CERN strategy
& future large scale projects

F. Zimmermann, CERN/BE

gratefully acknowledging input from
FCC global design study & CepC team

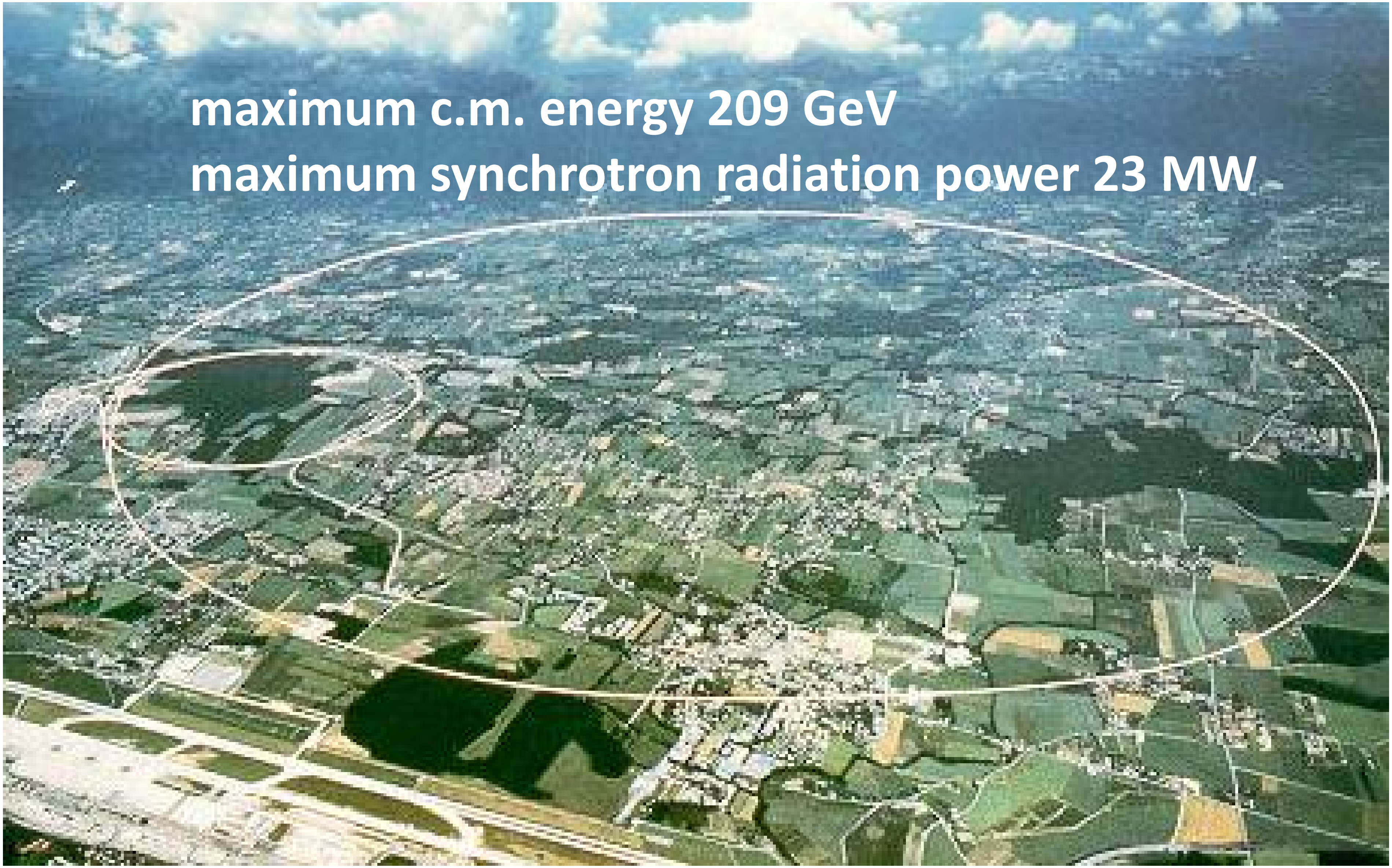
special thanks to M. Benedikt,
D. Schulte, S. Stapnes, J. Wenninger

YEARS / ANS CERN

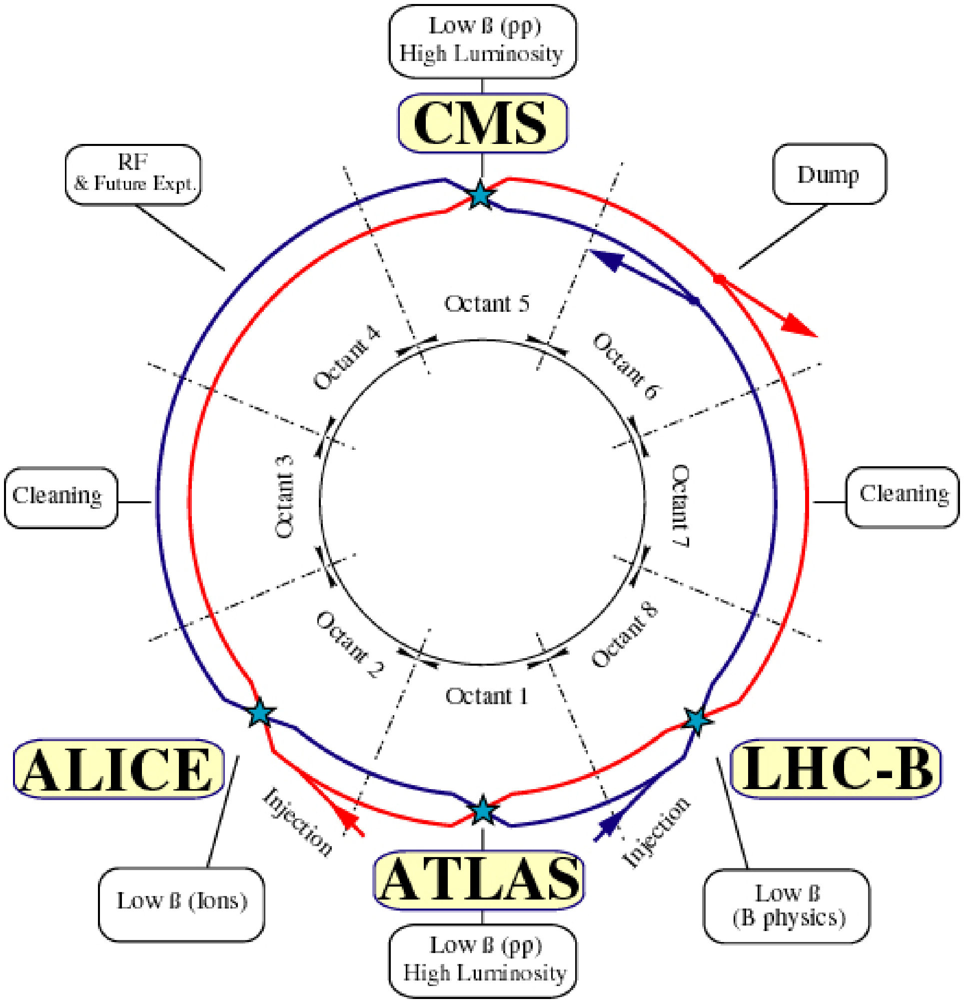
Channeling2014 Conference, Capri, 5 October 2014

*Work supported by the **European Commission** under Capacities 7th Framework Programme, Grant Agreement 312453*

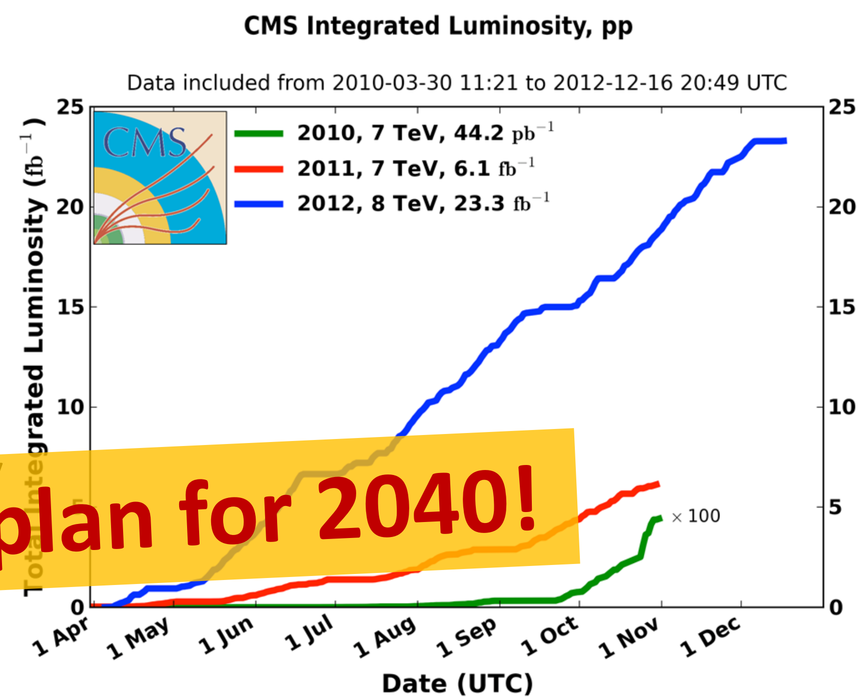
LEP – highest energy e^+e^- collider so far



Large Hadron Collider (LHC)



design:
c.m. energy 14 TeV (*pp*);
luminosity 10^{34} $cm^{-2}s^{-1}$;
1.15×10^{11} p/bunch;
2808 bunches/beam;
360 MJ / beam

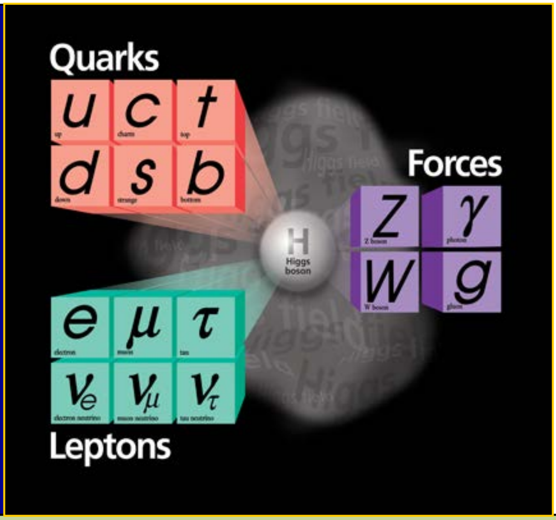


1983 first LHC proposal, launch of design study
1994 CERN Council: LHC approval
2010 first collisions at 3.5 TeV beam energy
2015 collisions at ∼design energy (plan)

now is the time to plan for 2040!

Prospects for Particle Physics

With the discovery of a Higgs boson in 2012, we have **completed the Standard Model** (almost 80 years of theoretical and experimental efforts !)



However: **SM is not a complete theory**

Several outstanding questions (e.g. composition of dark matter, cause of universe's accelerated expansion [dark energy / inflation], origin of matter-antimatter asymmetry, neutrino masses, why 3 families?, lightness of Higgs boson, weakness of gravity, …) which cannot be explained within the SM.

F. Gianotti et al.

These questions require NEW PHYSICS

Present knowledge is insufficient to determine energy scale of new physics ; **LHC will provide new information** from *pp* collisions at higher cm energy (13 TeV) **by 2017-18**

main questions in particle physics and main approaches to address them

question	high-energy colliders	high-precision experiments	neutrino experiments	dedicated searches	cosmic surveys
Higgs, EWSB	X				
neutrinos	X		X	X	X
dark matter	X			X	
flavour, CP violation	X	X	X	X	
new particles and forces	X	X	X	X	
universe acceleration					X

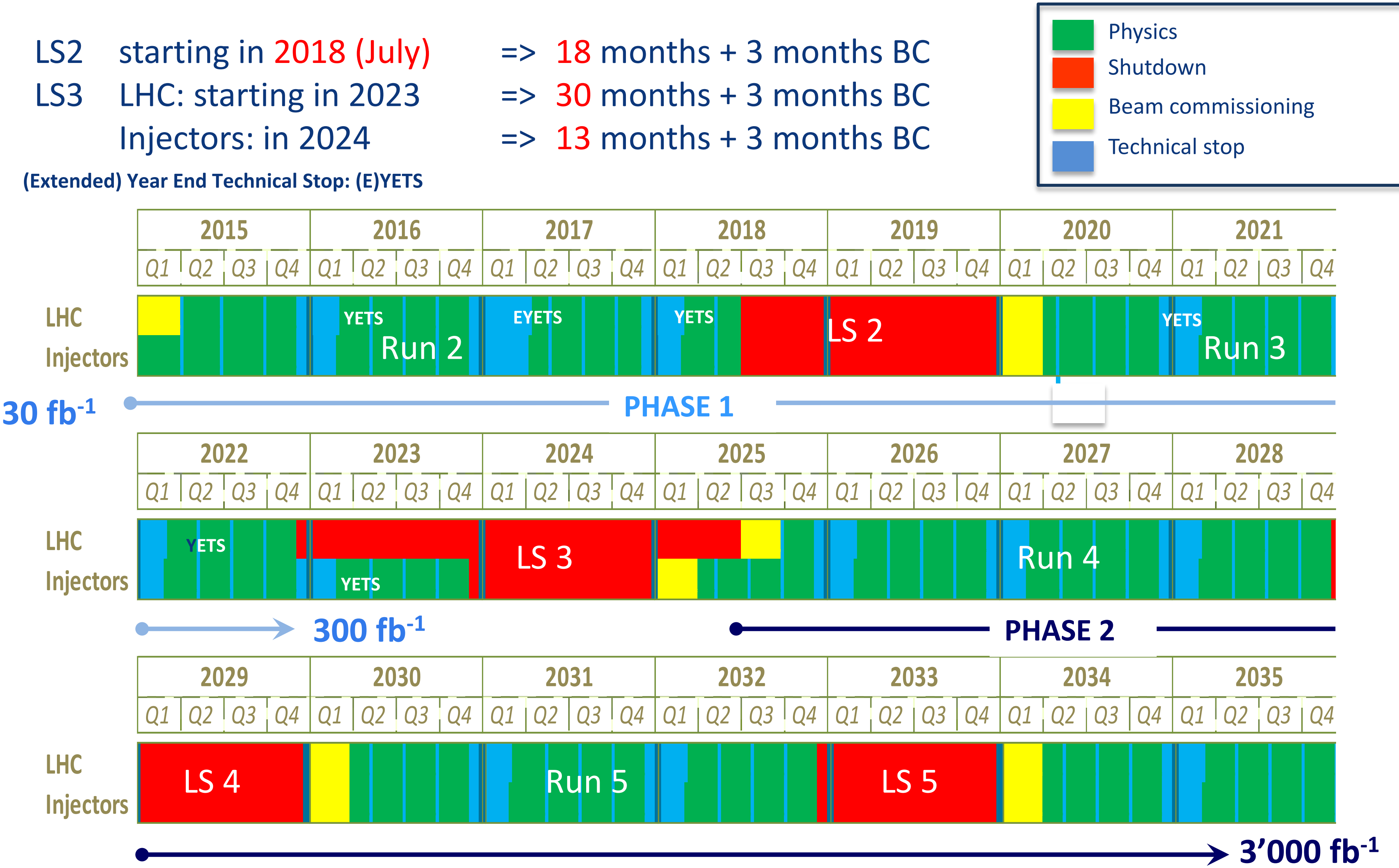
F. Gianotti et al.

most of these questions require high-energy and/or high-intensity accelerators

LHC roadmap: schedule until 2035

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

(Extended) Year End Technical Stop: (E)YETS



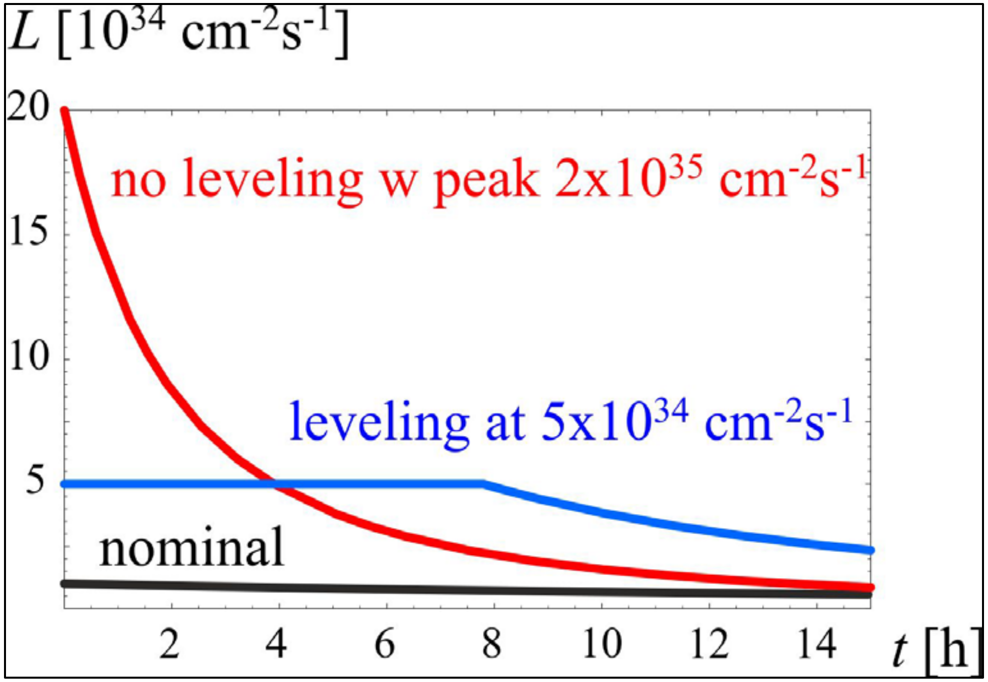
F. Bordry

Phase 2: HL-LHC

HL-LHC

M. Lamont

- 3000 fb^{-1} delivered in the order of 10 years
- High "virtual" luminosity with levelling anticipated
- Challenging demands on the injector complex
  - major upgrades foreseen



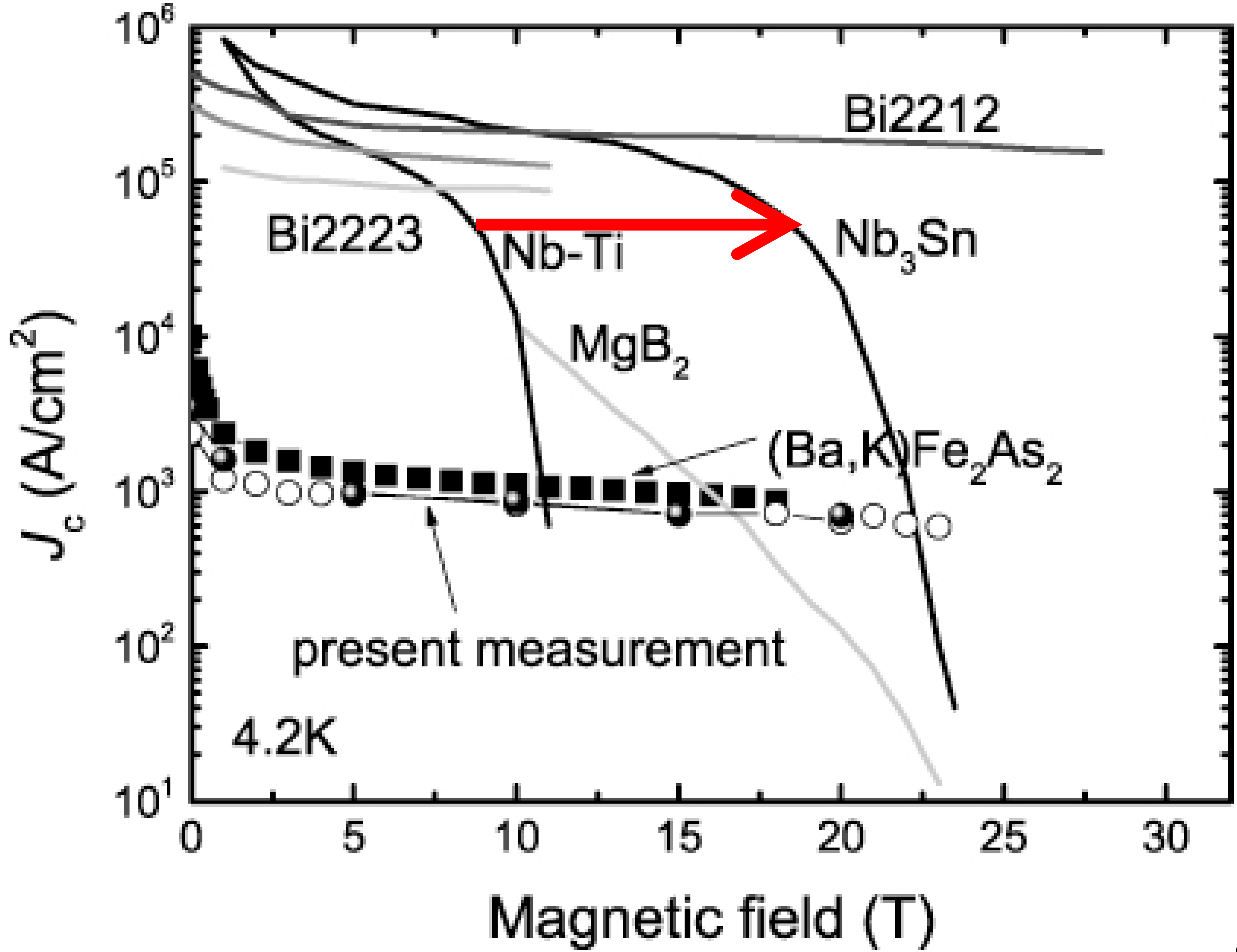
5×10^{34} $cm^{-2}s^{-1}$ levelled luminosity

Pile-up ~140

3 fb^{-1} per day

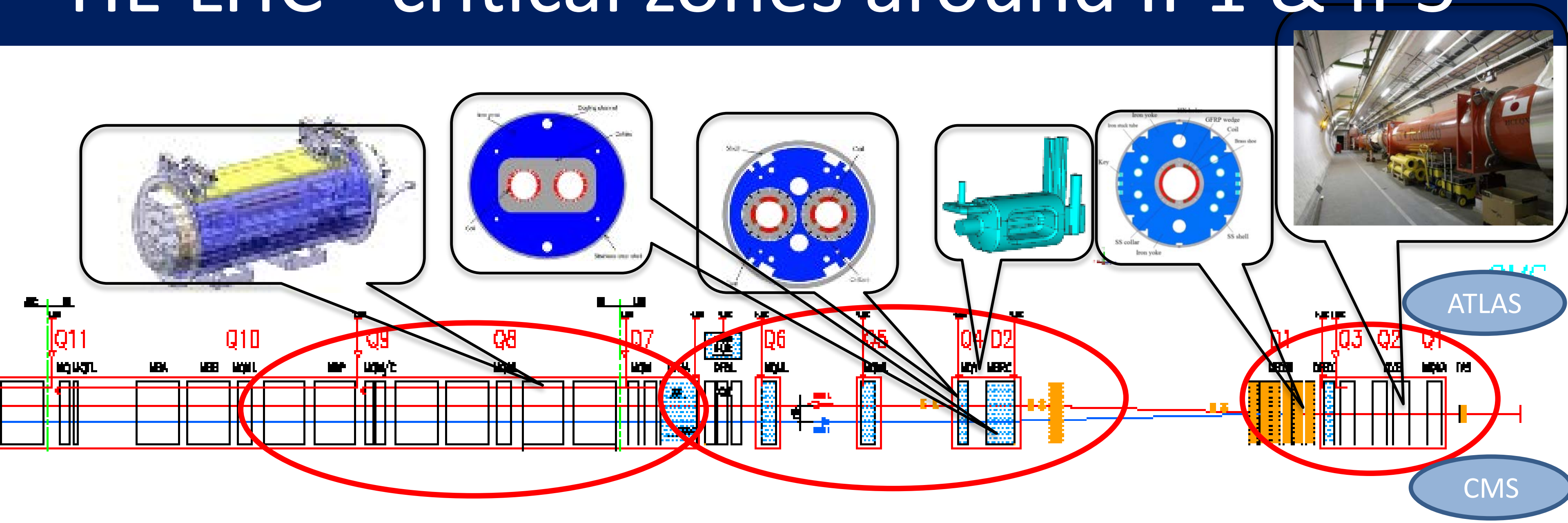
~250 fb^{-1} /year

technology transition: *Nb-Ti* → *Nb_3Sn*



O. Bruning

HL-LHC - critical zones around IP1 & IP5



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

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

1. **New quadrupole triplet based on Nb_3Sn (12 T at coil)** required due to:

-Radiation damage

-Need for more aperture

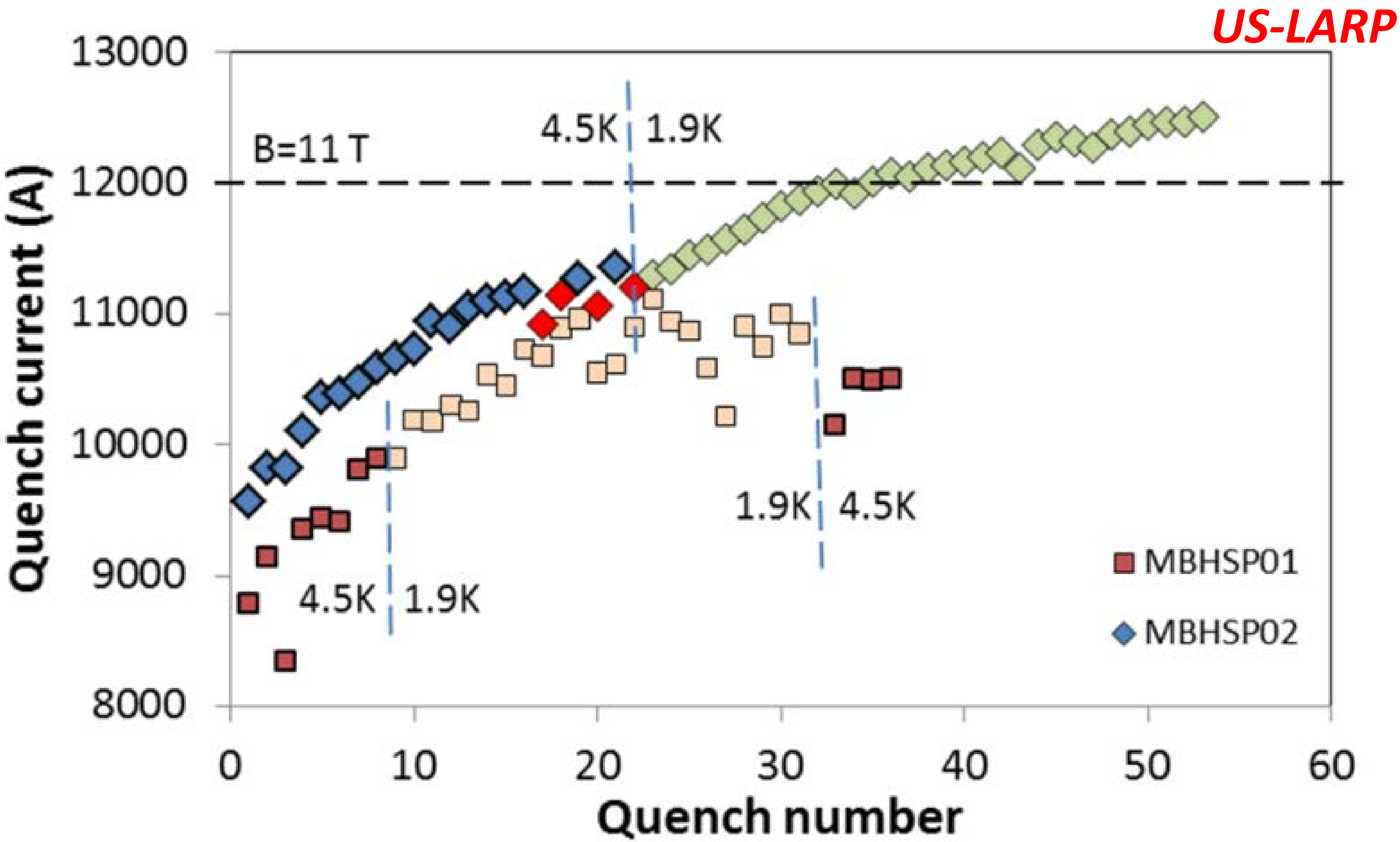
Changing the triplet region is not enough for reaching the HL-LHC goal!

→ **more than 1.2 km of LHC plus technical infrastructure (e.g. Cryo and Powering)**

→ ***Nb_3Sn* dipoles & quadrupoles**

O. Brüning, L. Rossi

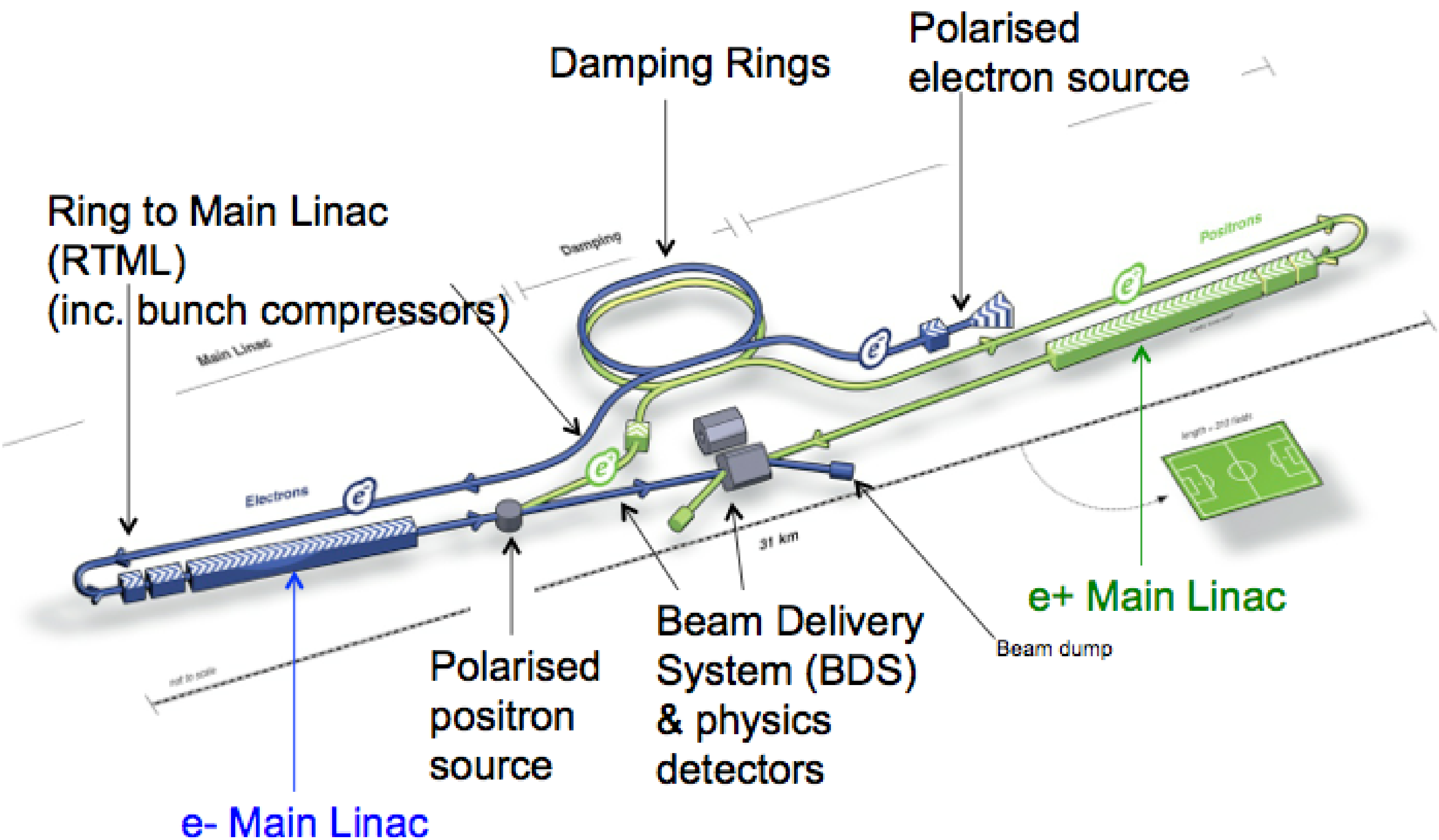
FNAL: Nb_3Sn dipole demonstrators



MBHSP02 (1 m) passed 11 T field during training at 1.9 K with *I* = 12080 A on 5 March 2013

International Linear Collider (ILC)

total length ~30 (500 GeV) - 50 km (1 TeV)

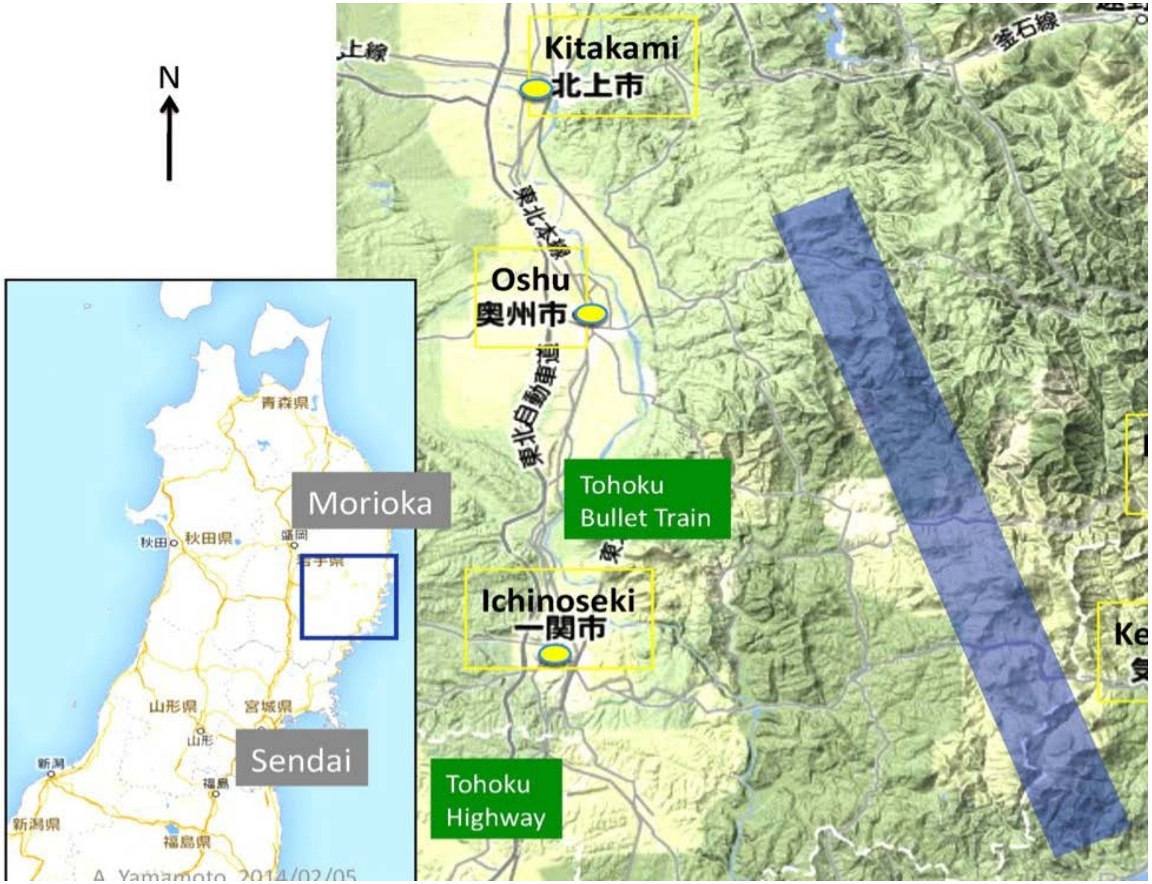


SC acceleration structures ~ 30 MV/m; **TDR completed in 2012**, ILC technology used for XFEL at DESY; present optimistic time line: construction start in 2018 & 1st physics in 2027?

International Linear Collider (ILC) - 2

Japanese HEP community expressed interest in hosting the ILC. Site chosen: 北上市 (Kitakami) in Northern Japan. Under review by Japanese ministry MEXT.

Courtesy F. Simon



European Strategy Update 2013

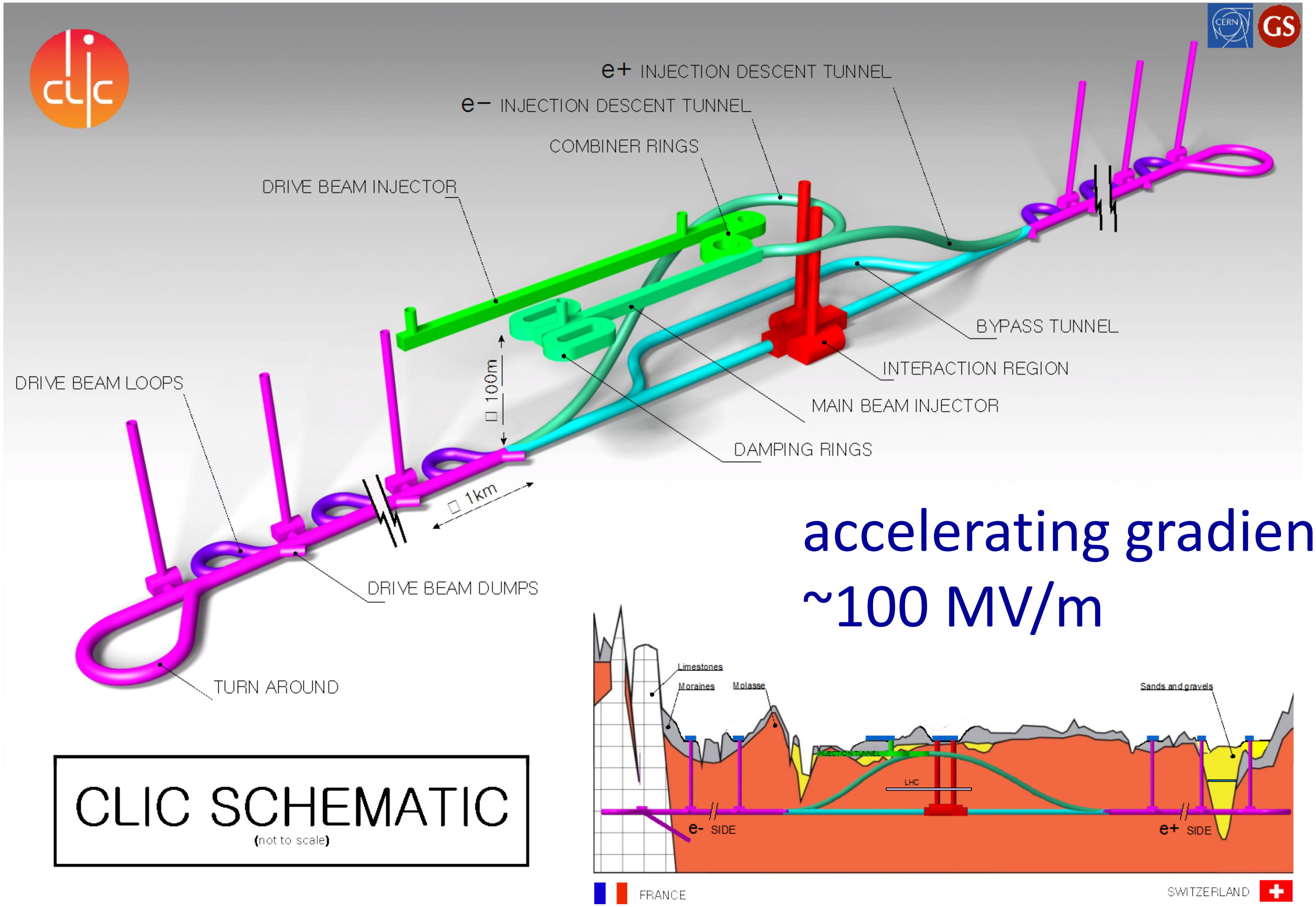
*"CERN should undertake **design studies** for accelerator projects in a **global context**, with emphasis on proton-proton and electron-positron **high-energy frontier** machines."*

http://cds.cern.ch/record/1567258/files/esc-e-106.pdf

strategy adopted by the CERN Council

Compact Linear Collider (CLIC)

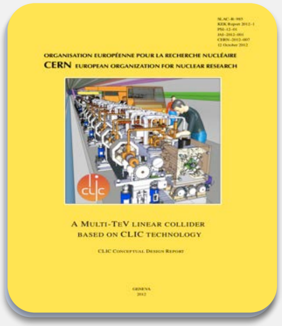
total length (main linac) ~11 (500 GeV) - 48 km (3 TeV)



accelerating gradient ~100 MV/m

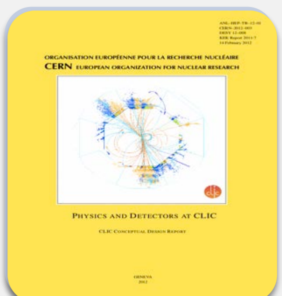
key technologies: 2-beam accel., drive-beam , X-band RF

CLIC Conceptual Design Report 2012



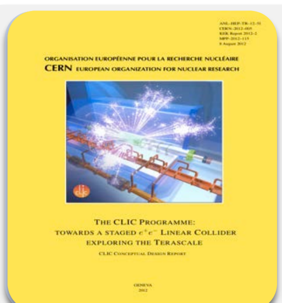
Vol 1: The CLIC accelerator and site facilities (H.Schmickler)

- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- Complete, presented in SPC in March 2011, in print: https://edms.cern.ch/document/1234244/



Vol 2: Physics and detectors at CLIC (L.Linssen)

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- Completed and printed, presented in SPC in December 2011 http://arxiv.org/pdf/1202.5940v1



Vol 3: "CLIC study summary" (S.Stapnes)

- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- Completed and printed, submitted for the European Strategy Open Meeting in September http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

~1400 authors, ~1200 pages

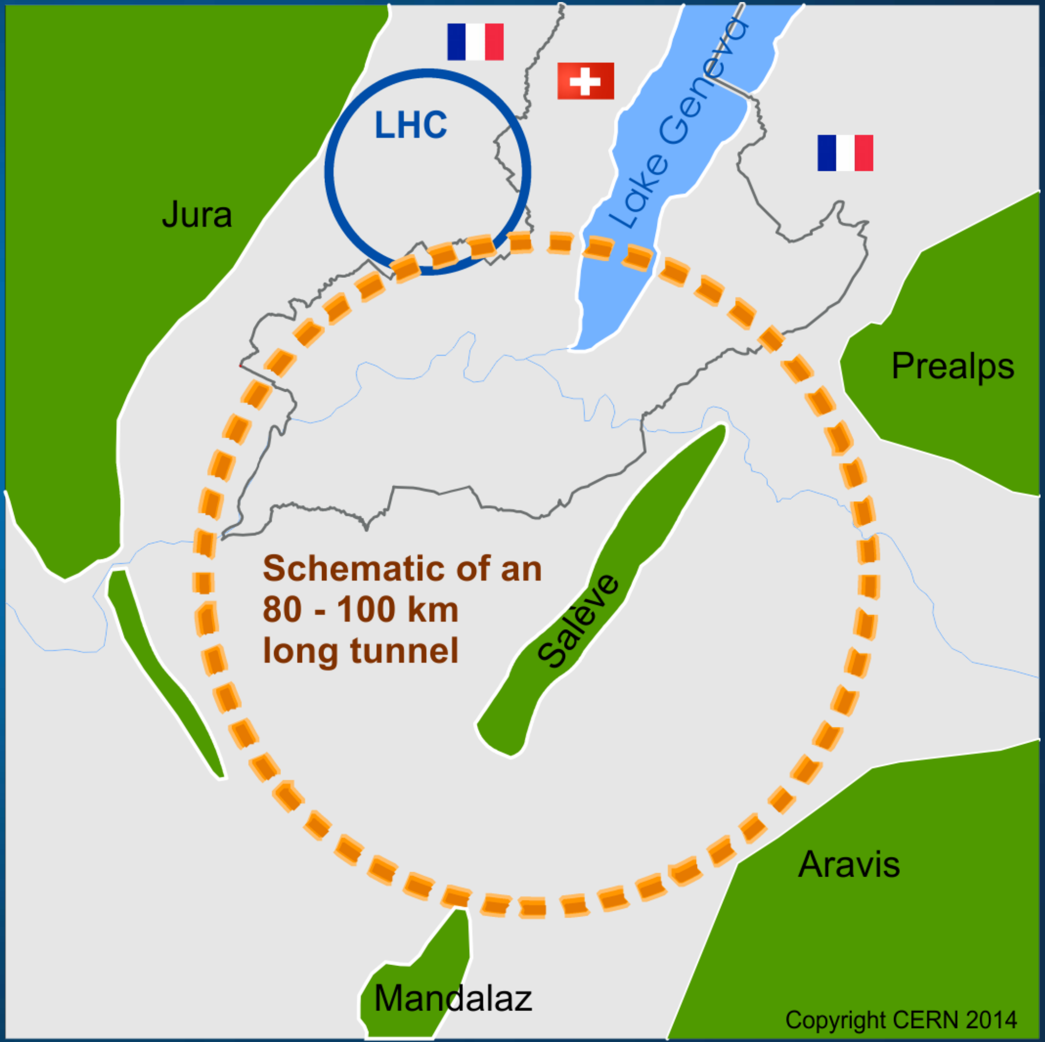
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

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

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **80-100 km infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**



CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, e^+e^- collisions ~2028; *pp* collisions ~2042

easy access

300 km from Beijing

3 h by car

1 h by train

"Chinese Toscana"

Yifang Wang

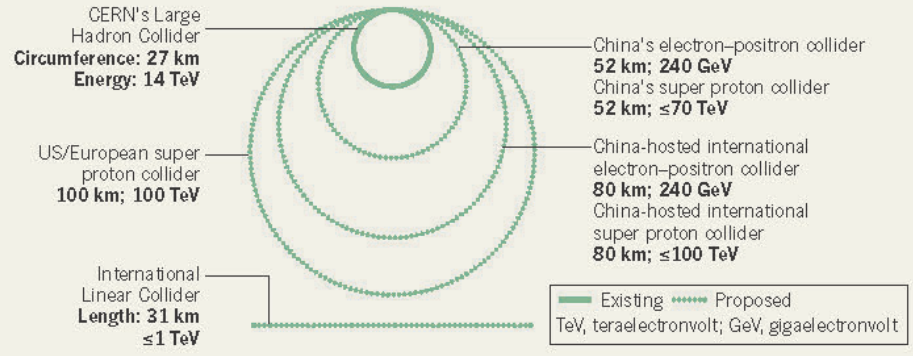
CepC/SppC project – recent news in *Nature*

24 J U LY 2014 | VO L 511 | NAT U R E | 3

IN FOCUS NEWS

COLLISION COURSE

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.



PARTICLE PHYSICS

China plans super collider

Proposals for two accelerators could see country become collider capital of the world.

BY ELIZABETH GIBNEY

For decades, Europe and the United States have led the way when it comes to high-energy particle colliders. But a proposal by China that is quietly gathering momentum has raised the possibility that the country could soon position itself at the forefront of particle physics.

Scientists at the Institute of High Energy Physics (IHEP) in Beijing, working with international collaborators, are planning to build a 'Higgs factory' by 2028 — a 52-kilometre underground ring that would smash together electrons and positrons. Collisions of these fundamental particles would allow the Higgs

China hopes that it would also be a stepping stone to a next-generation collider — a super proton–proton collider — in the same tunnel.

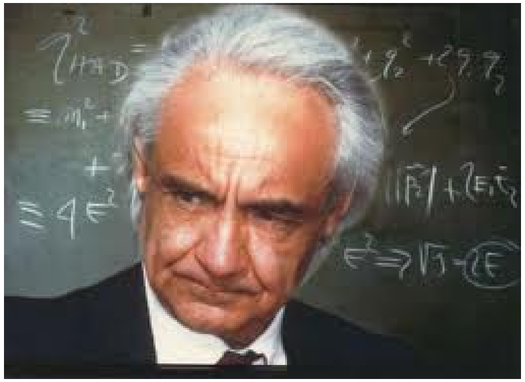
European and US teams have both shown interest in building their own super collider (see *Nature* **503**, 177; 2013), but the huge amount of research needed before such a machine could be built means that the earliest date either can aim for is 2035. China would like to build its electron–positron collider in the meantime, unaided by international funding if needs be, and follow it up as fast as technologically possible with the super proton collider. Because only one super collider is likely to be built, China's momentum puts it firmly in the driving seat.

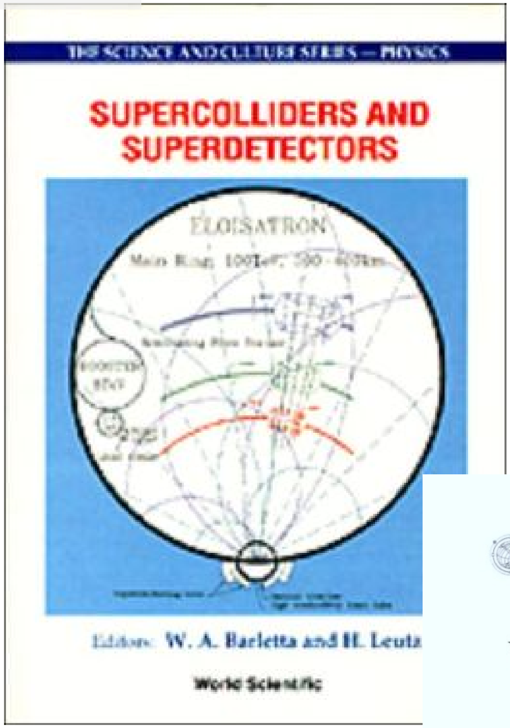
Electron–positron colliders and hadron colliders such as the LHC complement each other. Hadron colliders are sledgehammers, smashing together protons (a kind of hadron that comprises three fundamental particles called quarks) at high energies to see what emerges. Lower-energy electron–positron machines produce cleaner collisions that are easier to analyse, because they are already smashing together fundamental particles. By examining in detail the interactions of the Higgs boson with other particles, the proposed Chinese collider should, for example, be able to detect whether the Higgs is a simple particle or something more exotic. This would help physicists to work out whether the particle fits with

previous studies in Italy (ELOISATRON 300 km), US (SSC 87 km, VLHC/VLLC 233 km) & Japan (94 km)

ex. ELOISATRON

Supercolliders Superdetectors: Proceedings of the 19th and 25th Workshops of the INFN Eloisatron Project





ex. SSC


C.T. Murphy
SSC-SR-2020

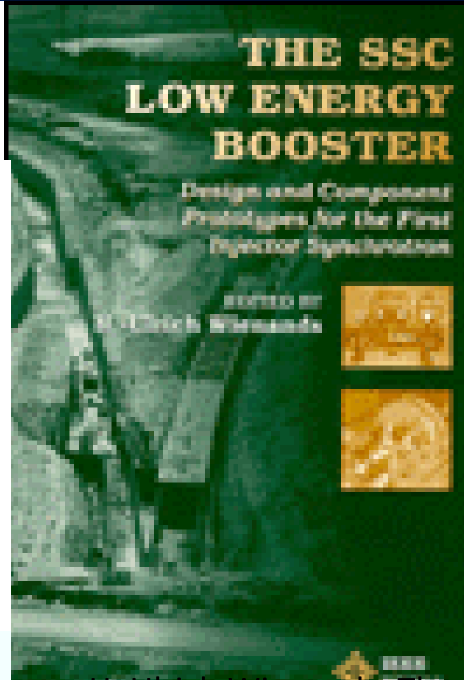
Conceptual Design of the Superconducting Super Collider

SSC Central Design Group*

March 1986

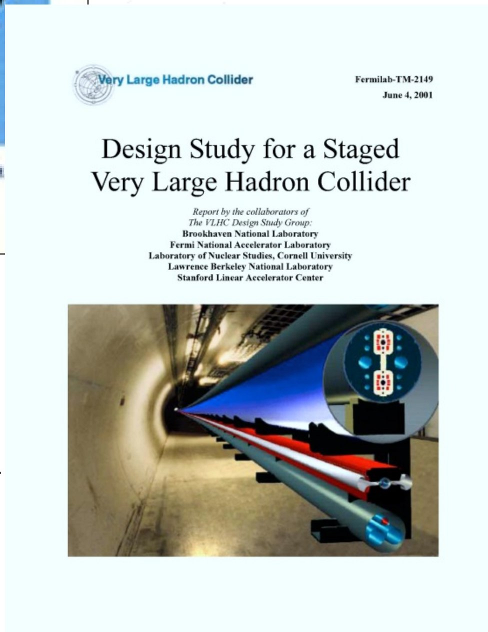
*Operated by Universities Research Association under contract with the U.S. Department of Energy

SSC CDR 1986



H. Ulrich Wienands, The SSC Low Energy Booster: Design and Component Prototypes for the First Injector Synchrotron, IEEE Press 1997

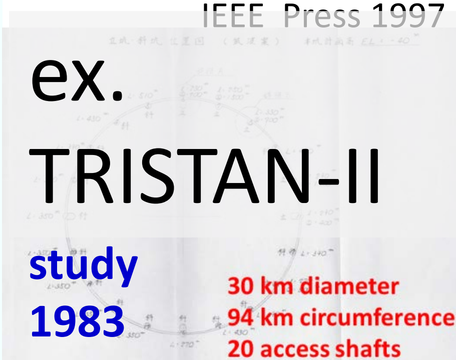
ex. VLHC



VLHC Design Study Group Collaboration **June 2001**. 271 pp. SLAC-R-591, SLAC-R-0591, SLAC-591, SLAC-0591, FERMILAB-TM-2149

http://www.vlhc.org/

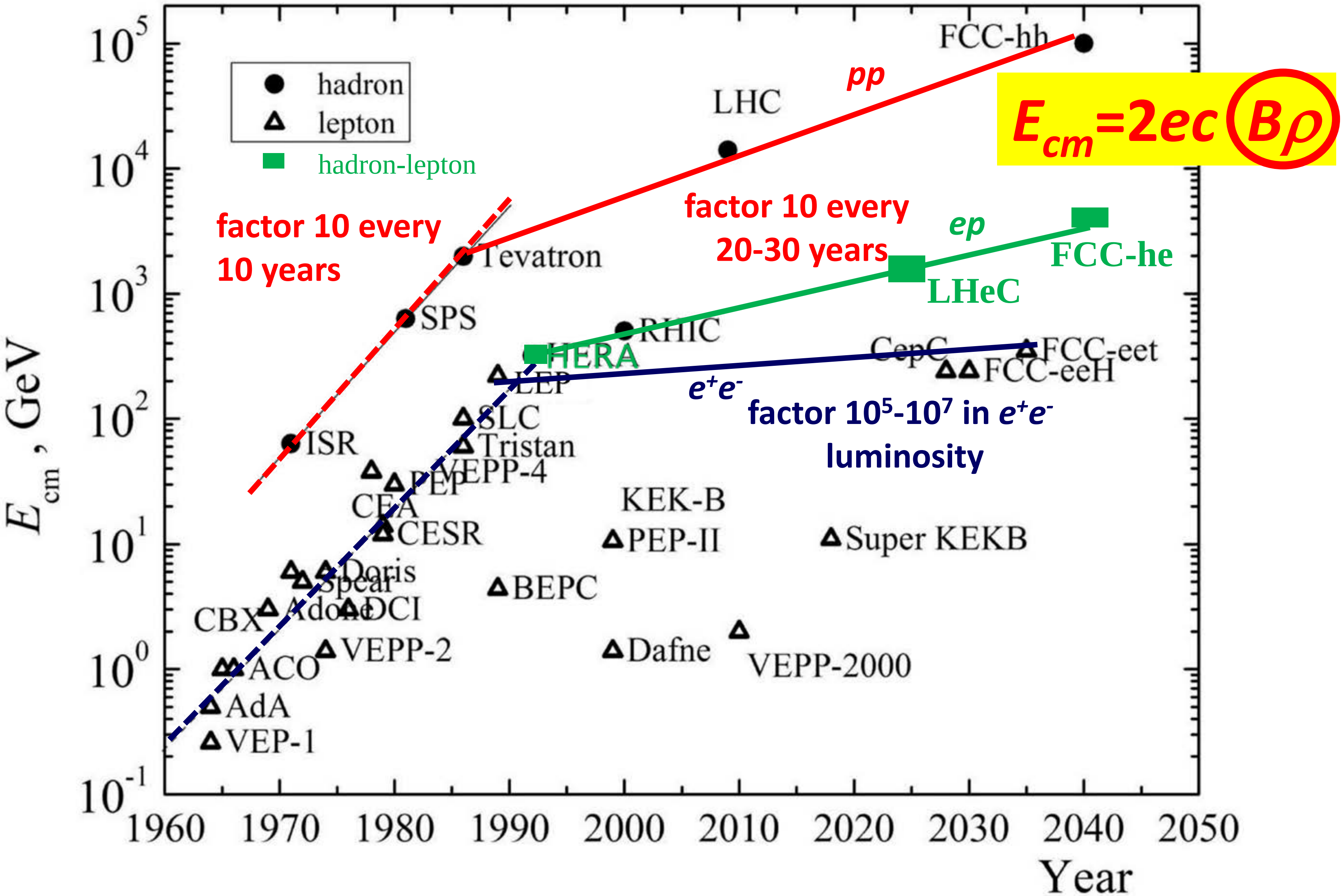
ex. TRISTAN-II



study 1983

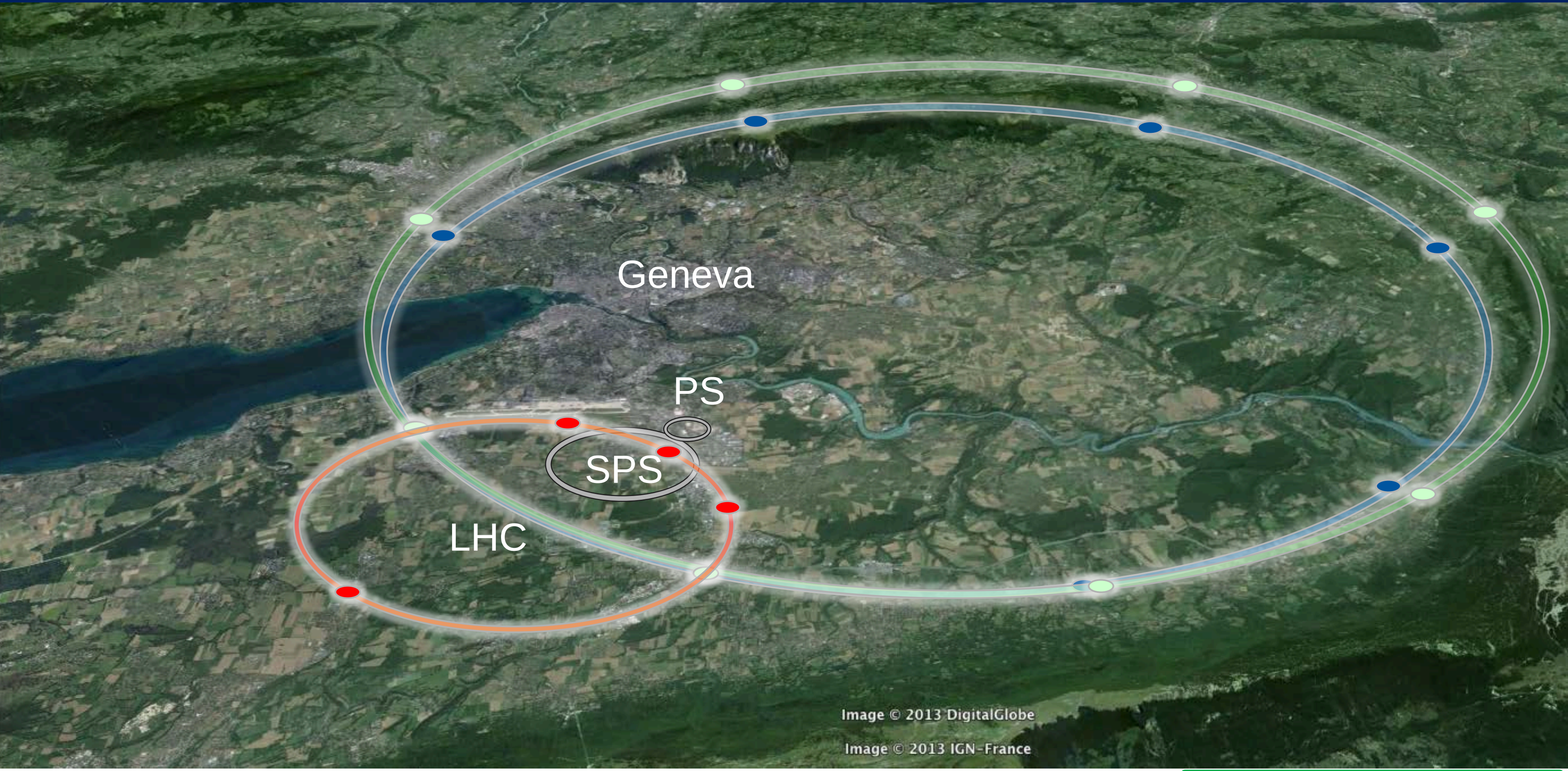
30 km diameter
94 km circumference
20 access shafts

collider c.m. energy vs. year



Courtesy V. Shiltsev

FCC-hh: 100 TeV *pp* collider



LHC	"HE-LHC"	FCC-hh (alternative)	FCC-hh (baseline)
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.m.)	33 TeV (c.m.)	100 TeV (c.m.)	100 TeV (c.m.)

L. Bottura
B. Strauss

FCC-hh opens three physics windows

➥ Access to new particles in the few TeV to 30 TeV mass range, beyond LHC reach

➥ Immense/much-increased rates for phenomena in the sub-TeV mass range → increased precision w.r.t. LHC and possibly ILC

➥ Access to very rare processes in the sub-TeV mass range → search for stealth phenomena, invisible at the LHC

M. Mangano

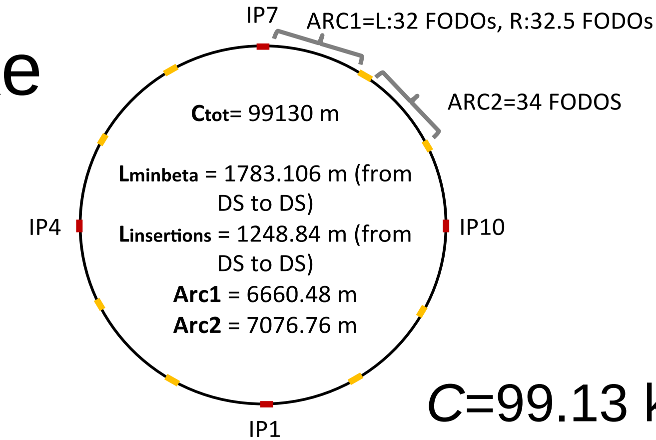
FCC-hh Key Parameters

Parameter	FCC-hh	LHC
Energy	**100 TeV c.m.**	14 TeV c.m.
Dipole field	**16 T**	8.33 T
# IP	2 main, +2	4
Luminosity/IP_{main}	**5×10^{34}** $cm^{-2}s^{-1}$	1×10^{34} $cm^{-2}s^{-1}$
Energy/beam	**8.4 GJ**	0.39 GJ
Synchr. rad.	28.4 W/m/apert.	0.17 W/m/apert.
Bunch spacing	25 ns (5 ns)	25 ns

Preliminary, subject to evolution

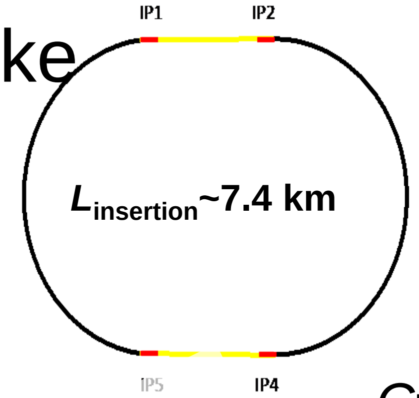
ring optics for alternative layouts

LHC-like circular



C=99.13 km

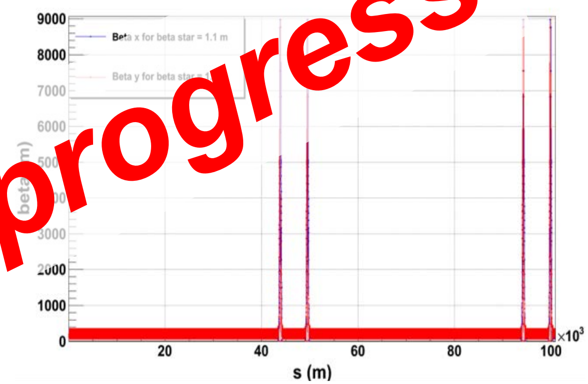
SSC-like race-track



C=100.8 km

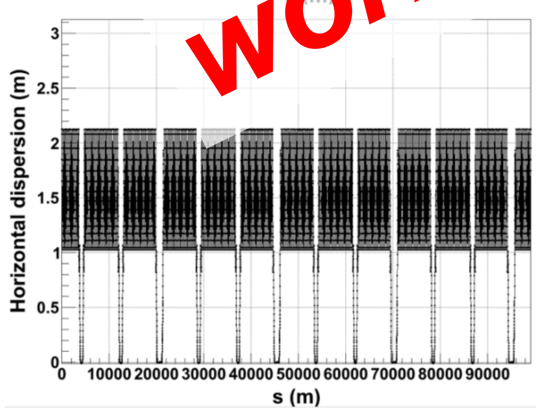
R. Alemany,
B. Holzer,
R. Tomas,
D. Schulte

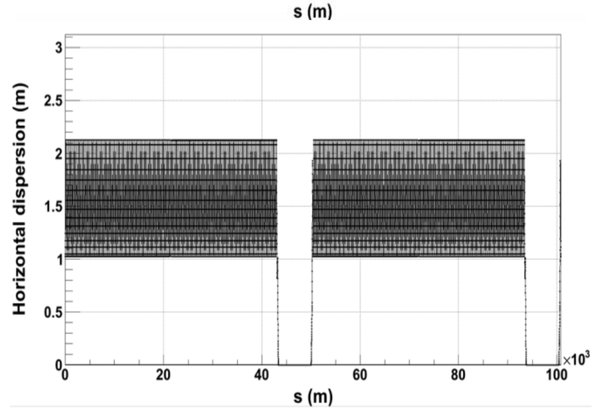
$\beta_{x,y}$ [m]



work in progress

D_x [m]

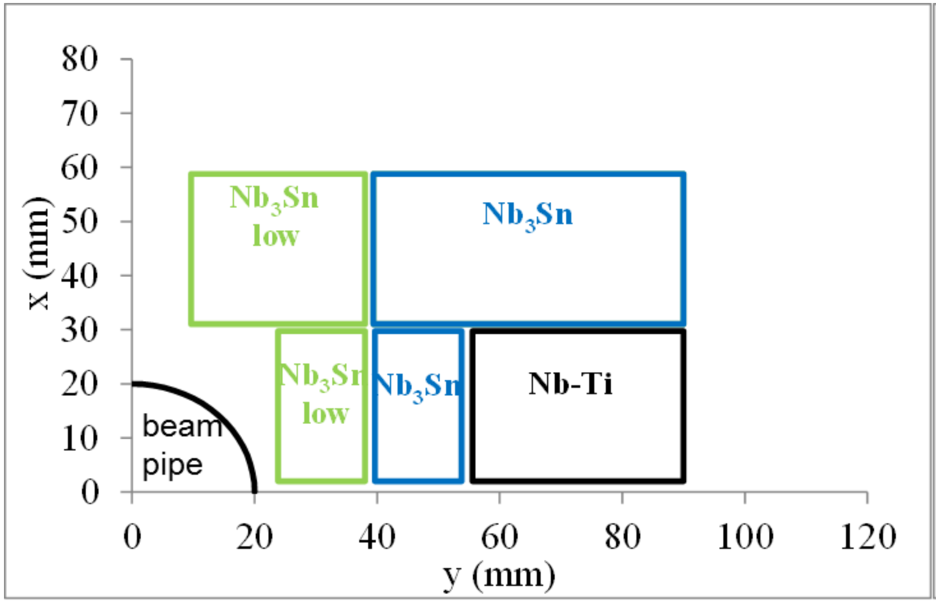




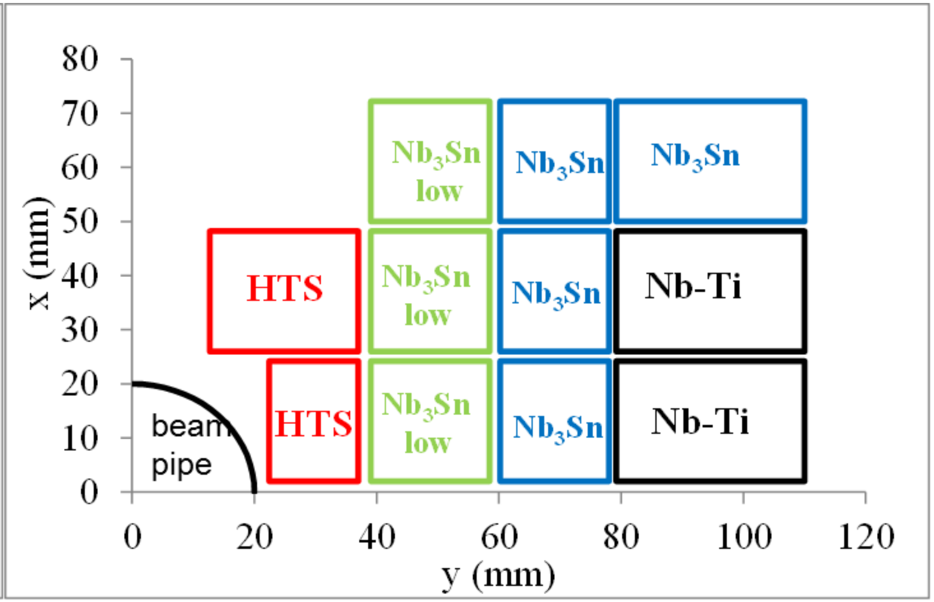
FODO arc optics,
cell length ~200 m

cost-optimized high-field dipole magnets

15-16 T: *Nb-Ti* & *Nb$_3$Sn*



20 T: *Nb-Ti* & *Nb$_3$Sn* & *HTS*



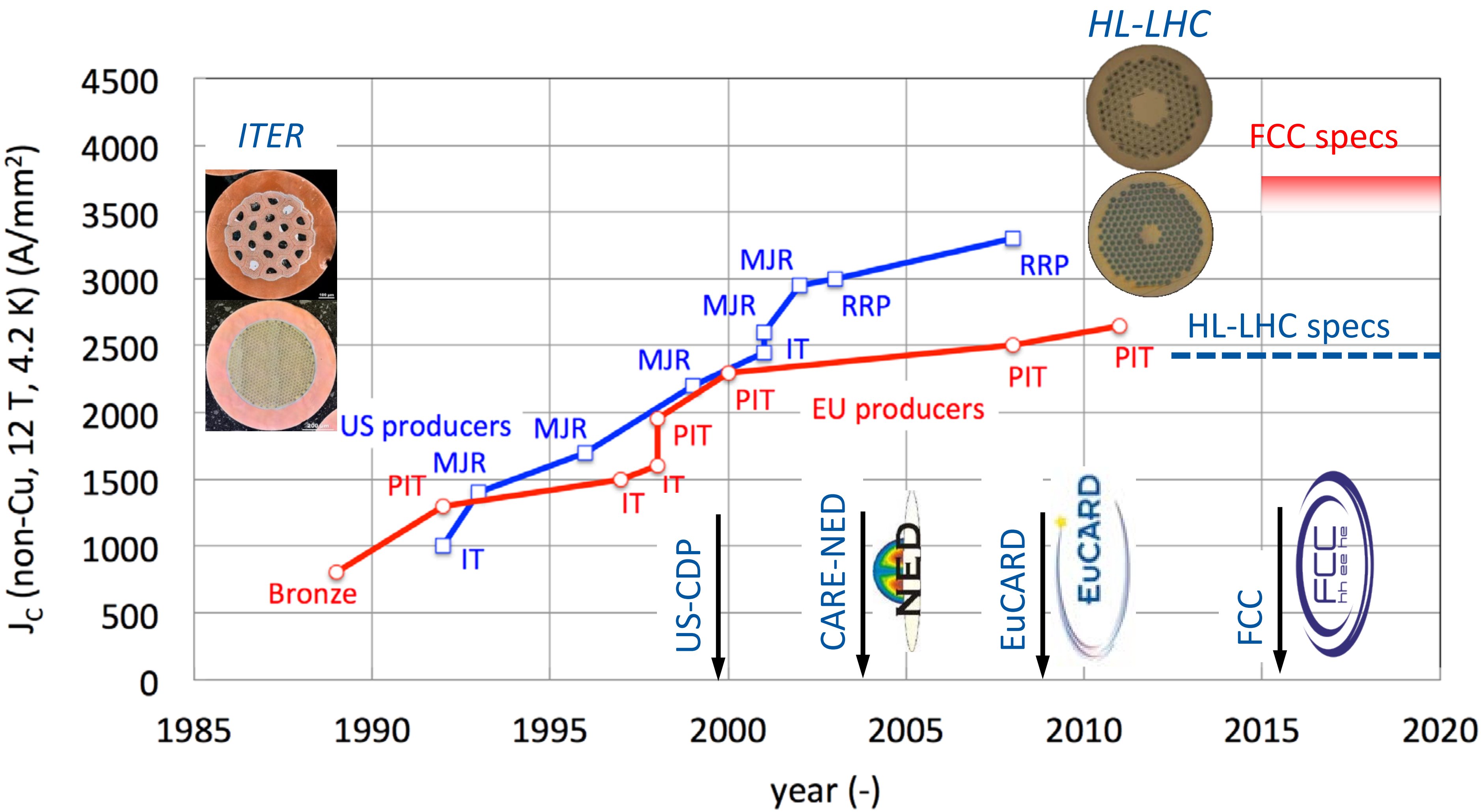
only a quarter is shown

“hybrid magnets”

example block-coil layout

L. Rossi, E. Todesco, P. McIntyre

From ITER- to HEP-class Nb_3Sn



L. Bottura

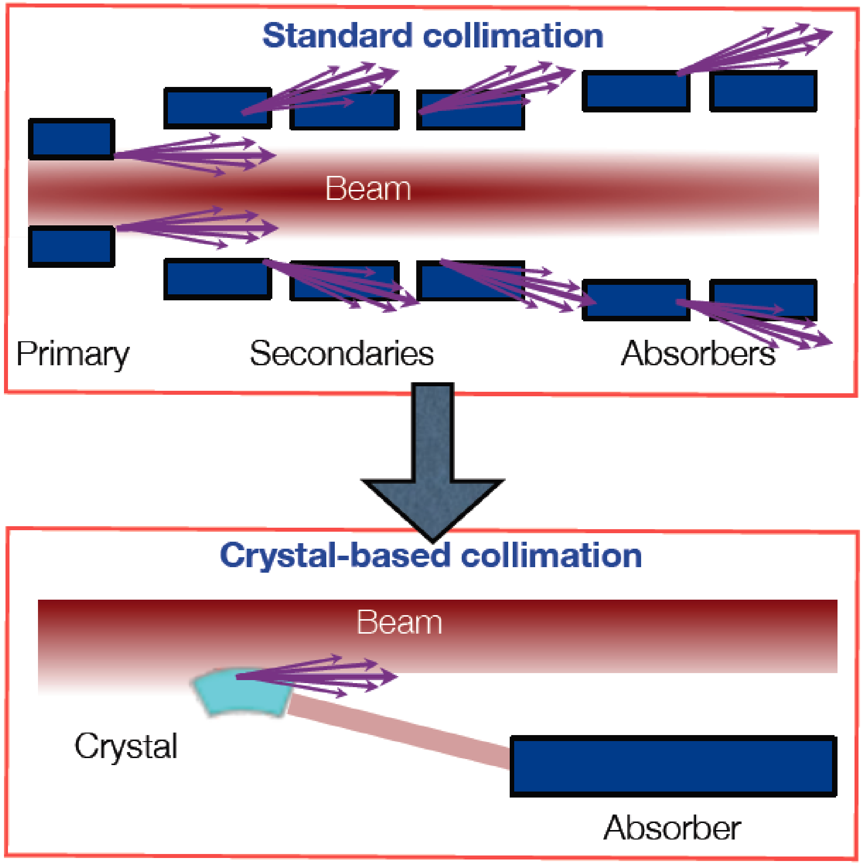
machine protection

energy per proton beam

LHC: 0.4 GJ → *FCC-hh*: 8 GJ (20x more !)

- kinetic energy of Airbus A380 at 720 km/h
- can melt 12 tons of copper, or drill a 300-m long hole

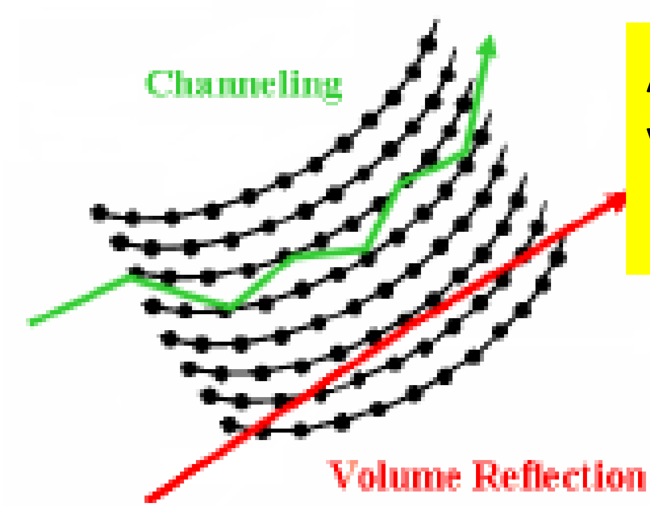
Crystal Collimation



LHC-type solution is baseline, but other approaches should be investigated:

- hollow e⁻ beam as collimator
- **crystals to extract particles**
- renewable collimators

D. Schulte,
S. Redaelli

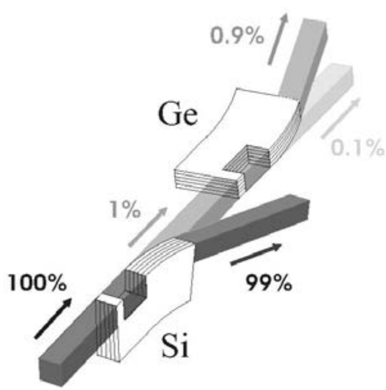


A. Lobko,
V. Tikhomirov,
INP Minsk

Channeling mode

− **crystal cut suppresses dechanneling**

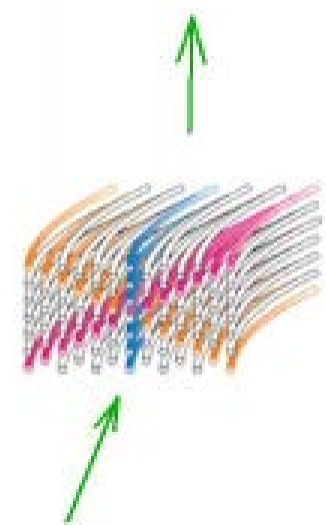
− increases channeling fraction from 85 to 99%



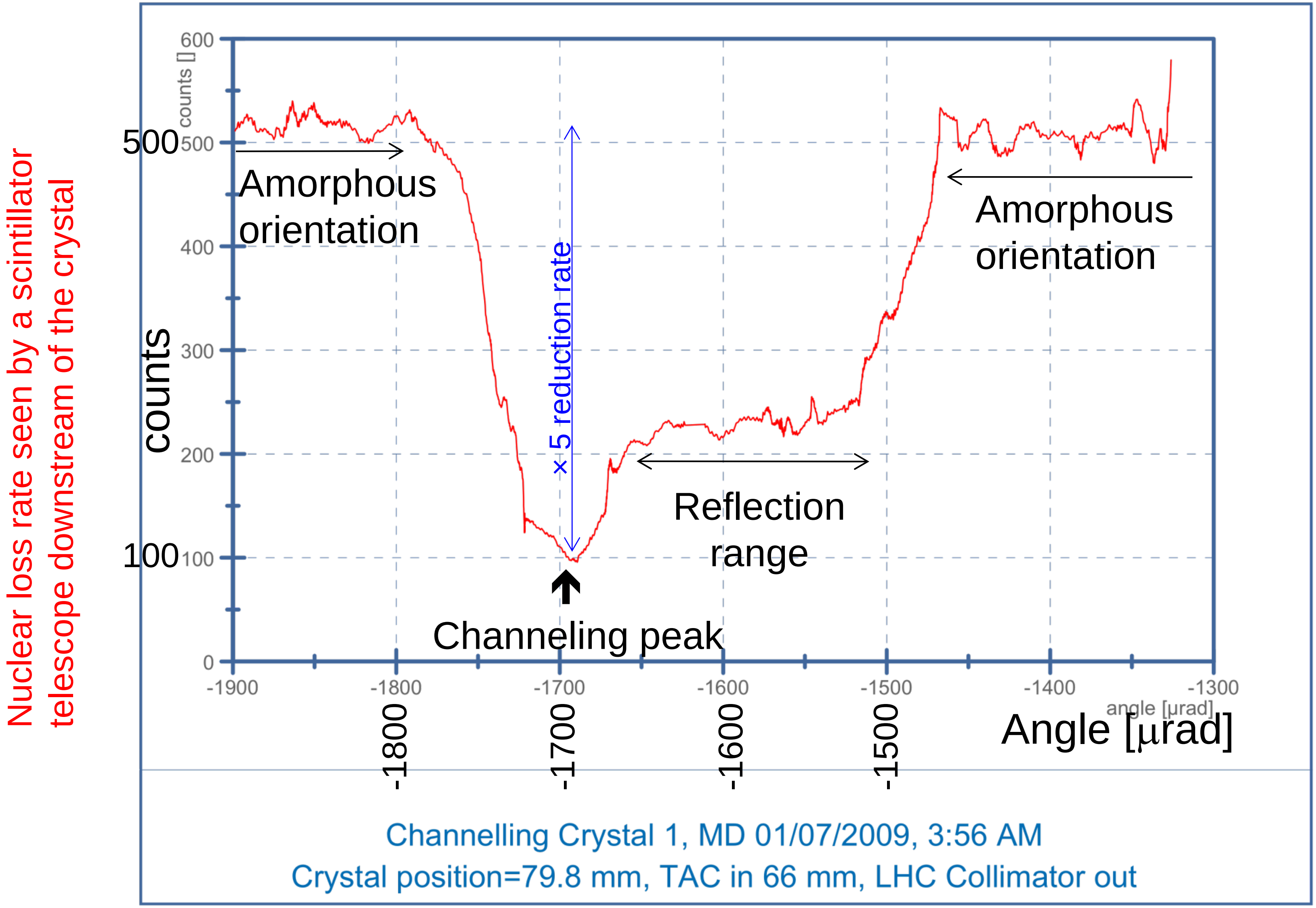
Volume reflection mode

− **multiple volume reflection** effect

− increases deflection angle to 5 times



crystal extraction experiment UA9



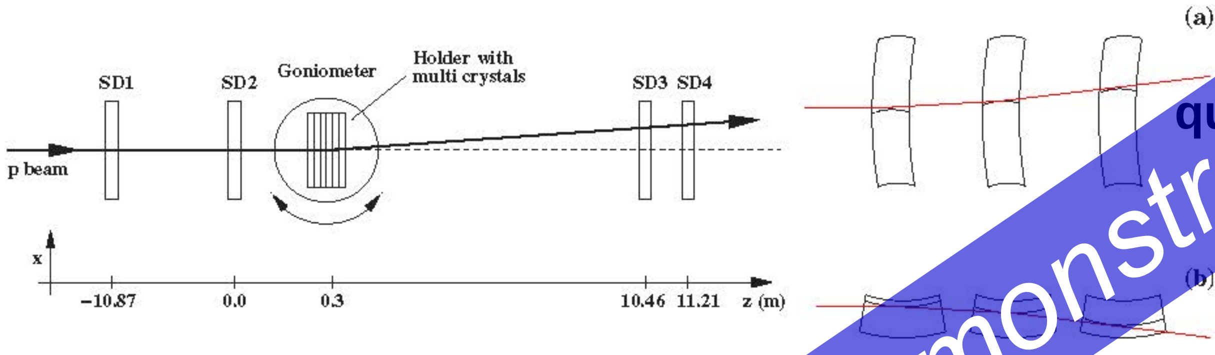
SPS

2009

Nuclear loss rate (including diffractive) strongly depressed

W. Scandale

staging of crystal deflectors

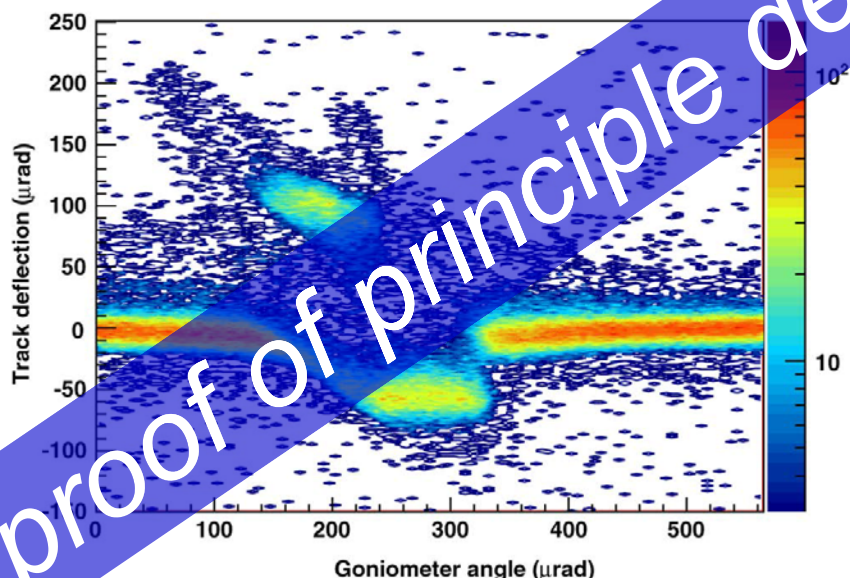


quasi-mosaic

strip crystals

schematic layout of the experimental setup used to study multiple volume reflection at the H8 beam line of the CERN SPS

proof of principle demonstration



6 strip crystals in series (each 2 mm long): **400 GeV/*c* protons reflected by 40±2 μrad** [effective field **16 T**] with **efficiency 0.93±0.04**

W. Scandale et al, Observation of Multiple Volume Reflection of Ultrarelativistic Protons by a Sequence of Several Bent Silicon Crystals, Phys.Rev.Lett. 102 (2009) 084801

Crystal Calorimetry

strong-field QED effects enhance radiation and pair production:

- production and measurement of e-, γ & hyperon polarization;
- reduced radiation length and calorimeter thickness;
- increased mass resolution

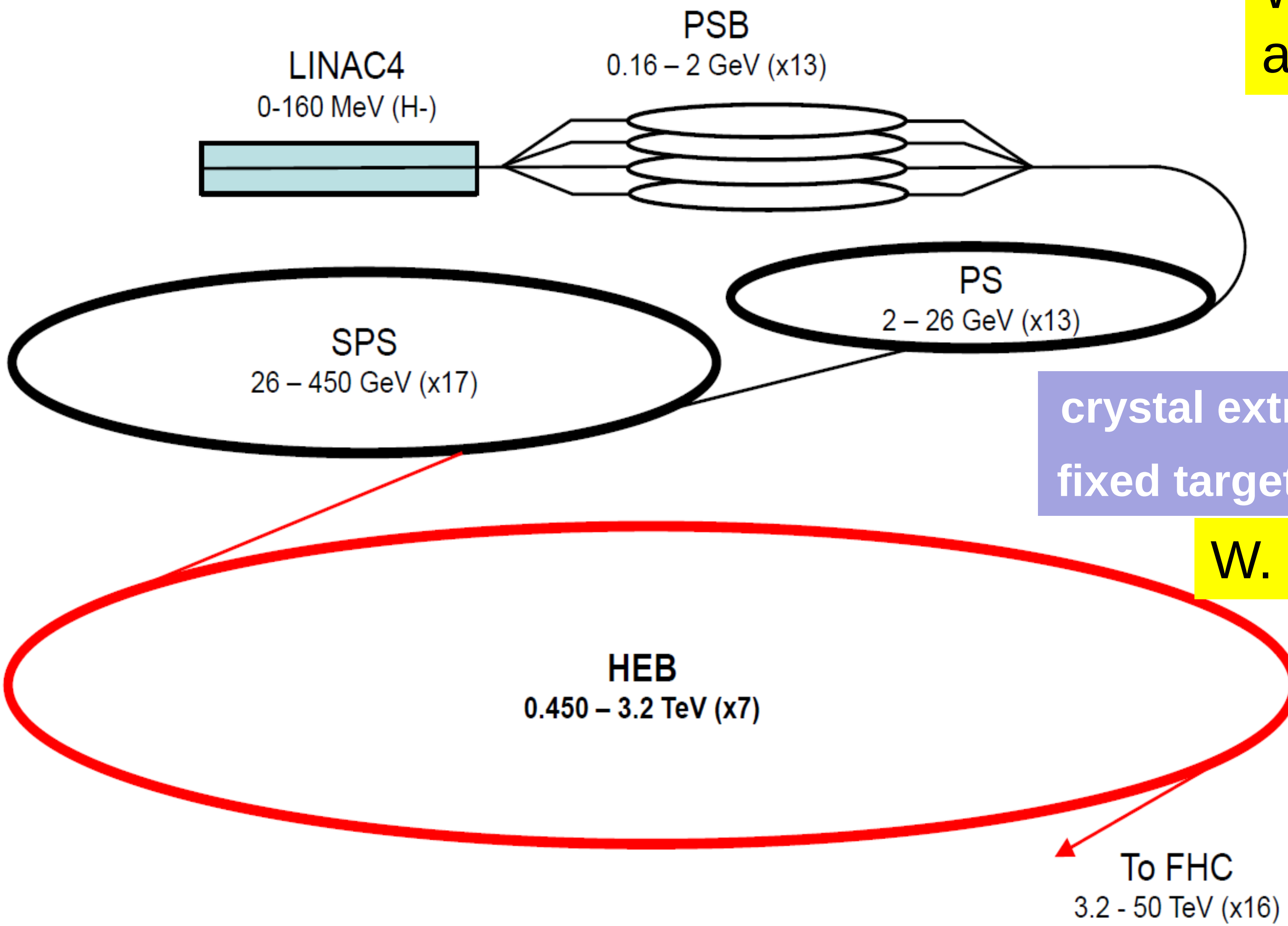
A. Lobko,
INP Minsk

FCC-hh injector complex

based on existing & planned (HL-LHC/LIU) injector chain;

HEB in LHC tunnel (e.g. modified LHC) or FCC tunnel

B. Goddard, W. Herr, et al.



crystal extraction for fixed target physics?!

W. Scandale

physics requirements for *FCC-ee*

- highest possible luminosity for a wide physics program ranging from the *Z* pole to the $t\bar{t}$ production threshold
  - *beam energy range from 45 GeV to 175 GeV*
- main physics programs / energies:
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *W (80 GeV): W pair production threshold,*
  - *H (120 GeV): ZH production (maximum rate of H's),*
  - *t (175 GeV): $t\bar{t}$ threshold*
- some polarization up to ≥80 GeV for beam energy calibration
- optimized for operation at 120 GeV?!

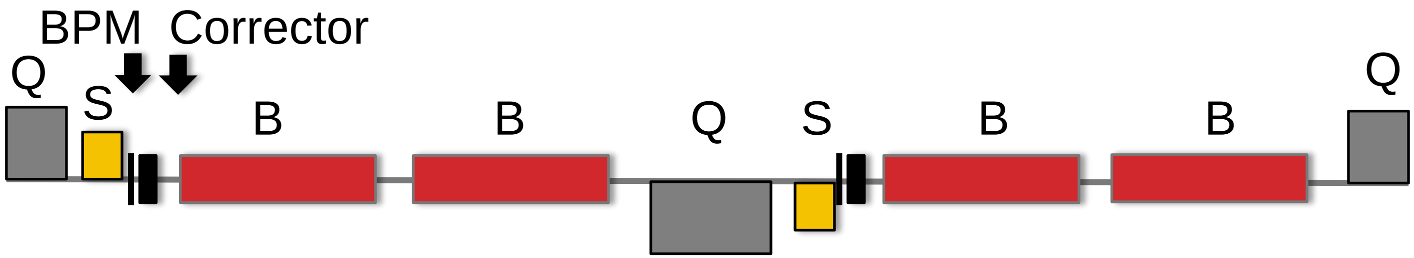
FCC-ee Key Parameters

Parameter	**FCC-ee**	LEP2
Energy/beam	45 – 175 GeV	105 GeV
Bunches/beam	**98 – 16700**	4
Beam current	**6.6 – 1450 mA**	3 mA
Luminosity/IP	**1.8-28** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$
Energy loss/turn	0.03-7.55 GeV	3.34 GeV
Synchr. power	**100 MW**	22 MW
RF Voltage	2.5 – **11 GV**	3.5 GV

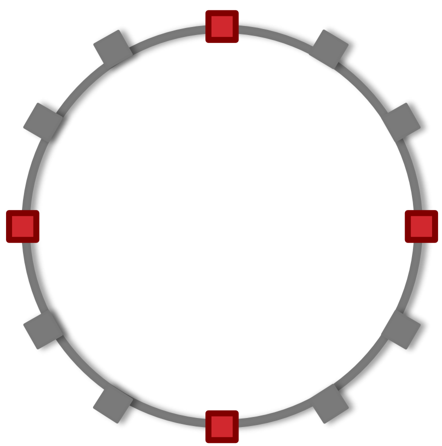
Preliminary, subject to evolution

LATTICE V12B-S

arc cell layout

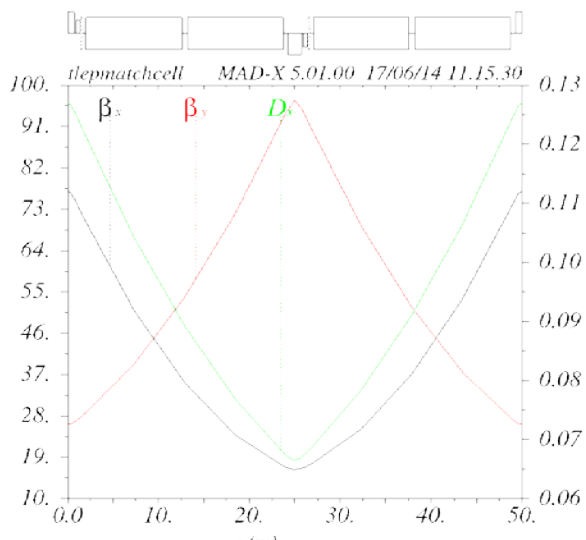


B = bending magnet, Q = quadrupole, S = sextupole

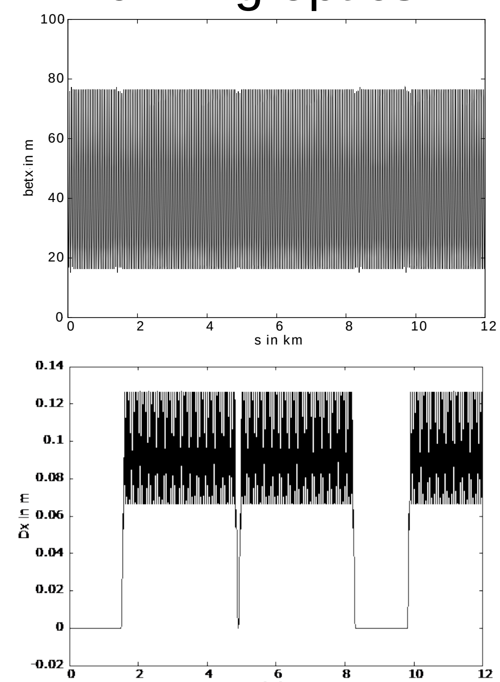


Circumference: **100 km**
Arc length: **2 × 3.4 km**
Straight section: **1.5 km**

FODO cell optics
cell length 50 m



full ring optics



B. Harer, B. Holzer

optics 175 & 120 → 80 & 45.5 GeV

80 GeV

175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

Half-bend dispersion suppressor

80 GeV: L_{cell} = 50 m, Ψ = 45°/45°

Dispersion suppressor based on quadrupoles

80 GeV: L_{cell} = 100 m, Ψ = 90°/60°

Arc cells

Dispersion Suppressor

Straight matching section (with RF)

Straight cells (with RF)

45.5 GeV

175 GeV and 120 GeV: L_{cell} = 50 m, Ψ = 90°/60°

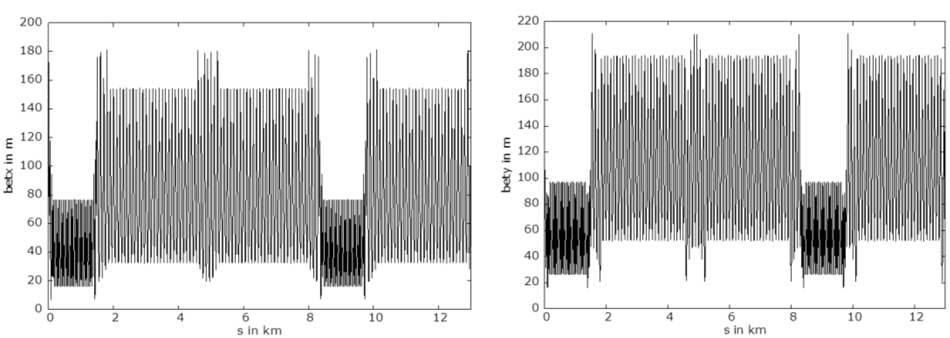
45.5 GeV: L_{cell} = 200 m, Ψ = 60°/60°

Dispersion suppressor based on quadrupoles

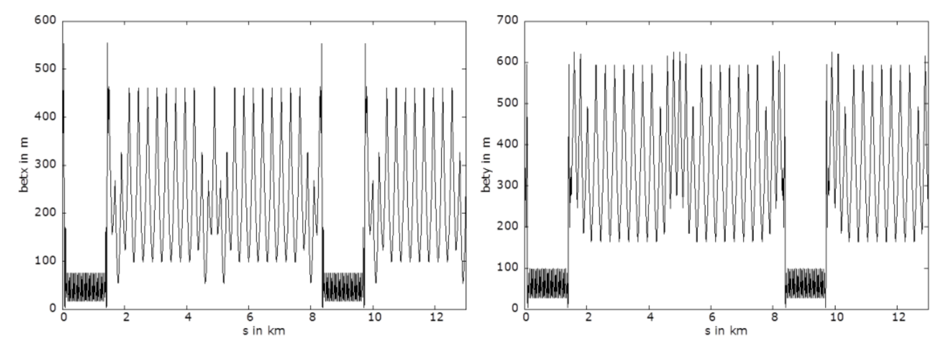
45.5 GeV: L_{cell} = 250 m, Ψ = 72°/72°

45.5 GeV: L_{cell} = 300 m, Ψ = 90°/60°

example: 100 m cell length



example: 300 m cell length



B. Harer, B. Holzer

all emittances ε_x ≤ 0.5 baseline

SC RF System

RF system requirements are characterized by two regimes.

- *High gradients for H and $t\bar{t}$ – up to ~11 GV.*
- *High beam loading with currents of ~1.5 A at the Z pole.*

RF system must be distributed over the ring to minimize energy excursions (~4.5% energy loss @ 175 GeV).

- *Optics errors driven by energy offsets, effect on η.*

Aiming for SC RF cavities with gradients of ~20 MV/m.

RF frequency of 400 or 800 MHz (current baseline).

- *Nano-beam / crab waist favors lower frequency, e.g. 400 MHz.*

Conversion efficiency (wall plug to RF power) is critical. Aiming for 75% or higher → R&D !

- *An important item for FCC-ee power budget.~65% achieved for LEP2.*

J. Wenninger, A. Butterworth, E. Jensen, et al.

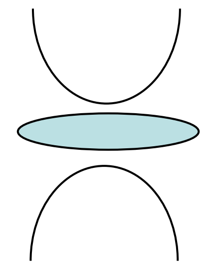
luminosity

$$e\,f\,k\,N = \text{beam current} \propto \frac{1}{E^4}$$

$$L = \frac{f\,k\,N^2}{4\pi\sigma_x\sigma_y} F\,H$$

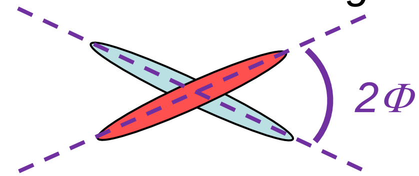
H ≤ 1

Hour-glass



F ≤ 1

Crossing angle



$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \le \xi_y^{\max}(E)$$

Beam-beam parameter

$$L \propto \frac{P_{SR}}{E^3}\frac{\xi_y}{\beta_y^*}$$

σ = beam size

k = no. bunches

f = rev. frequency

N = bunch population

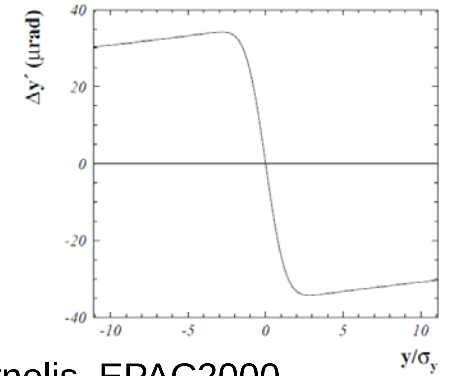
P_{SR} = synch. rad. power

β^* = betatron fct at IP (beam envelope)

J. Wenninger

beam-beam parameter

- beam-beam parameter ξ measures strength of field sensed by the particles in a collision
- beam-beam parameter limits are empirically scaled from LEP data (also 4 IPs)

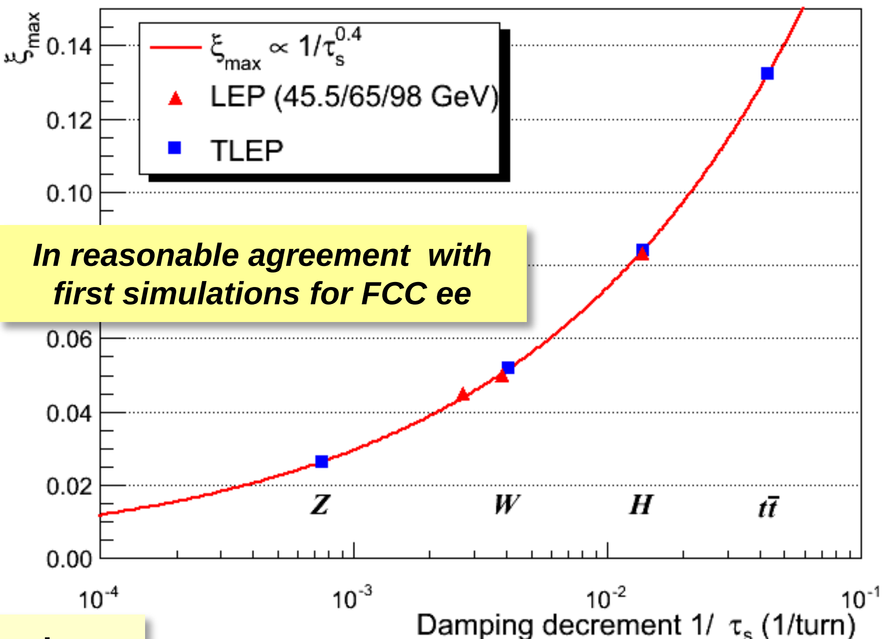


$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \le \xi_y^{\max}(E)$$

$$\xi_y^{\max}(E) \propto \frac{1}{\tau_s^{0.4}} \propto E^{1.2}$$

$$\Rightarrow \quad L \propto \frac{P_{SR}}{E^{1.8}} \frac{1}{\beta_y^*}$$

R. Assmann & K. Cornelis, EPAC2000



In reasonable agreement with first simulations for FCC ee

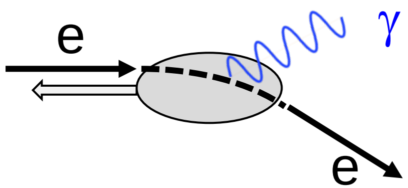
The beam-beam limit may be raised significantly with Crab-Waist schemes !

J. Wenninger, R. Assmann, S. White, K. Ohmi, D. Shatilov, et al.

beamstrahlung

- hard photon emission at the IPs, '*Beamstrahlung*', can become lifetime / performance limit for large bunch populations (N), small hor. beam size (σ_x) & short bunches (σ_s)

$$\tau_{bs} \propto \frac{\rho^{3/2}\sqrt{\eta}}{\sigma_s} \exp(A\eta\rho) \qquad \frac{1}{\rho} \approx \frac{N r_e}{\gamma \sigma_x \sigma_s}$$



ρ : mean bending radius at the IP (in the field of the opposing bunch)

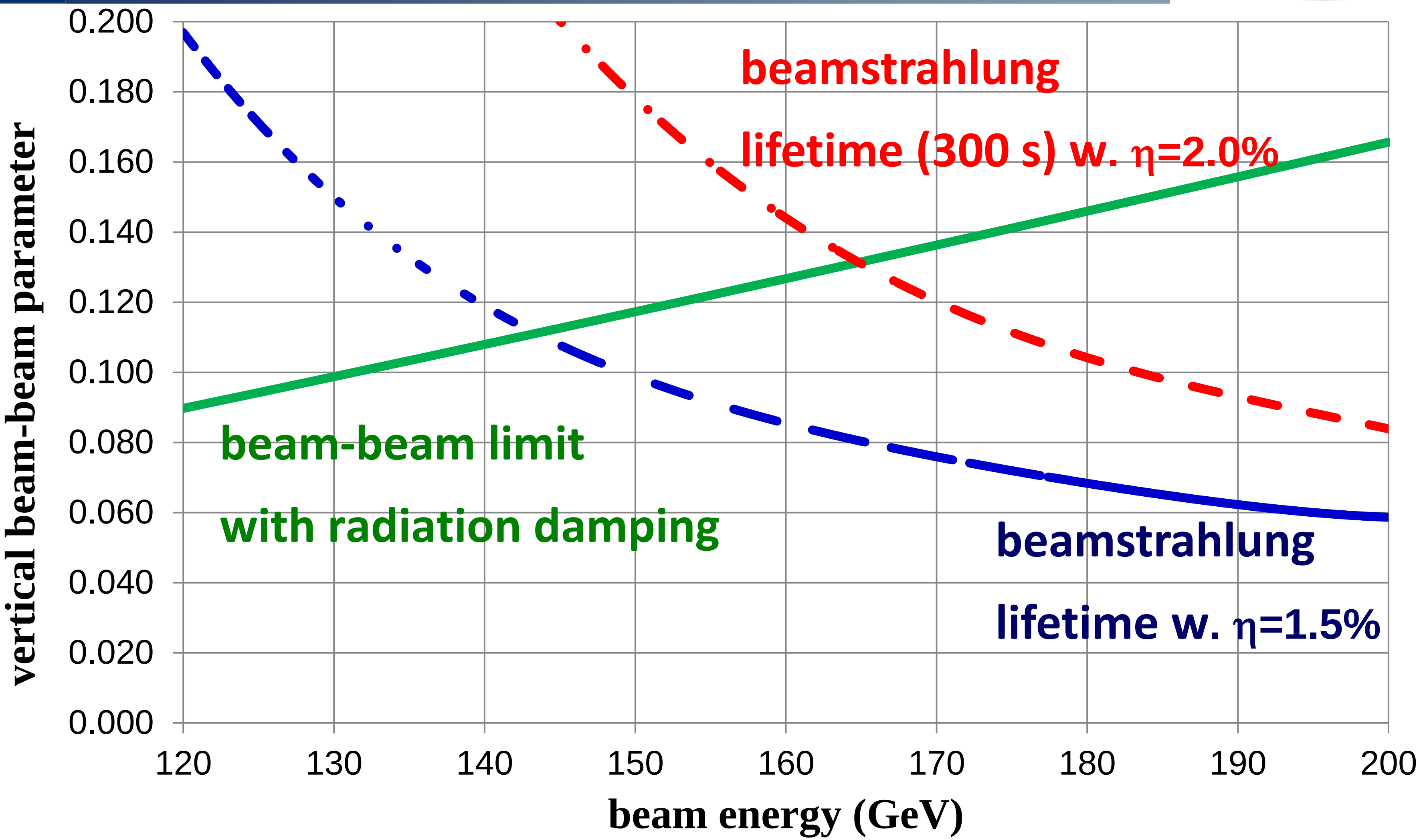
η : ring energy acceptance

lifetime expression by V. Telnov, modified version by A. Bogomyagkov et al

- to ensure an acceptable lifetime, ρ×η must be sufficiently large
  - *flat beams (large σ_x) !*
  - *bunch length !*
  - *large momentum acceptance of the lattice: **1.5 – 2% required**.*
    - LEP: < 1% acceptance, SuperKEKB ~ 1-1.5%.

J. Wenninger, et al

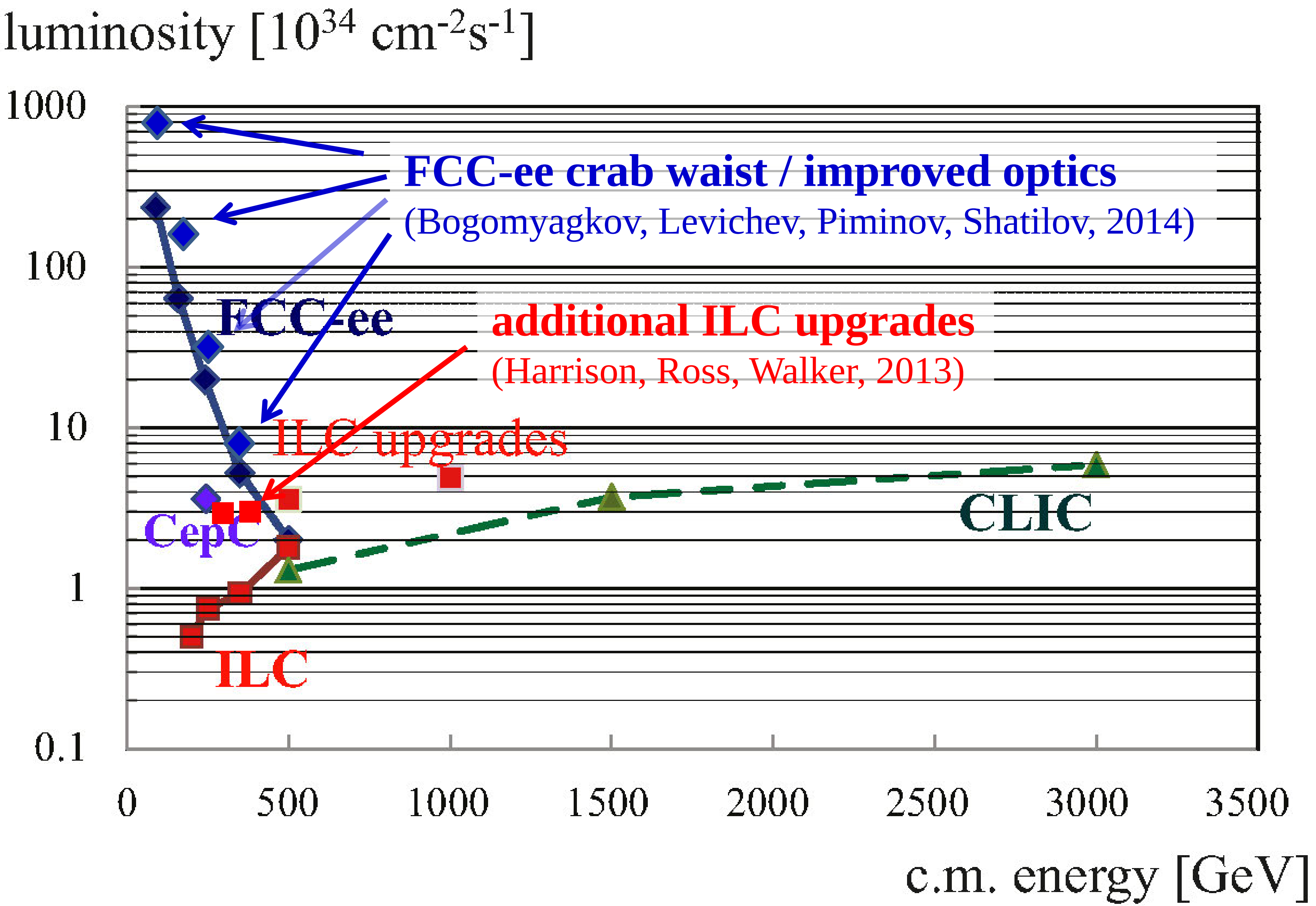
beam-beam limits: 2 regimes



ε_y = 2 pm,
β_y* = 1 mm

M. Koratzinos, A. Bogomyagkov, E. Levichev, D. Shatilov, K. Yokoya, V. Telnov, K. Oide, …

e^+e^- luminosity vs energy



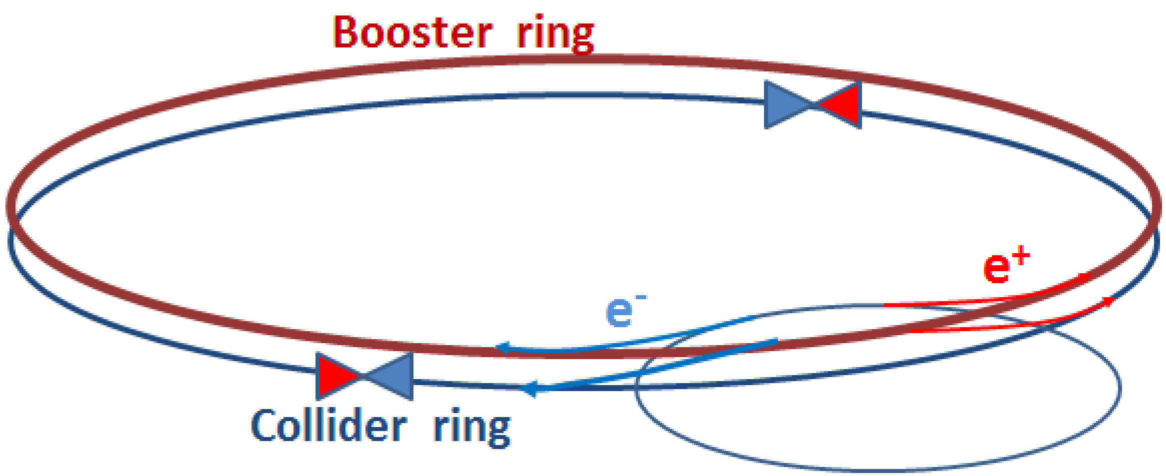
FCC-ee injection

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

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

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

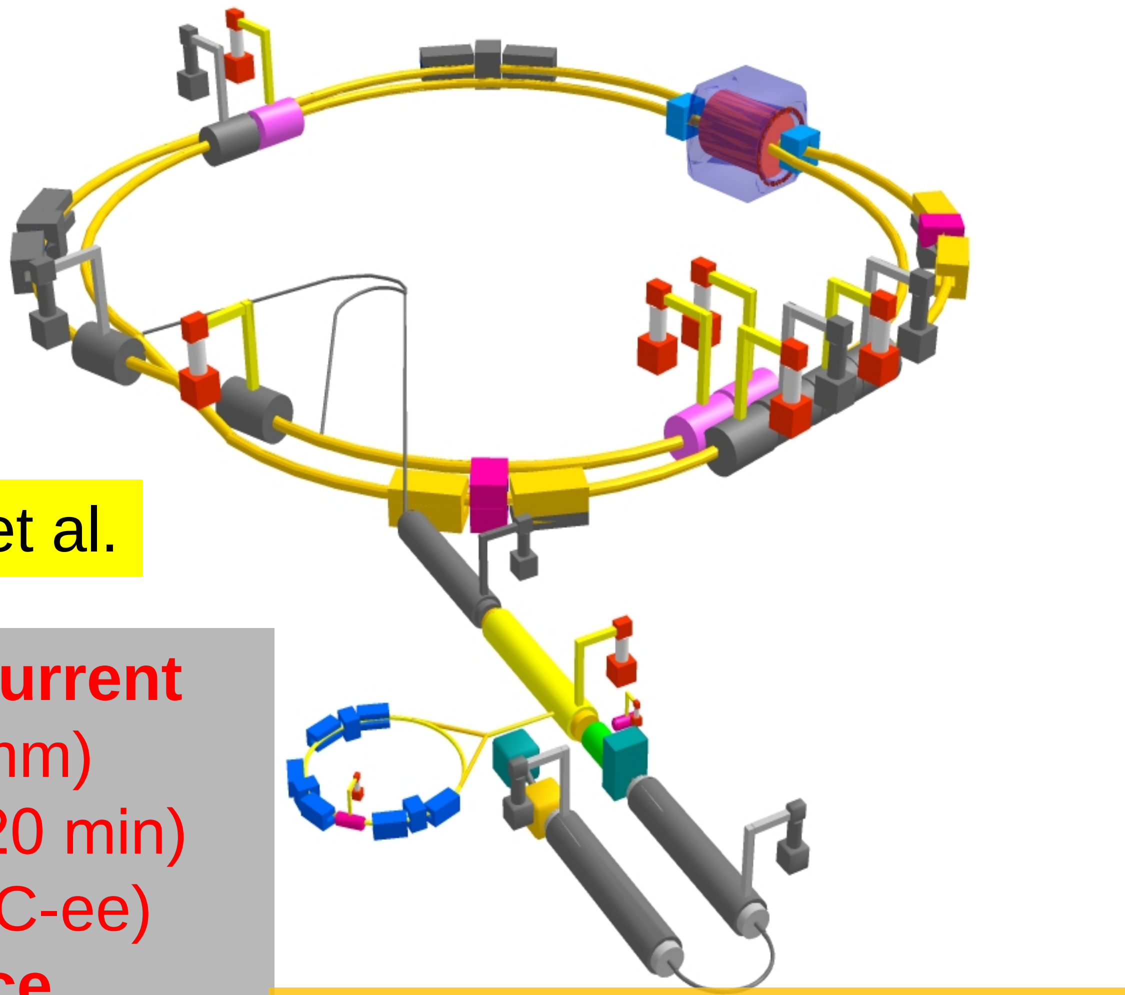
- Super-KEKB injector ~ almost suitable



A. Blondel

SuperKEKB = *FCC-ee* demonstrator

beam commissioning will start in 2015



K. Oide et al.

top up injection at high current

β_y^* =300 μm (FCC-ee: 1 mm)

lifetime 5 min (FCC-ee: ≥20 min)

$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)

off momentum acceptance
(±1.5%, similar to FCC-ee)

e^+ production rate (2.5×10^{12}/s,
FCC-ee: <1.5×10^{12}/s (*Z* cr.waist)

SuperKEKB goes beyond *FCC-ee*, testing all concepts

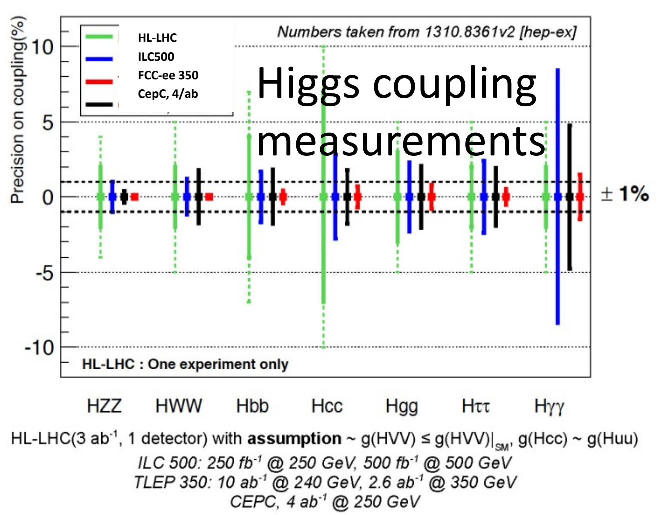
The Twin Frontiers of *FCC-ee* Physics

Precision Measurements

- Springboard for sensitivity to new physics
- Theoretical issues:
  - Higher-order QCD
  - Higher-order EW
  - Mixed QCD + EW

Rare Decays

- Direct searches for new physics
- Many opportunities
- Z: 10^{12}
- b, c, τ: 10^{11}
- W: 10^{8}
- H: 10^{6}
- t: 10^{6}



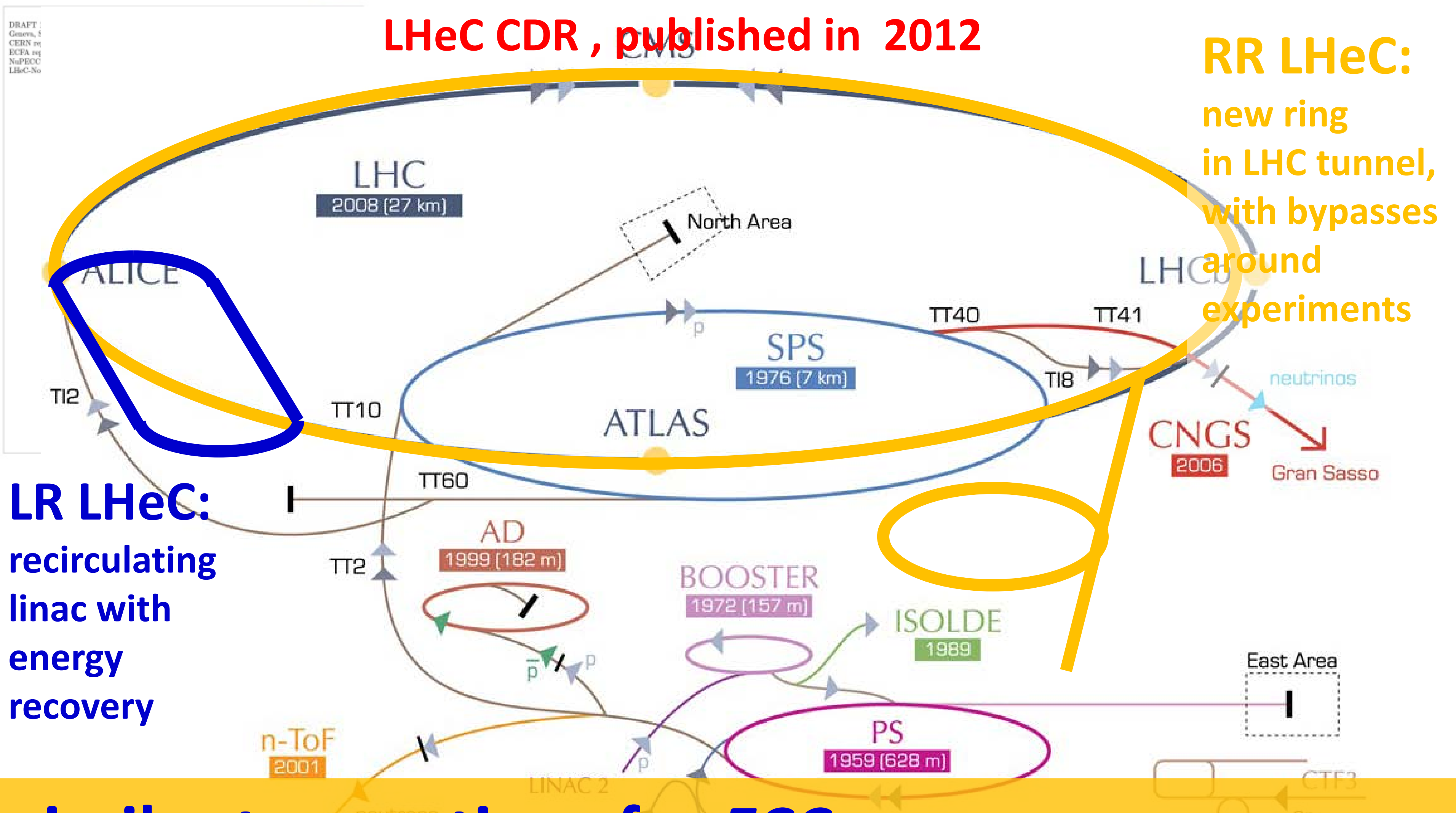
M. Bicer et al., “First Look at the Physics Case of TLEP,” JHEP 01, 164 (2014)
S. Dawson et al., arXiv:1310.8361v2

J. Ellis
P. Janot
M. Ruan

Crystal applications for FCC-ee, ILC or CLIC

- faster electromagnetic shower generation
- smaller electromagnetic calorimeters
- generation or measurement of beam polarization
- enhanced positron sources
- $e^{\pm}$ crystal collimation
- …

FCC-he: high-energy lepton-hadron collider



RR LHeC:
new ring
in LHC tunnel,
with bypasses
around
experiments

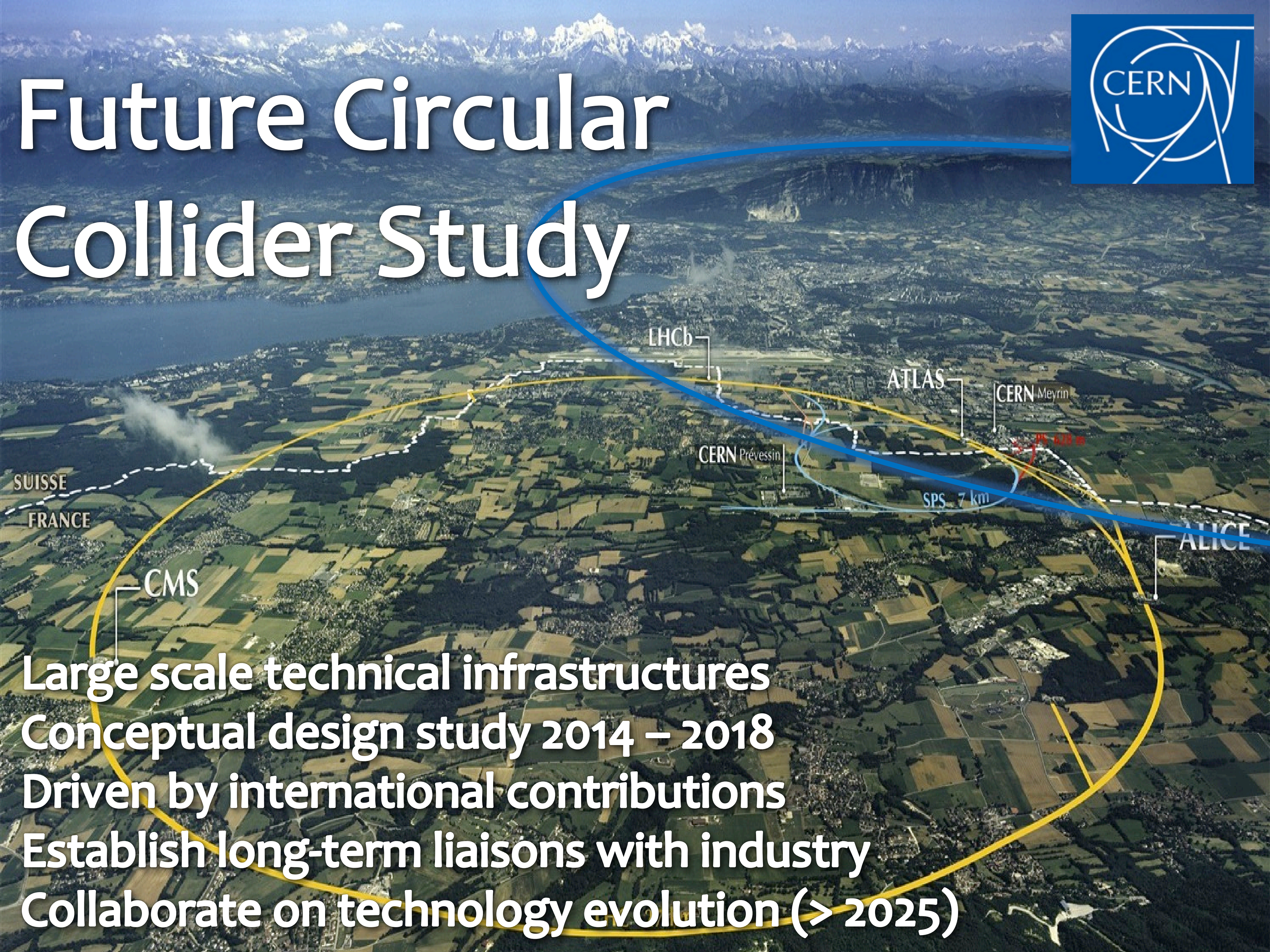
LR LHeC:
recirculating
linac with
energy
recovery

similar two options for *FCC*:
(1) *FCC-ee* ring, (2) ERL – from *LHeC* or new

FCC Key Technologies

- 16 T superconducting magnets
- Superconducting RF cavities
- RF power sources
- Affordable & reliable cryogenics
- Reliability & availability concepts

Future Circular Collider Study



- Large scale technical infrastructures
- Conceptual design study 2014 – 2018
- Driven by international contributions
- Establish long-term liaisons with industry
- Collaborate on technology evolution (> 2025)

presently signing FCC MoUs with partners

FCC MoU's 3 Oct. 2014

ALBA/CELLS, Spain
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CERN, Switzerland (Int'l)
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
CSIC/IFIC, Spain
DESY, Germany
EPFL, Switzerland
Gangneung-Wonju Nat. U., Korea
Goethe U. Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
IFJ PAN Krakow, Poland

INFN, Italy
INP Minsk, Belorussia
IPM, Iran
JAI/Oxford, UK
KEK, Japan
King's College London, UK
MEPhI, Russia
Northern Illinois U., USA
NC PHEP Minsk, Belorussia
Sapienza/Roma, Italy
UC Santa Barbara, USA
TU Darmstadt, Germany
TU Tampere, Finland
U. Geneva, Switzerland
U. Iowa, USA
U Silesia, Poland

FCC Study Coordination Group

Study Coordination	M. Benedikt, F. Zimmermann
Hadron Collider Physics and Experiments	F. Gianotti, A. Ball, M. Mangano
Lepton Collider Physics and Experiments	A. Blondel, J. Ellis, P. Janot
e-p Physics, Experiments, IP Integration	M. Klein, O. Bruning
Hadron Injectors	B. Goddard
Hadron Collider	D. Schulte, M. Syphers, J.M. Jimenez
Lepton Injectors	Y. Papaphilippou (tbc)
Lepton Collider	J. Wenninger, U. Wienands, J.M. Jimenez
Accelerator R & D Technologies	M. Benedikt, F. Zimmermann
Infrastructures and Operation	P. Lebrun, P. Collier
Costing Planning	F. Sonnemann, P. Lebrun

FCC Collaboration Board

- preparatory meeting 9-10 September 2014 at CERN (~80 participants, 1 / inst.)
- Leonid “Lenny” Rivkin (EPFL & PSI) unanimously elected as interim Collaboration Board Chair

FCC Horizon 2020 Design Study Proposal

submitted to Brussels on
2 September 2014

EuroCirCol

key aspects of 100 TeV energy frontier hadron collider:
conceptual design, feasibility, implementation scenario

Work Breakdown Structure

- **Physics and Experiments**
  - Hadron Collider Physics
  - Hadron Collider Experiments
  - Lepton Collider Physics
  - Lepton Collider Experiments
  - Lepton-Hadron Collider Physics
  - Lepton-Hadron Collider Experiment
- **Accelerators**
  - Hadron Injectors
  - Hadron Collider
  - Lepton Injectors
  - Lepton Collider
  - Lepton-Hadron Collider
  - Technology R&D
- **Infrastructures and Operation**
  - Civil Engineering
  - Technical Infrastructures
  - Operation and Energy Efficiency
  - Integration
  - Computing and Data Services
  - Safety, RP and Environment
- **Implementation and Planning**
  - Project Risk Assessment
  - Implementation Scenarios
  - Cost Models
- **Study and Quality Management**
  - Study Administration
  - Communications
  - Conceptual Design Report

M. Benedikt,
J. Gutleber

WBS – H2020 EU DS proposal

- **Physics and Experiments**
  - Hadron Collider Physics
  - Hadron Collider Experiments
  - Lepton Collider Physics
  - Lepton Collider Experiments
  - Lepton-Hadron Collider Physics
  - Lepton-Hadron Collider Experiment
- **Accelerators**
  - Hadron Injectors
  - Hadron Collider
  - Lepton Injectors
  - Lepton Collider
  - Lepton-Hadron Collider
  - Technology R&D
- **Infrastructures and Operation**
  - Civil Engineering
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  - Operation and Energy Efficiency
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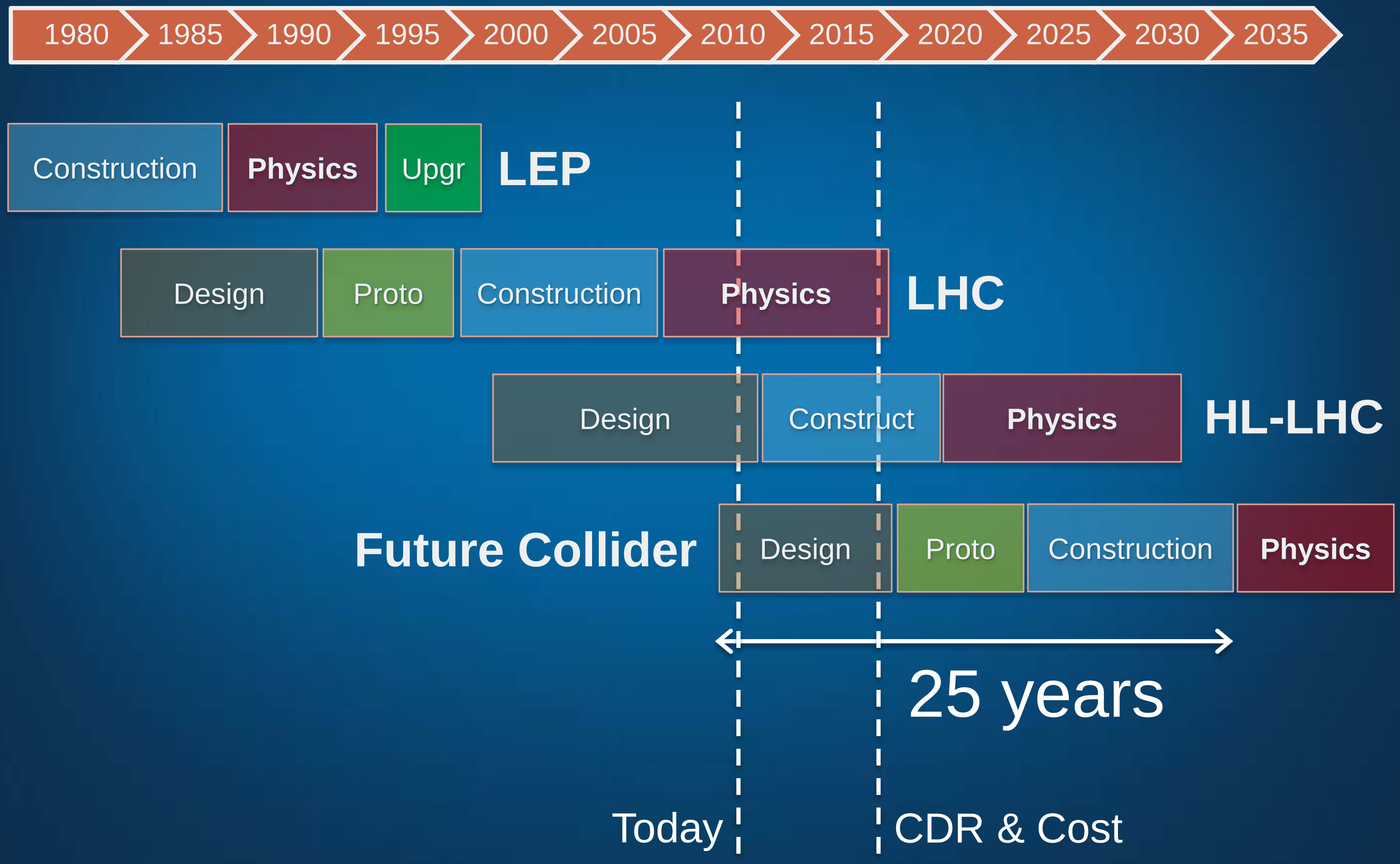
  - Study Administration
  - Communications
  - Conceptual Design Report

M. Benedikt, J. Gutleber

HEP Timescale



First FCC Week

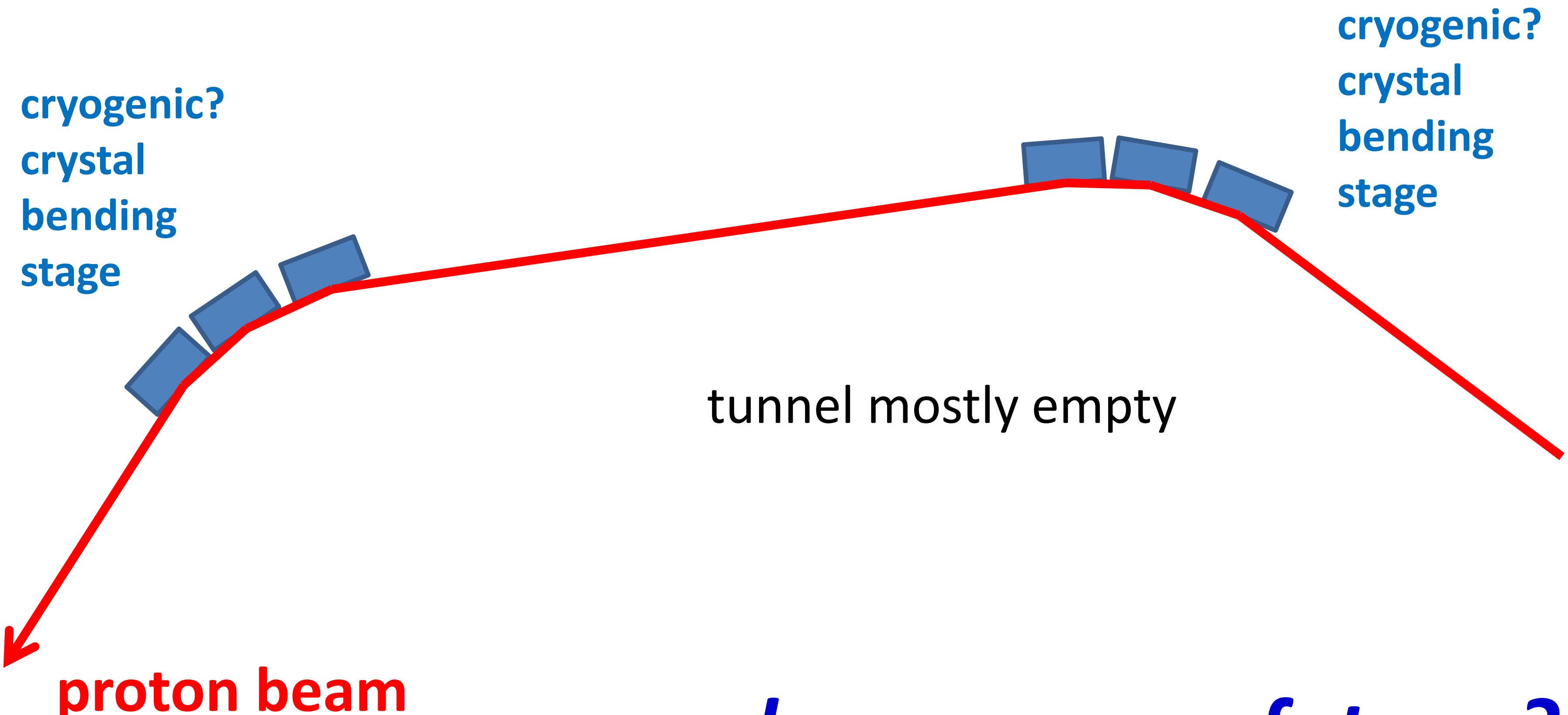
Conference

Washington DC
23-27 March 2015

http://cern.ch/fccw2015

how to go further?

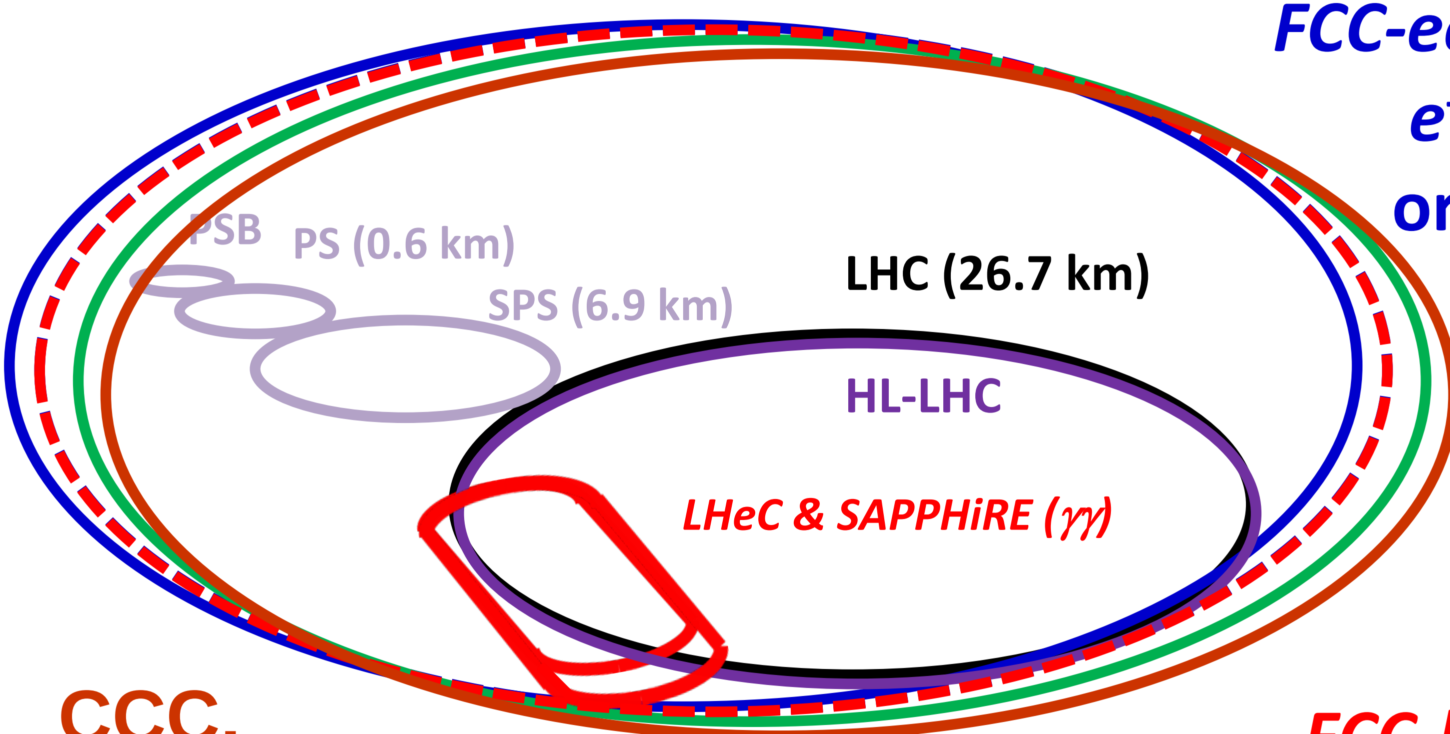
circular crystal collider?



a dream or our future ?

energy ramp using induction acceleration?

possible evolution of FCC complex



FCC-ee **(80-100 km, e^+e^-, up to 350 or 500 GeV c.m.)**

FCC-hh **(*pp* up to 100 TeV c.m. & *AA*)**

CCC, > 1 PeV

LHeC as FCC-ee injector?

LHeC-based FCC-he collider?!

FCC-he **as ring-ring collider ?!**

FCC-he: $e^{\pm}$ (60-250 GeV) – *p*(50 TeV)/A collisions

≥50 years e^+e^-, *pp*, $e^{\pm}p/A$ physics at highest energies

followed by >1 PeV circular crystal collider (CCC)?!?

and on the linear route …

dielectric & plasma accelerators

dielectric materials (quartz, diamond, garnets,.)

higher breakdown limits than metals;

dielectric structures driven in THz,

optical or near-IR regime

G=1-3 GV/m

driven by e^- beam or by laser (external fiber laser or integrated semiconductor laser)

plasma acceleration

G≈ 100 GV/m (n_0 [10^{18} cm^{-3}])$^{1/2}$; $n_0 \approx 10^{17}$-10^{18} cm^{-3}

driven by laser, e^- beam, or p beam

unlimited acceleration is predicted to be possible ?!

Kostyukov, Nerush, Litvak, 2012

crystal accelerators

acceleration in crystal channels

G≈ 10 TV/m (n_0 [10^{22} cm^{-3}]$)^{1/2}$; n_0 ≈10^{22}-10^{23} cm^{-3}

driven by x-ray laser

now/soon available!
LCLS, Spring-8, XFEL, SwissFEL …

<u>max. energy</u> set by radiation emission due to betatron oscillations between crystal planes

E_{max} ≈300 GeV for e^+, 10^4 TeV μ, 10^6 TeV for p ?!

Chen & Noble 1997; Dodin & Fisch 2008; Shiltsev '12

[*is there no equivalent limit for lower-density plasmas?*]

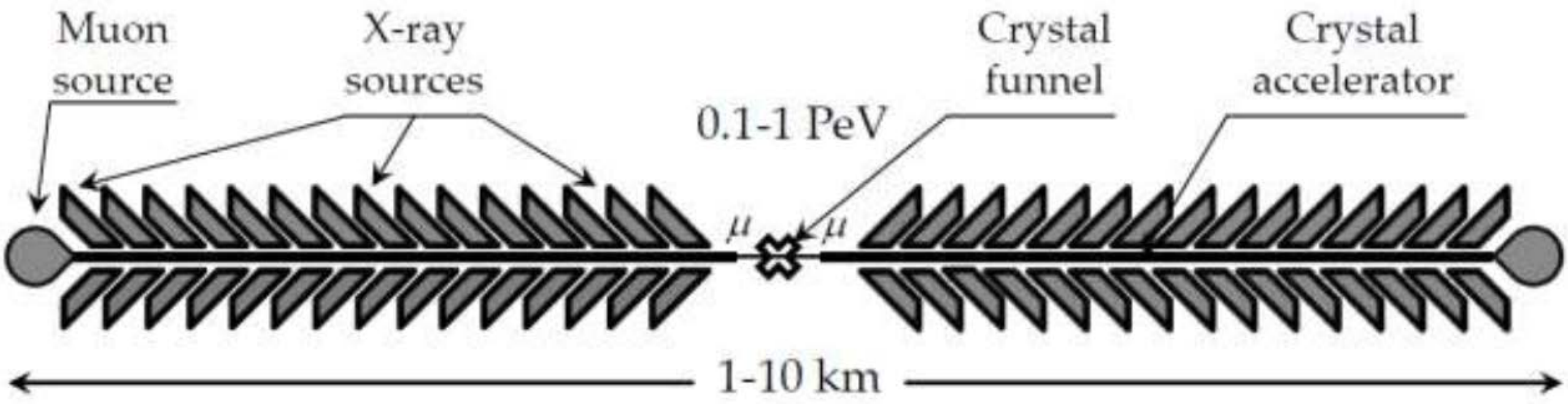
10 TV/m – disposable crystal accelerator

or 0.1 TV/m – reusable crystal accelerator

side injection of x-ray pulses using long fibers e$^{\pm}$ may soon run out of steam in the high-gradient world!

→ need to change particle type

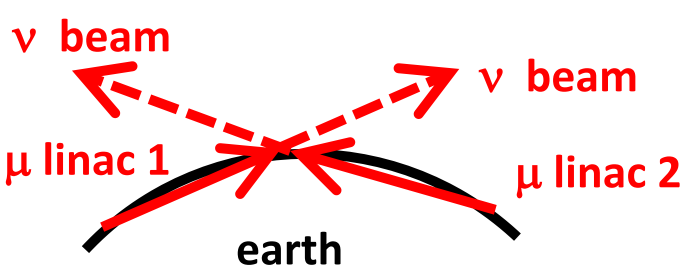
linear X-ray crystal μ collider



issues:

μ production rate

neutrino radiation



Vladimir Shiltsev, 2012

highest-energy particles

4 July 2012 CERN, Geneva, Switzerland

Higgs boson – "God particle"? – mass $1.25x10^{11}$ eV, neither matter nor force!

15 October 1991 Dugway Proving Ground, Utah, U.S.A.

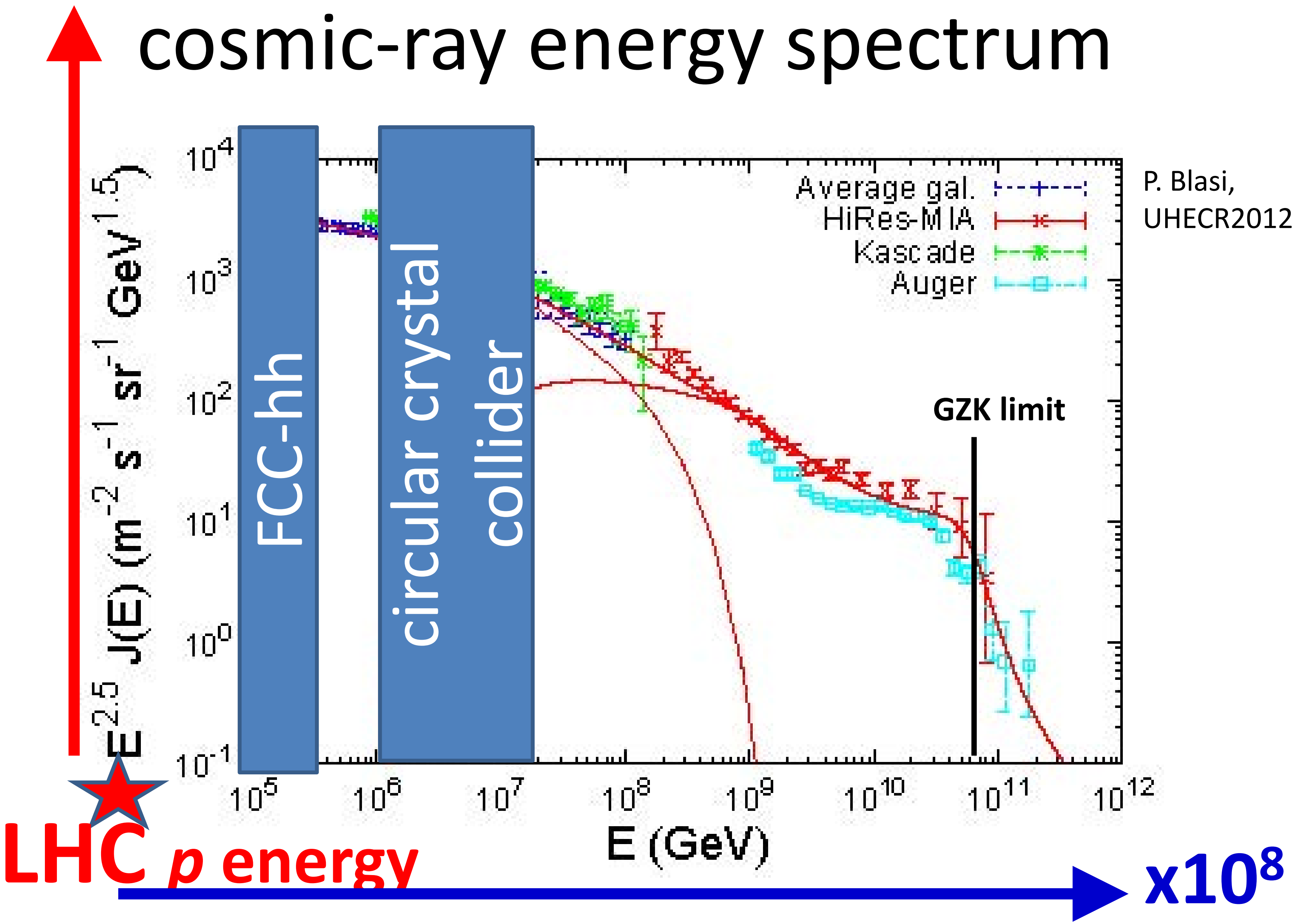
"Oh-my-God-particle"!

(kinetic) energy $3x10^{20}$ eV

($=3x10^{11}$ GeV = 300 EeV)!

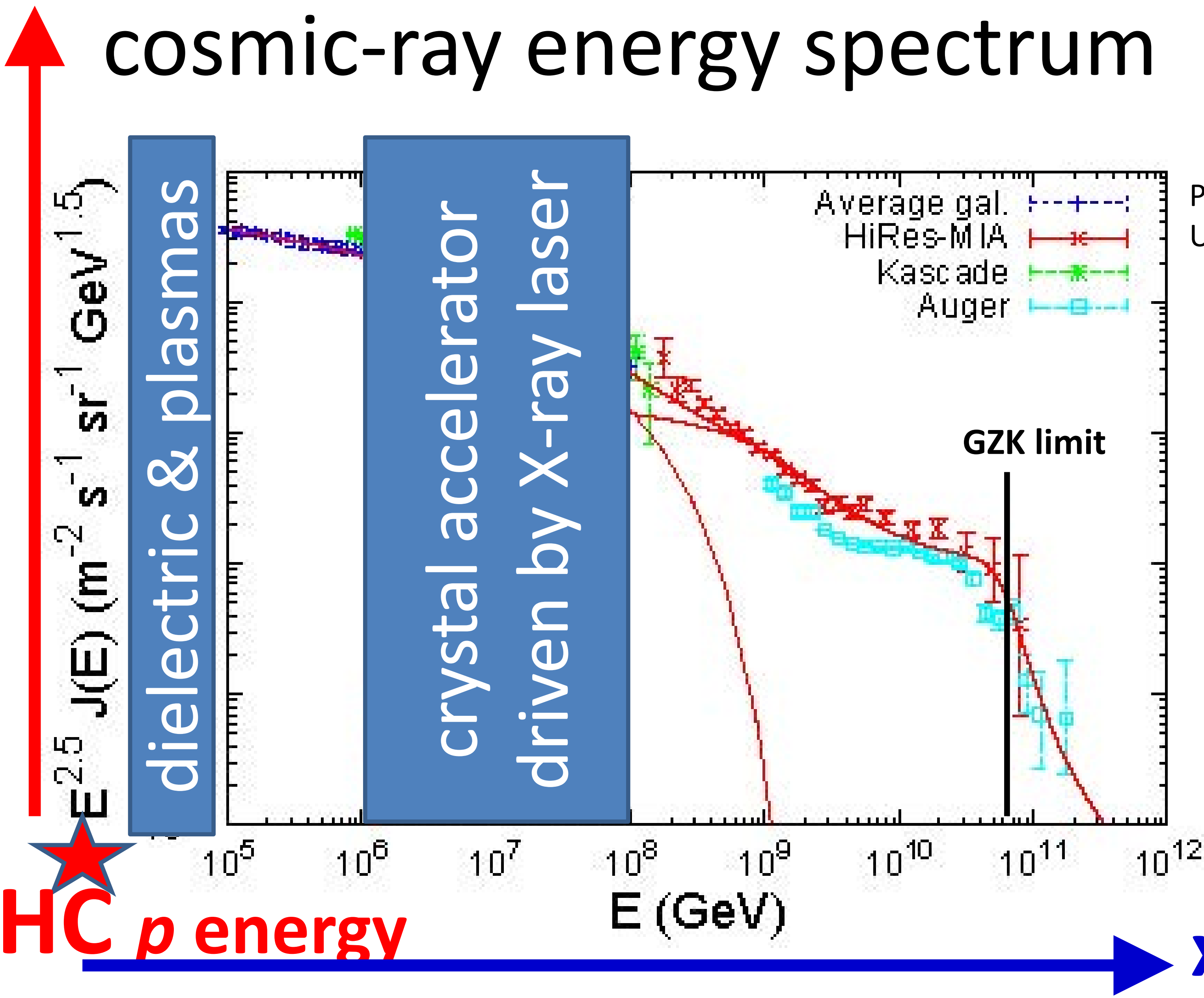
10^{45} m^{-2}s^{-1}sr^{-1}GeV$^{1.5}$!

cosmic-ray energy spectrum



cosmic-ray energy spectrum

10^{45} m^{-2}s^{-1}sr^{-1}GeV$^{1.5}$!



P. Blasi, UHECR2012

LHC *p* energy

x10^8

ultimate limit of electromagnetic acceleration

$E_{cr} \approx 10^{18}$ V/m critical field for e^+e^- pair creation - $\hbar/(m_e c)\, e\, E_{cr} \sim m_e c^2$

reaching Planck scale of 10^{28} eV would need 10^{10} m long accelerator [10^{10} m= 1/10th of distance earth-sun]

"*not an inconceivable task for an advanced technological society*"

P. Chen, R, Noble, SLAC-PUB-7402, April 1998

Summary

bright future for accelerator-based HEP!

- HL-LHC prepares FCC technology
- Channeling conferences look beyond

several different routes to 10-TeV/100-TeV & 1 PeV collisions

e.g. linear path: ILC→CLIC →DWAC→ XRCMC

circular path: FCC-ee→FCC-hh→CCC

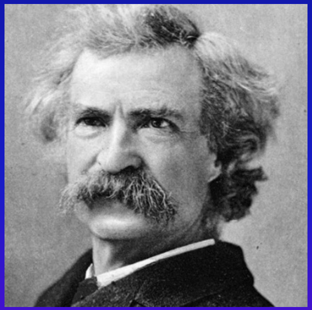
crystals are key for both:

bending and/or acceleration

eventually outer-space solar-system accelerator needed to reach Planck mass

is future circular or linear or both?

“A circle is a round straight line with a hole in the middle.”



Mark Twain,
in "English as She Is Taught",
Century Magazine, May 1887

First FCC Week

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http://cern.ch/fccw2015

spare slides

European Strategy Update 2013

Design studies and R&D at the energy frontier

….“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

d) ***CERN should undertake design studies for accelerator projects in a global context,***

- *with emphasis on **proton-proton and electron-positron high-energy frontier machines**.*
- *These design studies should be coupled to a vigorous accelerator **R&D programme, including high-field magnets and high-gradient accelerating structures**,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

strategy adopted at Brussels in May 2013, during exceptional session of the CERN Council in presence of the European Commission

parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		16 (20)
circumference [km]	26.7		100 (83)
luminosity [10^{34} $cm^{-2}s^{-1}$]	1	5	5 [→20?]
bunch spacing [ns]	25		25 (5)
events / bunch crossing	**27**	**135**	**170 (34)**
bunch population [10^{11}]	1.15	2.2	1 (0.2)
norm. transverse emitt. [μm]	3.75	2.5	2.2 (0.44)
IP beta-function [m]	0.55	0.15	1.1
IP beam size [μm]	16.7	7.1	6.8 (3)
synchrotron rad. [W/m/aperture]	0.17	0.33	28 (44)
critical energy [keV]	0.044		4.3 (5.5)
total syn.rad. power [MW]	**0.0072**	**0.0146**	**4.8 (5.8)**
longitudinal damping time [h]	**12.9**		**0.54 (0.32)**

FCC-hh as heavy-ion collider

preliminary parameters

	Unit	LHC Design	FCC-hh	FCC-hh
operation mode	-	*Pb-Pb*	*Pb-Pb*	*p-Pb*
number of bunches		592	432	432
part. / bunch	[10^8]	0.7	1.4	115(1.4)/1.4
β-functionat IP	[m]	0.5	1.1	1.1
RMS beam size at IP	[um]	15.9	8.8	8.8
initial luminosity	[$10^{27}cm^{-2}s^{-1}$]	1	3.2	267(3.2)
peak luminosity	[$10^{27}cm^{-2}s^{-1}$]	1	12.7	5477(3356)
integr. lumi. per fill	[μb^{-1}]	<15	83	30240
total cross-section	[b]	515	597	2
initial luminosity lifetime	[h]	<5.6	3.7	3.2 (10.6)

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parameter	LEP2	FCC-ee					CepC
		Z	Z (c.w.)	W	H	t	H
E_{beam} [GeV]	104	45	45	80	120	175	120
circumference [km]	26.7	100	100	100	100	100	54
current [mA]	3.0	1450	1431	152	30	6.6	16.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4	3.7
ε_x [nm]	22	29	0.14	3.3	0.94	2	6.8
ε_y [pm]	250	60	1	1	2	2	20
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0	0.8
β^*_y [mm]	50	1	1	1	1	1	1.2
σ^*_y [nm]	3500	250	32	130	44	45	160
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16	2.3
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49	2.7
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73	0.61
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7	1.8
τ_{beam} [min]	300	287	39	72	30	23	40

collider parameters	FCC ERL	FCC-ee ring		protons
species	e^- (e^+?)	$e^\pm$	$e^\pm$	*p*
beam energy [GeV]	60	60	120	50000
bunches / beam	-	10600	1360	10600
bunch intensity [10^{11}]	0.05	0.94	0.46	1.0
beam current [mA]	25.6	480	30	500
rms bunch length [cm]	0.02	0.15	0.12	8
rms emittance [nm]	0.17	1.9 (*x*)	0.94 (*x*)	0.04 [0.02 *y*]
$\beta_{x,y}$*[mm]	94	8, 4	17, 8.5	400 [200 *y*]
$\sigma_{x,y}$* [μm]	4.0	4.0, 2.0		equal
beam-b. parameter ξ	(*D*=2)	**0.13**	**0.13**	0.022 (0.0002)
hourglass reduction	0.92 (H_D=1.35)	**~0.21**	~0.39	
CM energy [TeV]	3.5	3.5	4.9	
luminosity[10^{34}cm^{-2}s^{-1}]	**1.0**	**6.2**	**0.7**	

preliminary FCC-he parameters shown at ICHEP'14

International Linear Collider (ILC) - 2

Japanese HEP community expressed interest in hosting the ILC. Site chosen: 北上市 (Kitakami) in Northern Japan. Now 2-year review process by Japanese MEXT.