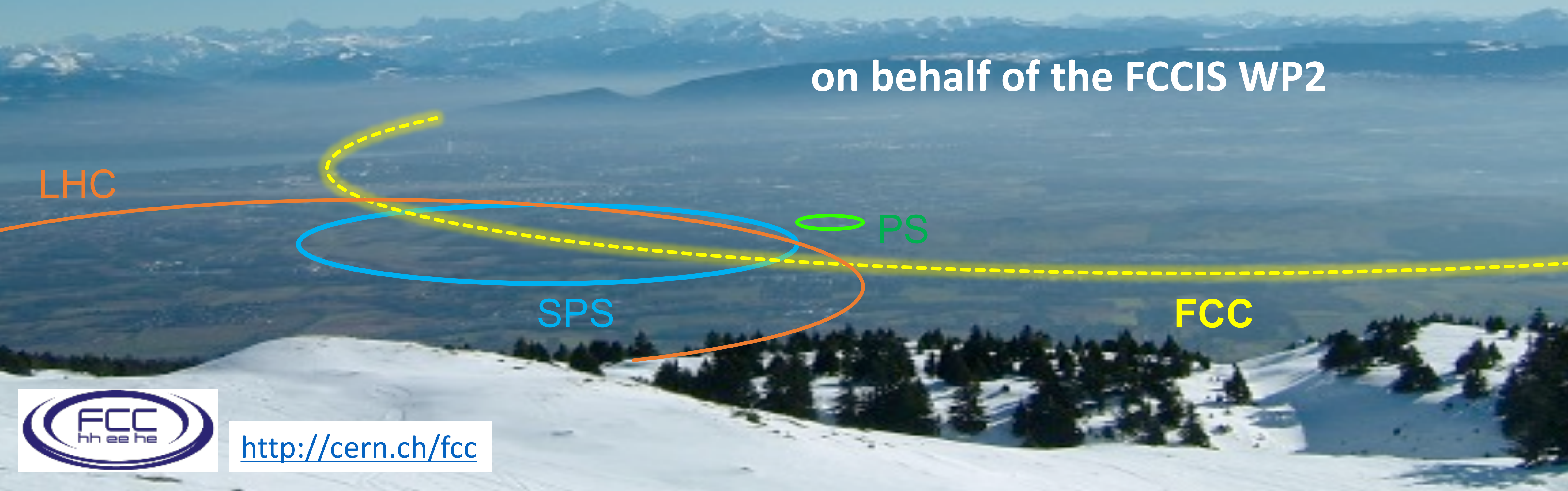
FCCIS WP2: Collider Design

Ilya Agapov

DESY

on behalf of the FCCIS WP2

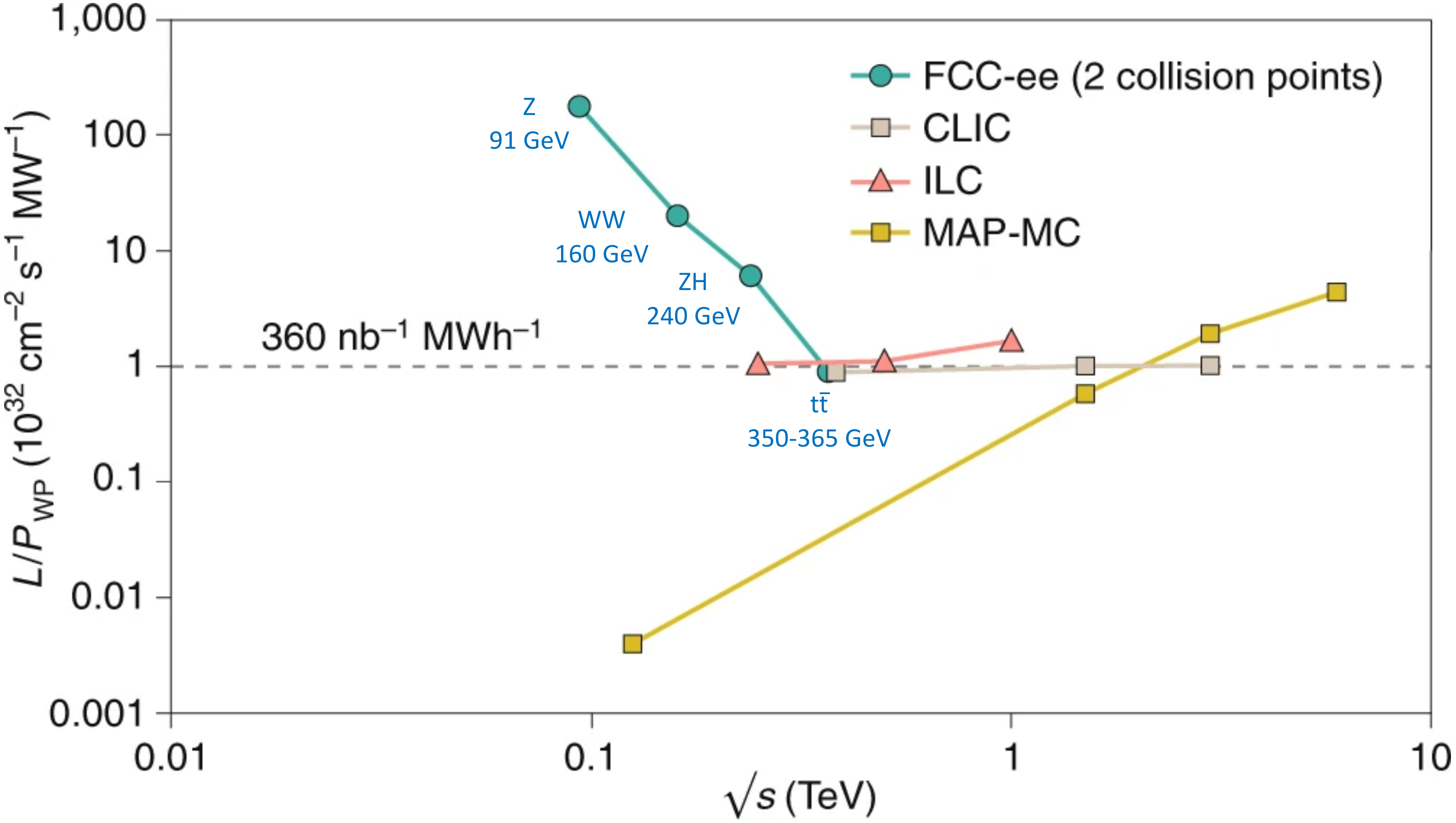


http://cern.ch/fcc

'The Future Circular Collider Innovation Study (FCCIS) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 951754

photo: J. Wenninger

FCC-ee: efficient Higgs/electroweak factory and a first step towards FCC-hh



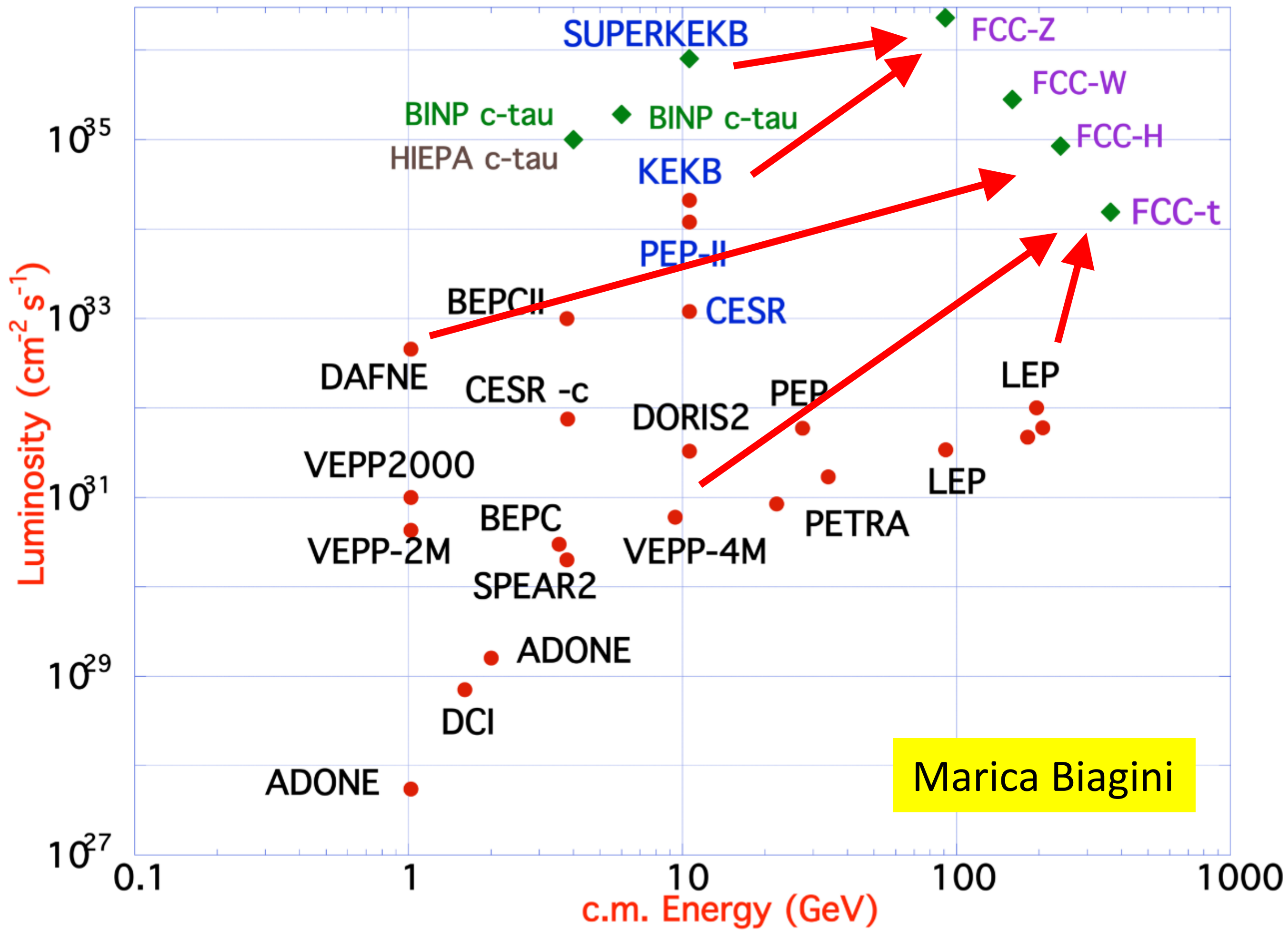
- Cost-efficient Higgs factory
- Technology ready
- First stage of an integrated programme for a 100 TeV collider
- Synergies with other accelerator projects (light sources, EIC, SuperKEKB)

M. Benedikt, A. Blondel, P. Janot, et al., **Nat. Phys. 16**, 402-407 (2020), and
European Strategy for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

FCC-ee Collider Parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

Design concept: using lessons and techniques from past colliders



B-factories: **KEKB & PEP-II:** double-ring lepton colliders, high beam currents, top-up injection

DAFNE: crab waist, double ring

LEP: high energy, SR effects

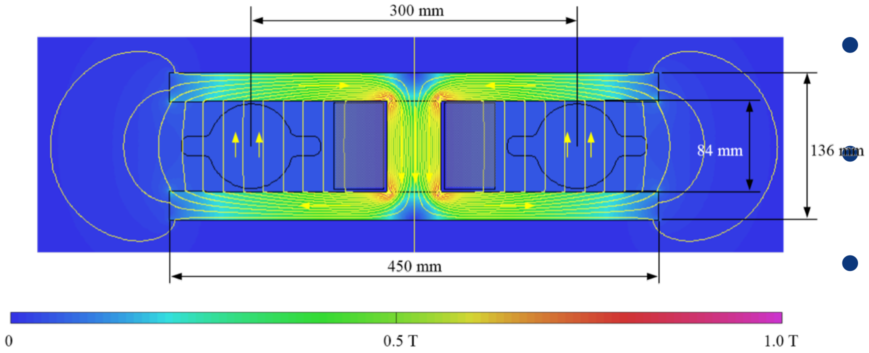
VEPP-4M, LEP: precision E calibration

KEKB: e^+ source

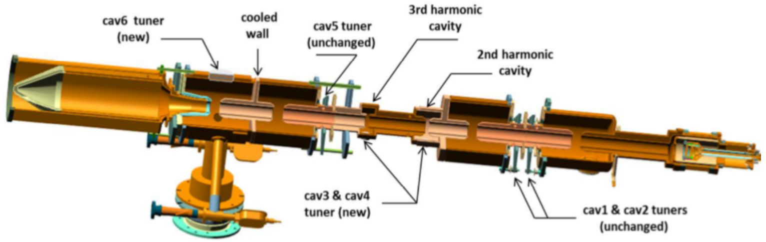
HERA, LEP, RHIC: spin gymnastics

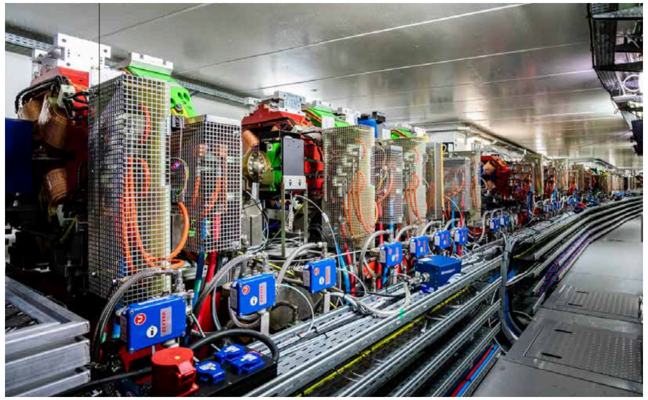
S-KEKB: low β_y*, crab waist

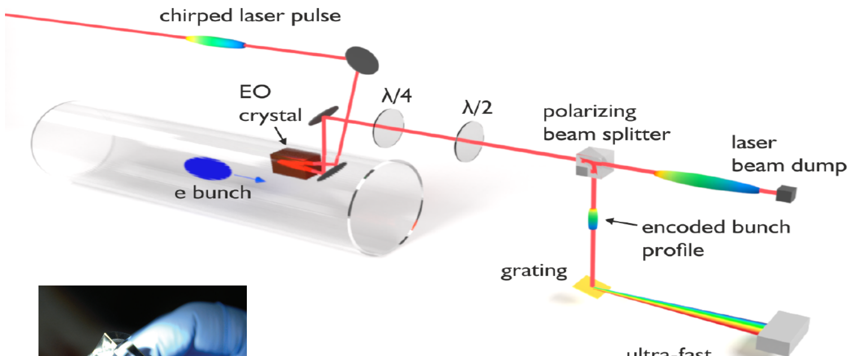
…but bringing in new technology and ideas

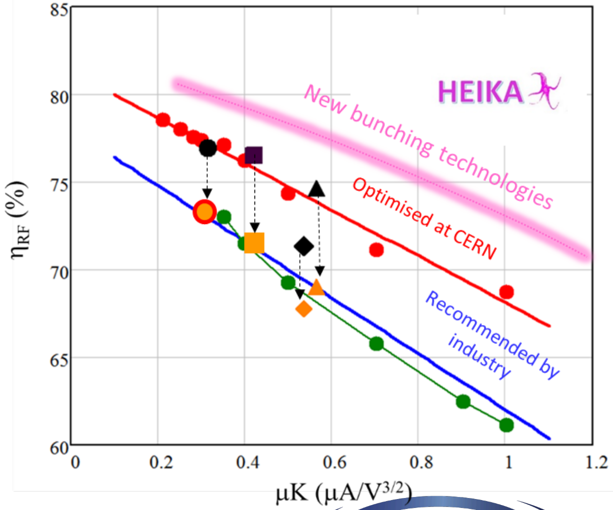


- Energy-efficient magnets
- Advanced RF
- Modern injectors
- Advanced diagnostics
- Advanced machine tuning and controls





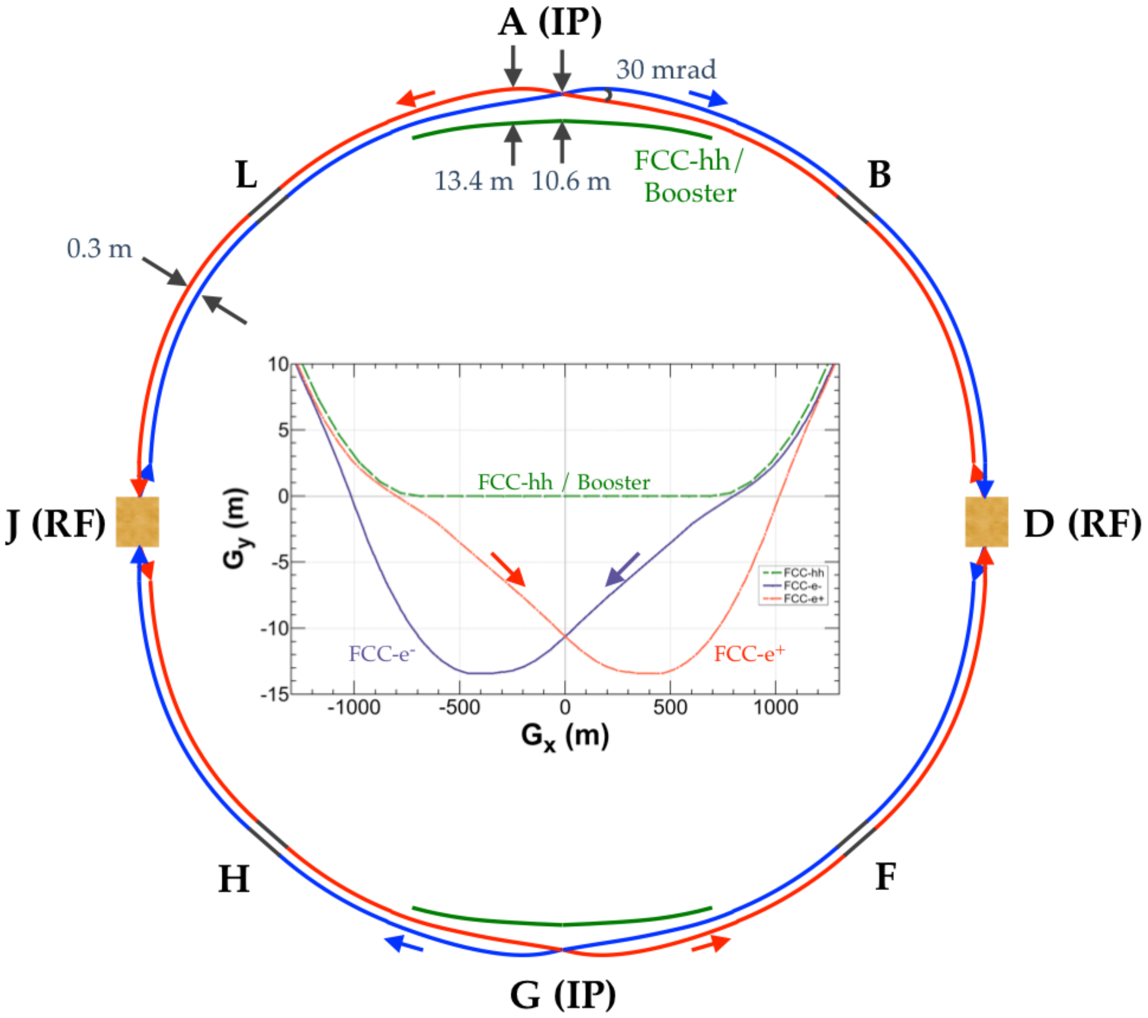




FCC-ee basic design choices

K. Oide et al.

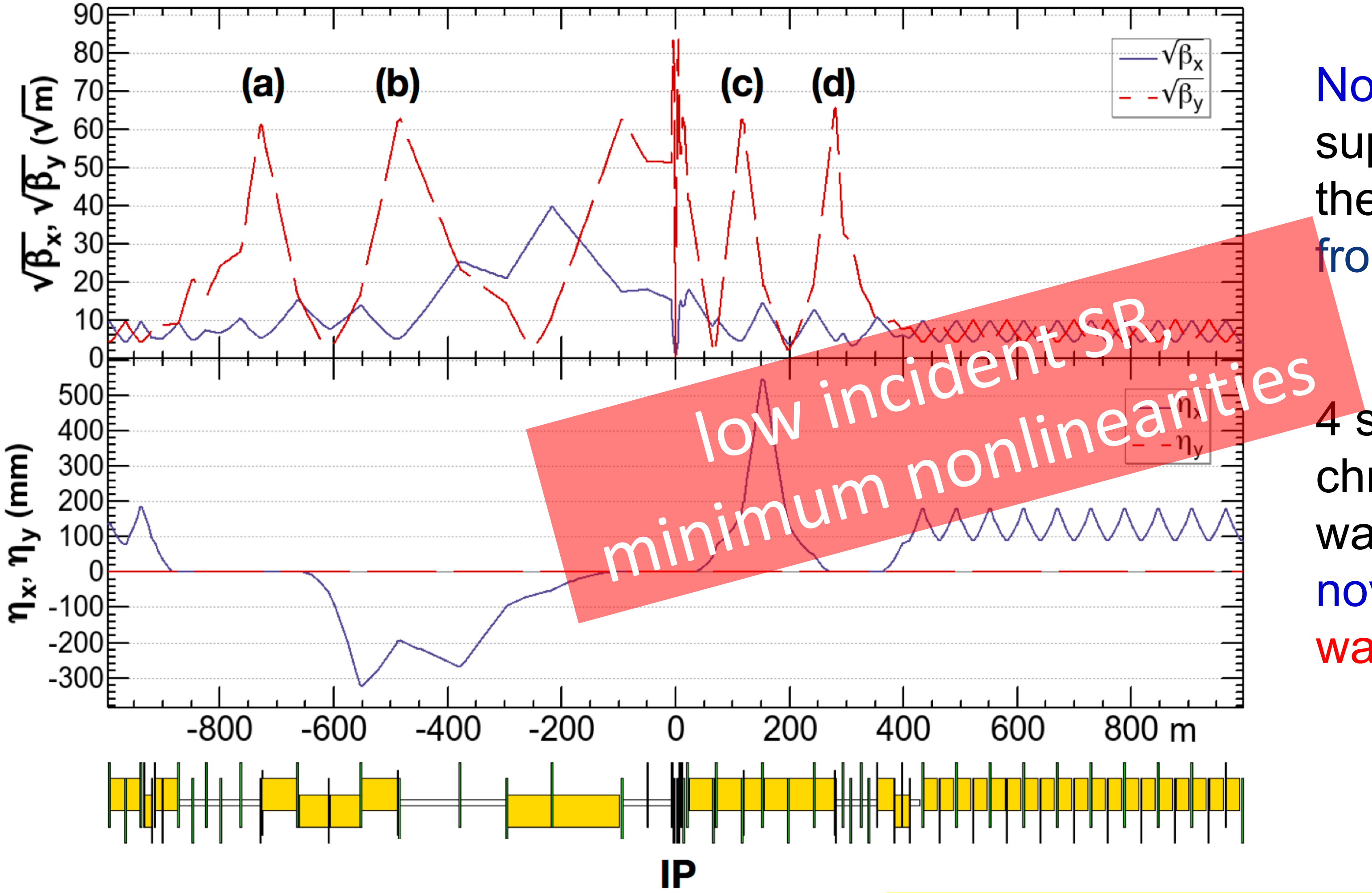
- **double ring** e^+e^- collider ~100 km
- **Rapidly cycling booster** required for **top-up injection** located in collider tunnel
- **presently 2 IPs** (4 IP option under study), **large** horizontal crossing angle **30 mrad, crab-waist optics**



- **asymmetric IR layout & optics** to limit synchrotron radiation towards the detector
- **common RF** for $t\bar{t}$ running
- **synchrotron radiation power 50 MW/beam** at all beam energies; **tapering of arc magnet** strengths to match local energy

FCC-ee: The Lepton Collider, **Eur. Phys. J. Spec. Top. 228**, 261–623 (2019)
K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

Key feature: asymmetric crab-waist IR optics



K. Oide et al.

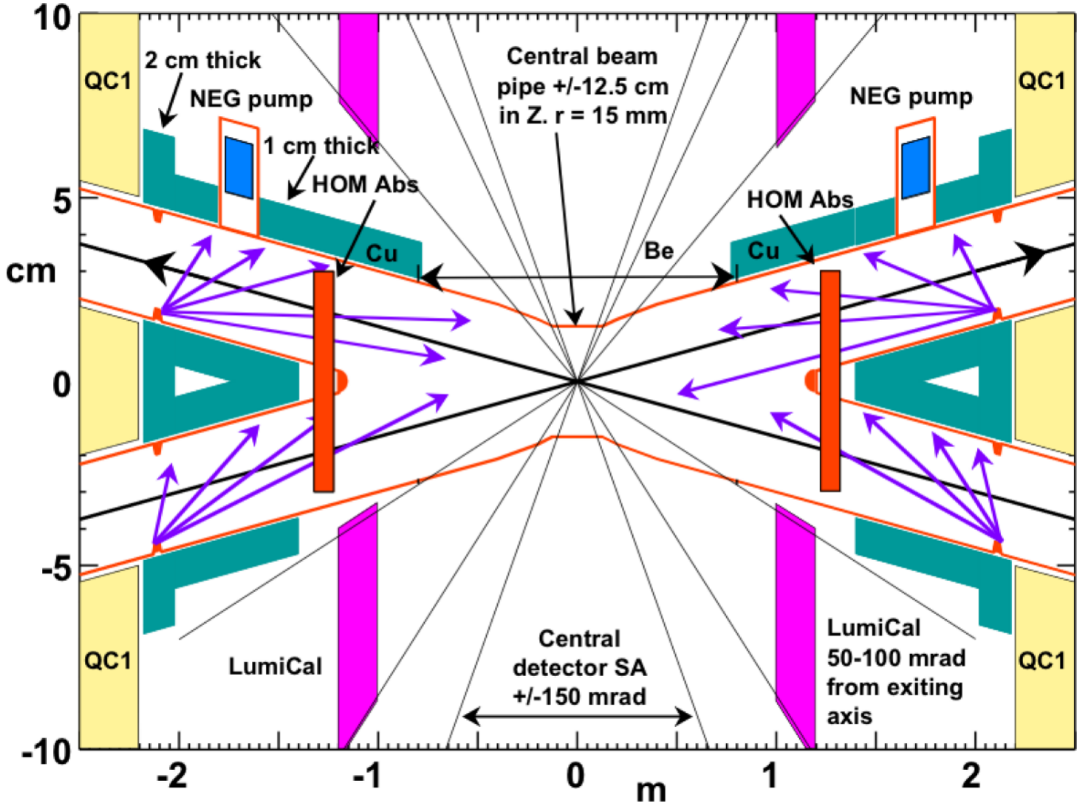
Novel asymmetric IR optics to suppress synchrotron radiation toward the IP, $E_{critical}$ <100 keV from 450 m from IP (lesson from LEP)

4 sextupoles (a–d) for local vertical chromaticity correction combined w. crab waist, optimized for each working point – novel "virtual crab waist", (standard crab waist demonstrated at DAFNE)

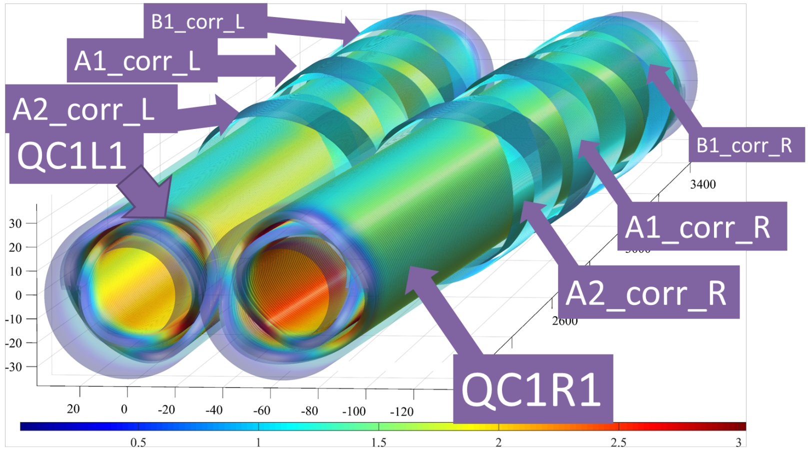
H. Burkhardt, A. Blondel, M. Koratzinos, K. Oide, et al.

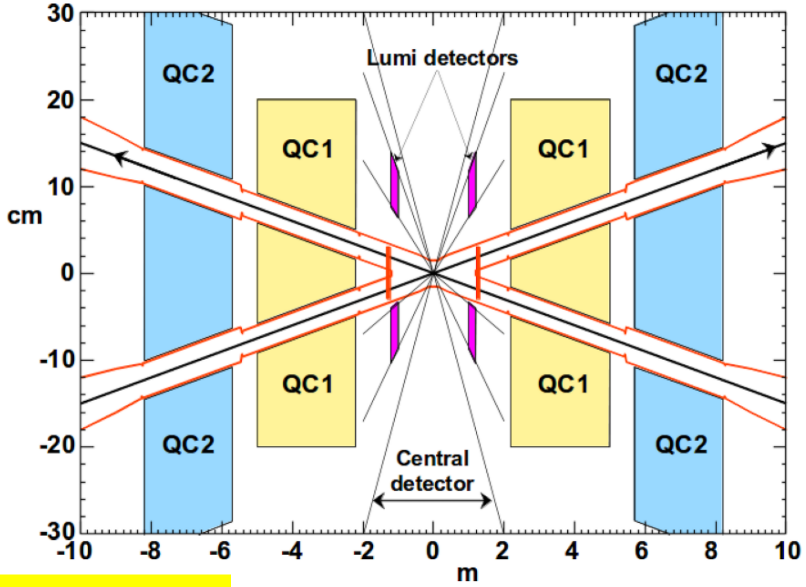
K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

FCC-ee Interaction Region Design



IR heat loads:
rad Bhabha (kW), beamstrahlung (MW), resistive wall (kW), HOMs, quadrupole synchrotron radiation





M. Boscolo, N. Bacchetta, A. Bogomyagkov, H. Burkhardt, M. Dam, D. El Khechen, M. Koratzinos, E. Levichev, M. Luckhof, A. Novokhatski, L. Pellegrino, S. Sinyatkin, M. Sullivan

M. Boscolo, H. Burkhardt, and M. Sullivan, **Phys. Rev. Accel. Beams 20**, 011008 (2017)
A. Novokhatski, M. Sullivan, E. Belli, M. Gil Costa, and R. Kersevan, **Phys. Rev. Accel. Beams 20**, 111005 (2017)

FCC-ee RF staging scenario

“Ampere-class” machine

	V_{rf} [GV]	# bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

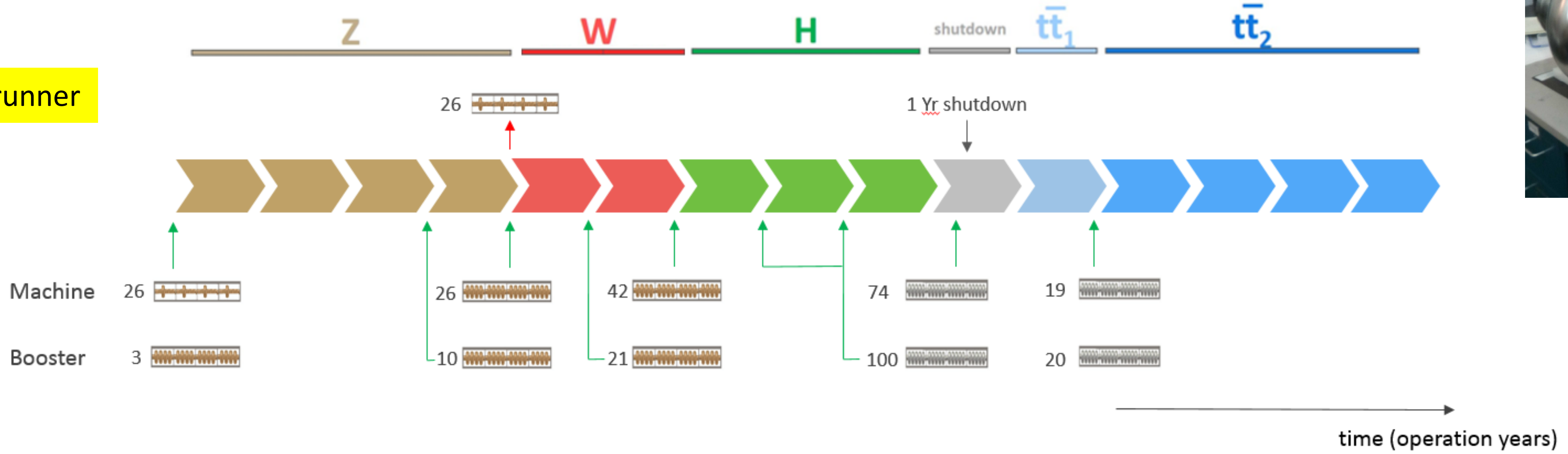
“high-gradient” machine

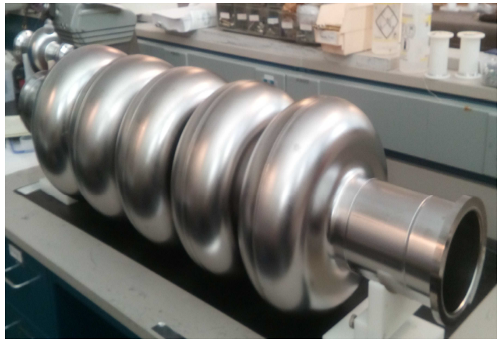
Three sets of RF cavities:

- high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.), Nb/Cu, 4.5 K
- higher energy (W, H, t): 400 MHz four-cell cavities (4/cryom.), Nb/Cu, 4.5 K
- $t\bar{t}$ machine complement: 800 MHz five-cell cavities (4/cryom.), bulk Nb, 2 K

Installation sequence comparable to LEP (≈ 30 cryomodules/shutdown)

O. Brunner

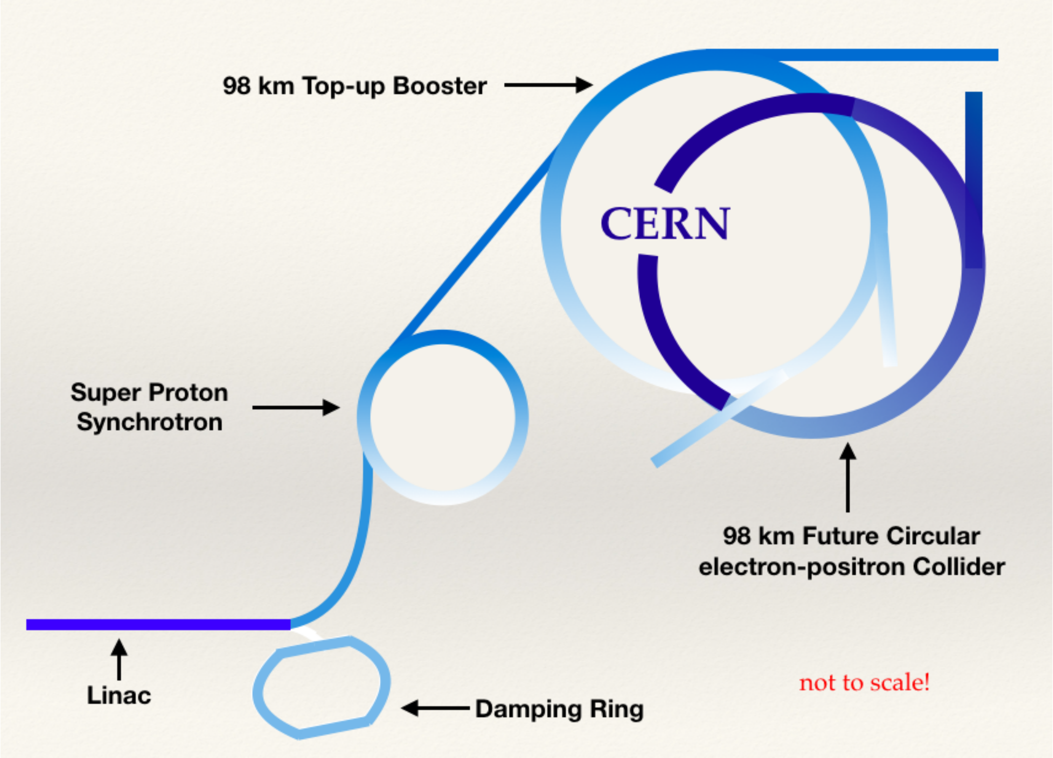


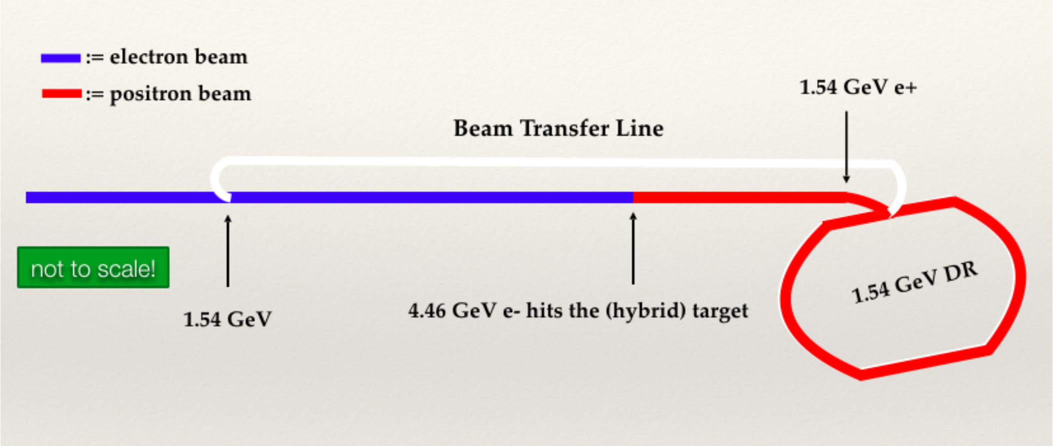


JLAB, Oct. 2017

F. Marhauser et al

FCC-ee injector layout, CDR version





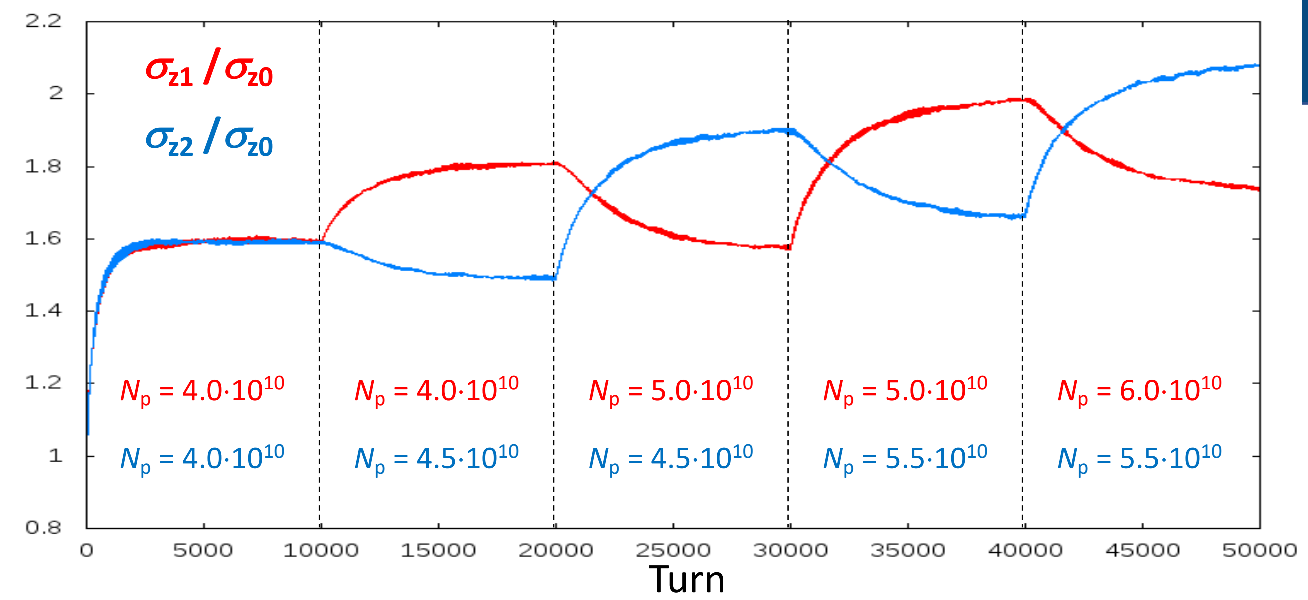
- S-band linac accelerating **1** or **2** bunches with repetition rate of **100-200 Hz**
- Same linac used for positron production at **4.46 GeV** Positron beam emittances reduced in DR at **1.54 GeV**
- Injection at **6 GeV** into of Pre-Booster Ring (SPS or new ring) and acceleration to 20 GeV.
- Alternatively a **20 GeV** linac
- Injection to main Booster at **20 GeV** with interleaved filling of e+/e- (below **20 min** for full filling) and continuous top-up.

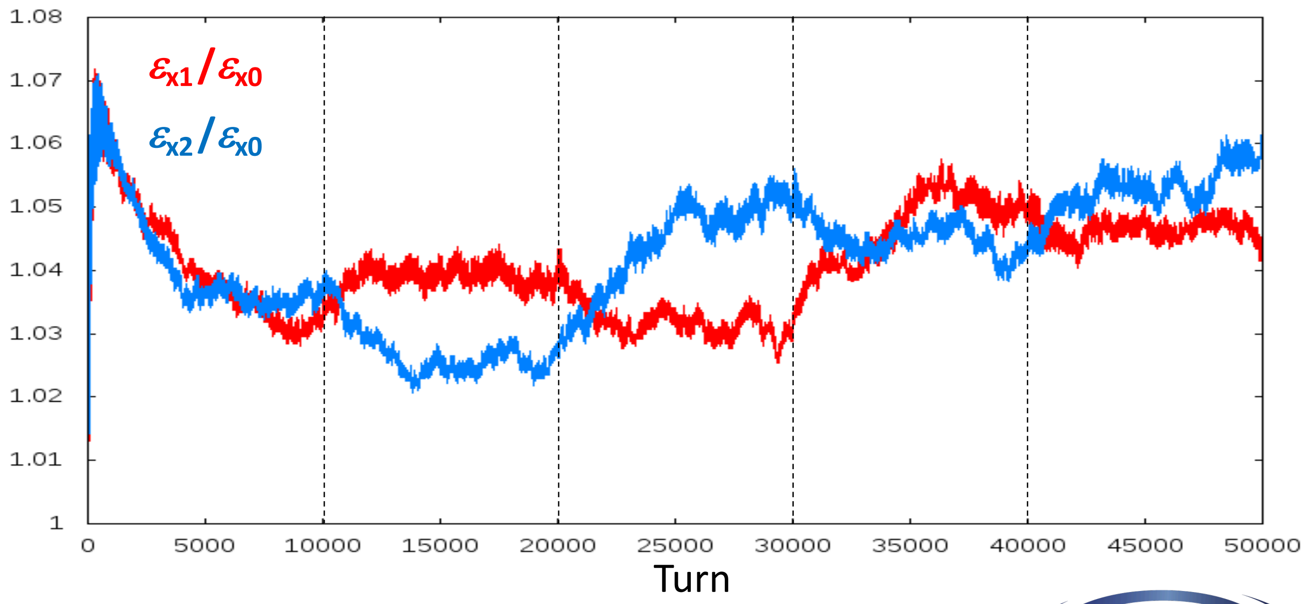
Reevaluated during the FCC feasibility phase

I. Chaikovska, O. Etisken, P. Martyshkin, S. Ogur, K. Oide, Y. Papaphilippou et al

Bootstrapping injection

- If we bring into collision such bunches with the “initial” σ_z (energy spread created only by SR), the beam-beam parameters will be far above the limits.
- The beams will be blown up and killed on the transverse aperture, before they are stabilized by the beamstrahlung.
- To avoid this, we have to gradually increase the bunch population during collision, so we come to *bootstrapping*.



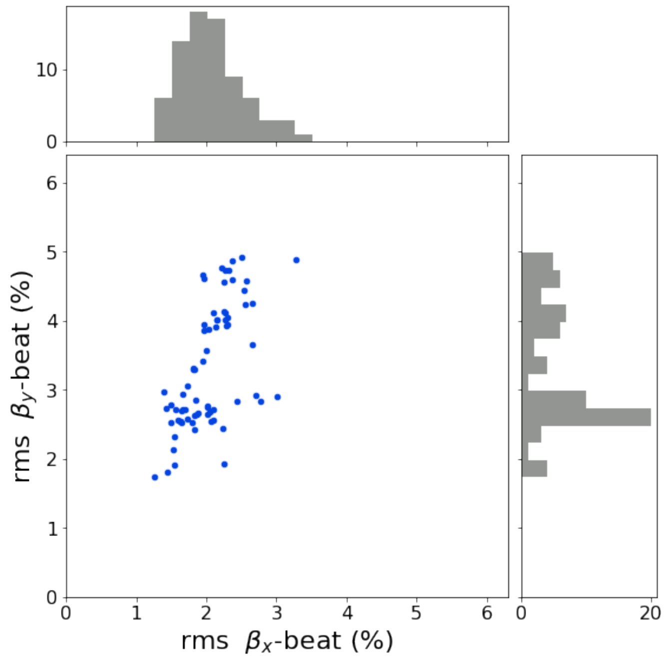


D. Shatilov et al.

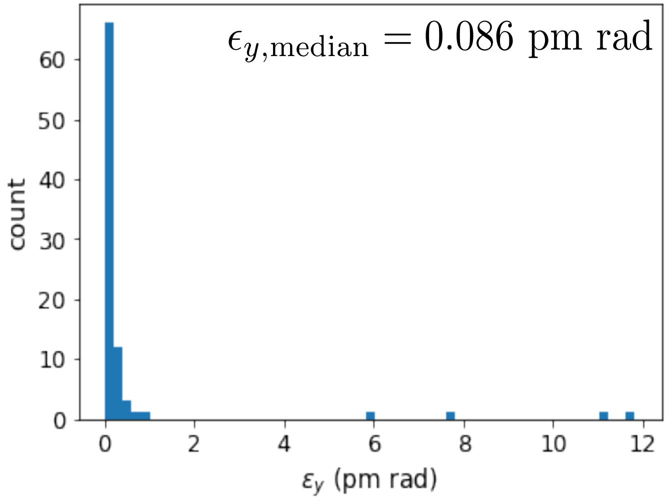
Emittance tuning

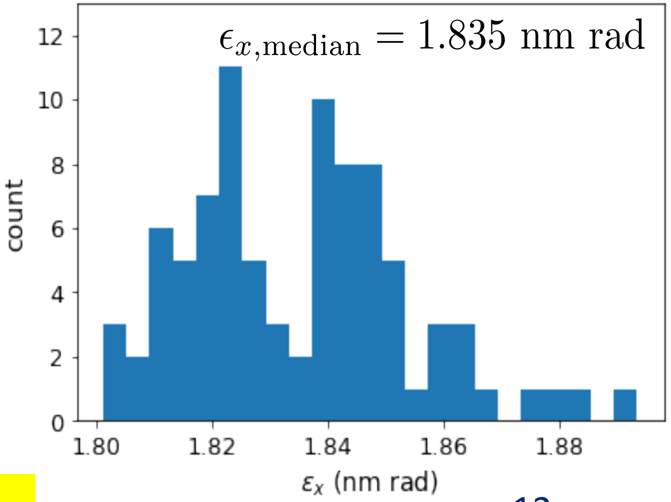
- Machine correction to achieve stable beam, lifetime, and ultra-low vertical emittance
- Simulations demonstrate that target emittances are achievable
- Refinement of alignment specification and correction procedures ongoing

Beta beating after correction:



ttbar (182.5 GeV) 4IP lattice,
Emittances after correction strategy:





RMS misalignment and field errors tolerances:

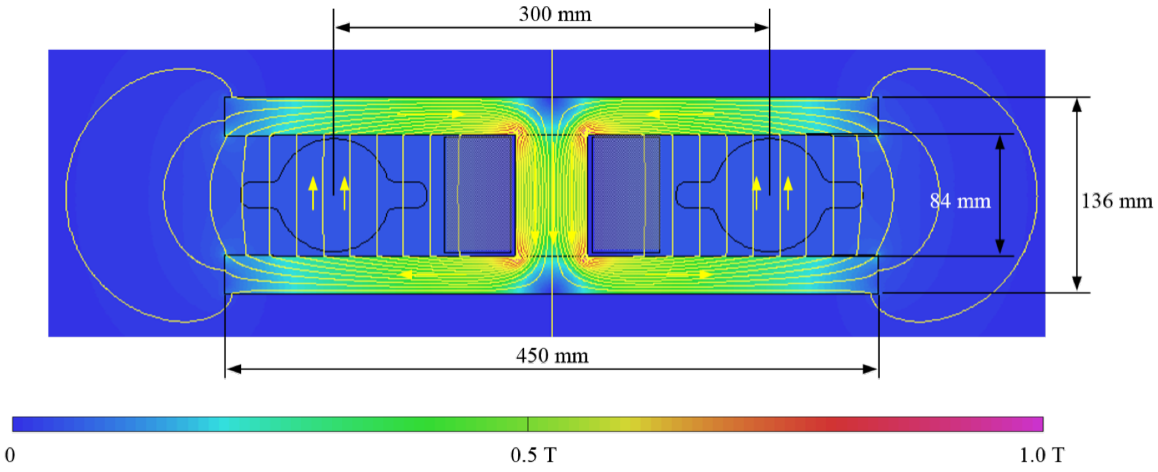
Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)
Arc quadrupole*	50	50	200	50
Arc sextupoles*	50	50	200	50
Dipoles	1000	1000	200	500
Girders	150	150	-	500
IR quadrupole	75	75	200	150
IR sextupoles	75	75	200	150
BPM**	40	40	100	-

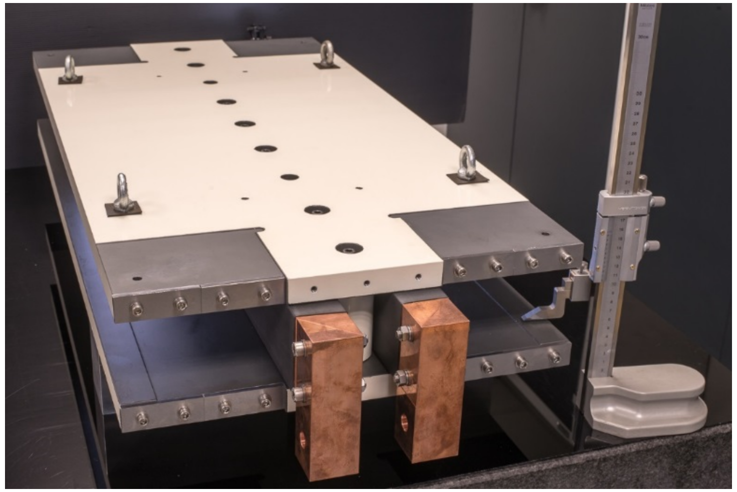
* misalignments relative to girder placement
** misalignments relative to quadruple placement

Type	Field Errors
Arc quadrupole	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

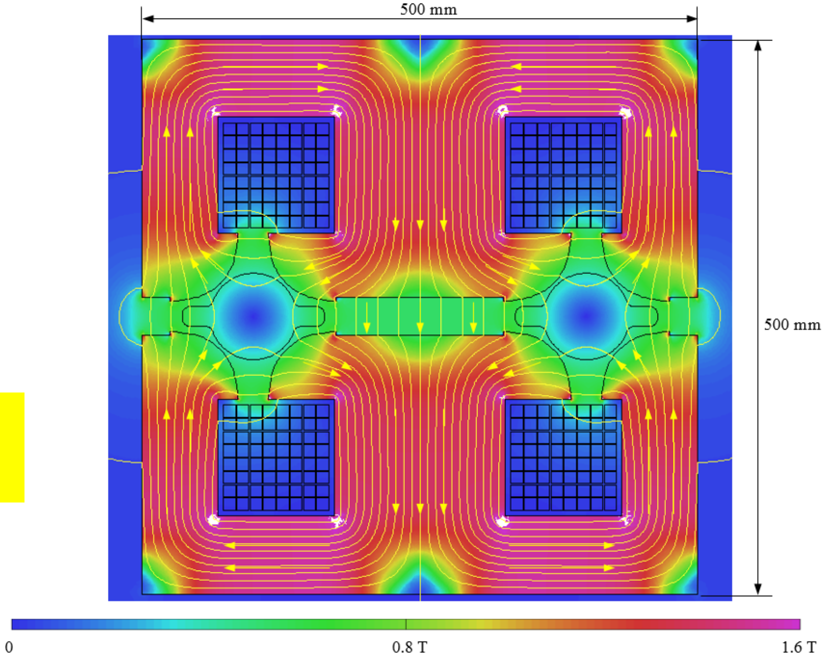
Cost-effective, energy-efficient arc magnets

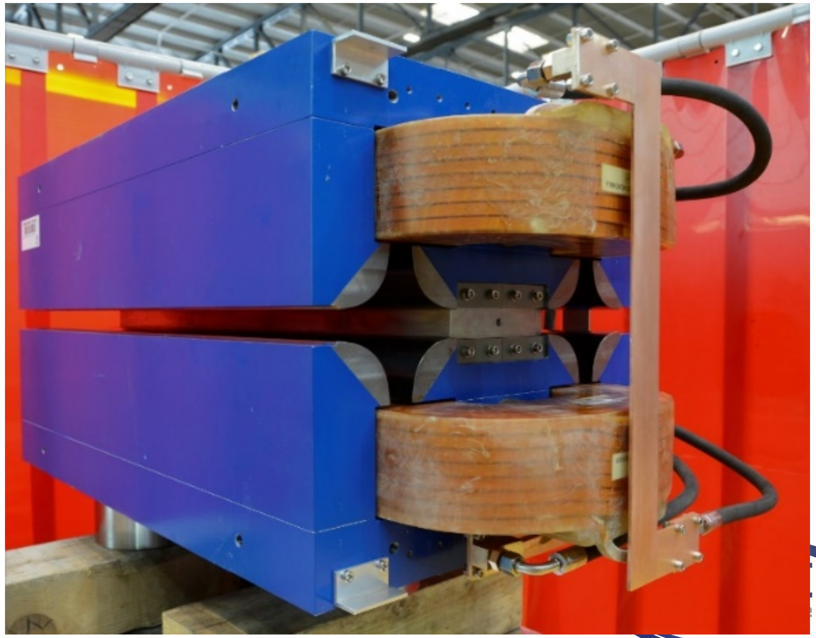
twin-dipole magnet design with 2× power saving 16 MW (at 175 GeV),





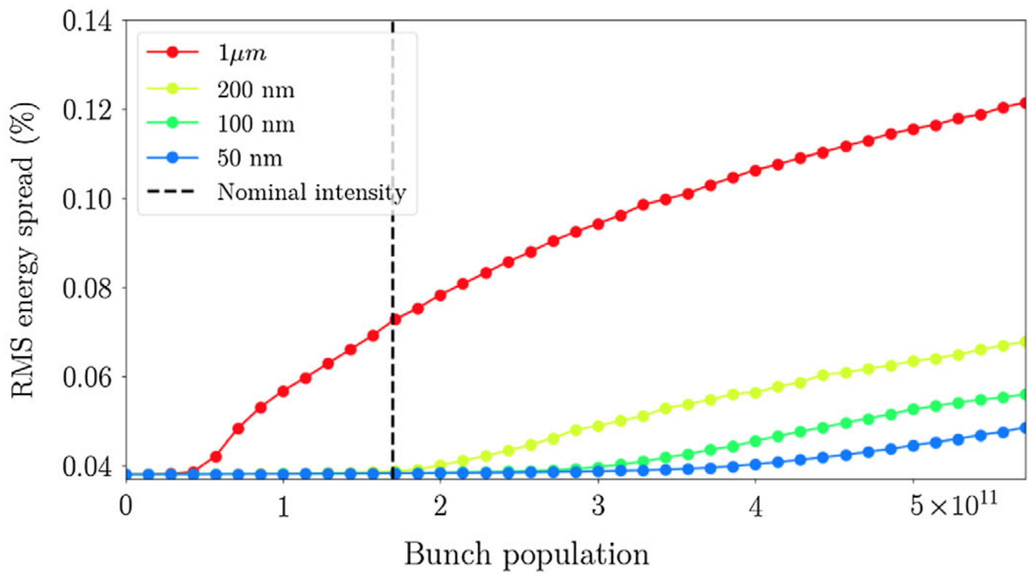
twin F/D arc quadrupole design with 2× power saving; 25 MW (at 175 GeV)





A. Milanese, **Phys. Rev. Accel. Beams 19**, 112401 (2016)

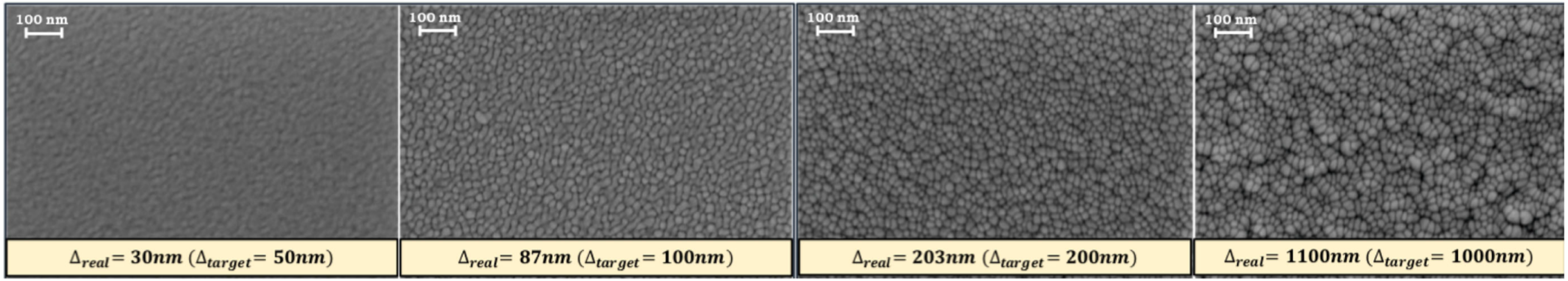
Ultrathin NEG coating to avoid μ-wave & e-cloud instability



Resistive wall impedance can lead to microwave instability.

E. Belli et al., **Phys. Rev. Accel. Beams 21**, 111002 (2018)

NEG coatings with thicknesses from 30 nm to 1.1 μm



morphology of NEG thin films analyzed by scanning electron microscope

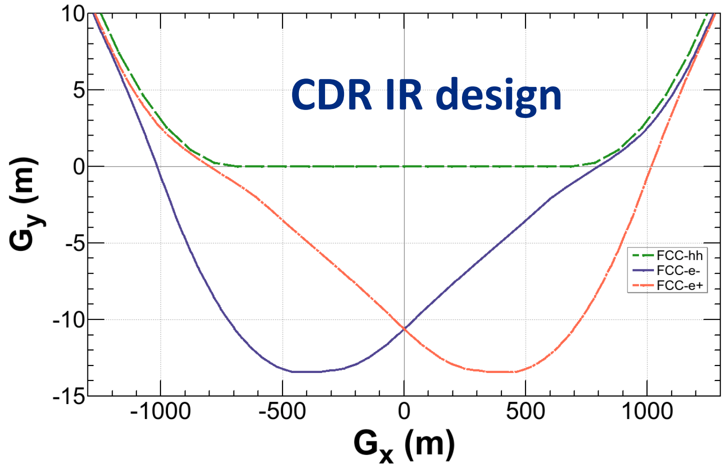
Collider design objectives within the FCCIS study

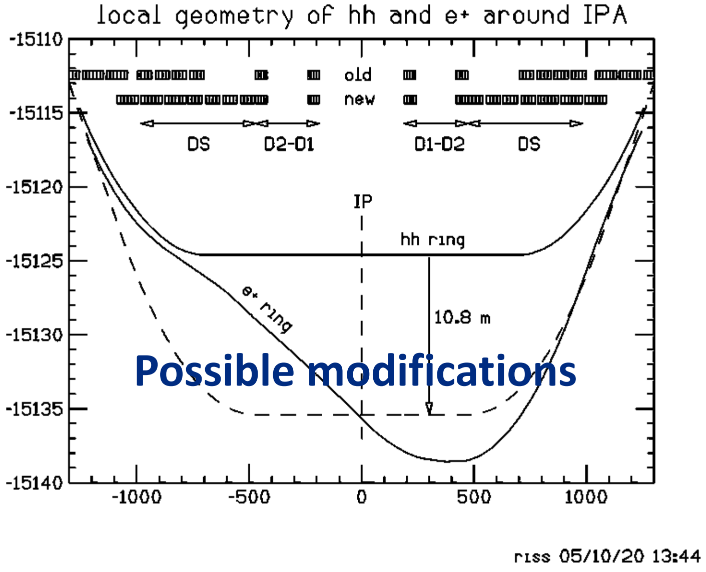
- Finalize beam optics design
- Complete design of subsystems: collimation and machine protection, diagnostics, MDI, injection and extraction
- Create high fidelity machine model including alignment and field errors, impedance model, beam-beam interactions, polarization
- Optimize injector complex design
- Build prototypes of critical components and establish procedures such as installation logistics, alignment etc.
- Refine machine operation procedures (luminosity tuning, optics correction, polarization, etc.) and give reliable prediction of operation parameters (luminosity, beam lifetime, backgrounds)

Optics design

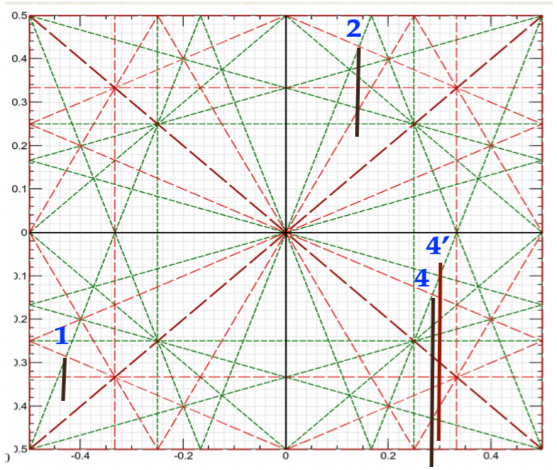
K. Oide, talk on Tuesday

- IP Layout
- Number of IPs and its influence on beam dynamics
- Engineering integration of FF and crab waist design

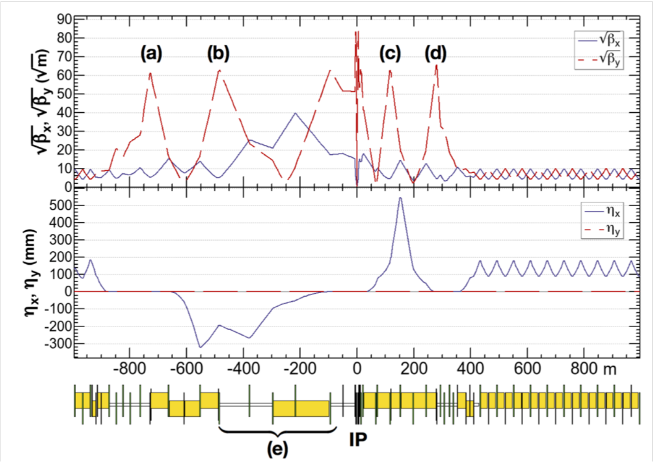




Beam-beam footprint
For different number of IPs

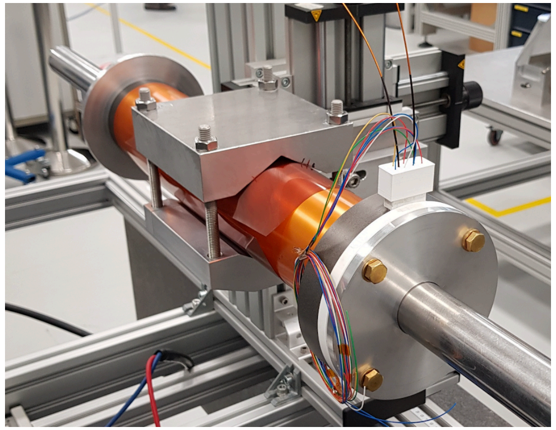


Crab waist optics with longer sextupole

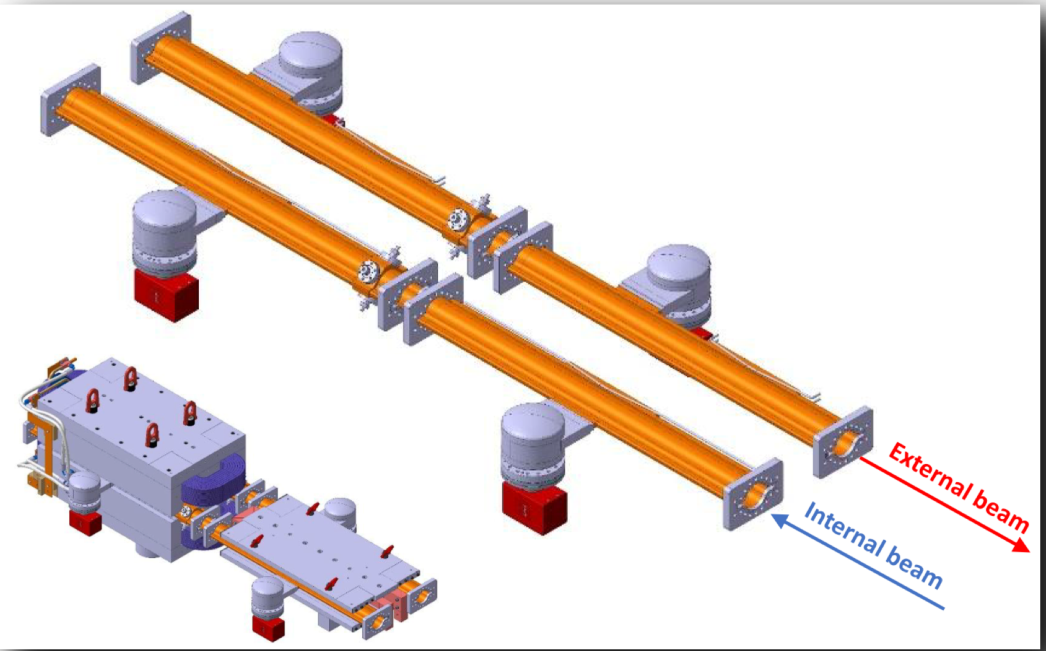


Optics design – objectives for technical integration

- Arc magnet parameters will be fixed: length, aperture, field distribution etc.
- Mock-up section will be built
- FF magnet design refinement and field characterization will be performed



M. Koratzinos , talk on Wed MDI Session



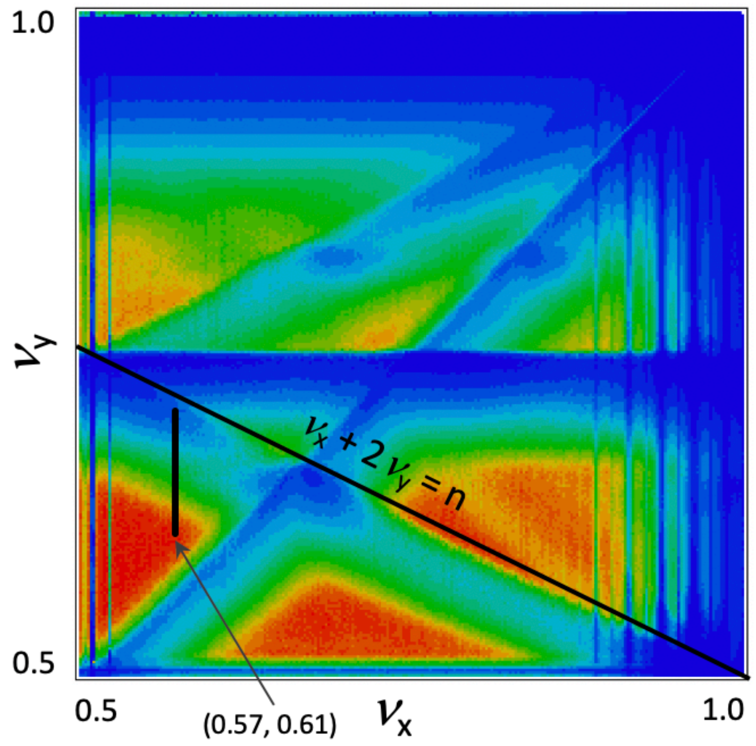
K. Oide, talk on Tuesday

Collective effects

- Beam parameters are dominated by beam-beam and Beamstrahlung effects
- Beam parameter optimization non-trivial
- Significant impedance in main and booster rings can lead to collective instabilities
- Intensity limitations in the booster mitigated by damping wigglers
- Refinement of impedance model required

D. Shatilov

Luminosity vs. betatron tunes, simplified model, weak-strong simulations. Colors from zero (blue) to $2.3 \cdot 10^{36}$ $cm^{-2}c^{-1}$ (red).



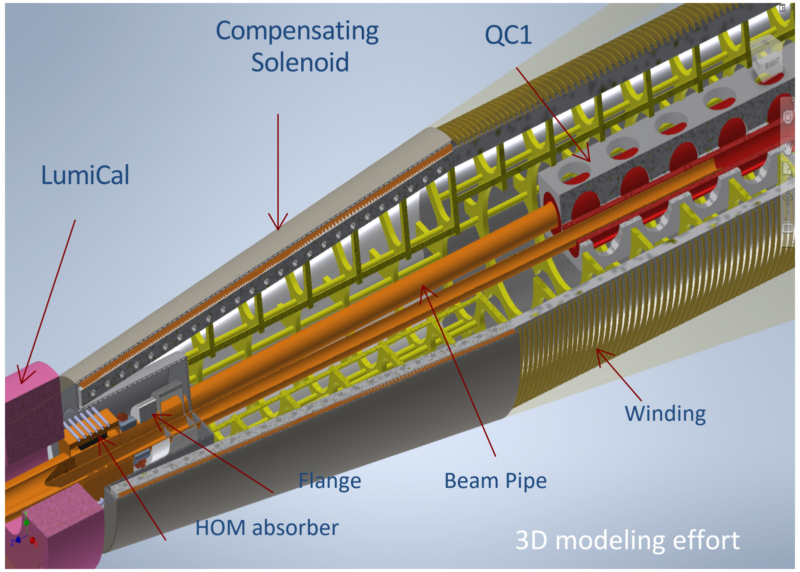
Collective effect session with talks from:
D. Shatilov
M. Migliorati
R. Wanzenberg

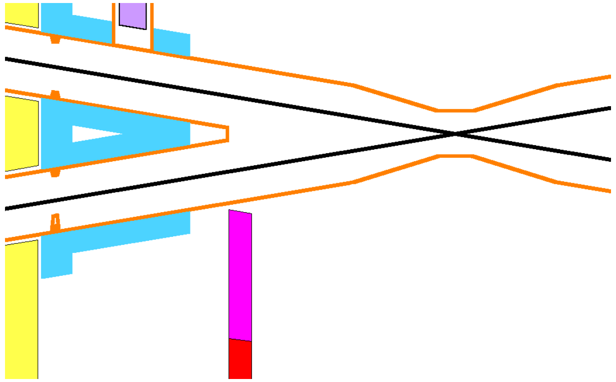
FCC-ee Interaction Region open issues

M. Boscolo, M. Sullivan et al.

Main MDI areas of study:

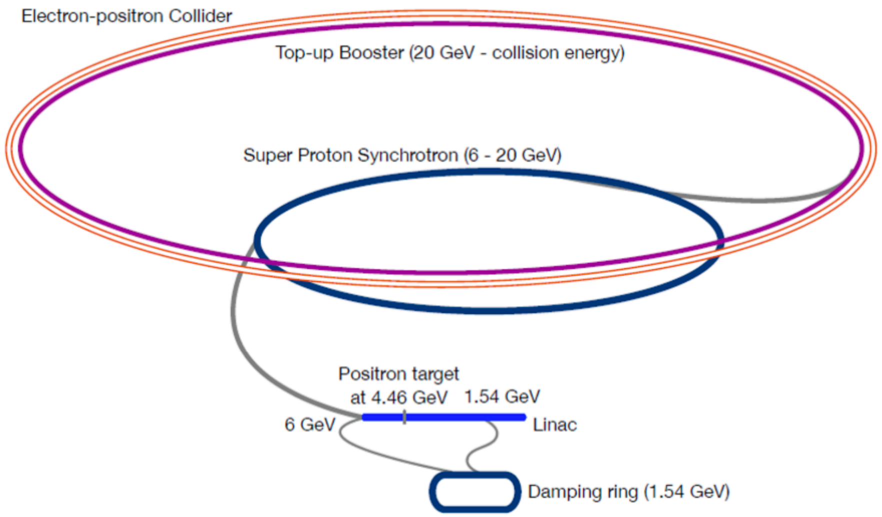
- Beam physics (optics, beam dynamics, collective effects)
- Beam induced backgrounds
- Development and update of new simulation tools
- Experimental environment
- Luminosity measurement
- Mechanical design and integration study
- Engineering sub-systems



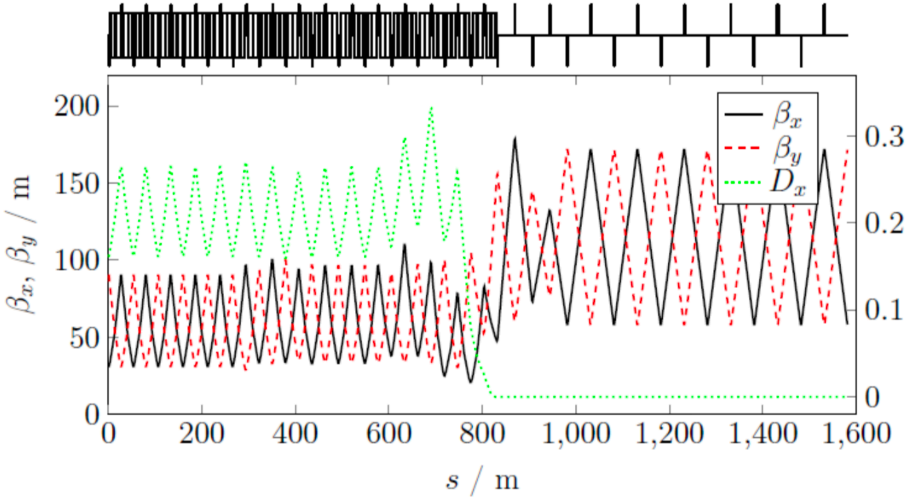


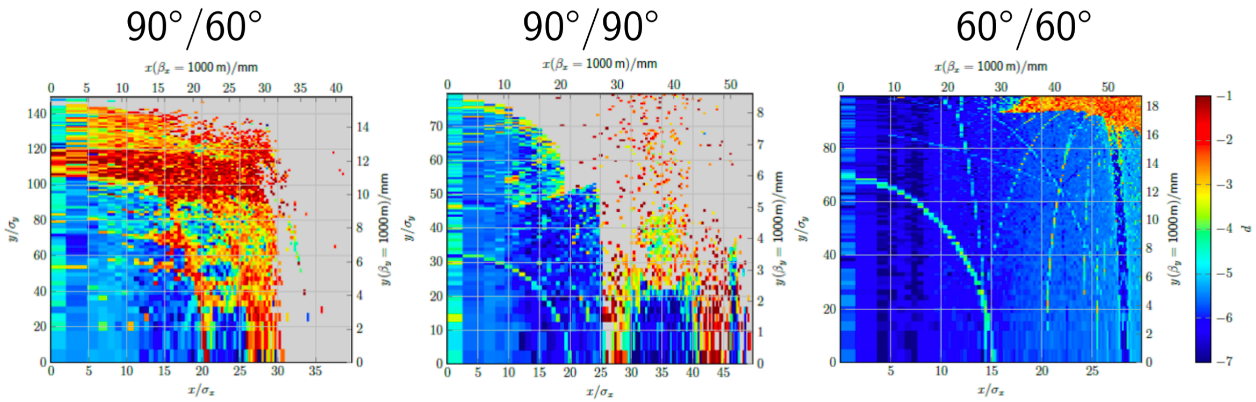
M. Boscolo, talk on Tue
More MDI-related talks: Ralph Assmann, L. Brunetti, H. Nakayama
Joint exp. Session on Wed

Booster: open issues



Booster optics





Dynamic Apertures of possible booster lattices

- Design of injection into booster
- Field errors at low energy
- Intensity limitations at low energy
- Alternative instability damping schemes
- Layout and optics adjustments to main ring

A Chance, talk on Tue

Machine tuning

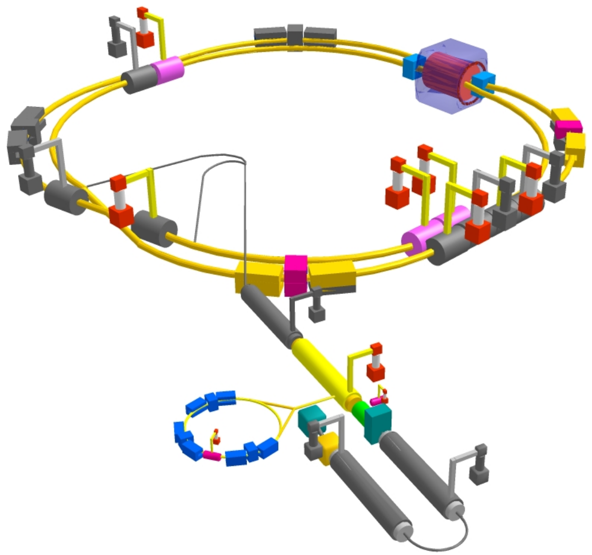
- Continuation of emittance tuning simulations including more detail
  - Include solenoid misalignment into simulations
  - Apply correction technique to low energy, Z lattice
  - Local corrections for dispersion at the IP
  - Determine how to apply corrections quickly
  - Possible simulation of commissioning process
  - Investigate the few seeds that results in vertical emittances > 2 pm rad.
  - Dynamic Aperture and lifetime with errors

- Closing the loop with beam-beam, luminosity optimization, and possibly polarization and developing the integrated software

T. Charles, talk Tue
Software session, Thu

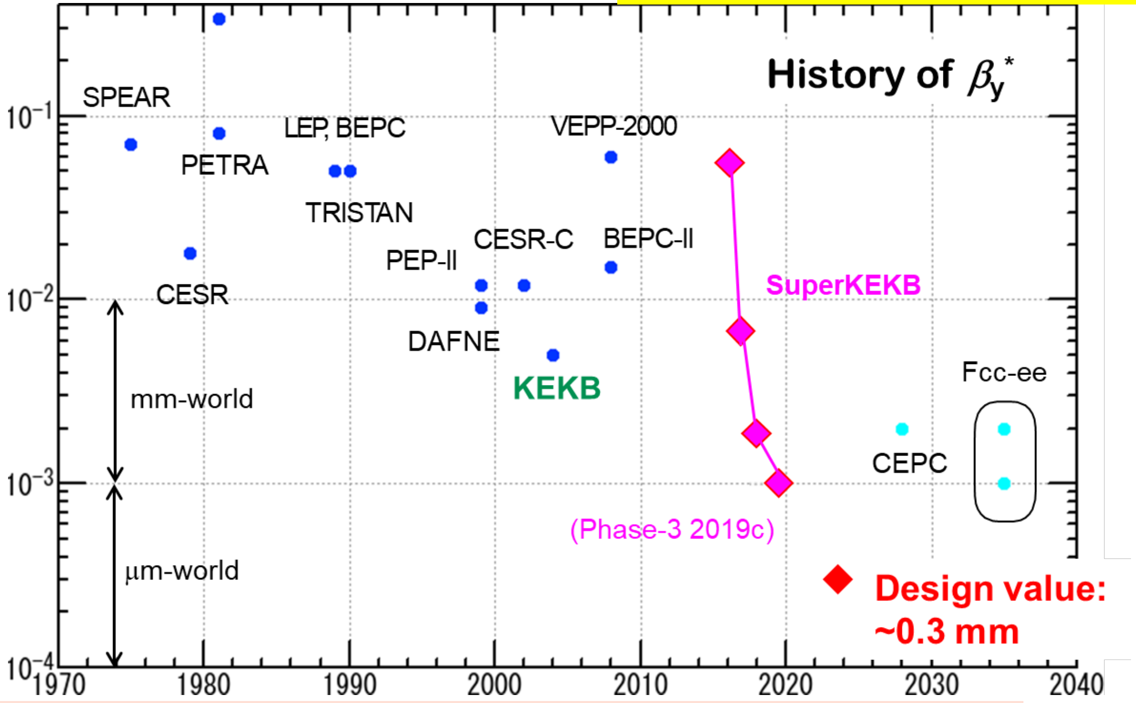
Lessons learned and to be learned

- SuperKEKB: luminosity and beam current
- Cooperations with the burgeoning light source community
- Possible synergies with EIC



SuperKEKB: double ring e^+e^- collider as *B*-factory at 7(e^-) & 4(e^+) GeV; design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; b_y^* ~ 0.3 mm; nano-beam – large crossing angle collision scheme (crab waist w/o sextupoles); beam lifetime ~5 minutes; top-up injection; e^+ rate up to ~ 2.5 10^{12} /s ;

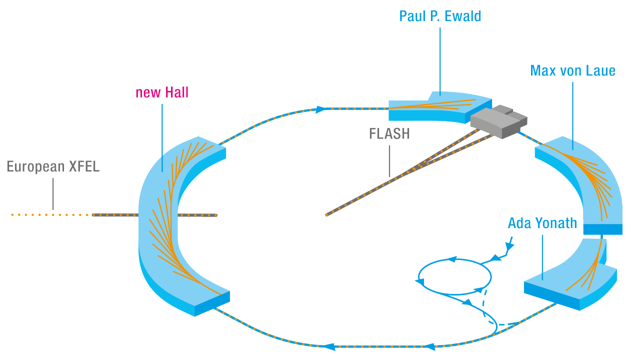
Y. Funakoshi, Y. Ohnishi, K. Oide, et al



β_y^* = 0.8 mm achieved in both rings - world record! 🏆
crab-waist collisions implemented recently

Beam tests: learning from existing electron storage rings

- PETRA III at DESY: optics correction and tuning
- KARA: beam diagnostics
- DAFNE: crab waist collision scheme, high beam current
- VEPP-4M: polarization and energy calibration studies
- SuperKEKB: learning from experience of collider operation
- SwissFEL: positron source test

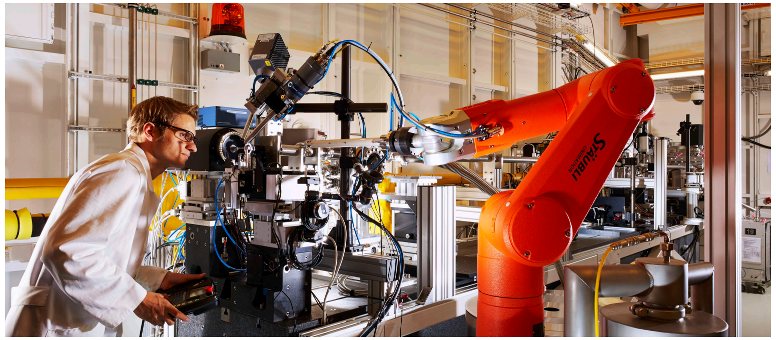


Diagnostics and beam test session on Tue:
A.S. Mueller
J. Keintzel
I. Agapov
S. Nikitin
P. Craevich
G. Balik

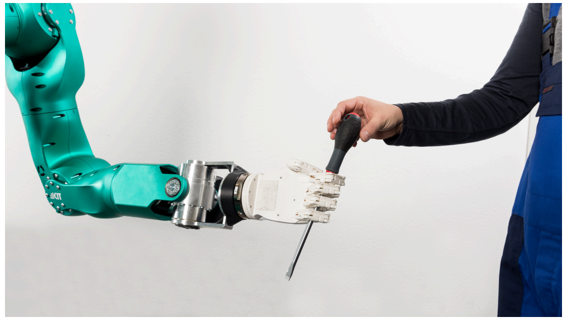
Possible advanced technologies

- Plasma wakefield injectors
- AI for machine design and operation

Robot inspecting the XFEL tunnel at DESY



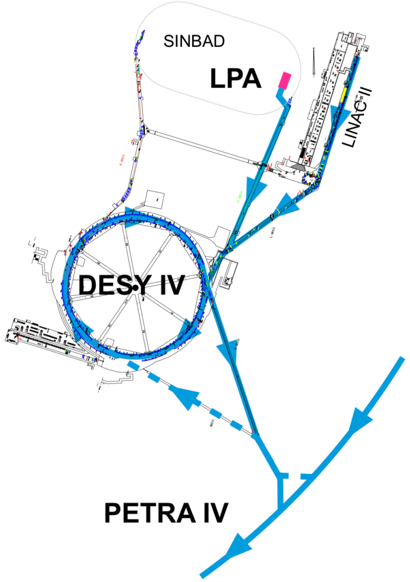
Robotic arm at a PETRA III beamline at DESY

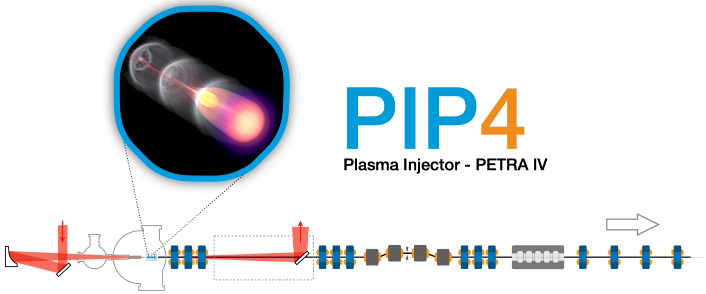


AMAR robot at KIT

PETRA IV. NEW DIMENSIONS

cSTART





KIT Karlsruher Institut für Technologie

DESY.

program status WP2 sessions at FCCIS kick off

Monday 14h00-14h30	FCC-ee collider design - overview and plan	Ilya AGAPOV, DESY
Tuesday	**FCC-ee optics**	Chair: Ralph ASSMANN, DESY
8h30-9h00	Lattice status and open questions/ next steps	Katsunobu OIDE, KEK & CERN
9h00-9h30	Emittance tuning simulations and next steps	Tessa CHARLES, U Liverpool
9h30-10h00	Status and plan for the FCC-ee booster design	Antoine CHANCE, CEA
	FCC-ee collective effects	Chair: Katsunobu OIDE, KEK/CERN
10h30-11h00	Beam-beam and parameter studies	Dmitry SHATILOV, BINP
11h00-11h30	Single-beam collective effects	Mauro MIGLIORATI, Sapienza & INFN
11h30-12h00	Collective effects – expertise and plans at DESY	Rainer WANZENBERG, DESY
	MDI - joint accelerator & experiments	Chair: Eugene LEVICHEV, BINP
13h30-14h00	MDI challenges toward the TDR	Manuela BOSCOLO, INFN-LNF
14h00-14h20	SuperKEKB experience	Hiroshi NAKAYAMA, KEK
14h20-14h40	Vibration/stabilization: from SuperKEKB to FCC-ee	Laurent BRUNETTI, LAPP
14h40-15h00	Possible contributions to MDI	Ralph ASSMANN, DESY
	FCC-ee beam diagnostics, beam tests, and girders	Chair: Phil BURROWS, Oxford
15h30-15h55	Developing and testing beam diagnostics for FCC-ee	Anke-S. MÜLLER, Gudrun NIEHUES, KIT
15h55-16h05	Possible beam studies at SuperKEKB	Jacqueline KEINTZEL, TU Vienna & CERN
16h05-16h15	Possible beam studies at DAFNE	Jacqueline KEINTZEL, TU Vienna & CERN
16h15-16h25	Possible beam studies at PETRA III	Ilya AGAPOV, DESY
16h25-16h35	Possible beam studies at VEPP-4M	Sergei NIKITIN, BINP
16h35-16h45	FCC-ee injector update & e+ source test at PSI	Paolo CRAIEVICH, PSI
16h45-17h00	Arc girder/support concept for FCC-ee	Gaël BALIK, LAPP

Wednesday Joint Accel. and Exper. session: MDI,Polarization, monochromatization

14:00-14:20	Polarimetry	N. Muchnoi
14:20-14:40	Monochromatization schemes and beamstrahlung	M.A. Valdivia
14:40-15:00	Monochromatization and large crossing angle	A. Bogomyagkov
15:00-15:20	Mechanical IR design	L. Pellegrino
16:00-16:20	Final Focus magnets	M. Koratzinos
16:20-16:40	Beam backgrounds impact on detectors	G. Voutsinas
16:40-17:00	SR collimation in the MDI area	M. Luckhof
17:00-17:20	SR backgrounds including the effect for a 1 cm radius beam pipe	M. Sullivan
17:20-17:40	A new low impedance IR FCC-ee beam chamber	Alexander Novokhatski

Thursday

	Accelerator Code Development	chair: Mike SEIDEL, PSI
8h30-8h45	Desirable optics code features	Katsunobu OIDE, KEK & CERN
8h45-9h00	Code development plan	Tatiana PIELONI, EPFL
9h00-09h10	Modelling tapering	Leon van RIESEN HAUPT, CERN
09h10-09h20	The tilted solenoid	Tobias PERSSON, CERN
09h20-09h30	Tracking tool for background simulations	Andrea CIARMA, INFN-LNF
09h30-09h40	The polarization code challenge	Eliana GIANFELICE-WENDT, FNAL
09h40-10h00	Discussion	
	EIC/FCC 1	chair: Andrei SERYI, JLAB
13h30-13h50	impedances, beam instabilities, and beam feedbacks	Michael BLASKIEWICZ, BNL
13h50-14h10	lepton polarisation	Alain BLONDEL, U Geneva & CNRS
14h10-14h30	beam instrumentation, SR monitors	Thibaut LEFEVRE, CERN
14h30-14h50	MDI, IR shielding and IR handling equipment	Walter WITTMER, JLAB
	EIC/FCC 2	chair: Frank ZIMMERMANN, CERN
15h30-16h00	SRF	Robert RIMMER, JLAB
16h00-16h30	vacuum system	Roberto KERSEVAN, CERN
16h30-17h00	final-focus quadrupoles	Brett PARKER, BNL

Summary

FCC-ee is an efficient Higgs & electro-weak factory at c.m. energies from 90 to 365 GeV and a cost-effective first step towards a 100 TeV collider

Key FCC-ee concepts and parameters have been demonstrated or exceeded at various past & present machines (crab waist collisions, β_y^*~1 mm, ~1.5 A beam current, e^+ source with required rate, target emittances, top up, SR power / unit length, MeV photon energies,…)

Technology is ready. Modern advanced concepts can be used to improve efficiency and sustainability

FCCIS study will result in an optimized design for the project implementation to start

Exciting time in the FCCIS ahead!!!