FCC study & Forward Physics

by **Helmut Burkhardt** (CERN)

Future Circular Collider Study, FCC   http://fcc.web.cern.ch   Indico / Projects / FCC

status : good progress - goals and timescale as planned and presented last time

The Future Circular Collider study has an emphasis on proton-proton and electron-positron (lepton) high-energy frontier machines. It is exploring the potential of hadron and lepton circular colliders, performing an in-depth analysis of infrastructure and operation concepts and considering the technology research and development programs that would be required to build a future circular collider.

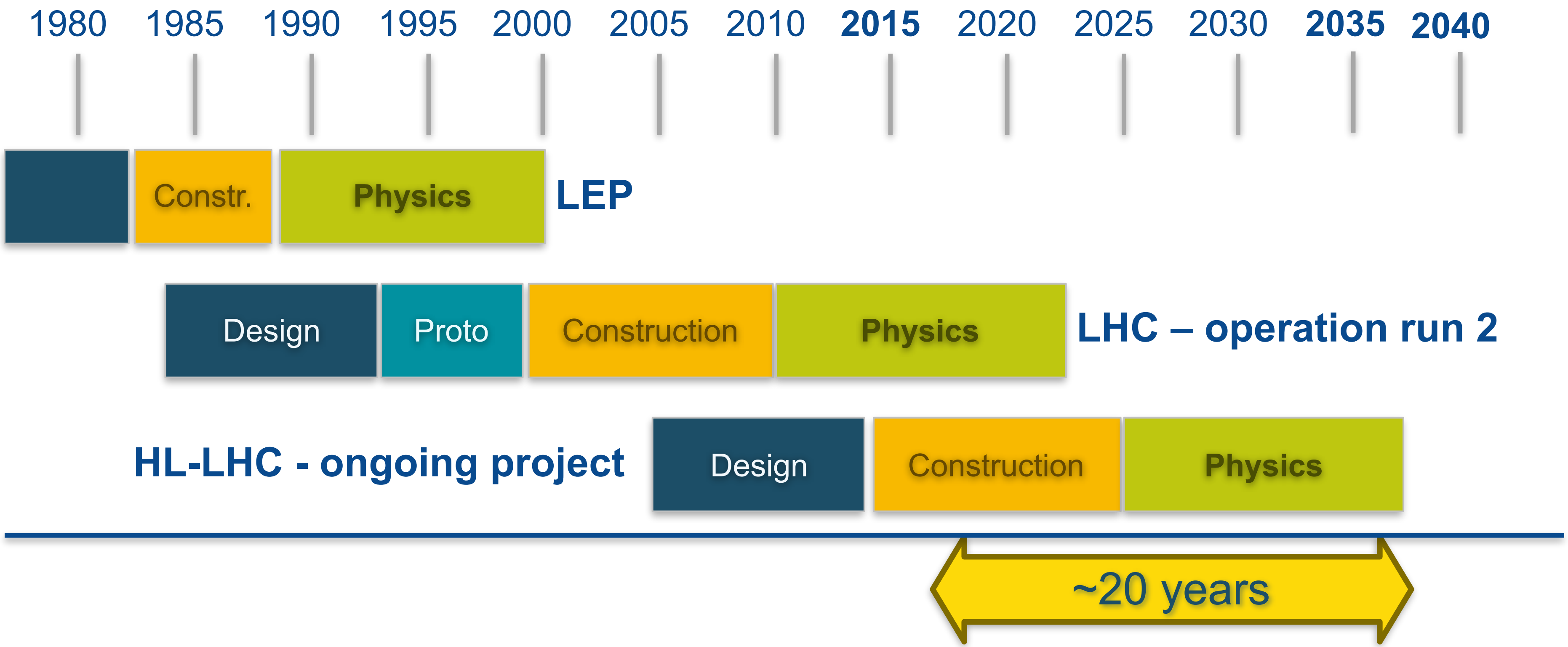
2017 : finalizing baseline designs FCC-hh & ee; start preparation of FCC CDR

Studies on the accelerator and machine-detector interface for 2 high luminosity interaction regions & detector concepts well advanced

FCC week April 2016 Rome 468 registered participants, **Phys Workshop Jan. 2017**
May 2017 Berlin, registration open (379 so far, collaboration still growing)

Acknowledgment :
discussion with FCC-hh design team, Daniel Schulte, Xavier Buffat, Michael Hofer et al.
On status using slides from M. Benedikt + F. Zimmermann, Physics workshop 1/2017

Time scale



1980 1985 1990 1995 2000 2005 2010 **2015** 2020 2025 2030 **2035** **2040**

Constr. | **Physics** | **LEP**

Design | Proto | Construction | **Physics** | **LHC – operation run 2**

HL-LHC - ongoing project | Design | Construction | **Physics**

~20 years

Status of the FCC project, Michael Benedikt, 1st FCC Physics Workshop Jan. 2017

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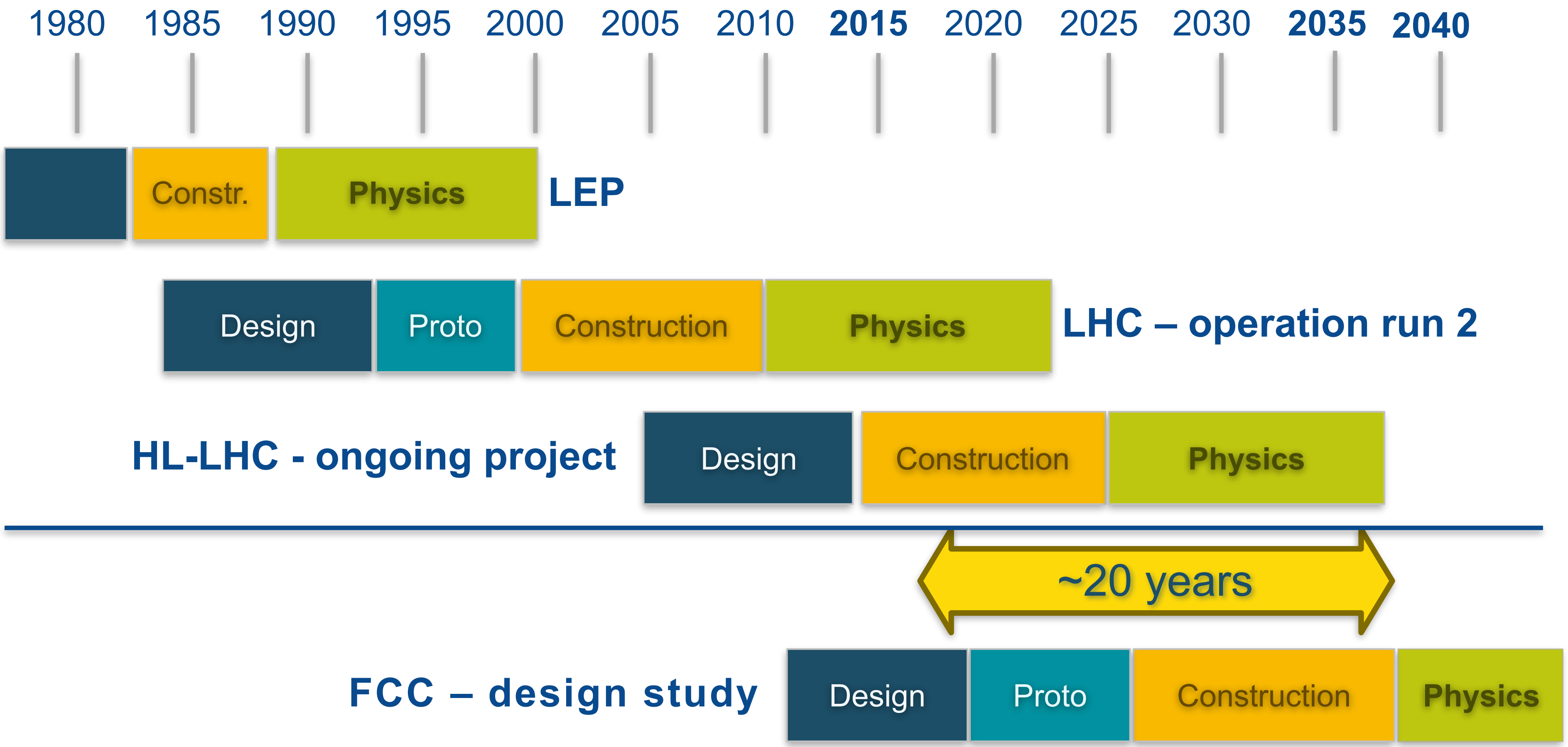

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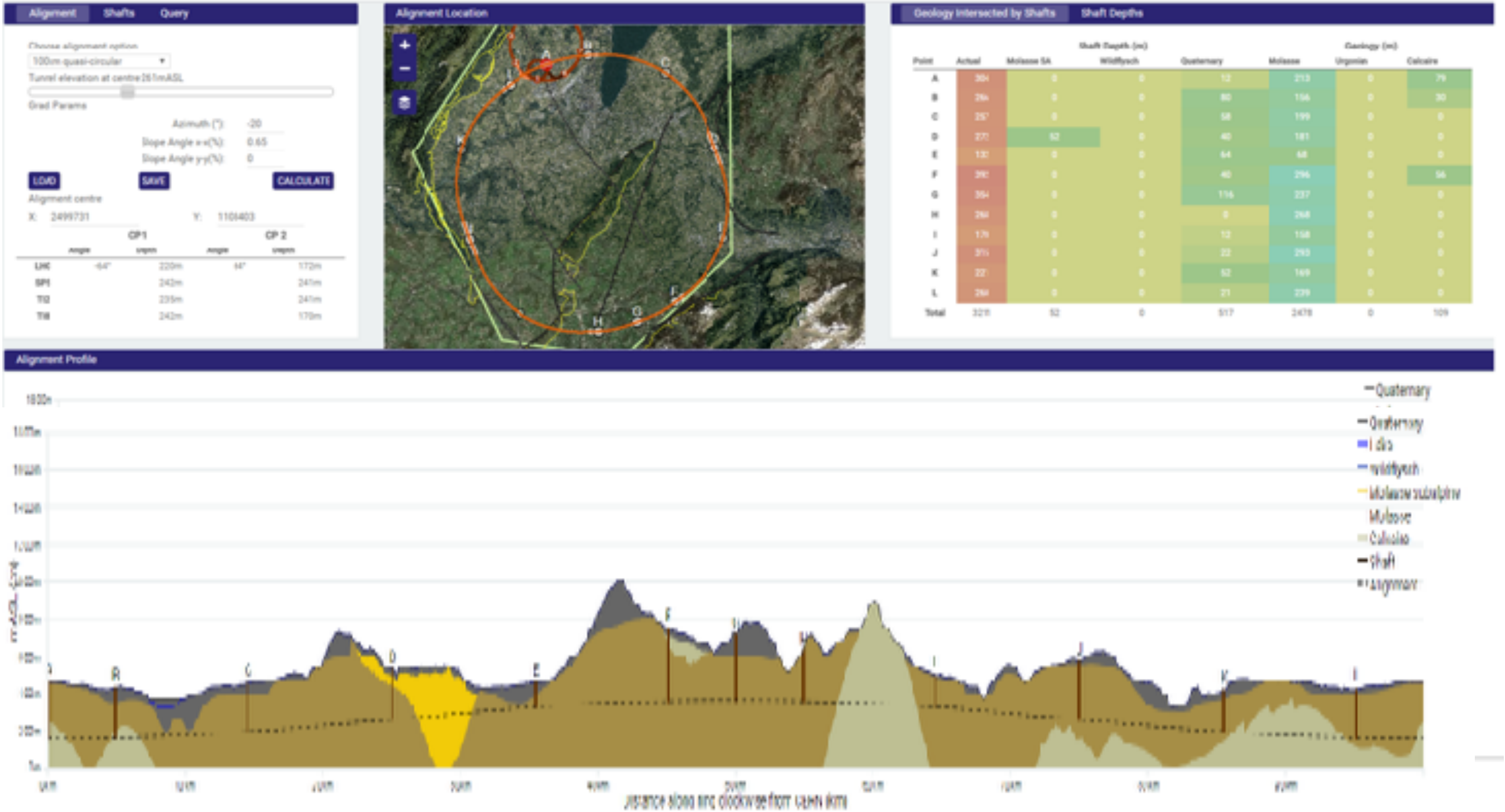
FCC – design study | Design | Proto | Construction | **Physics**

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

Goal of phase 1: CDR by end 2018 for next update of European Strategy

Status of the FCC project, Michael Benedikt, 1st FCC Physics Workshop Jan. 2017

Progress on site investigations



Choose alignment option

100km quasi-circular

Tunnel elevation at centre:261mASL

Grad Params

Azimuth (°): -20

Slope Angle x-x(%): 0.65

Slope Angle y-y(%): 0

Alignment centre

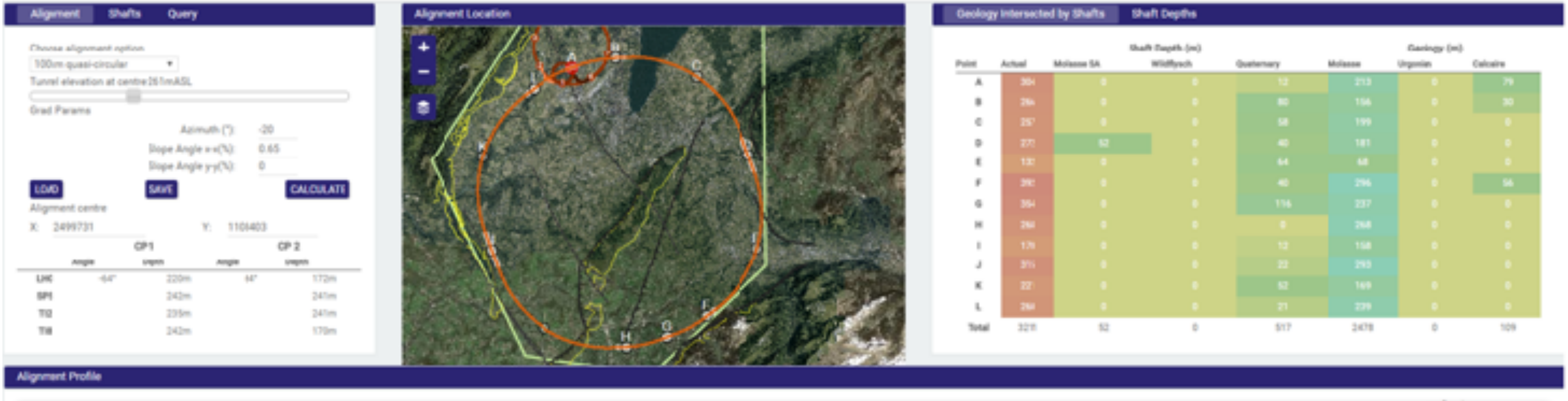
X: 2499731 Y: 1101403

	CP1		CP 2	
	Angle	Depth	Angle	Depth
LHC	-64°	220m	64°	172m
SPS		242m		241m
TI2		235m		241m
TI8		242m		170m

			Shaft Depth (m)				Geology (m)
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	284	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	271	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	264	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	264	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

Status of the FCC project, Michael Benedikt, 1st FCC Physics Workshop Jan. 2017

Progress on site investigations



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- 90 – 100 km fits geological situation well
- LHC suitable as potential injector
- The 97.75 km version, tangent to LHC, is now being studied in more detail

[Status of the FCC project](), Michael Benedikt, 1st FCC Physics Workshop Jan. 2017

Hadron collider parameters (pp)

parameter	FCC-hh		HE-LHC*	(HL) LHC
collision energy cms [TeV]	100		25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.27	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.2)	1 (0.2)	2.5	(2.2) 1.15
bunch spacing [ns]	25 (5)	25 (5)	25 (5)	25
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	34	(5) 1
peak #events/bunch crossing	170	1020 (204)	1070 (214)	(135) 27
stored energy/beam [GJ]	8.4		1.4	(0.7) 0.36
synchrotron rad. [W/m/beam]	30		4.1	(0.35) 0.18
transv. emit. damping time [h]	1.1		4.5	25.8
initial proton burn off time [h]	17.0	3.4	2.3	(15) 40

compared to LHC : 3× in size, 7× in energy

FCC accelerator parameters, Frank Zimmermann, 1st FCC Physics Workshop Jan. 2017

Layout, new Nov. 2016

8 straight sections
6× 1.4 km 4 with collisions
2× 2.8 km collimation & dump

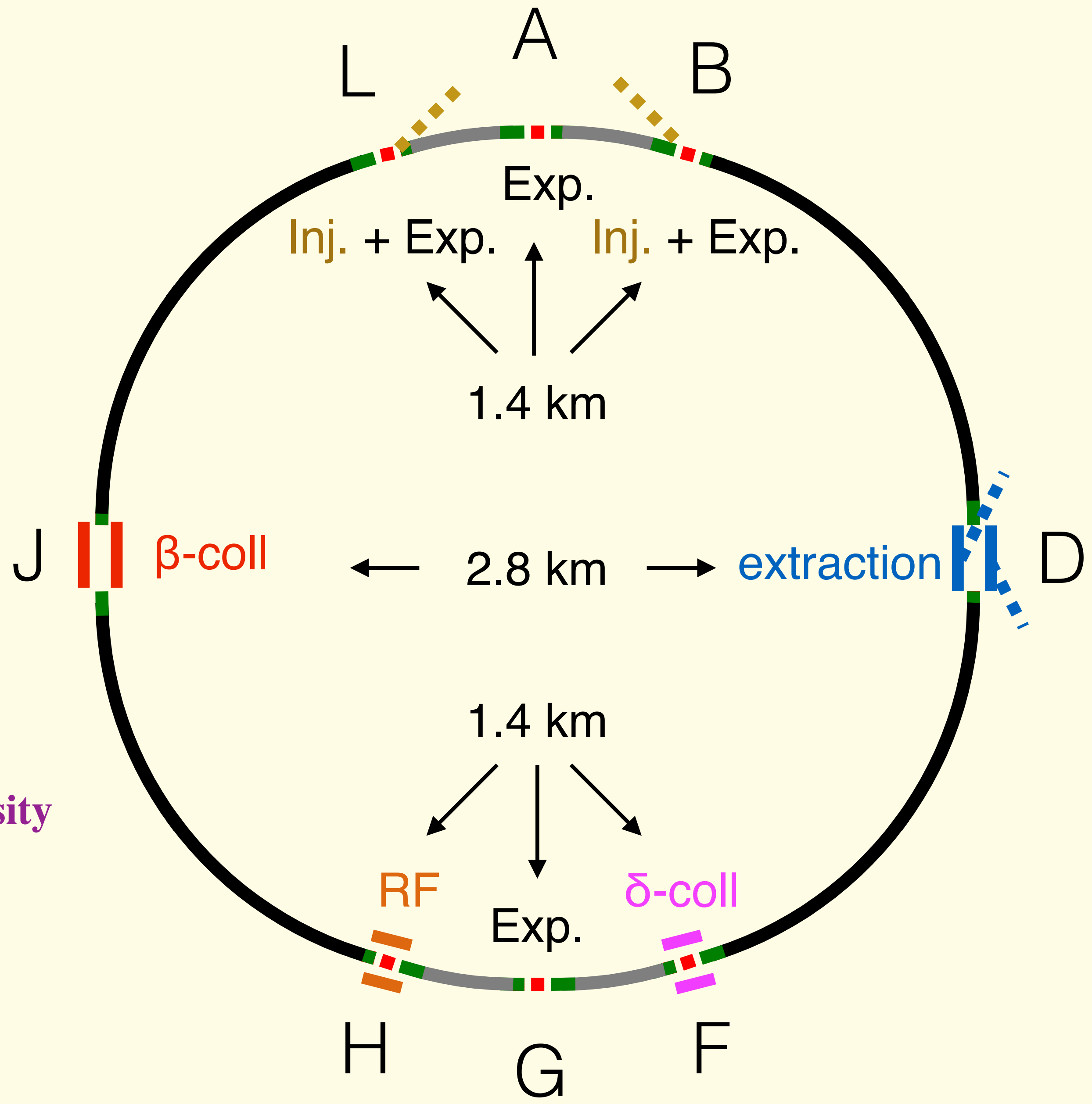
L = 97.75 km
16.14 km arc length
3.2 km short arcs
0.4 km long DS

Baseline:
round beams

4 interaction regions

A, G dedicated to high luminosity
H-V crossing
(IR1, 5 in LHC)

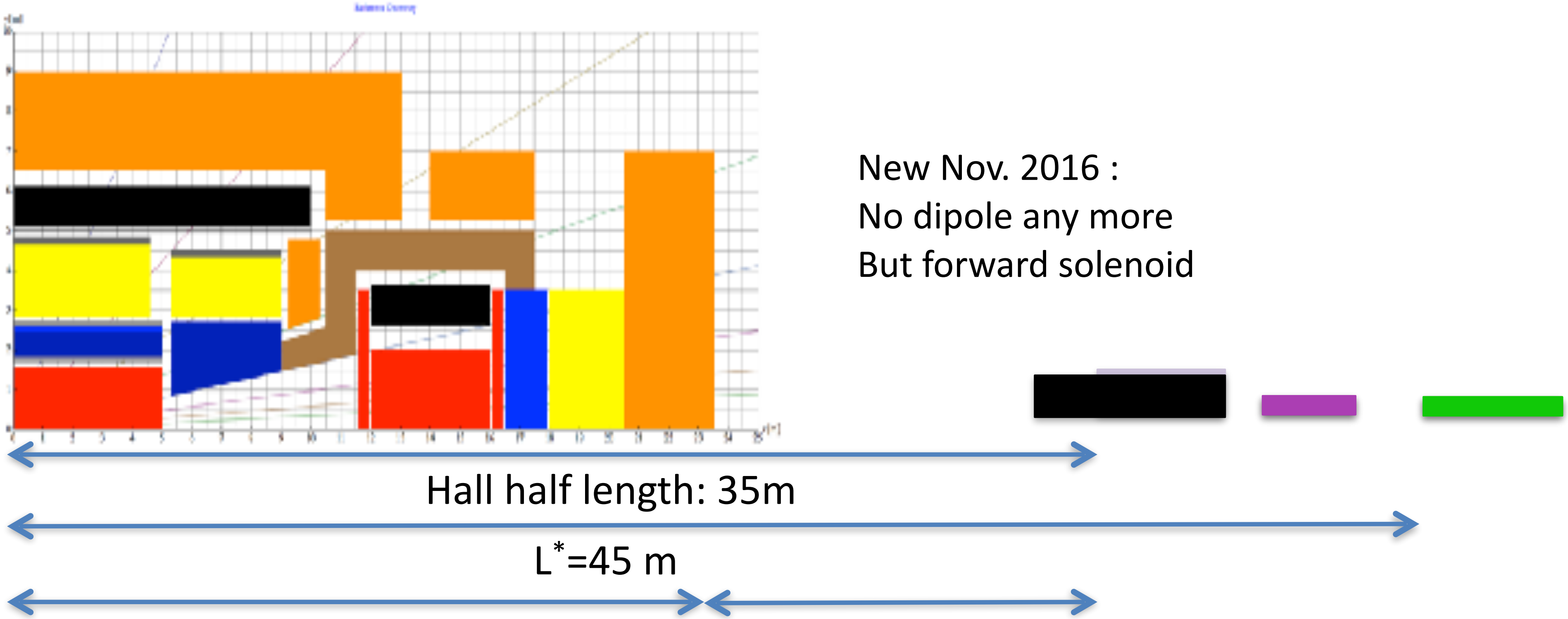
L, B shared with injection
(~ IR1, IR8 in LHC)
here half or 700 m for injection



FCC-hh high-lumi region, (new) detector layout

Experiments like to stay at L^*=45m to allow for other solutions
But high cost for this

Tracking
Ecal
HCAL
Magnets and cryostat
Muons



New Nov. 2016 :
No dipole any more
But forward solenoid

Hall half length: 35m

L^*=45 m

Detector half length 23.5m

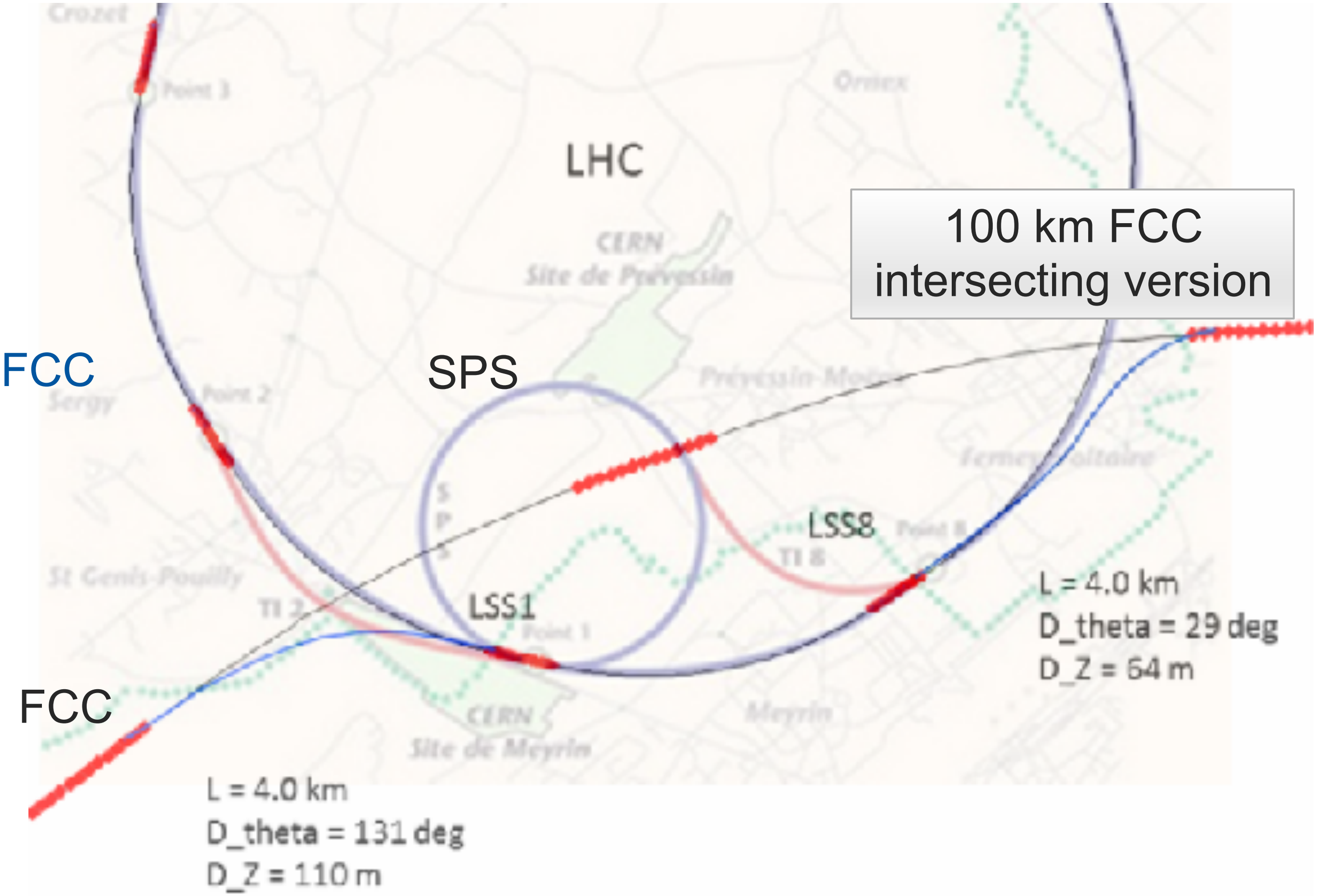
Space to open 11.5m

FCC, MDI, Werner Riegler, Daniel Schulte et al.

Injector studies

injector options:

- **SPS → LHC → FCC**
- SPS/SPS$_{\text{upgrade}}$ → FCC
- SPS -> FCC booster → FCC

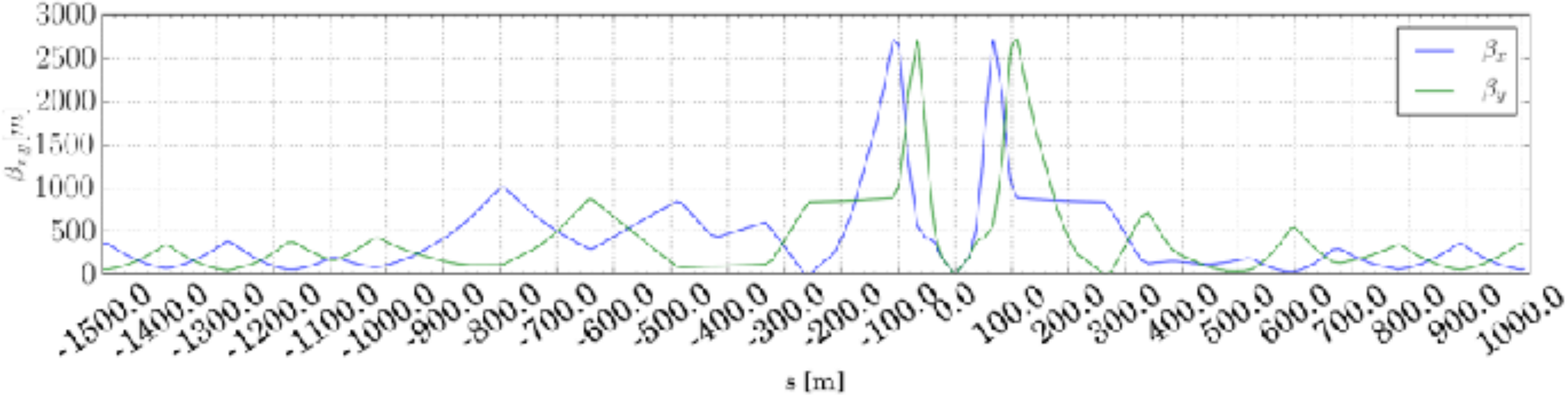


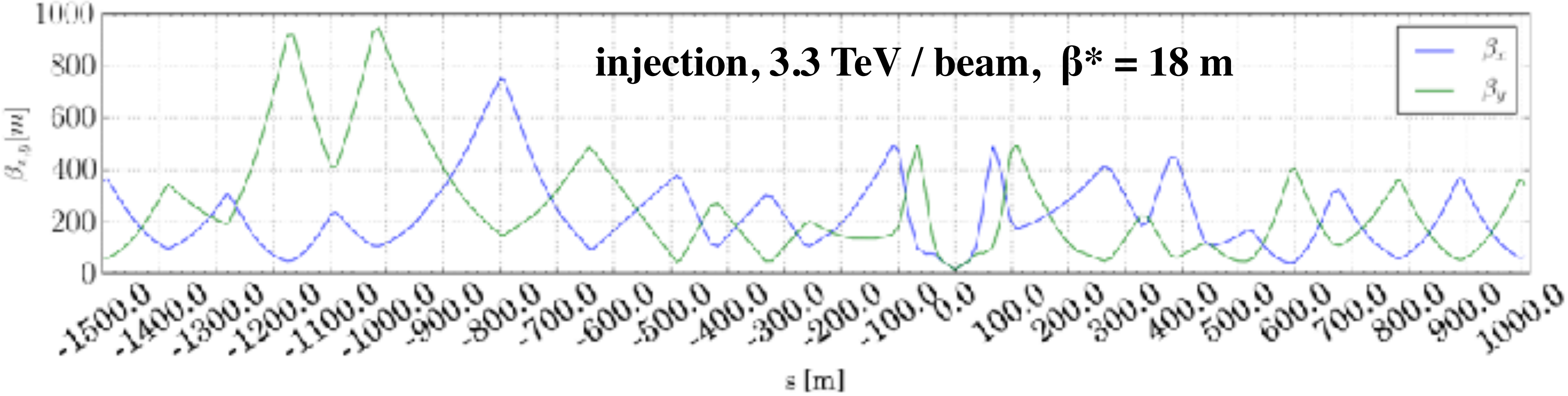
current baseline is to fully re-use the existing CERN accelerator complex

- **injection energy 3.3 TeV from LHC**

IR L, B optics

β* = 3 m , collision, top energy 50 TeV / beam, 30 µrad crossing angle

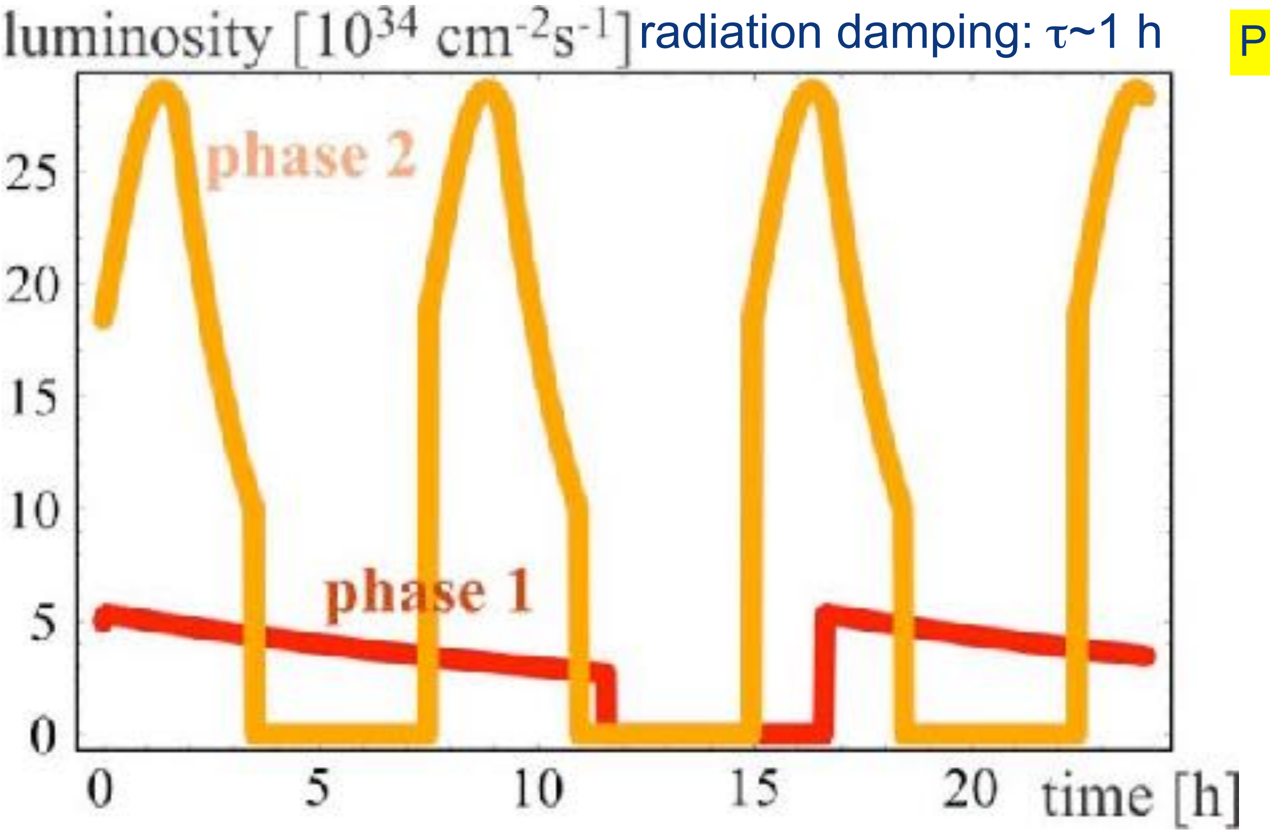




injection, 3.3 TeV / beam, β* = 18 m

Optics / plots : Michael Hofer

Luminosity evolution over 24h



PRST-AB 18, 101002 (2015)

for both phases:

beam current 0.5 A, unchanged!

total synchrotron radiation power ~5 MW.

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

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

FCC accelerator parameters, Frank Zimmermann, 1st FCC Physics Workshop Jan. 2017

Damping time ~ 1h, shrinking beam size

potentially very useful for forward physics, follow with Roman pots ?

Some principles, high vs low β*

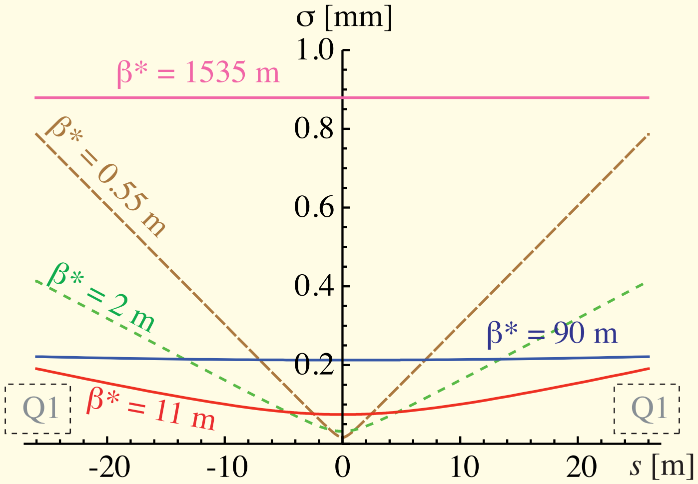
β* << L* **low beta** small beams at IP. 90° phase advance L/R and strong focusing triplet
high angular divergence

β* >> L* **high beta** large parallel beams, low angular divergence ~ no phase advance and focusing

LHC design numbers :

L* = 26.15 m (centre of 6.37 m long "Q1", `MQXA.1R1`)

β* = 0.55 m design value of low β*

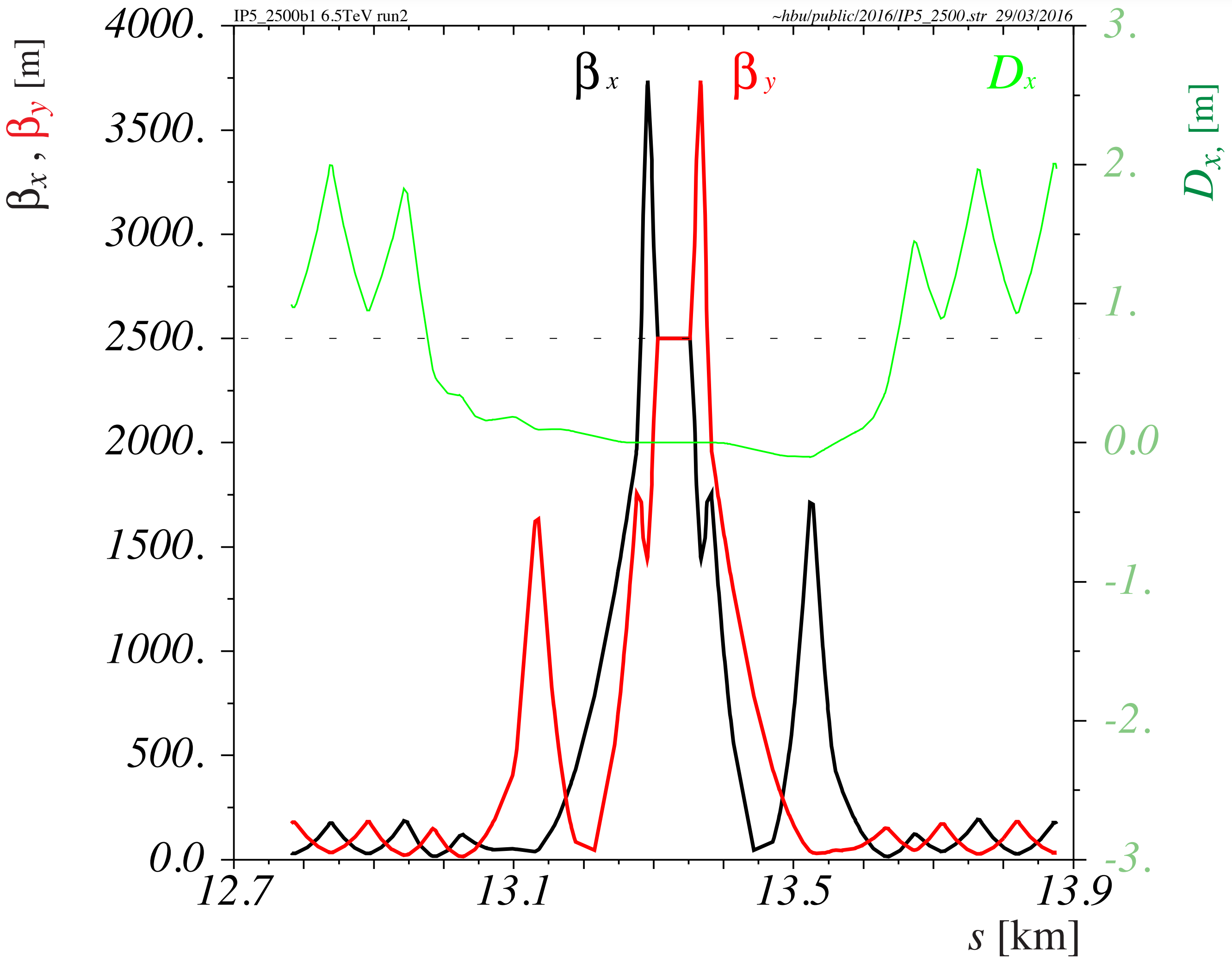


FCC length scale for IR, roughly 2× the LHC

L* = 45 m

β* = 1.1 m design value of low β*, ultimate 30 cm

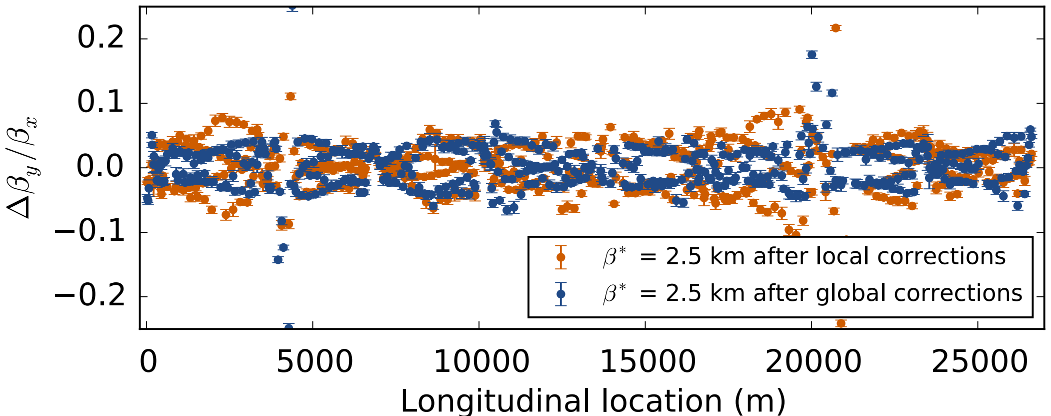
LHC 2016 : new record high β* = 2500 m



- injection
- ramp de-squeeze to 60 m
- 36 steps to 2.5 km

Successful physics run for ATLAS-ALFA and TOTEM precision measurement proton cross-section down to Coulomb interference region

Optics well measured and corrected



Scaling, from LHC to FCC

FCC : E, γ increases by factor 100 / 14 = 7 in $\sqrt{\gamma}$ by 2.7

		scaling
Beam size at IP	$\sigma^* = \sqrt{\beta^* \epsilon} = \sqrt{\beta^* \epsilon_N / \gamma}$	$\sqrt{\gamma}$
Angular beam divergence	$\sigma' = \sqrt{\varepsilon / \beta^*} = \sqrt{\varepsilon_N / (\gamma \beta^*)}$	
Luminosity, round beams	$\mathcal{L} = \dfrac{N^2 f}{4\pi\, \sigma^2} = \dfrac{N^2 f\, \gamma}{4\pi\, \beta^* \varepsilon_N}$	γ
Minimum ***t*** with RP at n_σ	$-\,t_{\min} = \dfrac{2\, p\, n_\sigma^2\, \epsilon_N\, m_p}{\beta^*}$	γ

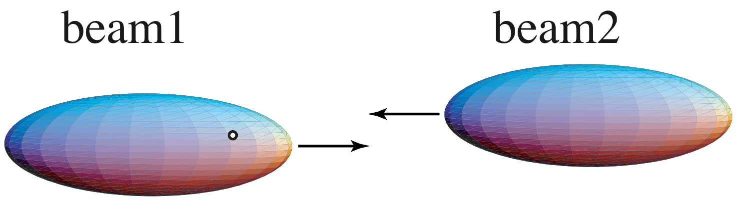
Normalized emittance $\gamma\varepsilon = \varepsilon_N \sim 2\ \mu\mathrm{m}$ constant in (lower energy) proton machines, determined by injectors, similar for all proton machines. Beams shrink when accelerated.

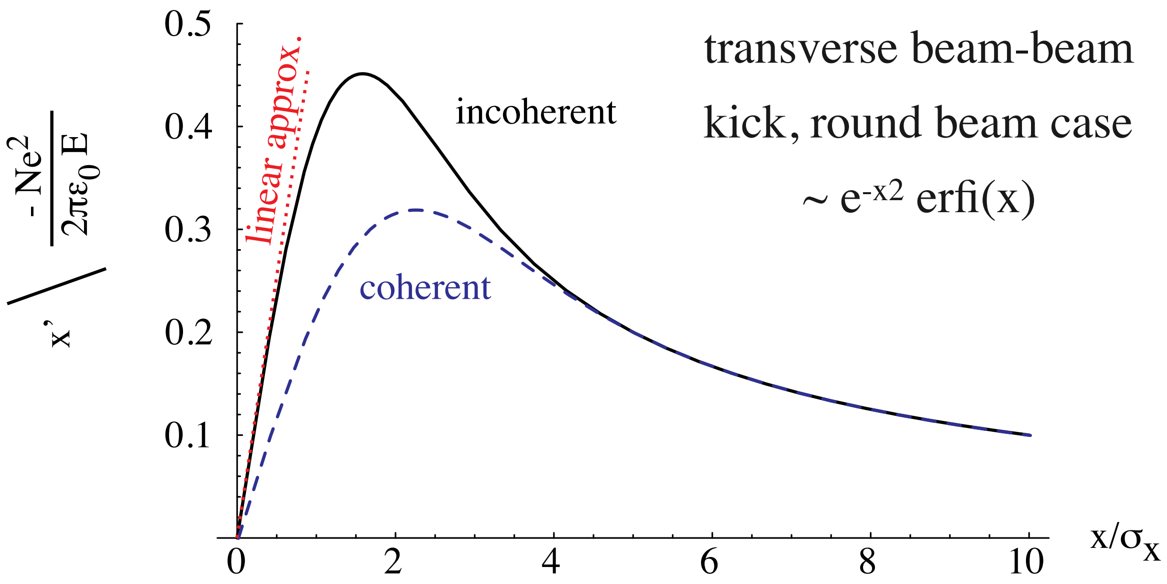
Coulomb region : **β* ~ 2.5 km in LHC@13 TeV ---> 20 km FCC@50 TeV**
LHC experience --- very high β* challenging -- but not impossible.

New FCC : **damping** from SR+RF significant, opens up possibility to get significantly lower emittance --- **potentially very useful for dedicated runs**

Reminder : Low luminosity ≠ No interference

Beam-beam interaction





transverse beam-beam kick, round beam case

$\sim e^{-x^2}\,\mathrm{erfi}(x)$

separation in σ

Quantified by tune shift parameter ξ

$$\xi = \frac{r_c\, N}{4\pi\, \epsilon_N}$$

head-on, round beams

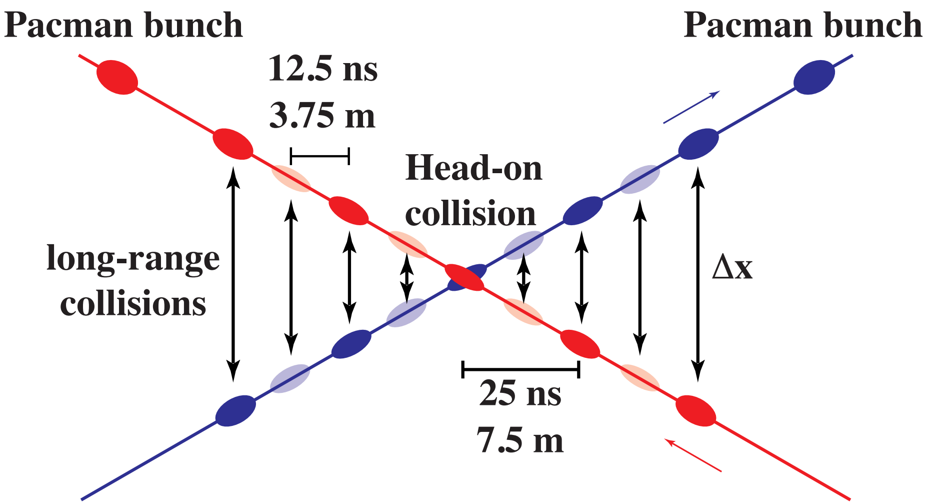
depends only on N / ε_N

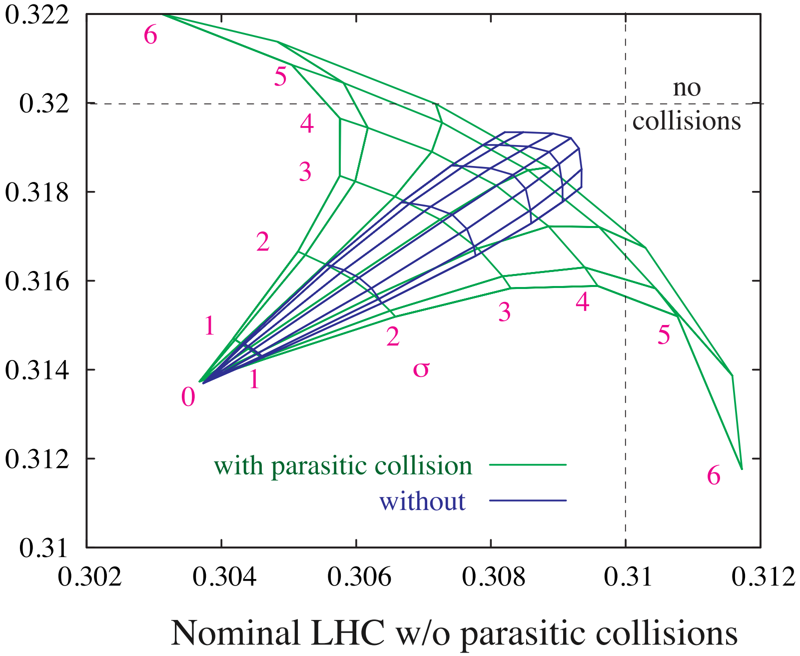
not on energy and **not on β***

Head on : same beam-beam from low lumi high-β as high lumi IPs

To reduce b.b. would require to run separated by several σ

Principle of separation by crossing angle at higher β*





Low β* (< L*)

beam size and separation increase ∝ Δs,

⇒ separation in units of σ about constant around IP

all parasitic crossings adding up with similar contribution

Instead high β* :

beam size ~ constant = σ*, separation in σ increases as ΦΔs

where Φ is the crossing angle,   dominated by 1st parasitic crossing

100 ns bunch spacing 4× more separated than 25 ns, used for 90m LHC

and negligible contribution from next 200, 400 ns ...

Running scenarios (1/2)

Parasitic running in standard physics next to high luminosity IP, with tens of kilowatts of collision debris will be difficult. Important to plan this before.

Consider 3 scenarios - of which 1.+2. best at dedicated lower luminosity IP

1. **Dedicated very high β* operation for cross section measurements**
   Few bunches, no crossing angle. Few dedicated runs.
   Roman pots very close (few sigma).
   Minimize beam-beam (no collisions in other IPs, moderated bunch intensities) :
   Profit from SR/RF radiation damping : $\boldsymbol{\varepsilon_N = 2.2\ \mu m \times \exp(-t/\tau)}$
   where τ = 1 h. After ~ 4 hours at **reduced equilibrium emittance** (limit 0.05 μm without IBS)
   very high β* > 10 km may not be needed
   at reduced bunch intensities, more bunches compatible with no crossing angle to get sufficient luminosity
   to be checked and optimized : damping partition, beam-beam, bunch schemes, IBS

Key ingredients for very high β* :

- flexible quadrupole powering (bipolar) and large aperture
- sufficient # (≳ 6) of independently powered quads IP to RPs
- well separated IR, DS sections
- getting there - de-squeeze from β* > L*

Running scenarios (2/2)

2. Moderately high β* some ~ 100 m operation for forward / diffractive physics

(and minimum bias, proton vs / ion calibration ..) with kind of "ALICE+TOTEM" IR and detectors

Design IP such that enough corrector strength and aperture available for sufficient crossing angle ($\gtrsim$ 10 σ) and parallel separation to operate with full number of bunches with 25 ns spacing

What about : B or L insertion optimized for forward physics such that

higher β* + good acceptance for diffractive compatible with standard physics

- no need for limited special runs, high ∫ L dt
- well screened and positioned roman pots at ~ 10 sigma ? (after some h in physics)

3. Very forward detectors in very high luminosity insertions A/G "FP420"

tagging of protons (ξ in the range 0.01 - 0.10 ?) at full luminosity

using (fast timing) detectors in the dispersion suppressor

needs early planning --- space and integration with magnet / cryo / collimation design

Goals and required machine parameters

Goal : contribute section(s) to FCC-hh CDR

- physics motivation
- requirements in terms of target machine parameters
- perspectives, machine & detector

For each of the running scenarios considered, define the requirements :

- phase advance between IP and RPs
- plane (x, y), w/o crossing angle
- local dispersion between IP and RPs ("ξ" acceptance, $D / \sqrt{\beta}$)
- detector acceptance (η - ranges)
- closest approach of RPs to beam axis n_σ and real space (mm, w/o dead space)
- if required limits on transfer matrix magnification $\nu = r_{1,1}$ eff. length $L = r_{1,2}$
- $\int L\, dt$
- Pile-up

Concluding remarks

Very encouraging LHC experience :

- no fundamental limit seen so far in going to very high β,   2.5 km reached in 2016
- very stable and reproducible   -- possible to de-squeeze over large range of β*
- roman pots -- possible to measure very close to beam, already demonstrated :

  3 σ in special runs

  15 σ compatible with standard very high luminosity operation

There appears to be very good potential for forward / diffractive physics at FCC

could profit a lot from :

- More space and flexibility
- Reduced emittance   (significant damping)
- Higher β* operation potentially compatible with standard operation
- Detectors in higher dispersion sections   (dogleg, DS)