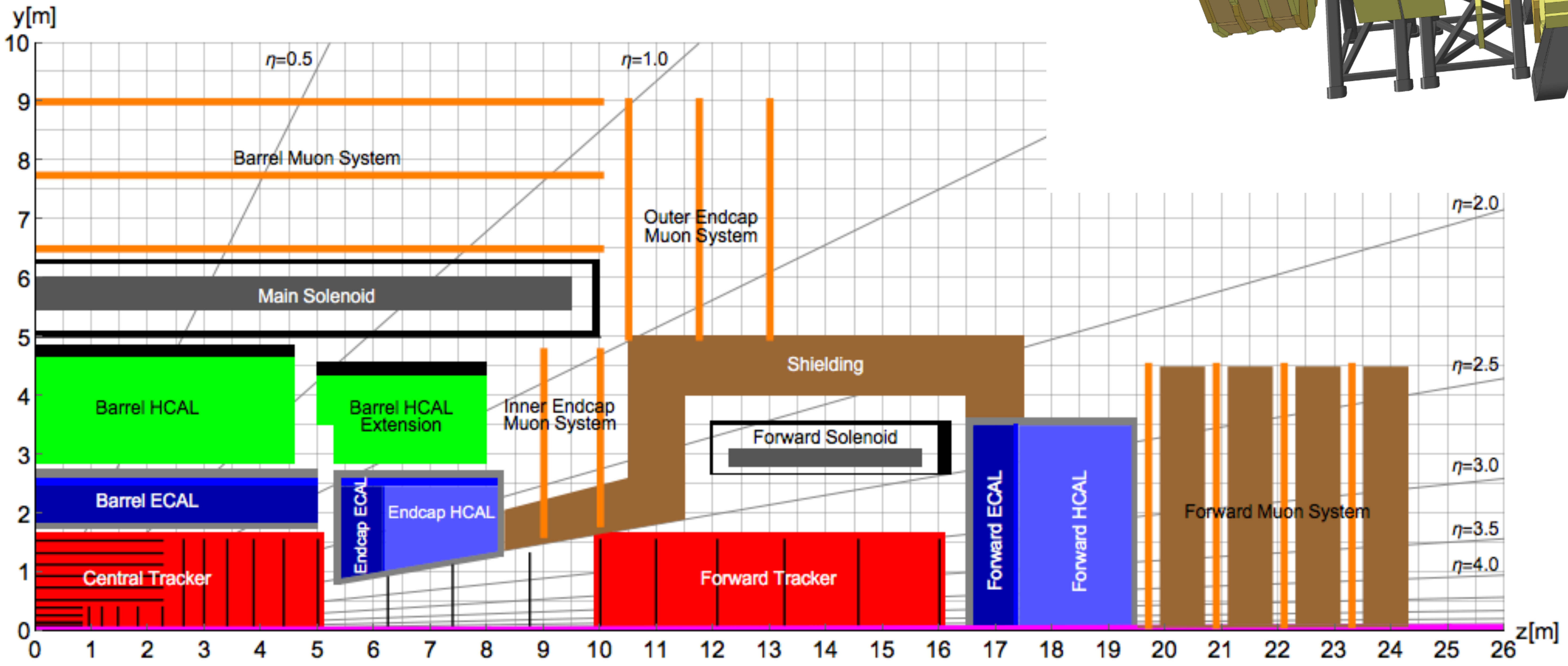




FCC-hh Reference Detector

- Not too different to ATLAS or CMS
- Focus on forward spectroscopy
- Radiation hardness is an issue



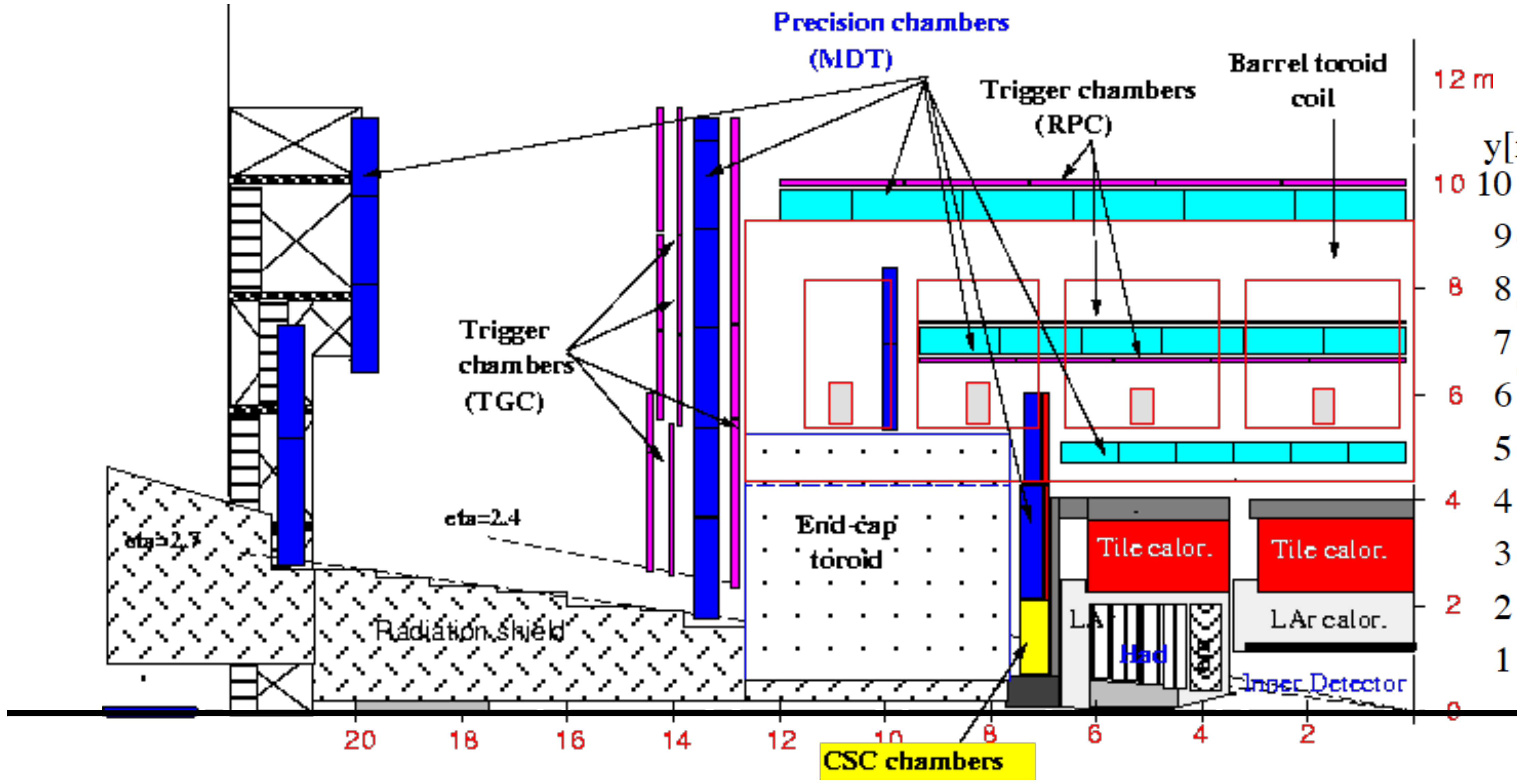


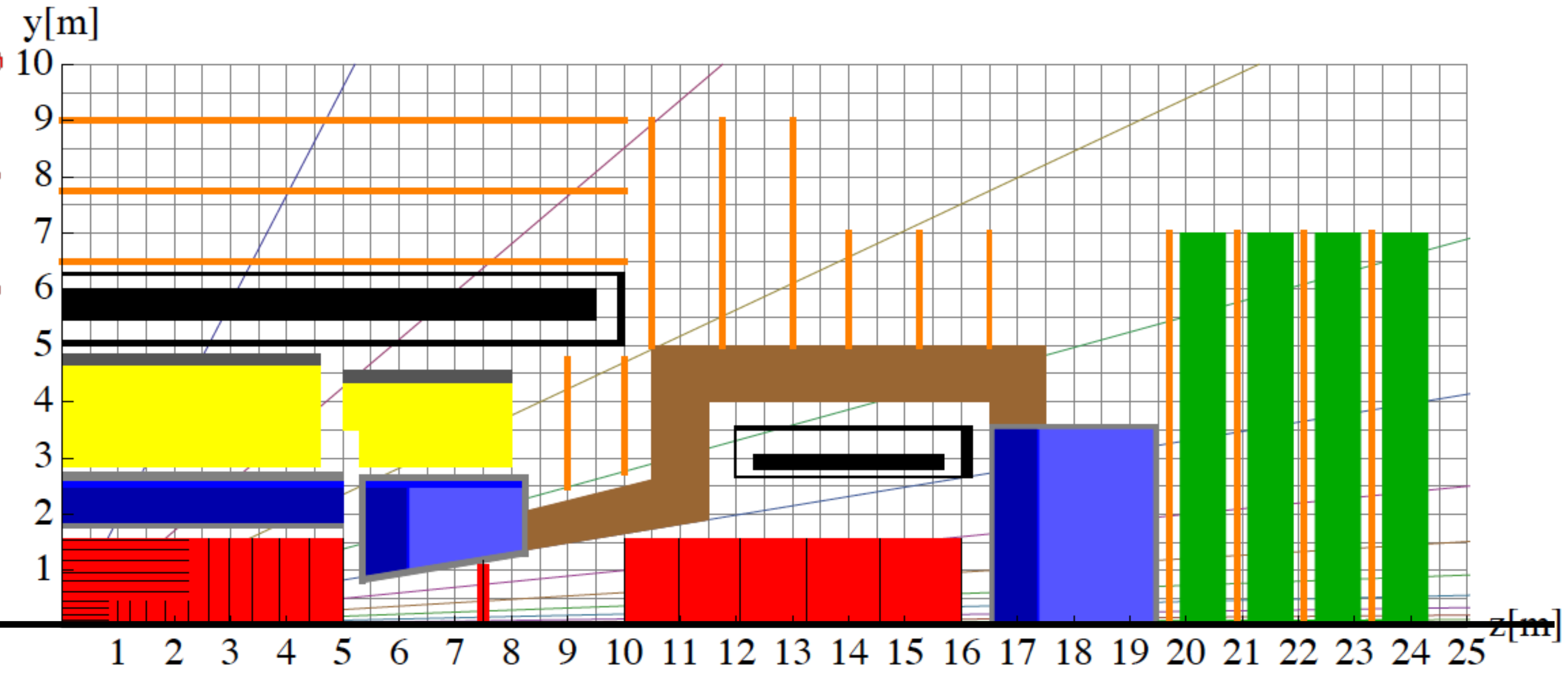
A. Zaborovska

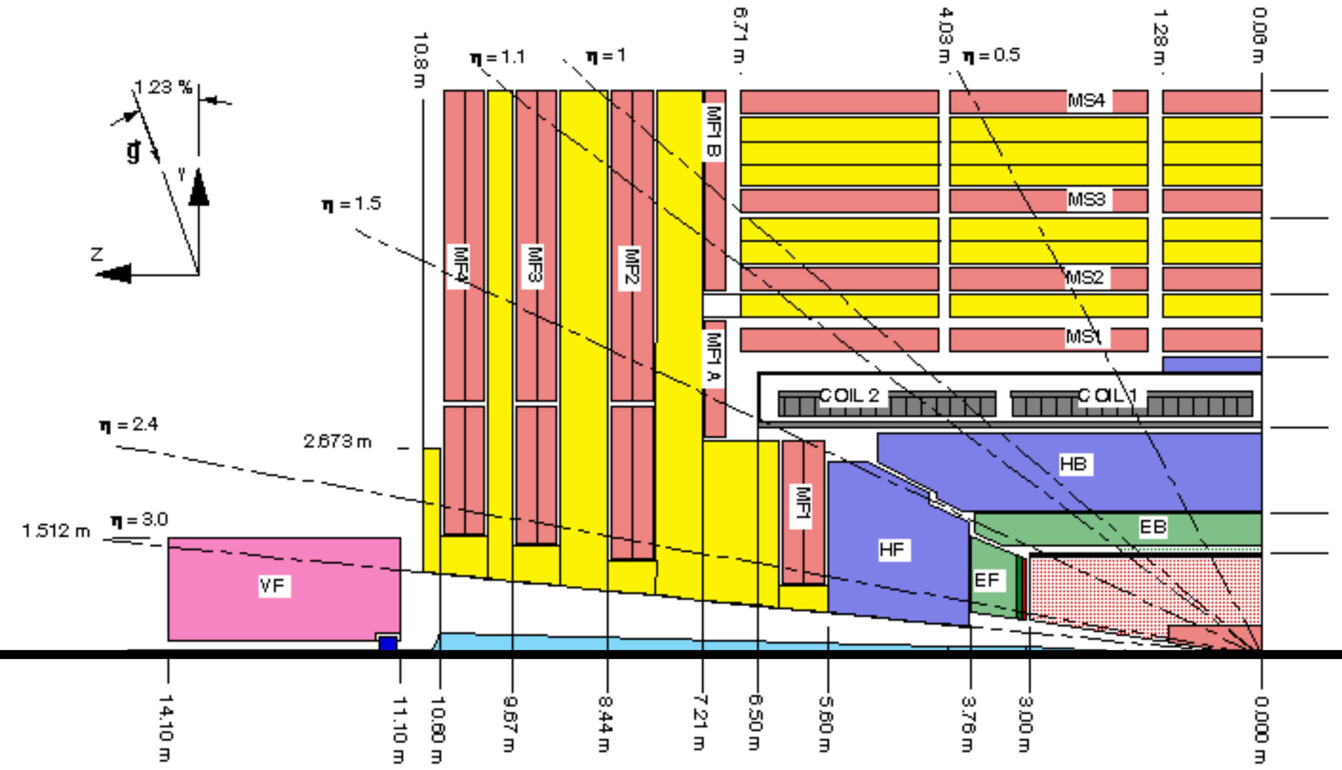
FCC-hh Detector Studies

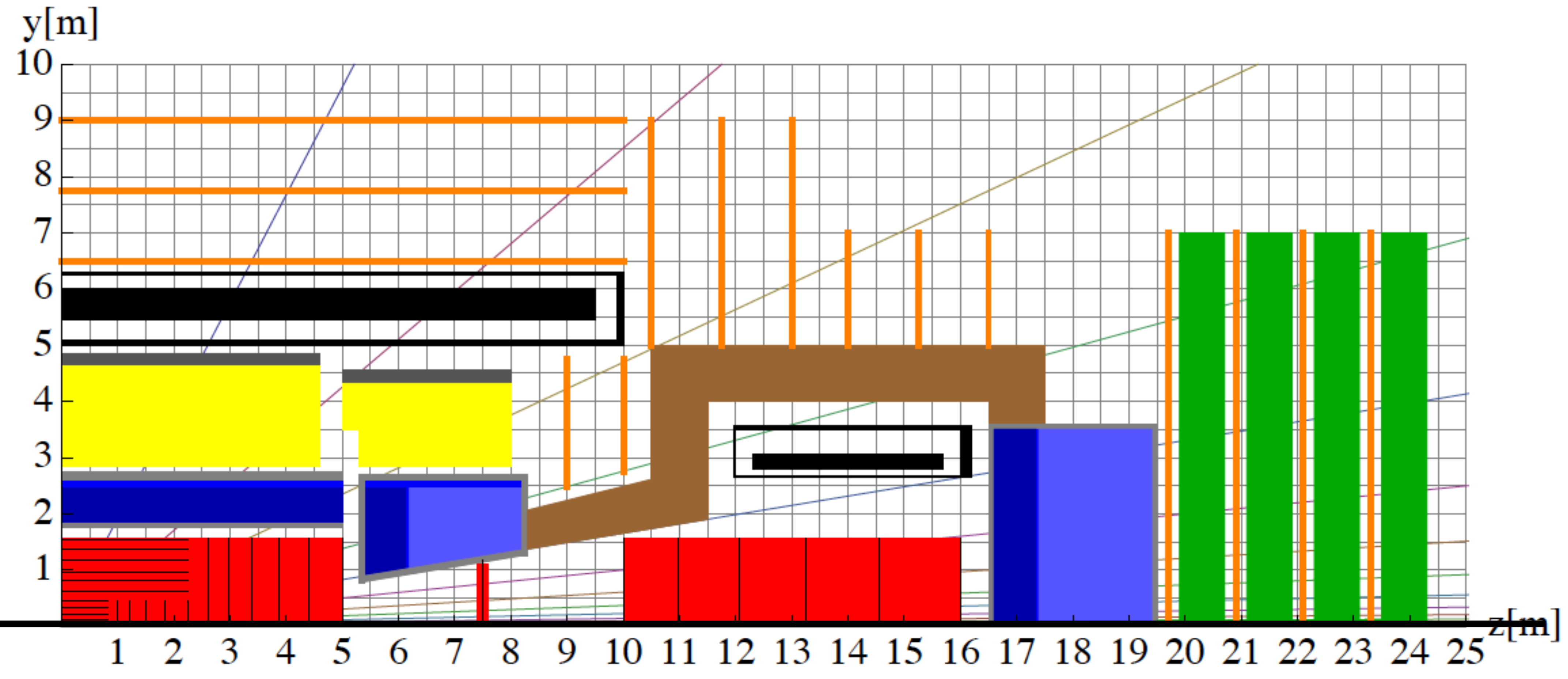
Comparison to ATLAS & CMS

W. Riegler





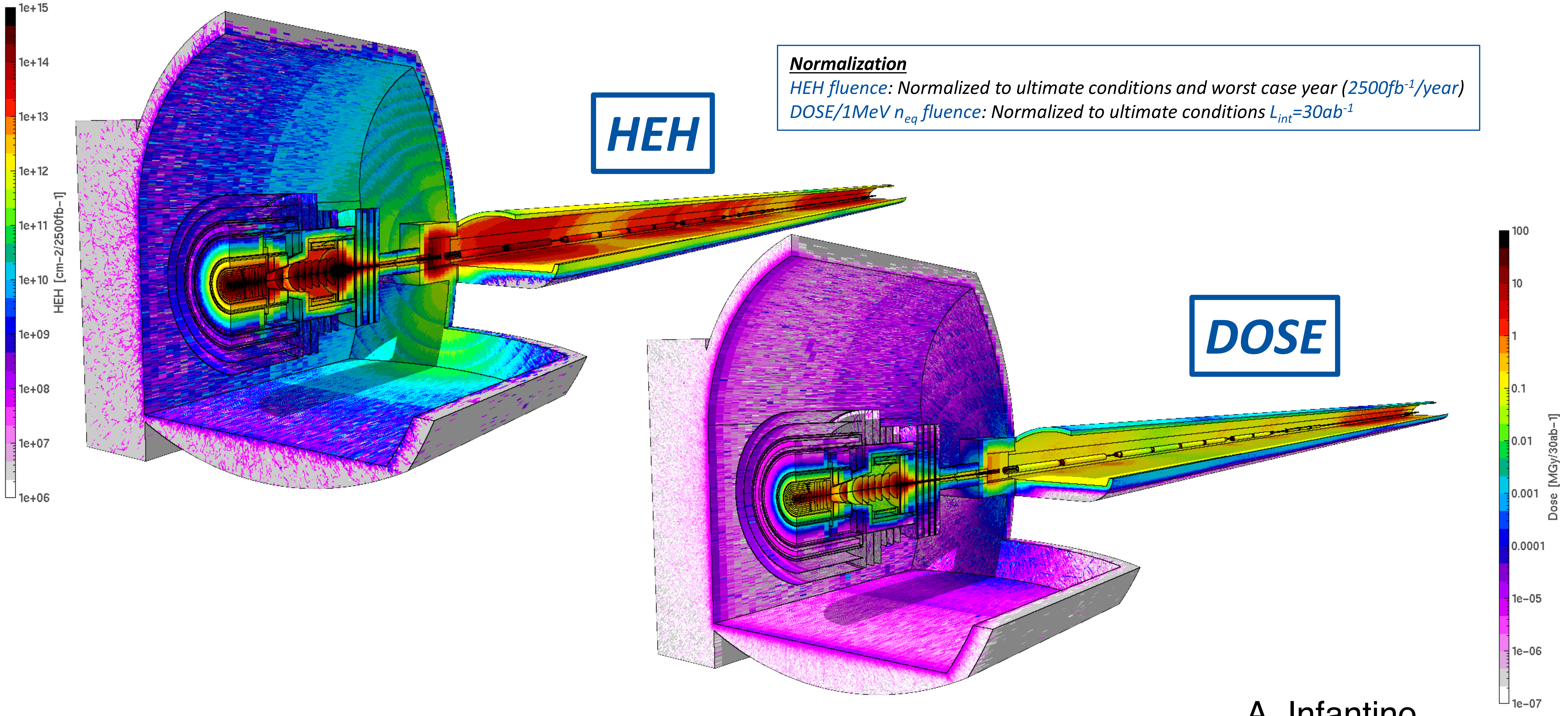




Radiation Issues

Results: High Energy Hadrons & Dose

Normalization
HEH fluence: Normalized to ultimate conditions and worst case year (2500fb^{-1}/year)
DOSE/1MeV n_{eq} fluence: Normalized to ultimate conditions L_{int}=30ab^{-1}



A. Infantino

High-Energy LHC

High-Energy LHC

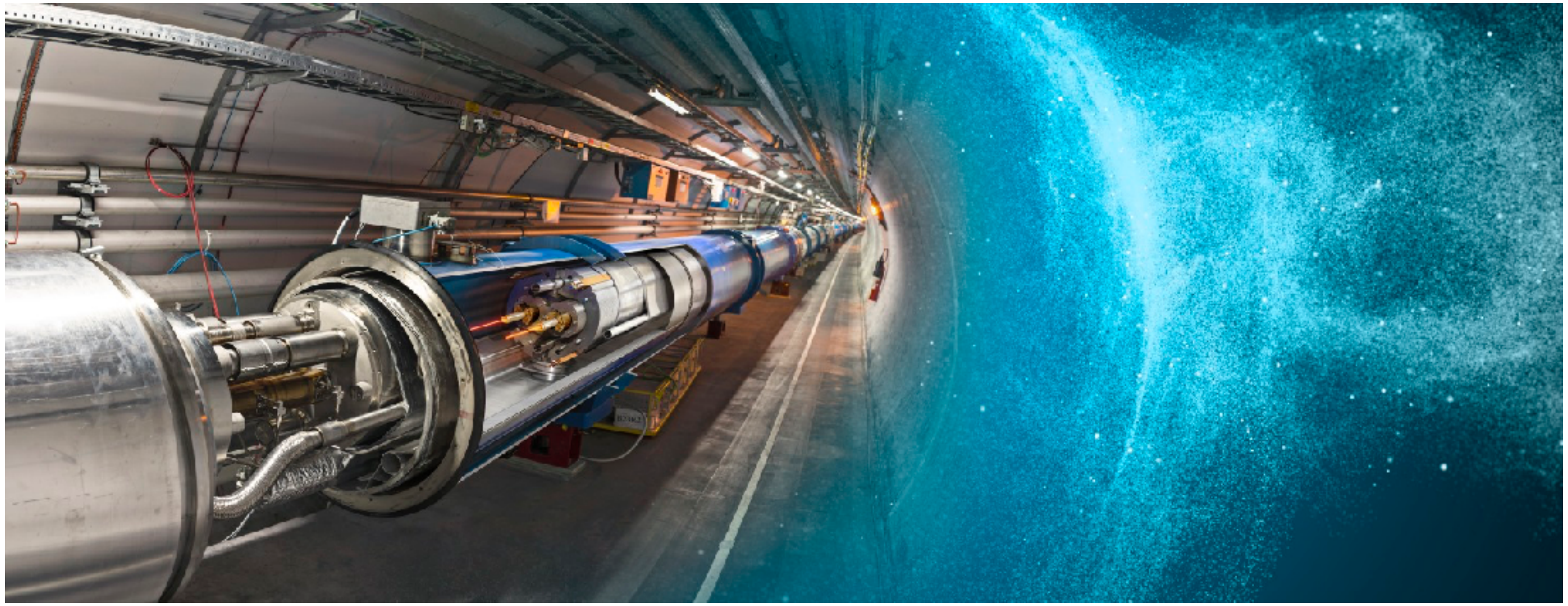
The „poor man's option" (therefore maybe realistic?)

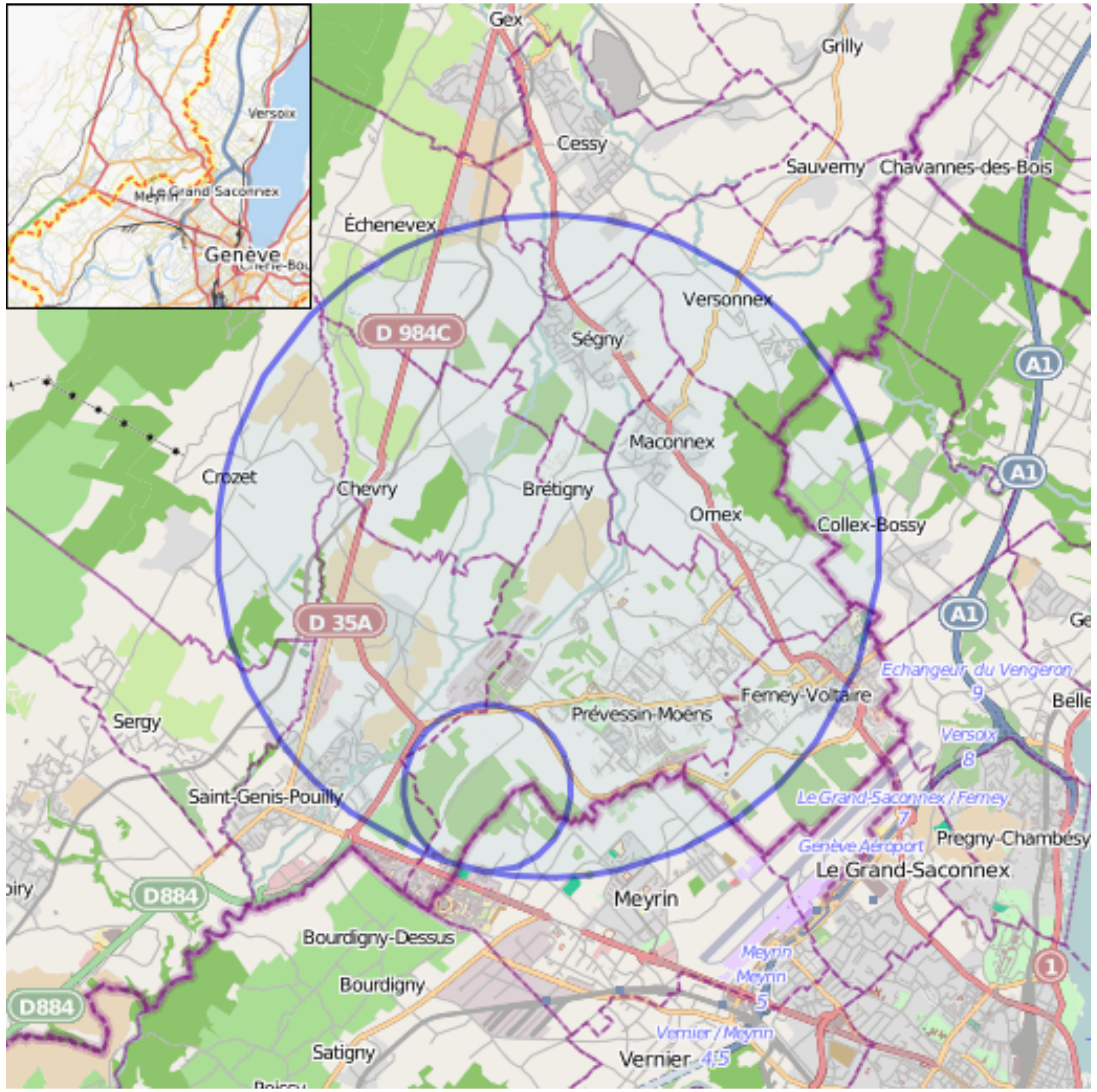
- though probably not cheap at all….

Do the 16-20 T magnet developments as for FCC-hh

- Replace the magnets in the existing 27 km LHC tunnel
- Reach ~28 TeV collision energy

Luminosity ~4 x HL-LHC





HE-LHC Tunnel

M. Benedikt

HE-LHC integration aspects

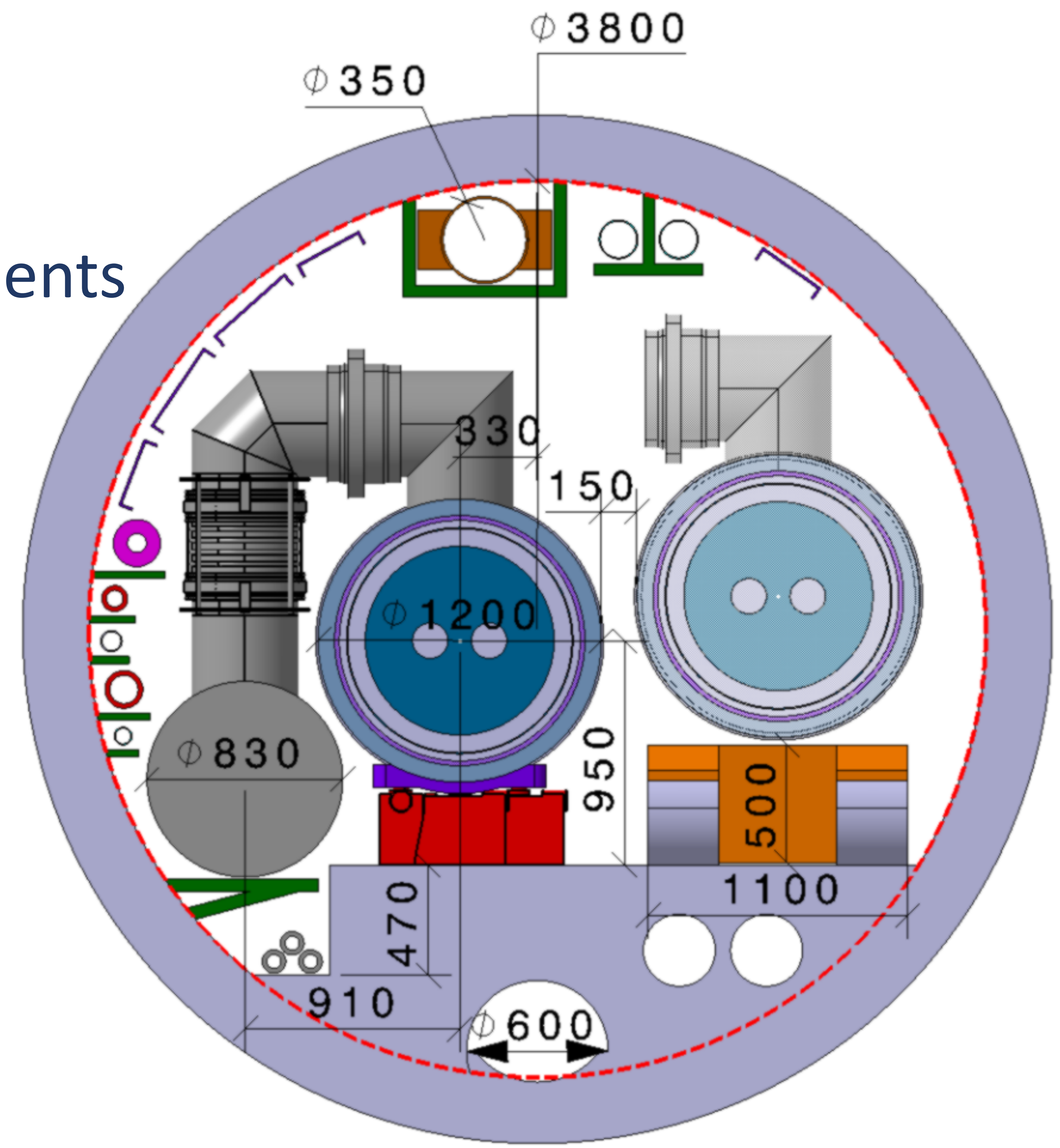
Working hypothesis for HE LHC design:

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 strategy:

- Development of optimized 16 T magnet, compatible with both HE LHC and FCC-hh
- New cryogenic layout to limit QRL dimension



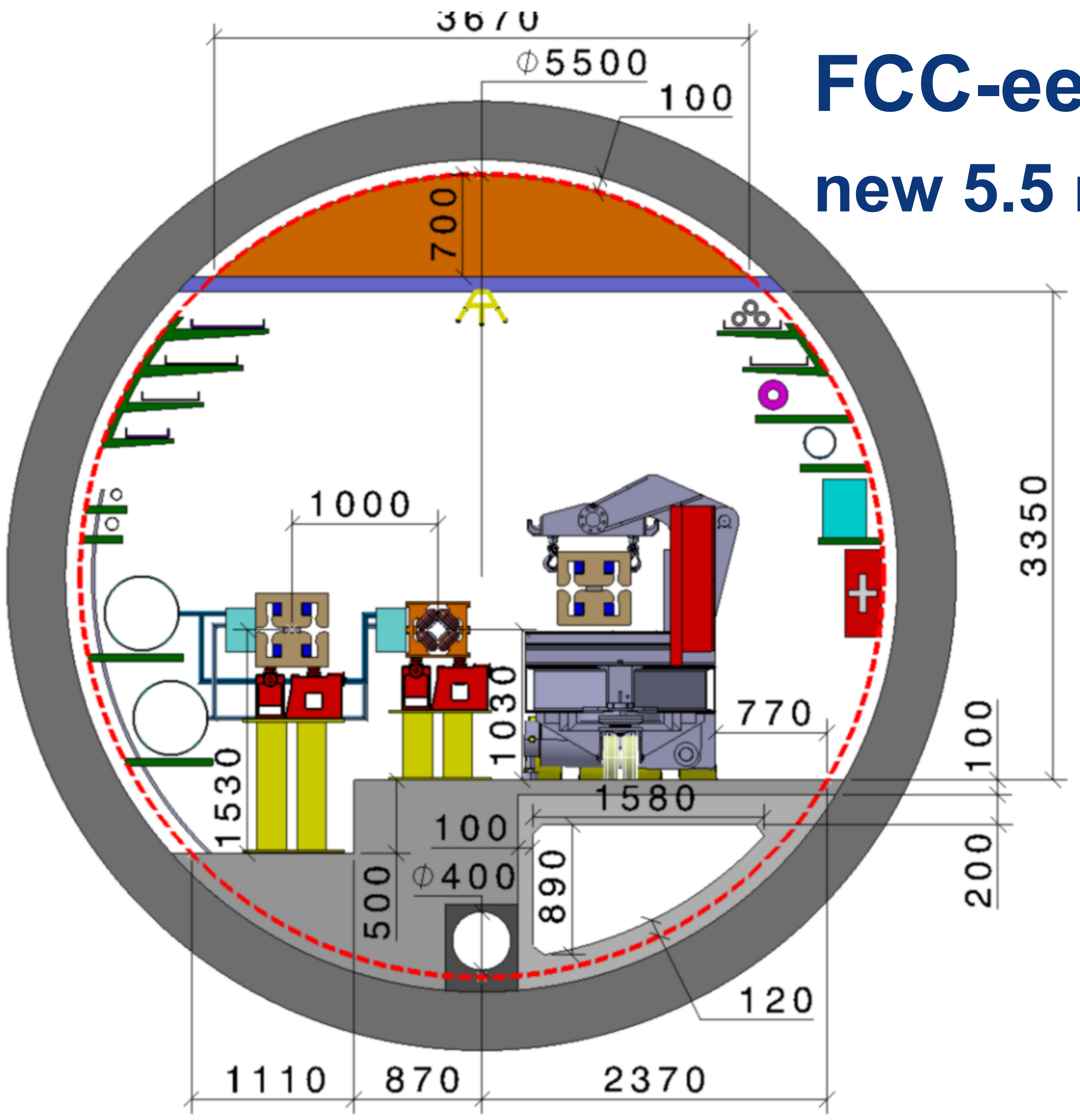
FCC-ee

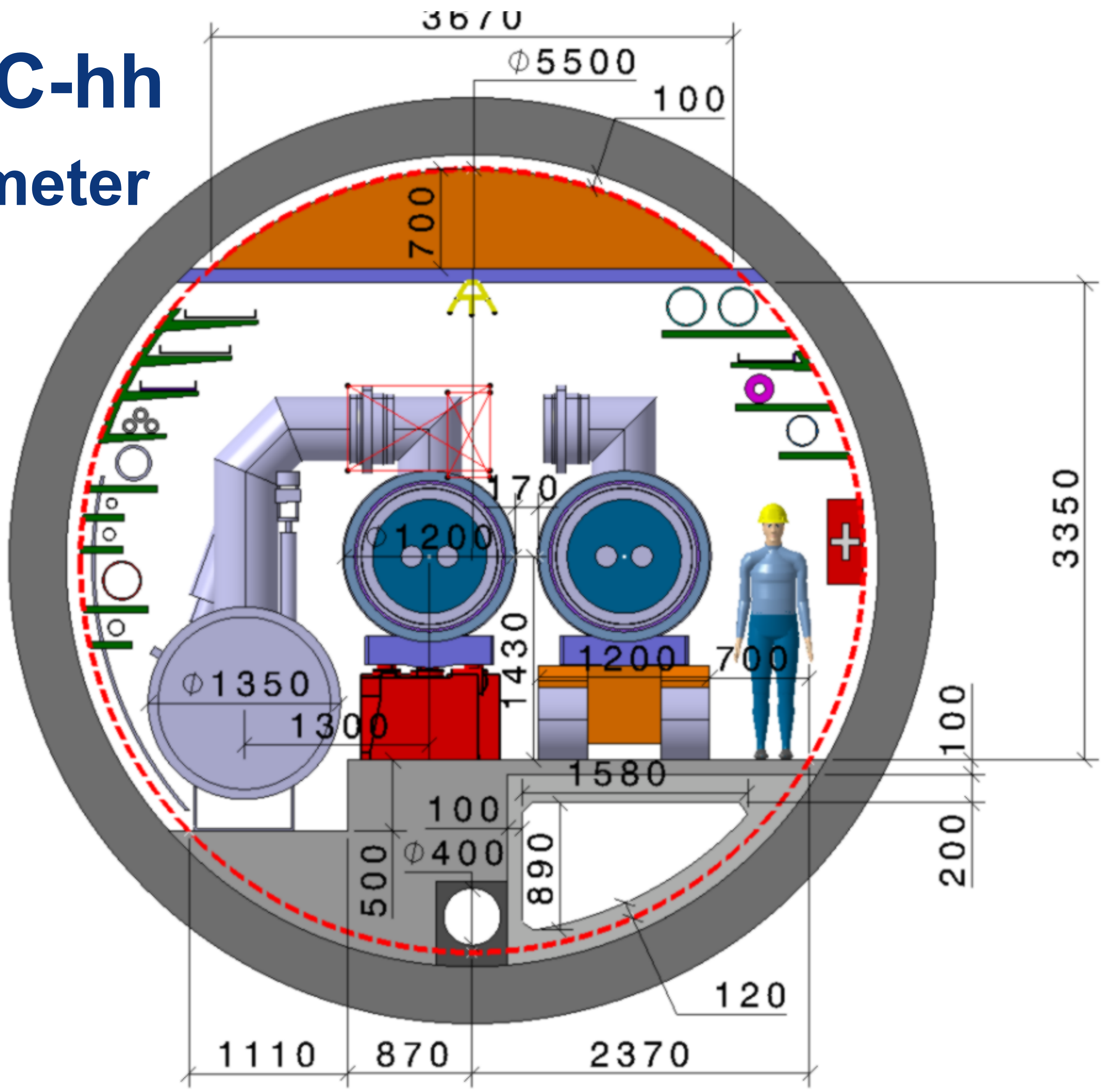
FCC-ee as a precursor to FCC-hh

Use magnet development time for FCC-hh to install and run an electron positron collider in the 100km tunnel…

FCC-ee **FCC-hh**

new 5.5 m inner diameter





M. Benedikt

FCC-ee Parameters

Limited in energy to below ~350 GeV (synchrotron radiation)

- can do Higgs physics, but not e.g. Higgs self coupling

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

M. Benedikt

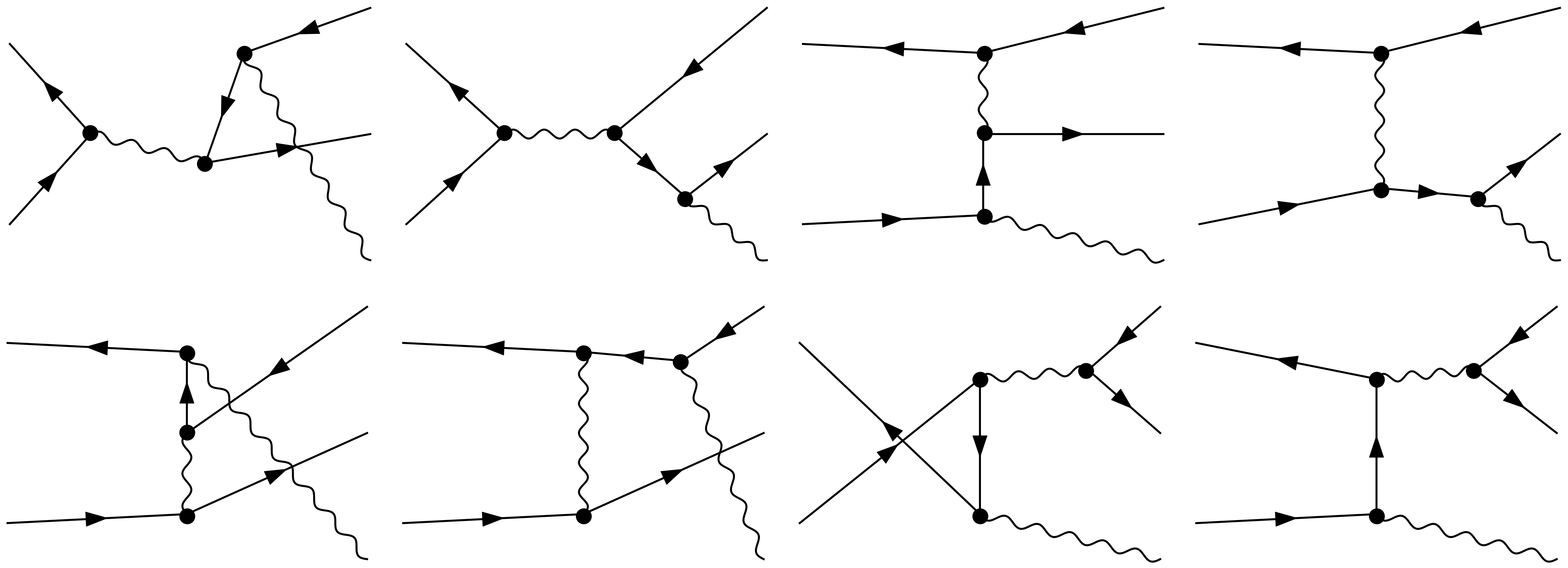
FCC-ee Beam Lifetime

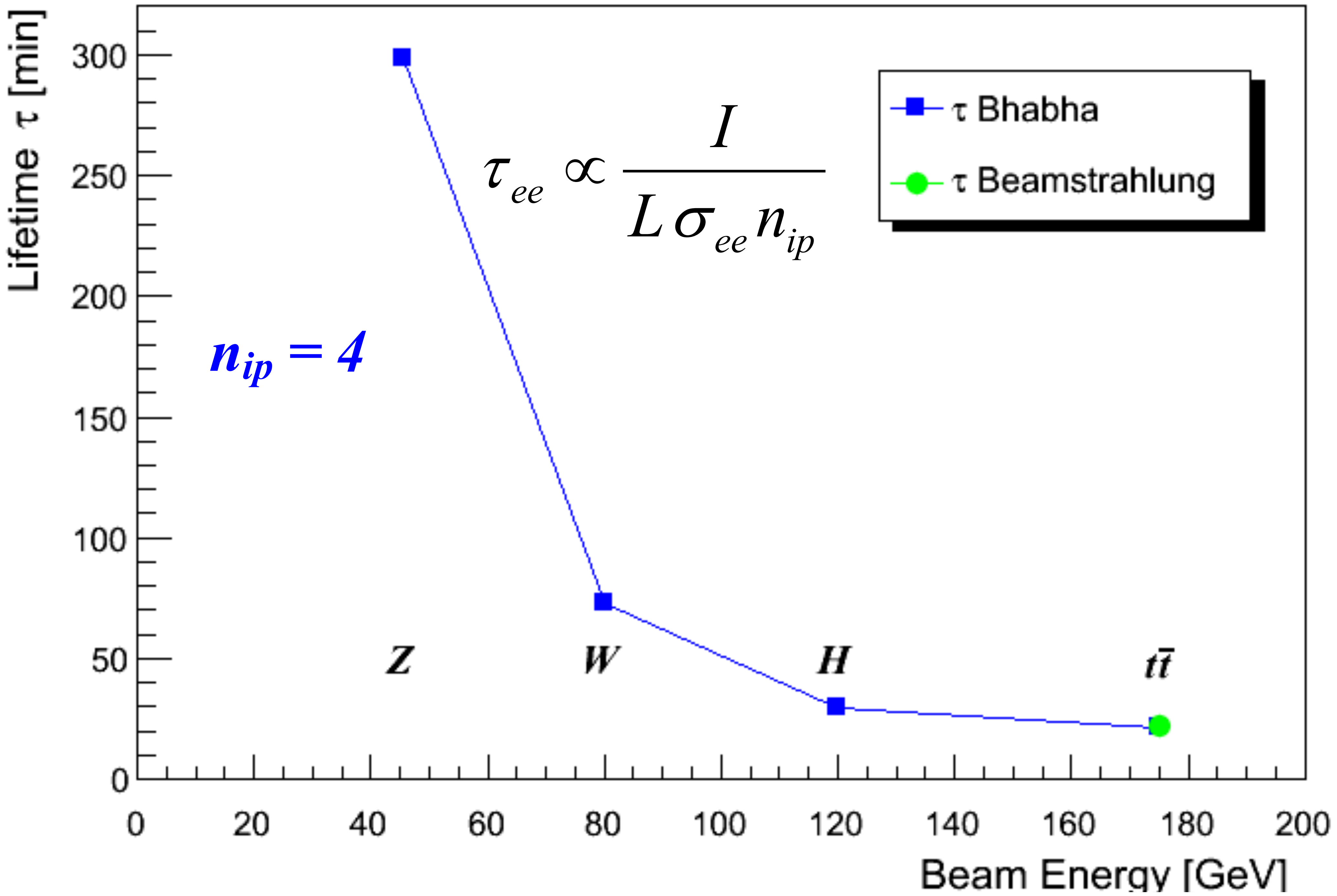
Energy loss in IP and limited acceptance cause limited lifetime:

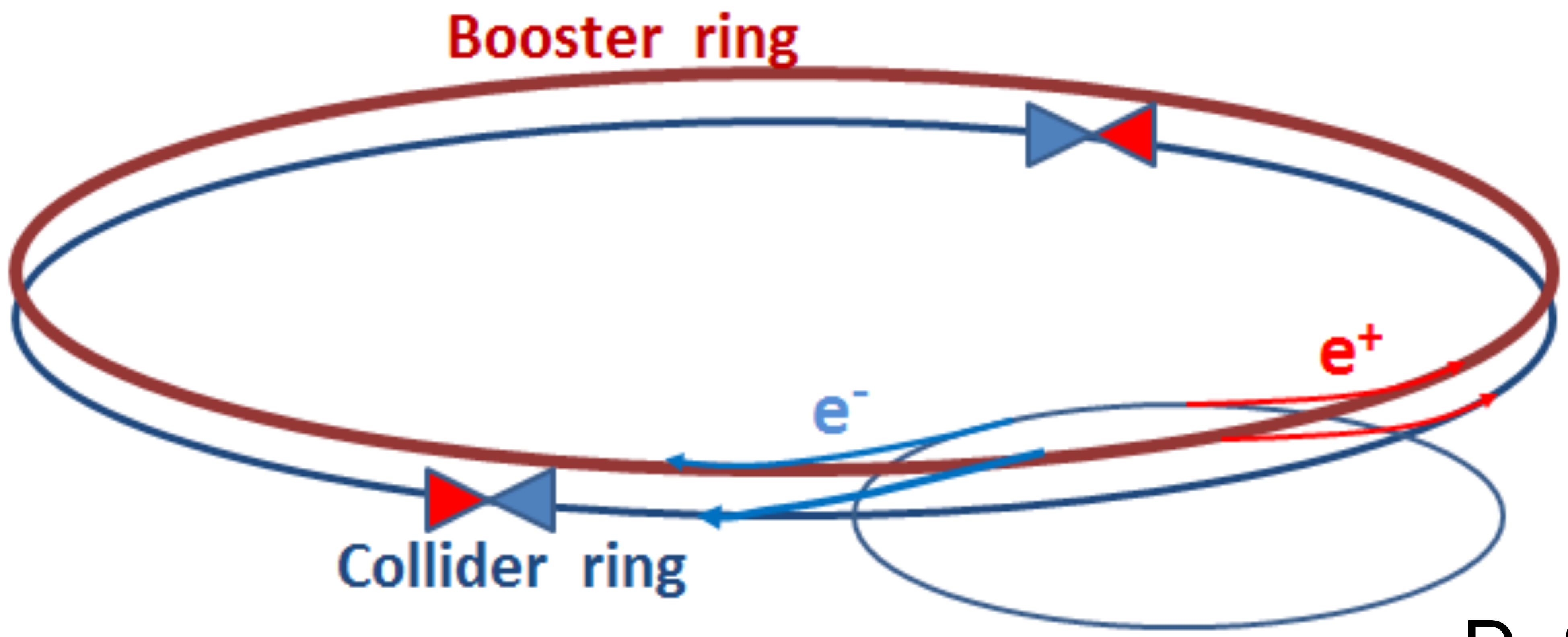
- Radiative Bhabha scattering is proportional to luminosity
- Correlated beam-beam interactions at higher energies in addition

Need continuous top-up injection

- Practised in modern light sources or b-factories today
    - PETRA-III
    - KEK-B (Belle-II)

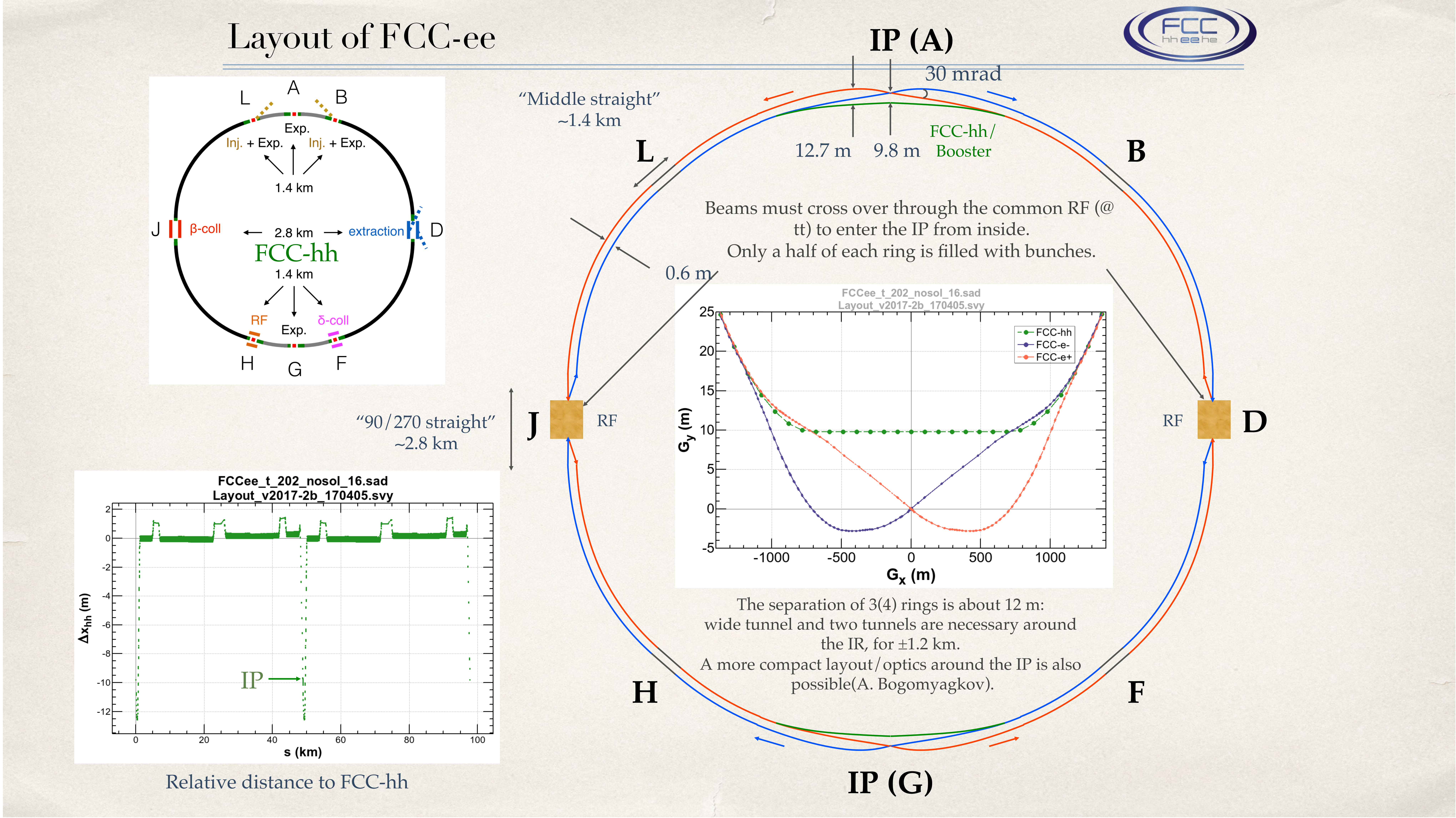






D. Schulte

FCC-ee Layout



Relative distance to FCC-hh

K. Oide

FCC-ee Operation Model

A time-limited experiment

FCC-ee operation model

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	25	7 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 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	0.36 ab^{-1}/year	**1.5 ab^{-1}**	**4**

total program duration: 14 years - ***including machine modifications***

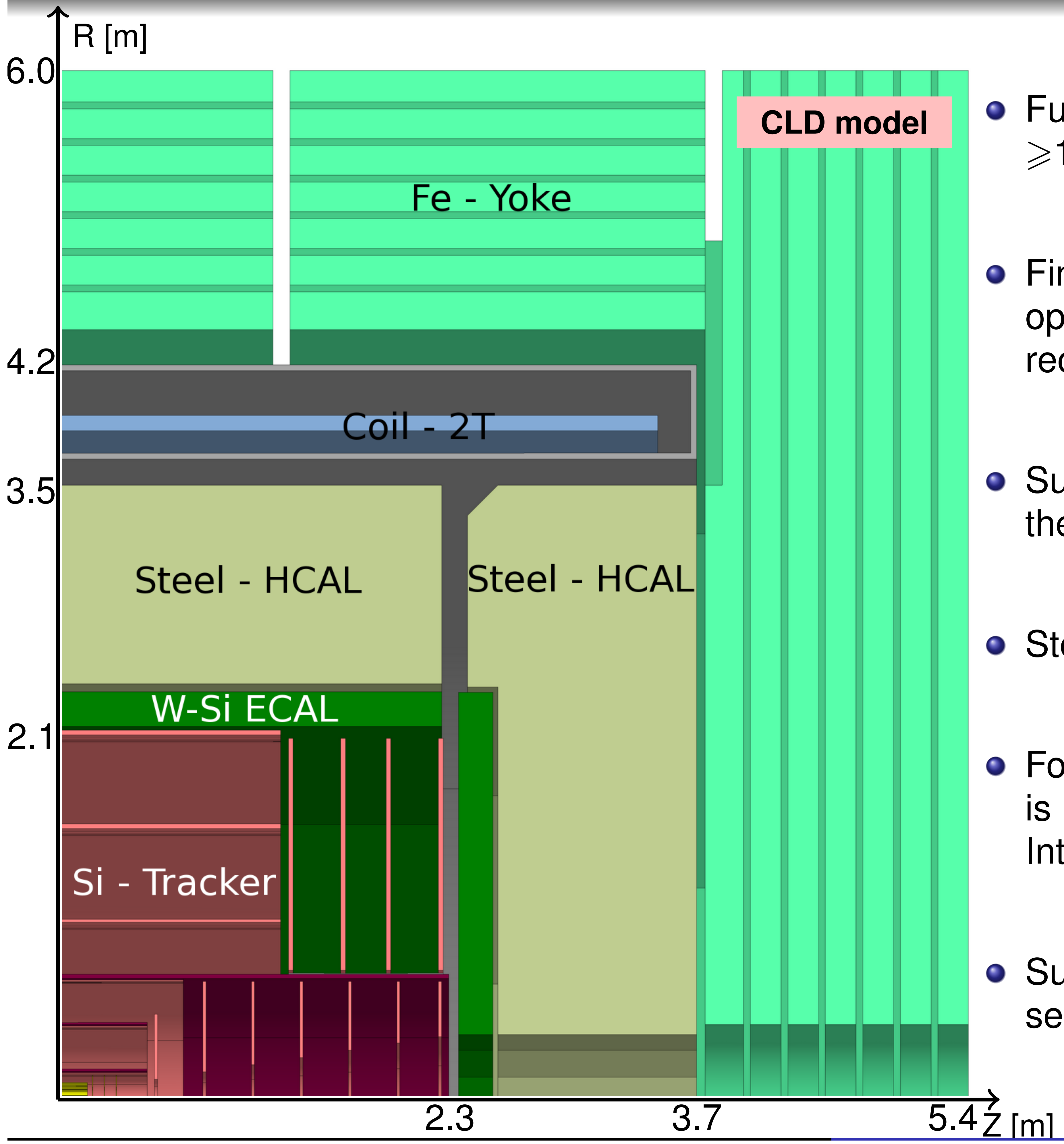
phase 1 (*Z, W, H*): 8 years, **phase 2 (top): 6 years**

M. Benedikt

FCC-ee Detector Concepts

Relying on decade-long studies for linear collider detectors

CLD detector layout



- Full silicon tracking system - provides $\geqslant$12 hits per track
- Fine-grained ECAL and HCAL optimised for particle flow reconstruction
- Superconducting solenoid is outside of the calorimeter
- Steel return yoke with muon chambers
- Forward detector region ($<$ 150 mrad) is reserved for Machine-Detector Interface (accommodates LumiCal)
- Support structures, cables and services are included in the model

O. Viazlo

The Power Challenge

Synchrotron radiation is a problem…

FCC-ee total power

subsystem	Z	W	ZH	*tt*	LEP2 (av.2000*)	TLEP*tt* * M. Ross	TLEP*tt* ** 2013
collider total RF power	163	163	145	145	42	217	185
collider cryogenics	2	5	23	39	18	41	34
collider magnets	3	10	23	50	16	14	14
booster RF + cryo	4	4	6	7	-	5	5
booster magnets	0	1	2	5	-	-	-
injector complex	10	10	10	10	<10	?	?
physics detectors (2)	10	10	10	10	9	?	?
cooling & ventilation***	47	49	52	62	16	62	26
general services	36	36	36	36	9	20	20
total	**275**	**288**	**308**	**364**	**120**	**359**	**284**

for comparison, total CERN complex in 1998 used up to 237 MW

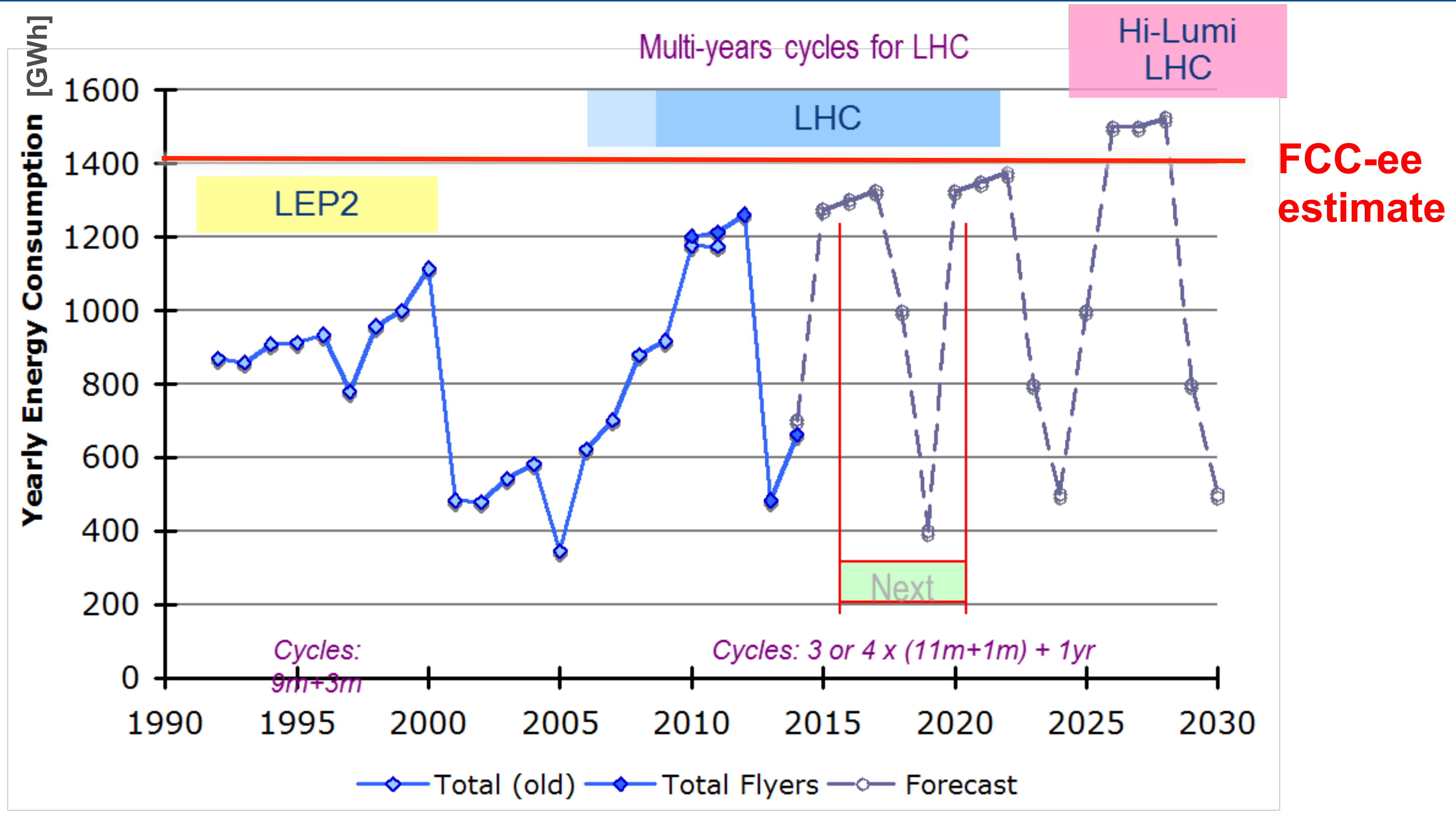
*M. Ross, ``Wall-Plug (AC) Power Consumption of a Very High Energy e+/e- Storage Ring Collider,'' 3 August 2013, http://arxiv.org/pdf/1308.0735.pdf ; **M. Koratzinos et al., ``TLEP: A High-Performance Circular e+e- Collider to Study the Higgs Boson", Proc. IPAC2013 Shanghai, 12--17 May 2013, {http://arxiv.org/pdf/1305.6498.pdf 2013,
*** private discussions with M. Nonis

presentation at IPAC'16

*dividing total energy used by 200 days

FCC-ee technologies, time lines, analysis highlights
Frank Zimmermann
KET workshop, Munich, 2 May 2016 20

CERN energy consumption



S. Claudet - CERN
Procurement Strategy

3rd Energy Workshop 29-30 October 2015

FCC-ee technologies, time lines, analysis highlights
Frank Zimmermann
KET workshop, Munich, 2 May 2016 22

F. Zimmermann

FCC integrated project technical schedule

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

LHC run 3 | LS 3 | LHC run 4 | LS4 | LHC run 5 | LS5 | LHC run 6

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Update Permission, Funding

M. Benedikt

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

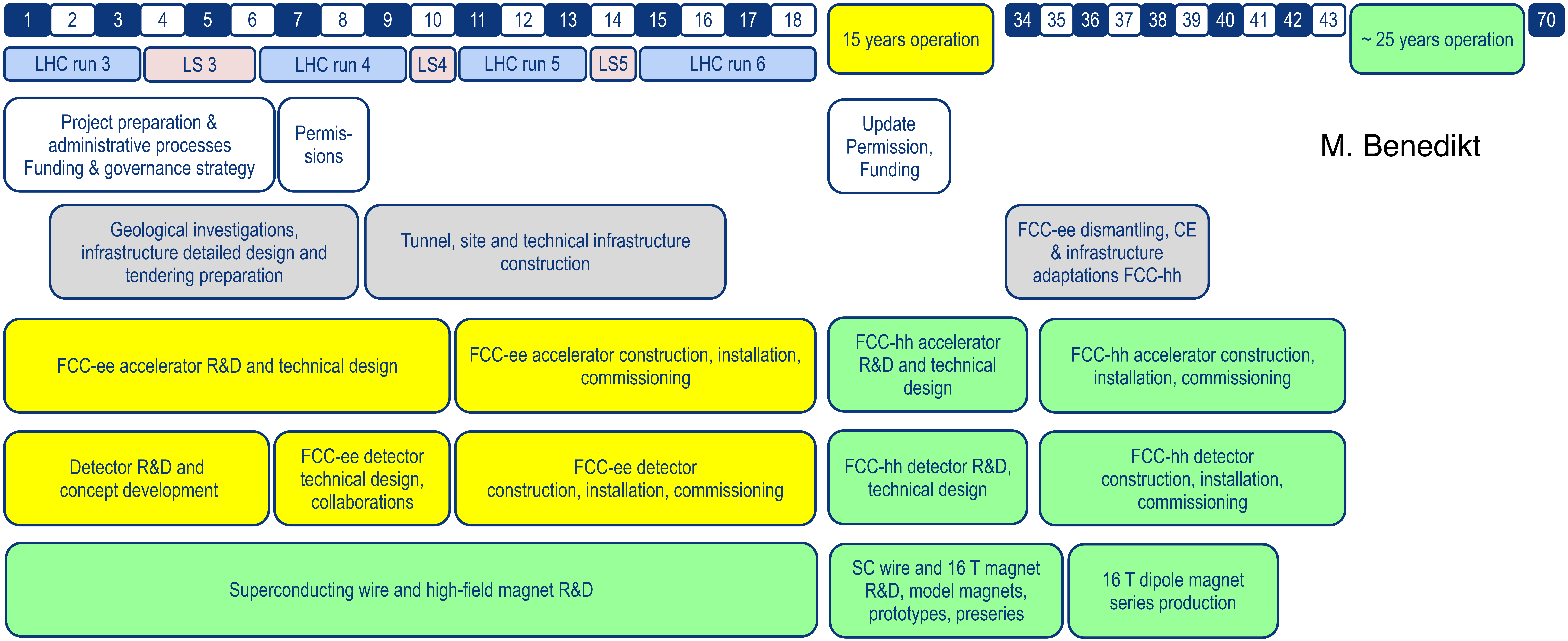
FCC-hh detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC integrated project technical schedule



FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.

Outline

A little bit of history: how the rush for high energy accelerators came on (and why)

Which particles to collide? And how?

The Circular Path:

- The Present: LHC
- The Near Future: LHC Luminosity Upgrade
- The Far Future:
  - Future Circular Collider / High-Energy LHC
  - Circular ep Collider (CepC), Super pp Collider (SppC)

The Linear Path:

- The Faster Track: International Linear Collider ILC
- The Further Future: Compact Linear Collider CLIC

High-energy Neutrinos from Accelerators:

- LBNF/DUNE

The Very Far Future:

- Muon Collider
- Plasma Wakefield Accelerators

The Real Axis - the Real Frontier…

CepC / SppC

CepC/SppC Study in China

CepC: „Circular Electron-Positron Collider"

SppC: „Super Proton-Proton Collider"

- Phase 1: e^+e^- Higgs factory, E_{cm} = 240 GeV, L = ~2 x 10^{34} $cm^{-2}s^{-1}$
- Phase 2: pp collisions at E_{cm}=~90 TeV

100 km circumference

Discussed timeline:

- Construction start: ~2021
- Data taking e+e-: 2028-2035
- Data taking pp: >2042

A good example is Qinghungdao (秦皇岛)

Feb. 24, 2014

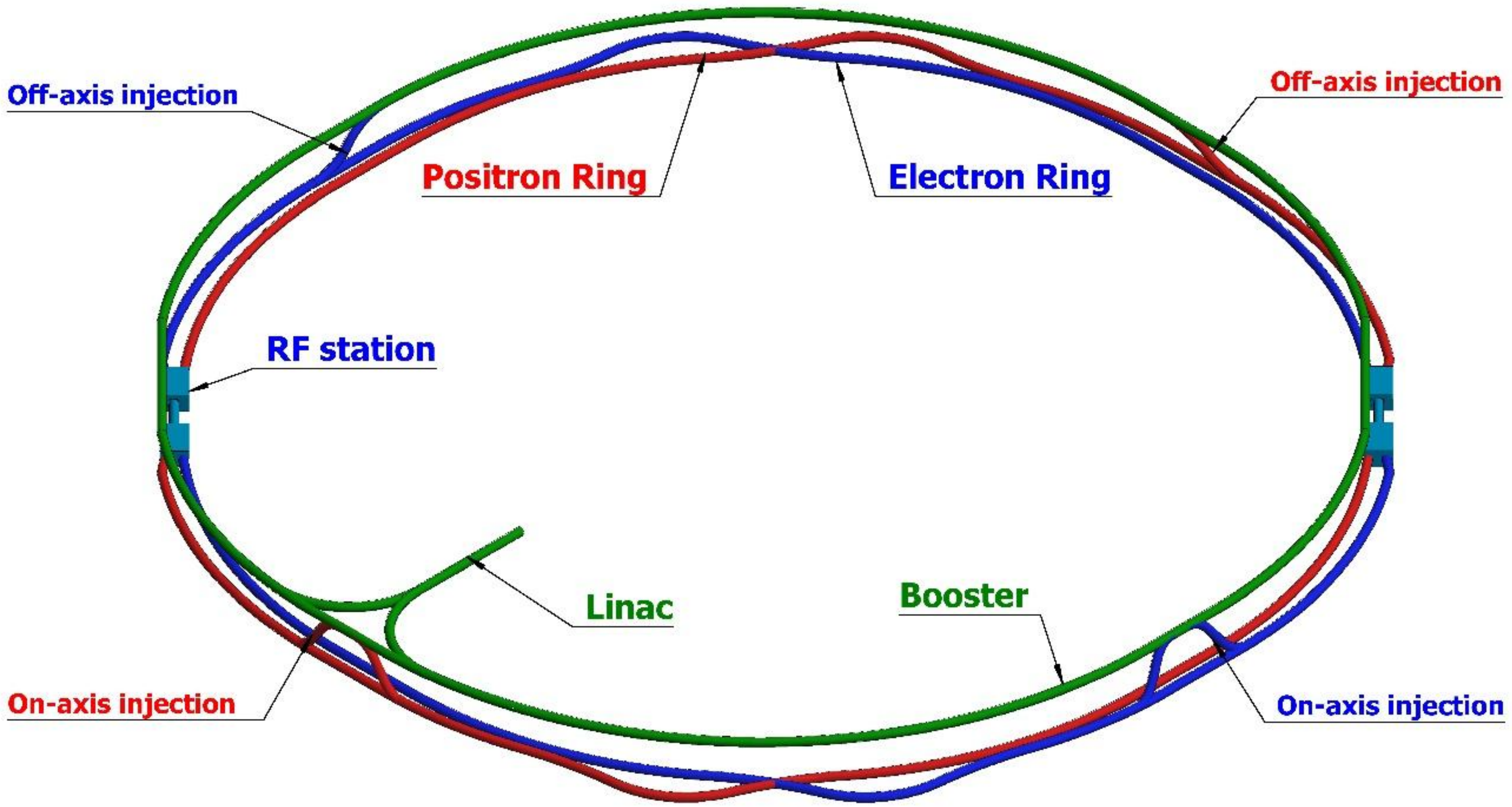
Y. F. Wang

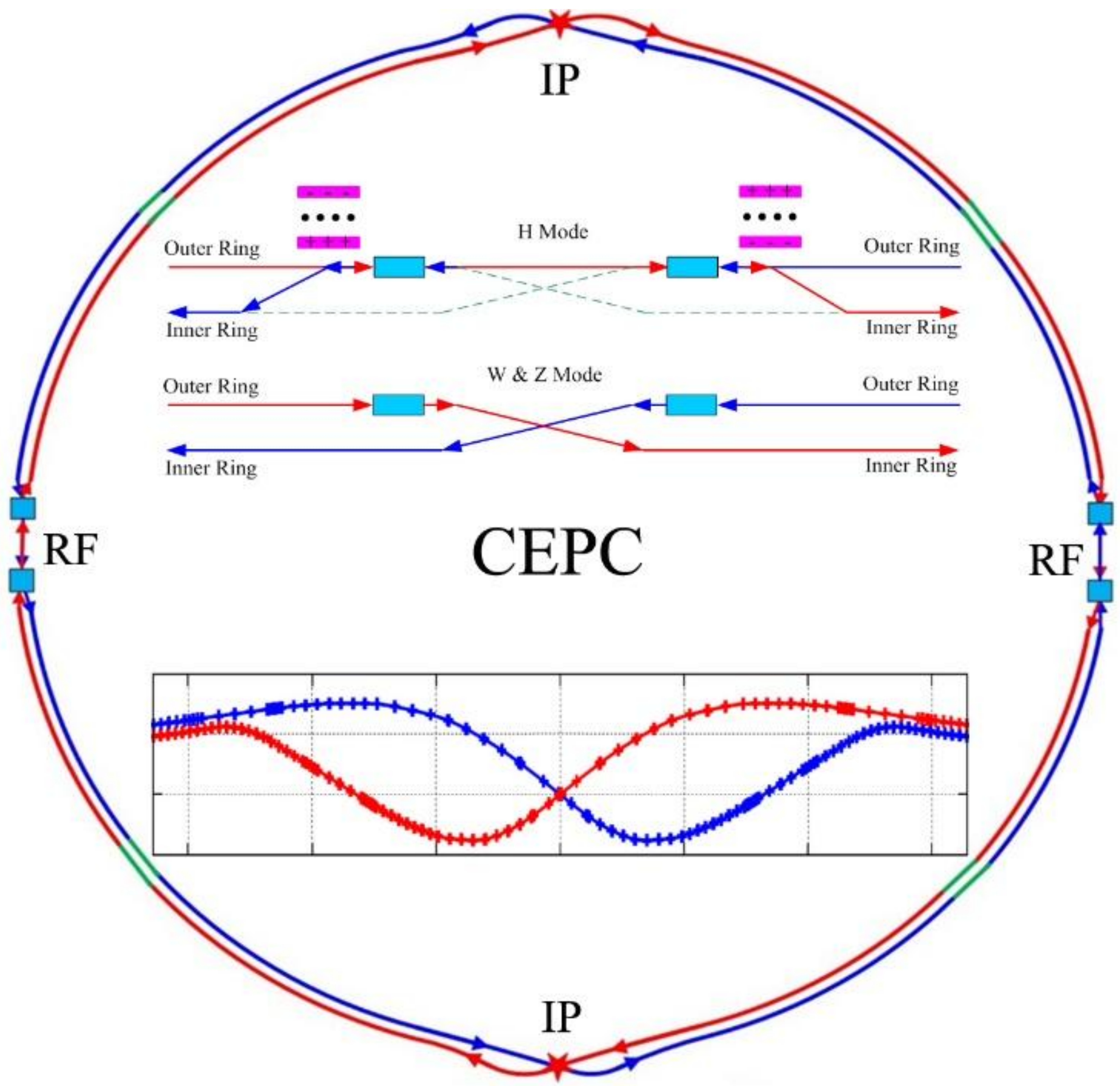
Y. Wang

CepC

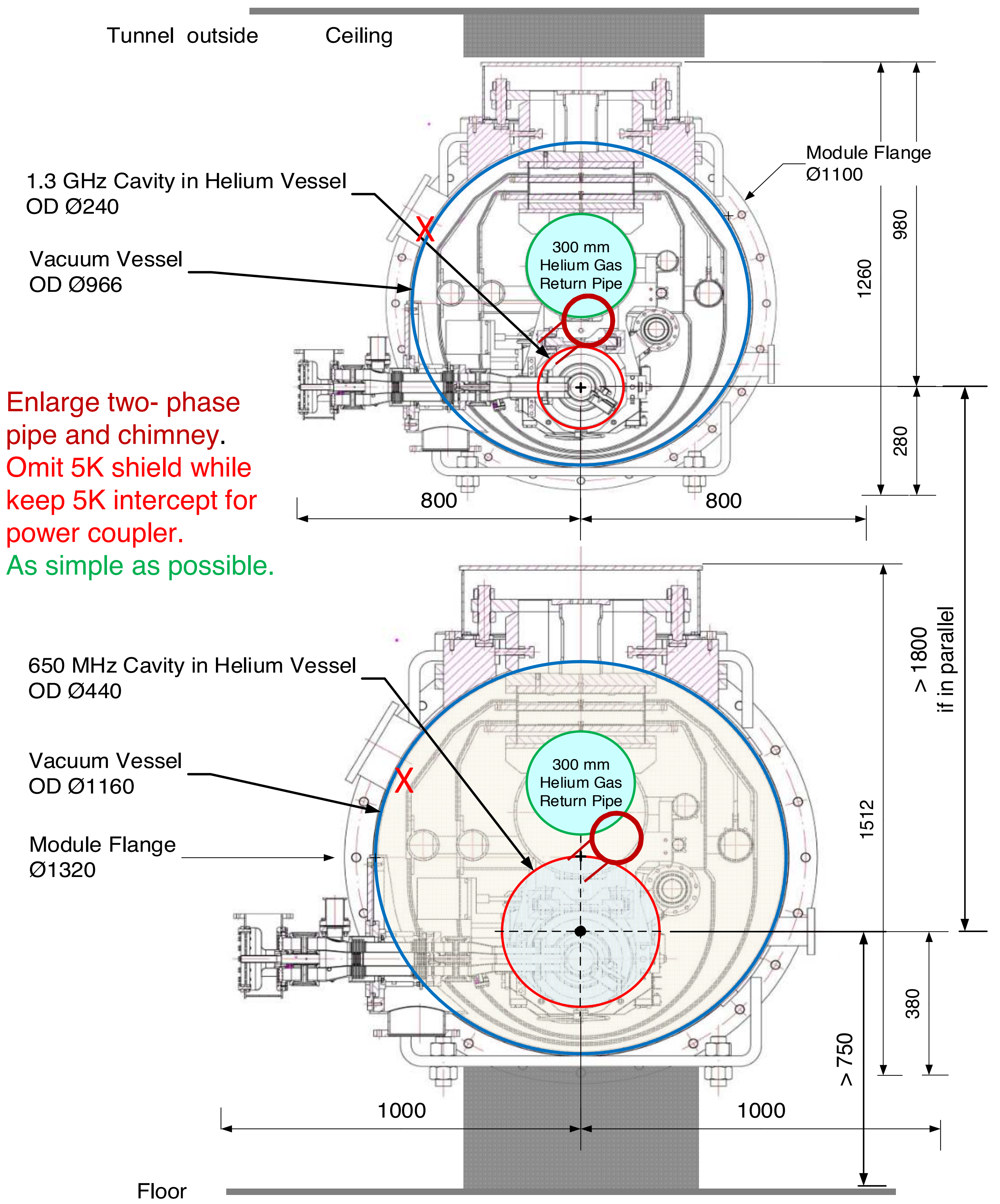
Electron-Positron Collider

- 100 km circumference
- 240 GeV cms energy
- SR power loss ~50 MW/beam
- 2 Interaction Points

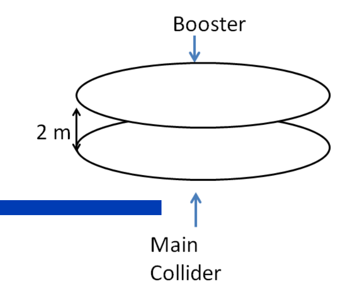


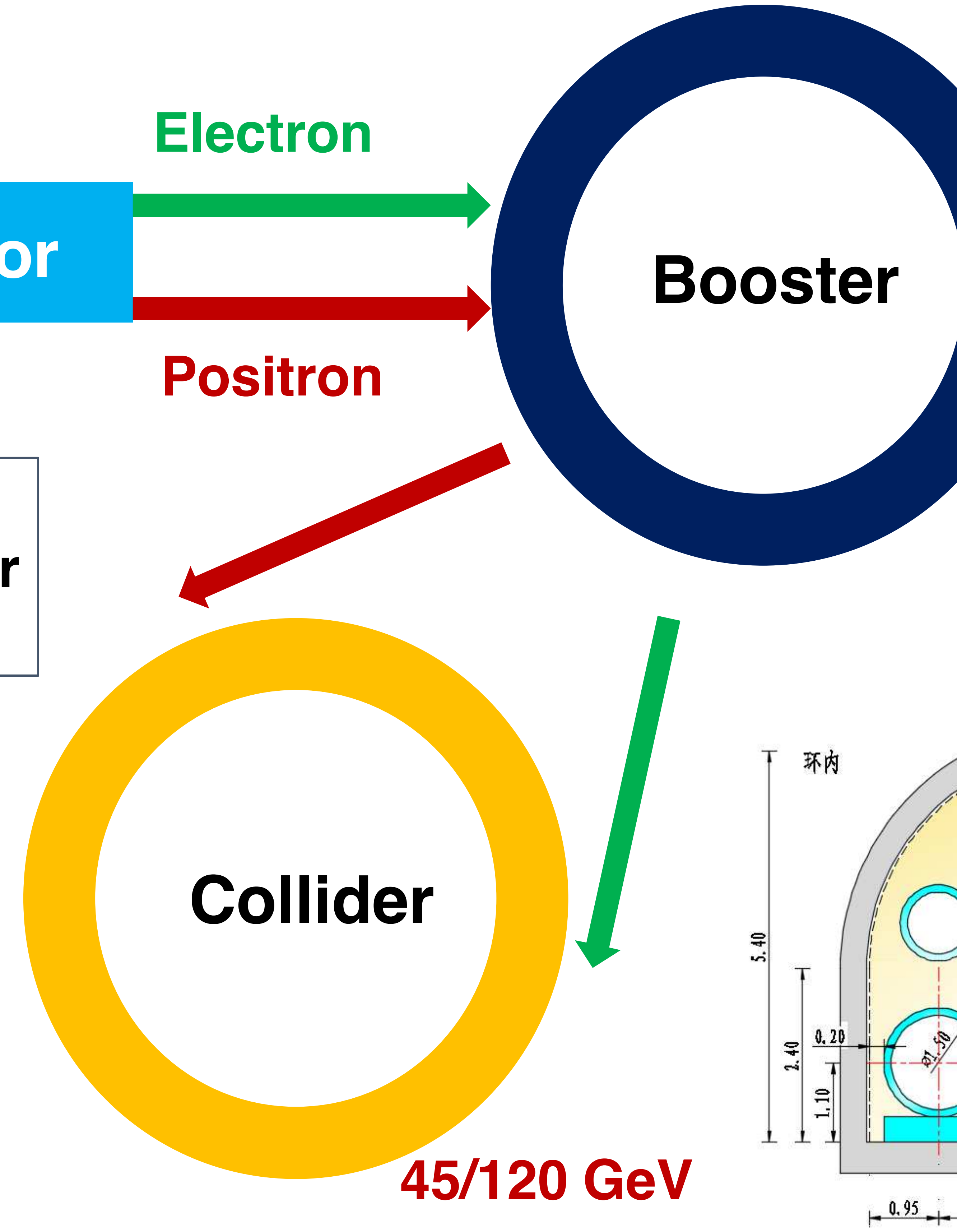


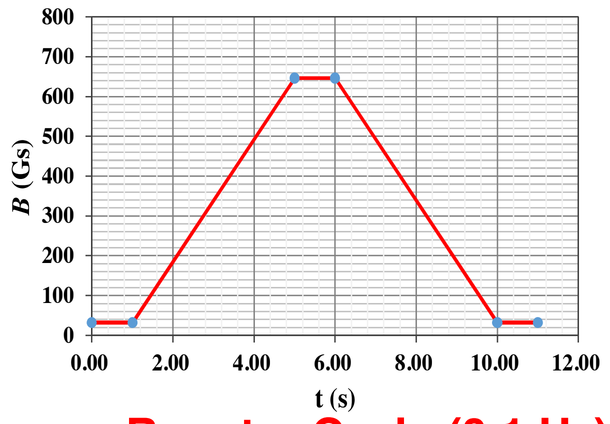
CEPC Technology



CEPC Accelerator

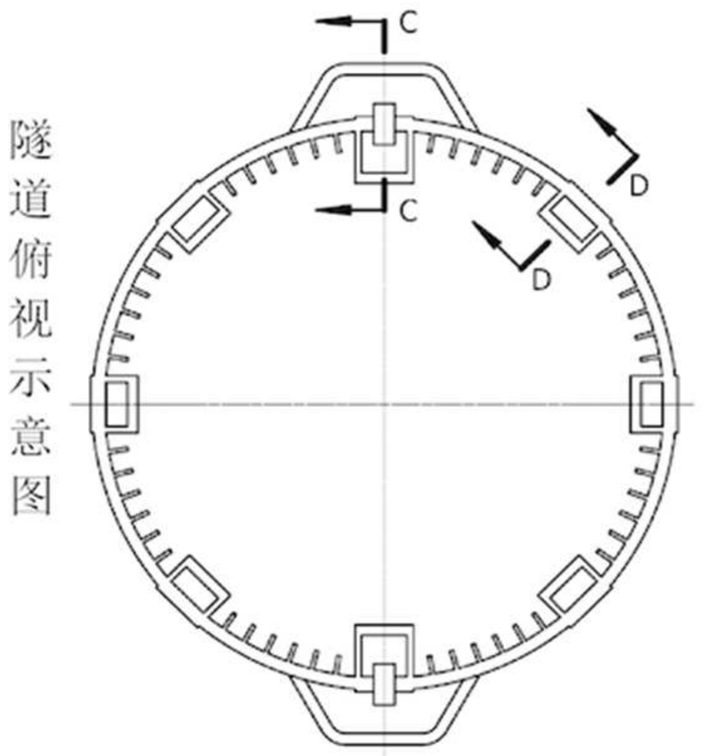


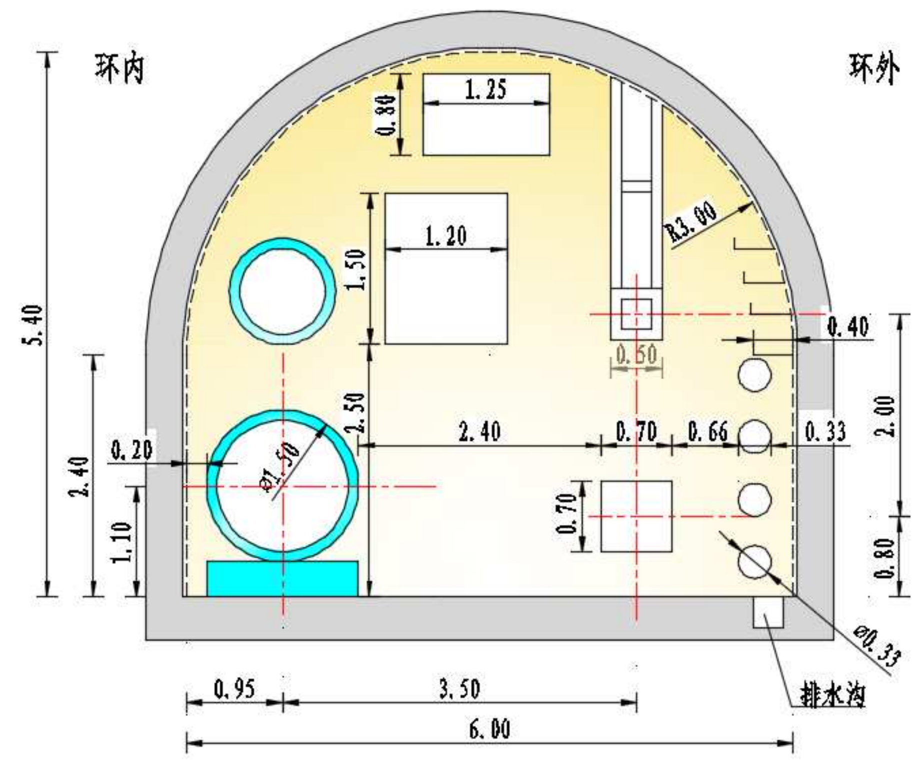




Booster Cycle (0.1 Hz)

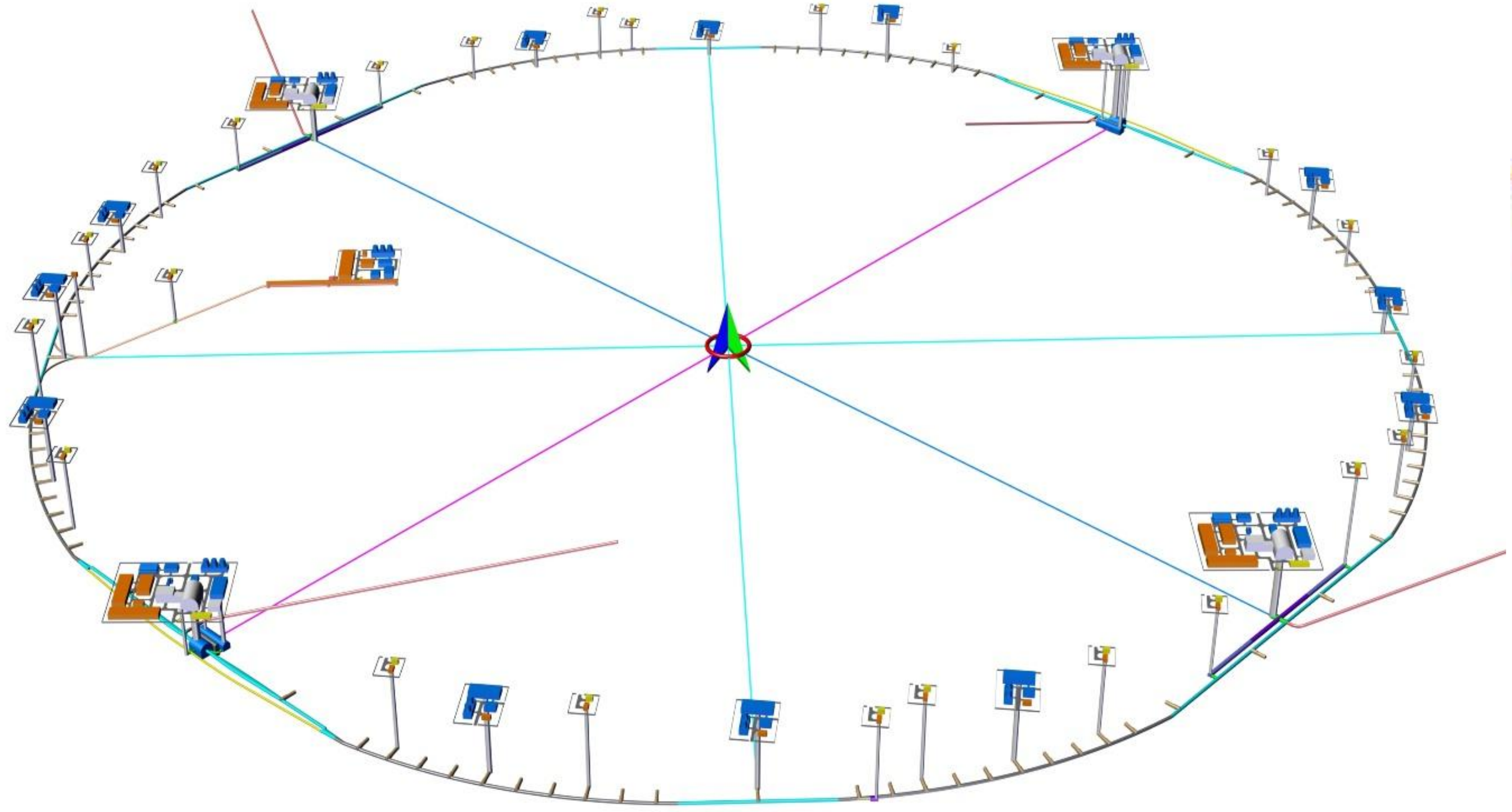
In the same tunnel：
- CEPC & booster
- SppC





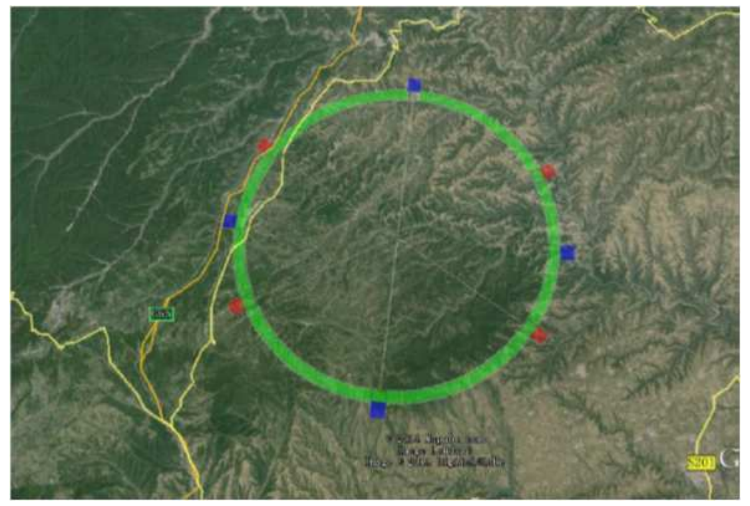
Y. Wang

Possible CepC Sites



Site selections (some main places)

1)



2)

3)

1) Qinhuangdao

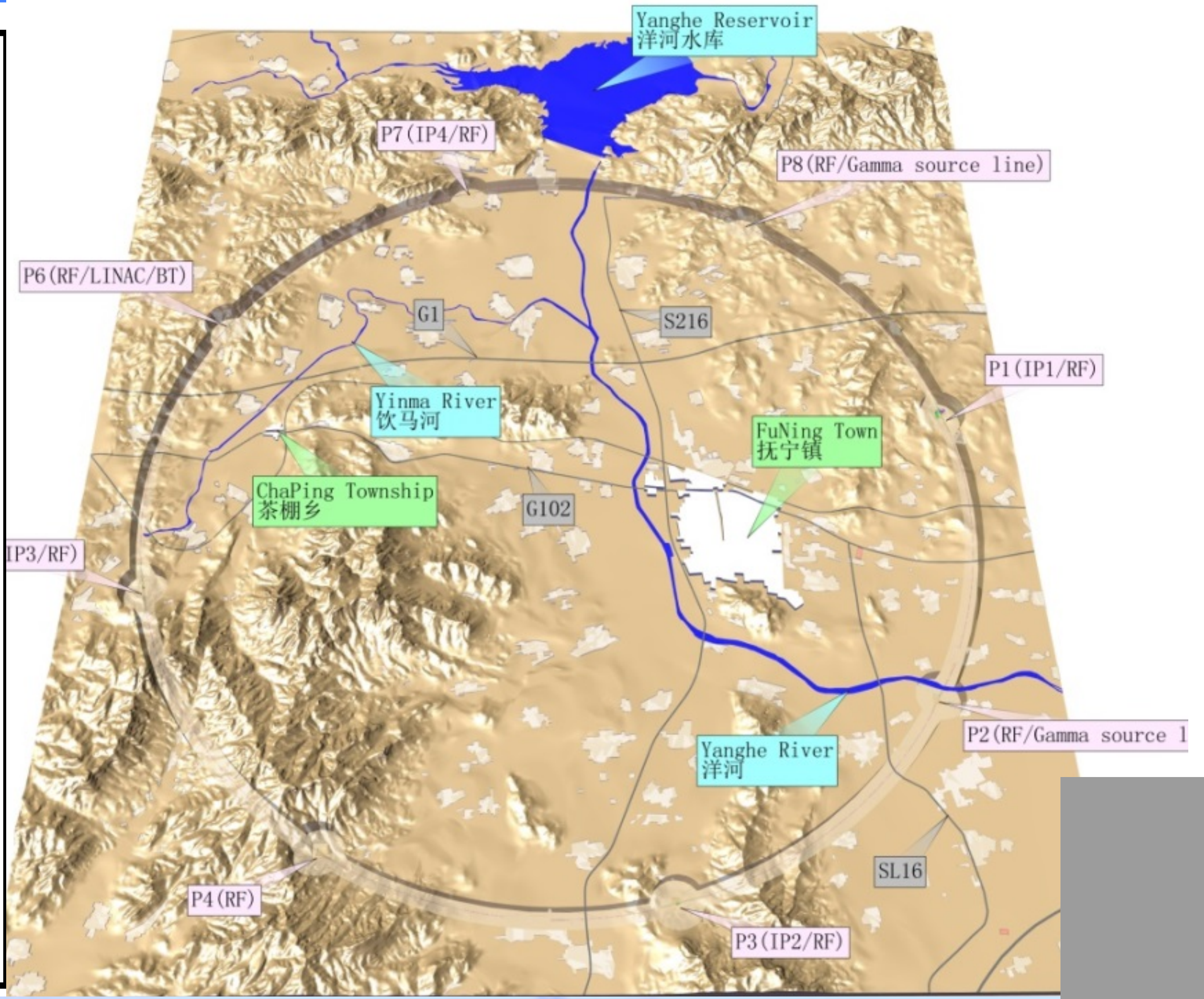
2) Shanxi Province

3) Near Shenzhen and Hongkong

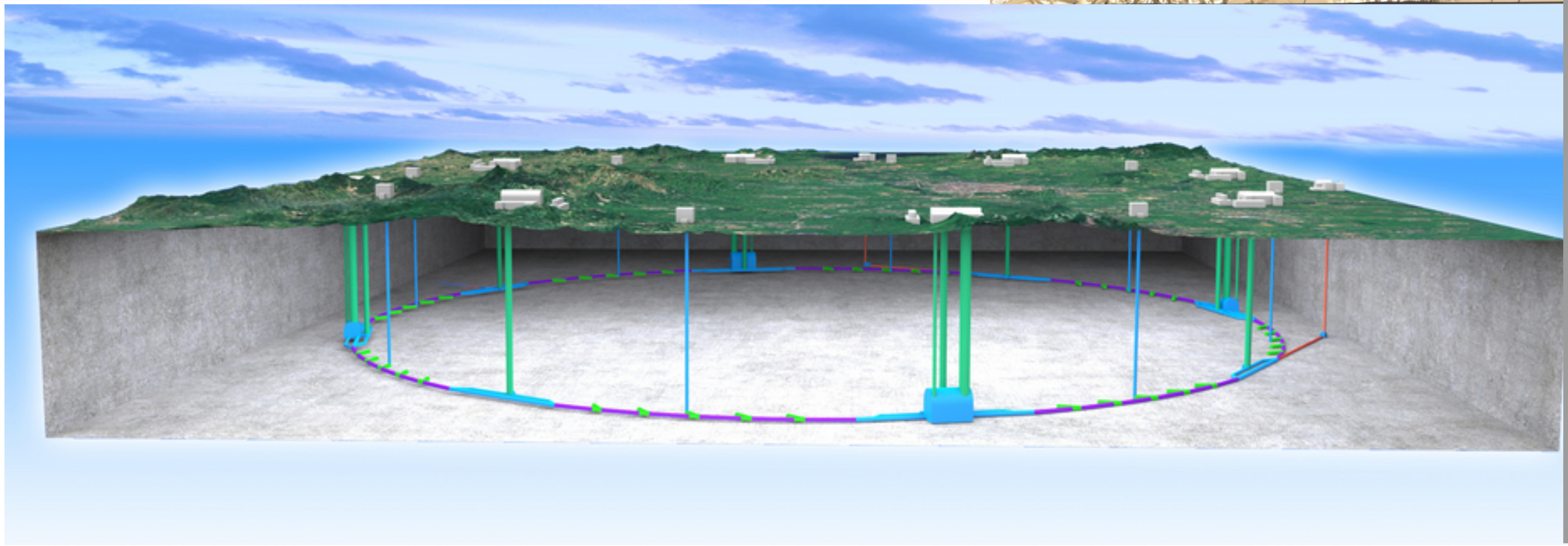
Y. Wang

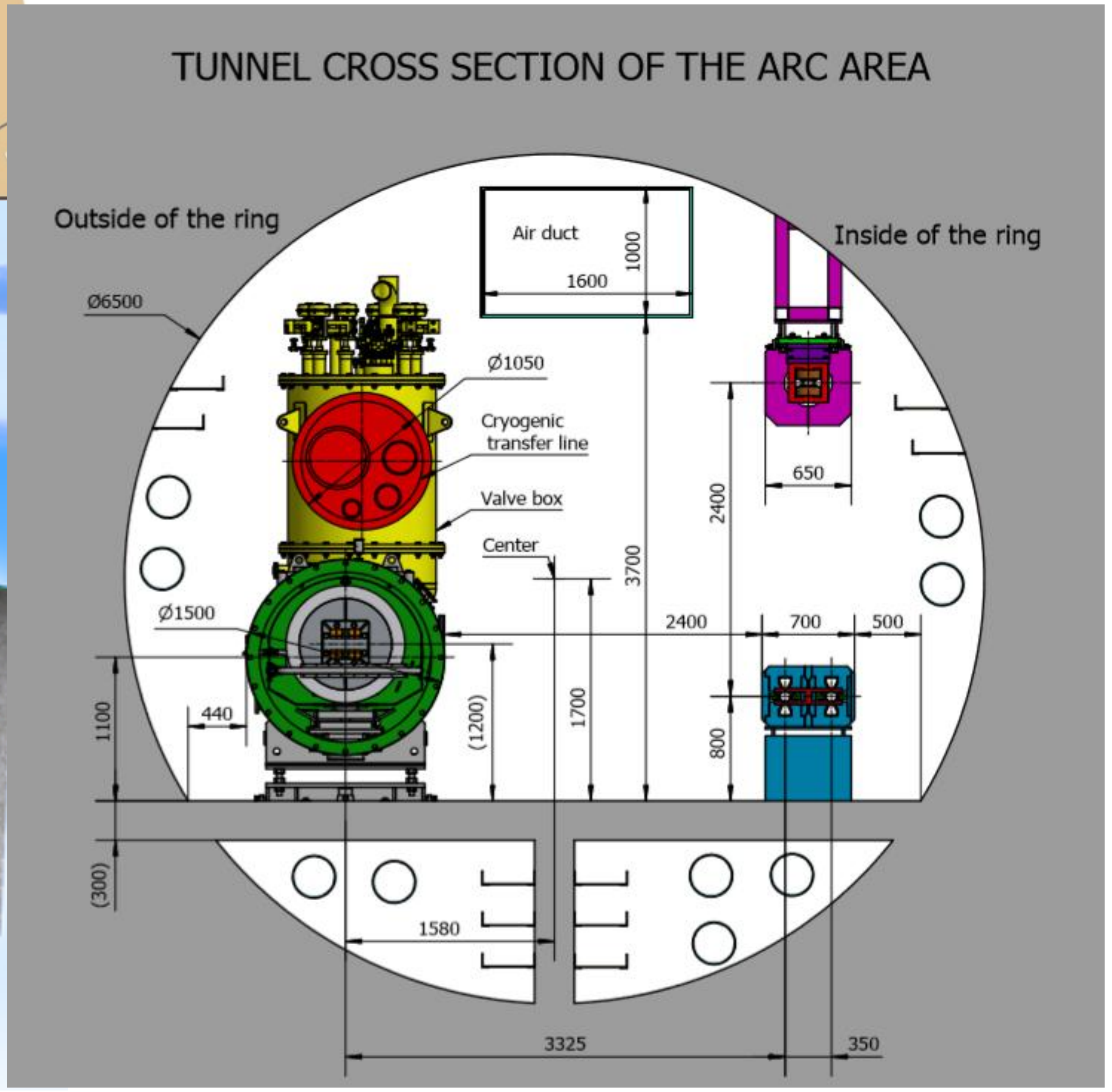
Civil Construction

- A floor map for surface and underground facilities
- Geological survey and site selection
- Try to get a credible design with cost estimate
- Try to keep the cost low
- Utilities with power consumption estimate



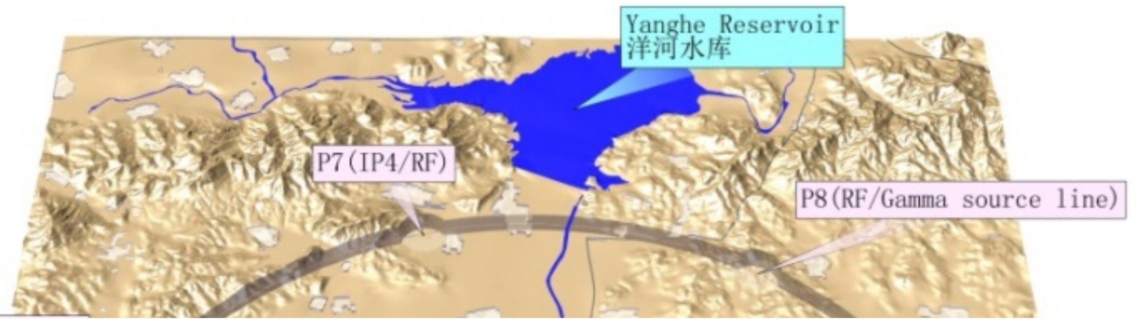
Y. Wang





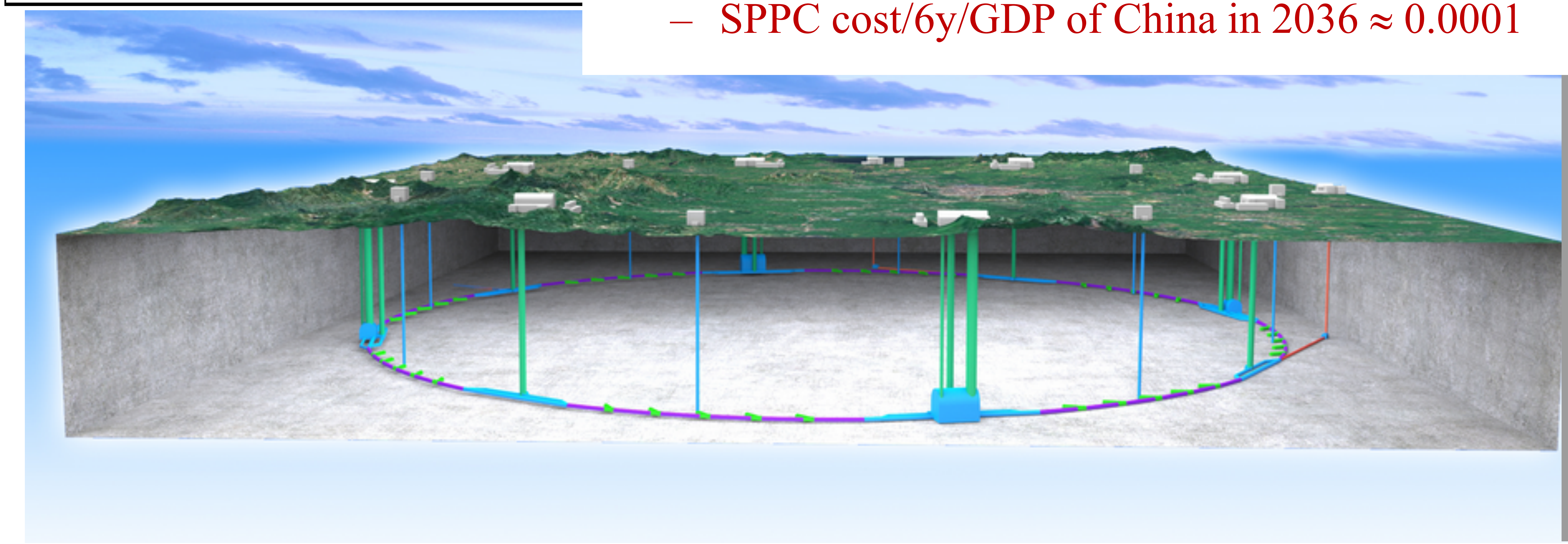
Civil Construction

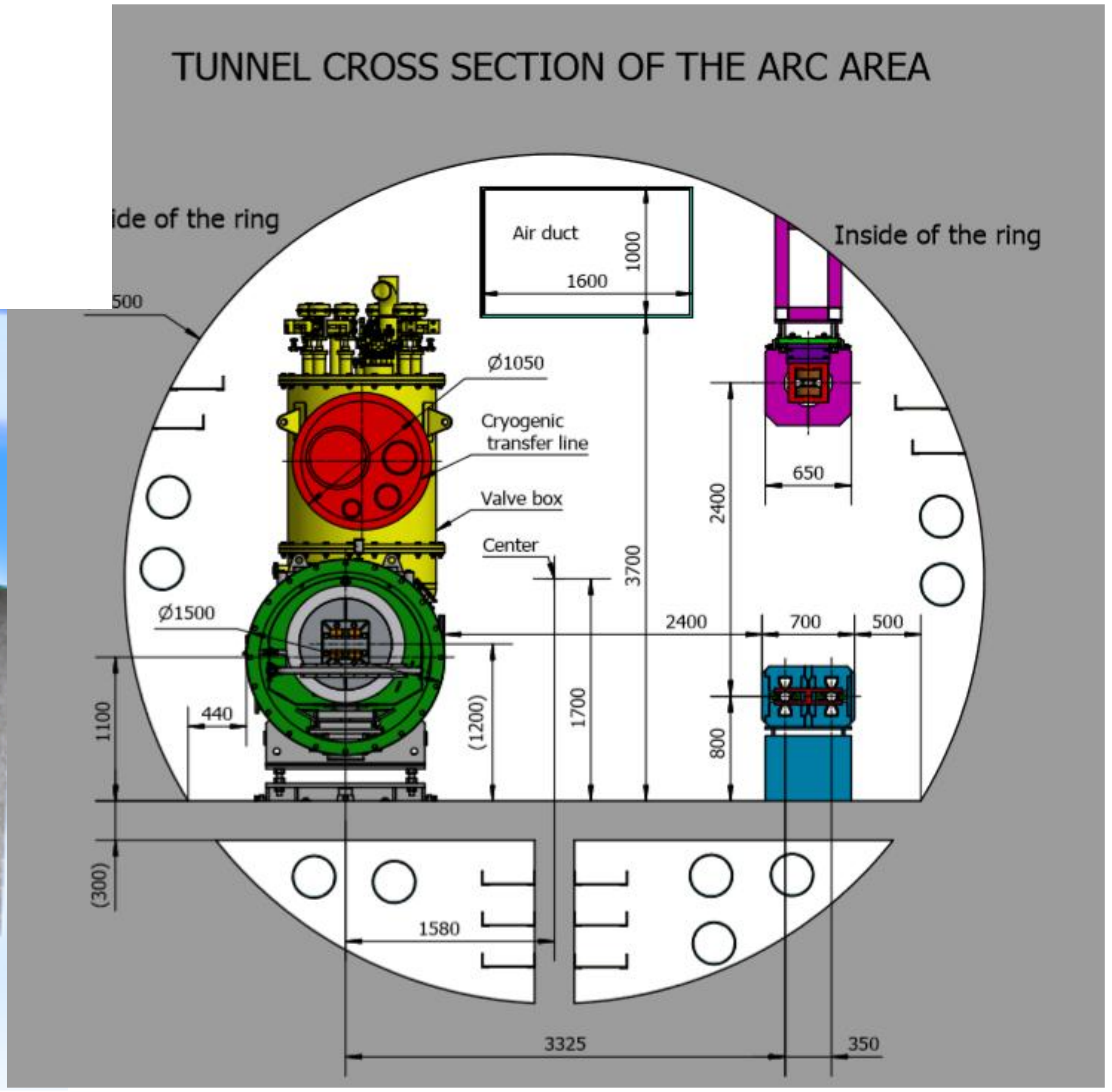
- A floor map for surface and underground facilities
- Geological survey and
- Try to get a credible de estimate
- Try to keep the cost lov
- Utilities with power con estimate



- Practical issues: too costly ?
  - BEPC cost/4 y/GDP of China in 1984 ≈ 0.0001
  - SSC cost/10y/GDP of US in 1992 ≈ 0.0001
  - LEP cost/8y/GDP of EU in 1984 ≈ 0.0002
  - LHC cost/10y/GDP of EU in 2004 ≈ 0.0003
  - ILC cost/8y/GDP of Japan in 2018 ≈ 0.0002
  - CEPC cost/6y/GDP of China in 2020 ≈ 0.00005
  - SPPC cost/6y/GDP of China in 2036 ≈ 0.0001

Y. Wang





CepC/SppC Timeline (preliminary)

Technical timeline (not folding in politics)…

CepC:

SppC comes after:

- exact plans depend on R&D progress for magnets

FCC-ee vs CepC - Beam Parameters

Beam parameters at 240 GeV cms energy

- similar parameter space
- FCC-ee wants smaller emittances
  - smaller beam spots, higher luminosity
- FCC-ee has more bunches in the beam
  - larger currents, higher luminosity

CepC has a more conservative approach

- smaller currents, larger emittances
  - less challenging beam dynamics
- less luminosity
- longer lifetimes
- smaller energy reach

parameter	FCC-ee	CepC
beam energy [GeV]	120	120
beam current [mA]	29	16.6
no. bunches/beam	393	50
bunch intensity $[10^{11}]$	1.5	3.8
SR energy loss / turn [GeV]	1.72	3.11
total RF voltage [GV]	2.0	6.9
long. damping time [turns]	70	39
horizontal beta* [m]	0.3	0.8
vertical beta* [mm]	1	1.2
horiz. geometric emittance [nm]	0.63	6.12
vert. geom. emittance [pm]	1.3	18.4
bunch length with SR / BS [mm]	3.3 / 5.3	2.1 / 2.7
luminosity per IP $[10^{34}\ cm^{-2}s^{-1}]$	>7	>2
beam lifetime rad Bhabha / BS [min]	38 / 18	51 / 47

Outline

A little bit of history: how the rush for high energy accelerators came on (and why)

Which particles to collide? And how?

The Circular Path:
- The Present: LHC
- The Near Future: LHC Luminosity Upgrade
- The Far Future:
  - Future Circular Collider / High-Energy LHC
  - Circular ep Collider (CepC), Super pp Collider (SppC)

The Linear Path:
- The Faster Track: International Linear Collider ILC
- The Further Future: Compact Linear Collider CLIC

High-energy Neutrinos from Accelerators:
- LBNF/DUNE

The Very Far Future:
- Muon Collider
- Plasma Wakefield Accelerators

The Real Axis - the Real Frontier…

International Linear Collider

Scaling Electron Colliders

Cost scalings of ~200 GeV colliders estimated a long time ago:

- B. Richter, NIM 136 (1972) 47-60

Storage ring costs scale with $\sim E^2$

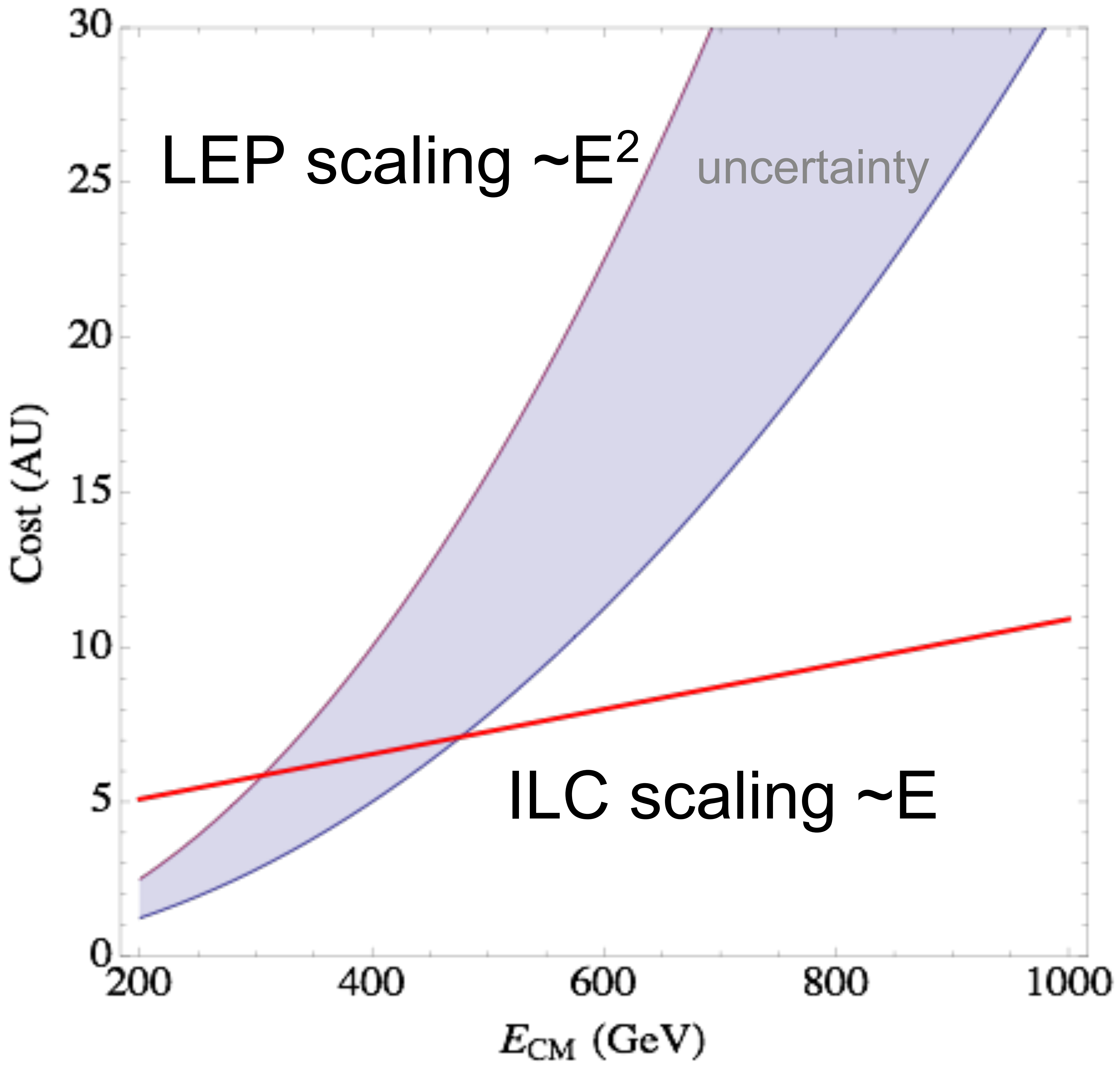
Linear collider costs scale with ~E

Transition energy somewhere around 300 GeV…

- uncertainties not well known

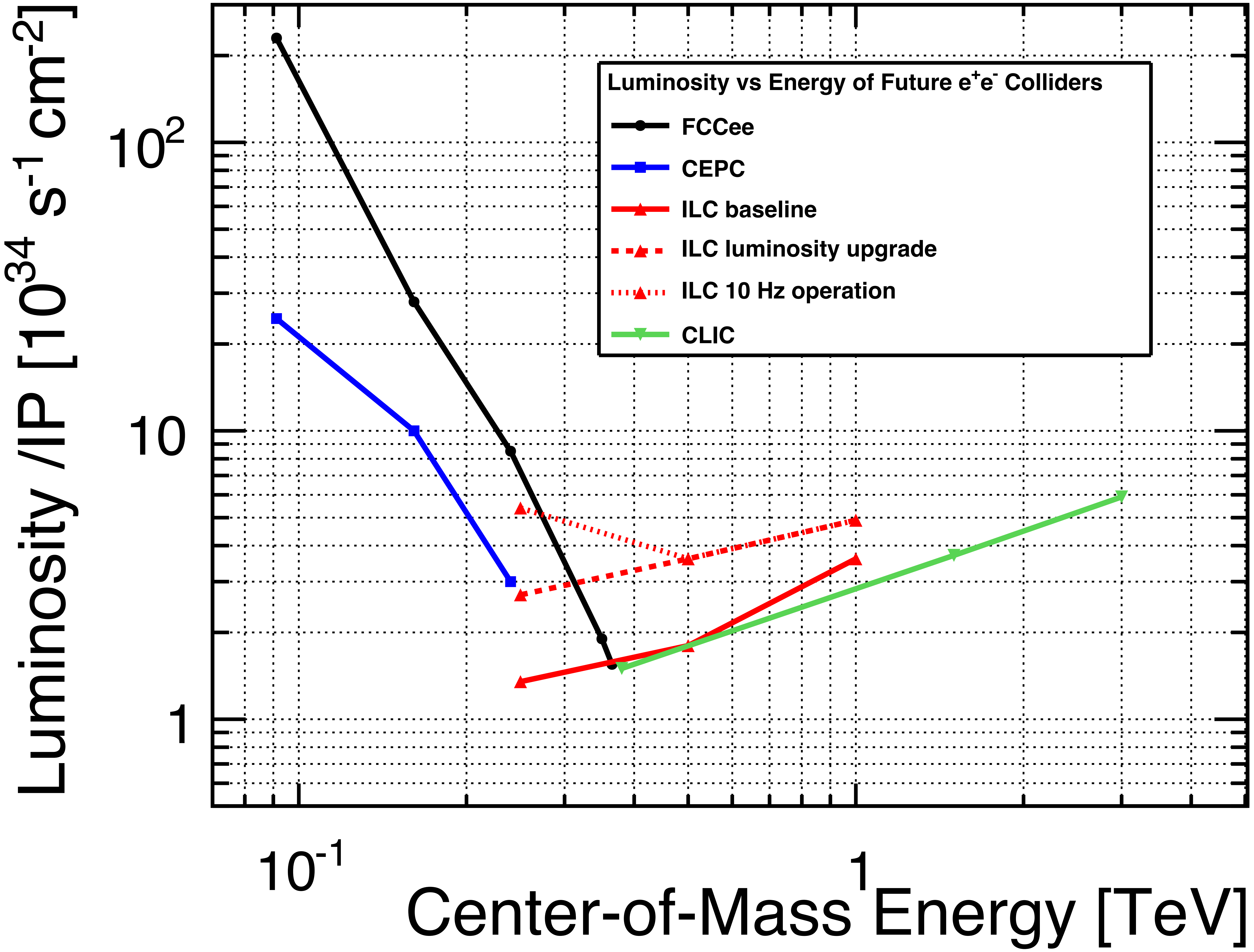
The ultimate future (if any) of e^+e^- colliders must be linear

- because circular rings do not scale!



N. Walker

Lepton Collider Luminosities



J. List et al.

Stanford Linear Collider - the Grandfather…

The Luminosity Challenge

The luminosity [$cm^{-2}s^{-1}$] for a collider with Gaussian beams is given by:

$$L = \frac{n_b N^2 f_{\mathrm{re}p}}{4\pi\sigma_x\sigma_y} H_D$$

- n_b = bunches per train
- N = particles per bunch
- f_{rep} = repetition frequency
- $4\pi\sigma_x\sigma_y$ = beam cross section at the interaction point
- H_D = beam-beam enhancement factor

The Luminosity Challenge

Introducing the beam power:

$$n_b N f_{\mathrm{rep}} \mathrm{E}_{cm} = P_{beams}$$
$$= \eta_{RF\text{->}beam} P_{RF}$$

yields

$$L = \frac{(\mathrm{E}_{cm} n_b N f_{\mathrm{rep}}) N}{4\pi\sigma_x\sigma_y \mathrm{E}_{cm}} H_D \longrightarrow L = \frac{\eta_{RF} P_{RF} N}{4\pi\,\sigma_x\sigma_y \mathrm{E}_{cm}} H_D$$

$\eta_{\mathrm{RF}\longrightarrow\mathrm{beam}}$: conversion efficiency RF to beam

RF Power

Some numbers:

- E_{cm} = 500 GeV
- N = 10^{10}
- n_b = 1000
- f_{rep} = 10 Hz
- ⇒ P_{beams} = 8 MW

$$L = \frac{\eta_{RF} P_{RF} N}{4\pi\, \sigma_x \sigma_y \mathrm{E}_{cm}} H_D$$

$$L = \frac{n_b N^2 f_{\mathrm{rep}}}{4\pi \sigma_x \sigma_y} H_D$$

adding efficiencies

- Wall plug ⟶ RF ⟶ beam

yields AC power needs >100 MW just to accelerate beams and maintain luminosity!!!

Storage Ring vs Linear Collider

LEP

- f_{rep}: 44 kHz

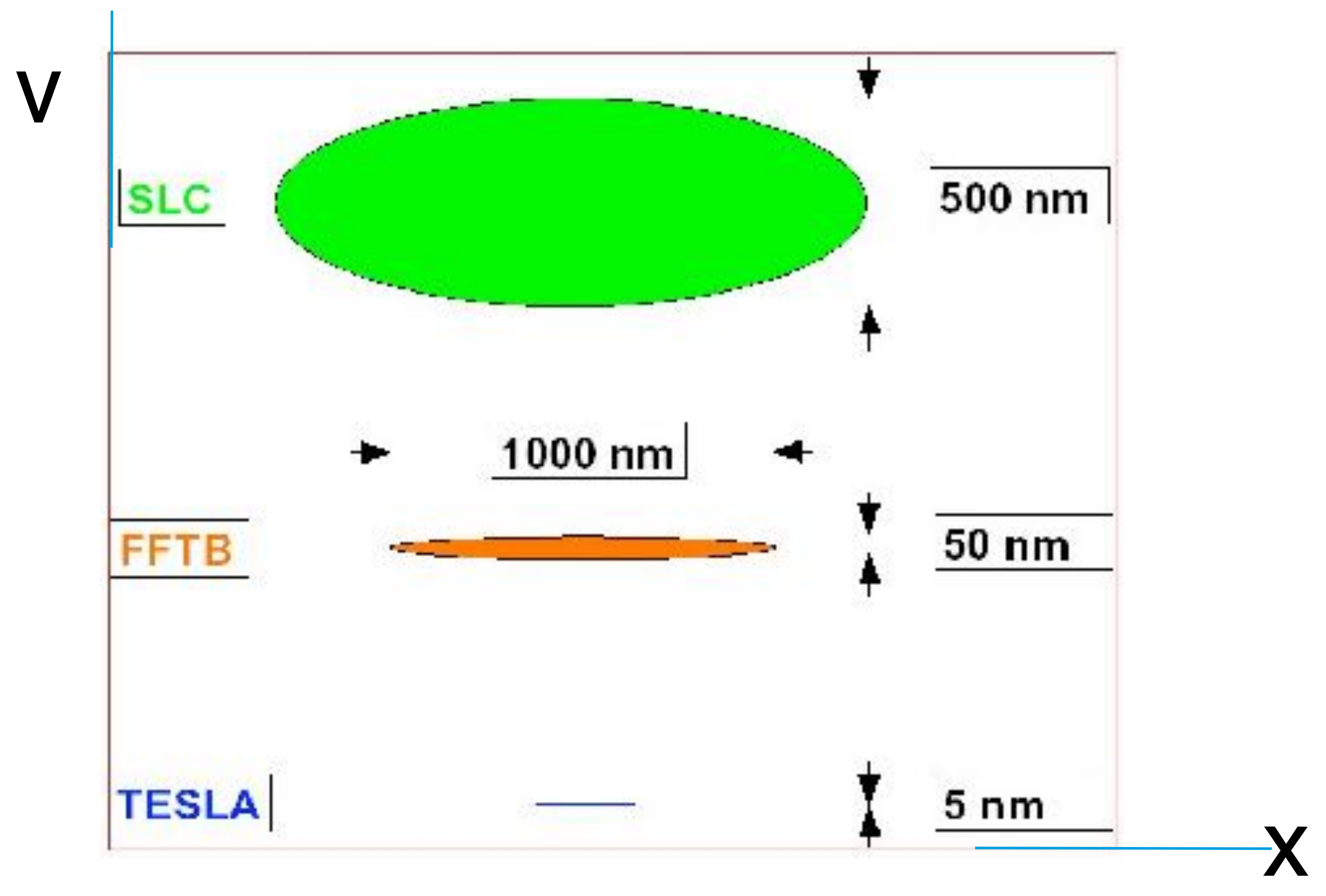
ILC

- f_{rep}: few to 100 Hz (power limited)
- Factor ~1000 in Luminosity already lost!

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y} H_D$$

Recover by pushing hard on the beam spot sizes at collision:

- LEP: 130 x 6 µm^2
- ILC: 500 x 5 nm^2

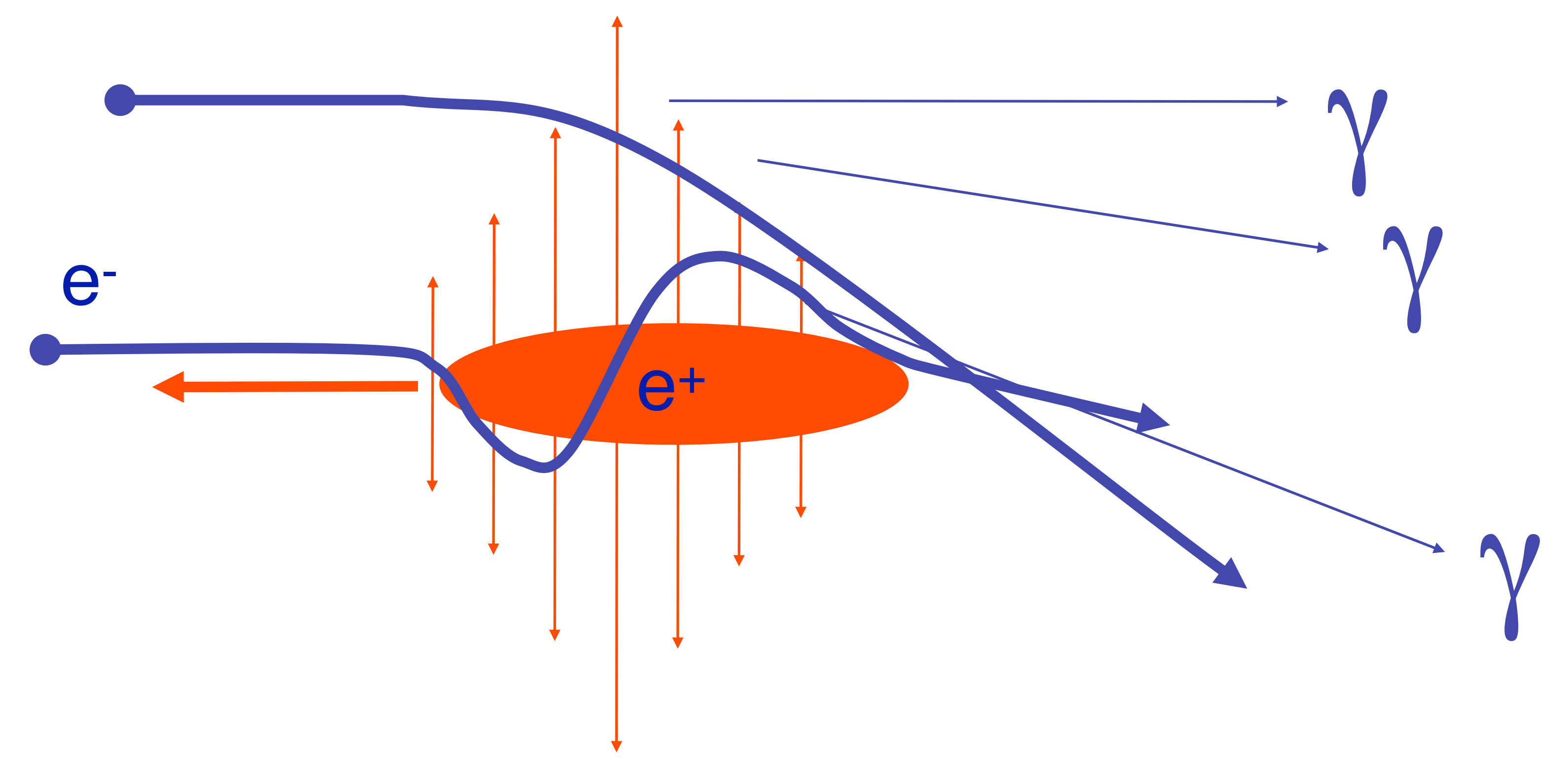


Needed to achieve L=O(10^{34} cm^{-2} s^{-1})

Beamstrahlung

Strong mutual focusing of beam gives rise to significant luminosity enhancement (Hd≈2)

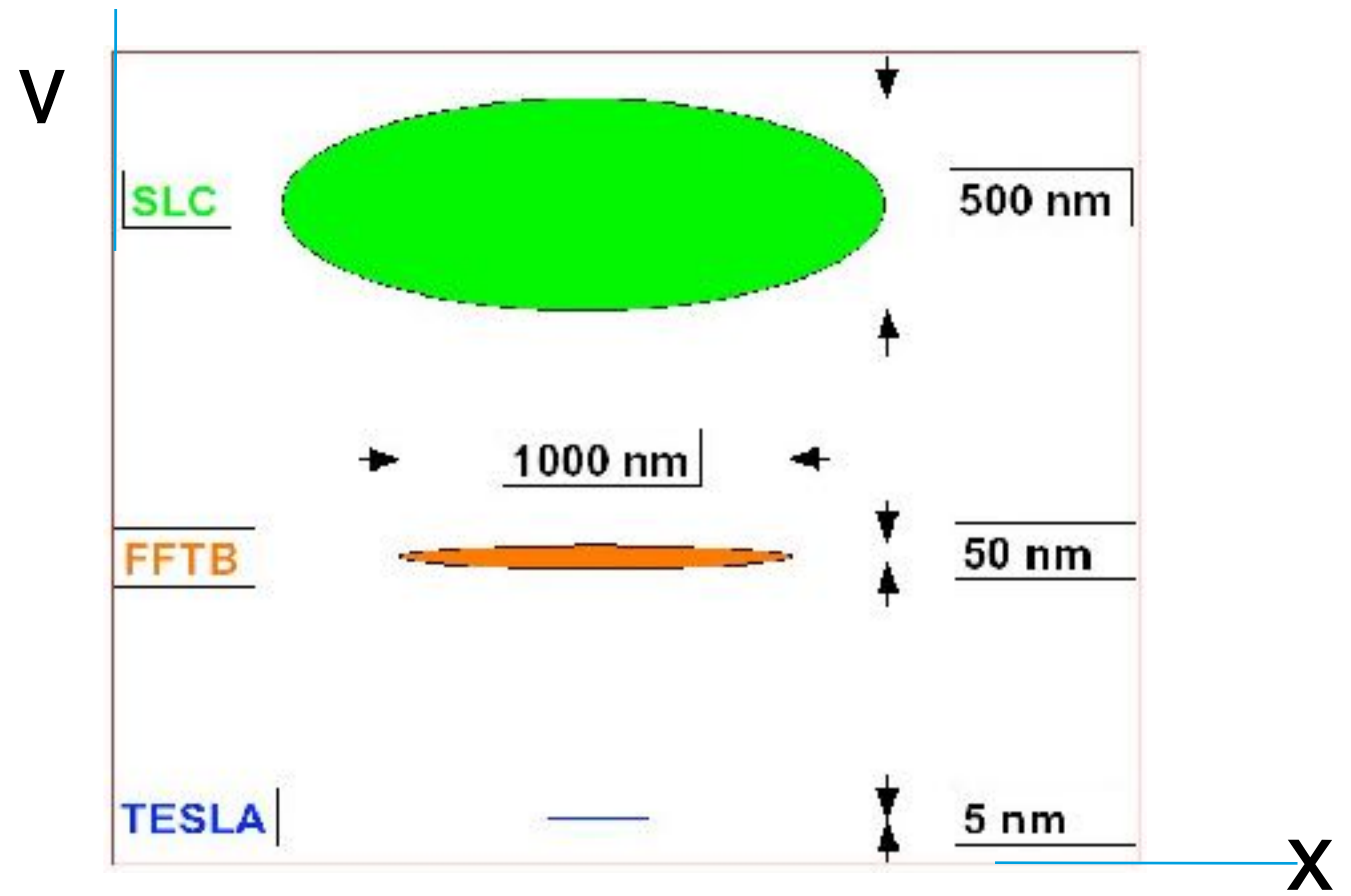
- „Pinch effect“
- electrons/positrons pass through intense field of opposite beam, radiate hard photons: Beamstrahlung



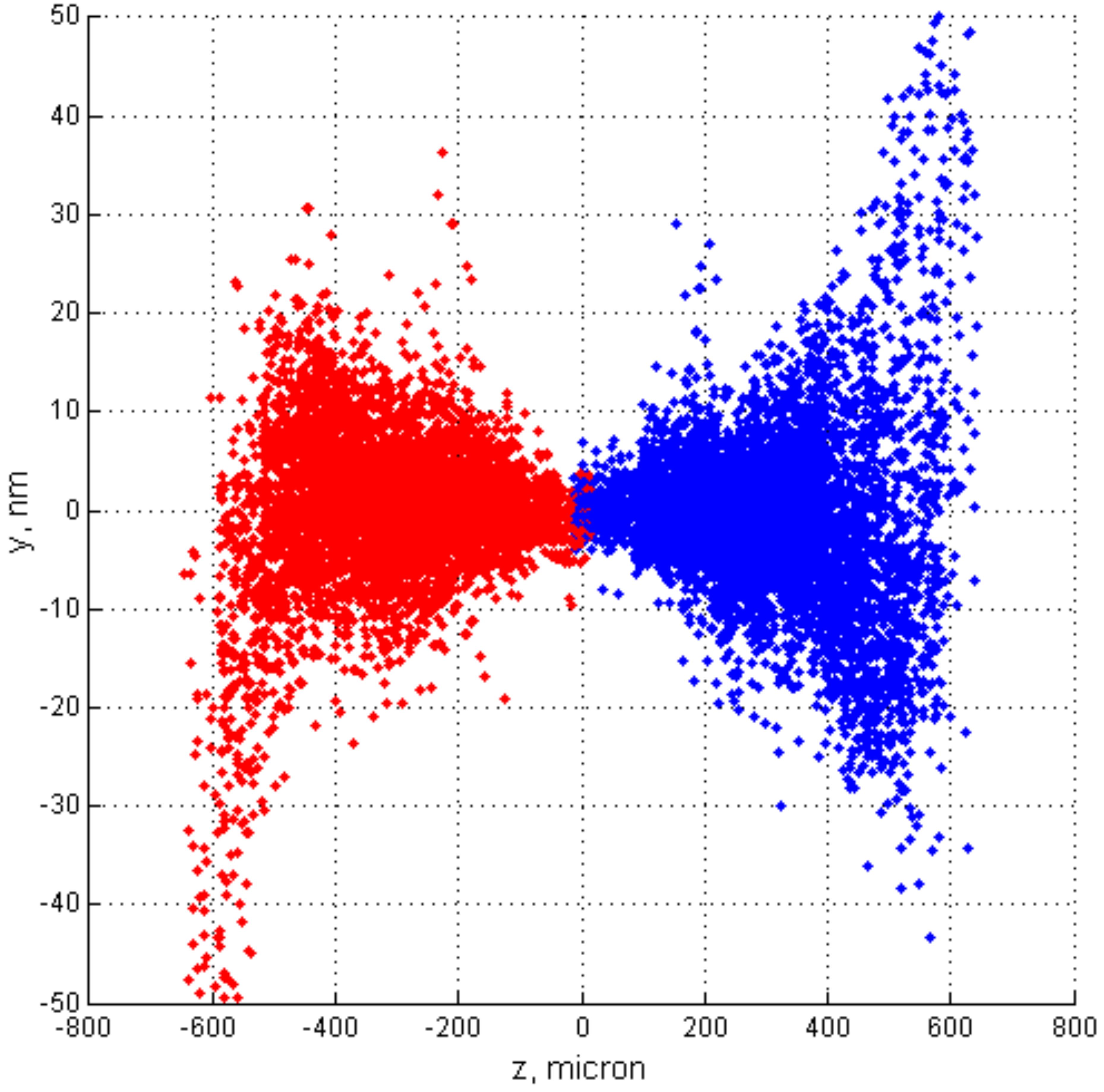
$$\delta_{BS} \approx 0.86 \frac{e r_e^3}{2 m_0 c^2} \left(\frac{\mathrm{E}_{cm}}{\sigma_z} \right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

$$L = \frac{n_b N^2 f_{\mathrm{rep}}}{4\pi \sigma_x \sigma_y} H_D$$

$\}$ Chose flat beams!

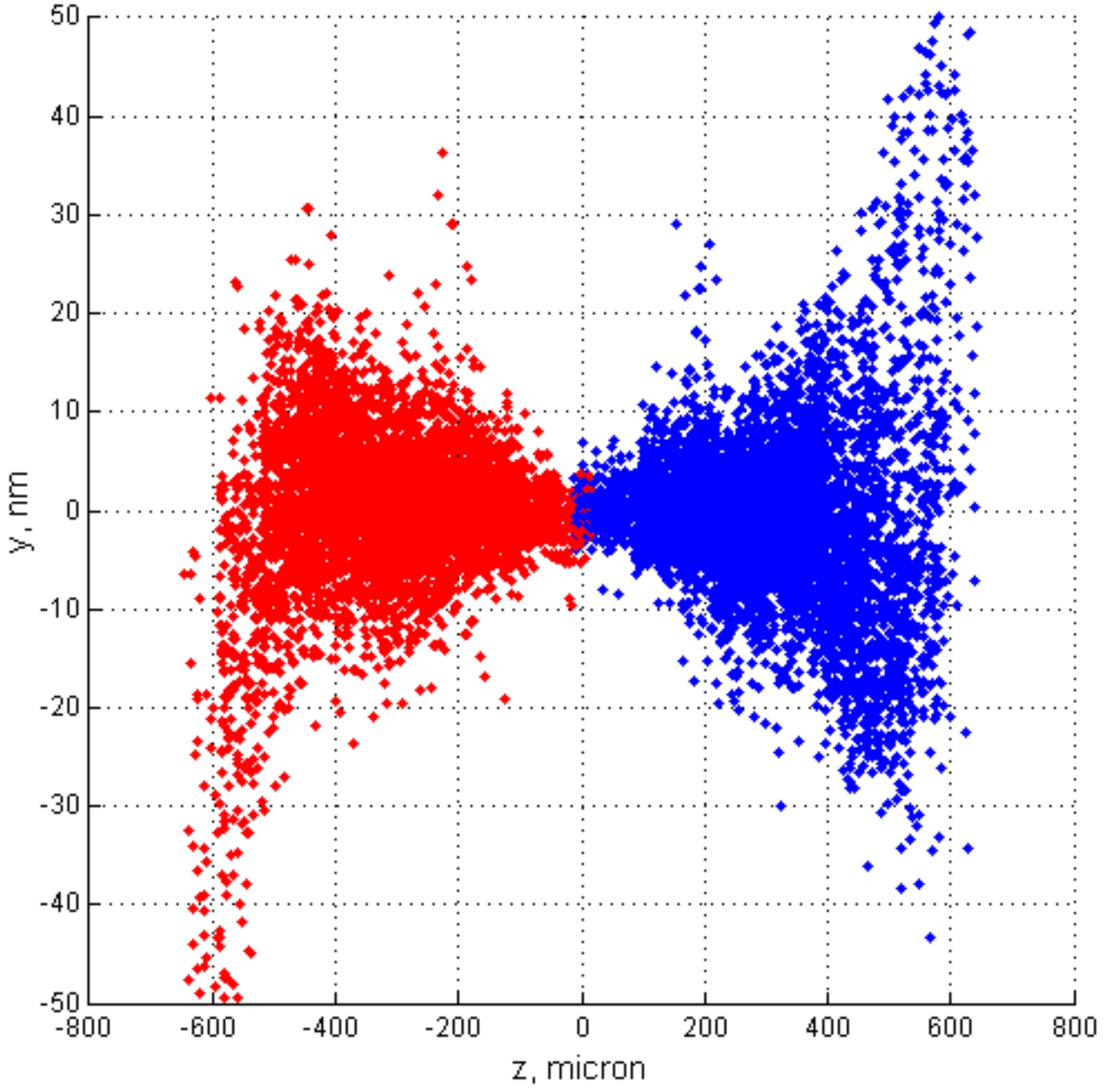


Beam-Beam Interaction



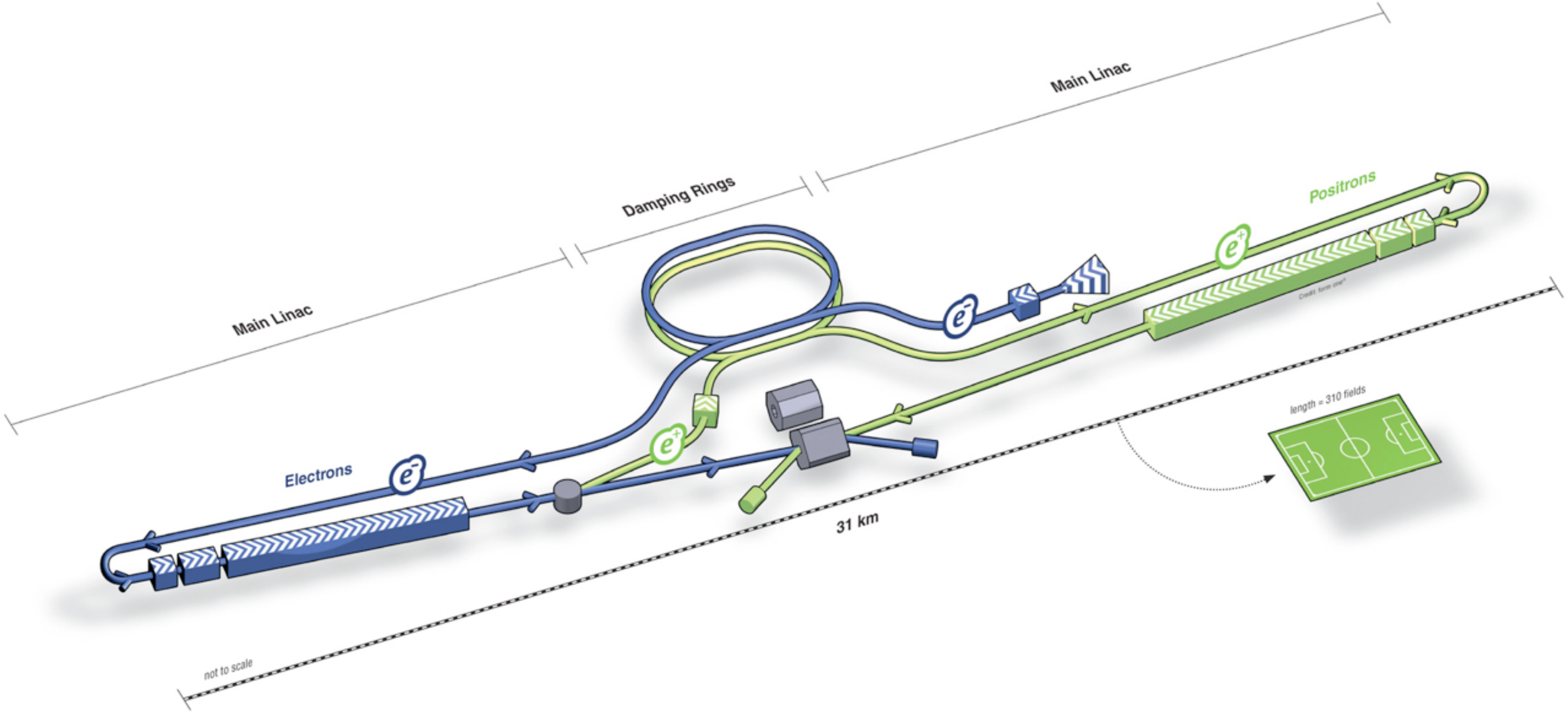
A. Seryi

Beam-Beam Interaction



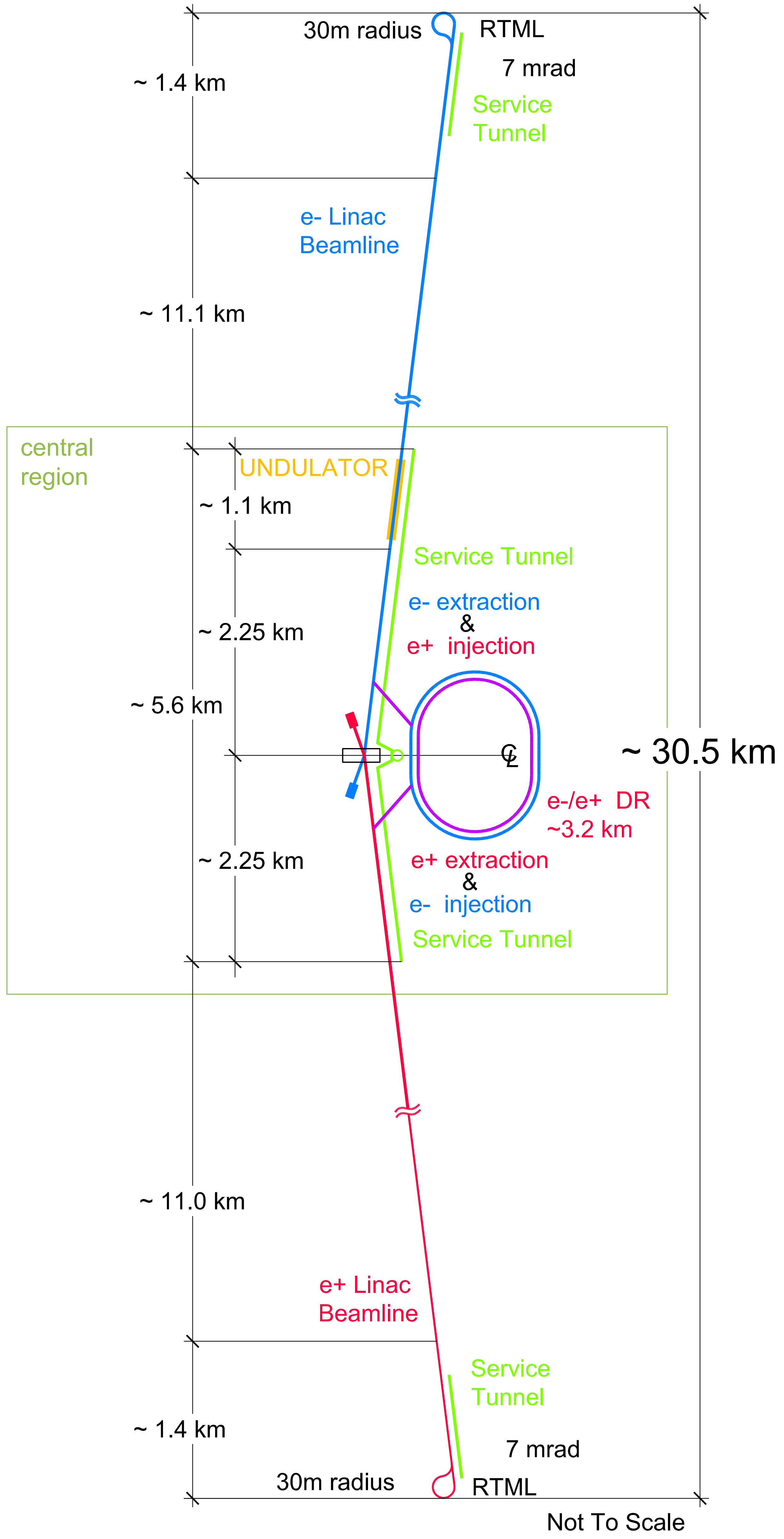
A. Seryi

International Linear Collider ILC



ILC Scheme | © www.form-one.de

ILC Baseline Design (500 GeV)

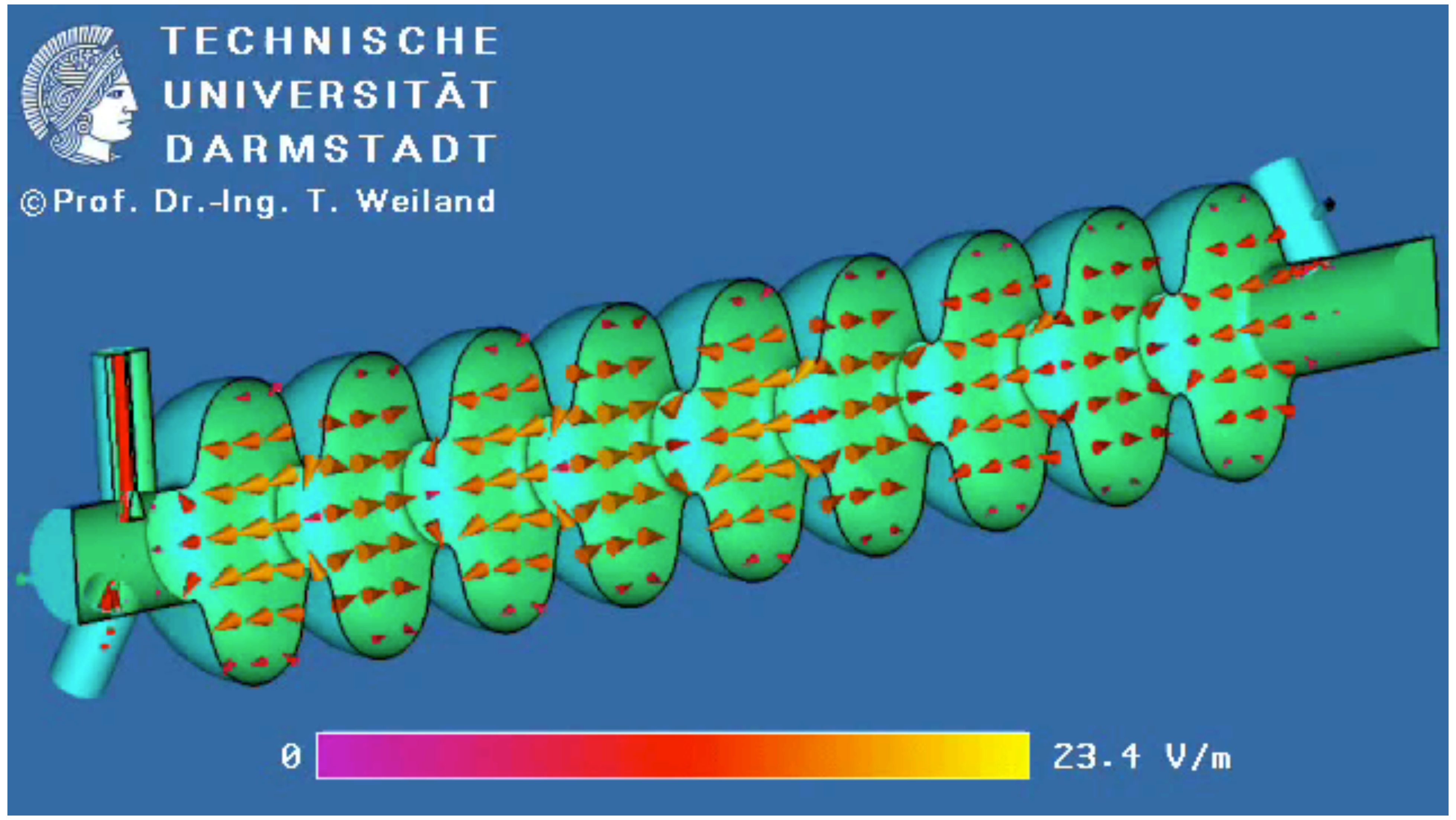


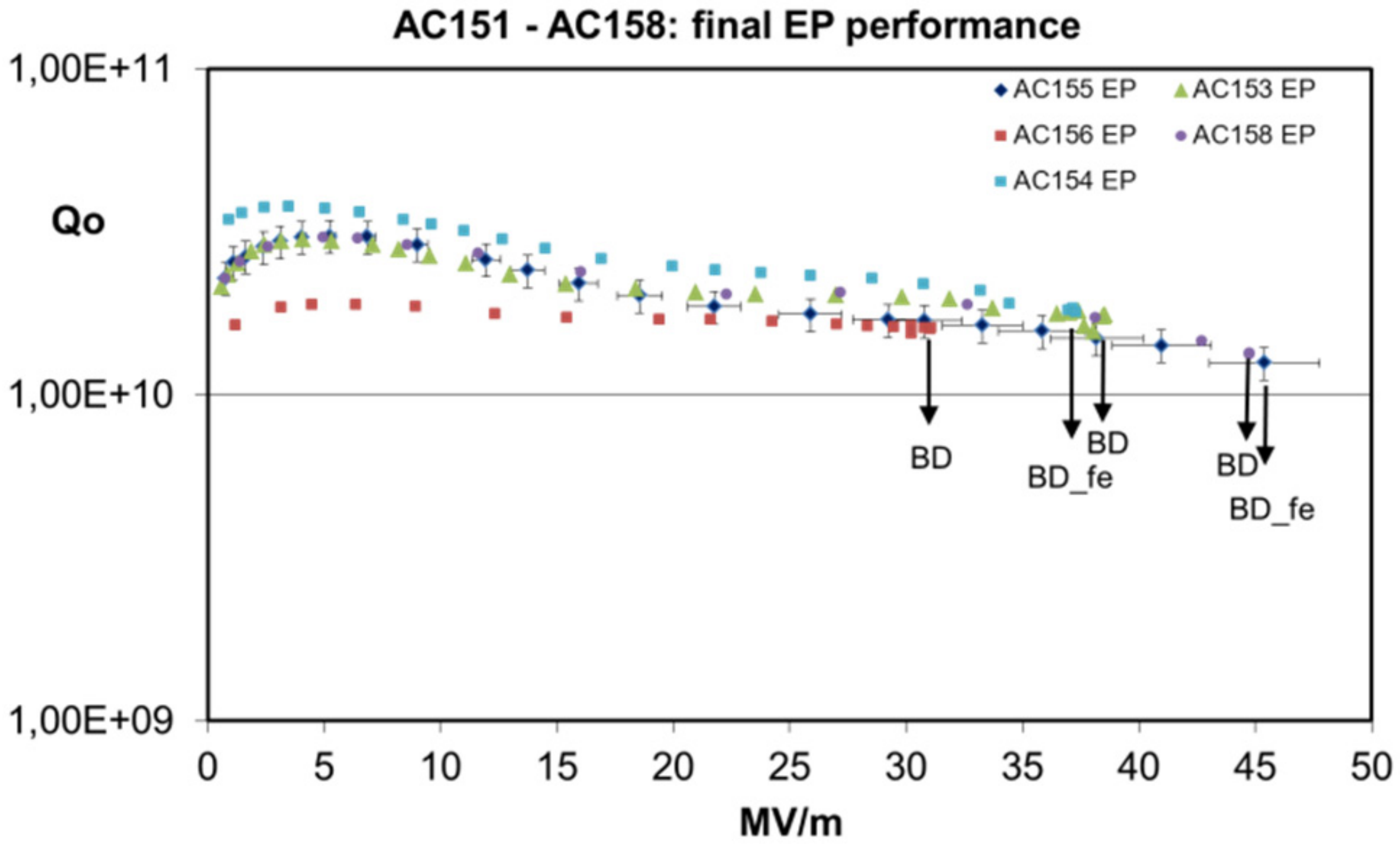
Physics	Max. E_{cm}	500 GeV
	Luminosity	1.8×10^{34} cm^{-2}s^{-1}
	Polarisation (e-/e+)	80% / 30%
	δ_{BS}	4.5%
Beam (interaction point)	σ_x / σ_y	574 nm / 6 nm
	σ_z	300 μm
	$\gamma\varepsilon_x$ / $\gamma\varepsilon_y$	10 μm / 35 nm
	β_x / β_y	11 mm / 0.48 mm
	bunch charge	2×10^{10}
Beam (time structure)	Number of bunches / pulse	1312
	Bunch spacing	554 ns
	Pulse current	5.8 mA
	Beam pulse length	727 μs
	Pulse repetition rate	5 Hz
Accelerator (general)	Average beam power	10.5 MW (total)
	Total AC power	163 MW
	(linacs AC power	107 MW)

N. Walker

ILC: the Superconducting Collider

Superconducting cavities for the ILC
- 2K He cooled
- 16.000 cavities in 1800 cryomodules
- gradient: ~35 MV/m
- cost-driver!





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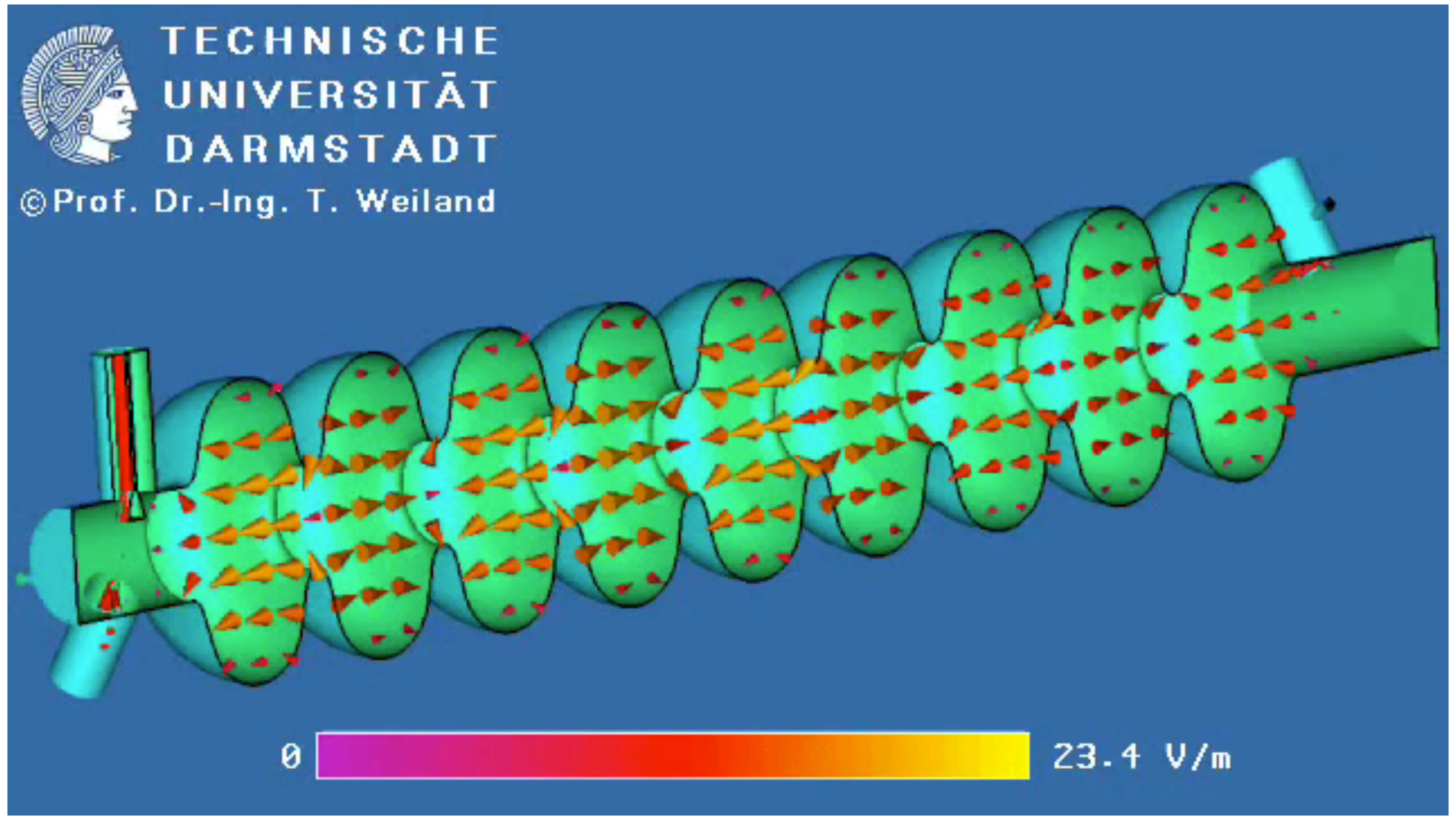
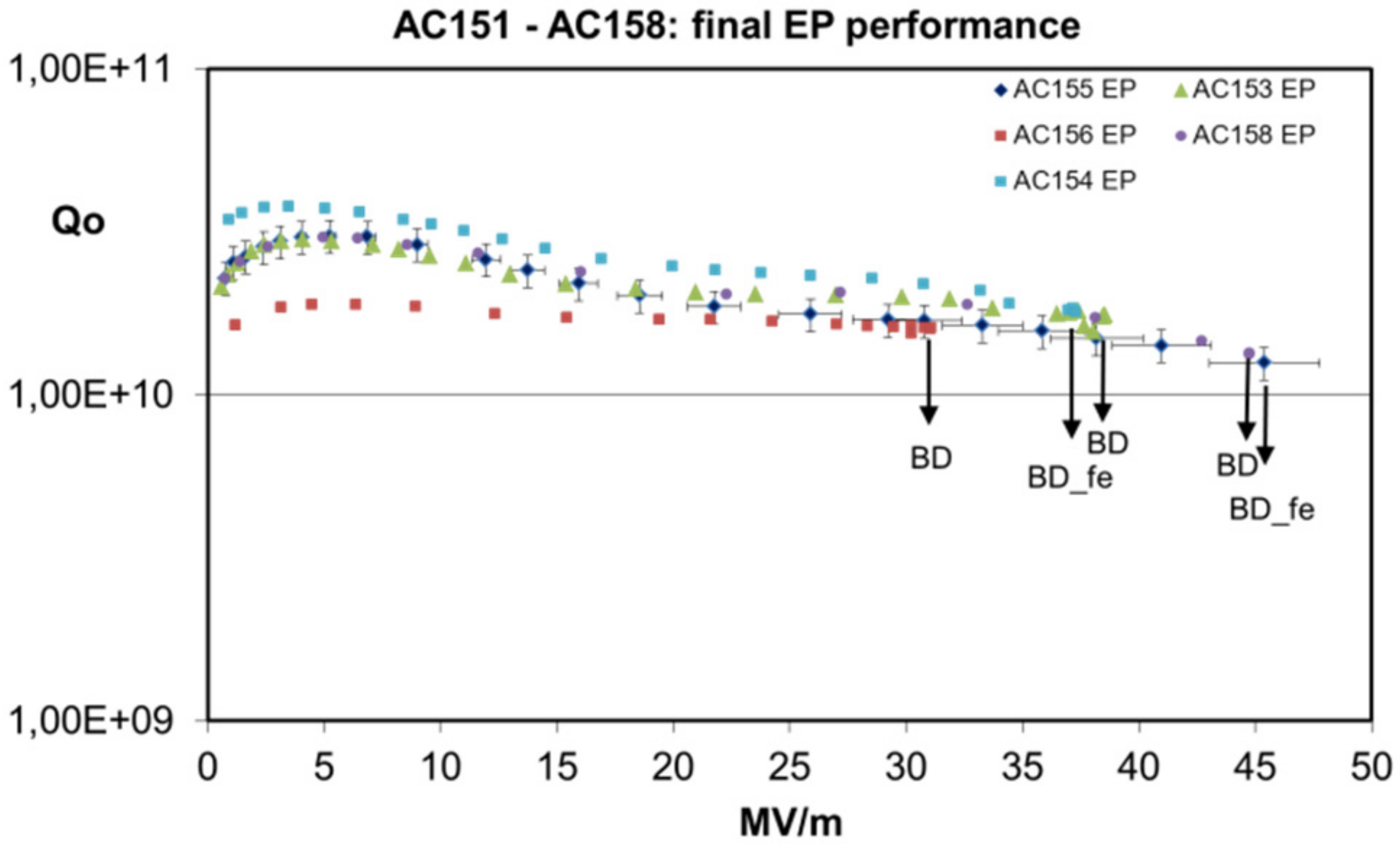
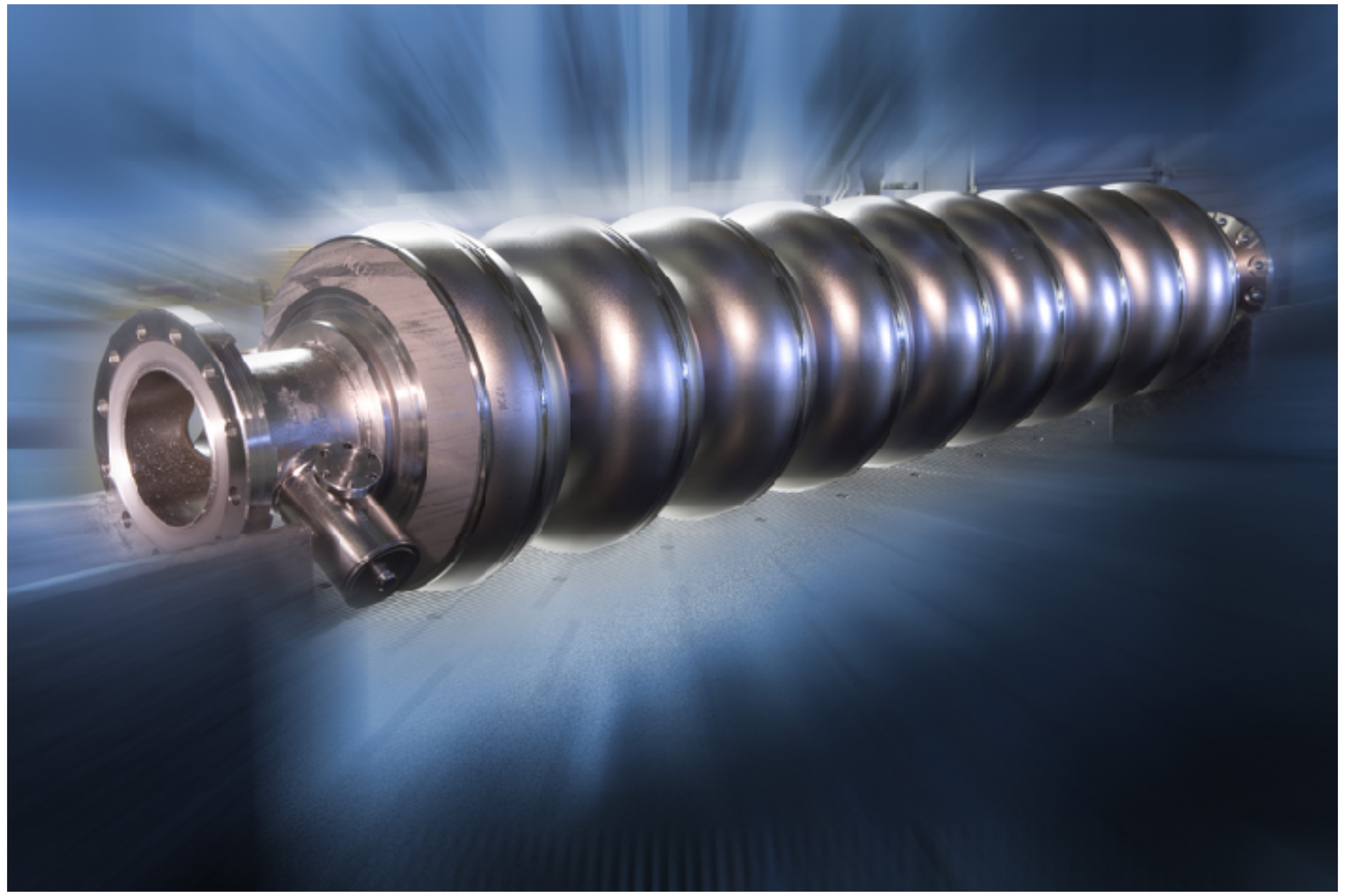


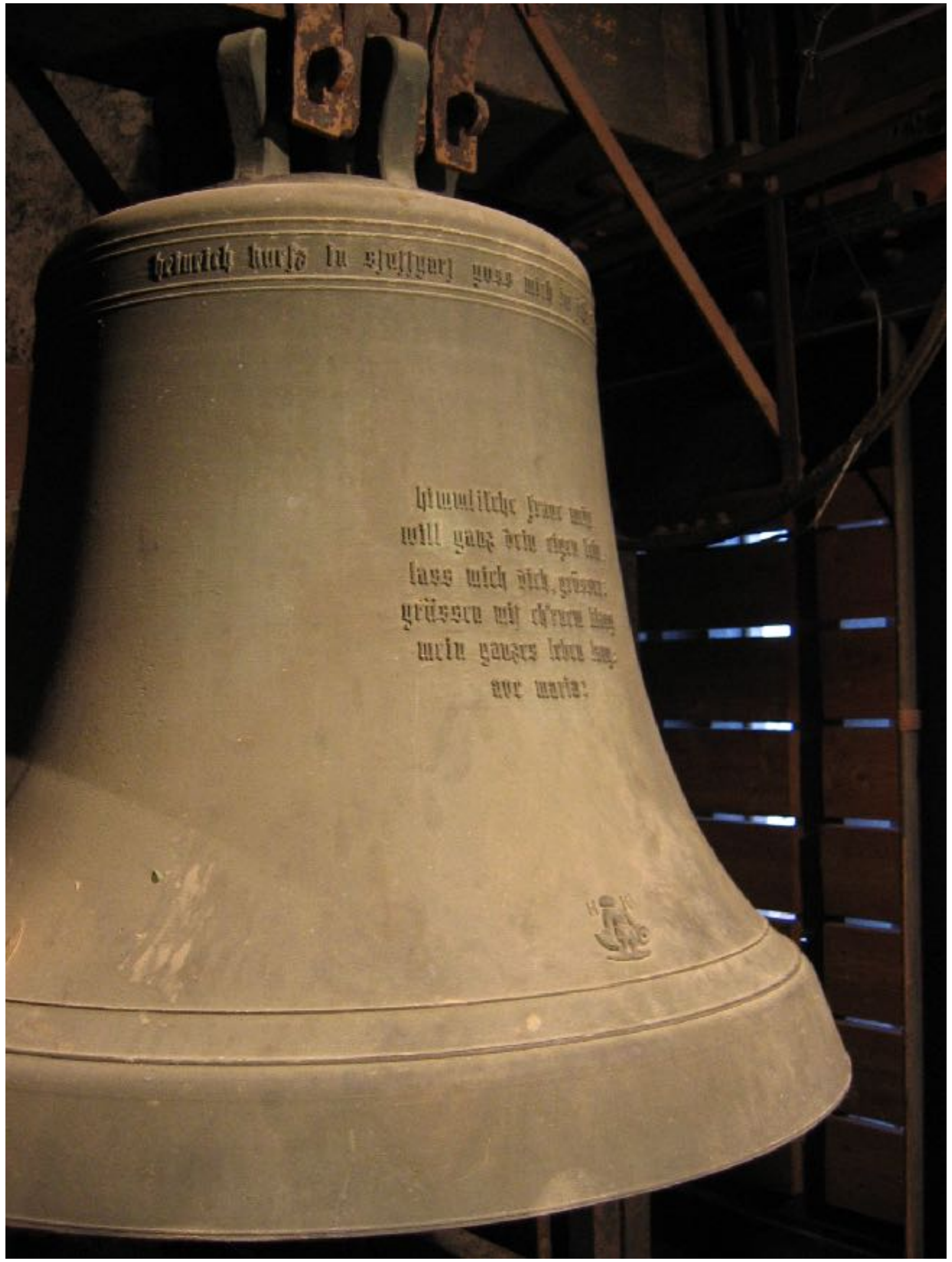


Q Factor

Superconducting cavity: $Q>10^{10}$

- A church bell (300 Hz) with $Q=5 \times 10^{10}$ would ring – once excited – longer than one year!





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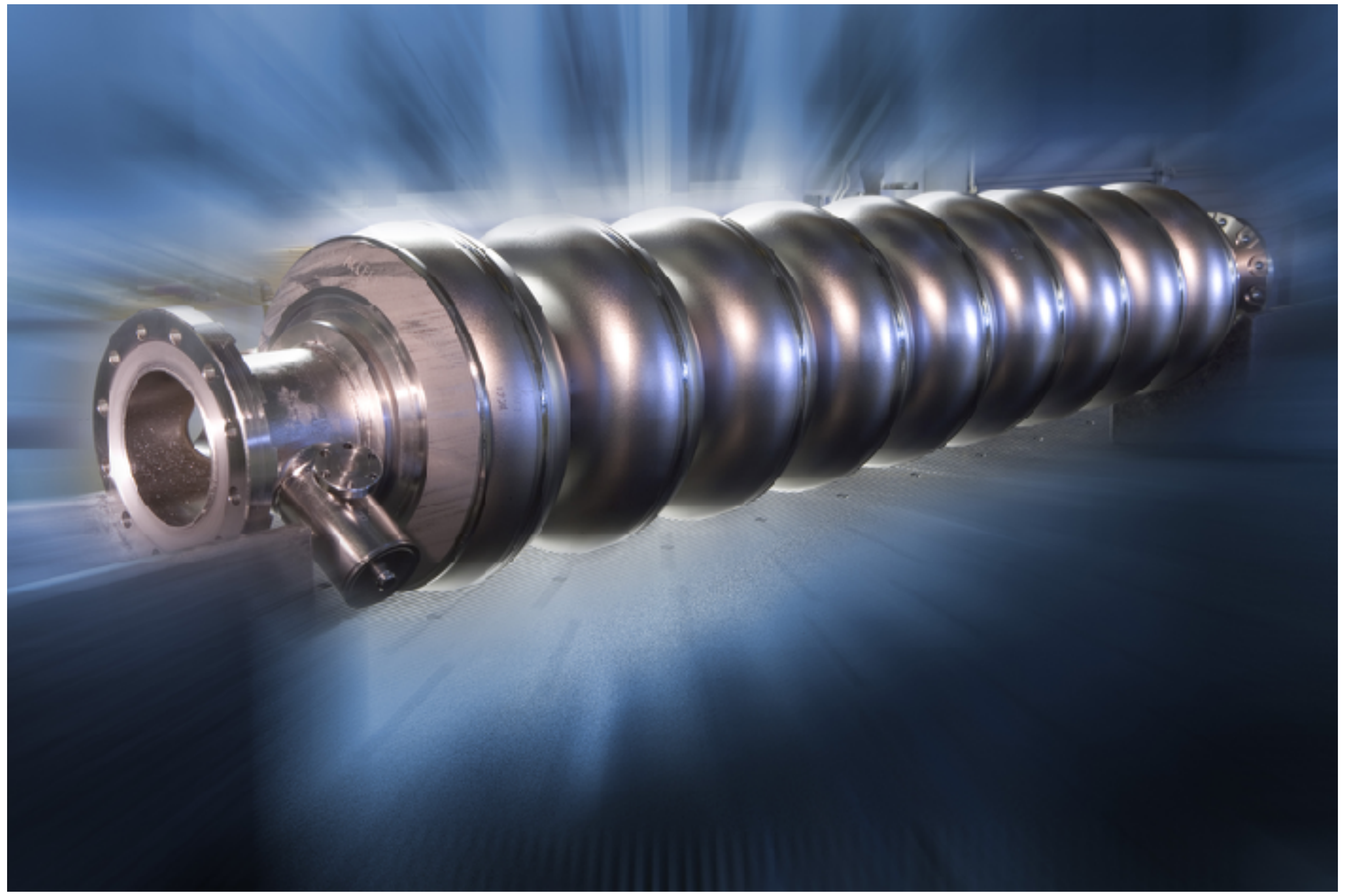
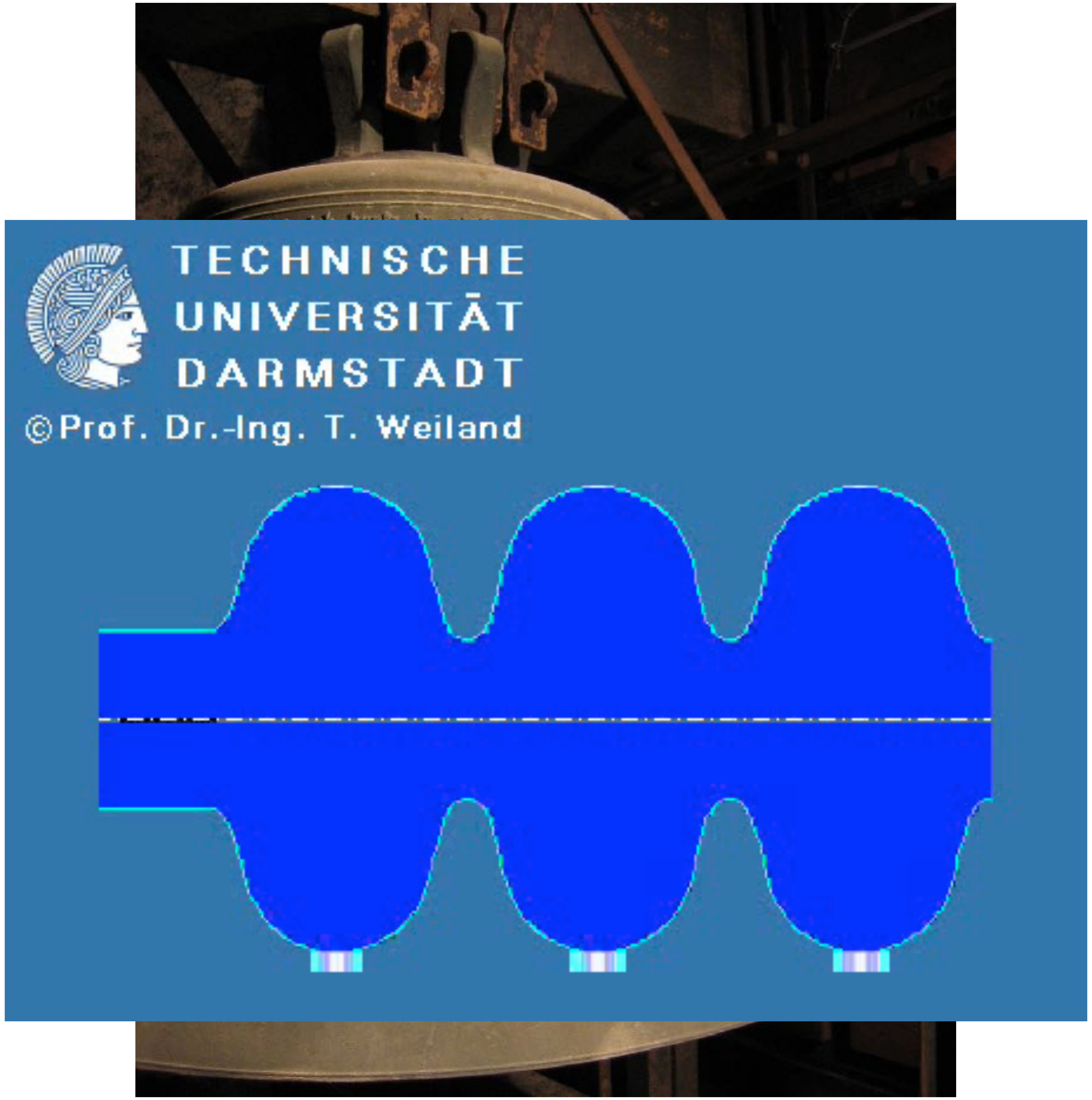
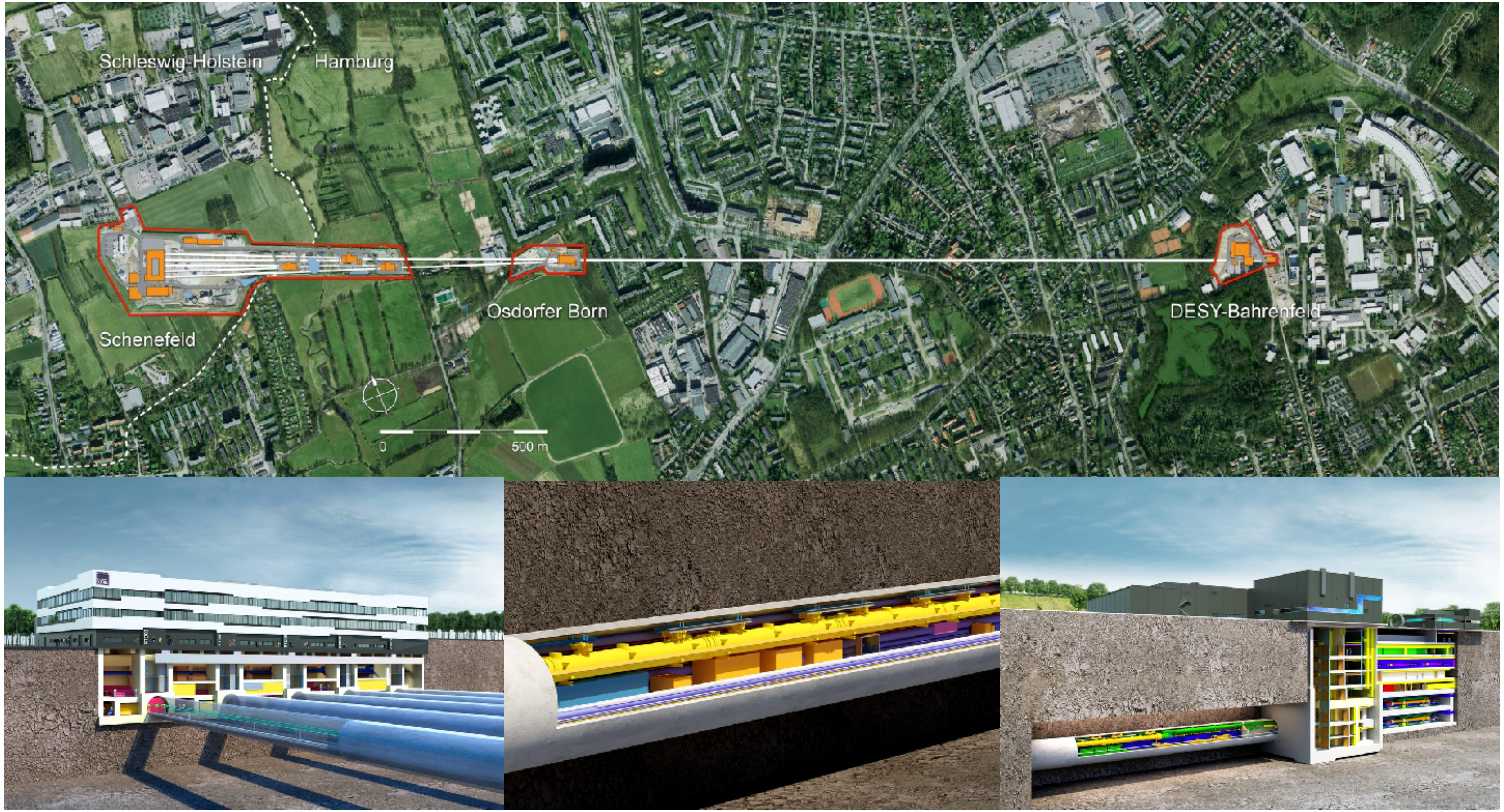




European XFEL @ DESY



XFEL-Linac: 10% Prototype of ILC

Industrialisation for XFEL

Mass production:

- 100 cryomodules
- 800 cavities

Largest deployment of this SCRF technology to date....

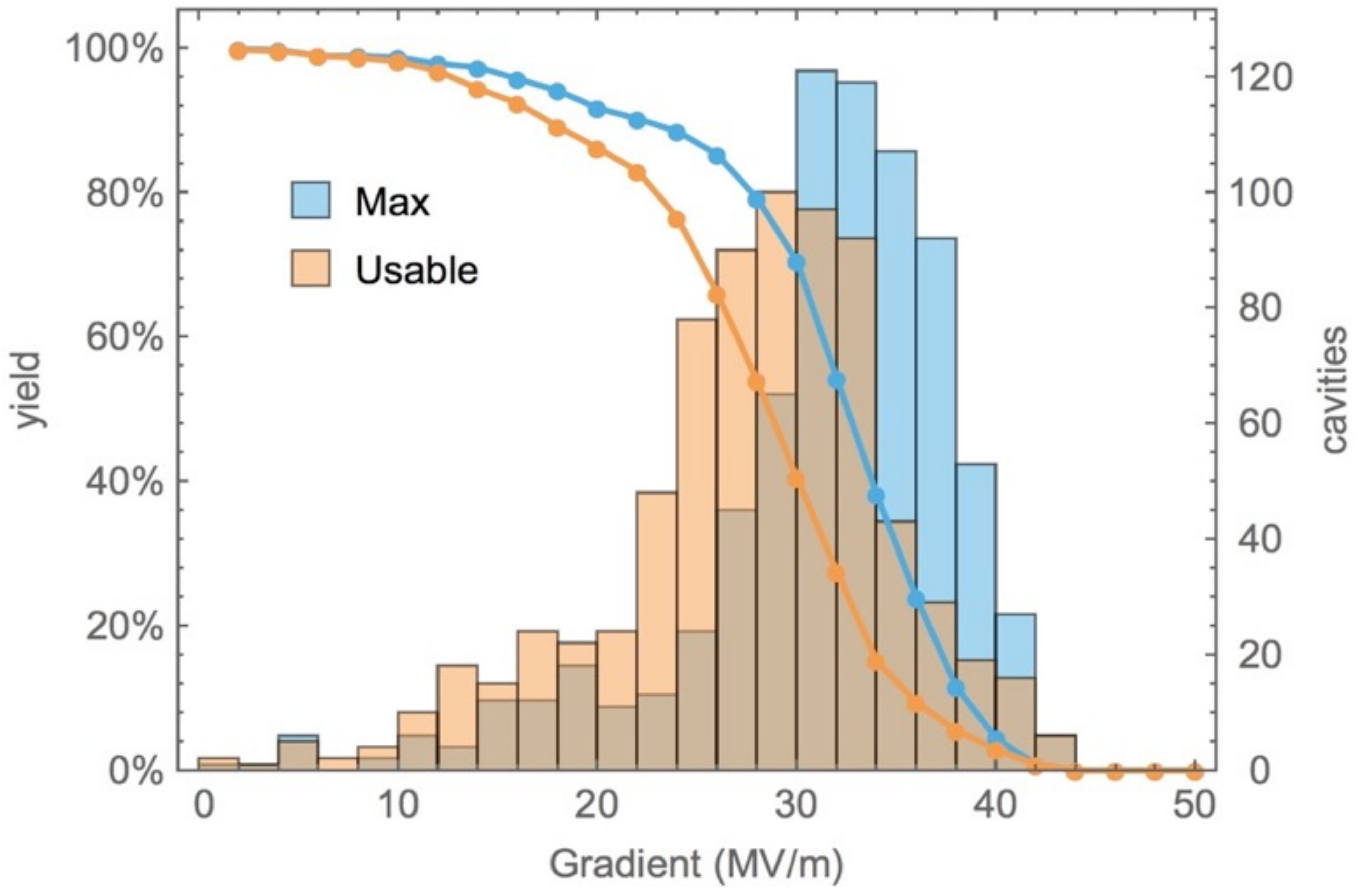
Large unbiased sample

- critical for ILC

XFEL Cavity Production

N. Walker

„As received“ tests of XFEL cavities:



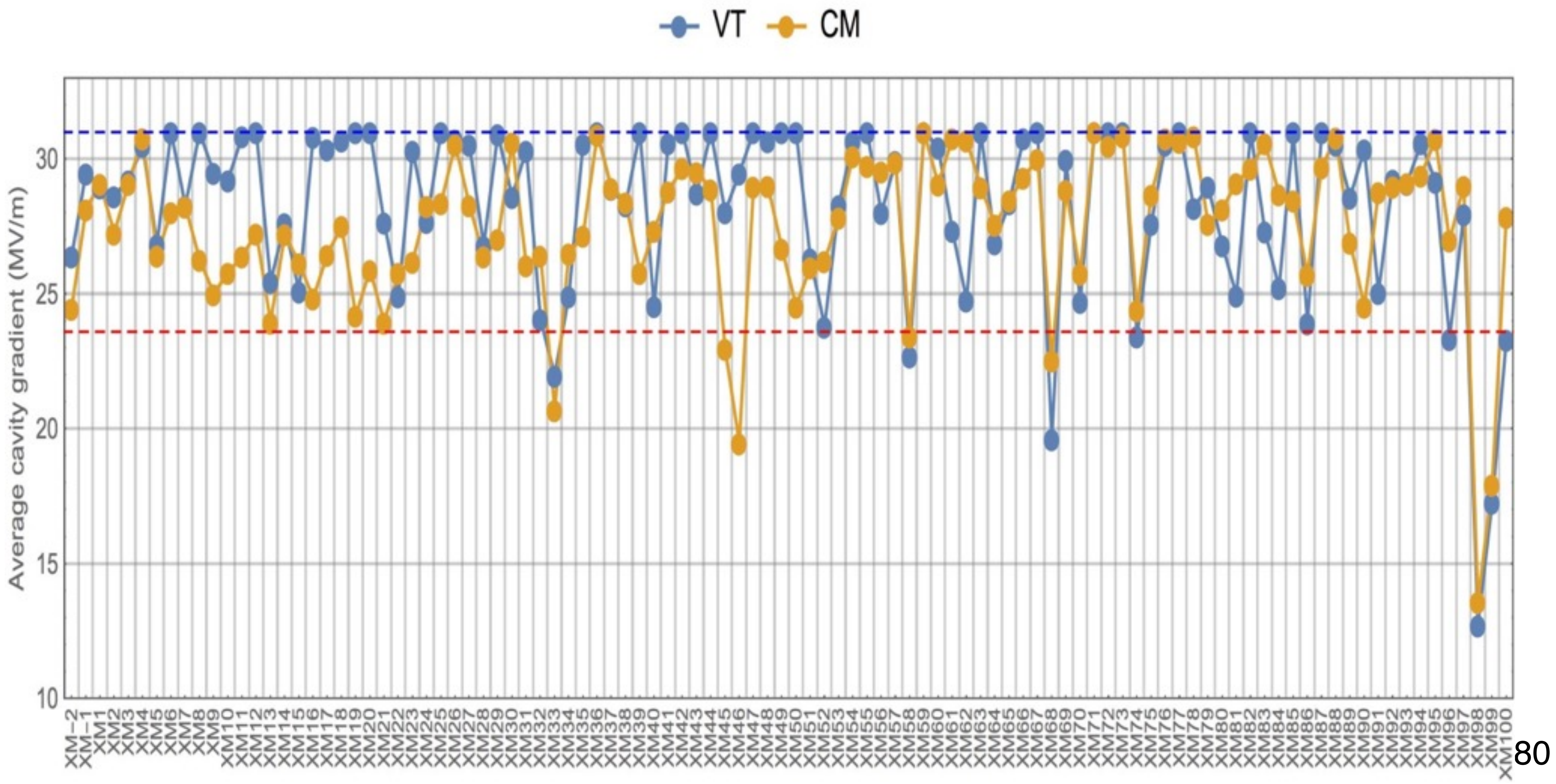
ILC Goal: 31.5 MeV/m@90% yield
(XFEL: 23.6 MeV/m)

- Adapting XFEL re-treatment model to ILC (prediction):

RI results only (ILC recipe)		ILC TDR (assumed)	XFEL max	XFEL usable
First-pass	Yield >28 MV/m	75%	85%	63%
	Average >28 MV/m	35 MV/m	35.2 MV/m	33.5 MV/m
First+Second pass	Yield >28 MV/m	90%	94%	82%
	Average >28 MV/m	35 MV/m	35.0 MV/m	33.4 MV/m
First+Second+third pass	Yield >28 MV/m	-		91%
	Average >28 MV/m	-		33.4 MV/m

but close!

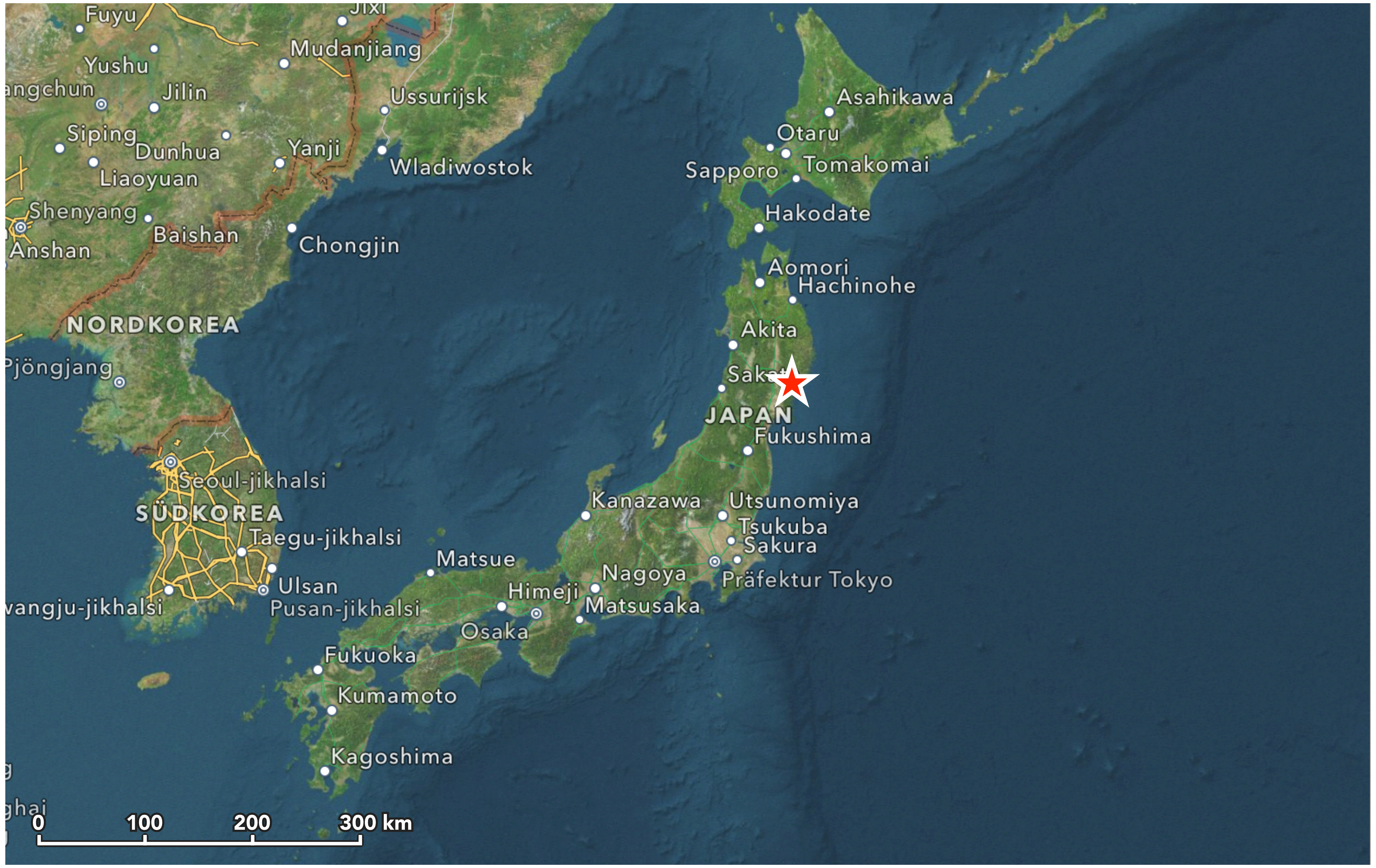
- XFEL cryomodule performance



ILC in Japan

Japan has indicated possible interest to host the ILC as an international project

- Initiative is welcomed in the HEP strategies of the US (P5) and Europe (CERN Council)
- A potential site for the ILC has been identified in the Kitakami mountains



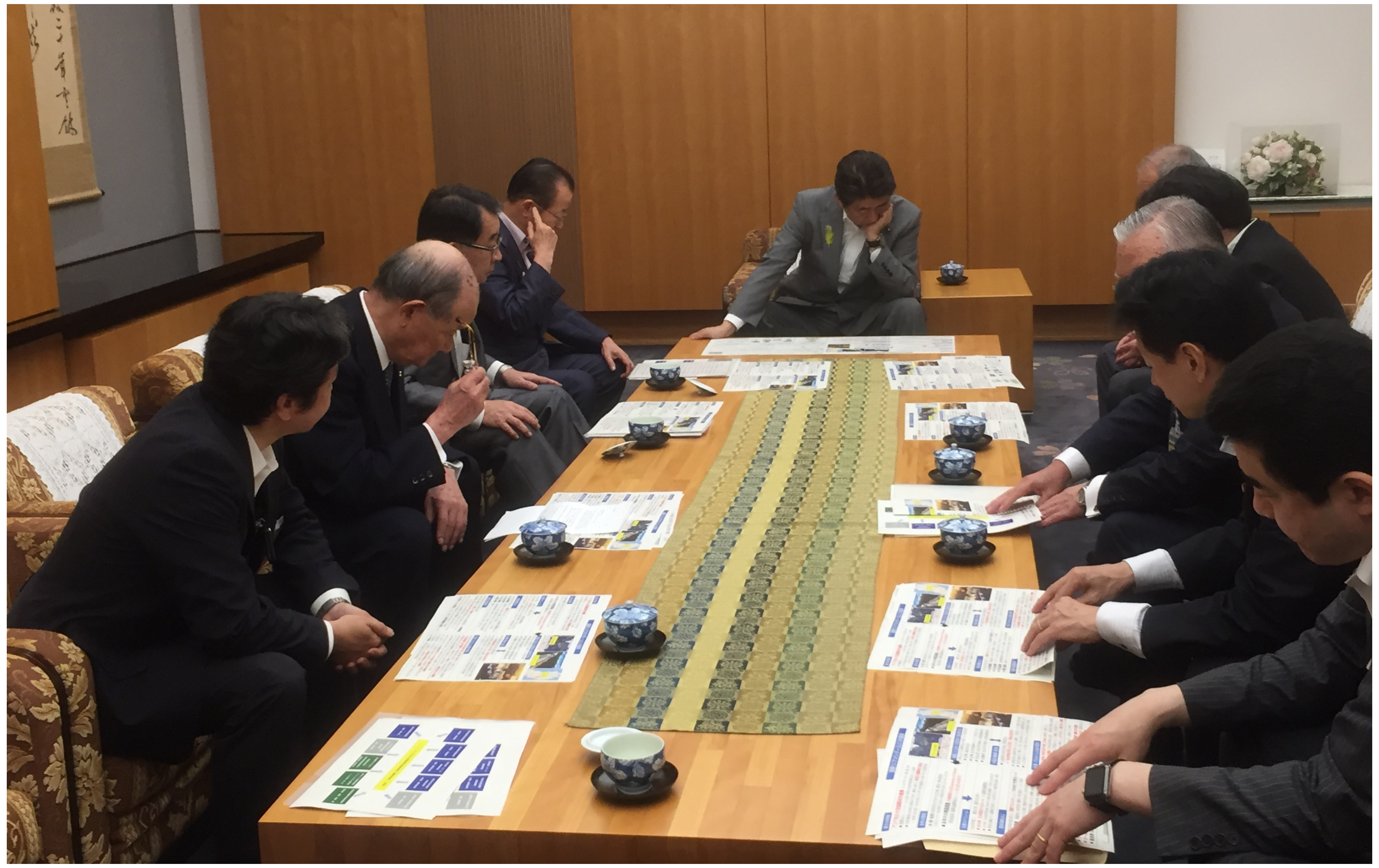
Political Developments

Japanese Government has started evaluation of ILC as a possible international science project in Japan in 2013

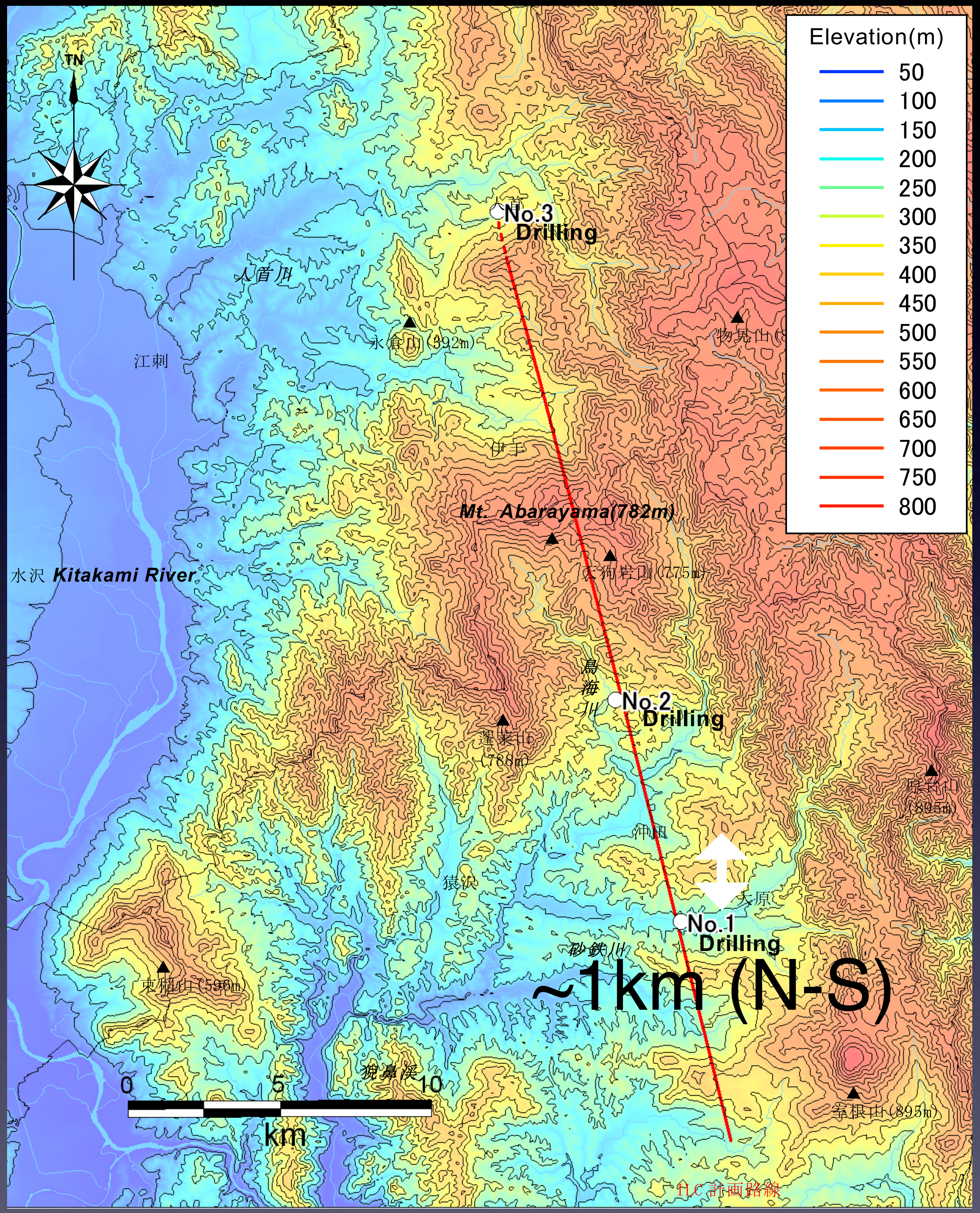
- Evaluation process under direction of the MEXT ministry (science, education, technology,…)
- It is understood that some message has to come from the government before the finalisation of the European Strategy of Particle Physics process
- First step would be a 250 GeV energy ILC, with the potential of future energy upgrades
  - money, money, money…

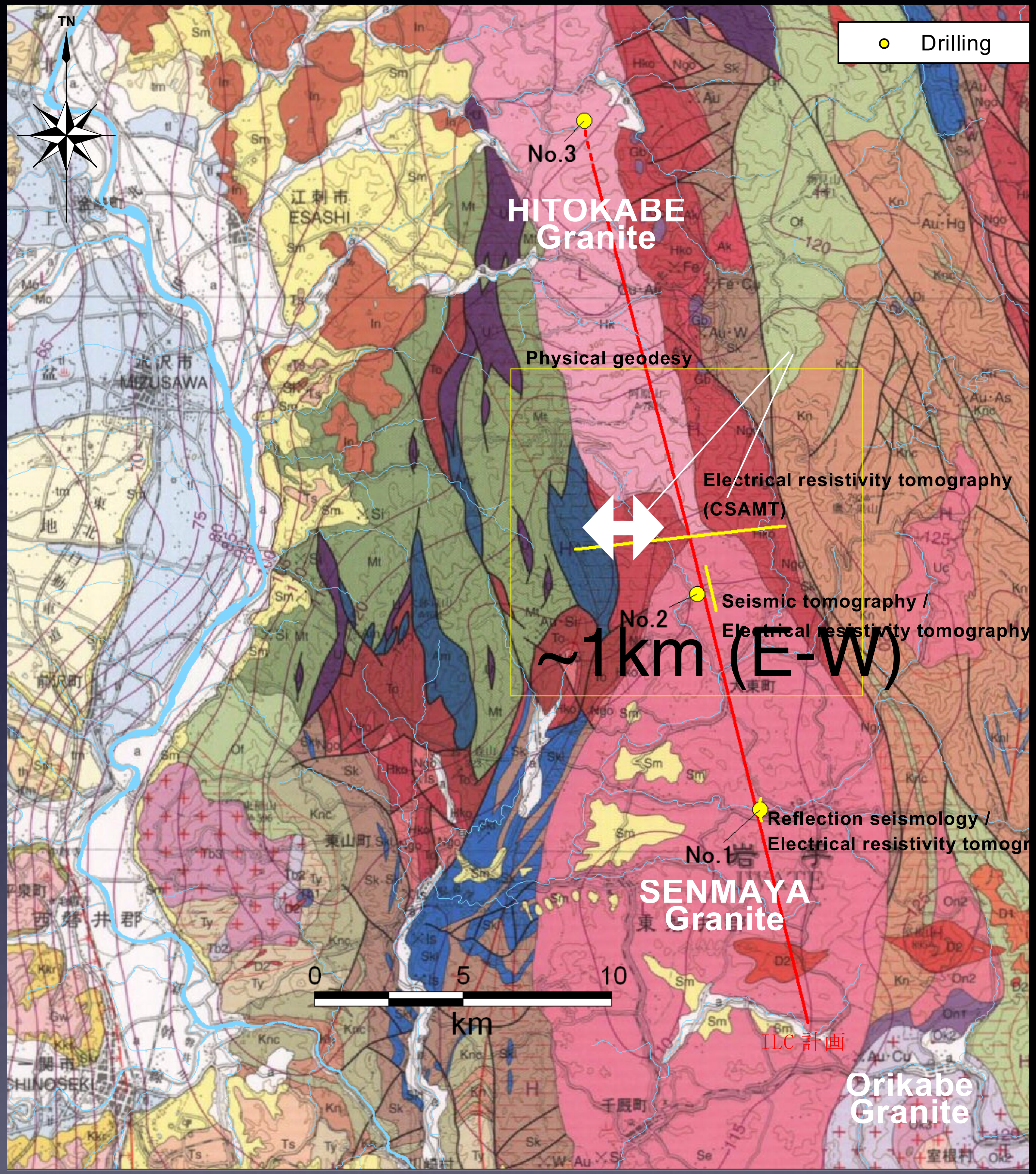
March 2013

July 2018

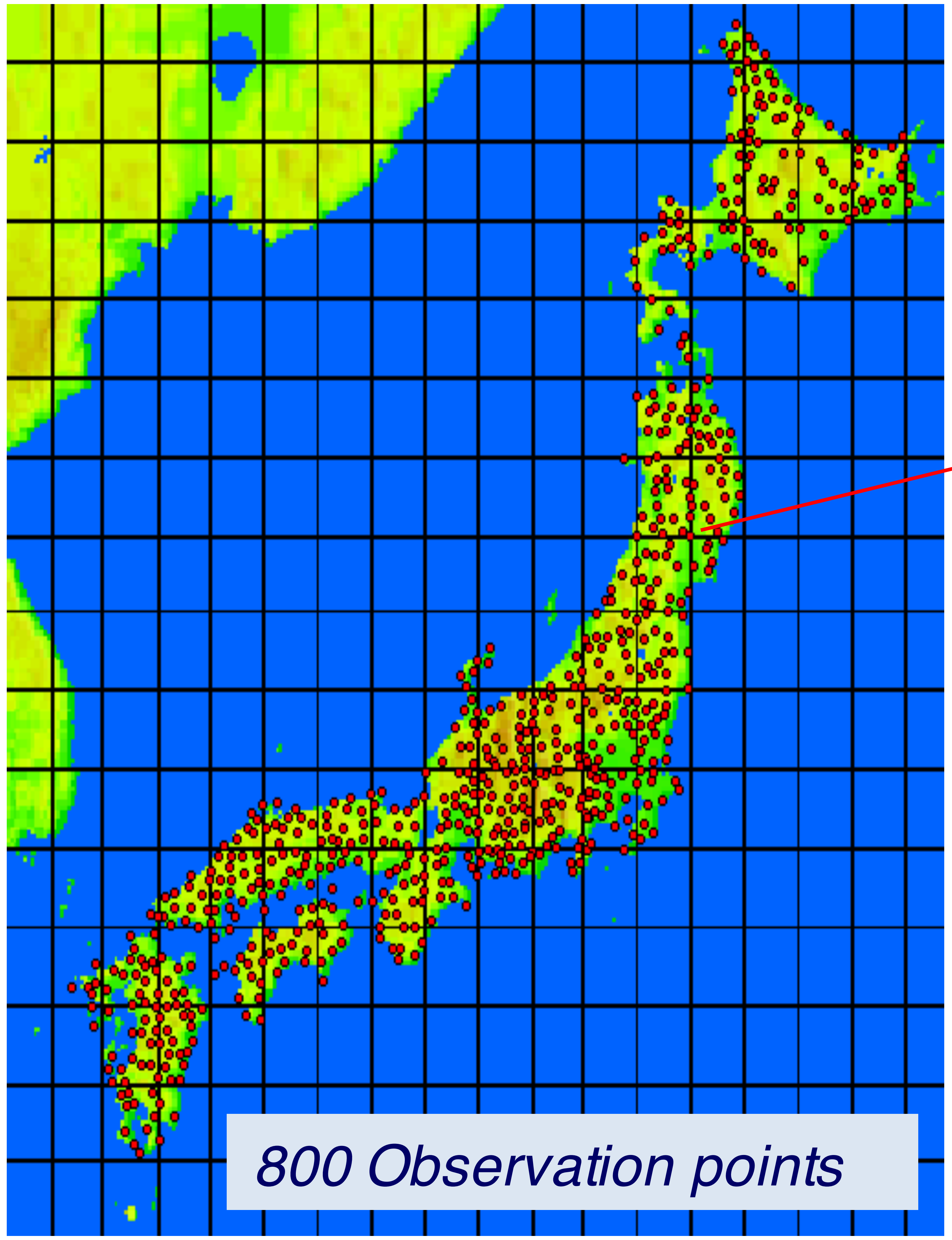



HITOKABE-GAWA
HITOKABE Granite
ML-Tn
OKITA-GAWA
SENMAYA Granite
EH
HAYAMA-SAN
EL110m
SATETSU-GAWA
KANOKURA Formation
ORIKABE Granite
INAI Grope
TOKUSENJO-YAMA
PM-12
PM-10
PM-8
PM+8
PM+10
PM+12
PM+13
PM+14
PM+16


Elevation(m)
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
TN
No.3
Drilling
Mt. Abarayama(782m)
Kitakami River
No.2
Drilling
No.1
Drilling
~1km (N-S)
0
5
10
km


Drilling
TN
No.3
HITOKABE
Granite
ESASHI
MIZUSAWA
Physical geodesy
Electrical resistivity tomography
(CSAMT)
Seismic tomography /
Electrical resistivity tomography
No.2
~1km (E-W)
Reflection seismology /
No.1
SENMAYA
Granite
0
5
10
km
Orikabe
Granite

3.11 Seismic Observation

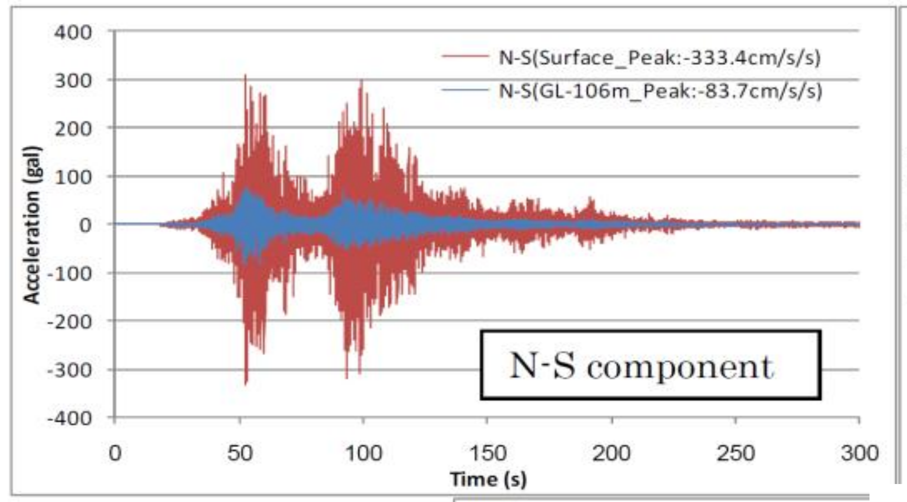


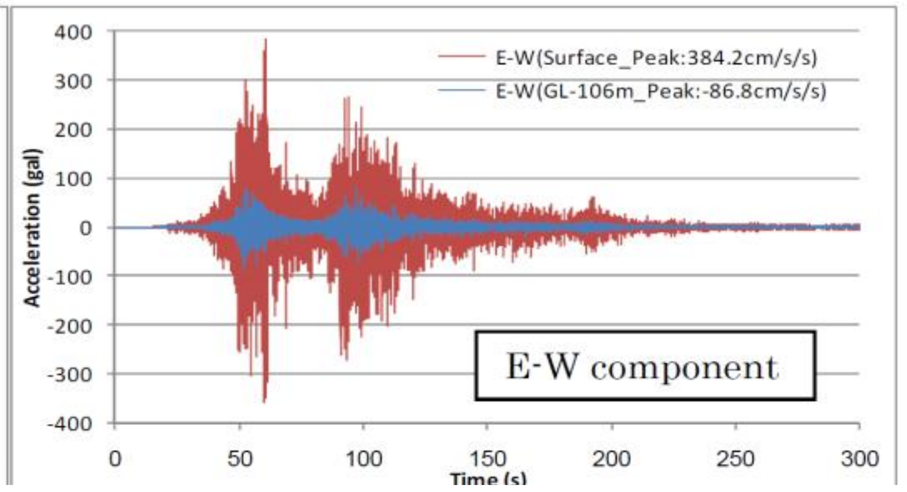
***KiK-net** Observation Network*

(Kiban:Bedrock, Kyoshin:Strong-Motion)

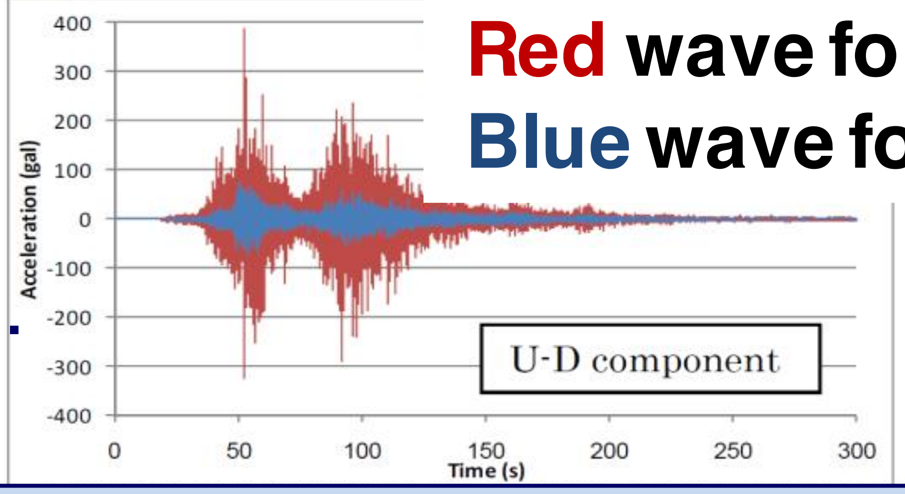
M. Miyahara

Data by "National Research Institute for Earth Science and Disaster Prevention"





SUMITA on Granite Zone in IWATE Pre.



Red wave form: Surface
Blue wave form: -106m

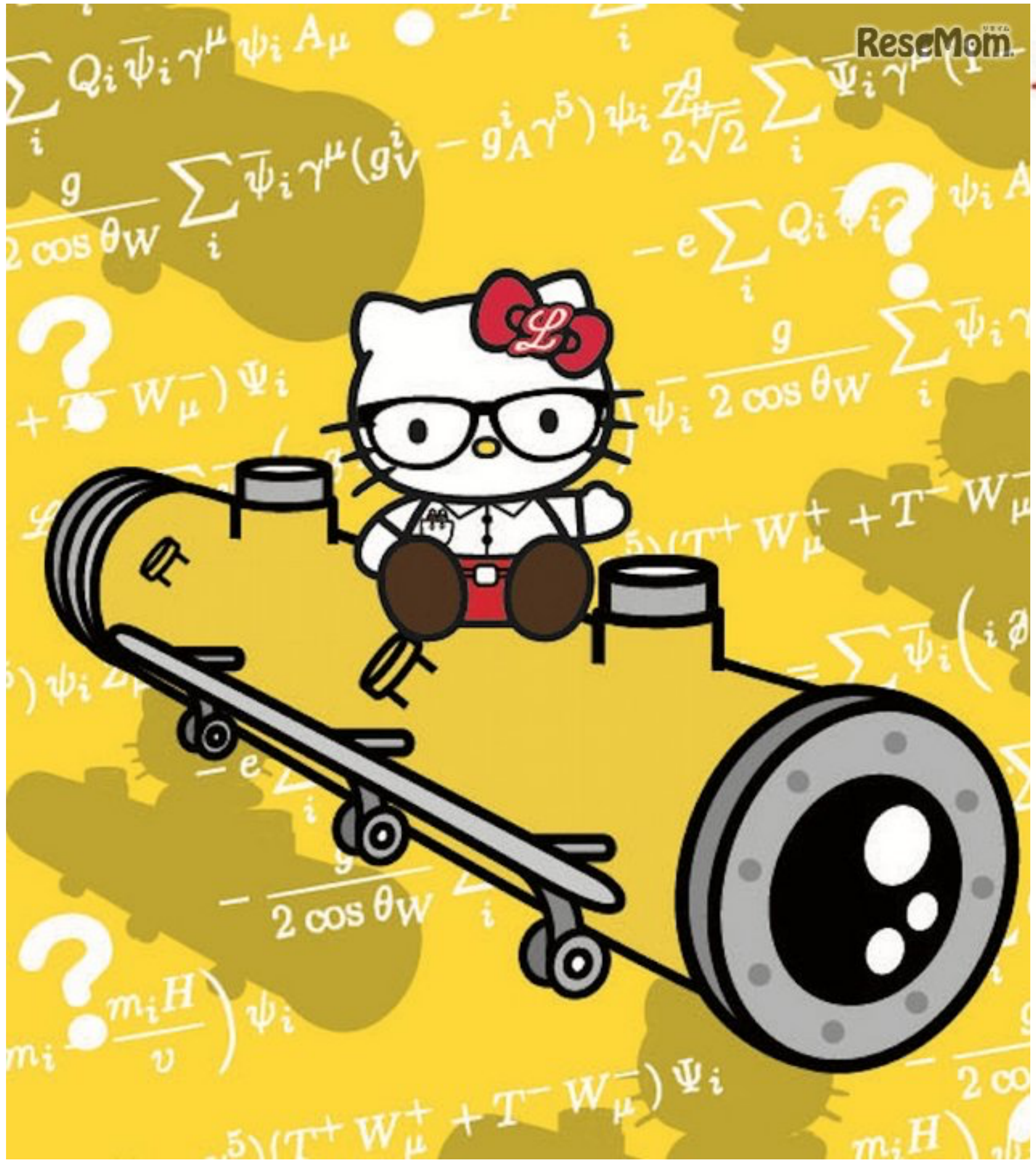
Acceleration comparison of the Surface & underground at SUMITA in IWATE

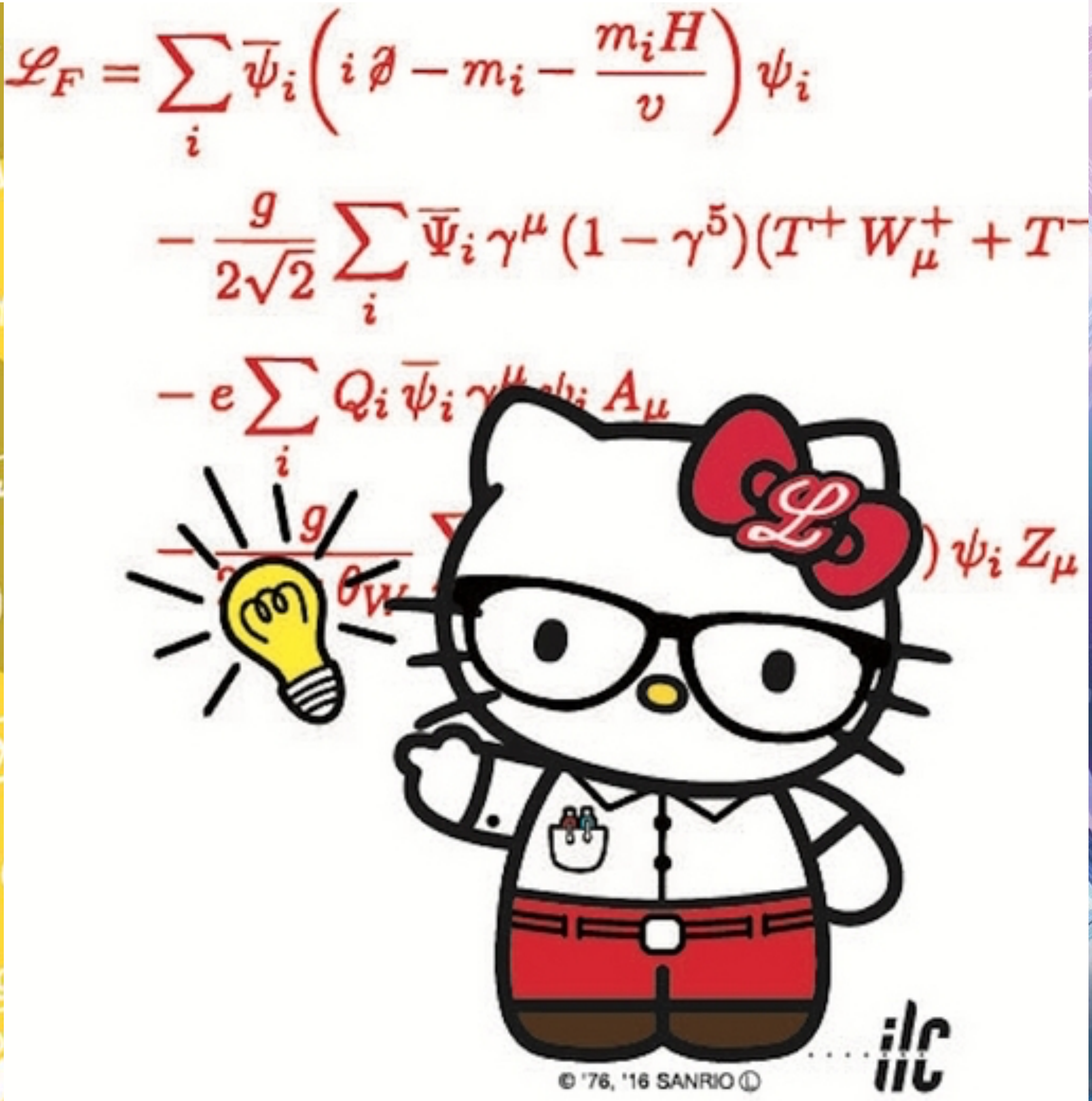
Observation Data

Direction	Acceleration (gal)		Rate
	Surface	Underground	Undergrund /Surface
N-S	333.4	83.7	0.25
E-W	384.2	86.8	0.23
U-D	388.9	73.5	0.19

Local Support

ILC in Japanese Culture…






©Rey.Hori/KEK

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- The Near Future: LHC Luminosity Upgrade
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High-energy Neutrinos from Accelerators:

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- Muon Collider
- Plasma Wakefield Accelerators

The Real Axis - the Real Frontier…

CLIC

CLIC - the multi-TeV Linear Collider Option at CERN

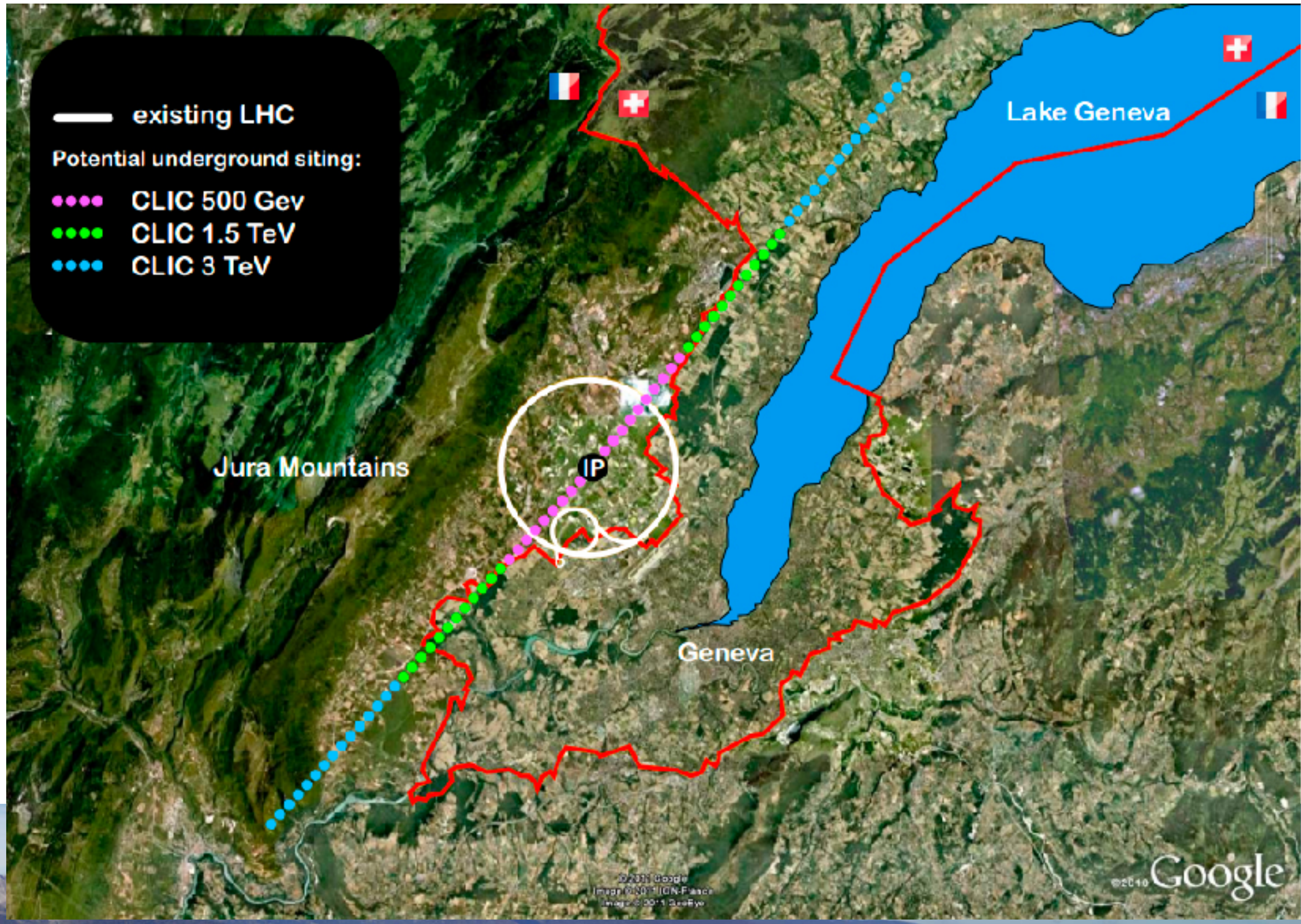
What if ~1 TeV is not enough (for leptons)?

need higher acceleration gradients

- normal conducting cavities

novel RF generation method

- two-beam acceleration



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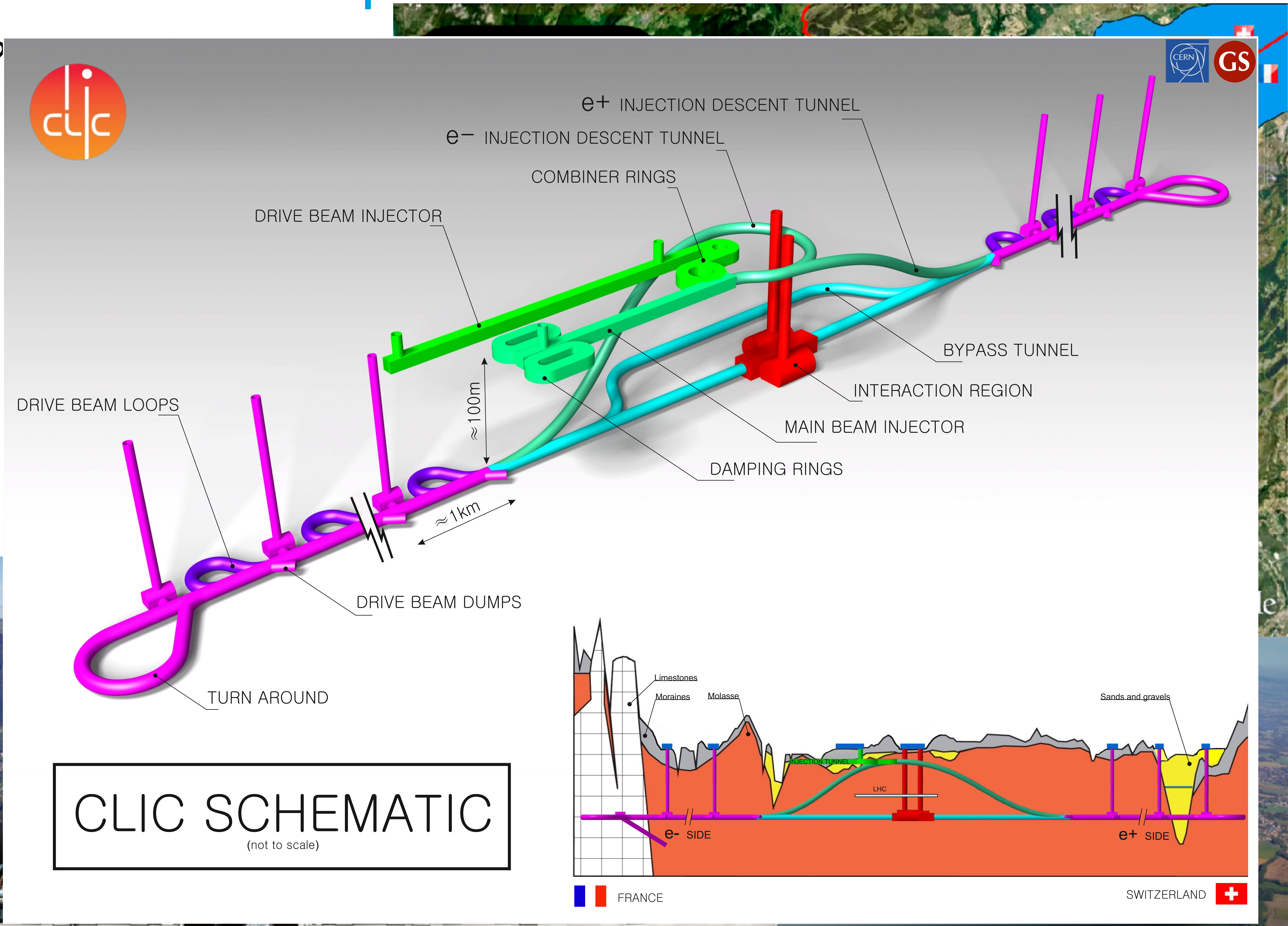
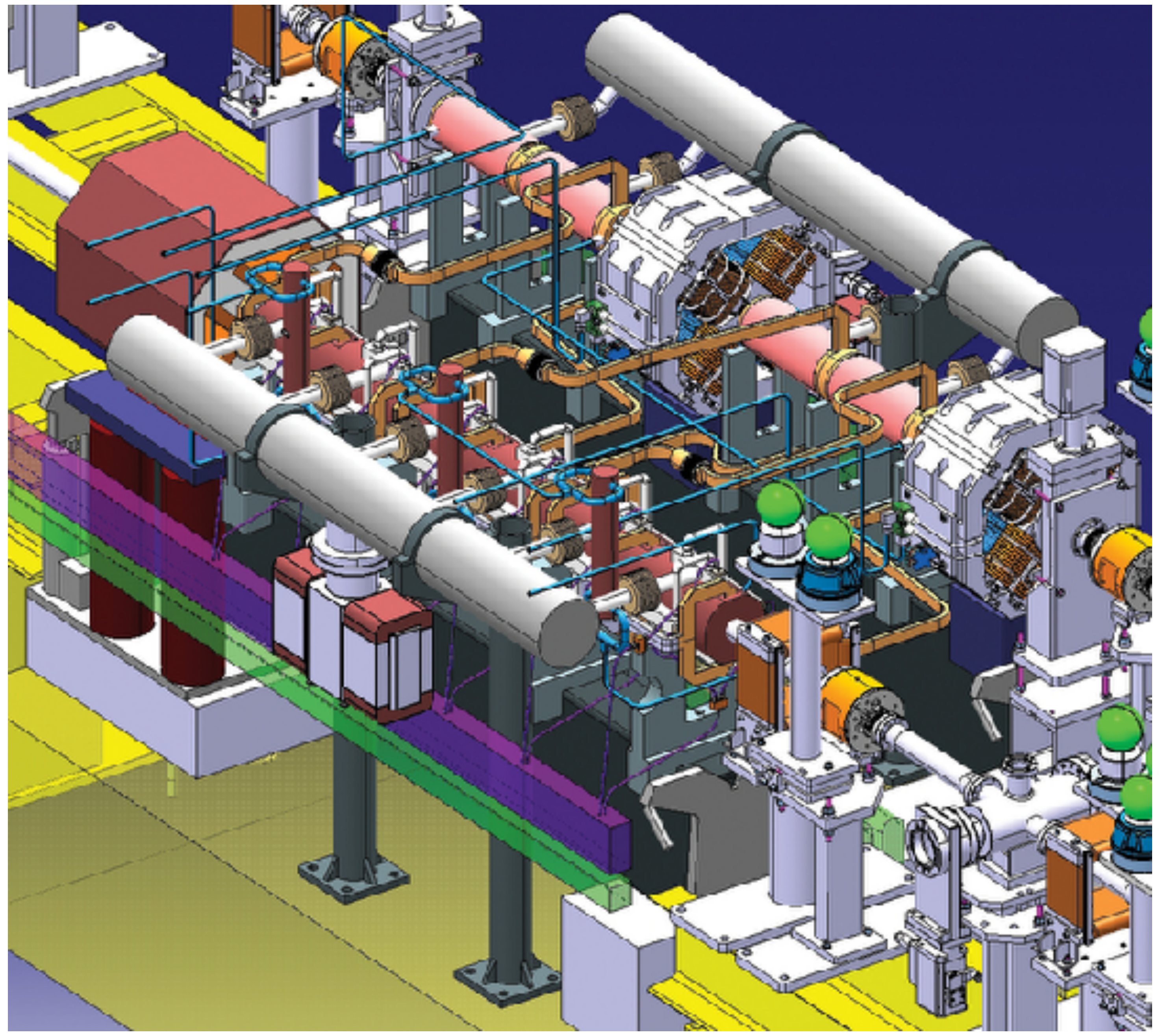


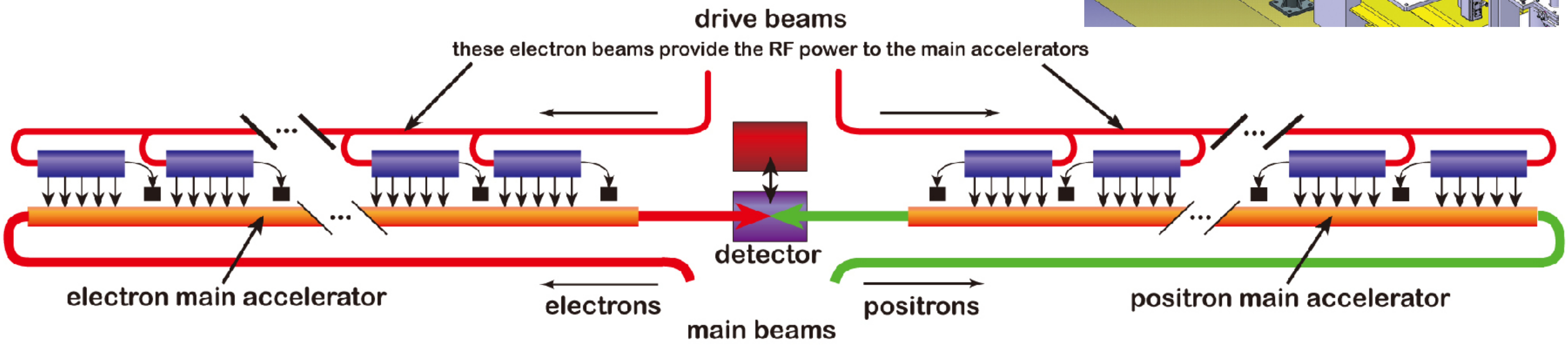
Two-Beam Acceleration Concept

Low energy high current beam produces RF for high-gradient accelerating cavities

Project technically not as advanced as ILC, i.e. is not yet „construction-ready“

- possible „next big thing“ at CERN?
- in competition with FCC/ HE-LHC!

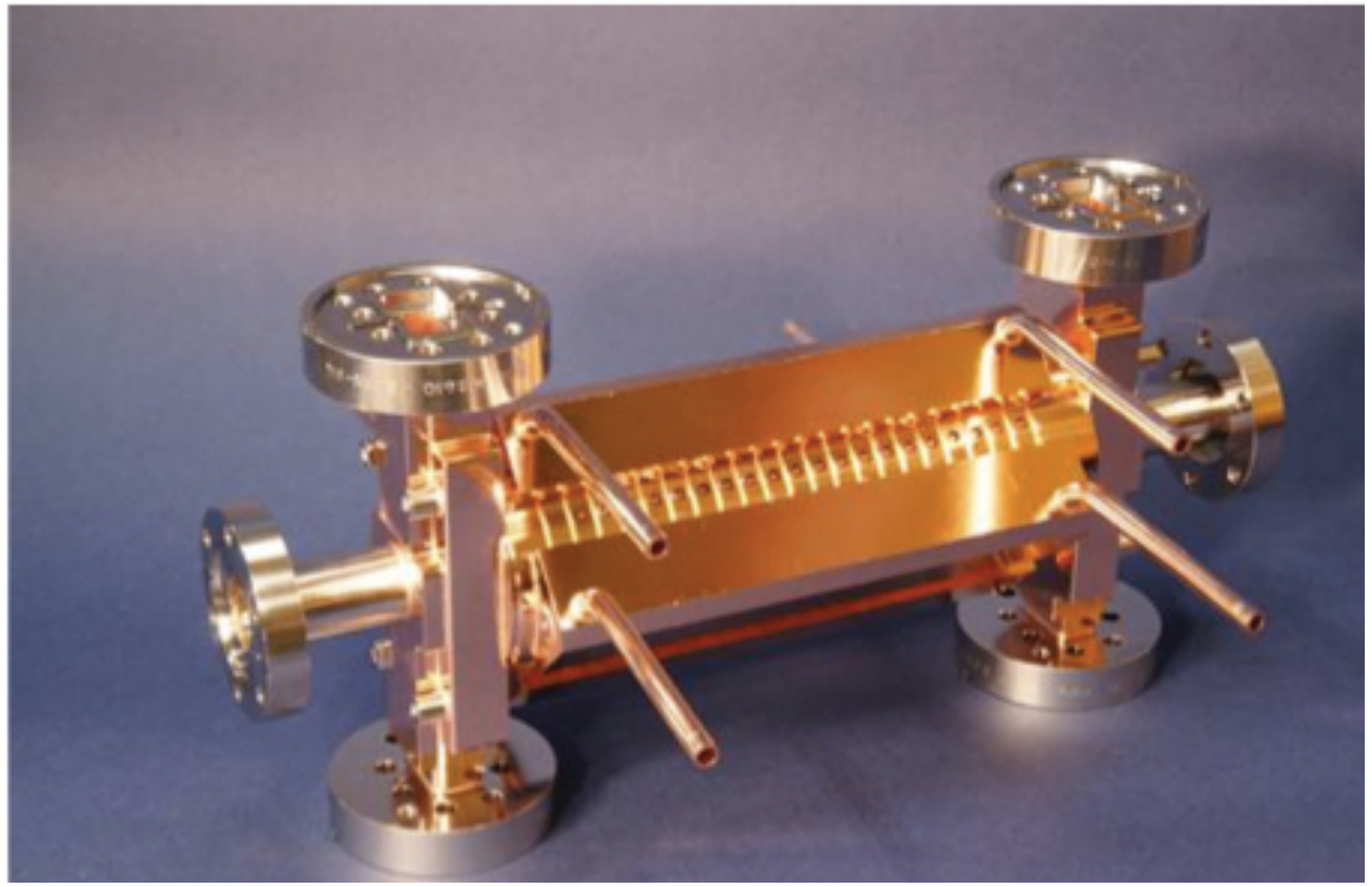


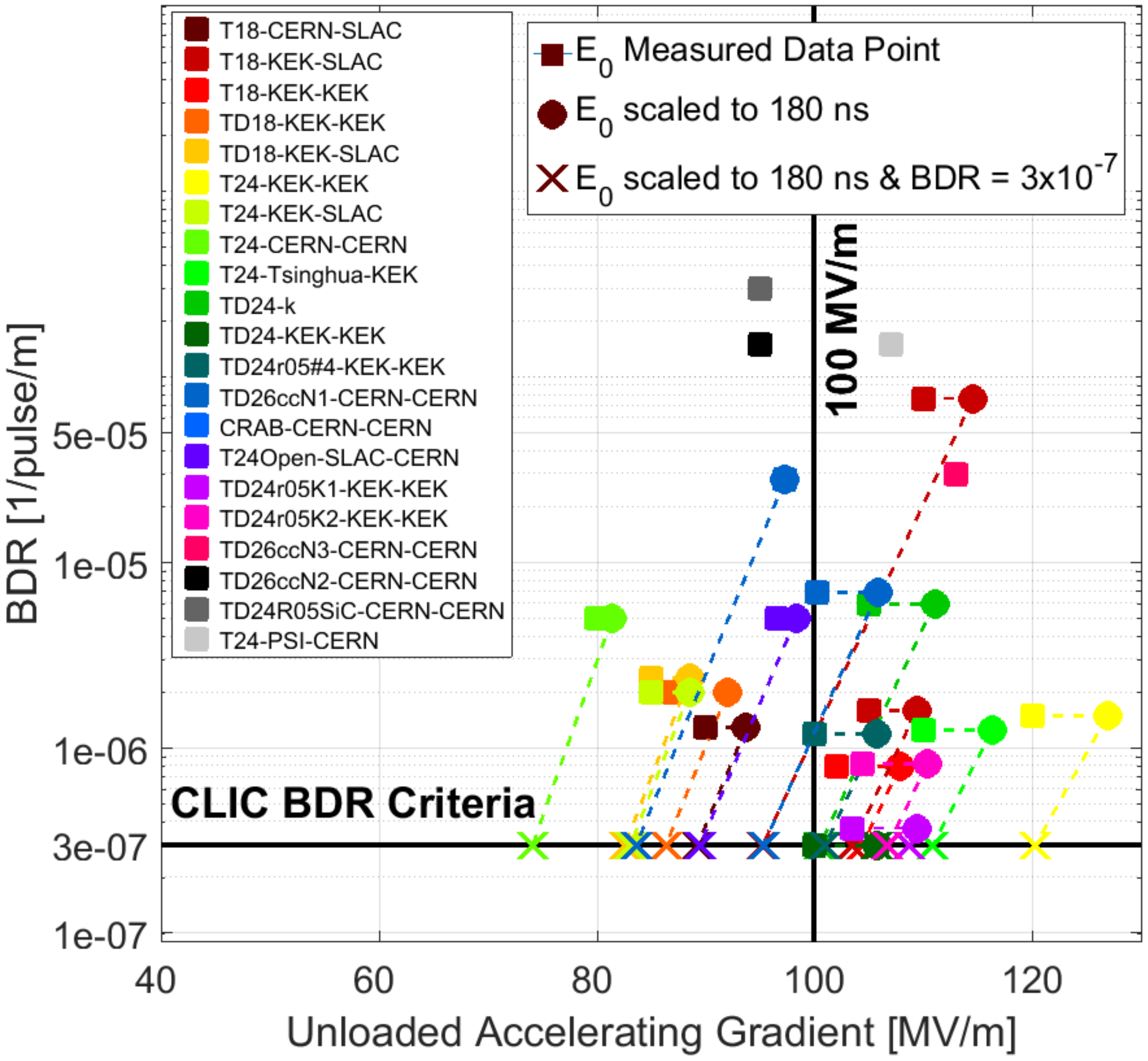


CLIC Cavities

Normal-conducting copper cavities, 12 GHz

- Higher gradients up to ~100 MV/m
- Need to keep breakdown rate by electrical discharges under control





W. Wünsch

CLIC Optimisation

Staging scenarios are under study:

- start with Higgs-Factory up to the tt threshold
- multi-TeV upgrade later

LINEAR COLLIDER COLLABORATION

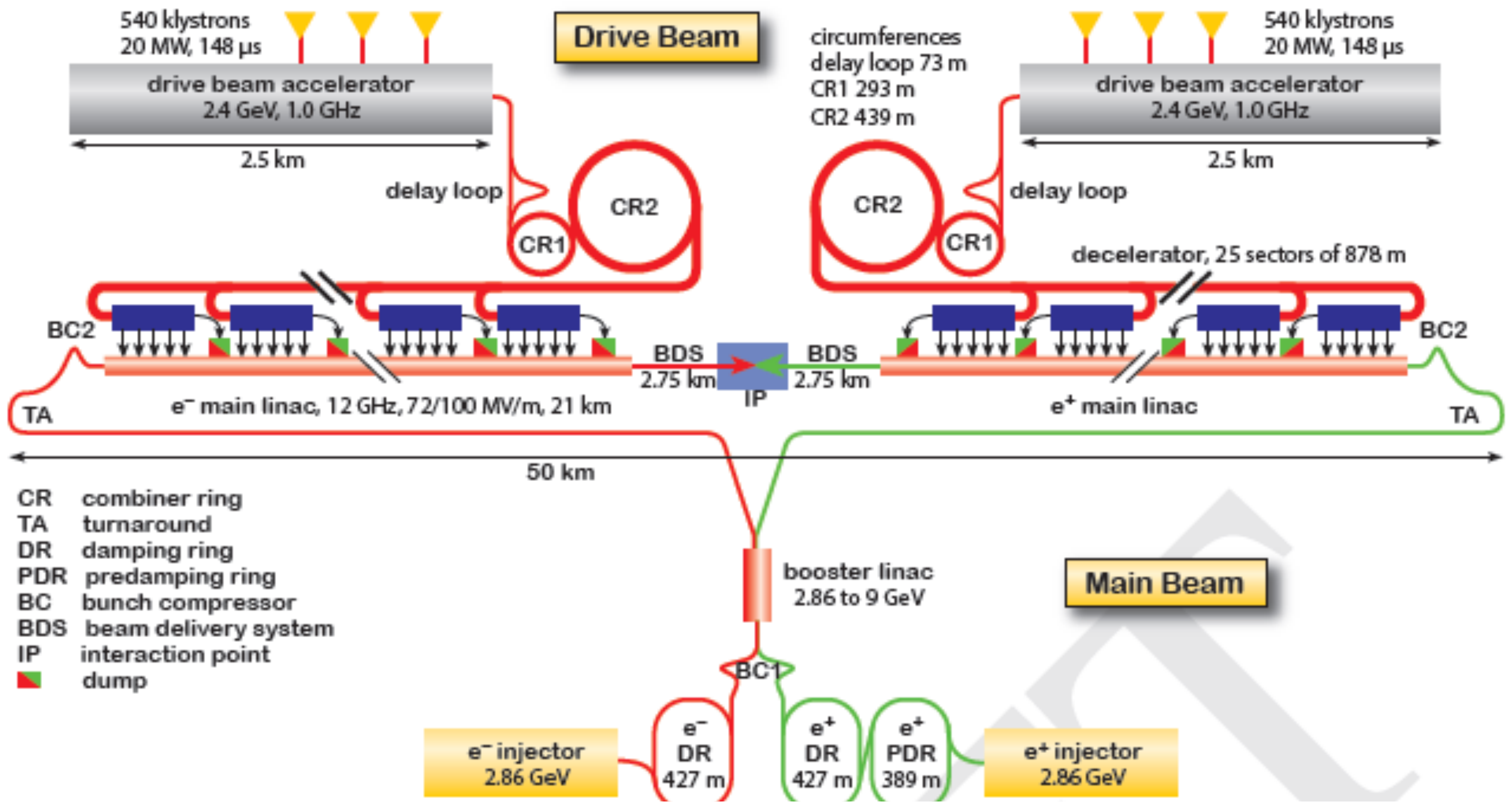
Rebaselining: first stage energy ~ 380 GeV

Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	10^{34}cm^{-2}s^{-1}	1.5	5.9
Luminosity above 99% of √s	10^{34}cm^{-2}s^{-1}	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

22

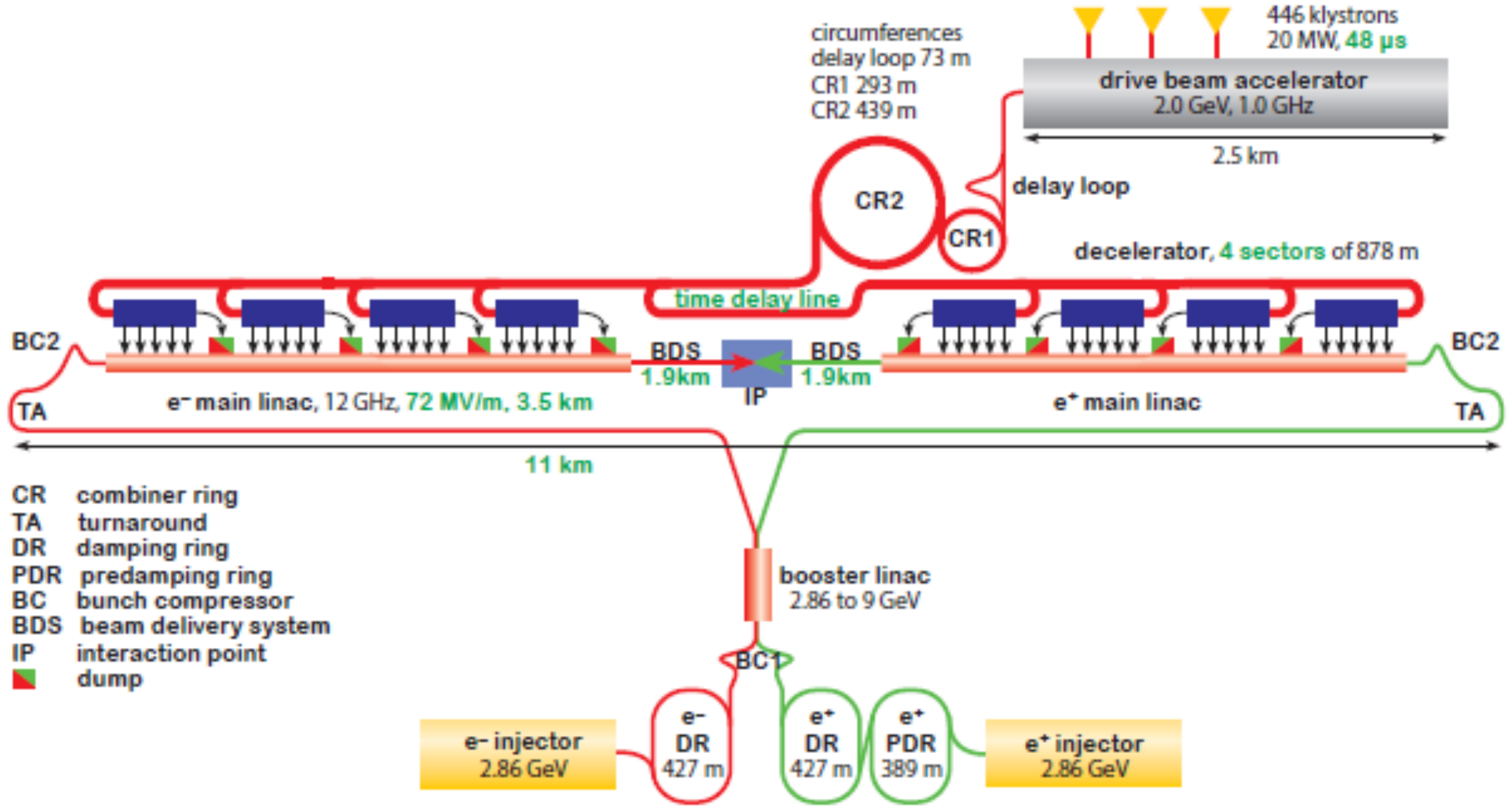
LINEAR COLLIDER COLLABORATION

New CLIC layout 3 TeV



LINEAR COLLIDER COLLABORATION

New CLIC layout 380 GeV

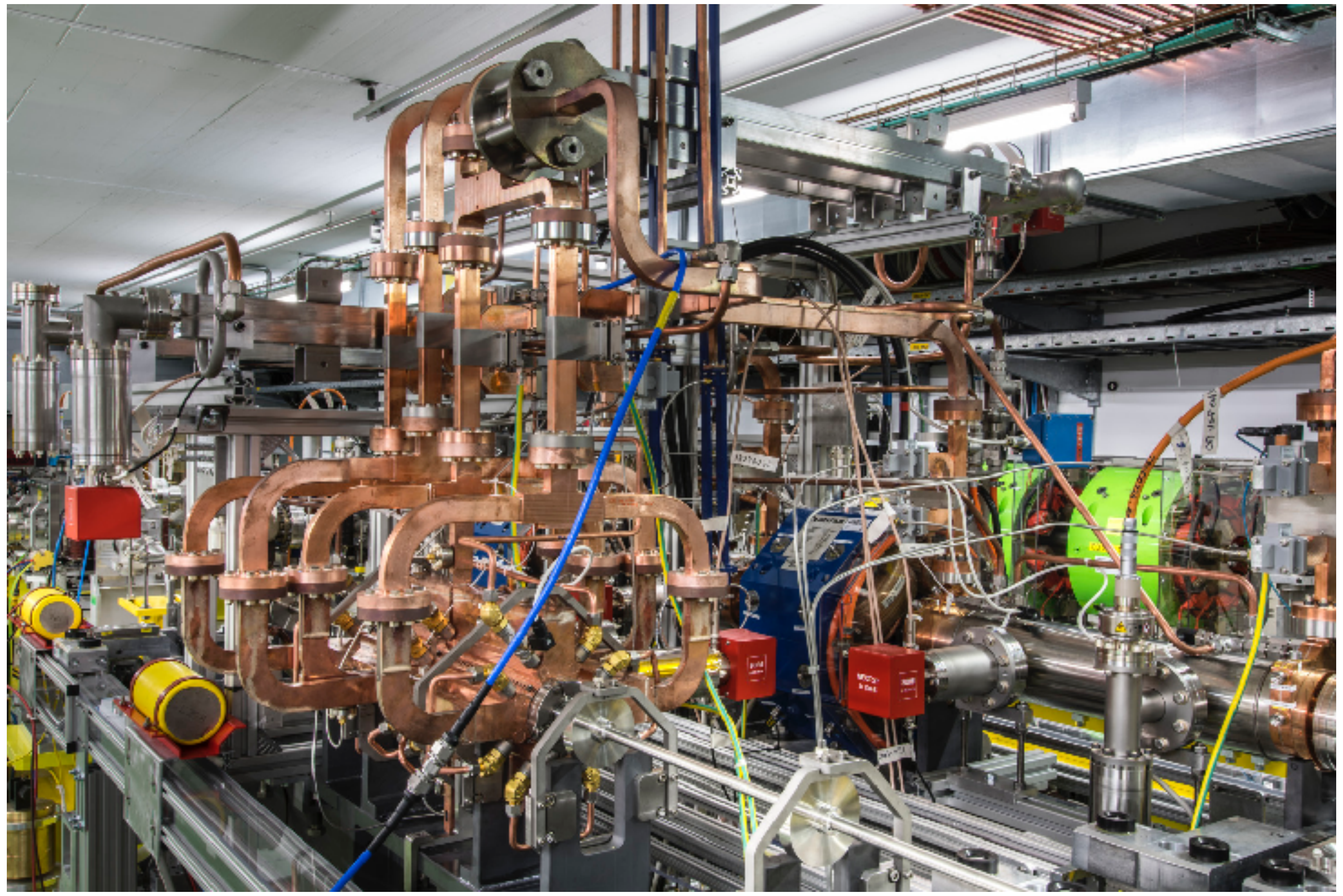


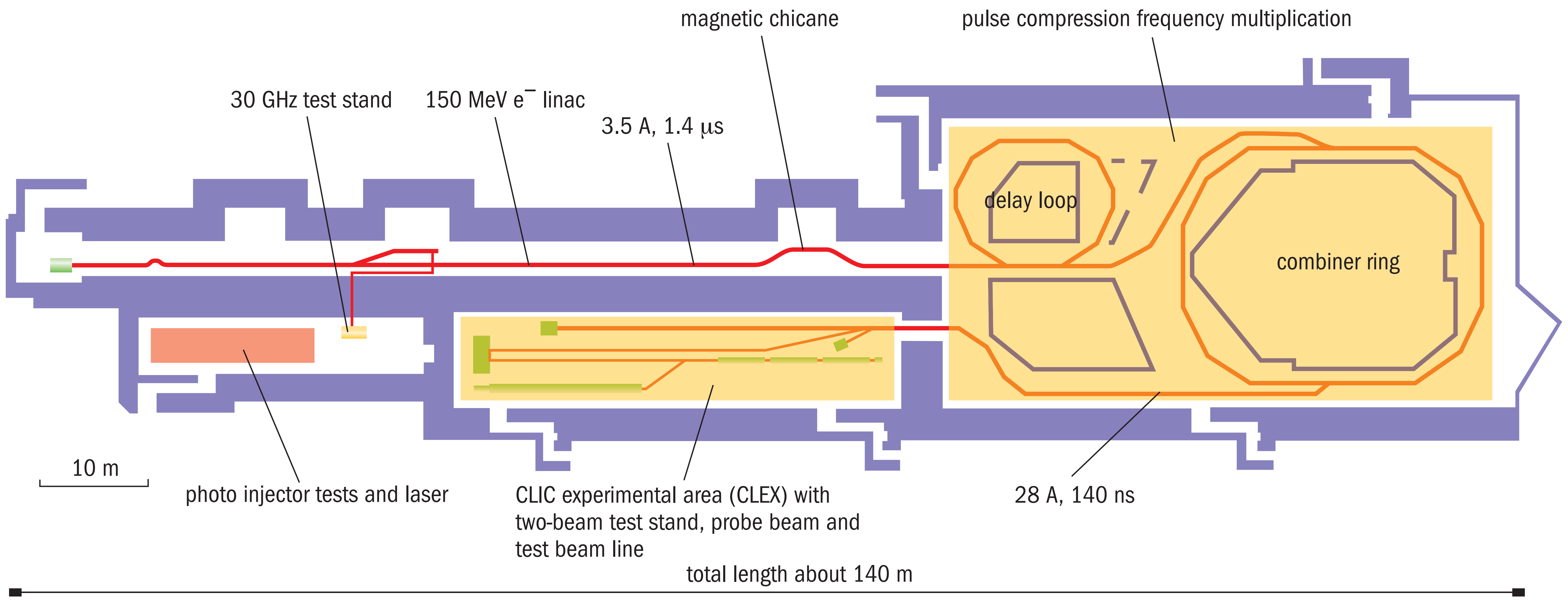
P. Burrows

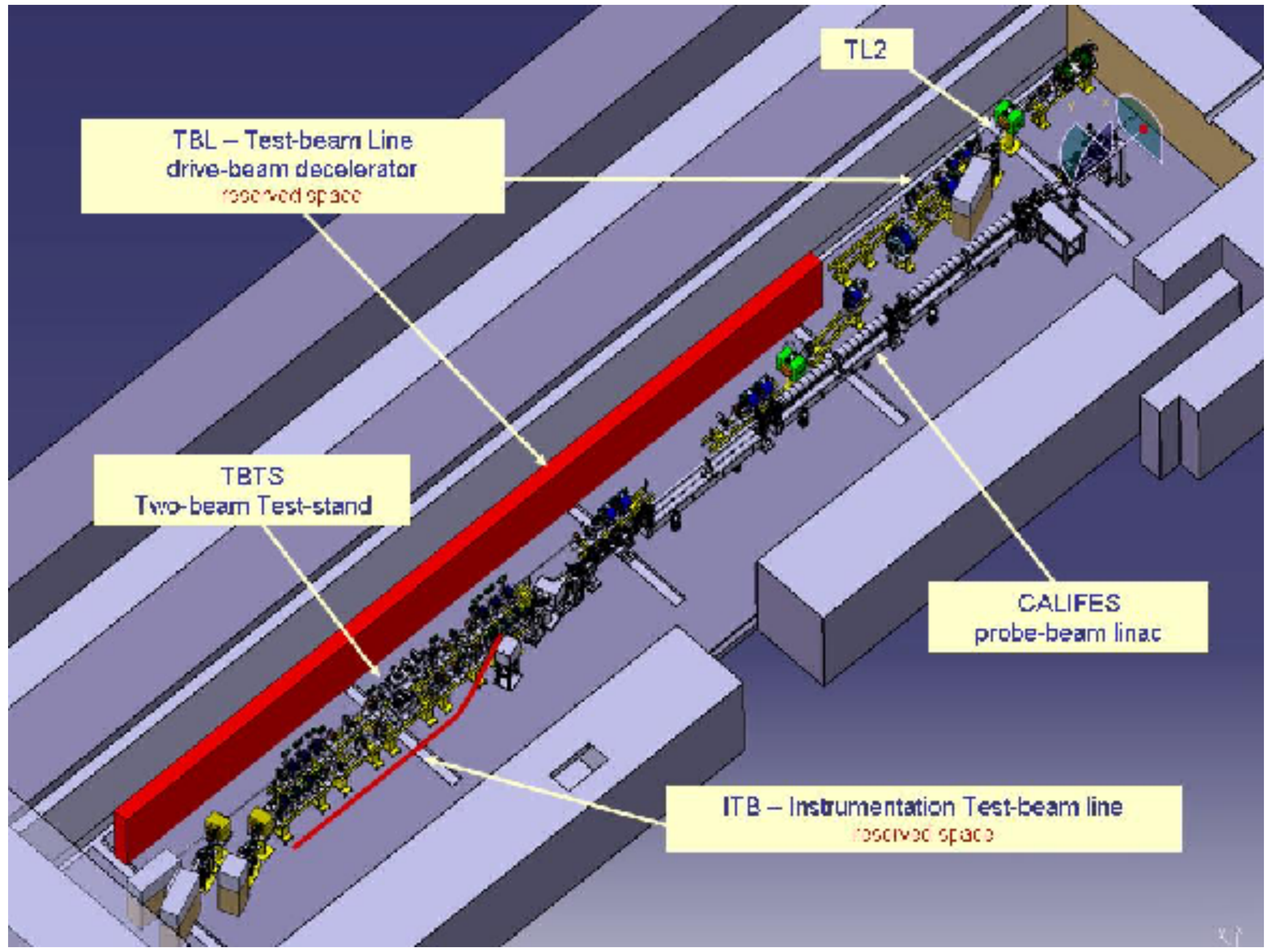
CLIC Test Facility at CERN

CTF-3

- Mostly to test the drive beam arrangements with delay and combiner loops
- Also first two-beam acceleration test stand







The Staged Linear Collider

In principle, the ILC can run on any energy between ~90 GeV and several TeV

- Linear colliders are scalable, it is mostly a question of cost....

Rationale of a staged approach

- Start where interesting physics is guaranteed, extend to higher energies later

ILC$_{250}$: Higgs measurements (mass, spin, couplings), EW physics, (...)

ILC$_{350}$: Top physics, (...)

ILC$_{500}$: Higgs self coupling, Top-Higgs Yukawa coupling, (...)

ILC$_{1000+}$: SUSY, whatever comes, (...)

CLIC, Plasma Wakefield Accelerator as multi-TeV option

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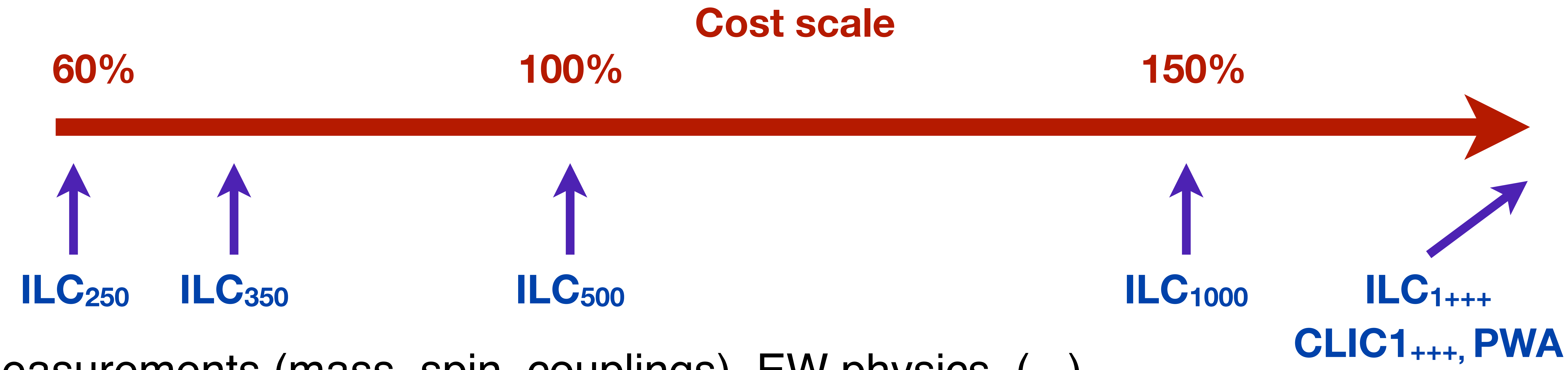

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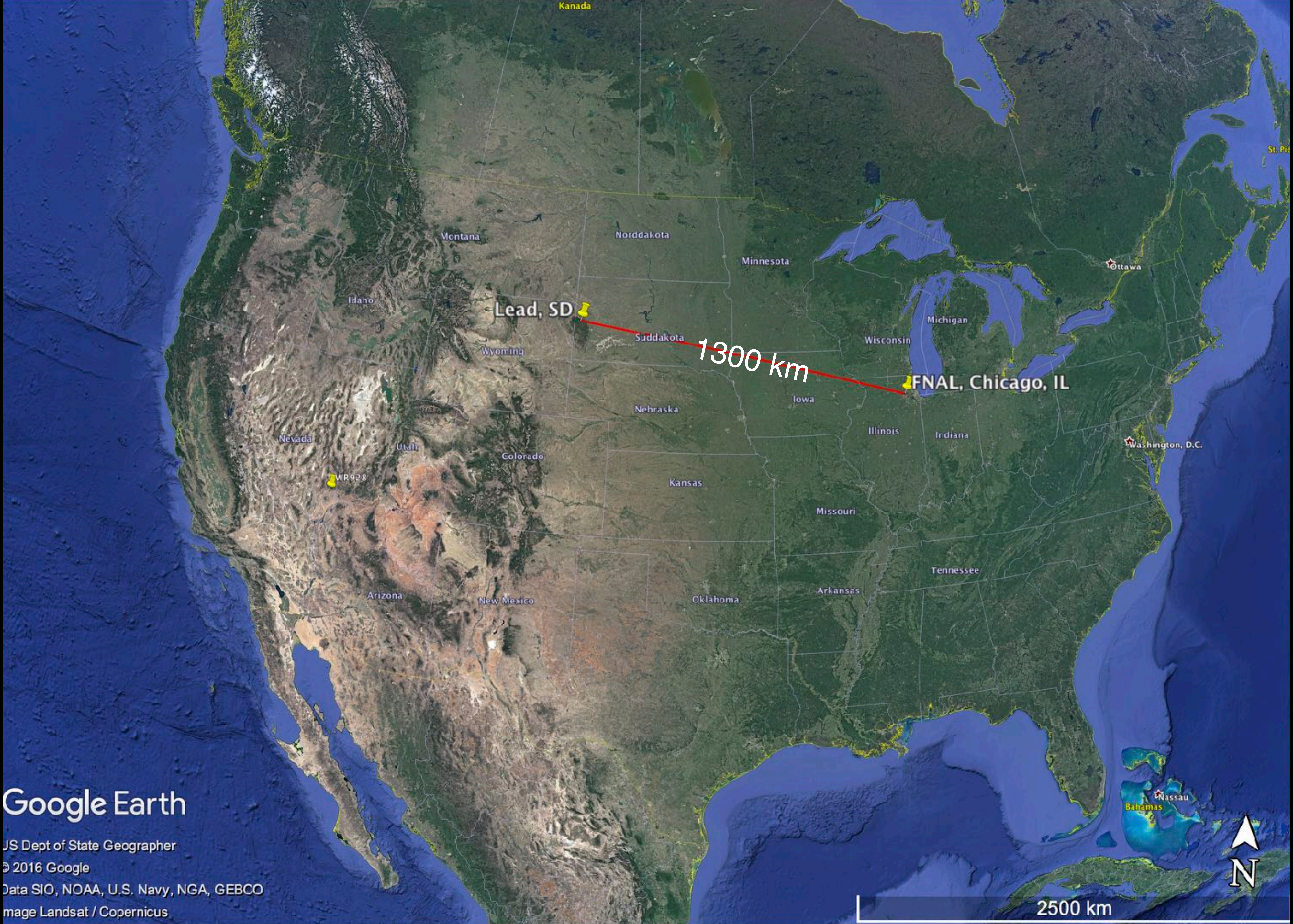
The Real Axis - the Real Frontier…

Neutrinos: LBNF / DUNE

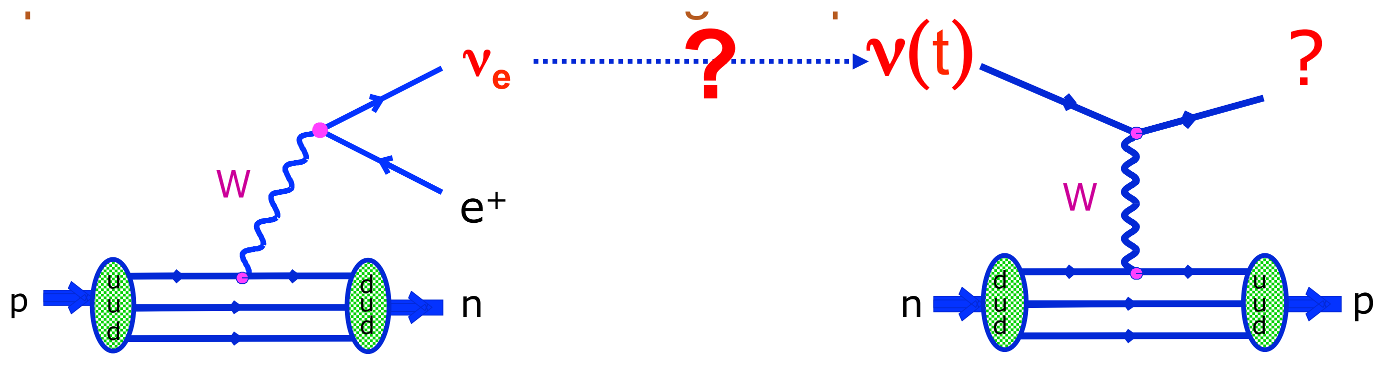
Long-Baseline Neutrino Facility



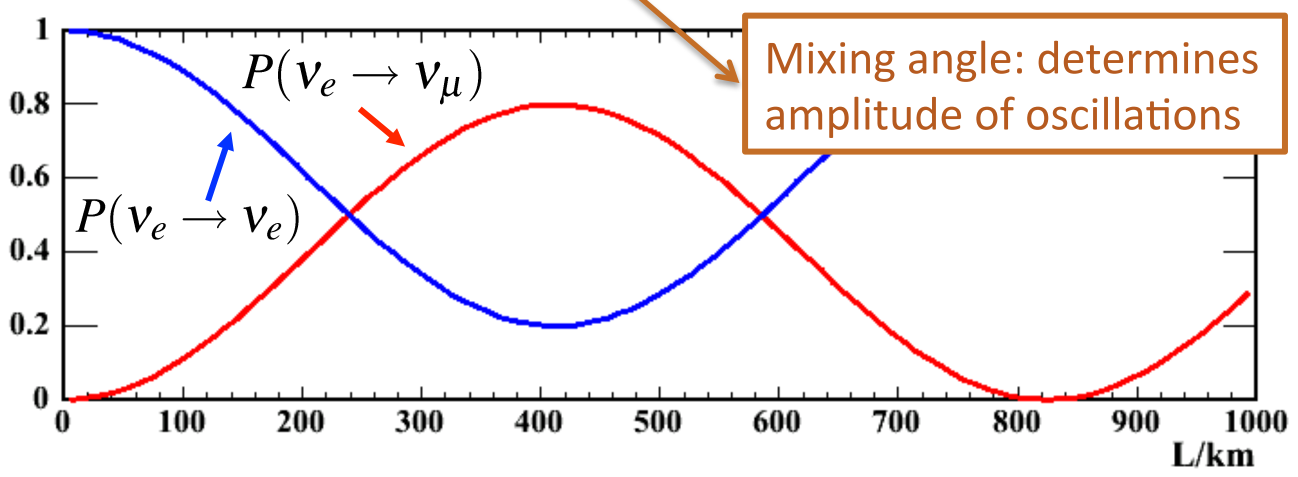
Kanada
Montana
Norddakota
Minnesota
Idaho
Lead, SD
Suddakota
1300 km
Wyoming
Wisconsin
Michigan
FNAL, Chicago, IL
Ottawa
Iowa
Nebraska
Illinois
Indiana
Nevada
Utah
Colorado
Washington, D.C.
WR928
Kansas
Missouri
Tennessee
Arkansas
Arizona
New Mexico
Oklahoma
Nassau
Bahamas
Google Earth
US Dept of State Geographer
© 2016 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
N
2500 km

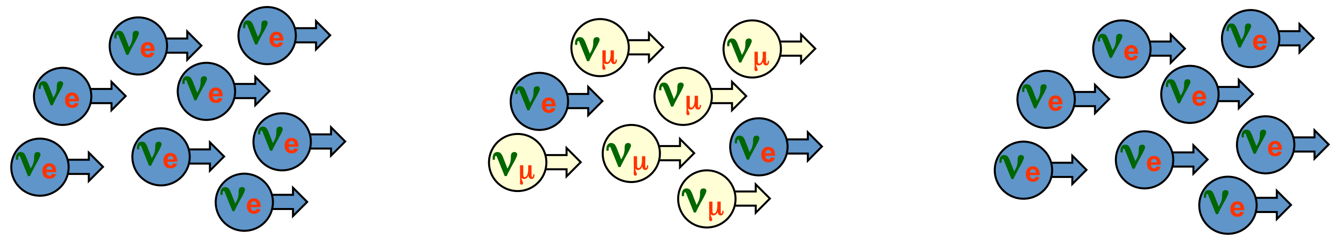
CP Violation in Neutrino Sector?

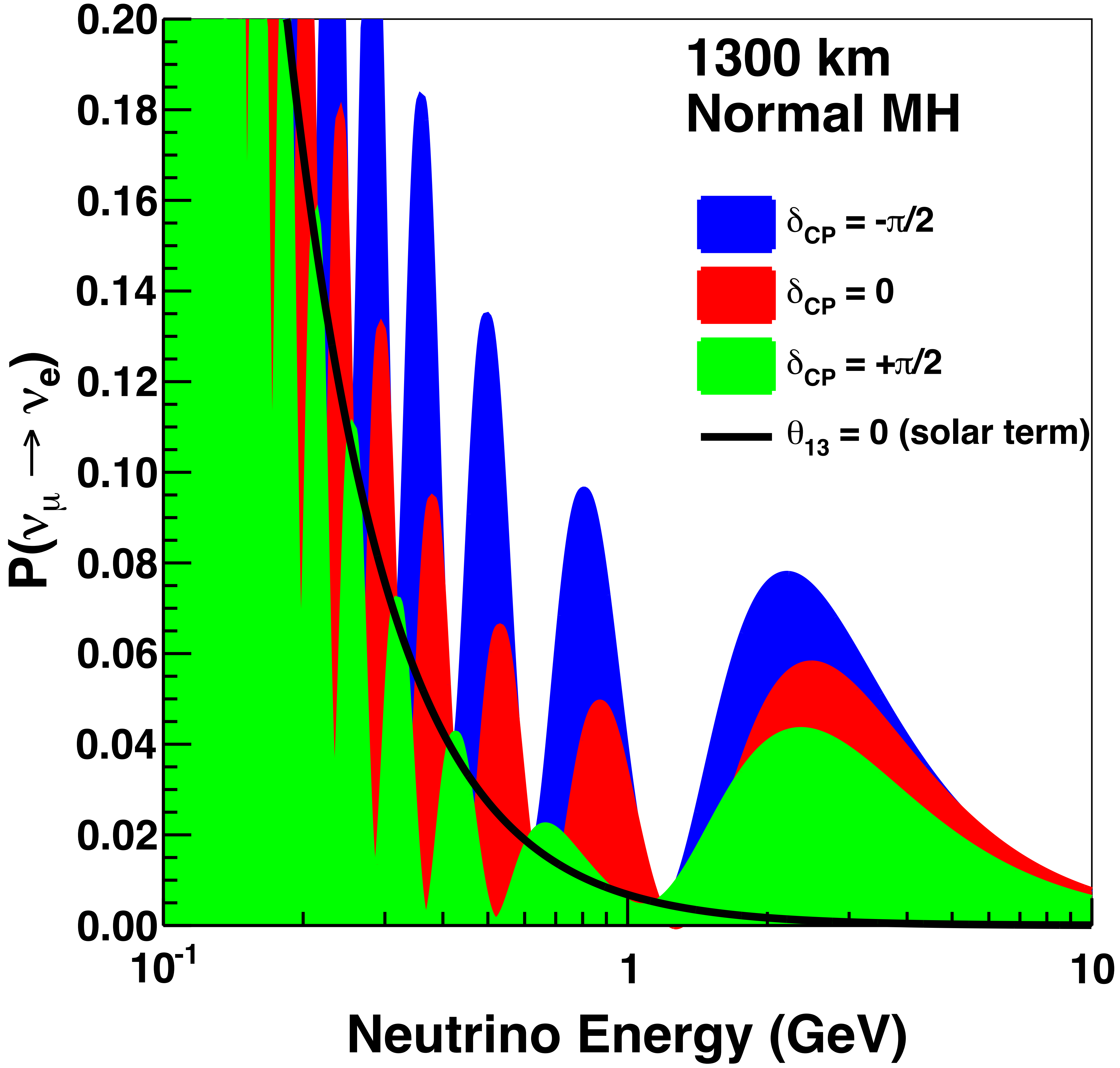
- Smallness of neutrino masses may point to physics at GUT scale
- Neutrino oscillation probe mass and mixing matrix
- 2012: θ_{13} large: CP violation measurable



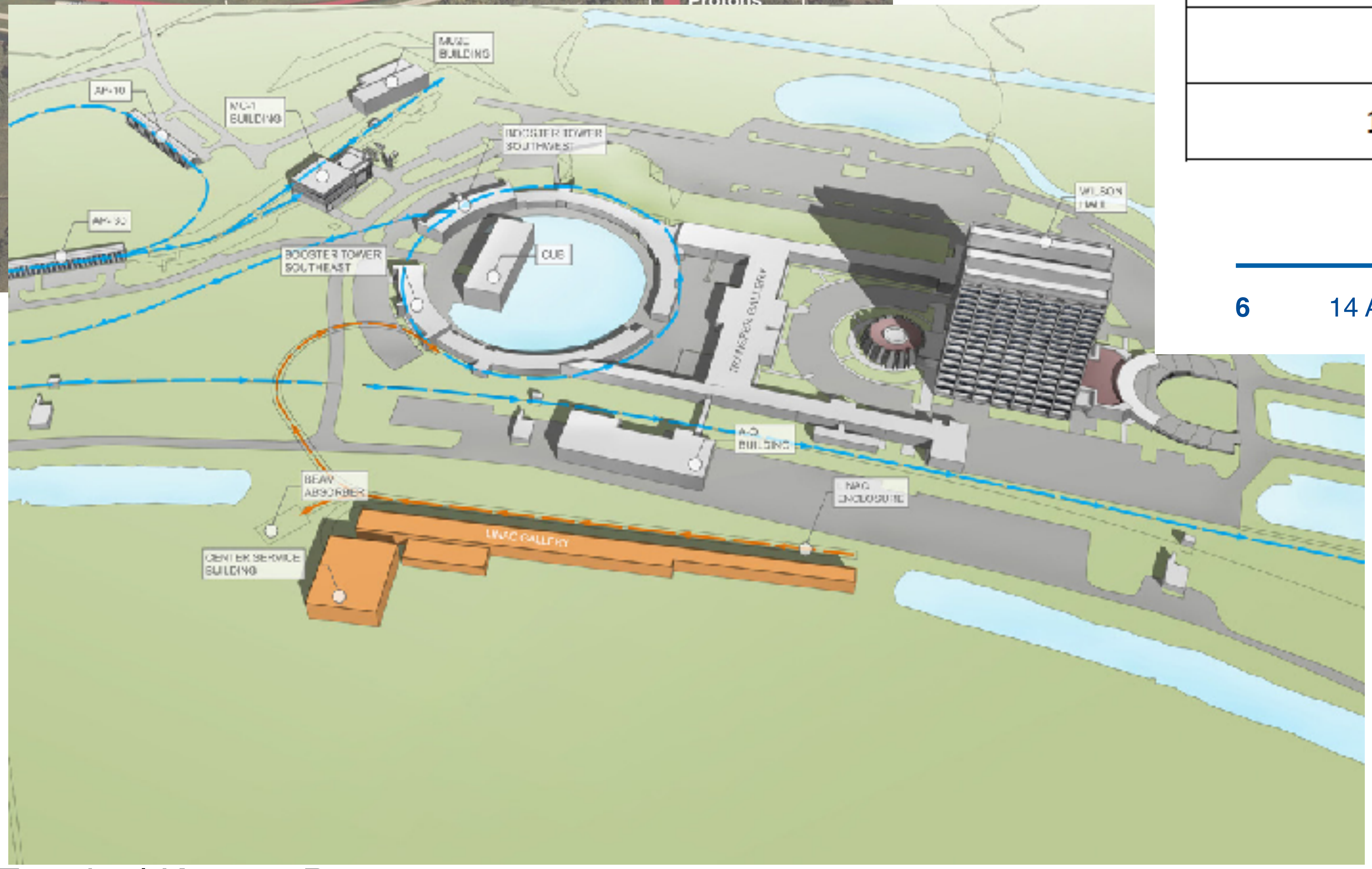
$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$







The Accelerator Challenge



LBNF Beam Operating Parameters:

Main Injector Complex with PIP-II and PIP-III upgrades

Summary of key Beamline design parameters for ≤1.2 MW and ≤2.4 MW operation

Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase			
Proton Beam Energy (GeV):			
60	1.5E+14	0.7	2.06
80	1.5E+14	0.9	2.14
120	1.5E+14	1.2	2.40

PIP-II

$(1.1 – 1.9)\times10^{21}$ POT/yr

PIP-III

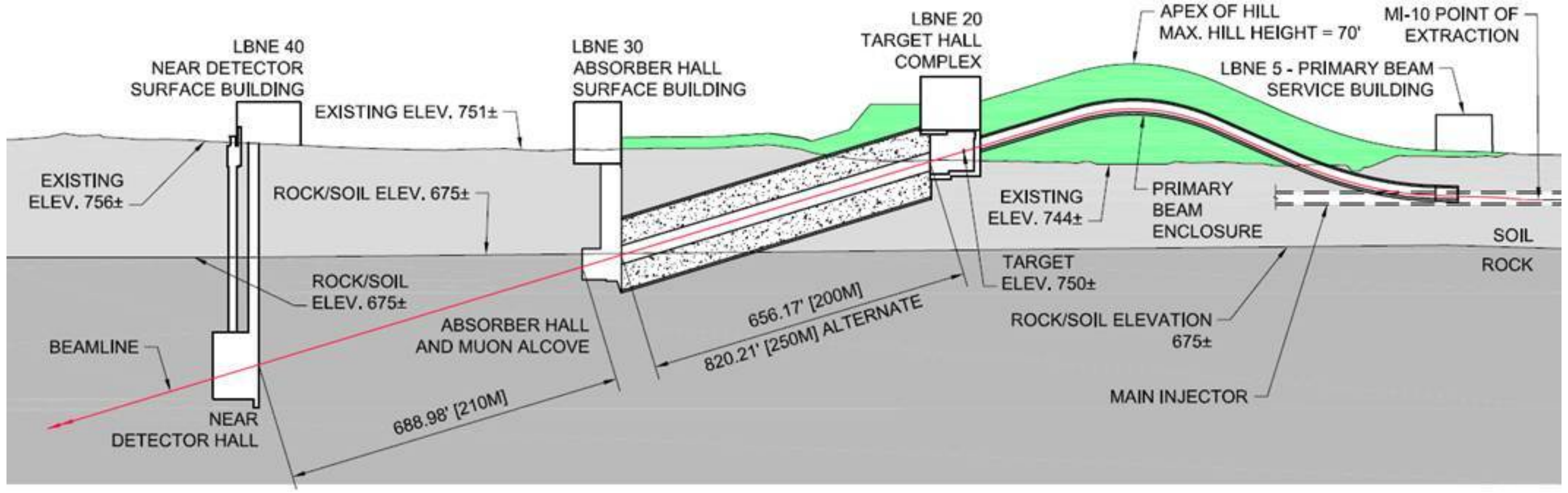
Pulse duration: 10 μs
Beam size at target: tunable 1.0-4.0 mm

6 14 Aug 2015 Jim Strait I LBNF Neutrino Beam LBNF

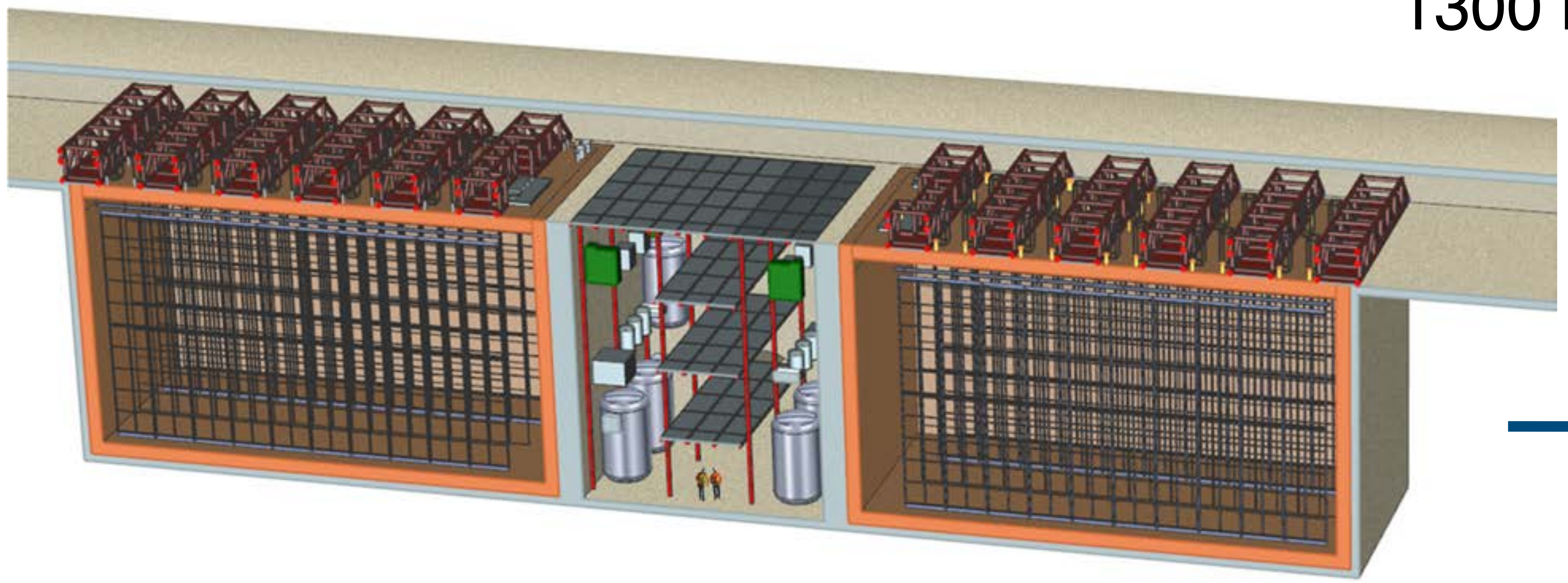
J. Strait

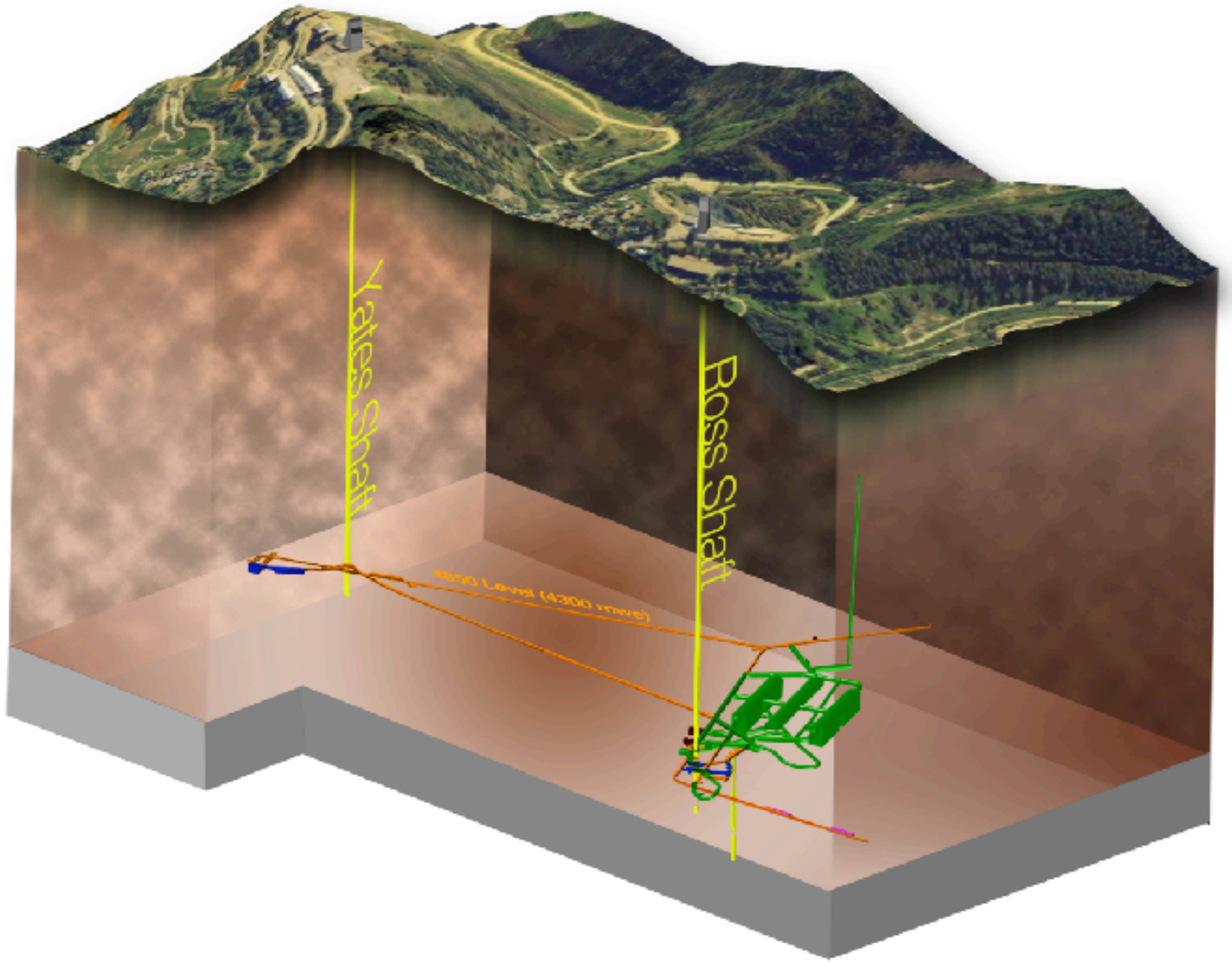
LBNF/DUNE

DUNE: LAr detector in Homestake Mine

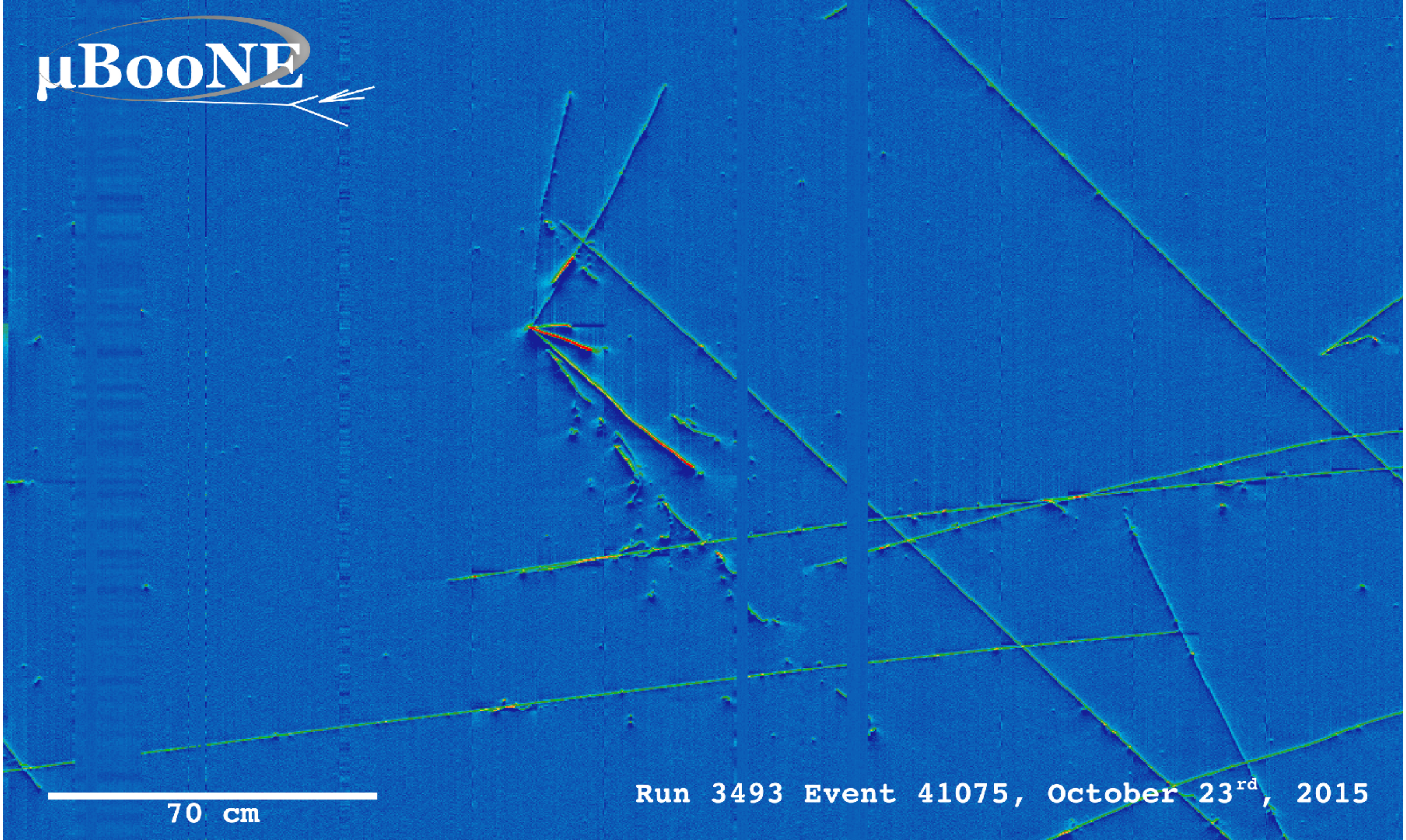


1300 km



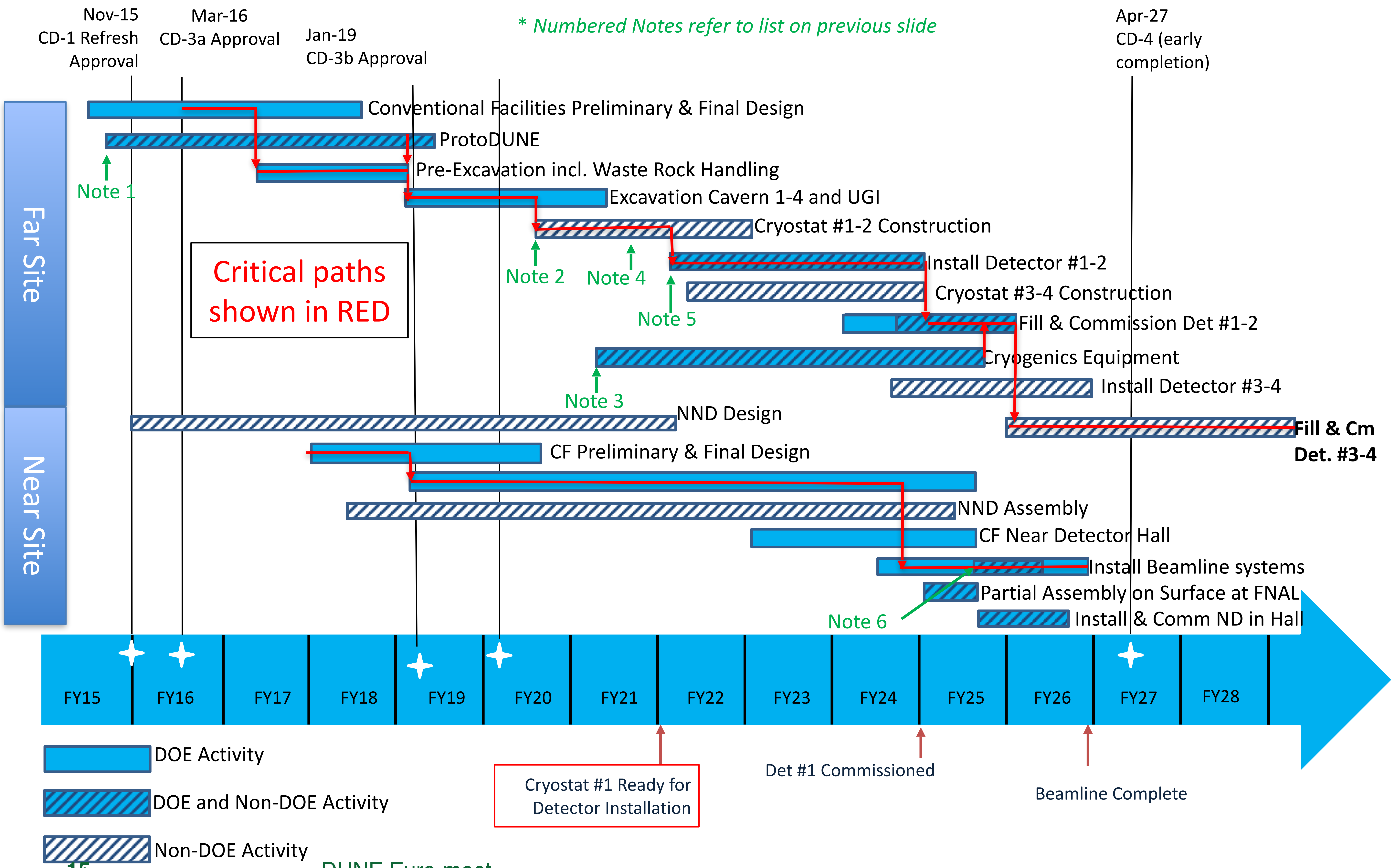


Homestake-Mine



μBooNE
70 cm
Run 3493 Event 41075, October 23rd, 2015

LBNF/DUNE – Construction Summary Schedule Overview



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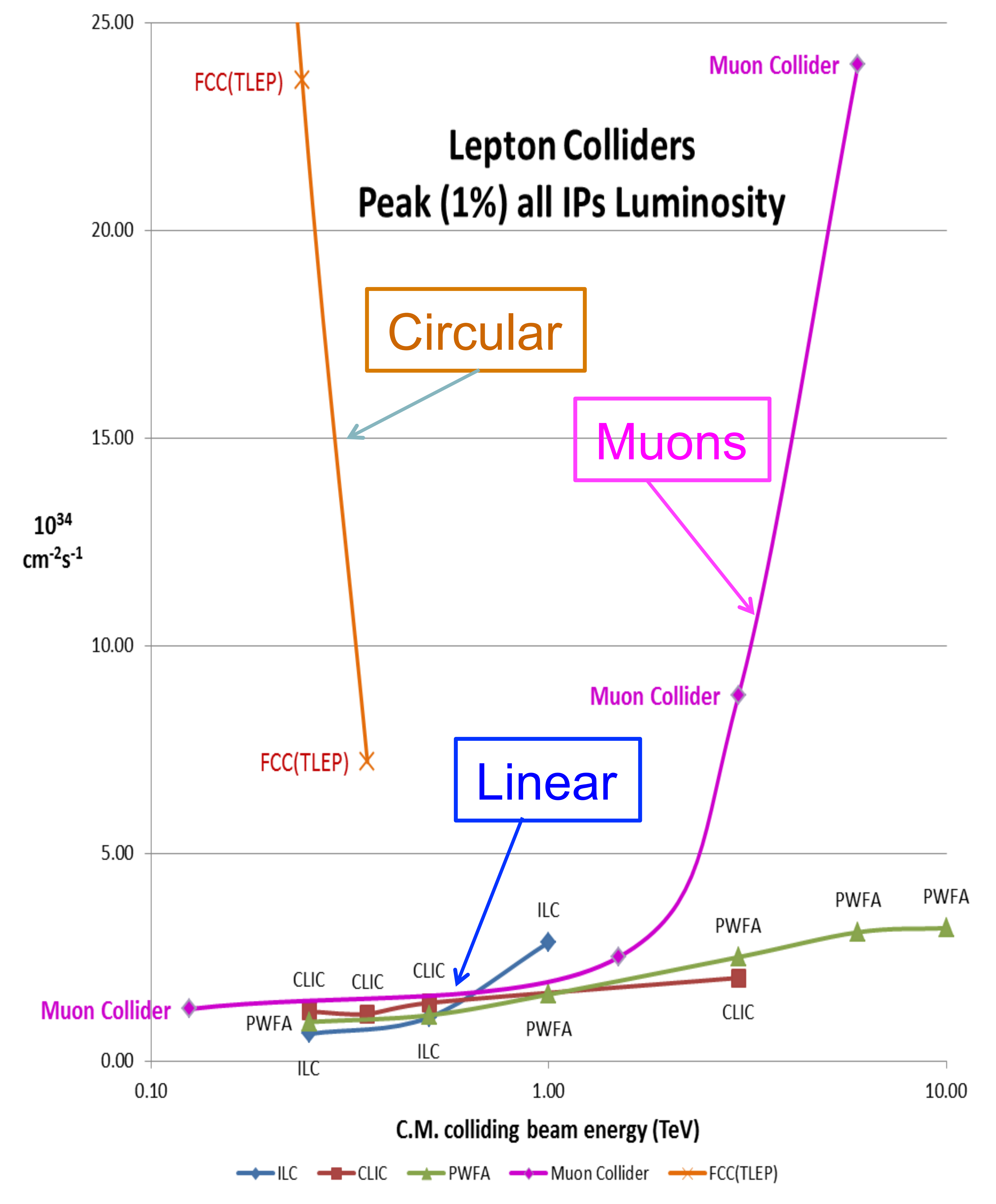
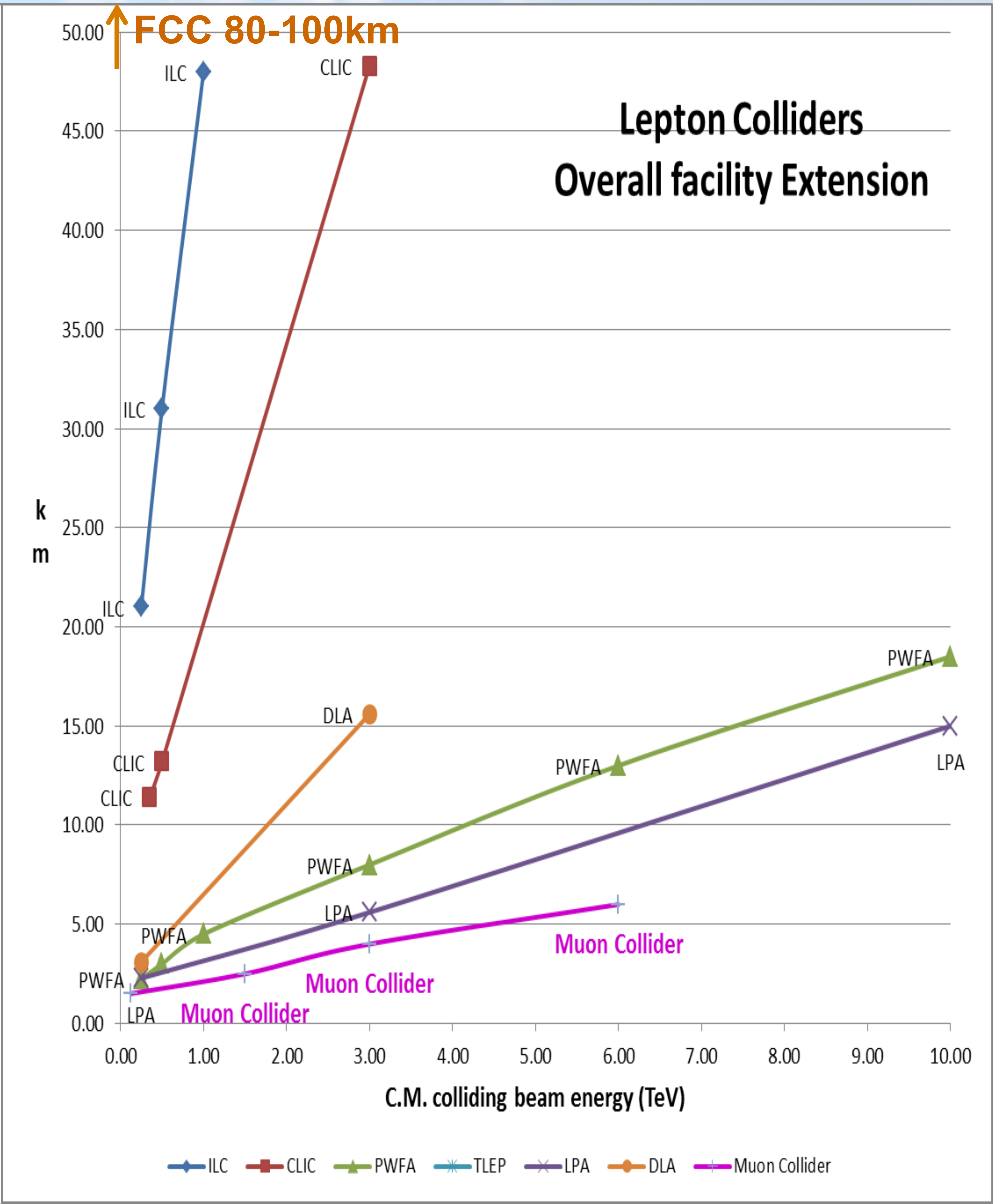
The Real Axis - the Real Frontier…

Muon Collider

Muon Colliders extending high energy frontier [with potential of considerable cost savings]





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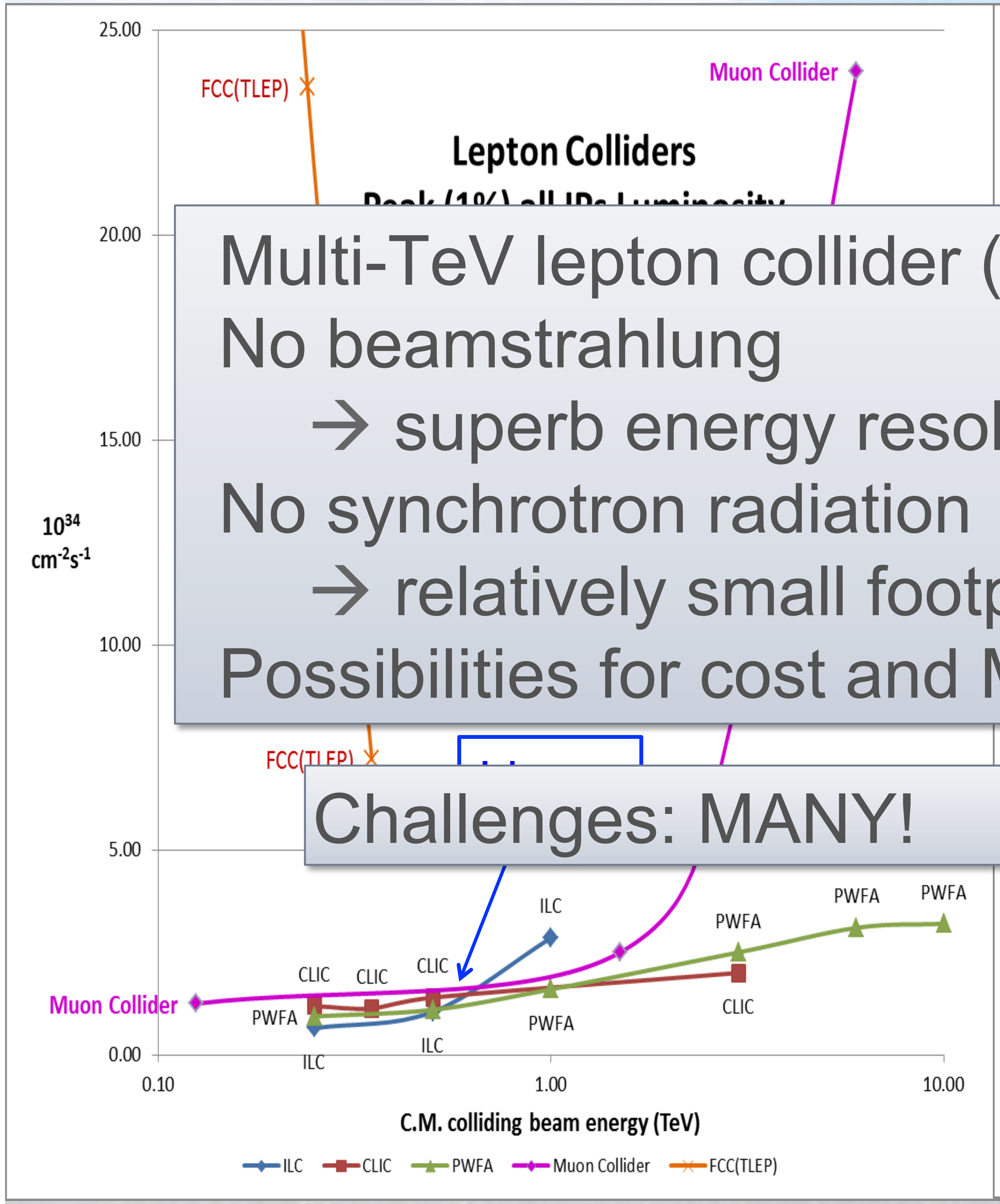
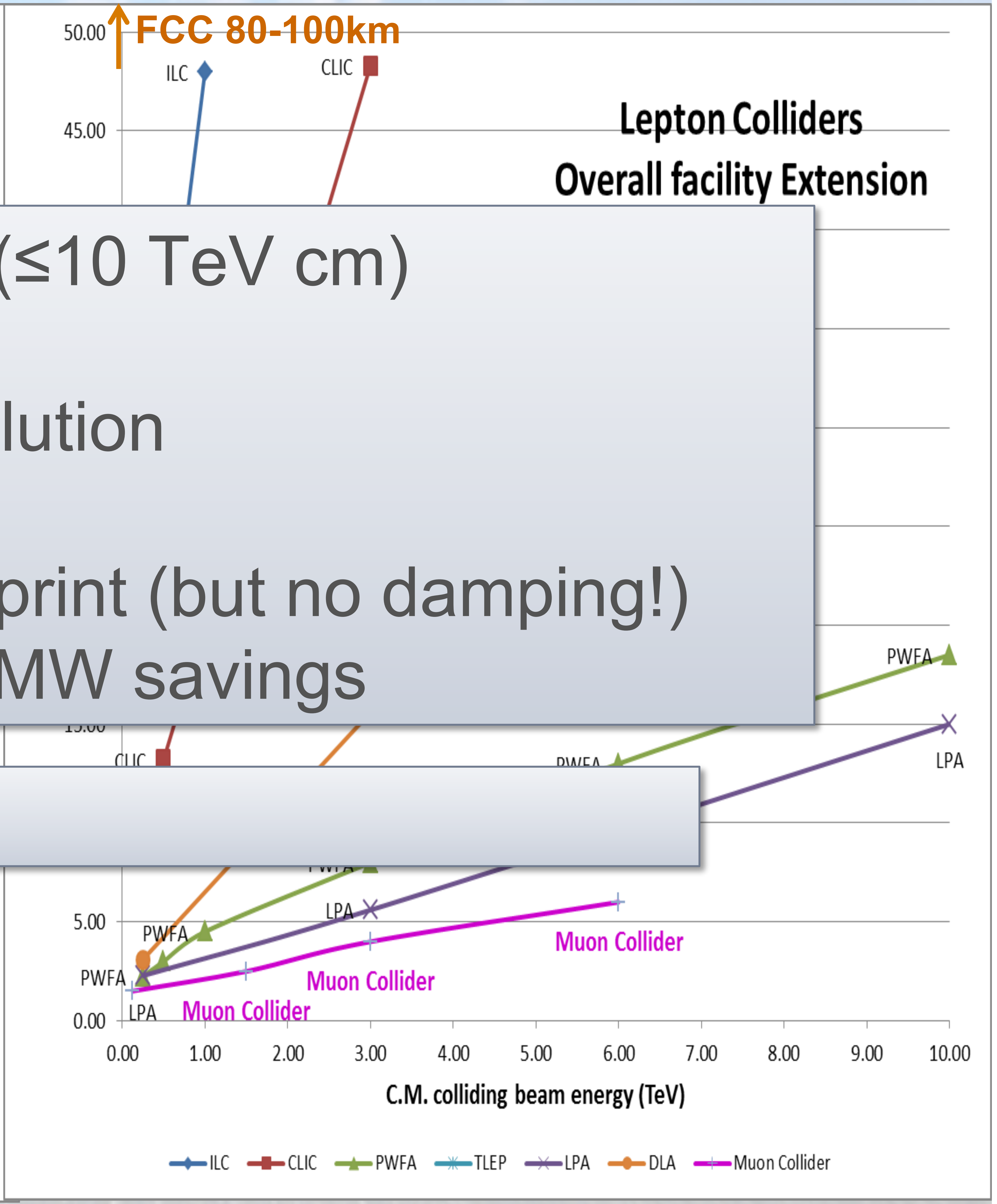




Multi-TeV lepton collider (≤10 TeV cm)

No beamstrahlung

→ superb energy resolution

No synchrotron radiation

→ relatively small footprint (but no damping!)

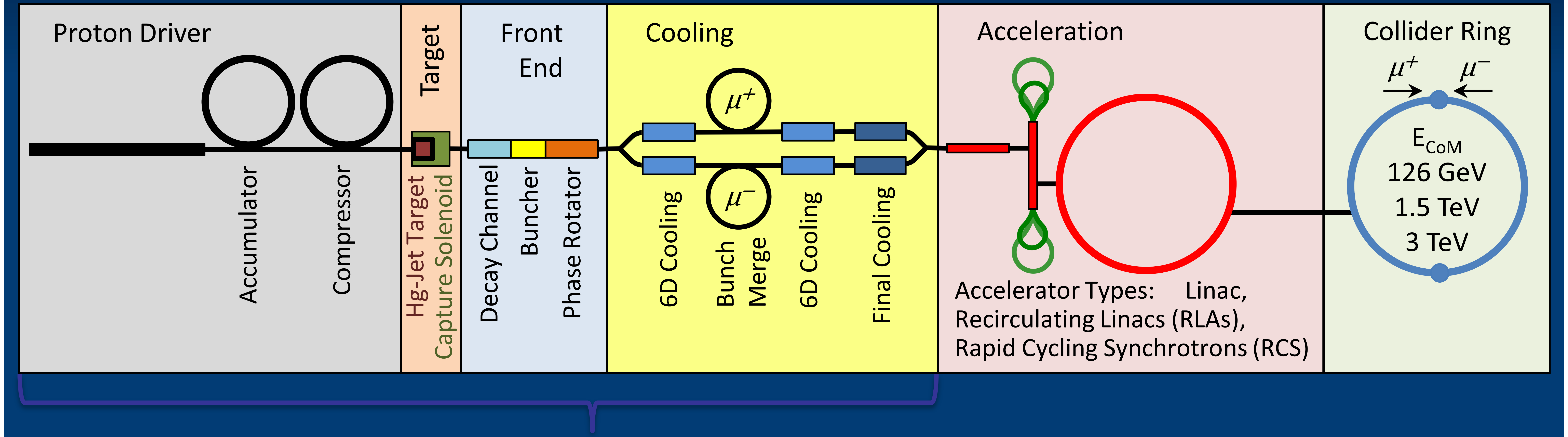
Possibilities for cost and MW savings

Challenges: MANY!

Courtesy J.P.Delahaye, IPAC14

Muon Collider Concept

Muon Collider Block Diagram

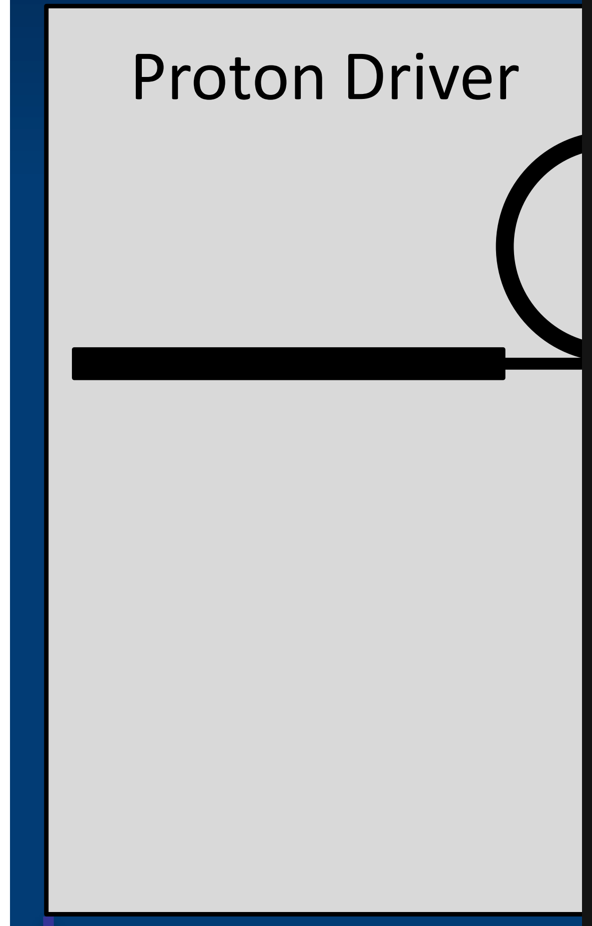


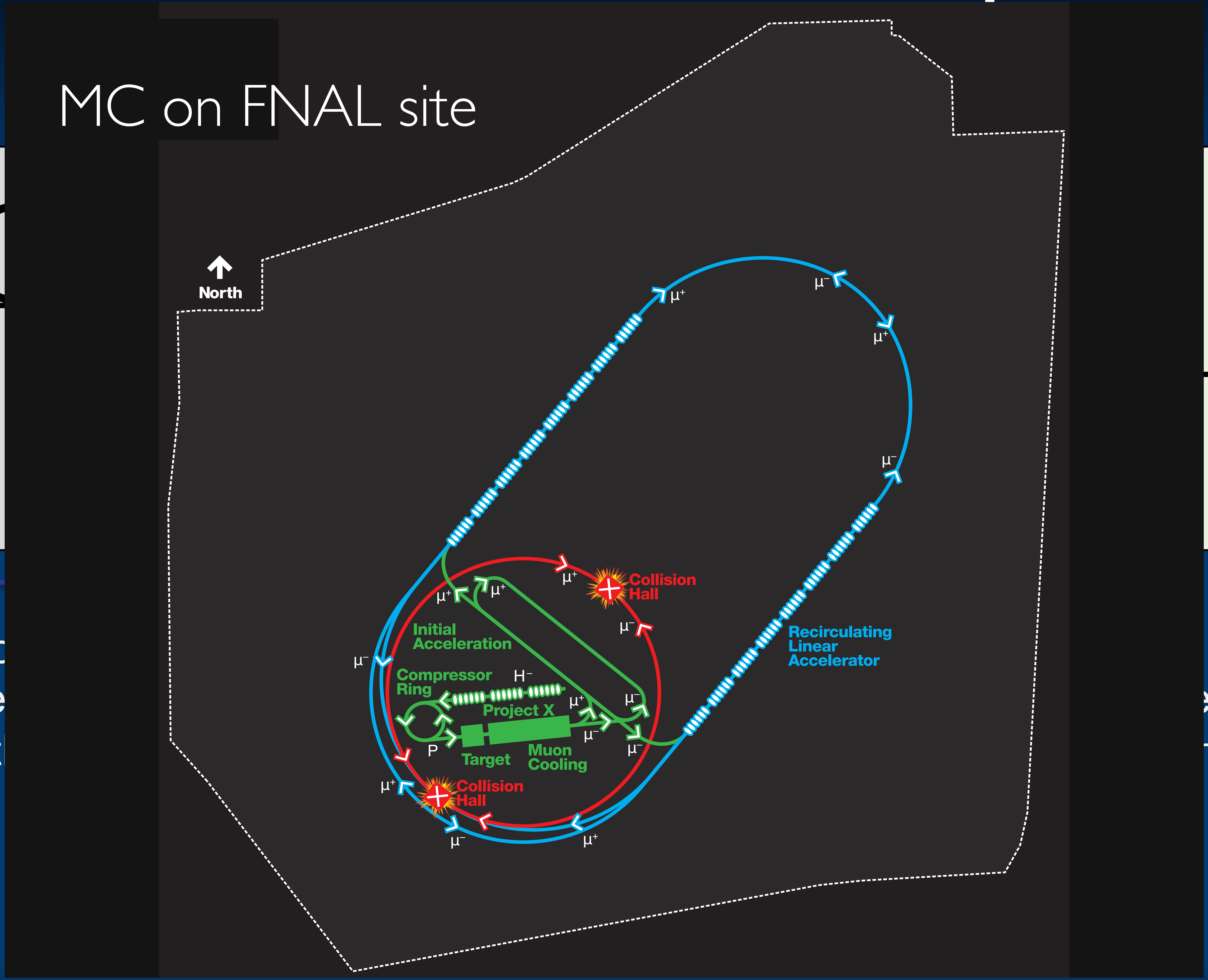
Proton source:
For example PROJECT X at 4 MW, with 2±1 ns long bunches

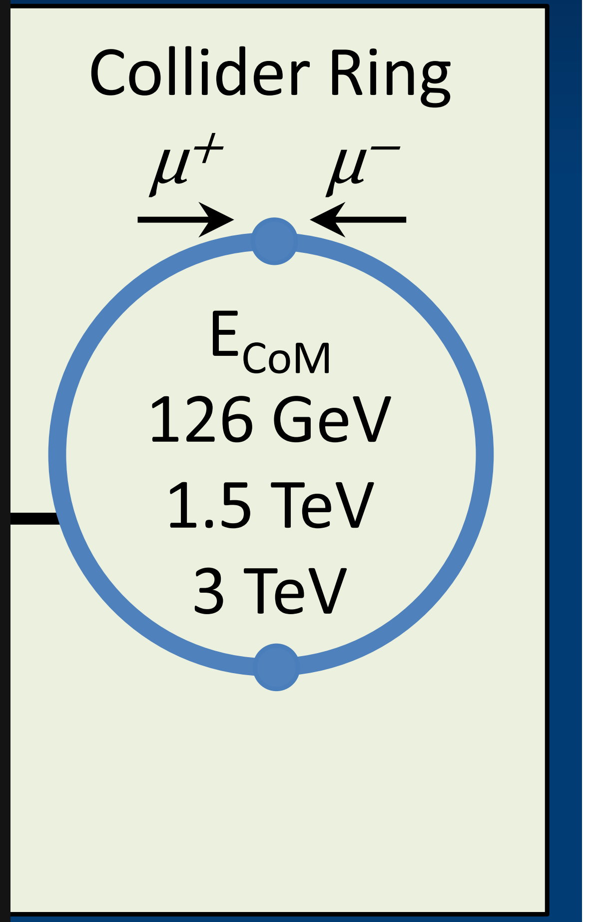
Goal:
Produce a high intensity m beam whose 6D phase space is reduced by a factor of ~10^6-10^7 from its value at the production target

Collider: √s = 3 TeV
Circumference 4.5km
$L = 3\times10^{34}$ cm^{-2}s^{-1}
m/bunch = $2\text{x}10^{12}$
s(p)/p = 0.1%
$e_{\perp N}$ = 25 mm, $e_{//N}$=72 mm
*b** = 5mm
Rep. Rate = 12 Hz

Muon Collider Concept







Proton sourc
For example
at 4 MW, wit
bunches

3 TeV
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The Real Axis - the Real Frontier…

Plasma Wakefield Collider

Next Lecture by Jens Osterhoff!

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Take Home Message

Pushing the Envelopes

Physics rules:

- Energy and Luminosity reach
- Scope and Technology are driven by Energy/Luminosity

Energy is a cost driver:

- Hadrons: high-field magnets
- Leptons: high-gradient RF

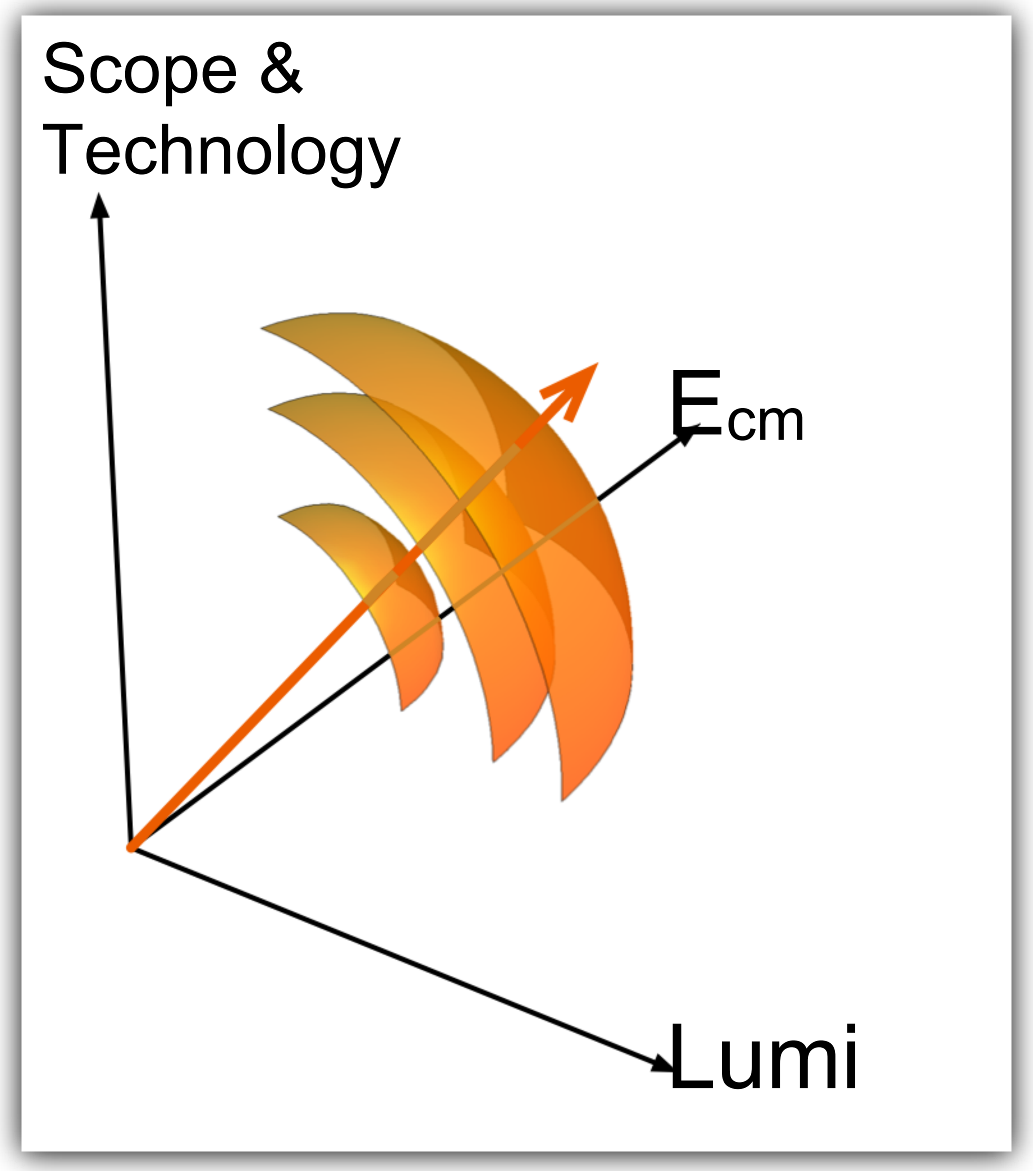
Luminosity drives the power needs:

- at least for leptons
- this drives the operating costs
- environmental aspects

In the end it is all about EUR per GeV and fb^{-1}

- for a given tolerable risk level

R&D is the only viable mitigation strategy



N. Walker

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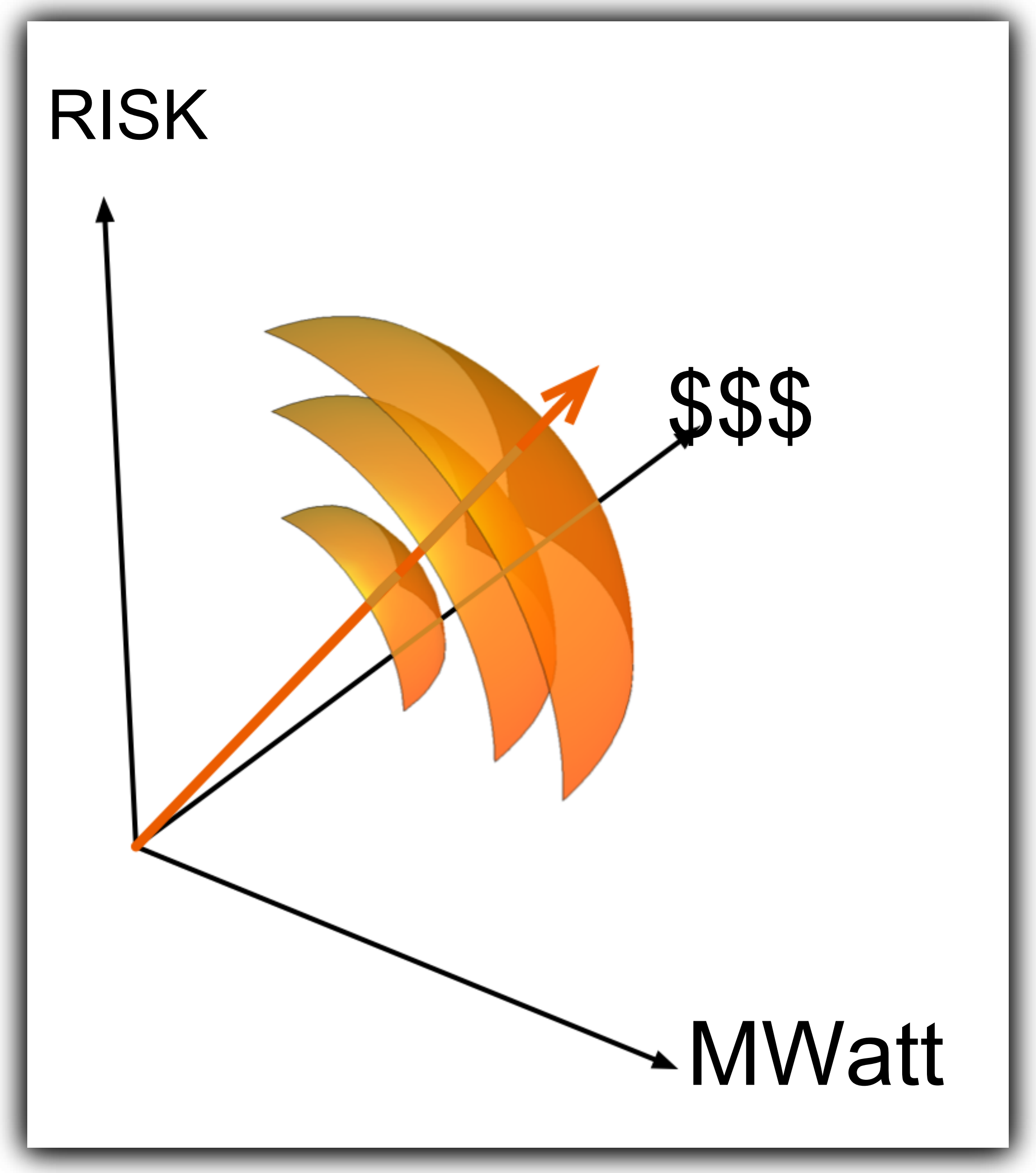

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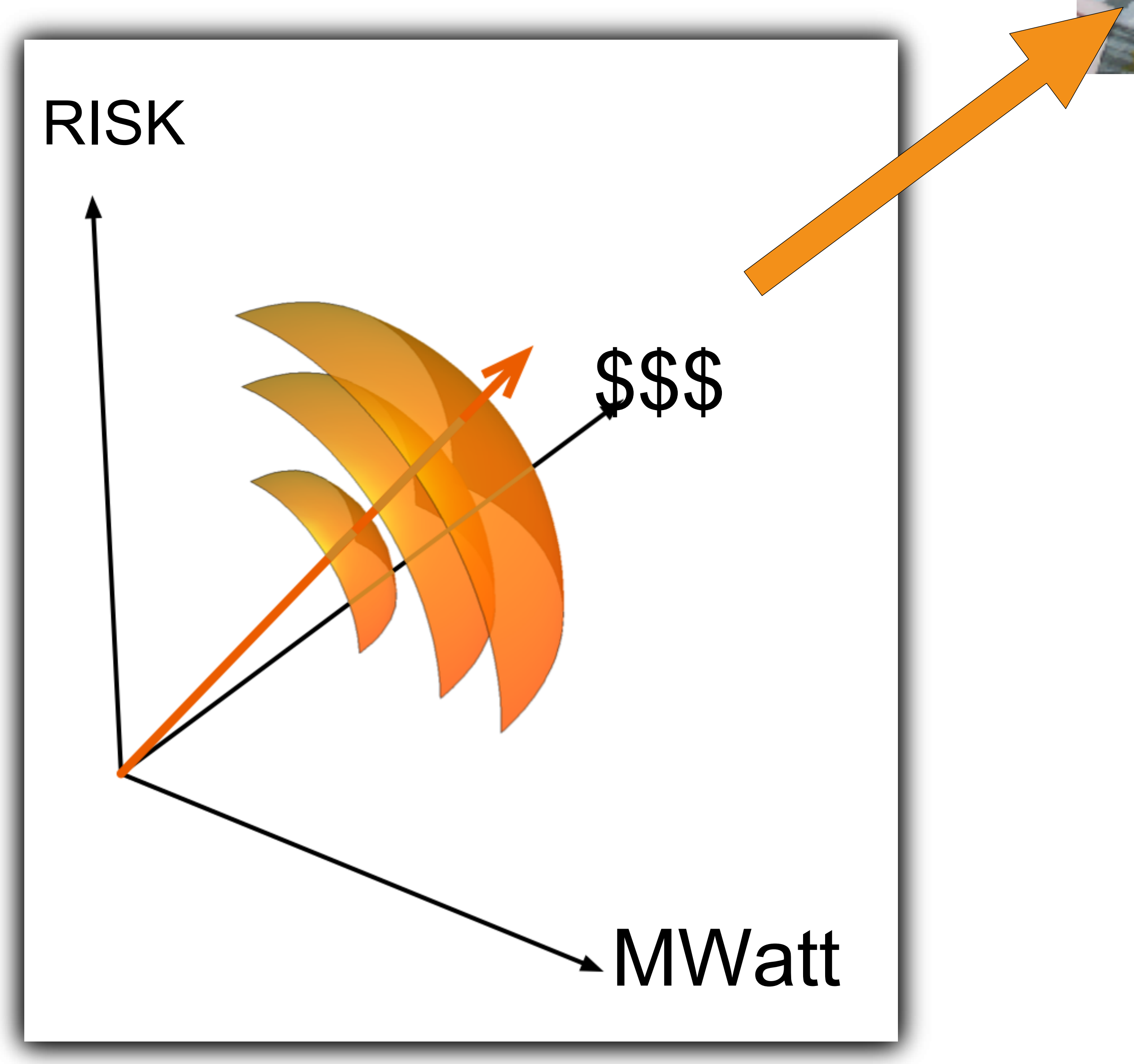

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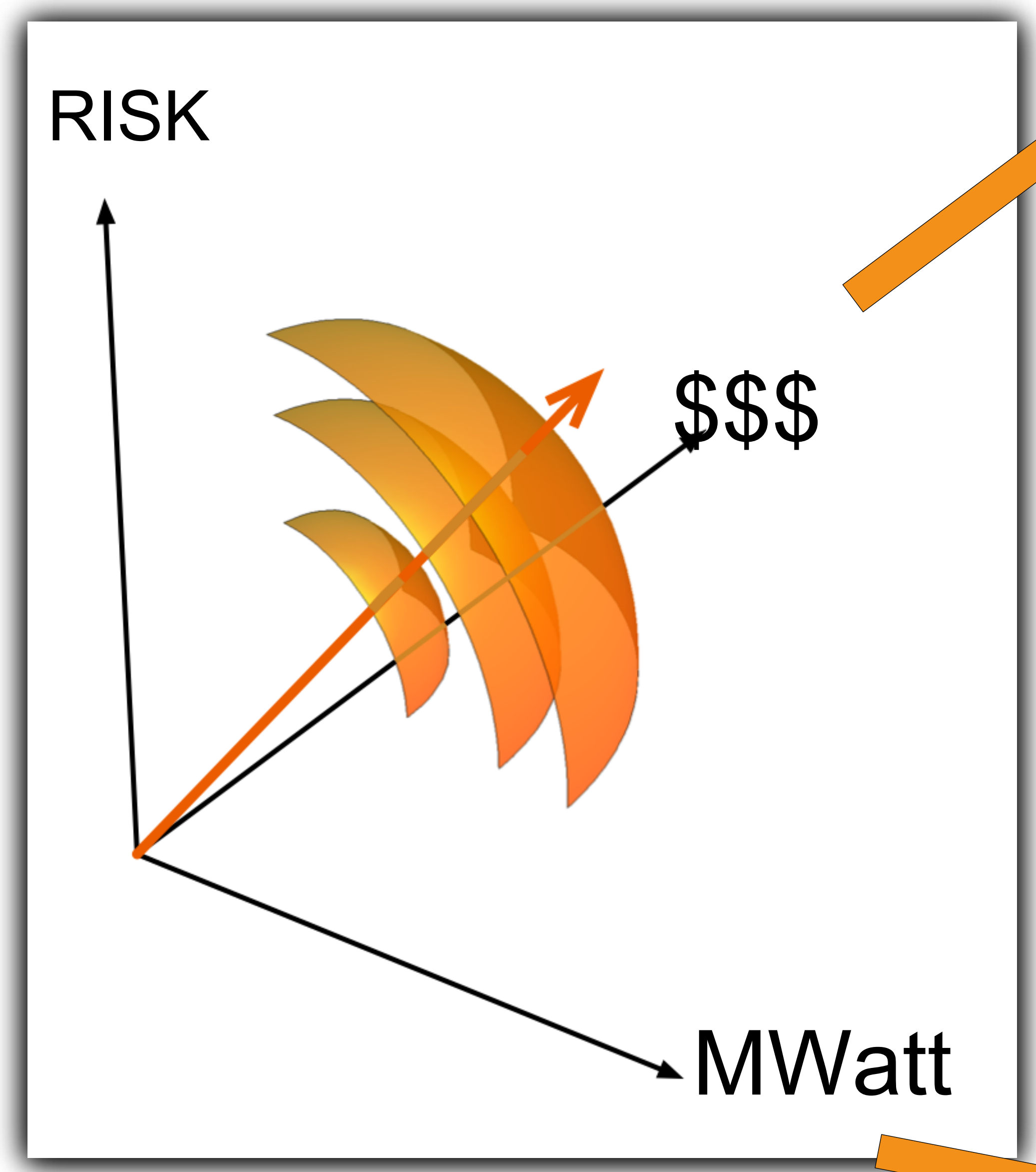

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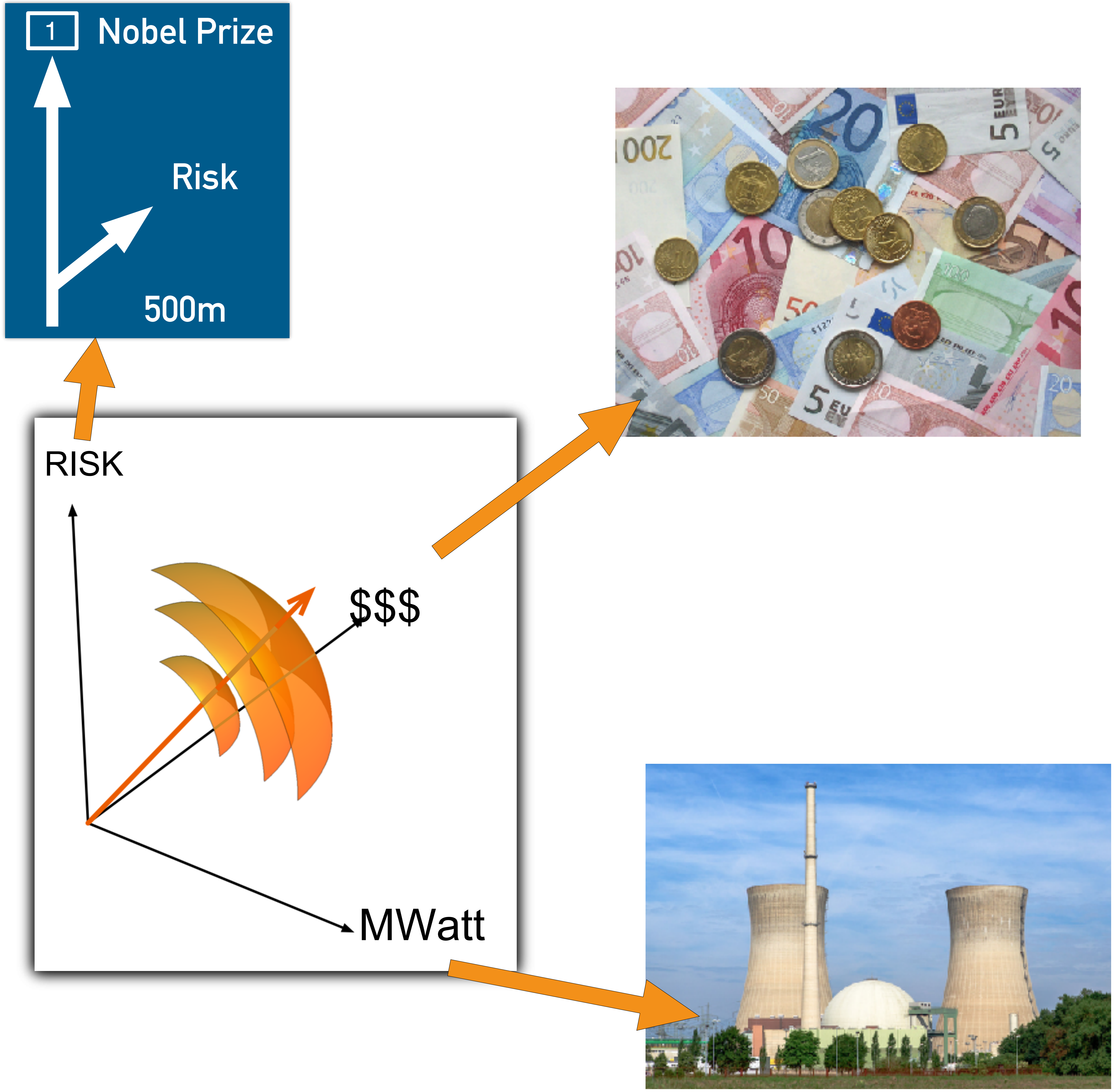


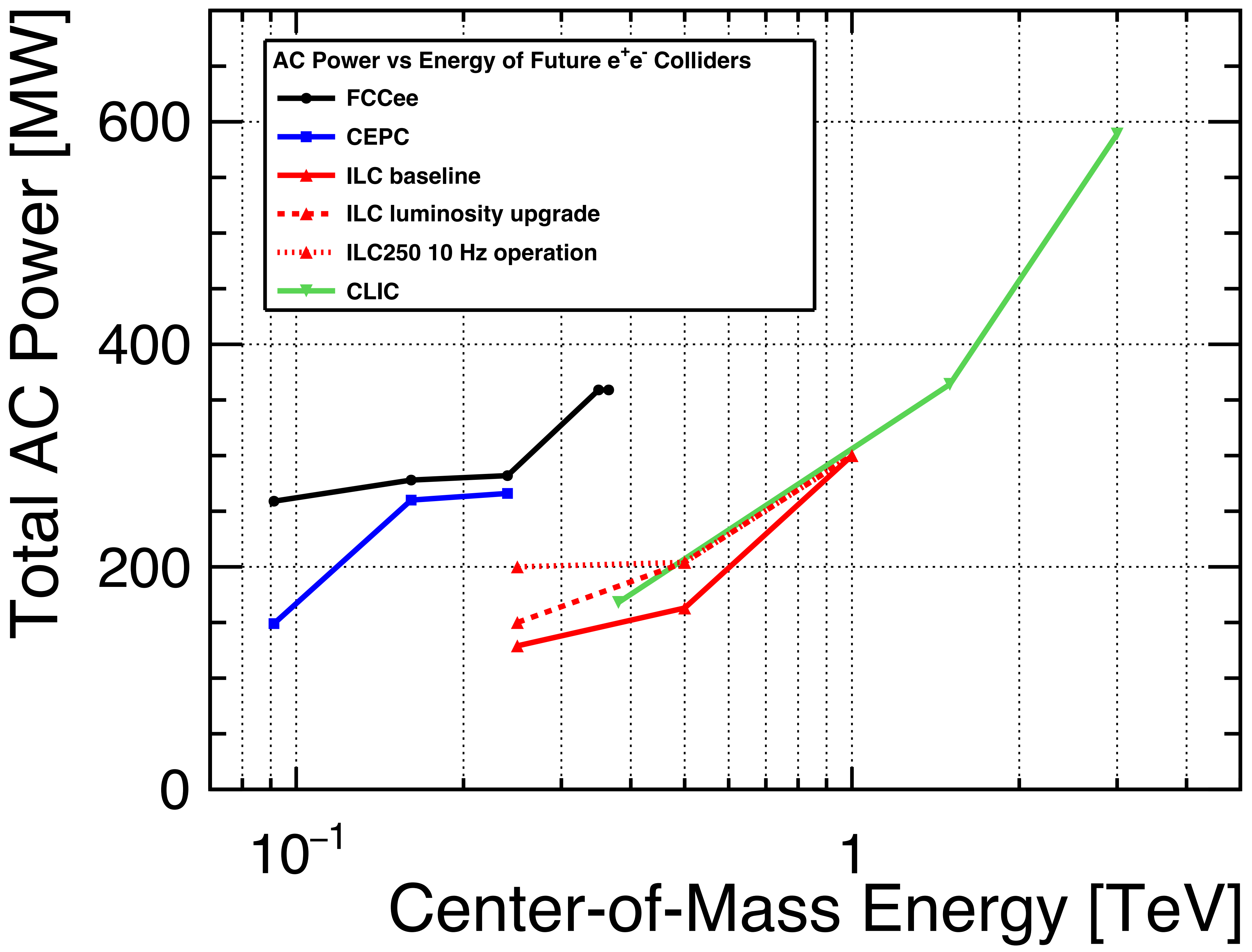
N. Walker

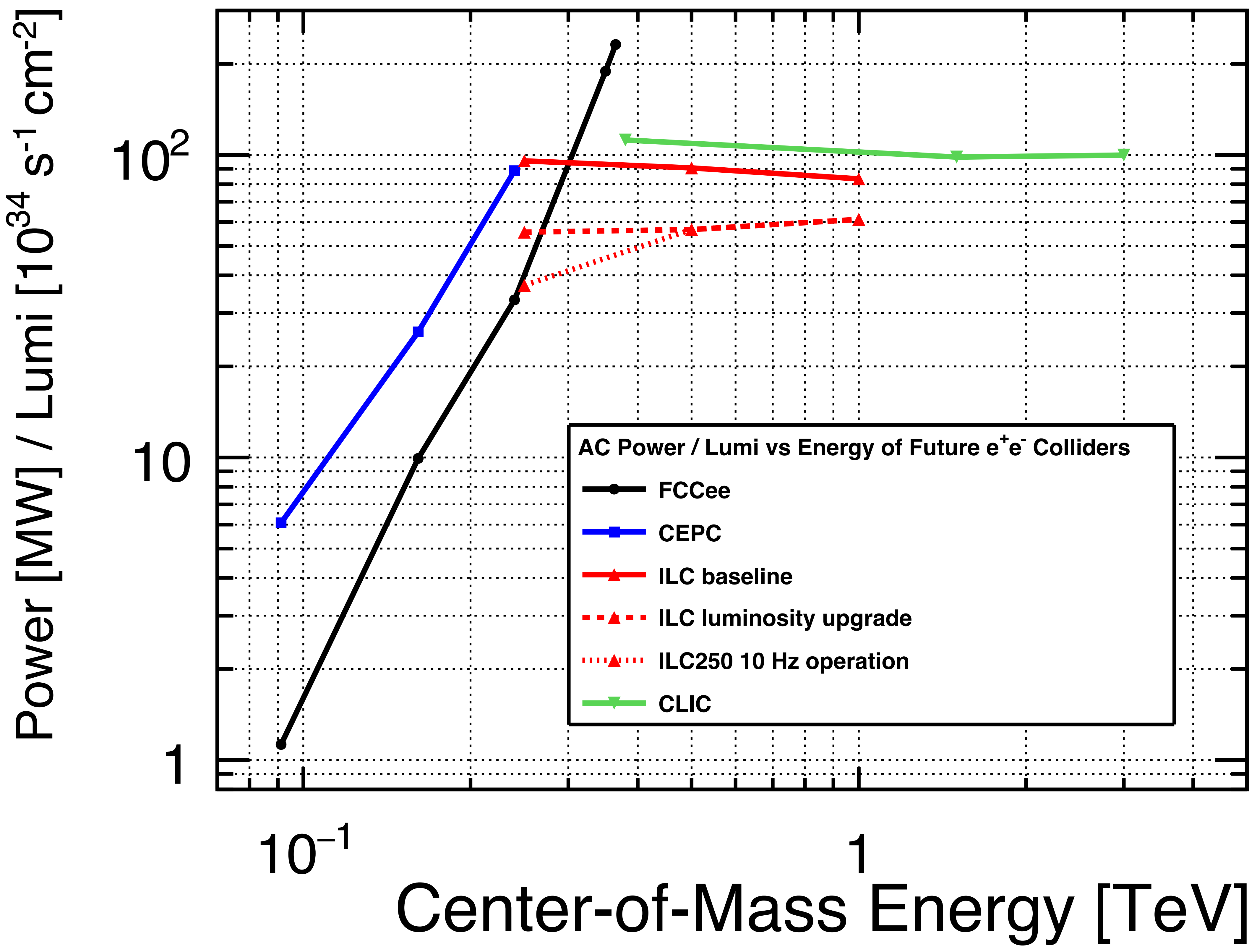
The Power Challenge

J. List et al.

For lepton machines: high luminosity means high power consumption

- for comparison LHC machine <100 MW
- high power means high running costs…

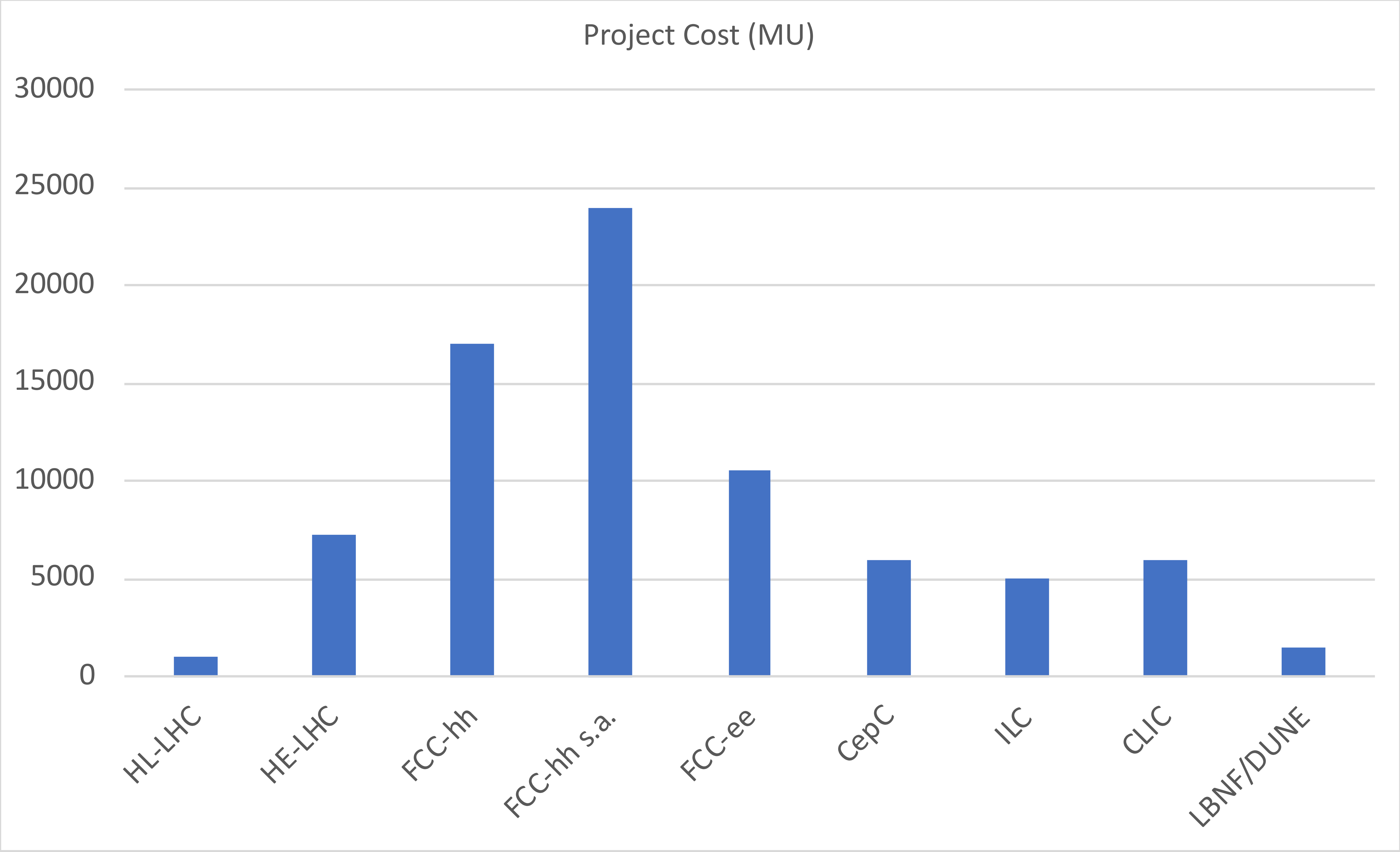




Project	Particles	Energy	Status	Power	Cost	First Beam	Host
LHC-HL	pp (pA/AA)	14 TeV	approved	O(100 MW)	~ 950 MCHF	~2025	CERN
LHC-HE	pp (pA/AA)	~28 TeV	pre-conceptual	?	~7.2 GCHF	>>2035 (post-LHC)	CERN
SppC	pp (pA/AA/ep)	50-100 TeV	pre-conceptual	?	?	>2042	China
FCC-hh	pp (pA/AA/ep)	80-100 TeV	conceptual	?	~17/24 GCHF	>>2035 (post-LHC)	CERN
FCC-ee	e^+e^-	90-350 GeV	conceptual	~250-300 MW	10.5 GCHF	>>2035 (post-LHC)	CERN
CepC	e^+e^-	90-250 GeV	pre-conceptual	~300 MW	~6 G$	>2030	China
ILC	e^+e^-	0.25-1 TeV	construction-ready	120-300 MW	~5 G$ (250 GeV)	>2030	Japan
CLIC	e^+e^-	0.5-3 TeV	conceptual	270-590 MW	~6 GHF (380 GeV)	>>2035 (post-LHC)	CERN
LBNF/DUNE	Neutrinos	60-120 GeV (p) <10 GeV (ν)	approved	?	~1.5 G$	2028	FNAL
Muon	$\mu^+\mu^-$	3 TeV	pre-conceptual	???	???	???	???

Project Cost Estimates

MU - Mega Unit = 1 MCHF = 1 MEUR = 1 MUS$



Possible scenarios of future colliders

S. Bethge

Possible scenarios of future colliders

Worldwide HEP Work Sharing in the year 2000

Worldwide HEP Work Sharing in the year 2000

Work Sharing in 2040?

Work Sharing in 2040?

Work Sharing in 2040?

Conclusion

The Higgs detection defined the first energy scale for a new collider:

- ~200-500 GeV: Higgs mass, quantum numbers, couplings, Top
- up to ~1 TeV for Higgs potential
- with precision and at higher energies: searches for the unexpected

LHC (HL-LHC) is the only approved high energy collider for this scale

LBNF/DUNE is the other (more or less) approved HEP accelerator based project on these scales

What comes then?

Electron-positron collider would complement the LHC results with precision measurements

- Linear colliders (ILC, CLIC) are the most advanced path into the leptonic TeV world; and they are the only scalable way forward!
- Very large storage rings are attractive up to ~350 GeV: CepC, FCC-ee

Future very large hadron colliders for ~100 TeV energies under discussion

- SppC, FCC-pp
- intensive R&D on s/c magnets needed

Muon colliders or PWA colliders still need a long way to go

„Take home message“: it takes long and it needs the world….