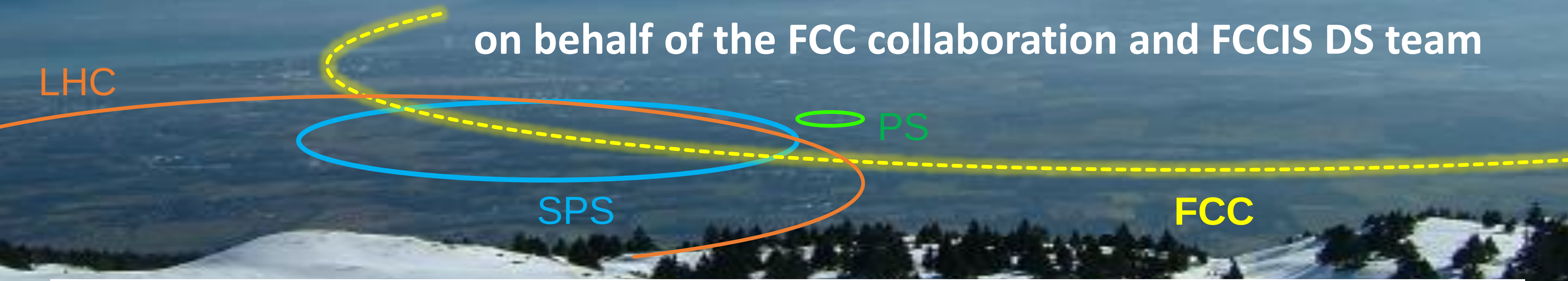
The e^-e^+ Future Circular Collider FCC-ee

Frank Zimmermann, CERN

Thanks to Michael BENEDIKT, Ilkay TÜRK ÇAKIR, Orhan ÇAKIR, Haluk DENIZLI, Kenan Abbas ÇİFTÇİ, Rena ÇİFTÇİ, Özgür ETIŞKEN, Salim OĞUR, Gokhan UNEL, Saleh SULTANSOY, Fatih YAMAN

UPHUK8, Bodrum, 5 September 2022

on behalf of the FCC collaboration and FCCIS DS team



FUTURE CIRCULAR COLLIDER Innovation Study

http://cern.ch/fcc

*Work supported by the **European Commission** under the **HORIZON 2020 projects EuroCirCol**, grant agreement 654305; **EASITrain,** grant agreement no. 764879; **iFAST**, grant agreement no. 101004730, **FCCIS**, grant agreement 951754, and **E-JADE,** contract no. 645479*

European Commission

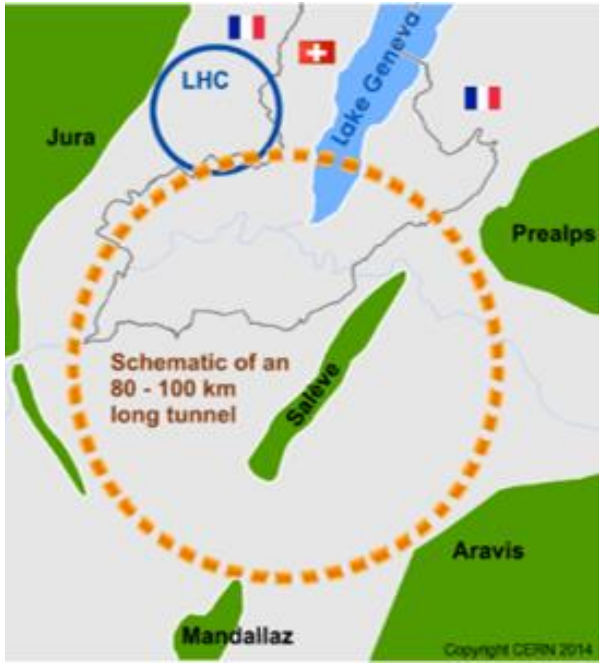
Horizon 2020 European Union funding for Research & Innovation

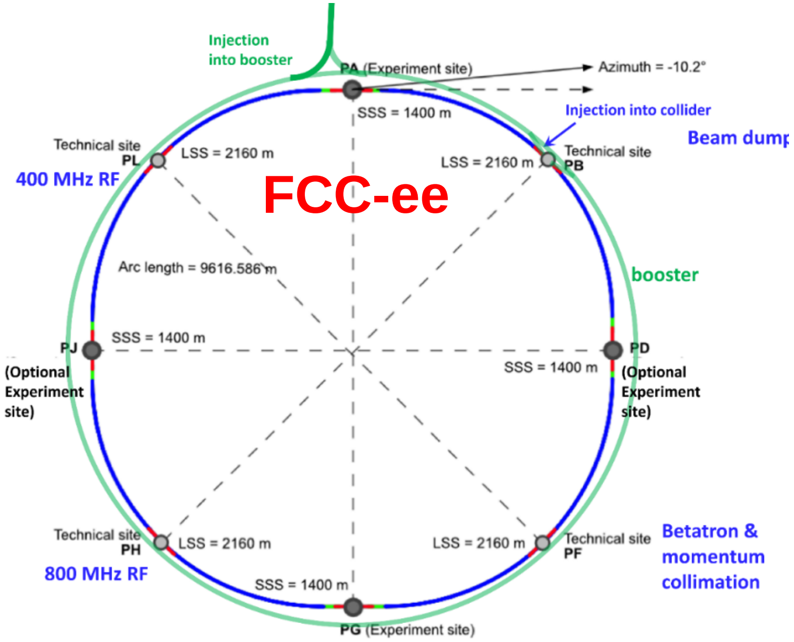
photo: J. Wenninger

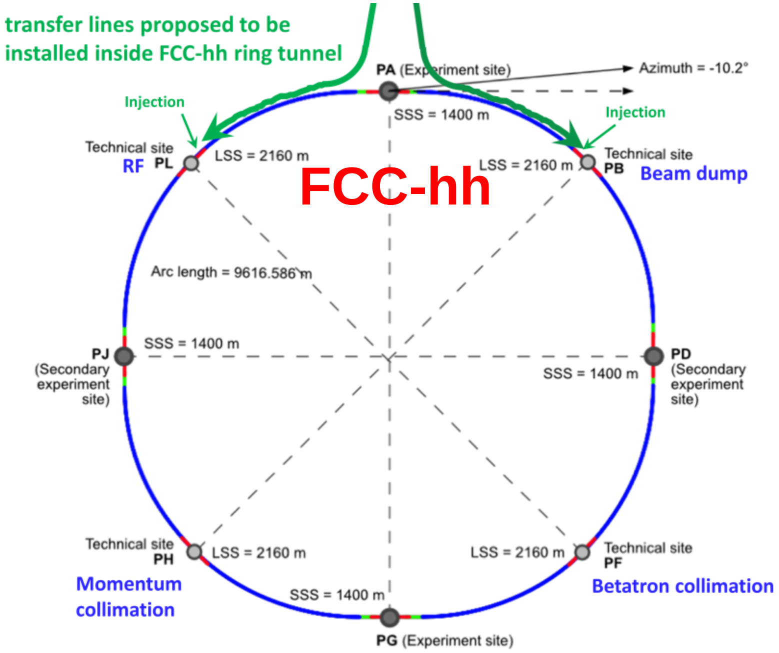
The FCC integrated program inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program



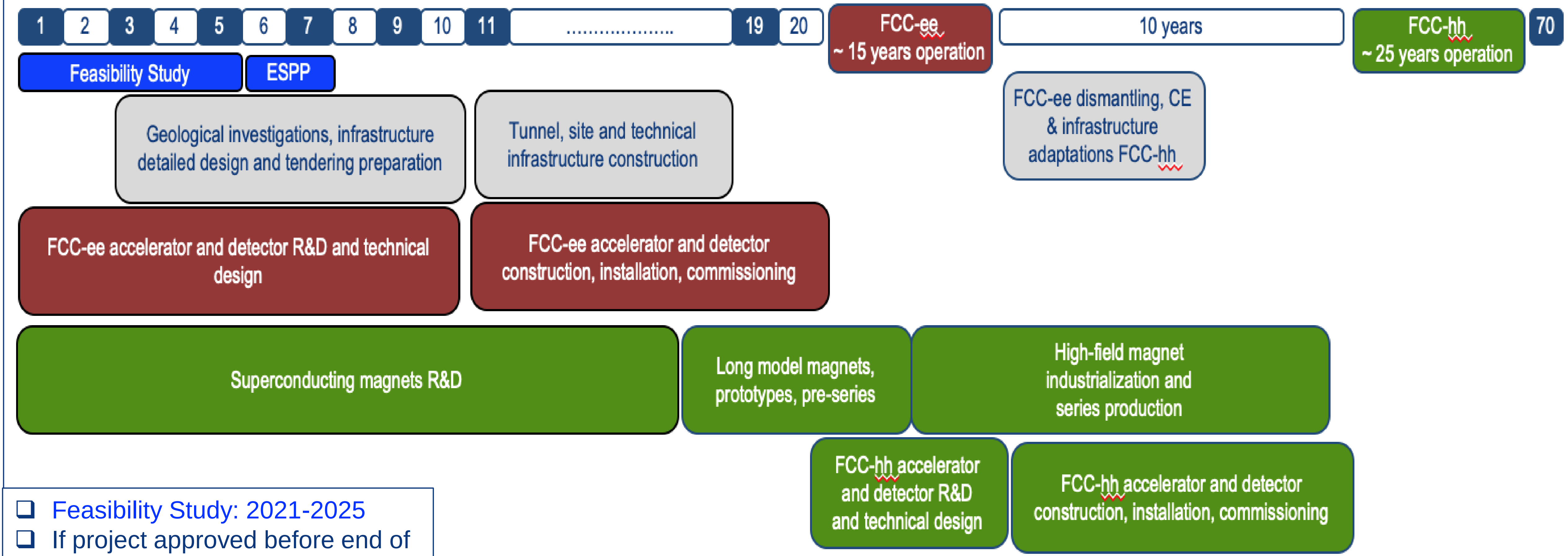




2020 - 2040 | **2045 - 2060** | **2065 - 2090**

a similar two-stage project CEPC/SPPC is under study in China

technical timeline of FCC integrated programme



- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

F. Gianotti

FCC-ee in a nutshell

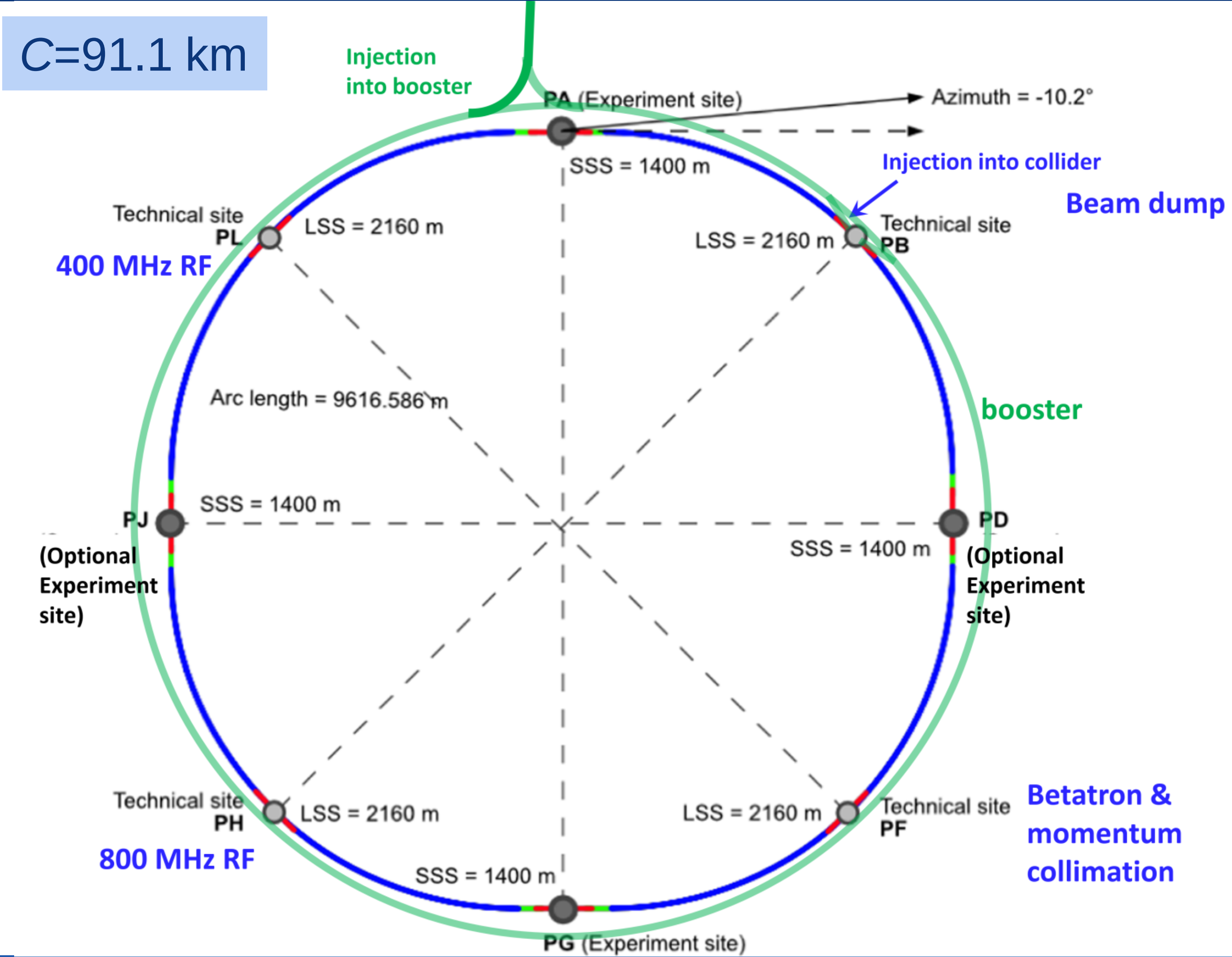
- **High luminosity precision study of Z, W, H, and $t\bar{t}$** 2×10^{36} cm^{-2}s^{-1}/IP at Z (or total $\sim10^{37}$ cm^{-2}s^{-1} with 4 IPs), 7×10^{34} cm^{-2}s^{-1} at ZH, 1.3×10^{34} cm^{-2}s^{-1} at $t\bar{t}$, unprecedented energy resolution at Z (<100 keV) and W (<300 keV)
- **Low-risk technical solution** based on 60 years of e^+e^- circular colliders and particle detectors ; R&D on components for improved performance, but no need for "demonstration" facilities; LEP2, VEPP-4M, PEP-II, KEKB, DAΦNE, or SuperKEKB already used many of the key ingredients in routine operation
- Infrastructure will support a **century of physics**
  - FCC-ee → FCC-hh → FCC-eh and/or several other options (FCC-μμ, Gamma Factory ..)
- **Utility requirements** similar to CERN existing use
- **Strong support** from CERN, partners, and 2020 ESPPU
- **Detailed multi-domain feasibility study underway** for 2026 ESPPU

FCC-ee parameters

Parameter [4 IPs, 91.1 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1400	135	26.7	5.0
number bunches/beam	8800	1120	336	42
bunch intensity [10^{11}]	2.76	2.29	1.51	2.26
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.5/8.8
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	10	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ 0.159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.32 / 15.2	3.55 / 7.02	2.5 / 4.45	1.67 / 2.54
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	181	17.3	7.2	1.25
tot. integr. luminosity / yr [ab^{-1}/yr]	86	8	3.4	0.6
beam lifetime rad Bhabha / BS [min]	19 / ?	20 / ?	10 / 19	12 / 46

FCC-ee Design Outline

FUTURE CIRCULAR COLLIDER



Double ring e^+e^- collider

Common footprint with FCC-hh

Asymmetric IR layout and optics to limit SR towards the detector

Large crossing angle **30 mrad, "virtual" crab-waist collision, four-fold superperiodicity**: 2 or 4 IPs

SR power 50 MW/beam

Top-up injection requires **booster synchrotron in collider tunnel**

a case for four IPs & experiments

Four different FCC-ee detectors to optimally address:

(1) Higgs factory program; (2) Ultraprecise electroweak & QCD physics; (3) Heavy Flavour physics; (4) Search for feebly coupled particles

For FCC-hh, two high-luminosity general-purpose experiments and two specialized experiments are foreseen, similar to present LHC detectors

FCC-ee & hh would share the 4 experimental caverns

M. Dam, ECFA Det. R&D Roadmap, 2021, https://indico.cern.ch/event/994685/

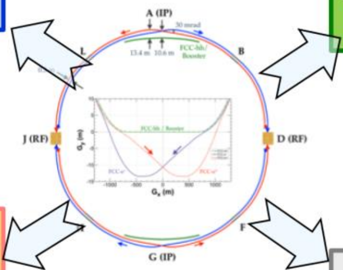
Detector Requirements in Brief

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

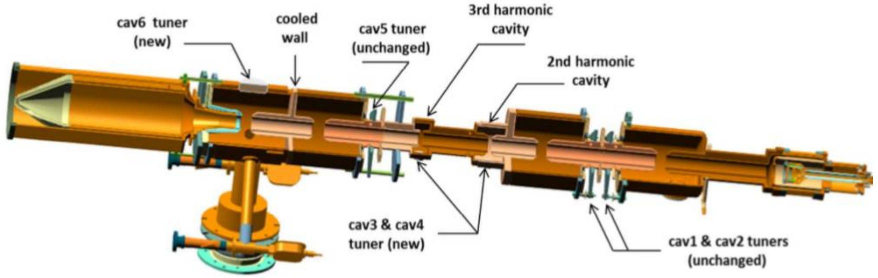
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

accelerator R&D examples

efficient RF power sources

(400 & 800 MHz)

I. Syratchev



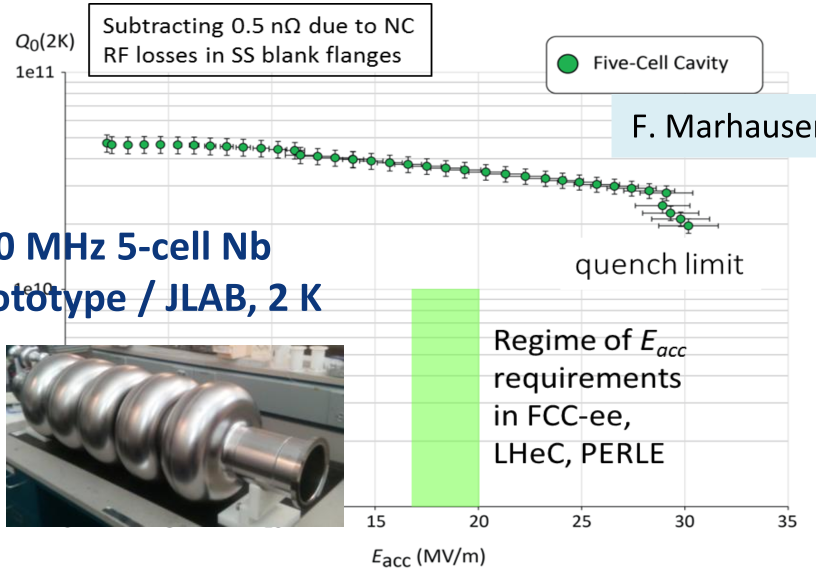
FPC & HOM coupler, cryomodule, thin-film coatings…

efficient SC cavities

Jefferson Lab

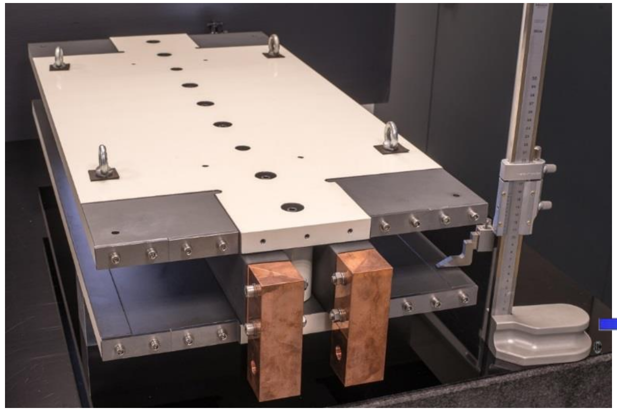
400 MHz 1-,2- & 4-cell Nb/Cu , 4.5 K

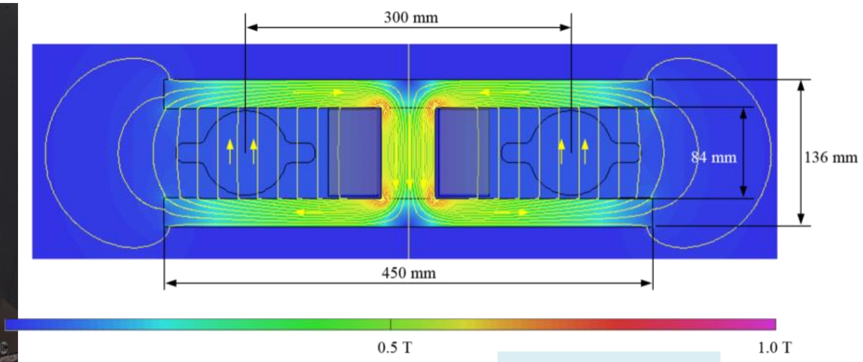
800 MHz 5-cell Nb prototype / JLAB, 2 K



F. Marhauser

energy **efficient** twin aperture **arc dipoles**

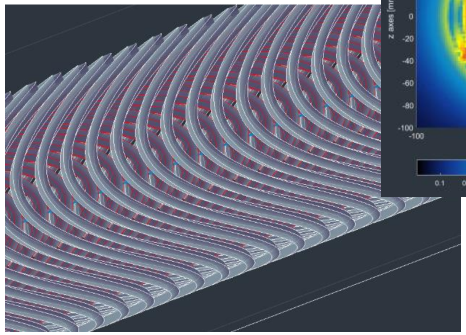


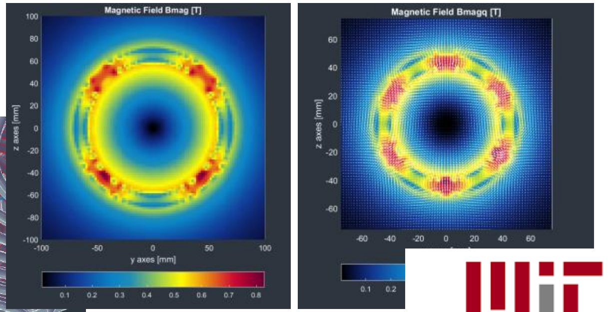


A. Milanese

under study: **CCT HTS quad's & sext's for arcs**

PAUL SCHERRER INSTITUT PSI





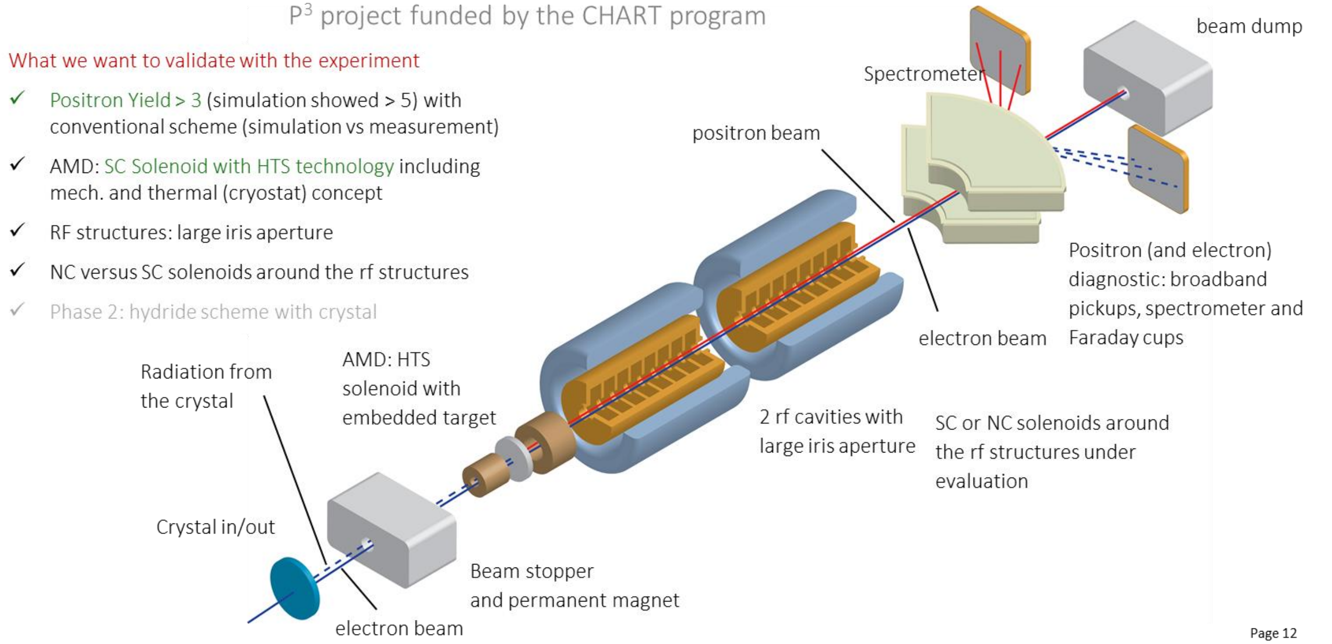
Massachusetts Institute of Technology

M. Koratzinos

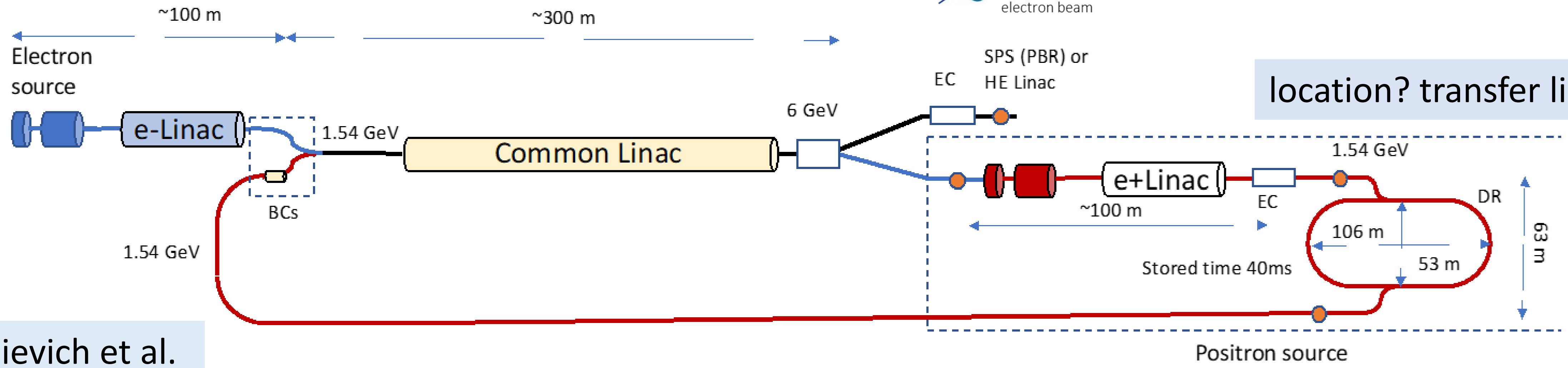
FCC-ee Pre-Injector - Swiss CHART 2 program

Collaboration between PSI and CERN with external partners: CNRS-IJCLab (Orsay), INFN-LNF (Frascati), KEK/SuperKEKB as observer, INFN-Ferrara – radiation from crystal

P³: PSI e⁺ production experiment with HTS solenoid at SwissFEL planned for 2024/25



Latest FCC-ee pre-injector layout



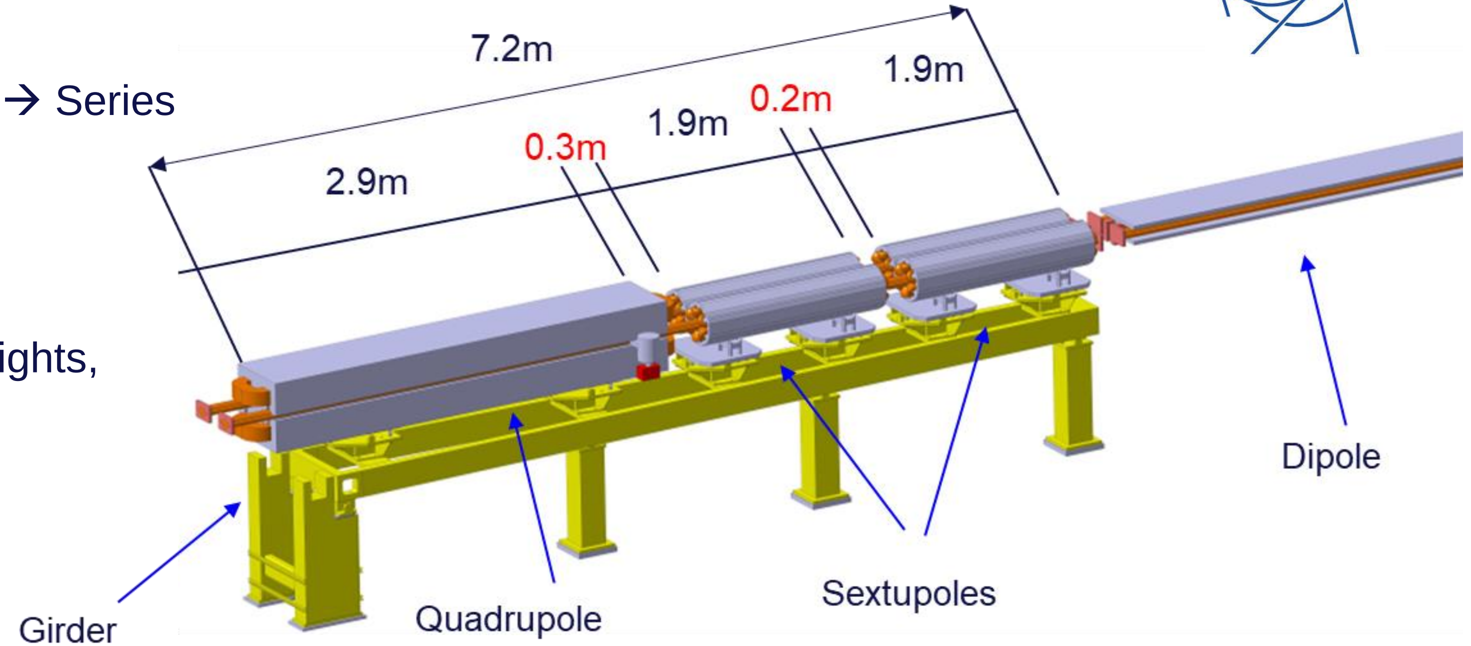
P. Craievich et al.

FCC-ee mock-ups for arcs and IR

F. Carra et

Arc half-cell mock-up

- **Arc half-cell**: most recurrent assembly of mechanical hardware in the accelerator (~1500 similar FODO)
- **Mock-up** → Functional prototype(s) → Pre-series → Series
- Building a mock-up allows optimizing and testing **fabrication, integration, installation, assembly, transport, maintenance**
- Working with structures of equivalent volumes, weights, stiffness

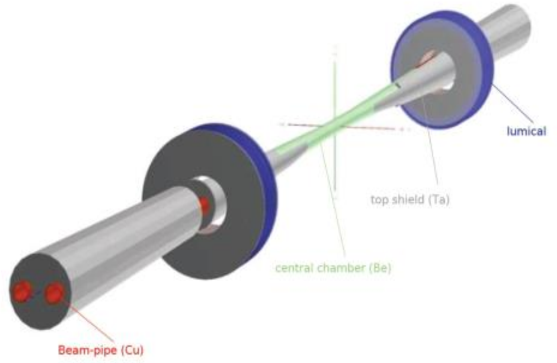


IR mock-up

M. Boscolo et al.

Step 1: Central IP vacuum chamber (test the cooling system and the vacuum system), **AlBeMet162 & steel transition** (study the shape of the transition, EBW process), **Bellows** (vacuum and thermal tests), **Welding** (EBW for elliptical geometry)

Step 2: Trapezoidal vacuum chamber with remote vacuum connection, **first quadrupole QC1, cryostat,** beam pipe and quadrupole and **cryostat support**, **vibration & alignment sensors**

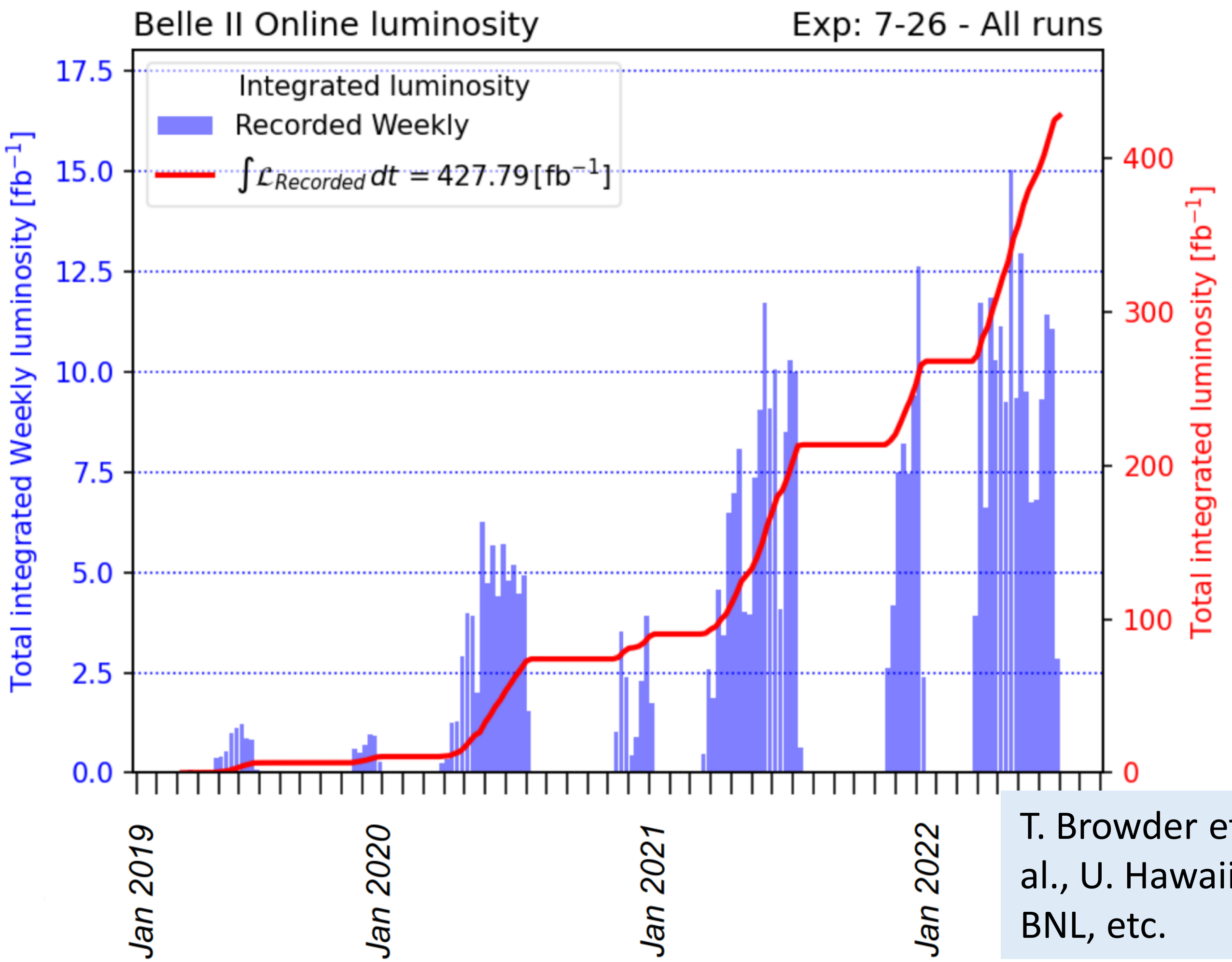


Istituto Nazionale di Fisica Nucleare

Laboratoire d'Annecy de Physique des Particules

SuperKEKB / Belle II

Design: double ring e^+e^- collider as *B*-factory at 7(e^-) & 4(e^+) GeV; target luminosity ~6 x 10^{35} $cm^{-2}s^{-1}$; β_y^* ~ 0.3 mm; beam lifetime ~5 min; top-up inj.; e^+ rate up to ~ 2.5 10^{12} /s ; under commissioning



T. Browder et al., U. Hawaii, BNL, etc.

$\mathcal{L}_{peak}$ = 4.7 x 10^{34}/cm²/sec
nanobeams: vertical beam spot size 300nm (design 50nm)

This is four-times PEP-II peak with much lower beam currents.

>2 x higher than KEKB

Not easy:
ran throughout the two years of the COVID-pandemic with social distancing.

Integrated a BaBar size data sample, 428 fb^{-1}. Need more running time.

world record luminosity of 4.71x10^{34} $cm^{-2}s^{-1}$ on 22 June 2022, β_y^* = 1.0 mm in routine operation, also β_y^* = 0.8 mm demonstrated in both rings – with FCC-ee-style "virtual" crab-waist collision scheme originally developed for FCC-ee (K. Oide)

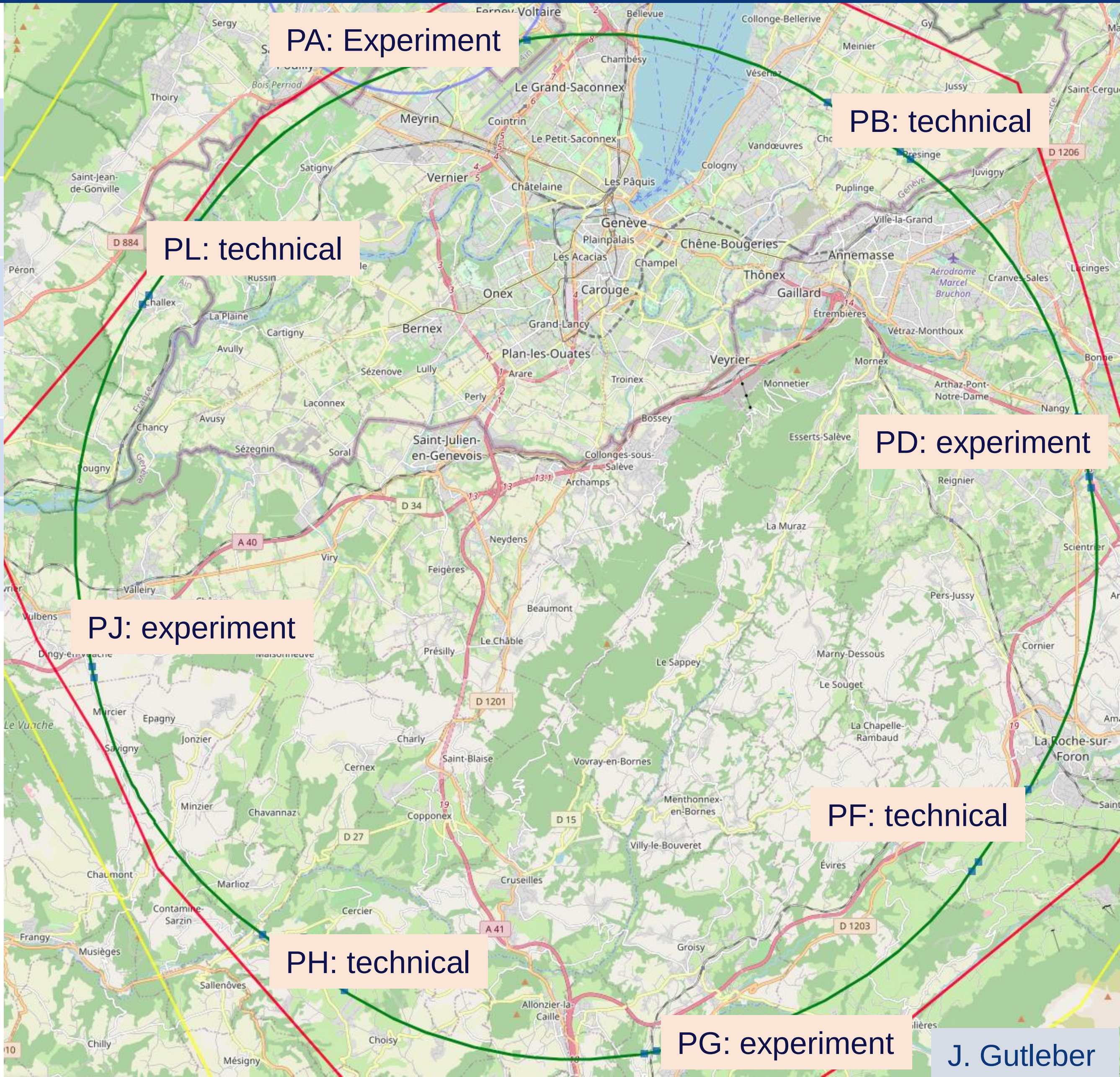
FUTURE CIRCULAR COLLIDER

optimized placement and layout

8-site baseline “PA31”

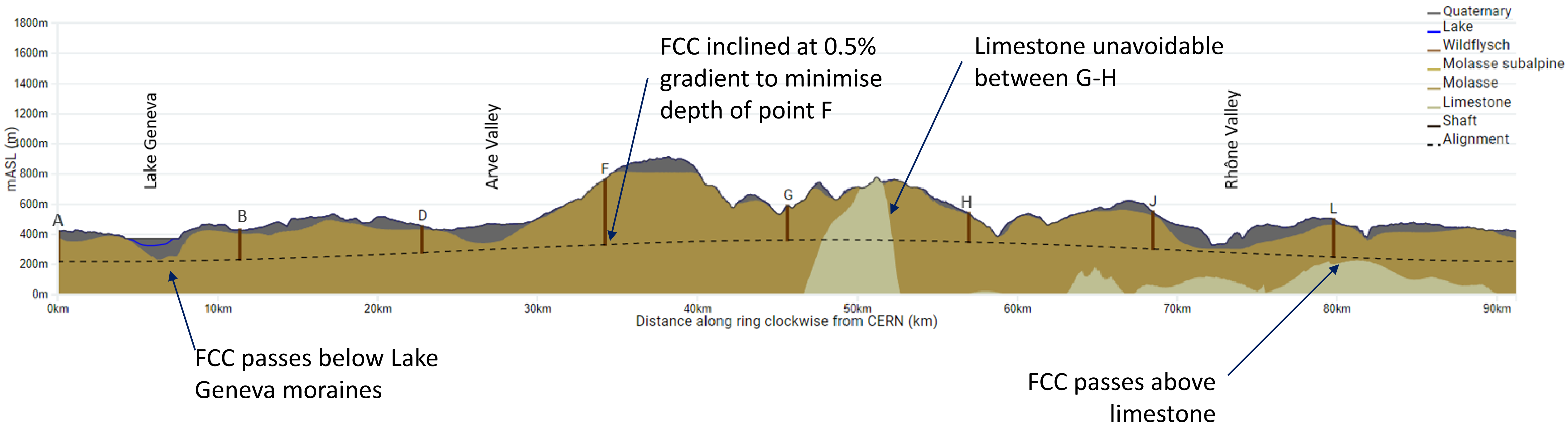
Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP



J. Gutleber

FCC Long Section – PA31-1.0

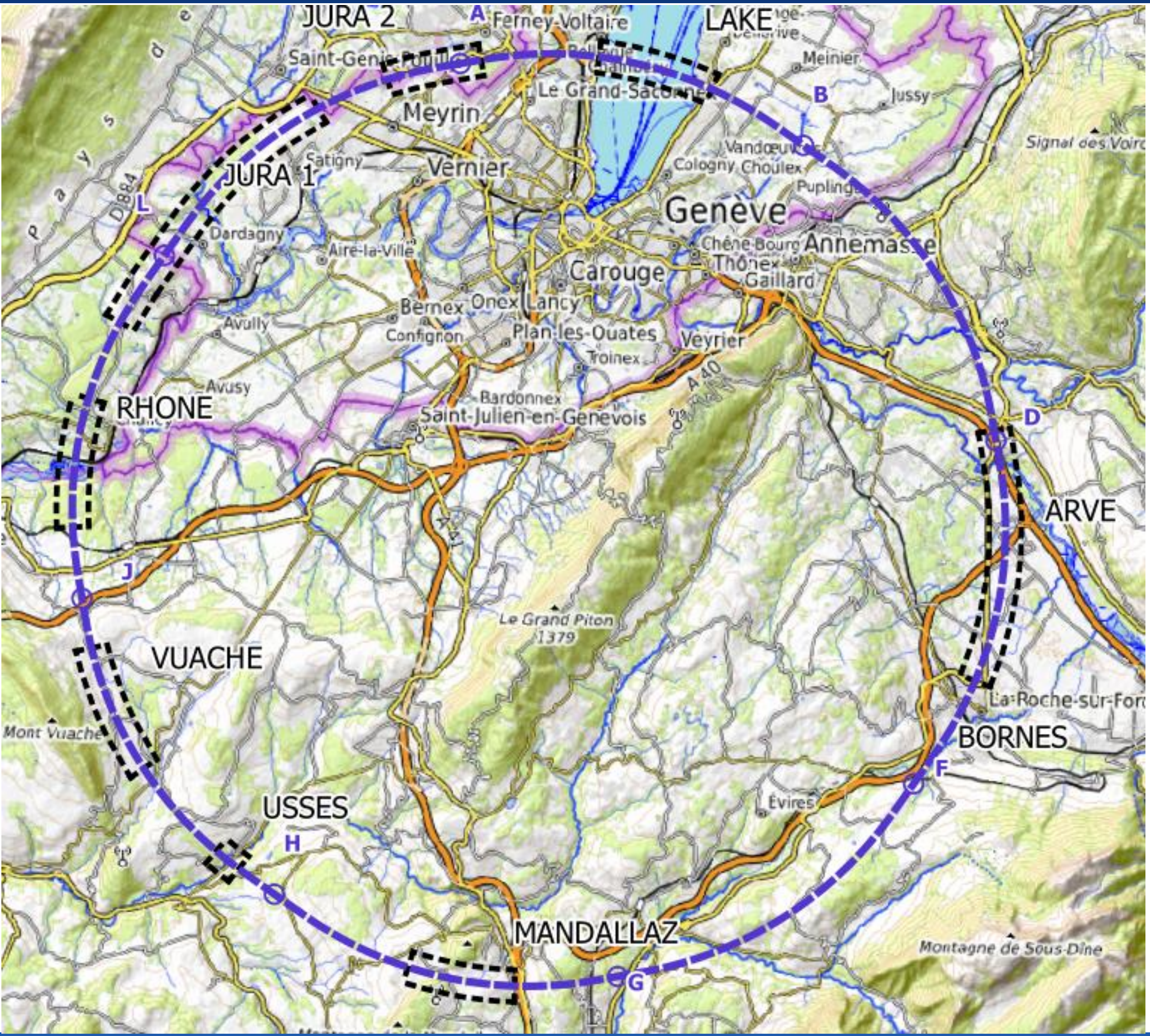


Shaft depth:

A: 202 m B: 200 m D: 177 m F: 399 m G: 228 m H: 139 m J: 251 m L: 253 m

John Osborne

plans for high-risk area site investigations



JURA, VUACHE (3 AREAS)
Top of limestone
Karstification and filling-in at the tunnel depth
Water pressure

LAKE, RHÔNE, ARVE AND USSES VALLEY (4 AREAS)
Top of the molasse
Quaternary soft grounds, water bearing layers

MANDALLAZ (1 AREAS)
Water pressure at the tunnel level
Karstification

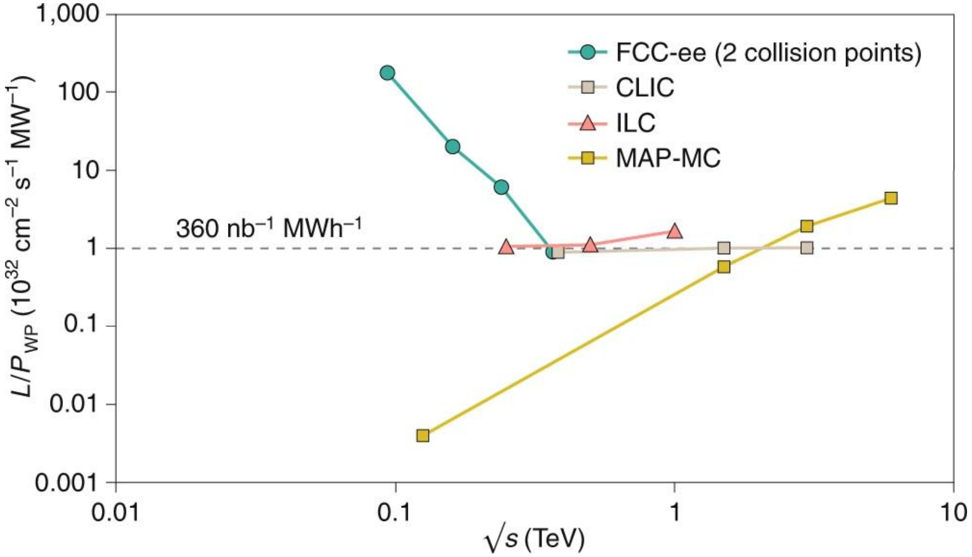
BORNES (1 AREA)
High overburden molasse properties
Thrust zones

Site investigations planned for 2024 – 2025:
~40-50 drillings, some 100 km of seismic lines

sustainability and carbon footprint studies

highly sustainable Higgs factory

luminosity vs. electricity consumption



Thanks to twin-aperture magnets, thin-film SRF, efficient RF power sources, top-up injection

optimum usage of excavation material

int'l competition "mining the future®"

https://indico.cern.ch/event/1001465/

FCC-ee annual energy consumption ~ LHC/HL-LHC

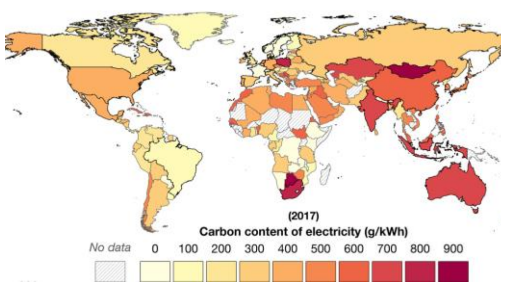
120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880					69	199872	MWh
Energy consumption / year	365	8760						1.52	TWh
Average power								174	MW

J.-P. Burnet, FCC Week 2022

incl. CERN site & SPS

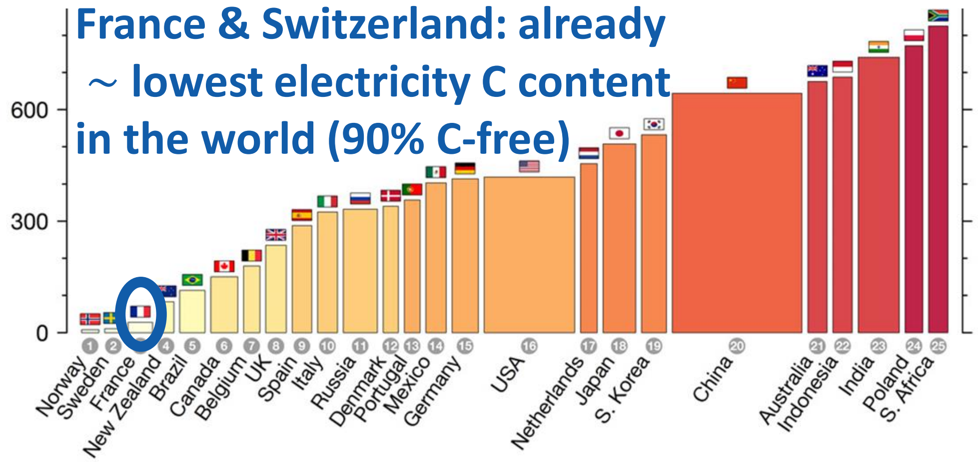
CERN Meyrin, SPS, FCC	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Energy consumption (TWh/y)	1.82	1.92	2.09	2.54

powered by mix of renewable & other C-free sources



https://www.carbonbrief.org/

France & Switzerland: already ~ lowest electricity C content in the world (90% C-free)



sustainability compared with other Higgs factories

Patrick Janot

https://indico.cern.ch/event/1178975/

TWh / year for the "Higgs factory" centre-of-mass energy

$\sqrt{s}$ = 240 GeV for CEPC/FCC-ee, 250 GeV for ILC/C3, 380 GeV for CLIC

CLIC	ILC	C3	FCC-ee	CEPC
0.8	0.9	0.9	1.1	2.0

Energy consumption in MWh / Higgs

CLIC	ILC	C3	CEPC	FCC-ee
30	20	21	10	3.3

becomes 2 MWh / Higgs for FCC-ee with 4 IPs

Present carbon footprint for electrical energy in tons CO_2 / Higgs

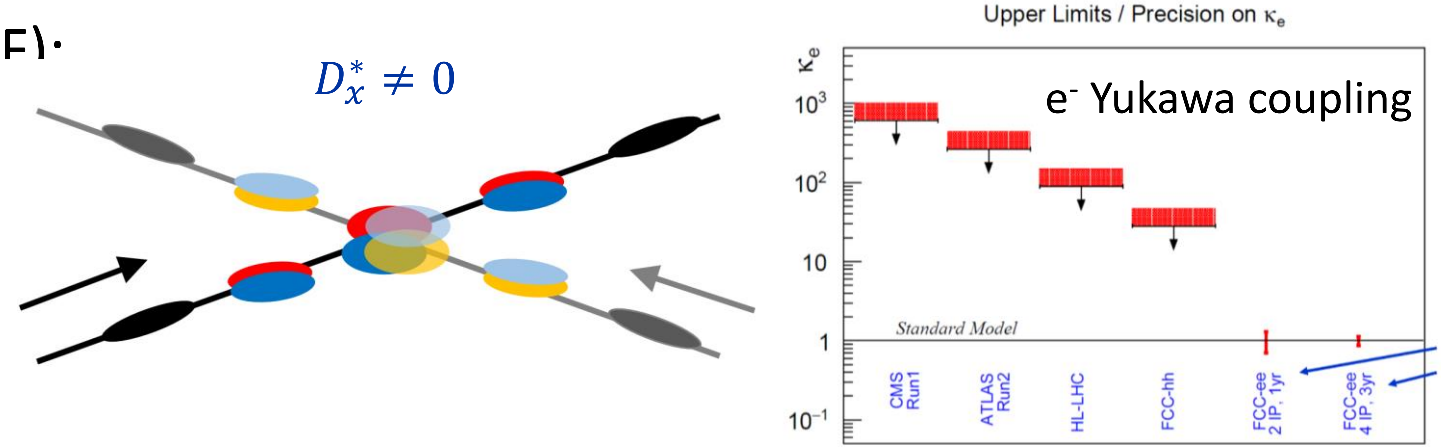
CLIC@CERN	ILC@KEK	C3@FNAL	CEPC@China	FCC-ee@CERN
2.1	7.8	8.5	6.1	0.24

0.14 ton CO_2 / Higgs for FCC-ee with 4 IPs

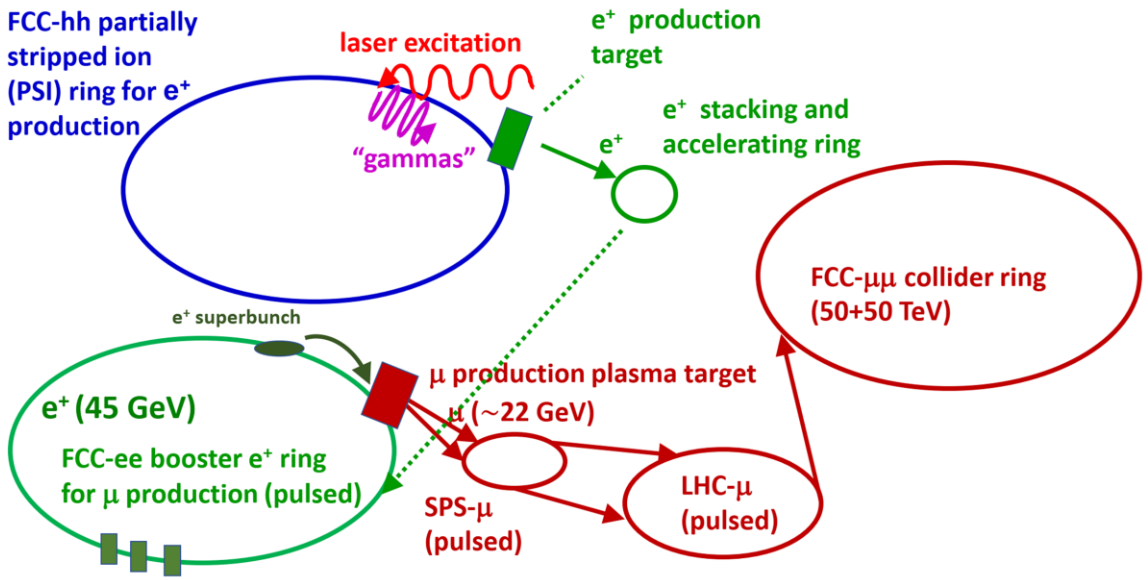
future upgrades and uses

- FCC-ee: not only Higgs, but **Z and W factory** (TeraZ); **$t\bar{t}$ upgrade** (~1 BCHF);
- optional **direct *s*-channel Higgs production** at 125 GeV with **monochromatization**
- **civil construction & technical infrastructures shared with** [and prepare] 100 TeV **hadron collider FCC -hh – stage 2 of FCC integrated program** (next slide)
- numerous other possible extensions (ep/eA/AA, Gamma Factory, LEMMA-type μ collider FCC-μμ ? …, ERL upgrade ? …)

A. Faus-Golfe et al., Eur. Phys. J. Plus, 137 (2022) 31



F. Zimmermann et al., PAC'22, Bangkok, WEPOST009



preparing for FCC stage 2 (FCC-hh)

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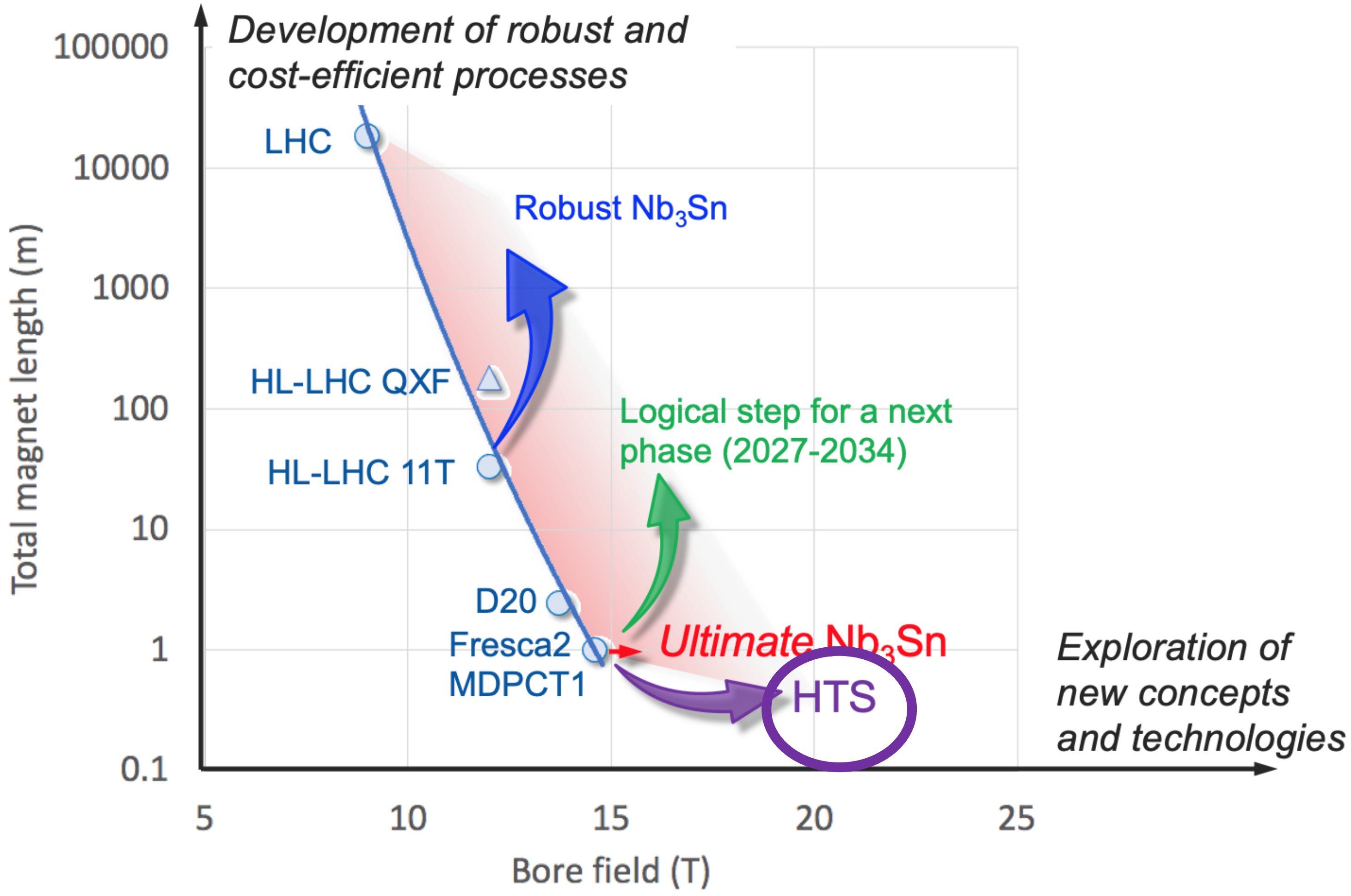
In parallel to FCC studies, High Field Magnet development program as long-term separate R&D project



CERN budget for high-field magnets doubled in 2020 Medium-Term Plan (~ 200 MCHF over ten years)

Main R&D activities:

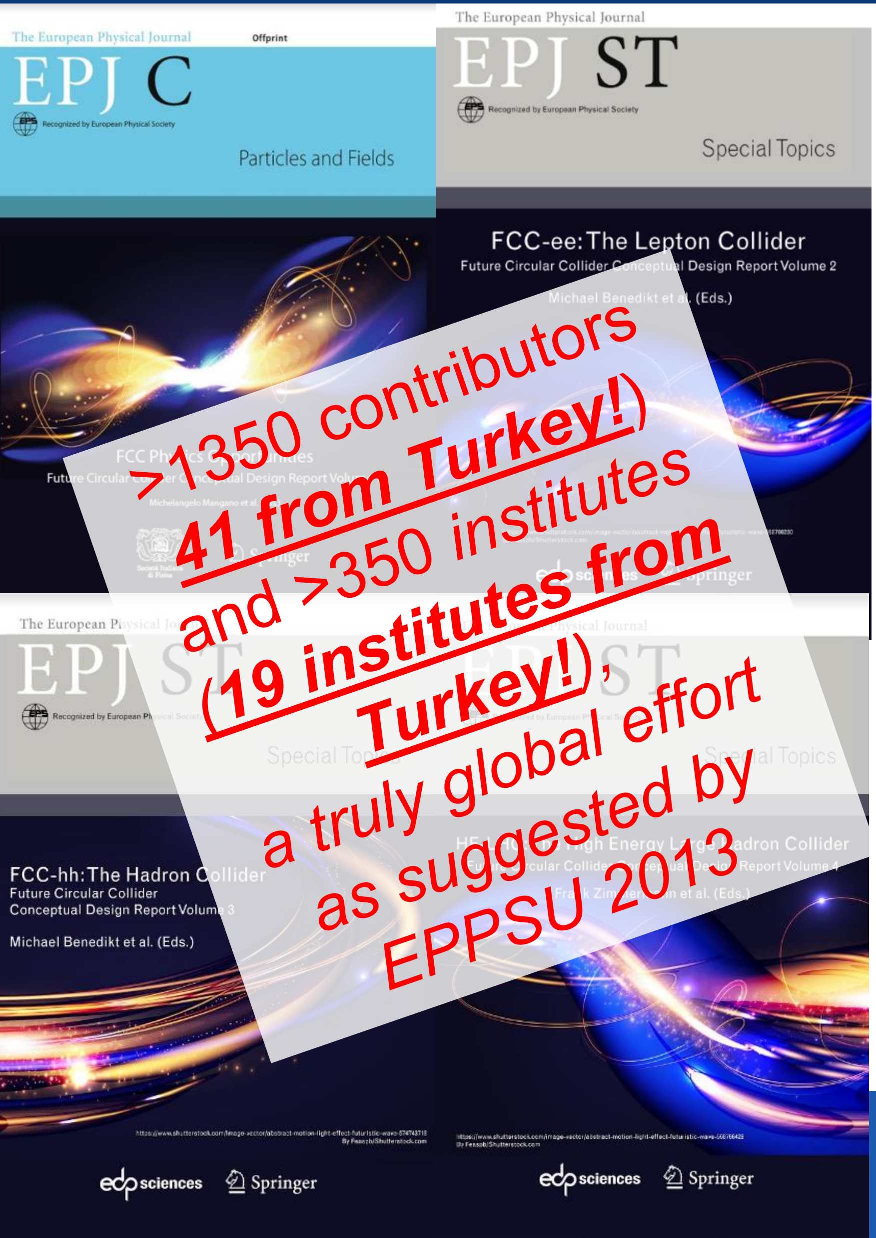
- materials: goal is ~16 T for Nb_3Sn, at least ~20 T for HTS inserts
- magnet technology: engineering, mechanical robustness, insulating materials, field quality
- production of models and prototypes: to demonstrate material, design and engineering choices,
  industrialisation and costs
- infrastructure and test stations: for tests up to ~ 20 T and 20-50 kA

Detailed deliverables and timescale being defined through Accelerator R&D roadmap under development

L. Bottura, F. Gianotti, A. Siemko

FCC CDR published in 2018/19

FUTURE CIRCULAR COLLIDER
Innovation Study



>1350 contributors (**41 from Turkey!**) and >350 institutes (**19 institutes from Turkey!**), a truly global effort as suggested by EPPSU 2013

- **FCC-Conceptual Design Reports:**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4) [Springer]**

    EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 ,

    EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

- EPJ is a merger and continuation of *Acta Physica Hungarica, Anales de Fisica, Czechoslovak Journal of Physics, Fizika A, Il Nuovo Cimento, Journal de Physique, Portugaliae Physica* and ***Zeitschrift für Physik***. 25 European Physical Societies are represented in EPJ, including the DPG.

- **Summary documents provided to EPPSU SG**
  - **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
  - Accessible on http://fcc-cdr.web.cern.ch/

from ESPP Update 2020

High-priority future initiatives:

An **electron-positron Higgs factory is the highest-priority next collider**. For the longer term, the European particle physics community has the ambition to operate a **proton-proton collider at the highest achievable energy**. Accomplishing these compelling goals will require innovation and cutting-edge technology:

"the particle physics community should ramp up its **R&D effort** focused on advanced accelerator technologies, in particular that for **high-field superconducting magnets, incl. high-temperature superconductors**"

"Europe, together with its international partners, should investigate the **technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV** and with an **electron-positron Higgs and electroweak factory as a possible first stage**. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be **completed on the timescale of the next Strategy update**.."

FCC Feasibility Study (FS)

FUTURE CIRCULAR COLLIDER

2013 ESPPU requested FCC Conceptual Design four-volume report → 4 volumes delivered in 2018/19, describing the physics cases, the design of the lepton and hadron colliders, and the underpinning technologies and infrastructures. Fol-

2020 ESPPU→ **2021 Launch of FCC Feasibility Study (FCC FS) by CERN Council**

- Feasibility Study Report (FSR) expected by the end of 2025 , not only the technical design, but also numerous other key feasibility aspects, including tunnel construction, financing, and environment
- FSR will be an important input to the next ESPPU expected in 2026/27.

FCC FS is organized as international collaboration.

The FCC FS and a possible future project will profit from CERN's decade-long experience with successful large international accelerator projects, e.g., the LHC and HL-LHC, and the associated global experiments, such as ATLAS and CMS.

Organisational Structure of the FCC Feasibility Study
http://cds.cern.ch/record/2774006/files/English.pdf

Main Deliverables and Timeline of the FCC Feasibility Study
http://cds.cern.ch/record/2774007/files/English.pdf

CERN/SPC/1155/Rev.2
CERN/3566/Rev.2
Original: English
21 June 2021

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken		Voting Procedure
For decision	RESTRICTED COUNCIL 203rd Session 17 June 2021	Simple majority of Member States represented and votin

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:
PROPOSED ORGANISATIONAL STRUCTURE

This document sets out the proposed organisational structure for the Feasibility Study of t Future Circular Collider, to be carried out in line with the recommendations of the Europe Strategy for Particle Physics updated by the CERN Council in June 2020. It reflects discussi at, and feedback received from, the Council in March 2021 and is now submitted for the latte approval.

CERN/SPC/1161
CERN/3588
Original: English
21 June 2021

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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Action to be taken		Voting Procedure
For information	RESTRICTED COUNCIL 203rd Session 17 June 2021	-

FUTURE CIRCULAR COLLIDER FEASIBILITY STUDY:
MAIN DELIVERABLES AND MILESTONES

This document describes the main deliverables and milestones of the study being carried out to assess the technical and financial feasibility of a Future Circular Collider at CERN. The results of this study will be summarised in a Feasibility Study Report to be completed by the end of 2025.

Post FS & ESPPU2027: Project Cost & Profile

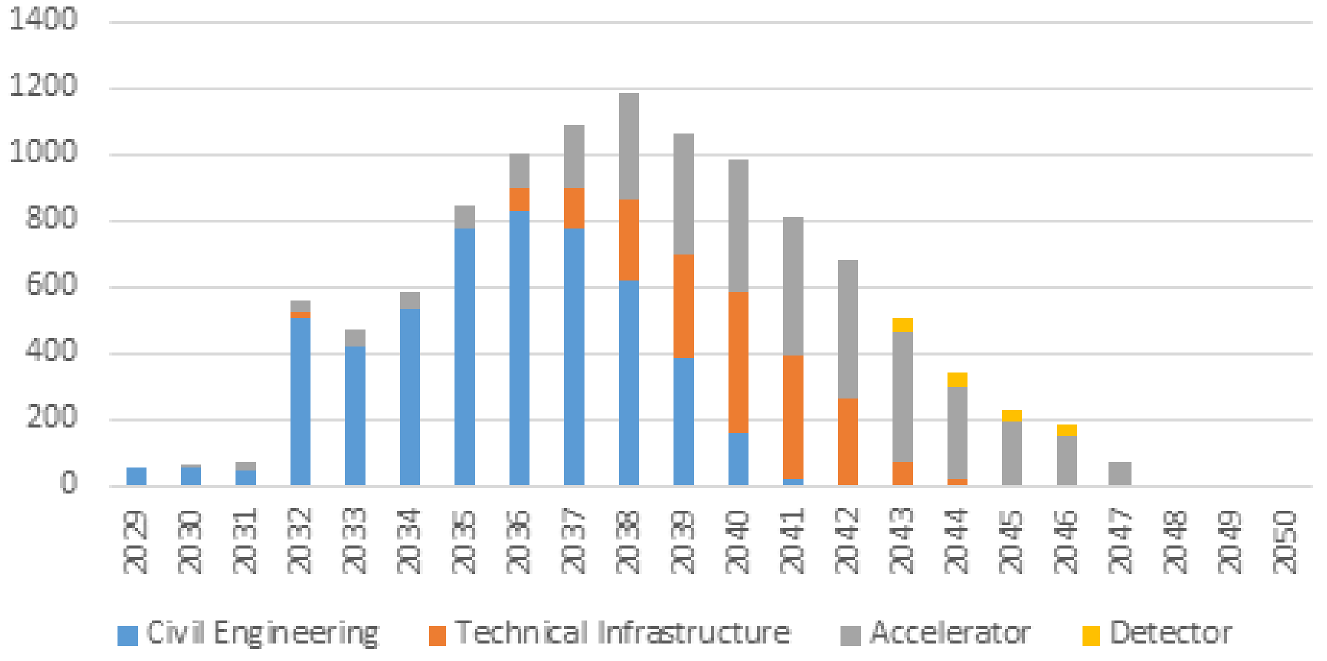
Construction cost estimate for FCC-ee (from CDR 2018, update in 2025)

- Machine configurations for Z, W, H working points included
- Baseline configuration with 2 detectors
- CERN contribution to 2 experiments incl.

cost category	[MCHF]	%
civil engineering	5.400	50
technical infrastructure	2.000	18
accelerator	3.300	30
detector	200	2
total cost (2018 prices)	10.900	100

Spending profile for FCC-ee

- CE construction 2032 - 2040
- Technical infrastructure 2037 - 2043
- Accelerator and experiment 2032 – 2045
- Commissioning and operation start 2045 -2048.



FUTURE CIRCULAR COLLIDER

Status of Global FCC Collaboration

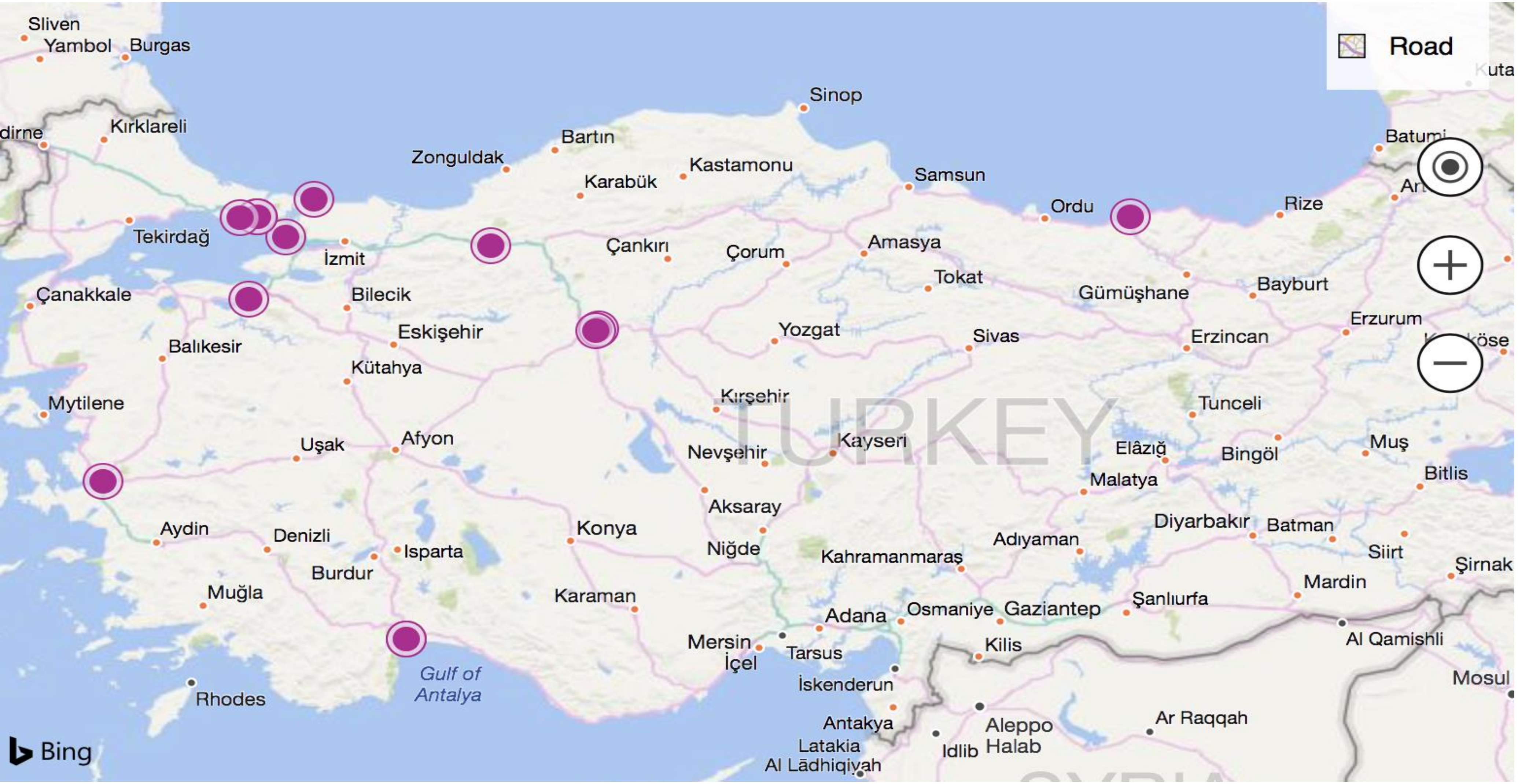
Increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

147 Institutes	30 Companies	34 Countries	EC H2020

FCC Feasibility Study: 58 fully-signed previous members, 17 new members. MoU renewal of remaining CDR participants in progress

Turkish members of FCC collaboration



15 or 16 institutes from Turkey: *AIBU*, Bolu; *Akdeniz U*, Antalya; *Ankara U*, Tandogan/ Ankara; *EgeU*, Bornova-Izmir; *Giresun U*, Giresun; *Isik U*, Sile, Istanbul; *Istanbul Aydin U*, Istanbul; *Istanbul U*, Vezneciler-Istanbul; *Istinye U*, Istanbul; *IUE*, Balcova-Izmir; *IYTE*, Urla-Izmir; *Kirrikale U*; *Okan U*, Istanbul; *PRU*, Tuzla/Istanbul; *TOBB ETU*, Ankara; *ULUDAG*, Nilüfer-Bursa

FUTURE CIRCULAR COLLIDER
Innovation Study

FCC workshops organized by Turkish FCC community

S. KUDAY (İstanbul Aydın U.)
B.C. LÜTFÜOĞLU (Akdeniz U.)
A. OZANSOY (Ankara U.)
İ. ÖZ (TAEK)
E. RECEPOĞLU (TAEK)
S. ŞAHİN (Akdeniz U.)
K. TAŞDÖVEN (Akdeniz U.)
Z.Ş. TURHAN IRAK (Igdir U.)
E. YILDIZ (Kırıkkale U.)
A. YÜKSEL (TAEK)

İ.H. MUTLU (Akdeniz U.)
W. RIEGLER (CERN)
S. SULTANSOY (TOBB ETU.)
A. ŞENOL (BAİB U.)
G. ÜNEL (UCI & CERN)
Y. ÖNEL (Iowa U.)
E .V. ÖZCAN (Bogazici U.)
M. SELVAGGI (CERN)
F. ZIMMERMANN (CERN)

http://aknam.akdeniz.edu.tr/fcc-workshop/
aknam@akdeniz.edu.tr

Publications by FCC groups in Turkey

1) The 28 GeV Dimuon Excess in Lepton Specific 2HDM, A. Cici, S. Khalil, B. Niş, C. S. Un, arXiv:1909.02588v1 [hep-ph]

2) Study on Anomalous Neutral Triple Gauge Boson Couplings from Dimension-eight Operators at the HL-LHC, A. Senol, H. Denizli, A. Yilmaz, I. Turk Cakir, O. Cakir., arXiv:1906.04589 [hep-ph].

3) Sensitivity on Anomalous Neutral Triple Gauge Couplings via ZZ Production at FCC-hh, A. Yilmaz, A. Senol, H. Denizli, I. Turk Cakir, O. Cakir., arXiv:1906.03911 [hep-ph].

4) Top quark anomalous FCNC production via tqg couplings at FCC-hh, K.Y. Oyulmaz, A. Senol, H. Denizli, O. Cakir, Phys.Rev. D99 (2019) no.11, 115023. 10.1103/PhysRevD.99.115023.

5) Testing for observability of Higgs effective couplings in triphoton production at FCC-hh, H. Denizli, K.Y. Oyulmaz, A. Senol., arXiv:1901.04784 [hep-ph]

6) Linac and Damping Ring Designs for the FCC-ee, S. Ogur et al., Proceedings of International Particle Accelerator Conference (IPAC 2019), pp. 420-423, 2019

7) FCC-ee: The Lepton Collider : Future Circular Collider Conceptual Design Report Volume 2, FCC Collaboration (A. Abada et al.)., Eur.Phys.J.ST 228 (2019) no.2, 261-623, 10.1140/epjst/e2019-900045-4.

8) FCC-hh: The Hadron Collider : Future Circular Collider Conceptual Design Report Volume 3, FCC Collaboration (A. Abada et al.)., Eur.Phys.J.ST 228 (2019) no.4, 755-1107, 10.1140/epjst/e2019-900087-0.

9) HE-LHC: The High-Energy Large Hadron Collider, FCC Collaboration (A. Abada et al.)., Eur.Phys.J.ST 228 (2019) no.5, 1109-1382. 10.1140/epjst/e2019-900088-6.

10) FCC Physics Opportunities : Future Circular Collider Conceptual Design Report Volume 1, FCC Collaboration (A. Abada et al.)., Eur.Phys.J. C79 (2019) no.6, 474. 10.1140/epjc/s10052-019-6904-3.

11) Probing anomalous tq\gamma and tqg couplings via single top production in association with photon at FCC-hh, K.Y. Oyulmaz, A. Senol, H. Denizli, A. Yilmaz, I. Turk Cakir, O. Cakir., Eur.Phys.J. C79 (2019) no.1, 83. 10.1140/epjc/s10052-019-6593-y.

12) Probing top quark FCNC tq\gamma and tqZ couplings at future electron-proton colliders, O. Cakir, A. Yilmaz, I. Turk Cakir, A. Senol, H. Denizli, Nucl.Phys. B944 (2019) 114640. ,10.1016/j.nuclphysb.2019.114640.

13) Probing the Effects of Dimension-eight Operators Describing Anomalous Neutral Triple Gauge Boson Interactions at FCC-hh, A. Senol, H. Denizli, A. Yilmaz, I. Turk Cakir, K.Y. Oyulmaz, O. Karadeniz, O. Cakir., Nucl.Phys. B935 (2018) 365-376, 10.1016/j.nuclphysb.2018.08.018.

14) Light stops and fine-tuning in MSSM, A. Çiçi, Z. Kırca, C. S. Ün; , Eur. Phys. J. C (2018) 78: 60. https://doi.org/10.1140/epjc/s10052-018-5549-y

15) Probing the Anomalous FCNC Couplings at Large Hadron Electron Collider , I. Turk Cakir, A. Yilmaz, H. Denizli, A. Senol, H. Karadeniz, O. Cakir. Adv.High Energy Phys. 2017 (2017) 1572053.

15) Top quark FCNC couplings at future circular hadron electron colliders , H. Denizli, A. Senol, A. Yilmaz, I. Turk Cakir, H. Karadeniz, O. Cakir. Phys.Rev. D96 (2017) no.1, 015024.

16) Probing Charged Higgs Boson Couplings at the FCC-hh Collider , I.T. Cakir, S. Kuday, H. Saygin, A. Senol, O. Cakir. , Phys.Rev. D94 (2016) 015024.

17) Single production of the excited electrons in the future FCC-based lepton–hadron colliders, Abdullatif Caliskan, Seyit Okan Kara., Int.J.Mod.Phys. A33 (2018) no.24, 1850141.

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19) Pre-Booster Ring Considerations for the FCC e^+e^- Injector, Ozgur Etisken, Fanouria Antoniou, Abbas Çiftçi, Yannis Papaphilippou, DOI: 10.18429/JACoW-IPAC2018-MOPMF002.

20) Bunch Schedules for the FCC-ee Pre-injector, Salim Ogur, Katsunobu Oide, Yannis Papaphilippou, Dmitry Shatilov, Frank Zimmermann. DOI: 10.18429/JACoW-IPAC2018-MOPMF001.

21) First Look at the Physics Case of TLEP , TLEP Design Study Working Group (M. Bicer et al.). , JHEP 1401 (2014) 164.

22) Excited muon searches at the FCC based muon-hadron colliders , A. Caliskan, S.O. Kar[illegible] Ozansoy. arXiv:1701.03426 [hep-ph]. Adv.High Energy Phys. 2017 (2017) 15[illegible].

23) Azimuthal Angular Decorrelation of Jets at Future High Energy Colliders , [illegible] Saygin, S. Kuday. arXiv:1809.01505 [hep-ph].

24) Projections for Neutral Di-Boson and Di-Higgs Interactions at FCC-he Collider , S. Kuday, H. Saygin, İ. Hoş, F. Çetin., Nucl.Phys. B93[illegible] (2018) [illegible]-14. 10.1016/j.nuclphysb.2018.05.00[illegible]

25) FCC Based Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics, Y. [illegible] Acar, A. N. Akay, S. Beser, H. Karadeniz, U. Kaya, B. B. Oner, S. Sultansoy, arXiv:1[illegible]3.02150 [physics.acc-ph].

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28) I. Turk Cakir, A. Senol, A. T. Tasci and O. Cakir. "Probing Anomalous WWγ and WWZ Couplings with Polarized Electron Beam at the LHeC and FCC-Ep Collider". World Academy of Science, Engineering and Technology International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering (201[illegible]) Vol:9, No:1.

29) I. Turk Cakir, B. Hacisahinoglu, S. Kartal, A. Yilmaz, A. Yilmaz, Z. Uysal, O. Cakir, "Search for Flavour Changing Neutral Current Couplings of Higgs-up Sector Quarks at Future Circular Collider (FCC-eh)". World Academy of Science, Engineering and Technology, Open Science Index 132, International Journal of Physical and Mathematical Sciences (2017), 11(12), 525-529.

30) I. Turk Cakir, M. Altinli, Z. Uysal, A. Senol, O. Yalcinkaya, A. Yilmaz, "The Search of Anomalous Higgs Boson Couplings at the Large Hadron Electron Collider and Future Circular Electron Hadron Collider". World Academy of Science, Engineering and Technology, Open Science Index 132, International Journal of Physical and Mathematical Sciences (2017), 11(12), 519-524.

31 F. Yaman et al., "Mitigation of electron cloud effects in the FCC-ee collider", EPJ Techniques and Instrumentation volume 9, Article number: 9 (2022)

FCC-Turkey team extremely active and productive

FCC theses at Turkish universities

PhD theses

Ozgur ETISKEN, Ankara University, "Pre-Booster Ring Design for FCC-e^+e^- Injector complex", CERN/Ankara

Umit KAYA, Ankara University, "Search for Color Octet Electron (e8) at TeV Energy Scale Colliders"

Kaan Yuksel OYULMAZ, Bolu Abant Izzet Baysal University, "Upgrade and performance studies of CMOS sensors for future colliders"

Salim OGUR, Bogazici University, "Linac and Damping Ring Designs of the future Circular e+e- Collider of CERN", CERN/Bogazici PhD April 2019 – Izter CERN fellow

…

MSc theses

Yunus Emre OKYAYLI, 2018, "Search for R-parity violation interactions of scalar leptons at future circular collider", Istanbul U.

Gökhan HALİMOĞLU, 2018, "Measurement of lepton + jets at 100 TeV at future circular collider", Istanbul U.

Rokia Omar Ali ALAMIN, 2017, "Anomalous heavy down type b' quark production at the future circular collider", Kastamonu University

Burak HACIŞAHİNOĞLU, 2017, "Search for flavour changing neutral current couplings of higgs-up sector quarks at electron-proton colliders", Istanbul U.

Murat ALTINLI, 2017, "Investigation of gauge boson anomalous couplings with higgs particle at electron-proton colliders", Istanbul U.

Çağla ÇAĞLAR, 2019, "Search for quarkonium consists of E6 model predicted isosinglet quark at future colliders,", Ege University

Alev Ezgi DEMİRCİ, 2017, "Production and decay channels of charged higgs boson at high energy hadron colliders", Ankara U.

Simulation Tools: PyECLOUD, CST

Fatih Yaman

PyECLOUD

- **2D Electrostatic PIC simulation**
- **effects of space charge and secondary electrons are included**
- **adaptive scheme to control the number of electrons per macro particle during the simulation**
- **ECLOUD and Furman-Pivi SEY models**

G. Iadarola, "Electron cloud studies for CERN particle accelerators and simulation code development" PhD Thesis, U. Naples, CERN-THESIS-2014-047, (2014).

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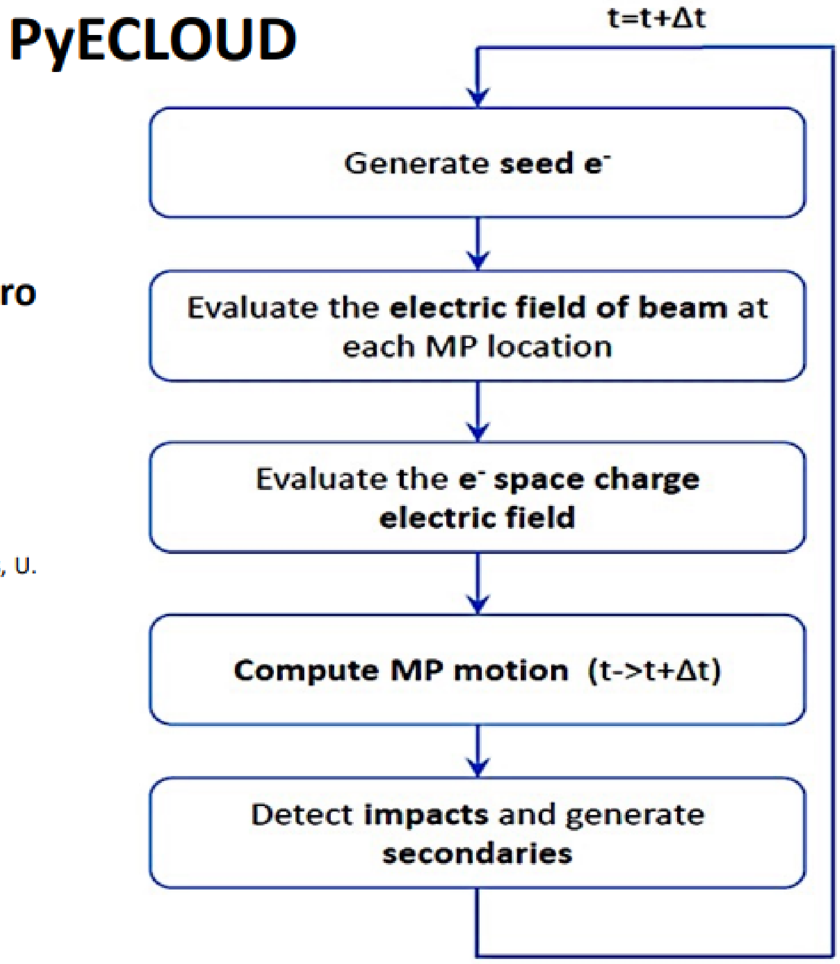
CST-PS

- **3D Electromagnetic PIC simulation**
- **effects of space charge and secondary electrons are included**
- **Furman-Pivi SEY model**
- **Photoemission mechanism is not included in this work**



with the courtesy of G. Iadarola

FCC-ee e-cloud build up studies

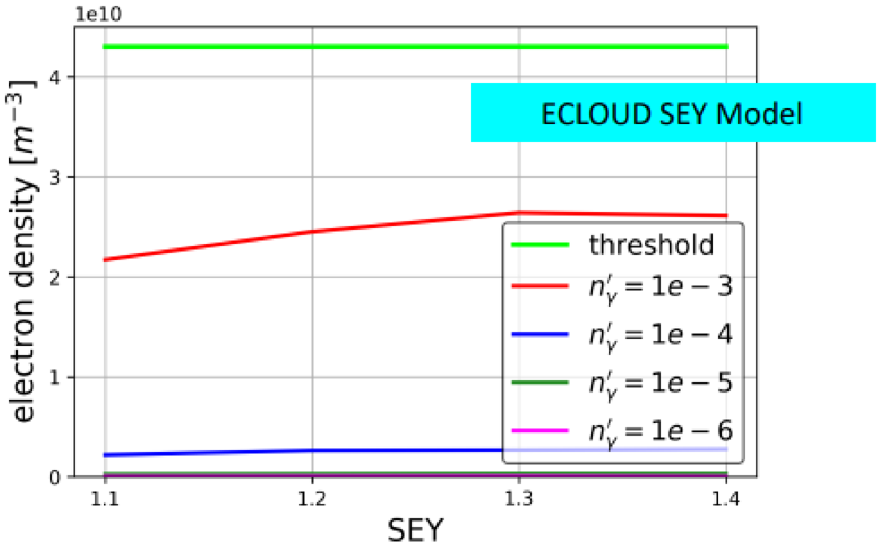
FUTURE CIRCULAR COLLIDER
Innovation Study

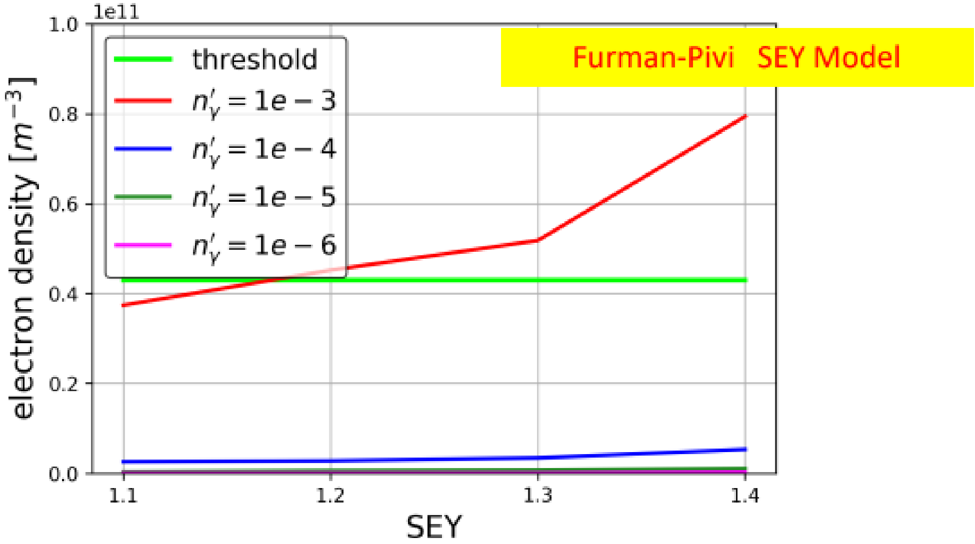
İZMİR YÜKSEK TEKNOLOJİ ENSTİTÜSÜ
Türkiye'nin Teknoloji Üssü

Average of min. for center e⁻ density, FCCee Collider Arc Dipol

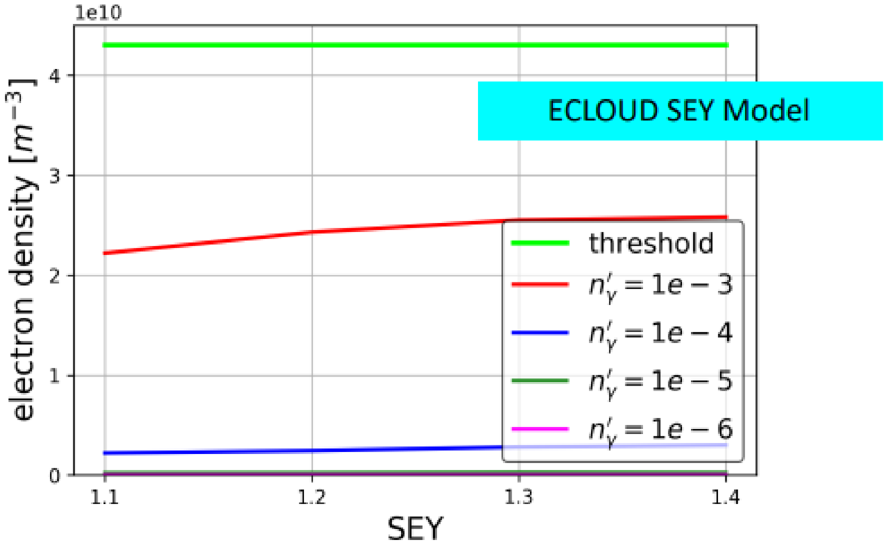
Fatih Yaman

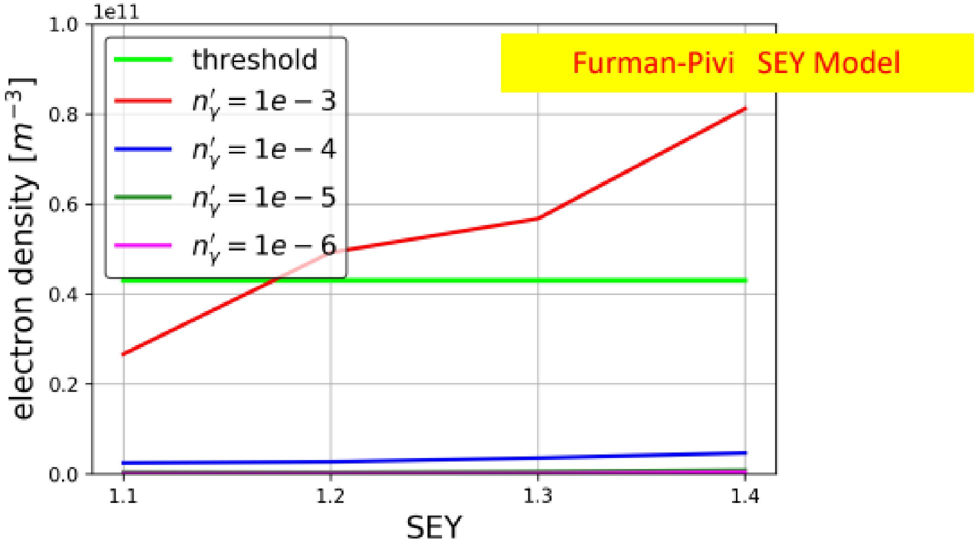
bunch space : 30 [ns]





bunch space : 32 [ns]

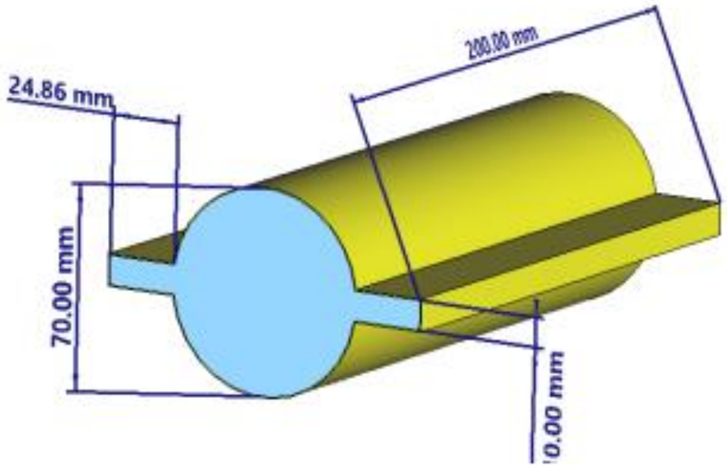


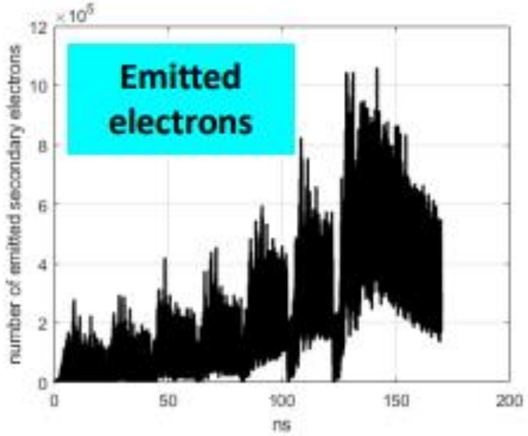


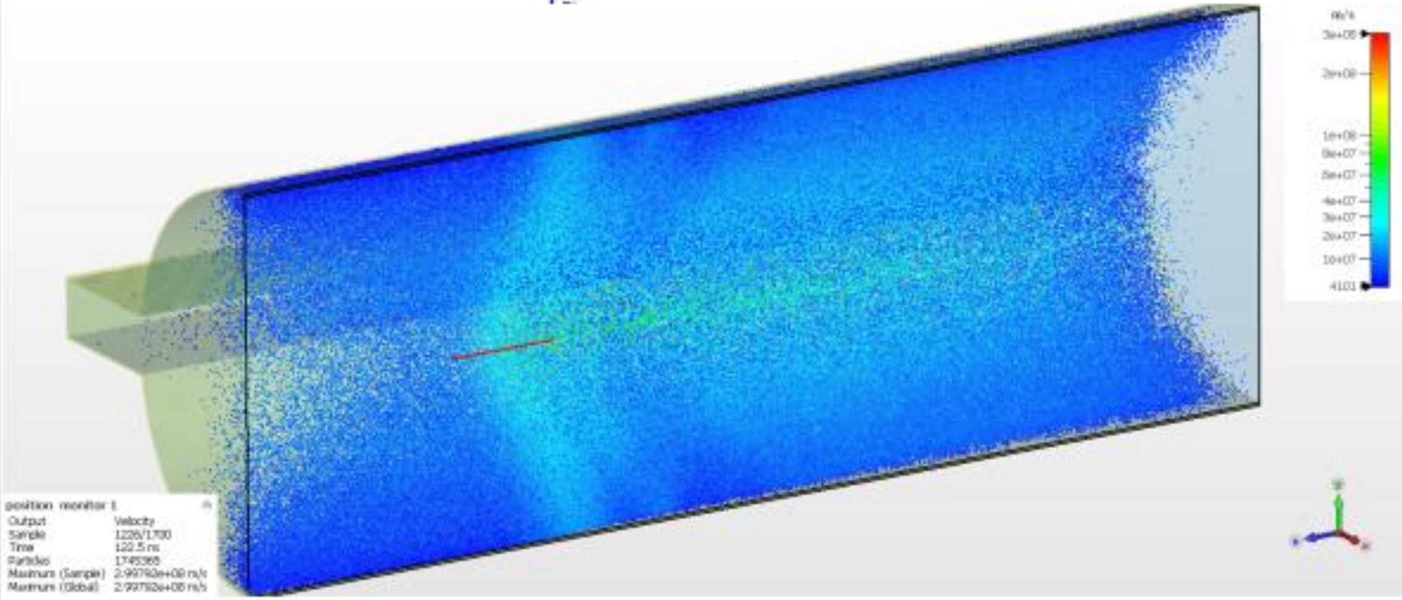
FCC-ee e-cloud build up studies

Electron Cloud Build-up Simulations with CST-PS

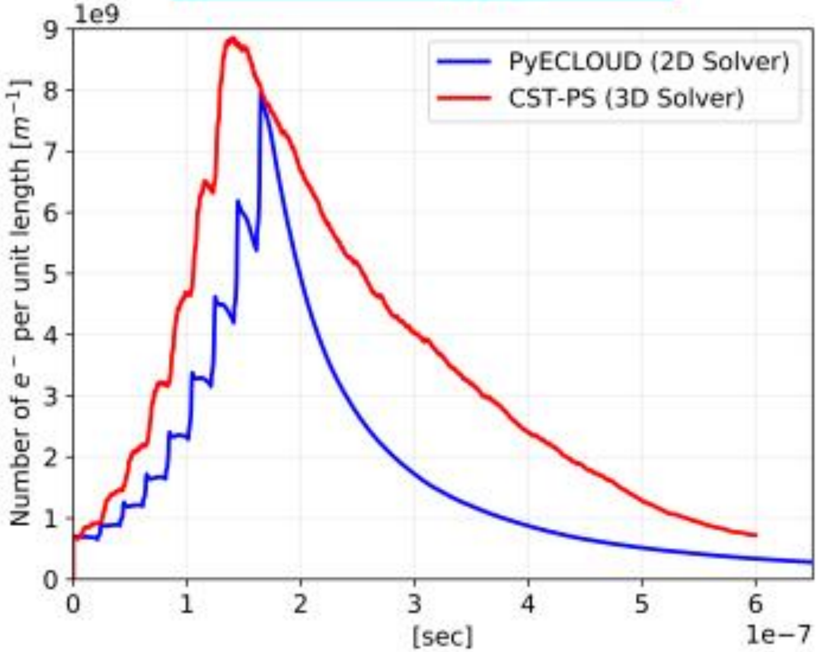
Fatih Yaman







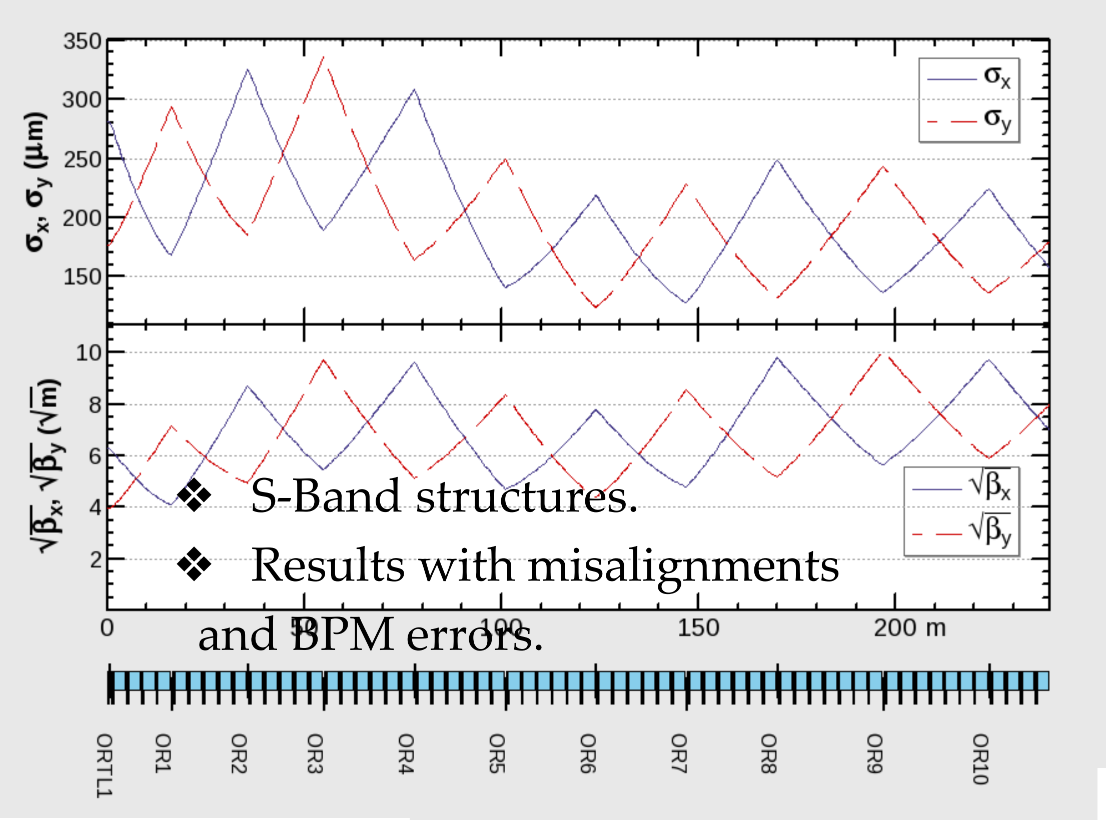
FCCee 2IPs Arc Dipole test (circular beam pipe)



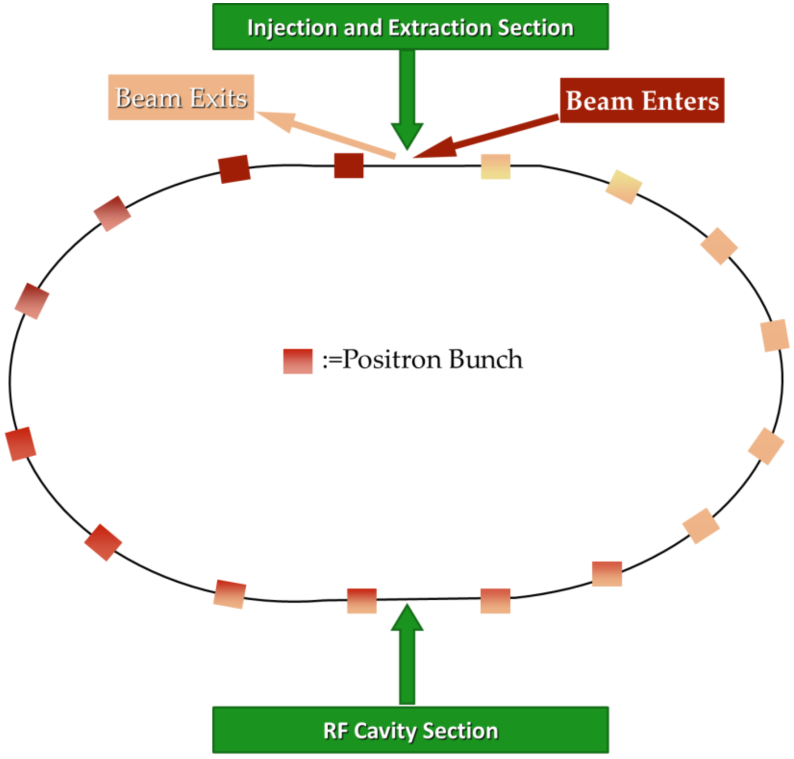
FUTURE CIRCULAR COLLIDER
Innovation Study

linac and damping ring design

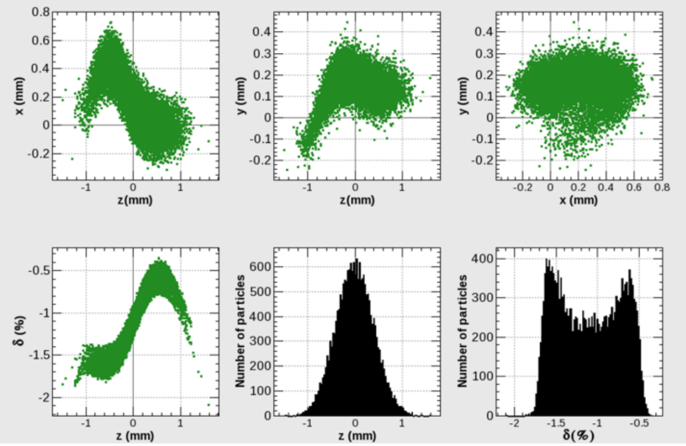
Salim Ogur

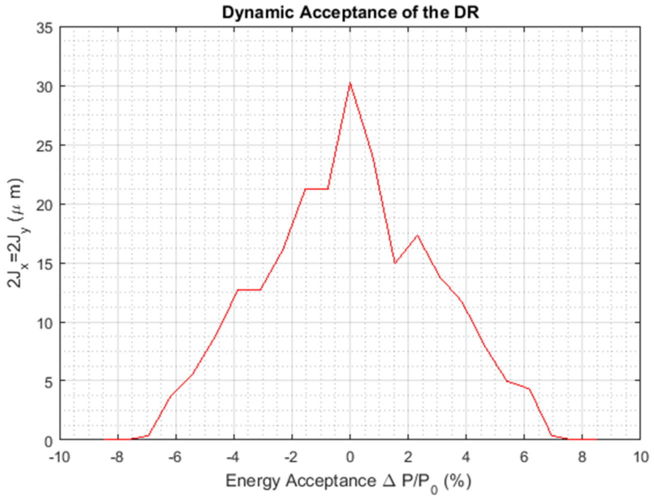


- S-Band structures.
- Results with misalignments and BPM errors.



- 2 wigglers each in Straight Sections.
- 400 MHz LHC like 2 SC cavities (1.5 + 2x1 meter long)

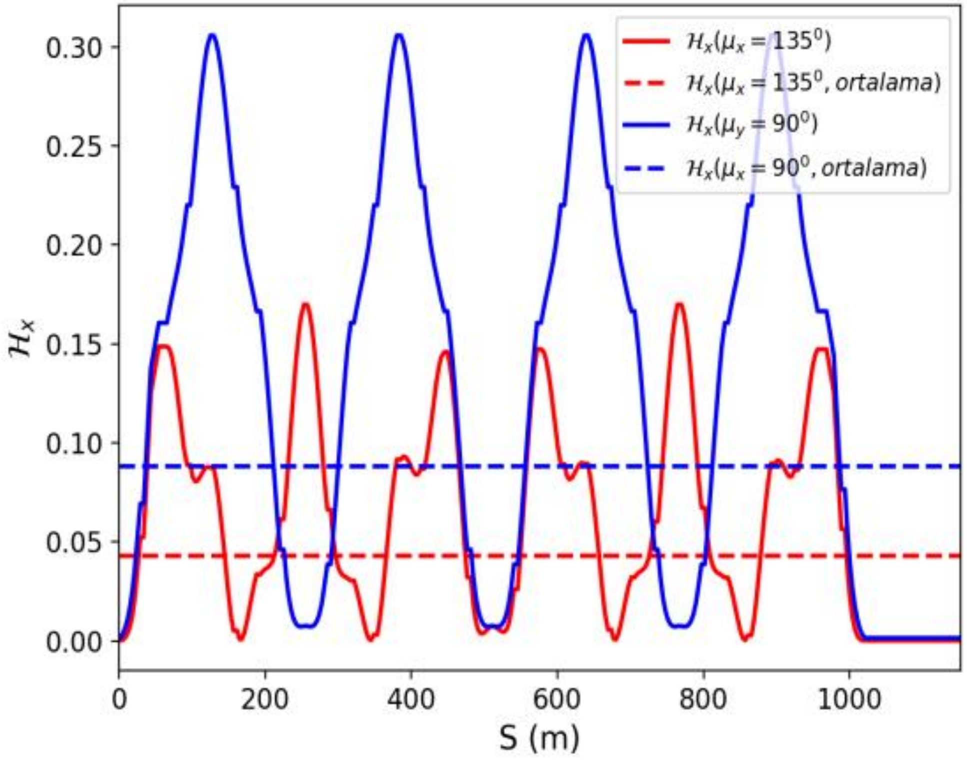




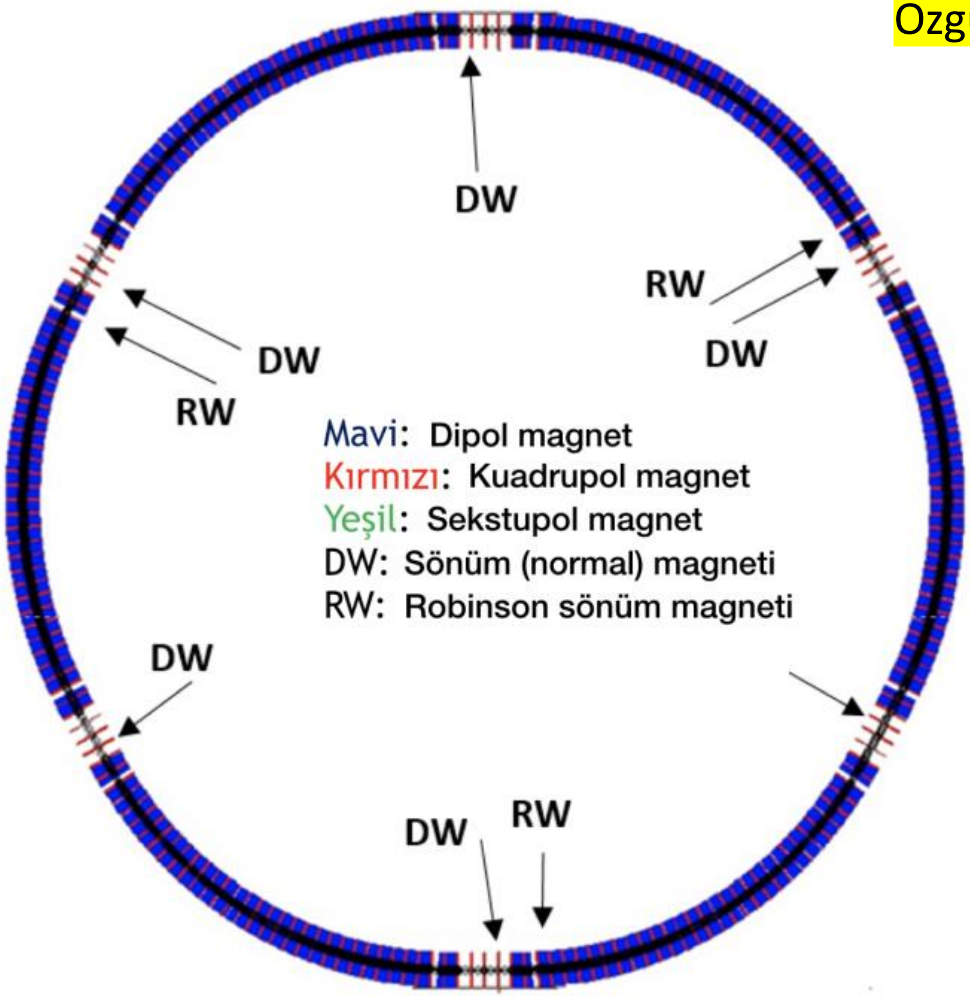
parameter	value
natural emittance (x, y, z)	1.39 nm, 0.28 nm, 1.75 μm
damping time (τ_x, τ_y, τ_z)	10.6/11.0/5.6 ms
bending radius, wiggler field	7.75 m, 1.8 T
acceptance (x, y, z)	22.4 μm, 22.4 μm, 14.7 mm
energy spread	7.74×10^{-4}
bucket height	8.0 %
energy acceptance	±7.8 %
injected emittance (x, y, z)	1.29, 1.22, 75.5 μm
extracted emittance (x, y, z)	1.81 nm, 0.37 nm, 1.52 μm

pre-booster design: SPS & greenfield

Ozgur Etisken



Şekil 4.1 SPS hızlandırıcısı için iki farklı faz ilerlemesine karşılık gelen $\mathcal{H}_x$ fonksiyonu: Mevcut değer (mavi çizgi, 90^0) ve optimum değer (kırmızı çizgi, 135^0). Ortalama değerler kesikli çizgi ile gösterilmiştir



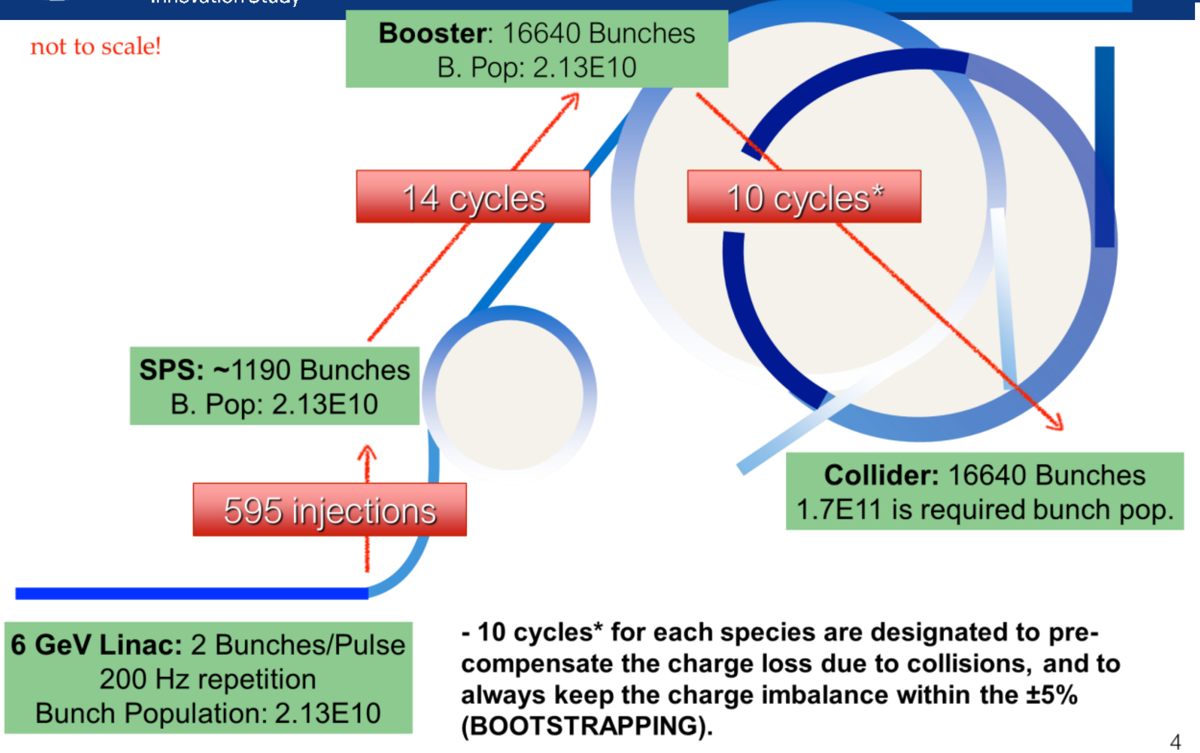
Şekil 4.6 SPS hızlandırıcısının şematik gösterimi

injector & collider filling schemes

FUTURE CIRCULAR COLLIDER Innovation Study

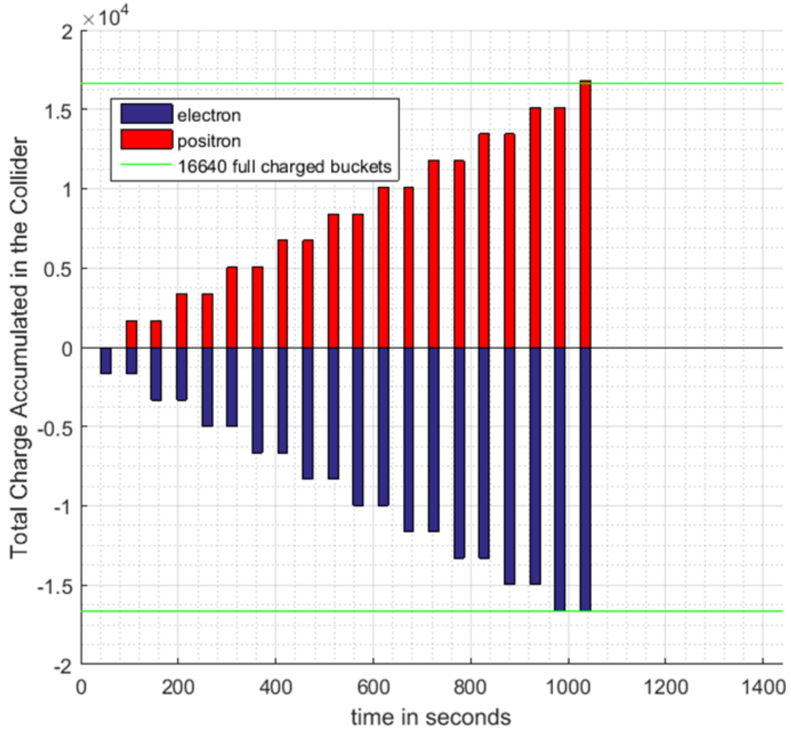
Salim Ogur

not to scale!



- 10 cycles* for each species are designated to pre-compensate the charge loss due to collisions, and to always keep the charge imbalance within the ±5% (BOOTSTRAPPING).

4



- **Linac up to 6 GeV (Bunch Charge = 3.5 x 10^{10})**
  200 Hz 2 bunches of 3.5 x 10^{10} per RF pulse

90% Transmission between each downstream machines

- **SPS (Bucket Charge=** 3.15 x 10^{10}**):**

  Accumulation of 755 Bunches : 1.89 s
  Emittance cooling (Damping time τ_x=0.03 s) : 0.12 s
  Ramp up and down time (6 - 20* GeV) : 0.28 s (net acceleration gradient= 100 GeV/s)
  SPS Cycle time : 2.29 s

- **BR (Bucket Charge=** 2.83 x 10^{10}**):**

  Accumulation of 9060 Bunches : 27.48 s
  Emittance cooling (Damping time τ_x=0.1 s) : 0.4 s
  Ramp up and down time (14 - 45.6 GeV) : 0.63 s (net acceleration gradient= 100 GeV/s)
  BR Cycle time : 28.53 s

- **Collider (Bucket Charge=** 2.53 x 10^{11}**):**
  10 BR Injections i.e. 10 x 2.53 x 10^{10} = 2.53 x 10^{11} **for each species will result the collider to be filled for Z- mode in 570.6 seconds while luminosity lifetime is 1089 s.**

- **Linac up to 14-20 GeV:**
  200 Hz 2 bunches of 3 x 10^{10} per RF pulse

~ 90% Transmission between each downstream machines

- **Top-up Booster (Bucket Charge=** 2.8 x 10^{10}**):**

  Accumulation of 9600 Bunches : 24 s
  Emittance cooling (Damping time τ_x=0.1 s) : 0.4 s
  Ramp up and down time (14 - 45.6 GeV) : 0.63 s (net acceleration gradient= 100 GeV/s)
  BR Cycle time : 25.03 s

- **Collider:**
  9 BR Injections i.e. 10 x 90% x 2.53 x 10^{10} = 2.53 x 10^{11} **for each species will result the collider to be filled for Z-mode in 500.6 seconds while luminosity lifetime is 1089 s.**

FUTURE CIRCULAR COLLIDER
Innovation Study

Physics Studies

teams in Turkey are extremely productive !

Probing top quark FCNC $tq\gamma$ and tqZ couplings at future electron-proton colliders

O. Cakir [a], A. Yilmaz [b], I. Turk Cakir [c,*], A. Senol [d], H. Denizli [d]

[a] Department of Physics, Ankara University, 06100, Ankara, Turkey
[b] Department of Electrical and Electronics Engineering, Giresun University, 28200, Giresun, Turkey
[c] Department of Energy Systems Engineering, Giresun University, 28200, Giresun, Turkey
[d] Department of Physics, Bolu Abant Izzet Baysal University, 14280, Bolu, Turkey

Received 26 January 2019; received in revised form 12 May 2019; accepted 13 May 2019
Available online 16 May 2019
Editor: Tommy Ohlsson

Investigating Top-Higgs FCNC Couplings at the FCC-hh

O. M. Ozsimsek*
Graduate School of Science and Engineering, Hacettepe University, 06800 Ankara, Turkey

V. Ari† and O. Cakir‡
Department of Physics, Ankara University, 06100 Ankara, Turkey
(Dated: April 29, 2022)

Why should we search for vector-like leptons?

Feyza Baspehlivan[1], Burak Dagli[1*], Osman Emre Delialioglu[1], Saleh Sultansoy[1,2]

[1] TOBB University of Economics and Technology, Ankara, Turkey
[2] ANAS Institute of Physics, Baku, Azerbaijan

General structure of democratic mass matrix of quark sector in E_6 model

AIP Conference Proceedings **1722**, 070004 (2016); https://doi.org/10.1063/1.4944158

R. Ciftci[1, a)] *and* A. K. Çiftci[2, b)]

Probing Anomalous $WW\gamma$ and WWZ Couplings with Polarized Electron Beam at the LHeC and FCC-Ep Collider

I. Turk Cakir, A. Senol, A. T. Tasci, O. Cakir

Investigation of charged Higgs boson in the bottom and top quark decay channel at the FCC-hh

I. Turk Cakir [a,*], O. Cakir [b], H. Denizli [c], A. Senol [c], A. Yilmaz [d]

[a] Department of Energy Systems Engineering, Giresun University, 28200 Giresun, Turkey
[b] Department of Physics, Ankara University, 06100 Ankara, Turkey
[c] Department of Physics, Bolu Abant Izzet Baysal University, 14280, Bolu, Turkey
[d] Department of Electrical and Electronics Engineering, Giresun University, 28200 Giresun, Turkey

Sensitivity on Anomalous Neutral Triple Gauge Couplings via ZZ Production at FCC-hh

A. Yilmaz*
Department of Electrical and Electronics Engineering, Giresun University, 28200, Giresun, Turkey

A. Senol† and H. Denizli‡
Department of Physics, Bolu Abant Izzet Baysal University, 14280 Bolu, Turkey

I. Turk Cakir§
Department of Energy Systems Engineering, Giresun University, 28200 Giresun, Turkey

O. Cakir¶
Department of Physics, Ankara University, 06100 Ankara, Turkey

Future Circular Collider Based Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics

Y. C. Acar,* A. N. Akay,† S. Beser,‡ and B. B. Oner§
TOBB University of Economics and Technology, Ankara, Turkey

A. C. Canbay¶ and U. Kaya**
TOBB University of Economics and Technology, Ankara, Turkey and Ankara University, Ankara, Turkey

H. Karadeniz††
Giresun University, Giresun, Turkey

S. Sultansoy‡‡
TOBB University of Economics and Technology, Ankara, Turkey and ANAS Institute of Physics, Baku, Azerbaijan

Sensitivity on anomalous neutral triple gauge couplings via ZZ production at FCC-hh

A. Yilmaz[1,a], A. Senol[2,b], H. Denizli[2,c], I. Turk Cakir[3,d], O. Cakir[4,e]

[1] Department of Electrical and Electronics Engineering, Giresun University, 28200 Giresun, Turkey
[2] Department of Physics, Bolu Abant Izzet Baysal University, 14280 Bolu, Turkey
[3] Department of Energy Systems Engineering, Giresun University, 28200 Giresun, Turkey
[4] Department of Physics, Ankara University, 06100 Ankara, Turkey

FCC opportunities for Turkey

ongoing collaborations

FCC-ee injector design (*Ankara, Bogazici, IEU, Kirikkale.…)*
FCC-ee beam dynamics studies (*IYTE*,…)
FCC detector studies (*AIBU, Uludag,* …)
FCC physics (*Akdeniz, Ankara, Tandogan, EgeU, Giresun, Isik, Istanbul Aydin, Istanbul U, IEU, Okan, PRU, TOBB ETU, ULUDAG*…)

potential further contributions

FCC civil engineering
FCC-ee vacuum system prototype (*IEU* proposal)
FCC-ee damping ring and booster designs (Ankara, Kirikkale, ...)

FUTURE CIRCULAR COLLIDER
Innovation Study

Summary and Outlook

- The European Strategy Update 2020 has issued a high-priority **request for a feasibility study of the FCC integrated programme**, and suggestions for key technology R&D areas
- **Main activities of the FCC Feasibility Stud**… **ete local/regional implementation scenario** in c… **state authorities**, accompanied by … **sics studies and technology R&D**, performed … **laboration** and supported by **EC H2020 Design Study F**… **ls, to prove FCC feasibility by 2025/26**

Teşekkür ederim !

- Long term goal: **world-leading HEP infrastructure for 21st century** to push the particle-physics **precision and energy frontiers** far beyond present limits.
- **Success of FCC relies on global participation**
- **Strong participation from Turkey with many addt'l opportunities !**


FCC
WEEK
2023
5 – 9 June
STAY
TUNED