FCC Accelerator Studies

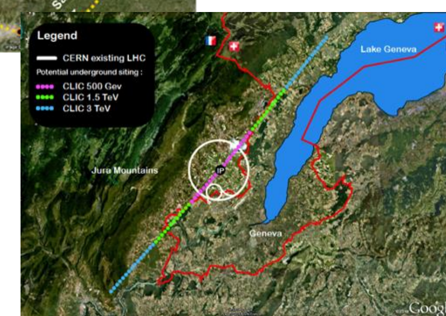
Daniel Schulte for the FCC team
LCWS 214, Belgrade October 2014

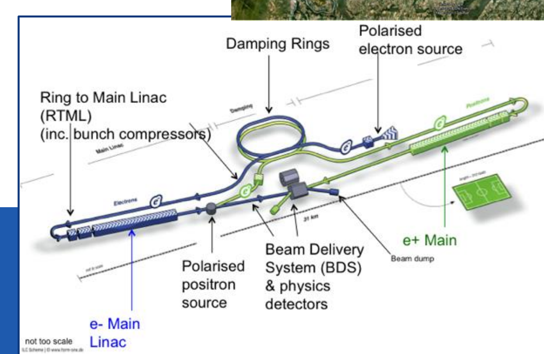
European Strategy

Approved by CERN council, ESFRI roadmap

Identified four highest priorities:

- Highest priority is exploitation of the LHC including luminosity upgrades
- Europe should be able to propose an ambitious project at CERN after the LHC
  - Either high energy proton collider (**FCC-hh**)
  - Or high energy linear collider (**CLIC**)
- Europe welcomes Japan to make a proposal to host **ILC**
- Long baseline neutrino facility





FCC Overview

FCC-hh hadron collider with 100TeV proton cms energy

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

FCC-ee a lepton collider as a potential intermediate step

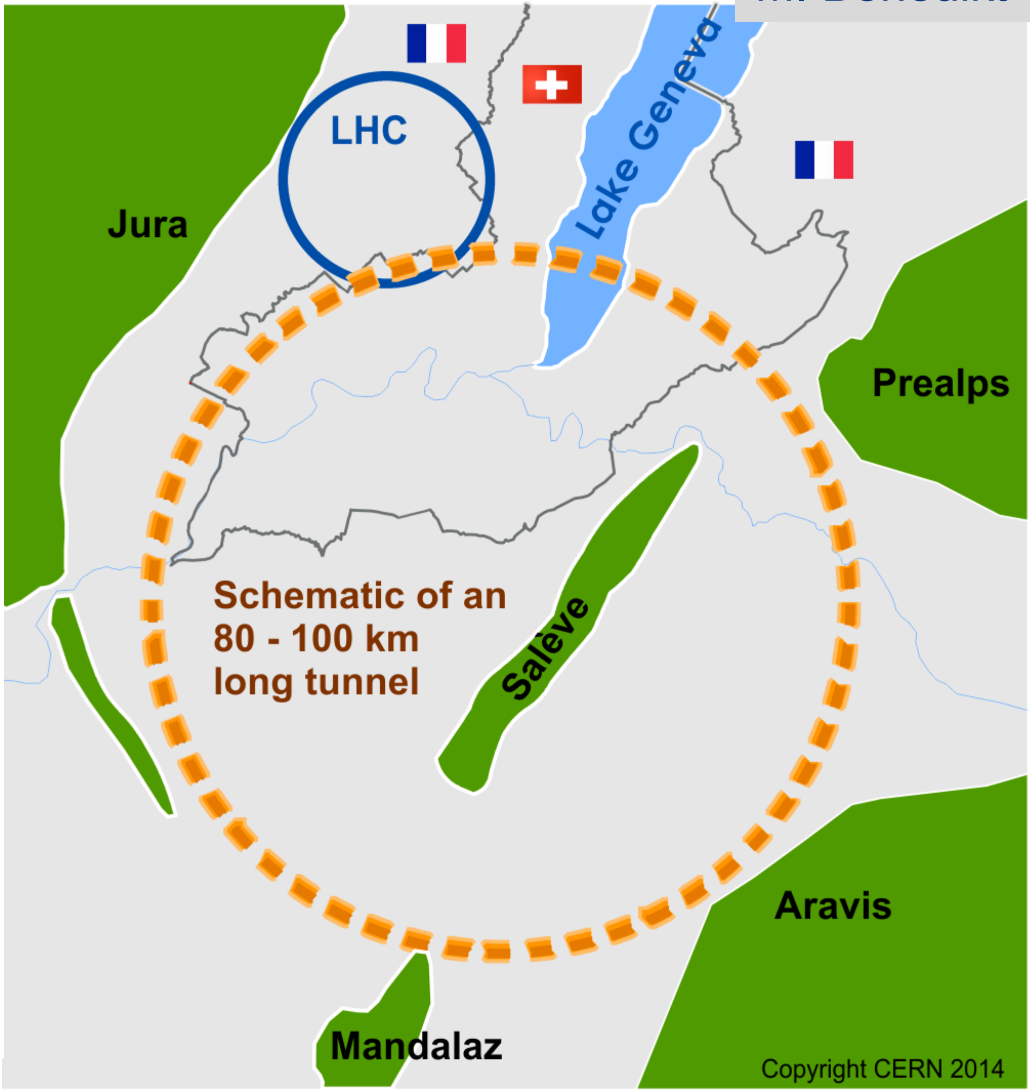
FCC-eh lepton hadron option

International collaboration

Site studies for Geneva area

CDR for EU strategy update in 2018

M. Benedikt



FCC-hh

A baseline parameter list exists: http://indico.cern.ch/event/282344/material/3/

A somewhat conservative first approach, will now make a conceptual design and optimise the parameters and look at alternative parameters

	LHC	HL-LHC	FCC-hh
Cms energy [TeV]	14	14	100
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	5	5
Bunch distance [ns]	25	25	25
Background events/bx	27	135	170
Bunch length [cm]	7.5	7.5	8

- Two main experiments sharing the beam-beam tuneshift
  - Two reserve experimental areas not contributing to tuneshift

- 80% of circumference filled with bunches

Preliminary Layout

First layout developed (different sizes under investigation)

⇒ Collider ring design (lattice/hardware design)

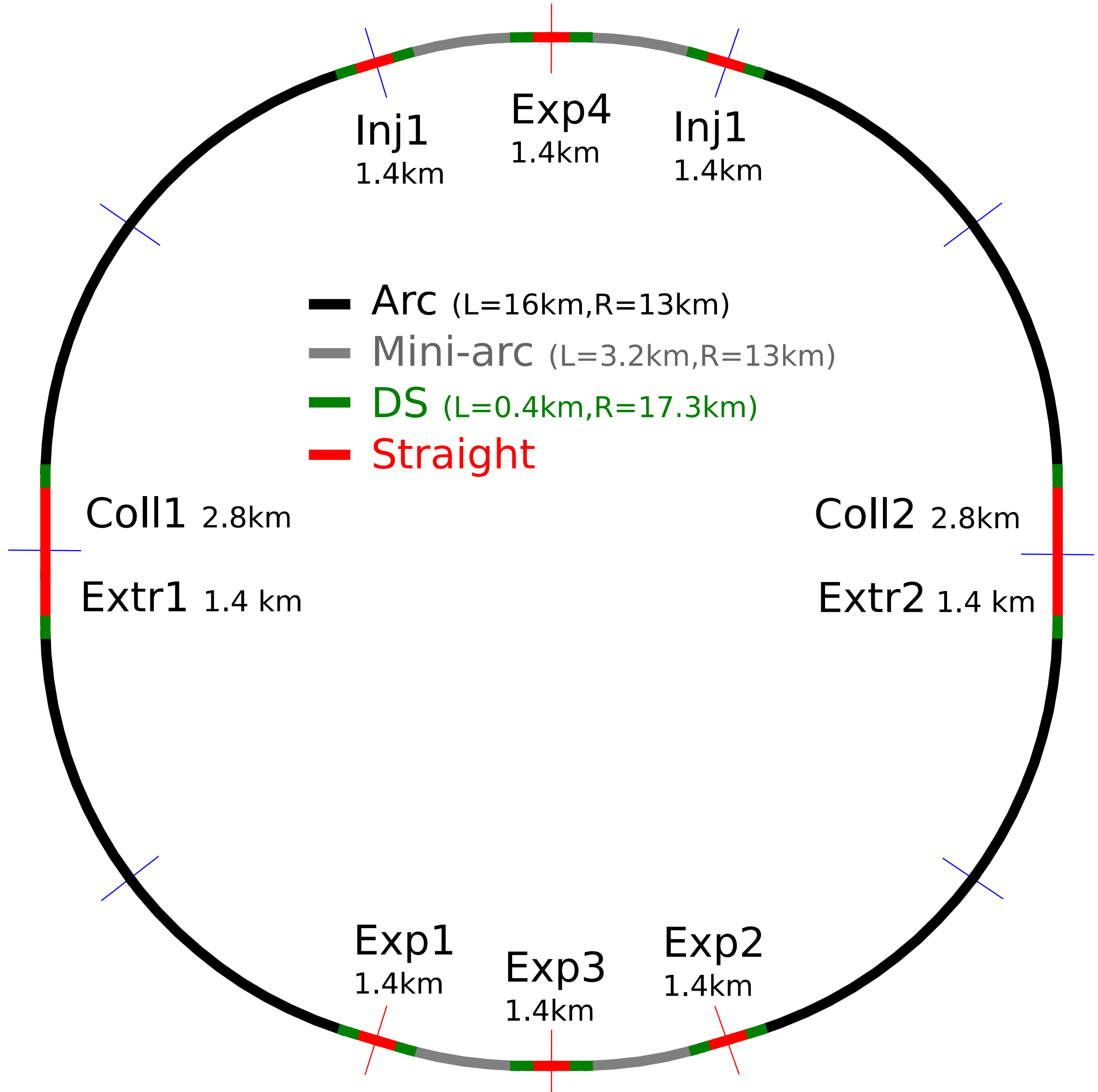
⇒ Site studies

⇒ Injector studies

⇒ Machine detector interface

⇒ Input for lepton option

Will need iterations

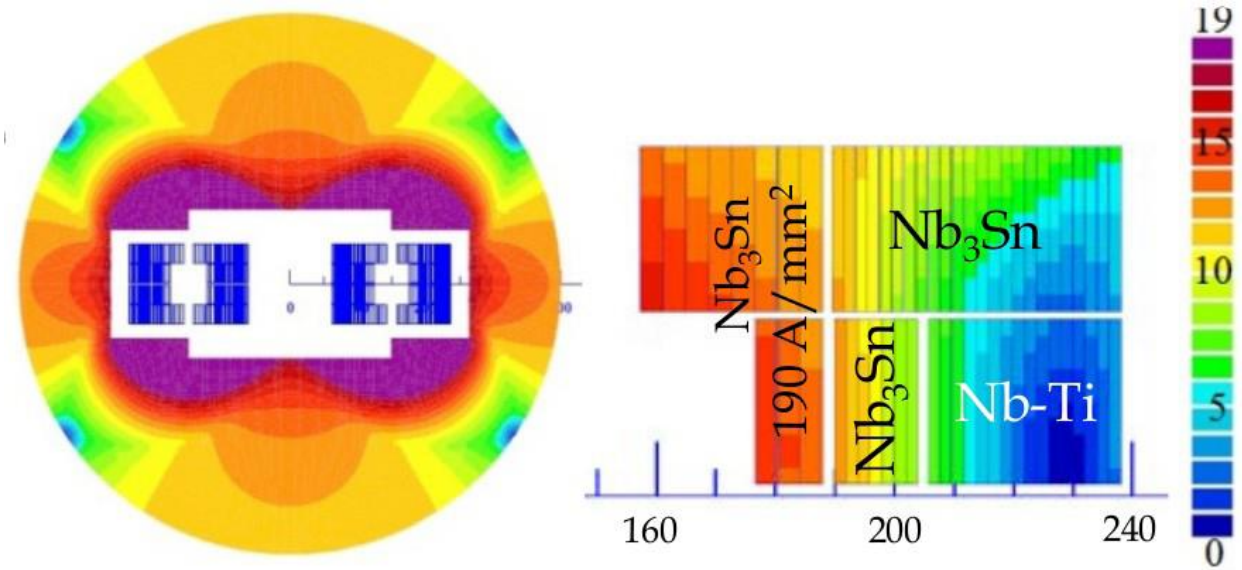


FCC-hh Challenges: Magnets

Arc dipoles are the main cost and parameter driver

Baseline is Nb_3Sn at 16T

HTS at 20T also to be studied as alternative



Coil sketch of a 15 T magnet with grading, E. Todesco

Field level is a challenge but many additional questions:

- Aperture
- Field quality

Different design choices (e.g. slanted solenoids) should be explored

Goal is to develop prototypes in all regions, US has world-leading expertise

Beam Parameters

	LHC	HL-LHC	HE-LHC	FCC-hh
Bunch charge [10^{11}]	1.15	2.2	1	1 (0.2)
Norm. emitt. [μm]	3.75	2.5	1.38	2.2(0.44)
IP beta-function [m]	0.55	0.15	0.35	1.1
IP beam size [μm]	16.7	7.1	5.2	6.8 (3)
RMS bunch length [cm]	7.55	7.55	7.55	8

- Values in brackets for 5ns spacing
- Same values for 16T and 20T design

$$\mathcal{L} \propto \xi \frac{1}{\beta_y} N n_b f_r$$

- Beam-beam tuneshift for two IP 0.01
- Beta-function at IP scaled with sqrt(E) from one LHC insertion line design with 0.4m (some safety margin)

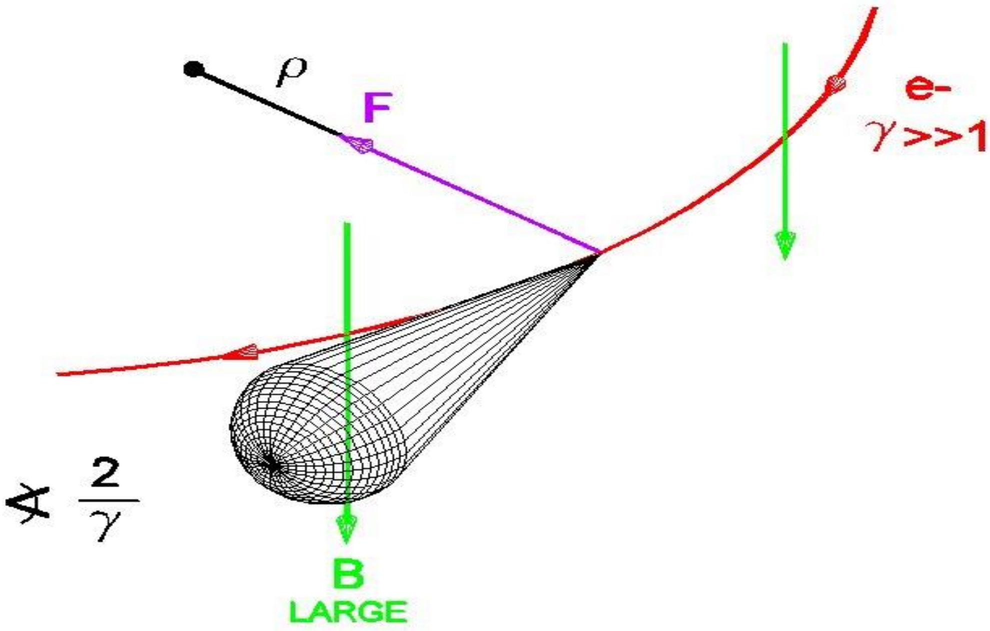
Synchrotron Radiation

At 100 TeV even protons radiate significantly

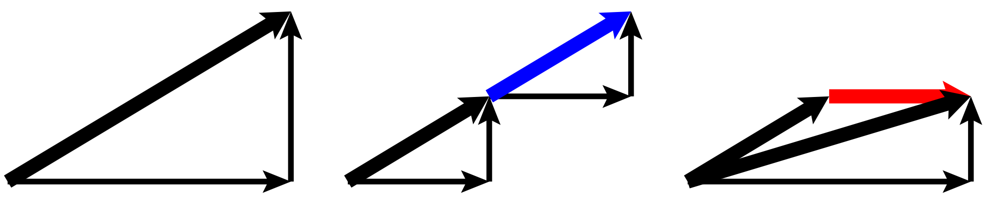
Total power of 5 MW (LHC 7kW)
⇒ Needs to be cooled away

Equivalent to 30W/m /beam in the arcs

- LHC <0.2W/m, total heat load 1W/m



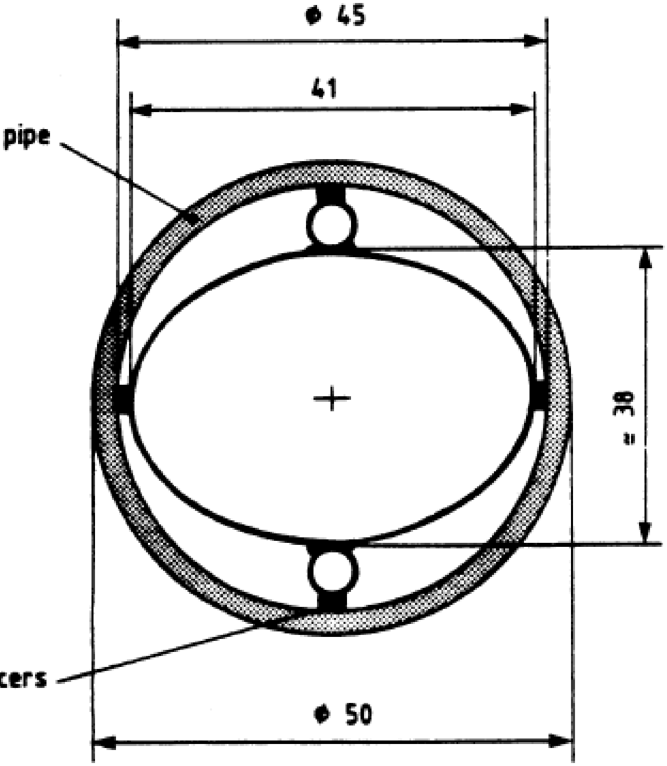
Critical energy 4.3keV, close to B-factory

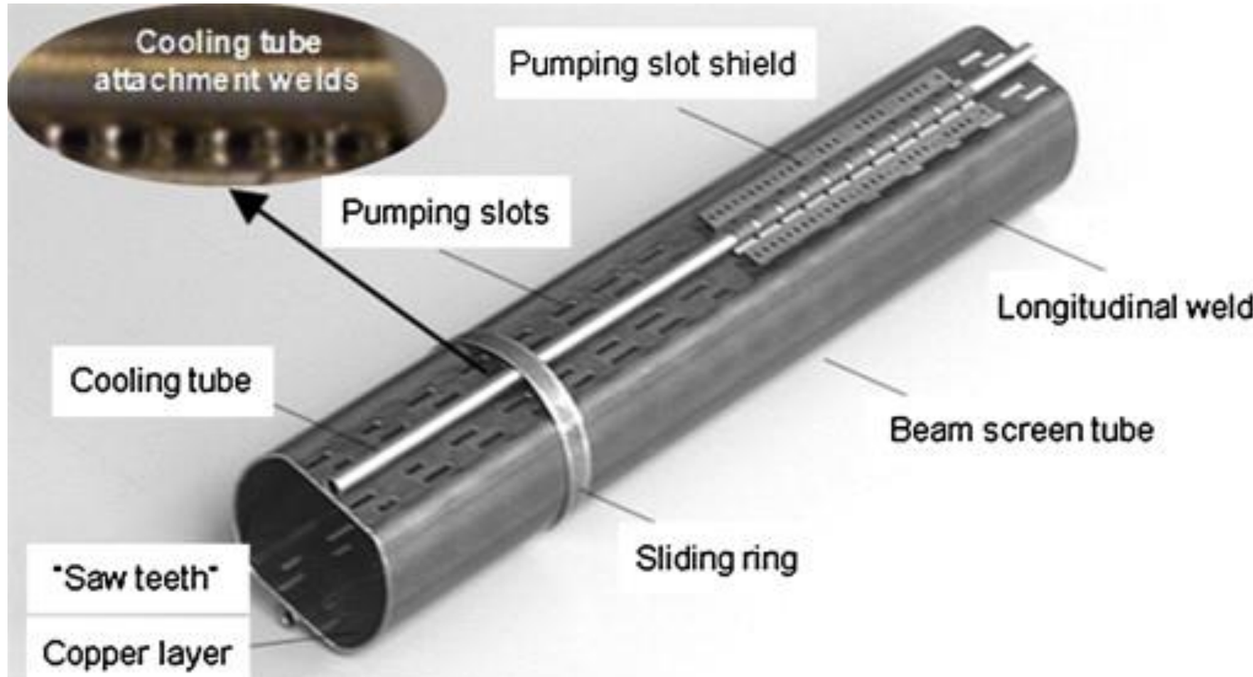


Protons loose energy
⇒ They are damped
⇒ Emittance improves with time

- Typical transverse damping time 1 hour

LHC-Type Beam Pipe Design





Current ambitious goal

beam aperture: 2x13mm

magnet aperture: 2x20mm

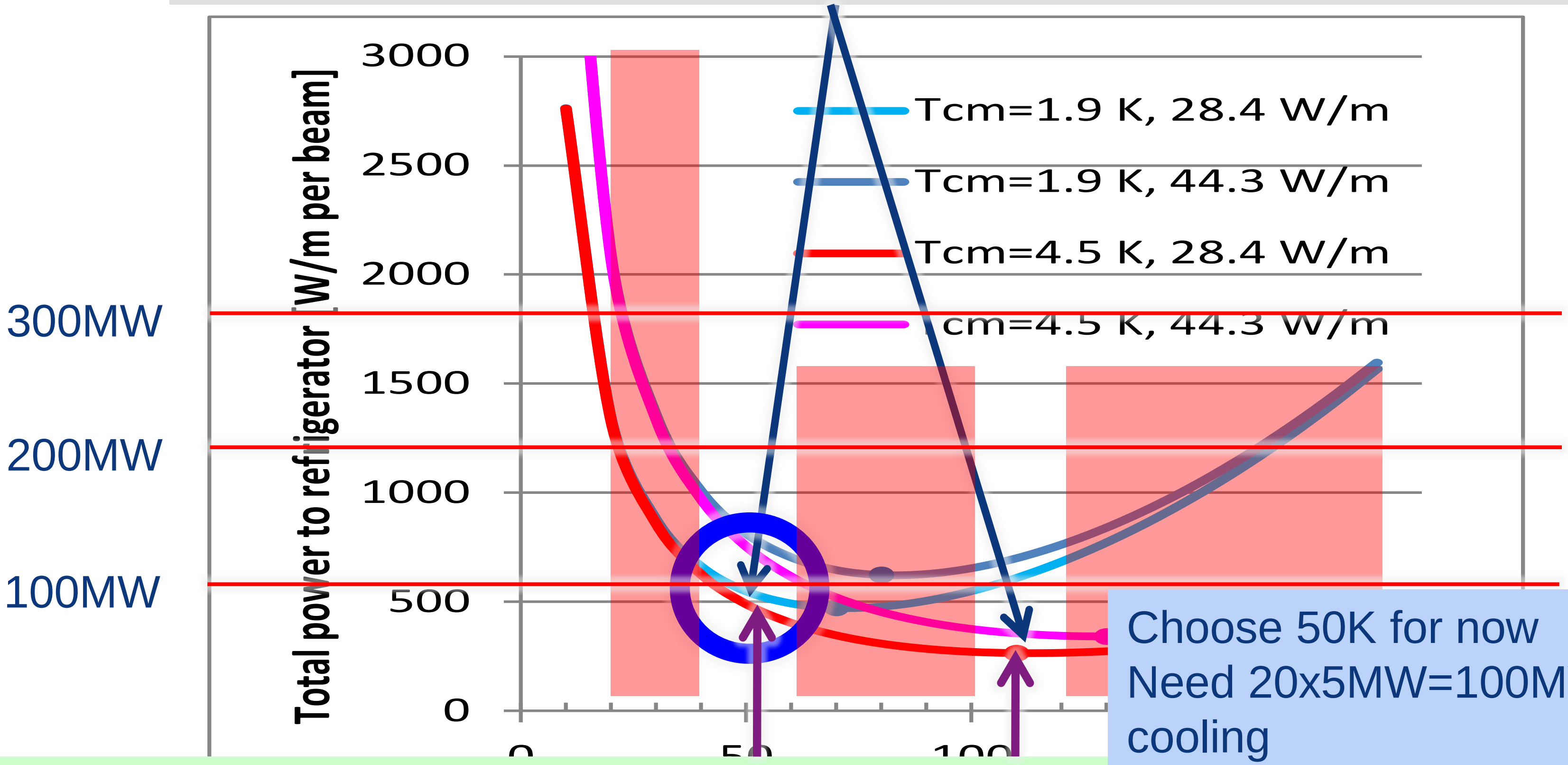
Space for shielding: 7mm

Most of the power will be cooled at the beam screen, i.e. at its temperature

A part is going into the magnets, i.e. cooled at 2-4K

Power for Cooling

Better use only some temperatures in order to maintain good vacuum
<20, 40K-60K, 100K-120K, >190K



Multi-bunch instability growth time: 25 turns 9 turns
(ΔQ=0.5)

Choose 50K for now
Need 20x5MW=100MW for cooling

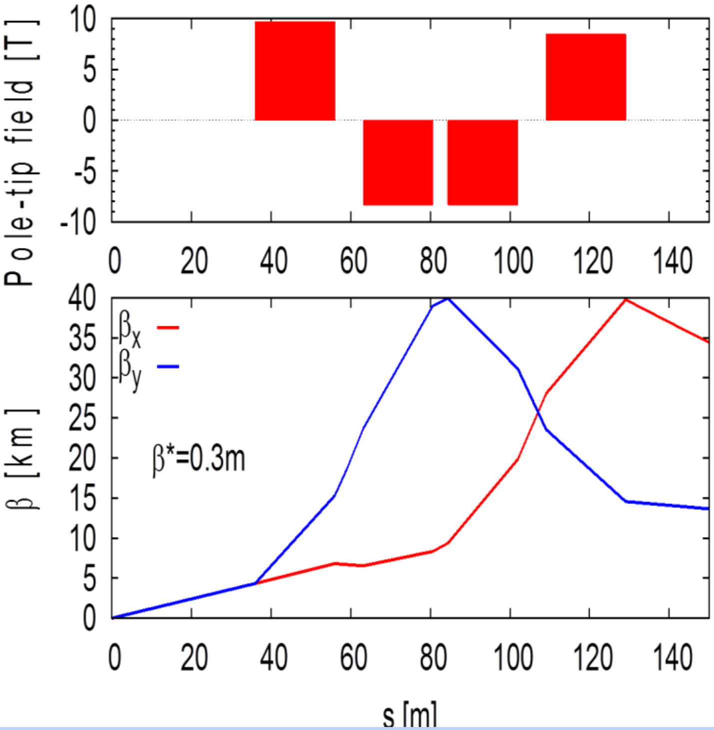
Photon stops? Open midplane?

Interaction Region and Final Focus Design

R. Tomas

Two design being investigated:

- L^* = 46m / 38m (how much is needed?)
- β^* = 0.8m / 0.3m (goal <1.1m)



It is easier to obtain small beta-functions with shorter L*

Will have a tendency to reduce L*

Need to understand detector requirements as soon as possible

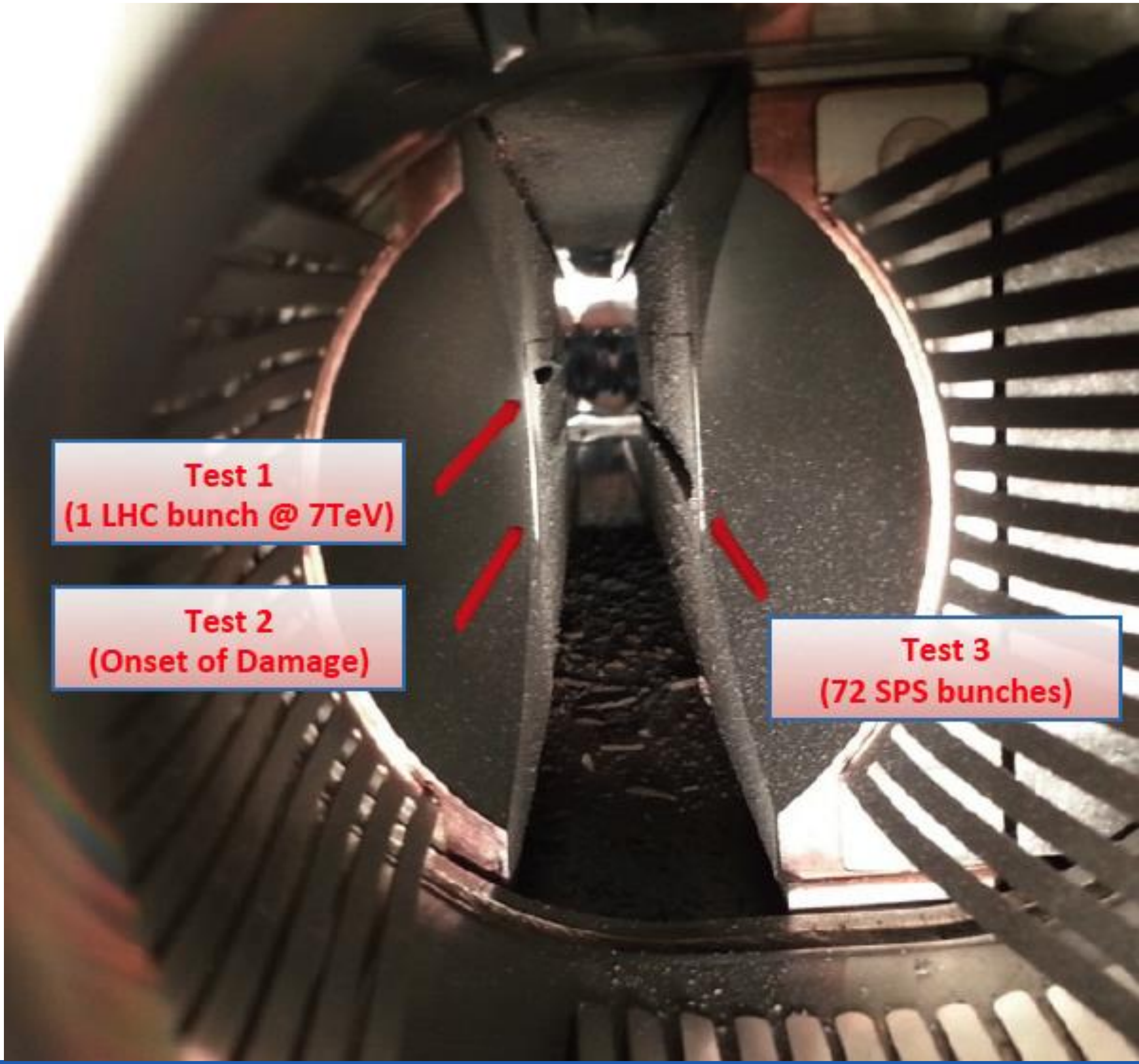
Many issues need to be addressed

- Magnet performance
- Radiation effects
- Space constraints from experiments
- Beam-beam effects and mitigation
- …

Machine Protection and Friends

- >8GJ kinetic energy per beam
  - Airbus A380 at 720km/h
  - 24 times larger than in LHC at 14TeV
  - Can melt 12t of copper
  - Or drill a 300m long hole
  - ⇒ Machine protection

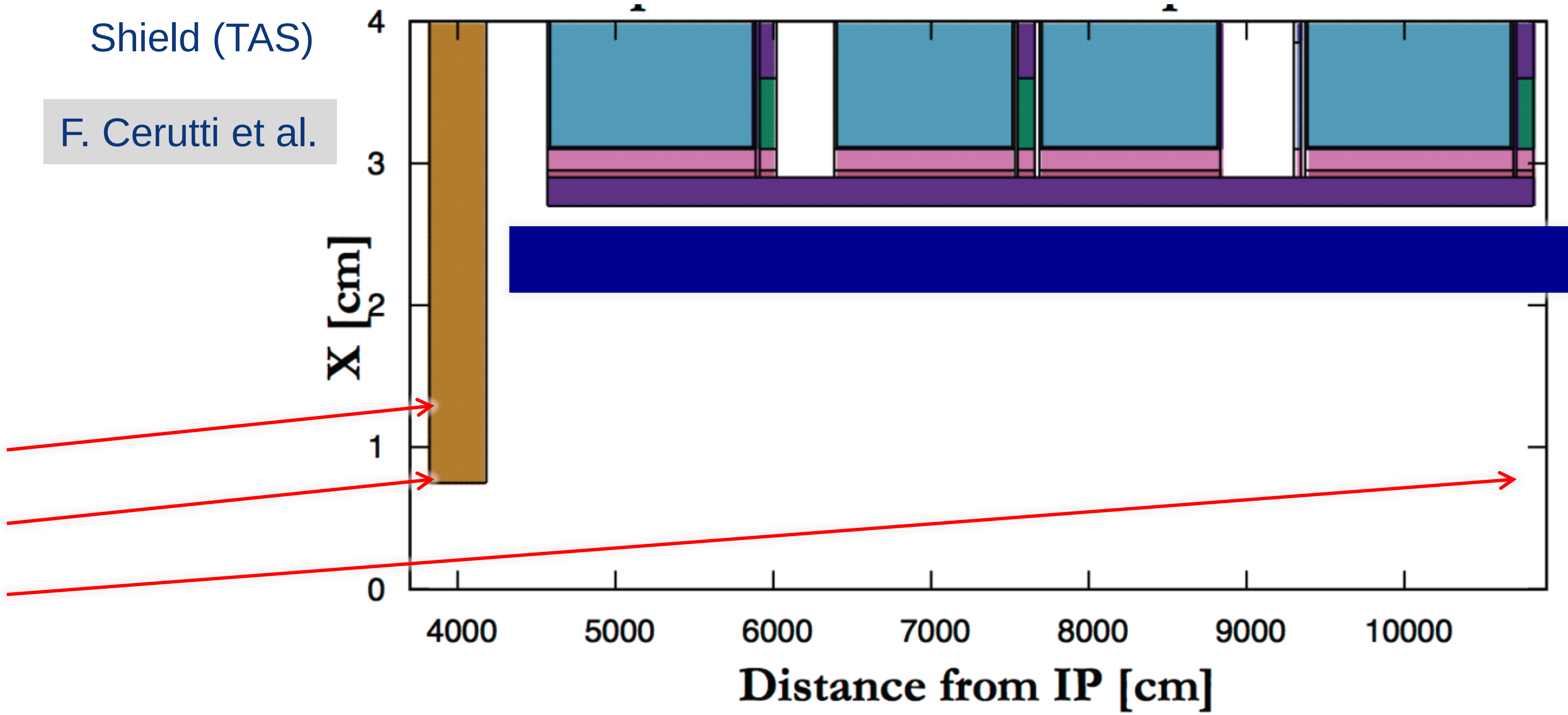
- Also small loss is important
  - E.g. beam-gas scattering, non-linear dynamics
  - Can quench arc magnets
  - Background for the experiments
  - Activation of the machine
  - ⇒ Collimation system



Machine Protection and Friends II

Shield (TAS)

F. Cerutti et al.



- Total power of background events 100kW per experiment (a car engine)
- Already a problem in LHC and HL-LHC (heating, lifetime)

⇒ Improved shielding required

More Issues

- Lattice design/optimisation, choice of working point, dynamic aperture, …
- Impact and mitigation of magnet imperfections
- Beam current limitations, impedances, electron cloud, …
- Beam-beam effects (head-on and parasitic), crossing angle and potential compensation
- Availability
- Hardware components
  - Collimators
  - Crab cavities or other beam-beam devices?
  - Feedback
  - Shilding
  - …
- Cost
  - Most issues will be pushed when this reduces cost

FCC-ee

Parameter	Z	W	H	t	LEP2
E (GeV)	45	80	120	175	104
I (mA)	1400	152	30	7	4
No. bunches	16’700	4’490	1’330	98	4
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	1000 / 1	1500 / 50
ε_x (nm)/ε_y (pm)	29/60	3.3/7	1/2	2/2	30-50/~250
σ_x(μm)/σ_y(nm)	120/250	40/84	22/45	45/45	250/3500
ξ_y	0.03	0.06	0.09	0.09	0.07
L (10^{34} cm^{-2}s^{-1})	28	12	6.0	1.8	0.012

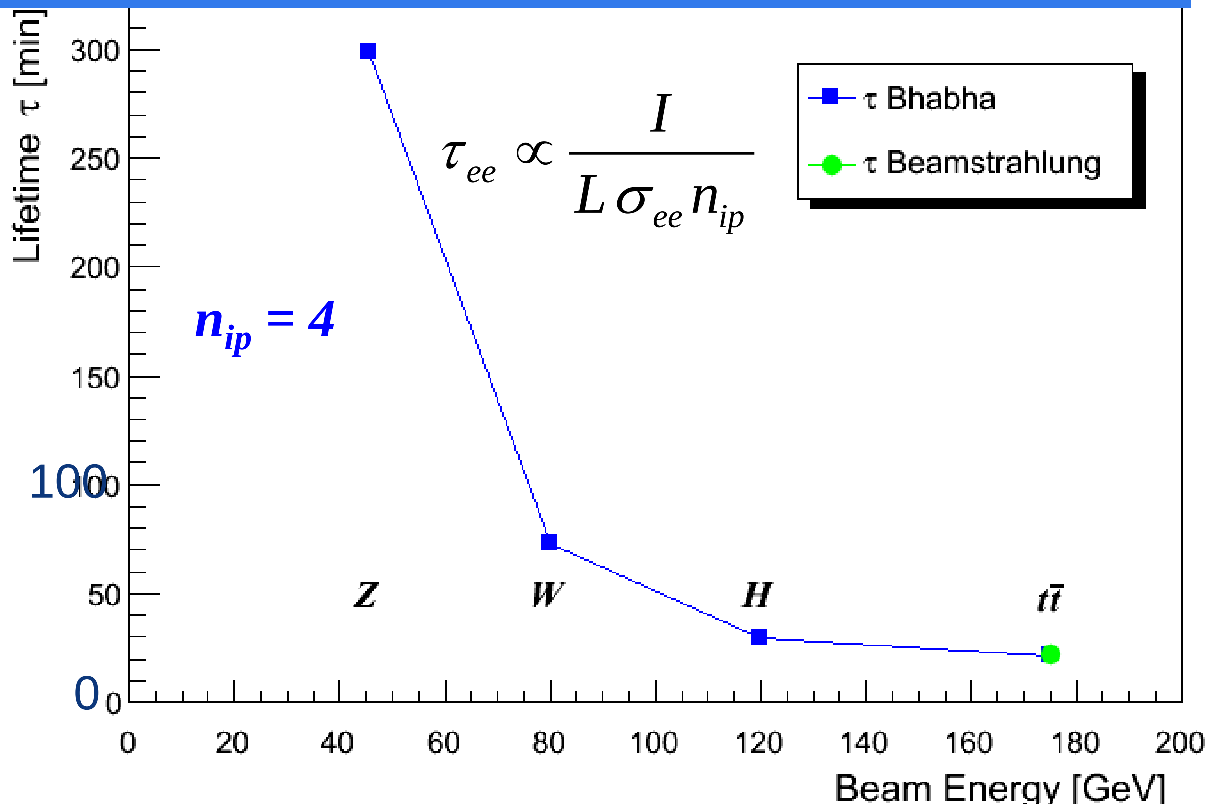
Four experiments foreseen, luminosity given is per experiment

$$L = \frac{f k N^2}{4\pi\sigma_x\sigma_y} F H \;\Rightarrow\; L \mu \frac{P_{SR}}{E^3}\frac{x_y}{b_y^*} \;\Rightarrow\; L \propto \frac{P_{SR}}{E^{1.8}}\frac{1}{\beta_y^*}$$

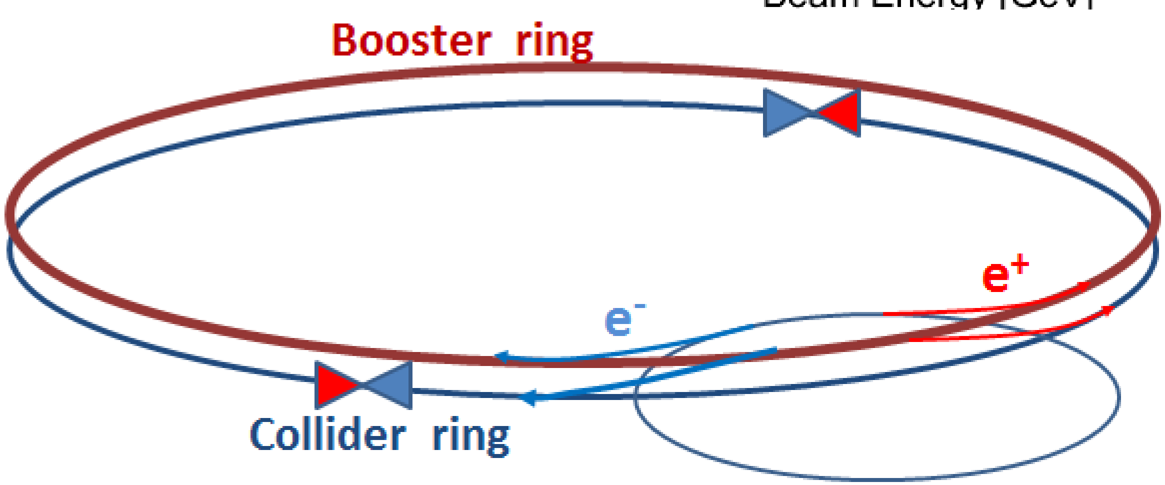
Luminosity Lifetime

Large particle energy loss in IPs and limited energy acceptance (2%) cause limited lifetime

- Radiative Bhabha scattering is proportional to luminosity
- Beamstrahlung as in linear colliders



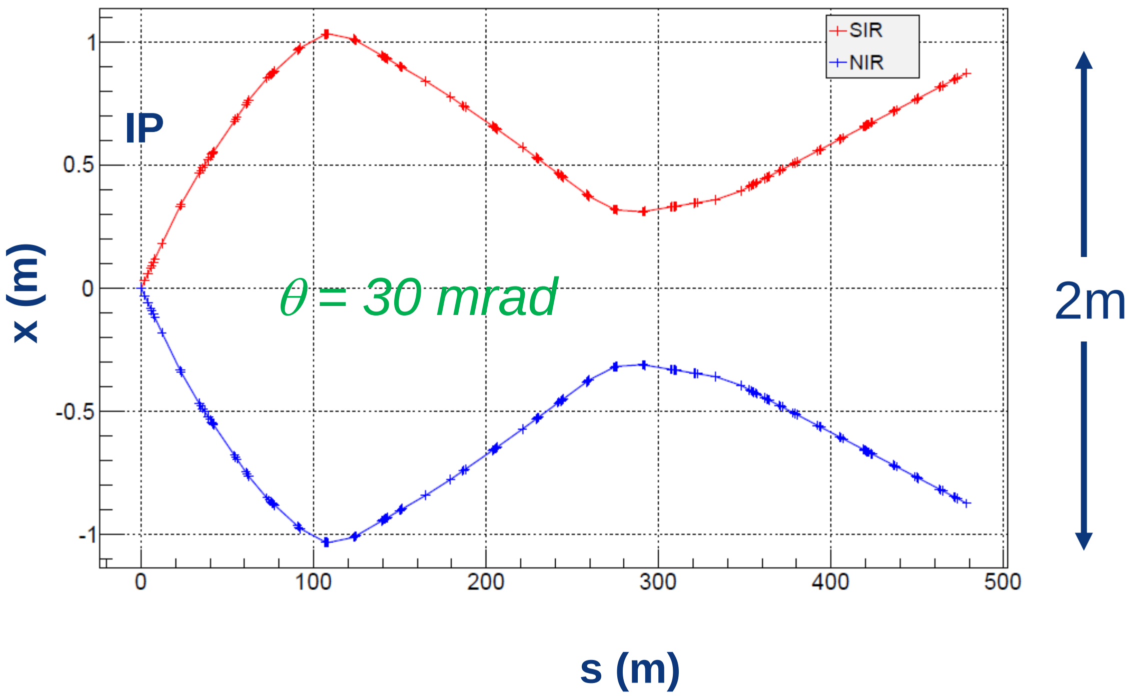
Need continuous injection (top-up)



FCC-ee Beam Dynamics Challenges

Energy bandwidth of the experimental insertion with small beta-function is challenging
Goal is 2%

Significant synchrotron radiation produced in experimental insertion, which can be important background



Other issues

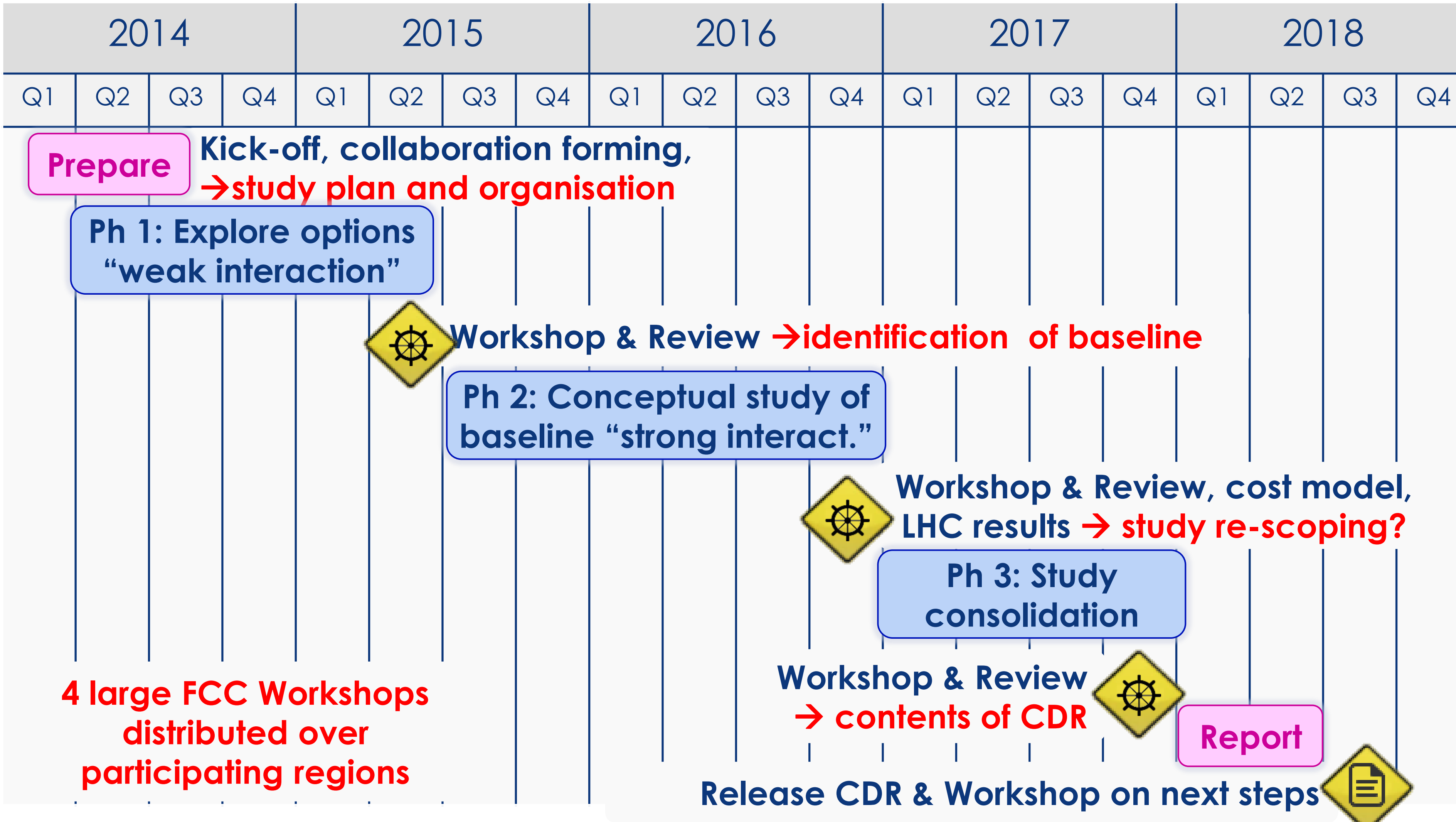
- High beam current at low energies
- Polarisation for low energies
- Integration with FCC-hh layout
- …

SC RF System

- RF system requirements are characterized by two different 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.*
- The RF system must be distributed over the ring to minimize the 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 the FCC-ee power budget.~65% was achieved for LEP2.*

J. Wenninger

Proposed FCC Timeline



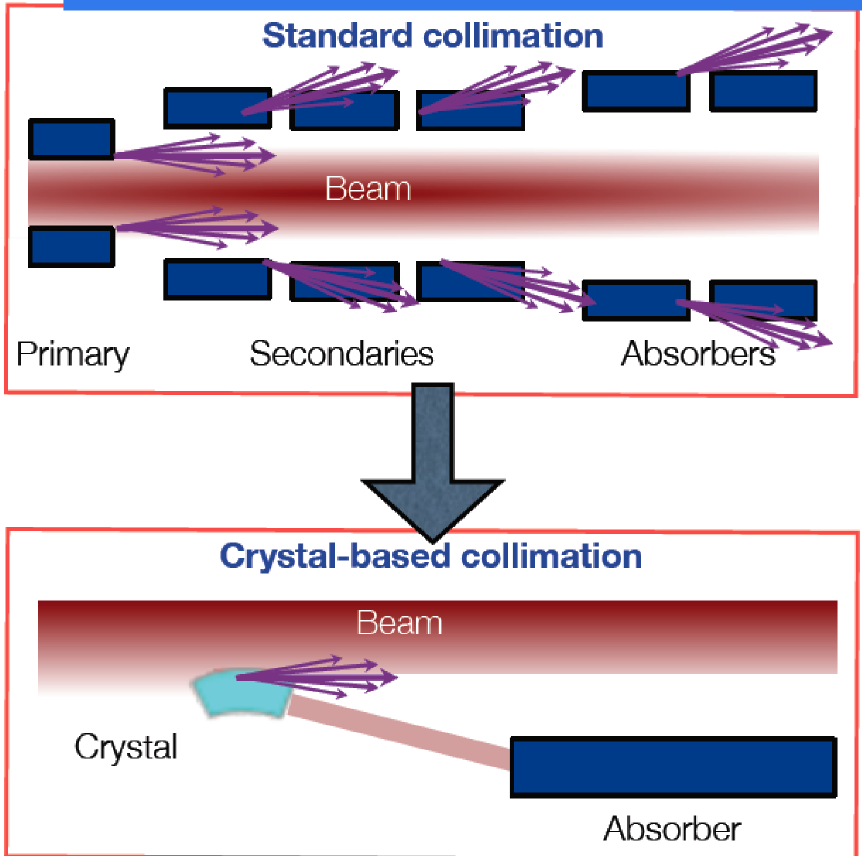
Conclusion

- The studies toward a high energy hadron collider have been launched in a strong international collaboration
  - Technological challenges must be addressed
    - The high field magnets
    - Large beam power and energy
    - …
  - A site next to CERN is being investigated
  - Theoretical and experimental beam studies are required
    - Have the largest test facility ever

- As a potential intermediate step FCC-ee is investigated
  - Based largely on well known technology
  - With ambitious luminosity goals

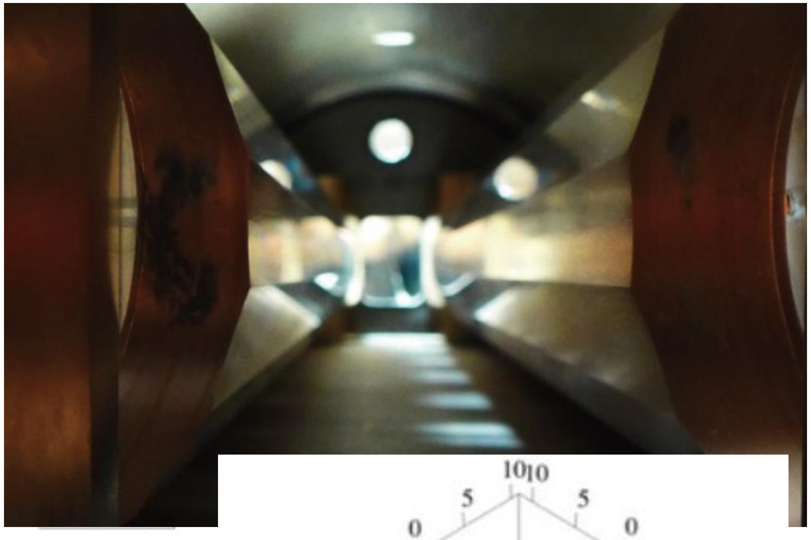
Reserve

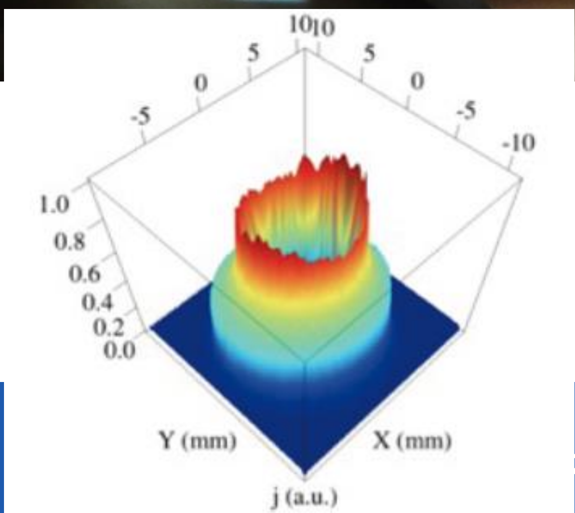
Collimation

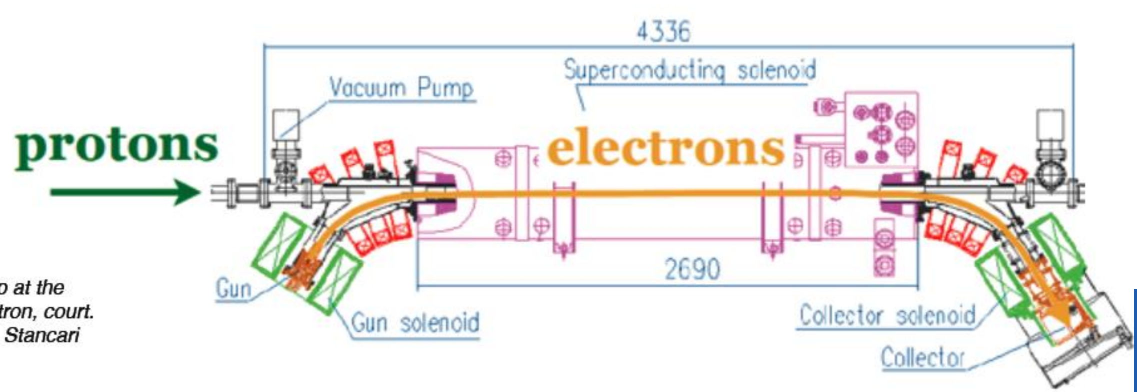


LHC-type solution but other solutions should be investigated

- hollow beam as collimator
- crystals to guide particles
- renewable collimators







Setup at the Tevatron, court. of G. Stancari

FCC-he

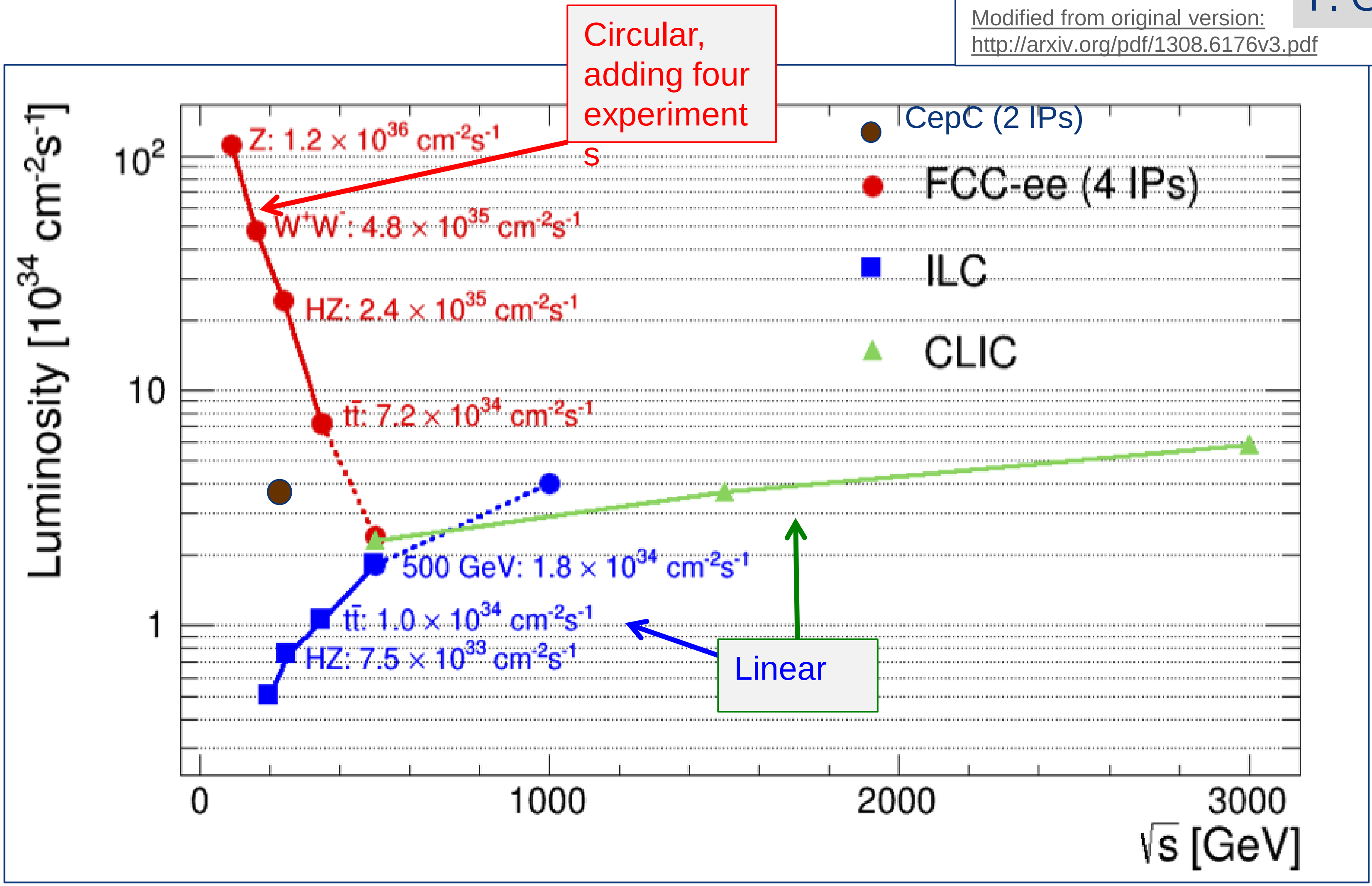
- Tentative design choice: beam parameters as available from *hh* and *ee*
  - Max. $e^{\pm}$ beam current at each energy determined by 50 MW SR limit.
  - 1 physics interaction point, optimization at each energy
- Could consider linac-ring design

collider parameters	**$e^{\pm}$ scenarios**			**protons**
species	***$e^{\pm}$*** (polarized)	***$e^{\pm}$***	***$e^{\pm}$***	***p***
beam energy [GeV]	**80**	**120**	**175**	**50000**
luminosity [10^{34}cm^{-2}s^{-1}]	**2.3**	**1.2**	**0.15**	
bunch intensity [10^{11}]	0.7	0.46	1.4	1.0
#bunches per beam	4490	1360	98	10600
beam current [mA]	152	30	6.6	500
$\sigma_{x,y}^*$ [micron]	4.5, 2.3			

FCC-ee vs. Linear Colliders

F. Gianotti

Modified from original version:
http://arxiv.org/pdf/1308.6176v3.pdf



Expectations after Long Shutdown 1 (2015)

- Cms energy **13 TeV**
- Bunch spacing **25 ns**
- Expected maximum luminosity: **1.6 x 10^{34} cm^{-2} s^{-1}** ± 20%
  - Limited by inner triplet heat load limit, due to collisions debris

- Other conditions:
  - Similar turn around time
  - Similar machine availability
  - β^* ≤ 0.5m (was 0.6 m in 2012)
  - Using new injector beam production scheme (BCMS), resulting in brighter beams.

F. Bordry

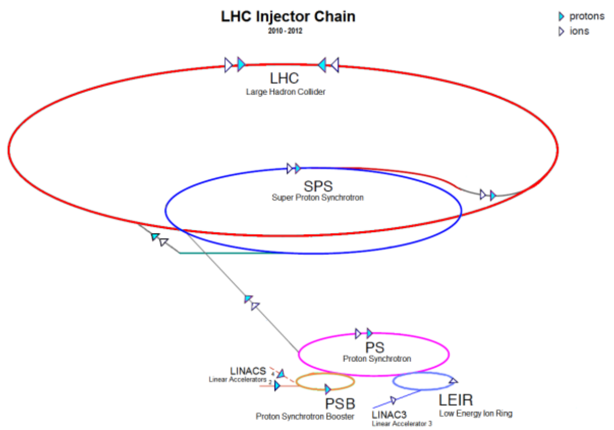
	Number of bunches	Intensity per bunch	Transverse emittance	Peak luminosity	Pile up	Int. yearly luminosity
25 ns BCMS	2508	1.15×10^{11}	1.9 μm	1.6×10^{34} $cm^{-2}s^{-1}$	~43	~40-45 fb^{-1}

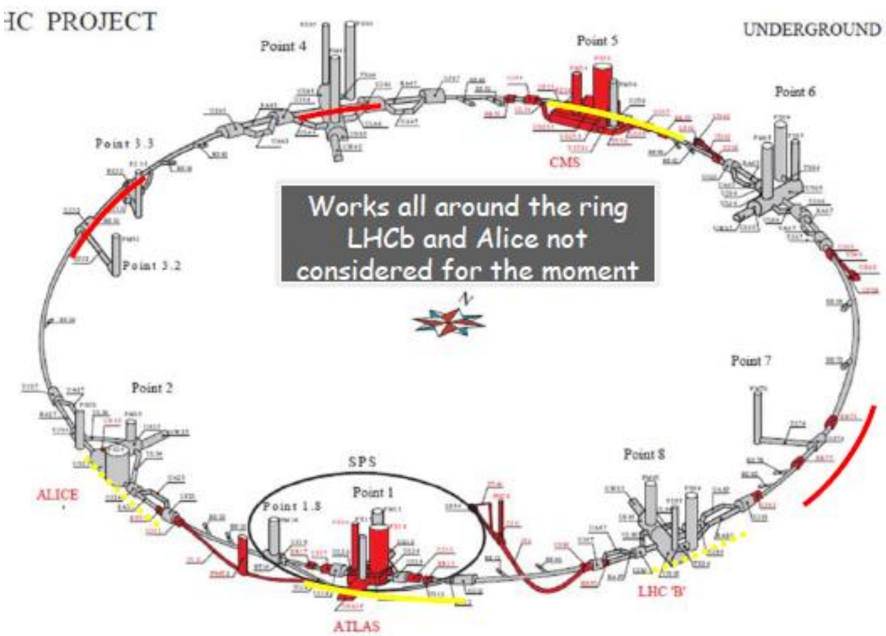
The HL-LHC Project

Goal is to obtain about 3 - 4 fb^{-1}/day (250 to 300 fb^{-1}/year)

Many improvements on the injector chain

- Linac 4 - PS booster
- PS
- SPS





Many improvements on the LHC ring

- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Example of International Collaboration

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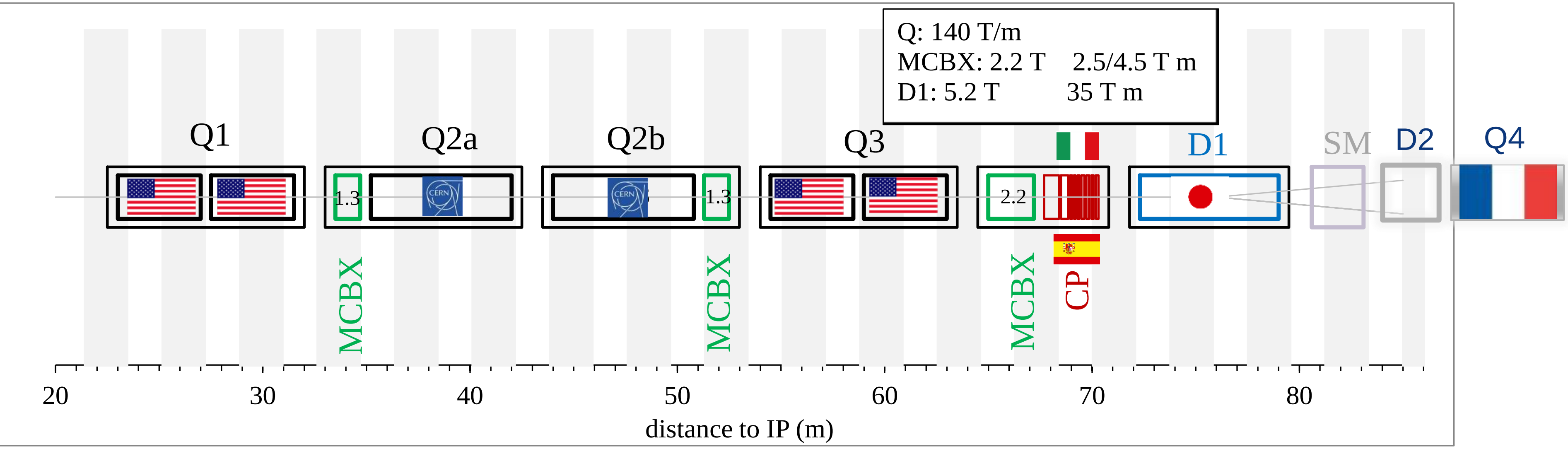
Baseline layout of HL-LHC IR region

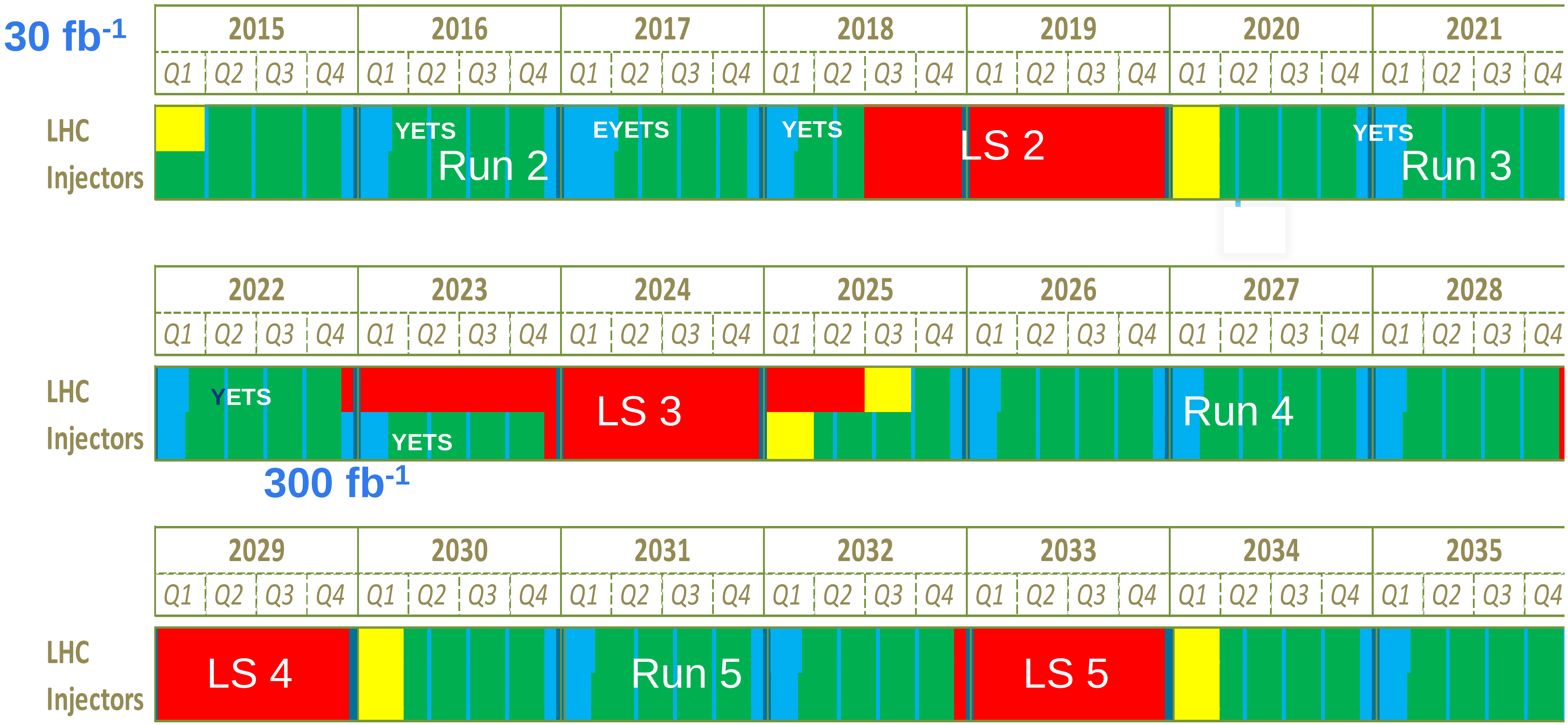


with national laboratories but also involving industrial firms

LHC 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

- Physics
- Shutdown
- Beam commissioning
- Technical stop



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

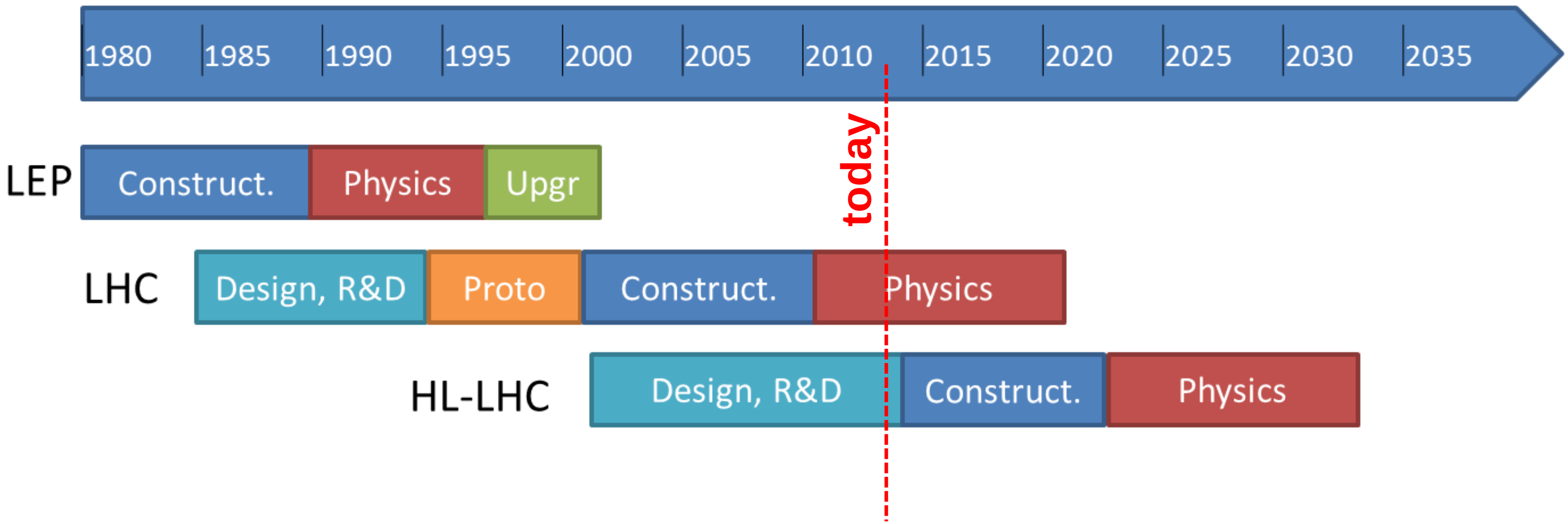
F. Bordry

3’000 fb^{-1}

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)

LHC and HL-LHC

c) … *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. …*

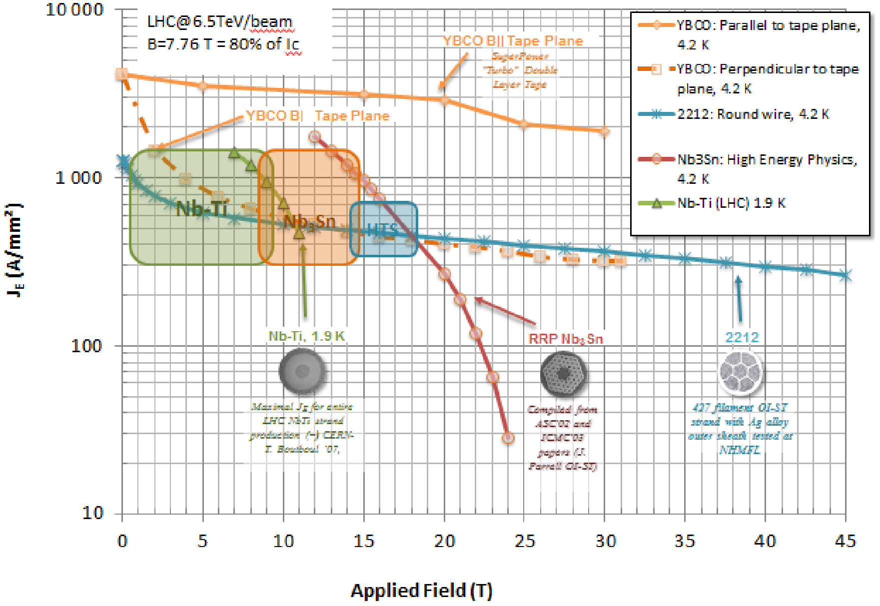


Future Project at CERN

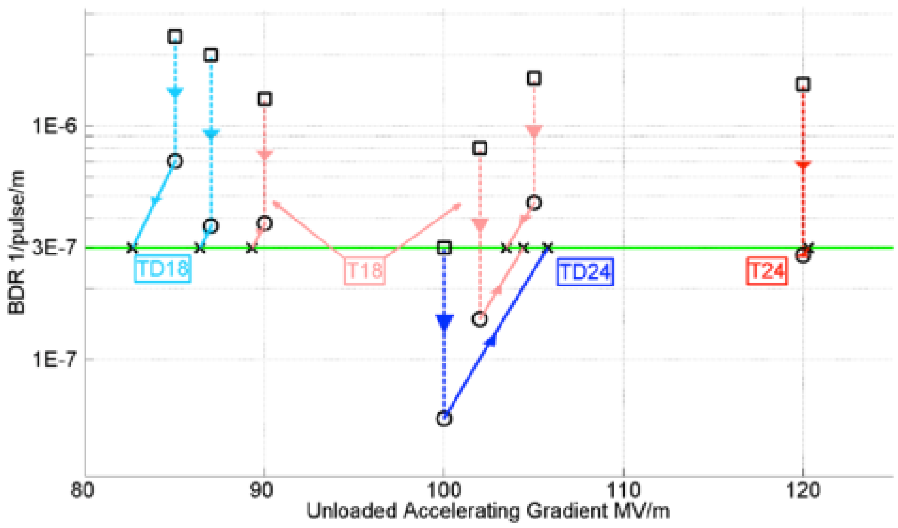
d) …to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update…

… 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.***

HFM – FCC-hh

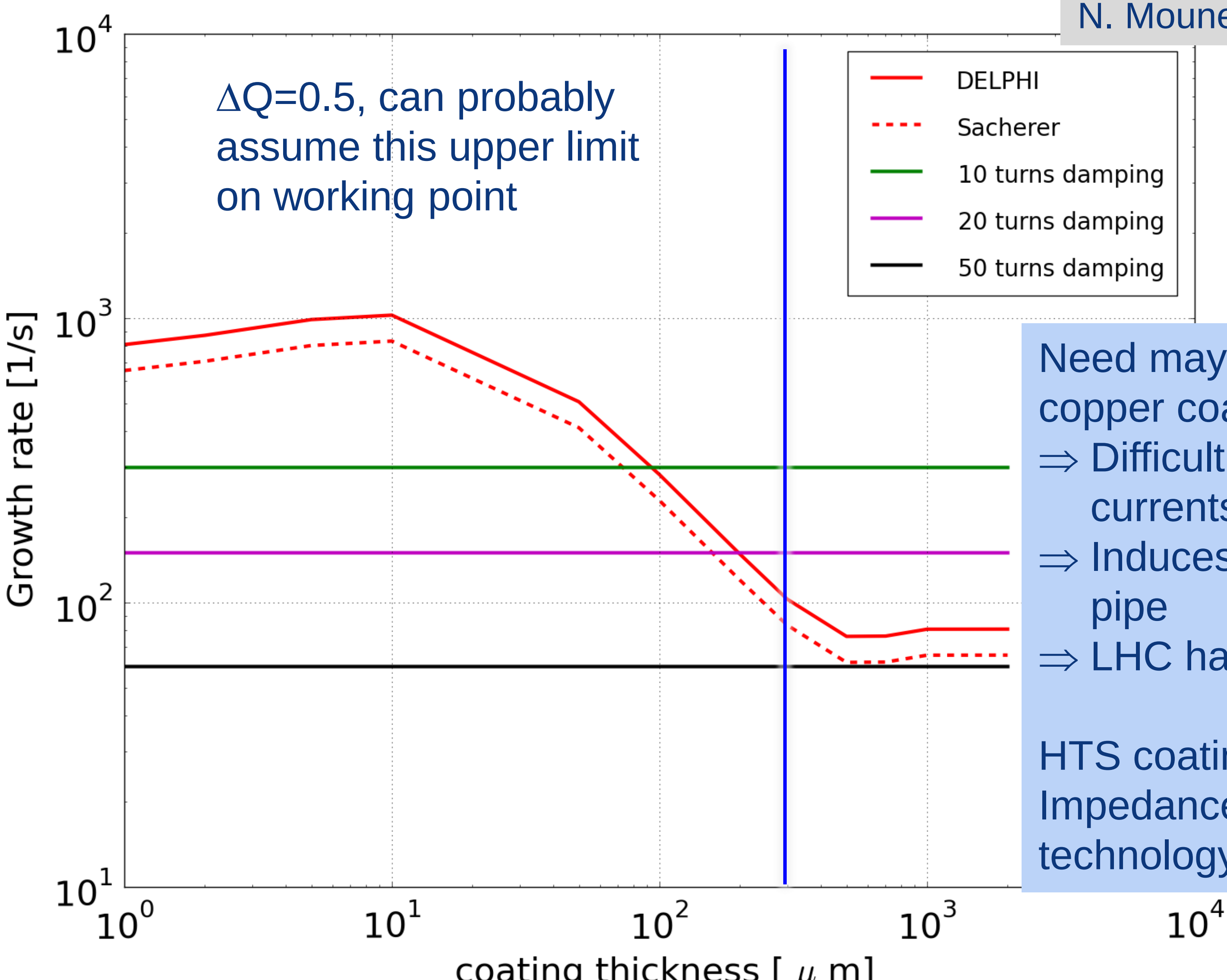


HGA - CLIC



Copper Coating

N. Mounet



ΔQ=0.5, can probably assume this upper limit on working point

Need maybe 300μm of copper coating

⇒ Difficult because of eddy currents in quench

⇒ Induces stress on beam pipe

⇒ LHC has 50μm

HTS coating? Lots of work
Impedance, coating technology, ecloud, …

FCC-hh Challenges II

Optics and beam dynamics

- IR design, dynamic aperture studies, SC magnet field quality, beam-beam, e-cloud, resistive wall, feedback systems design, luminosity levelling, emittance control, …

High synchrotron radiation load on beam pipe

- Up to 30 W/m/aperture in arcs, total of ~5 MW

Machine protection, collimation etc.

- >8GJ stored in each beam (24x LHC at 14TeV, 747-100 at 800km/h)
- Collimation against background and arc magnet quench
- 100kW of hadrons produced in each IP
- Stored energy in magnets will be huge (O(180GJ))

Injection system

…