FUTURE CIRCULAR COLLIDER

FCC Week 2021: Summary of Accelerator Sessions

24 talks FCC-ee & FCCIS WP2, 10 talks FCC-ee other, 3 talks FCC-hh, 3 talks FCC-eh → 40 talks in total !

Ilya Agapov, DESY

Frank Zimmermann, CERN

Friday, 2 July 2021

FUTURE CIRCULAR COLLIDER

Overview

Version: 0.14 Date: 17.06.2021

FCC Week 2021 Programme

Day / Time	Monday 28 June	Tuesday 29 June		Wednesday 30 June			Thursday 1 July		Friday 2 July	Day / Time
	Plenary	Parallel 1	Parallel 2	Parallel 1	Parallel 2	Parallel 3	Parallel 1	Parallel 2	Plenary	
08:30-09:00										08:30-09:00
09:00-09:30	Opening	Technology R&D	FCCIS WP3 (Integrate Europe)	SRF Technologies	FCC-hh accelerator		FCC-ee IR and MDI	Technical Infrastructures	Summaries	09:00-09:30
09:30-10:00										09:30-10:00
10:00-10:30										10:00-10:30
10:30-11:00										10:30-11:00
11:00-11:30	FCC feasibility phase	FCC-ee parameters, layout, overview, with booster	FCCIS WP4 (Impact & Sustainability)	FCC-ee electron cloud & vacuum	Software and Physics Highlights	EASITrain	FCC-ee impedance & collective effects	Technical Infrastructures	Summaries	11:00-11:30
11:30-12:00										11:30-12:00
12:00-12:30										12:00-12:30
12:30-13:00										12:30-13:00
13:00-13:30		SRF: Direction for R&D						SRF Technologies		13:00-13:30
13:30-14:00										13:30-14:00
14:00-14:30	Physics, Experiments & Detectors		Collaborative Writing & Publishing tools	FCC-eh	Civil Engineering		FCC-ee other applications & upgrades			14:00-14:30
14:30-15:00										14:30-15:00
15:00-15:30										15:00-15:30
15:30-16:00								Detectors		15:30-16:00
16:00-16:30	Physics, Experiments & Detectors	FCC-ee optics, correction, beam stay-clear, dynamic aperture, collimation	Physics Performance highlights	FCC-ee injector complex	FCCIS communication & engagement		Technology R&D			16:00-16:30
16:30-17:00										16:30-17:00
17:00-17:30										17:00-17:30

Parameters, Layout

Tuesday from 11h00 – FCC-ee & FCCIS WP2: Parameters, Layout, Overview, with Booster – Eugene Levichev, BINP	
Parameters – Update and Plan	D. Shatilov, BINP
Optics and Layout – Update and plan	K. Oide, KEK & CERN
Experience at SuperKEKB	J. Keintzel, TU Vienna & CERN
Top up injection	M. Aiba, PSI

Parameters – Update and Plan

Dmitry Shatilov

impedance effect & beam-beam

→ reduced region in tune diagram at *Z*,

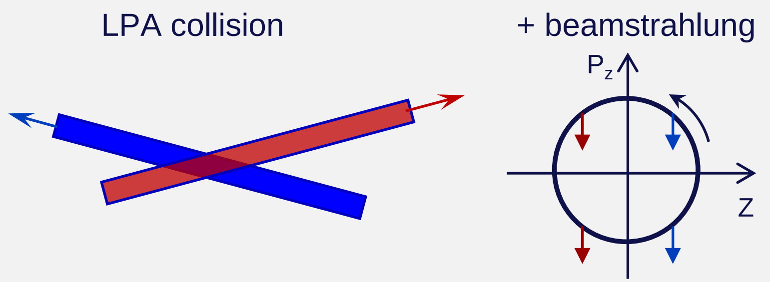
Q_x to be controlled to 10^{-3} level

→ **larger momentum compaction, 45 deg optics** (in addt'n to 60 and 90 deg)

600 or 650 MHz RF at the Z ? **3rd harmonic cavities** to control no of bunches ?

transient beam loading : new effect, **tighter tolerances for b-b flip-flop & top up**

4 IPs and realistic optics with errors, corrections & related tolerances



dZ [mm]	σ_z [mm]	σ_δ [10^{-3}]
0	12 / 12	1.3 / 1.3
5	11.3 / 12.4	1.24 / 1.33
10	8.7 / 14.5	0.97 / 1.55

- Geometrical loss of luminosity (small).
- Amplification of synchro-betatron resonances.
- Asymmetry in the energy loss due to BS → asymmetry in the bunch lengths and energy spreads. This can lead to a 3D flip-flop.

For dZ = 5 mm, requirements for the permissible asymmetry of the bunch currents are tightened from ± 5% to ± 3%.

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Optics & Layout – Update and Plan

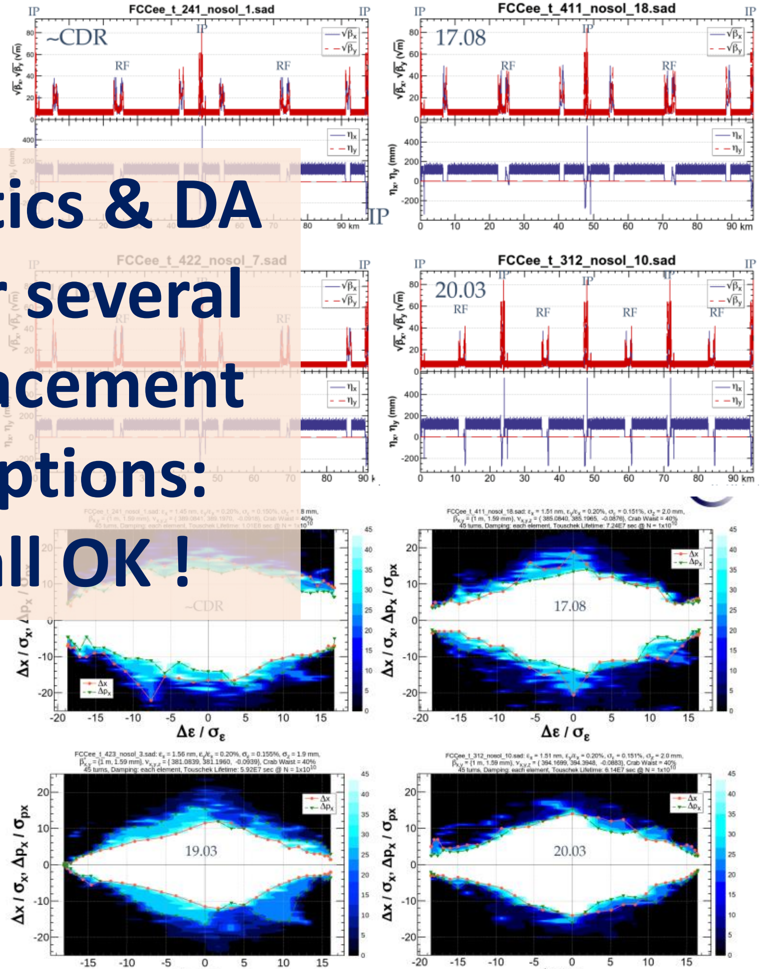
Katsunobu Oide

Layout	IP	Shafts	circumference	Arc radius of curvature	short arc A-B, F-G, G-H,	long arc B-D, D-F,	straight sections A, G	straight sections B, F, H, L	straight sections D, J
~CDR	2	12	97750	13329	4448	16489	1.4	1.4	2.8
17.08			96109	12922	5782	14517	1.4	1.4	3.25
19.03			91350	12380	3864	15582	1.36	1.36	2.69
20.03	4	8	95713	13058	10256	10256	1.45	2.0	1.45

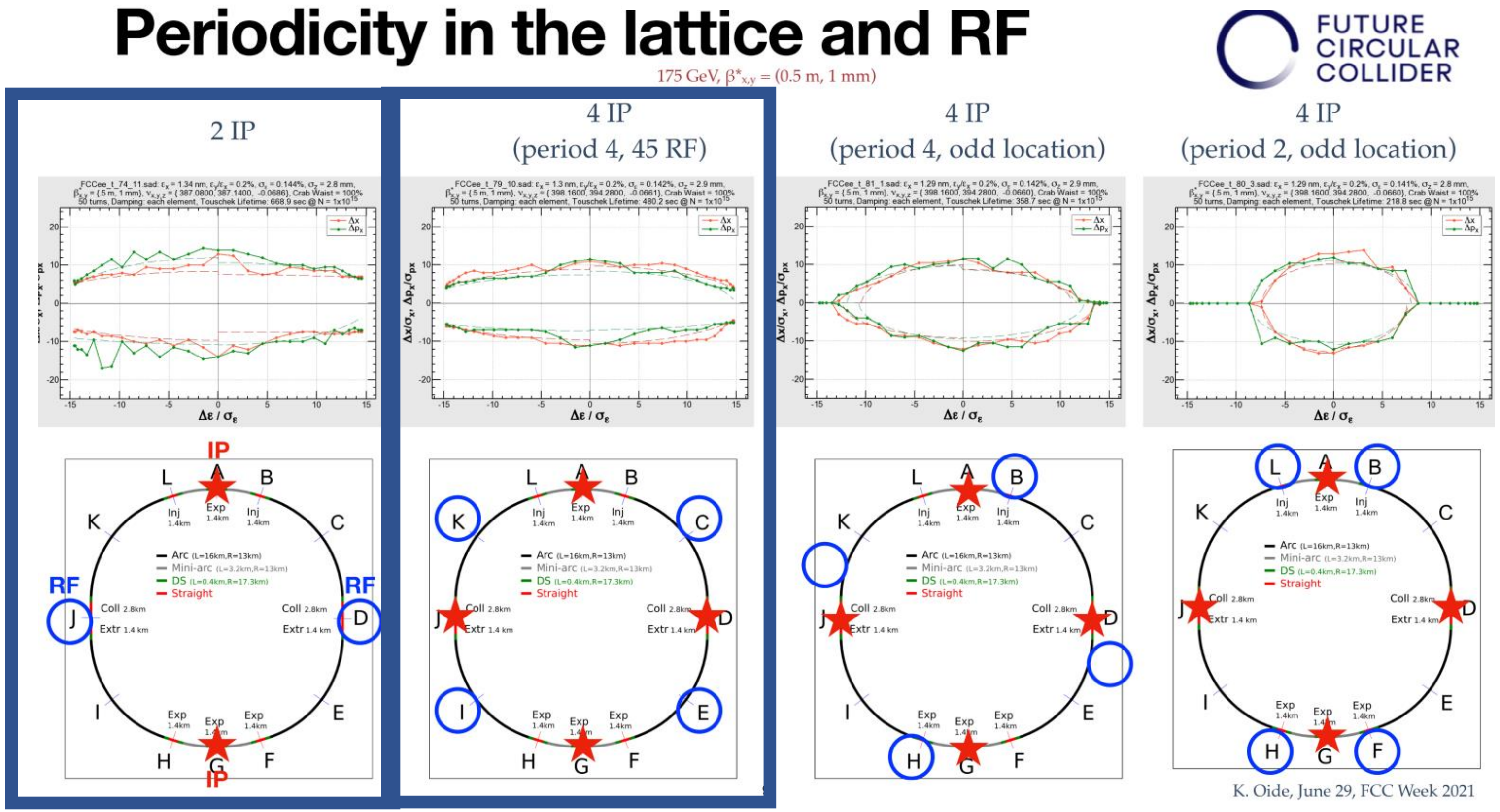
(km)

superperiodicity crucial !

lattice periodicity	RF (stations, location)	momentum acceptance (%)
4	4, symmetric	-2.8, +2.5
4	4, odd	±1.7
2	4, odd	±1.0
4	4, symmetric	-2.8, +2.5
4	2, symmetric	-2.8, +2.5

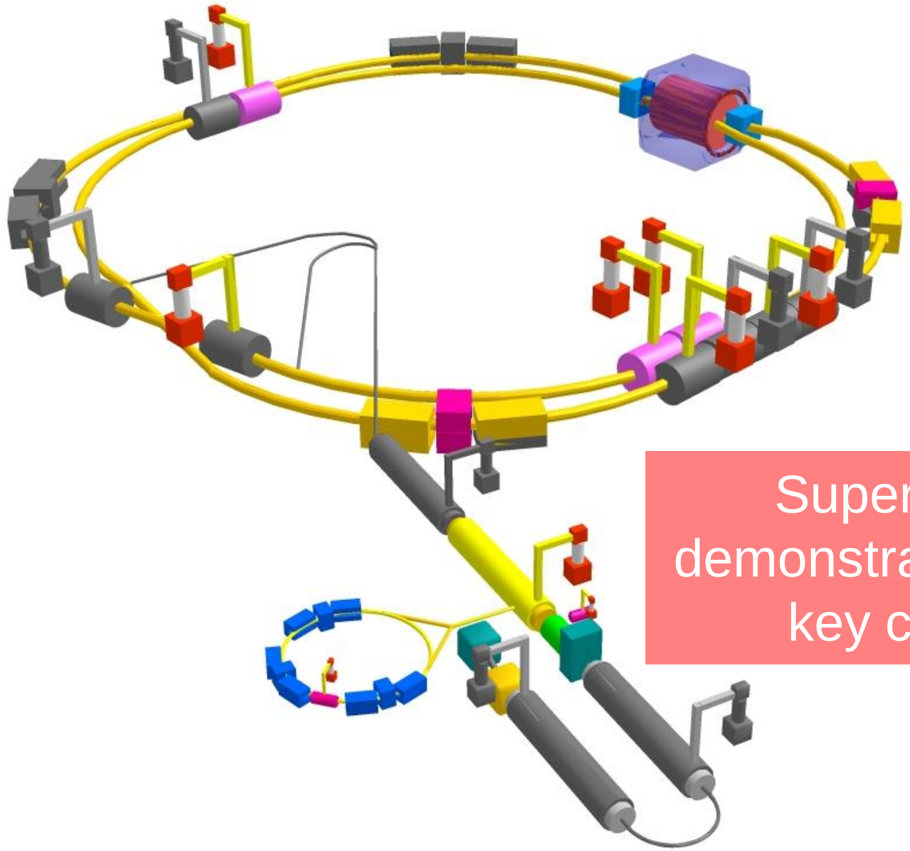


optics & DA for several placement options: all OK !

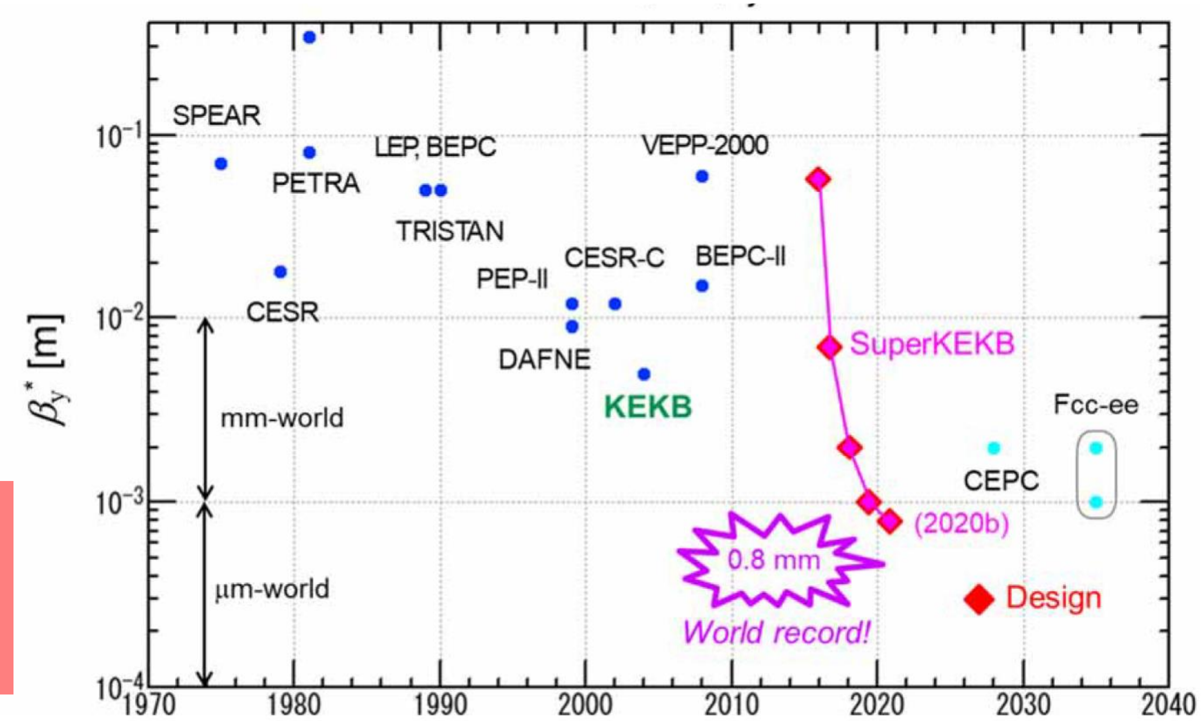


SuperKEKB: state of the art

Jacqueline Keintzel



SuperKEKB is demonstrating FCC-ee key concepts



β_y^* = 0.8 mm achieved in both rings – using the FCC-ee-style "virtual" crab-waist collision scheme

new world record luminosity 3.12x10^{34} cm^{-2}s^{-1} achieved last week (22 June 2021);
beam currents still much below design value

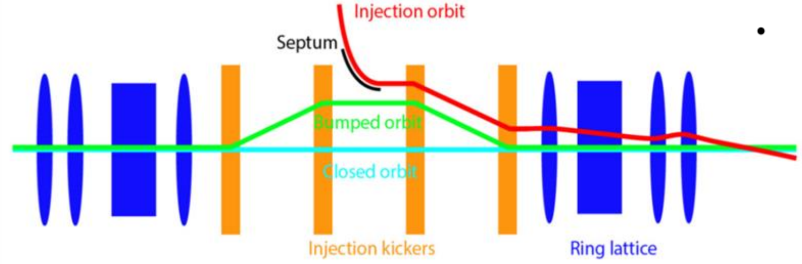
- LER: 80/1 mm with 80% CW
- HER: 60/1 mm with 40% CW

Top-up injection

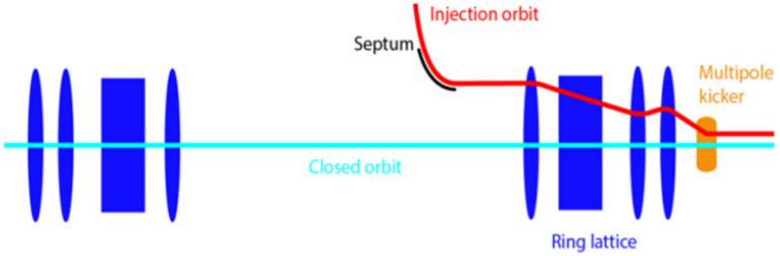
Masamitsu Aiba

Conventional & MK injection

Conventional injection:
Septum + Kicker bump

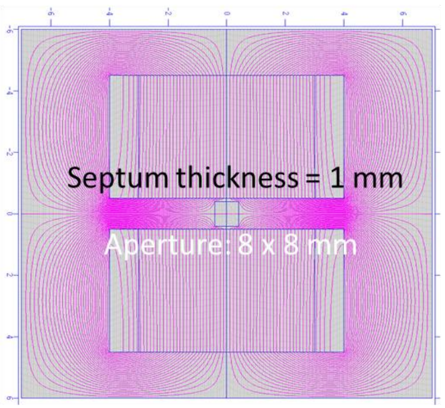


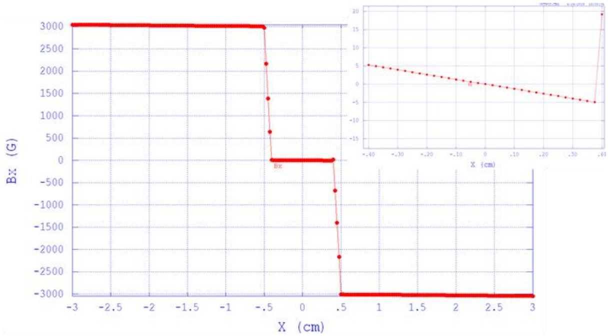
Multipole kicker injection:
Septum + Multipole kicker



Septum

- 1-mm septum ?
  - A la ALS septum (1.5 mm): Eddy-current septum with short pulse might be a choice if the pulse length can be compatible with filling scheme; Skin depth of copper ~0.2 mm at 100 kHz (10 us pulse)
  - Low field Lambertson septum seems attractive choice



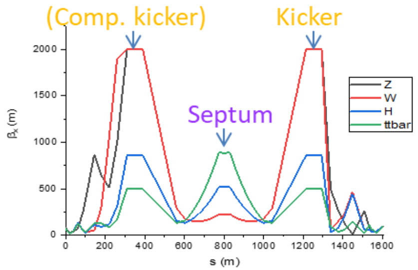


Symmetrised/linearlised leak field:
B~0.3 T for injection beam
B'~0.1 T/m for stored beam

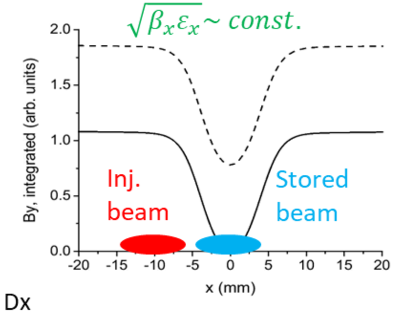
Optics integration

- Different operation mode → Different beam emittance
  - For off-axis CI, only need to adjust bump height
  - For off-axis MKI, need to change optics, adjusting stored and injection beam sizes to fit a fixed kicker transverse profile

Horizontal beta for 4 operation modes (MKI)



Approx. beam dimensions



  - For on-axis CI and MKI, need to change optics to introduce Dx

Off-energy (on-axis) injection is applicable to ttbar and possibly to Higgs while not to Z and W because of limited off-energy dynamic aperture

Summary and Next steps

- Previous studies revealed that top-up injection into FCC-ee collider is feasible
- Next steps
  - Optics integration
  - Tracking study
  - Further investigation needed to establish failure scenarios
  - Filling scheme update, etc.

Optics correction, DA, collimation

Tuesday from 14h00 – FCC-ee and FFCIS WP2: Optics Correction, Beam Stay-Clear, Dynamic Aperture, Collimation – Eliana Gianfelice-Wendt, FNAL	
Status and plans for optics corrections and emittance performance	Tessa Charles, Liverpool
Robust modelling of FCC-ee with analytical equations and simulations	Leon van Riesen Haupt , CERN
Multicode comparison	Felix Carlier, EPFL
Collimation optics	Michael Hofer, CERN
Aperture and Collimation	Andrey Abramov, CERN

Optics corrections & emittance

Tessa Charles

Correction Strategy (2/2)

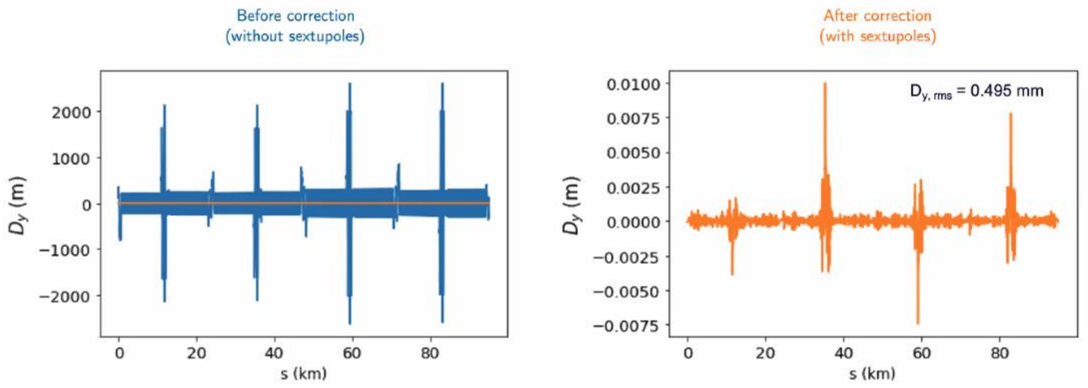
- **Sextupoles strengths set to zero.**
  (details on previous slide)
- **Sextupoles set to 10% of their design strength**
  - Orbit correction
  - Combined coupling and dispersion correction
  - Beta-beating correction applied.
  - Sextupole strengths increased by 10%

These two steps repeated ~12 times.

Constant checking of the tunes and orbit avoids running into resonances, or failure to find the closed orbit.

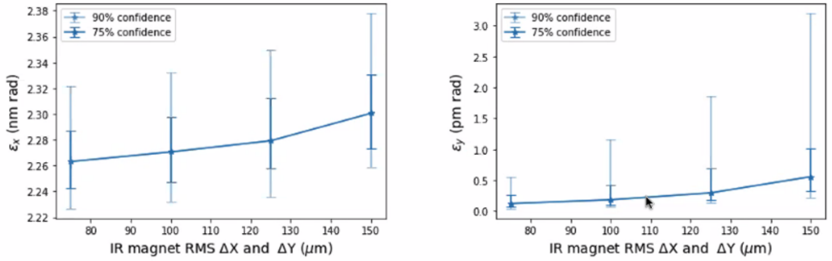
- **Final correction** (at 100% sextupole strength)
  - Additional coupling, dispersion and beta-beating correction was applied.
  - Step through corrections until beta beating threshold is reached (trade-off between beta beating and vertical emittance can be varied).
  - Vary SV cut off values

Vertical dispersion



IR magnets alignment - transverse misalignments (ΔX and ΔY)

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
IR quadrupole	varied	varied	250	200	100	100
IR sextupoles	varied	varied	250	200	100	100
All other magnets	as listed in Table on slide 7					



FCC-ee emittance tuning results

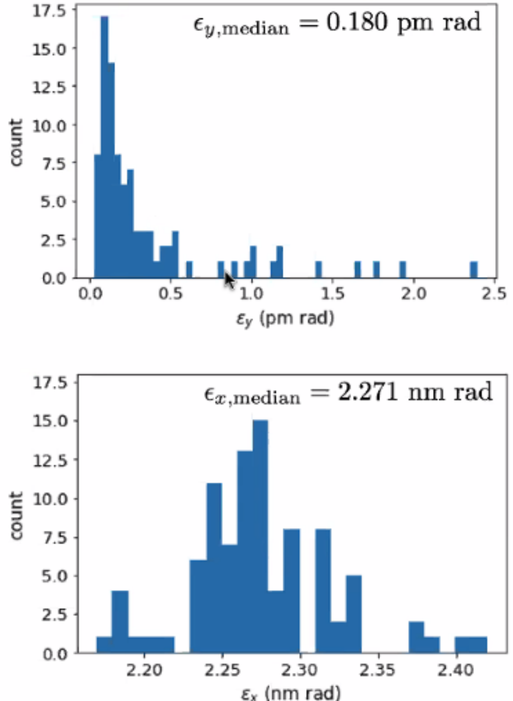
RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)
Arc quadrupole*	50	50	200	150	100	100
Arc sextupoles*	50	50	200	150	100	100
Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	200	100	100
IR sextupoles	100	100	250	200	100	100
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	$\Delta B/B = 1 \times 10^{-4}$
Girders	
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

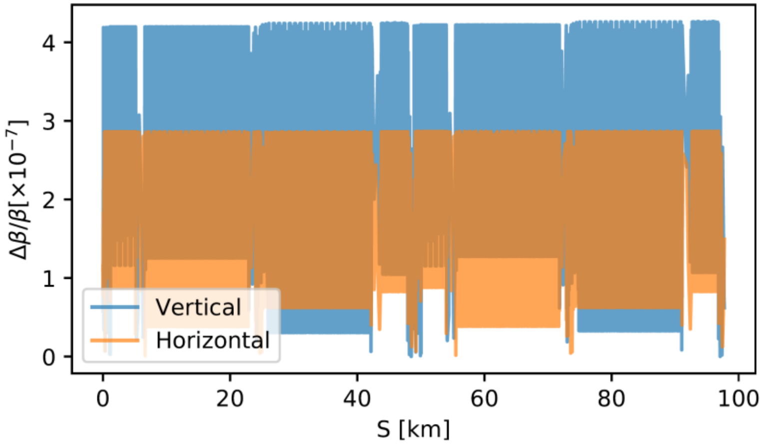
ttbar (182.5 GeV) 4IP lattice,
after correction strategy:

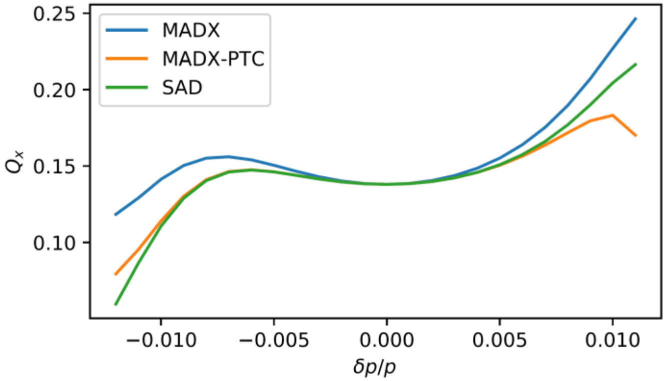


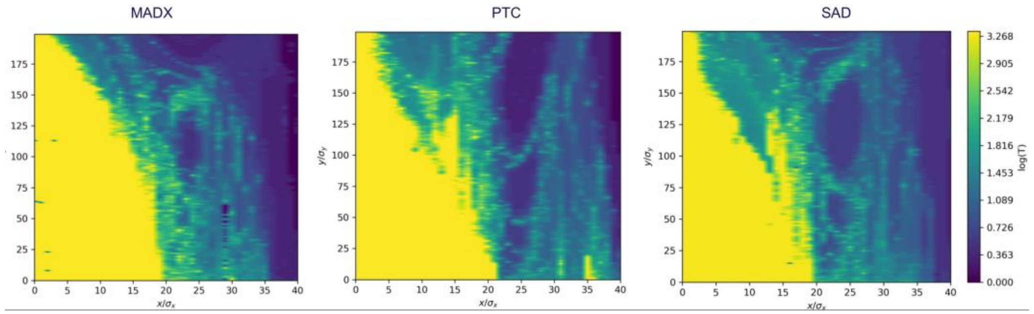
Robust Modelling w. Equations & Simulations

Leon Van Riesen Haupt

Code benchmarking performed







Analytical studies of emittance sensitivity can help define alignment strategy

Estimate using analytical formulas

- Formulas readily available in the literature, e.g. SLAC-PUB-4937

$$\frac{\epsilon_y}{< y_{sext}^2 >} \approx \frac{J_x(1-\cos(2\pi\nu_x)\cos(2\pi\nu_y))\epsilon_x}{J_y(\cos(2\pi\nu_x)-\cos(2\pi\nu_y))^2}\sum_{sext}\beta_x\beta_y\left(\frac{k_2L}{2}\right)^2 + \frac{J_z\sigma_\delta^2}{\sin^2(\pi\nu_y)}\sum_{sext}\beta_y\eta_x^2\left(\frac{k_2L}{2}\right)^2$$

$\frac{k_2L}{2} \to k_1L$ and $< y_{sext}^2 > \to < \theta_{quad}^2 >$ for quads

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Robust Modelling w. Equations & Simulations

Felix Carlier

Large effort at CERN to benchmark these two codes
(L. van Riesen-Haupt, T. Persson, K. Oide)

Exploration of other codes opens up new functionalities
(S. White, M. Rakic, D. Sagan, F. Carlier)

MAD-X

Prefered tool at CERN for accelerator design
- Powerful lattice descriptions
- Large community
- PTC connection

SAD

Currently the code of choice to create the FCC-ee lattice
- Expertise in KEK

Bmad

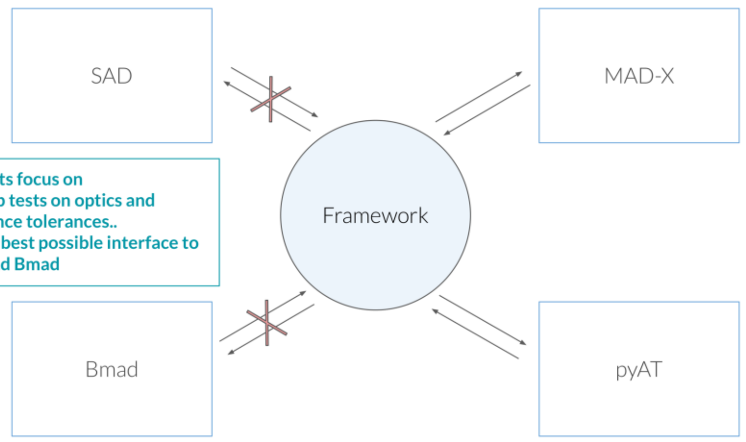
Accelerator simulation library
- Spin tracking
- Photon tracking
- Large library of functionalities
- PTC connection

pyAT

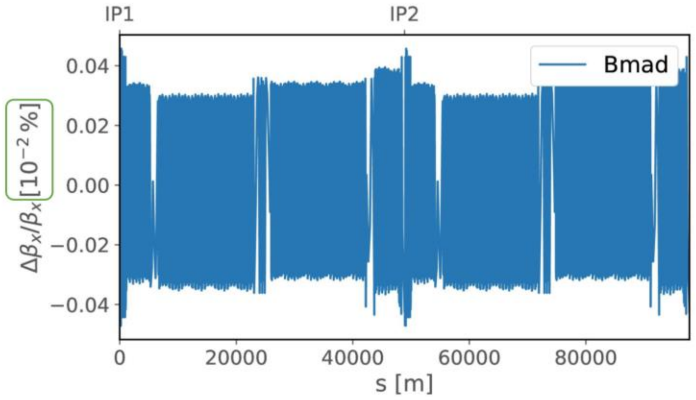
Python simulation framework
- Lightsource tools
- Fast development
- Interfaceable with ML tools

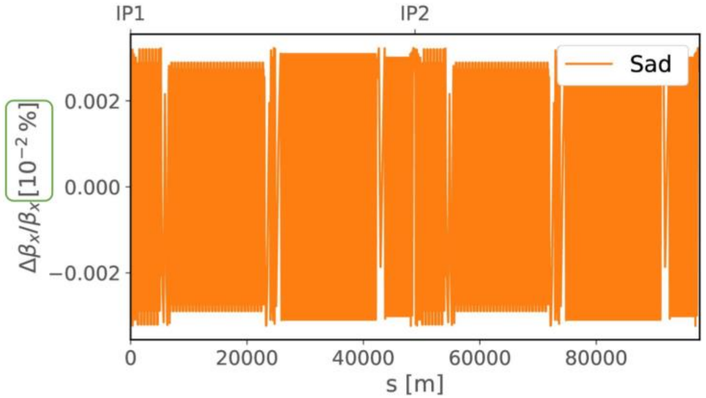
Results for Higgs physics '217' lattice without radiation

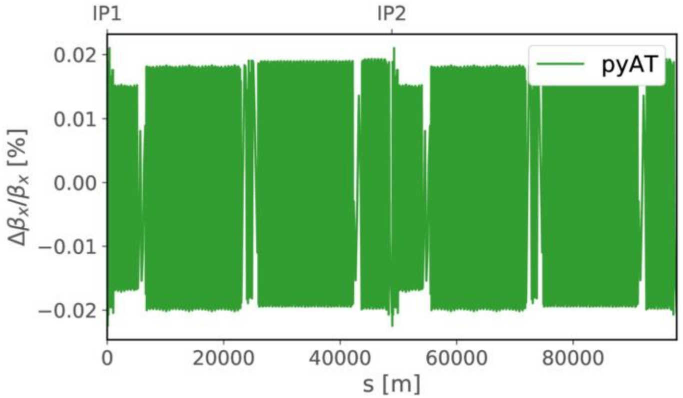
Excellent agreement between SAD, Bmad and pyAT
- Larger discrepancy with pyAT. Perhaps:
  - Fringe fields, nr. of slices? Under study.



Current efforts focus on
1. develop tests on optics and emittance tolerances..
2. finding best possible interface to SAD and Bmad

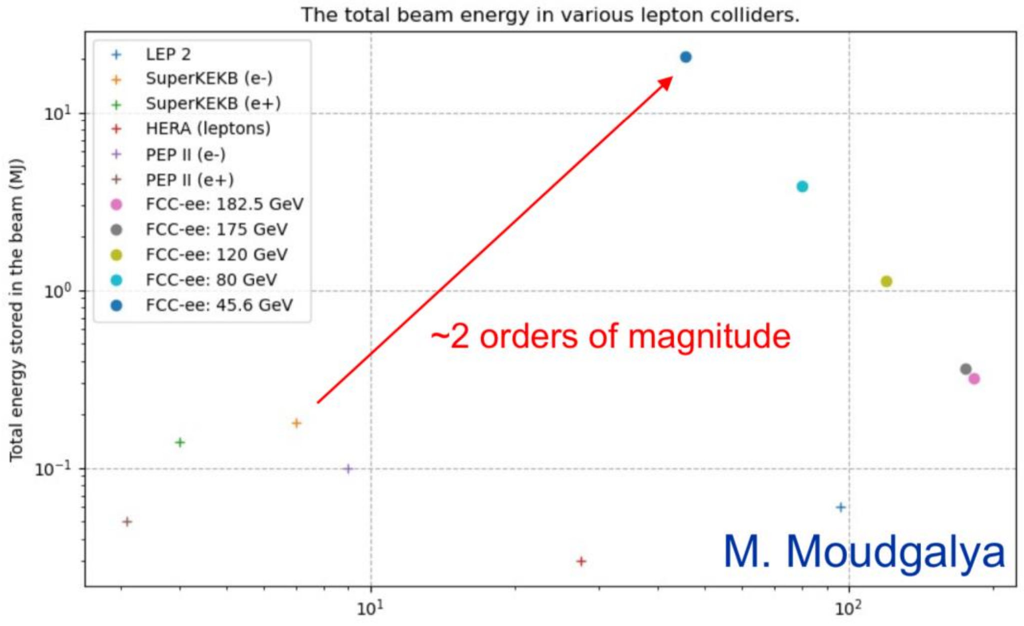






Aperture and collimation

Andrey Abramov



Simulation frameworks under investigation

SixTrack-FLUKA coupling

Framework linking tracking in SixTrack and matter interactions in FLUKA, used for proton and ion collimation studies for the LHC, HL-LHC, FCC-hh.

Required developments:

- Implement synchrotron radiation in SixTrack.
- Demonstrate tapered lattice tracking in SixTrack.

Merlin++

Tracking code originally designed for electron beams. Used for studies for the ILC and its damping rings, as well as for proton collimation studies for the LHC.

Required developments:

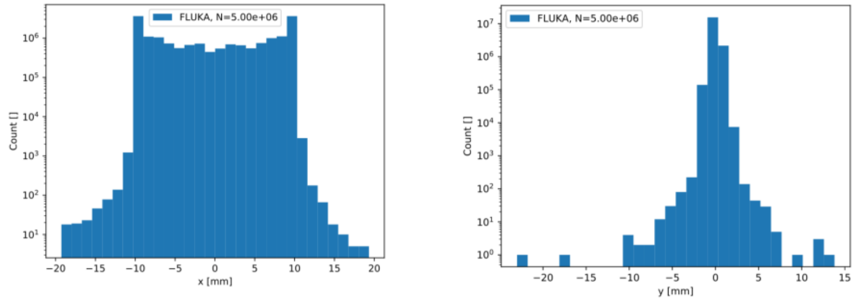
- Benchmark the tracking with radiation and tapering.
- Implement a connection with a scattering routine for collimator interactions.

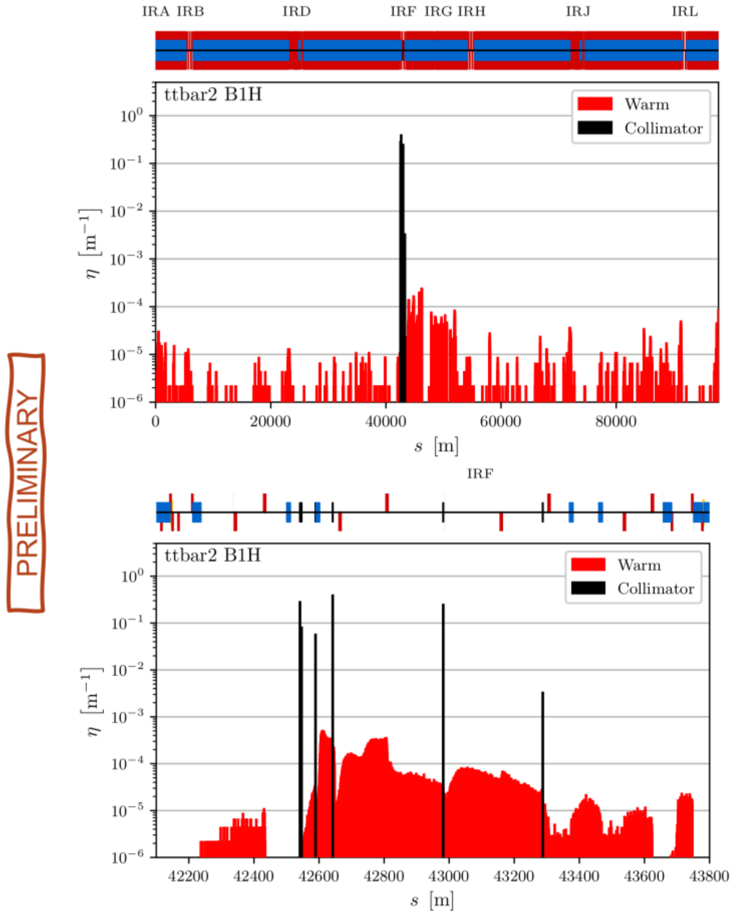
pyAT

Python interface to the tracking library Accelerator Toolbox. Actively used for studies for light sources such as ESRF.

Required developments:

- Implement a connection with a scattering routine for collimator interactions.
- Build a workflow for collimation studies.





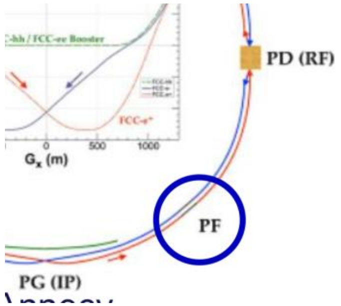
Layout and optics for a collimation section

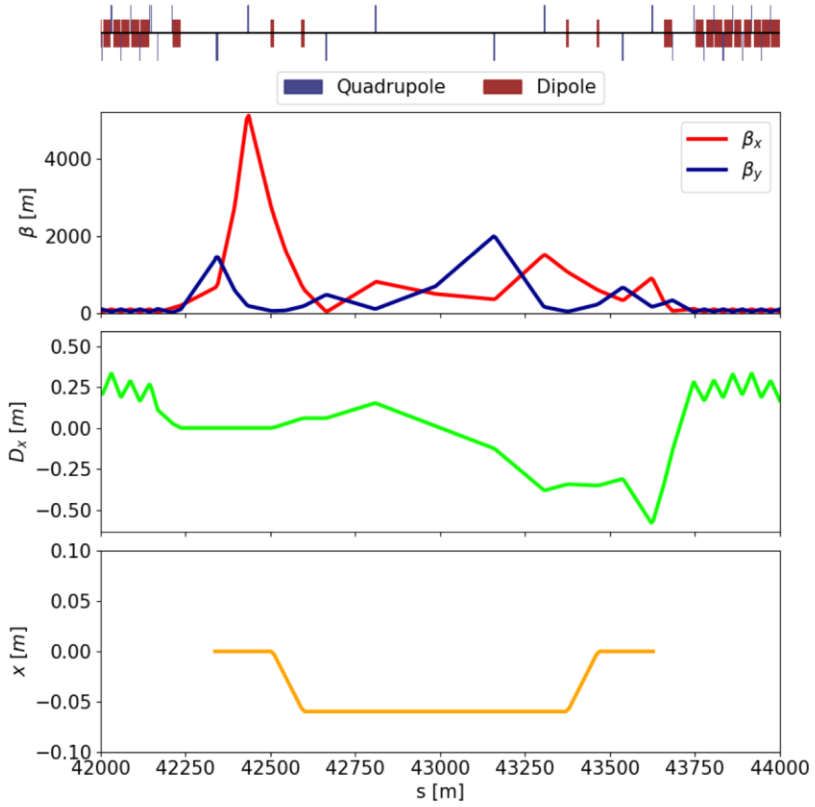
Michael Hofer

Optics

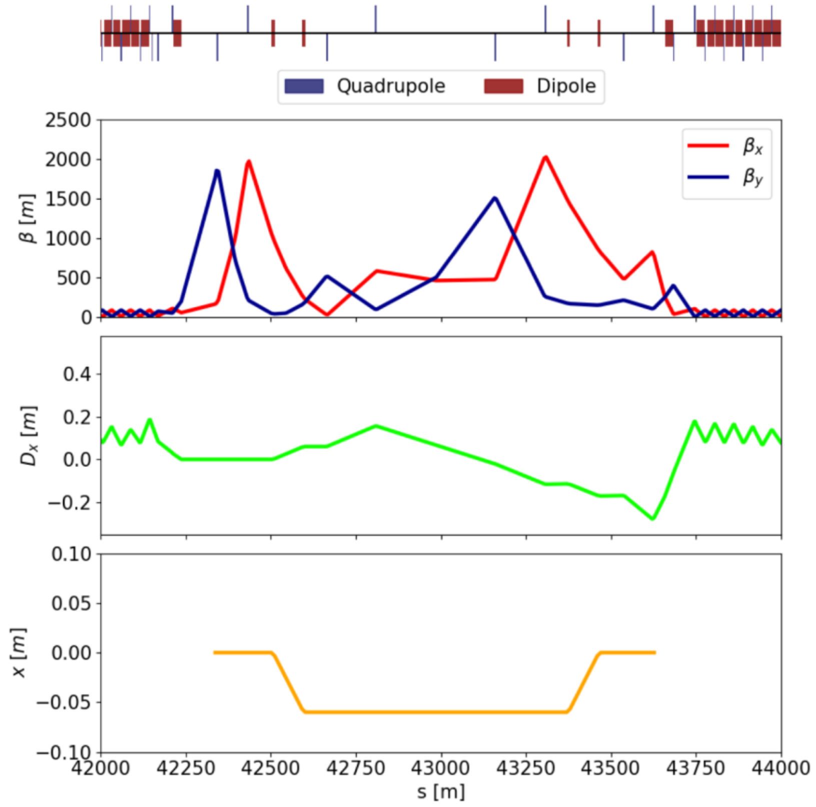
First integration into Z- and $t\bar{t}$-lattice

- Of particular interest since operation modes with the highest stored beam energy (Z with 20 MJ) and highest beam energy ($t\bar{t}$ with 182.5 GeV)





Z-lattice (45.6 GeV)



$t\bar{t}$-lattice (182.5 GeV)

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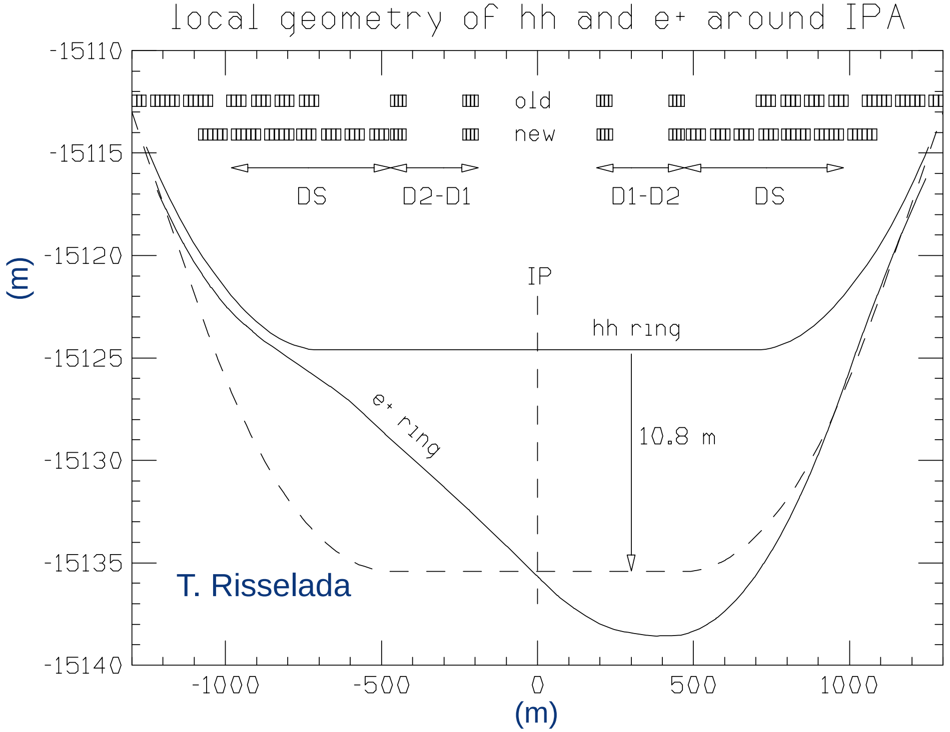
FCC-hh

Wednesday from 9h00 –FCC-hh – Frank Zimmermann, CERN	
Status and plans for FCC-hh optics studies	Massimo Giovannozzi, CERN
Modifications of injection and beam dump systems for new collider layout	Wolfgang Bartmann, CERN
Status and plans for FCC-hh collimation	Roderik Bruce, CERN

Status and plans for FCC-hh optics studies

Massimo Giovannozzi



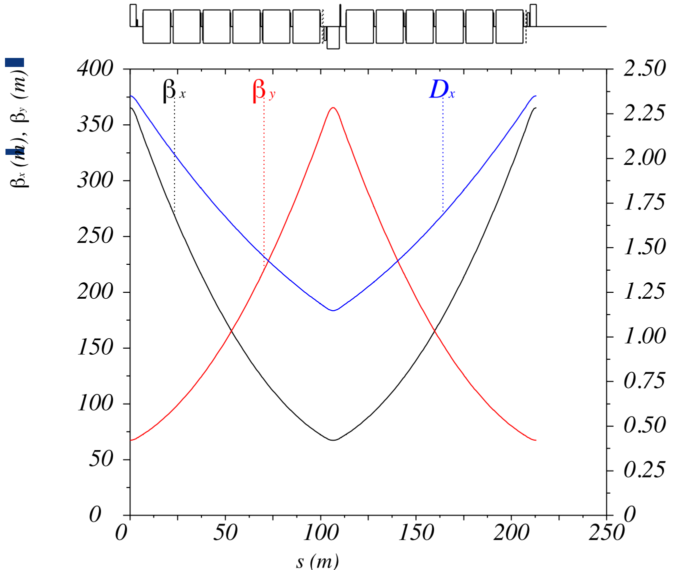
Improved layout with FCC-ee and FCC-hh IPs at same transverse position - Advantages:

- Size of detector cavern reduced
- Re-use FCC-ee detector for FCC-hh
- Tunnel width reduced over 2 x 500 m

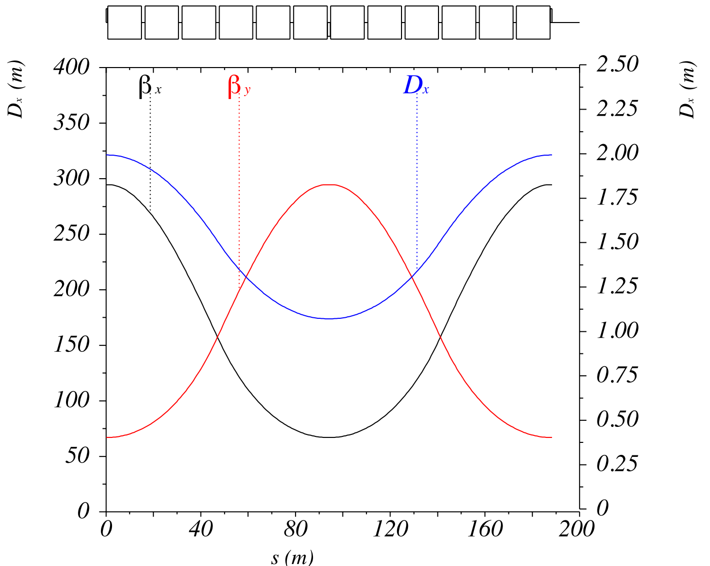
Combined-function (dipole-quad) option for FCC-hh - Possible advantages

- Increase filling factor
- Simplify production (a single magnet type for the arcs)

Nominal FCC-hh FODO cell



FCC-hh combined-function cell



hh injection and beam dump systems

Wolfgang Bartmann

Transfer lines

8 point options will require significantly more TL magnets

Joining the collider tunnel as early as possible– this requires a careful consideration of integration and cross-talk

Injection

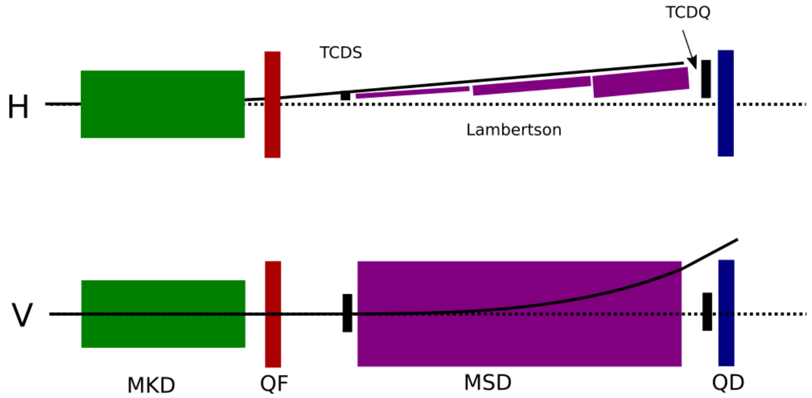
- New generator technologies required and studied
- Failure scenarios analyzed
- Can reduce system length to 450 m for injection equipment

Extraction – New Baseline

→ Higher field with same apparent septum blade thickness (25mm)

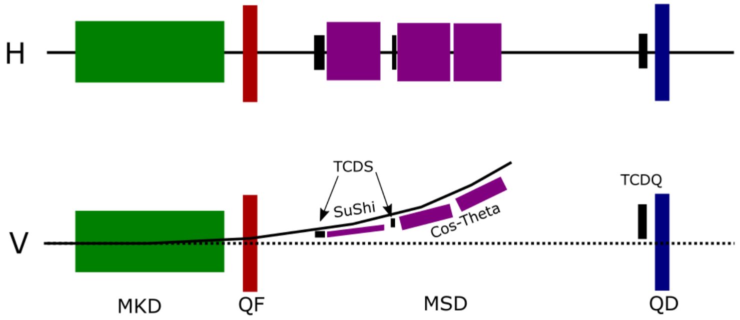
Old baseline: working backup solution

- Based on superferric Lambertson septa (1.3-1.55T / ~184m with 25 mm septum blade)
- Septa layout requires double plane extraction
- Highly segmented extraction kicker system (300 kicker)



…ed new baseline:

- …ased on novel septa: SuShi (3.2T) and Truncated CosTheta (4T). Total system length ~70m
- Septa Layout requires single plane extraction (vertical)
- Reduced kicker segmentation, still highly

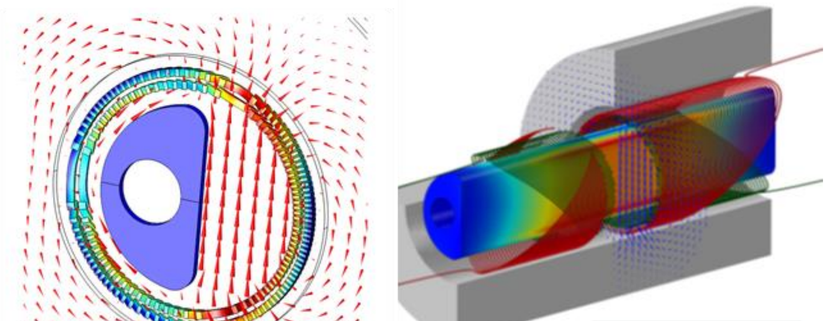


SuShi

D. Barna: Superconducting Shield (SuShi) septum

- 3.2 T
- Measurements on first prototype conducted
- Apparent septum blade: 25mm

  → can potentially be reduced to 20mm using NbTi for the shield **(reduced kick strength)**

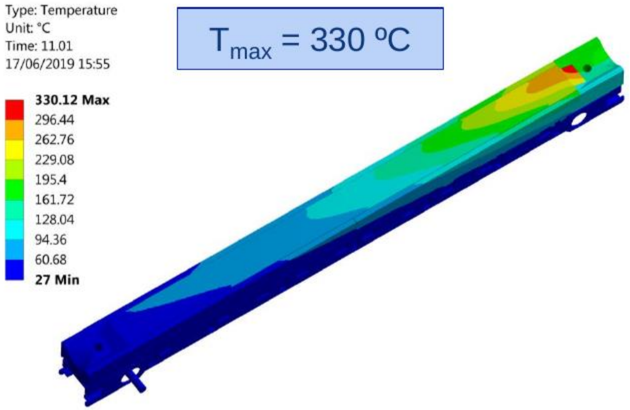


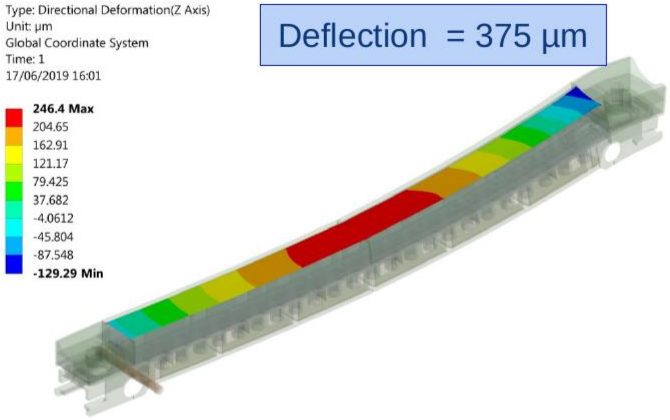
D. Barna

Length reduction from 2.8 km to 2.1 km → likely possible to find a feasible concept

Thermo-mechanical response, *p* 12 min lifetime, w FLUKA & ANSYS

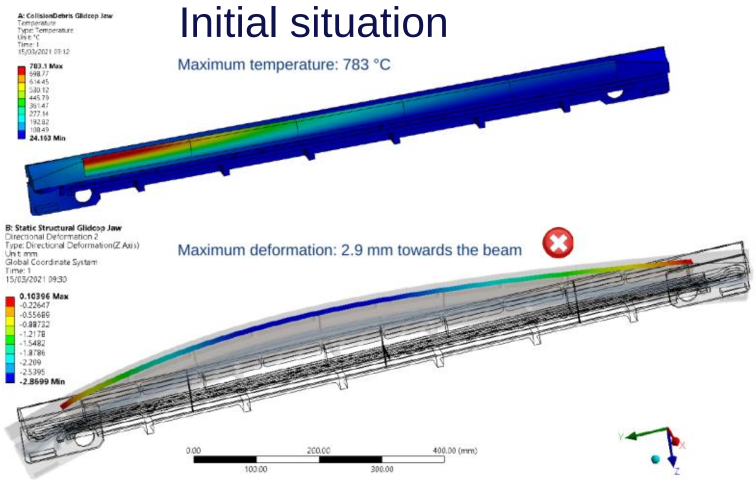
- most loaded collimators (vertical primary with highest peak power density 50kW/cm^3, first secondary w highest total power load 92 kW)





100's of micron displacement

Thermo-mechanical response, *Pb* secondary beam



DS collimator

Final situation, after mitigations

Table 2: Simulation results with different jaw designs.

Jaw	L	R	L	R	L	R
Housing	Cu	Cu	Mo	Mo	Mo	Mo
Sections	1	1	1	1	4	4
T_{max} (°C)	204	136	291	181	296	188
δ_{max} (μm)	1060	800	530	380	**150**	**90**

FUTURE CIRCULAR COLLIDER

Electron cloud and vacuum

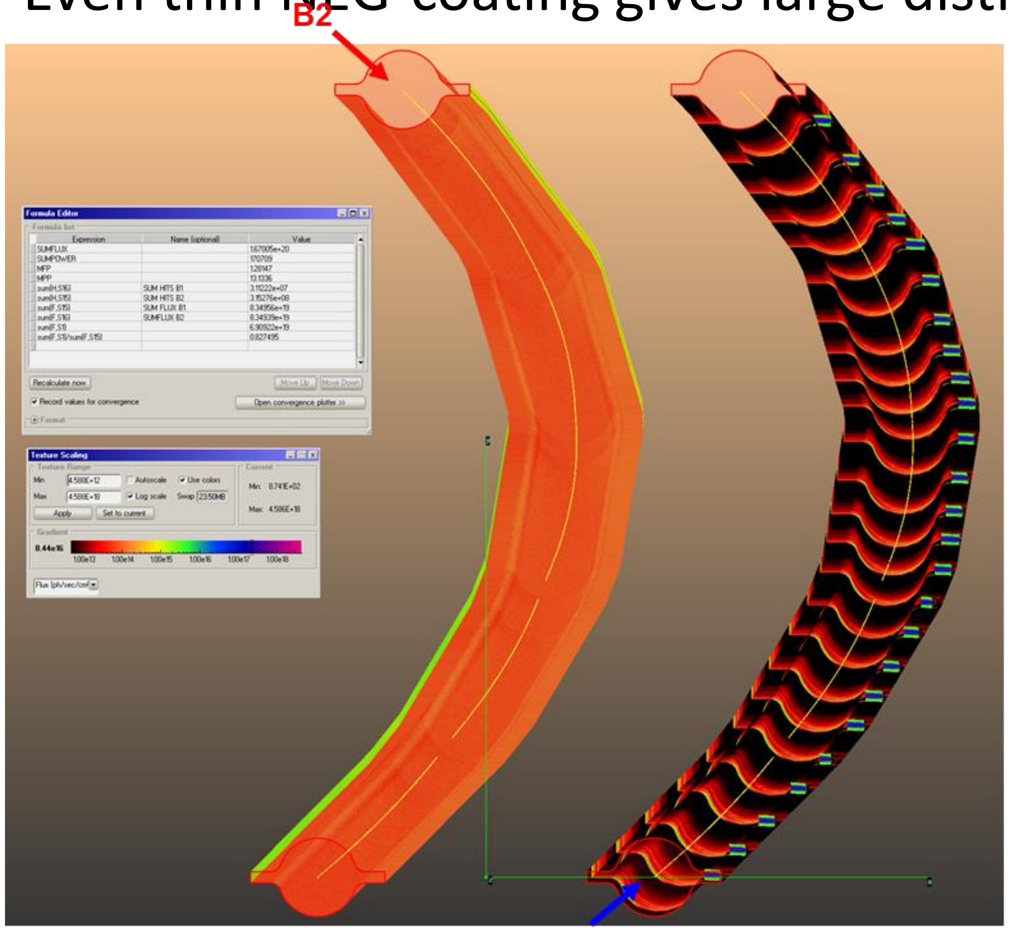
Wednesday from 11h00 – FCC-ee & FCCIS WP2: Electron cloud & vacuum – Kyo Shibata, KEK	
Arc vacuum system & synchrotron radiation	Roberto Kersevan, CERN
Synchrotron Radiation studies for the FCC-ee arc with FLUKA	Barbara Humann, CERN &TU Vienna
Key surface parameters	Roberto Cimino, INFN
Electron cloud simulations for arc dipoles	Fatih Yaman, IETY
Electron cloud simulations for arc quadrupoles	Damian Ayim, UADY

Arc vacuum system and synchrotron radiation

Roberto Kersevan

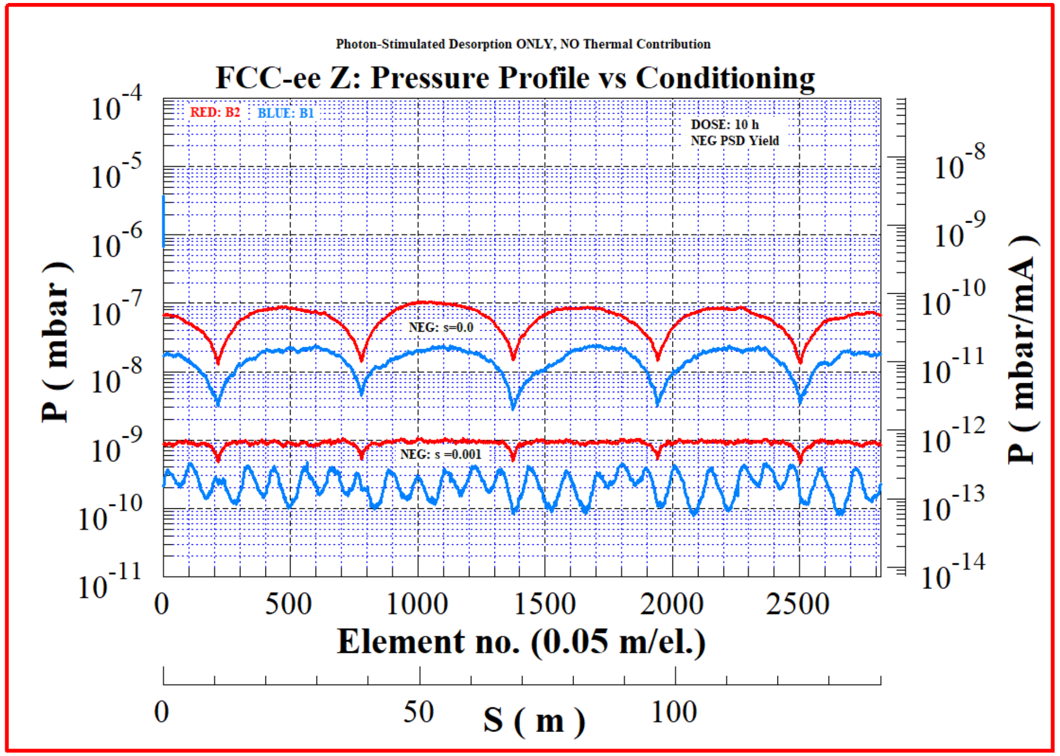
Thin (150 nm) NEG-coating to obtain low PEY and SEY ; “thin” to minimize RW impedance

Even thin NEG-coating gives large distributed pumping speed; **+ discrete photon absorbers**



B1: 25 absorbers at ~ 5.6 m average spacing

B2: no absorbers



Future work: prototyping and experiments

- test prototype chambers at light source (KARA/KIT?)
- test behavior of thin NEG-coating at light source
- define deposition technique for dipole vacuum chambers
- in-situ measurement of photoelectron yield at light …

SR studies for arcs with FLUKA

Barbara Humann

FUTURE CIRCULAR COLLIDER

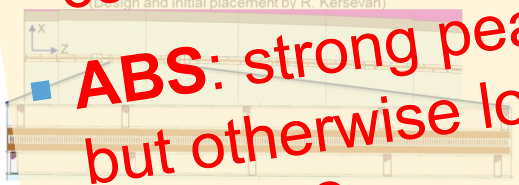
- **Cont**: higher values for dose and peak power on coils and BP over the whole magnet → cooling?
- **ABS**: strong peaks for dose and peak power, but otherwise low values → dose levels feasible?
- No strong differences for R2E related values

Model comparison: absorber vs continuous shielding

Absorbers (ABS):

- CuCrZr alloy
- Length: 30cm
- Angled surfaces for even power distribution
- Water cooled

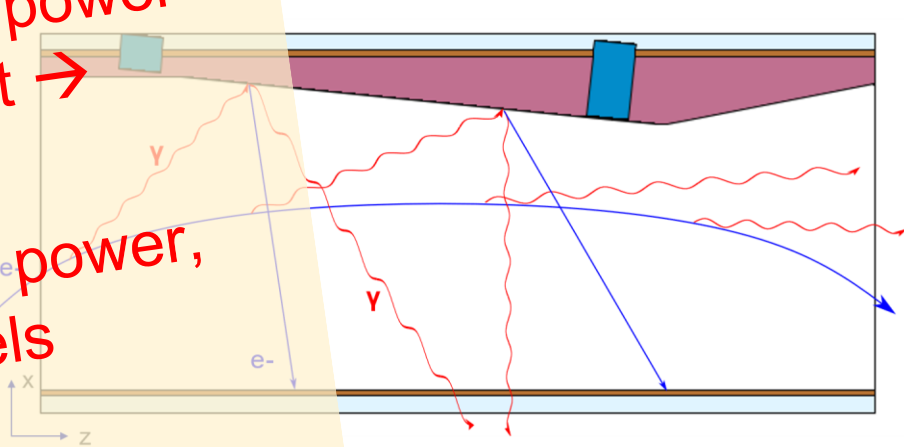
(Design and initial placement by R. Kersevan)

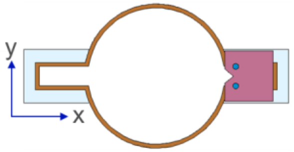


Continuous shielding:

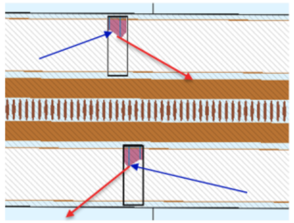
- Continuous shielding around VC and yoke
- Due to space restrictions from yoke and coils respectively, no shielding in MQs and MSs.
- Intermet180 (Tungsten alloy)
- Shielding thickness:
  - Sides: 1.3cm

Absorber working & reflection





External beam: reflected particle → magnet yoke

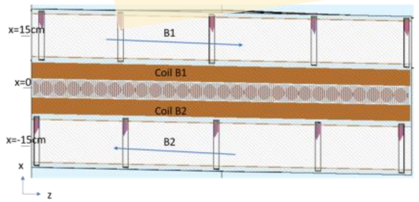


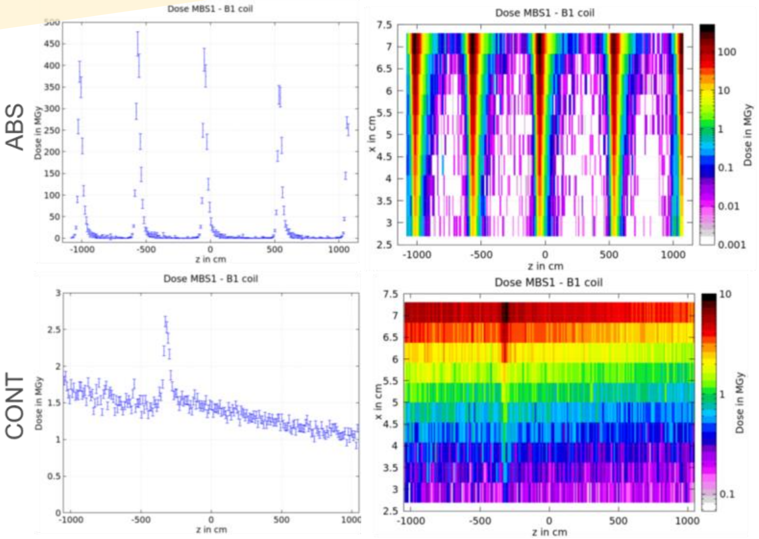
Internal beam: reflected particle → tunnel

Compton scattering: photon collides with electron and is scattered into a different direction, dominant in the MeV range

Dose and energy density on the coils (MB)

Top-View MB





- **ABS:**
  - Up to 500MGy at location of ABS;
  - Strongly localized around y=0
  - Other locations: <1MGy
- **CONT:** peak caused by missing lack of shielding in MQs
- Dose in coils of **MQs** negligible due to protection of yoke

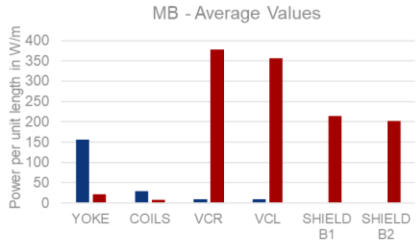
Power distribution on the tunnel & magnets

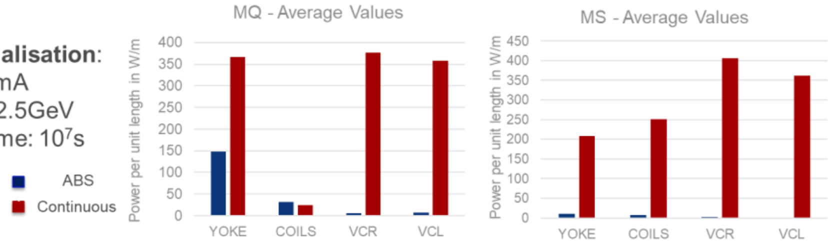
	ABS		Continuous	
MB *	23.4kW	14%	3.5kW	2%
MQ	2.9kW	1.7%	17.4kW	10.4%
MS	0.1kW	<0.1%	7.1kW	4.2%
ABS, Shield/VC	**131kW**	78%	**135kW**	81%
Tunnel	9.5kW	6%	3.5kW	2.1%
Total	**167kW**		**167kW**	

* Without VC and shielding

Component	Material
Yoke	Iron
Coils	Copper
VCR/VCL	Copper
ABS	CuCrZr
Shielding	INERM180

Normalisation:
I=5.4mA
E=182.5GeV
Runtime: 10^7s

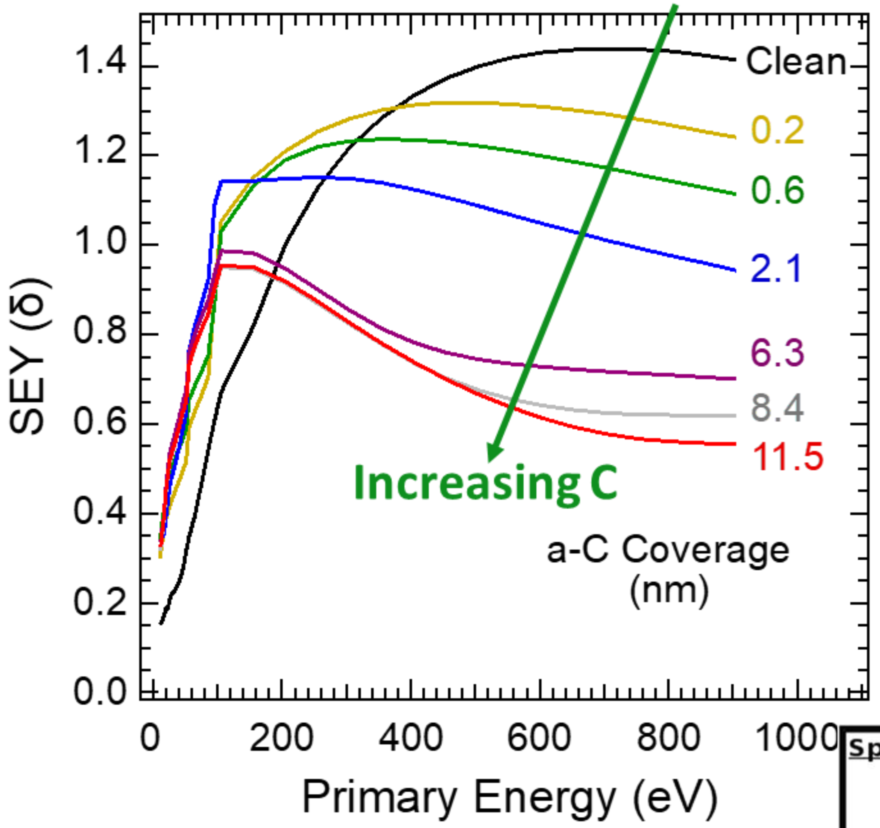


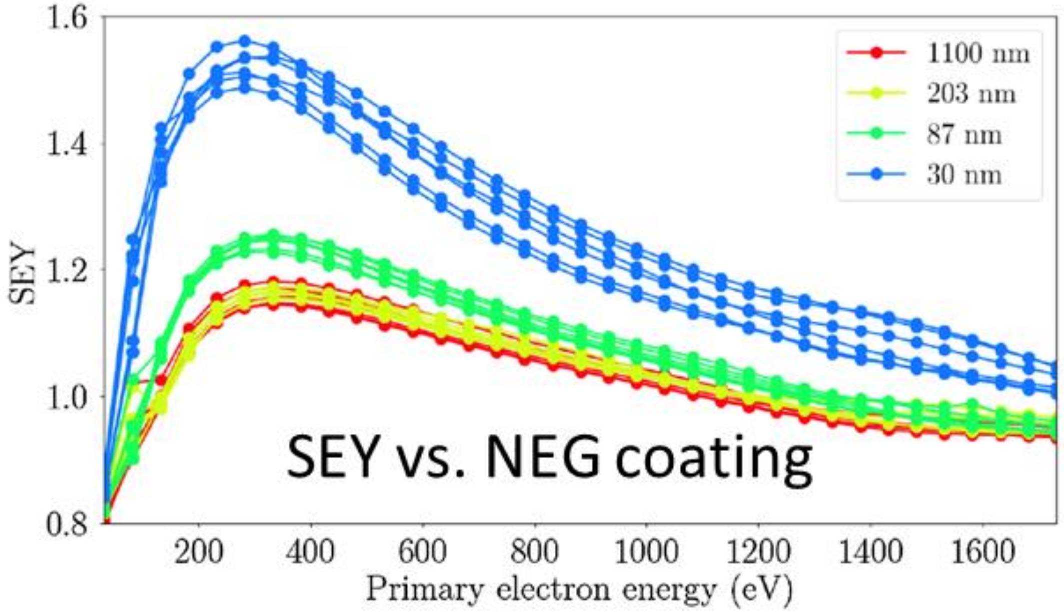


Key Vacuum Surface Parameters for FCC-ee

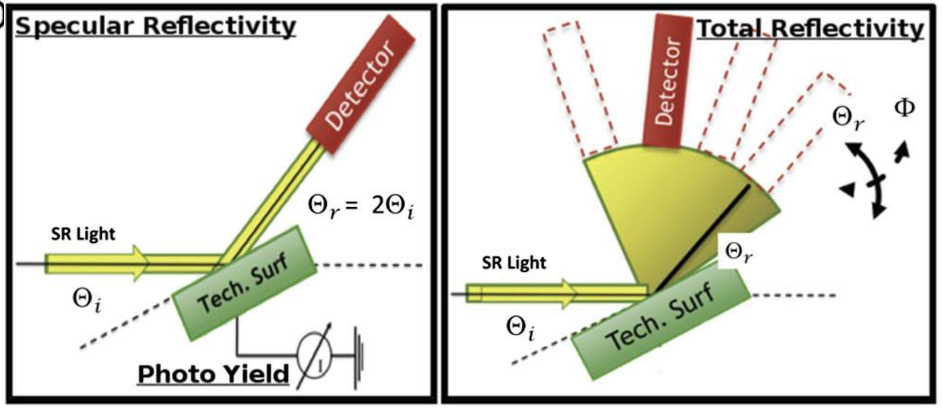
Roberto Cimino

how a coating modifies the SEY





exp. configurations for PEY & reflectivity measurements

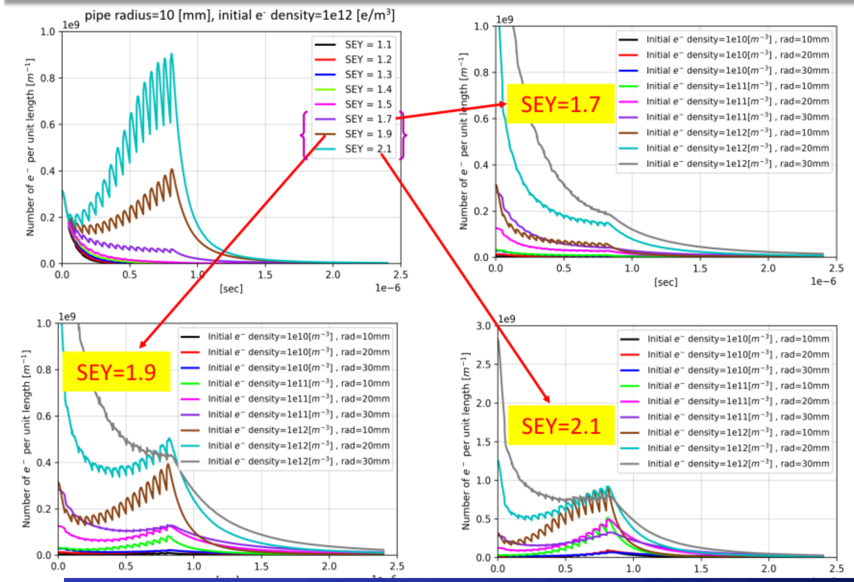


difficult to extrapolate results from energy range available (35 - 1800 eV) minimal grazing incidence angle achievable at BESSY2 to an energy range and angle of incidence of relevance for FCC-ee
→ experiments elsewhere !

e-cloud simulations for FCC-ee DR & collider dipoles

Fatih Yaman

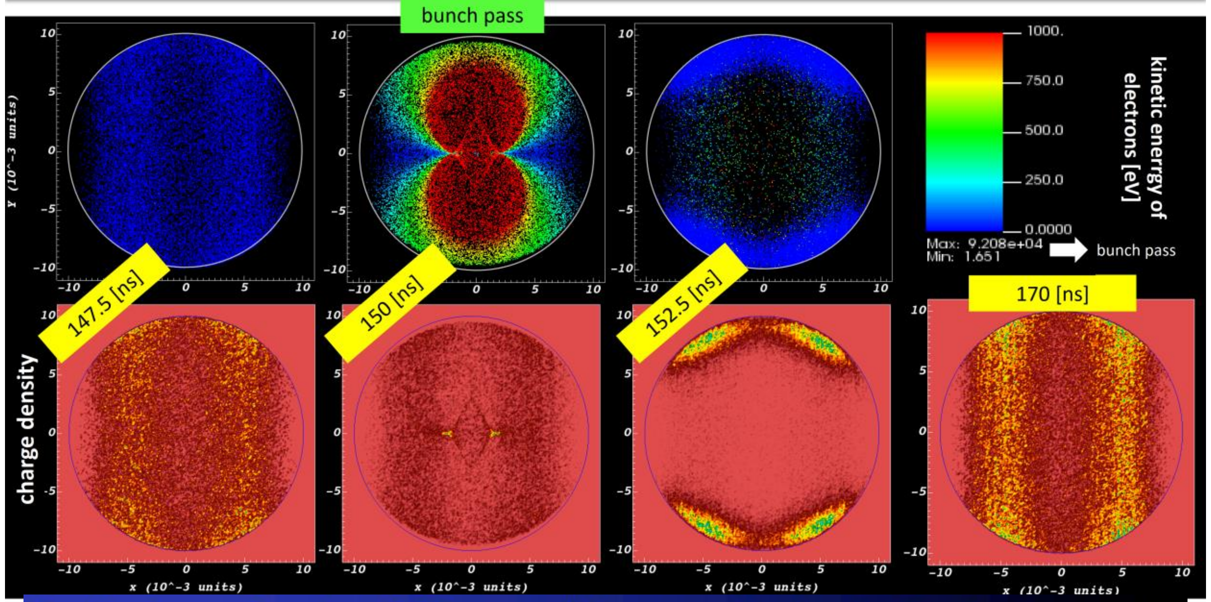
FCC-ee DR, Injection : PyECLOUD &Furman-Pivi Model



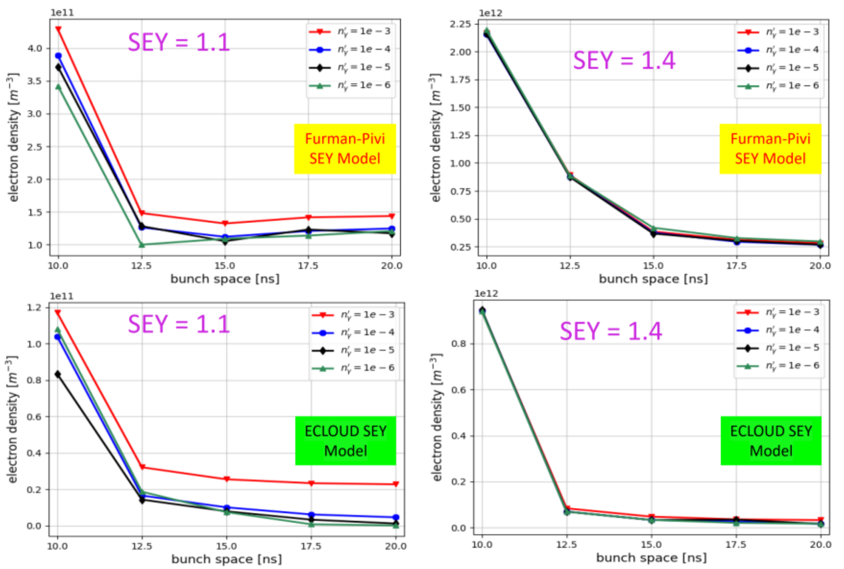
- SEY values scanned for the smallest radius and the highest initial electron density value
- SEY ≤ 1.5: electrons vanish for the initial electron densities 1e12[m^{-3}]
- SEY = 1.7: no electron build up from the initial seeds observed
- initial electron density 1e12[m^{-3}], beam pipe radius=10mm expresses electron density oscillations both for SEY=1.9 and SEY=2.1

Fatih Yaman, 'Electron-Cloud Simulations for the FCC-ee Collider Arcs and for the e+ Damping Ring', 121st FCC-ee Optics Design Meeting, July, 2020

FCC-ee DR, Extraction:VSim & Furman-Pivi Model



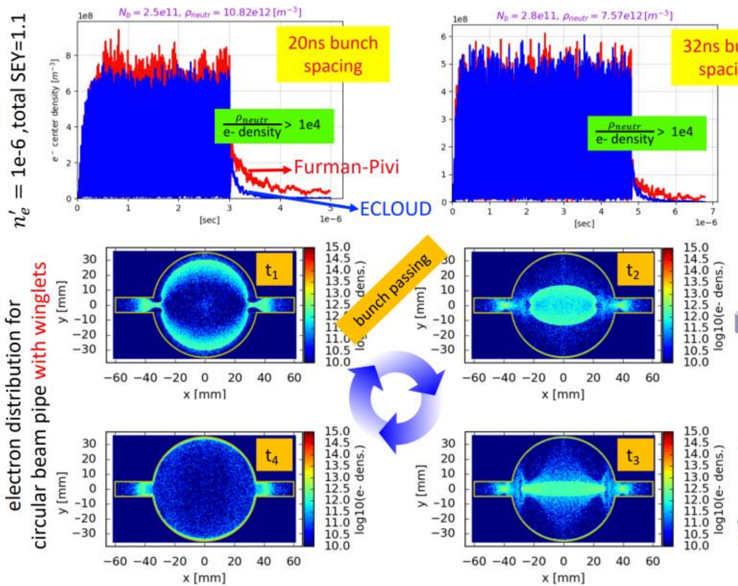
Average of min. for center e⁻ density, FCCee Collider: PyECLOUD

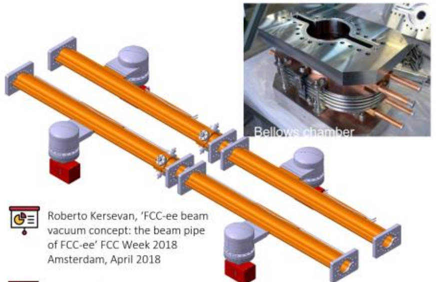


- for the SEY=1.1, electron density for the largest photoelectron generation rate is slightly higher
- impact of larger SEY dominates the effect of photoelectron generation rate
- for bunch spacing > 15ns the density values do not change drastically

Fatih Yaman, 'Electron cloud simulations for FCC-ee Collider Dipoles: Comparisons of SEY Models, Longer Bunch Spacing, and Higher Intensity', 135th FCC-ee Optics Design Meeting, 6th FCCIS WP2.2 Meeting, March 2021

Preliminary Results, FCC-ee collider arc dipole: PyECLOUD





Roberto Kersevan, 'FCC-ee beam vacuum concept: the beam pipe of FCC-ee' FCC Week 2018 Amsterdam, April 2018

Fatih Yaman, 'Electron cloud build up in the collider: towards lower density', 123rd FCC-ee Optics Design Meeting, July, 2020

e-cloud simulations for arc quadrupoles

Damian Ayim

Variation of bunch spacing using: SEY = 1.2 | $\eta_\gamma = 3.5e\text{-}5$, 1e-6

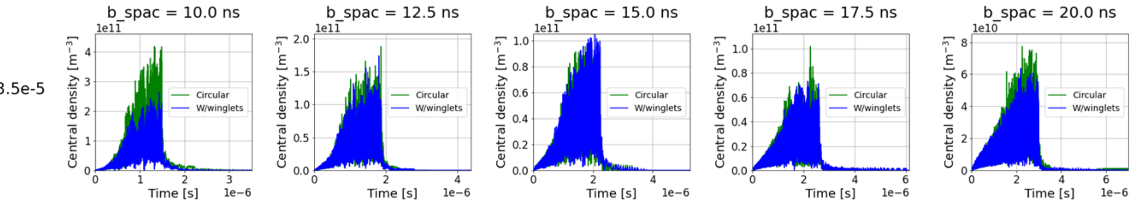


Figure 13 Figure 14 Figure 15 Figure 16 Figure 17

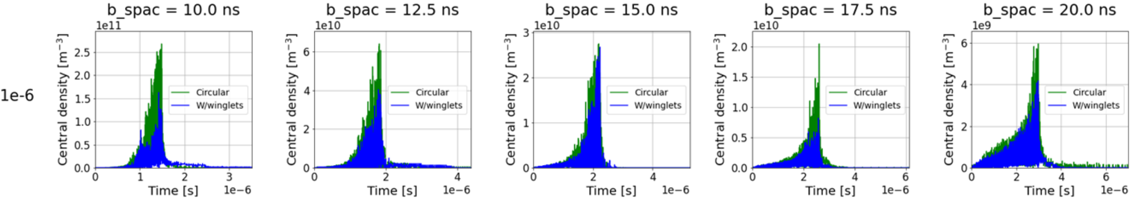


Figure 18 Figure 19 Figure 20 Figure 21 Figure 22

Variation of bunch spacing using: SEY = 1.3 | $\eta_\gamma = 3.5e\text{-}5$, 1e-6

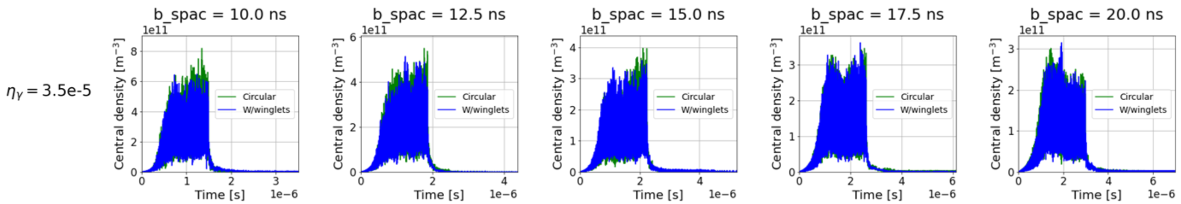


Figure 23 Figure 24 Figure 25 Figure 26 Figure 27

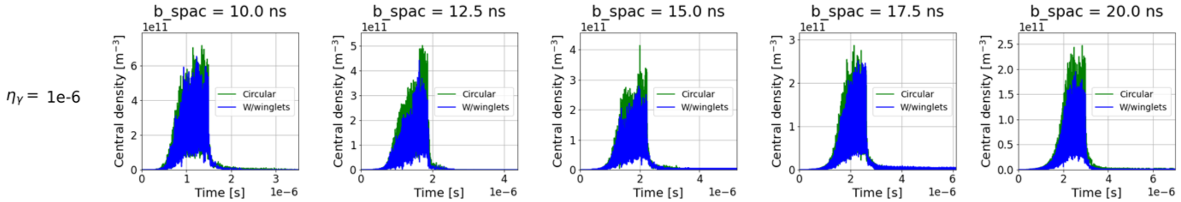
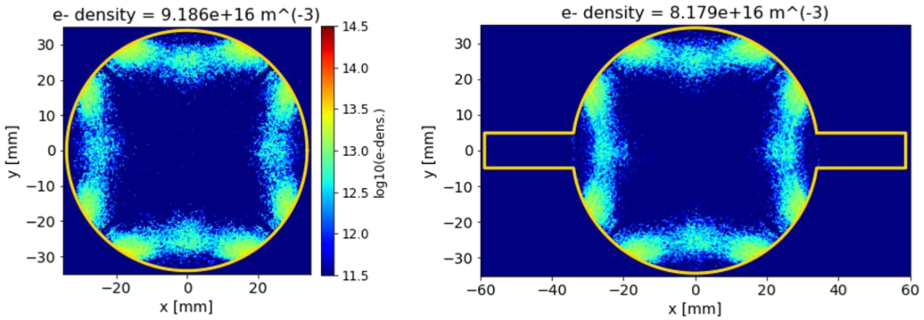
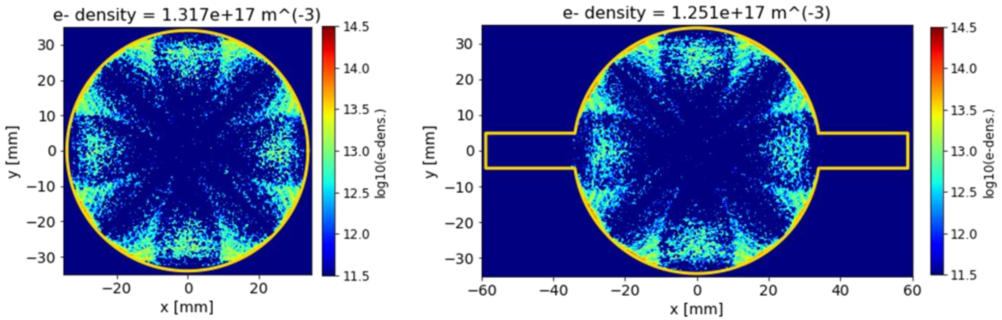


Figure 28 Figure 29 Figure 30 Figure 31 Figure 32

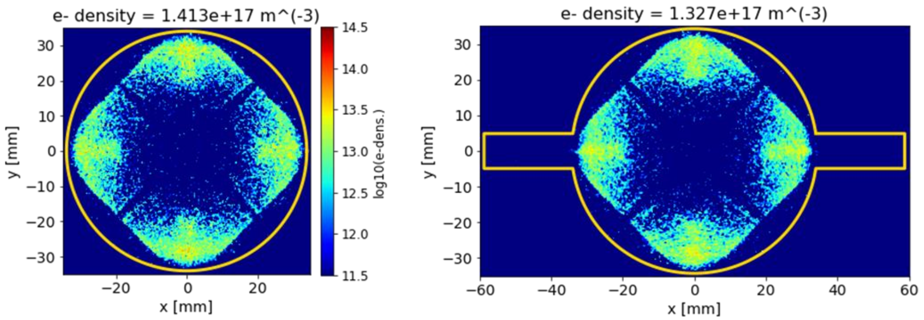
Space charge evaluation at t = 0.5 ns



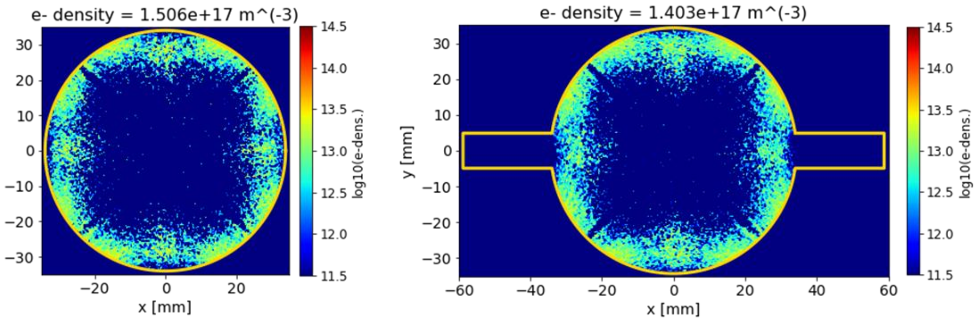
Space charge evaluation at t = 0.7053 ns



Space charge evaluation at t = 0.9531 ns



Space charge evaluation at t = 1.1003 ns



multipacting threshold at SEY ~1.25

e^- density is reduced for chamber with winglets

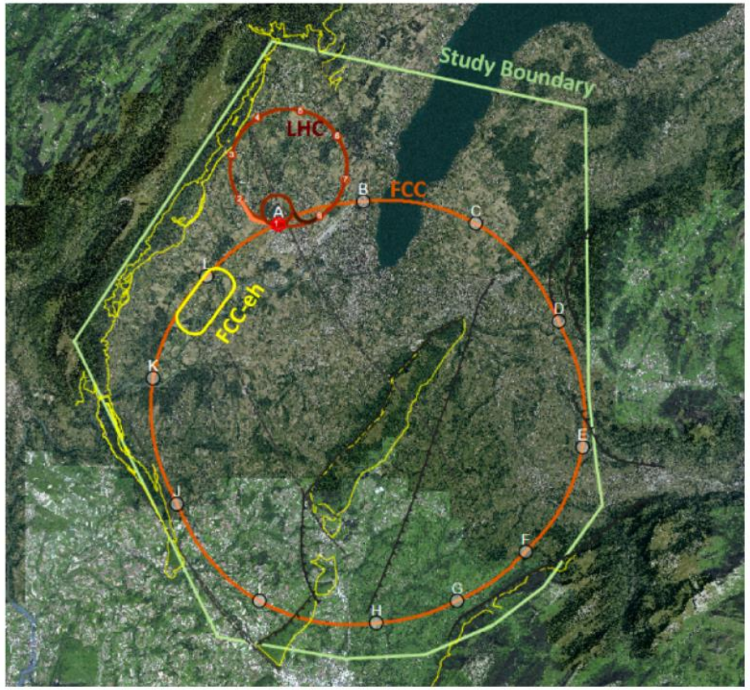
FCC-eh

Wednesday from 14h00 –FCC-eh – Gianluigi Arduini, CERN	
FCC.eh: Update and ERLs	Max Klein, U Liverpool
LHeC Racetrack as Injector to FCC-ee	Yannis Papaphilipppou, CERN
Interaction Region Design Optimization	Kevin Andre, U Liverpool

FCC-eh: Update and ERLs

FUTURE CIRCULAR COLLIDER

Max Klein



60 x 50000 GeV²: 3.5 TeV ep collider

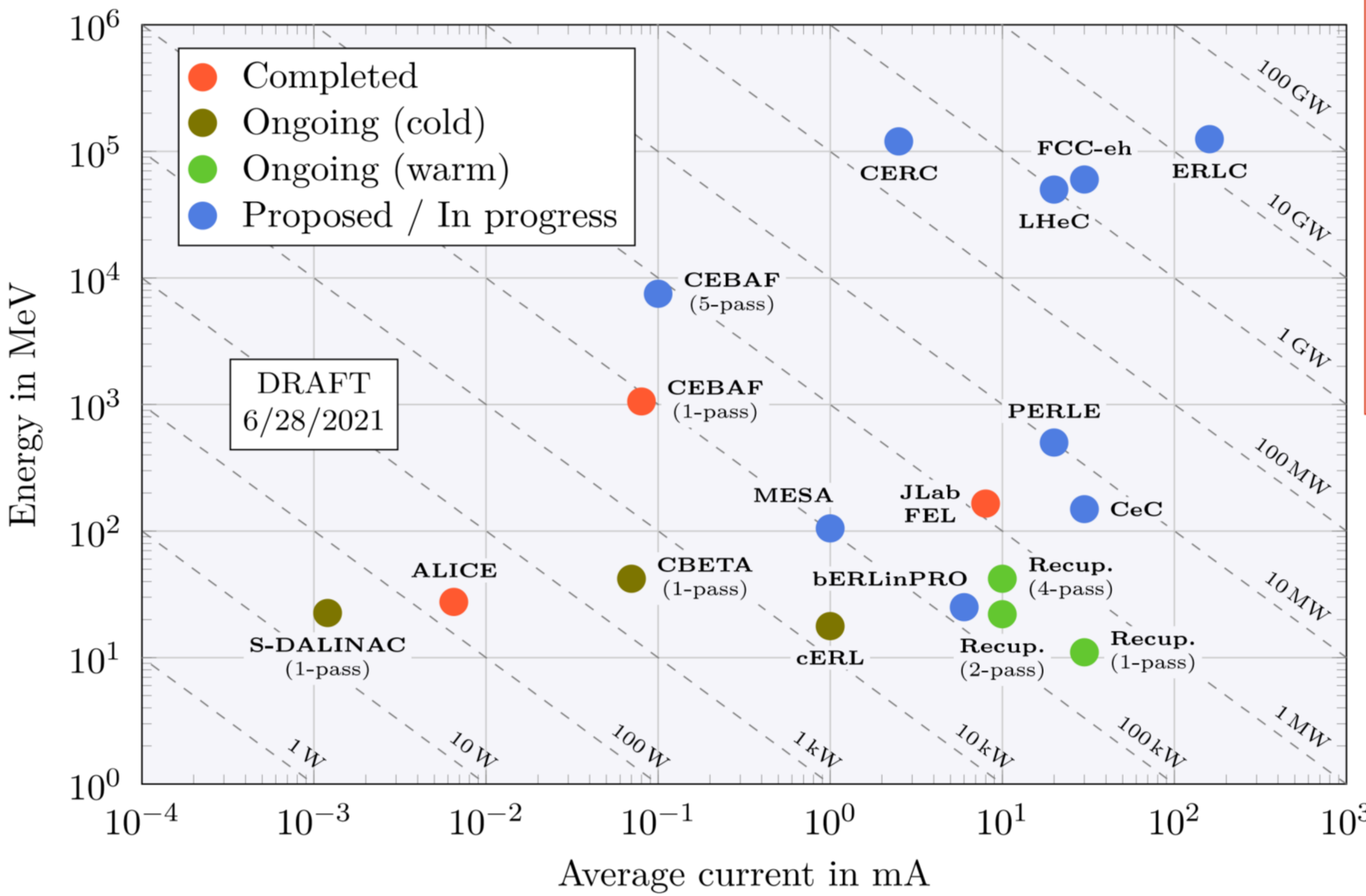
Operation: 2050+, Cost (of ep) O(1-2) BCHF

Concurrent Operation with FCC-hh

FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur.Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

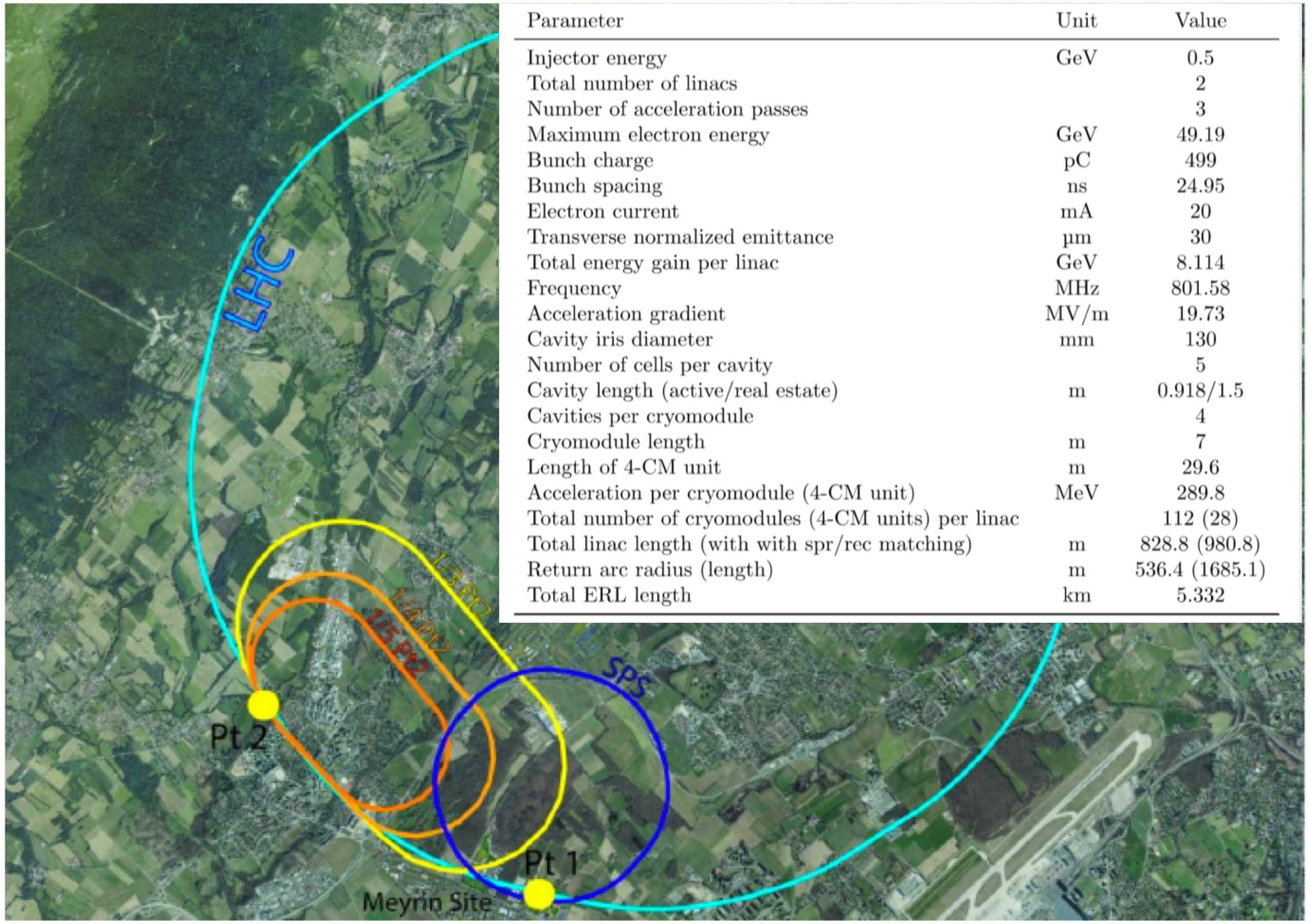
Future CERN Colliders: 1810.13022 Bordry+

A selection of past, present and proposed **ERL facilities**: Power = $E_e I_e$



LHeC Racetrack as Injector to FCC-ee

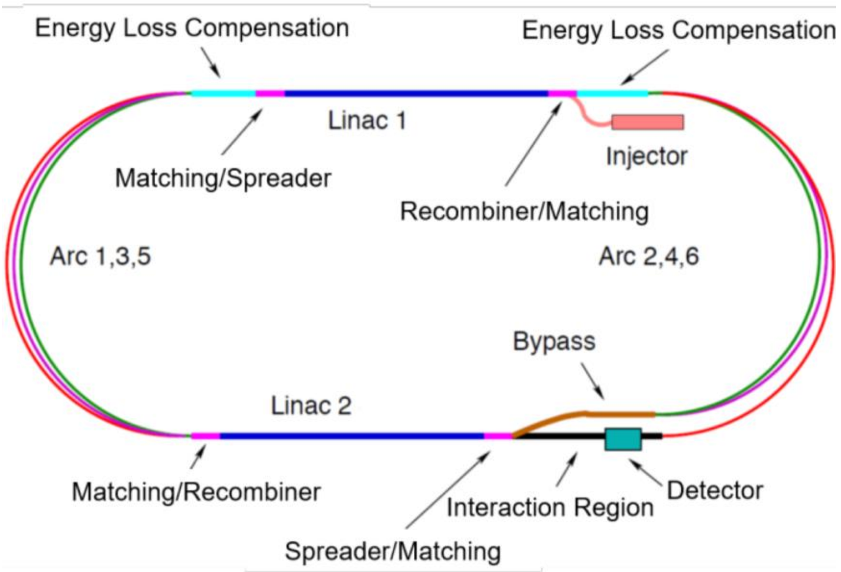
Yannis Papaphilippou



Parameter	Unit	Value
Injector energy	GeV	0.5
Total number of linacs		2
Number of acceleration passes		3
Maximum electron energy	GeV	49.19
Bunch charge	pC	499
Bunch spacing	ns	24.95
Electron current	mA	20
Transverse normalized emittance	µm	30
Total energy gain per linac	GeV	8.114
Frequency	MHz	801.58
Acceleration gradient	MV/m	19.73
Cavity iris diameter	mm	130
Number of cells per cavity		5
Cavity length (active/real estate)	m	0.918/1.5
Cavities per cryomodule		4
Cryomodule length	m	7
Length of 4-CM unit	m	29.6
Acceleration per cryomodule (4-CM unit)	MeV	289.8
Total number of cryomodules (4-CM units) per linac		112 (28)
Total linac length (with with spr/rec matching)	m	828.8 (980.8)
Return arc radius (length)	m	536.4 (1685.1)
Total ERL length	km	5.332

LHeC RLI would allow

- direct injection into collider at Z and perhaps W
- higher e- current than CDR baseline



50 x 7000 GeV^2: 1.2 TeV ep collider

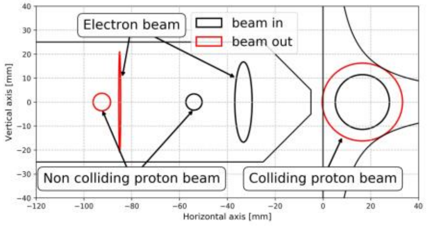
FUTURE CIRCULAR COLLIDER

eh Interaction Region Design Optimization

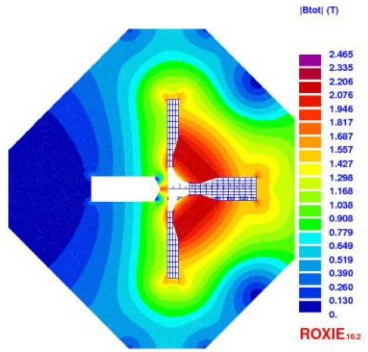
Kevin Andre

e/p separation scheme optimisation

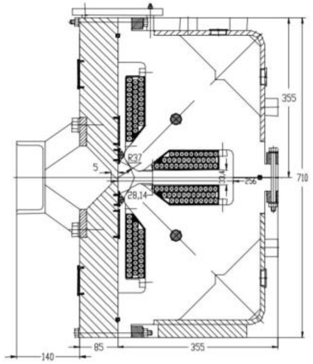
Magnet design with M. Liebsch using ROXIE in order to obtain a scaled half quadrupole.



Half quadrupole Q0 with proton and electron beam enveloppes

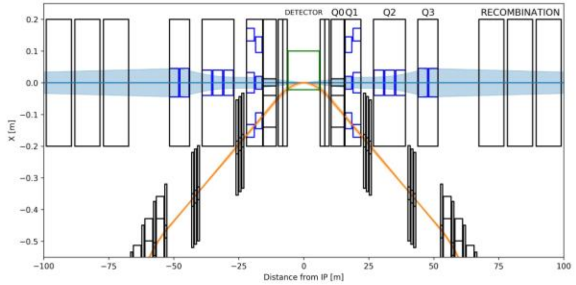


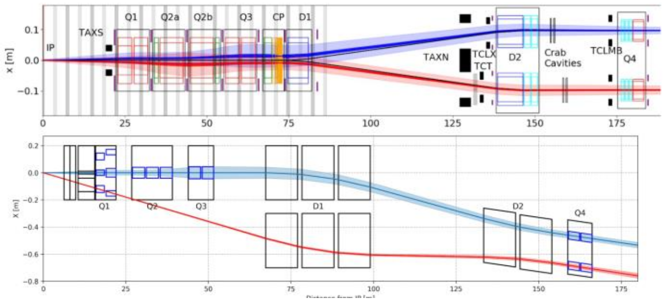
Half quadrupole Q0 magnet design



HERA "QM" magnet design

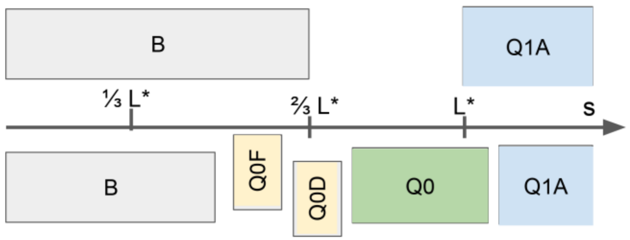
LHeC Interaction Region optimisation: proton & electron



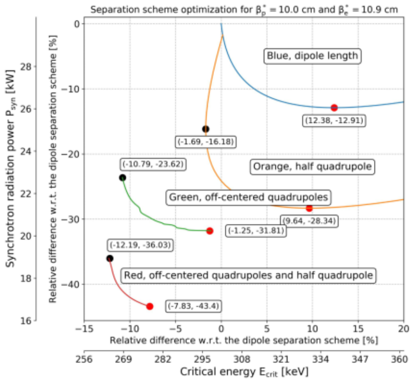


e/p separation scheme optimisation

The last optimisation combines the previous steps, using a Multi-Objective Genetic Algorithm : **NSGA-II**



B is ranging from 159 mT to 170 mT

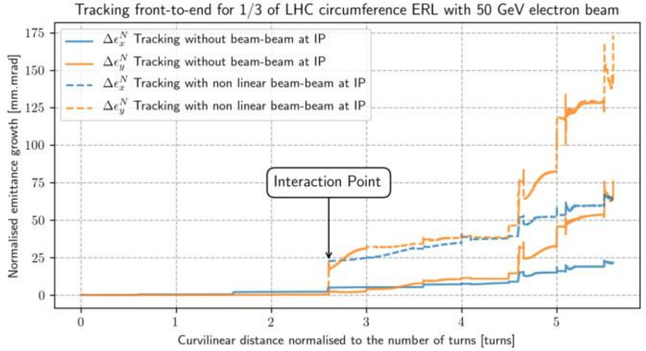


LHeC front-to-end tracking results and scaling to FCC-eh

Excellent beam transmission and energy recovery efficiency is achieved, **including synchrotron radiation and beam-beam disruption**.

ERL size	1/3 C_{LHC}	1/4 C_{LHC}	1/5 C_{LHC}
$\gamma\varepsilon_x^{\mathrm{inj}}$ [µm rad]	25.4	22.7	15.1
$\Delta p/p$ at IP	0.021 %	0.029 %	0.041 %
transmission	99.93 %	98.89 %	98.40 %
energy recovery	97.9 %	96.7 %	95.4 %

Table 2: Results of the tracking simulations including beam-beam and synchrotron radiation for several ERL designs.



The results of energy recovery for 1/3 of LHC with 60 GeV will be around 97 % energy recovery since the losses in the arcs are higher (1.9 GeV).

Injector Complex

Wednesday from 16h00 – FCC-ee : Injector complex – Tor Raubenheimer, SLAC	
Overview and layout	Paolo Craievich, PSI
Linac and electron sources	Alexej Grudiev, CERN
Positron source	Iryna Chaikovska, IJClab
Filling schemes through injector chain	Salim Ogur, IJCLab
Full energy booster	Antoine Chance, CEA

Overview and Layout

Paolo Craievich

→ Status in CDR: The bunches are accumulated in the collider in less than 20 min, for the initial filling, while in less than 2 min for the top-up

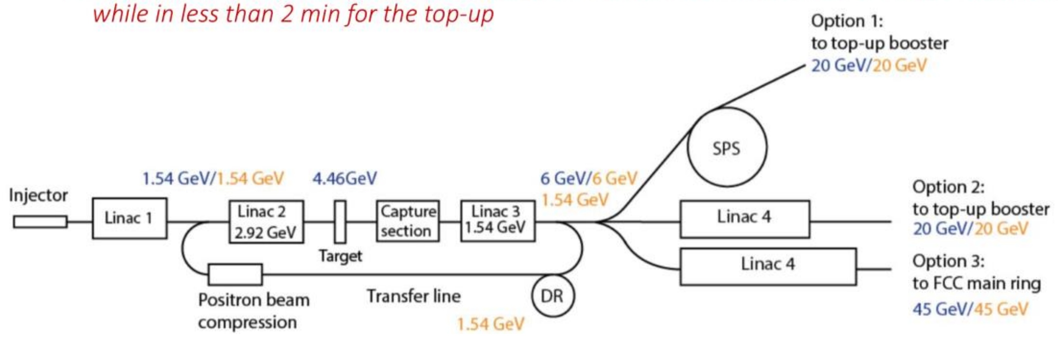
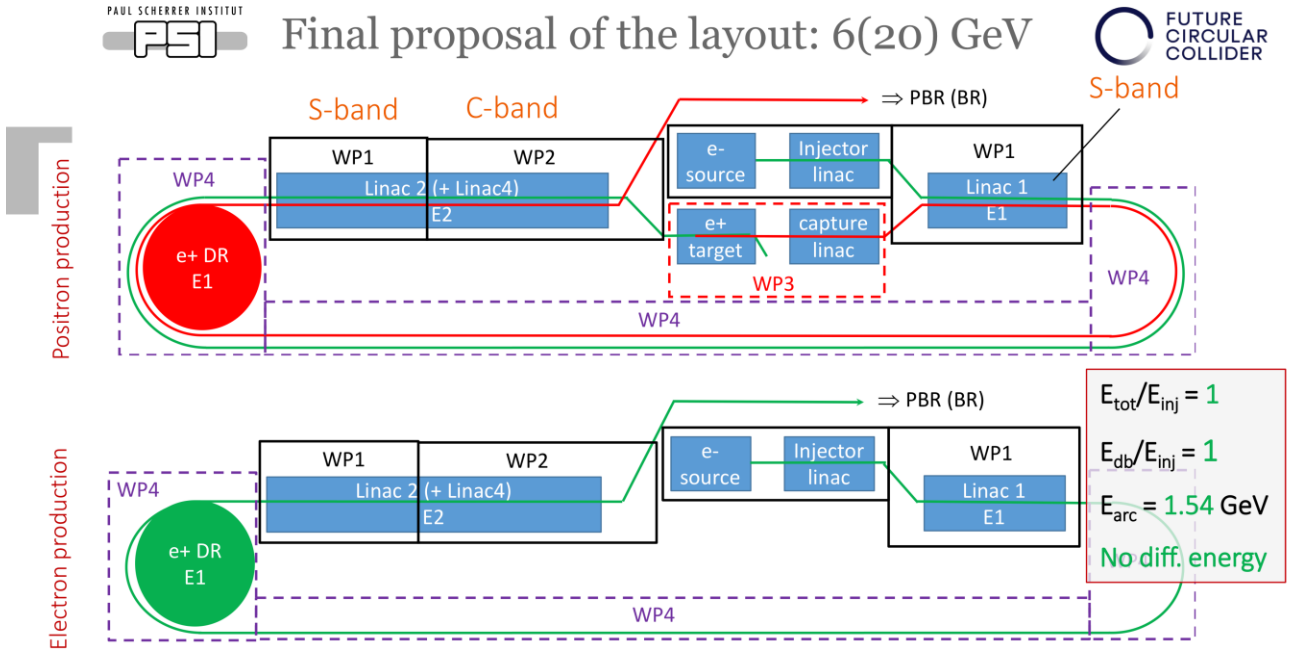


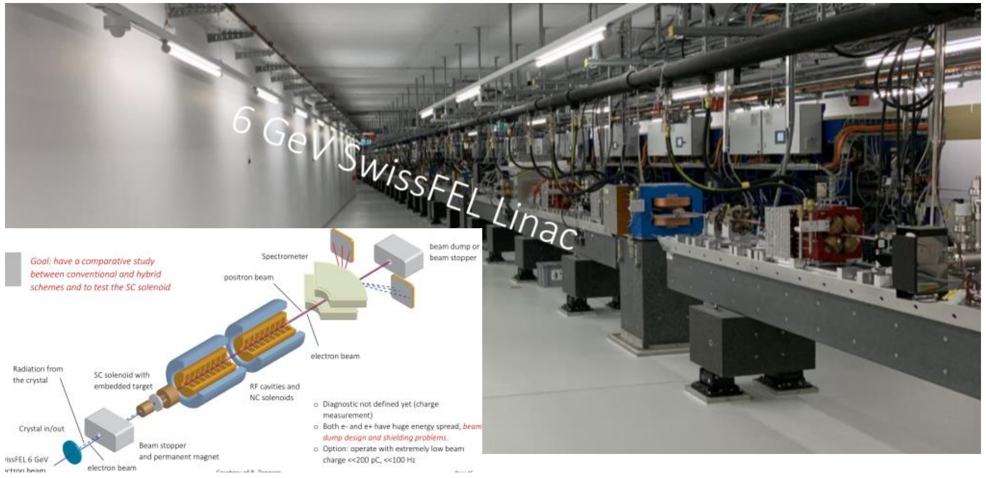
CHART collaboration



Extracted from the review report

1. adopt new layout for 6 GeV with only one energy in each linac & e+ production at 6 GeV
2. linac RF frequency should be chosen to be an appropriate multiple of the FCC-ee collider RF frequency to make potential future injection operation much easier to perform
3. check the acceptance of the booster ring in terms of emittance because this parameter will greatly influence the injector itself, i.e. RF guns and damping ring
4. carry out start-to-end simulations for the new baseline layout
5. rough relative cost comparison for new and old layout (probably only marginal differences)
6. concentrate on 2 bunch per pulse conservative scheme as recommended by review, with e+ target inspired by SLC's
7. study of 6-to-20 GeV linac, including rough cost estimate; e+ source performance at e- energy of 20 GeV
8. consolidation and confirmation of e+ yields expected at 6 and 20 GeV
9. preparation of PSI e+ experiment based on a target compatible with FCC 2-bunch operation

Positron Source R&D at SwissFEL

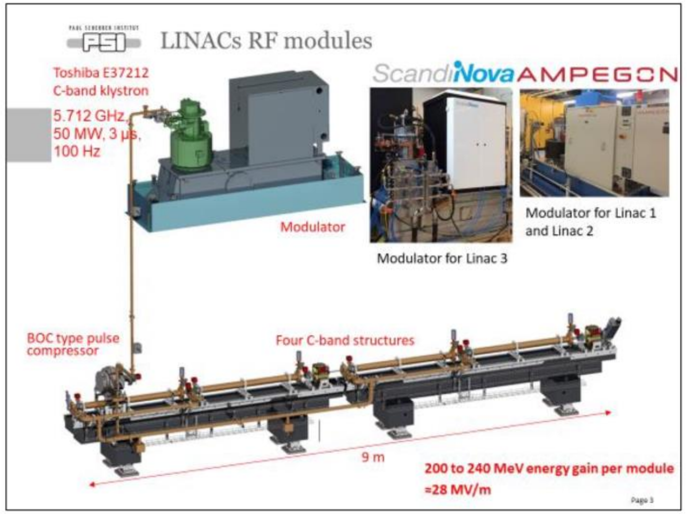


Linac and electron sources

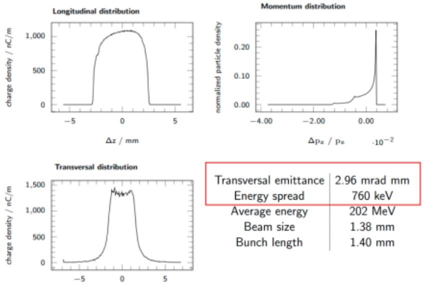
Alexej Grudiev

parameter	Baseline	Alternative	Comments
Ring for injection	PBR	BR	Destination
Injection energy [GeV]	6	20	Fixed
Bunch population [1e10]	2.1	2.1	Nominal
Number of bunches	2	2	
Bunch spacing [ns]	15, (17.5, 20)	15, (17.5, 20)	To be defined
Normalized transverse emittances (RMS): γε_x,y [um]	**50, 50**	**50, 8**	**Vertical acceptance of BR**
Bunch length (RMS) [mm]	~1	~1	<10 ring acceptance
Energy spread (RMS) [%]	~0.1	~0.1	

RF components reviewed

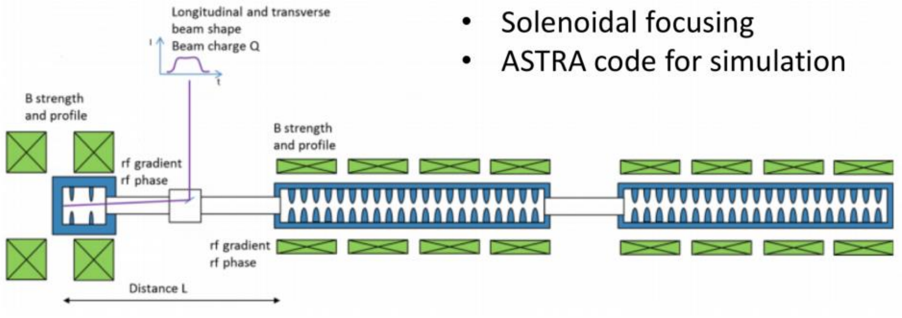


e- source
5nC bunch



Transversal emittance	2.96 mrad mm
Energy spread	760 keV
Average energy	202 MeV
Beam size	1.38 mm
Bunch length	1.40 mm

- 2.5 cell RF photo gun
- 2 S-band structures
- Solenoidal focusing
- ASTRA code for simulation



Summary

- Specification of the preliminary design parameters has been done together with the other WPs
- Adequate tools for RF and BD simulations have been identified and/or developed
- Linac design and optimization work can start now
- Linac 1 has been identified as a starting point for the design and optimization studies, which will begin soon after BD postdoc will join WP1
- Electron source based on photo-cathode RF gun looks promising to meet FCC-ee injector requirements

Positron source

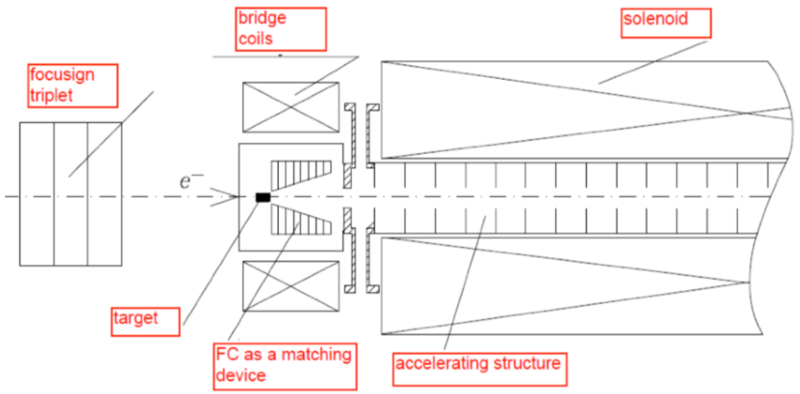
Iryna Chaikovska

The complete filling for Z running => **Requirement @ Injection ~2.1 × 10^{10} e+/bunch (3.5 nC)**

$$N_{e-}/\text{bunch} \times Y_{e+/e-} \geq 3.5\ \text{nC/bunch} \times 2$$

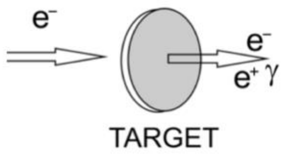
**A safety margin of 2 is currently applied for the whole studies.*

e+ production and capture section

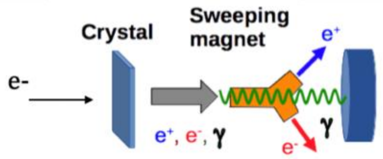


Production scheme:

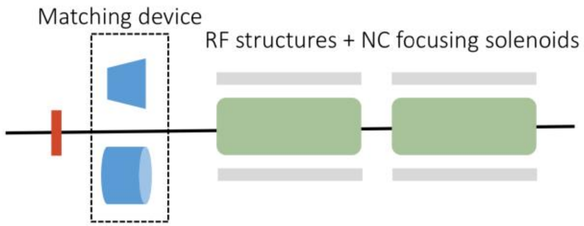
1) Conventional target



2) Hybrid target



Capture system:

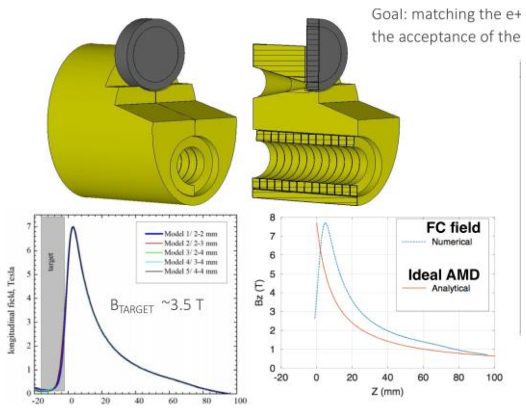


options to be considered for the Adiabatic Matching Device (AMD):

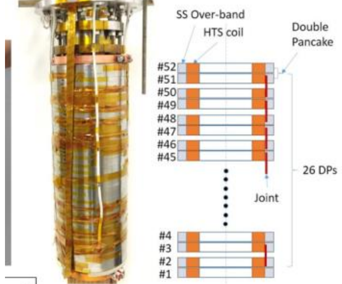
a. Flux concentrator (pulsed magnet)

b. Superconducting solenoid (new solution)

The capture linac is encapsulated inside the NC solenoid with the axial magnetic field of 0.5-0.8 T.
Options to be considered for the RF structures:
L-band (2 GHz) and large aperture S-band structures.



HTS solenoid



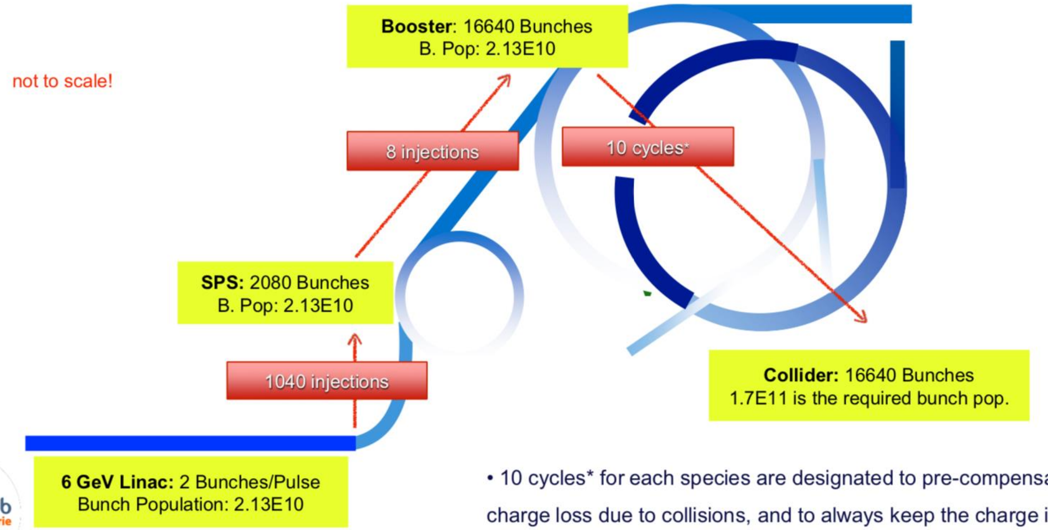
Plans to demonstrate at PSI

FUTURE CIRCULAR COLLIDER

Filling schemes through injector chain

Salim Ogur

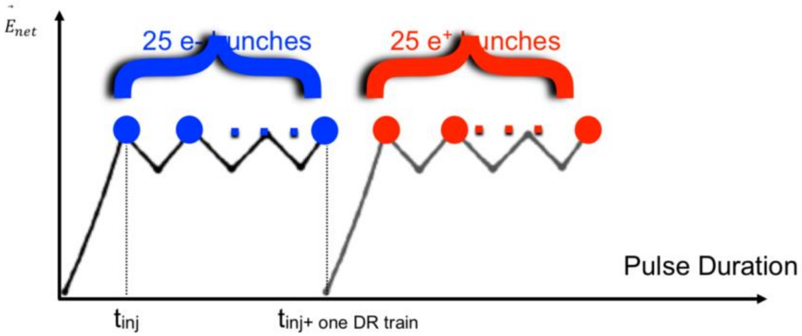
1.3. Fill From the Scratch in the CDR



- 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).

- **Linac:**
  200 Hz 2 bunches per RF pulse
- **SPS:**
  Accumulation of 2080 bunches : 5.2 s
  Emittance cooling (Damping time 0.1 s) : 0.7 s
  Ramp up time (6 - 20 GeV) : 0.2 s
  SPS Cycle time : 6.3 s
- **Top-up Booster:**
  Accumulation of 8 SPS Trains : 50.4 s
  Emittance cooling (Damping time 0.1 s) : 0.7 s
  Ramp up time (20 - 45.6 GeV) : 0.32 s
  BR Cycle time : 51.74 s
- **Collider:**
  10 BR Injections for each species will result the collider to be filled for Z- mode in 1035 seconds (17m15s)

2.1. Multi-bunch Linac Parameters

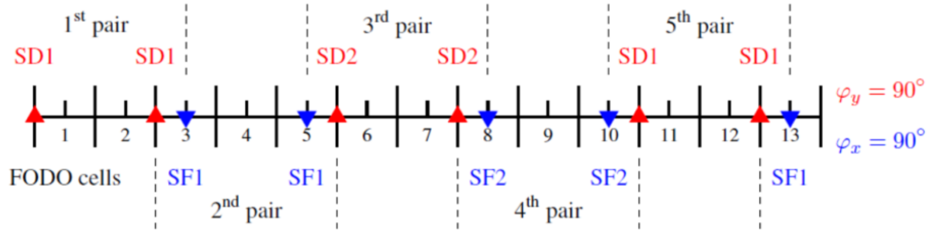


- **Linac:**
  100 Hz 25 bunches per RF pulse
- **SPS:**
  Accumulation of 1250 bunches : 0.5 s
  Emittance cooling (Damping time 0.03 s) : 0.12 s
  Ramp up time (6 - 20 GeV) : 0.175 s
  SPS Cycle time : 0.97 s
- **Top-up Booster:**
  Accumulation of 14 SPS Trains : 50.4 s
  Emittance cooling (Damping time 0.1 s) : 0.4 s
  Ramp up time (20 - 45.6 GeV) : 0.32 s
  BR Cycle time : 14.72 s
- **Collider:**
  10 BR Injections for each species will result the collider to be filled for Z- mode in 294.4 seconds (4m54s)

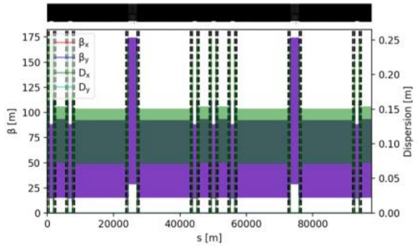
Full energy booster

Antoine Chance

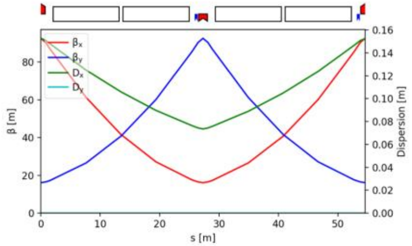
- A larger momentum compaction at Z (45.6 GeV) and W (80 GeV) operation mode to handle microwave instability and IBS → **phase advance of** $60°/60°$.
- A smaller equilibrium emittance (smaller $\mathscr{I}_5$) at H (120 GeV) and $t\bar{t}$ (182.5 GeV) operation mode → **phase advance of** $90°/90°$.
- **Non-interleaved sextupole scheme** gives the largest dynamic aperture.



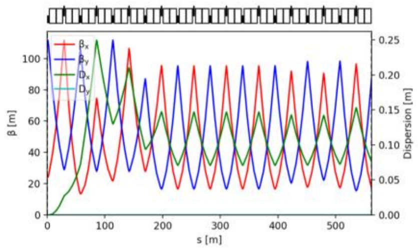
Ring



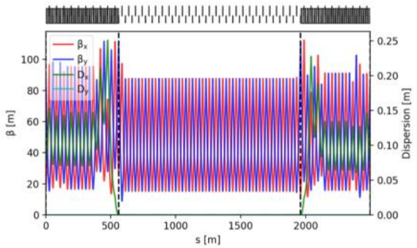
Arc FODO cell



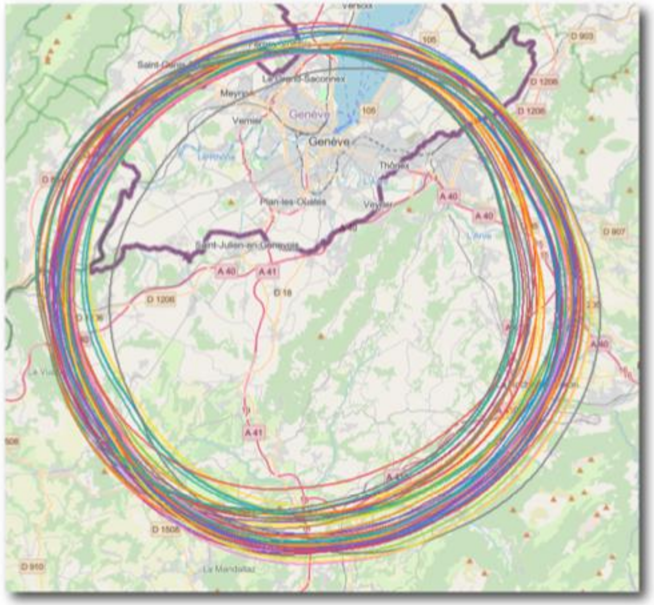
Dispersion suppressor



Insertion



Automated adaptation to MR layout modification



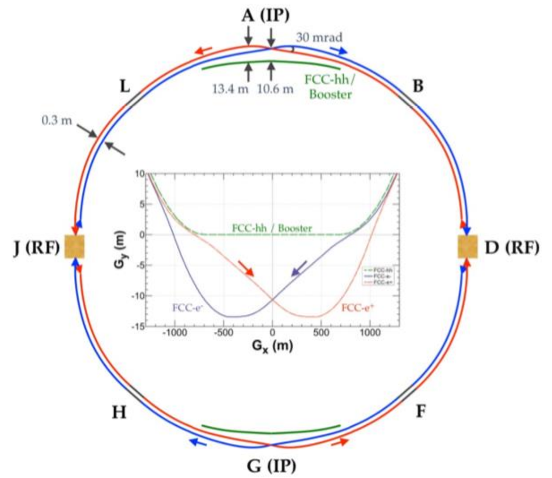
- **Determination of the minimum injection energy**.
- **New booster optics for the case of a 4 IPs layout**.

MDI

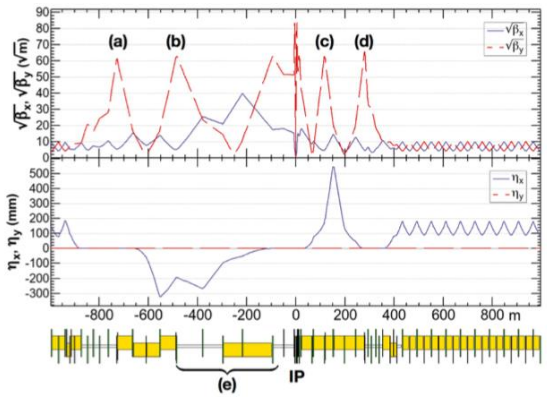
Thursday from 9h00 – FCC-ee & FCCIS WP2: IR & MDI – Wolfgang Hillert, U. Hamburg	
Overview, plan and open questions	Manuela Boscolo, INFN
Beam-beam background & beamstrahlung	Andrea Ciarma, CERN
News on the Q1 magnet prototype	Mike Koratzinos, MIT
Mechanical design of the MDI	Francesco Fransesini, INFN
IR alignment system	Leonard Watrelot, CERN

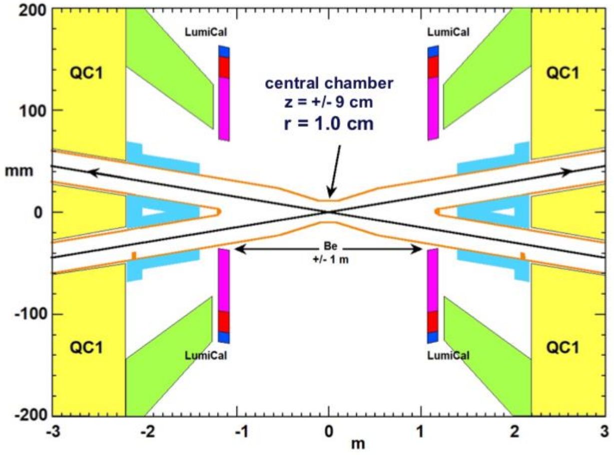
Overview

Manuela Boscolo

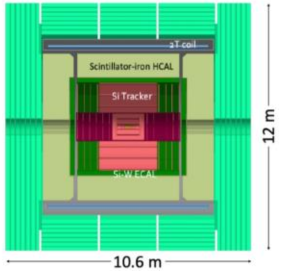


K. Oide



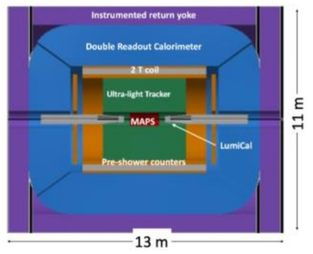


CLD



Based on CLIC detector design

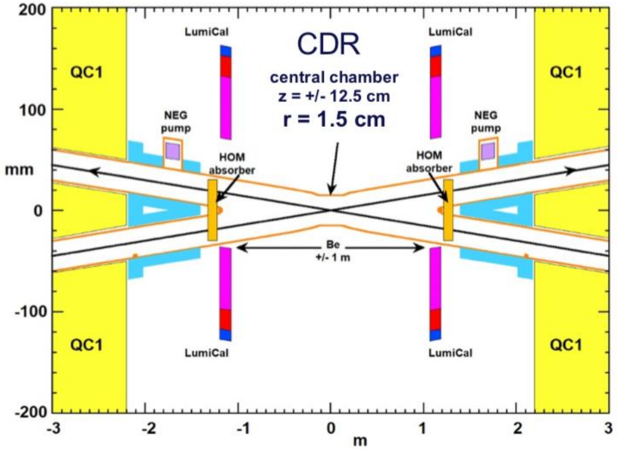
- Silicon-based vertex and tracker
- Coil outside calorimeter

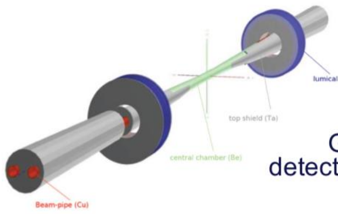


IDEA

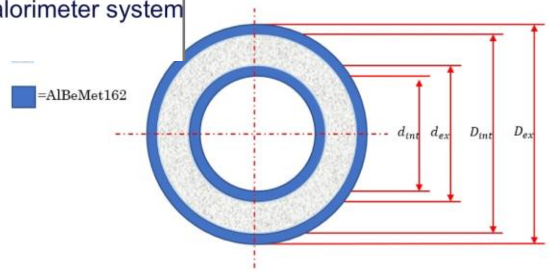
New, innovative

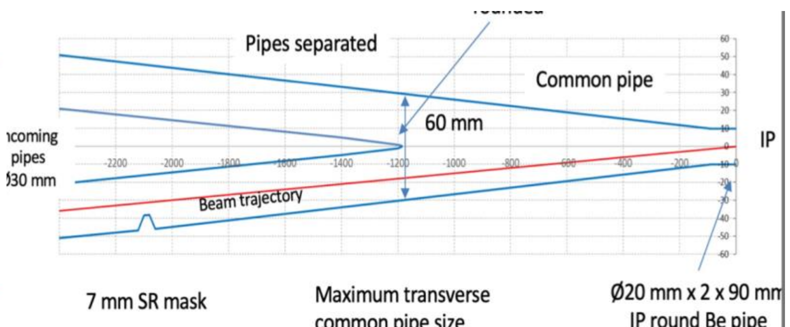
- Silicon vertex detector
- Dual-readout calorimeter
- Short-drift, ultra-light wire chamber
- Thin and light solenoid coil inside calorimeter system





Geant4 model for detector background studies

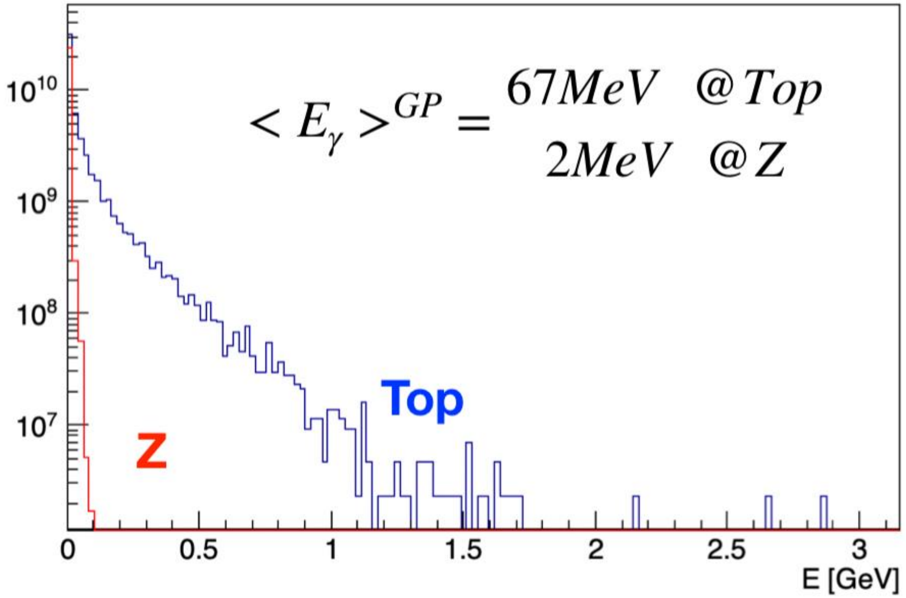




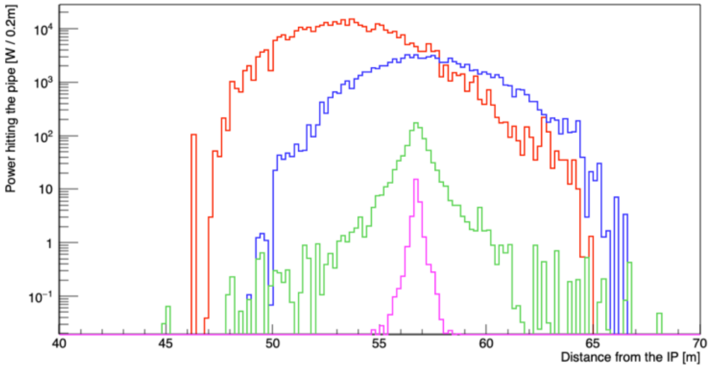
Beam-beam background

Andrea Ciarma

Beamstrahlung

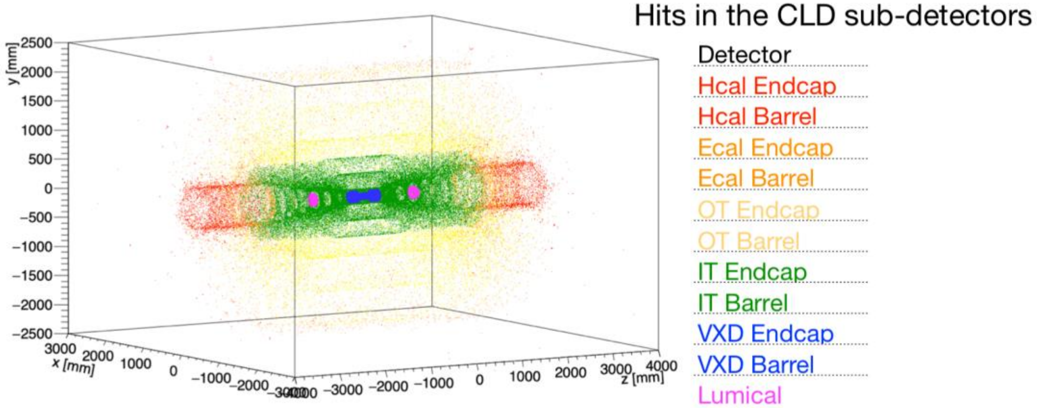


Bhabha and Beamstrahlung

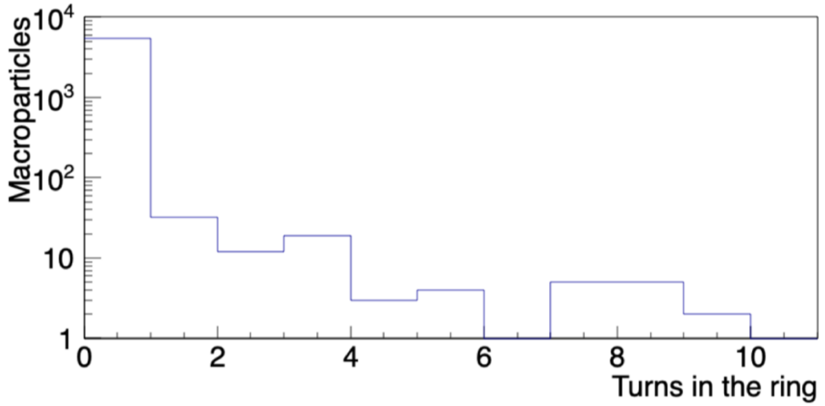


	Mean Energy	Tot Power	Deposited Power
Radiative Bhabha @182.5	26.4 GeV	27.9 W	0.14 W
Radiative Bhabha @45.6	6.6 GeV	928 W	4.73 W
Beamstrahlung @182.5	67 MeV	88.5 kW	0.39 kW
Beamstrahlung @45.6	2 MeV	386.9 kW	1.746 kW

Integration with the **key4hep** framework



Tracking of spent beam



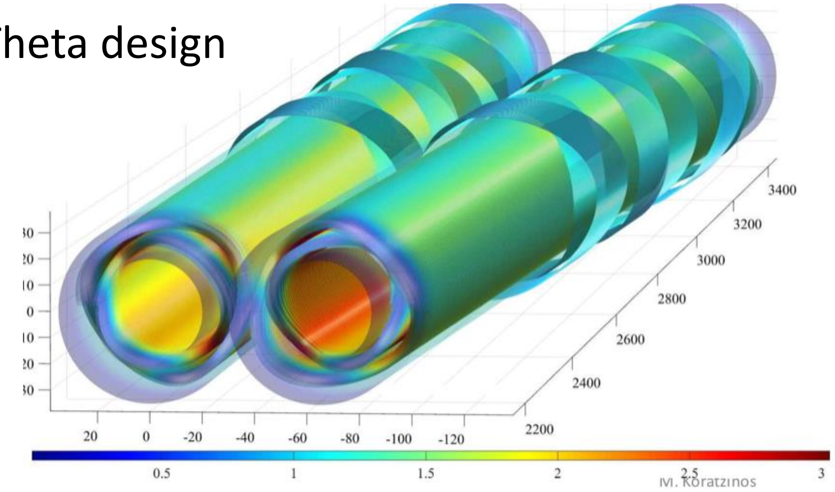
Q1 Magnet prototype

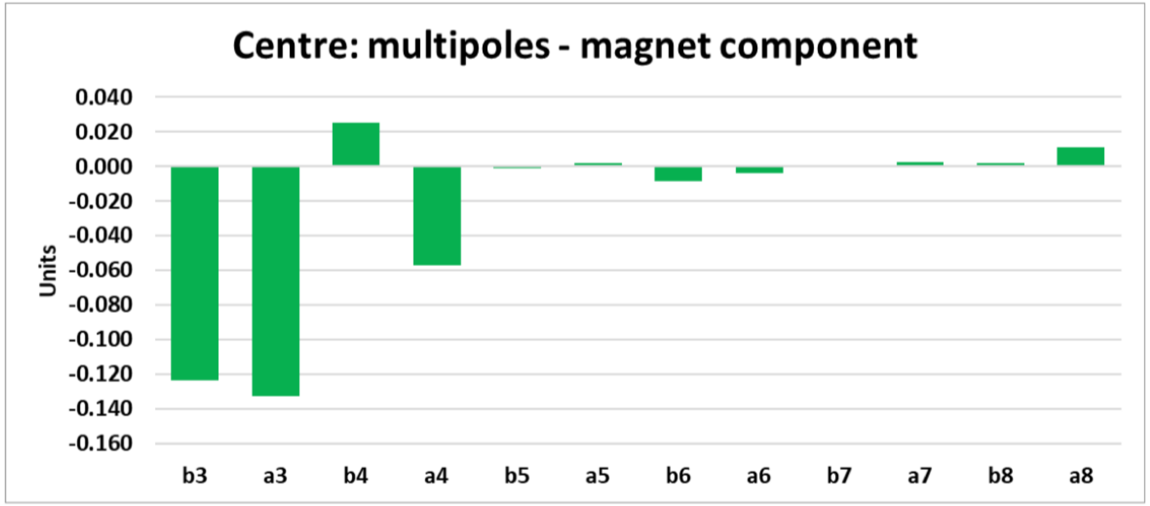
Mike Koratzinos

	Start position (m)	Length (m)	B' @Z (T/m)	B' @W (T/m)	B' @ H (T/m)	B' @ tt (T/m)
QC2L2	-8.44	1.25	25.05	43.82	61.30	69.50
QC2L1	-7.11	1.25	-0.18	0.00	7.32	56.85
QC1L3	-5.56	1.25	-19.35	-34.38	-53.08	-99.98
QC1L2	-4.23	1.25	-18.57	-32.94	-53.07	-99.98
QC1L1.1	-2.9	0.7	-40.95	-70.00	-99.71	-95.39
QC1L1.2	2.2	0.7	-40.95	-70.00	-99.71	-95.39
QC1R2	2.98	1.25	-25.44	-37.25	-51.94	-100.00
QC1R3	4.31	1.25	-19.54	-39.51	-53.65	-91.87
QC2R1	5.86	1.25	14.64	16.85	-2.65	37.19
QC2R2	7.19	1.25	19.50	44.32	67.52	94.43

M. Koratzinos

Canted Cosine Theta design



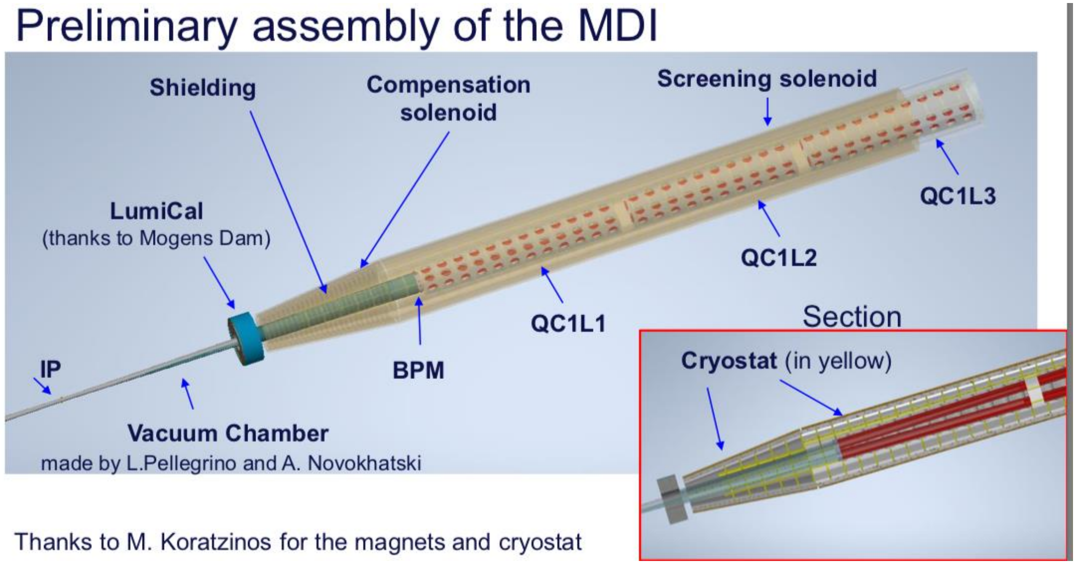


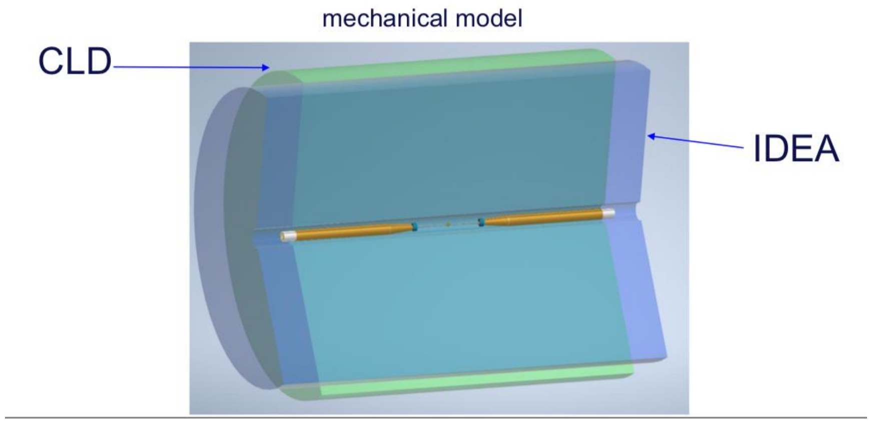
All multipoles are below 0.15 units and only b3, a3 is above 0.10 units. (this is barely above the sensitivity of the method)

Warm tests

MDI Mechanical Design

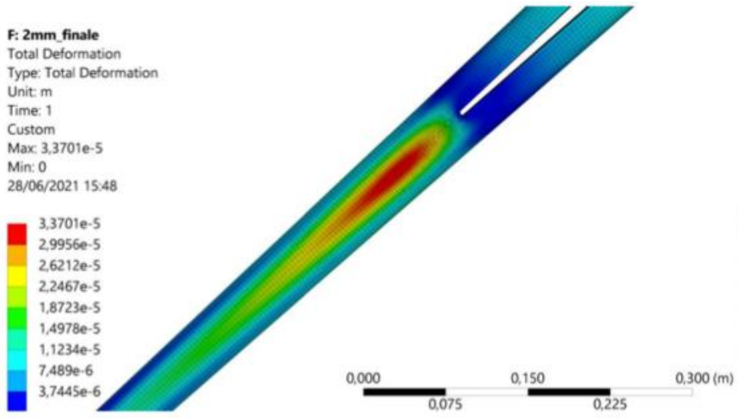
Francesco Fransesini

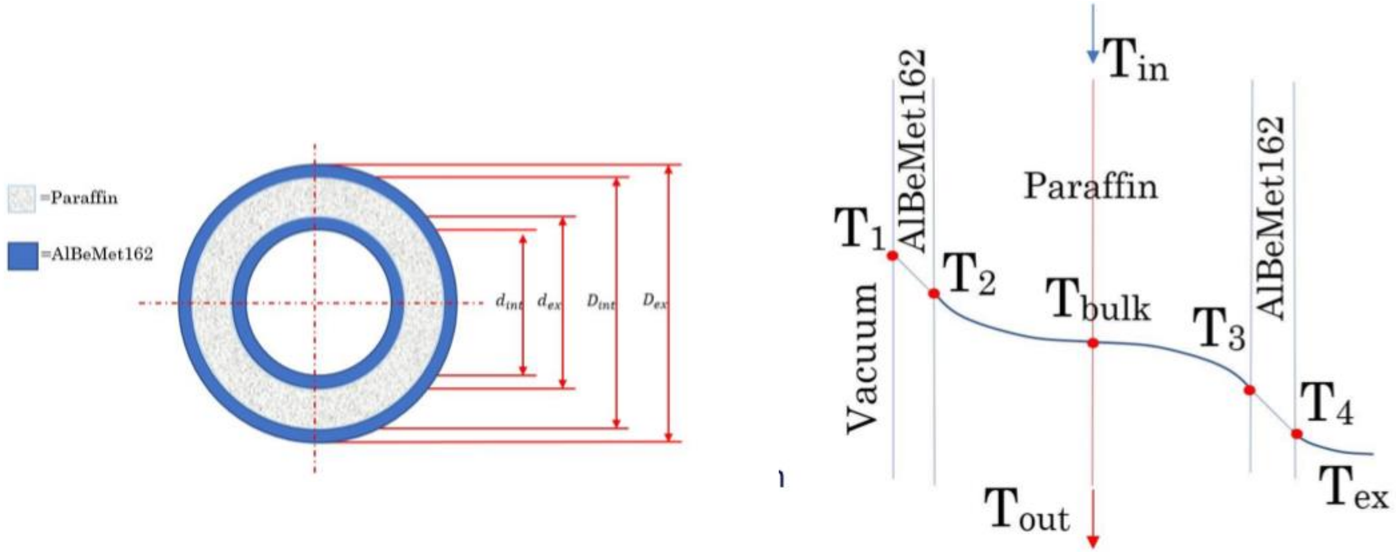




Thermal calculations/cooling

Stress calculations

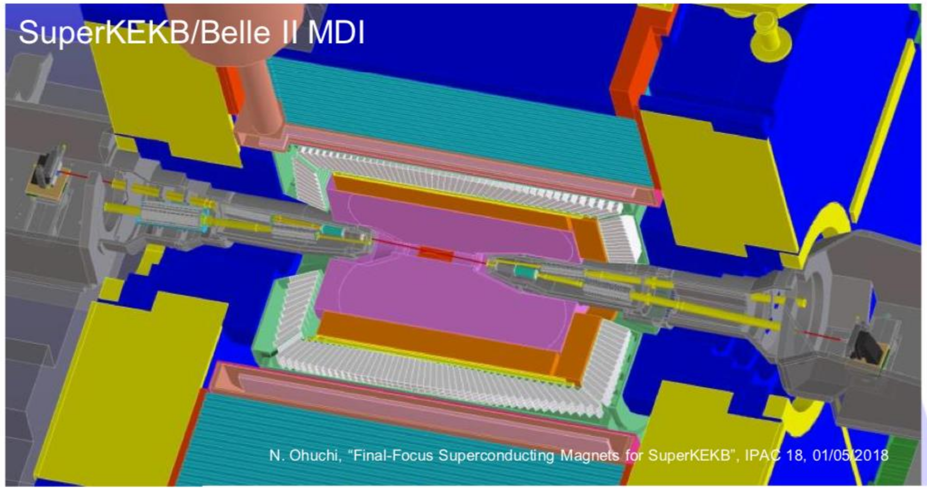


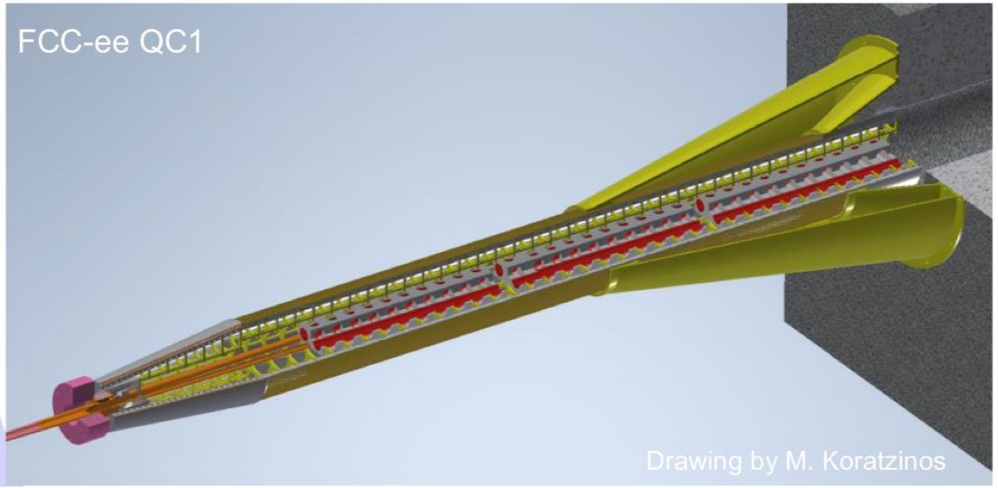


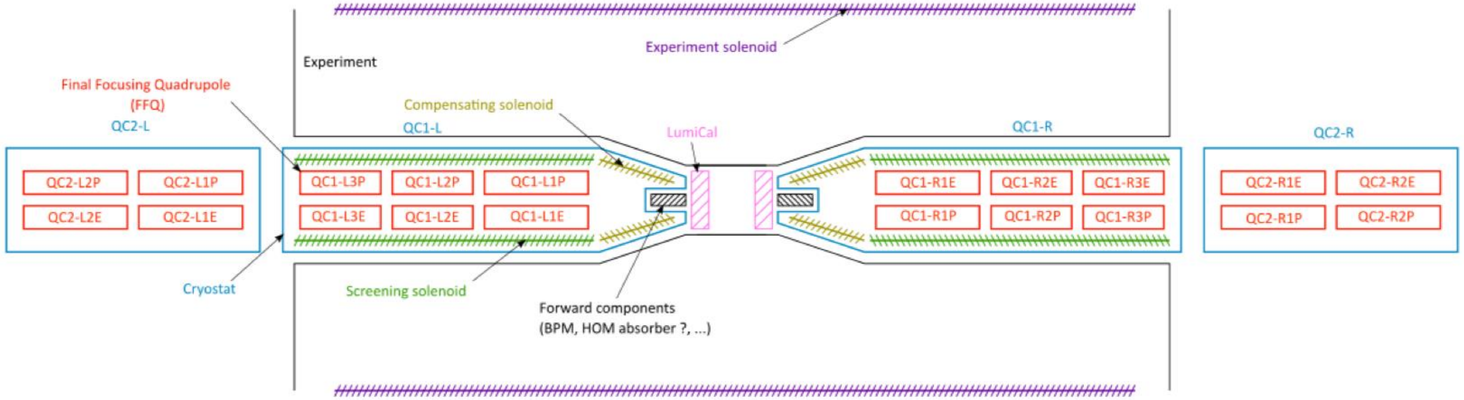
FUTURE CIRCULAR COLLIDER

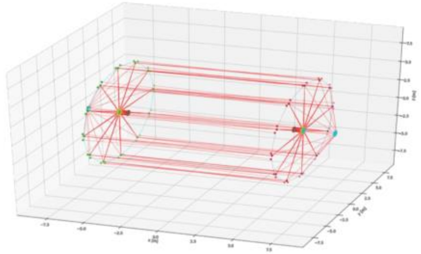
MDI Alignment

Leonard Watrelot









Alignment required for the final focusing quadrupoles, BPMs, Screening and Compensation solenoids and Lumical (for now …)

Evaluation of the existing concepts

Considering internal + external monitoring system

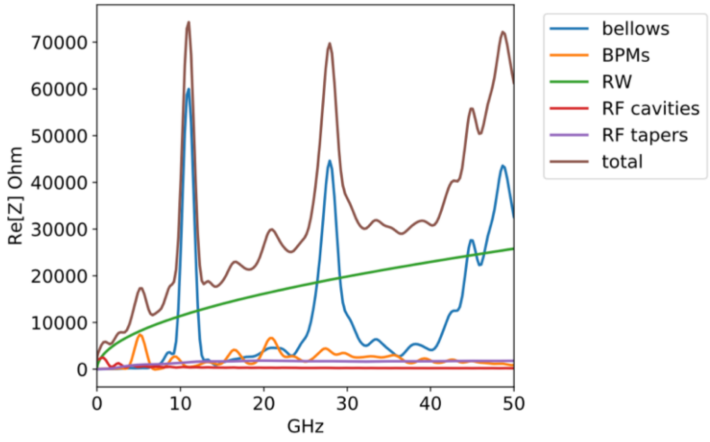
Impedance

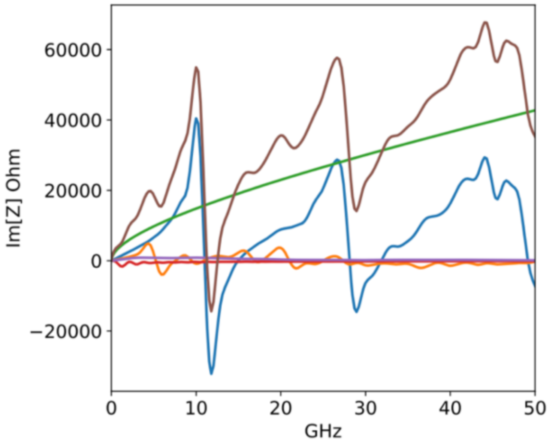
Thursday from 11h00 – FCC-ee & FCCIS WP2: impedance & collective effects – Ursula van Rienen / UROS	
Introduction and overview, incl. FEB	Mauro Migliorati , Sapienza
Impedance database and single-bunch instability thresholds	Emanuela Carideo, Sapienza & CERN
Status of bellows and flanges impedance studies	Chiara Antuono, Sapienza
Combined effect of impedance and beam-beam	Yuan Zhang, IHEP
SuperKEKB collimation	Takuya Ishibashi, KEK

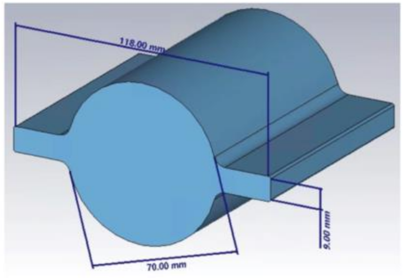
FUTURE CIRCULAR COLLIDER

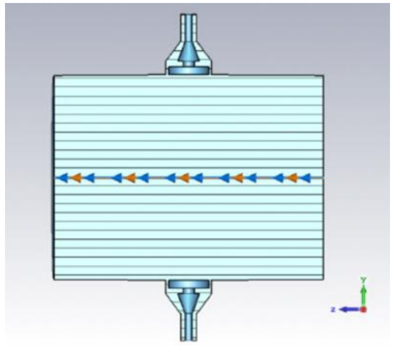
Impedance overview

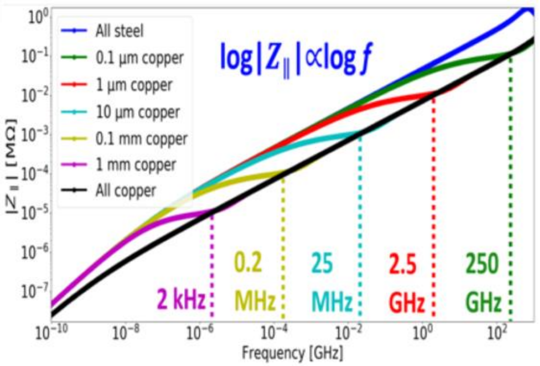
Mauro Migliorati

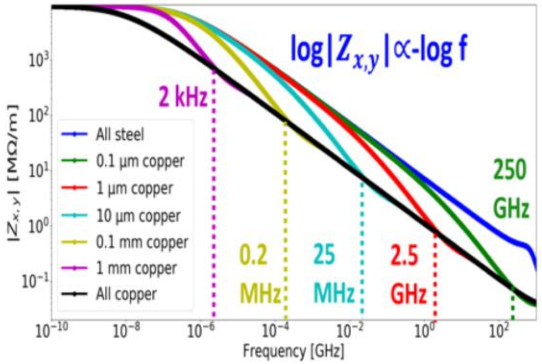


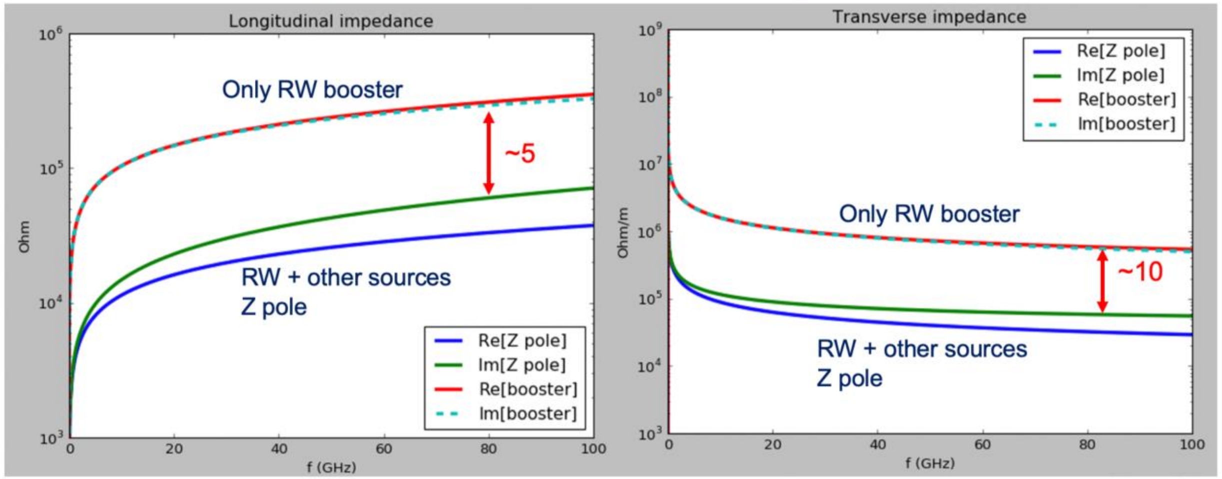


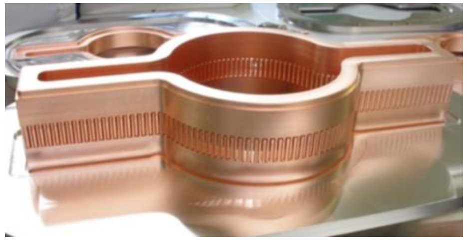


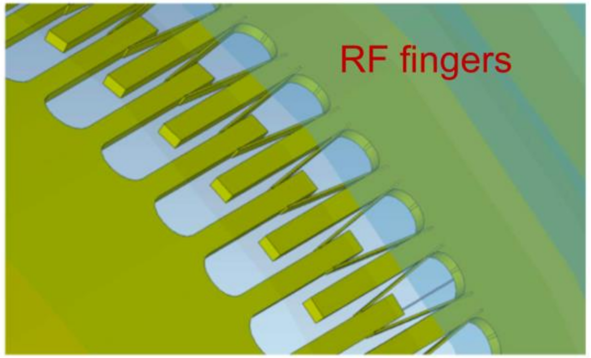








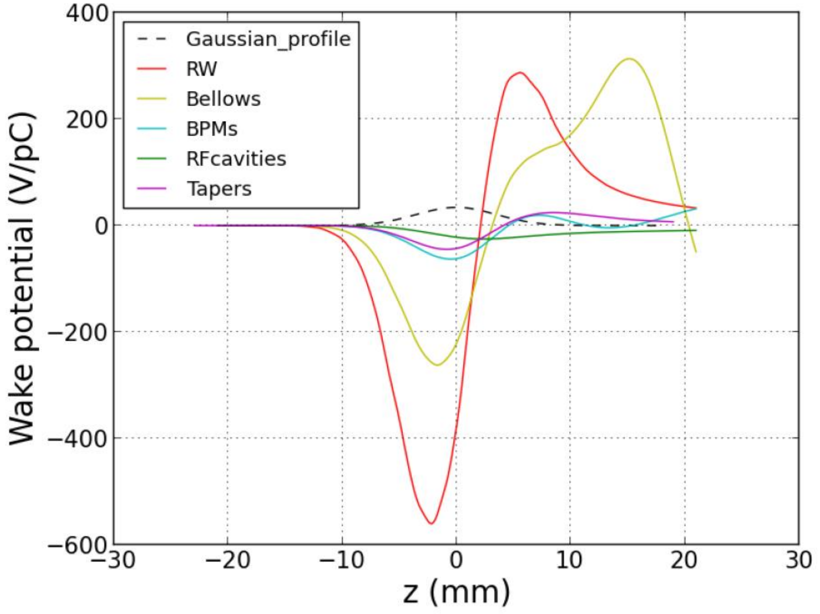




Collective effects & impedance database

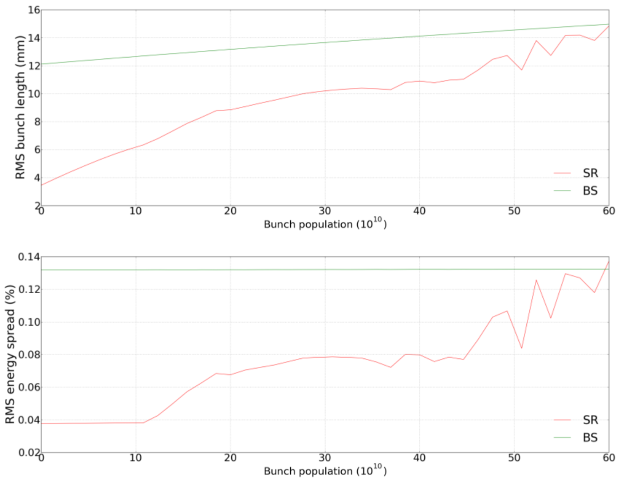
Emanuela Carideo

longitudinal wake potentials

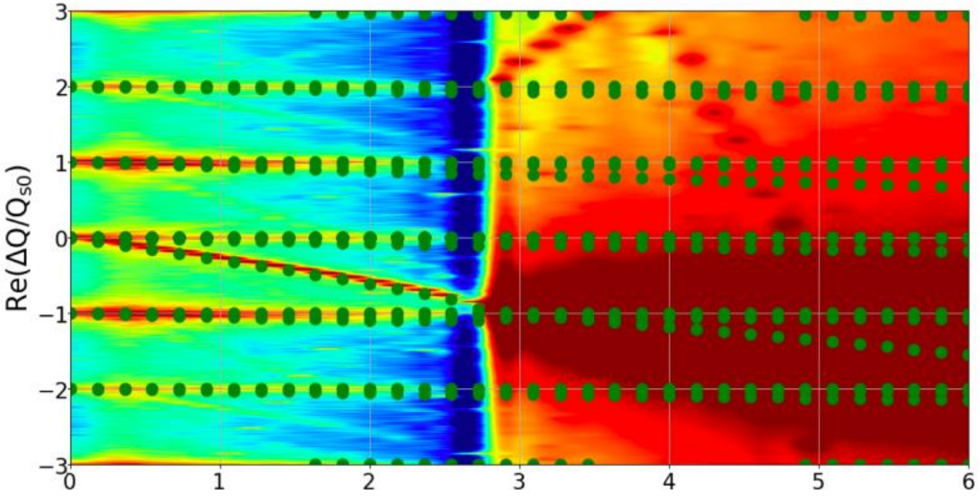


bunch lengthening & microwave inst.

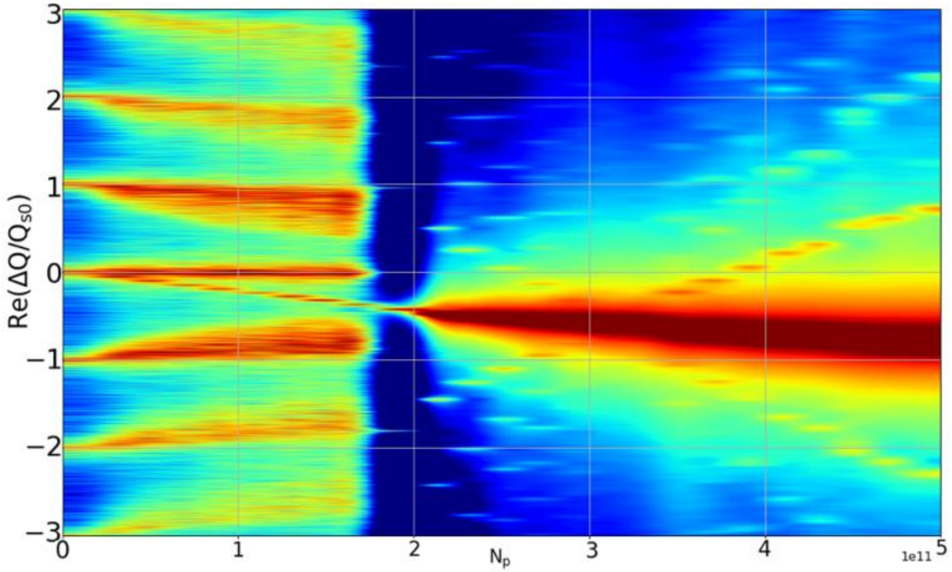
σ_z (top) & σ_δ (bottom) vs N_b with and without beam-strahlung



TMCI threshold



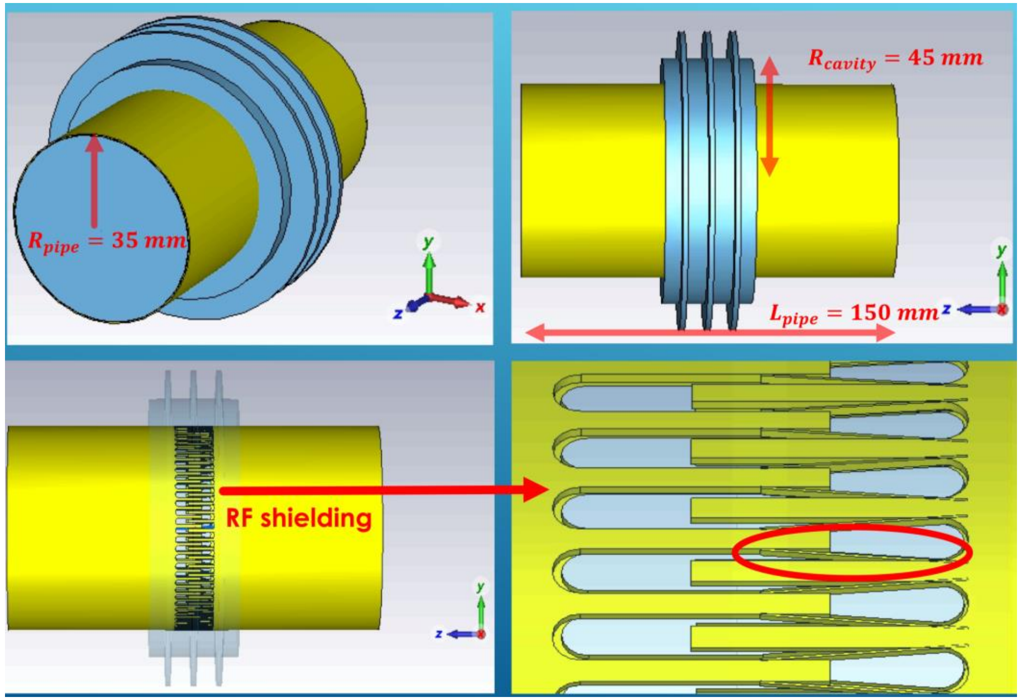
Re (Q_x) vs N_b, comparing PyHEADTAIL & DELPHI for transverse resistive wall wakefield

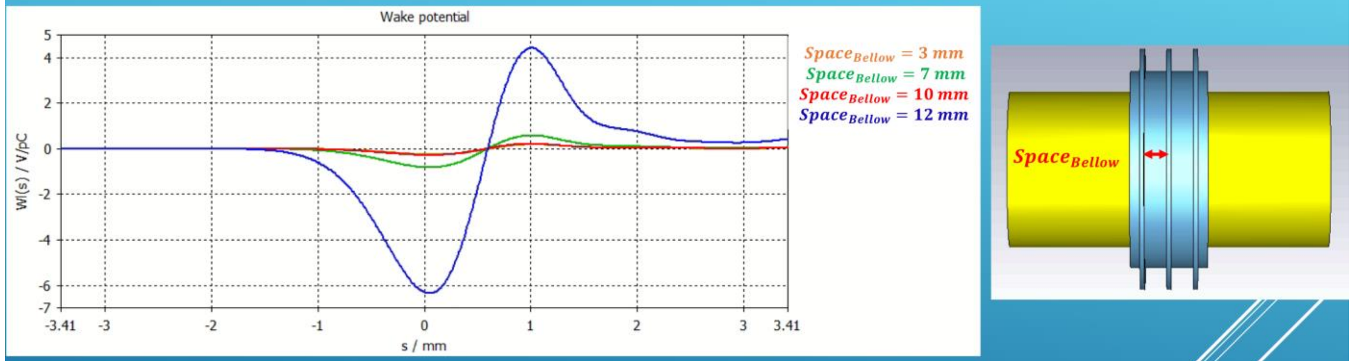


Re (Q_x) vs N_b, from PyHEADTAIL for combined effect of transverse & longitudinal resistive wall wakefield

Bellows and flanges

Chiara Antuono



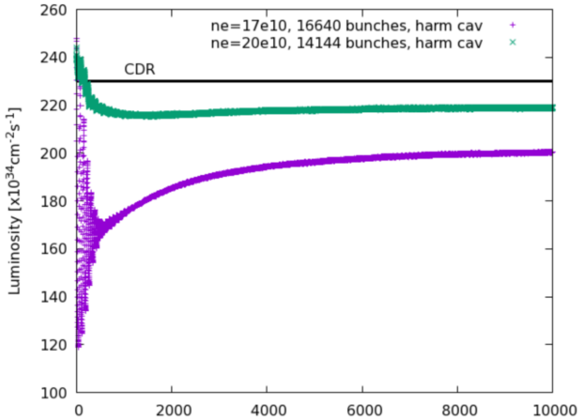


- The short range Wake Potential is affected by the space between the convolutions.

Combined effect of impedance and beam-beam

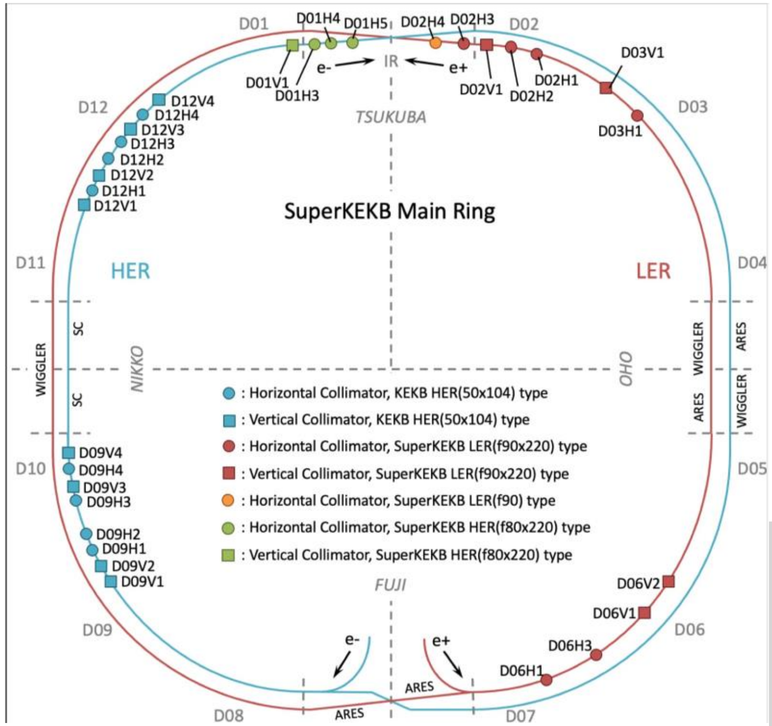
Yuan Zhang

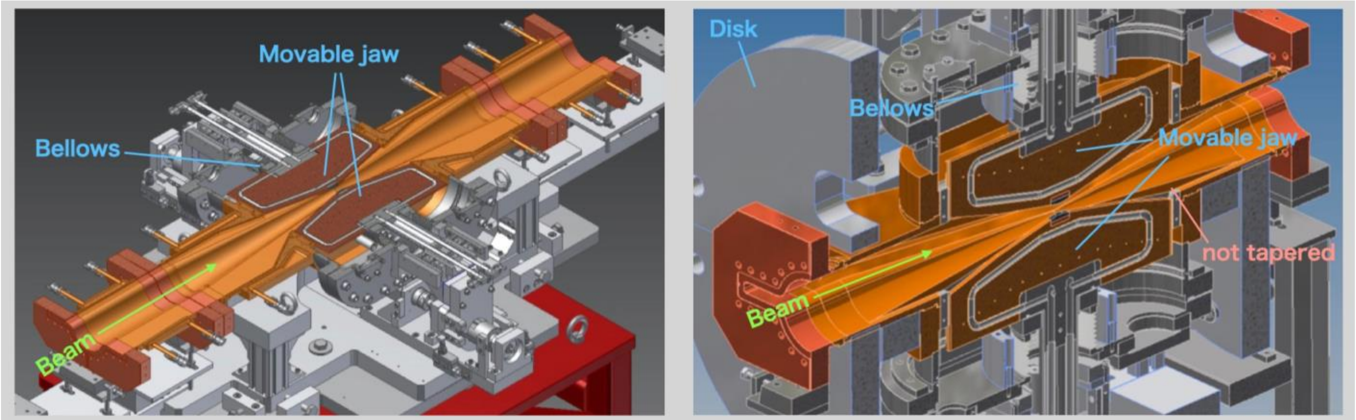
- The beam coupling impedance can have a substantial impact on the choice of beam parameters and the final collider performance.
- The principal effects are summarized:
  - Tune shift of stable tune areas
  - Smaller safe tune area
  - Smaller beam blowup
- Possible Mitigation Options:
  - Smaller β_x^*
  - Higher Harmonic Cavity (energy calibration?)
  - Higher Momentum compaction
- The effect for 4IP scheme is evaluated roughly
- it is expected that longitudinal impedance will certainly increase. The combined effect of impedance and beam-beam needs particular care since it may cause unwanted instabilities.



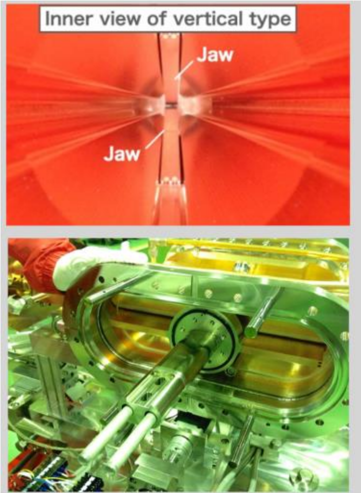
SuperKEKB Collimation

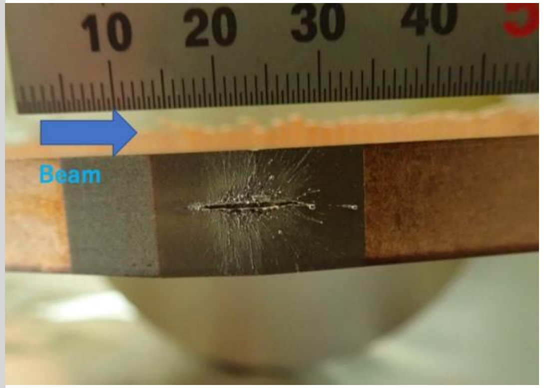
Takuya Ishibashi





Horizontal direction　　Vertical direction





Summary

- The SuperKEKB type collimators have been working well up to the beam current of approximately 1 A.
- These collimators have been indispensable for Belle II and SuperKEKB.
- We developed and installed carbon jaws to protect collimators for the BG suppression.

Plans

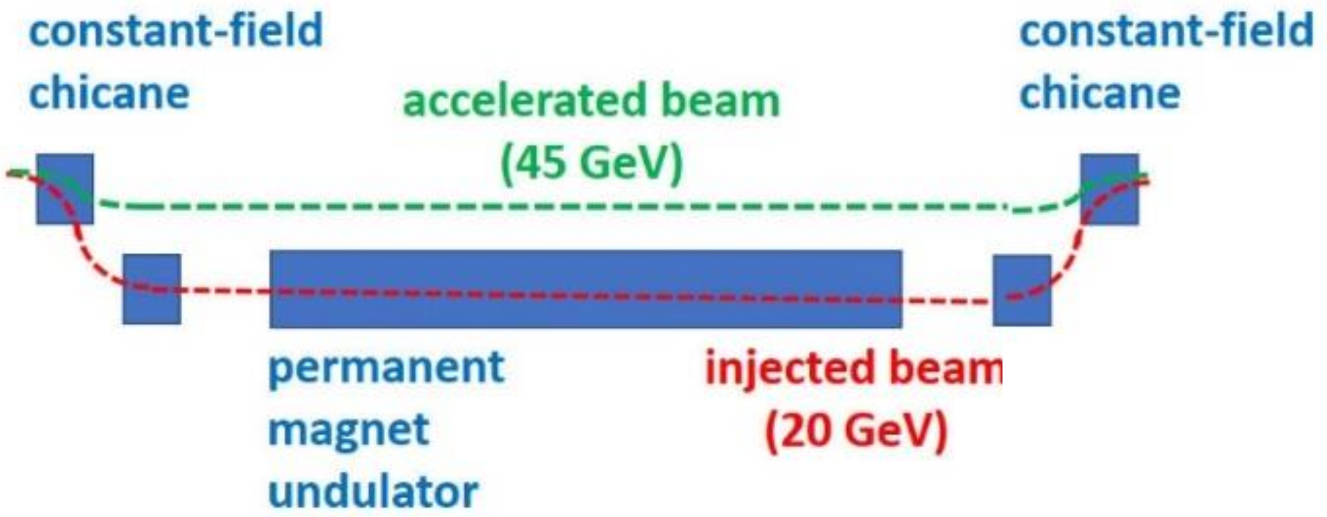
- Phase matching between D02V1 collimator and QC1RP in LER as much as possible by moving the collimator.
  - A simulation indicates that this configuration can reduce the detector background about 40%.
- Non-linear collimator (NLC) in LER by adding new skew sexts at OHO.

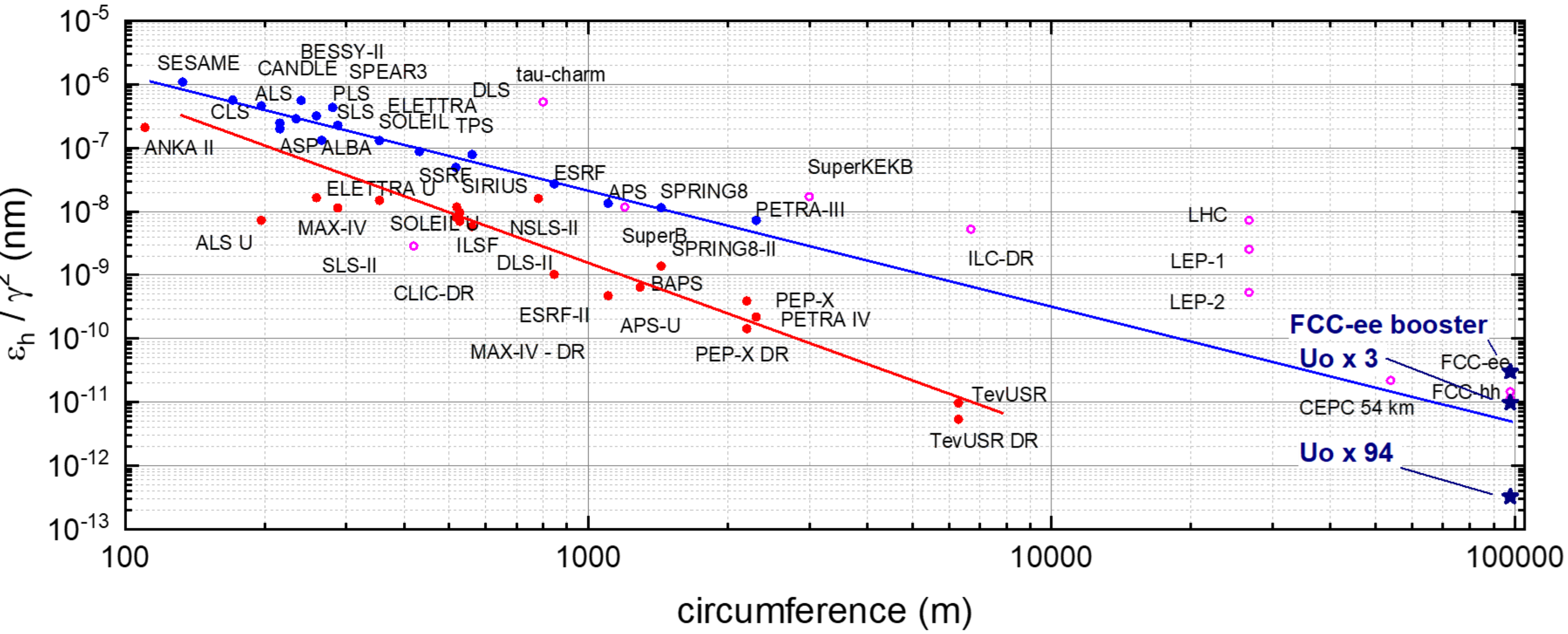
Other applications

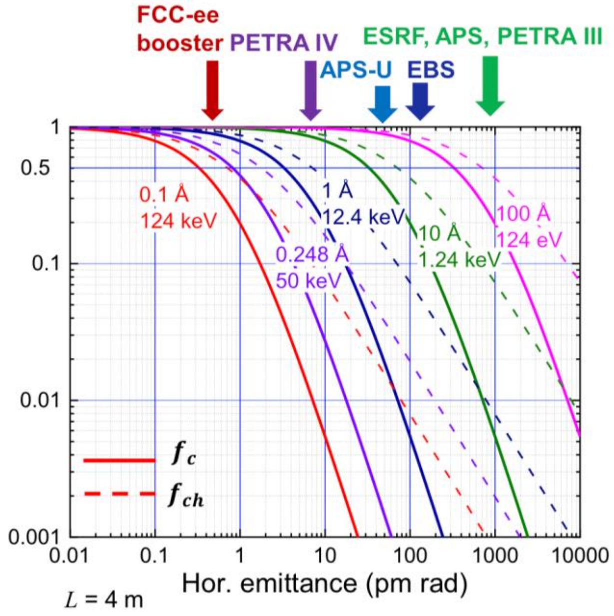
Thursday from 14h00 – FCC-ee: Other applications & upgrades - M. Seidel/PSI	
FCC-ee booster as ultimate storage ring photon source	Sara Casalbuoni, XFEL
Science case for high-energy photons	Anders Madsen, XFEL
FCC-ee e^+ options	Benjamin Rienacker, Ruggero Caravita, CERN
ERL-based e+e- collider	Vladimir Litvinenko, BNL
FCC-ee upgrade to muon collider	Daniel Schulte, CERN

FCC-ee booster as photon source

Sara Casalbuoni





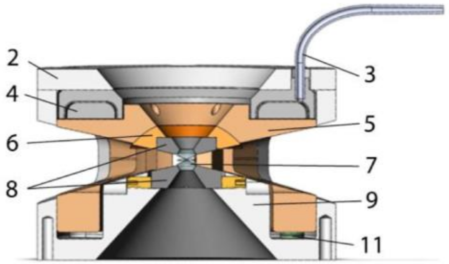


Science case for high energy photons

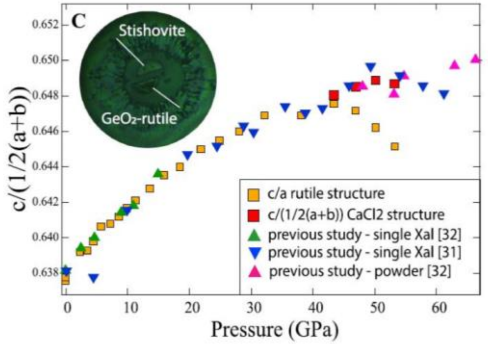
Anders Madsen

A number of imaging techniques could be interesting in the 30-100 keV range
At these energies radiation not diffraction-limited at conventional DLSR

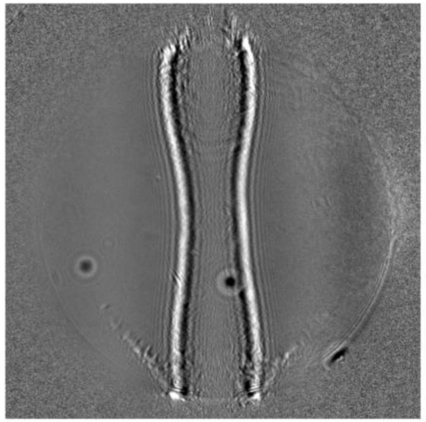
High pressure by Diamond Anvil Cell (DAC)



30 keV X-ray data (ESRF)



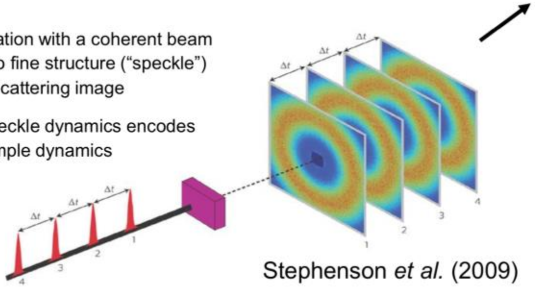
State-of-the-art X-ray holography (cone beam) requires smallest focus (diffraction limited beam)



Hagemann *et al.* (2021)

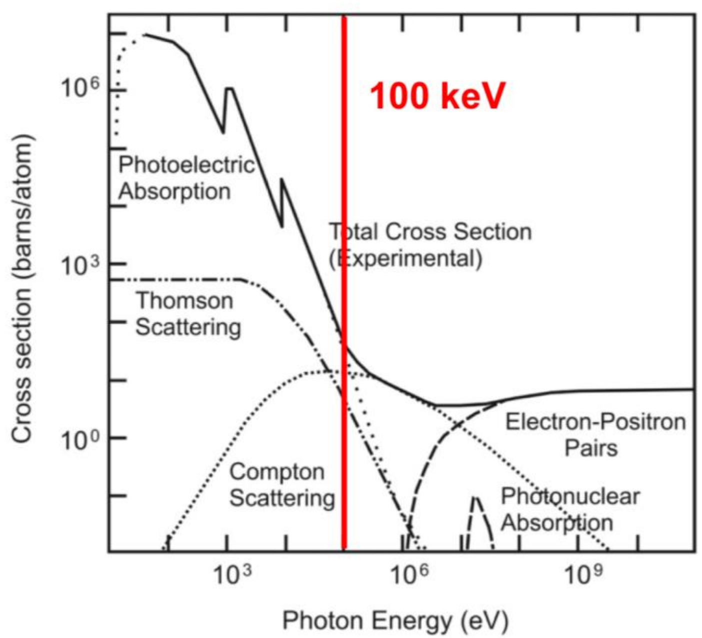
X-ray Photon Correlation Spectroscopy (XPCS)

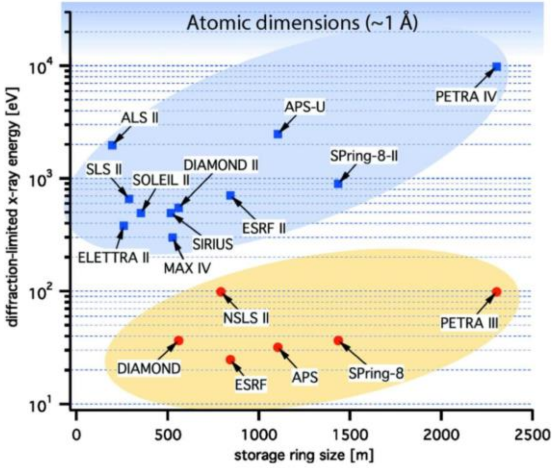
- Illumination with a coherent beam leads to fine structure ("speckle") in the scattering image
- The speckle dynamics encodes the sample dynamics



Stephenson *et al.* (2009)

Photon-matter interactions (for Cu)

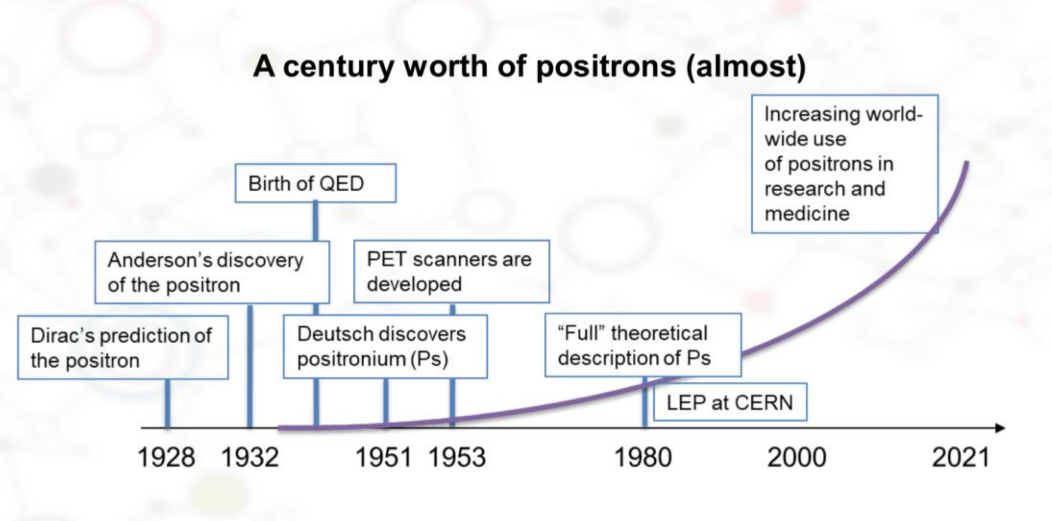




Schroer *et al.* (2018)

Positron source science case

Ruggero Caravita, Benjamin Rienäcker

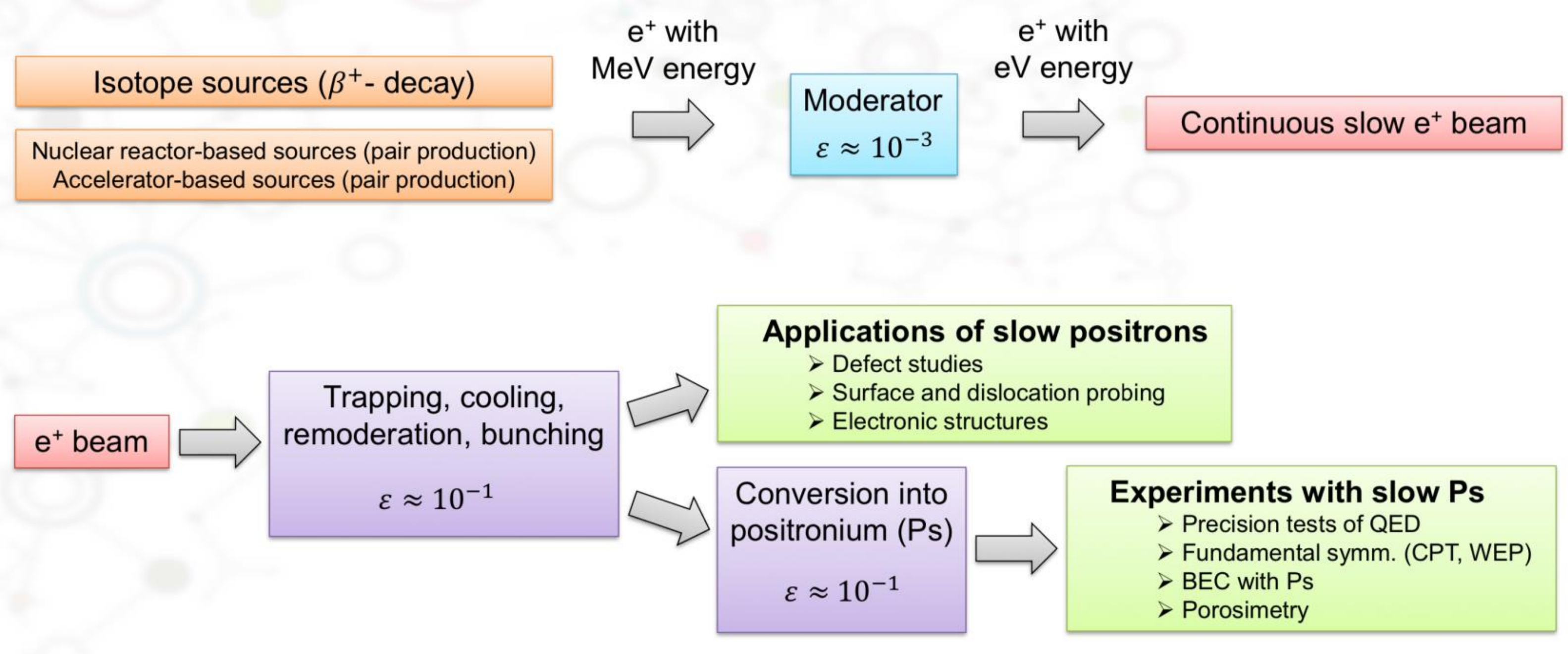


Low energy positron/positronium physics at one glance

Precision QED studies (annihilation lifetime, Ps spectroscopy)

Fundamental symmetry tests (CPT, WEP, invisible decays)

Material studies (defect studies)

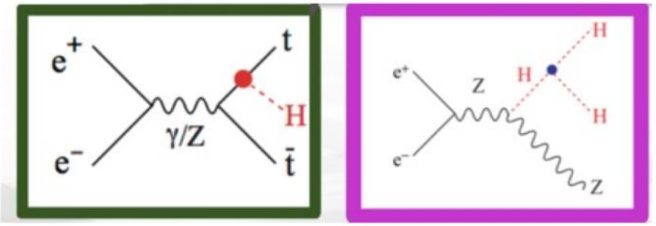


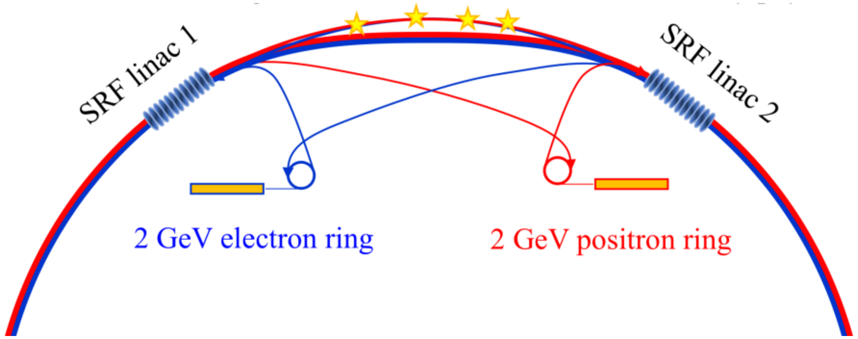
Energy recovery collider

Vladimir Litvinenko

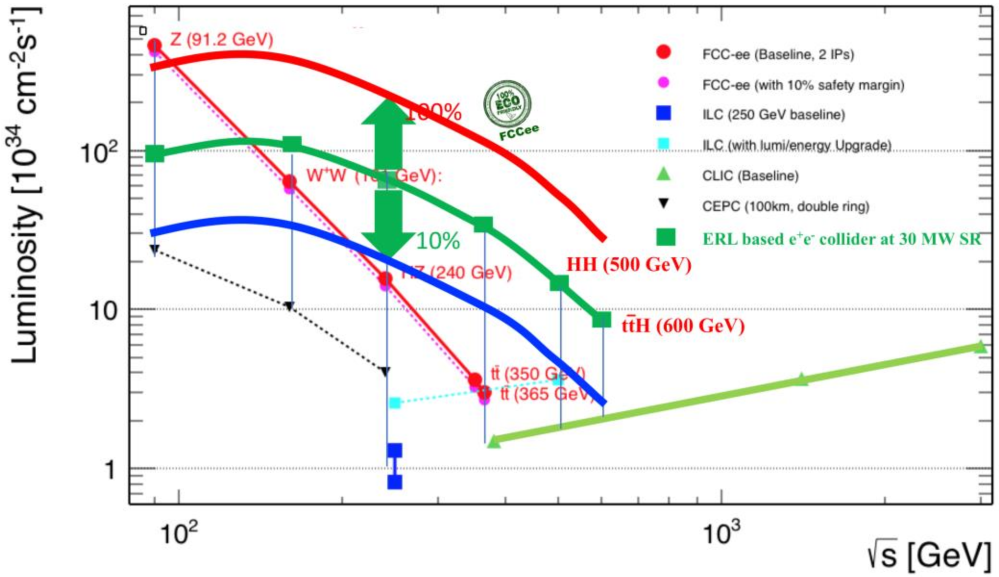
Key development: focus on reaching c.m. energy range of 500 - 600 GeV

Physics: Investigating details of:





- The ERL-based high-energy e^+e^- collider promises significantly higher luminosities at CM energies above 140 GeV while consuming a fraction ~ 30% of electric power required in a corresponding SR e^+e^- collider design
- The CM energy reach is extended to 500-600 GeV for double-Higgs and *ttH* production

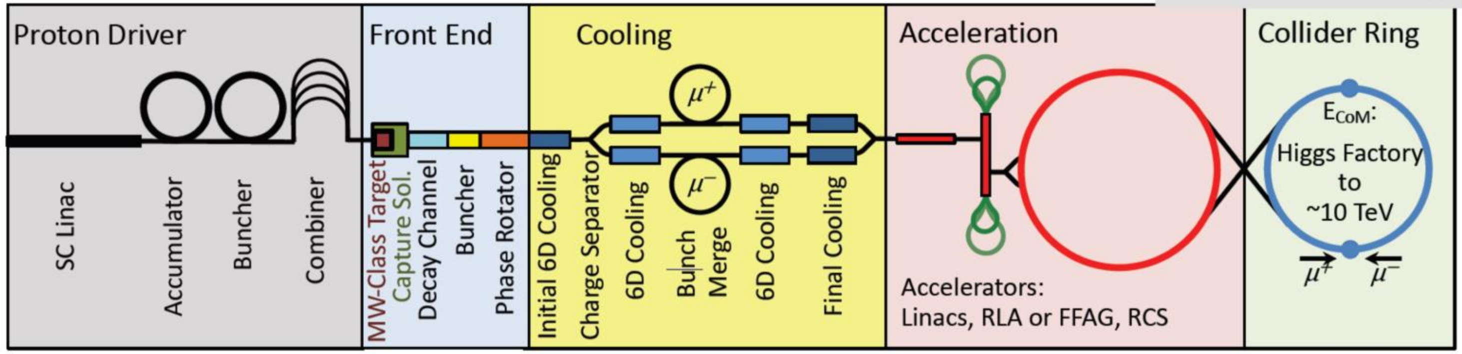


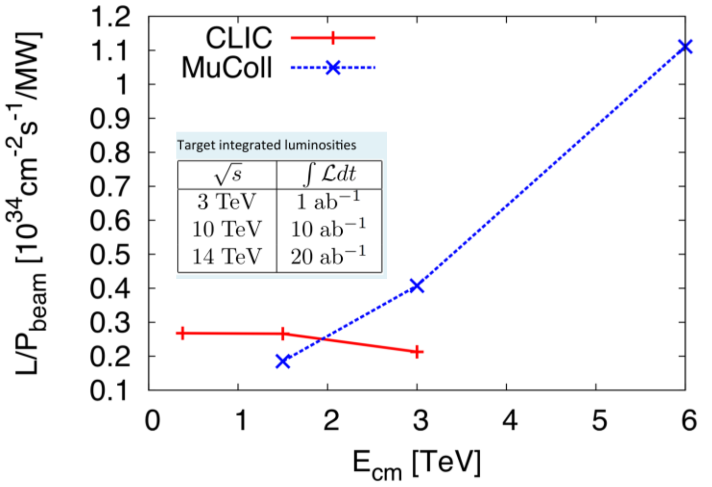
Muon collider

Daniel Schulte

The muon collider has been developed by the MAP collaboration mainly in the US
Muon cooling demonstration by MICE in the UK, some effort on alternative mainly at INFN

MAP collaboration





Objective:

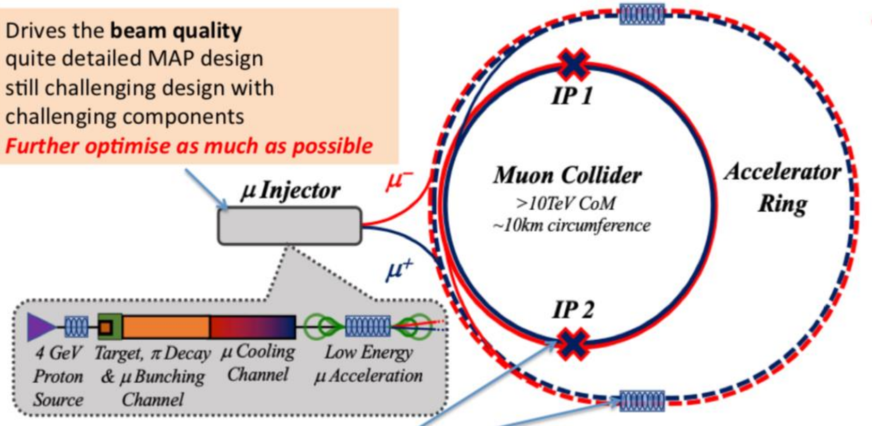
In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.

Scope:

- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 15-20 years
  - **10+ TeV**, with more advanced technology, **the reason to do muon colliders**
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
Further optimise as much as possible



Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**
Drives **neutrino radiation** and **beam induced background**
Improve compared to MAP design and design for high-energy

Could use FCC tunnel for accelerator would allow to go up to O(30 TeV) with normal magnets

The End

Congratulations to everyone for fantastic progress!