Beam Dynamics Issues in the FCC

Frank Zimmermann, CERN

HB2016, Malmö, 6 July 2016

on behalf of the FCC global design study team

W. Bartmann, M. Benedikt, M.I. Besana, R. Bruce, O. Brüning, X. Buffat, F. Burkart, H. Burkhardt, S. Calatroni, F. Cerutti, S. Fartoukh, M. Fiascaris, C. Garion, B. Goddard, W. Höfle, B. Holzer, J. Jowett, R. Kersevan, R. Martin, L. Mether, A. Milanese, T. Pieloni, S. Redaelli, G. Rumolo, B. Salvant, M. Schaumann, D. Schulte, E. Shaposhnikova, L. Stoel, C. Tambasco, R. Tomas, D. Tommasini, F. Zimmermann, **CERN**, Switzerland; G. Guillermo, **CINVESTAV** Merida, Mexico; V. Kornilov, **GSI** Darmstadt, Germany; O. Boine-Frankenheim, U. Niedermayer, **TU Darmstadt**, Germany; T. Mitsuhashi, K. Ohmi, **KEK**, Tsukuba, Japan; A. Chancé, B. Dalena, J. Payet, **CEA**, Saclay, France; P. Bambade, A. Faus-Golfe, J. Molson, **LAL** Orsay, France; J.-L. Biarrotte, A. Lachaize, **IPNO**, France; J. Fox, G. Stupakov, **SLAC**, U.S.A.;J. Abelleira, E. Cruz, A. Seryi, **JAI** Oxford, U.K.; R. Appleby, **U. Manchester**, U.K.; M. Boscolo, F. Collamati, A. Drago. **INFN-LNF**, Italy; J. Barranco, **EPFL**, Switzerland; S. Khan, B. Riemann, **TU Dortmund**, Germany, …

*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, as well as by the German BMBF*

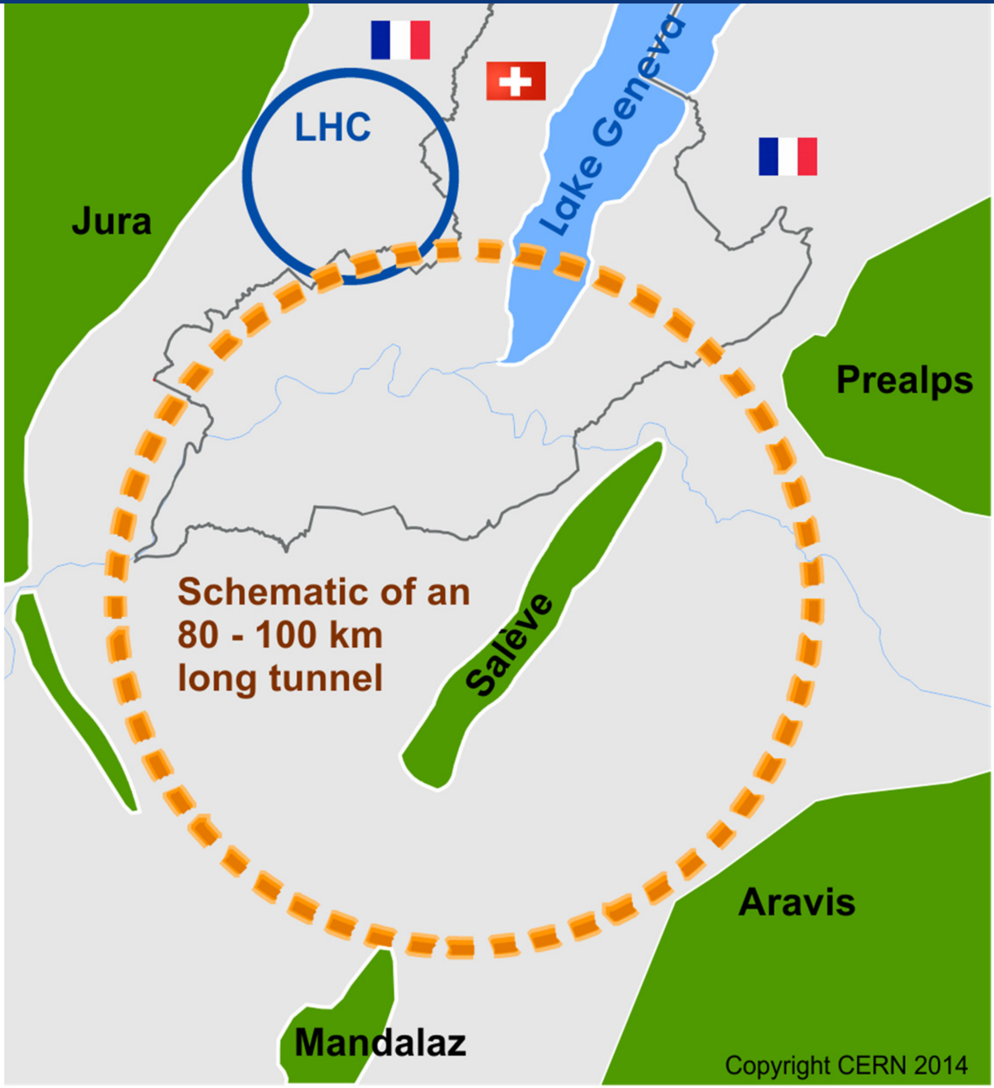
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

International FCC collaboration (CERN as host lab) to study:

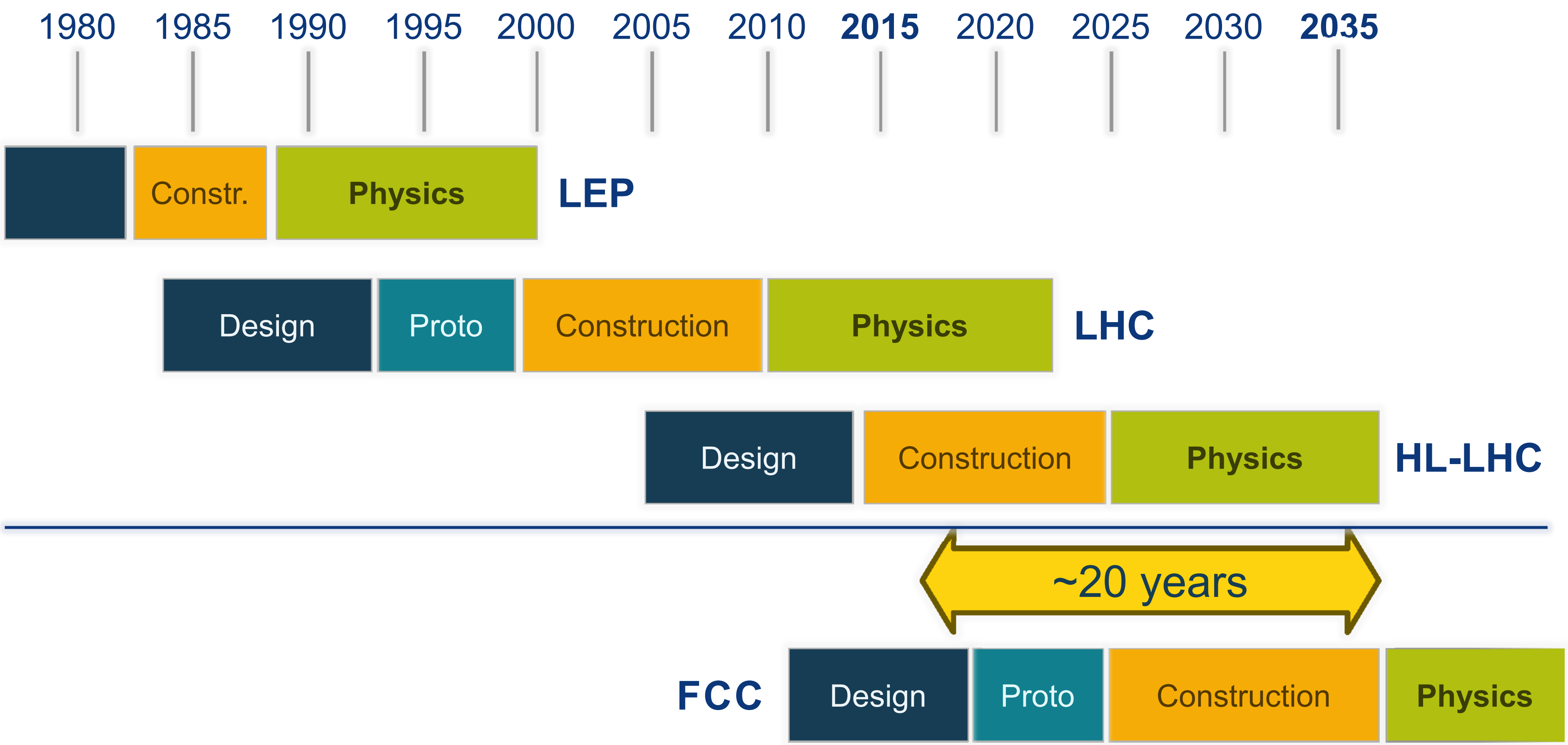
- ***pp* and *AA* collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



CERN Circular Colliders & FCC



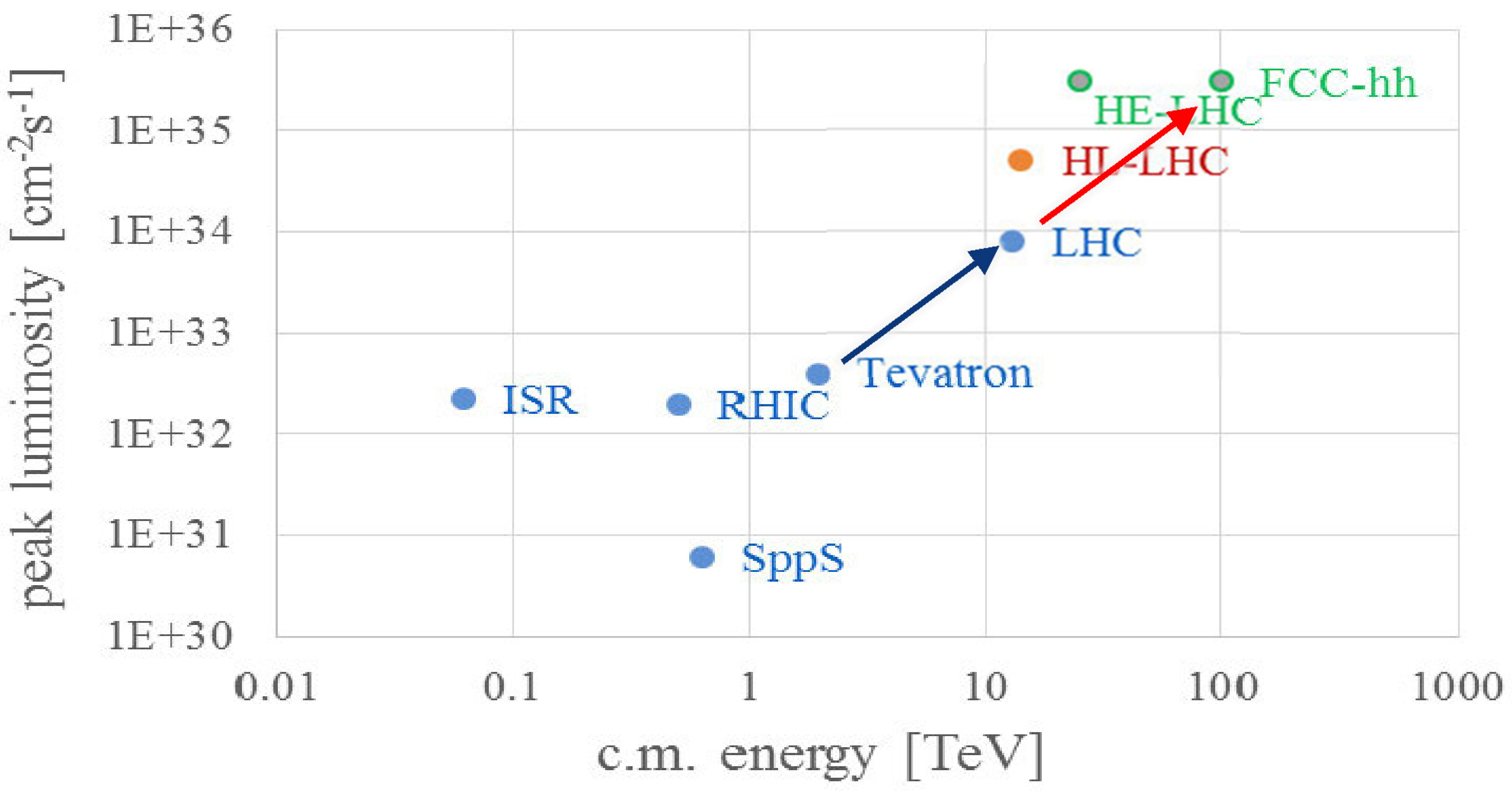
must advance fast now to be ready for the period 2035 – 2040
milestone: CDR by end 2018 for next update of European Strategy

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

*tentative

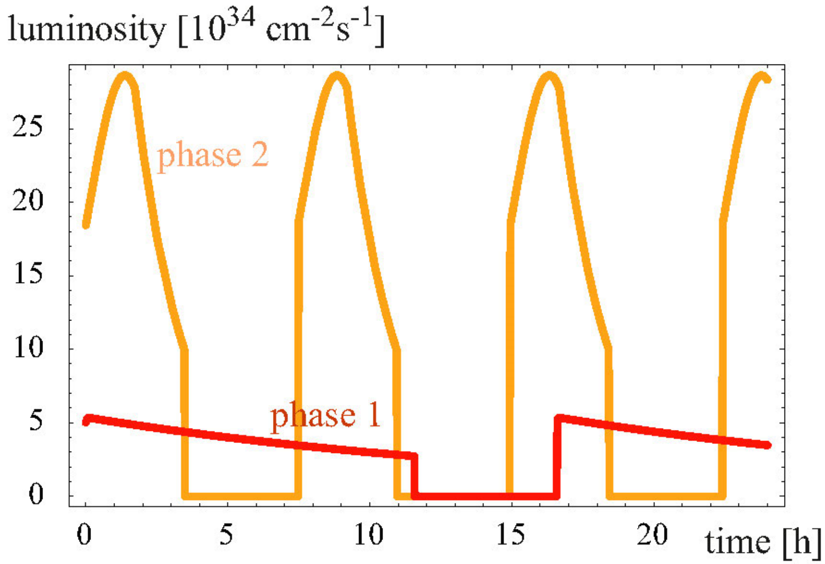
pp/p-pbar in the *L-E* plane

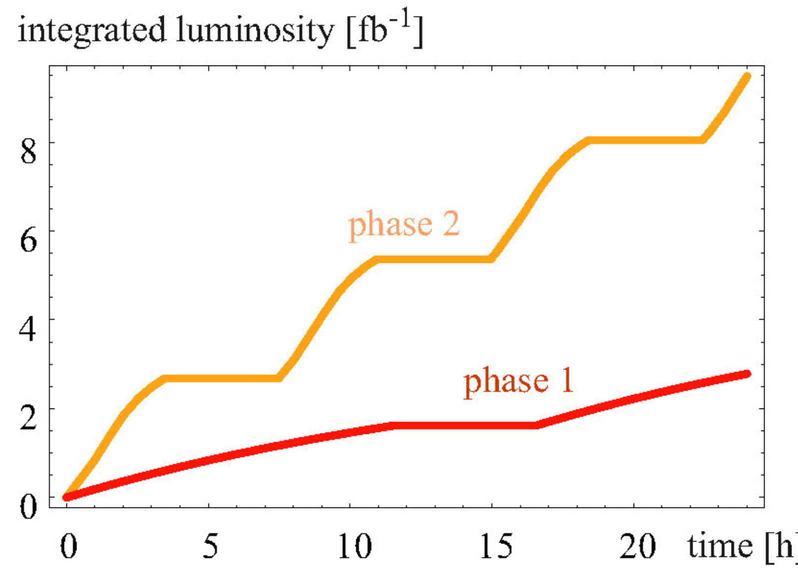


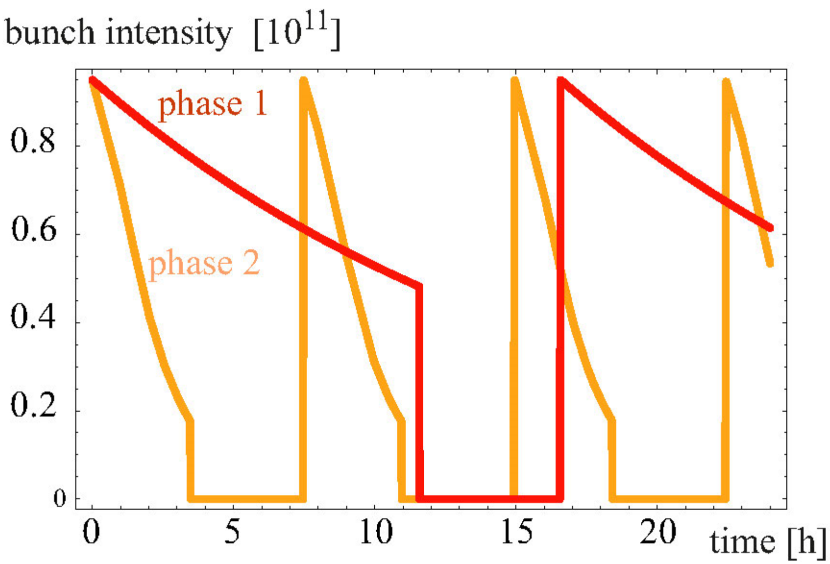
entering uncharted territories

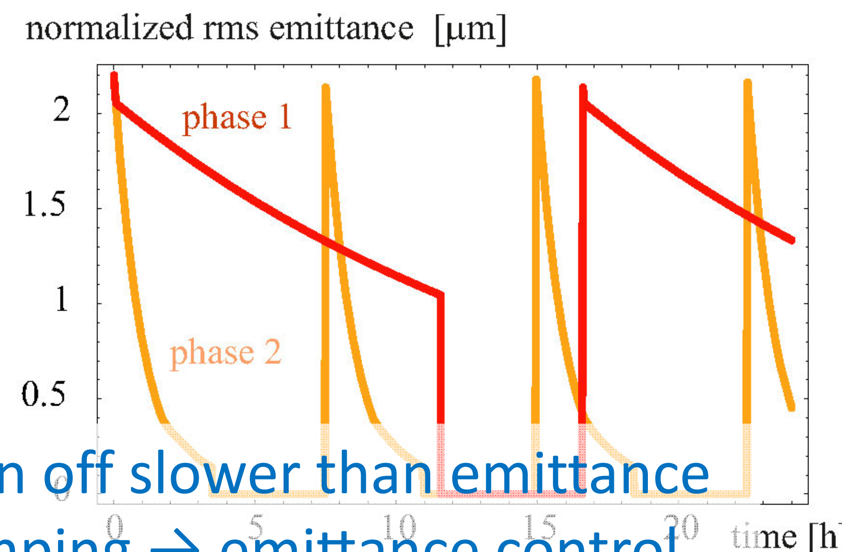
- **radiation damping**: naturally cooled hadron beams
- luminosity operation: **controlling tune shift and pile up,** optimizing integrated luminosity
- squeezing β^* with **enormous l^* and huge debris**
- **synchrotron radiation photons** – electron cloud, beam diagnostics, applications?
- **extremely low emittance**
- large circumference → instabilities
- low-energy injection? – first SC machine **accelerating through the "b3 minimum"?!**
- collimation and protection for **unprecedented beam power**
- heavy-ion collisions with **dream luminosity**

FCC-hh - 100 TeV c.m., 25 ns



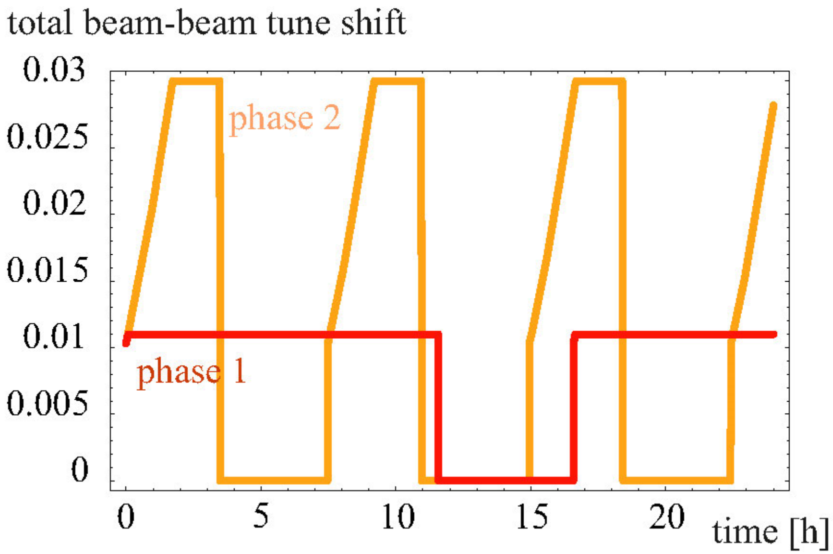




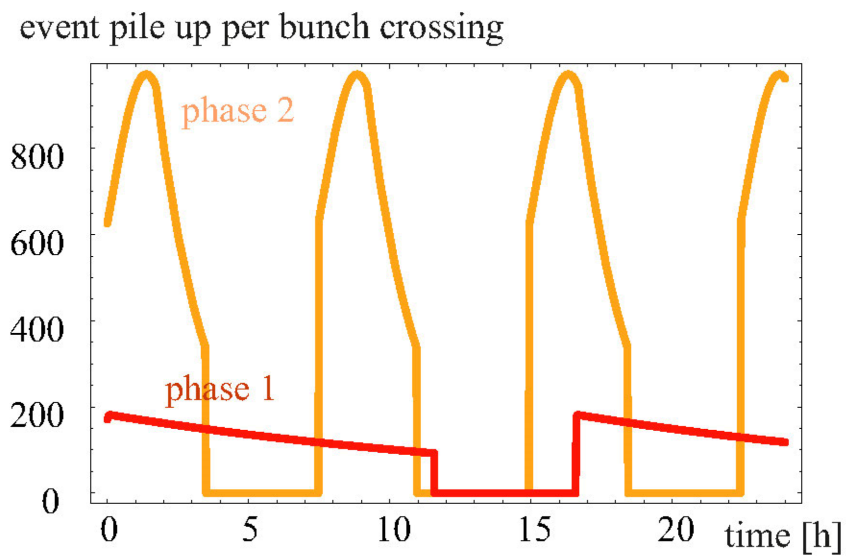


burn off slower than emittance damping → emittance control

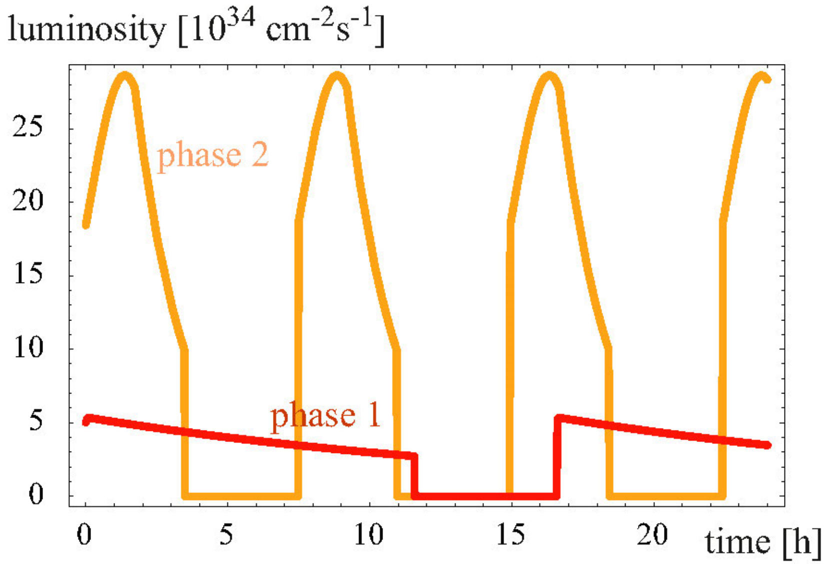
FCC-hh - 100 TeV c.m., 25 ns

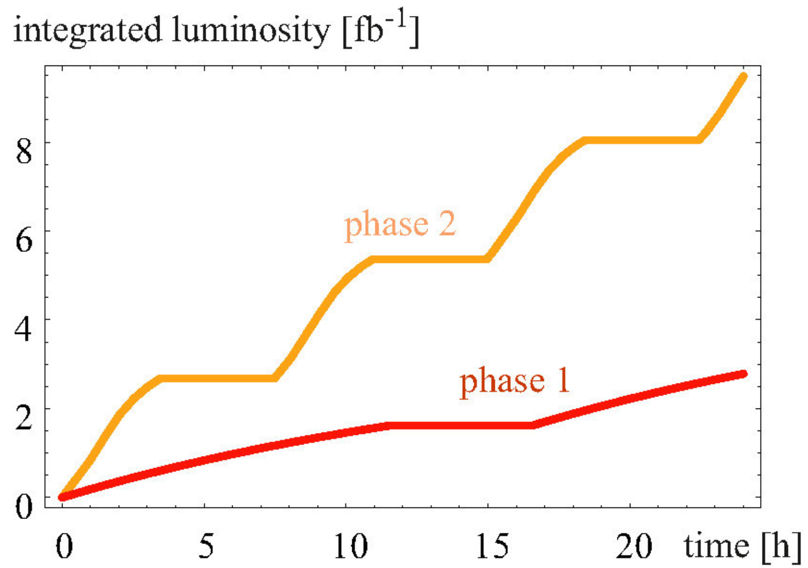


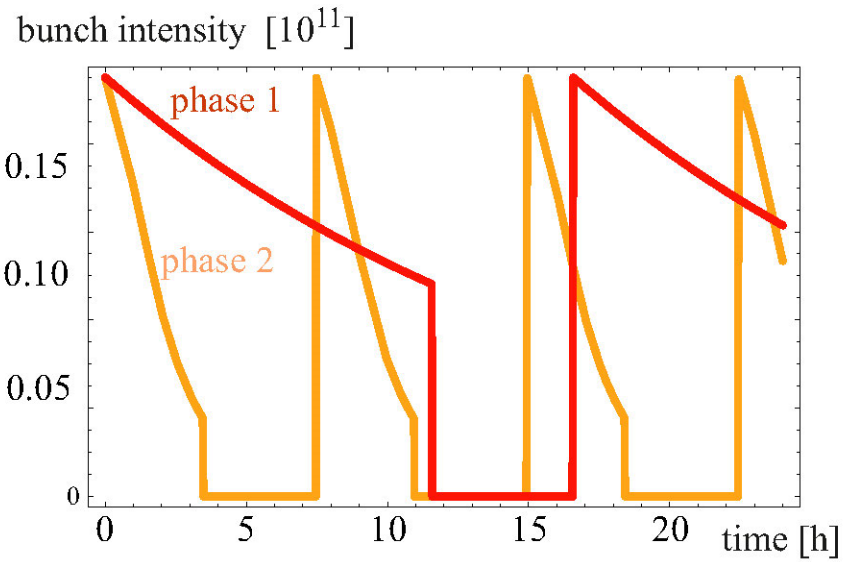
in phase 2, without (or with less) emittance control:
tune shift increases during fill

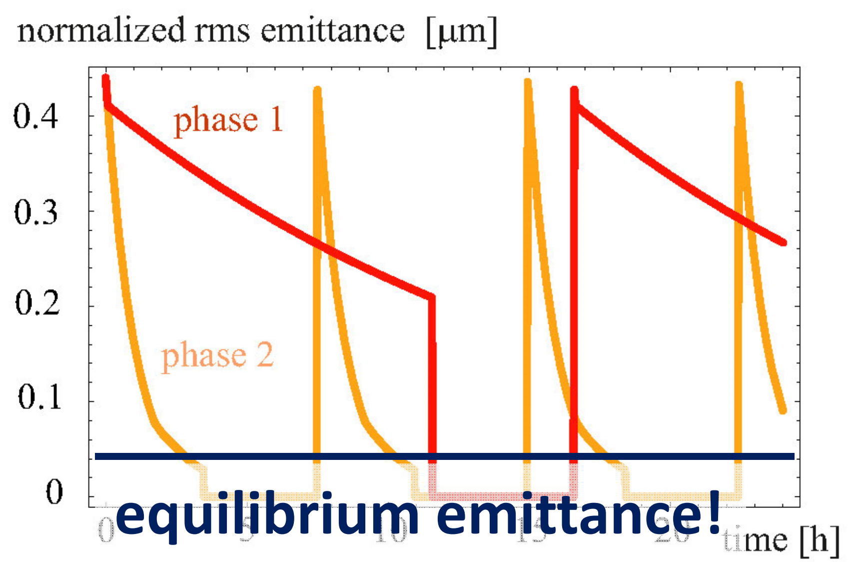


FCC-hh - 100 TeV c.m., 5 ns

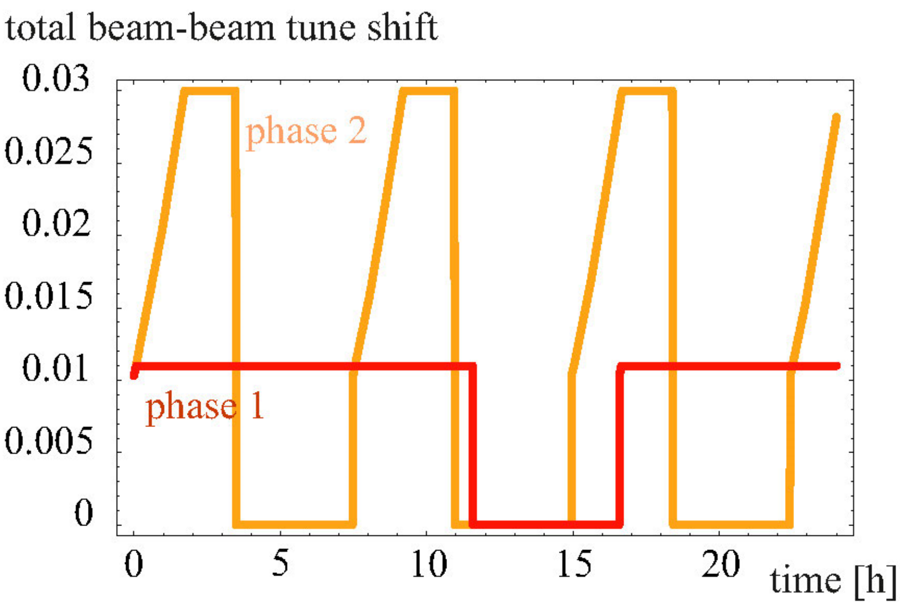




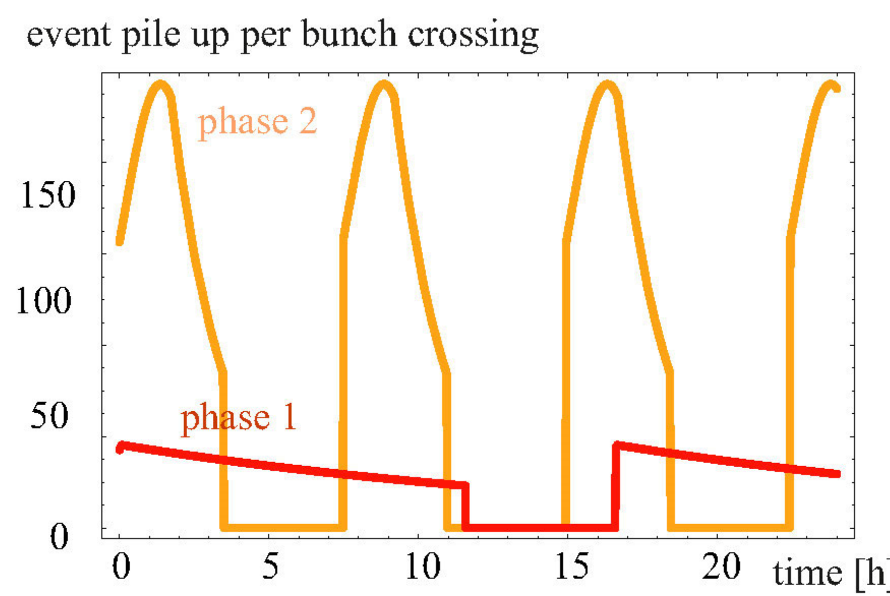




FCC-hh - 100 TeV c.m., 5 ns

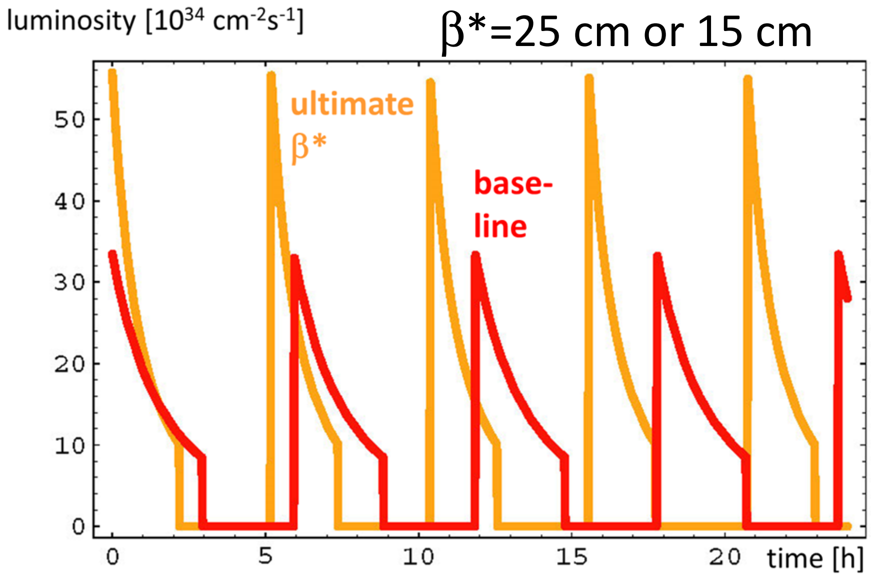


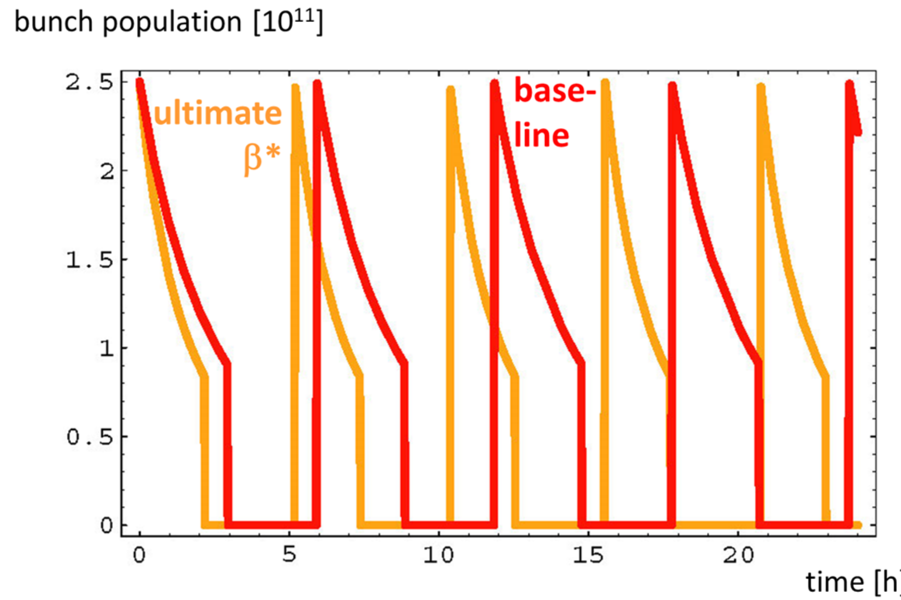
without emittance control (phase 2): tune shift increases during fill

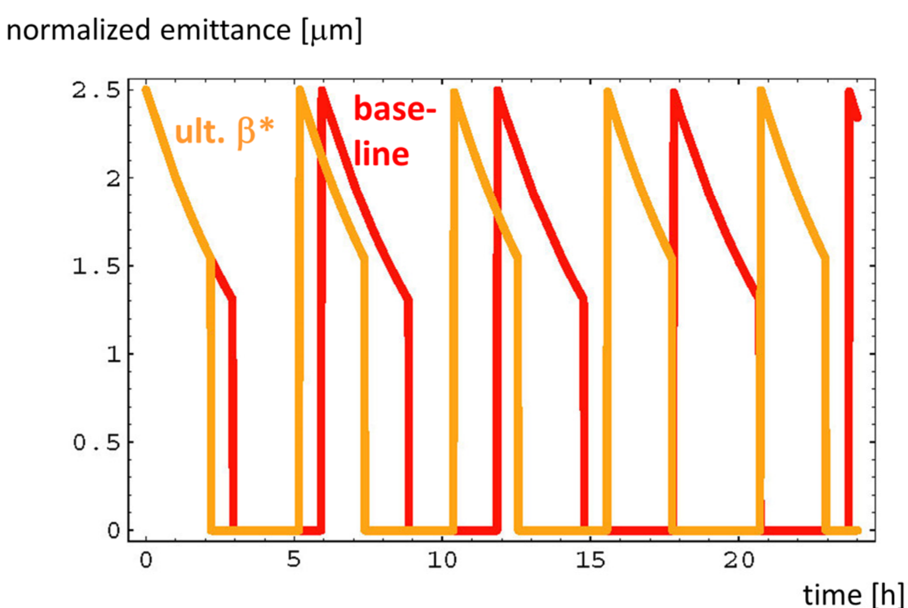


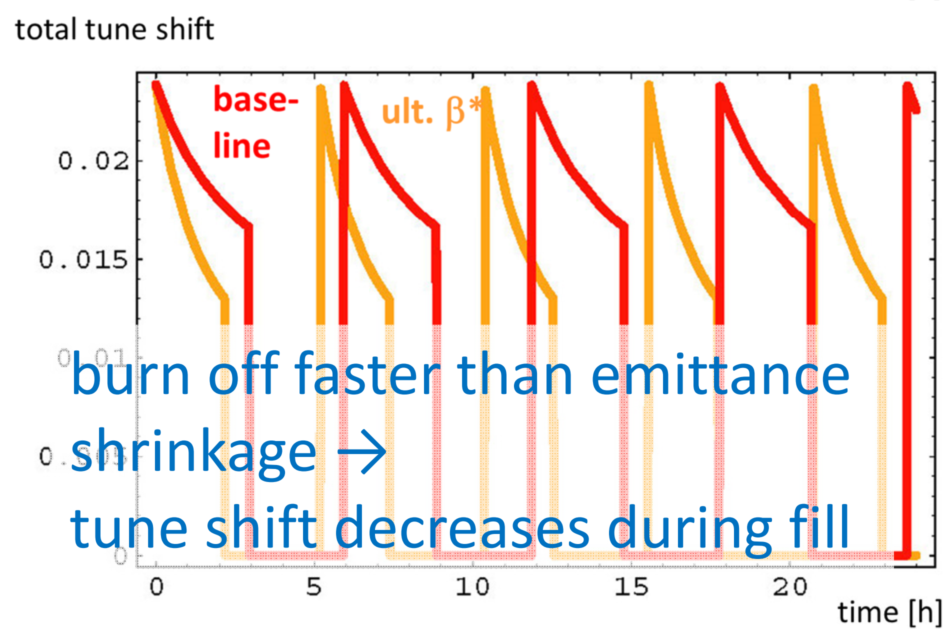
HE-LHC - 25 TeV c.m., 25 ns

β*=25 cm or 15 cm





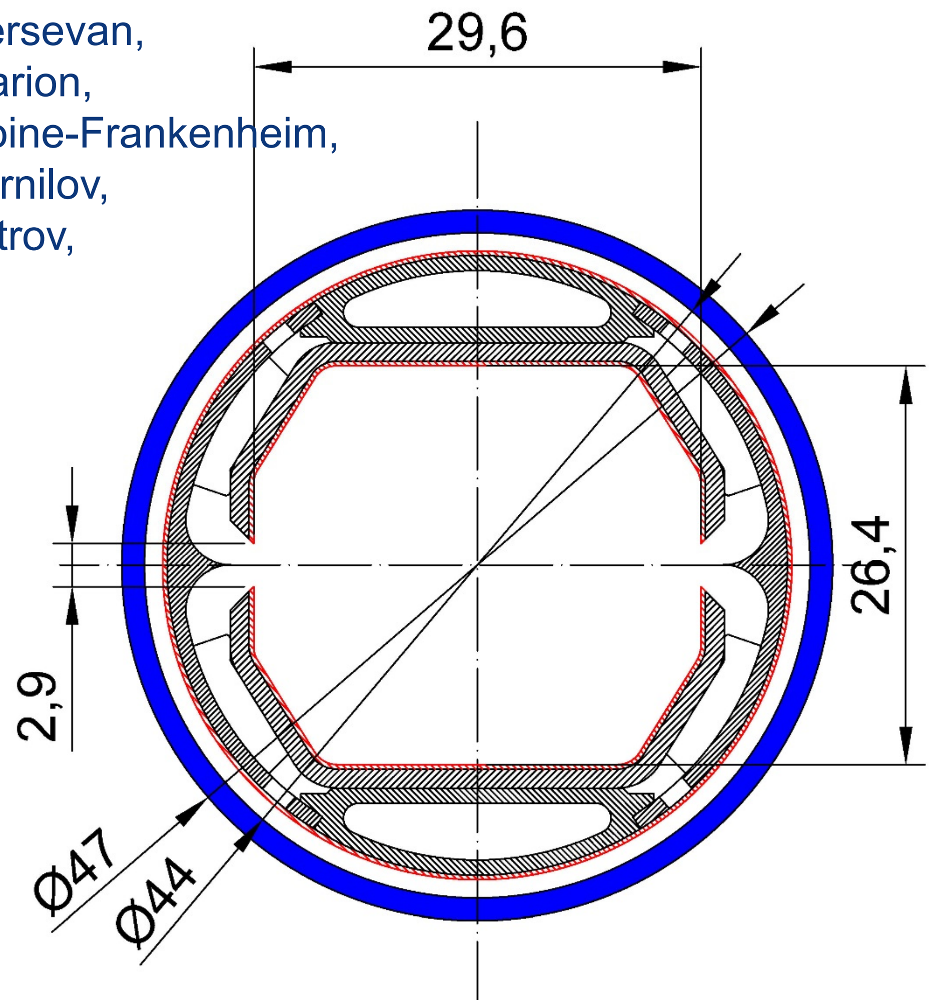




burn off faster than emittance shrinkage →
tune shift decreases during fill

handling SR, e-cloud & res. wall

R. Kersevan,
C. Garion,
O. Boine-Frankenheim,
V. Kornilov,
F. Petrov,
et al.



possible further improvements (under study):

- distributed feedbacks/ multiband feedbacks
- HTS coating to reduce the impedance

FCC-hh: ≈5 MW SR power emitted in cold arcs

beam screen at 40—60 K (LHC at 5—20 K) → better Carnot efficiency; but higher resistance → res. wall instability

slits & wedge capture and hide photons → no photoelectrons in beam pipe proper

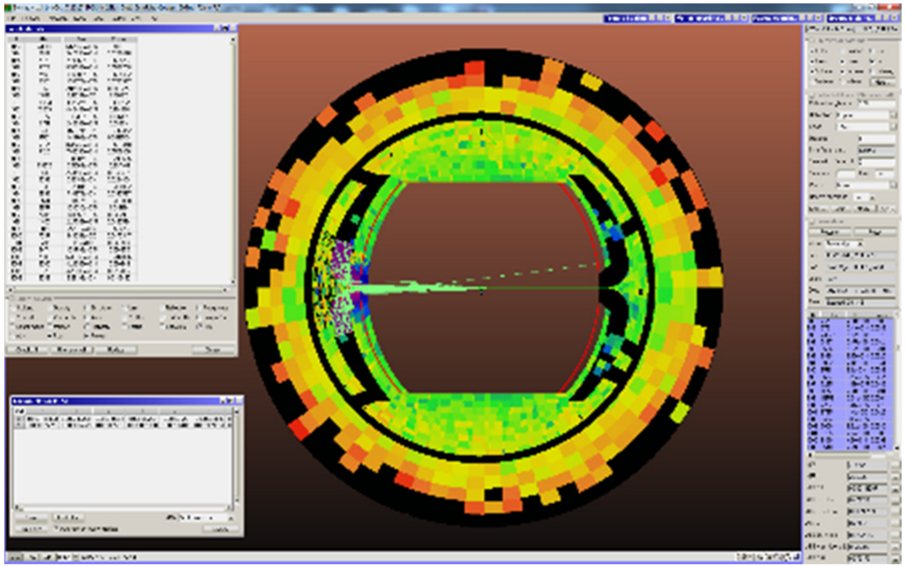
a-C coating or laser treatment to reduce SEY

beam screen development

first FCC-hh beam screen prototypes

testing 2017 at ANKA facility in Germany

simulated photon distribution



hadron collider as light sources?

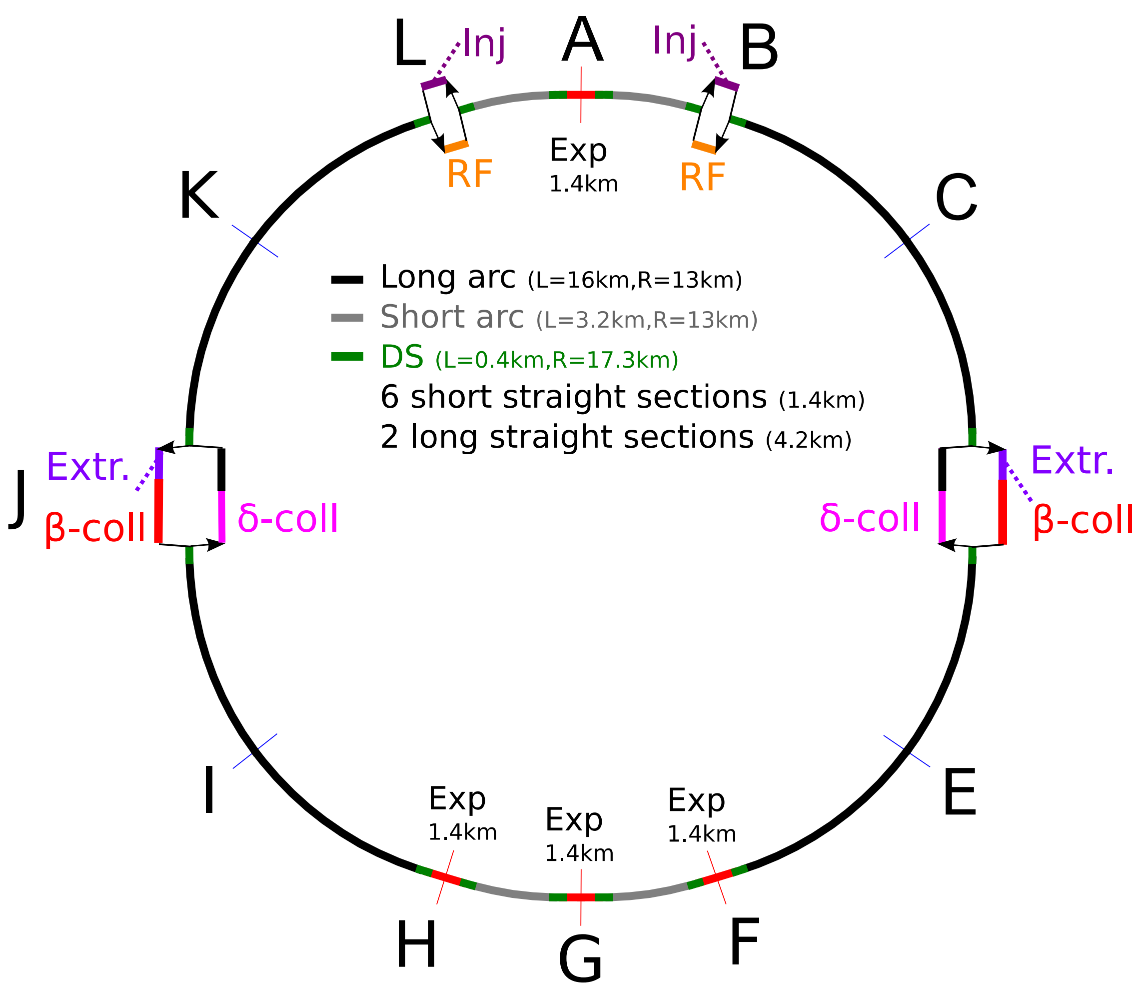
emittances and selected other parameters for LHC, HE-LHC (tentative), and FCC-hh, compared with the corresponding values at a modern electron-beam light source (MAX-IV)

parameter	FCC-hh Phase 1 (2)	HE-LHC	LHC	MAX-IV
beam energy [TeV]	50	12.5	7	0.003
bunch spacing [ns]	25, 5	25, 5	25	25
init. bunch population [10^{11}]	1.0 , .2	2.5, 0.5	1.15	0.3
init geom. rms emittance [pm]	41, 8	188, 38	500	200
final geometric rms emittance [pm]	19 (2), 4 (1)	98, 20	500	200
wave length at diffraction limit [nm]	**0.025 — 0.5,** **0.01 – 0.1**	1.2 – 2.4, **0.25-0.48**	6.3	**2.5**
arc bending radius [km]	10.4	2.8	32.8	0.019
critical photon energy [keV]	**4.3**	0.25	0.044	**3.1**

FCC-hh = the “ultimate storage ring”?!

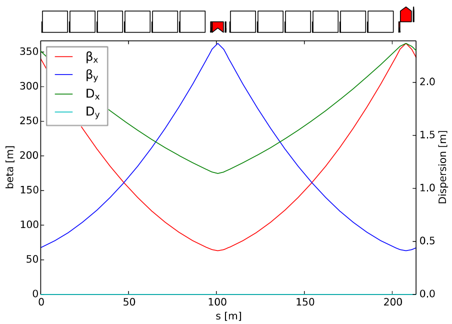
FCC-hh layout

- integrated lattice exists;
  - recent designs:
    - energy collimation
    - extraction
    - experiment
    - betatron collimation
    - injection
- first results on:
  - dynamic aperture
  - tolerances and alignment
  - detailed magnet specifications

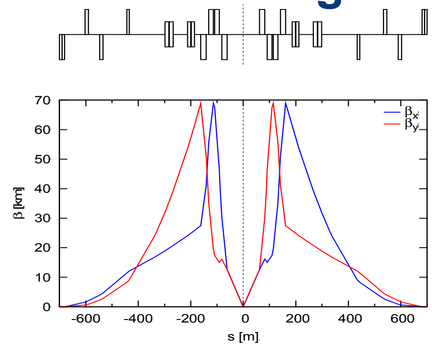


FCC-hh full-ring optics

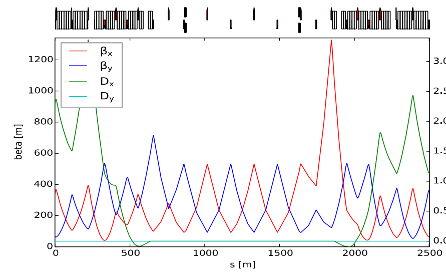
regular arc cell



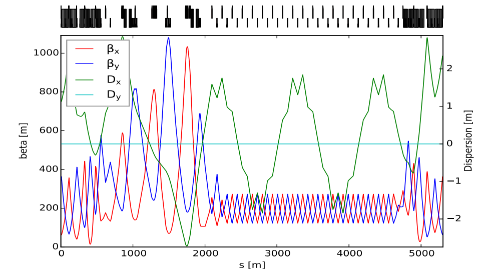
interaction region



injection with RF



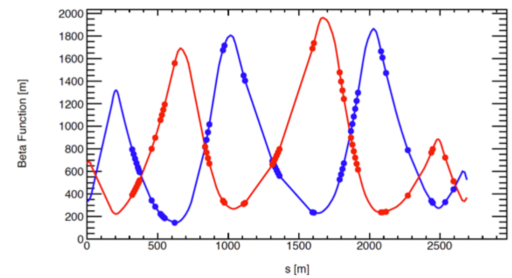
momentum collim.



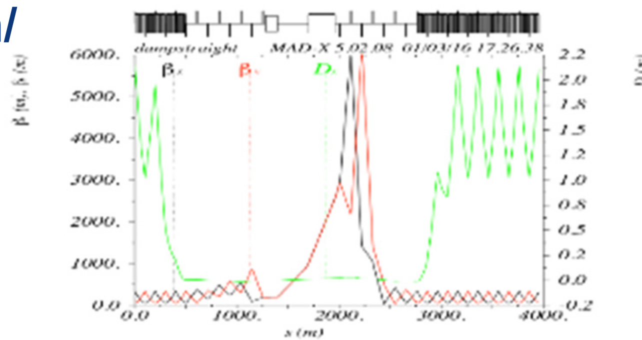
full ring lattice permits:

- beam dynamics studies
- optimisation of each insertion
- definition of system specifications (apertures, etc.)
- improvement of baseline optics and layout

betatron collimation

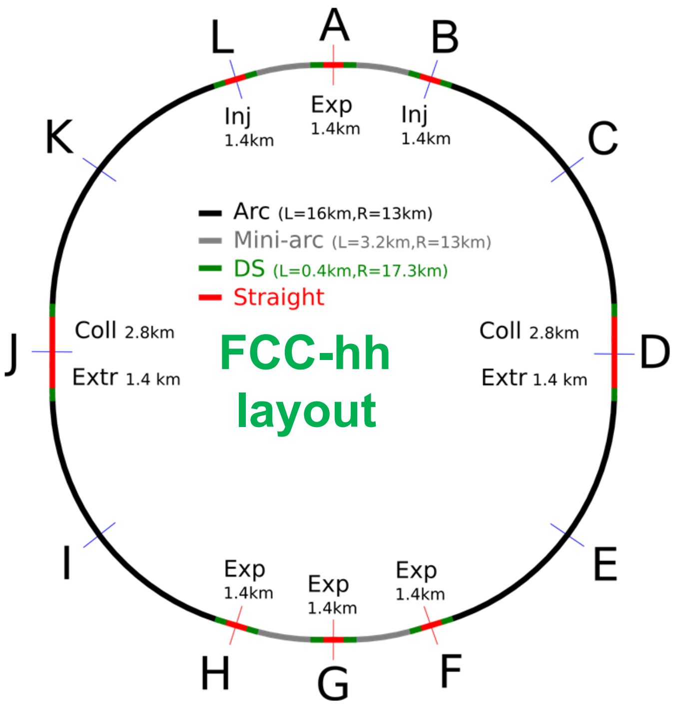


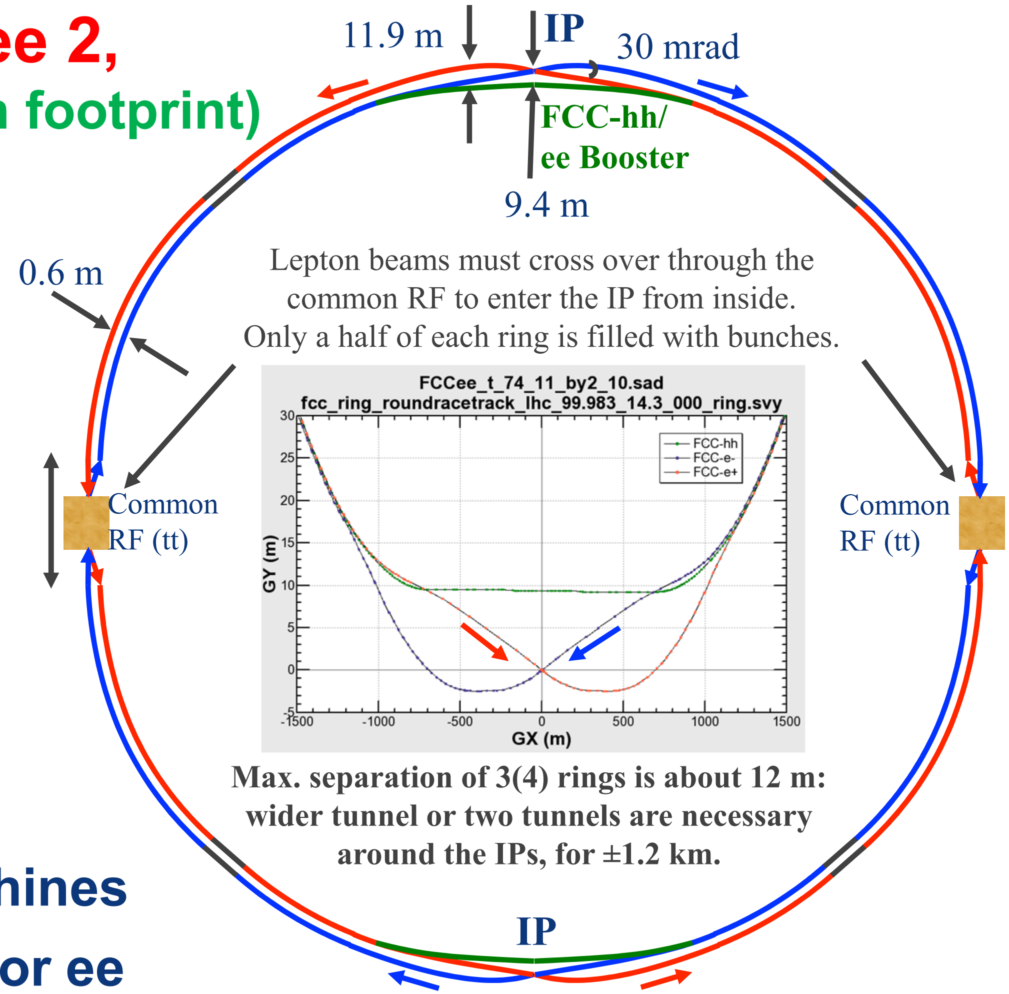
extraction/ dumping



matching layout for FCC-ee

FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)



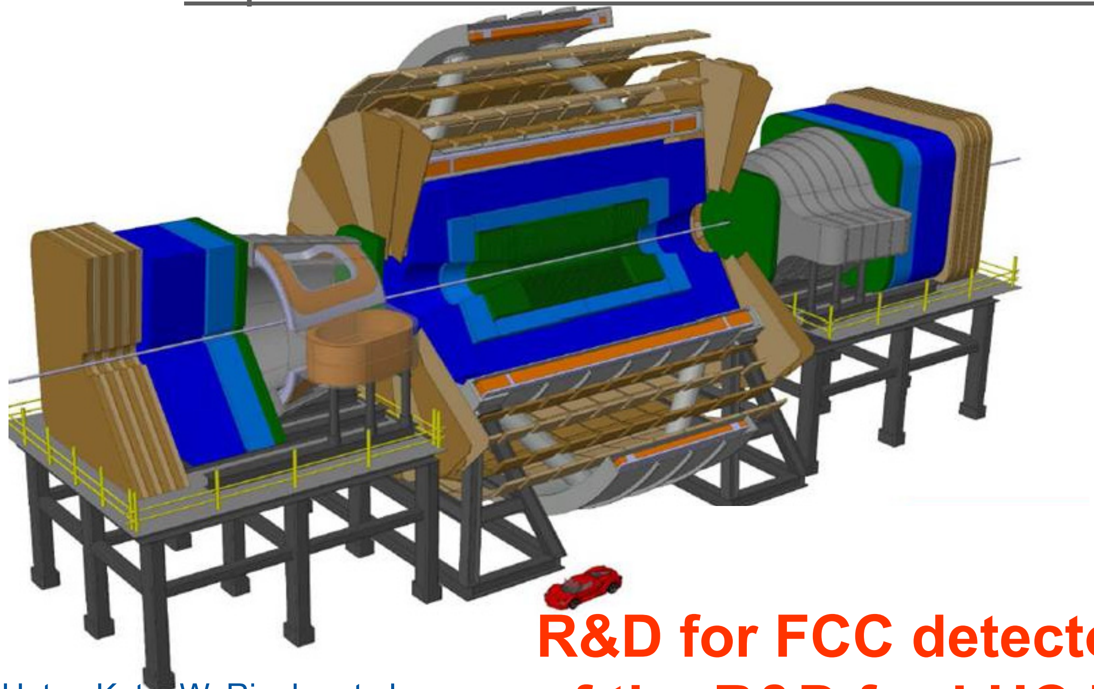


- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

K. Oide

detector concepts for 100 TeV pp

- a B=6 T, R=6 m solenoid with shielding coil and 2 dipoles has been engineered in detail. Alternative magnet systems are being studied
- parametrized detector performance model (DELPHES) is available and integrated in FCC software framework for physics simulations
  - https://twiki.cern.ch/twiki/bin/view/FCC/FccPythiaDelphes



H. ten Kate, W. Riegler et al.

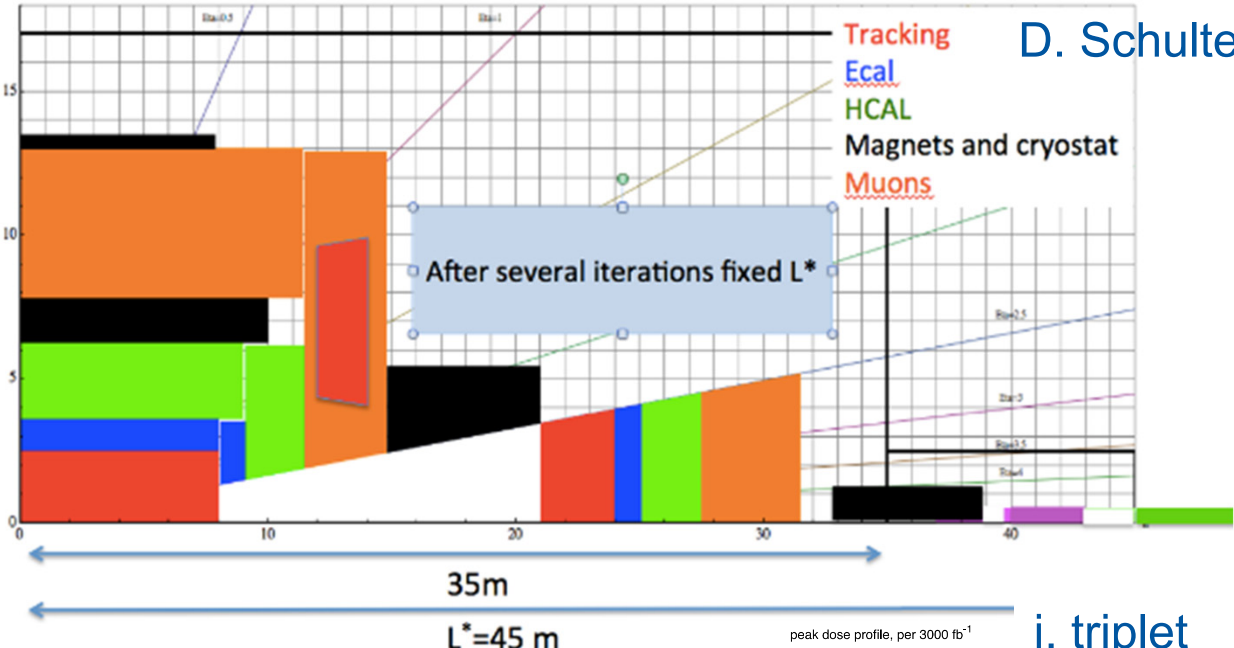
some design challenges:

- large η acceptance
- radiation levels of >50 x LHC Phase II
- pileup of ~1000

R&D for FCC detectors is a natural continuation of the R&D for LHC Phase II upgrade

FCC-hh BDS & MDI

D. Schulte



design of interaction region

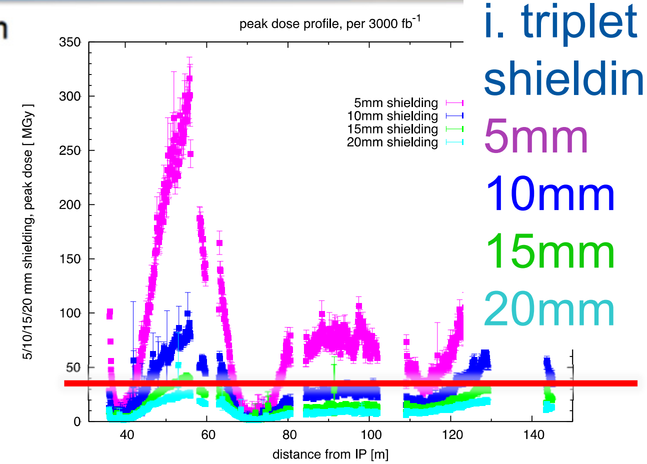
- consistent for machine and detector
  - L^*=45 m
  - integrated spectrometer and compensation dipoles
- optics with long triplet with large aperture
  - helps distributing collision debris
  - more beam stay clear

proton losses in dispersion suppressor are an issue

radiation dose for final quadrupoles

dose for 3000 fb^{-1}

30 MGy = present limit



i. triplet shielding

5mm

10mm

15mm

20mm

hadron-collider beam power

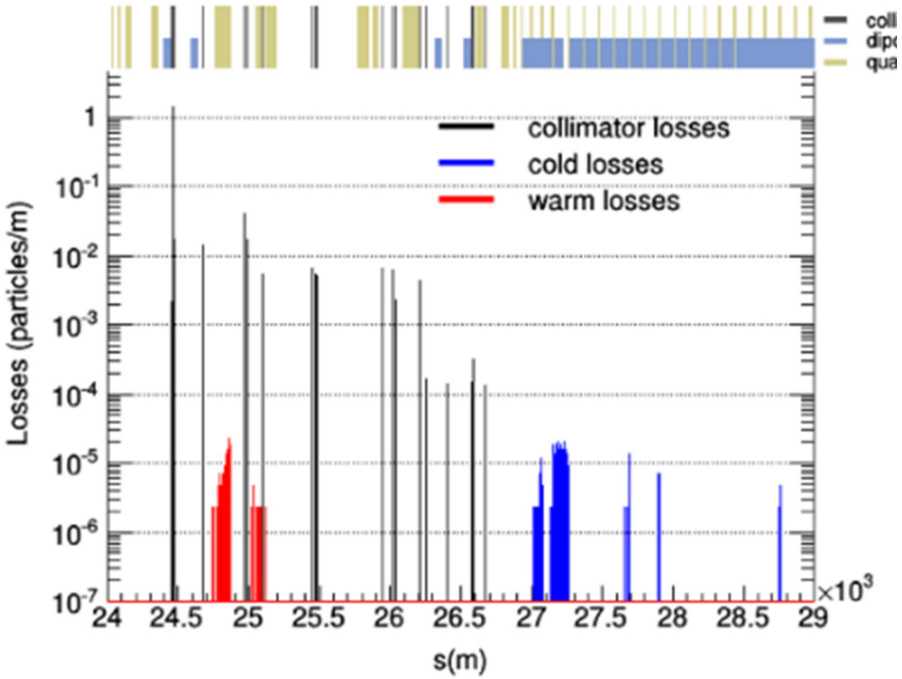
Collider	c.m. energy [TeV]	P_{el}: tot. el. power [MW]	P_b: IP beam power [GW]	luminosity L [$nb^{-1}s^{-1}$]	P_b/P_{el}	L/P_{el} (/IP) [$nb^{-1}s^{-1}$ / MW]
LHC	13.0	~150	8000	10	50000	0.07
FCC-hh	100.0	500 (target)	50000	300 (phase 2)	100000	0.6
SPPC	70.2	600 (guess)	70000	120	120000	0.2

J. Stadlmann

FCC-hh collimation

aperture model of machine established

system design developed
first efficiency studies
- found problem with dispersion suppressor losses
- heat load on primary collimators close to the limit



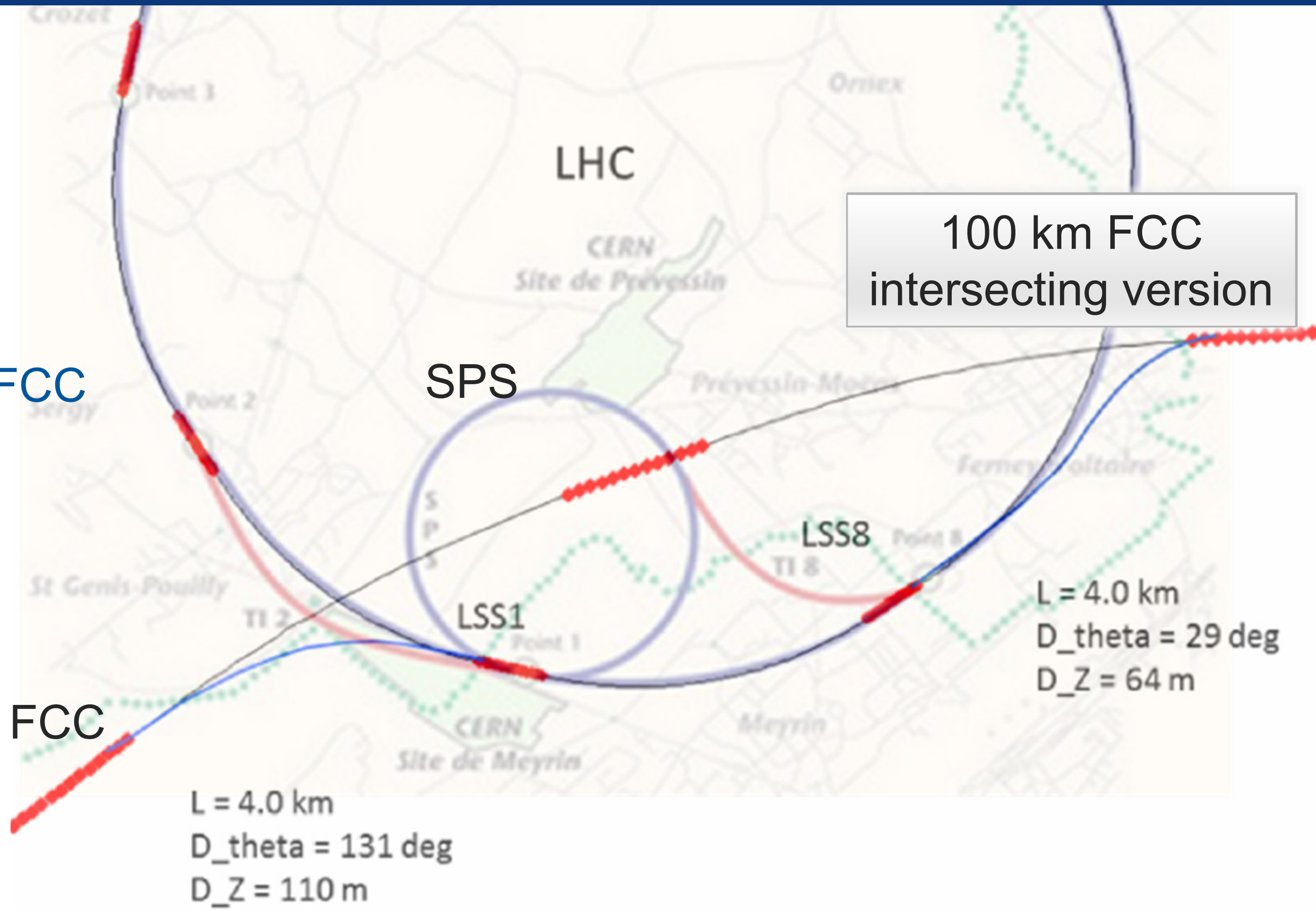
next:
need to study load on secondary collimators (expect this to be critical)
next step: shower simulations
operational robustness improvements:
crystal collimation?
hollow electron lens?
impact of 5 ns operation on design

M. Fiascaris,
S. Redaelli,
D. Schulte

FCC-hh injector studies

injector options:

- **SPS → LHC → FCC**
- SPS/$SPS_{upgrade}$ → FCC
- SPS -> FCC booster → FCC

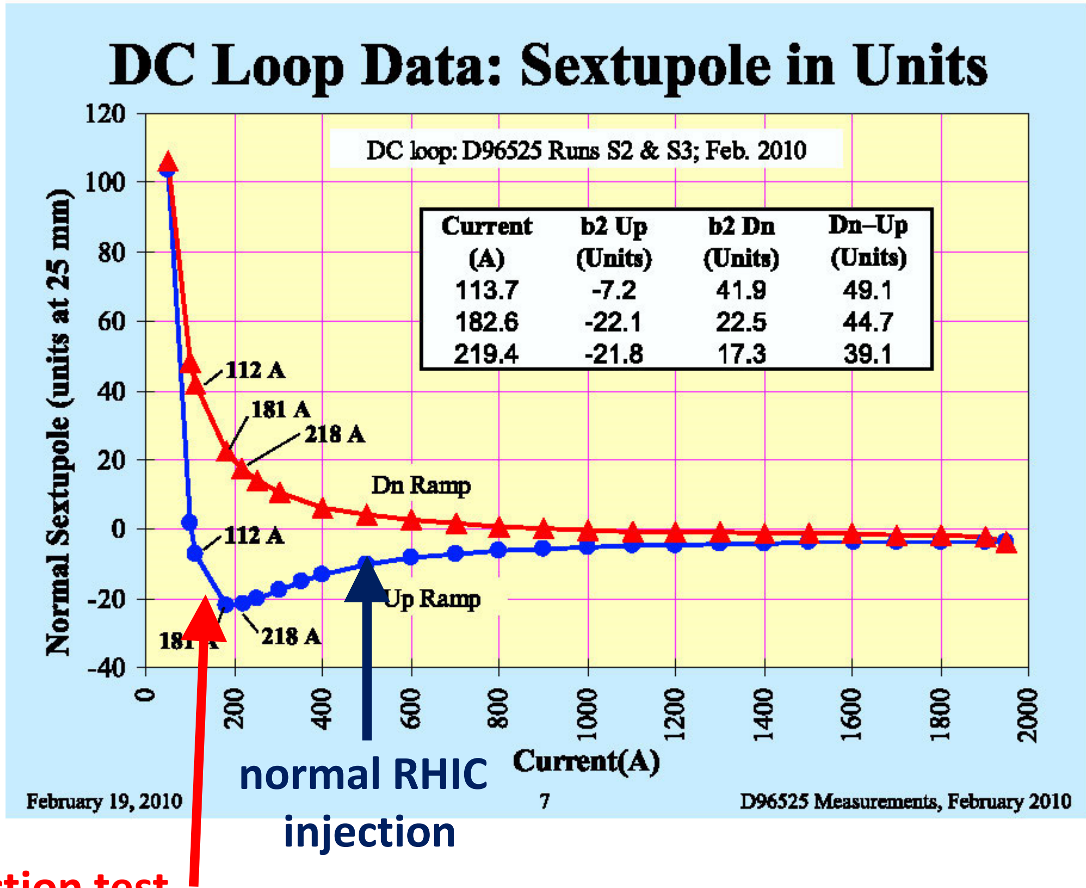


current baseline is to fully re-use the existing CERN accelerator complex

- **injection energy 3.3 TeV from LHC**

lower injection energy (1.5 TeV)?

beam studies proposed at LHC (injection at 225 GeV instead of 450 GeV) and at RHIC (*p* inj. at 7.3 GeV)



C. Montag

FCC-hh as A-A collider

	Pb-Pb	Pb-p
beam energy [TeV]	4100	50
c.m. energy/nucleon pair [TeV]	39.4	62.8
no. bunches / beam	2072	2072
IP beta function [m]	1.1	1.1
long. emit. rad. damping time [h]	**0.24**	0.5
init. luminosity [10^{27} cm^{-2}s^{-1}]	24.5	2052
peak luminosity [10^{27} cm^{-2}s^{-1}]	**57.8**	**9918**

based on existing LHC complex; fast radiation damping; secondary beams from IP require dedicated collimators,…

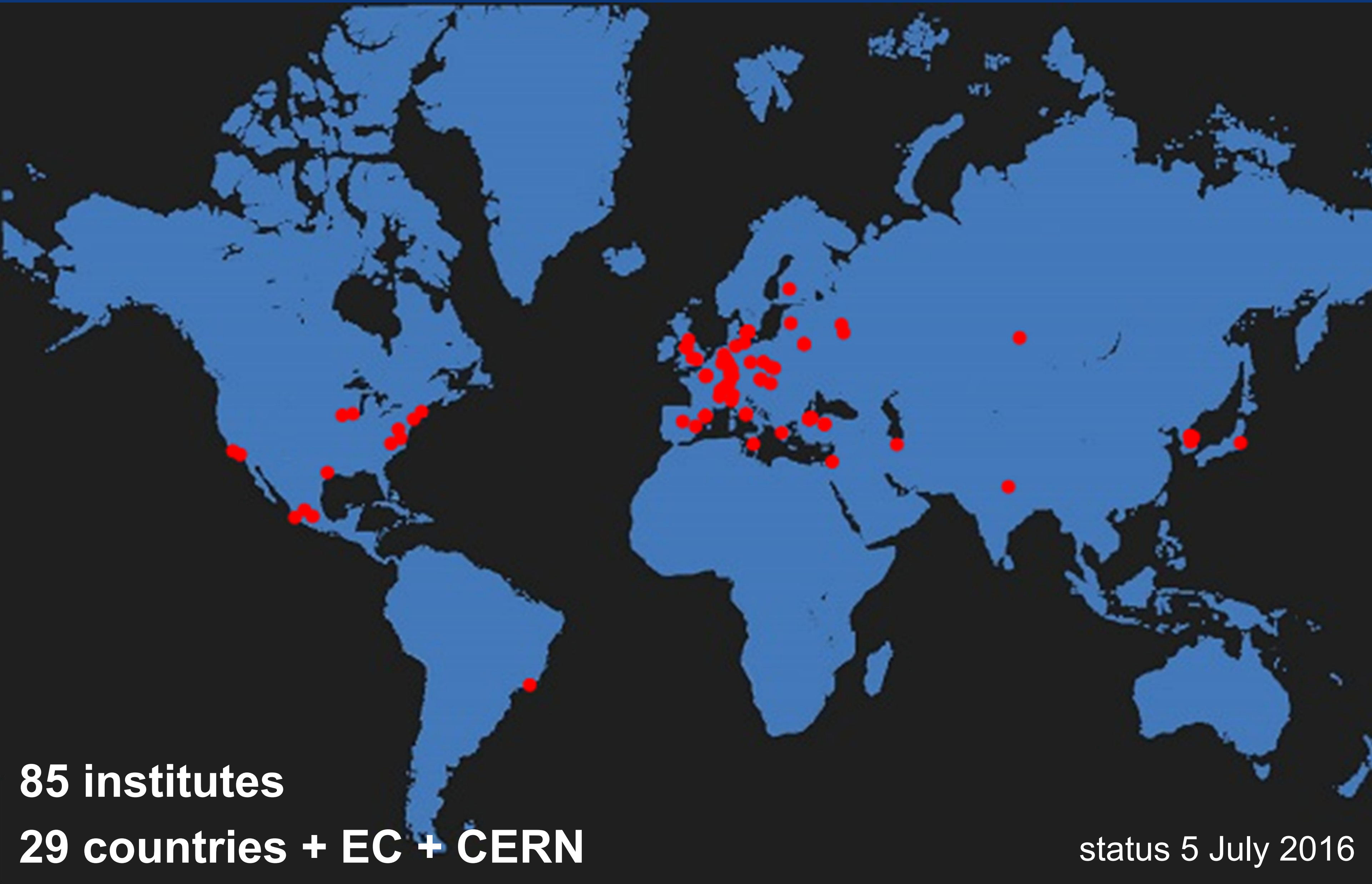
J. Jowett, M. Schaumann

M. Schaumann, "Potential performance for Pb-Pb, p-Pb, and p-p collisions in a future circular collider, Phys. Rev. ST Accel. Beams 18, 091002 (2015).
A. Dainese et al., "Heavy ions at the Future Circular Collider," contribution to forthcoming CERN Report on Physics at FCC-hh, http://arxiv.org/abs/1605.01389 .

conclusions

- future hadron colliders like FCC-hh and HE-LHC will enter new parameter regimes
  - ✓ novel challenges as well as novel opportunities in beam dynamics
  - ✓ innovative technological approaches
- rapidly growing global FCC collaboration is aiming at a cost-effective design with optimized performance
- contributions & ideas warmly welcome

FCC International Collaboration



85 institutes

29 countries + EC + CERN

status 5 July 2016

FCC Collaboration Status

85 collaboration members + EC + CERN as host

ALBA/CELLS, Spain
Ankara U., Turkey
Aydin U, Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
Cinvestav, Mexico
CNRS, France
CNR-SPIN, Italy
Cockcroft Institute, UK
U Colima, Mexico
UCPH Copenhagen, Denmark
CSIC/IFIC, Spain
TU Darmstadt, Germany
TU Delft, Netherlands
DESY, Germany
DOE, Washington, USA
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland
UT Enschede, Netherlands
ESS, Sweden
U Geneva, Switzerland

Goethe U Frankfurt, Germany
GSI, Germany
GWNU, Korea
U. Guanajuato, Mexico
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
ISMAB-CSIC, Spain
IFAE, Spain
IFIC-CSIC, Spain
IIT Kanpur, India
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Isikun, Turkey
Istanbul University, Turkey
JAI, UK
JINR Dubna, Russia
Jefferson LAB, USA
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany

KU, Seoul, Korea
Korea U Sejong, Korea
U Liverpool, UK
U Lund, Sweden
U Malta, Malta
MAX IV, Sweden
MEPhI, Russia
UNIMI, Milan, Italy
MIT, USA
Northern Illinois U, USA
NC PHEP Minsk, Belarus
OIU, Turkey
Okan U, Turkey
U Oxford, UK
PSI, Switzerland
U. Rostock, Germany
RTU, Riga, Latvia
UC Santa Barbara, USA
Sapienza/Roma, Italy
U Siegen, Germany
U Silesia, Poland
U Stuttgart, Germany
TAU, Israel
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wigner RCP, Budapest, Hungary
Wroclaw UT, Poland

status 5 July 2016

FCC Week 2015

IEEE International Future Circular Collider Conference

March 23 - 27, 2015 | Washington DC, USA

First FCC Week Conference

Washington DC 23-27 March 2015

Organising & Scientific Program Committee:

G. Apollinari (FNAL)	L.K. Len (DOE)
N. Arkani-Hamed (IAS Princeton)	E. Levichev (BINP)
A. Ball (CERN)	J. Lykken (FNAL)
T. Barklow (SLAC)	M. Mangano (CERN)
W. Barletta (MIT)	S. Nagaitsev (FNAL)
M. Benedikt (CERN)	T. Ogitsu (KEK)
A. Blondel (U. Geneva)	K. Oide (KEK)
F. Bordry (CERN)	V. Palmieri (INFN LNL)
[illegible] (CERN)	A. Patwa (DOE)
O. Bruning (CERN)	F. Perez (ALBA-CELLS)
W. Chou (FNAL,IHEP)	C. Potter (CERN)
P. Collier (CERN)	Q. Qin (IHEP)
E. Delucinge (CERN)	R. Rimmer (JLAB)
M. D'Onofrio (U. Liverpool)	T. Roser (BNL)
J. Ellis (King's College)	L. Rossi (CERN)
F. Gianotti (CERN)	D. Schulte (CERN)
B. Goddard (CERN)	M. Seidel (PSI)
S. Gourlay (LBNL)	A. Seryi (JAI)
C. Grojean (ICREA)	B. Strauss (DOE)
J. Gutleber (CERN)	[illegible]
[illegible] (Cornell U.)	R. Sundrum (U. Maryland)
J. Incandela (UCSB)	S. Su (U. Arizona)
P. Janot (CERN)	M. Syphers (MSU)
E. Jensen (CERN)	L. Tavian (CERN)
J.M. Jimenez (CERN)	E. Todesco (CERN)
M. Klein (U. Liverpool)	R. Van Kooten (Indiana U.)
M. Klute (MIT)	P. Vedrine (CEA)
[illegible]	J. Wenninger (CERN)
[illegible]	U. Wienands (SLAC)
P. Lebrun (CERN)	F. Zimmermann (CERN)

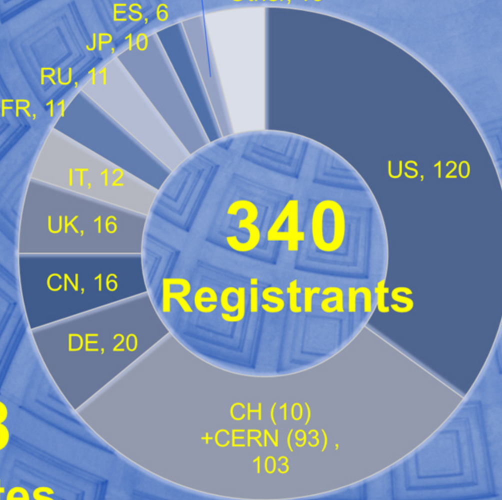
http://cern.ch/fccw2015

Further information and registration http://cern.ch/fccw2015

EuCARD² ECFA Accelerating News

U.S. DEPARTMENT OF ENERGY | Office of Science

FCC Week 2015 STATISTICS



128 Institutes

21 Countries

"head shots" from Bob Palmer (BNL)


FCCWEEK 2016
International Future Circular Collider Conference
ROME 11-15 APRIL
fccw2016.web.cern.ch
http://cern.ch/fccw2016
FCC hh ee he
ORGANISING & SCIENTIFIC PROGRAMME COMMITTEE:
G. Apollinari (FNAL)
S. Asai (U. Tokyo)
A. Ball (CERN)
A. Ballarino (CERN)
B. Barletta (MIT)
M. Benedikt (CERN)
A. Blondel (U. Geneva)
F. Bordry (CERN)
M. Boscolo (INFN LNF)
L. Bottura (CERN)
O. Brüning (CERN)
O. Brunner (CERN)
Y. Cai (SLAC)
P. Camarri (U. Tor Vergata)
P. Campana (INFN LNF)
F. Casarin (INFN LNF)
P. Charitos (U. Puebla)
P. Collier (CERN)
E. Delucinge (CERN)
J. Ellis (King's College)
B. Goddard (CERN)
S. Gourlay (LBNL)
C. Grojean (DESY)
J. Gutleber (CERN)
J. Hadre (CERN)
G. Hoffstaetter (U. Cornell)
J. Incandela (UC Santa Barbara)
K. Jakobs (U. Freiburg)
P. Janot (CERN)
E. Jensen (CERN)
J.M. Jimenez (CERN)
M. Klein (U. Liverpool)
M. Klute (MIT)
R. Van Kooten (U. Indiana)
A. Lankford (UC Irvine)
E. Levichev (BINP)
J. Lykken (FNAL)
M. Mangano (CERN)
V. Mertens (CERN)
B. Di Micco (U. Roma Tre)
M. Migliorati (U. Sapienza)
H. Murayama (U. Tokyo)
S. Nagaitsev (FNAL)
A. Nisati (INFN Roma)
T. Ogitsu (KEK)
K. Oide (KEK)
M. D'Onofrio (U. Liverpool)
V. Palmieri (INFN LNL)
F. Paolucci (U. Roma Tre)
Y. Papaphilippou (CERN)
A. Patwa (DOE)
F. Perez (ALBA-CELLS)
L. Pontecorvo (INFN Roma)
C. Potter (CERN)
Q. Qin (IHEP)
M. Rescigno (INFN Roma)
W. Riegler (CERN)
U. van Rienen (U. Rostock)
B. Rimmer (JLAB)
T. Roser (BNL)
L. Rossi (CERN)
D. Schulte (CERN)
M. Seidel (PSI)
A. Seryi (JAI)
B. Strauss (DOE)
M. Syphers (FNAL)
L. Tavian (CERN)
R. Tenchini (INFN Pisa)
D. Tommasini (CERN)
G. Tonelli (U. Pisa)
P. Vedrine (CEA)
A. Weiler (TU München)
J. Wenninger (CERN)
F. Zimmermann (CERN)
F. Zwirner (U. Padova)
CERN
INFN
SAPIENZA UNIVERSITÀ DI ROMA
ROMA TRE UNIVERSITÀ DEGLI STUDI
IEEE


Other Regions
Asia
U.S.
Middle East
Europe
468
Participants
168
Institutes
24
Countries

FCC Week 2017

29 May – 2 June 2017
Berlin, Germany

http://cern.ch/fccw2017