"Future Strategy and Technologies in Particle Acceleration"

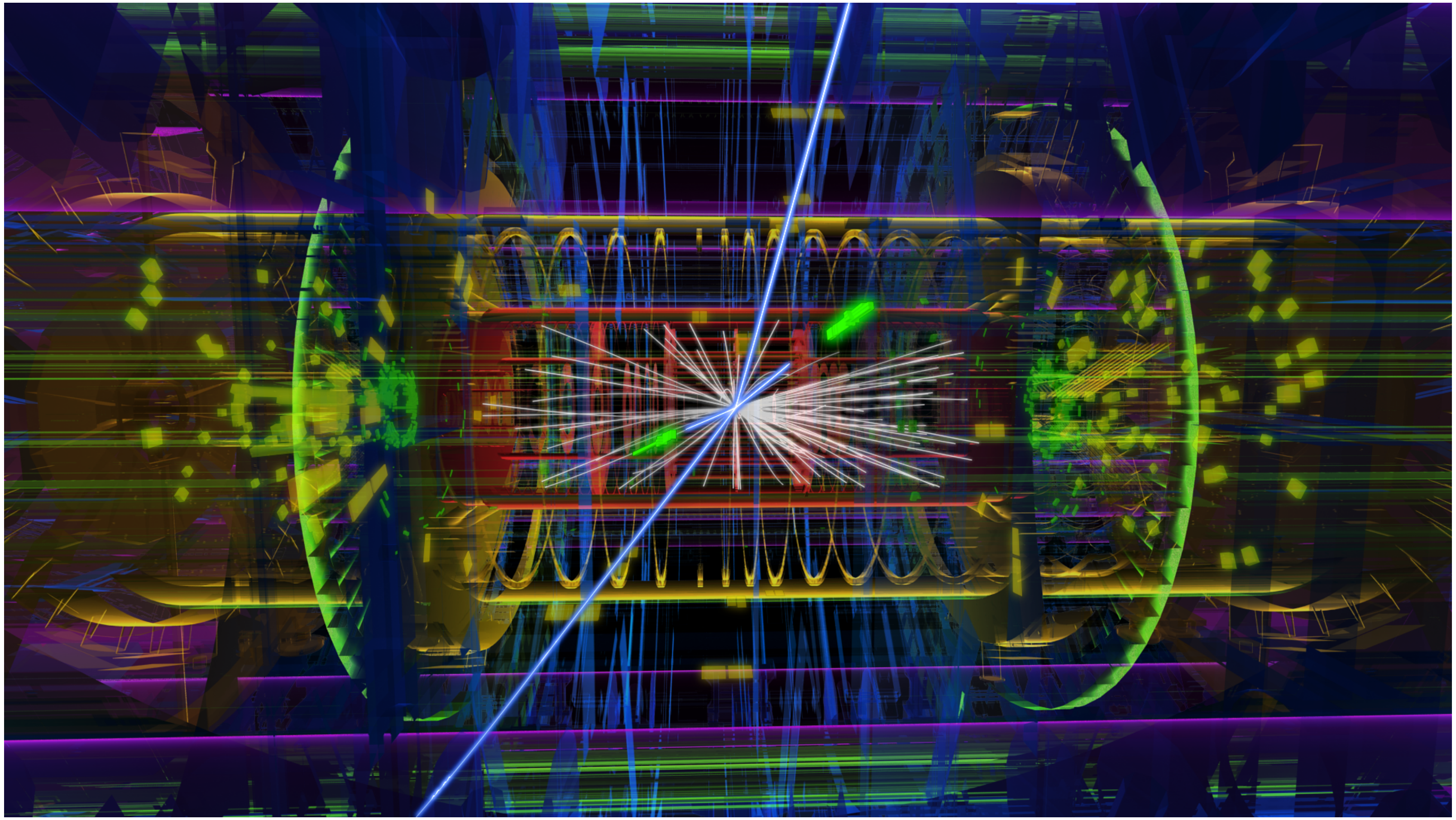
Bernhard Holzer,
CERN

FCC-ee Collider

The next Generation e+/e- Ring Collider

... and why all that ??

High Light of the HEP-Year 2012 / 13 naturally the HIGGS



ATLAS event display: Higgs => two electrons & two muons

Future Projects

Recommendations from European Strategy Group

#1 c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *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. This upgrade programme will also provide*

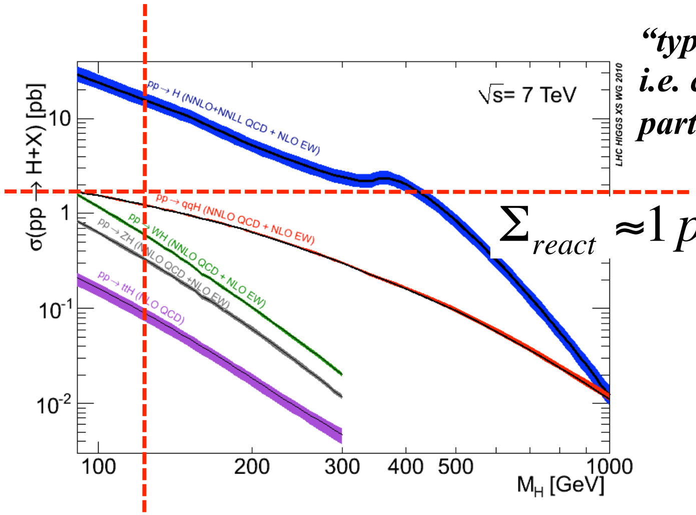
#2 d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator 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.*

→Proton –Proton Colliders ***=> e+/e- colliders***

LHC / HL-LHC, FCC-hh ***FCC-ee, CLIC***

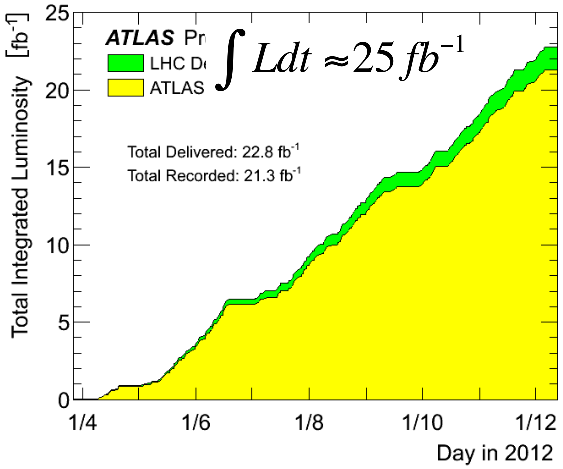
The High light of the year

production rate of events **is** *determined by* **the** *cross section* Σ_{react}
and a parameter L that is given by the design of the accelerator:
… the luminosity



$\Sigma_{react} \approx 1\,pb$

"typical particle size" i.e. cross section for particle production



$\int L dt \approx 25\, fb^{-1}$

accumulated collision rate in LHC run 1

$$1b = 10^{-24}\,cm^2 \quad = \quad 1/mio * 1/mio * 1/mio * \frac{1}{100}\,mm^2$$

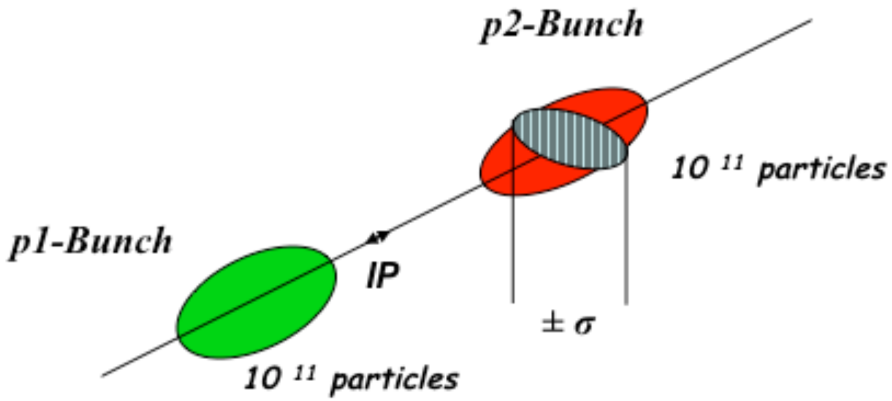
The particles are "very small"

$$R = L * \Sigma_{react} \quad \approx 10^{-12}\,b \cdot 25\,\frac{1}{10^{-15}\,b} = some\,1000\,H$$

During collider run we had in Run 1 …
1400 bunches circulating,
with 800 Mio proton collisions per second in the experiments
and collected only 450 Higgs particles in three years.

Luminosity of a particle collider

$$R = L * \Sigma_{react}$$



Example: Luminosity run at LHC

$$\beta_{x,y} = 0.55\ m \qquad f_0 = 11.245\ kHz$$

$$\varepsilon_{x,y} = 5 * 10^{-10}\ rad\ m \qquad n_b = 2808$$

$$\sigma_{x,y} = 17\ \mu m$$

$$I_p = 584\ mA$$

$$L = \frac{1}{4\pi e^2 f_0 n_b} * \frac{I_{p1} I_{p2}}{\sigma_x \sigma_y}$$

$$L = 1.0 * 10^{34}\ \frac{1}{cm^2 s}$$

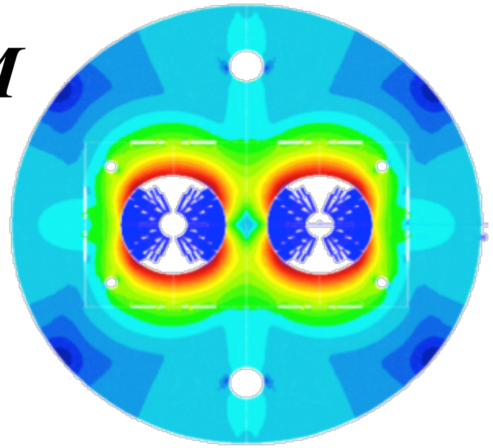
Make the beam size at the IP as small as possible → mini beta insertions

FCC-hh & FCC-ee

FCC-hh: *search for new physics beyond SM*

Main Challenges ...

- save handling of total beam power ≈ 8 GJ
- save beam abort
- cryogenics including extraction of synchrotron radiation
- 16 T bending magnets

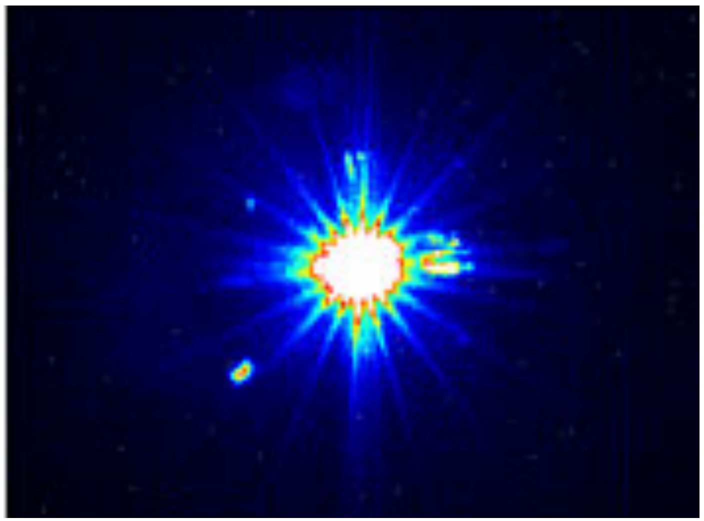


Nb_3Sn FCC type dipole coils, 11 T – 16 T

FCC-e+e-: *precision measurements on Z, W, H, t*

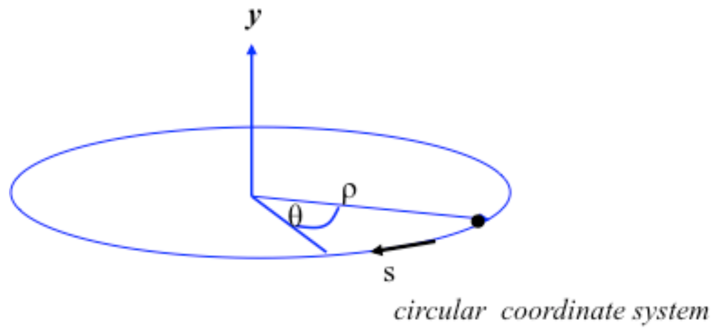
Main Challenges ...

- Optics design
- Handling of SR power
- Up to 10 GV energy loss/turn → Huge RF system
- 50MW synchrotron light losses
- ≈ 100MW Power need per beam



FCC-hh:
Maximum Beam Energy ⟷ Dipole Fields

Condition for an ideal circular orbit:



Lorentz force $F_L = e\, v\, B$

centrifugal force $F_{centr} = \frac{\gamma\, m_0\, v^2}{\rho}$

$$\frac{\gamma\, m_0\, v^2}{\rho} = e\, v\, B$$

$$\frac{p}{e} = B\, \rho$$

Search for highest B-field and largest size

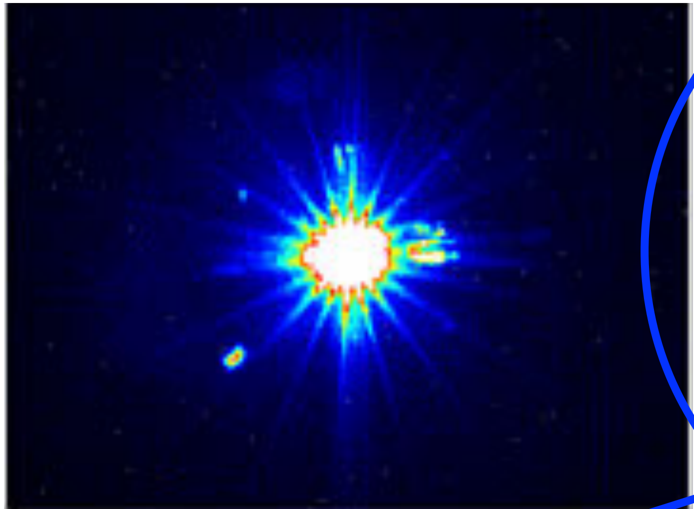
B = 16 T
C = 100 km

E_{cm} = 100 TeV

Nb_3Sn FCC type dipole coils,
11 T – 16 T

FCC-ee:

Maximum Beam Energy ⟷ Synchrotron Light



$$P_s = \frac{e^2 c}{6\pi\varepsilon_0} * \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^4}$$ Synchrotron radiation power

$$\Delta E = \frac{e^2}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{R}$$ Energy loss per turn

$$\omega_c = \frac{3c\gamma^3}{2R}$$ Critical energy

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar c}{(m_e c^2)^3} = 1.468 \cdot 10^{-6} \left[\frac{\text{m}}{\text{GeV}^2}\right]$$

$$\varepsilon_{x0} \equiv \frac{\sigma_{x\beta}^2}{\beta} = \frac{C_q E^2}{J_x} \cdot \frac{\langle \mathcal{H} \rangle_{mag}}{\rho}$$

ε depends quadratically on the beam energy and on the lattice structure -> design

Goal: Lowest possible fields, and largest size

B = 580 Γ
C = 100 km

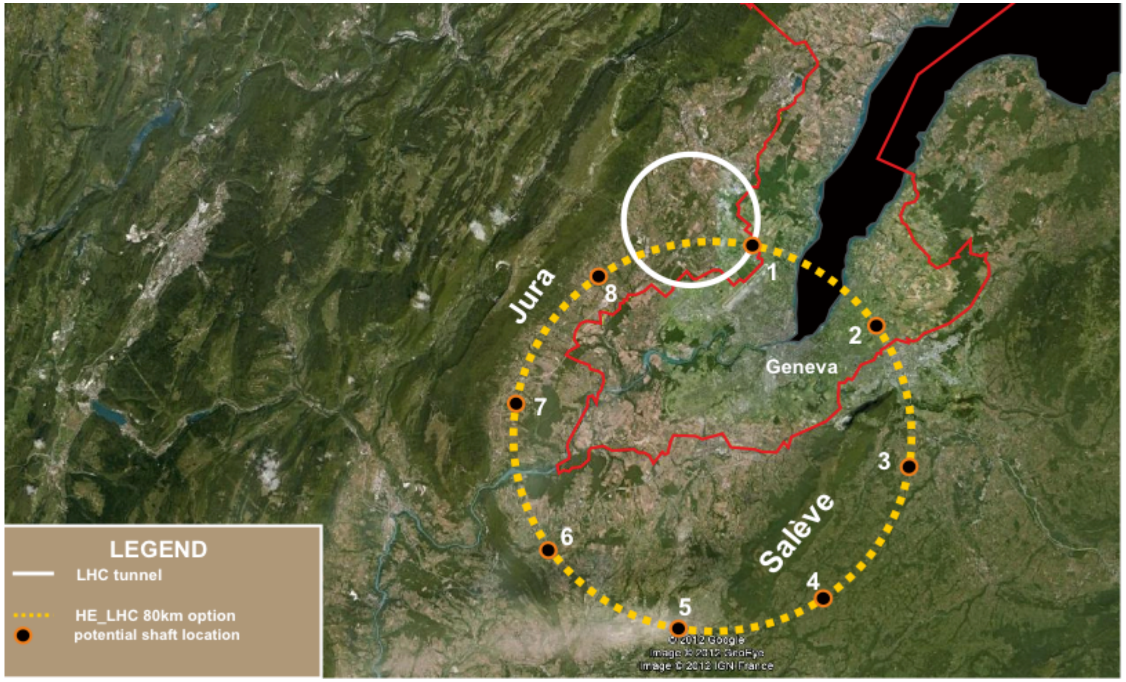
E_{cm} *= 350 GeV*

Sy-Rad Power limits Luminosity & Energy

Planning the next generation e+ / e- Ring Colliders

Design Parameters FCC-ee

E = 175 GeV / beam
L = 100 km



Energy loss per turn

$$\Delta E\,(keV) \approx \frac{89 * E^4 (GeV)}{\rho}$$

$$\Delta E \approx 8.62\; GeV$$

Synchrotron radiation power

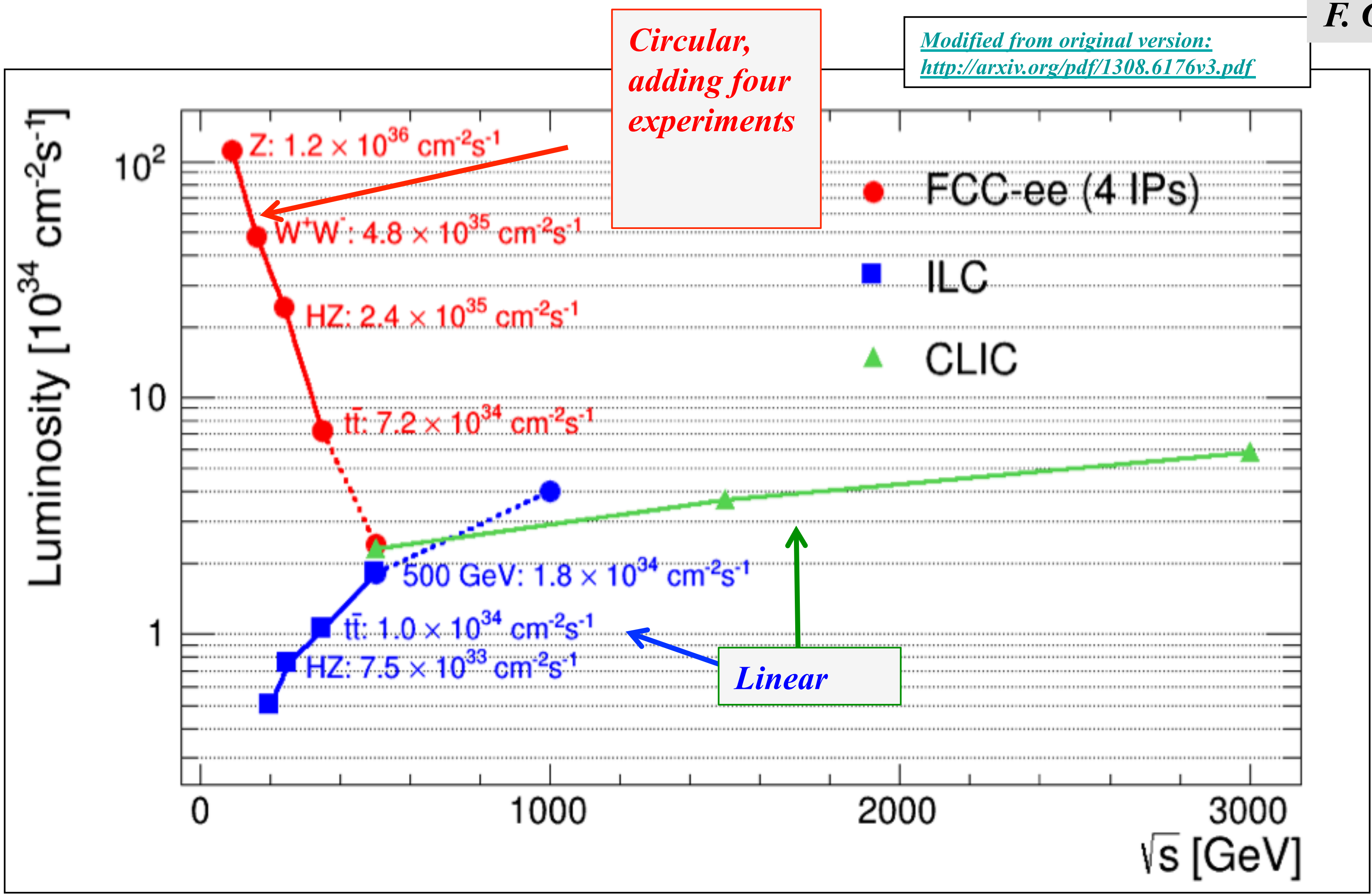
$$\Delta P_{sy} \approx \frac{\Delta E}{T_0} * N_p = \frac{10.4 * 10^6\, eV * 1.6 * 10^{-19}\, Cb}{263 * 10^{-6}\, s} * 1.4 * 10^{13}$$

$$\Delta P_{sy} \approx 50\; MW$$

Synchrotron radiation power determines the maximum intensity and thus the luminosity that can be reached ... for a given energy

Circular vs. Linear e+/e- Colliders

F. Gianotti



There is a moment (... in energy) where we have to go for Linear Acceleration

FCC-ee collider parameters

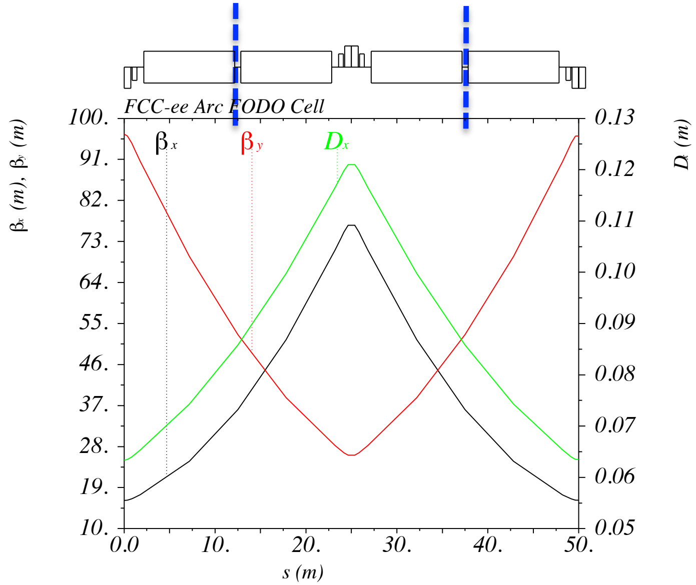
parameter	FCC-ee (400 MHz)					LEP2
Physics working point	Z		W	ZH	tt_{bar}	
energy/beam [GeV]	45.6		80	120	175	105
bunches/beam	30180	91500	5260	780	81	4
bunch spacing [ns]	7.5	2.5	50	400	4000	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
beam current [mA]	1450	1450	152	30	6.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3	0.0012
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.34
synchrotron power [MW]	100					22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	3.5

Strongest point of a Ring Collider:

large number of bunches & collision rate

Lattice Design (175 GeV)

The Standard Approach



L_{cell}=50m

Dipole: ***N_{dipole} = 2932***

L_{dipole} = 2 * 11 m

bending angle = 2.14 mrad

B_0 = 580 Γ

Quadrupole (arc): ***$L_{quadrupole}$ = 1.5 m***

$k=3.55*10^{-2}\ m^{-2}$

g=20.7 T/m

aperture: r_0=30σ =11mm

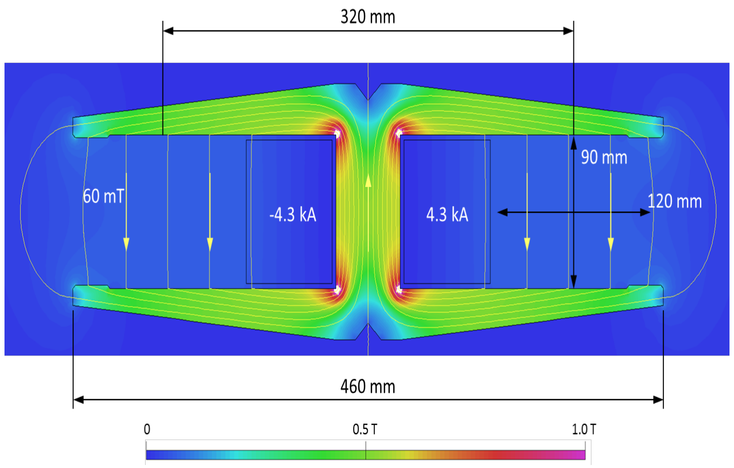
B_{tip}= 0.23 T

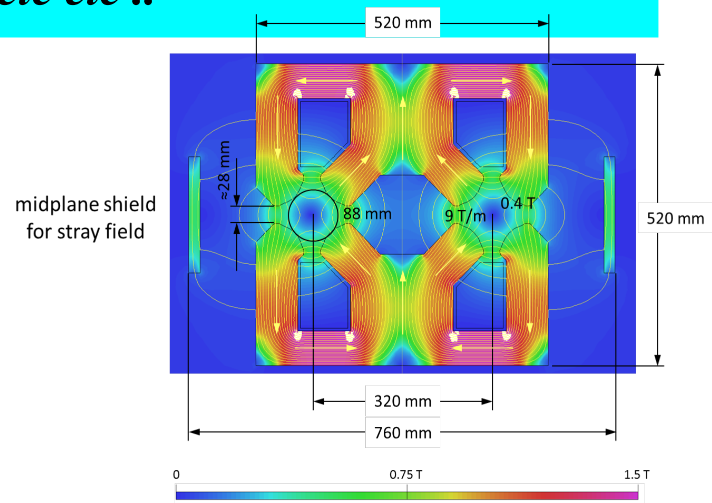
≈ 9000 main magnets,

3000 sextupoles,

3000 skew quads

etc etc ..





RF system requirements

The Standard Approach … BUT … Very large range of operation parameters

"Ampere-class" machines

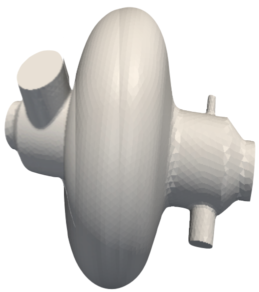
	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
hh	0.032		**500**	
Z	0.4/0.2	30000/90000	**1450**	0.034
W	0.8	5162	152	0.33
H	**5.5**	770	30	1.67
t	**10**	78	6.6	7.55

"high gradient" machines

Voltage and beam current ranges more than factor > 100

low energy high current
→ *single cell, low impedance*

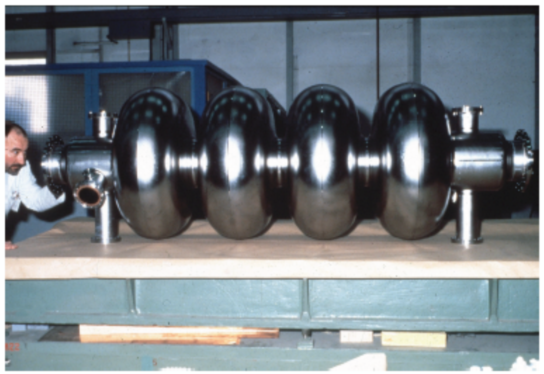
high energy low current
→ *multi cell, high voltage*



hh ≈ 16 cells per beam

Z ≈ 100 per beam (+ 100 for booster ring)

W ≈ 210 per beam (+ 210 for booster ring)

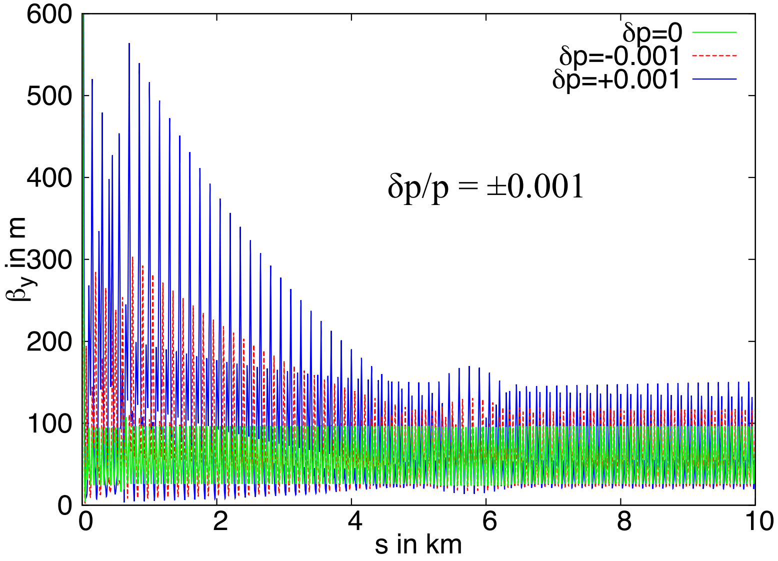


FCC-ee: The real problem

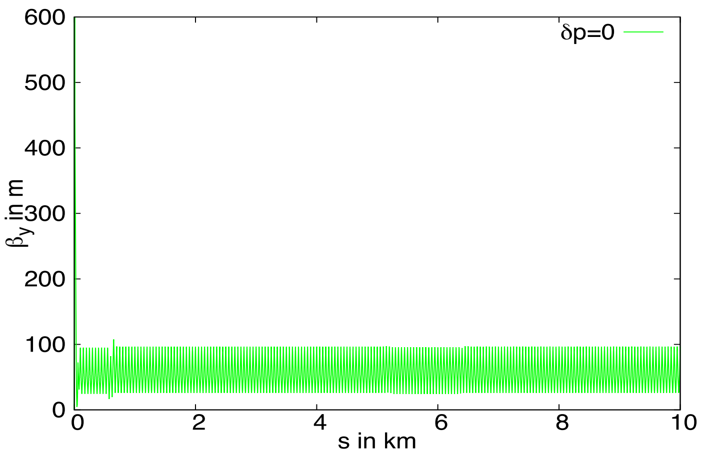
Non-linear Beam Dynamics

we lose energy via synchrotron radiation
→ adjust the ring magnets (tapering)

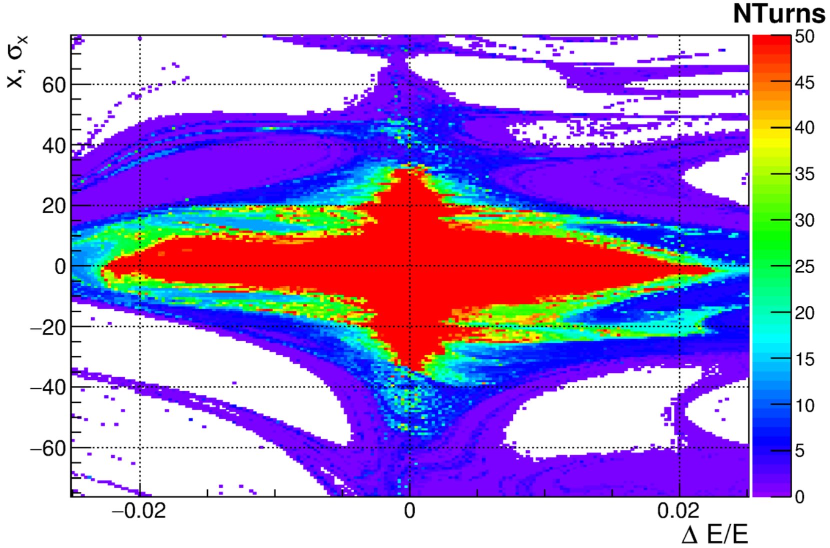
single particles lose energy in the coulomb field of the colliding bunches (beam strahlung)
→ INCOHERENT EFFECT
cannot be corrected
momentum accepetance Δp/p = +/- 2 %



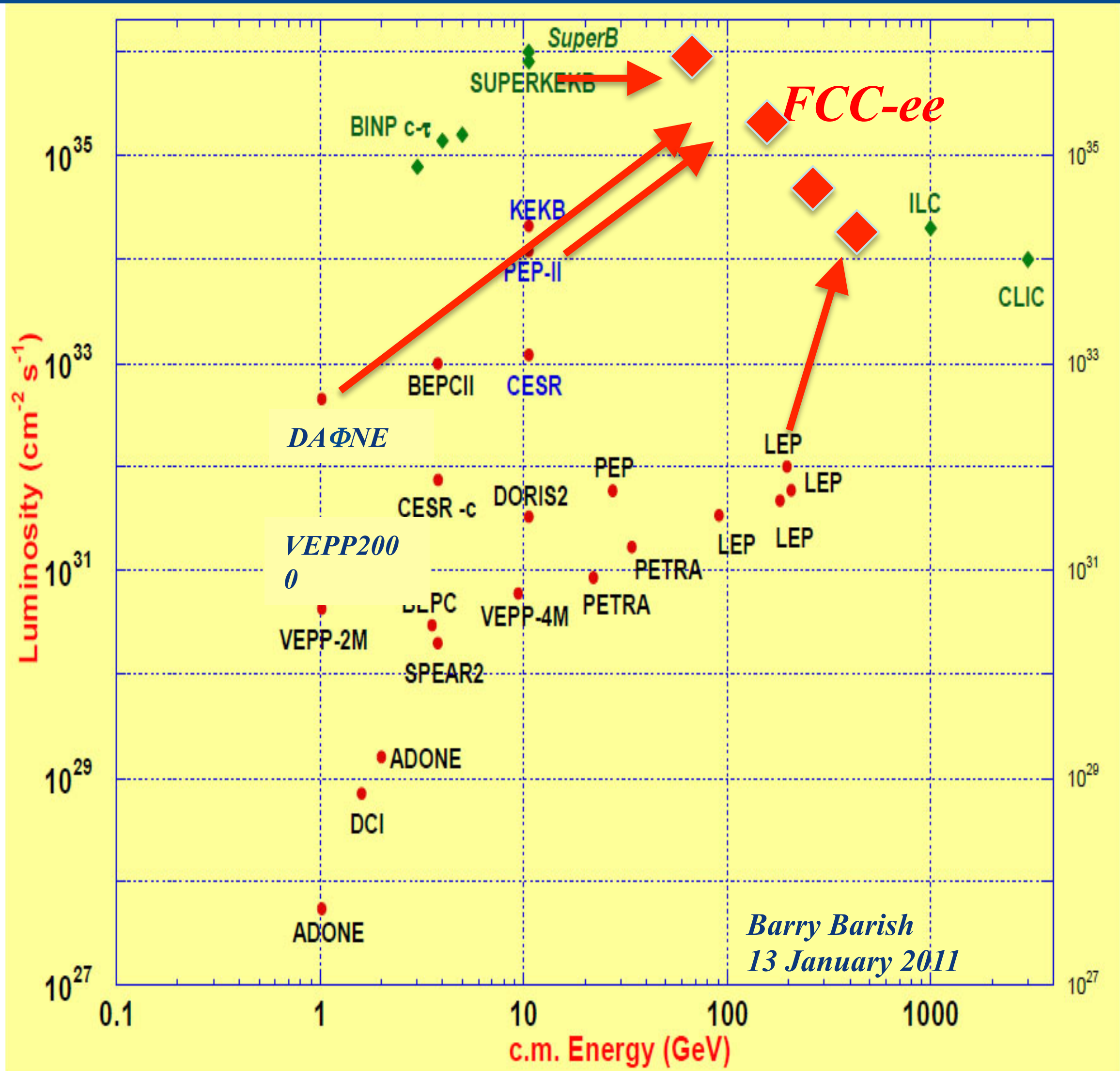
After chromaticity correction!



DA ≈ 10 σ



FCC-ee exploits lessons & recipes from past colliders



LEP:
high energy
SR effects

B-factories:
KEKB & PEP-II:
high beam currents
top-up injection

DAFNE: crab waist

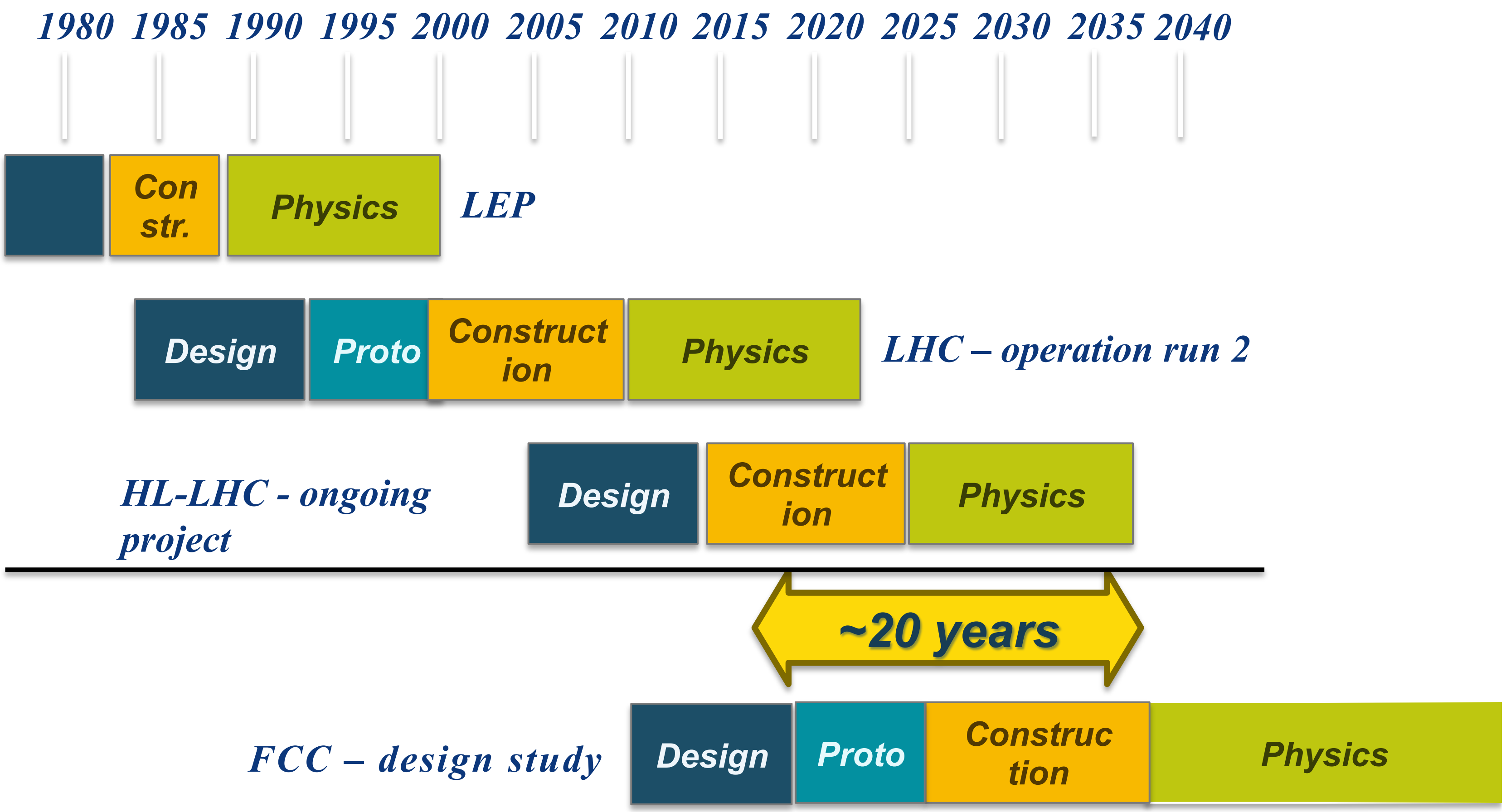
Super B-factories
*S-KEKB: low b_y**

KEKB: e^+ source

HERA, LEP, RHIC:
spin gymnastics

combining successful ingredients of recent colliders → extremely high luminosity at high energies

FCC-ee Status



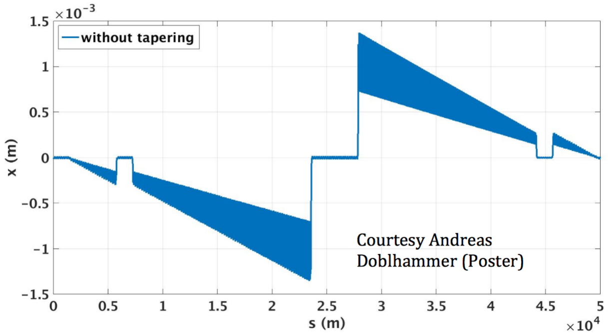
Must advance fast now to be ready for the period 2035 – 2040

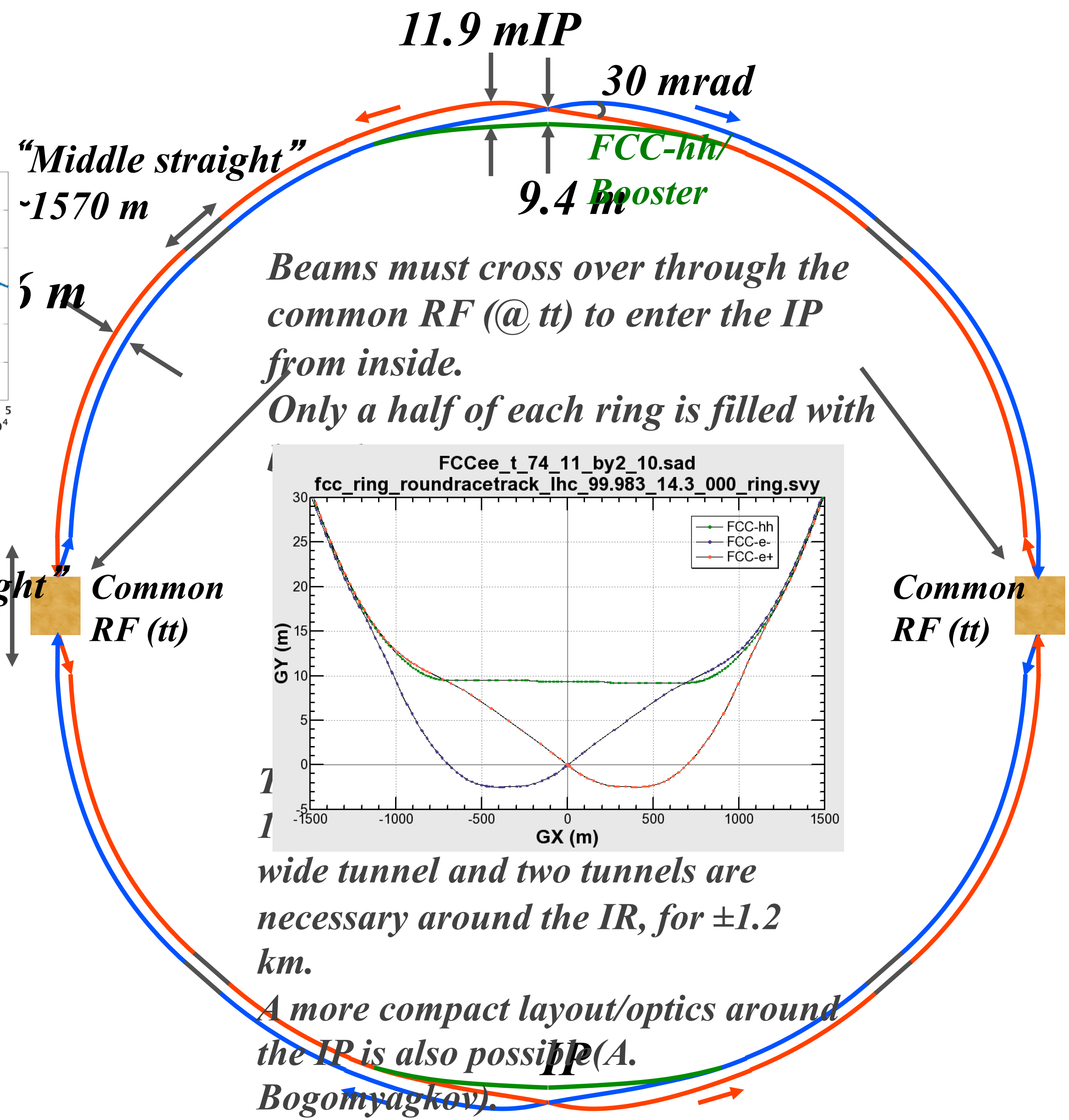
Goal of phase 1: CDR by end 2018 for next update of European Strategy Group

FCC International Collaboration

- **74 institutes**
- **26 countries + EC**

Status: April, 2016





Beams must cross over through the common RF (@ tt) to enter the IP from inside.

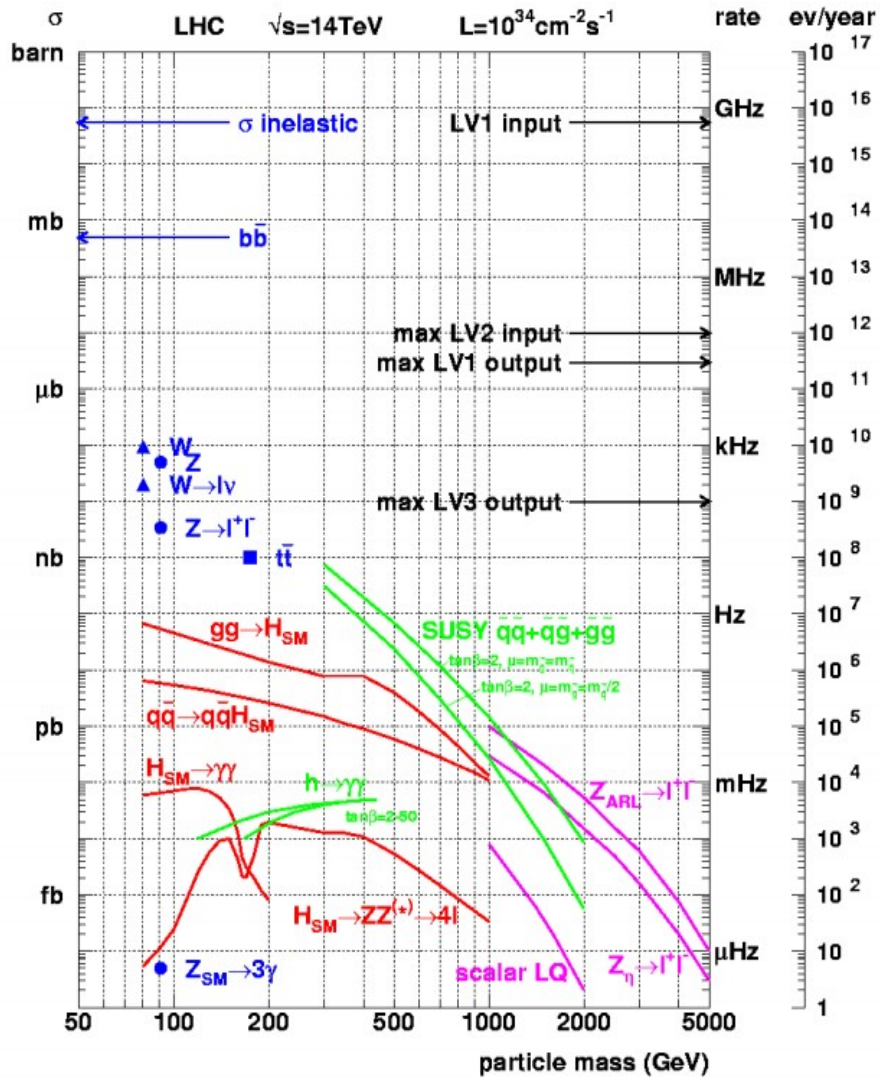
Only a half of each ring is filled with

wide tunnel and two tunnels are necessary around the IR, for ±1.2 km.

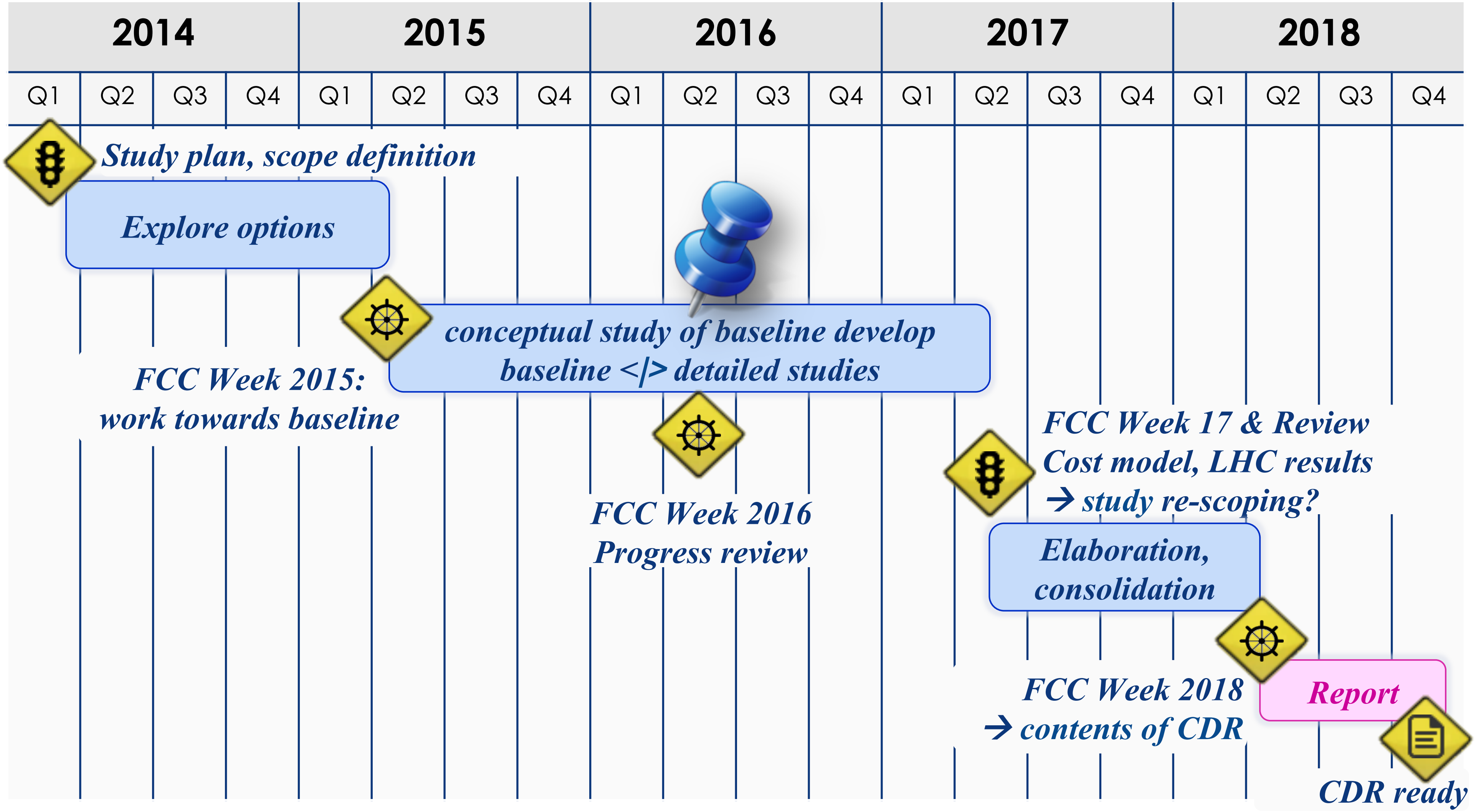
A more compact layout/optics around the IP is also possible (A. Bogomyagkov).

The LHC: signals much smaller than “bkg”

- **General event properties**
- **Heavy flavor physics**
- **Standard Model physics**
  - **QCD jets**
  - **EWK physics**
  - **Top quark**
- **Higgs physics**
- **Searches for SUSY**
- **Searches for ‘exotica’**



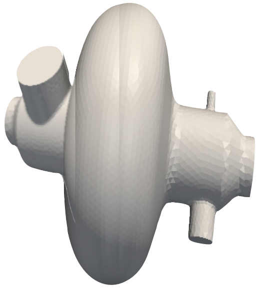
CDR Study Time Line



RF system R&D lines

400 MHz single-cell cavities preferred for FCC-hh and Z (few MeV/m)

low energy → high beam current → low HOM cavities



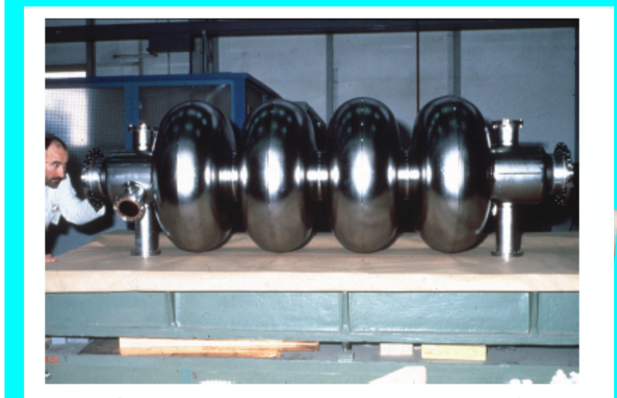
hh
≈ 16 cells per beam

Z
≈ 100 per beam
(+ 100 for booster ring)

W
≈ 210 per beam
(+ 210 for booster ring)

400 or 800 MHz multi-cell cavities preferred for H, top and W

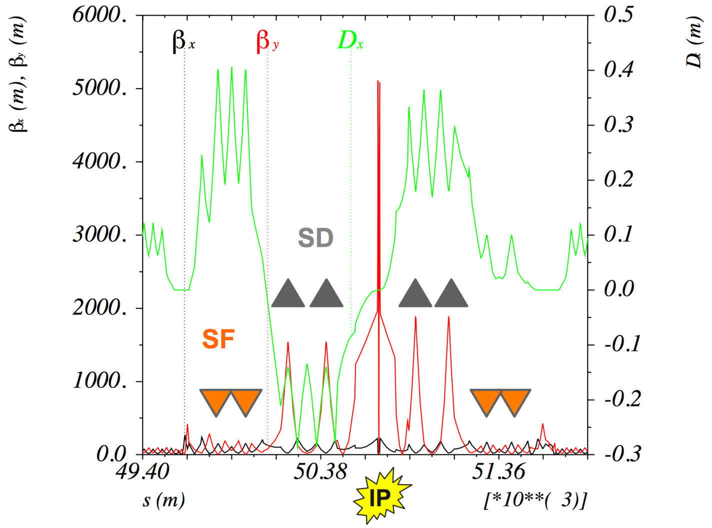
high energy → low beam current → high losses → RF-high voltage

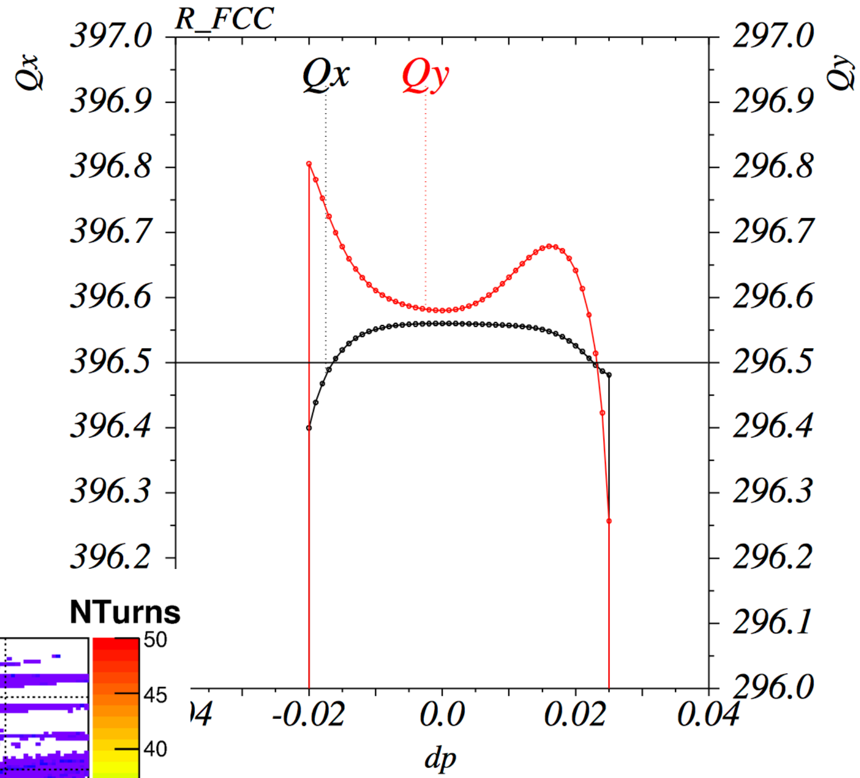


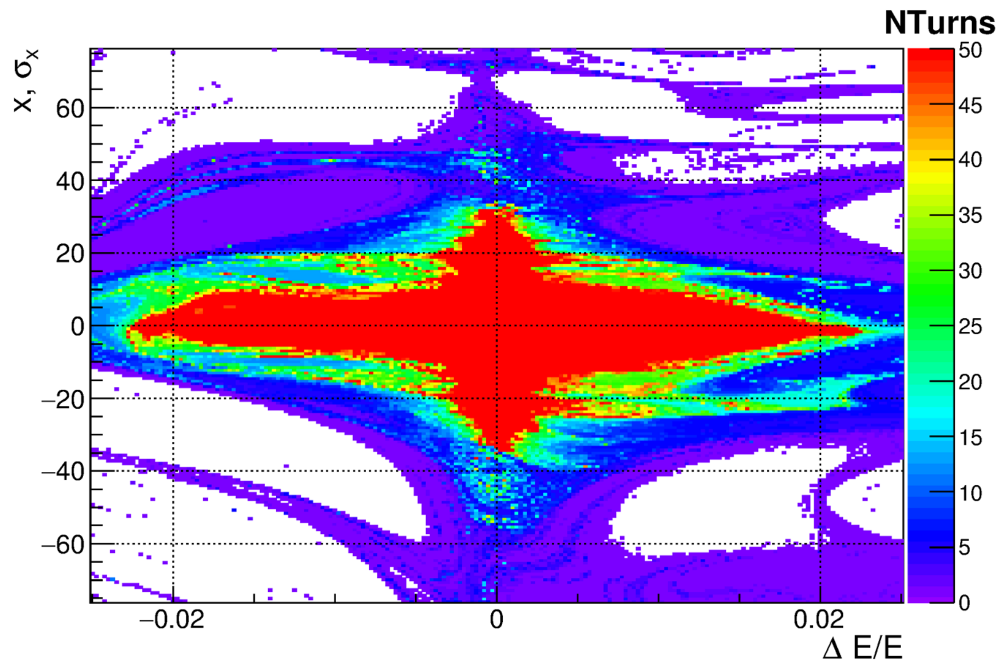
W
≈ 200 per beam
(+ 200 for booster)

H
≈ 800 per beam
(+ 800 for booster)

t
≈ common 2600 cells for both beams
(+ 2600 for booster)


βx (m), βy (m)
Dx (m)
βx
βy
Dx
SD
SF
IP
6000.
5000.
4000.
3000.
2000.
1000.
0.0
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
49.40
50.38
51.36
s (m)
[*10**(3)]


R_FCC
Qx
Qy
397.0
396.9
396.8
396.7
396.6
396.5
396.4
396.3
396.2
297.0
296.9
296.8
296.7
296.6
296.5
296.4
296.3
296.2
296.1
296.0
-0.02
0.0
0.02
0.04
dp


NTurns
x, σx
60
40
20
0
−20
−40
−60
−0.02
0
0.02
Δ E/E
50
45
40
35
30
25
20
15
10
5
0