Future Highest-Energy Circular Colliders

F. Zimmermann, CERN BE/ABP

Corfu Workshop, 12 September 2014

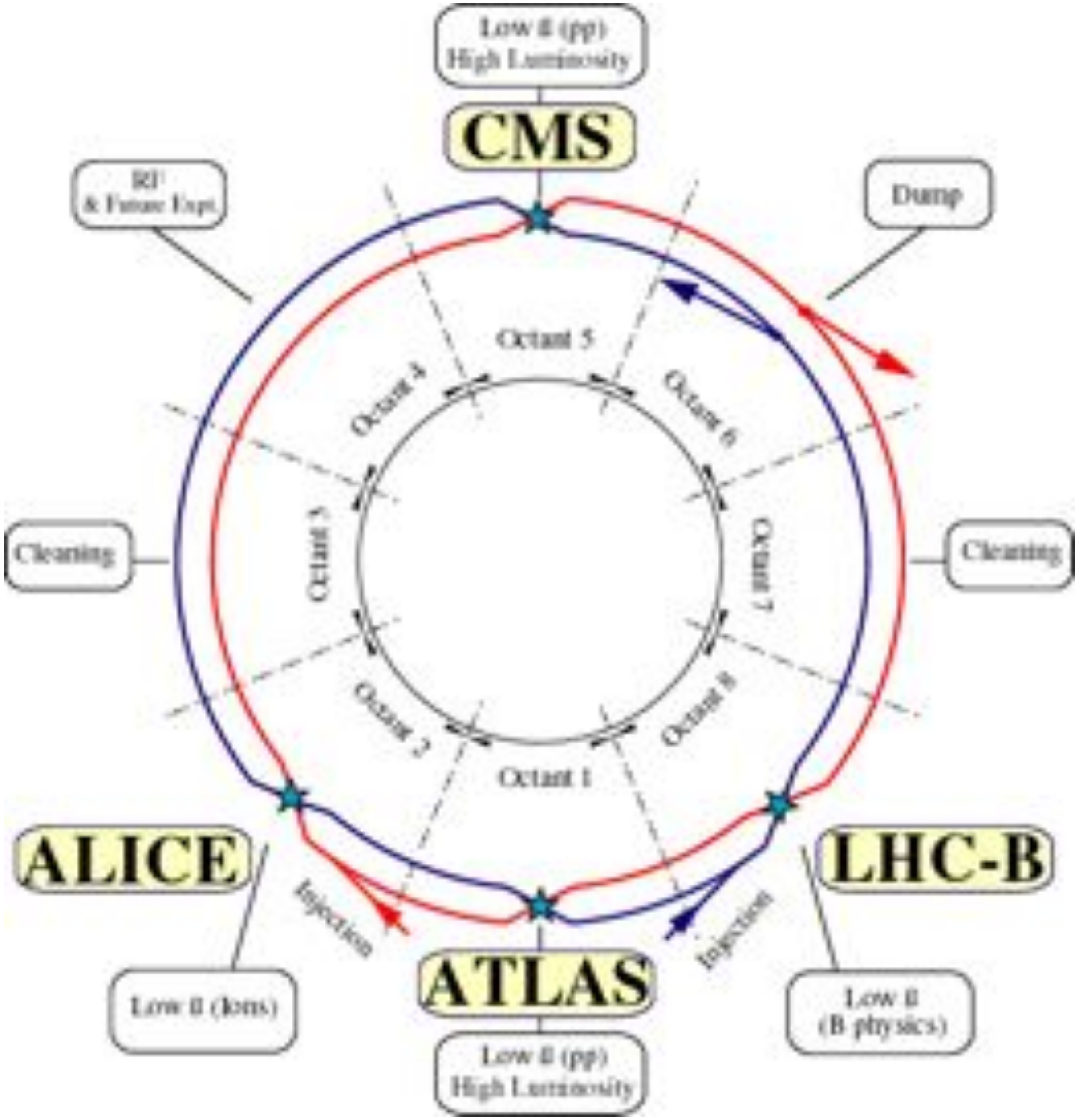
gratefully acknowledging input from FCC global design study & CepC/SppC team

YEARS/ANS CERN

FCC hh ee he

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

Large Hadron Collider (LHC)



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

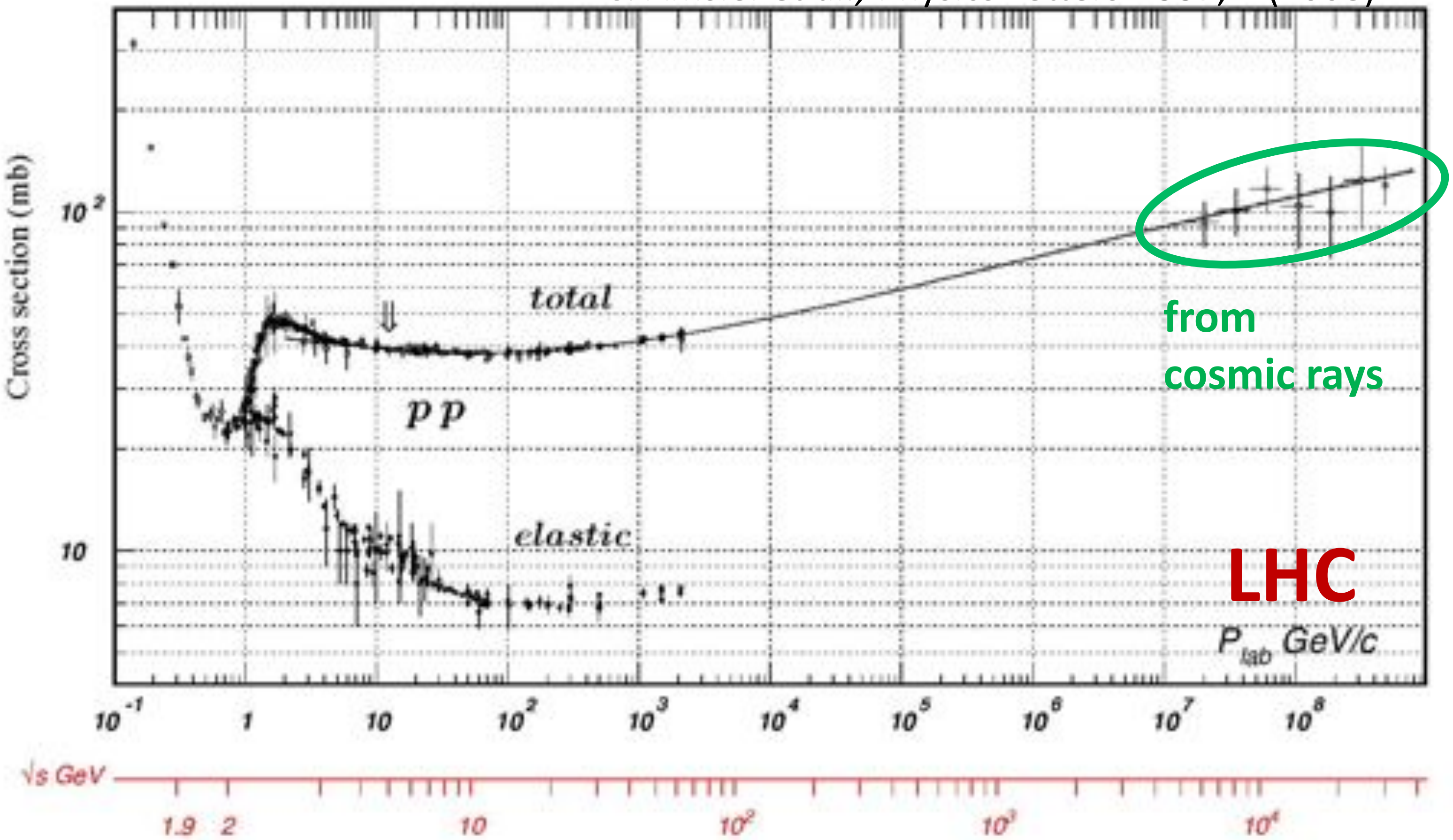
dipole field 8.33 T

luminosity

$$R = \sigma L$$

reaction rate — cross section — luminosity

C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)



σ_{tot}~
100 mbarn
~ 10^{-25} cm²

$\sigma_{inelastic}$~
60 mbarn~
$6\text{x}10^{-26}$ cm²

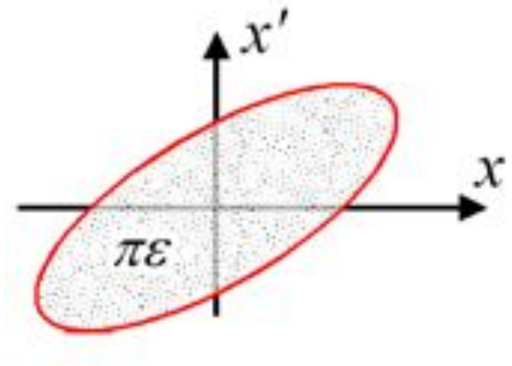
σ_{Higgs} ~ 30 pb → with 300 fb^{-1} LHC produces ~ 10 million Higgs

Luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x^* \sigma_y^*} F = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

N	**Number of particles per bunch**
k_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε	Emittance
ε_n	**Normalized emittance**
β*	**Beta function at IP**

Round beams, beam 1 = beam 2



$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

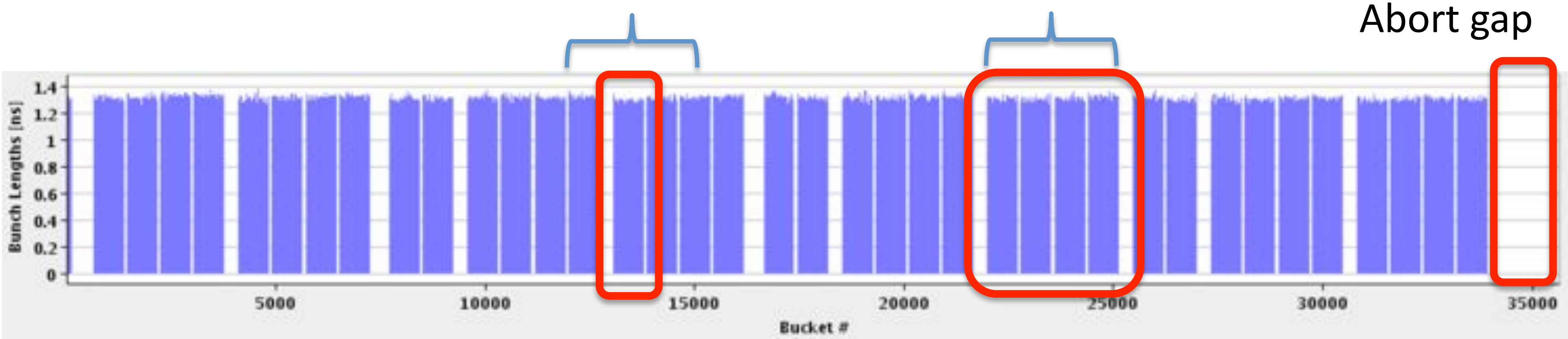
$$\varepsilon_n = \beta\gamma\varepsilon$$

M. Lamont

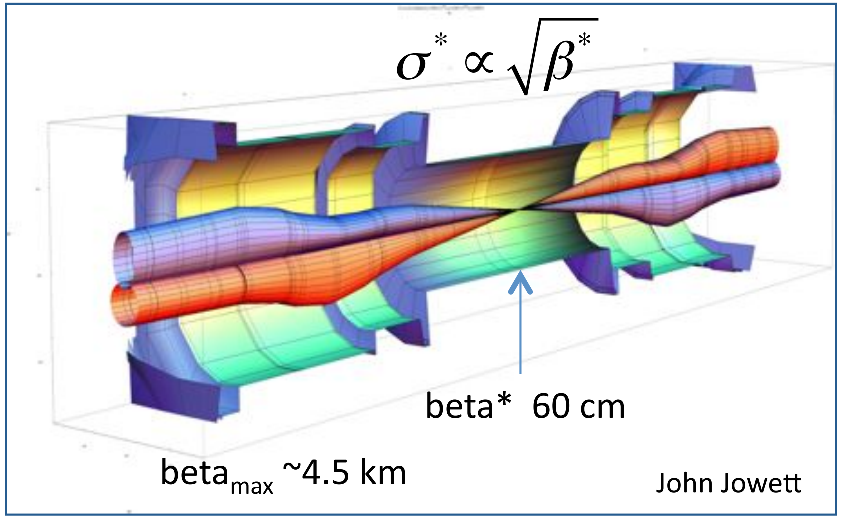
1 PS batch
(36 bunches)

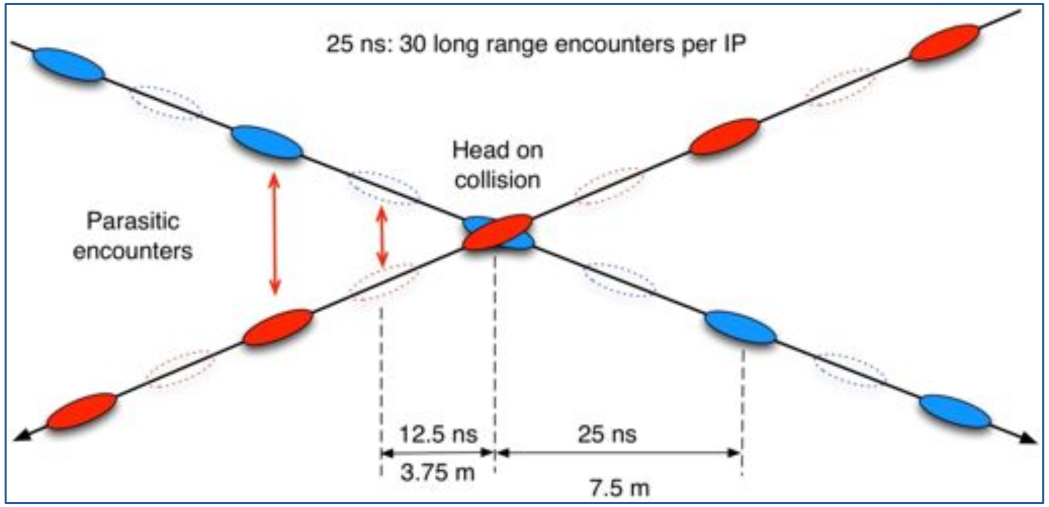
1 SPS batch
(144 bunches)

Abort gap



26.7 km - 1380 bunches in 2012, ~2800 in 2015





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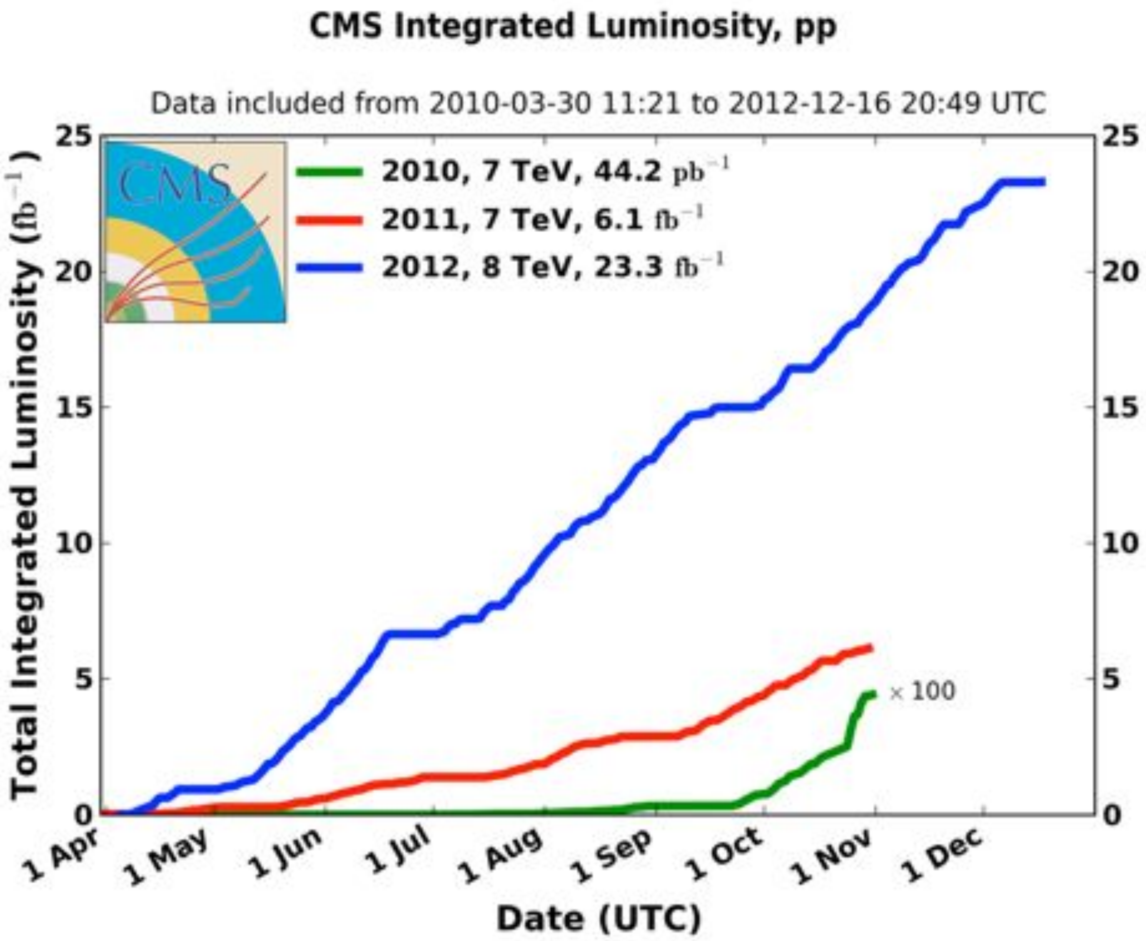
LHC Integrated luminosity 2010-2012



- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

peak performance through the years

	2010	2011	2012	Nominal
Bunch spacing [ns]	150	50	50	25
No. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
Max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized **emittance** [mm.mrad]	~2.0	~2.4	~2.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	**2.1×10^{32}**	**3.7×10^{33}**	**7.7×10^{33}**	1.0×10^{34}

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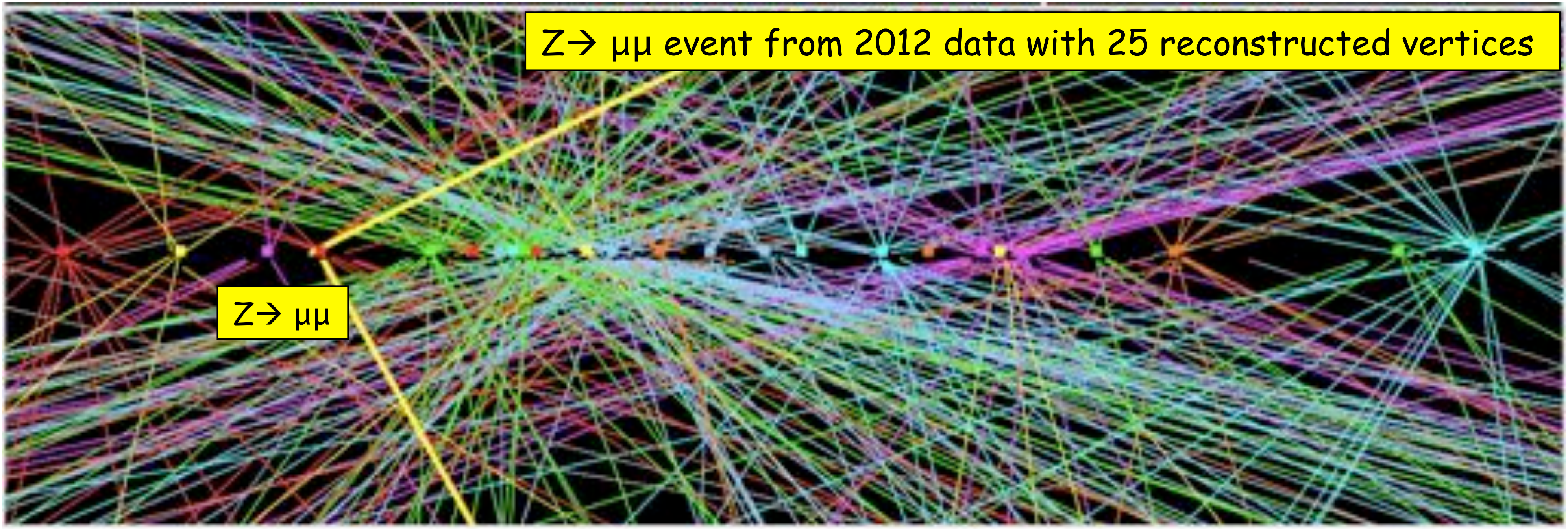
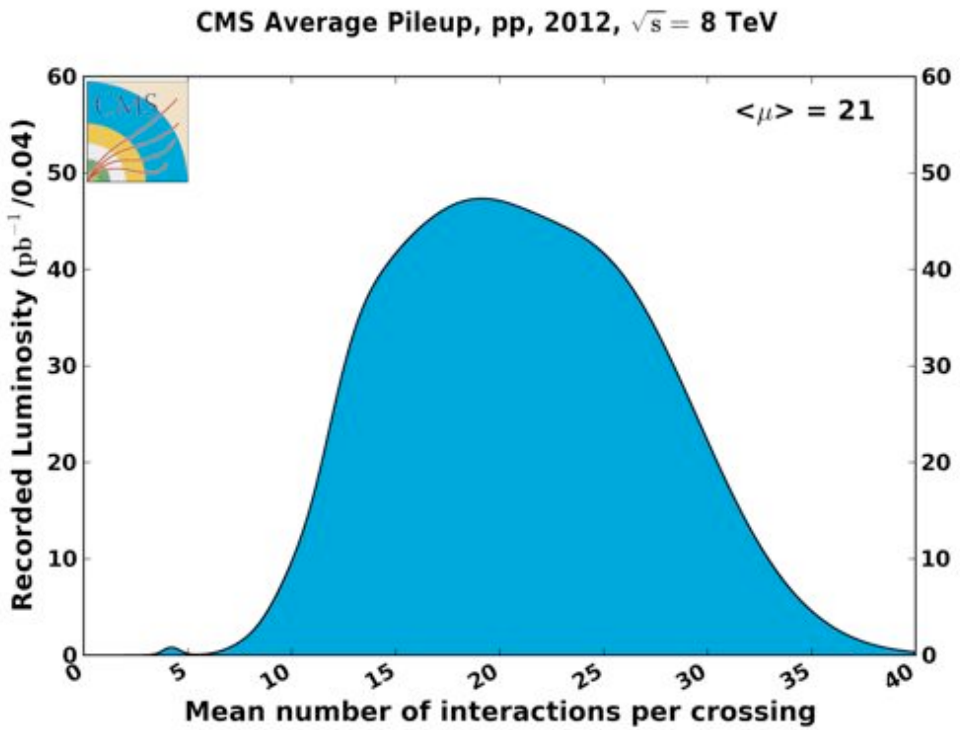
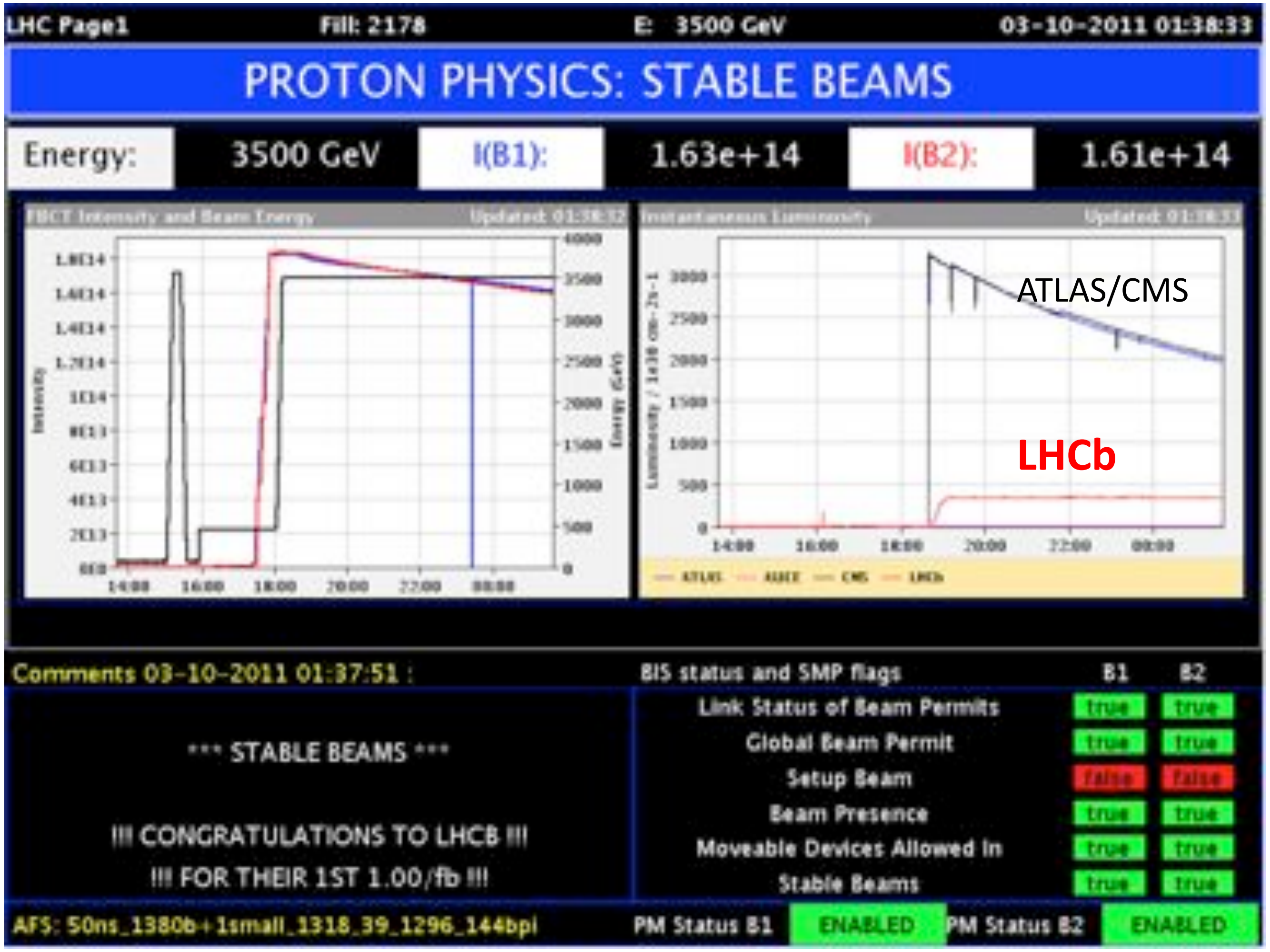




pile up
will increase
at higher energy
→
experiments
request
25 ns
operation
in 2015

M. Lamont, IPAC'13

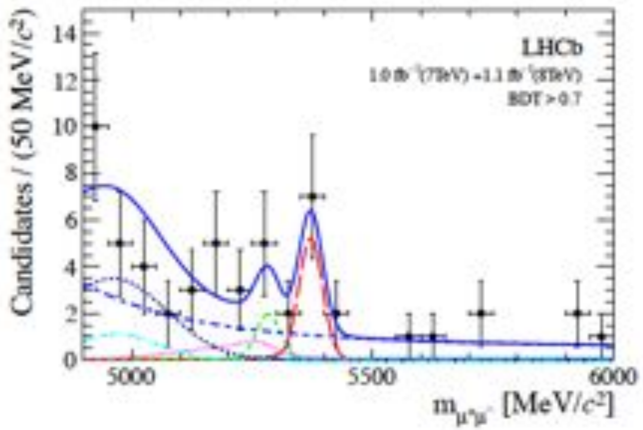
LHCb



luminosity levelling at around 4e32 $cm^{-2}s^{-1}$ via transverse separation

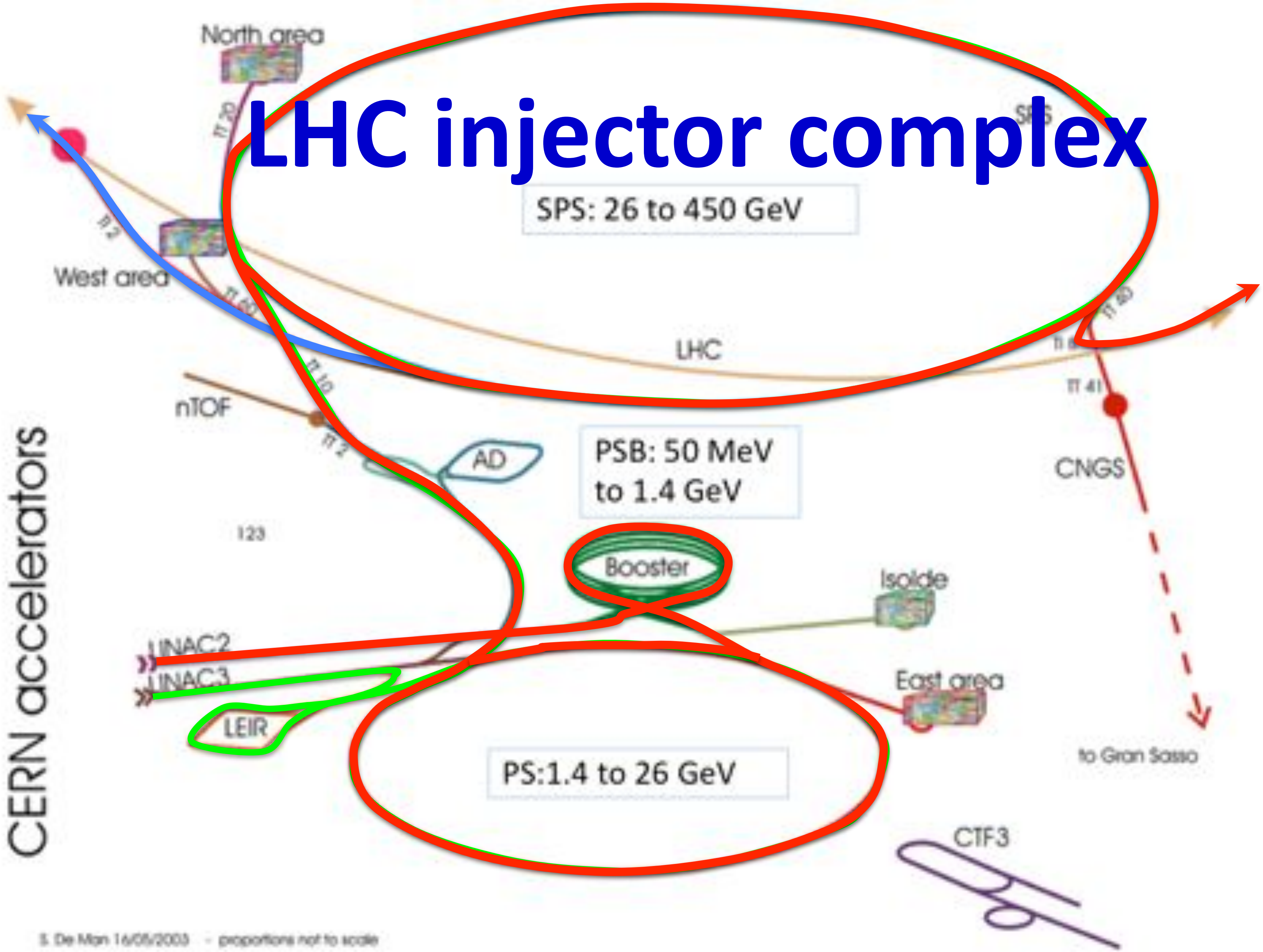
(with tilted crossing angle)

first evidence for the decay $B_s \rightarrow \mu^+ \mu^-$



M. Lamont, IPAC'13

LHC injector complex



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Long Shutdown 1: Superconducting Magnets and Circuits Consolidation (SMACC)

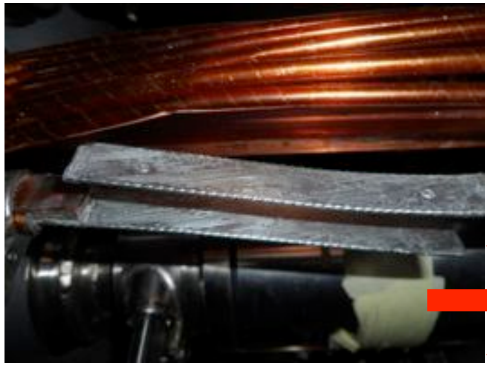
Monumental effort

- Over 350 persons involved
- Including preparation: ~1,000,000 working hours
- No serious accidents!

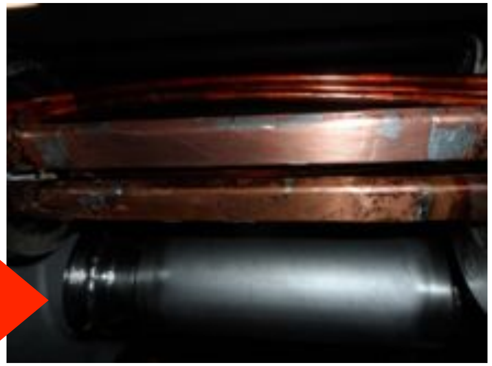
Jean-Philippe Tock

Collaborations with NTUA (Athens), WUT (Wroclaw) and support of DUBNA

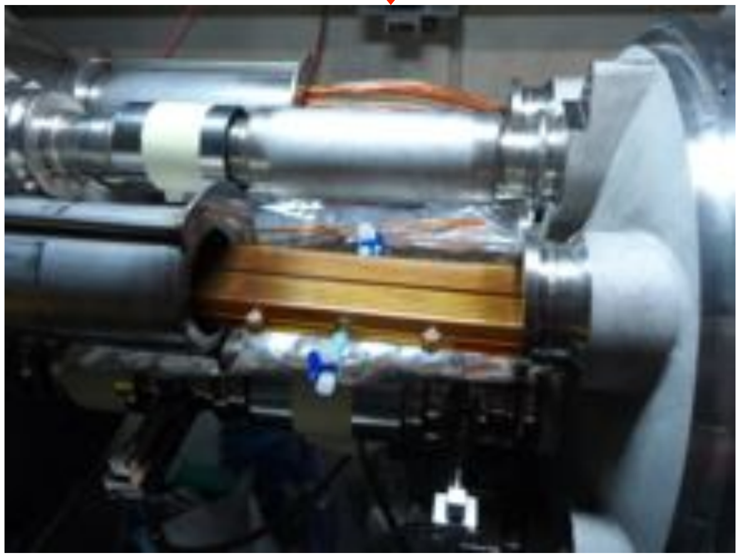
SMACC project : Closure of the last interconnection – 18.06.2014
Activity led by A Musso (TE-MSC)



« Cables »



« New Splice »



« Insulation box »

- Total interconnects in the LHC:
  - 1,695 (10,170 high current splices)
- Number of splices redone: ~3,000 (~ 30%)
- Number of shunts applied: > 27,000

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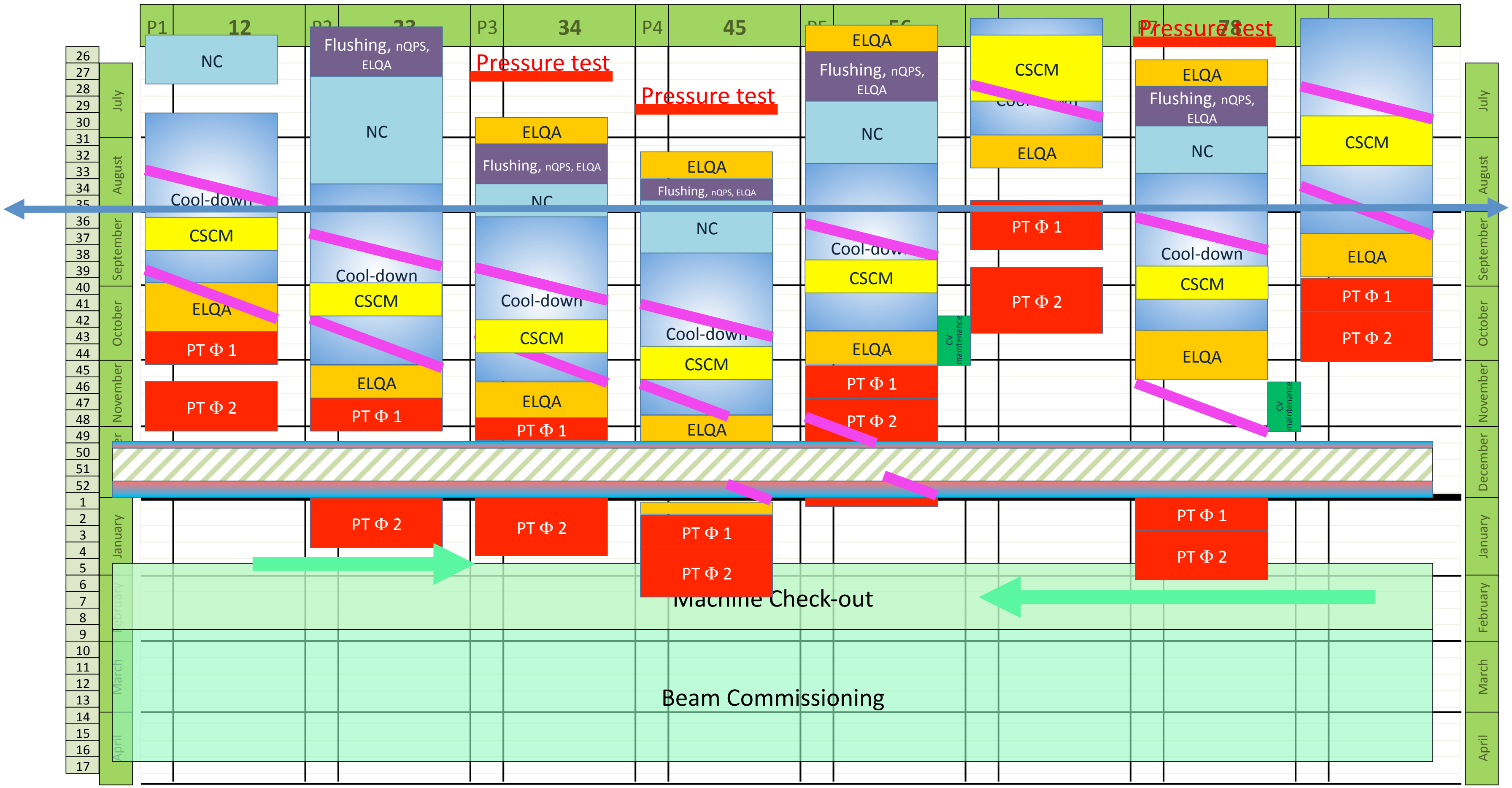
And a lot more besides…

Latest LS1 / restart schedule, V4.1

K. Foraz



- 2 sectors are being finalized
- 1 sector is cold – waiting for QPS readiness to start powering tests
- 5 sectors are being cooled-down
- LSS works almost complete

LHC - 2015

- Target energy: 6.5 TeV
  - to be confirmed at end of powering tests
- Bunch spacing: 25 ns
  - strongly favored by experiments (pile-up limit ~ 50)
- Beta*: 80 to 40 cm

Energy

- Lower quench margins
- Lower tolerance to beam loss
- Lower intensity set-up beams
- Hardware closer to maximum (beam dumps, power converters etc.)

25 ns

- E-cloud, UFOs
- More long range collisions
- Larger crossing angle, higher beta*
- Higher total beam current
- Higher intensity per injection

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2015 - potential performance

- Start with 50 ns – scrub – 25 ns operation
- Conservative beta* to start
- Conservative bunch population
- Reasonable emittance into collisions
- Assuming same machine availability as 2012…

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	Nc	beta* [cm]	ppb	EmitN [um]	Lumi [cm-2s-1]	Days (approx)	Int lumi	Pileup
50 ns	1300	80	1.2e11	2.5	4.6e33	21	**~1 fb^{-1}**	**27**
25 ns (1)	2496	80	1.1e11	2.5	7.4e33	75	**6.8 fb^{-1}**	**22**
25 ns (2)	2496	40	1.1e11	2.5	1.3e34	46	**9.2 fb^{-1}**	**39**

Will lay the foundations for Run 2…

10 year plan

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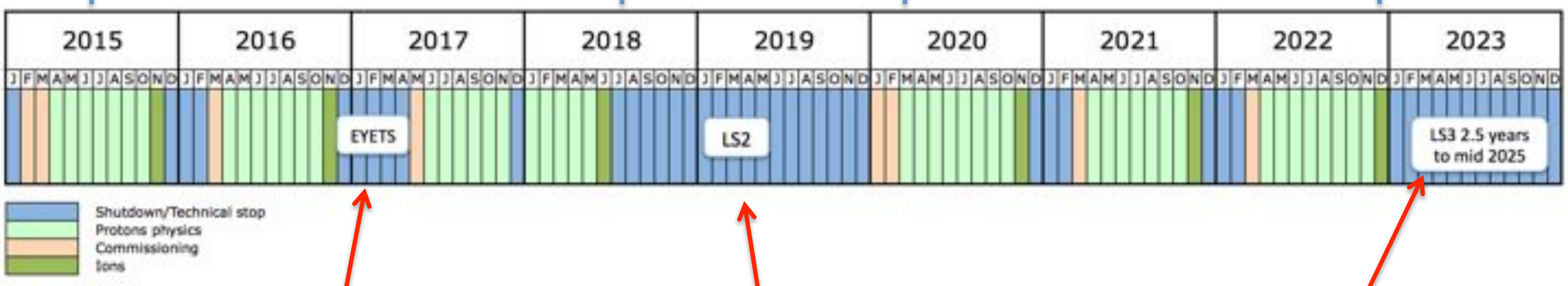
- Long years – 13 weeks Christmas stop
- Interspersed with long shutdown every 3 to 4 years
- Ions very much part of the plan

Run 2: 13 to 14 TeV c.m. with peak luminosity of ~1.7×10^{34} cm^{-2} s^{-1}

Run 3: 14 TeV c.m. with peak luminosity of ~2×10^{34} cm^{-2} s^{-1}



EYETS ~5 months
Extended year end technical stop (CMS)

LS2: 18 months
Connection of LINAC4
LHC Injectors Upgrade

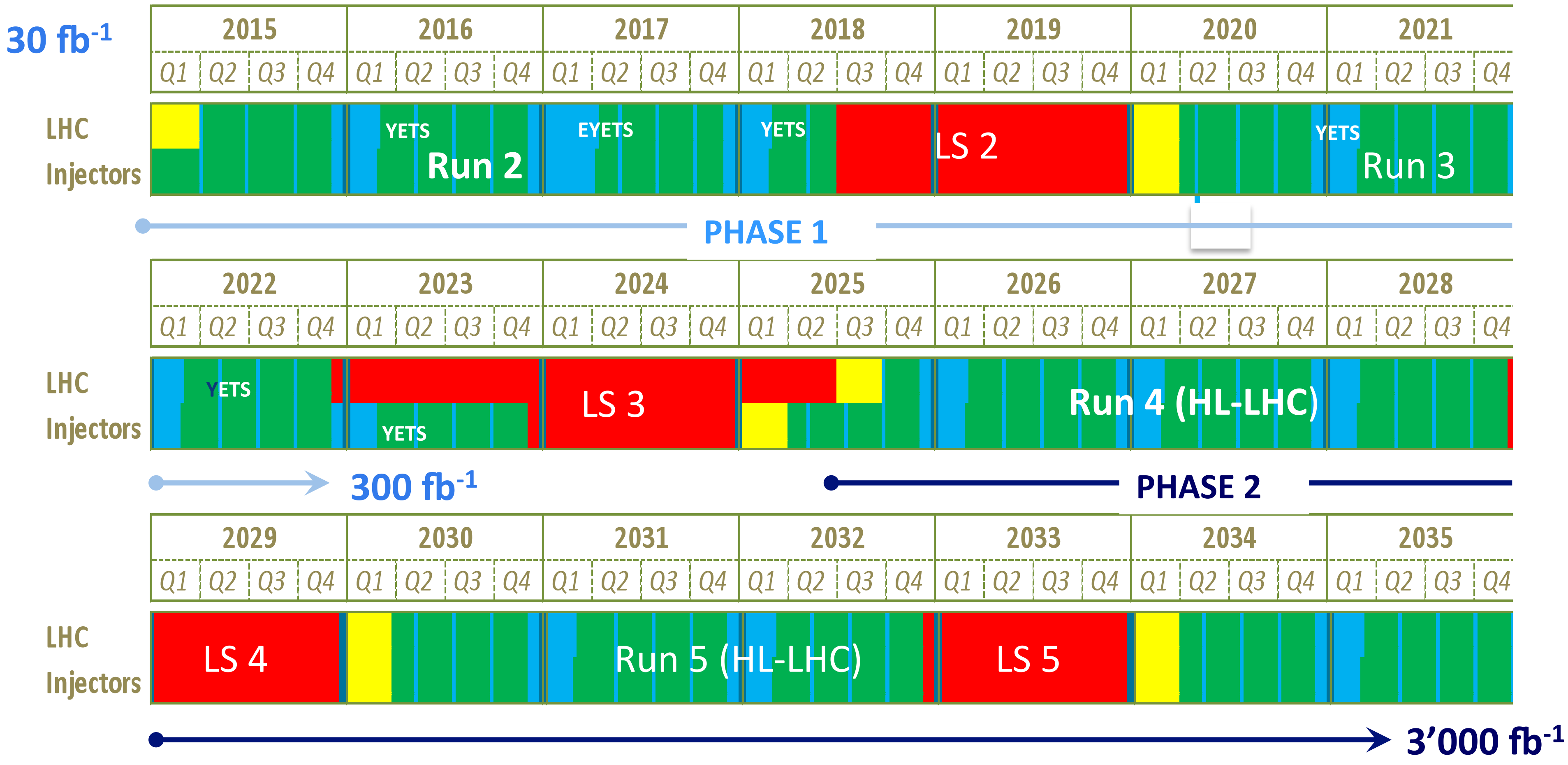
LS3: 30 months
High Luminosity LHC

LHC roadmap: 20-yr schedule beyond LS1

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

- Physics
- Shutdown
- Beam commissioning
- Technical stop

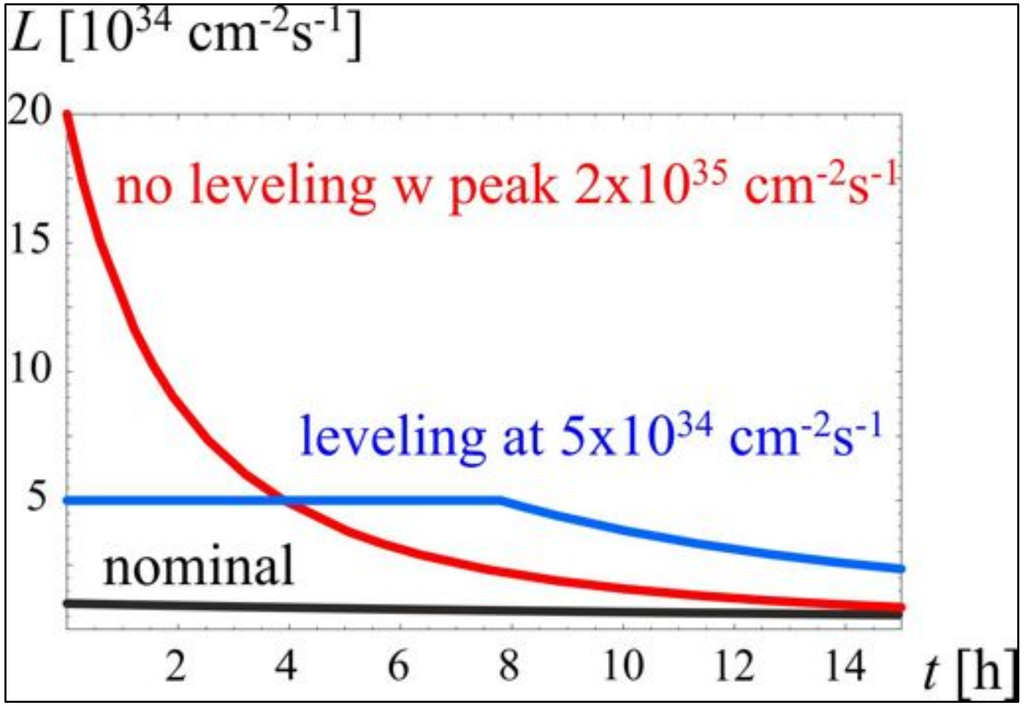


F. Bordry

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



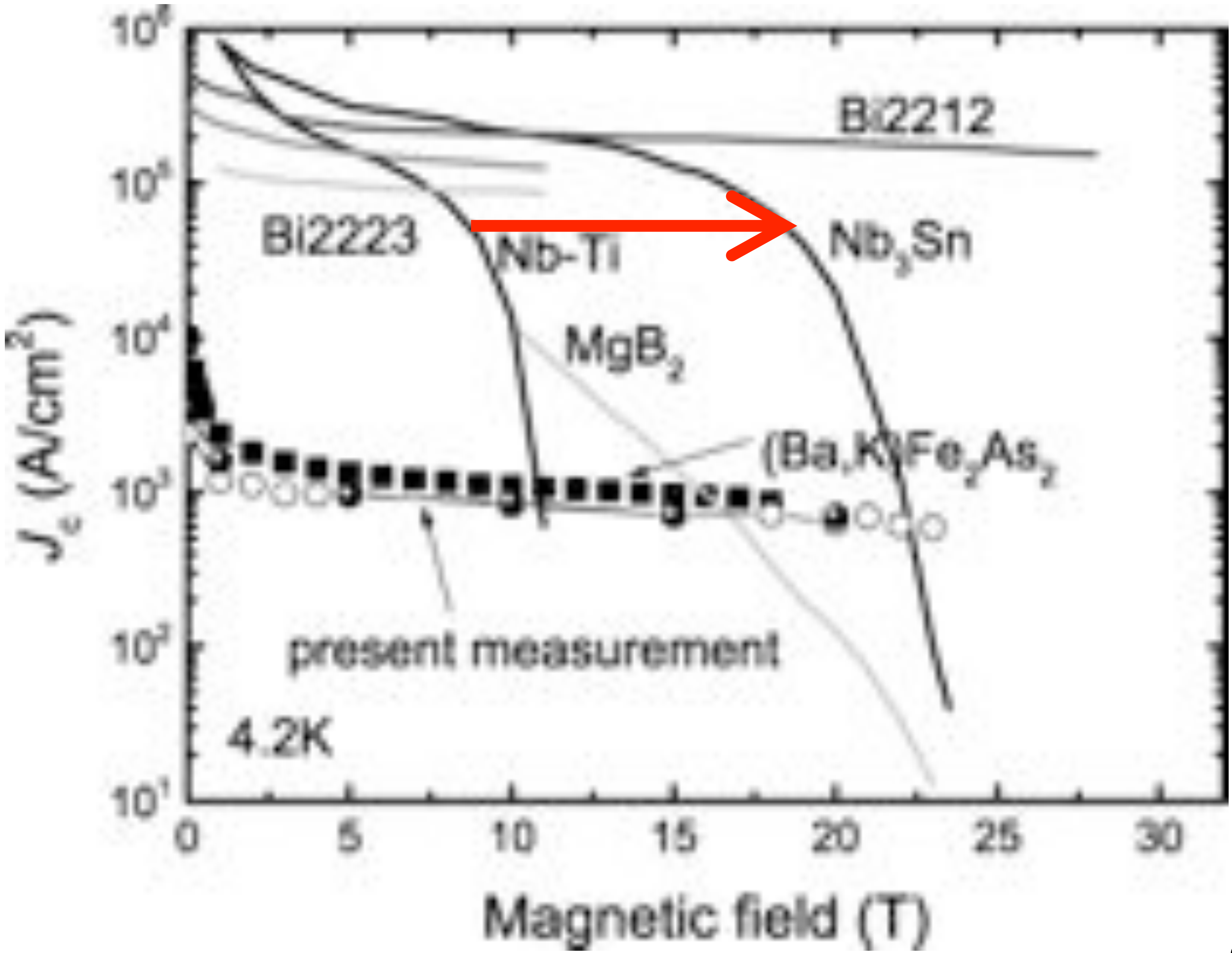
5 x 10^{34} $cm^{-2}s^{-1}$ levelled luminosity

Pile-up ~140

3 fb^{-1} per day

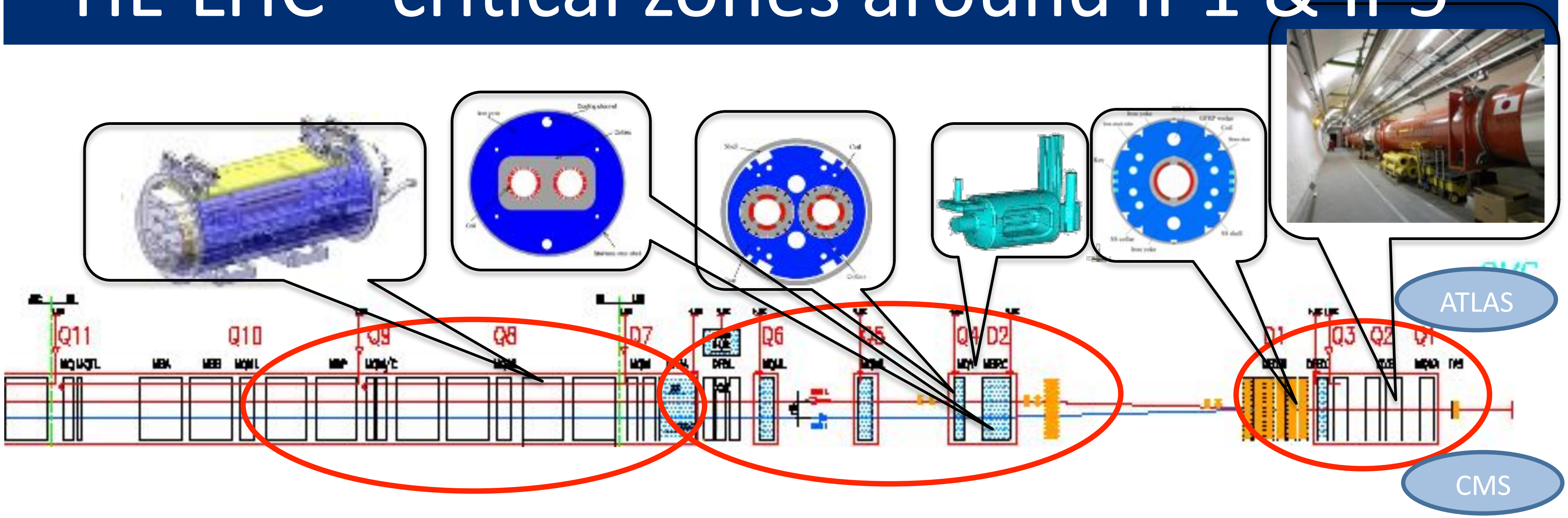
~250 fb^{-1} /year

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

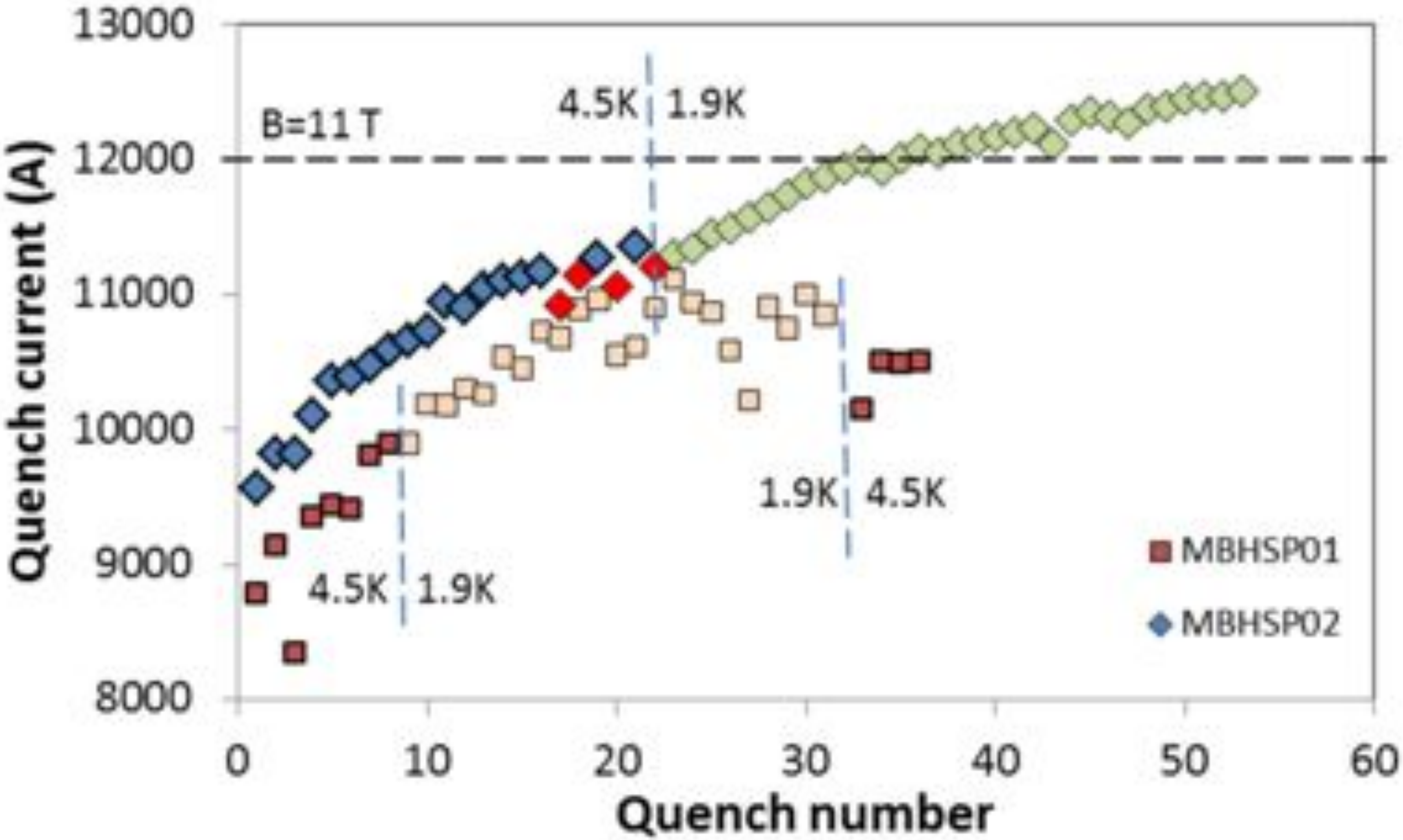
→ more than 1.2 km of LHC

→ plus technical infrastructure (e.g. Cryo and Powering)

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

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

LHC history

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!

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

Future Circular Collider (FCC) study ; goals: CDR and cost review for the next European Strategy Update (2018)

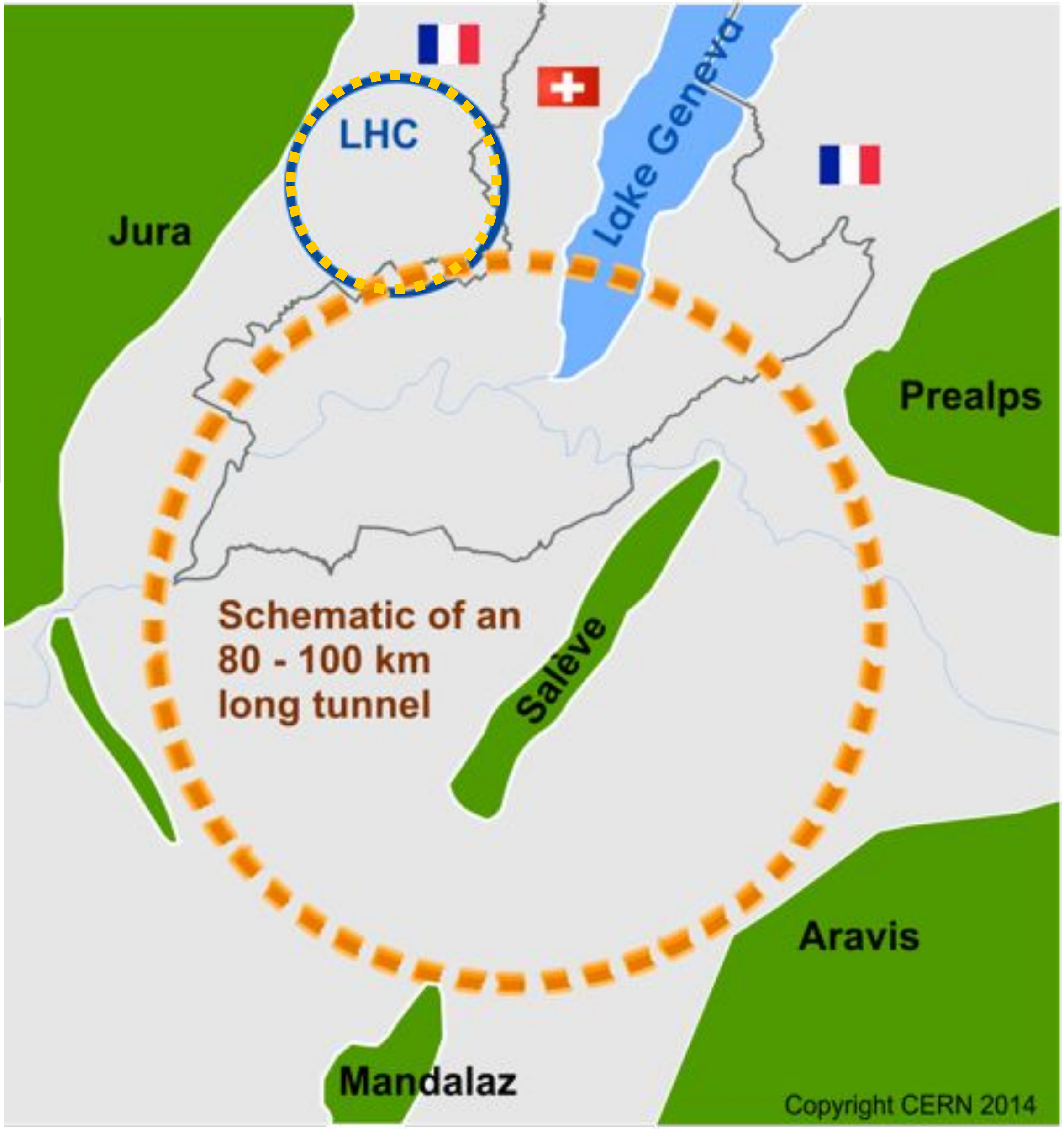
International collaboration :

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

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

- including ***HE-LHC*** option: 16-20 T in LHC tunnel
- ***e^+e^-* collider (*FCC-ee/ TLEP*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **100 km infrastructure** in Geneva area

M. Benedikt



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

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.

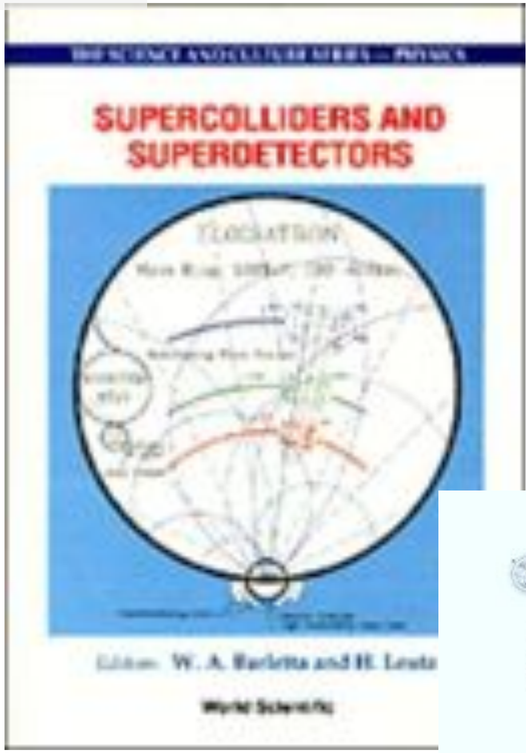
European and US teams have both shown interest in building their own super collider (see *Nature* **503**, 177; 2013), but the huge amount of research needed before such a machine could be built means that the earliest date either can aim for is 2035. China would like to build its electron–positron collider 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.

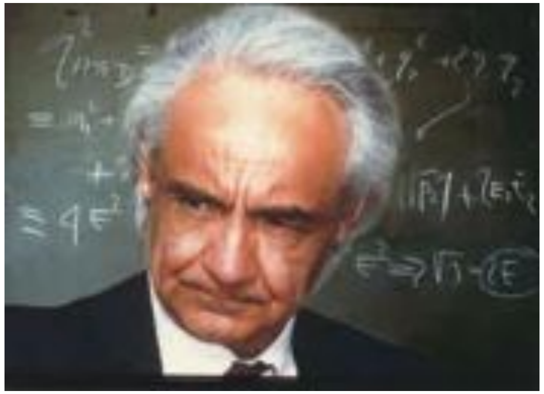
Electron–positron colliders and hadron colliders such as the LHC complement each other. Hadron colliders are sledgehammers, smashing together protons (a kind of hadron that comprises three fundamental particles called quarks) at high energies to see what emerges. Lower-energy electron–positron machines 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), USA (SSC 87 km, VLHC & VLLC 233 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

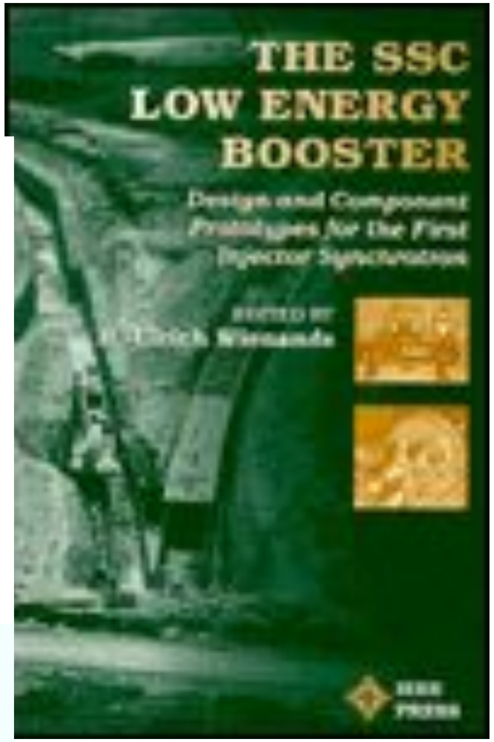
Conceptual Design of the Superconducting Super Collider

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


Very Large Hadron Collider

Fermilab-TM-2149
June 4, 2001

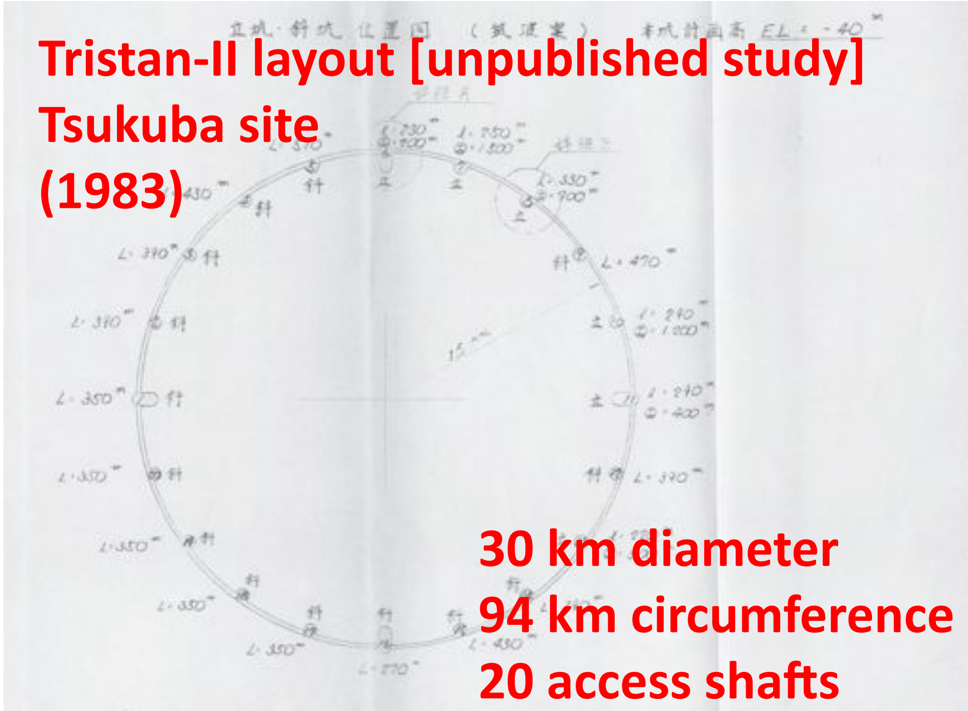
Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center

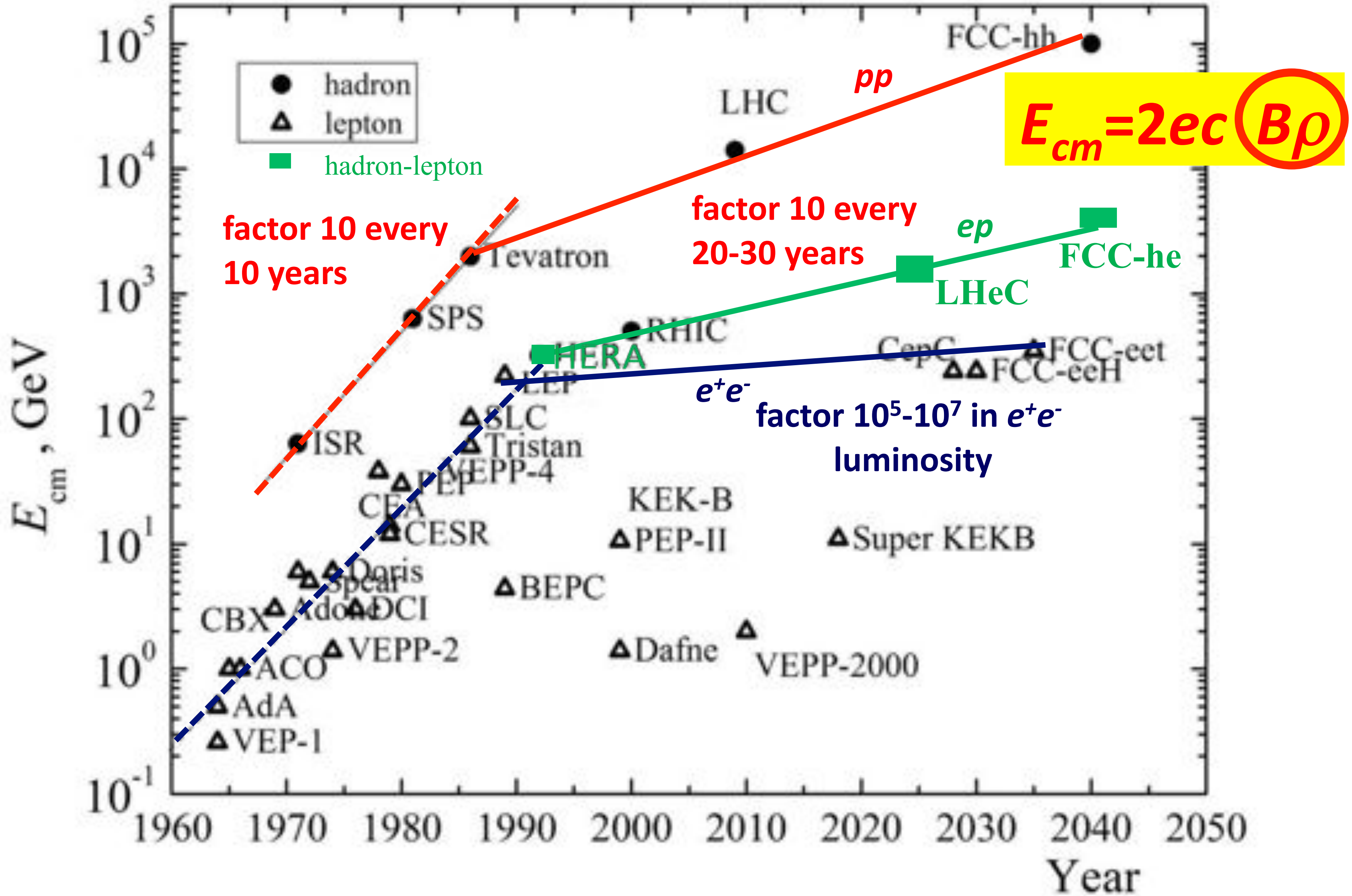
VLHC Design Study Group Collaboration **June 2001**. 271 pp. SLAC-R-591, SLAC-R-0591, SLAC-591, SLAC-0591, FERMILAB-TM-2149

http://www.vlhc.org/

previous studies in Italy (ELOISATRON), USA (SSC, VLHC, VLLC), and Japan ("TRISTAN-II")



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

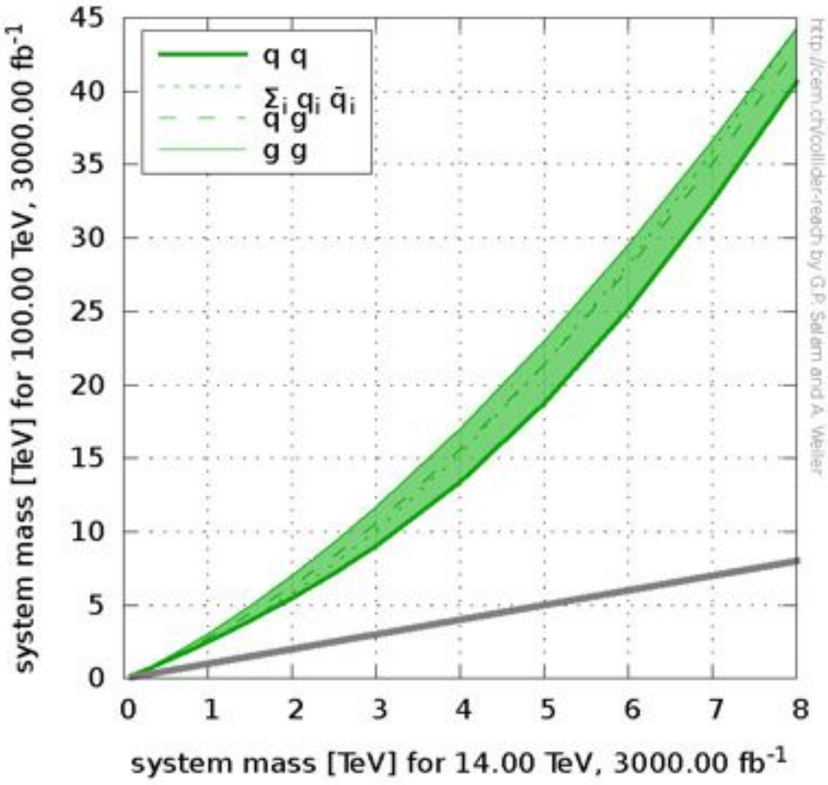
M. Mangano

physics requirements for *FCC-hh*

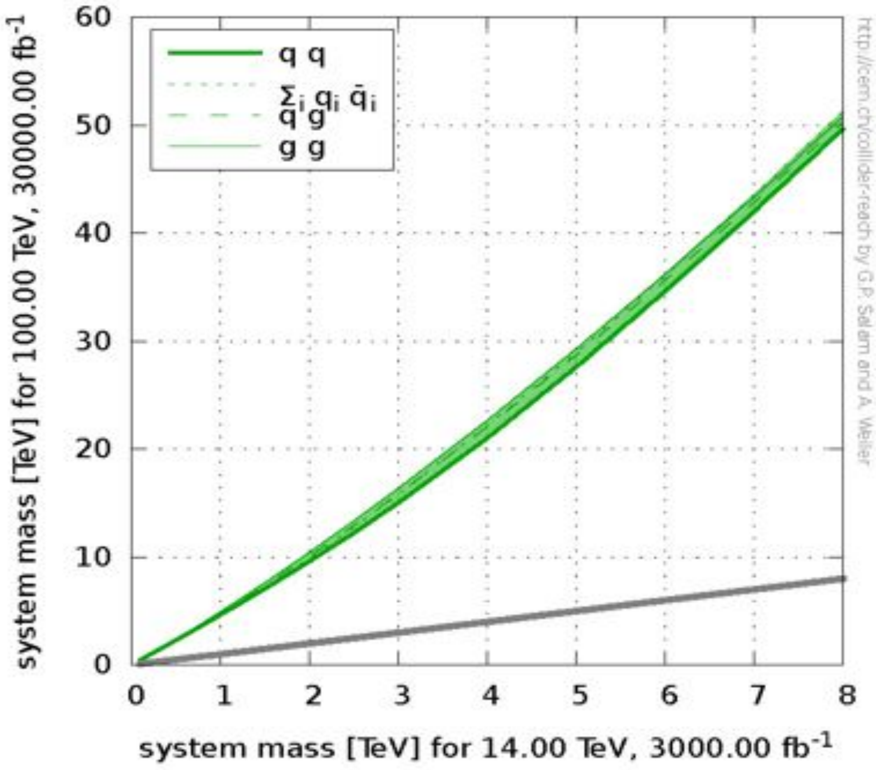
- highest possible *pp* luminosity at 100 TeV
  - present baseline L=5x10^{34} cm^{-2}s^{-1} (as for HL-LHC)
  - higher luminosity appears possible,
  - but has implications for pile up, bunch spacing, shielding, cost, …
- also heavy-ion collisions & ion-proton collisions
- 2-4 experiments (like LHC, two special purpose detectors)
- proton polarization? (demonstrated at RHIC)

which *pp* luminosity?

FCC-hh, 14 TeV, 3 ab^{-1}



FCC-hh, 14 TeV, 30 ab^{-1}



HL-LHC
14 TeV
3 ab^{-1}

HL-LHC
14 TeV
3 ab^{-1}

G. Salam and A. Weiler, http://collider-reach.web.cern.ch/

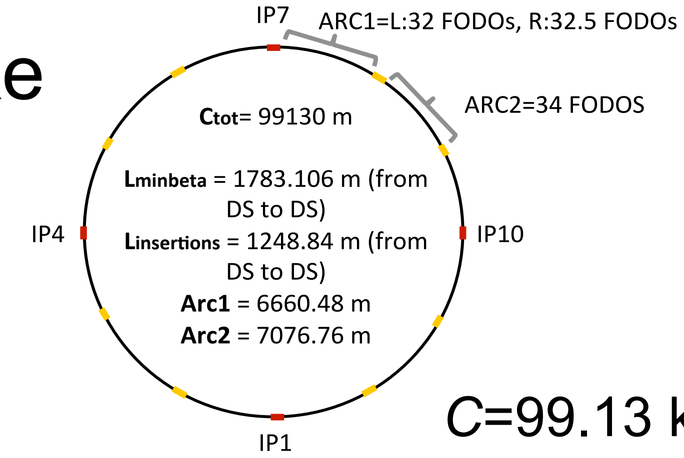
parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		16 (20)
circumference [km]	26.7		100 (83)
luminosity [10^{34} $cm^{-2}s^{-1}$]	1	5	5 [→20?]
bunch spacing [ns]	25		25 (5)
events / bunch crossing	**27**	**135**	**170 (34)**
bunch population [10^{11}]	1.15	2.2	1 (0.2)
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)**

parameter	LHC	HL-LHC	FCC-hh	SppC (May14)
c.m. energy [TeV]	14		100	63
dipole magnet field [T]	8.33		16 (20)	20
circumference [km]	26.7		100 (83)	50
luminosity [10^{34} $cm^{-2}s^{-1}$]	1	5	5 [→20?]	12
bunch spacing [ns]	25		25 (5)	25
events / bunch crossing	**27**	**135**	**170 (34)**	**373**
bunch population [10^{11}]	1.15	2.2	1 (0.2)	2
norm. transverse emitt. [μm]	3.75	2.5	2.2 (0.44)	3.3
IP beta-function [m]	0.55	0.15	1.1	0.75
IP beam size [μm]	16.7	7.1	6.8 (3)	8.5
synchrotron rad. [W/m/ aperture]	0.17	0.33	28 (44)	46
critical energy [keV]	0.044		4.3 (5.5)	2.2
total syn.rad. power [MW]	**0.0072**	**0.0146**	**4.8 (5.8)**	**3**
longitudinal damping time [h]	**12.9**		**0.54 (0.32)**	**1.0**

ring optics for alternative layouts

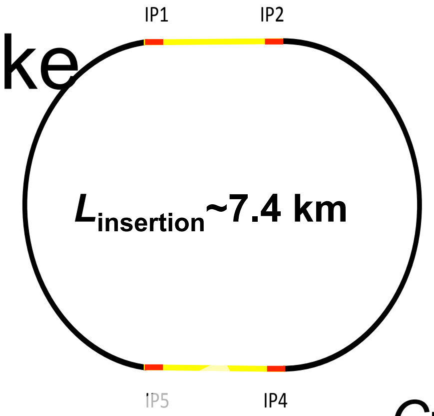
R. Alemany,
B. Holzer,
R. Tomas,
D. Schulte

LHC-like circular



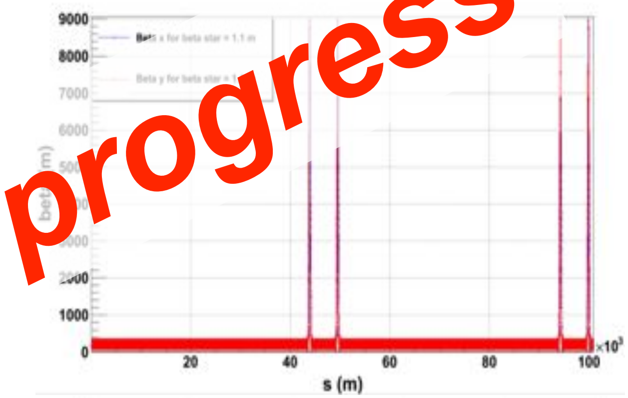
C=99.13 km

SSC-like race-track

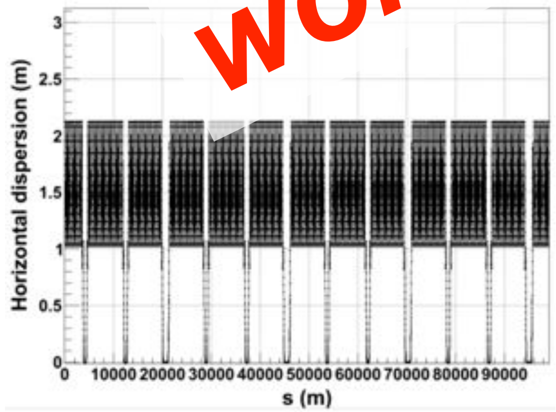


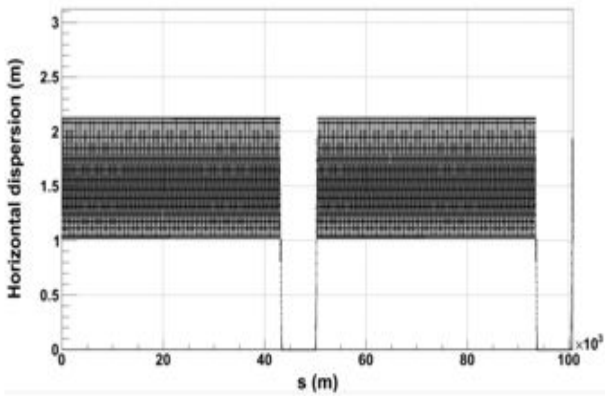
C=100.8 km

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



D_x [m]



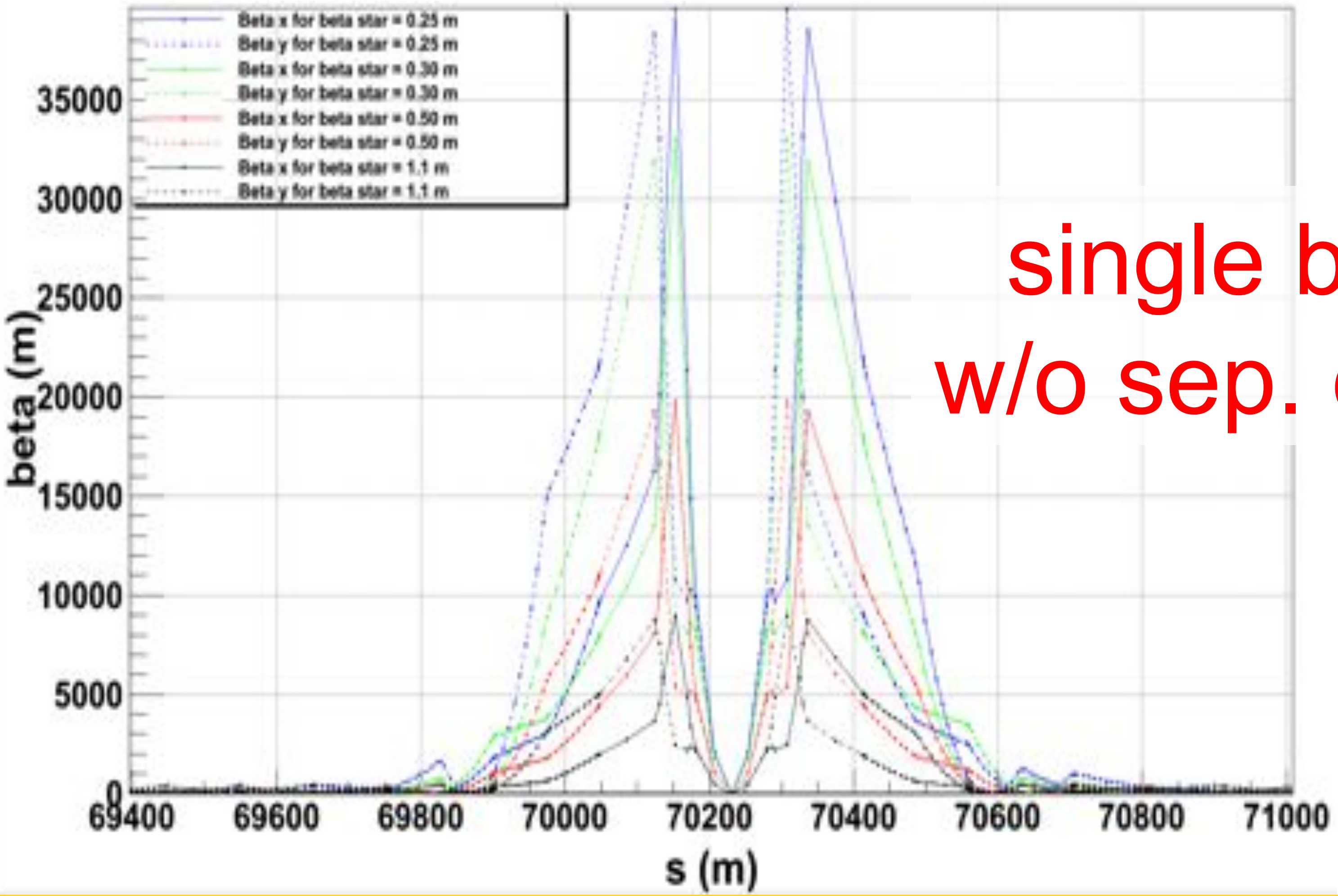


work in progress

IR optics for different β*

$\beta^* = 0.25$ m, 0.30 m, 0.50 m and 1.1 m

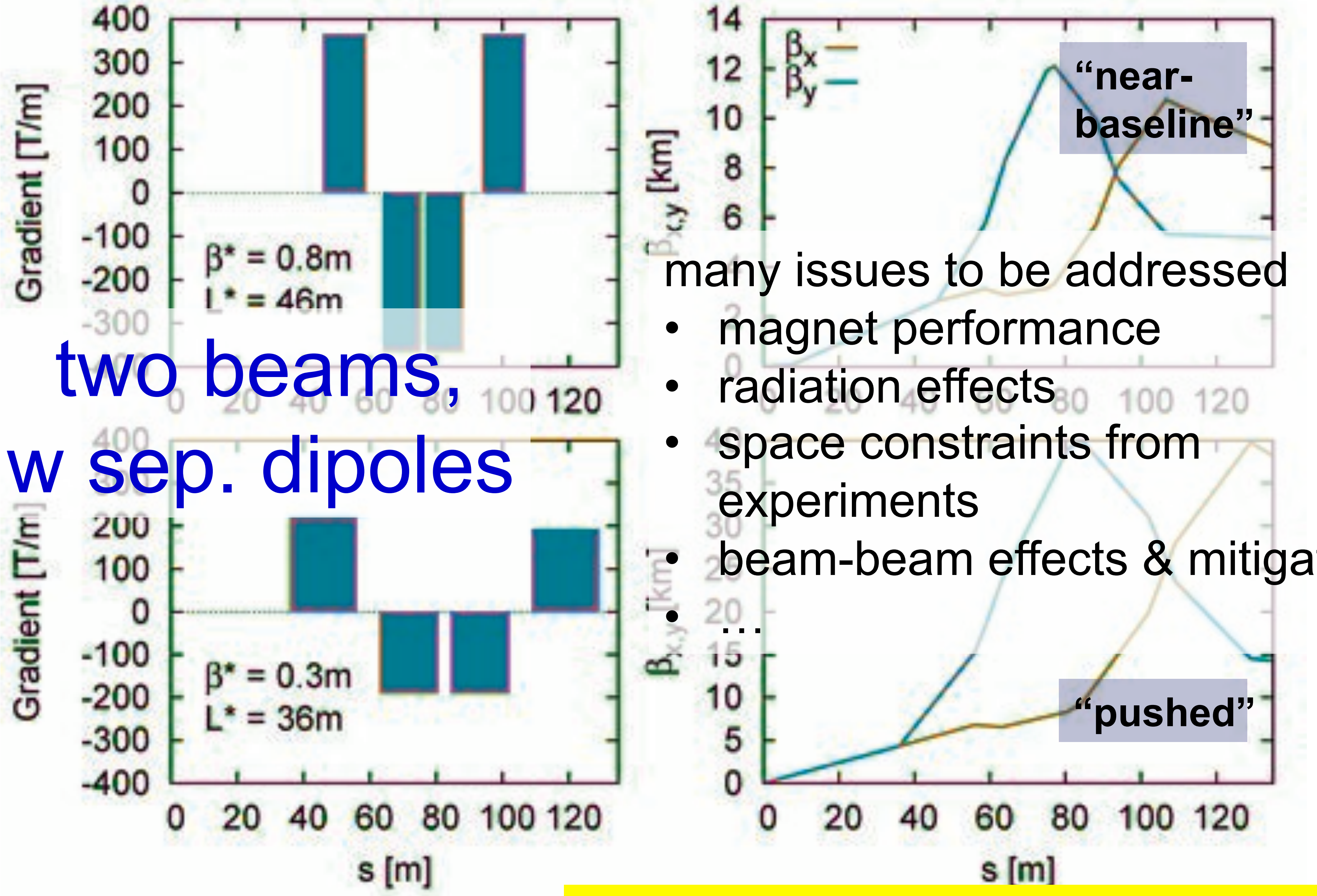
R. Alemany
B. Holzer



single beam,
w/o sep. dipoles

β^*=1.1→0.25 m: beam current & SR power lower by factor ~2 at constant average luminosity

full IR optics: β* =0.8 & 0.3m



two beams,
w sep. dipoles

many issues to be addressed

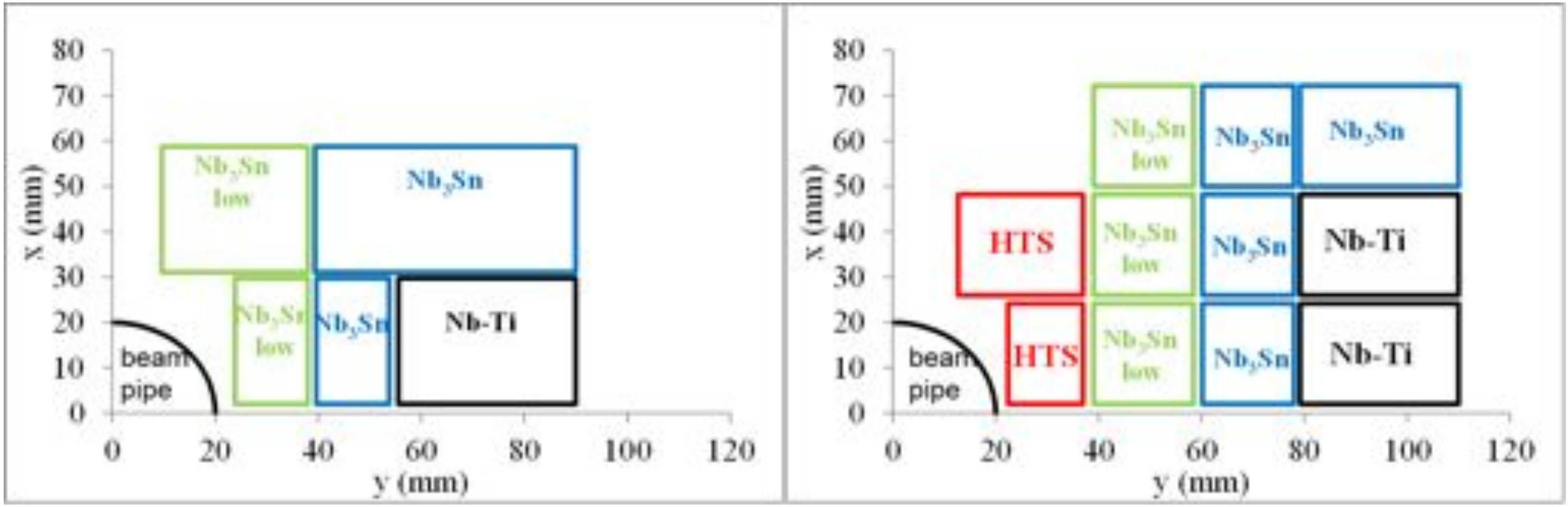
- magnet performance
- radiation effects
- space constraints from experiments
- beam-beam effects & mitigation
- …

R. Tomas, R. Martin, E. Todesco et al.

cost-optimized high-field dipole magnets

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

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



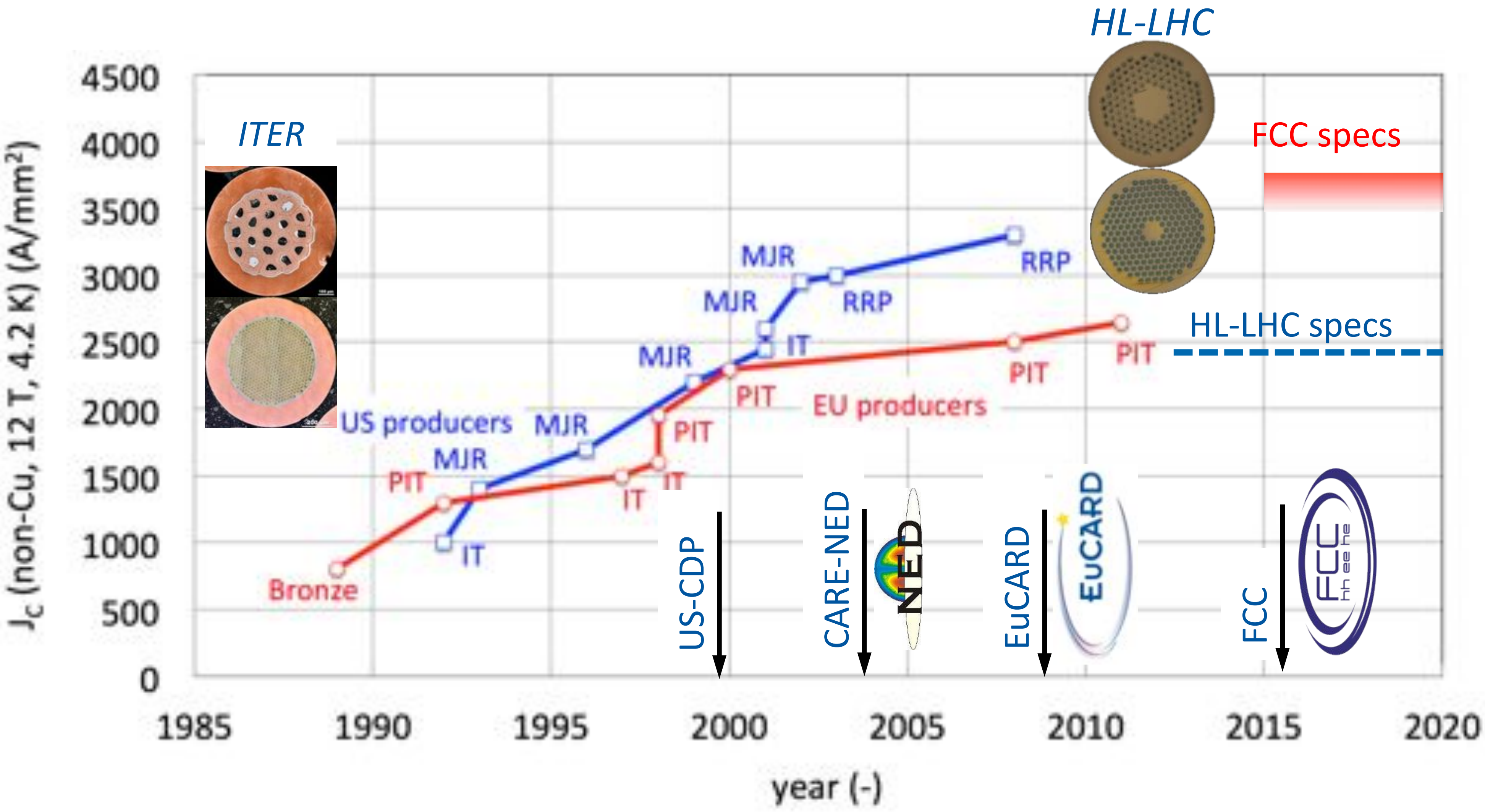
only a quarter is shown

“hybrid magnets”

example block-coil layout

L. Rossi, E. Todesco, P. McIntyre

From ITER- to HEP-class Nb_3Sn



L. Bottura

Nb_3Sn challenges and opportunities

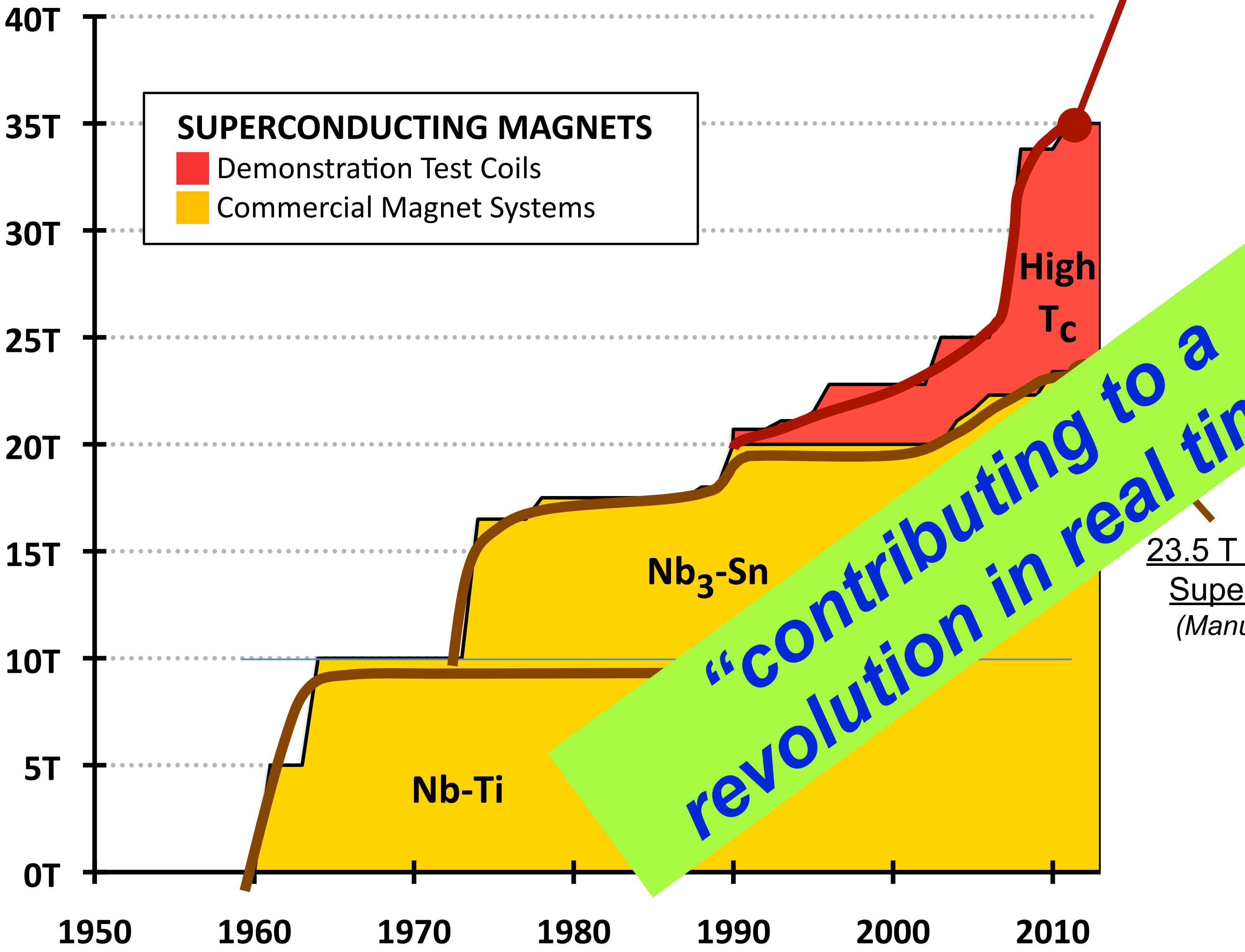
- HL-LHC
  - Demonstrate Nb_3Sn technology for use in the LHC – 2016
  - Prepare HL-LHC in LS2 – 2018
  - Install HL-LHC in LS3 – 2023
- FCC technologies
  - CDR for European Strategy Review – 2017
  - Prototyping of FCC magnets – 2018-2025
  - Production of FCC magnets – 2025-2035

- Secure robust HEP Nb_3Sn for the first large scale use in HEP
- Squeeze out of Nb_3Sn its full potential
- Improve quality, affordable production
- How ?
  - A coordinated, worldwide R&D to foster progress and spread technology
  - Material research (on LTS !)
  - Other industrial actors

L. Bottura

superconducting magnet technology

SC solenoid magnets (dipoles to follow)



35 T Proof-of-Principle Demo

(4T HTS Test Coil in a 31T Background Magnetic Field)

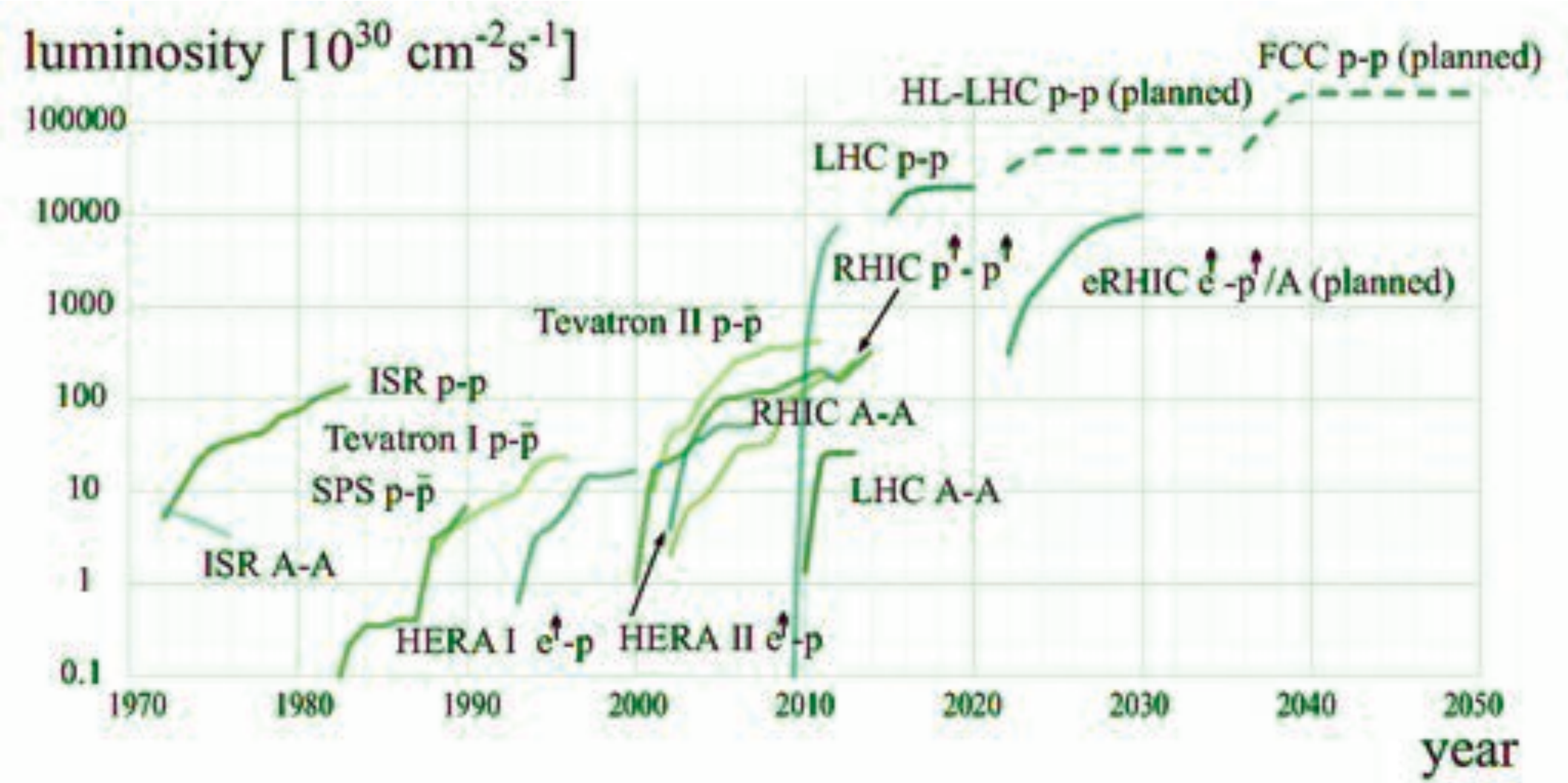
ϕ 39 mm

23.5 T (1GHz NMR) Nb_3-Sn Superconducting Magnets

(Manufactured Commercially)

G. Boebinger, NHMFL

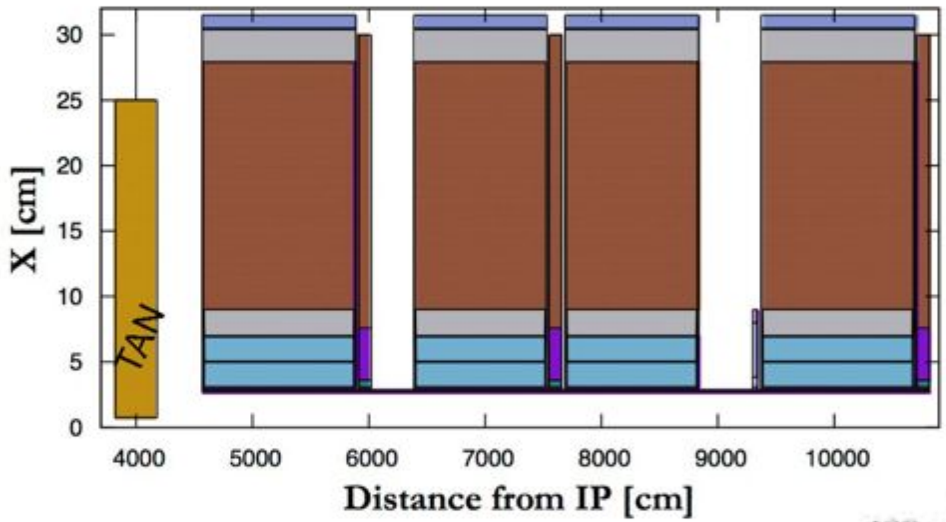
hadron-collider peak luminosity vs. year



Courtesy W. Fischer

LHC run 1 (2012-13) accumulated more integrated luminosity than all previous hadron colliders together!

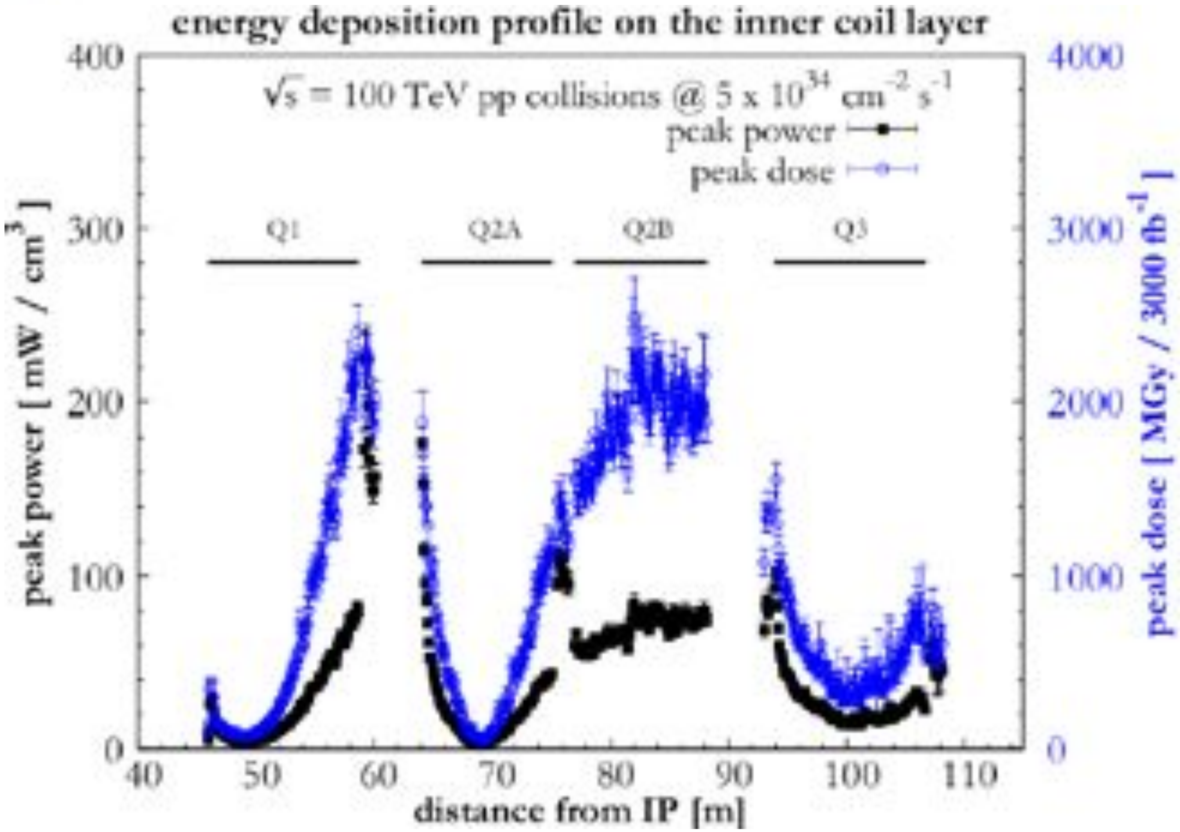
pp IR – radiation from collision debris



F. Cerutti and L. Esposito

FLUKA model

IR peak power and dose



HL-LHC **IR can handle 10x more radiation than *LHC***

FCC-hh **IR radiation another 10-100x higher**

R. Tomas

machine protection

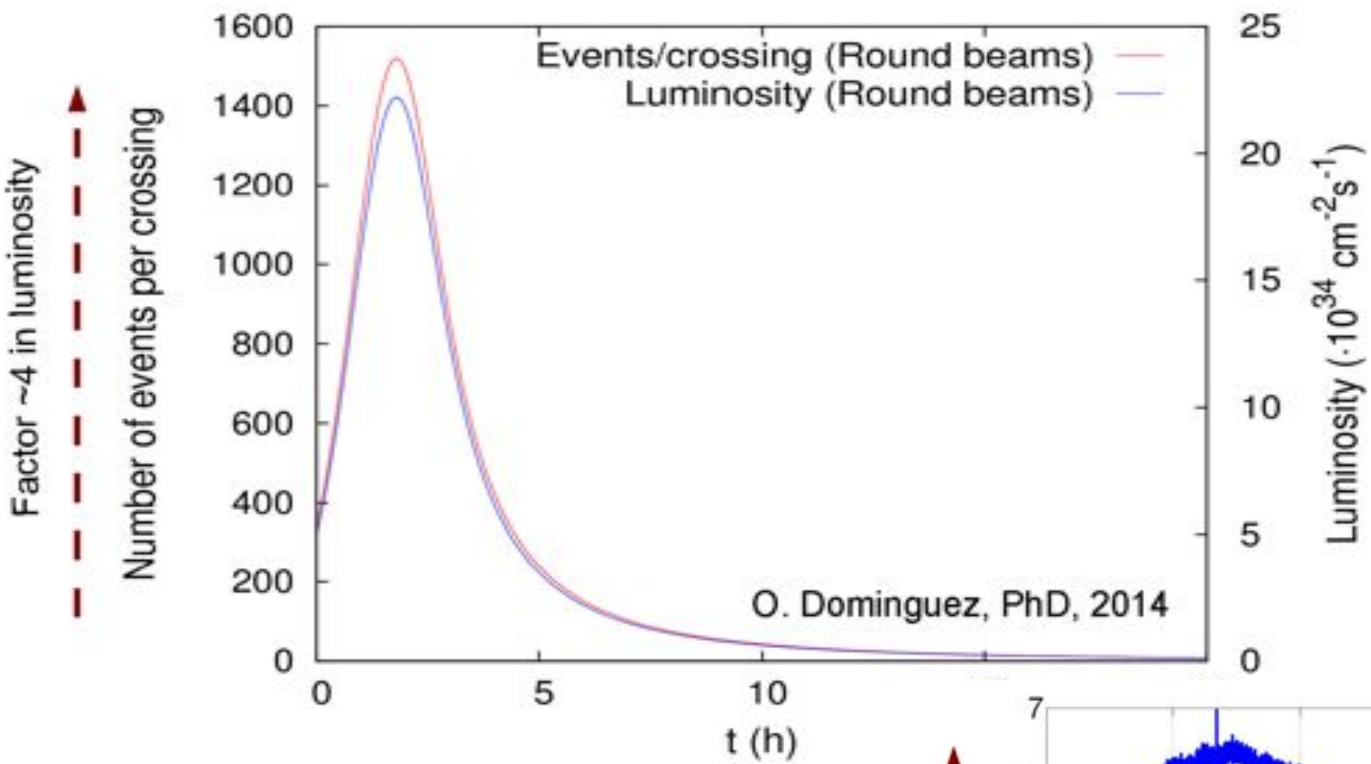
energy per proton beam

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

– kinetic energy of Airbus A380 at 720 km/h

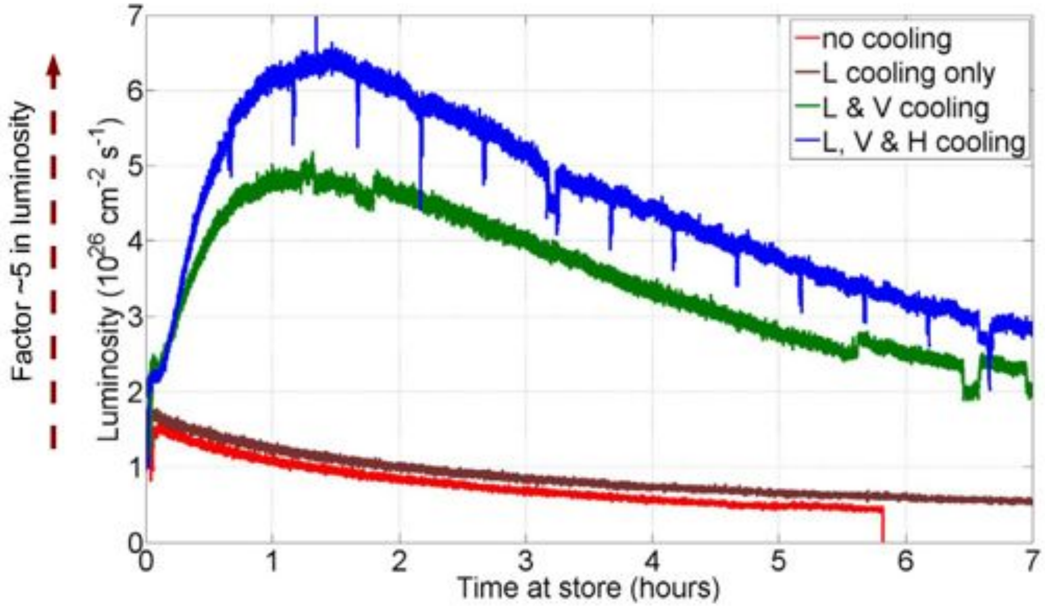
– can melt 12 tons of copper, or drill a 300-m long hole

luminosity evolution with syn. rad. damping



emittance control by noise excitation

M. Blaskiewicz et al.



extremely similar to RHIC operation with stochastic cooling

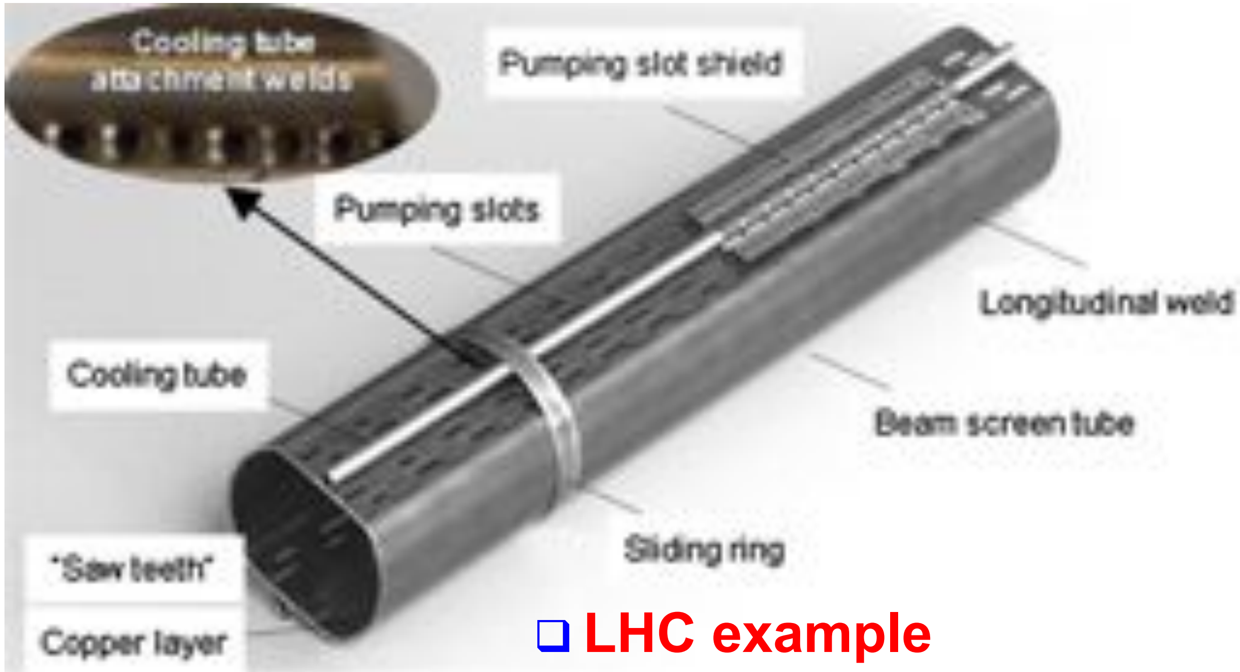
R. Tomas

cryo beam vacuum system

synchrotron radiation (SR): 28 W/m/beam ;

total power: 5 MW

by 2018 prototype tests at ANKA (same crit. energy E_c)!?



❑ **LHC example**

SR power mostly cooled at beam screen temperature; part going to magnets at 2-4 K

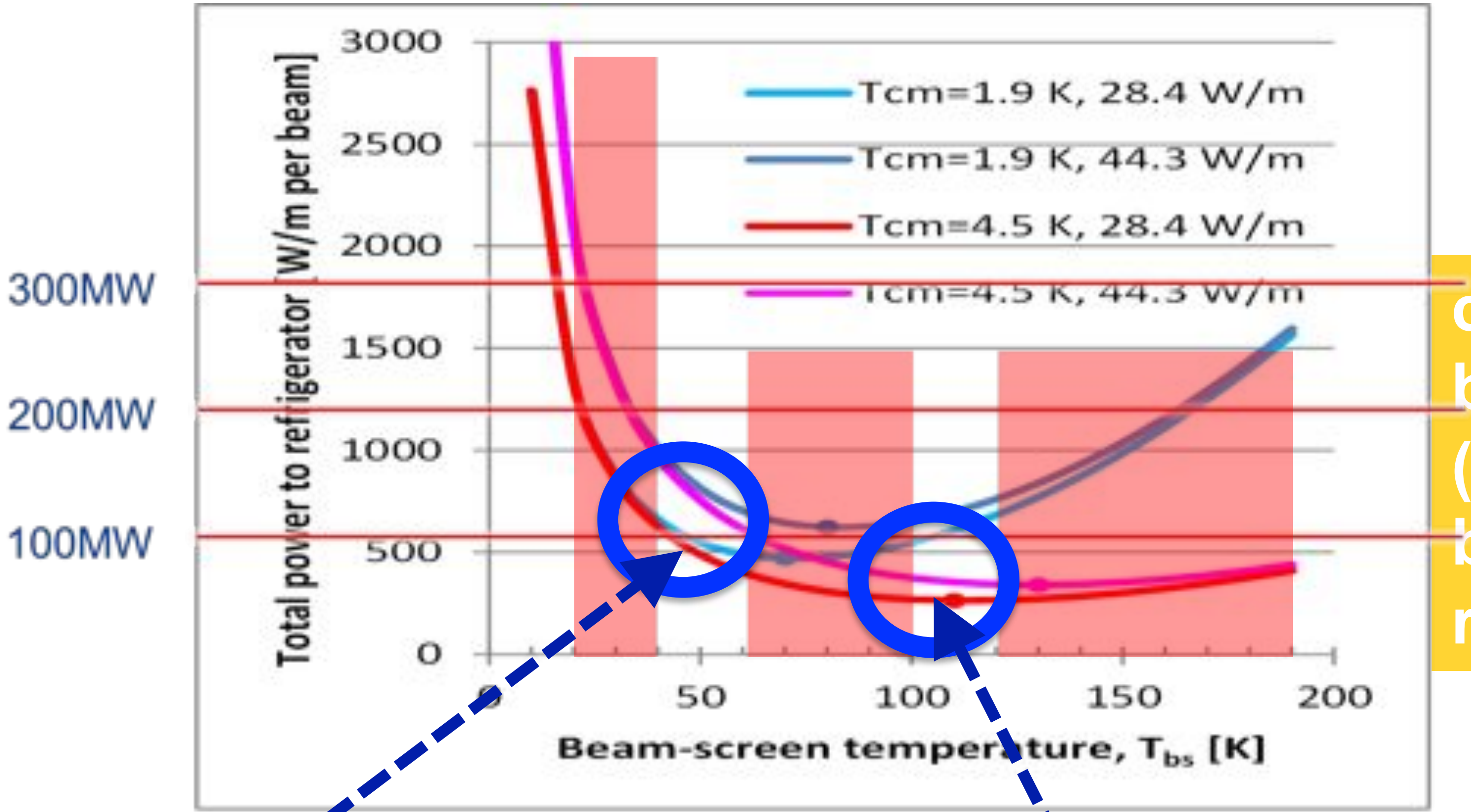
options:

- LHC-type copper coated beam screen (baseline)
- LHC-type beam screen coated with HTS (L. Rossi) + novel cryogens (*He-Ne* mixtures)
- photon stops at room temperature

D. Schulte, M. Jimenez et al.

total cryo power for SR cooling

P. Lebrun, L. Tavian



contributions: beam screen (BS) & cold bore (BS heat radiation)

at 1.9 K cm optimum BS temperature range: 50-100 K; 40-60 K favoured by impedance & vacuum considerations

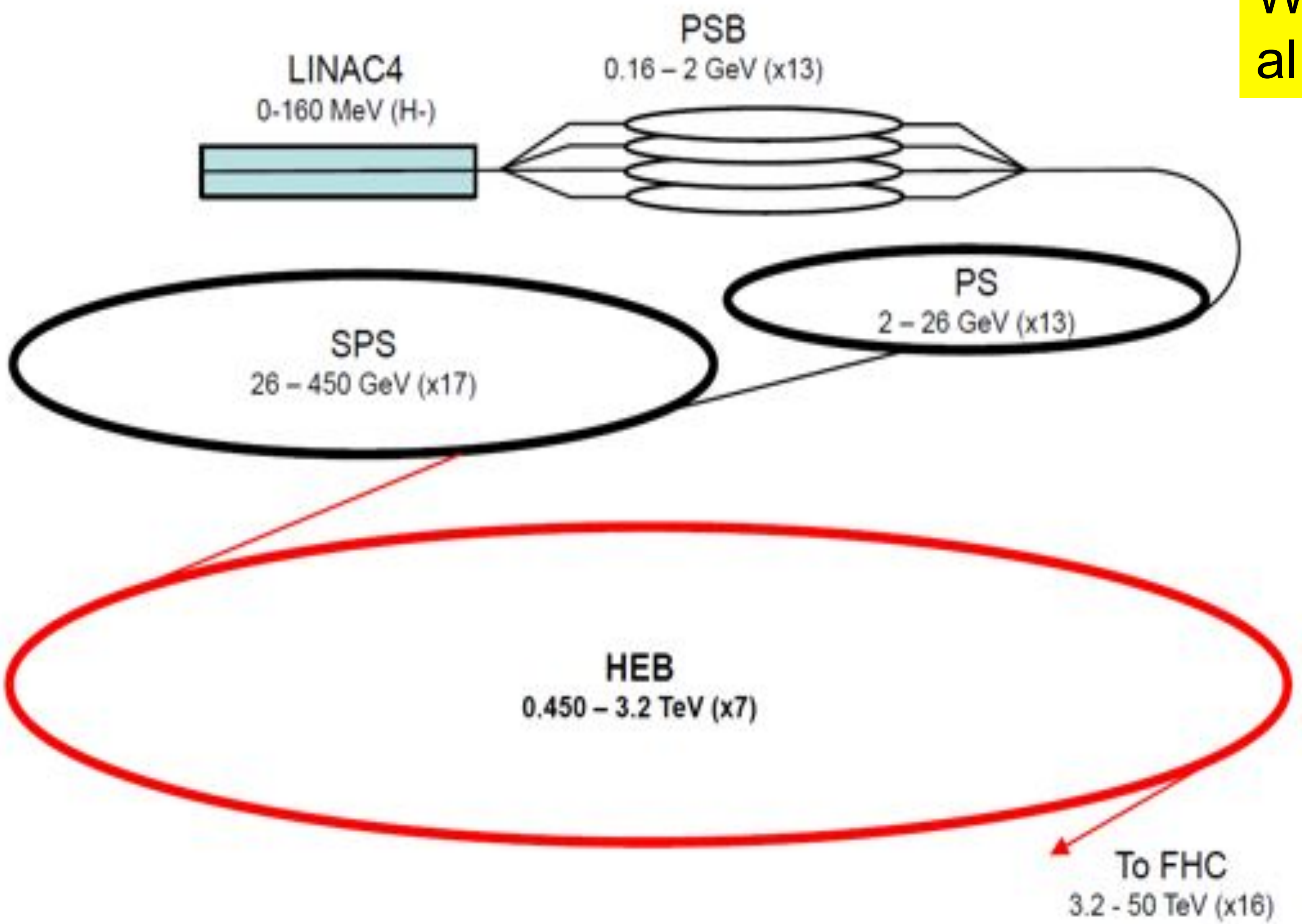
at higher magnet temperature (4.5 K instead of 1.9 K) optimum BS temperature increases & power decreases

FCC-hh injector complex

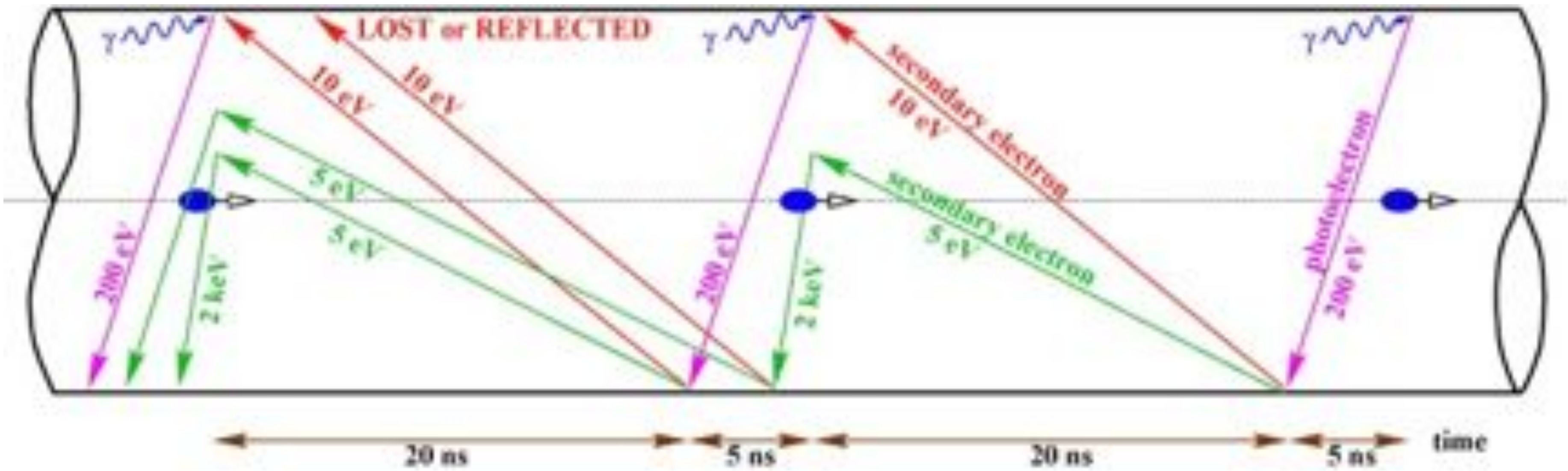
based on existing & planned (HL-LHC/LIU) injector chain;

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

B. Goddard, W. Herr, et al.



electron cloud



schematic of e⁻ build up inside beam pipe with SR photons, emitted photoelectrons and secondary electrons. Horizontal axis is time. Electrons are accelerated in the field of passing bunches [Courtesy F. Ruggiero]

FCC-hh critical photon energy = 4.3 keV, similar to 2-3 GeV light sources, 100 x LHC

electron-cloud effects:
beam instabilities, emittance growth, heat load, …

e-cloud: δ_{max} threshold at injection

FCC injection, 3.3 TeV

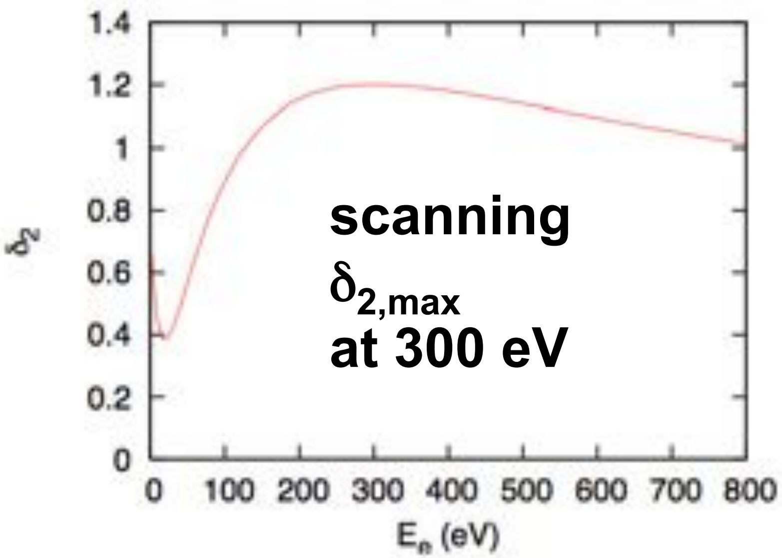
E_p=3.3 TeV, B=1 T

25 ns: N_b=10^{11}, ε=630 pm

5 ns: N_b=2x10^{10}, ε=13 pm

β=200 m,

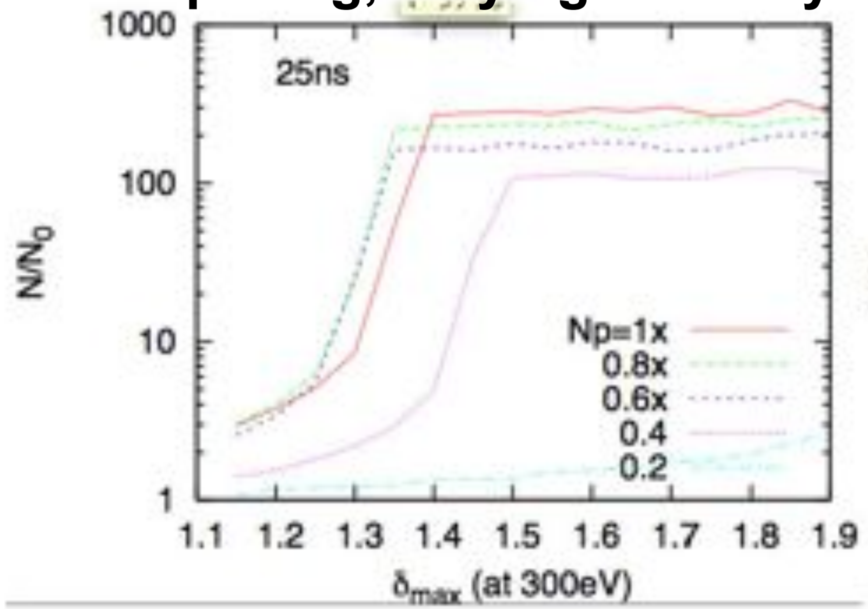
σ_z=8 cm, R=1.3 cm



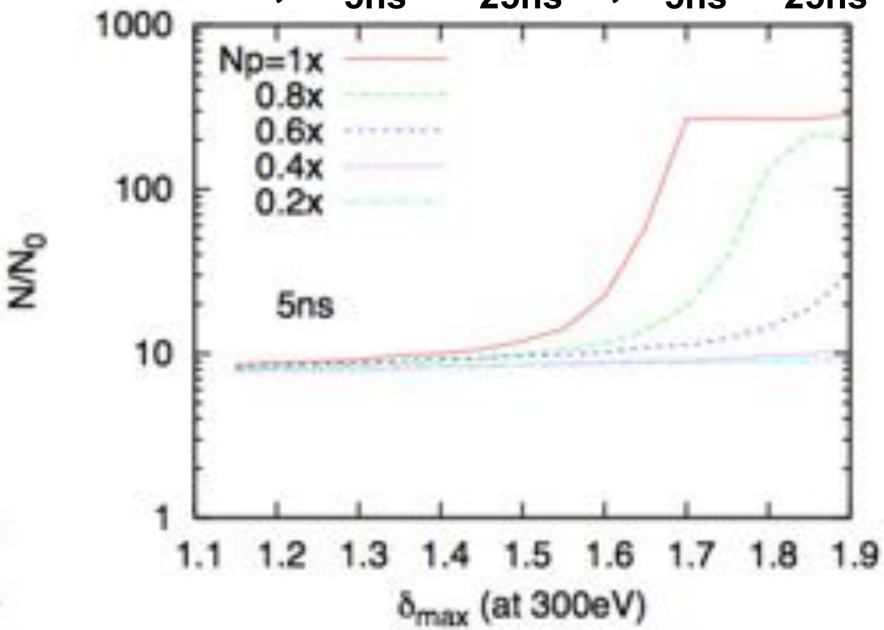
scanning $\delta_{2,max}$ at 300 eV

K. Ohmi,
O. Dominguez

25 ns spacing, varying intensity



5 ns, N_{5ns}=N_{25ns}/5, ε_{5ns}=ε_{25ns}/5

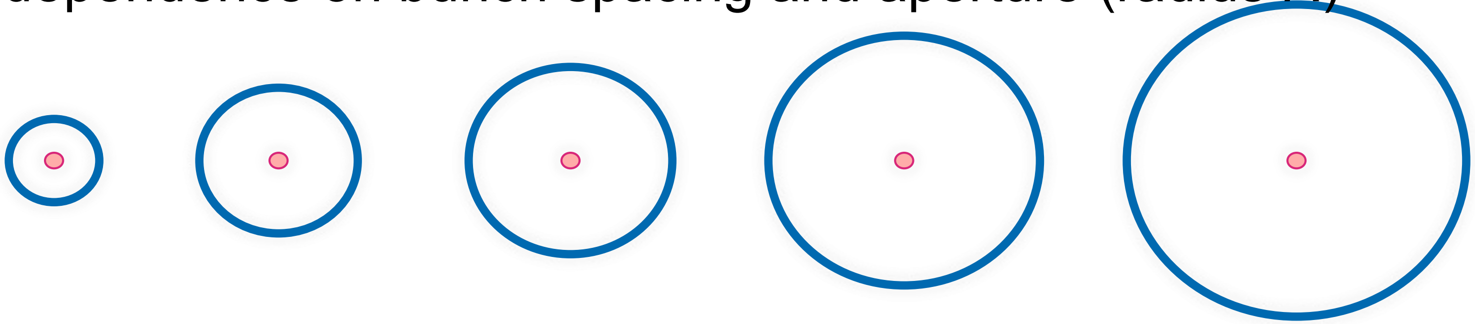


e-cloud in FCC-hh HEB: heat load

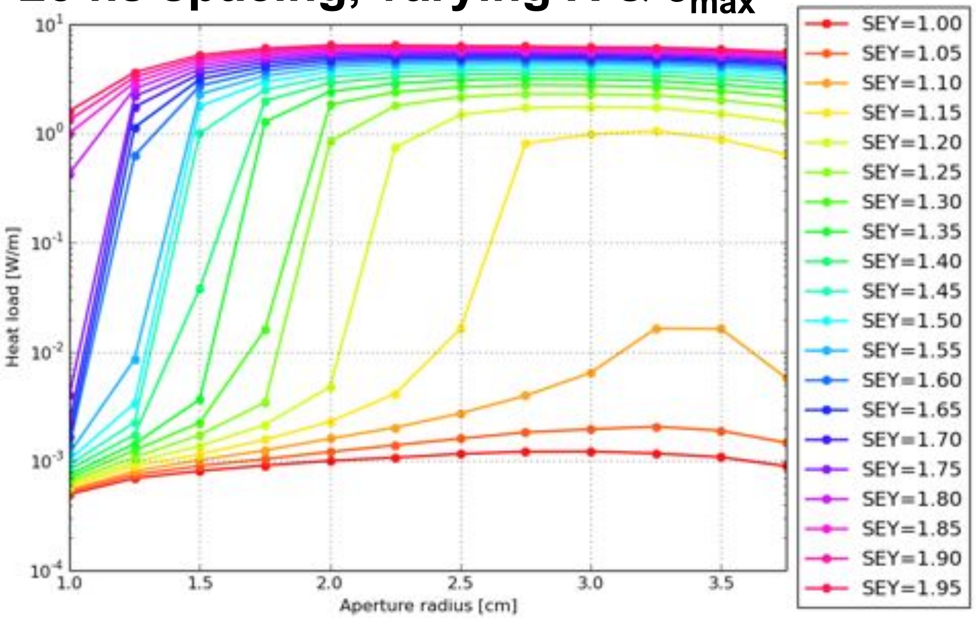
HEB injection 450 GeV

L. Mether,
G. Iadarola,
G. Rumolo

dependence on bunch spacing and aperture (radius *R*)

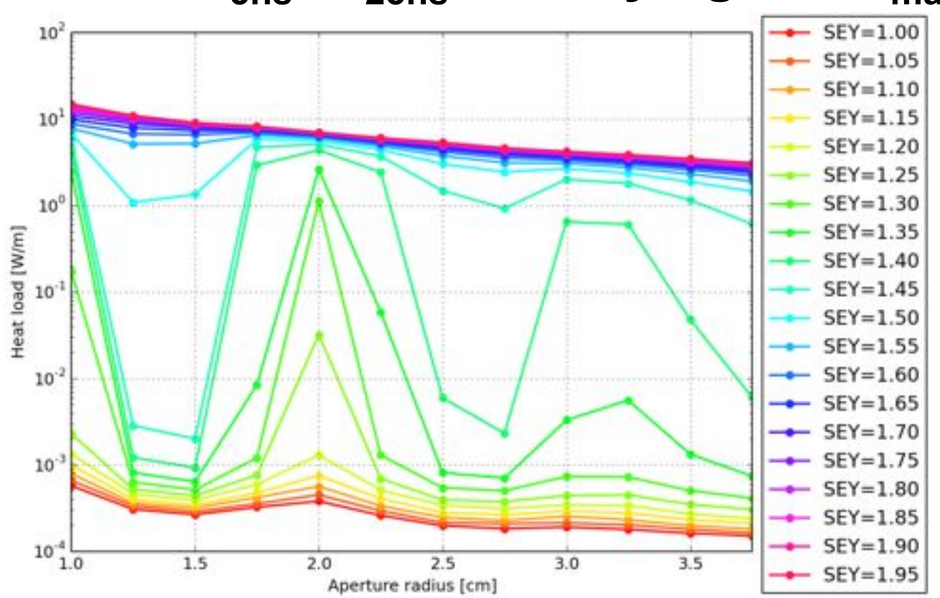


25 ns spacing, varying *R* & δ_{max}



heat load first increases with *R* and then decreases for large *R*

5 ns, N_{5ns}=N_{25ns}/5 , varying *R* & δ_{max}



heat load decreases with growing *R*, but oscillates

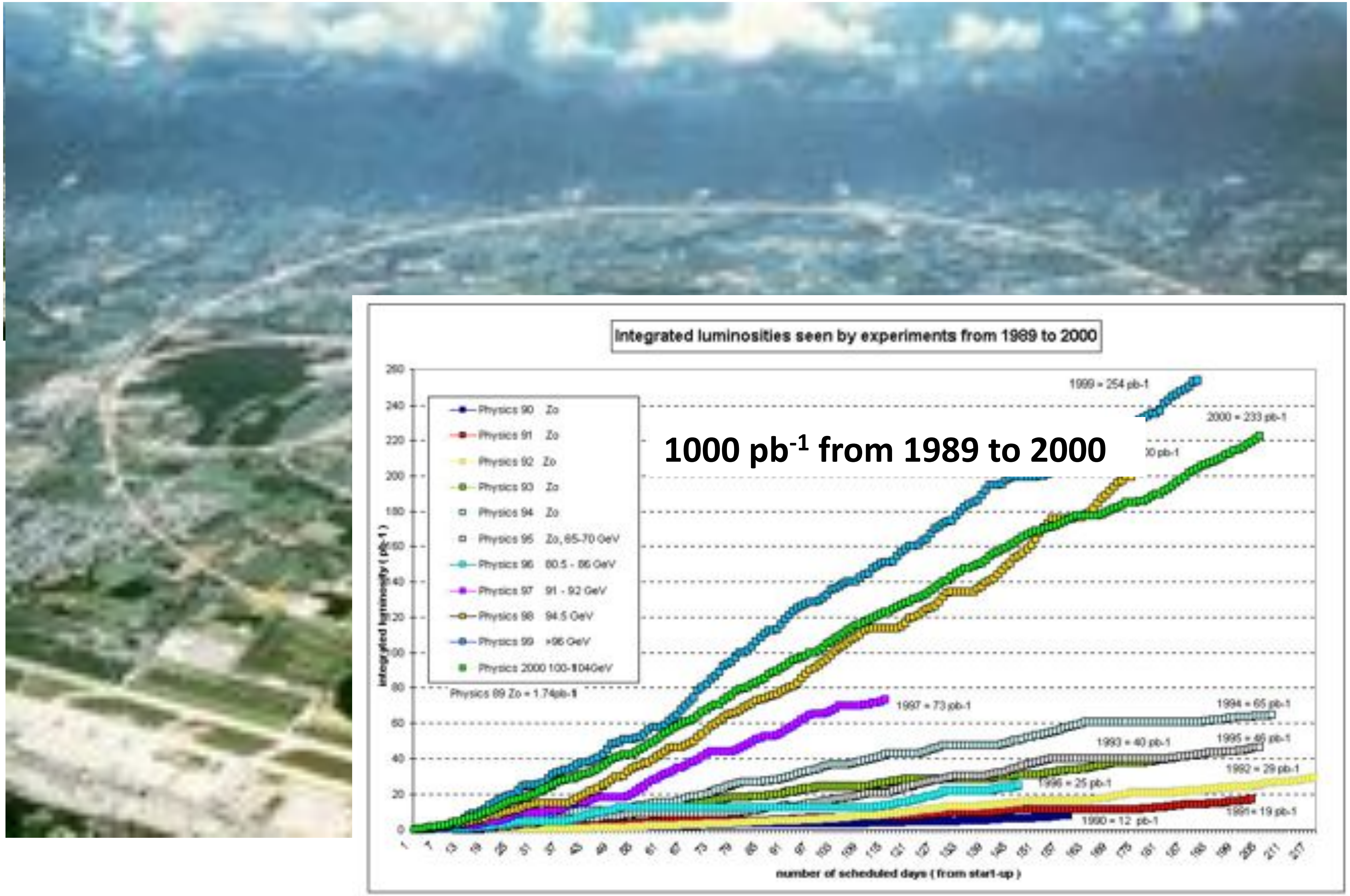
FCC-hh as heavy-ion collider

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)

M. Schaumann, J. Jowett

LEP – largest circular e^+e^- collider so far

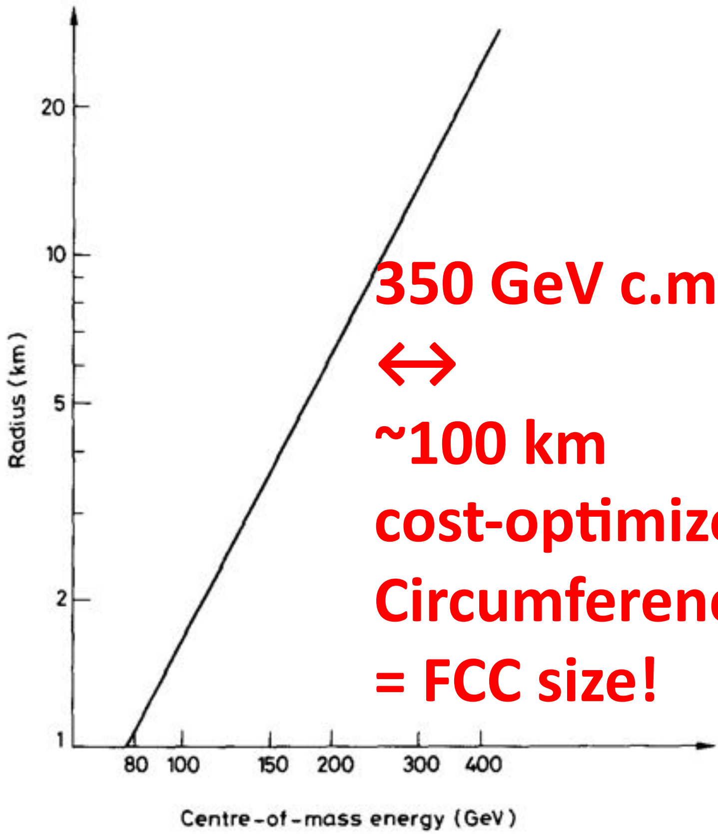


1000 pb^{-1} from 1989 to 2000

“An e^+-e^- storage ring in the range of a few hundred GeV in the centre of mass can be built with present technology. ...would seem to be … most useful project on the horizon.”

(original LEP proposal, 1976)

B. Richter, *Very High Energy Electron-Positron Colliding Beams for the Study of Weak Interactions*, NIM 136 (**1976**) 47-60



350 GeV c.m.
↔
~100 km
cost-optimized
Circumference
= FCC size!

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?!

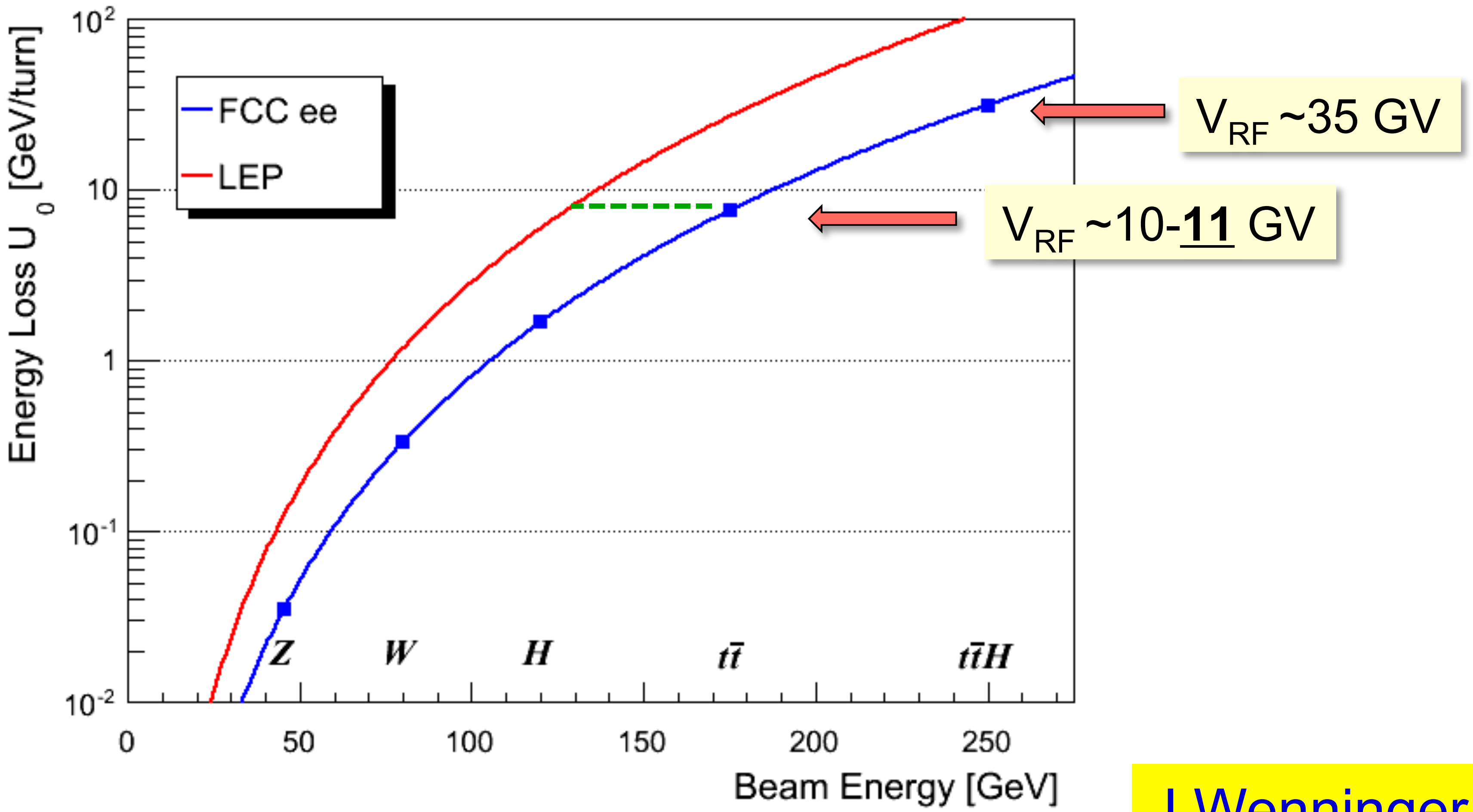
parameter	LEP2	FCC-ee					CepC
		Z	Z (c.w.)	W	H	t	H
E_{beam} [GeV]	104	45	45	80	120	175	120
circumference [km]	26.7	100	100	100	100	100	54
current [mA]	3.0	1450	1431	152	30	6.6	16.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	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

Synchrotron radiation power

The maximum synchrotron radiation (SR) power P_{SR} is set to **50 MW per beam** – design choice ⇔ power dissipation.

⇒ *defines the maximum beam current at each energy.*

Note that a margin of a few % is required for losses in straight sections.



J.Wenninger

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).

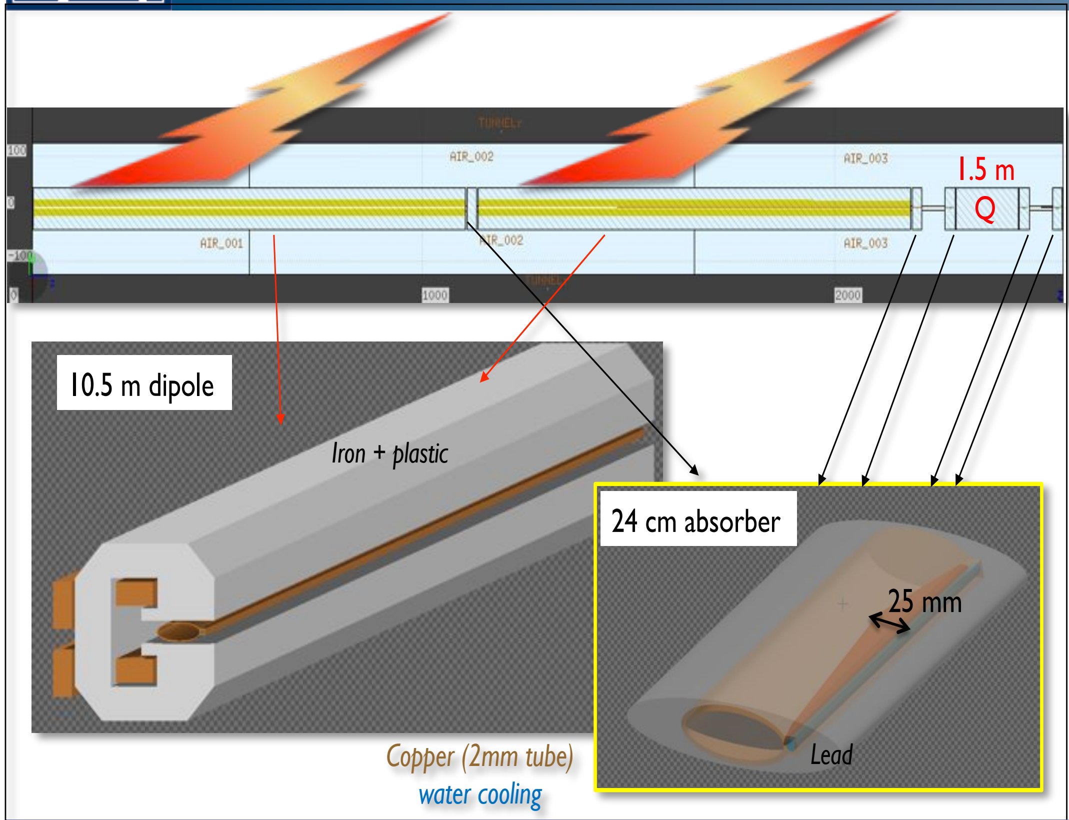
- *Nano-beam / crab waist favors lower frequency, e.g. 400 MHz.*

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.*

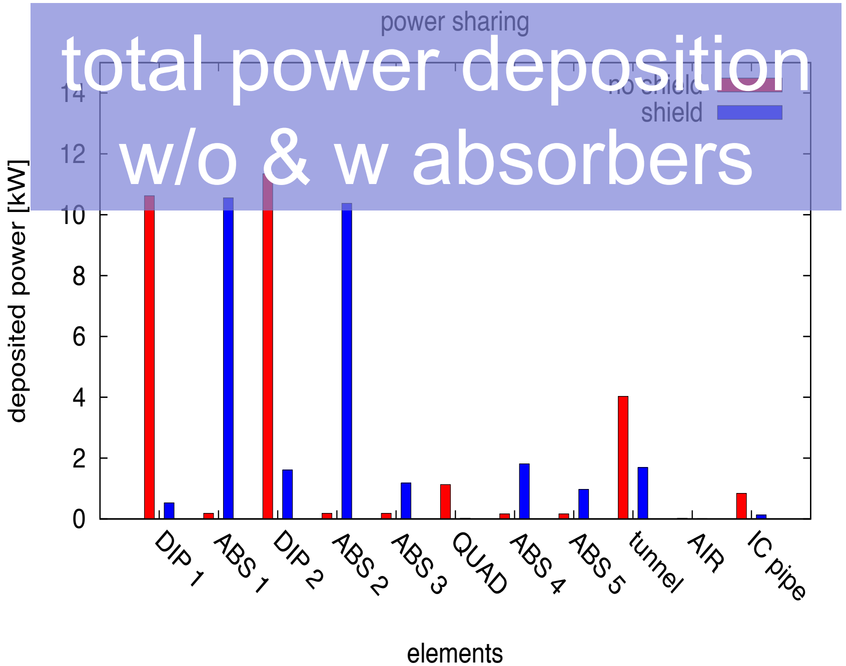
J. Wenninger, A. Butterworth, E. Jensen, et al.

shielding 100 MW SR at 175 GeV

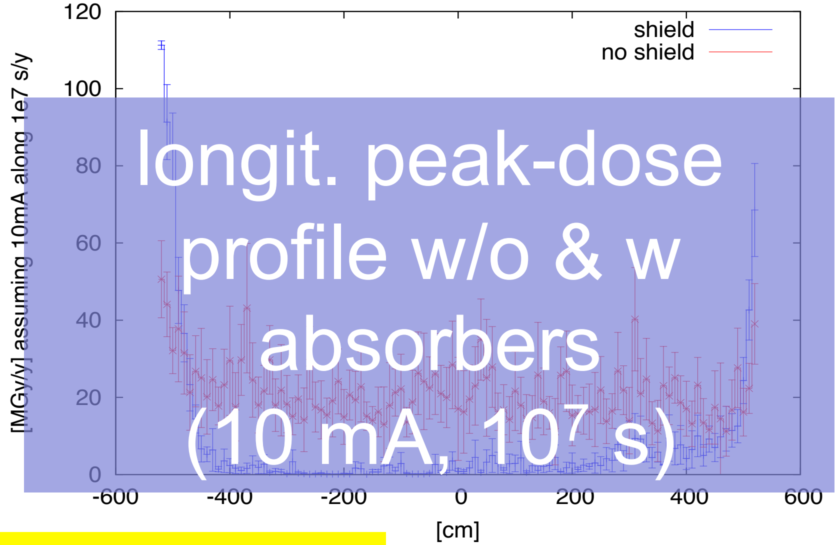


FLUKA geometry layout for half FODO cell, dipole details, preliminary absorber design incl. 5 cm external *Pb* shield

total power deposition w/o & w absorbers



longit. peak-dose profile w/o & w absorbers (10 mA, 10^7 s)



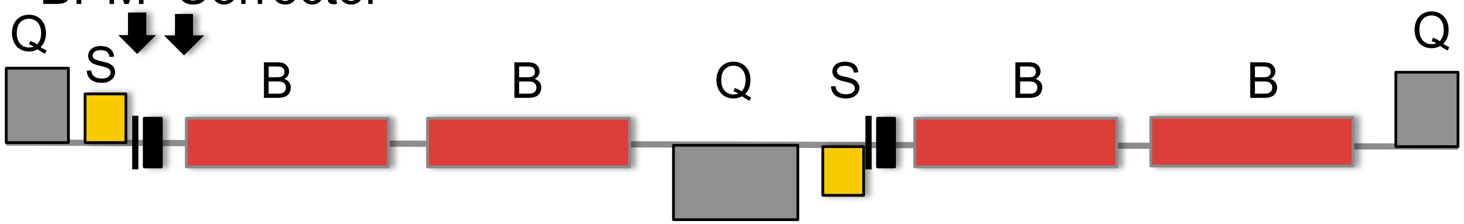
L. Lari, F. Cerutti, A. Ferrari, A. Mereghetti

layout & optics at 120 & 175 GeV

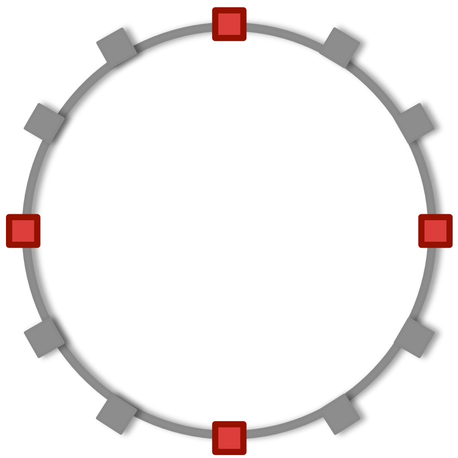
LATTICE V12B-S

arc cell

layout

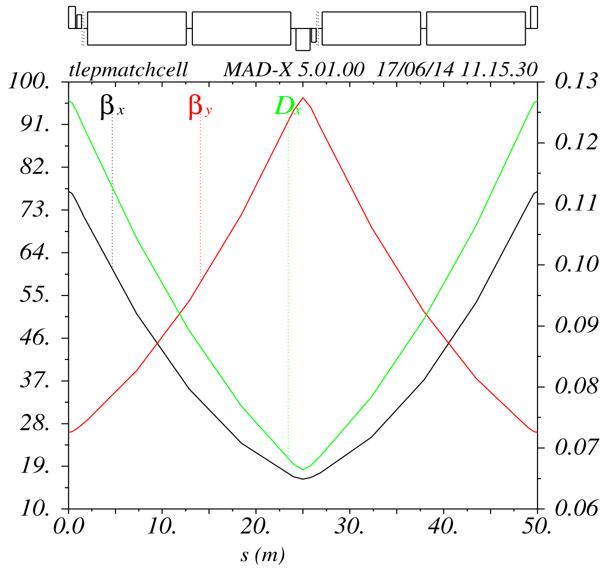


B = bending magnet, Q = quadrupole, S = sextupole

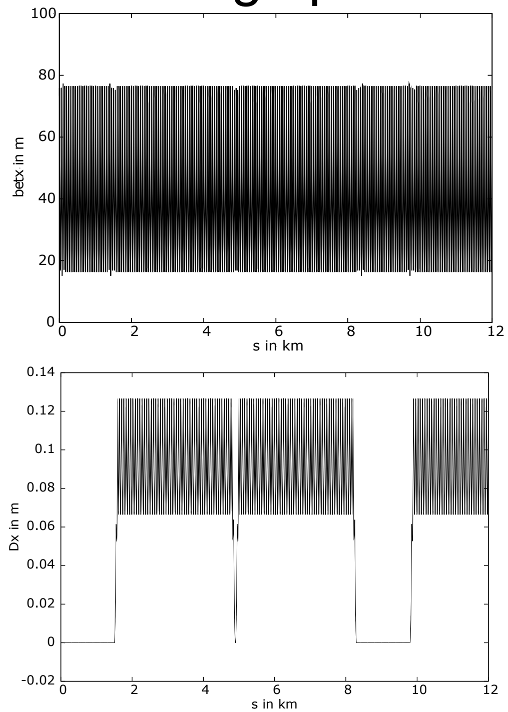


Circumference: 100 km
Arc length: 2 × 3.4 km
Straight section: 1.5 km

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°

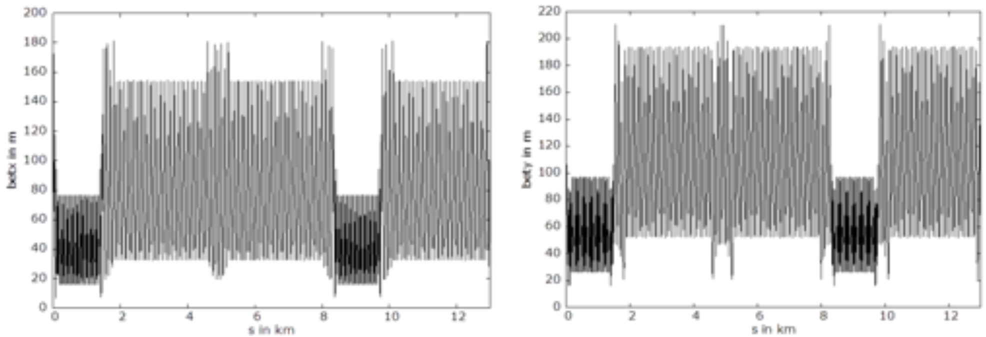
45.5 GeV: L_{cell} = 200 m, Ψ = 60°/60°

Dispersion suppressor based on quadrupoles

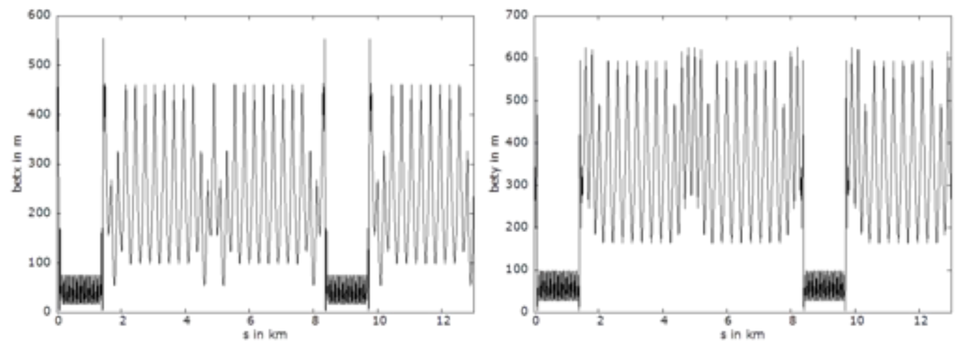
45.5 GeV: L_{cell} = 250 m, Ψ = 72°/72°

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 $\varepsilon_x \leq 0.5$ baseline

IR parameters

smallest possible β^* desired; target β^*_y = **1 mm**; so small a value of β^* requires local chromaticity correction

- *design inspired by linear collider IR;*
- *additional complexity that beam does not pass the IR only once → effects of optical aberrations critical*
- *bending magnets close to the IP → SR fan !*

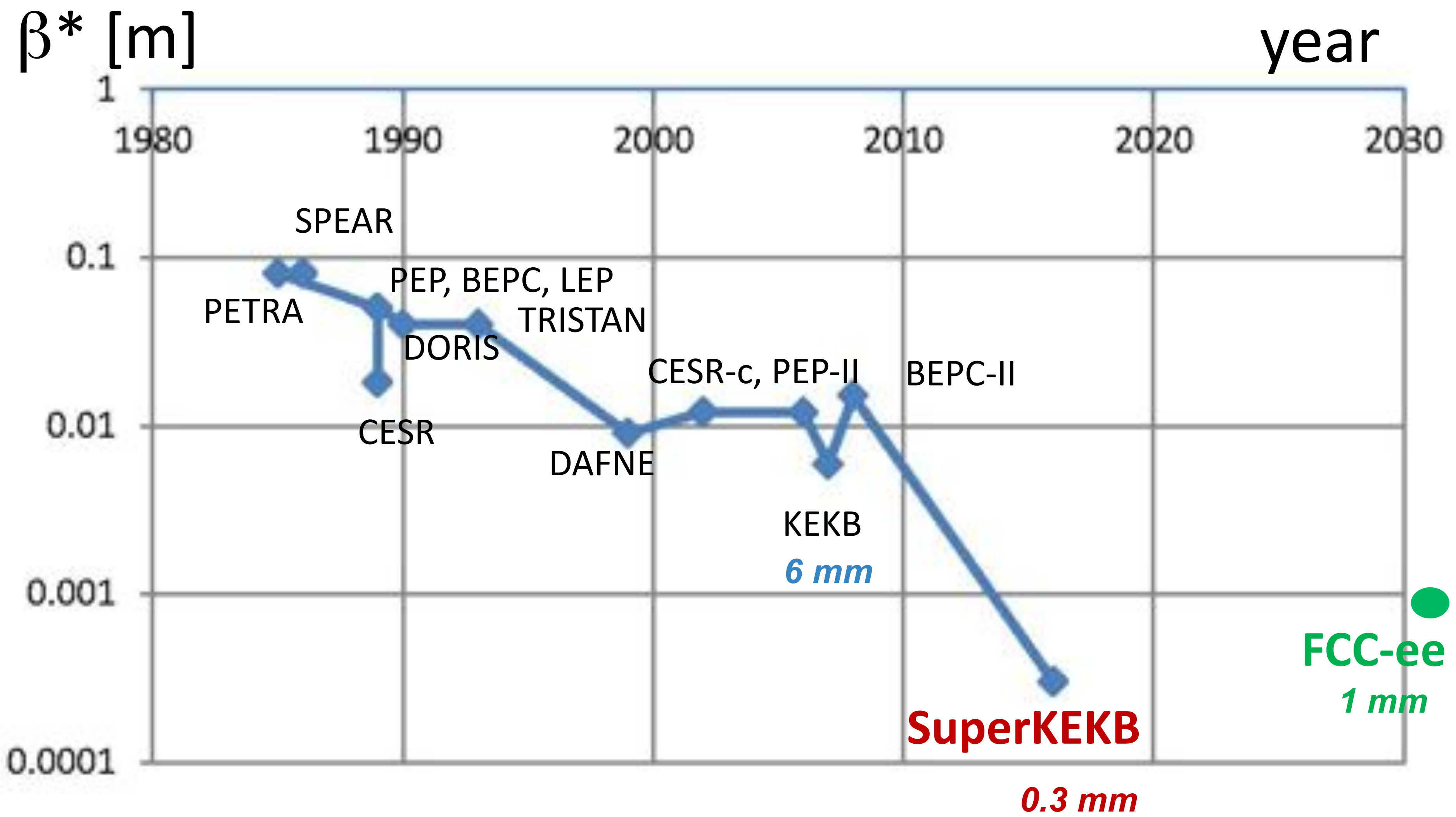
distance between IP and front-face of first quadrupole currently set to **L* ≥ 2 m** (SuperKEKB ~1 m)

- *detector acceptance, luminosity measurement,… .*

combination of very small β_y^* and required large energy acceptance is challenge for optics design !

J. Wenninger, R. Tomas,…

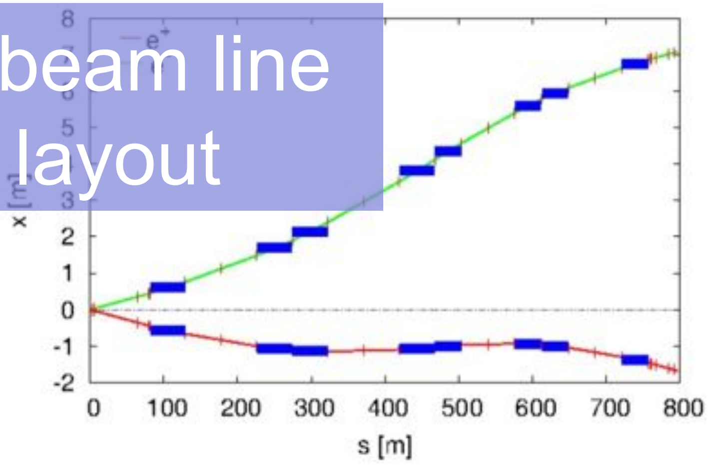
β* evolution



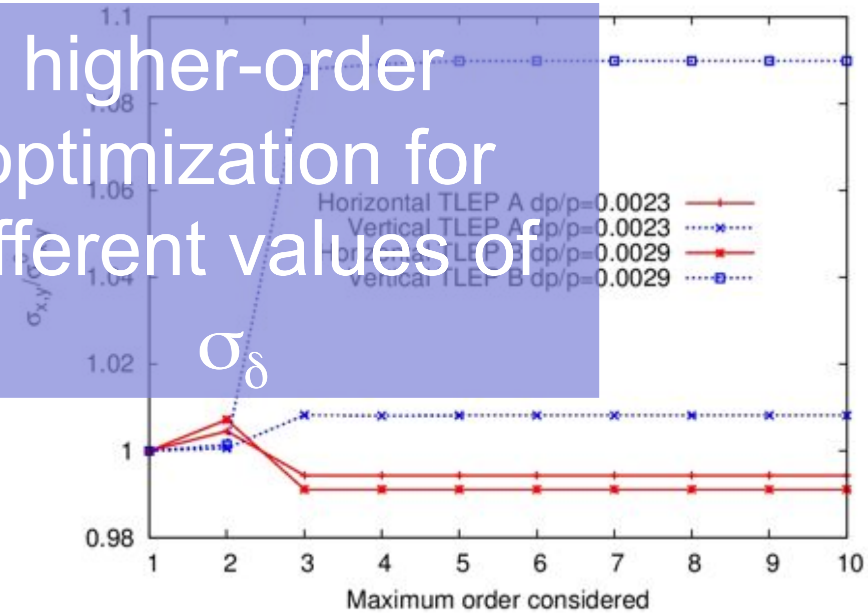
SuperKEKB will be an *FCC-ee* demonstrator for certain optics aspects !

FCC-ee IR design #1

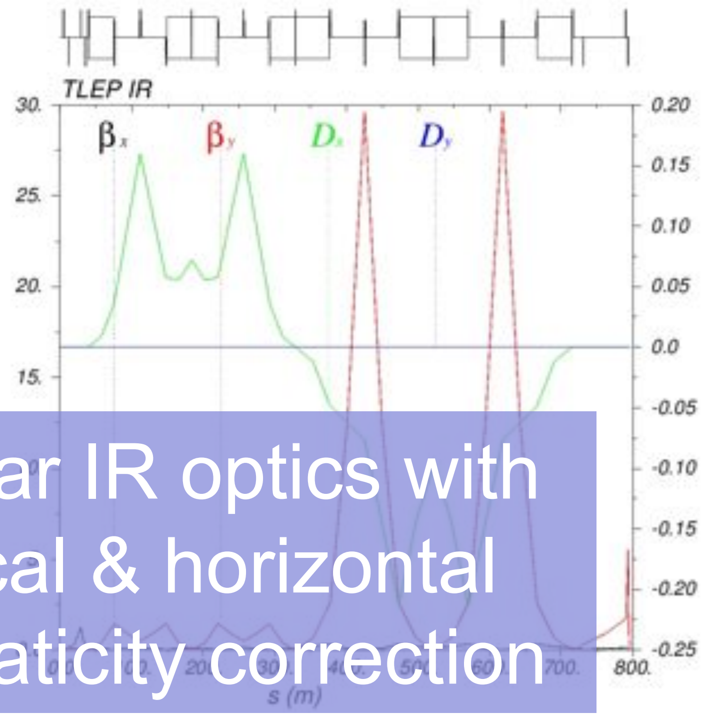
$e^{\pm}$ beam line layout



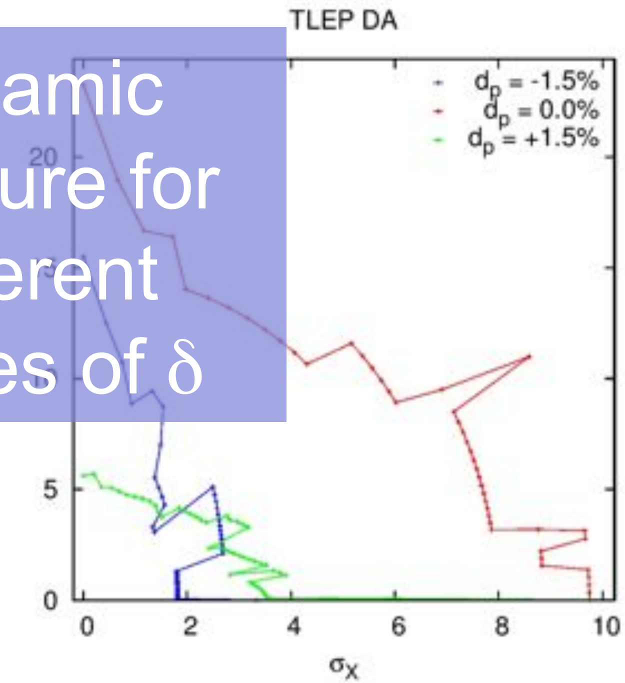
higher-order optimization for different values of σ_δ



modular IR optics with vertical & horizontal chromaticity correction

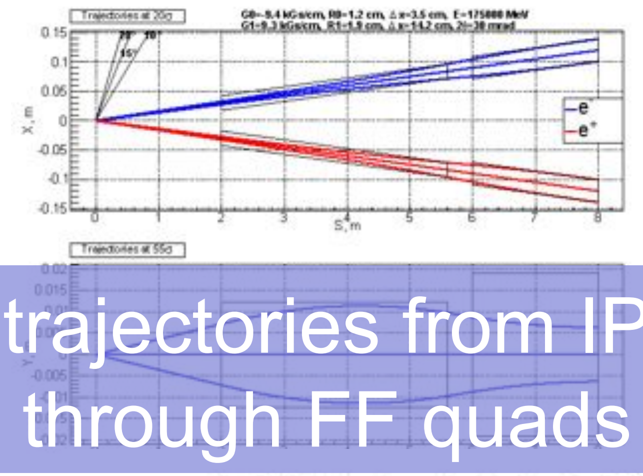


dynamic aperture for different values of δ

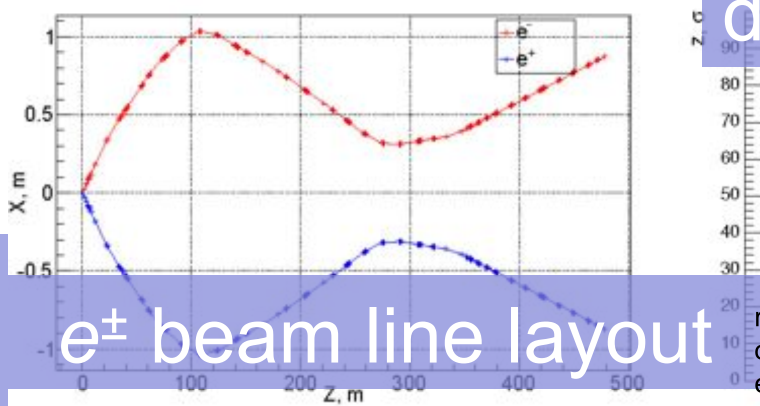


H. Garcia, L. Medina, R. Tomas

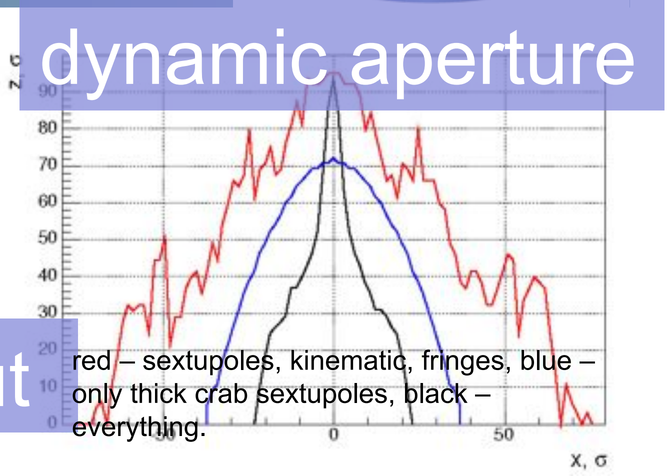
FCC-ee IR design #2



trajectories from IP through FF quads

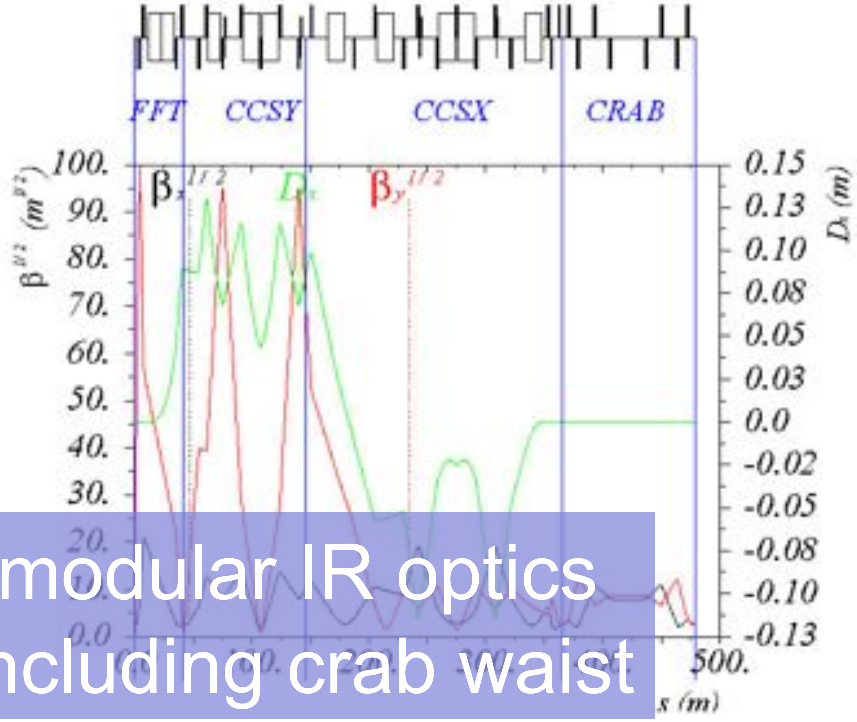


e± beam line layout

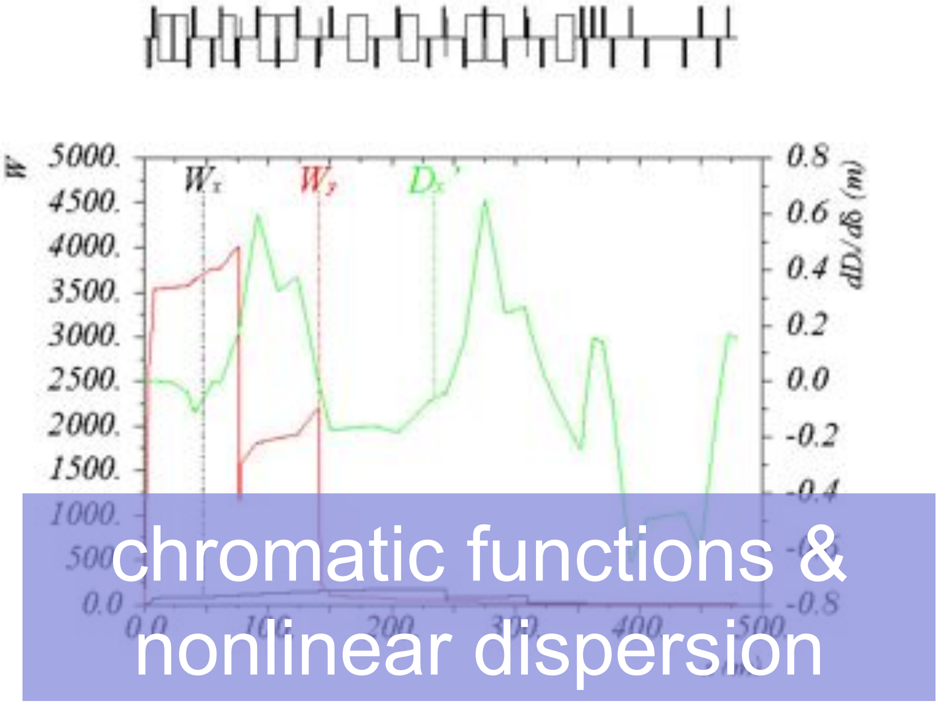


dynamic aperture

red – sextupoles, kinematic, fringes, blue – only thick crab sextupoles, black – everything.



modular IR optics including crab waist



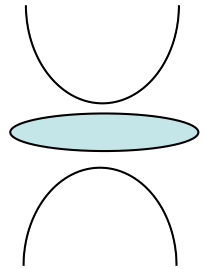
chromatic functions & nonlinear dispersion

A. Bogomyagkov, E. Levichev, P. Piminov

luminosity

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

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

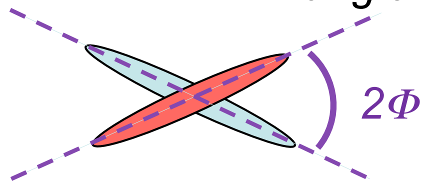


H ≤ 1

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

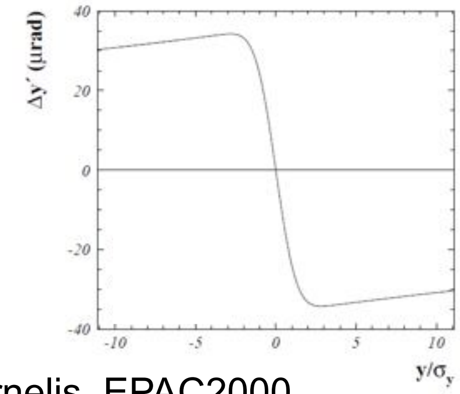
P_{SR} = synch. rad. power

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)

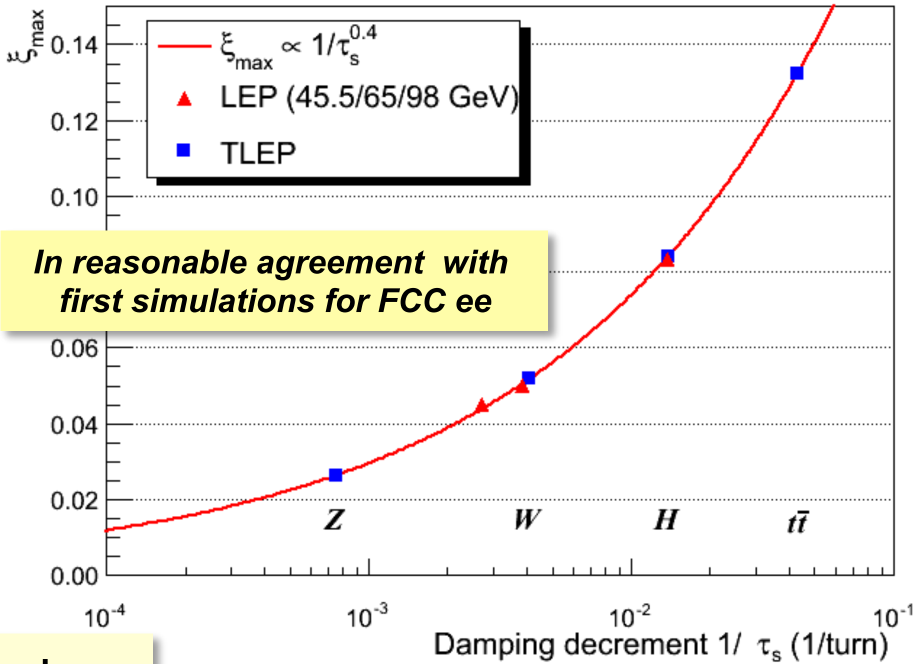


$$\xi_y \propto \frac{\beta_y^* N}{E\sigma_x\sigma_y} \le \xi_y^{\max}(E)$$

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

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

R. Assmann & K. Cornelis, EPAC2000



In reasonable agreement with first simulations for FCC ee

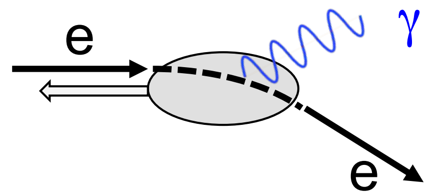
The beam-beam limit may be raised significantly with Crab-Waist schemes !

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)

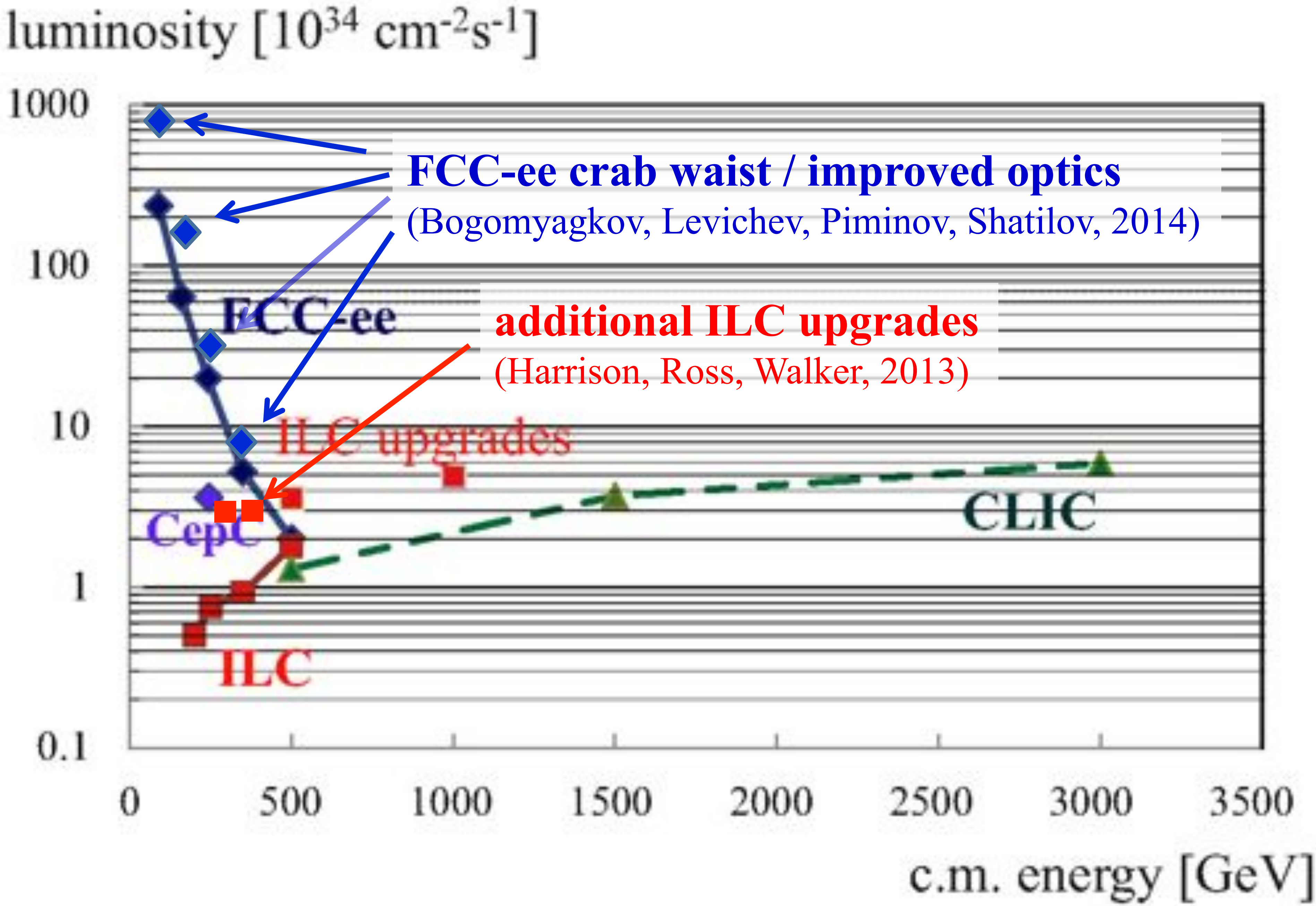
η : ring energy acceptance

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

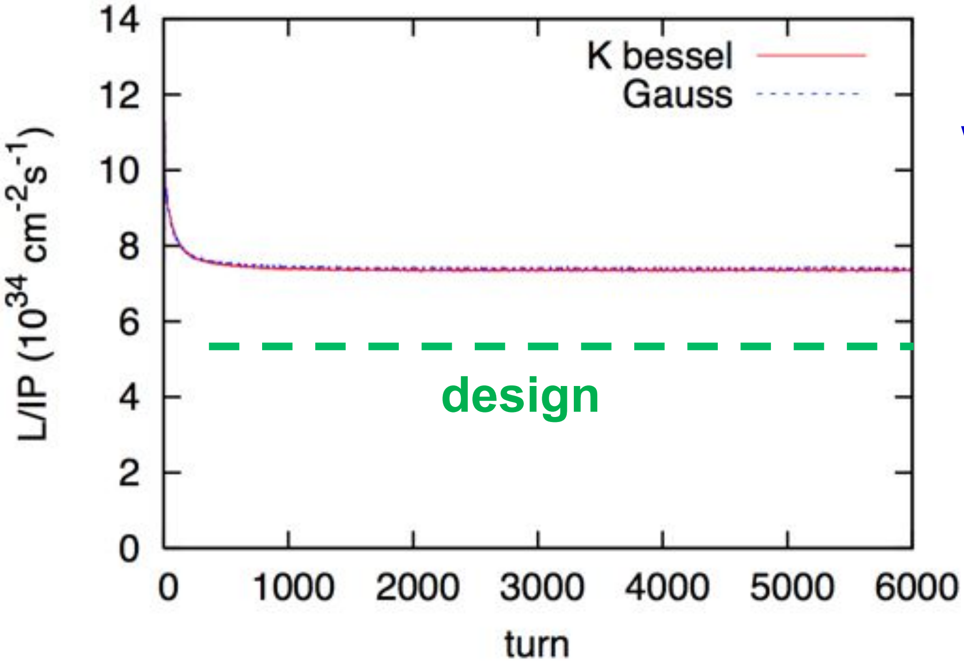
- to ensure an acceptable lifetime, ρ×η must be sufficiently large
  - *flat beams (large σ_x) !*
  - *bunch length !*
  - *large momentum acceptance of the lattice: **1.5 – 2% required**.*
    - LEP: < 1% acceptance, SuperKEKB ~ 1-1.5%.

J. Wenninger, et al

e^+e^- luminosity vs energy



beam-beam performance checks

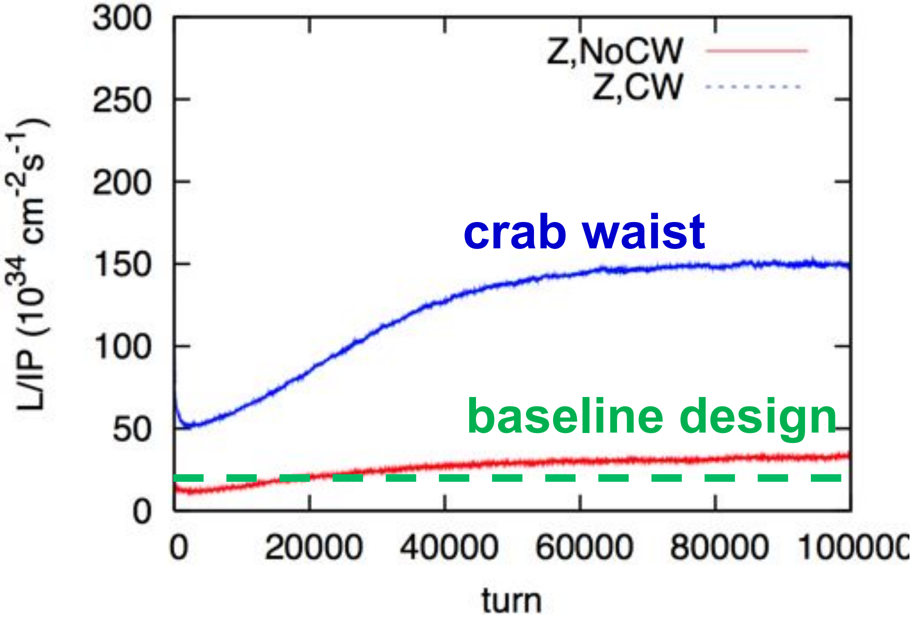


BBSS strong-strong simulation
w beamstrahlung

FCC-ee in Higgs production mode (240 GeV c.m.):
$L \approx 7.5\text{x}10^{34}$ cm^{-2}s^{-1} per IP

BBWS weak-strong simulation
w beamstrahlung

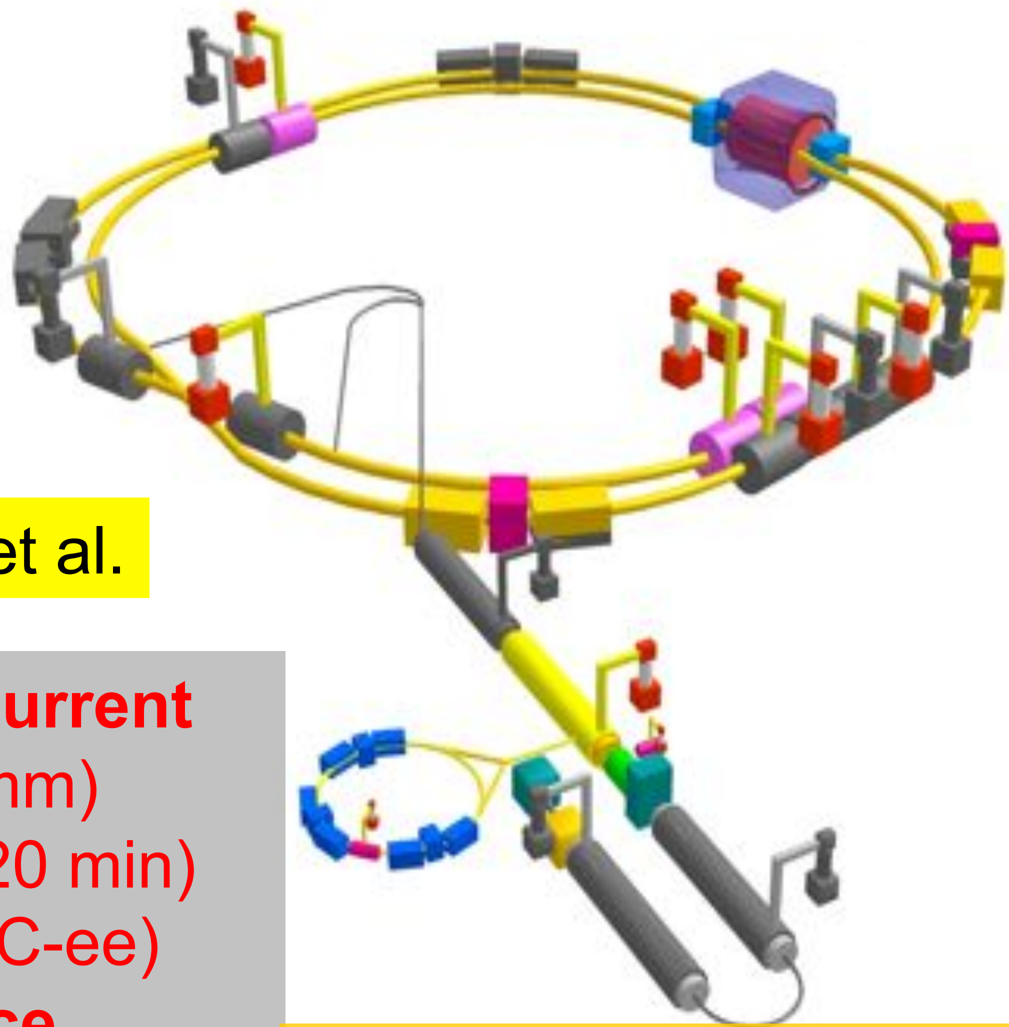
FCC-ee in crab-waist mode at the Z pole (91 GeV c.m.):
$L \approx 1.5\text{x}10^{36}$ cm^{-2}s^{-1} per IP



K. Ohmi, A. Bogomyagkov, E. Levichev, P. Piminov

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 (2.5x10^{12}/s,
FCC-ee: <1.5x10^{12}/s (Z cr.waist)

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

The Twin Frontiers of *FCC-ee* Physics

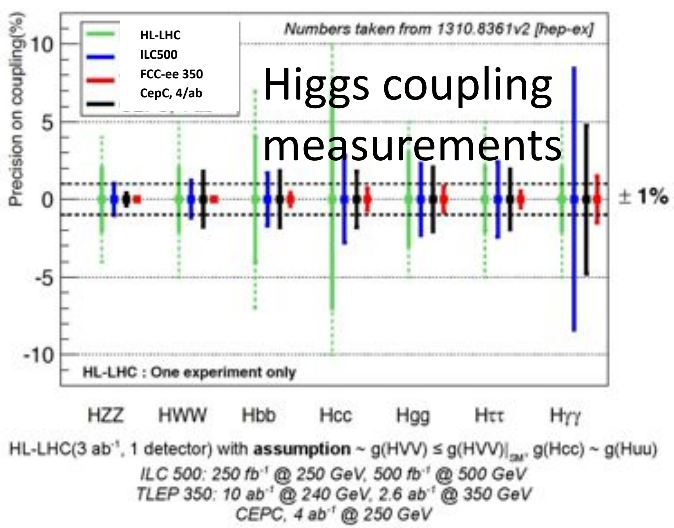
Precision Measurements

- 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
- W: 10^8
- H: 10^6
- t: 10^6

***FCC-ee* promises much higher precision & and many more rare decays than any competitors**



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

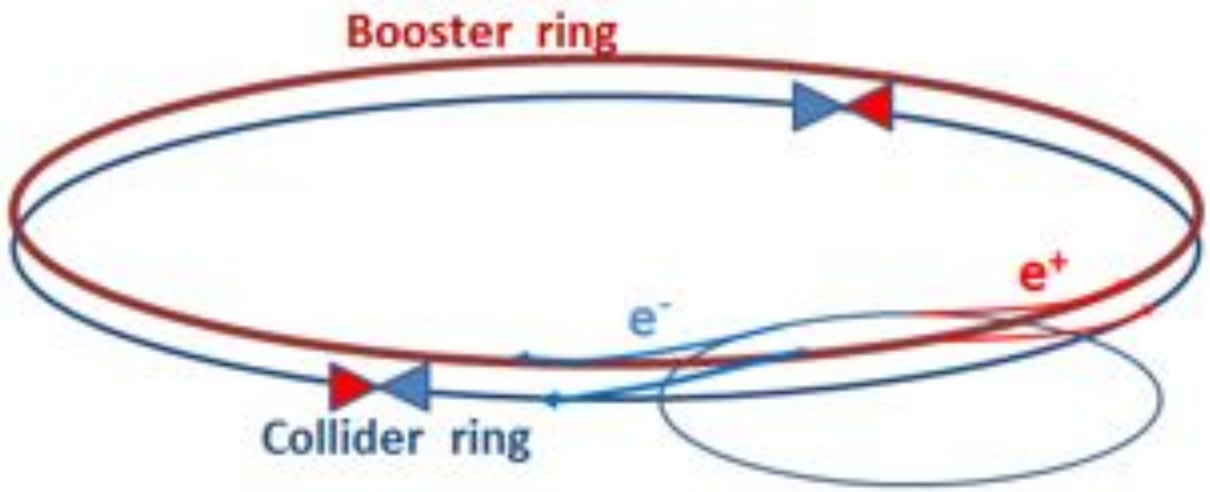
FCC-ee injection

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



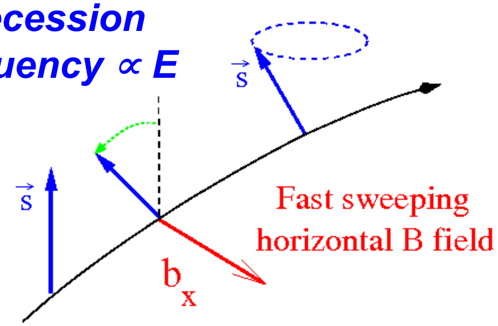
A. Blondel

polarization

two primary interests:

accurate energy calibration using resonant depolarization ⇒ measurement of M_Z, Γ_Z, M_W

- *nice feature of circular machines, δM_Z, $\delta\Gamma_Z$ ~ 0.1 MeV*



physics with longitudinally polarized beams

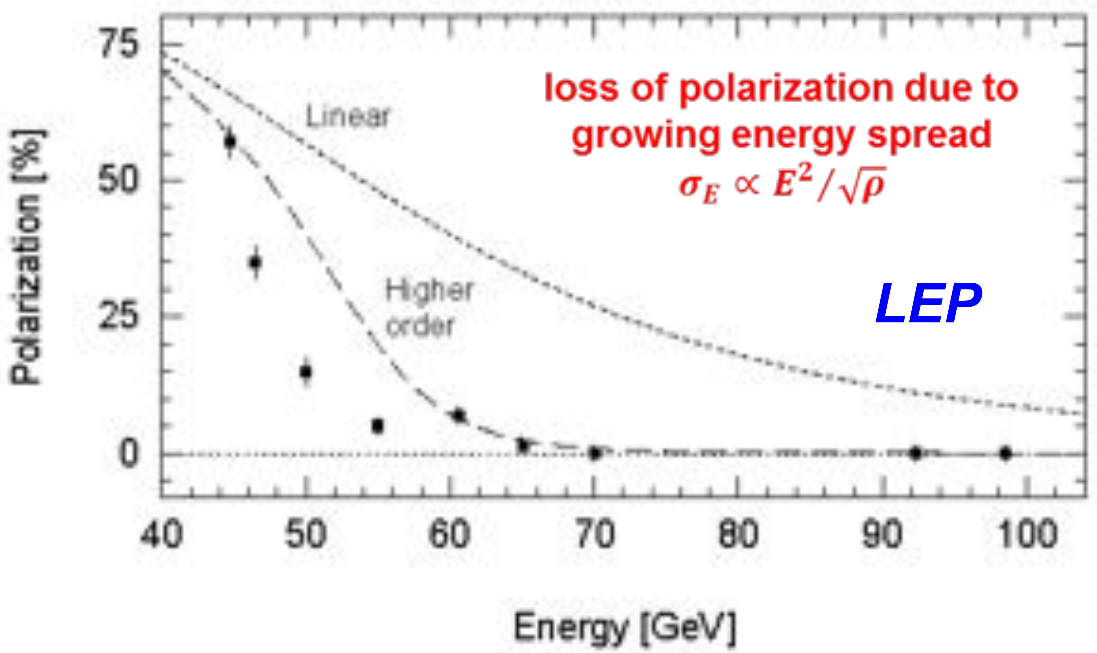
- *transverse polarization must be rotated in the longitudinal plane using spin rotators (see e.g. HERA)*

scaling from LEP observations :

polarization expected up to the WW threshold !

integer spin resonances are spaced by 440 MeV:

energy spread should remain below ~ 60 MeV



A. Blondel, S. Mane, U. Wienands, J. Wenninger, et al.

polarization build up

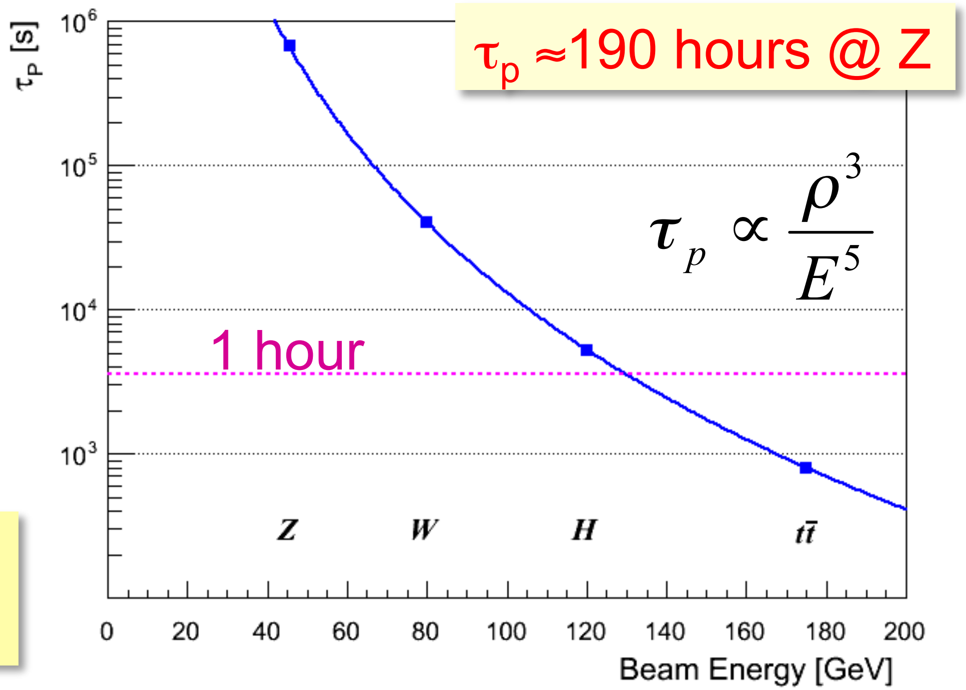
transverse polarization build-up (Sokolov-Ternov) is slow at *FCC-ee* (large bending radius ρ)

build-up is ~40 times slower than at LEP

wigglers may lower τ_p to ~12 h, limited by $\sigma_E \leq 60$ MeV and power

due to power loss the wigglers can only be used to pre-polarize some bunches (before main injection)

≈ OK for energy calibration (few % P sufficient)



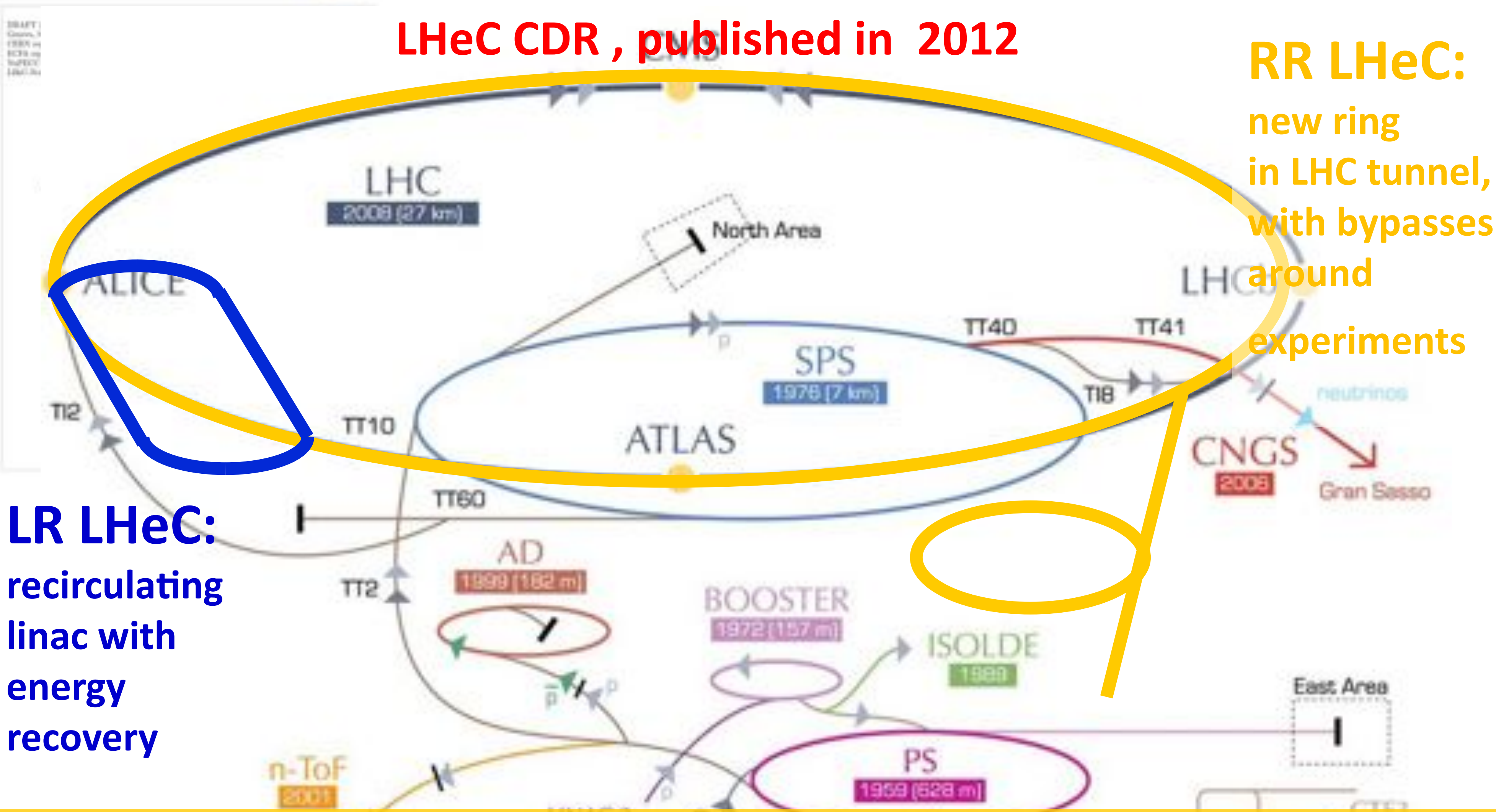
<u>longitudinal polarization</u>: levels of ≥ 40% required on both beams; excellent resonant compensation needed

expected to be difficult, requires spin rotators or snakes, most likely only possible at lower intensity and luminosity

A. Blondel, U. Wienands, J. Jowett, R. Rossmanith, J.Wenninger

FCC-he: high-energy lepton-hadron collider

LHeC CDR , published in 2012

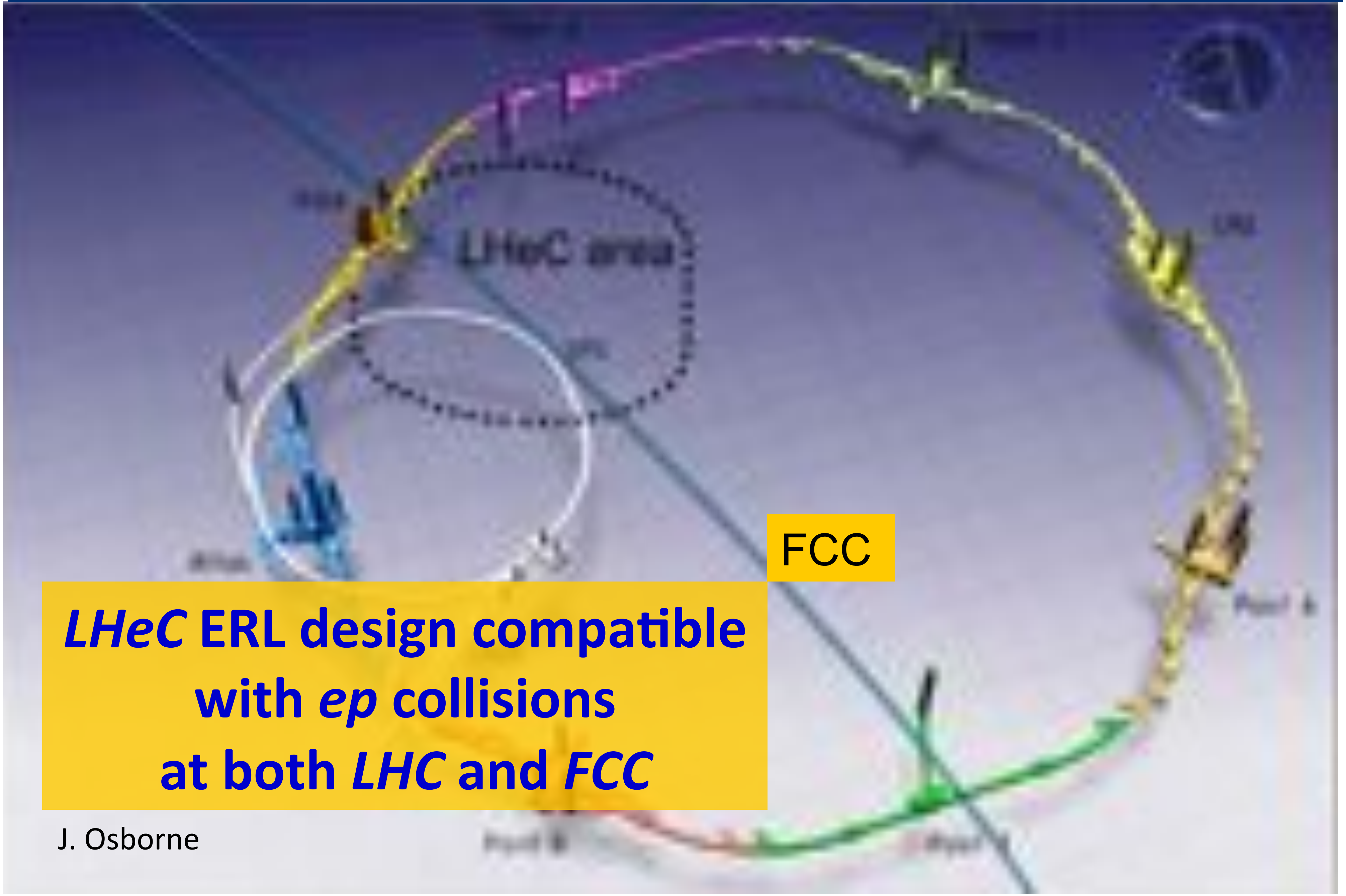


RR LHeC:
new ring
in LHC tunnel,
with bypasses
around
experiments

LR LHeC:
recirculating
linac with
energy
recovery

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

FCC-he – 2nd option: based on *LHeC*



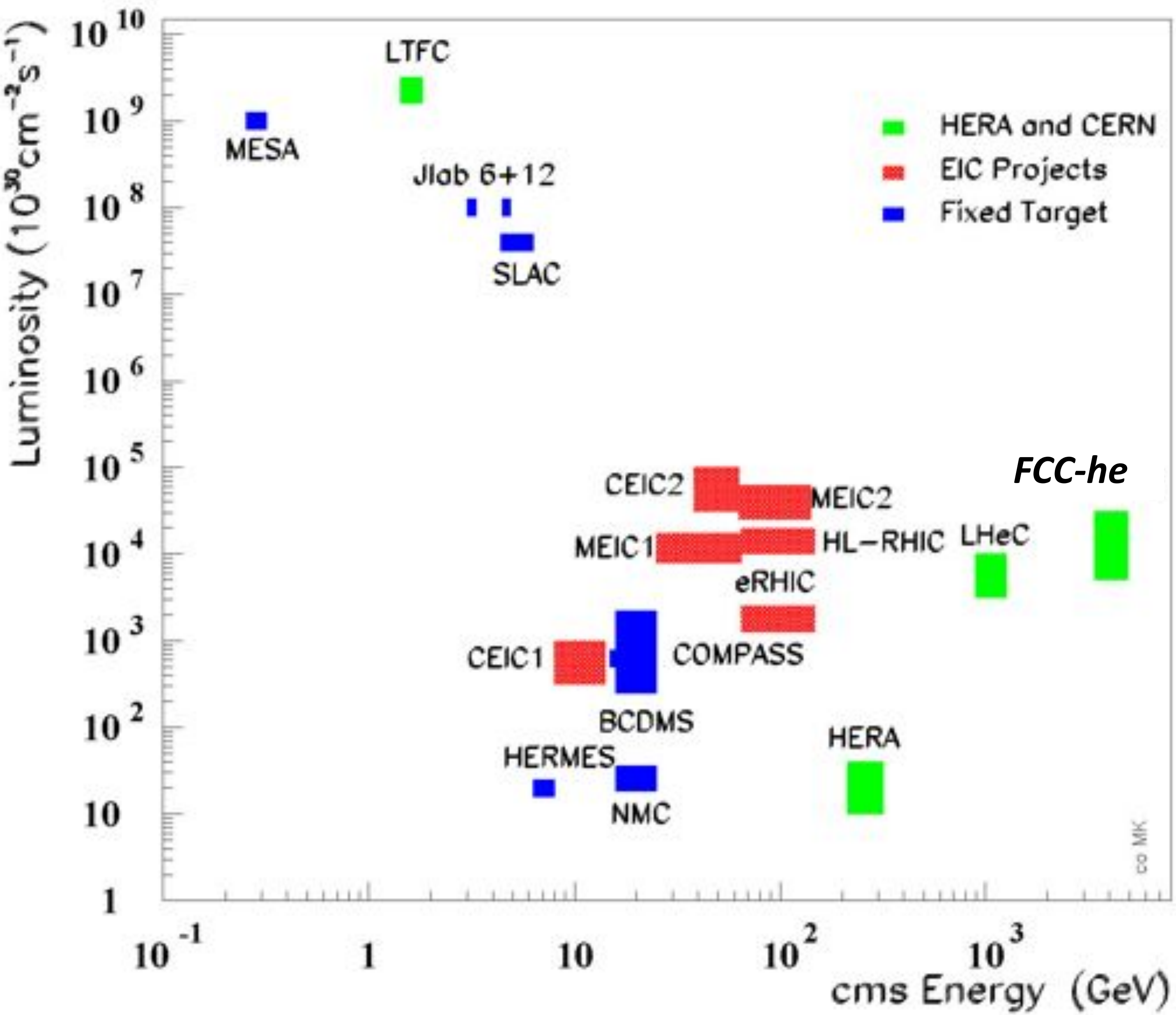
LHeC* ERL design compatible with *ep* collisions at both *LHC* and *FCC

J. Osborne

preliminary FCC-he parameters shown at ICHEP'14

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**	

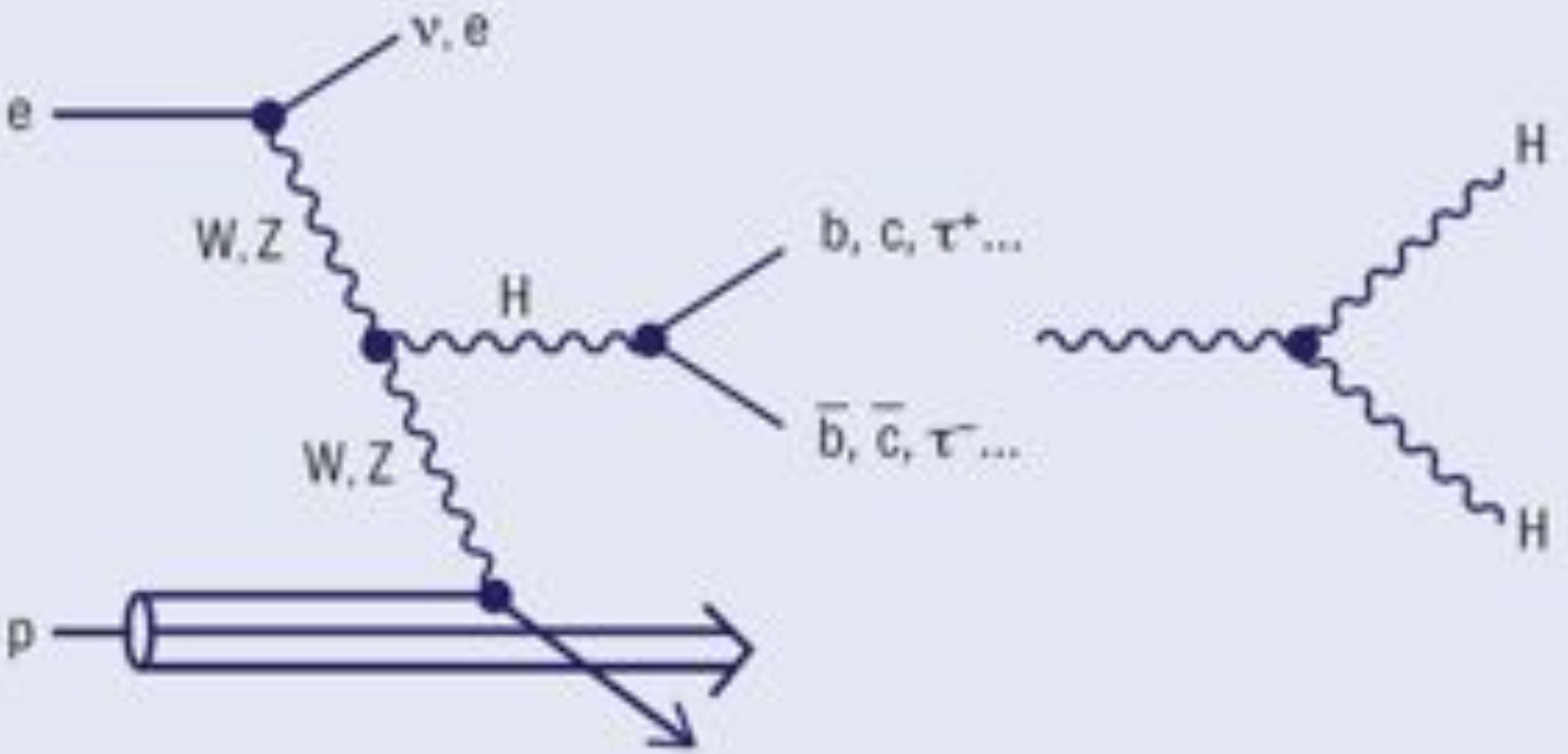
lepton-hadron scattering facilities till *FCC-he*



M. Klein and H. Schopper

CERN Courier June 2014

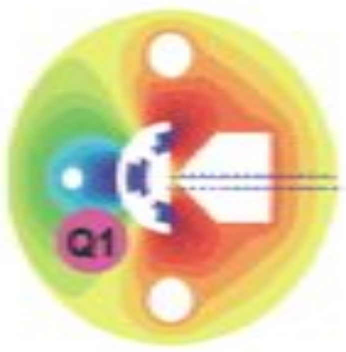
Higgs physics at *LHeC* & *FCC-he*

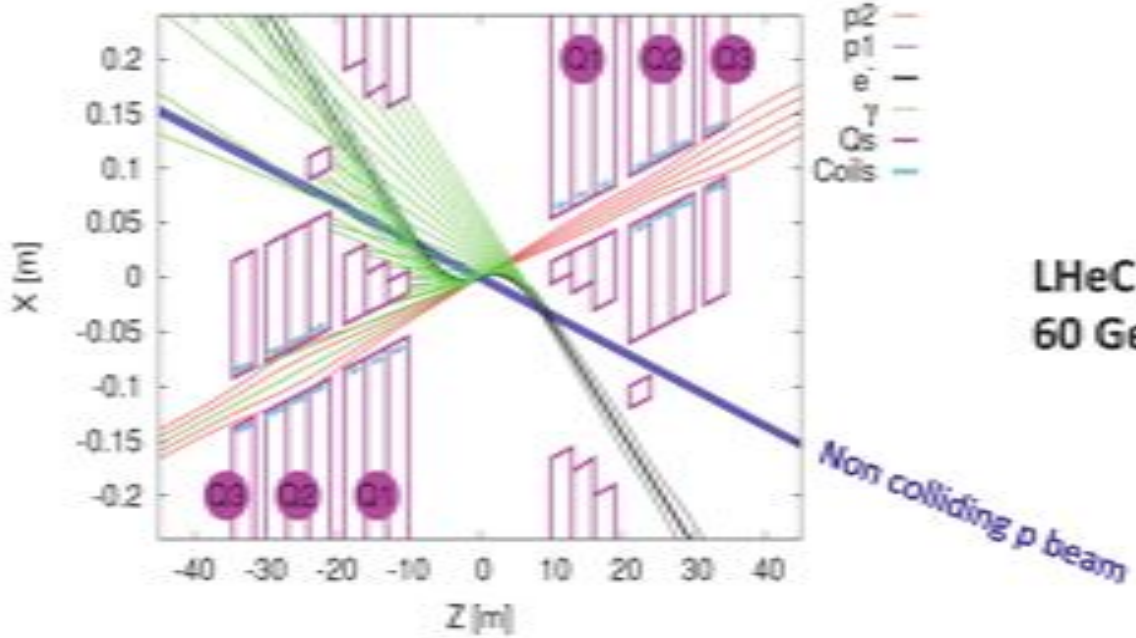


h-e* Higgs-boson production and decay**; and precision measurements of the ***H–bb* coupling** in ***WW–H* production**; *FCC-he* also gives access to **Higgs self-coupling *H–HH (<10% precision!? - under study), to **lepto-quarks up to ≈4 TeV** & to **Bjorken *x* as low as 10^{-7} - 10^{-8}** [of interest for ultra high energy ν scattering]

M. Klein and H. Schopper, CERN Courier June2014

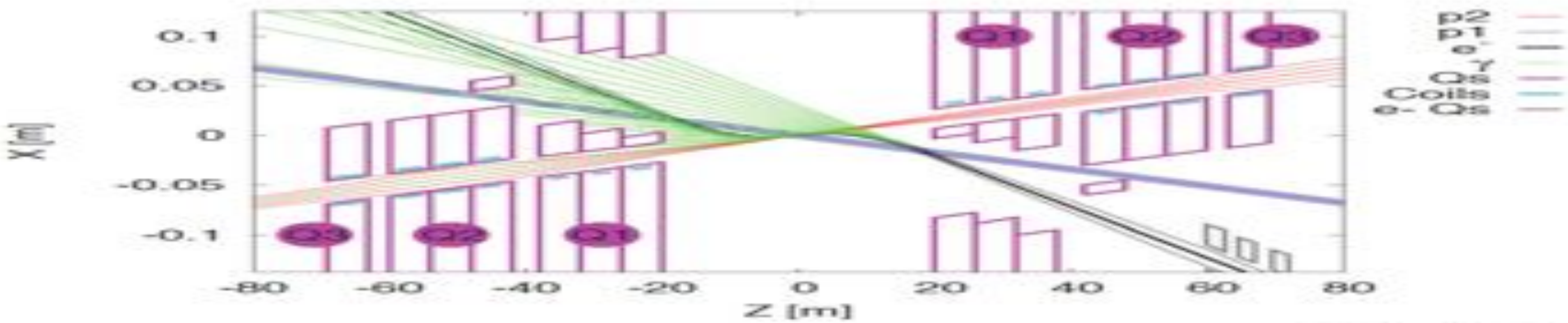
eh IR with parallel *pp* operation





Still work in progress: may not need half quad if L*(e) < L*(p)

LHeC (CDR)
60 GeV * 7 TeV



Tentative: ε_p=2μm, β*=20cm → σ_p=3μm ≈σ_e matched! ε_e=5μm ..

FCC-he (ERL)
60 GeV * 50 TeV

R. Tomas, M. Klein

FCC hh ee he

FCC Kick-off Meeting
University of Geneva
12-15 February 2014

>340 participants

http://indico.cern.ch/e/fcc-kickoff
http://cern.ch/fcc


UNIVERSITÉ DE GENÈVE
FCC Kick-Off 2014
Future Circular Collider (FCC) Study
FCC hh ee he
R-D Heuer, CERN


maticity correction similar to SuperKEKB,
tum acceptance will be similar, about ±1.4%.


HL-LHC (3000 fb-1)
LHC 13-14 TeV (300 fb-1)
LHC 7-8 TeV (30 fb-1)
Beautiful Place for a Science Center
Best beach & cleanest air
Summer capital of China
Starting point of the Great Wall
Wine yard
Future Circular Collider Study
Kick-off Meeting

FCC Kick-Off Parallel Sessions

Session	# Participants
Technical infrastructure and civil engineering	47
Hadron collider design (+ SC magnets + injectors)	75
Lepton collider design (+ SC RF + injectors)	62
Hadron Physics, Experiments, Detectors	93
Lepton Physics, Experiments, Detectors	54
e-p Option	18
Overall physics and phenomenology	63

presently signing FCC MoUs with partners

FCC MoU's 10 Sept. 2014

- ALBA/CELLS, Spain
- BINP, Russia
- CASE SUNY, USA
- CBPF, Brazil
- CIEMAT, Spain
- Cockcroft Institute, UK
- CSIC/IFIC, Spain
- DESY, Germany
- EPFL, Switzerland
- Hellenic Open U, Greece
- INP Minsk, Belorussia
- JAI/Oxford, UK
- KEK, Japan
- King's College London, UK
- MEPhI, Russia
- Northern Illinois U., USA
- Sapienza/Roma, Italy
- TU Darmstadt, Germany
- TU Tampere, Finland
- U. Geneva, Switzerland
- U. Iowa, USA
- U. C. Santa Barbara, USA
- U Silesia, Poland

- 15 further institutes will join shortly

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

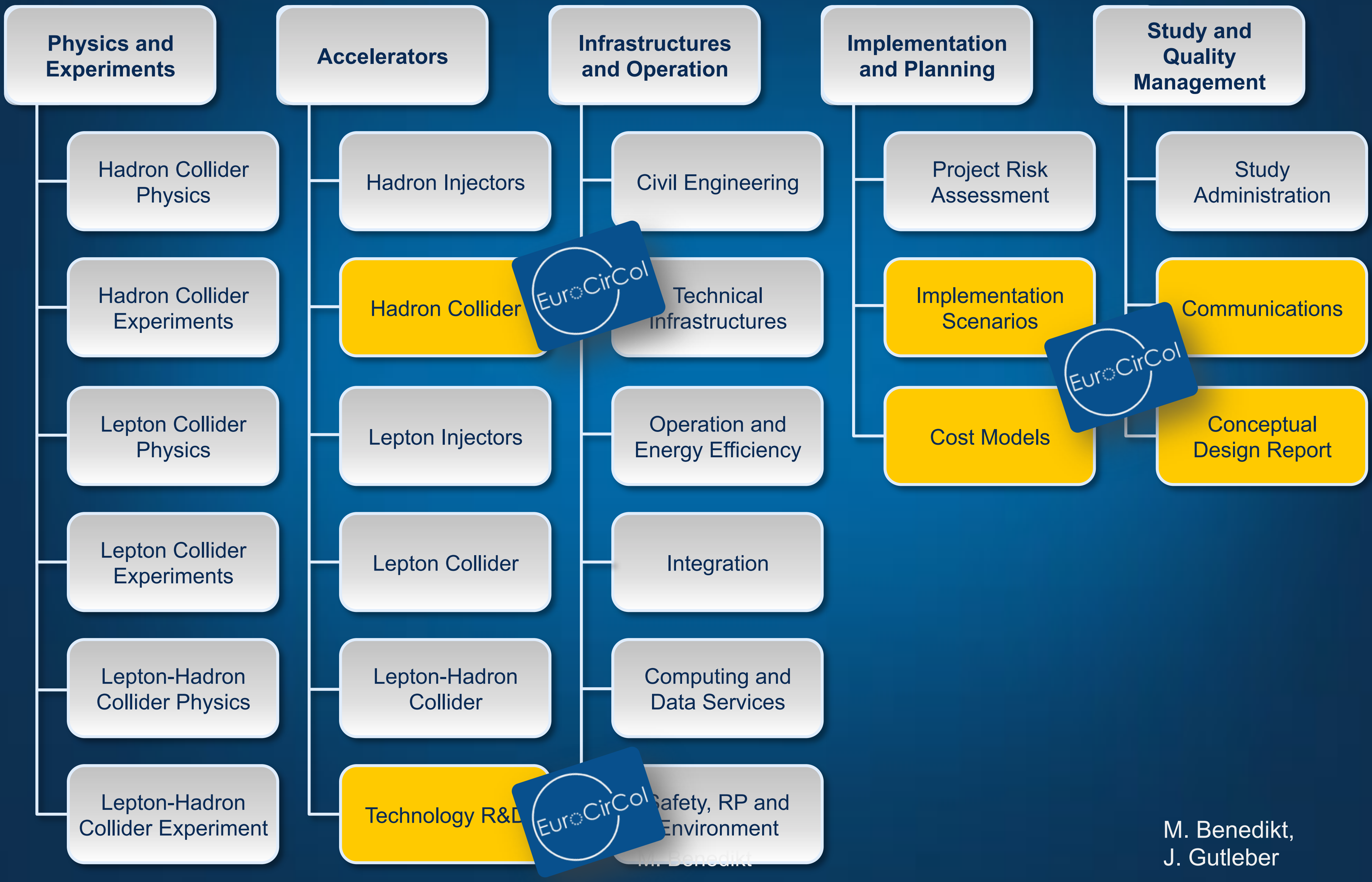
key aspects of 100 TeV energy frontier hadron collider:
conceptual design, feasibility, implementation scenario

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

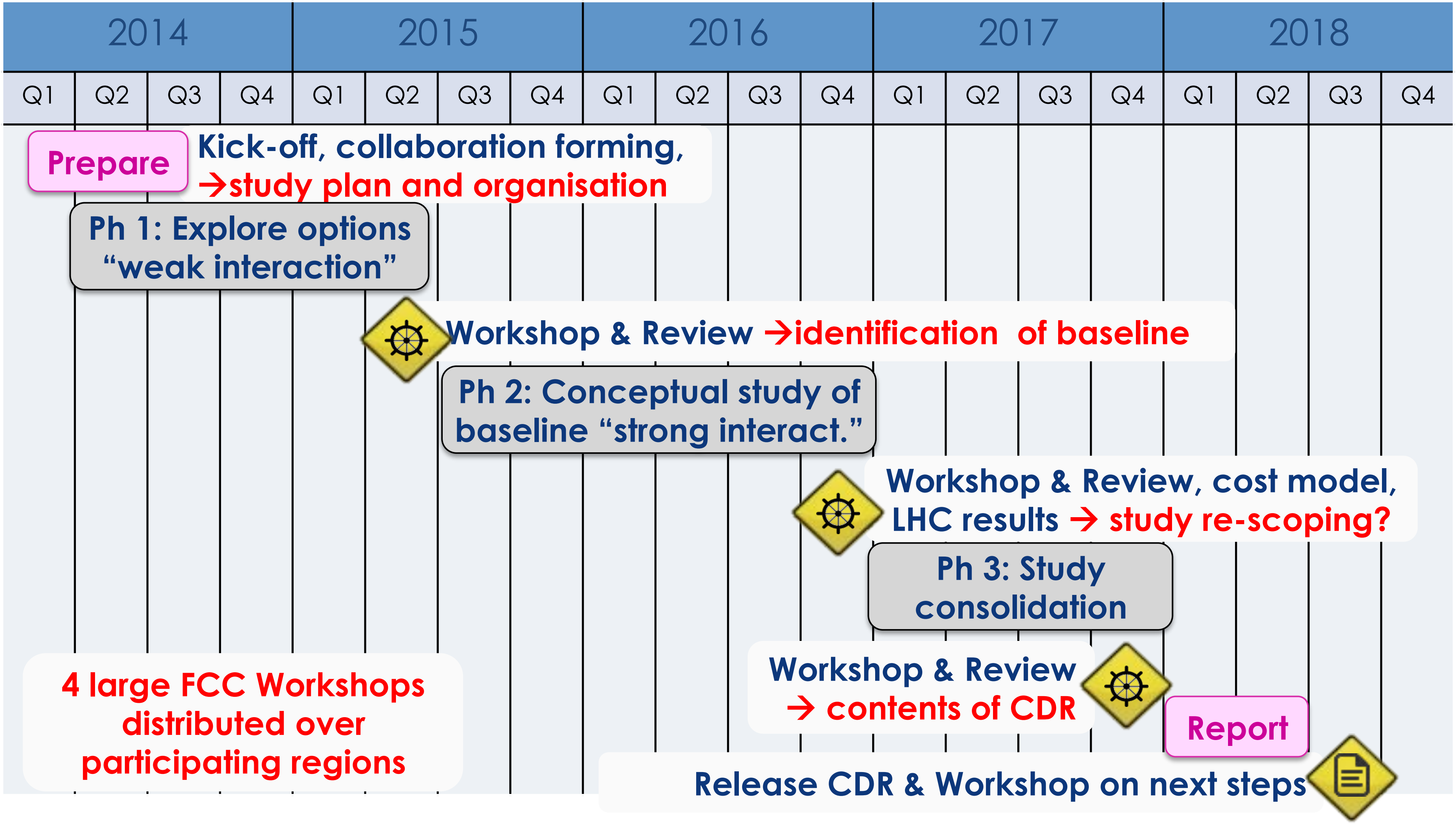
M. Benedikt,
J. Gutleber

WBS – H2020 EU DS proposal



M. Benedikt,
J. Gutleber

FCC global design study – time line



- 1st Yearly FCC Workshop 23 – 27 March 2015, Washington DC

M. Benedikt

main questions in particle physics and main approaches to address them

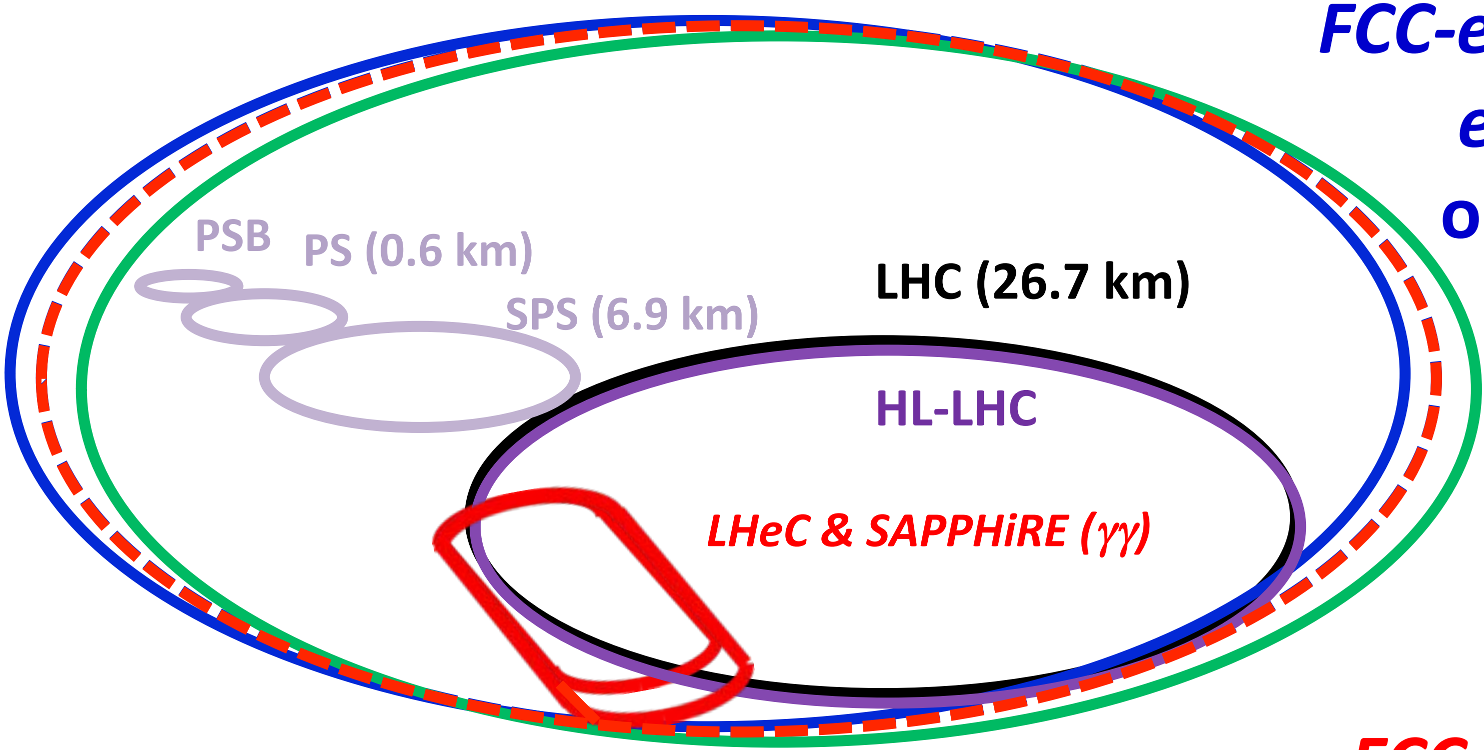
question	high-energy colliders	high-precision experiments	neutrino experiments	dedicated searches	cosmic surveys
Higgs, EWSB	X				
neutrinos	X		X	X	X
dark matter	X			X	
flavour, CP violation	X	X	X	X	
new particles and forces	X	X	X	X	
universe acceleration					X

within the scope of FCC

F. Gianotti et al.

many questions require high-energy and/or high-intensity accelerators

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)**

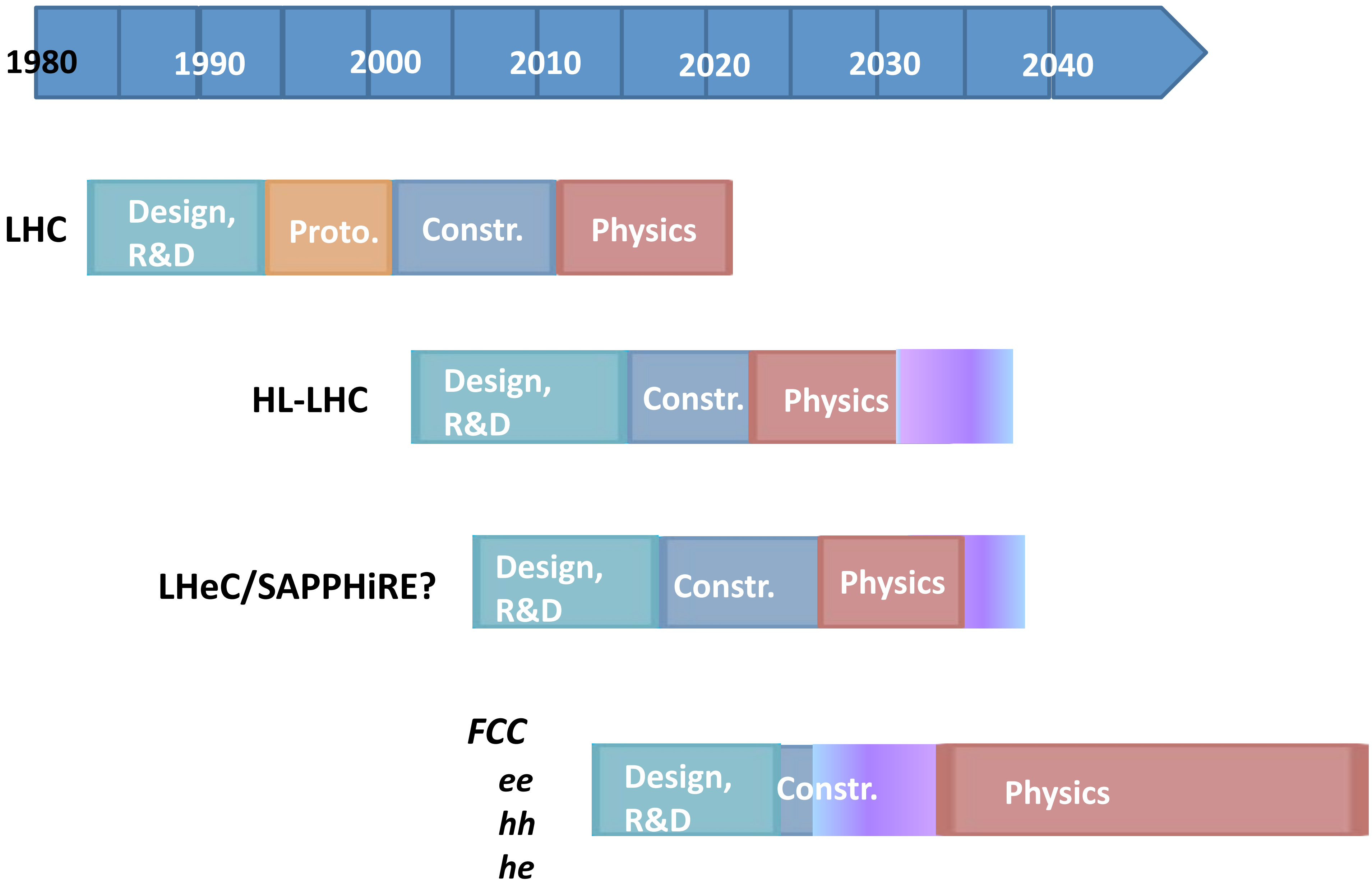
FCC-he **as ring-ring collider ?!**

LHeC-based FCC-he 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

tentative time line



conclusions

since >50 years circular colliders are primary tool to push the energy frontier, with spectacular success

LHC will deliver data at 13 TeV from April/May 2015

HL-LHC upgrade to accumulate 3000 fb^{-1} by ~2035

we now need to prepare for post-LHC period

circular hadron collider - only path available in this century towards 10s of TeV energy scales

FCC-hh further develops the new Nb_3Sn magnet technology of the *HL-LHC*, it also promotes many other technological innovations (cryogenics, chamber production,…)

FCC-ee an attractive intermediate step towards *FCC-hh*, and highly synergetic (infrastructure, time, physics, + SRF)

great worldwide interest

FCC workshop Washington March '15

„A really good idea is easily recognizable. It's one whose implementation seems doomed at the outset."

Albert Einstein

YEARS / ANS **CERN**

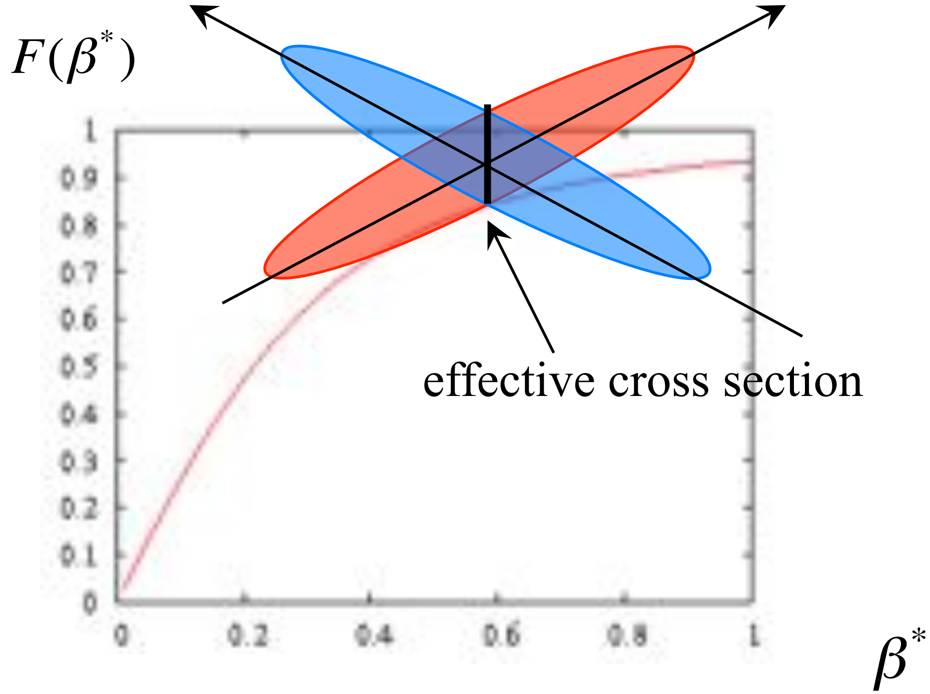
reserve slides

crab crossing

crossing angle reduces luminosity, reduction factor

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

effect worse for smaller β*,



principle of crab crossing: