Accelerators - 2

Frank Zimmermann

2015 CERN-Fermilab HCP Summer School

3 July 2015

gratefully acknowledging input
from Michael Benedikt & Johannes Gutleber

*Work supported by the **European Commission** under Capacities 7th Framework Programme project EuCARD-2, Grant Agreement 312453, and the HORIZON 2020 project EuroCirCol, Grant Agreement 654305*

Photo: courtesy J. Wenninger

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!

Hadron collider motivation: pushing the energy frontier

- A very large circular hadron collider seems the only approach to reach 100 TeV c.m. range in coming decades
- Access to new particles (direct production) in the few TeV to 30 TeV mass range, far beyond LHC reach.
- Much-increased rates for phenomena in the sub-TeV mass range →increased precision w.r.t. LHC and possibly ILC

M. Mangano

The name of the game of a hadron collider is energy reach

$$\boxed{E \propto B_{dipole} \times \rho_{bending}}$$

Cf. LHC: factor ~4 in radius, factor ~2 in field → O(10) in E_{cms}

Strategic Motivation

- **European Strategy for Particle Physics 2013:**

  “…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines…..”

- **ICFA statement 2014:**

  ”…. ICFA supports studies of energy frontier circular colliders and encourages global coordination…..”

- **US P5 recommendation 2014:**

  ”….A very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window….”

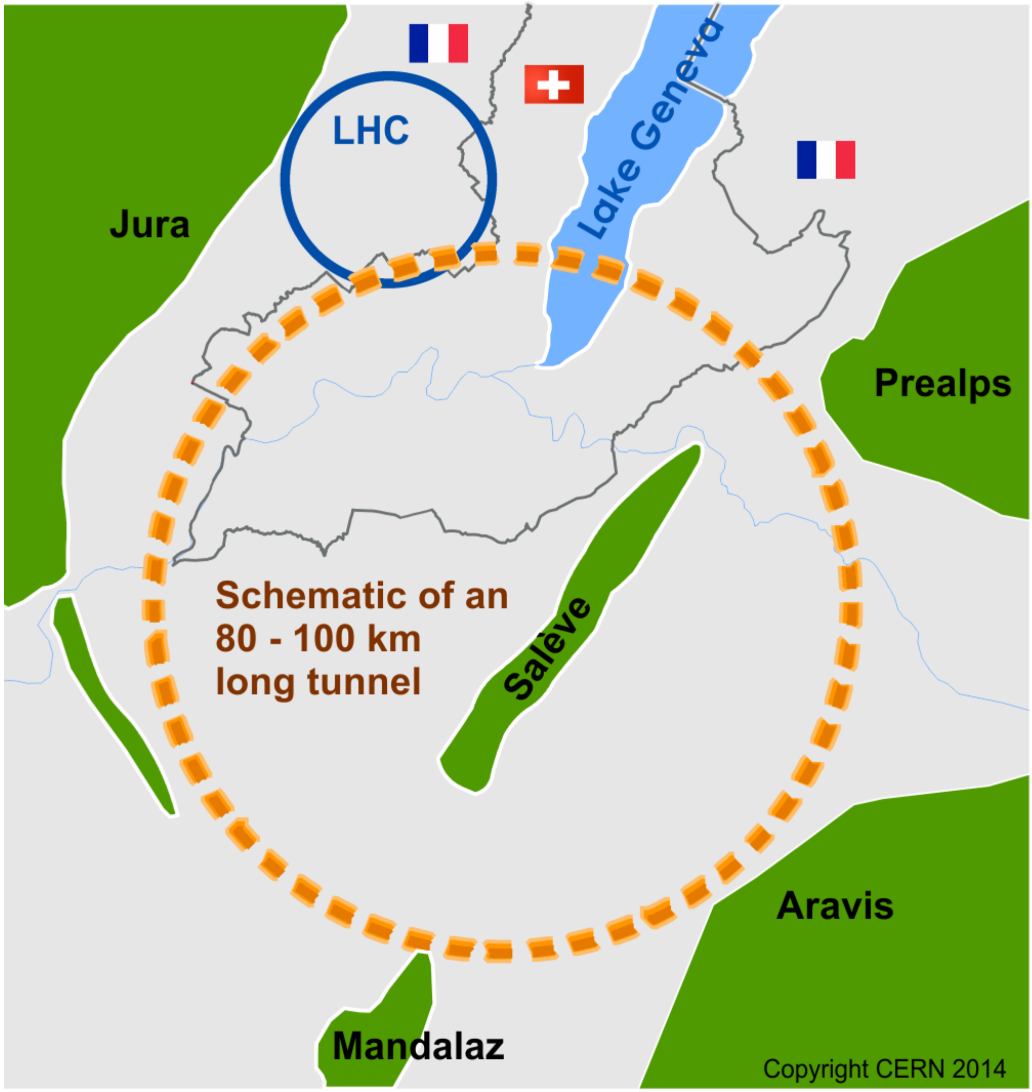
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration to study:

- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure

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

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



CepC/SppC study (CAS-IHEP) 50-70 km

e^+e^- collisions ~2028; *pp* collisions ~2042

easy access

300 km from Beijing

3 h by car

1 h by train

"Chinese Toscana"

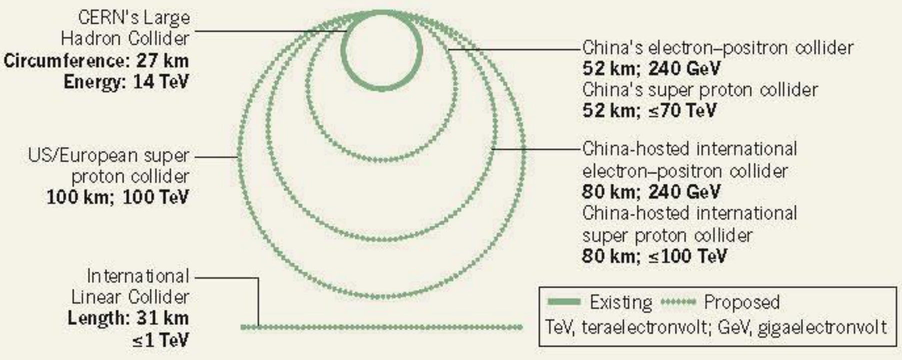
Yifang Wang

CepC/SppC project – recent news in *Nature*

24 JULY 2014 | VOL 511 | NATURE | 3

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.

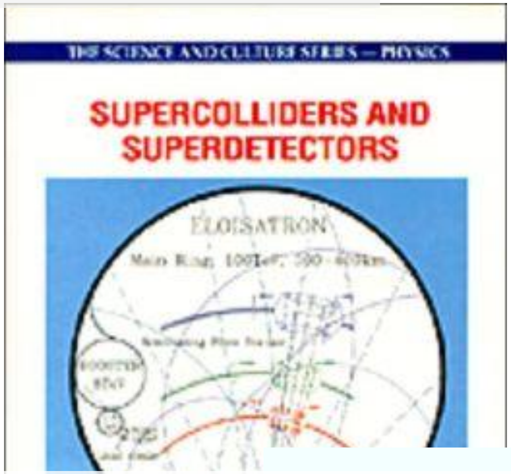
European and US teams have both shown interest in building their own super collider (see *Nature* **503**, 177; 2013), but the huge amount of research needed before such a machine could be built means that the earliest date either can aim for is 2035. China would like to build its electron–positron collider 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 300km), USA (SSC 87km, VLHC 233km), Japan (TRISTAN-II 94km)

ex. ELOISATRON

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



THE SCIENCE AND CULTURE SERIES — PHYSICS

SUPERCOLLIDERS AND SUPERDETECTORS

ex. SSC

C.T. Murphy

SSC-SR-2020

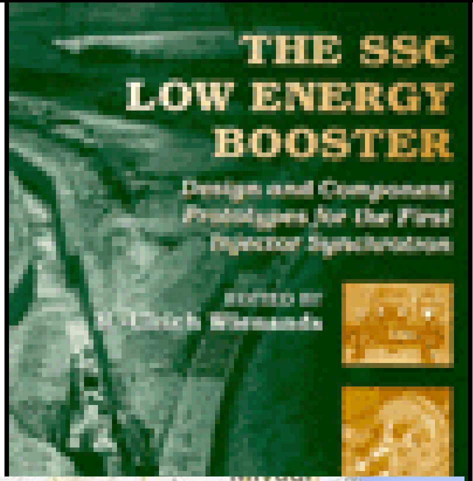
Conceptual Design of the Superconducting Super Collider

SSC Central Design Group*

March 1986

*Operated by Universities Research Associatio

SSC CDR 1986



THE SSC LOW ENERGY BOOSTER

ex. TRISTAN II

F. Takasaki

many aspects of machine design and R&D non-site specific.
→ exploit synergies with other projects and previous studies

ex. VLHC

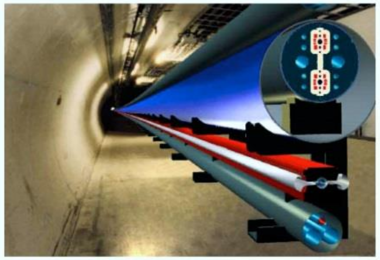
VLHC Design Study Group Collaboration
June 2001. 271 pp.
SLAC-R-591, SLAC-R-0591, SLAC-591, SLAC-0591, FERMILAB-TM-2149

Very Large Hadron Collider

Fermilab-TM-2149
June 2001

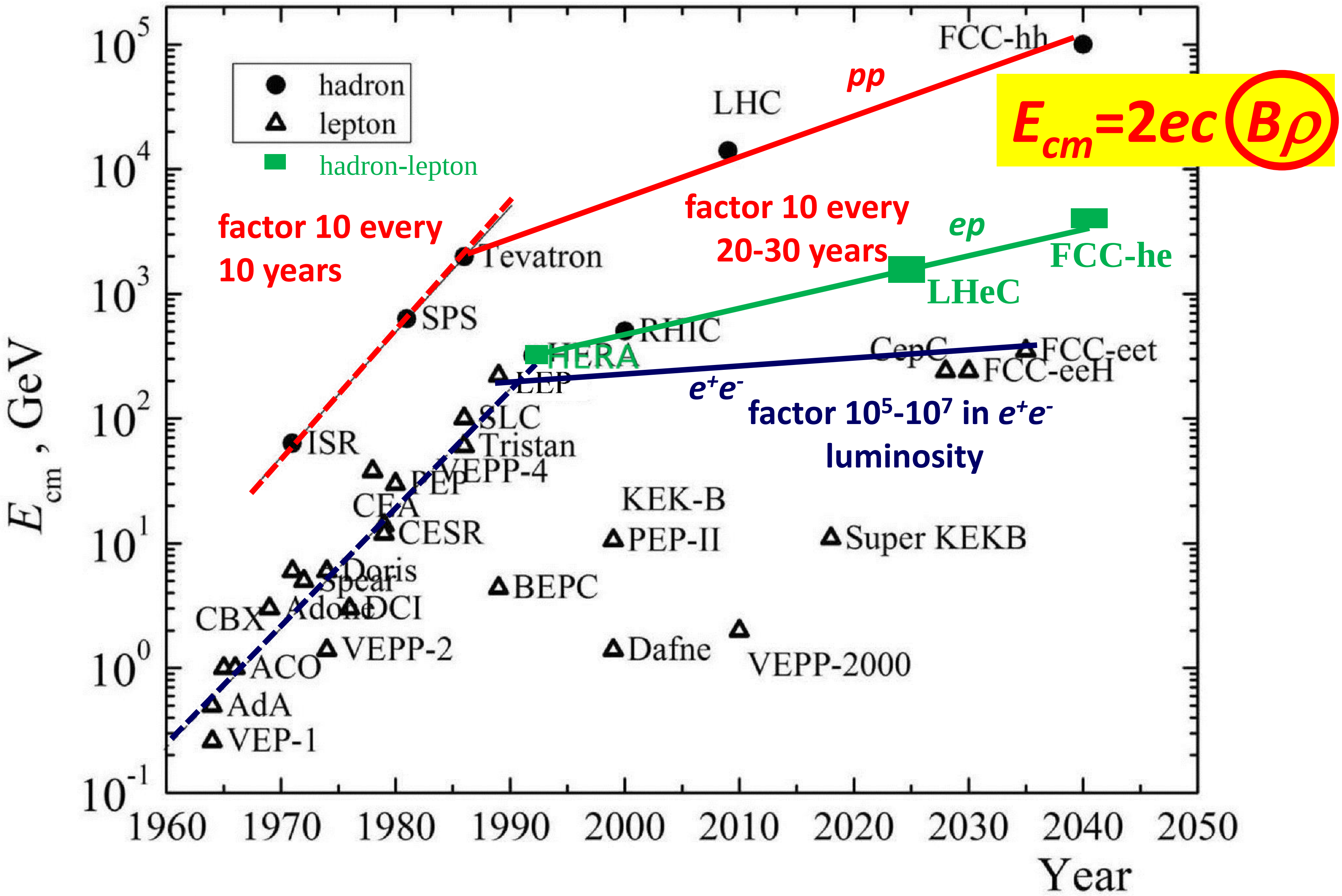
Design Study for a Staged Very Large Hadron Collider

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



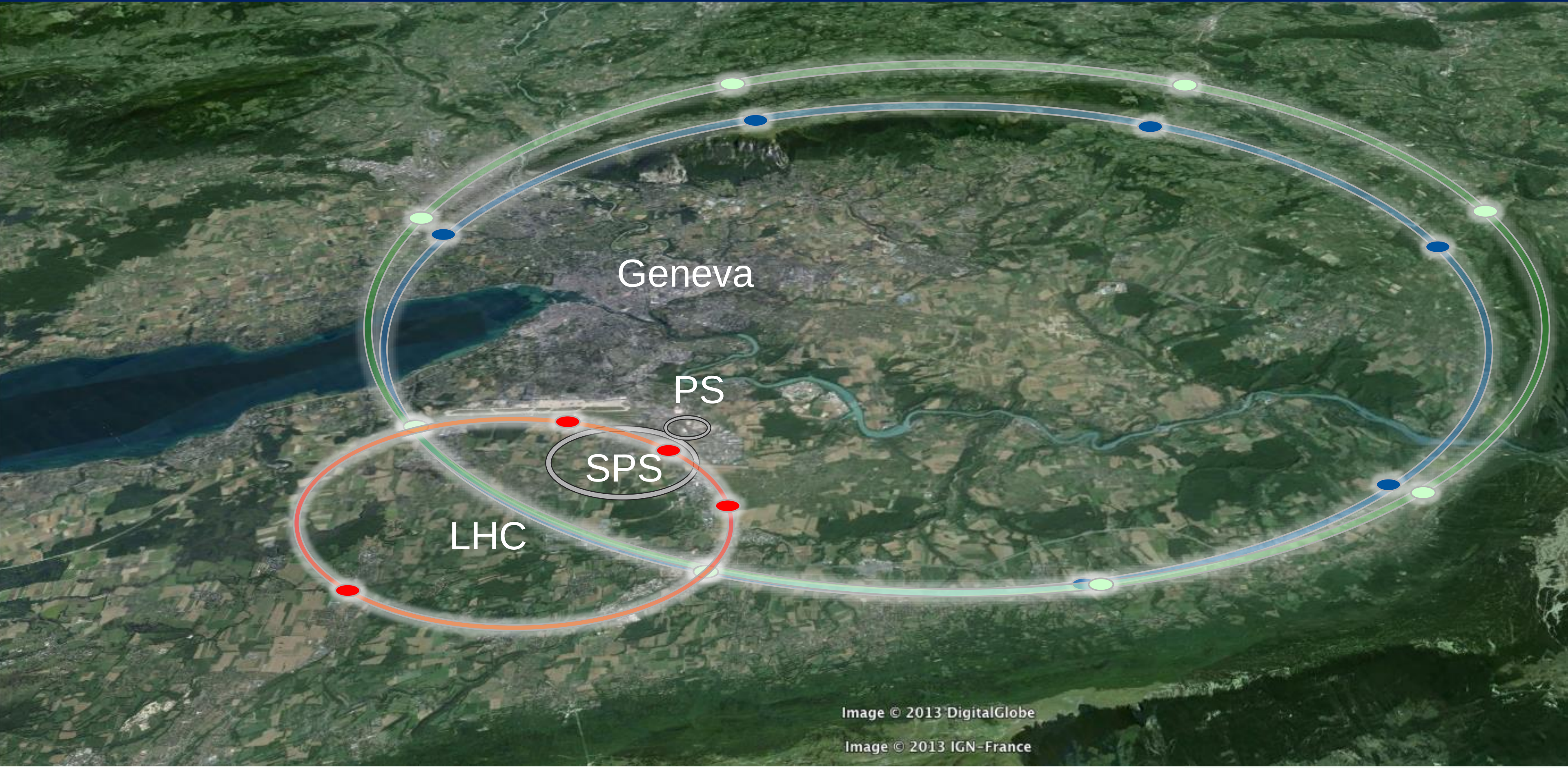
http://www.vlhc.org/

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

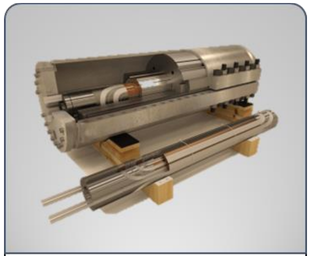
key challenges for FCC-hh/SppC

- High energy
  - ⇒ **High field superconducting magnets**
  - ⇒ **Large tunnel infrastructures**
- High luminosity
  - ⇒ Beam optics
  - ⇒ Beam current
  - ⇒ **Synchrotron radiation to SC magnets**
  - ⇒ **IR shielding** and component lifetime
- High stored beam energy
  - ⇒ **Machine protection**
  - ⇒ Beam handling
  - ⇒ **Beam injection and beam dumping**

FCC Study Scope: Accelerator and Infrastructure

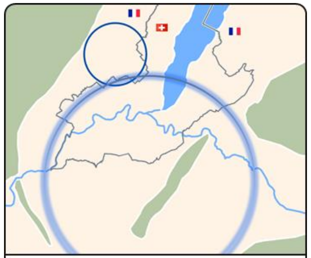
Collider Designs

FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e$^+$e$^-$ collider**, potential intermediate step
FCC-he: **integration aspects** of pe collisions



R&D Programs

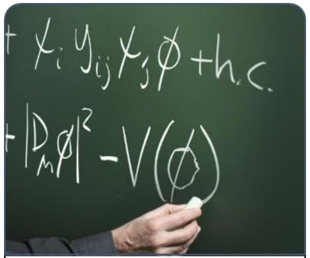
Push key technologies
in dedicated R&D programmes e.g.
16 Tesla magnets for **100 TeV** pp in **100 km**
SRF technologies and RF power sources



Infrastructures

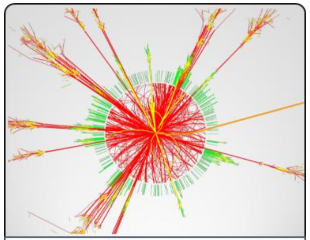
Tunnel infrastructure in Geneva area, linked to CERN accelerator complex
Site-specific, requested by European strategy

FCC Scope: Physics & Experiments



Physics Cases

Elaborate and document
- Physics opportunities
- Discovery potentials



Experiments

Experiment concepts for hh, ee and he
Machine Detector Interface studies
Concepts for worldwide data services

Cost Estimates

Overall cost model
Cost scenarios for collider options
Including infrastructure and injectors
Implementation and governance models

FCC-hh parameters

parameter	FCC-hh		LHC	HL LHC
energy cms [TeV]	100		14	
dipole field [T]	16		8.3	
# IP	2 main & 2		2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	20	1	5
events/bx	170	680 (136)	27	135
stored energy/beam [GJ]	8.4		0.36	0.7
synchr. rad. [W/m/apert.]	30		0.2	0.35

FCC-hh preliminary layout

100 km layout for FCC-hh (different sizes under investigation)

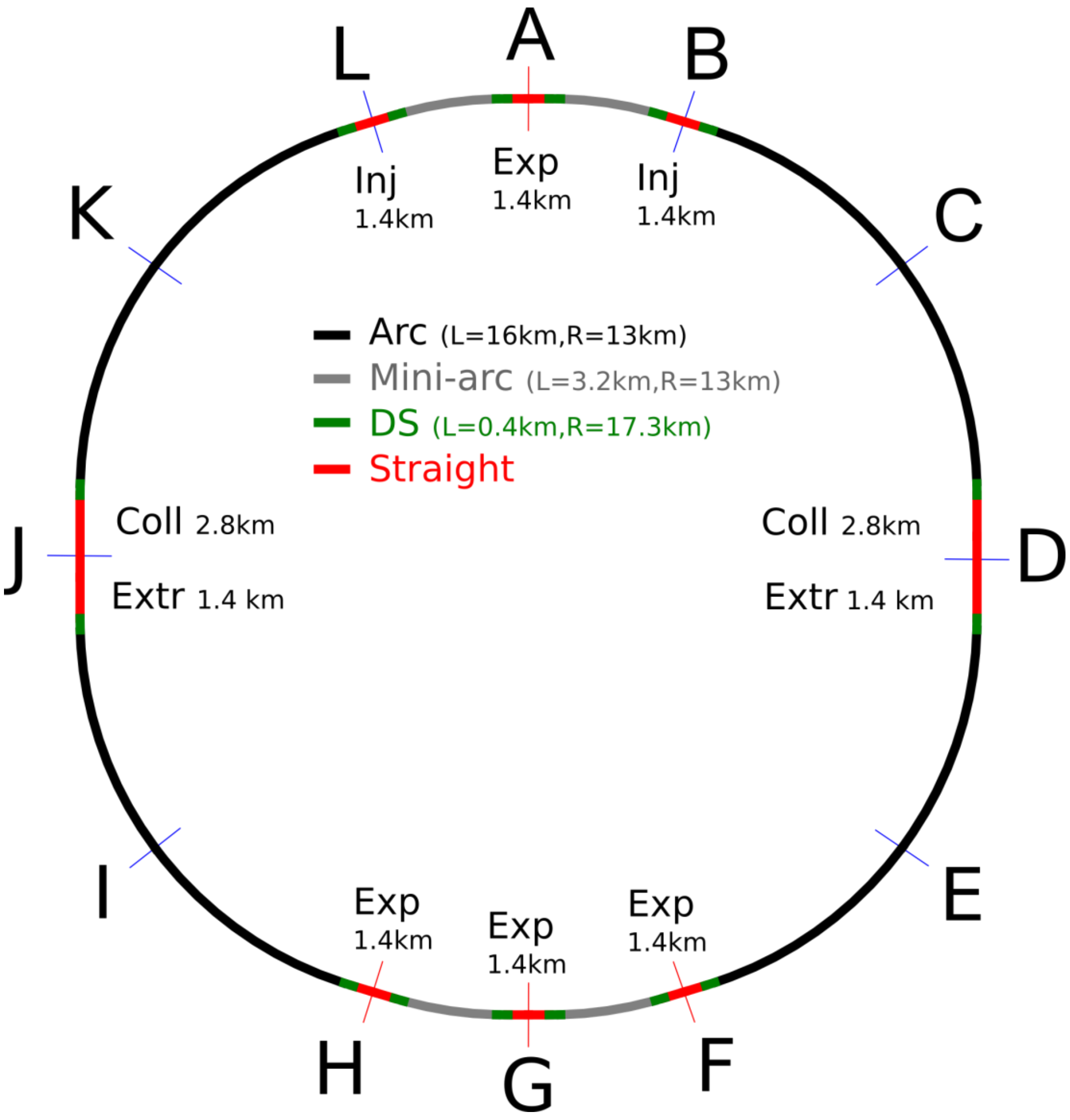
⇒ two high-luminosity experiments (A and G)

⇒ two other experiments (F and H)

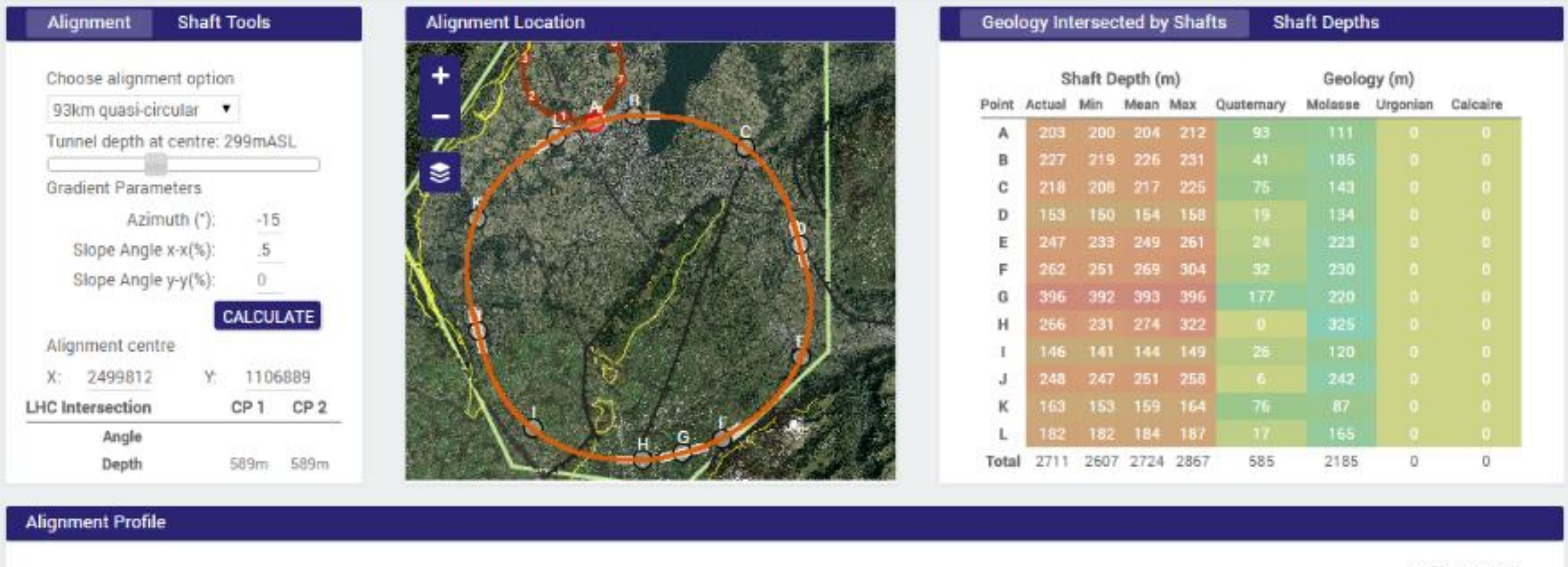
⇒ two collimation straights

⇒ two injection and two extraction straights

orthogonal functions for each insertion section



Site study 93 km example



Choose alignment option: 93km quasi-circular

Tunnel depth at centre: 299mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .5

Slope Angle y-y(%): 0

Alignment centre

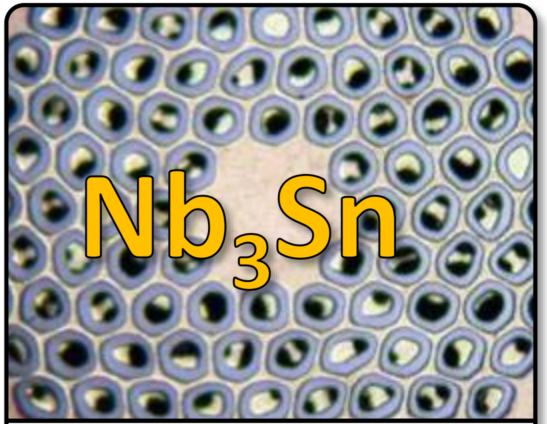
X: 2499812 Y: 1106889

LHC Intersection	CP 1	CP 2
Angle		
Depth	589m	589m

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	203	200	204	212	93	111	0	0
B	227	219	226	231	41	185	0	0
C	218	208	217	225	75	143	0	0
D	153	150	154	158	19	134	0	0
E	247	233	249	261	24	223	0	0
F	262	251	269	304	32	230	0	0
G	396	392	393	396	177	220	0	0
H	266	231	274	322	0	325	0	0
I	146	141	144	149	26	120	0	0
J	248	247	251	258	6	242	0	0
K	163	153	159	164	76	87	0	0
L	182	182	184	187	17	165	0	0
Total	2711	2607	2724	2867	585	2185	0	0

- 90 – 100 km fits geological situation well
- LHC suitable as potential injector

Key Technology R&D - HFM



Conductor R&D

- Increase critical current density
- Obtain high quantities at required quality
- Material Processing
- Reduce cost

Magnet Design

- Develop 16T short models
- Field quality and aperture
- Optimum coil geometry
- Manufacturing aspects
- Cost optimisation

FCC Magnet Technology Program

Main Milestones of the FCC Magnets Technologies

Milestone	Description	15	2016		2017		2018		2019		2020		21
M0	Supporting wound conductor program	■	■	■	■	■	■	■	■	■	■	■	■
M1	Design of an RMM with existing wire	■	■	■									
M2	Manufacture and test of a first 16T RMM			■	■	■							
M3	Procurement 35 km state of the art high J_c wire	■	■	■	■								
M4	Design of a 16T demonstrator with above wire			■	■	■							
M5	Manufacture and test of the 16T demonstrator					■	■	■					
M6	Procurement 70 km of enhanced high J_c wire				■	■	■	■	■				
M7	EuroCirCol design 16T accelerator quality model	■	■	■	■	■	■	■	■				
	Manufacture and test of the EuroCirCol model									■	■	■	■

FCC-hh: some design challenges

stored beam energy: 8 GJ/beam (0.4 GJ LHC) = 16 GJ total

➔ equivalent to an Airbus A380 (560 t) at full speed (850 km/h)

- **collimation, beam loss control, radiation effects: important**
- **injection/dumping/beam transfer: critical operations**
- **magnet/machine protection: to be considered early on**

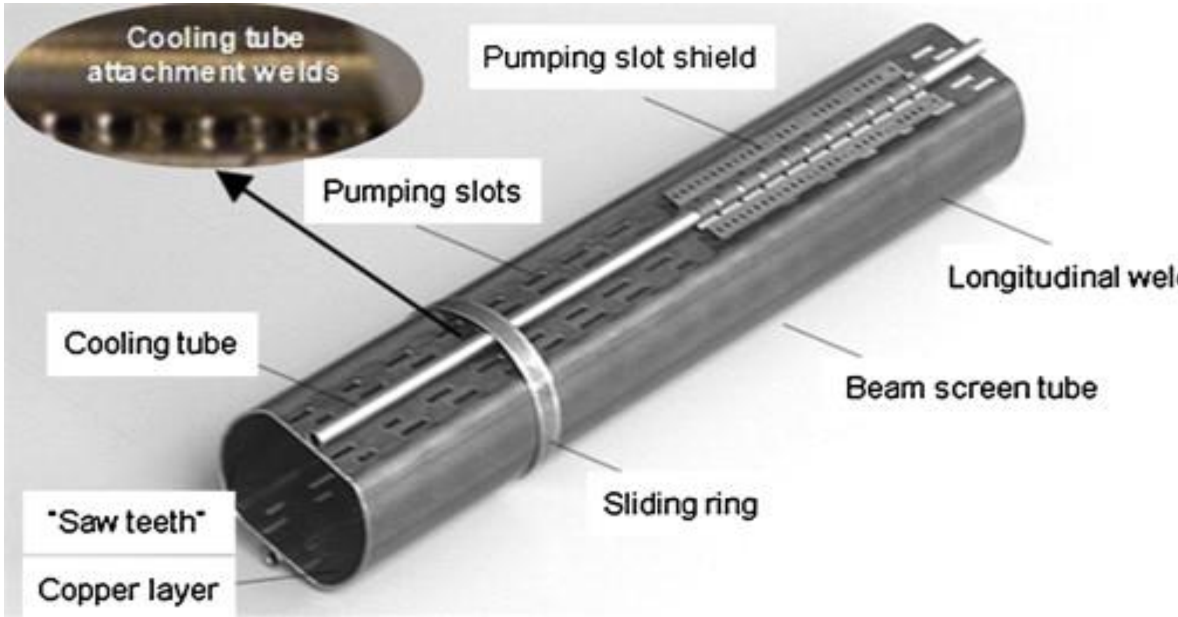
Synchrotron radiation/beam screen

high synchrotron radiation load (SR) of protons @ 50 TeV:

~30 W/m/beam (@16 T)

→ **5 MW total in arcs**

→ (LHC <0.2W/m)

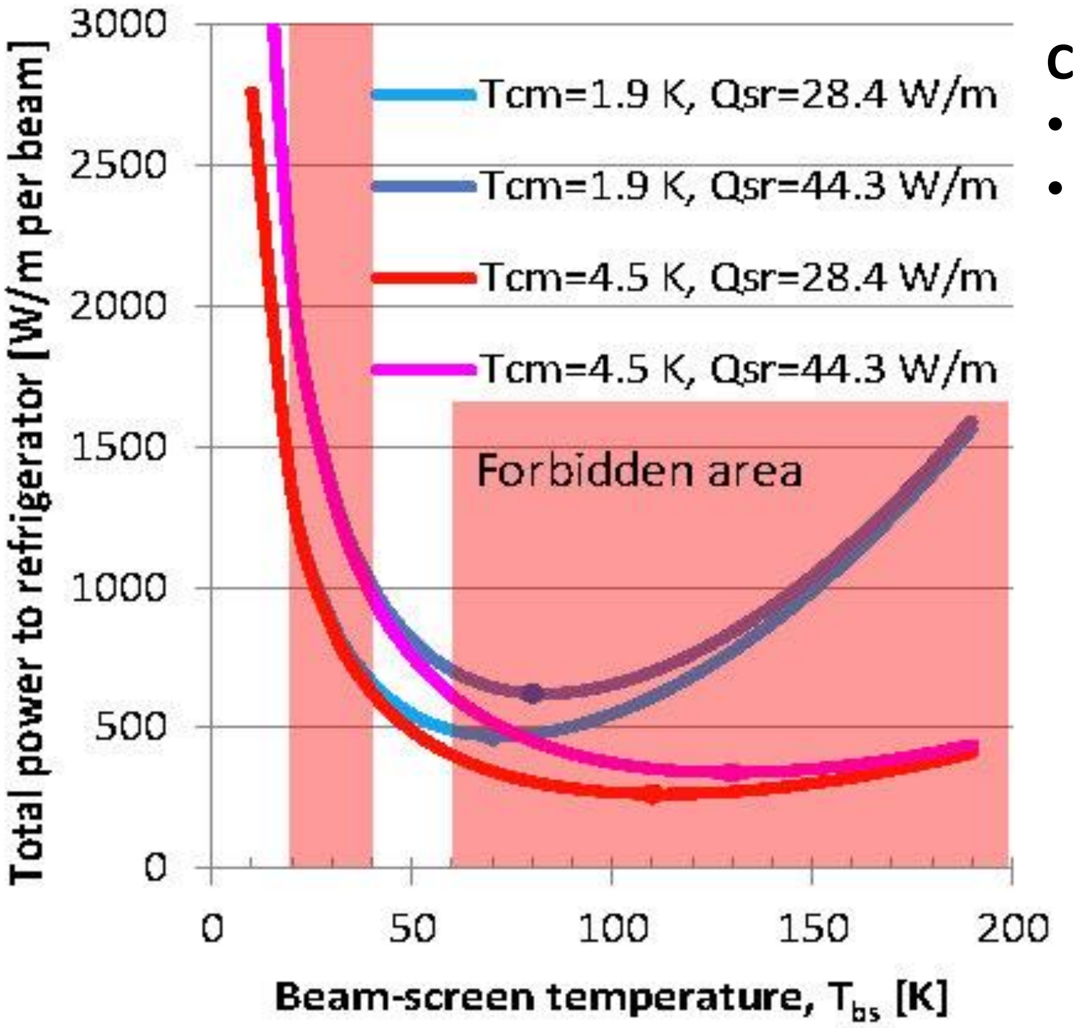


- **beam screen to capture SR and "protect" cold mass**
- **power mostly cooled at beam screen temperature**
- **only fraction reaches magnets at 2 – 4 K**

→ optimization of temperature, space, vacuum, impedance, e-cloud, etc.

D. Schulte

cryo power for cooling of SR heat



Contributions to cryo load:

- beam screen (BS) &
- cold bore (BS heat radiation)

At 1.9 K cm optimum BS temperature range: 50-100 K; but impedance increases with temperature → instabilities

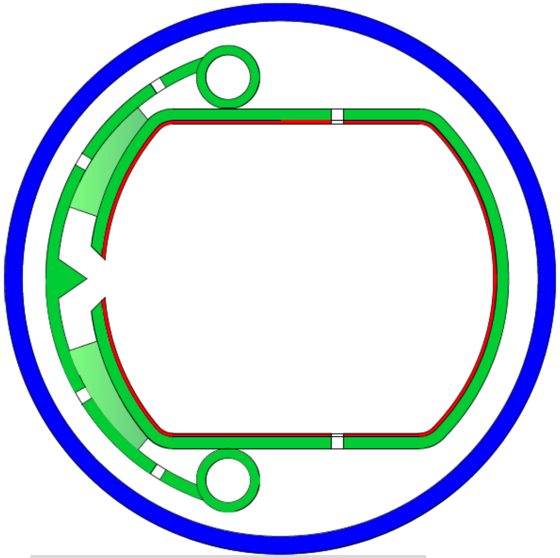
40-60 K favoured by vacuum & impedance considerations

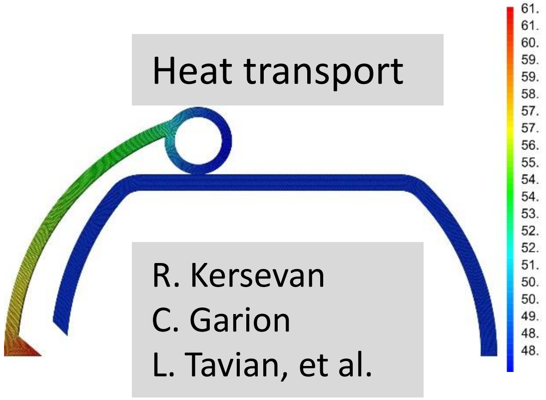
→ 100 MW refrigerator power on cryo plant

At 4.5 K cold bore, one could potentially increase beam-screen temperature and lower refrigerator power to 50 MW.

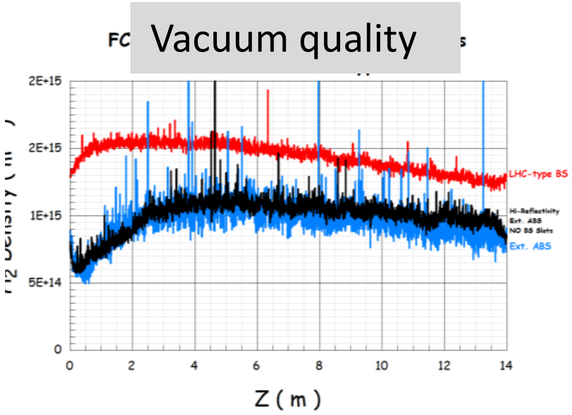
P. Lebrun, L. Tavian

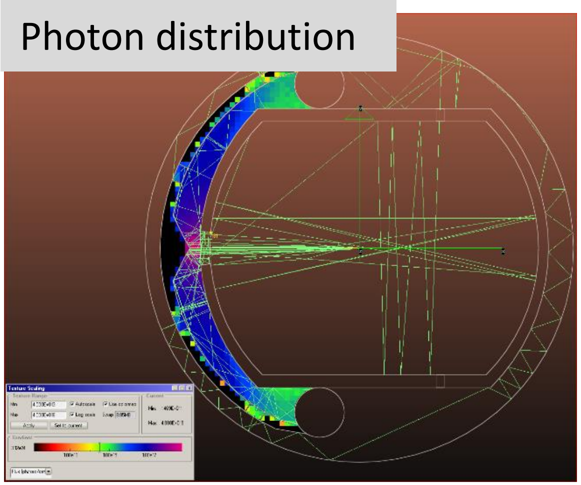
novel beam screen - design example




Heat transport

R. Kersevan
C. Garion
L. Tavian, et al.


Vacuum quality

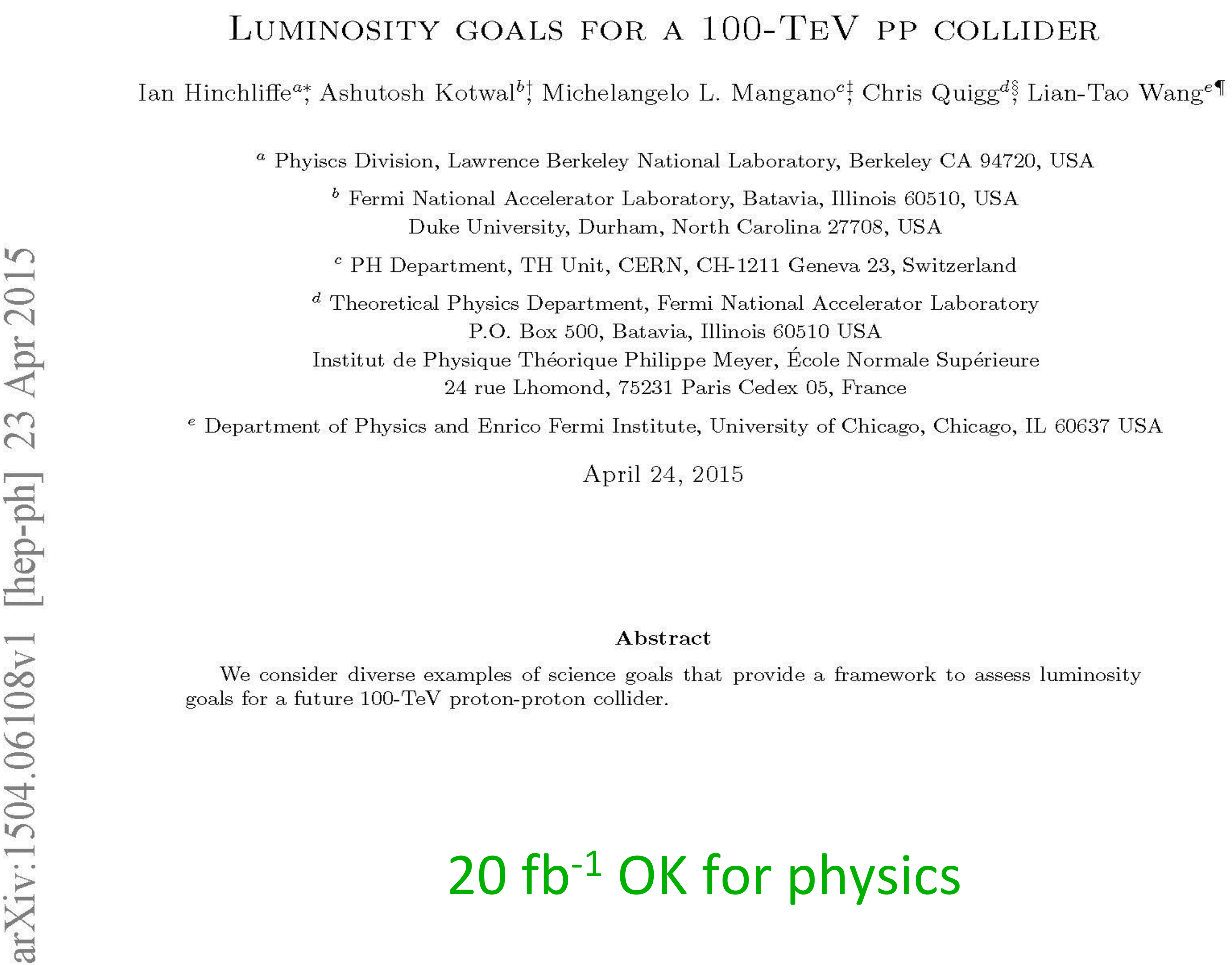

Photon distribution

New type of ante-chamber

- Absorption of synchrotron radiation
- Avoid photo-electrons
- Help beam vacuum

FCC-hh luminosity goals & phases

- **Two parameter sets for two operation phases:**
  - **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
    250 fb^{-1}/year (averaged)
    2500 fb^{-1} within 10 years (~HL LHC total luminosity)
  - **Phase 2 (ultimate): ≈2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
    1000 fb^{-1}/year (averaged)
    → 15,000 fb^{-1} within 15 years
  - **Yielding total luminosity O(20,000) fb^{-1} over ≈ 25 years of operation**



LUMINOSITY GOALS FOR A 100-TEV PP COLLIDER

Ian Hinchliffe[a*], Ashutosh Kotwal[b†], Michelangelo L. Mangano[c‡], Chris Quigg[d§], Lian-Tao Wang[e¶]

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Duke University, Durham, North Carolina 27708, USA

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Institut de Physique Théorique Philippe Meyer, École Normale Supérieure
24 rue Lhomond, 75231 Paris Cedex 05, France

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April 24, 2015

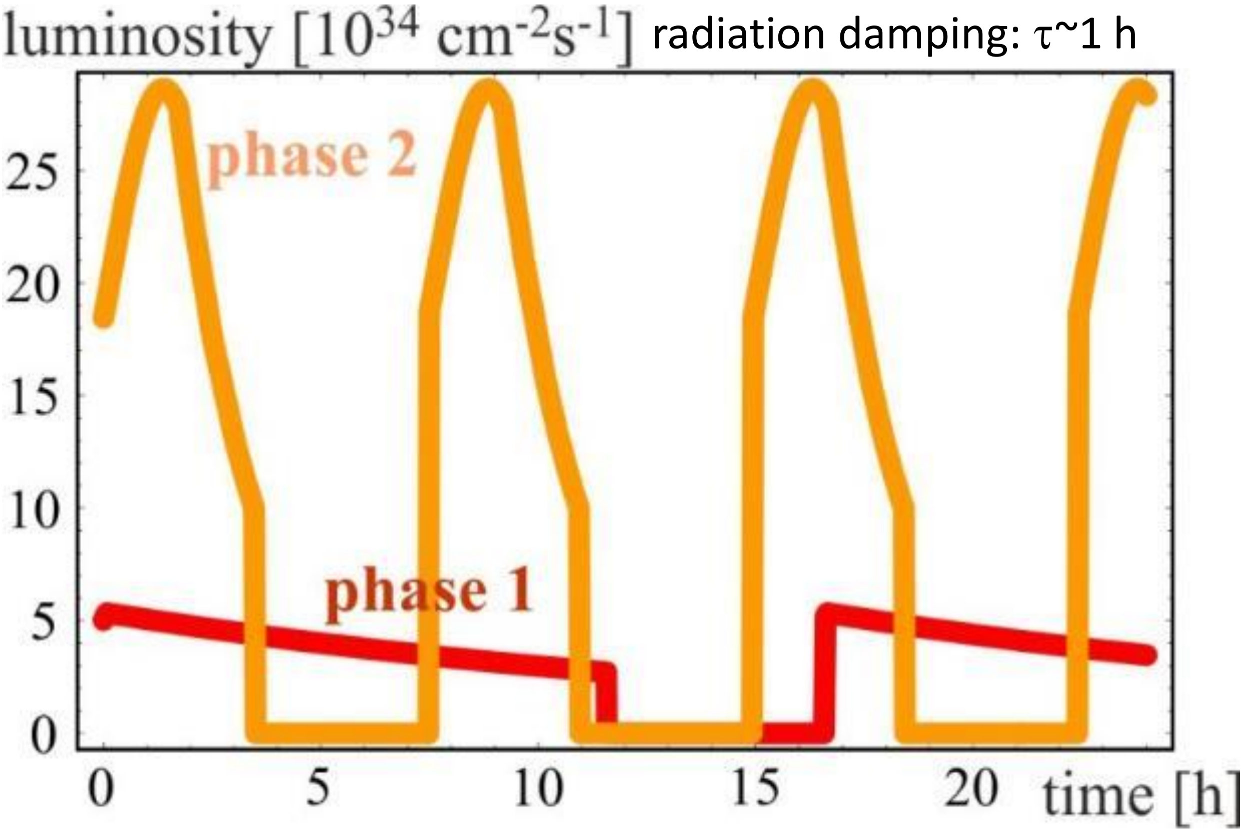
Abstract

We consider diverse examples of science goals that provide a framework to assess luminosity goals for a future 100-TeV proton-proton collider.

20 fb^{-1} OK for physics

luminosity evolution over 24 h

radiation damping: τ~1 h



for both phases:

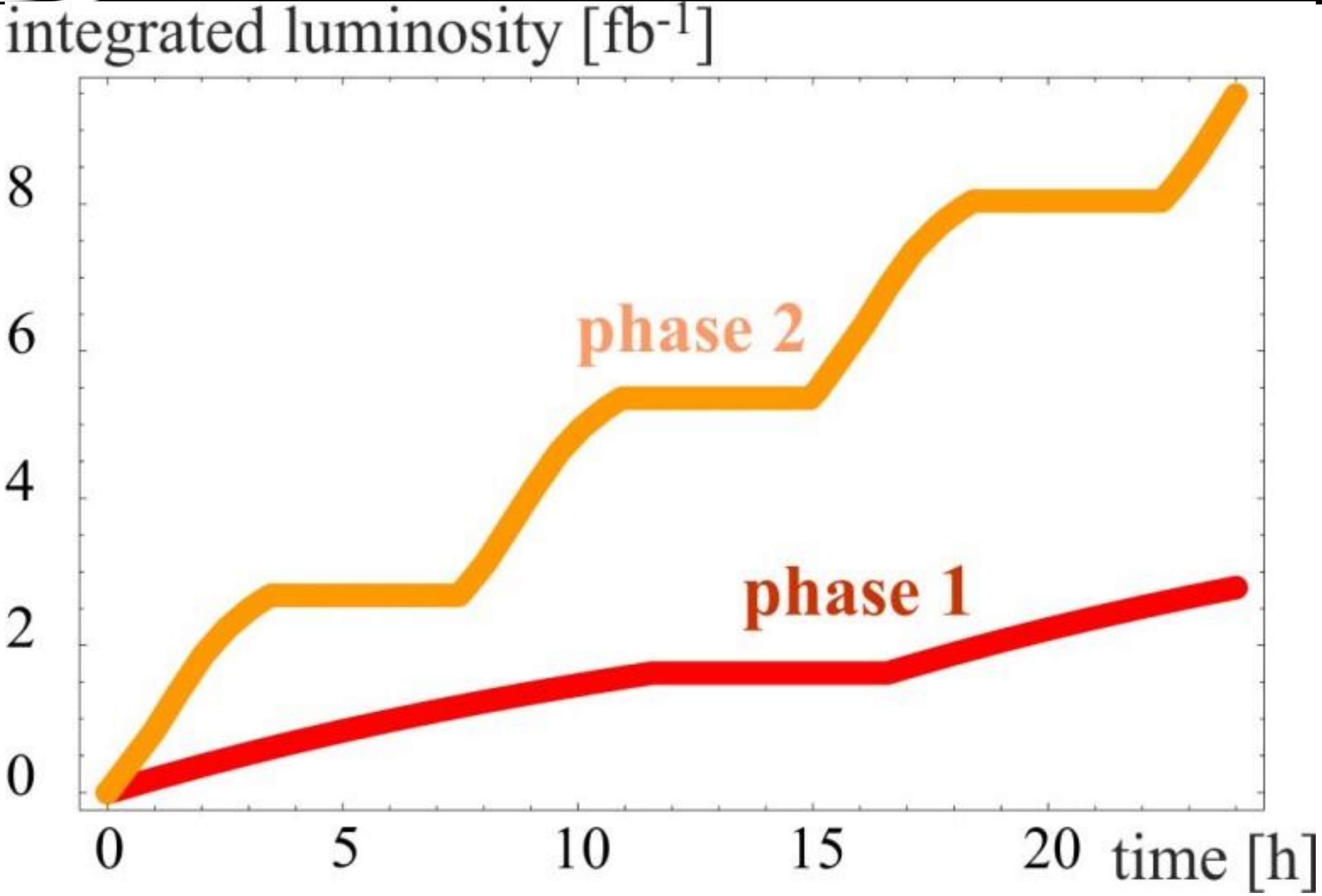
beam current 0.5 A unchanged!

total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h

phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h

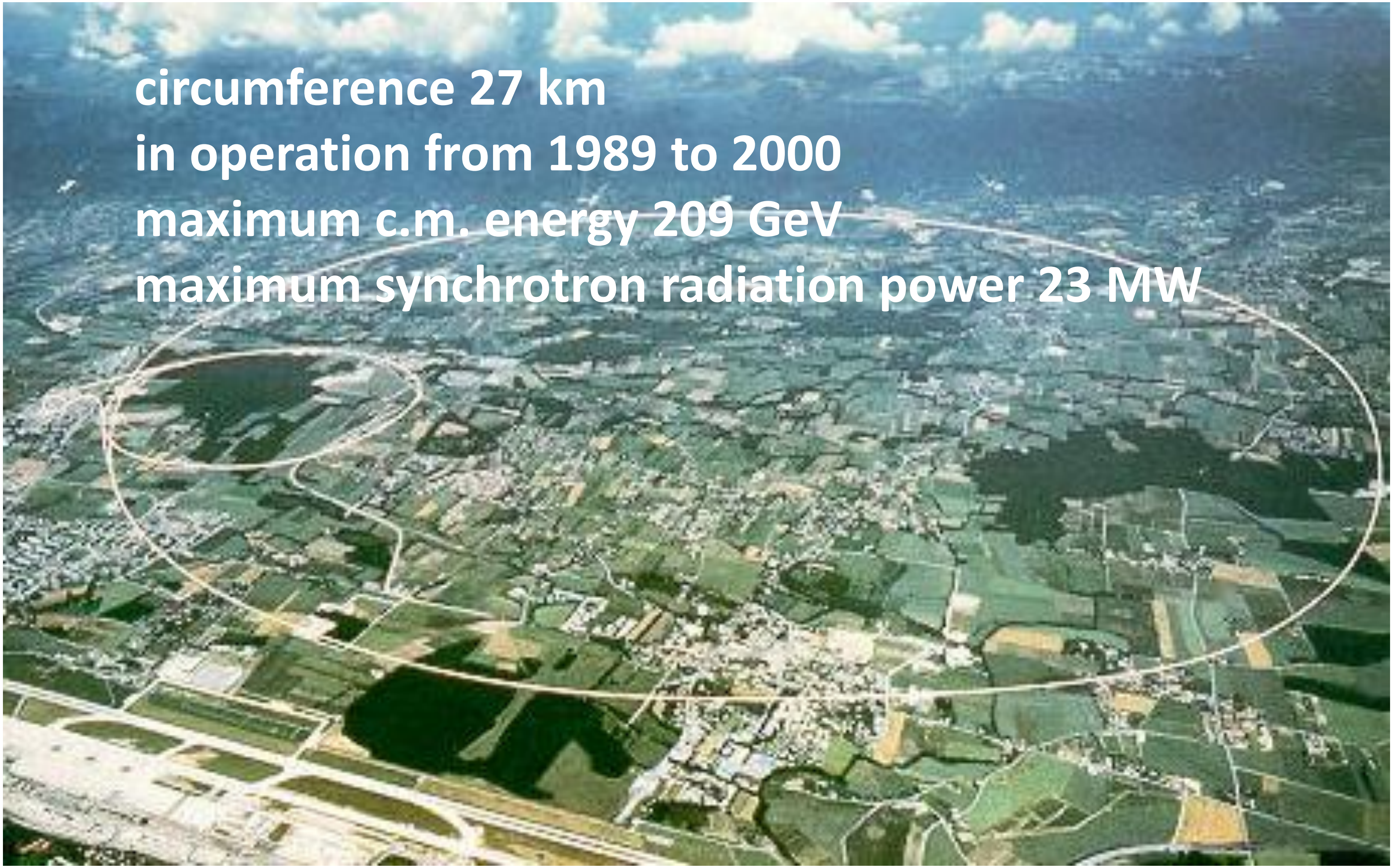
integrated luminosity / day



phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h

phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h

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



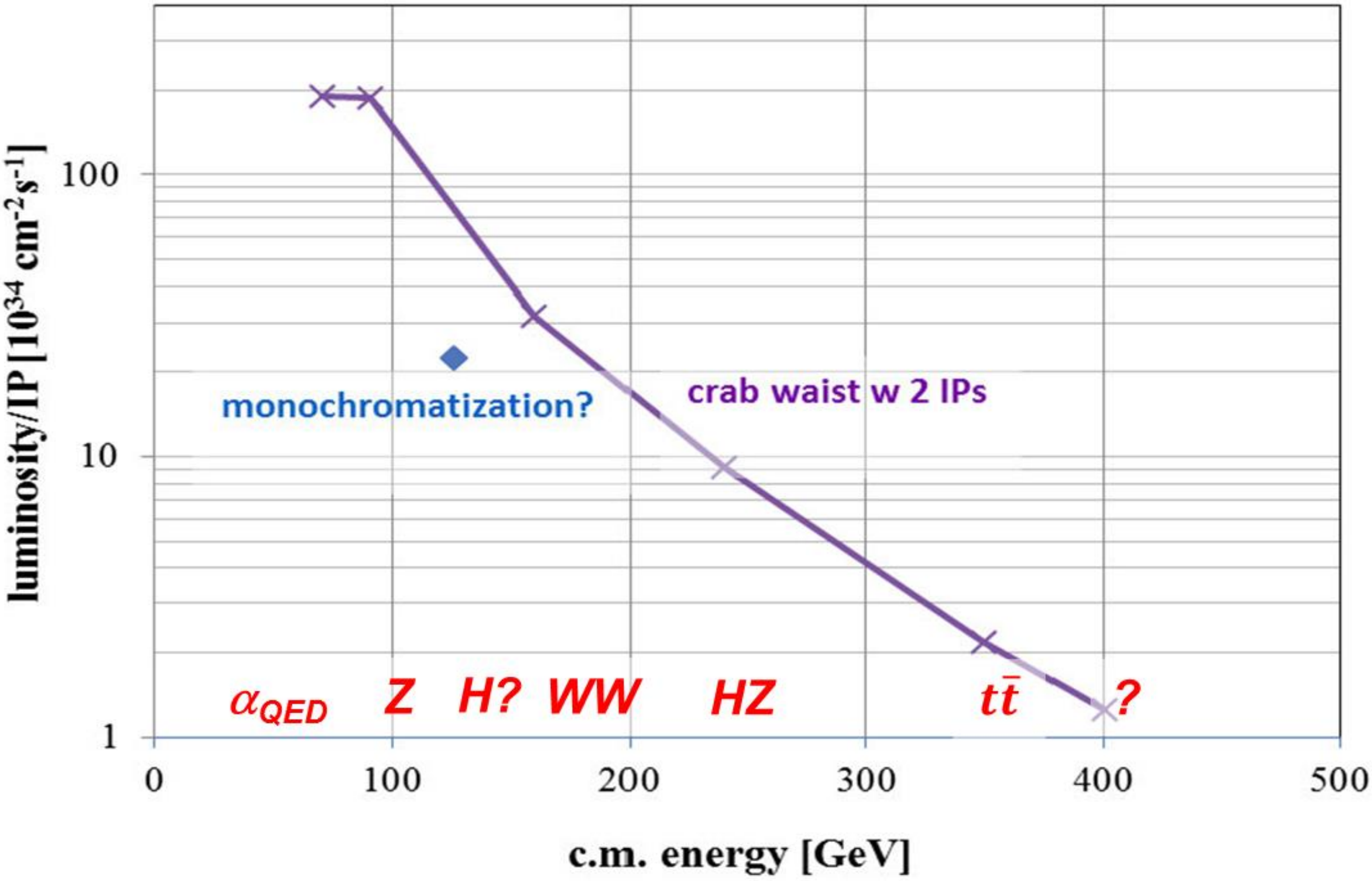
circumference 27 km
in operation from 1989 to 2000
maximum c.m. energy 209 GeV
maximum synchrotron radiation power 23 MW

physics requirements for *FCC-ee*

A. Blondel, P. Janot et al.

- ☐ highest possible luminosity
- ☐ *beam energy range from 35 GeV to ≈200 GeV*
- ☐ physics programs / energies:
  - ➢ *α_{QED} (35 GeV): running coupling constant close to the Z pole ?*
  - ➢ *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - ➢ *H (63 GeV): H production in s channel (w. mono-chromatization) ??*
  - ➢ *W (80 GeV): W pair production threshold, high precision M_W*
  - ➢ *H (120 GeV): ZH production (maximum rate of H's),*
  - ➢ *t (175 GeV): $t\bar{t}$ threshold*
  - ➢ *>175 GeV: physics?*
- ☐ some polarization up to ≥80 GeV for beam energy calibration
- ☐ optimized for operation at 120 GeV?! (2nd priority "*Tera-Z*")

luminosity vs c.m. energy



Key Parameters FCC-ee

Parameter	**FCC-ee**			**LEP2**
Energy/beam [GeV]	45	120	175	105
Bunches/beam	13000-60000	500-1400	51- 98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} cm^{-2}s^{-1}	**21 - 280**	**5 - 11**	**1.5 - 2.6**	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchrotron Power [MW]	100			22
RF Voltage [GV]	0.2-2.5	3.6-5.5	11	3.5

Dependency: crab-waist vs. baseline optics and 2 vs. 4 IPs

SC RF System

RF system requirements are characterized by two regimes.

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

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

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

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

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

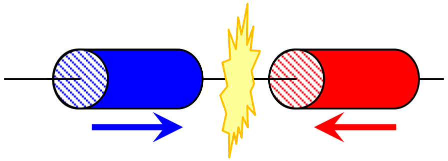
- *Nano-beam / crab waist favors lower frequency, e.g. 400 MHz.*

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

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

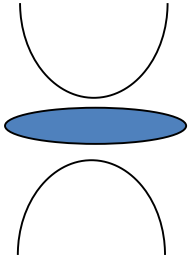
J. Wenninger, A. Butterworth, E. Jensen, et al.

luminosity scaling: larger *E* & ρ



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

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

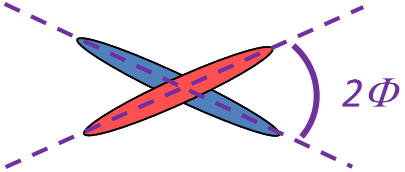


H ≤ 1

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

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

σ = beam size

k = no. bunches

f = rev. frequency

N = bunch population

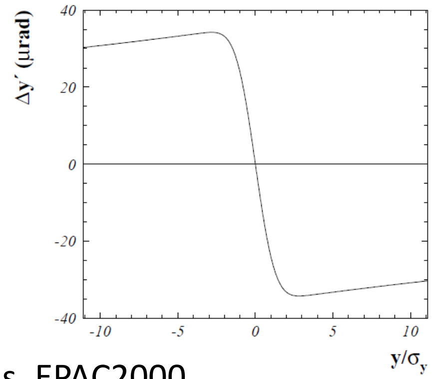
P_{SR} = synch. rad. power

β^* = betatron fct at IP

(beam envelope)

J. Wenninger

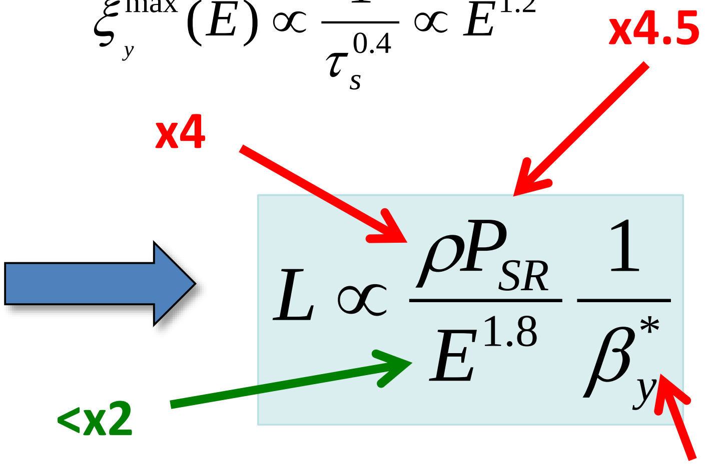
luminosity scaling: damping



- 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 (4 IPs)

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

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



FCC-ee vs LEP

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

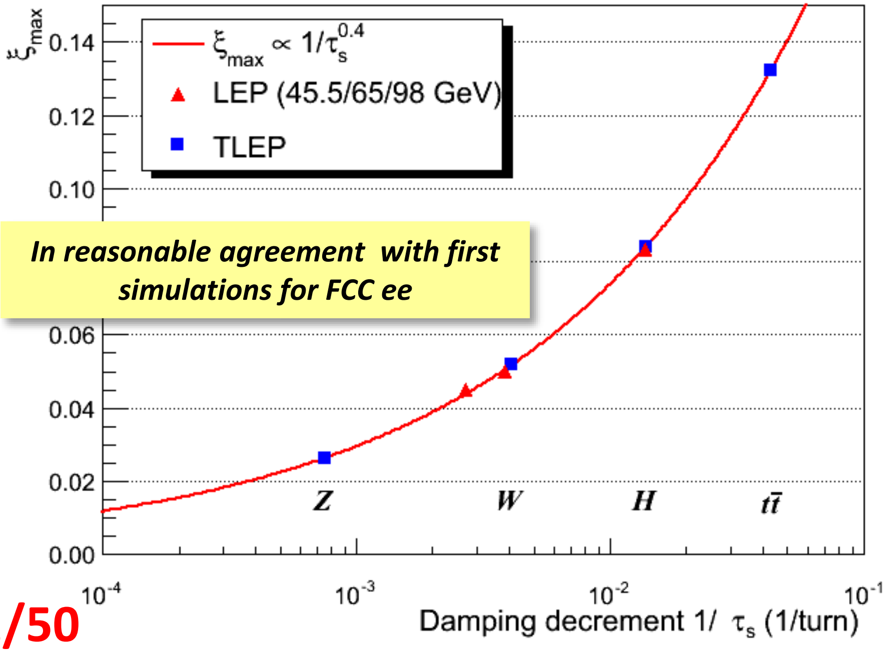
x4

x4.5

<x2

x1/50

R. Assmann & K. Cornelis, EPAC2000

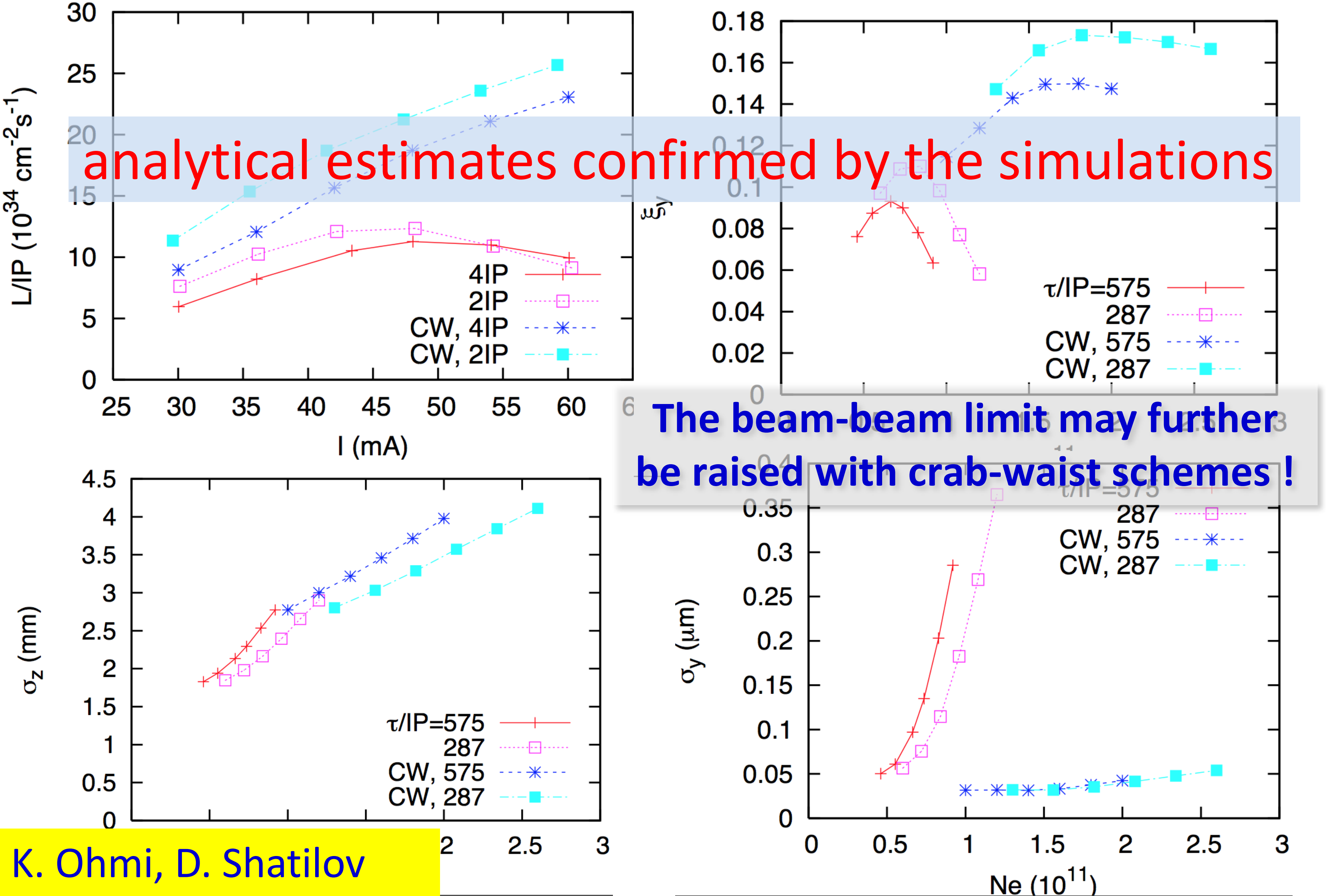


In reasonable agreement with first simulations for FCC ee

→ extremely high luminosity

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

beam-beam simulations



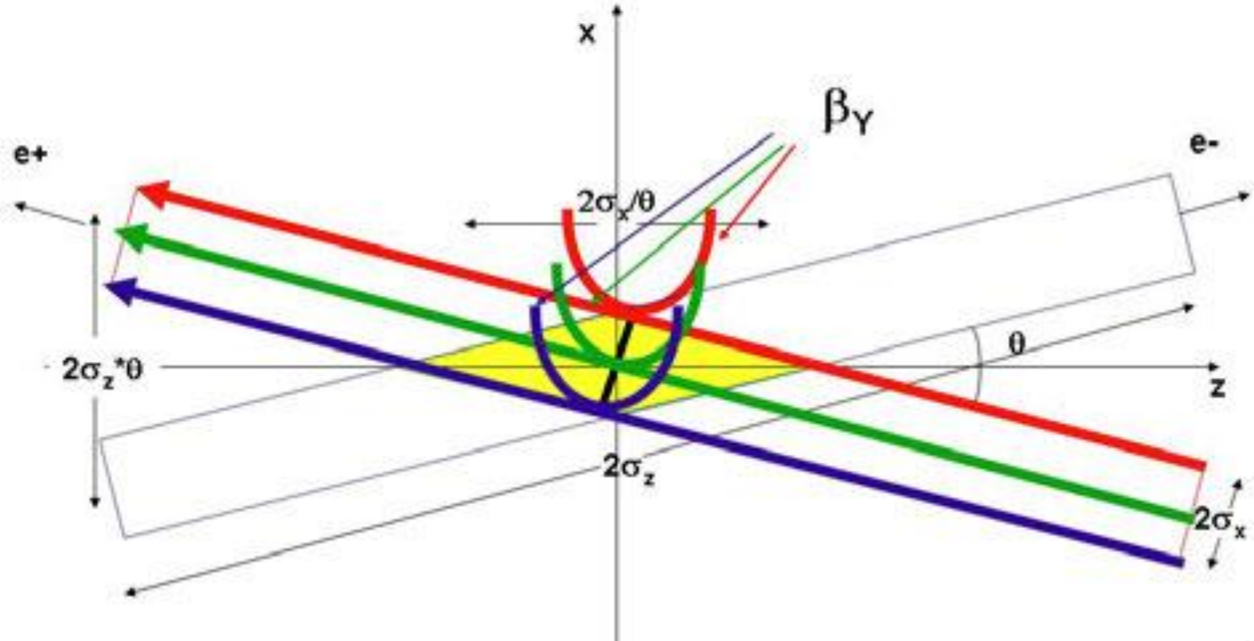
analytical estimates confirmed by the simulations

The beam-beam limit may further be raised with crab-waist schemes !

K. Ohmi, D. Shatilov

crab-waist crossing for flat beams

regular crossing

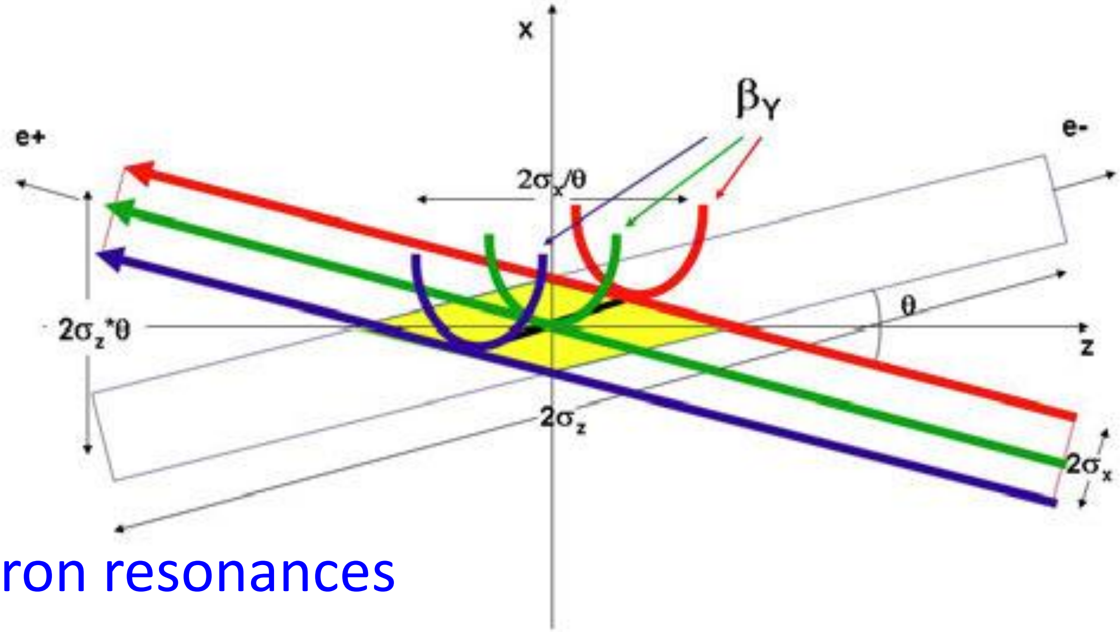


M. Zobov, P. Raimondi, et al.

crab waist -

vertical waist position in *s* varies with horizontal position *x*

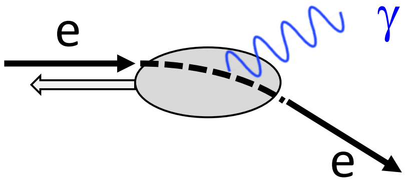
- allows for small β_y*
- and avoids synchrobetatron resonances



beamstrahlung – a new limit at 175 GeV

- ☐ 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)

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



η : ring energy acceptance

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

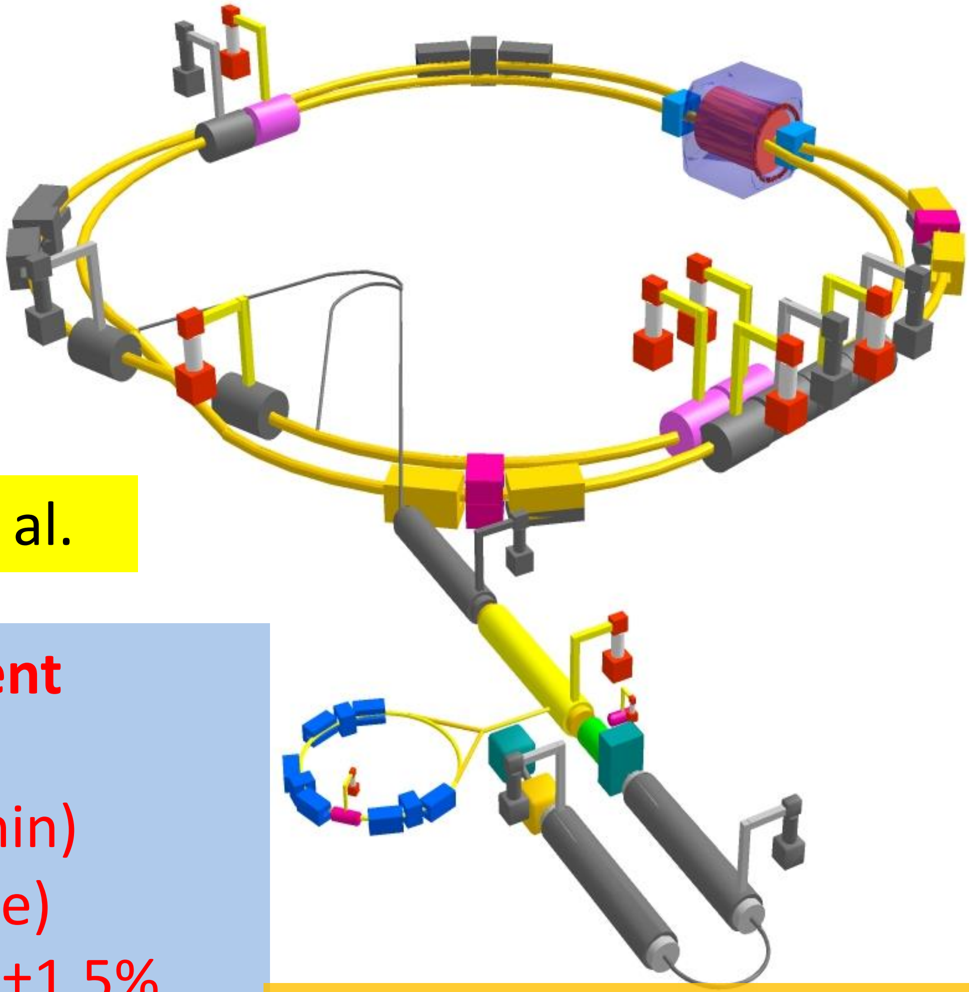
lifetime expression by V. Telnov, modified version by A. Bogomyagkov et al

- ☐ for acceptable lifetime, ρ×η must be sufficiently large
  - ○ *flat beams (large σ_x) !*
  - ○ *bunch length !*
  - ○ *large momentum acceptance:* ***≥1.5% at 175 GeV***
    - LEP: <1% acceptance, SuperKEKB ~ 1.5%

J. Wenninger, et al

SuperKEKB = *FCC-ee* demonstrator

beam commissioning will start in 2015

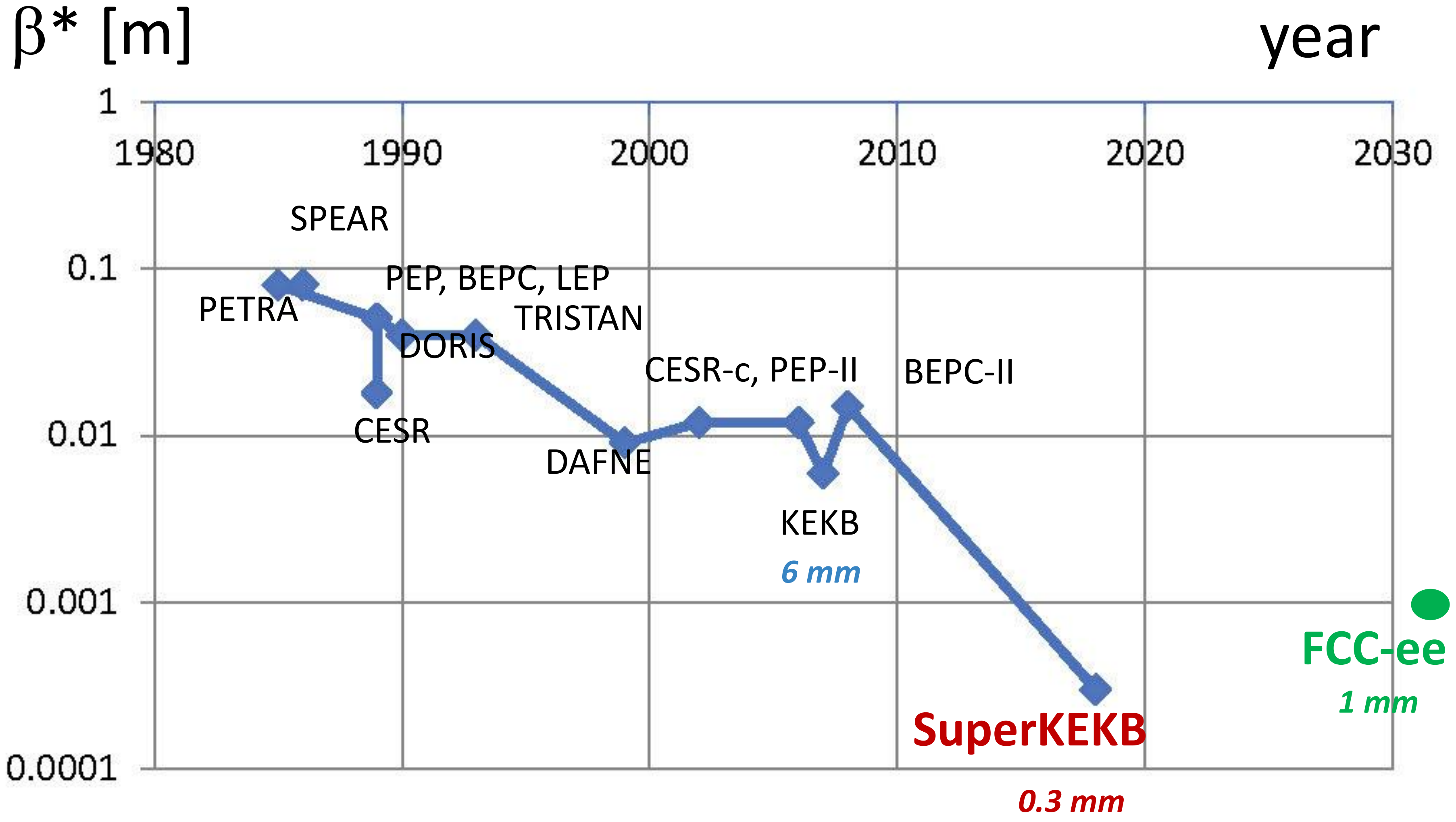


K. Oide et al.

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* crab waist)

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

β_y^* evolution over 40 years



entering a new regime for ring colliders –
SuperKEKB will pave the way towards $\beta^* \leq 1$ mm

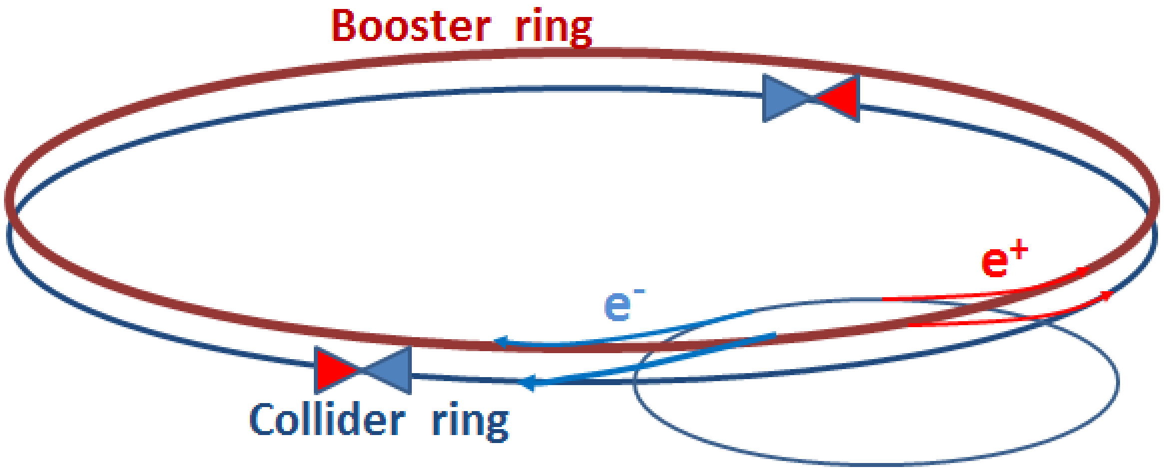
FCC-ee injection

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

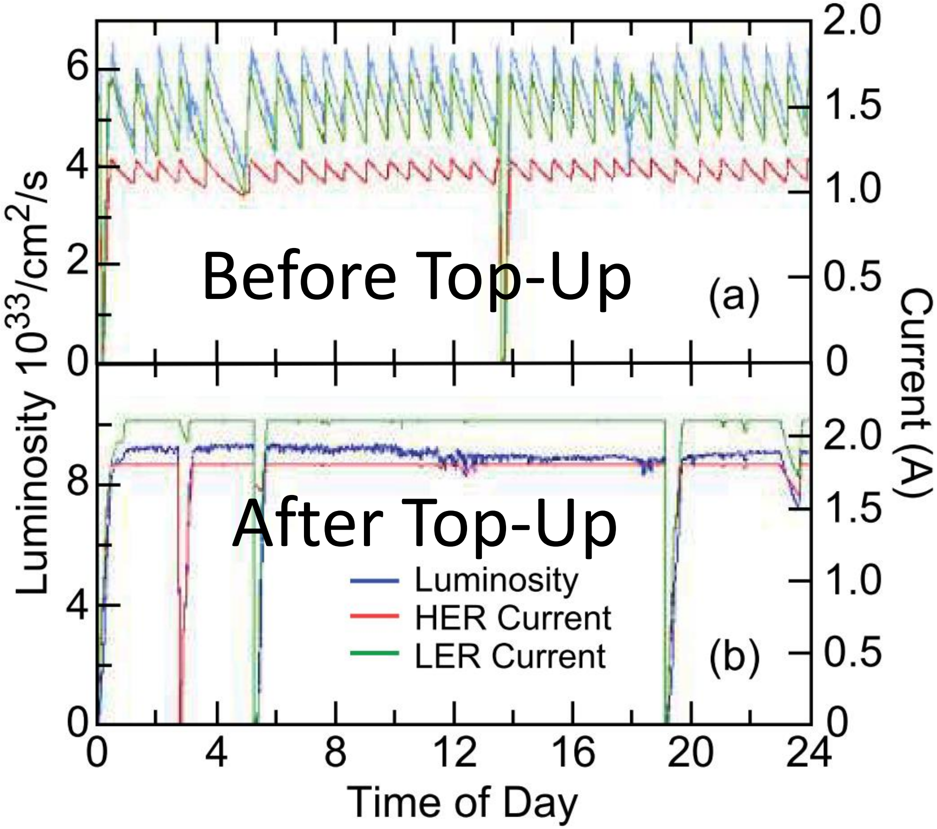
injector complex for e^+ and e^- beams of 10-20 GeV

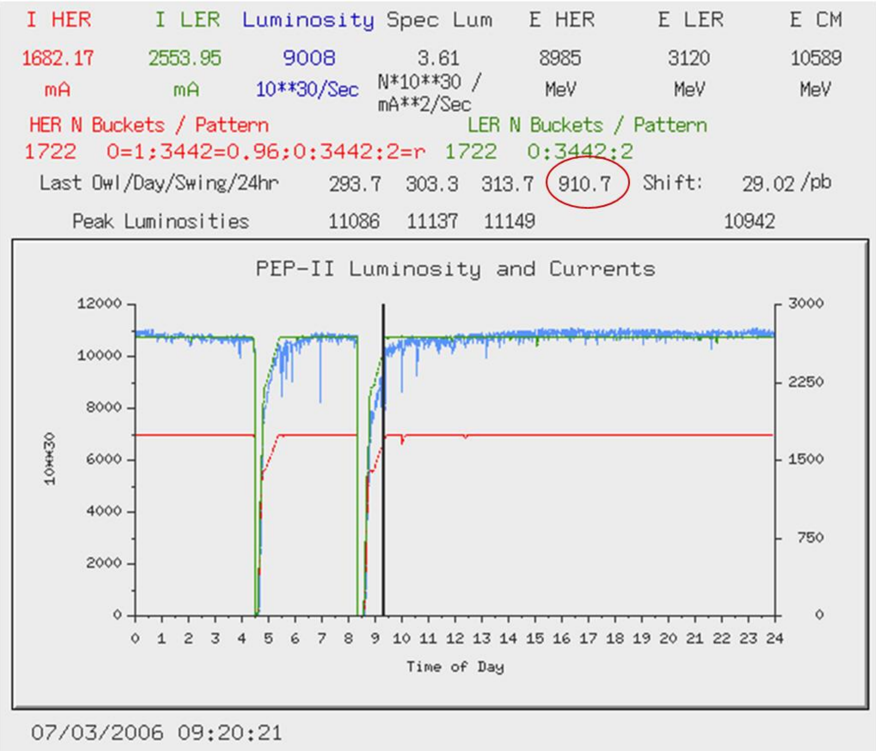
- Super-KEKB injector ≈ almost suitable



A. Blondel

top-up injection at PEP-II





```
I HER      I LER     Luminosity  Spec Lum      E HER     E LER     E CM
1682.17    2553.95   9008        3.61          8985      3120      10589
mA         mA        10**30/Sec  N*10**30 /    MeV       MeV       MeV
                                 mA**2/Sec
HER N Buckets / Pattern                     LER N Buckets / Pattern
1722  0=1;3442=0.96;0:3442:2=r  1722  0:3442:2
Last Owl/Day/Swing/24hr    293.7  303.3  313.7  910.7  Shift:  29.02 /pb
Peak Luminosities          11086  11137  11149                 10942
```

07/03/2006 09:20:21

average luminosity ≈ peak luminosity

similar results from KEKB

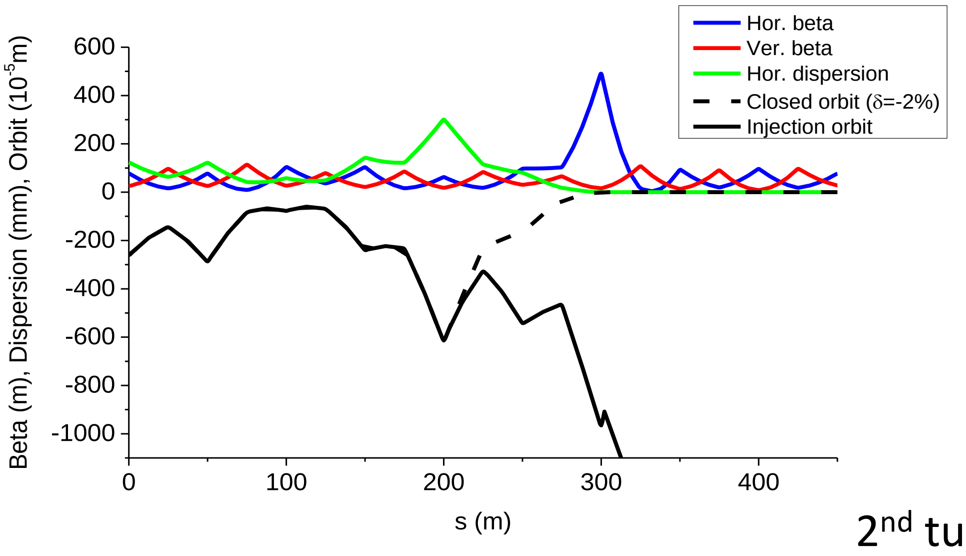
J. Seeman

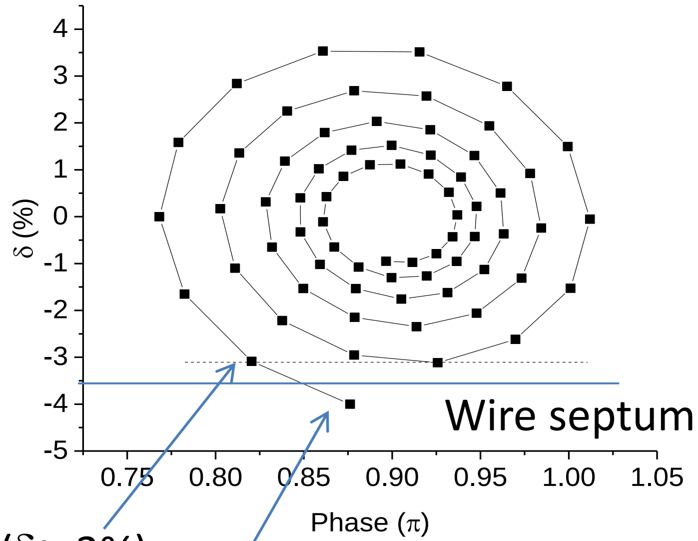
FCC-ee top-up

two new options for top-up:

(1) off-momentum multipole kicker injection

(2) or kicker-less ("dream injection") *





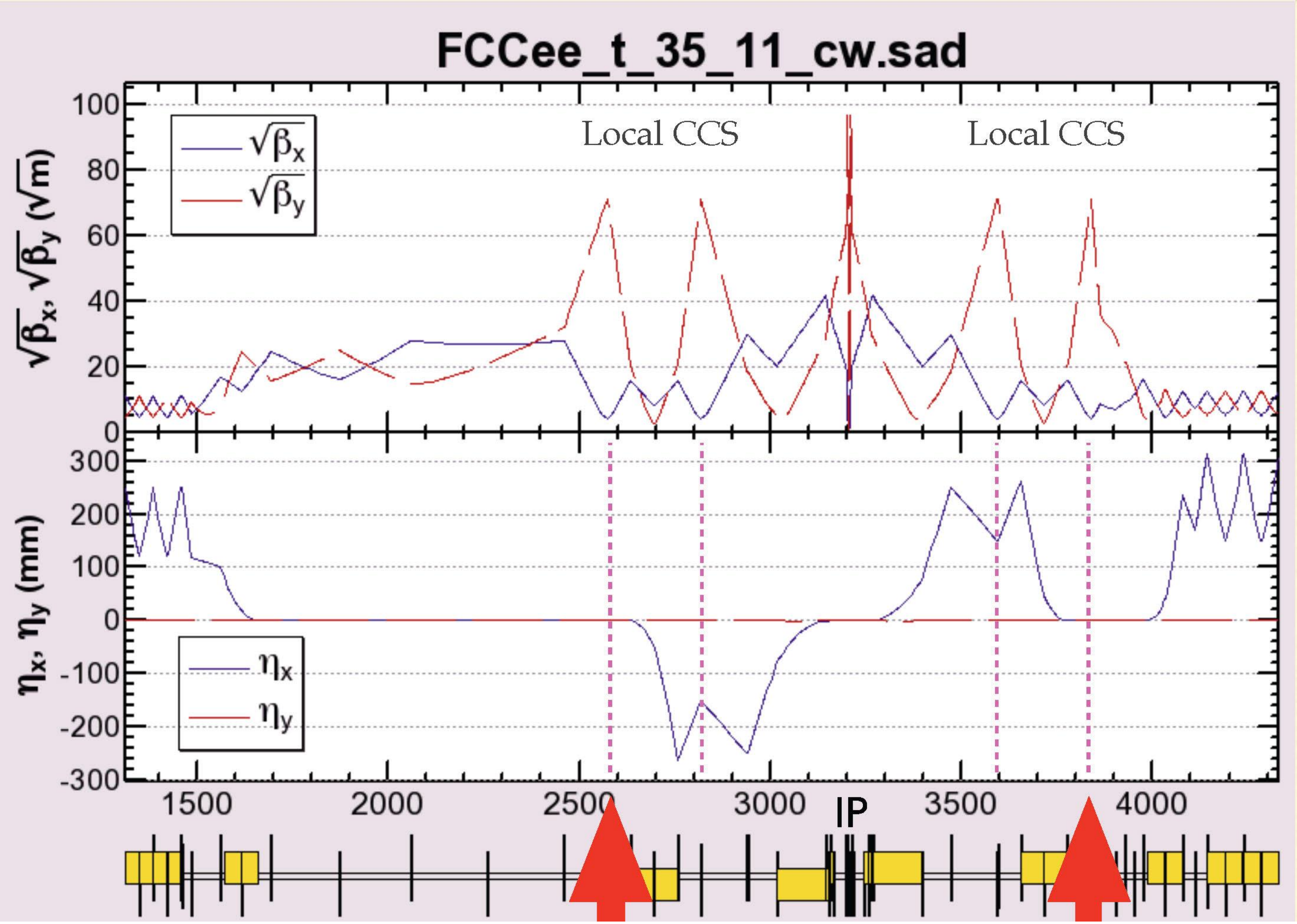
2nd turn (δ~-3%)

Injection point (δ=-4%)

M. Aiba, A. Saa Hernandez, PSI

* earlier proposal by R. Talman

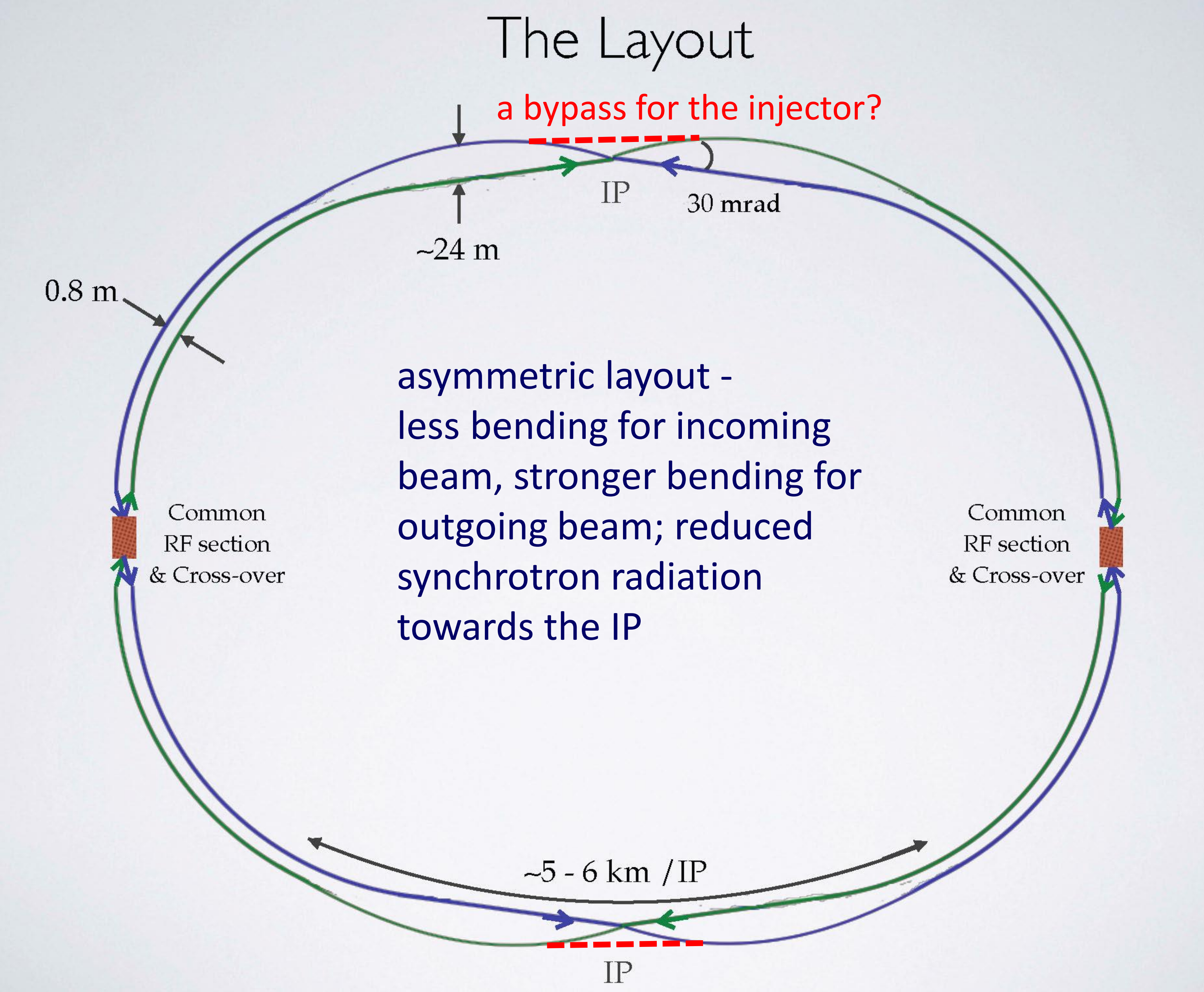
IR optics with crab waist and solenoids



these sextupoles work as crab waist sextupoles

K. Oide

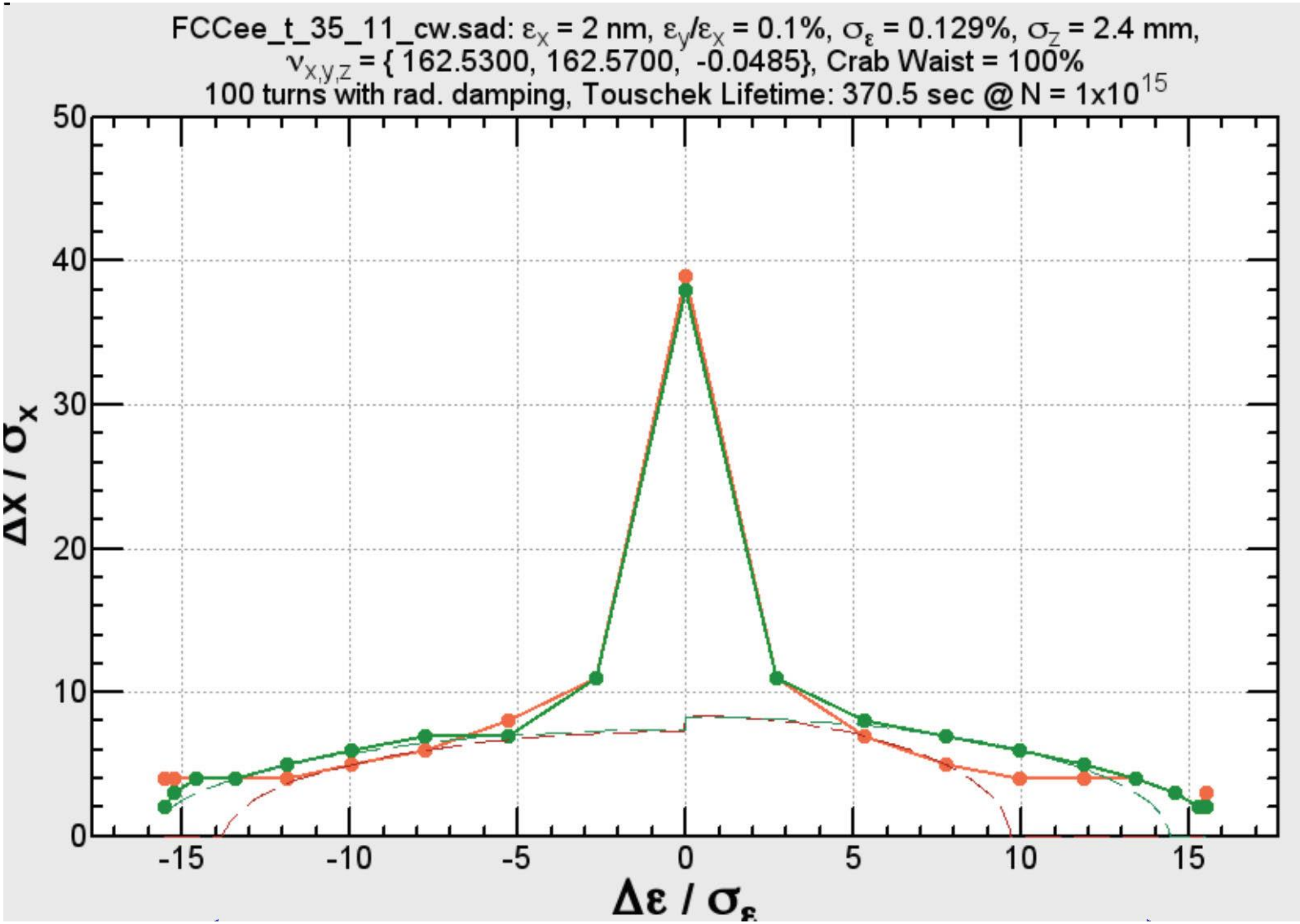
complete draft optics & geometry for FCC-ee



asymmetric layout - less bending for incoming beam, stronger bending for outgoing beam; reduced synchrotron radiation towards the IP

K. Oide

dynamic aperture

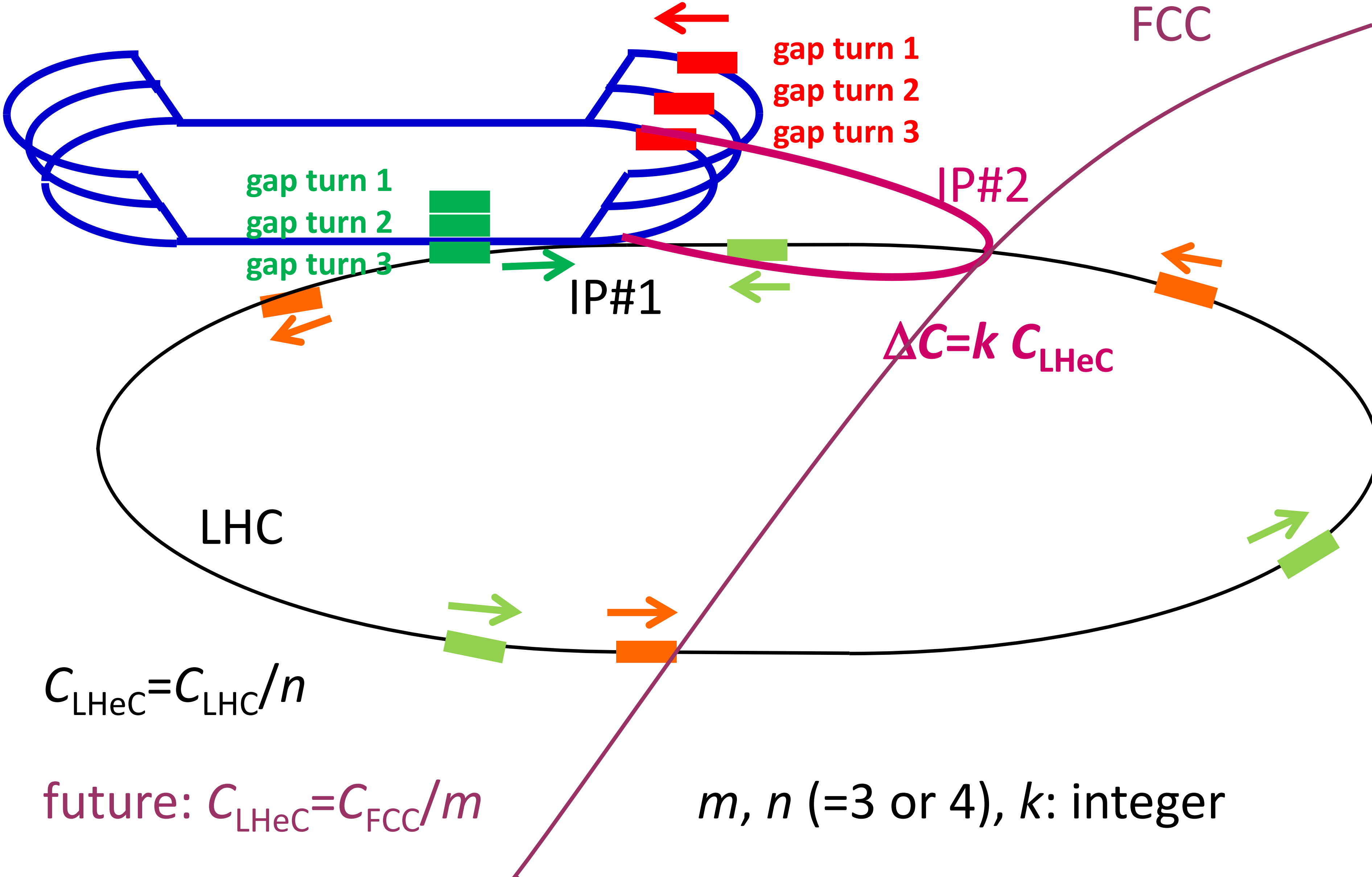


±2%

K. Oide

how about FCC-he?

one option: reuse the LHeC



$C_{\mathrm{LHeC}} = C_{\mathrm{LHC}}/n$

future: $C_{\mathrm{LHeC}} = C_{\mathrm{FCC}}/m$

m, n (=3 or 4), k: integer

FCC-he linac-ring luminosity

luminosity of LR collider:

(round beams)

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

H_D~1.3

D. Schulte
LHeC2010

highest proton beam brightness available

smallest possible proton β* function:
- reduced l^*
- squeeze only one *p* beam

average e^- current limited by energy recovery efficiency

I_e=25.6 mA (HF)

maximize geometric overlap factor
- head-on collision
- small e- emittance

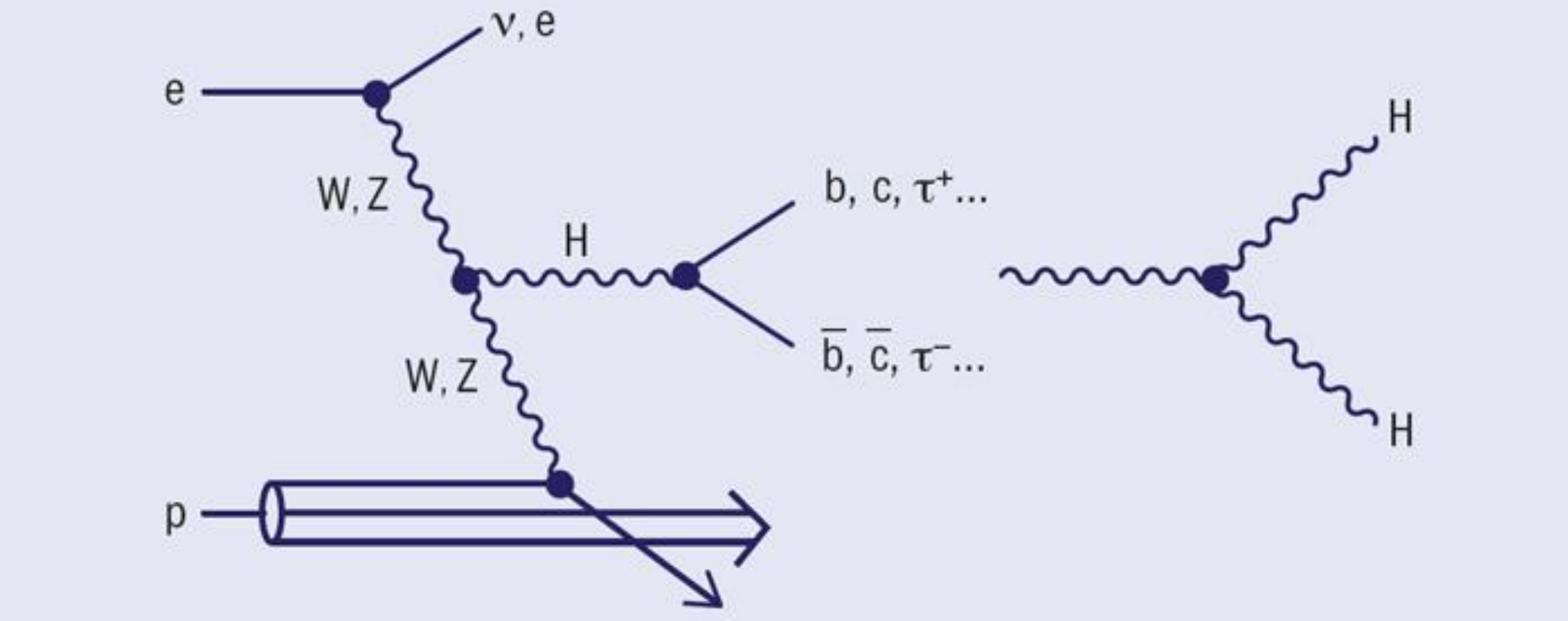
$\theta_c=0$

$H_{hg}\geq 0.7$

LHeC HF → FCC-he (phase 2)

parameter [unit]		**FCC-hh**
species	***e-***	***p***
beam energy (/nucleon) [GeV]	60	7000→ **50000**
bunch spacing [ns]	25	25
bunch intensity (nucl,) [10^{10}]	**0.4**	**22→ 10**
beam current [mA]	**25.6**	**1110 → 500**
normalized rms emittance [μm]	20 → **10**	**2.5 → 0.75**
geometric rms emittance [nm]	**0.17→0.085**	**0.34 → 0.014**
IP beta function $\beta_{x,y}$* [m]	**0.10→0.048**	**0.05 → 0.3**
IP rms spot size [μm]	4.1 → **2.0**	4.1 →**2.0**
lepton *D* & hadron ξ	**23 → 48**	**0.0002→0.0007**
hourglass reduction factor H_{hg}	0.80→ **0.80**	
pinch enhancement factor H_D	~1.35	
luminosity/nucl. [10^{33}cm^{-1}s^{-1}]	**14.4 → 27.6**	

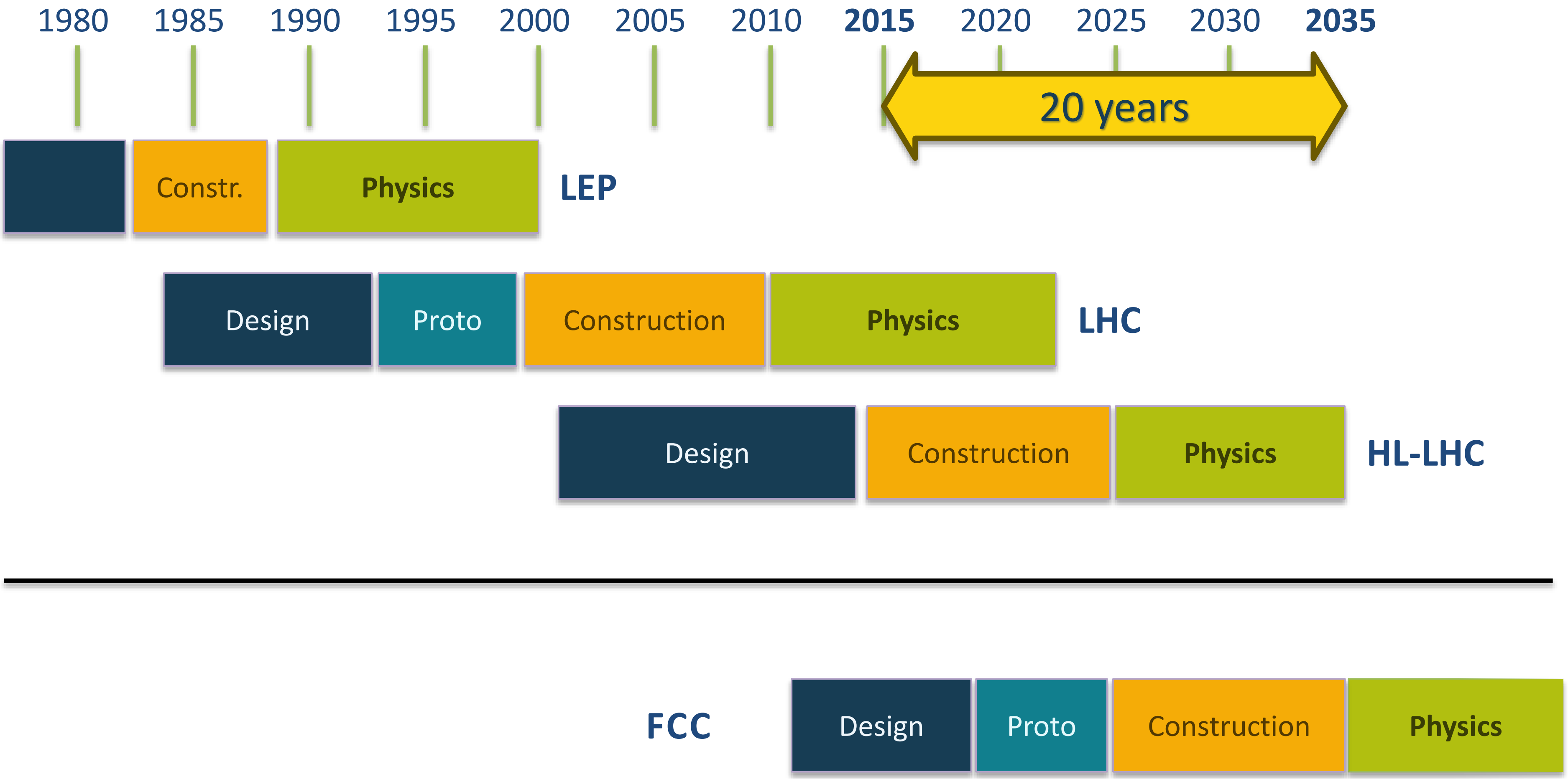
Higgs physics at FCC-he



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

CERN Circular Colliders + FCC



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

20 years

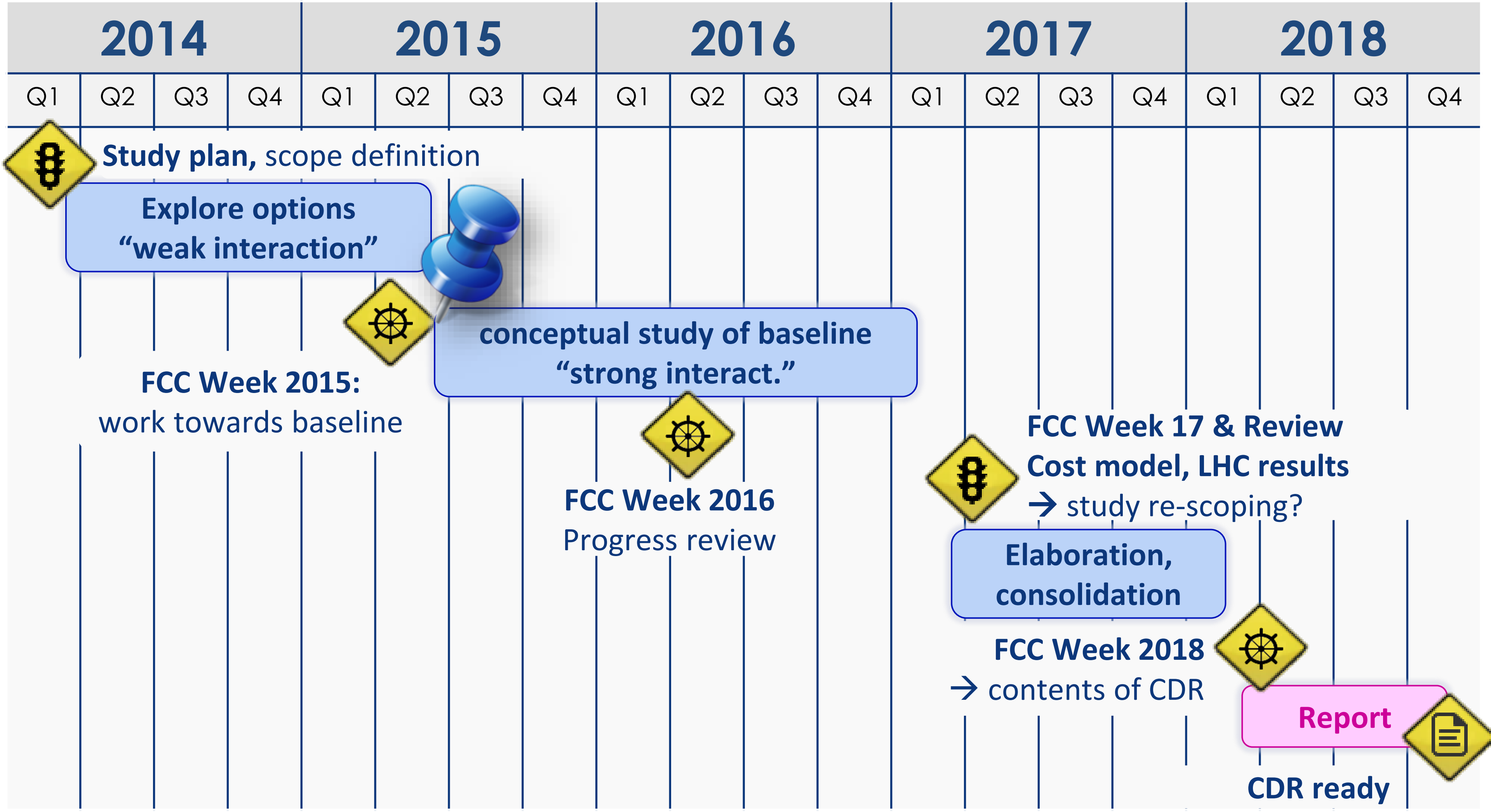
Constr. | **Physics** | **LEP**

Design | Proto | Construction | **Physics** | **LHC**

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

FCC | Design | Proto | Construction | **Physics**

Study time line towards FCC CDR



2014 2015 2016 2017 2018

Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4

Study plan, scope definition

Explore options “weak interaction”

FCC Week 2015:
work towards baseline

conceptual study of baseline “strong interact.”

FCC Week 2016
Progress review

FCC Week 17 & Review
Cost model, LHC results
→ study re-scoping?

Elaboration, consolidation

FCC Week 2018
→ contents of CDR

Report

CDR ready

FCC Collaboration Status

- 57 institutes
- 22 countries + EC

FCC Collaboration Status

57 collaboration members & CERN as host institute, 29 June 2015

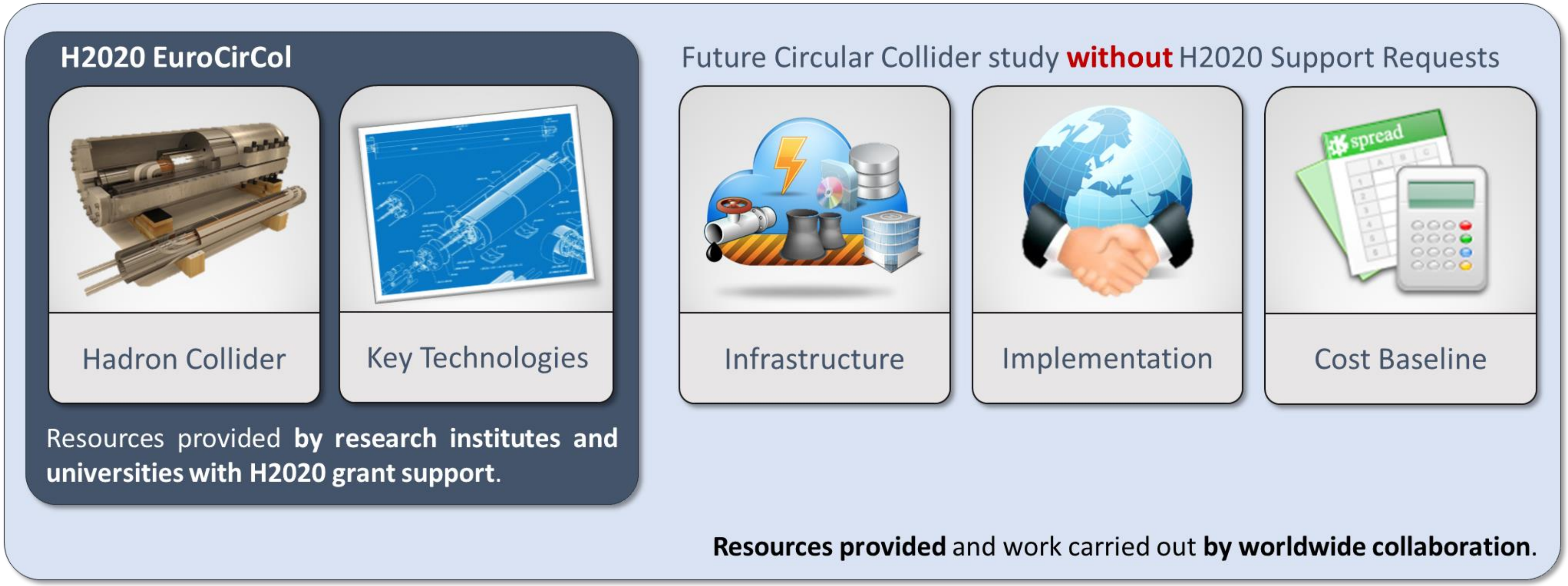
ALBA/CELLS, Spain
Ankara U., Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
DESY, Germany
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland

GWNU, Korea
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI/Oxford, UK
JINR Dubna, Russia
FZ Jülich, Germany
KAIST, Korea
KEK, Japan

KIAS, Korea
King’s College London, UK
KIT Karlsruhe, Germany
Korea U Sejong, Korea
MEPhI, Russia
MIT, USA
NBI, Denmark
Northern Illinois U., USA
NC PHEP Minsk, Belarus
U. Liverpool, UK
U Oxford, UK
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
Wroclaw UT, Poland

EuroCirCol EU Horizon 2020 Grant

EC contributes with funding to FCC-hh study



H2020 EuroCirCol

Hadron Collider

Key Technologies

Resources provided **by research institutes and universities with H2020 grant support.**

Future Circular Collider study **without** H2020 Support Requests

Infrastructure

Implementation

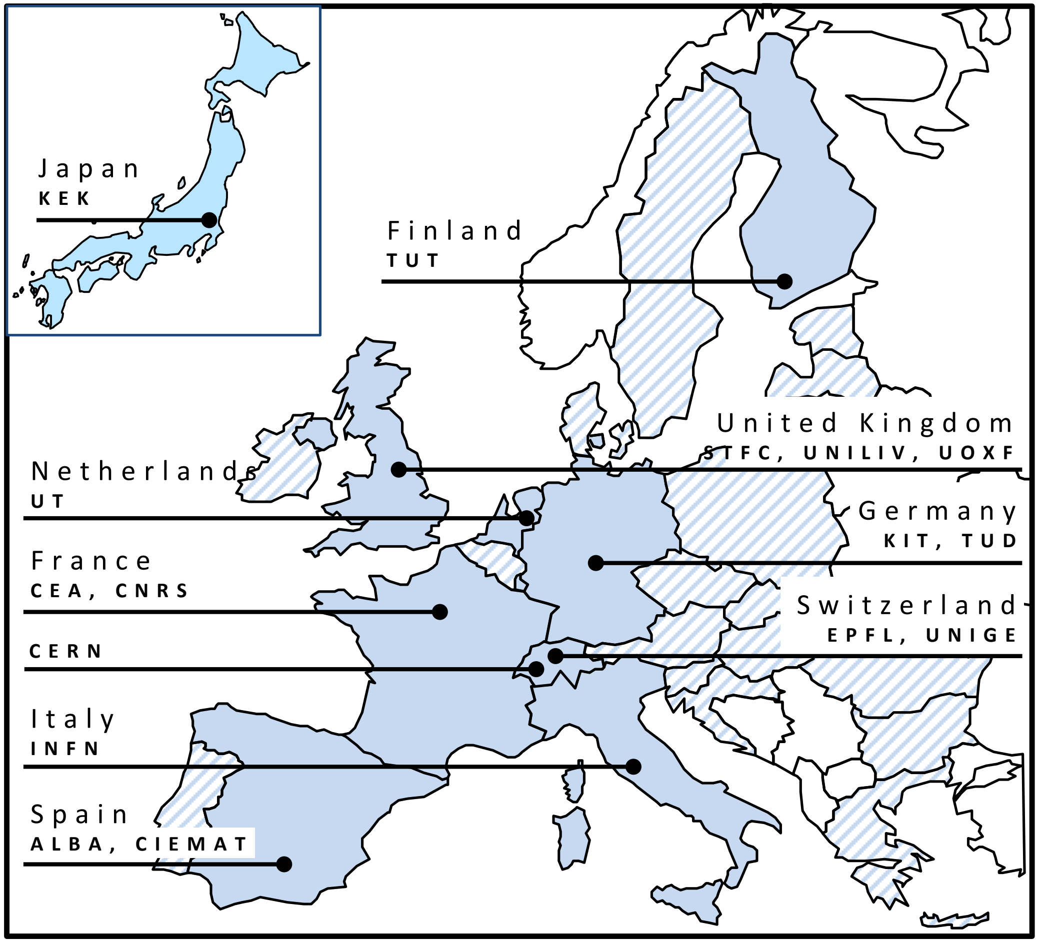
Cost Baseline

Resources provided and work carried out **by worldwide collaboration.**

- Core aspects of hadron collider design: arc & IR optics design, 16 T magnet program, cryogenic beam vacuum system
- **Recognition of FCC Study by European Commission**

EuroCirCol Consortium + Associates

CERN	IEIO
TUT	Finland
CEA	France
CNRS	France
KIT	Germany
TUD	Germany
INFN	Italy
UT	Netherlands
ALBA	Spain
CIEMAT	Spain
STFC	United Kingdom
UNILIV	United Kingdom
UOXF	United Kingdom
KEK	Japan
EPFL	Switzerland
UNIGE	Switzerland
NHFML-FSU	USA
BNL	USA
FNAL	USA
LBNL	USA



Consortium Beneficiaries, signing the Grant Agreement

FCC Week 2016

Rome, 11-15 April 2016

how to go beyond the FCC?

limits to accelerating gradients

G_{max}≈30 MV/m (*Nb* **superconductor**)

G_{max}≈100 MV/m (**normalconducting metal**)

due to surface breakdown

today

G_{max}≈ 1-3 GV/m (**dielectrics**)

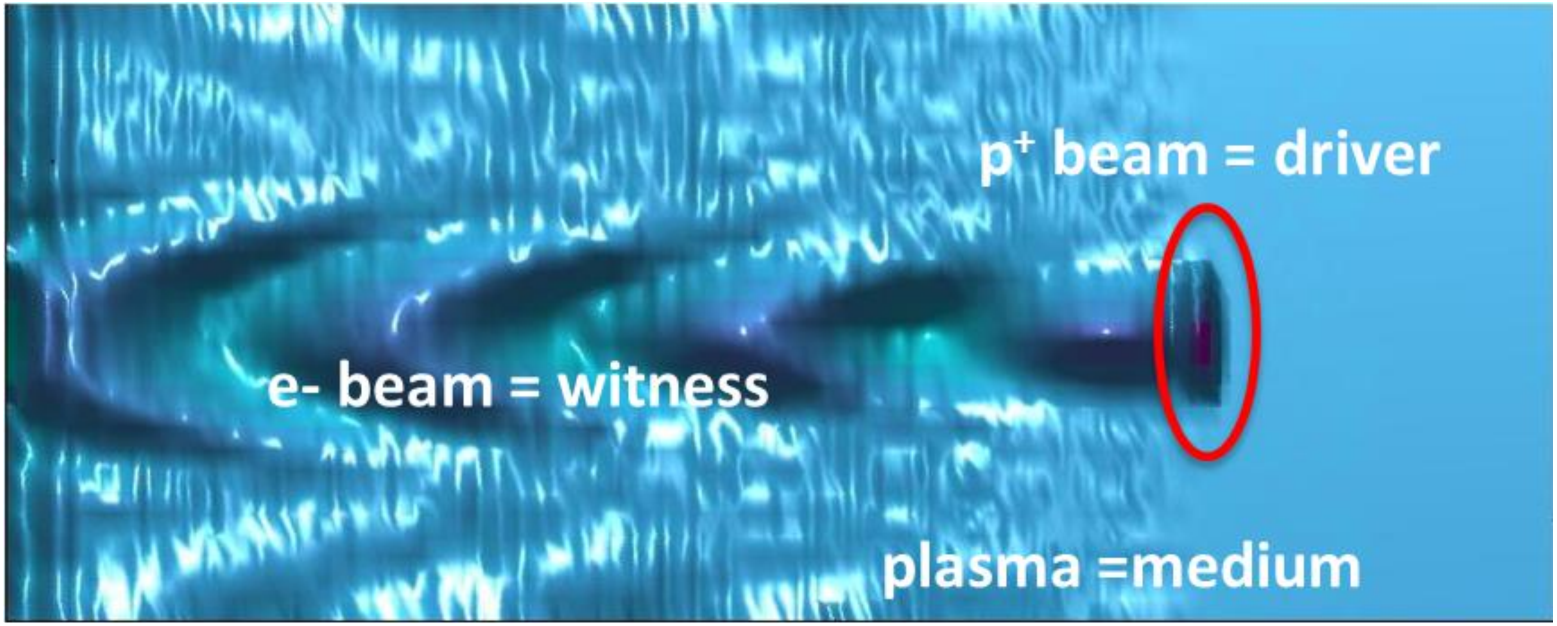
G_{max}≈ 100 GV/m (n_0 [10^{18} cm^{-3}])$^{1/2}$ (**plasma**
with n_0 ≈10^{17}-10^{18} cm^{-3} plasma density)

G_{max}≈ 10 TV/m (n_0 [10^{22} cm^{-3}])$^{1/2}$ (**crystal**
with n_0 ≈10^{22}-10^{23} cm^{-3})

tomorrow?

G_{max}≈ 10^{18} V/m (Schwinger critical field,
vacuum breakdown)

proton-driven plasma acceleration

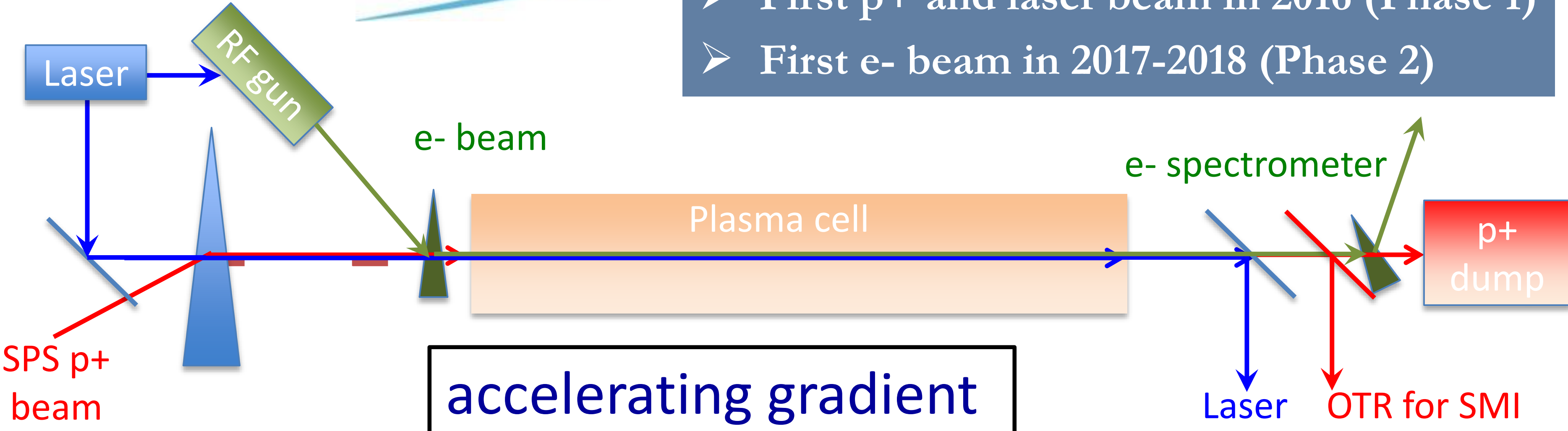


- plasma = energy transformer: energy transfer from driver to the witness bunch
- maximum energy gain of witness bunch in a single plasma stage is limited by driver energy (e- bunch, laser pulse, etc.)
- current proton synchrotrons produce high energy protons, up to multi TeV (LHC) ➔ *p* bunches are the most promising drivers of wakefields to accelerate *e*'s to TeV energy scale

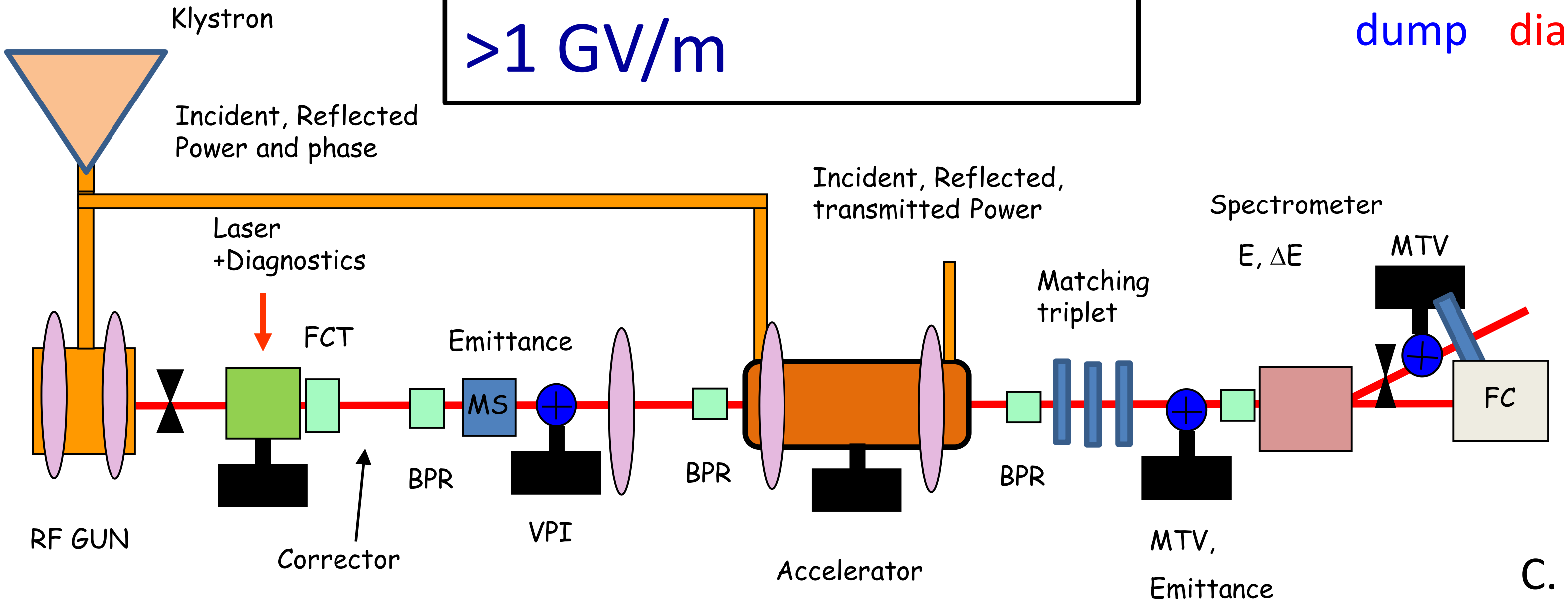
C. Bracco

PoP Experiment: Awake

- ➢ Approved in August 2013
- ➢ First p+ and laser beam in 2016 (Phase 1)
- ➢ First e- beam in 2017-2018 (Phase 2)



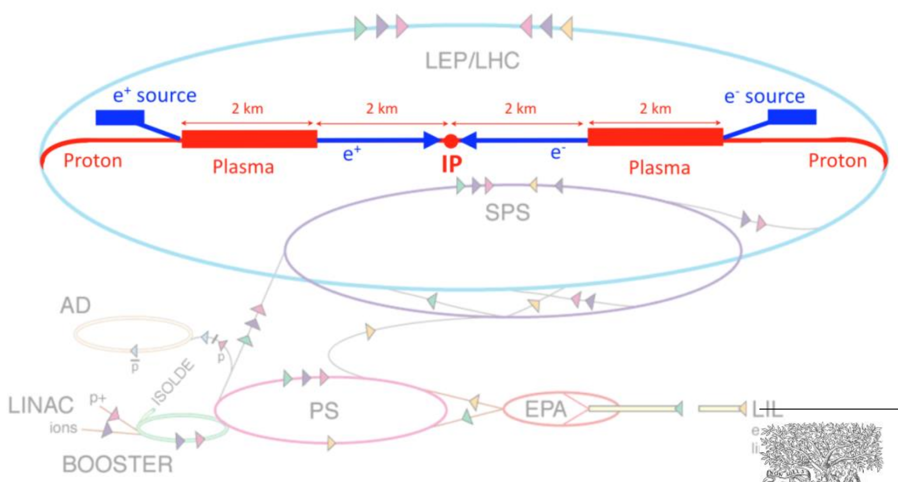
accelerating gradient >1 GV/m



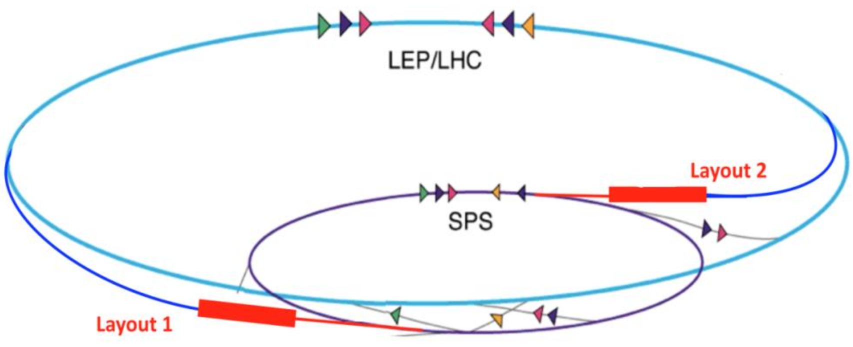
C. Bracco

far future *p*-driven plasma collider designs

An e+ e- collider

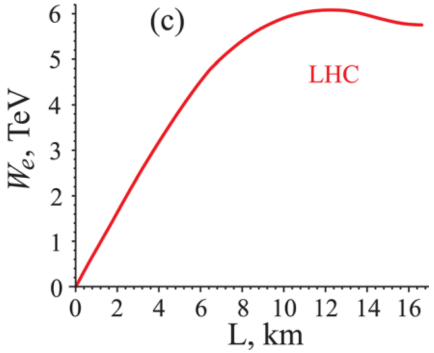


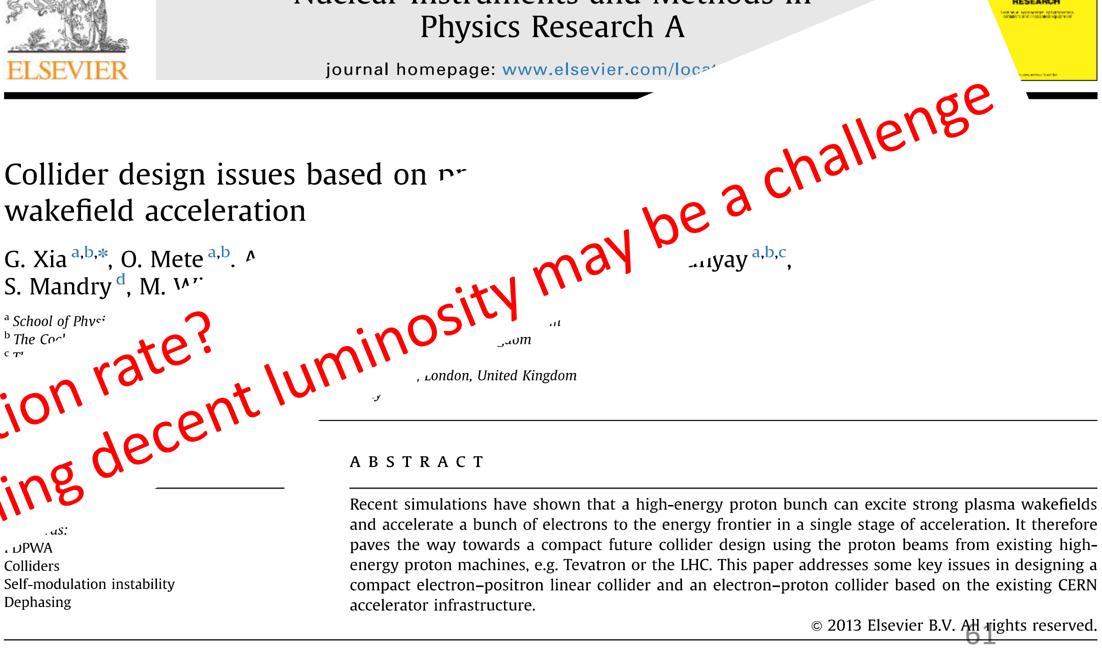
An e-p collider



accelerating gradient

>1 GV/m





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journal homepage: www.elsevier.com/loca

Collider design issues based on pr
wakefield acceleration

G. Xia [a,b,*], O. Mete [a,b], A ...ıyay [a,b,c],
S. Mandry [d], M. W

[a] School of Phys
[b] The Coc

, London, United Kingdom

A B S T R A C T

DPWA
Colliders
Self-modulation instability
Dephasing

Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy proton machines, e.g. Tevatron or the LHC. This paper addresses some key issues in designing a compact electron–positron linear collider and an electron–proton collider based on the existing CERN accelerator infrastructure.

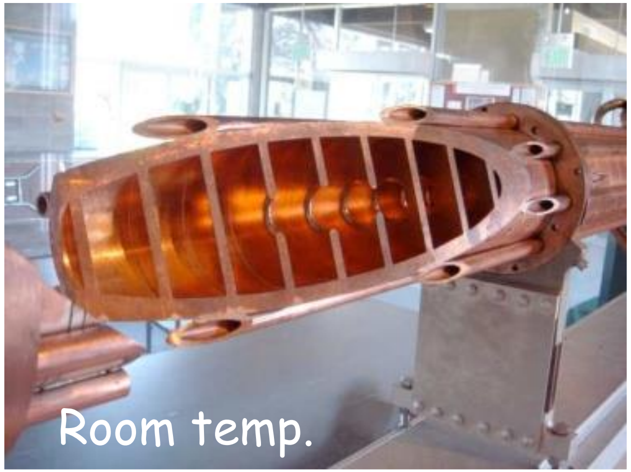
repetition rate?

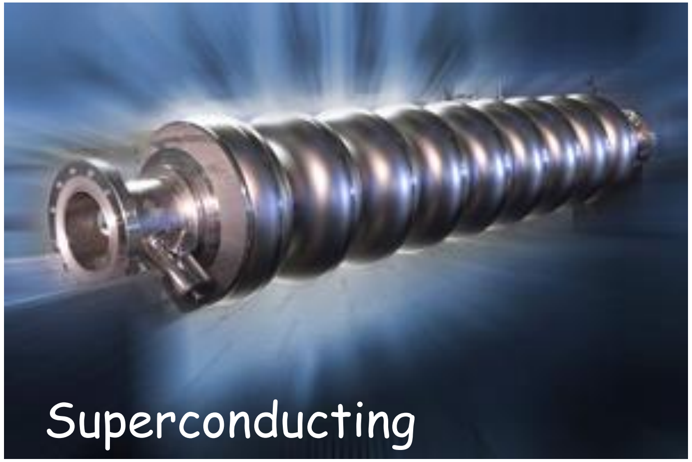
reaching decent luminosity may be a challenge

S. Chattopadhyay

(r)evolutionary advancement: DLA

Traditional Manufacturing

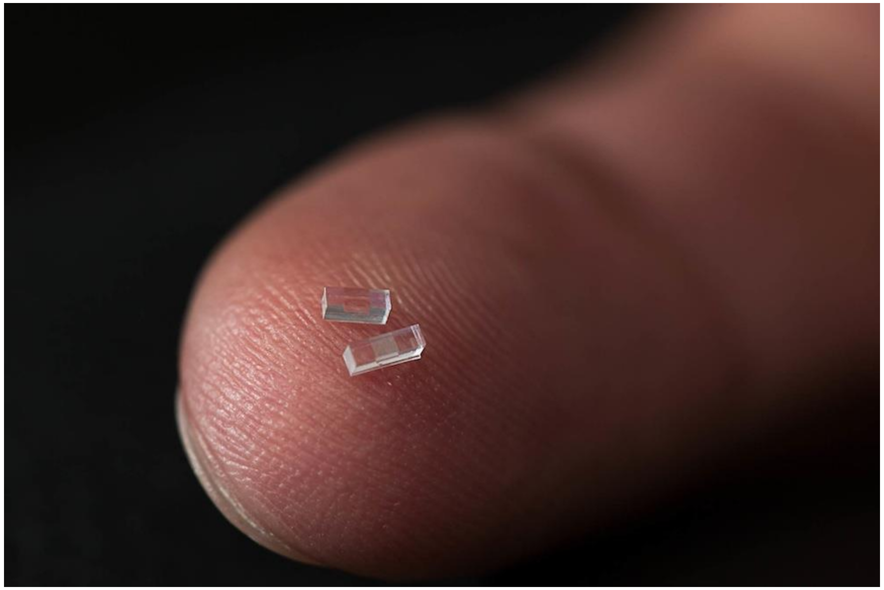


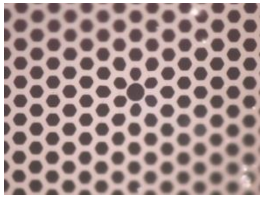


E_{acc} = 30 MV/m
λ = 10 cm

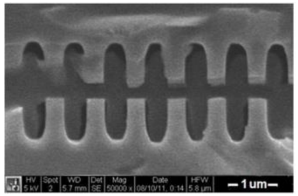
10E-4

Semiconductor Manufacturing

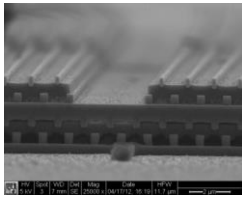




Fibers



Gratings



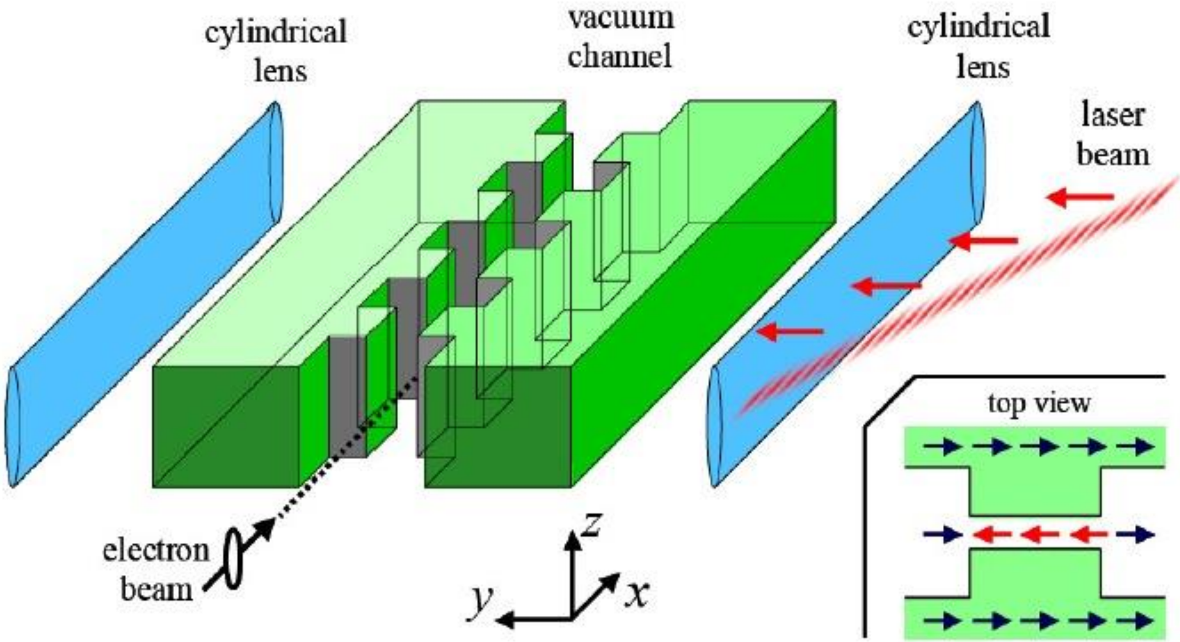
Crystals

E_{acc} = 2 GV/m *
λ = 1 - 2 μm

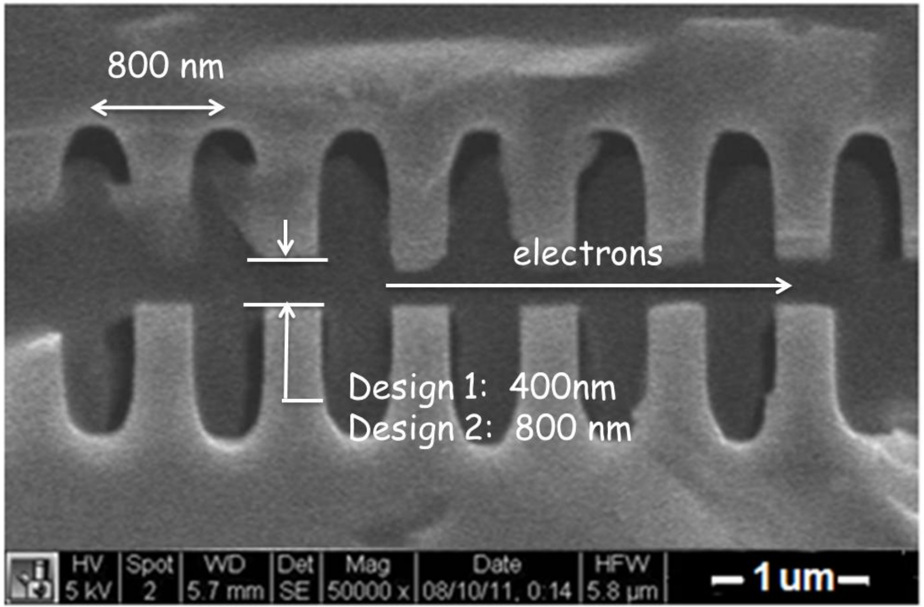
* in theory

R. Byer

dielectric laser-driven accelerator

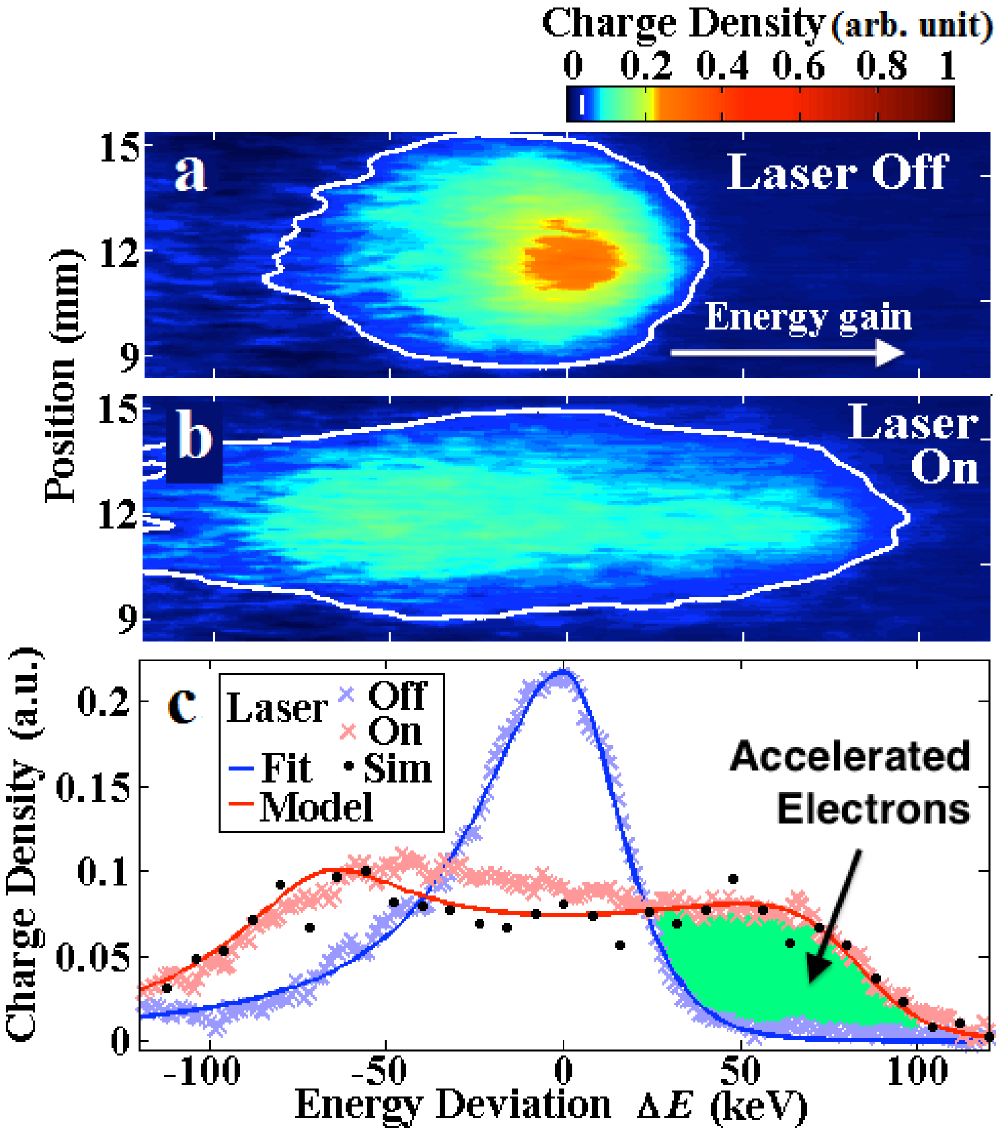


T. Plettner, et al.
PRST-AB **9**, 111301
(2006).



Electron microscope image of the bonded structure

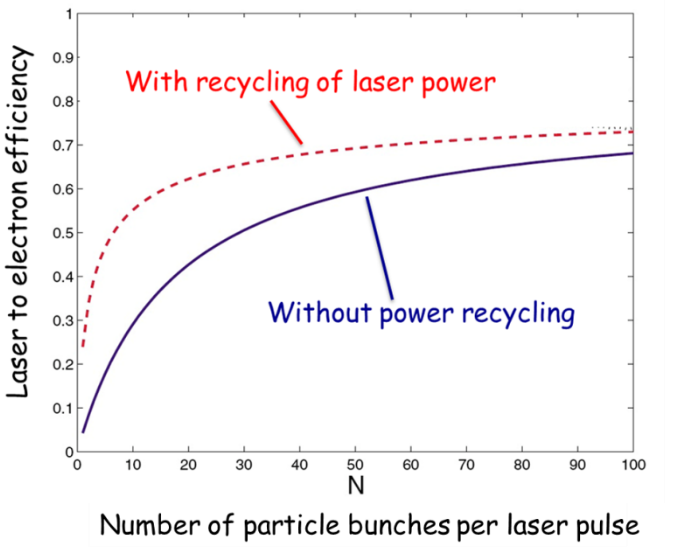
experimental results from SLAC



measuring the gradient by observing the resultant energy broadening

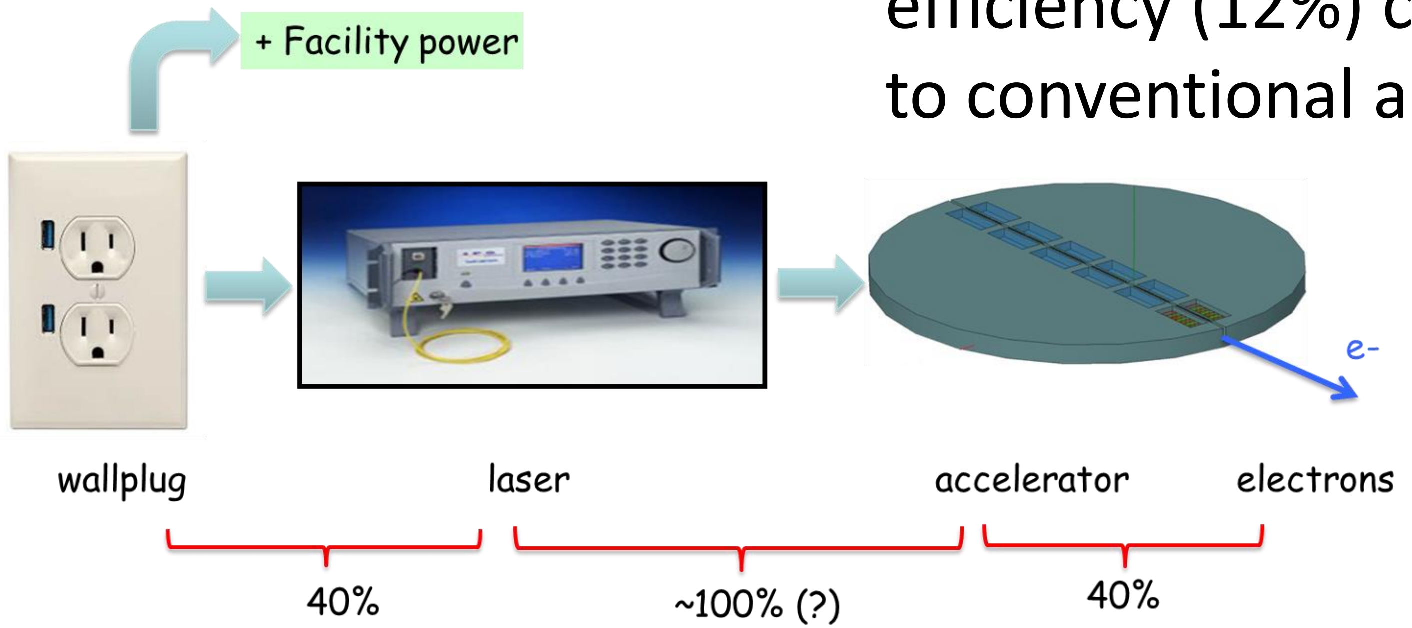
R. Byer

power transfer efficiency


Na, Siemann, and Byer, PR-STAB **8**, 031301 (2005).

with particles appropriately bunched, the laser to electron power transfer efficiencies approach 60%

total wallplug to electron efficiency (12%) comparable to conventional accelerators



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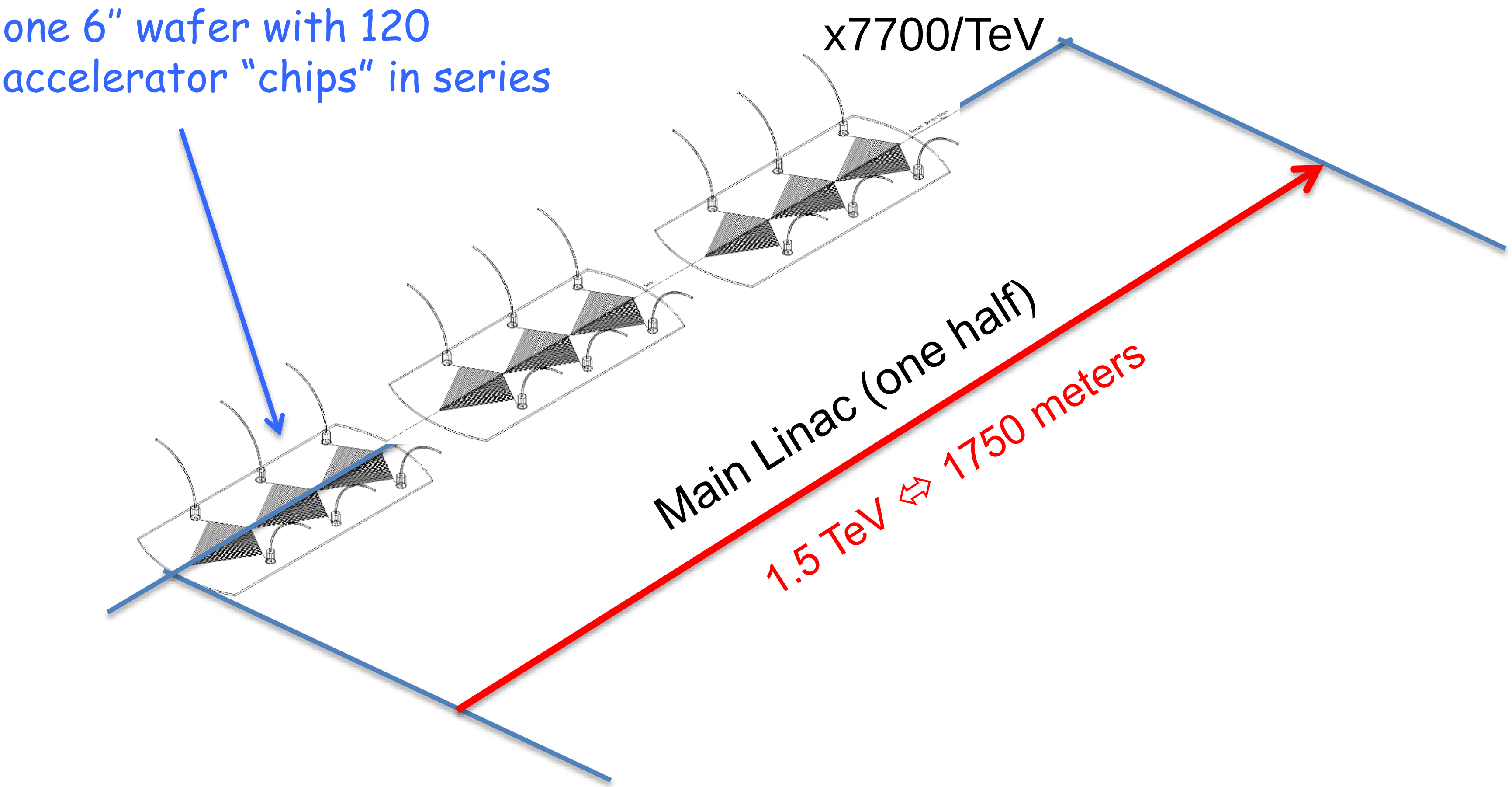
3-TeV particle collider based on DLA

total length of collider ~3.5 km

bunches of 10^4 electrons at 100 MHz



one 6" wafer with 120 accelerator "chips" in series

x7700/TeV

Main Linac (one half)

1.5 TeV ⇔ 1750 meters

E. R. Colby, R. J. England, R. J. Noble, "A Laser-Driven Linear Collider: Sample Machine Parameters and Configuration", PAC 2011.

R. Byer

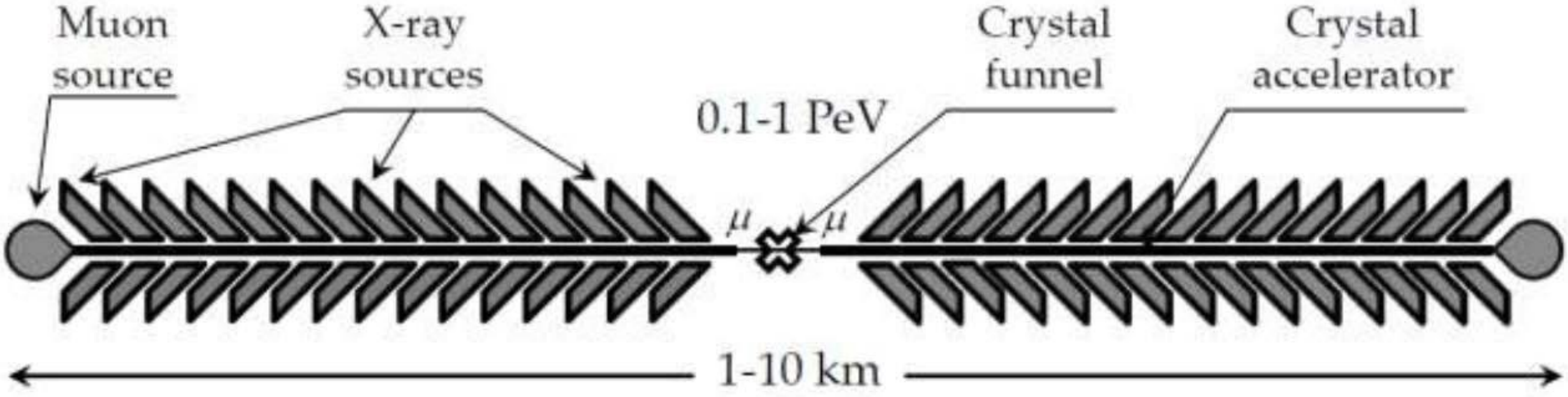
radiation emission due to betatron oscillations

“$e^{\pm}$ may soon run out of steam in the high-gradient world!” V. Shiltsev

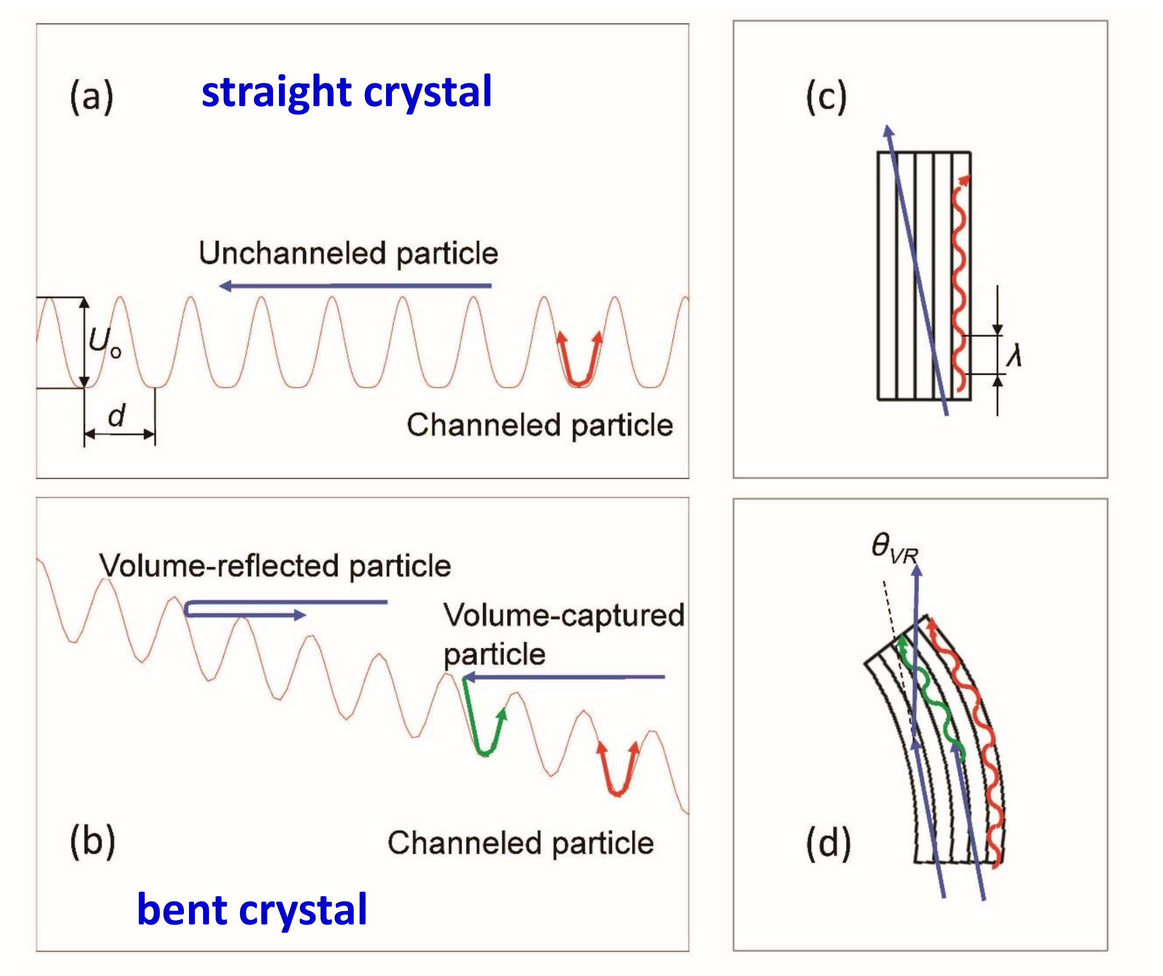
$E_{\max}$ ≈300 GeV for e^{+}, 10^{4} TeV μ, 10^{6} TeV for p ?!

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

linear X-ray crystal μ collider?



another (circular) possibility: use crystals as bends: world's strongest magnets



crystal focusing strength

ϕ~20-60 eV/Å^2

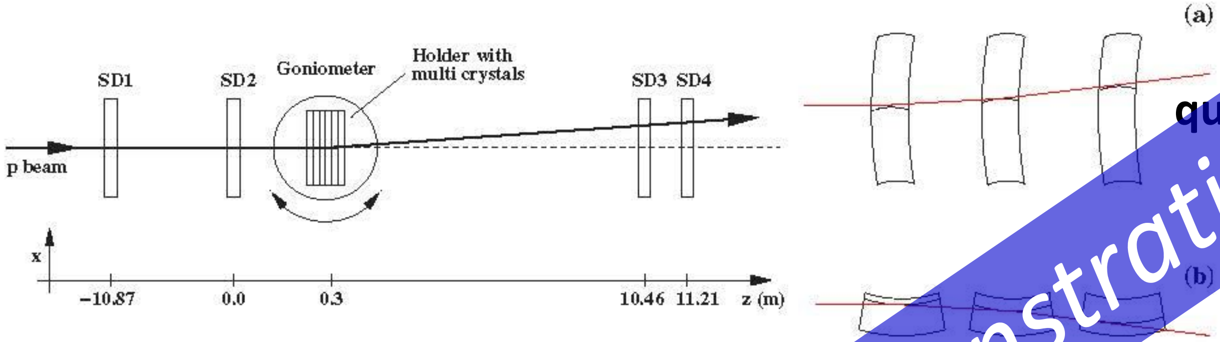
B_{max}≈2000 T !

$\lambda = 2\pi\beta = 2\pi\ (E/\phi)^{1/2}$

W. Scandale, MPL A (2012)

S.A. Bogacz, D. Cline, 1997

staging of crystal deflectors

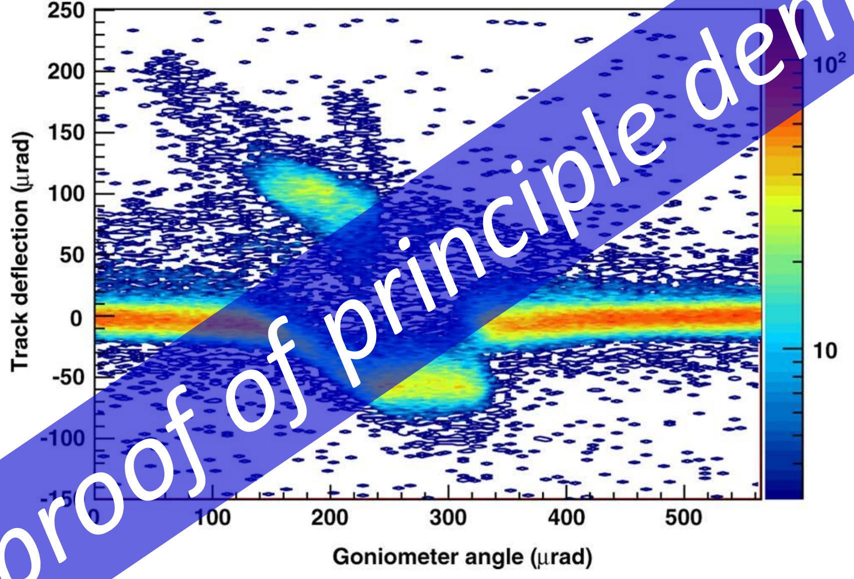


quasimosaic

strip crystals

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

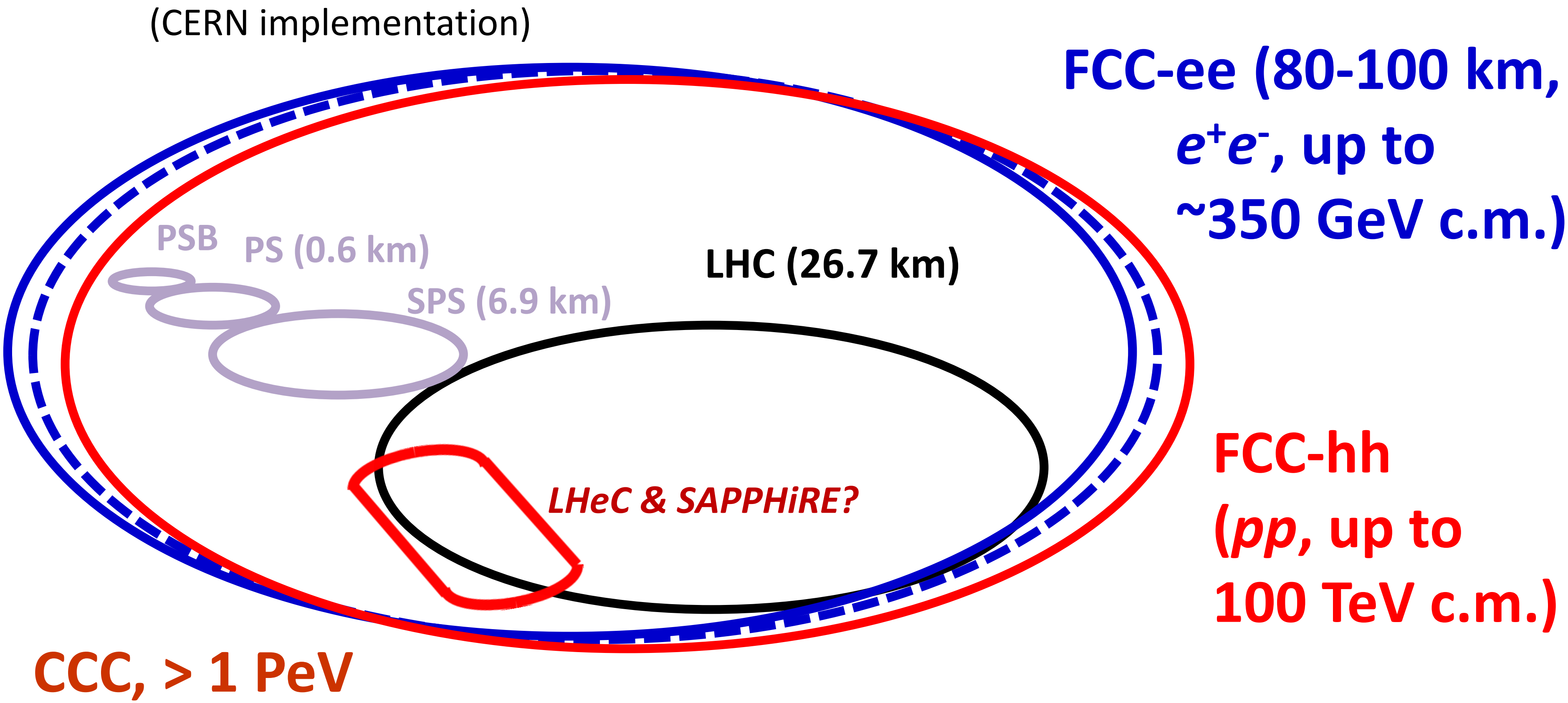
proof of principle demonstration!



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

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

possible long-term strategy

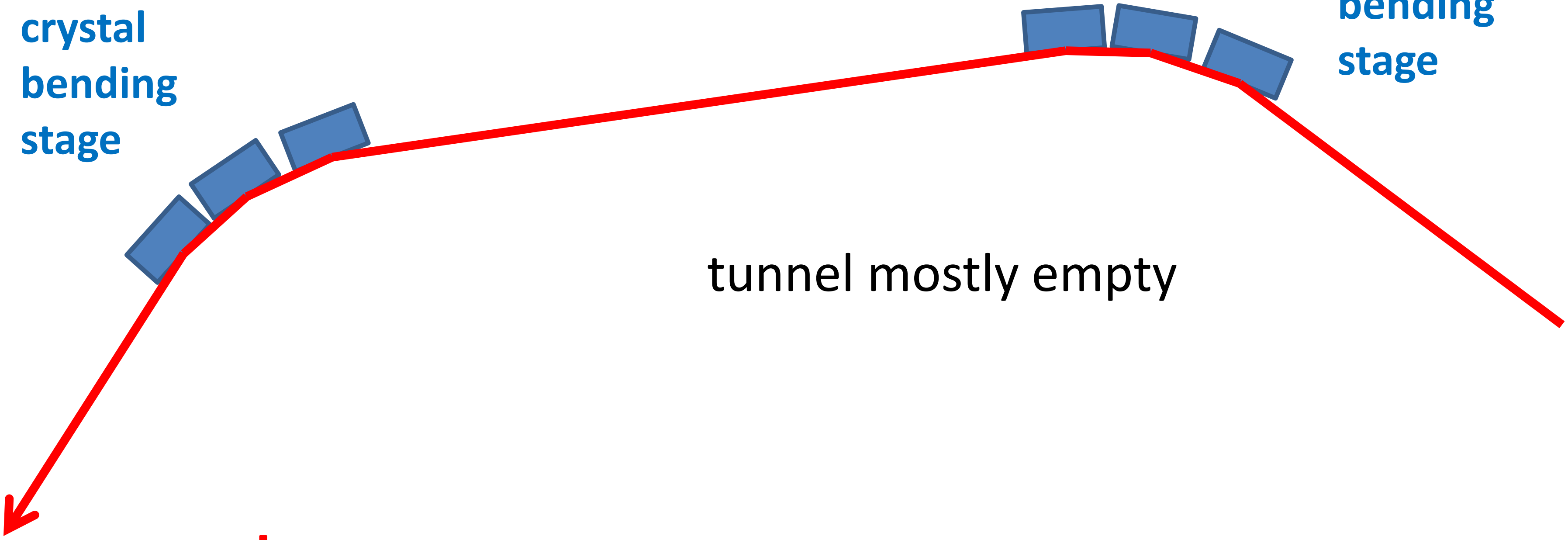


& $e^\pm$ (120 GeV) – *p* (7, 16 & 50 TeV) collisions (**FCC-he**)

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

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

circular crystal collider?



cryogenic?
crystal
bending
stage

cryogenic?
crystal
bending
stage

tunnel mostly empty

proton beam

energy ramp using induction acceleration

(K. Takayama)

highest-energy particles

4 July 2012 CERN, Geneva, Switzerland

Higgs boson – “God particle”? – mass 1.25×10^{11} eV, neither matter nor force!

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

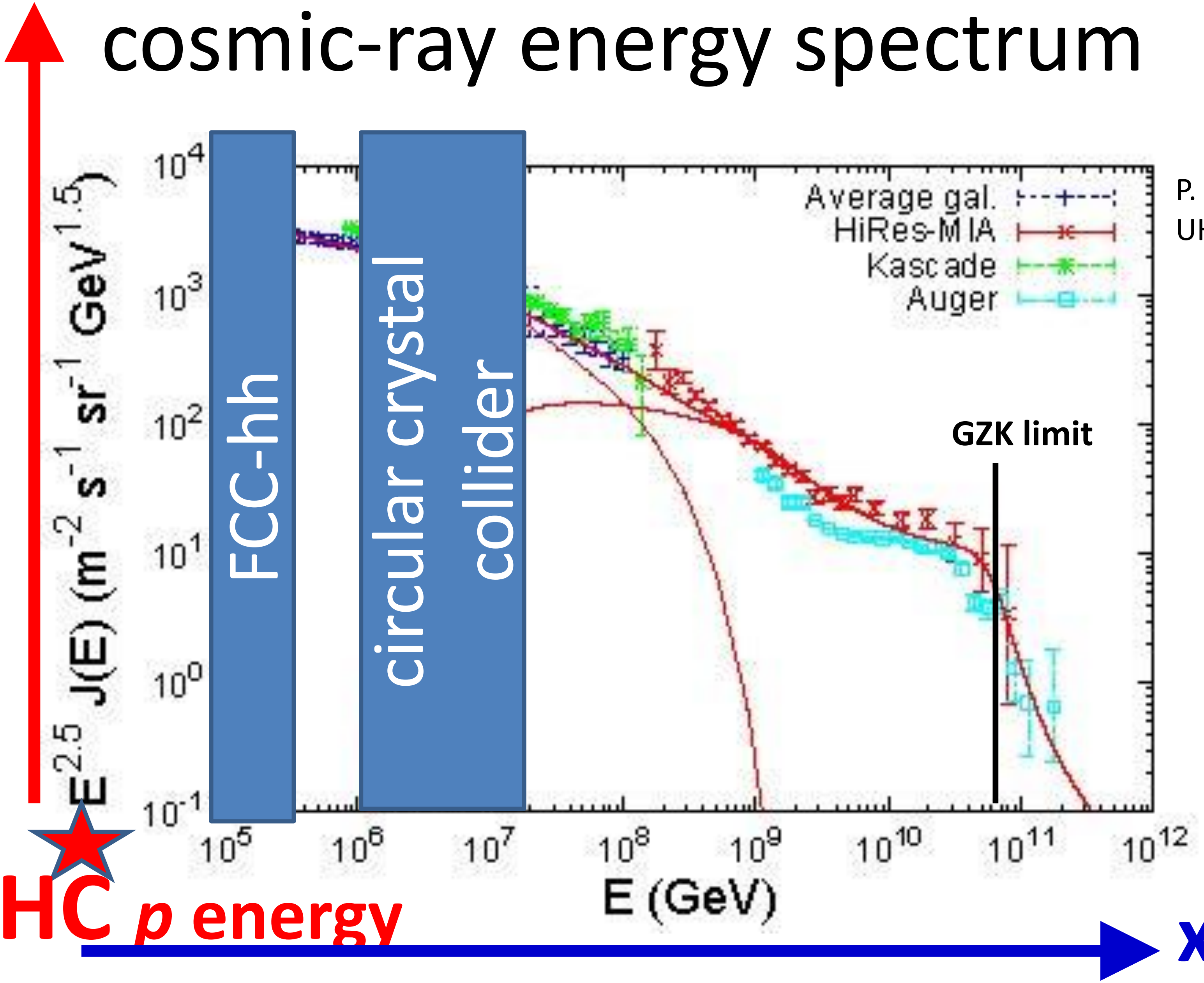
“Oh-my-God-particle”!

(kinetic) energy 3×10^{20} eV

(=3×10^{11} GeV = 300 EeV)!

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

cosmic-ray energy spectrum



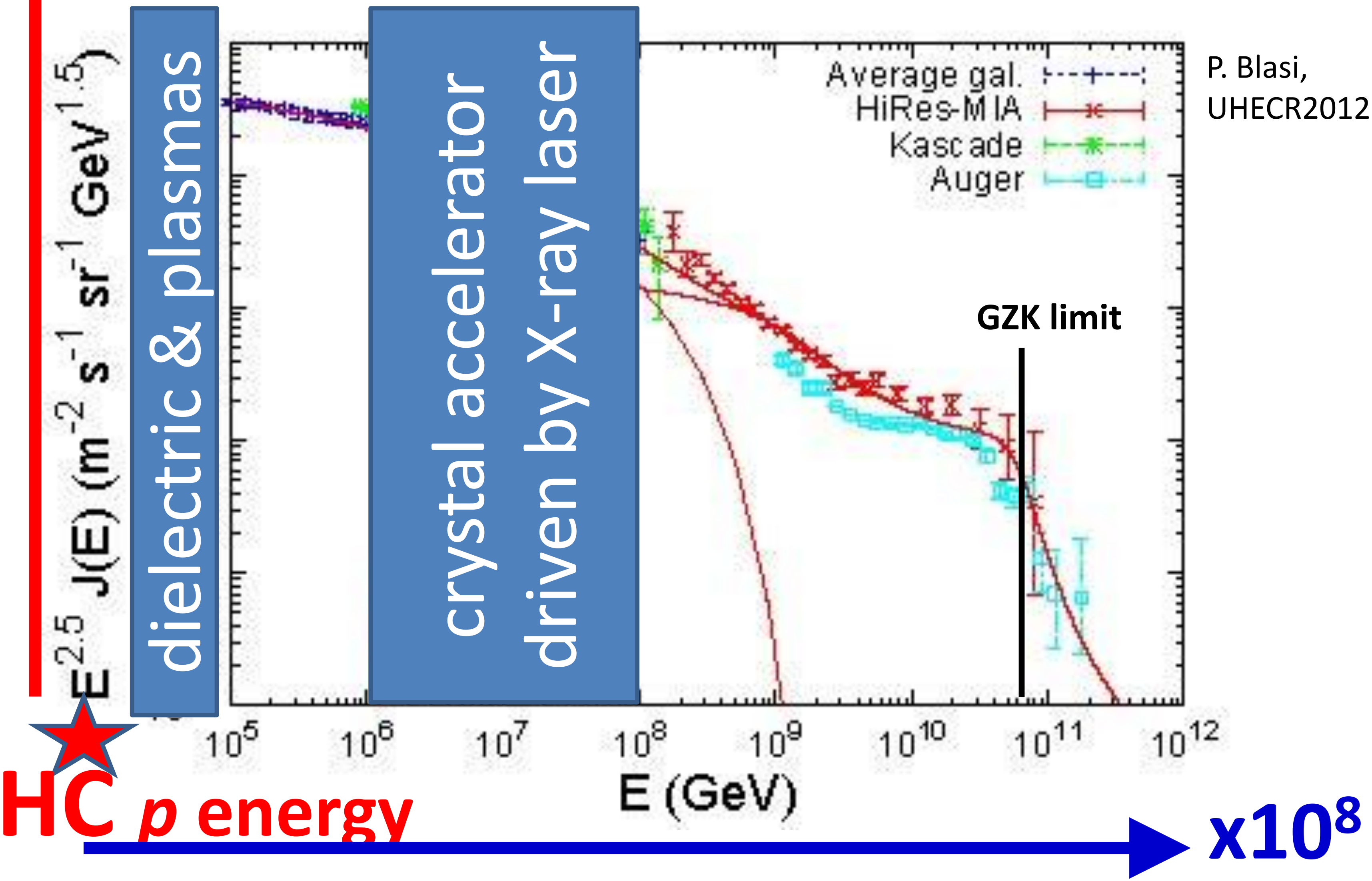
P. Blasi, UHECR2012

LHC *p* energy

x10^8

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

cosmic-ray energy spectrum



dielectric & plasmas

crystal accelerator driven by X-ray laser

P. Blasi, UHECR2012

LHC *p* energy

x10^8

ultimate limit on electromagnetic acceleration

Schwinger critical fields $E_{cr} \approx 10^{12}$ MV/m, B_{cr}=4.4 x10^{9} T

Planck scale: 10^{28} eV

“not an inconceivable task for an advanced technological society”

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

circular & linear Planck-scale colliders:
size ≈1/10 distance earth-sun

Conclusions – FCC

- bright future for accelerator-based HEP!
- we now need to start preparing 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*: attractive intermediate step towards *FCC-hh* & highly synergetic (infrastructure, time, physics, + SRF)
- *FCC-he*: complementary physics, extension of LHeC
- great worldwide interest - forming global collaboration

Conclusions – beyond FCC

- several different routes to 1 PeV collisions

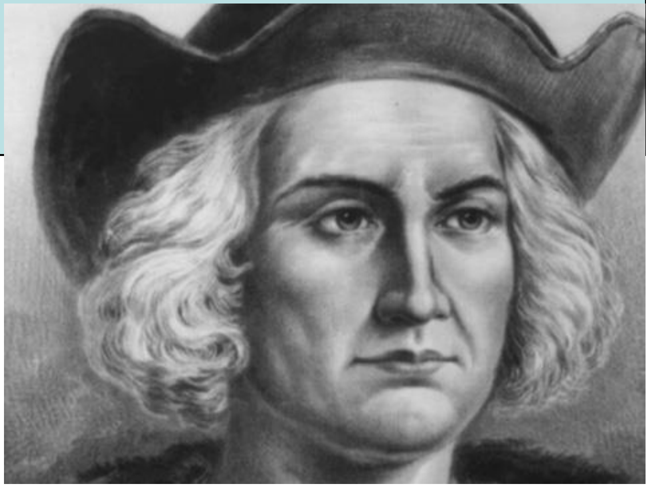
  e.g. linear path: DWAC→ XRCMC

  circular path: FCC-ee→FCC-hh→CCC
- crystals are key for both: bending and/or acceleration
- eventually outer-space solar-system accelerator will be needed to reach the Planck scale

New Physics?

"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"

- Spanish Royal Commission, rejecting Christopher Columbus' proposal to sail west, < 1492



J. Ellis