FCCIS 2022 Workshop WP2, 5 – 9 Dec 2022

- *summaries and highlights*

40 talks in total

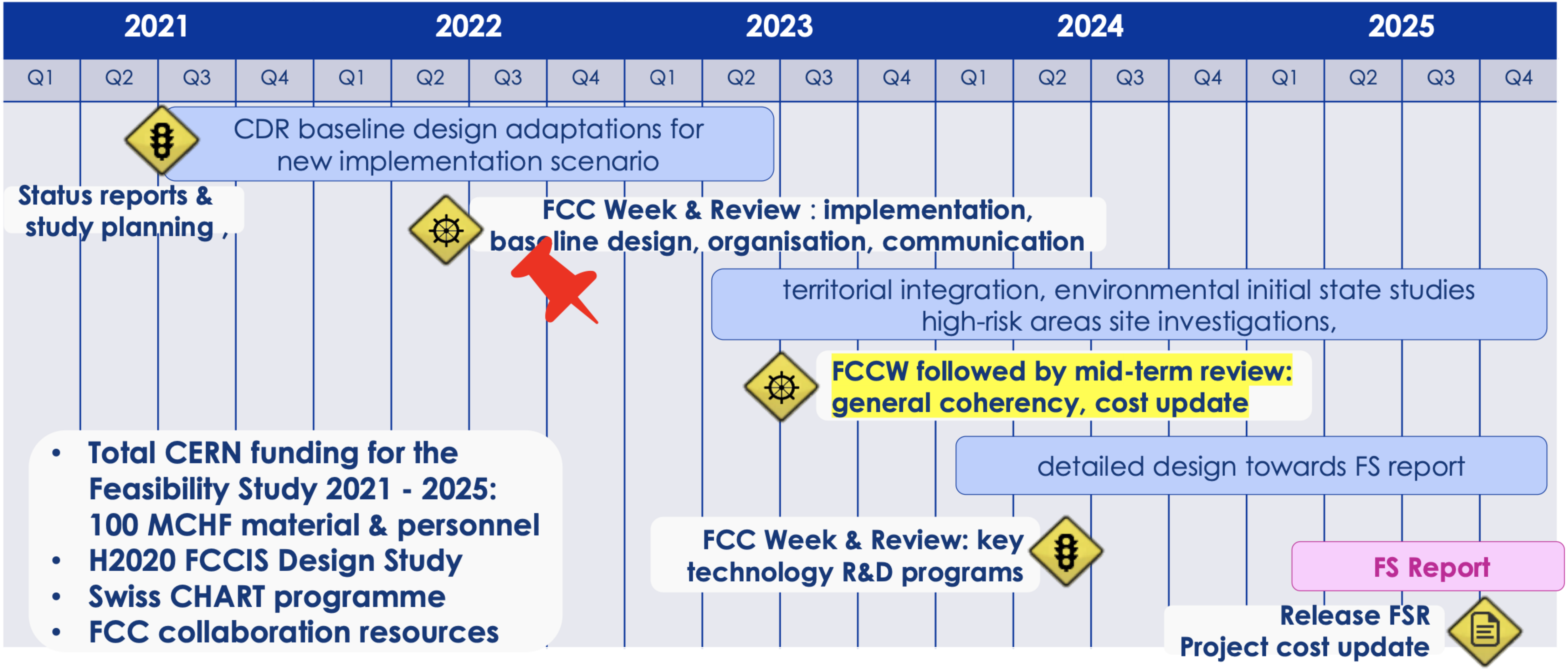
Ilya Agapov, DESY
Frank Zimmermann, CERN

9 December 2022

FUTURE CIRCULAR COLLIDER
Innovation Study

FUTURE CIRCULAR COLLIDER

Michael Benedikt



Patrick Janot

The uniqueness of FCC-ee

With respect to linear collider's 1st stage

Optimal energy range for SM particles

Sharpen and challenge our knowledge of already existing physics

LEP1 statistics in a few minutes

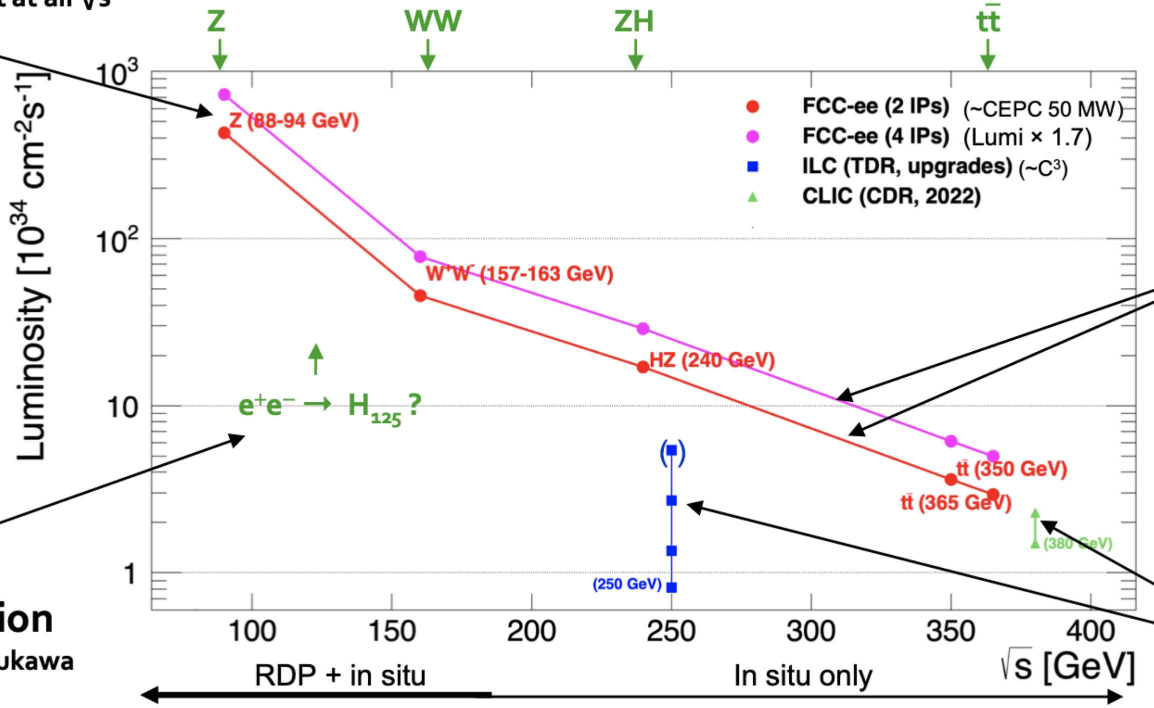
Detector calibration/alignment at all √s

Highest luminosities

Less running time for a given physics outcome
Better physics outcome for a given running time
Increase discovery potential

Serve up to 4 interaction points

Net overall gain in MW/ab⁻¹ or CO2-eq/ab⁻¹
Essential redundancy for precision measurements
May satisfy all detector requirements
Increase discovery potential
Enhance the community (FCC/CERN clients)



√s Monochromatisation

Unique opportunity for electron Yukawa

Motivates the competition

Luminosity is the name of the game

Precise and continuous √s, √s spread, boost determination

Both with resonant depolarisation (RDP) and with collision events in up to four detectors
Essential for precision measurements

Patrick Janot

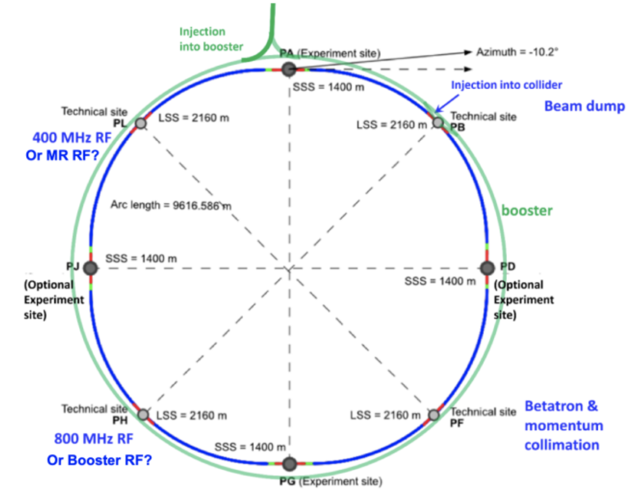
See M. Benedikt's presentation

- The FCC-ee is becoming a very concrete collider project
  - With the steady progress of the technical feasibility study
    - And the in-depth contacts with the representatives of the local population
- The FCC-ee arguably offers the best science value for the (long-term) investment
  - With the smallest energy consumption and carbon footprint per physics outcome
  - With the most ambitious scientific prospects for the many decades to come
  - Will be driving computational change forward (quantum computing, AI, ~ the Web for LEP)
- It is time to start unifying the particle physicist community around the project
  - The artificially maintained competition in Europe between Higgs factories is confusing
    - … and may even be dangerous for Europe and CERN (with, e.g., CEPC in China)
  - The funding agencies will support at most one project
    - Meanwhile, the resources are far too scarce for physics and experiments studies in all of them
  - The young generation is expecting a clear signal before actually committing
- CERN Council can tremendously help in this perspective

Tor Raubenheimer

Accelerator Design Status

- New ~90 km circumference placement with 8 access points
- Layout with 4 IP’s that is consistent with upgrade to FCC-hh
- Optimizing allocation of straight sections
- New FCC-ee optics to optimize beam-beam
- 400 MHz and 800 MHz RF systems
- Starting tunnel integration studies for RF and Arc sections
- Full energy booster that will fit in FCC tunnel for top-up injection
- e+ / e- injector to fill booster 24 / 7



Tor Raubenheimer

FCC accelerator summary and timeline

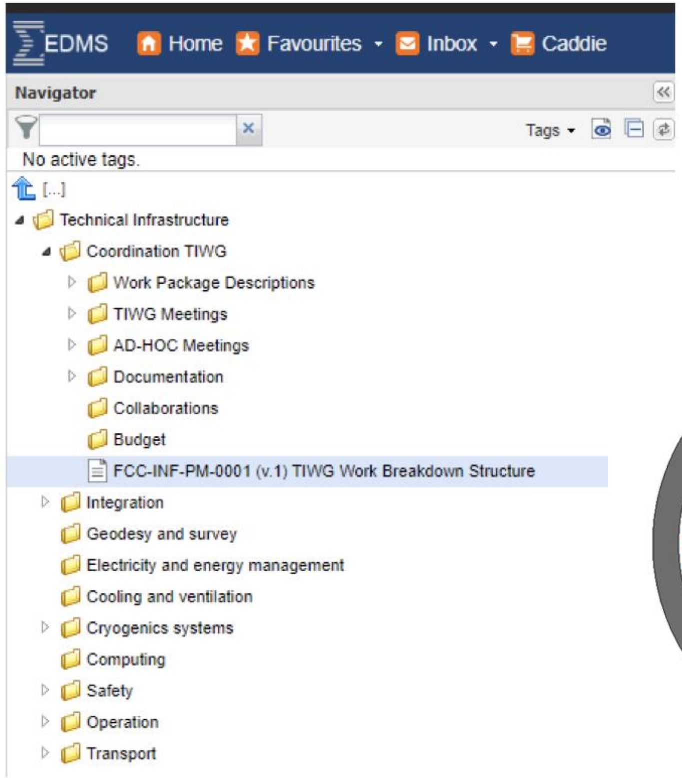
- **Finalizing layouts with correct circumference**
- **FCC-ee baseline parameters are established**
  - Main ring substems, full-energy booster, and injector all being defined
- **Technical systems making good progress**
  - Vacuum, magnets, SRF, cryogenics, diagnostics, integration, …
  - Already most efficient Higgs solution but working to improve overall η
  - Extensive world-wide R&D program
- **Luminosity requires all systems work together in large facility**
  - Still many challenges in developing robust integrated design
- **Will have baseline established in 2023 and optimize further to complete feasibility study at end of 2025**

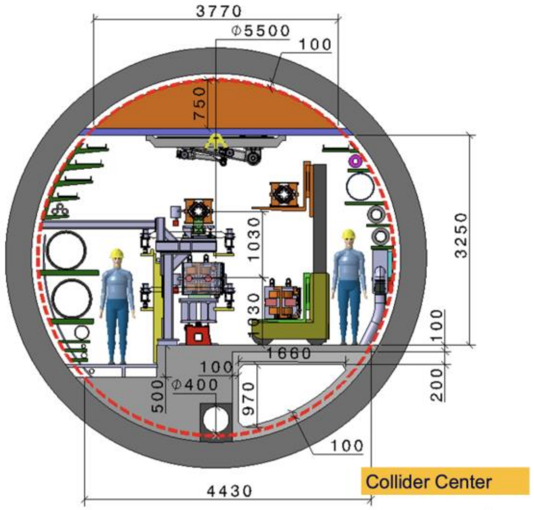
Coordination

Work Breakdown Structure WBS

Technical Infrastructure WG	responsible (in bold), WG members
1 coordination	**K Hanke (ATS-DO)** ex officio M Benedikt (ATS-DO), F Zimmermann (BE-ABP), J Gutleber (ATS-DO)
2 integration	**JP Corso (EN-ACE)** F Valchkova-Georgieva (EN-ACE) JP Tock (EN-ACE)
3 geodesy and survey	**H Mainaud Durand (BE-GM)** L Watrelot (BE-GM) Prof. Dr. A Wieser / ETH
4 electricity and energy management	**JP Burnet (SY)** N Bellegarde (EN-EL) M Parodi (EN-EL) D Aguglia (SY-EPC) F R Blanquez Delgado (SY-EPC), K Kahle (SY-EPC), M Colmenero Moratalla (SY-EPC)
5 cooling and ventilation	**G Peon (EN-CV)** M Nonis (EN-PAS), I Ruehl (EN-CV)
6 cryogenic systems	**L P Delprat (TE-CRG)** L Tavian (ATS-DO) K Brodzinski (TE-CRG), R van Weelderen (TE-CRG), P Tavares (TE-CRG)
7 computing and controls infrastructure, communication and networks	**P Saiz (IT-CM)** C Roderick (BE-CSS)
8 safety	**T Otto (ATS-DO)** S La Mendola (HSE-OHS), A Henriques (HSE-OHS) O Rios (HSE-OHS) G Roy (BE-ABP) M Widorski (HSE-RP) t.b.d. (HSE-ENV)
9 operation and maintenance, availability and reliability	**J Nielsen (BE-OP)**
10 transport & handling, installation concepts, logistics	**R Rinaldesi (EN-HE)** C Prasse / FIML

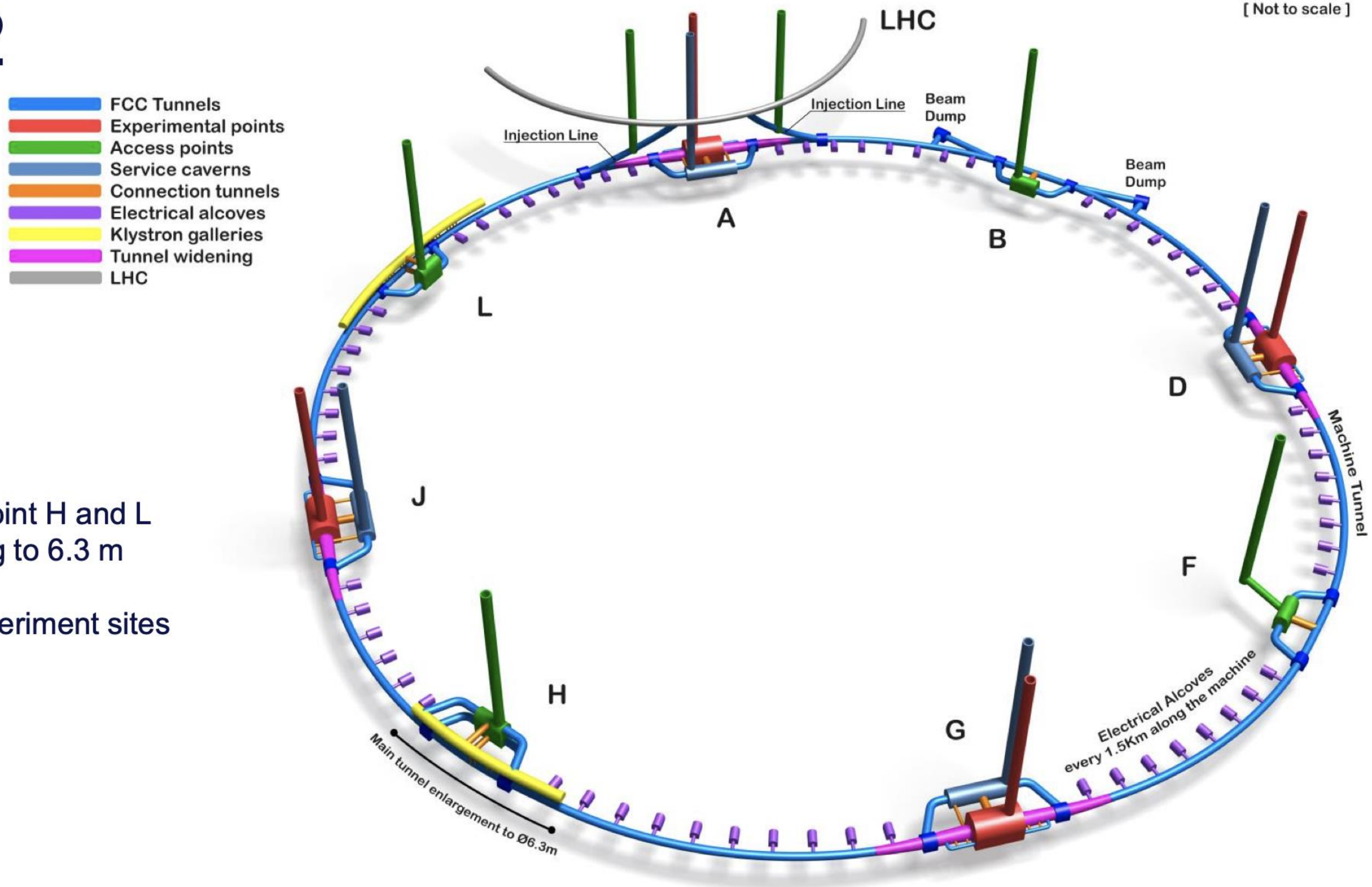
- WBS with responsible WP Holders
- Work Package Descriptions
- Bi-weekly Working Group Meetings
- Ad-hoc meetings to address specific topics
- Minutes & Documentation on EDMS
- Interfacing with Study Mgmt. and other Pillars





Liam Bromiley

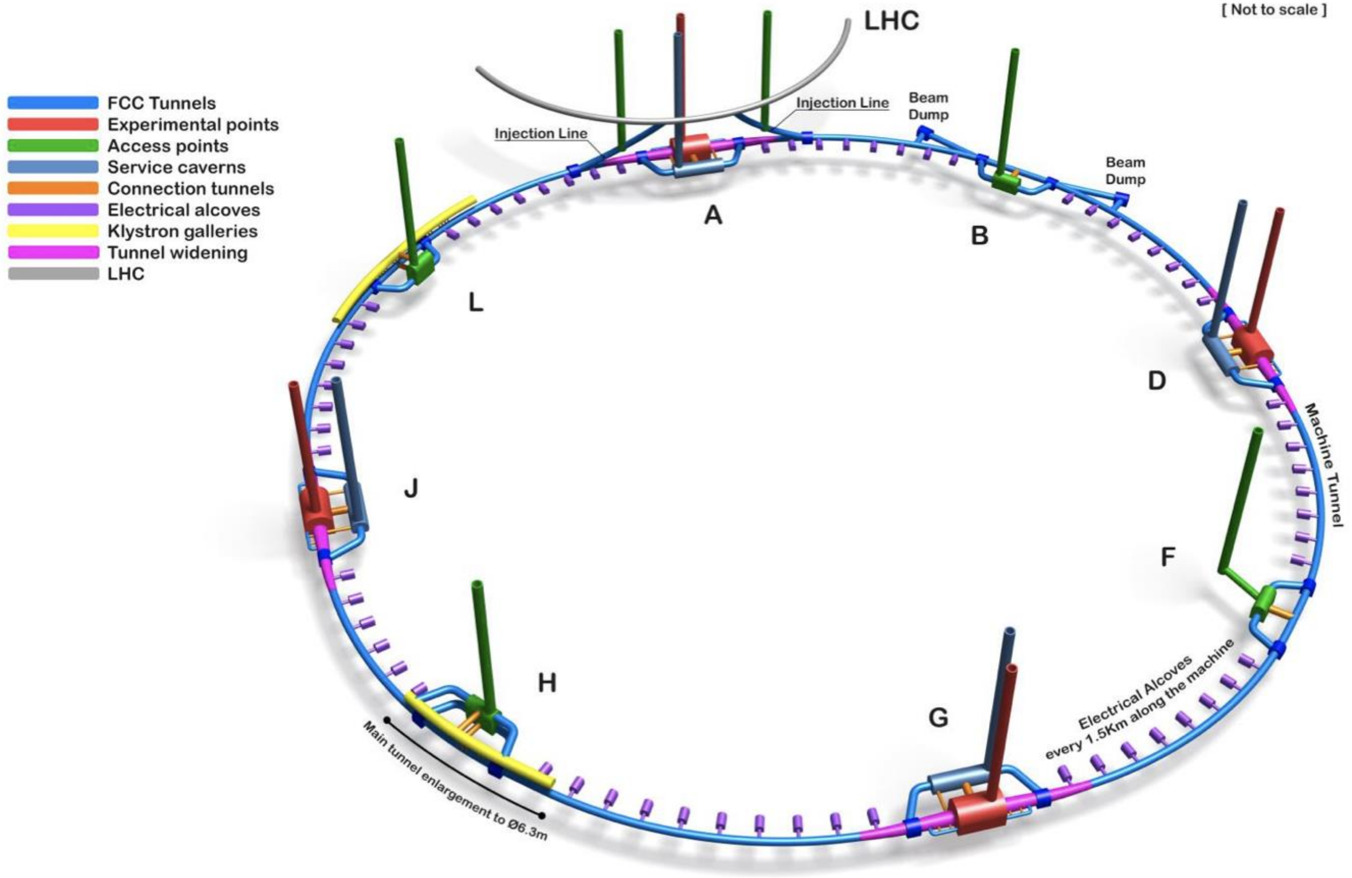
FCC 2022



- 91.2 km
- 8 Surface Sites
- 4 Experimental Areas
- 4 Technical Areas
- 14 shafts
- Klystron Galleries at Point H and L
- Point H tunnel widening to 6.3 m diameter
- Tunnel widening at experiment sites
- Beam dump at point B

Liam Bromiley

Tasks Ahead



Credit: Angel Navascues Cornago

- Baseline FCC underground structures to be frozen by early 2023.
  - ➢ TBM drive directions
  - ➢ Injection lines from LHC/SPS
  - ➢ Tunnel widening/Beamstrahlung
  - ➢ Alcove design
  - ➢ Beam dump
- Updated cost / schedule to be provided for the FCC mid-term review, October 2023.
- Lifecycle assessment study for underground civil engineering.
- On site investigations for areas of geological uncertainty.

Eight–Point placement challenges

The surface sites are mainly located in rural areas although in some cases existing developments are within a few hundred metres.

Typical impacts will include:

- Visual impact (buildings, water vapour)
- Noise impacts (cooling towers, transformers, cryoplant)
- Environmental impacts and releases to the Environment (dust, water, air)
- Impacts on future land use
- Heightened traffic
- Demand on local services

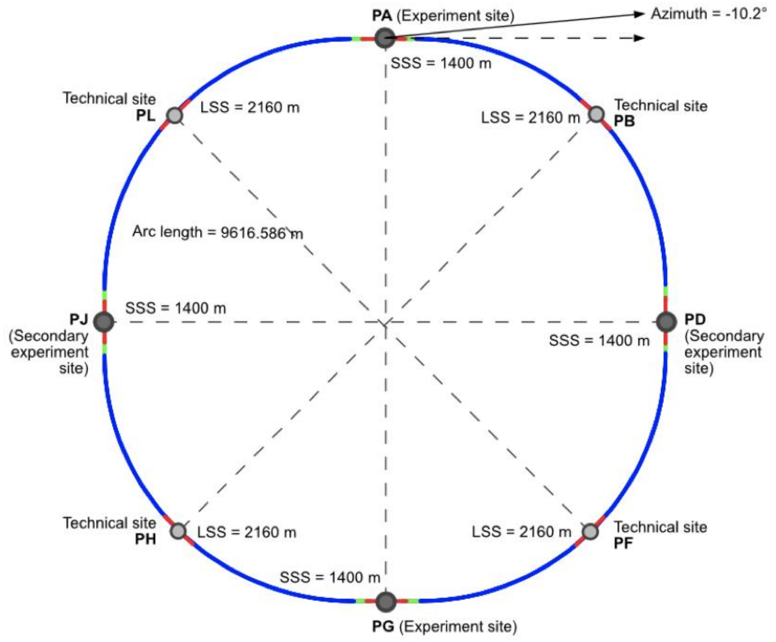
Typical existing semi-rural location – LHC Surface Site

Katsunobu Oide

The 4 IP layout

FUTURE CIRCULAR COLLIDER

- The new layout "31" series has been presented by J. Gutleber in the last optics meeting.
  - 8 surface sites, 4 IP.
  - complete period-4 + mirror symmetries.
- Let us choose "PA31-1.0" for the baseline, for the time being.
  - The adaptation to other variants, if necessary, will be minor.
  - An update "PA31-2.0" has been proposed with a change in the length of IP straights. The optics will adapt it soon with several other changes.



PA31-1.1 & 1.6 fallback alternatives

J. Gutleber

Scenario	PA31-1.0	PA31-1.1	PA31-1.6
Number of surface sites	8 (potential additional small access shafts at CERN or for ventilation at sites with long access tunnels, e.g. PF)		
Number of arc cells	42		
Arc cell length	213.04636573 m		
SSS@IP (PA, PD, PG, PJ)	1400 m	1400 m	1410 m
LSS@TECH (PB, PF, PH, PL)	2160 m	2100 m	2110 m
Azimuth @ PA (0 = East)	-10.75°	-10.45°	-10.2°
Sum of arc lengths	76 932.686 m		
Total length	91 172.686 m	90 932.686 m	91 052.686 m

Further reduction of circumference is planned to solve several placement issues (J. Gutleber, M. Benedikt).

Katsunobu Oide

“latest” (Dec. 06, 2022) parameters

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-?			
# of IPs		4			
Circumference	[km]	90.836848[a]			
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.94 / 2.74
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.1 / 9.2
Harmonic number for 400 MHz		121648[a]			
RF freuqeuncy (400 MHz)	MHz	400.793257[a]			
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[b]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	[$10^{34}/\mathrm{cm}^2\mathrm{s}$]	182	19.4	7.26	1.25
Lifetime (q + BS + lattice)	[sec]	840	–	< 1065	< 4062
Lifetime (lum)	[sec]	1129	1070	596	741

Coming modifications

- Change circumference, lengths of straight sections according to the placement study.
- Enlarge the separation of two beams in the arc from 30 cm to 35 cm.
- Refine the RF section to match the size of the cryomodules optimized for 400/800 MHz each.
- The crossing optics at FGHL using vertical chicane.
- Circumference adjuster at each FGHL to correct the initial misalignment and change due to tidal force.
- Injection/extraction/collimation optics at FGHL.
- Make lengths of some dipoles handleable, by dividing into shorter pieces.
- Reflect the alignment strategy on magnets and/or girders.
- Employ field profiles estimated by magnet design.
- Place BPMs and correctors.
- …and more…

[Some of] Potential Problems at Low Energy (Z)

- In order to avoid coherent beam-beam instability in configuration with 4 IPs, it will be necessary to reduce β_x^* from 15 to 10 cm. *And this will affect the DA and momentum acceptance*. The problem with instability could be solved in another way: by reducing the synchrotron tune, but this is incompatible with the requirements of energy calibration by resonant depolarization.

- Decrease in DA and energy acceptance due to lattice errors and misalignments will lead to the need to reduce the bunch population and, hence, to increase the number of bunches. And this, in turn, will enhance the problems with e-clouds and ion instabilities, which are solved by a large bunch spacing.

These could be solved by increasing the bunch length, but it's not that easy...

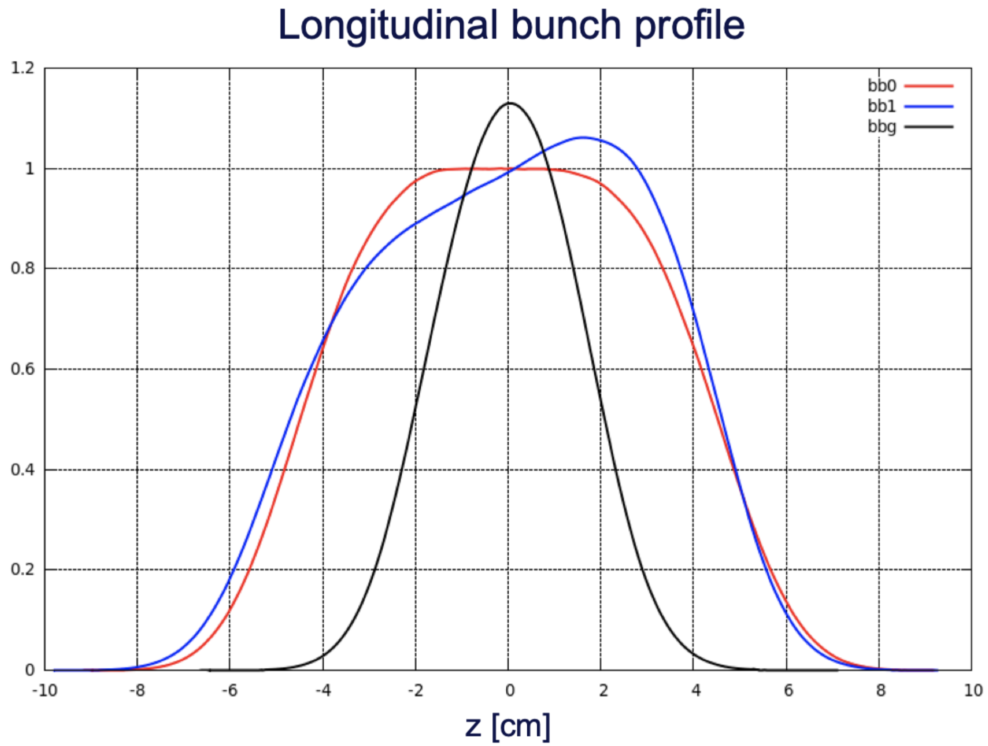
Half-Integer (e.g. 3.5) Harmonic Cavities (P. Raimondi)

- For odd RF buckets the synchrotron tune will increase, for even ones it will decrease. Our number of bunches is more than one order of magnitude less than the number of RF buckets, so we can easily place them as needed: for pilot bunches, ν_z will increase, and for colliding bunches, it will decrease.

- By correctly choosing the voltage of the second RF system, one can obtain an almost rectangular bunch profile ("flat top"). Then, for the same luminosity, we have a smaller peak in the bunch linear density, and we can expect:
  - reducing the vertical beam-beam tune shift
  - reducing the maximum critical energy of BS photons, that leads to
  - reducing the beam-beam induced energy spread

Dmitry Shatilov

Beam-Beam Simulations with and w/o 3.5 Harmonics



Bunch profile	Gaussian	"Flat top"
E [GeV]	45.6	
U_{RF} 400 MHz [MV]	120	
U_{RF} 1400 MHz [MV]	0	32.16
N_p [10^{11}]	2.43	4.86
n_b	10000	5000
ν_z	0.037	0.004
$\Delta\nu_x / \Delta\nu_y$	0.0036 / 0.097	0.0009 / 0.083
σ_δ	0.00133	0.00122
L / IP [10^{36} cm^{-2}c^{-1}]	1.85	1.85

Lattice Errors and Misalignments

- Misalignments and errors can lead to a significant decrease in the DA and momentum acceptance. This limits the luminosity per IP even in the case of ideal super-periodicity.
- The full beam-beam footprint from 2 or 4 IPs can cross a number of strong resonances, e.g. 1/2, 1/3, etc. The width of these resonances depends on the level of symmetry breaking, which depends on the magnitude of misalignments and the quality of corrections.
- Ways to solve the problem: improve the quality of corrections, and reduce the magnitude of misalignments (can be expensive!). Probably, the best solution: beam based alignment.
- Correction and tuning should consist of several stages: obtain a stable orbit and designed emittances, then enlarge the DA and momentum acceptance, and special attention must be paid to obtaining designed lattice parameters at the IPs and crab sextupoles (dedicated knobs in the IR).
- A realistic assessment of the beam dynamics, luminosity and lifetime is possible only in simulations, taking into account all errors, corrections and beam-beam effects. Work in progress.

Rogelio Tomas

FCC-ee tuning team & WG meetings

CERN e-group FCCee_tuning-team:

Ongoing discussions with Colombia and Pakistan

+ *Anyone is welcome*

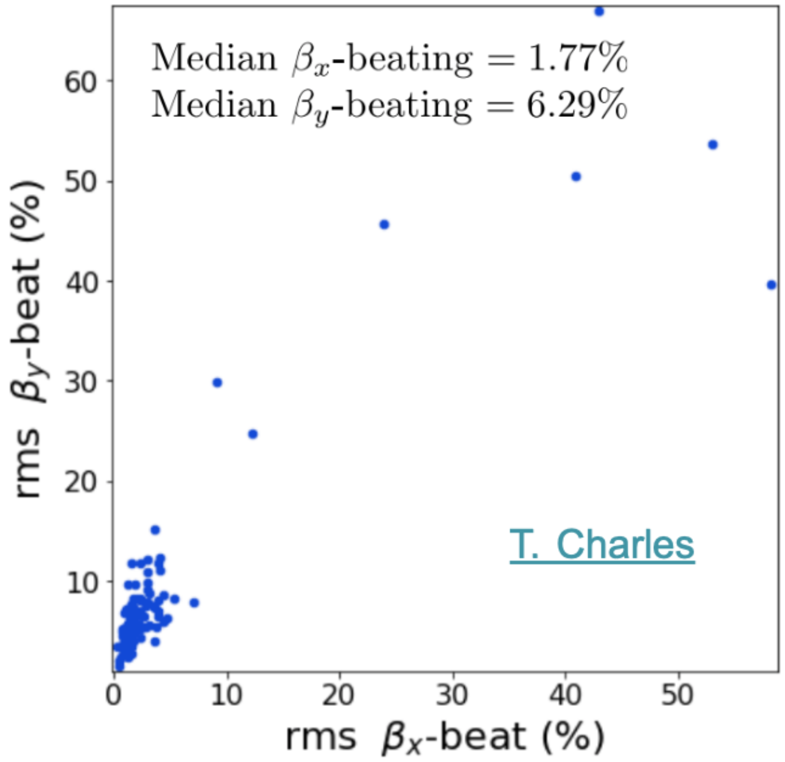
Meetings so far: 2 Dec, 1 Dec, 10 Nov, 3 Nov, 22 Sept, 25 Aug, 21 July, 14 Jul, 30 Jun, 9 Jun, 22 Apr, 22 Mar, 17 Mar, 10 Feb, 17 Nov and 10 Nov.

Last tuning team report in: CEPC 2022 workshop, 157th FCC-ee Optics Design

Optics tuning after reaching 10 μm beam-based alignment in FCC-ee

Type	ΔX (μm)	ΔY (μm)
Arc quadrupole*	50	50
Arc sextupoles*	10	10
Dipoles	1000	1000
Girders	150	150
IR quadrupole	100	100
IR sextupoles	10	10

Assuming beam-based alignment possibly with movers+BPMs+displacement sensors (design concept needed to reach 10 μm).



Very promising improvement in the tuning of the FCC-ee linear optics, including chromaticity correction. To-do: include BPM alignment errors, IP tuning, DA & lifetime optimization. Yet, need to monitor IR sextupole drifts at 1μm level.

Rogelio Tomas

Summary & Outlook

The FCC-ee performance with realistic errors is one of the fundamental questions to answer by 2025.

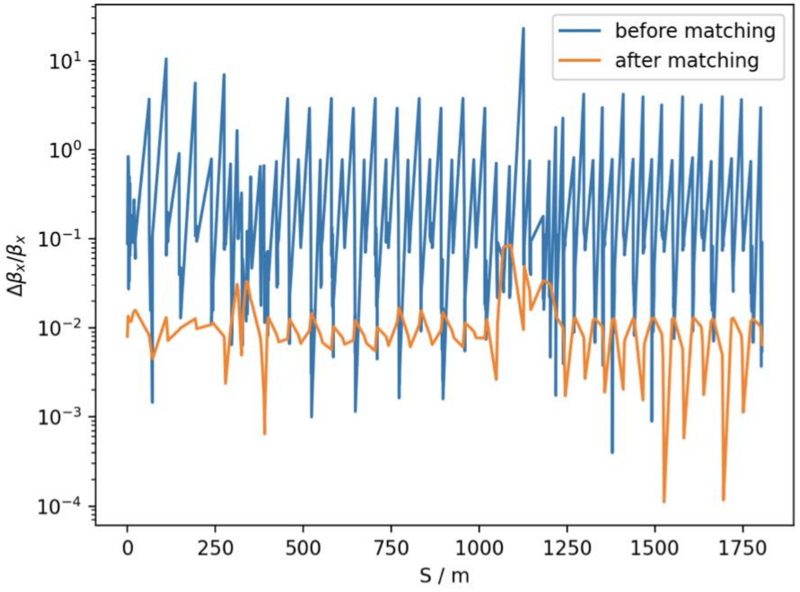
Excellent progress in the last year in identifying key problems, tools and progress with simulations and new concepts.

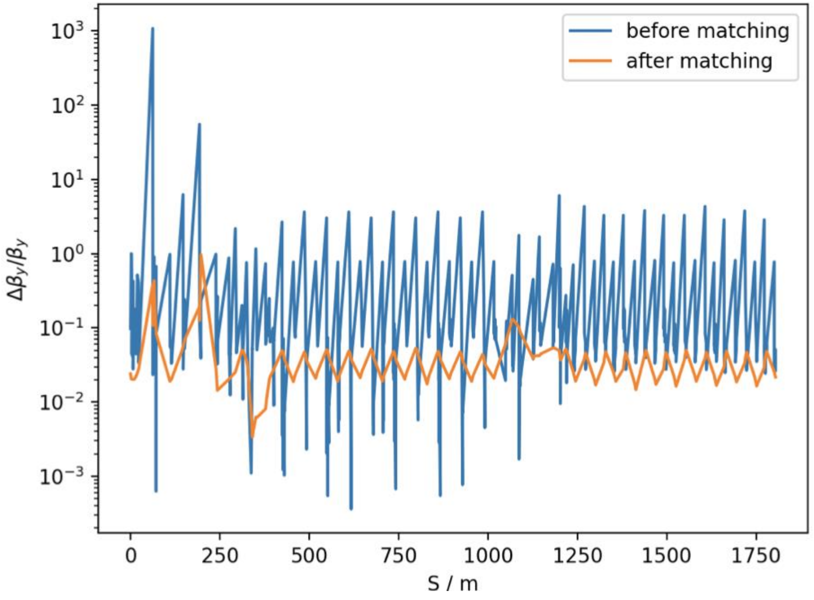
Next year critical to be able to finalize studies in 2024. Need a thorough workshop / review in 2023.

Leon van Riesen-Haupt

Optics Matching in Lattices with Errors

- Apply additional optics matching to **globally corrected lattices** with errors
  - Requested by **D. Shatilov**
  - Corrected lattices provided by **T. Charles**
- Scripts changed to **correct and save** each **quarter separately**
  - **Decouple** common strengths in quarters
- Insertion style **correction does not consider** non-zero **closed orbit**
  - Small **residual beating** when simulating closed machine
  - **Closed matching requires individual powering** of machine quarters
- IP β-beating reduced from ~20% to **~2% percent**
  - Need to explore how this affects other parameters
    - E.g. increased coupling, increased β-beating in certain areas
    - Coupling increase reported by **D. Shatilov**





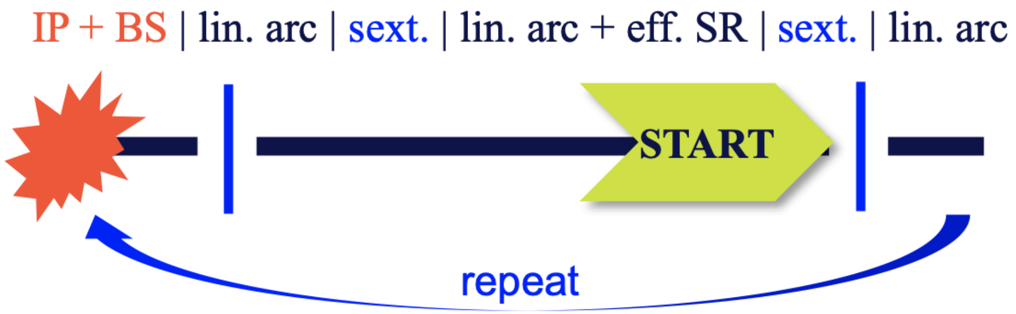
Next Steps

- Implement matching in **sequence converter**
  - Store **constraints** and **variables** in **sequence definition**
  - Match after every **conversion** either by
    - Generating **matching scripts** in accelerator code
    - Performing **matching in python**, calling accelerator code for twiss
- Improve matching code in **MAD-X for users**
  - **Adjust constraints** in consultations with users
  - Produce (a method that creates) scripts for **all lattice versions**
- Improve **realism** of matching scripts for users
  - Understand **how precisely** different optics properties can be **measured** in various locations
  - Artificially **reduce accuracy of matching** to reflect realistic scenarios

Stefano Mazzoni

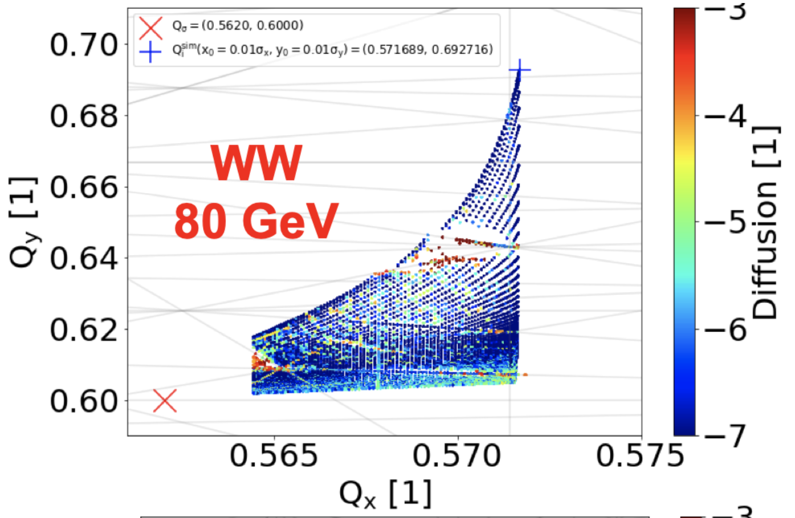
Simplified tracking simulations with xsuite

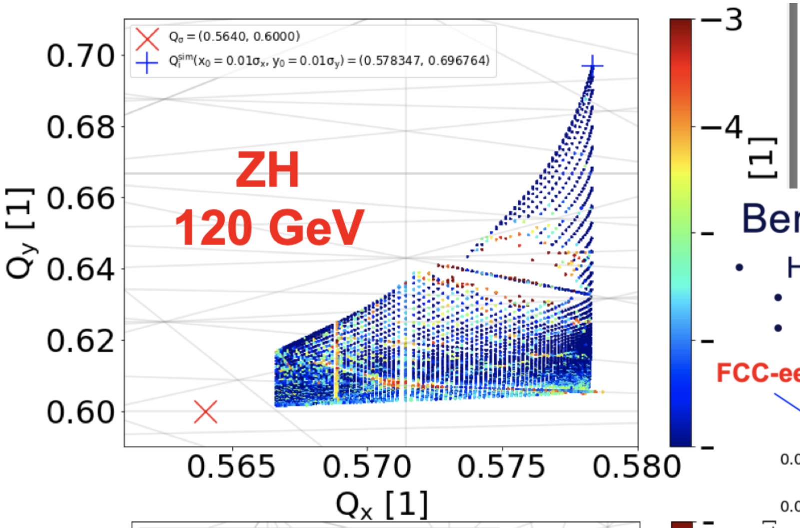
- Exploit superperiodicity of machine (2 IP case)
- In code:
  - 1 IP + tracking over half arc with linear transfer matrix

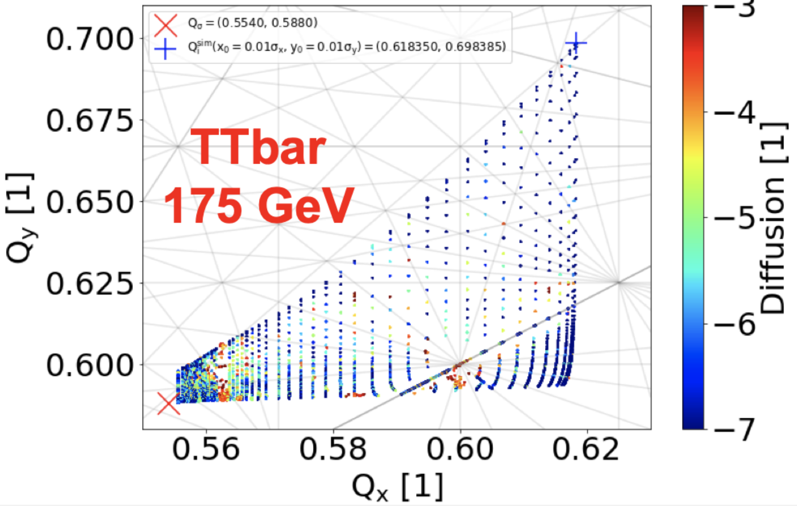


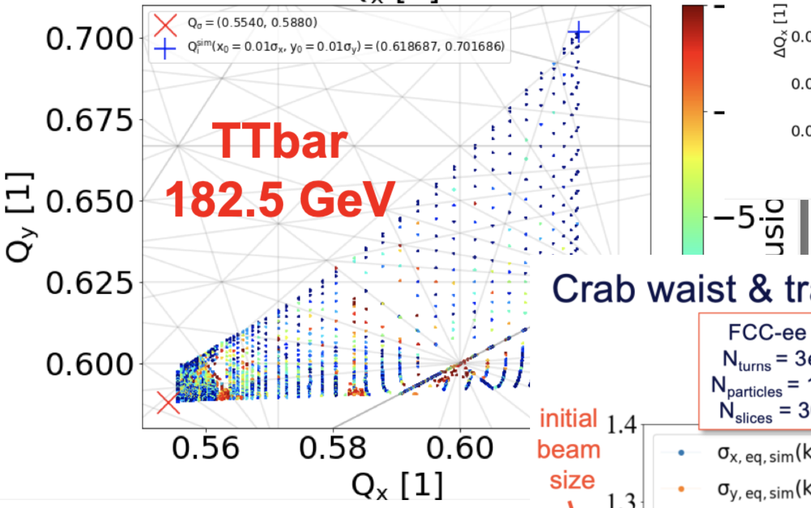
  - Arc split into 3 segments
  - 2 crab sextupoles between arc segments (β_x=3 m, β_y=5000 m)
  - A «turn» begins in front of the right sextupole:
    - Observation point for coordinates
  - Effective radiation (damping+noise) in arc, beamstrahlung in beam-beam
    - No radiation for FMA

Peter Kiscinz





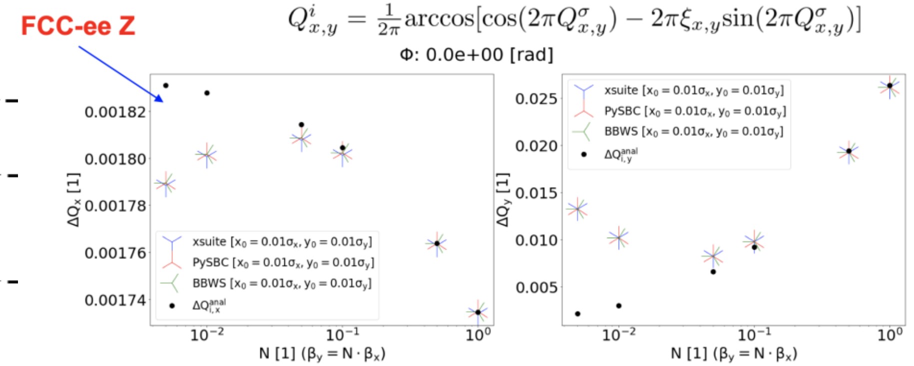




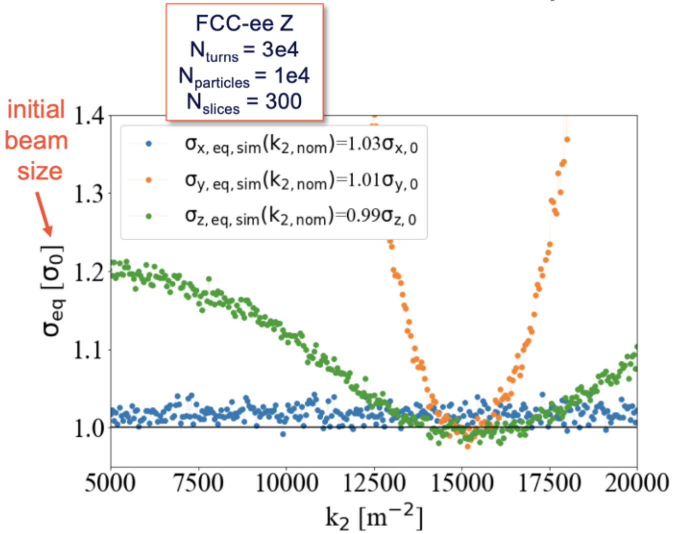
Benchmark against analytical formula ξ

- Head on collision with flat beams (N_b = 1e8)
  - All codes agree (xsuite, PySBC, BBWS)
  - Analytical estimate does not account for hourglass effect

$$Q^i_{x,y} = \frac{1}{2\pi}\arccos[\cos(2\pi Q^\sigma_{x,y}) - 2\pi\xi_{x,y}\sin(2\pi Q^\sigma_{x,y})]$$



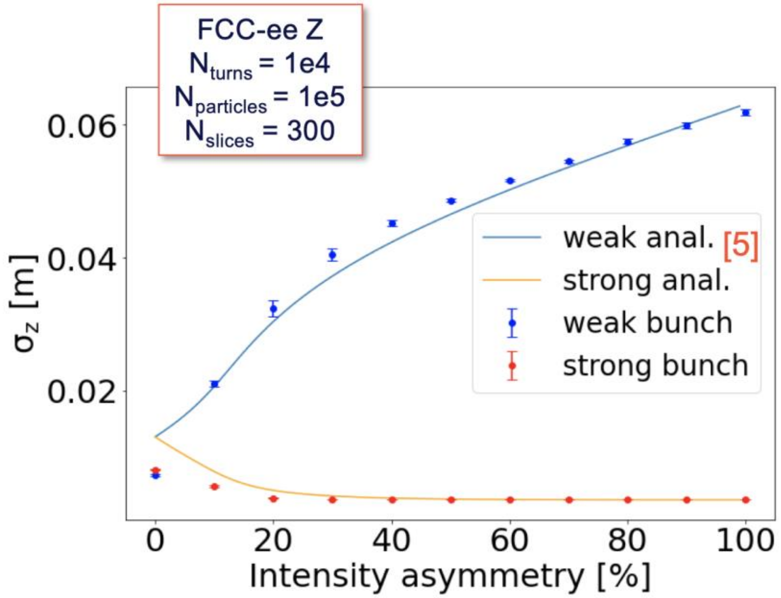
Crab waist & transverse blowup



- **Weak-strong** model
- Optimum k_2 close to nominal value (~0.97*$k_{2,nom}$ for Z resonance)
- No transverse blowup in optimum setting

Peter Kisciny

xsuite benchmark of 3D flip-flop



- First results are promising
- Need more particles and turns
- Improvement of parallelization ongoing
- Symmetric case instability to be understood
- Study ongoing

Summary

- Successful code benchmarks in weak-strong case
  - xsuite benchmarked against several existing tools, such as GUINEA-PIG, LIFETRAC, PySBC, BBWS
  - Beamstrahlung (feature released on Github [6]), tune footprint
- Ongoing benchmarking and simulations of 3D flip-flop and coherent head-tail instability with the strong-strong model
- Next steps:
  - Link element by element lattice (SAD / MAD-X) to xsuite beam-beam
  - Bhabha scattering

Beamstrahlung equilibrium length: approaching equilibrium

$$\delta_{BS,w} \equiv \frac{1}{\tau_{z,BS,w}} \approx \frac{2}{3} r_e \gamma_w^3 I_{2,w}$$

$$\{N_{ph,w}\langle u^2\rangle\}_{z,w,BS} \approx \frac{55}{24\sqrt{3}} \frac{r_e^2 \gamma_w^5}{\alpha} I_{3,w}$$

K. Le Nguyen Nguyen

- Bunch length increases due to quantum excitation from synchrotron (SR) and beamstrahlung (BS) emission but decreases due to SR and BS damping with characteristic damping times $\tau_{z,SR/BS}$:

$$\frac{d\sigma_{z,w/s}^2}{dt} = \frac{1}{2}\{\dot{N}_{ph}\langle u^2\rangle\}_{z,w/s,SR} + \frac{1}{2}\{\dot{N}_{ph}\langle u^2\rangle\}_{z,w/s,BS} - \left(\frac{2}{\tau_{z,SR}} + \frac{2}{\tau_{z,w/s,BS}}\right)\sigma_{z,w/s}^2$$

- This can be rewritten as

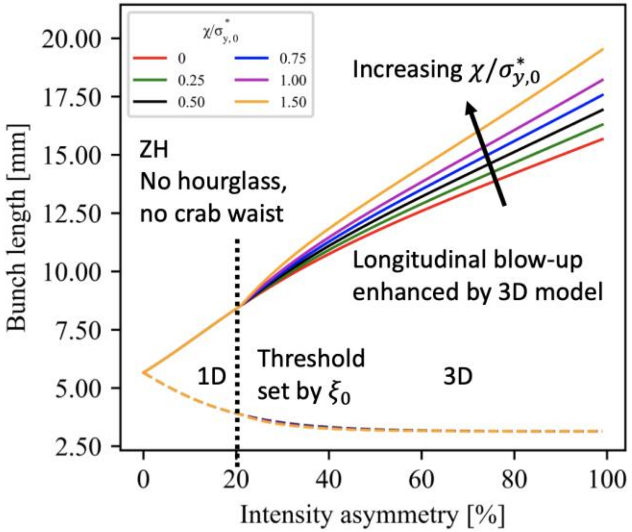
$$\frac{d\sigma_{z,w/s}^2}{dt} \equiv f_{w/s}(\sigma_{z,w}^2, \sigma_{z,s}^2) = \frac{2}{\tau_{z,SR}}\left(\sigma_{z,w/s,SR}^2 + A_{w/s} I_{3,w/s}\right) - \left(\frac{2}{\tau_{z,SR}} + B_{w/s} I_{2,w/s}\right)\sigma_{z,w/s}^2,$$

where

$$A_{w/s} \equiv \frac{n_{IP}\tau_{z,w/s,SR}}{4T_{rev}}\left(\frac{\alpha_p C}{2\pi Q_{sync}}\right)^2 \frac{55}{24\sqrt{3}} \frac{r_e^2\gamma_{w/s}^5}{\alpha}, \qquad B_{w/s} \equiv n_{IP}\frac{4}{3} r_e \gamma_{w/s}^3.$$

- Equilibrium bunch lengths imply two simultaneous equations:

$$\frac{2}{\tau_{z,w/s,SR}}\left(\sigma_{z,w/s,SR}^2 + A_{w/s} I_{3,w/s}\right) = \left(\frac{2}{\tau_{z,SR}} + B_{w/s} I_{2,w/s}\right)\sigma_{z,w/s,eqm}^2$$

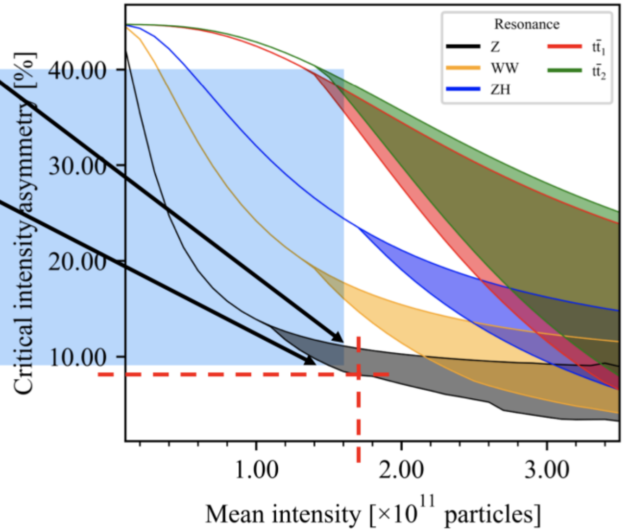


Lower bound: $\chi/\sigma_{y,0}^* = 0$ (effectively 1D)

Upper bound: $\chi/\sigma_{y,0}^* = 1.50$

Model: No hourglass, no crab waist

$L_{rel,\,thres} = 80\%$
$\xi_0 = 0.20$



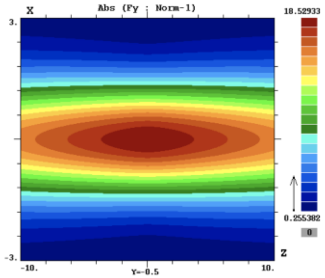
Relative luminosity sets different intensity asymmetry tolerances for different resonances. eg. Z resonance has critical asymmetry of **~8%** for largest $\chi/\sigma_{y,0}^*$.

Dmitry Shatilov

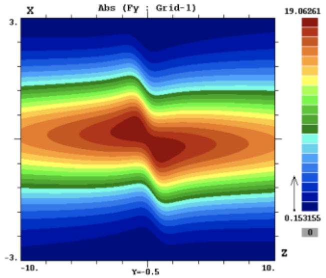
Simulation Codes

1. Lifetrac (D. Shatilov)
   - WS and QSS simulations
   - Realistic lattice with errors, misalignments and corrections
   - Upcoming updates: tapering, realistic SR in all magnets
2. BBWS, BBSS (K. Ohmi)
   - WS and SS simulations
   - Linear lattice with possible consideration of chromaticity, impedance, etc.
3. SAD (K. Oide et al.) + BBWS
   - Realistic lattice with errors, misalignments and corrections
   - Tapering, realistic SR in all magnets, spin tracking, etc.
   - Beam-beam (WS) is provided by BBWS code
4. IBB (Y. Zhang)
   - WS, SS and QSS simulations
   - Linear lattice with possible consideration of chromaticity, impedance, etc.
   - Next steps: realistic lattice with errors, misalignments, SR in all magnets
5. Xsuite (P. Kicsiny, X. Buffat et al. – for BB module)
   - WS, SS and QSS simulations (now testing, work in progress)
   - Realistic lattice with all effects included

Beam-Beam Kick: Gaussian vs. CW

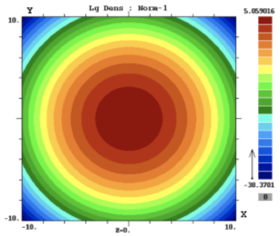


F_y (Gaussian, Y=-0.5 σ_y)

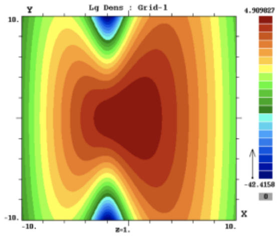


F_y (Crabbed, Y=-0.5 σ_y)

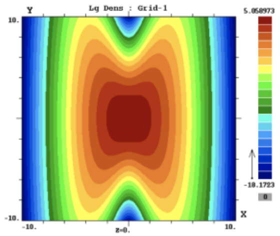
Transverse Distribution for CW Bunches



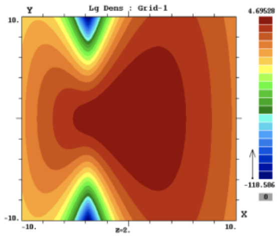
Gaussian, Z=0



Crabbed, Z=1 cm



Crabbed, Z=0



Crabbed, Z=2 cm

Log (density)

The axes are x/σ_x and y/σ_y

Z is the distance to IP

Next Steps

Chromatic waist to obtain monochromatization (P. Raimondi)

- The beam distribution will be more complicated. We need to build it from a realistic tracking in nonlinear lattice, all sextupoles included. This is like SS model, but we don't need to update the grid it every turn. With large statistics (many turns), the "grid noise" will be much smaller.
- At each grid point, we need to collect not only the density and average transverse momentum, but also the energy and energy spread.
- Then for every elementary particle-slice collision, we will know not only the kicks and luminosity, but also the c.m. energy and the energy spread. Finally, we will be able to produce the luminosity vs. $E_{c.m.}$ histogram, thus obtaining a realistic mono-chromatization parameter.

Arc Beam-Based Alignment

Tor Raubenheimer

- **Two challenges: absolute alignment and long-term stability**
  - Large separation between magnets makes mechanical alignment more challenging. 100 um over 100 meters is SOA
  - Mechanical alignment over 90 km will be time consuming
- **Use BBA to relax mechanical requirements**
  - Transfer mechanical alignment challenge into a beam diagnostic challenge and sets requirements on diagnostic resolution, magnetic center variation and temperature stability
- **Many approaches dating back to 1980's including quadrupole dithering, dispersion-free steering, LOCO, FICO, RCDS, PBBA, …**
  - Need also to determine timescales and how to establish alignment, e.g. trims, movers, or correctors. Track changes → Hourly? Daily? Monthly?

Tor Raubenheimer

Proposed Alignment and Ground Motion model I

- **Develop a model that is easy to implement in MAD-X**
  - Mechanical misalignments as a function of length scale
  - Slow ATL-type motion combined with waves and incoherent vibration
  - Include response functions for girders and supports
  - Use this to test BBA and feedback concepts and specify diagnostic and hardware req.

Initial Mechanical alignment		
Length scale	tolerance	
6	20 to 50 um	mechanical installation tolerance of components on quad/sext girder - main issue is corrector and f
50	200 um	mechnical installation and alignment of girder to girder - need to be able to transport first beam
200	500 um	mechnical installation
1000	2 mm	mechnical installation smoothed around the ring
10000	5 mm	Installation tolerance based on surface alignment network and GPS

Tor Raubenheimer

Proposed Alignment and Ground Motion model II

- **Dynamic variation**
  - **Some combination of incoherent waves, plane waves, systematic variation, and ATL-type diffusion**
  - **Verify feedback, feed-forward, and BBA timescales**

Timescale	tolerance	Correlation	https://cds.cern.ch/record/554622/files/woab009.pdf
f > 100 Hz	1 nm	none	https://www.slac.stanford.edu/cgi-bin/getdoc/slac-pub-8595.pdf
100 > f > 10 Hz	5 nm	none	
10 > f > 1 Hz	20 nm	none	
1 > f > 0.01	100 nm	none	
1 > f > 0.01	1 um	10 km	
tidal	1 mm	1000 km	systematic horizontal motion across the ring
diurnal	??		
Seasonal	100 um	around lake region	systematic vertical deformation
ATL		1x10-5 um^2/m/s	PRL 104, 238501 (2010)

Tor Raubenheimer

- # Expectation for BBA

BBA alignment requirements			
Length scale	tolerance		
6	10 um	BBA alignment of quadrupole to sextupole to bpm	How do we reference long girder to BPM?
50	20 um	BBA alignment of quadrupoles to BPM using dither and smoothing with steering	
200	20 um		
1000	100 um	BBA alignment of trajectory	
10000	1 mm	BBA alignment from circumference and trajectory	

- # Requirements
  - 0.1 um BPM resolution at high current for stored multi-bunch beam
  - Trims on quadrupoles and sextupoles without coupling to magnetic center
  - Clarification on location of dipole and skew correctors is required
  - Correctors or movers to implement corrections (dipoles for quads and maybe quad/skew quad trims on the sextupoles)
  - Timescale for correction faster than degradation

alignment options

Option 1: Combination of automated laser tracker measurements + permanent metrological network

Concept:

- A metrological network consisting of overlapping references (stretched wire or Structured Laser Beam) will be installed along the tunnel walls/ceiling, with regular external references, to:
    - Limit the error propagation
    - Provide a permanent accurate reference of alignment, from the installation (the metrological network will be installed asap) to the maintenance periods
- Laser tracker measurements performed from a robot/train w.r.t. targets installed permanently on the components; laser tracker measurements could be replaced by absolute distance measurements (trilateration measurements)

Pros:

- Could provide a fast way for re-adjustment: measuring locally w.r.t. permanent references

Option 2: permanent alignment sensors

Concept:

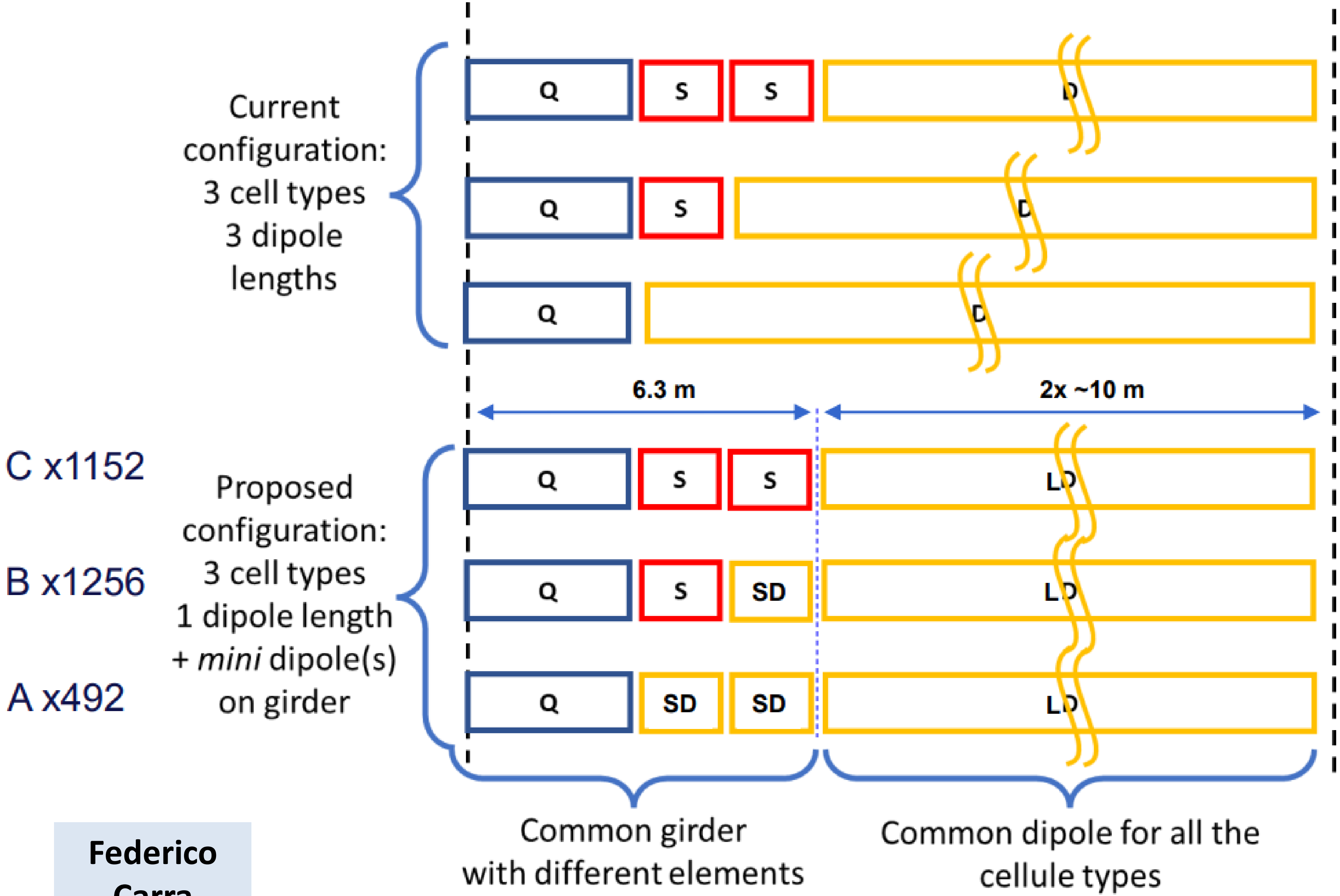
- A permanent reference network is installed between the booster and the main ring, consisting o overlapping references (either a stretched wire or Structured Laser Beam)
- Low-cost alignment sensors attached to the girders measuring w.r.t. these references

Pros:

- Such a configuration would allow a permanent monitoring of the girder position and as a consequence o the quadrupoles / sextupoles alignment, integrating temperature gradient, etc.
- Very low propagation of error

Helene Mainaud Durand

Short arc half-cell (high energy, H and ttbar)



L. Baudin, J. Bauche

- Instead of having 3 different lengths for the long dipoles → **2 types of dipoles**
  - SD ~ 1.5m
  - LD ~ 10m(x2)
- Instead of having 2 (/3) different girder lengths → **1 common girder**
  - Girder ~ 6.3m
- **"Hot spares" for each SSS module ready for installation in case of faults**, leaks, etc. of single elements
- *(→ more in the "supporting systems" part, later in these slides)*

Federico Carra

Federico Carra

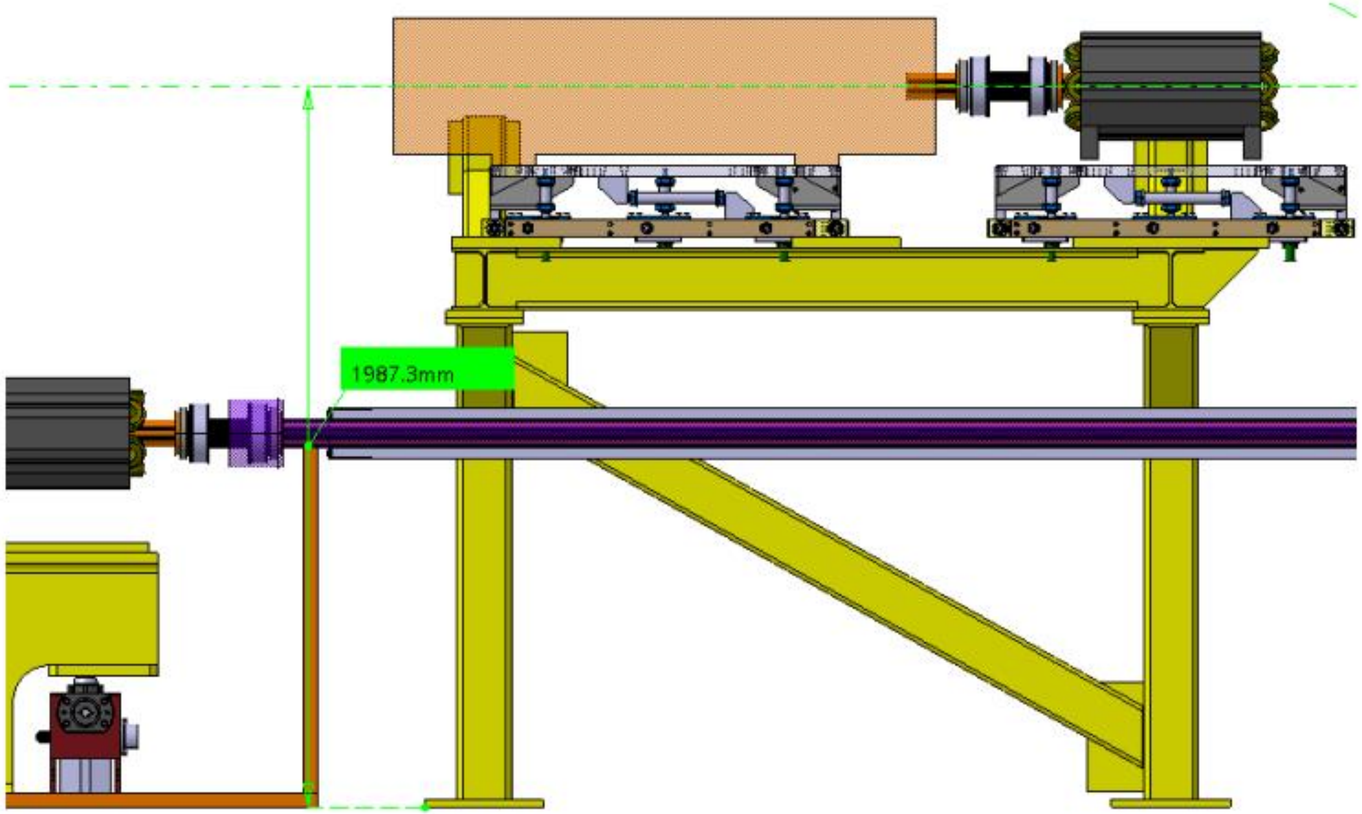
Tunnel Layout – Vertical placement booster to collider

C. Tetrault

Vertical placement considers that:

- **The booster SSS is azimuthally offset from the collider SSS**
  - Decrease vertical distance between booster and collider beam axis
  - Better stability of booster supports
  - Eases integration in Φ5.5m tunnel
  - *(periodicity/offset maintained across the ring)*

- *Proposed and approved at <u>159th FCC-ee Optics Design Meeting</u>*



Booster SSS on top of collider dipoles

Short Straight Sections configuration

Federico Carra

- **Collider**
  - SSS elements supported by common girder
  - Enhance strategy for chamber insertion / splittable magnets
- **Booster**
  - TE-MSC and TE-VSC started the design of the booster elements
  - EN-MME produced the first version of a robust and compact supporting system → fed to calculations
  - Two supporting principles studied: common girder (preferable for TE-VSC, allows a single chamber) vs. individual adjustment system (e.g. HL-LHC UAP, designed by BE-GM)

Collider SSS:

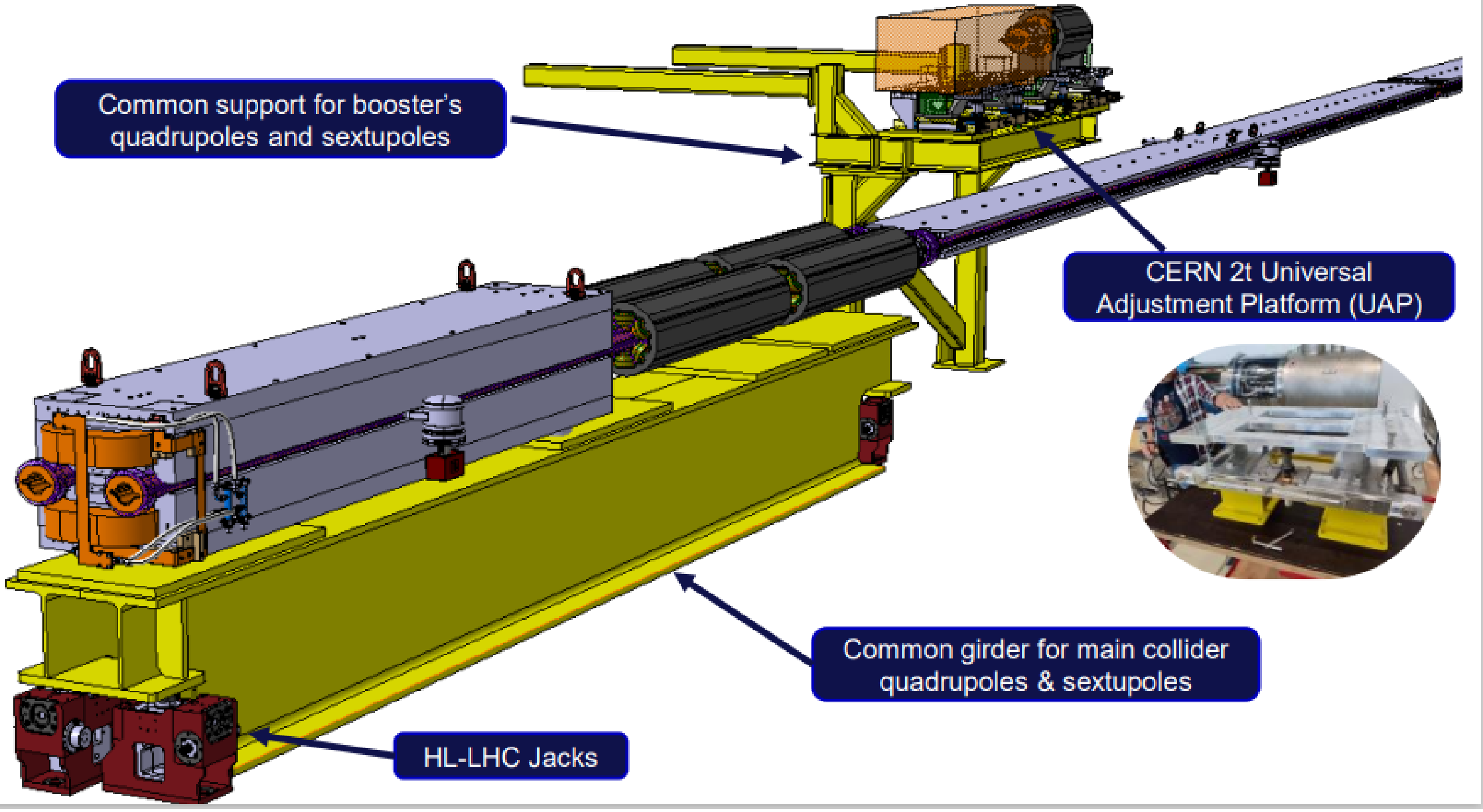
Quadrupole weight: ~5300 Kg.

Sextupole weight: ~680 Kg individual, 2720 Kg total.

Total: ~8020 Kg

Preliminary girder weight: ~3000 Kg
Girder: 650 mm x 720 mm x 6500 mm

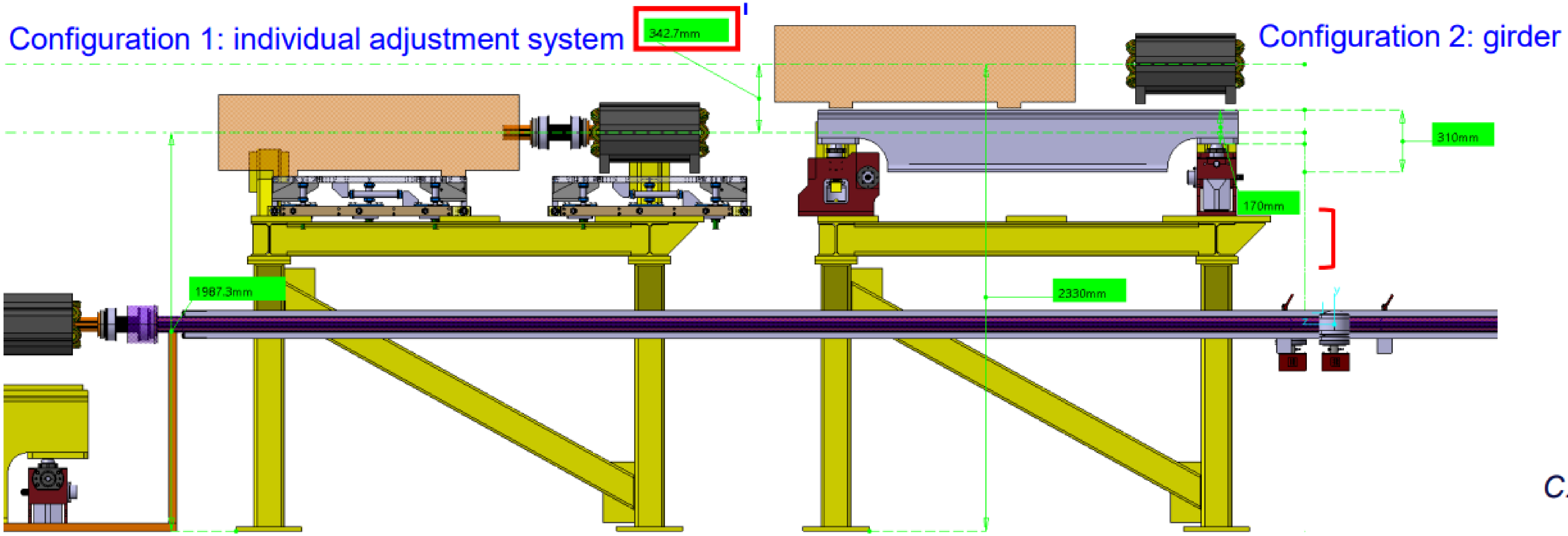
C. Tetrault



Federico Carra

Short Straight Sections configuration

- Booster SSS supports, two preliminary configurations:



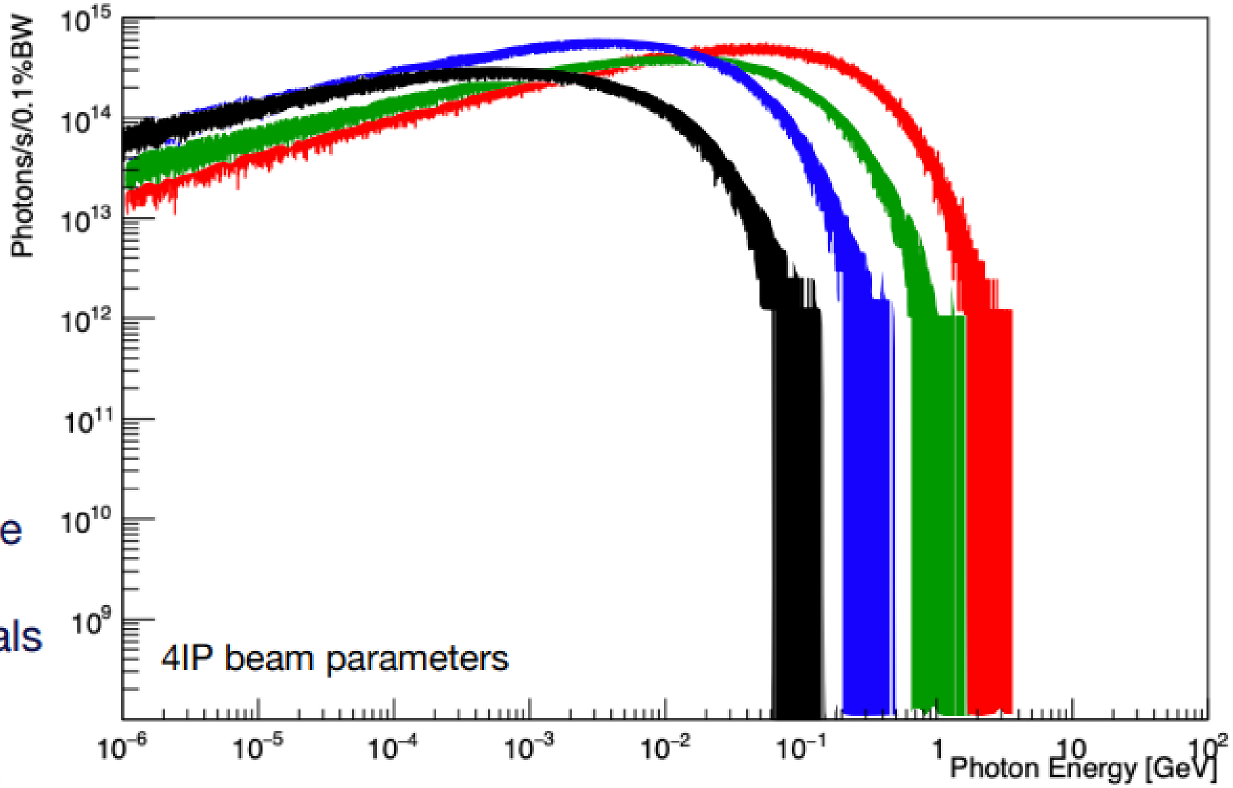
C. Tetrault

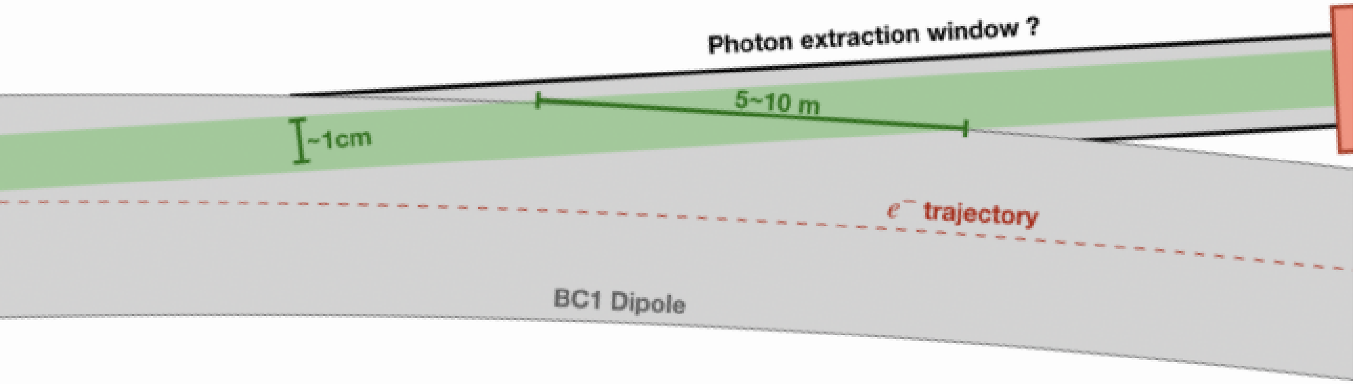
Beamstrahlung radiation Characterisation

(more in: A. Ciarma - MDI Workshop 2022 - 24/10/2022)

The photons are emitted **collinear to the beam** with an angle proportional to the beam-beam kick. This radiation is extremely intense **O(100kW)** and **hits the beam pipe** at the end of the first downstream dipole.

The design of a dedicated **extraction line** and **beam dump** for the beamstrahlung photons is currently in progress, exploring tunnel integration, magnets design, cooling system, and different materials for the beam dump.



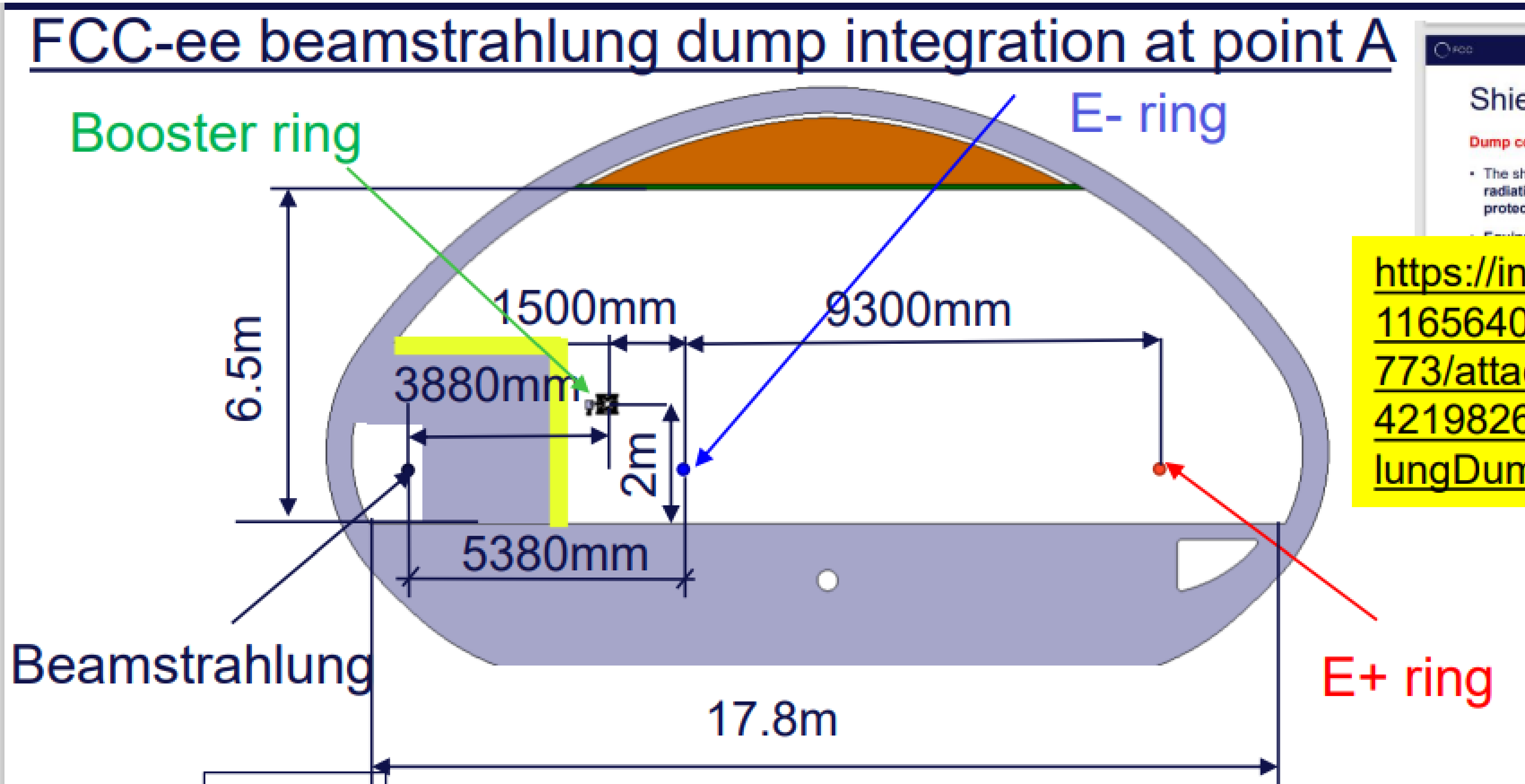


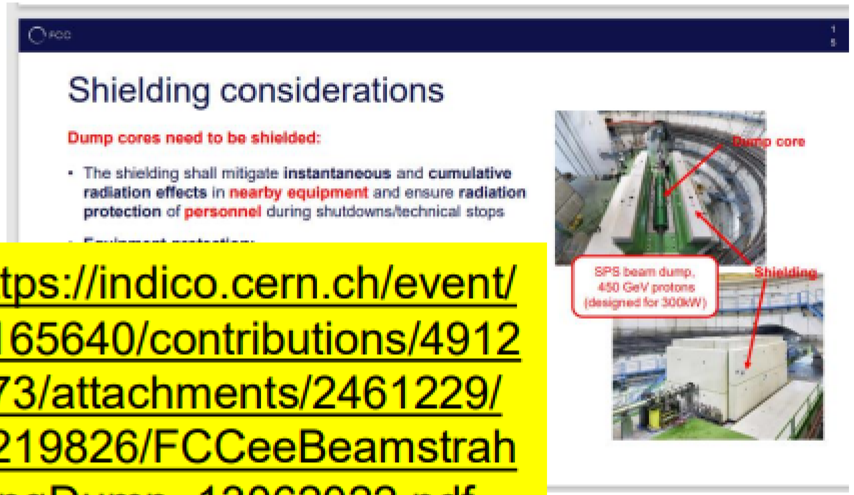
	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

Andrea Ciarma

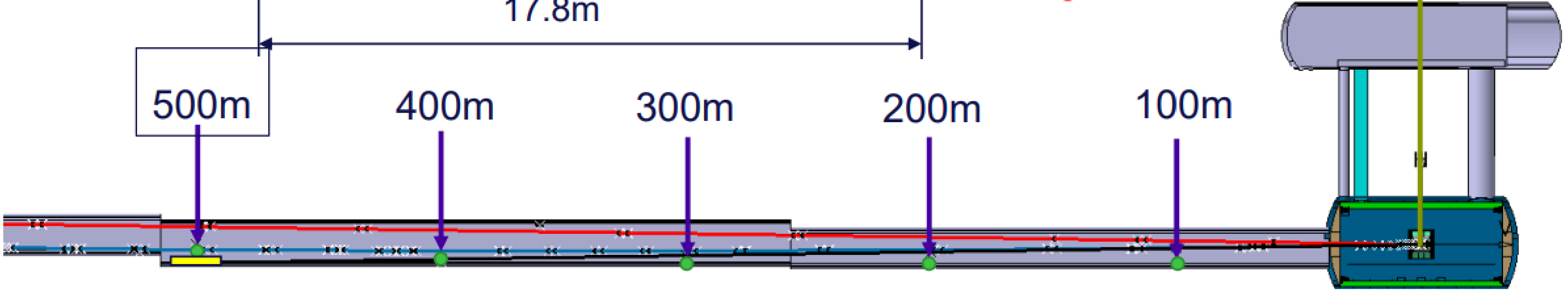
handling of beamstrahlung

Fani Valchkova





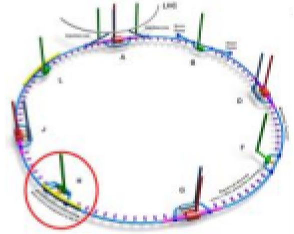
https://indico.cern.ch/event/1165640/contributions/4912773/attachments/2461229/4219826/FCCeeBeamstrahlungDump_13062022.pdf



booster RF integration in Point H

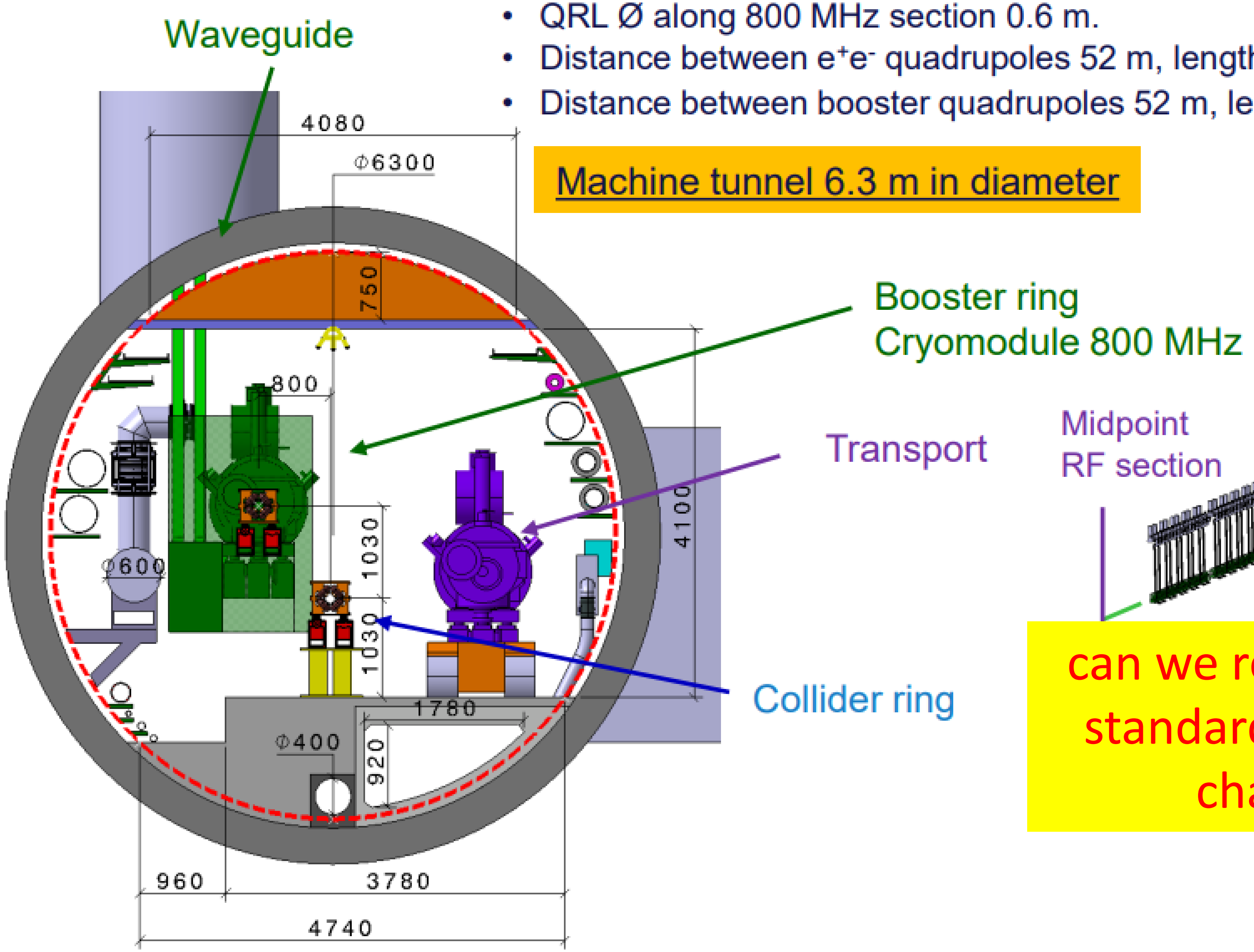
Fani Valchkova

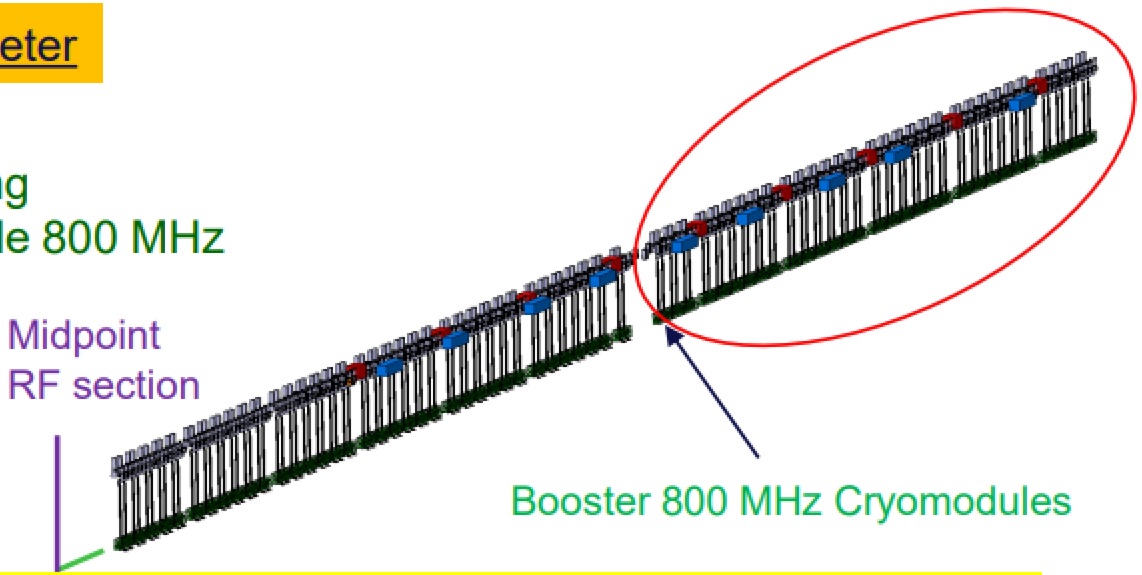
FCC-ee RF Machine tunnel cross section (ttbar machine)



- QRL Ø along 800 MHz section 0.6 m.
- Distance between e^+e^- quadrupoles 52 m, length 3.1 m.
- Distance between booster quadrupoles 52 m, length 1.5 m.

Machine tunnel 6.3 m in diameter





can we reduce the tunnel diameter to standard 5.5 m? what happens if we change the RF frequency?

Collider Center

Franck Peauger

Cavity performances specification

07-Dec-22	Bare cavity in vertical test stand		Jacketed cavity with HOM couplers in vertical test stand		Cryomodule (with FPC) in horizontal test stand		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
1-cell 400 MHz	6.9	3.3E+09	6.6	3.15E+09	6.3	3.0E+09	5.7	2.7E+09
2-cell 400 MHz	13.2	3.3E+09	12.6	3.15E+09	12	3.0E+09	10.8	2.7E+09
5-cell 800 MHz	27.6	3.3E+10	26.3	3.15E+10	25	3.0E+10	22.5	2.7E+10

+5% margin +5% margin -10% margin

- Performances degradation between bare and dressed cavity, as well as between vertical test and cryomodule configuration are well known phenomena

  → margins refinement possible after construction and testing of few prototype cavities

- Additional margin in operation is essential for reliable operation

400 MHz Nb/Cu

Franck Peauger

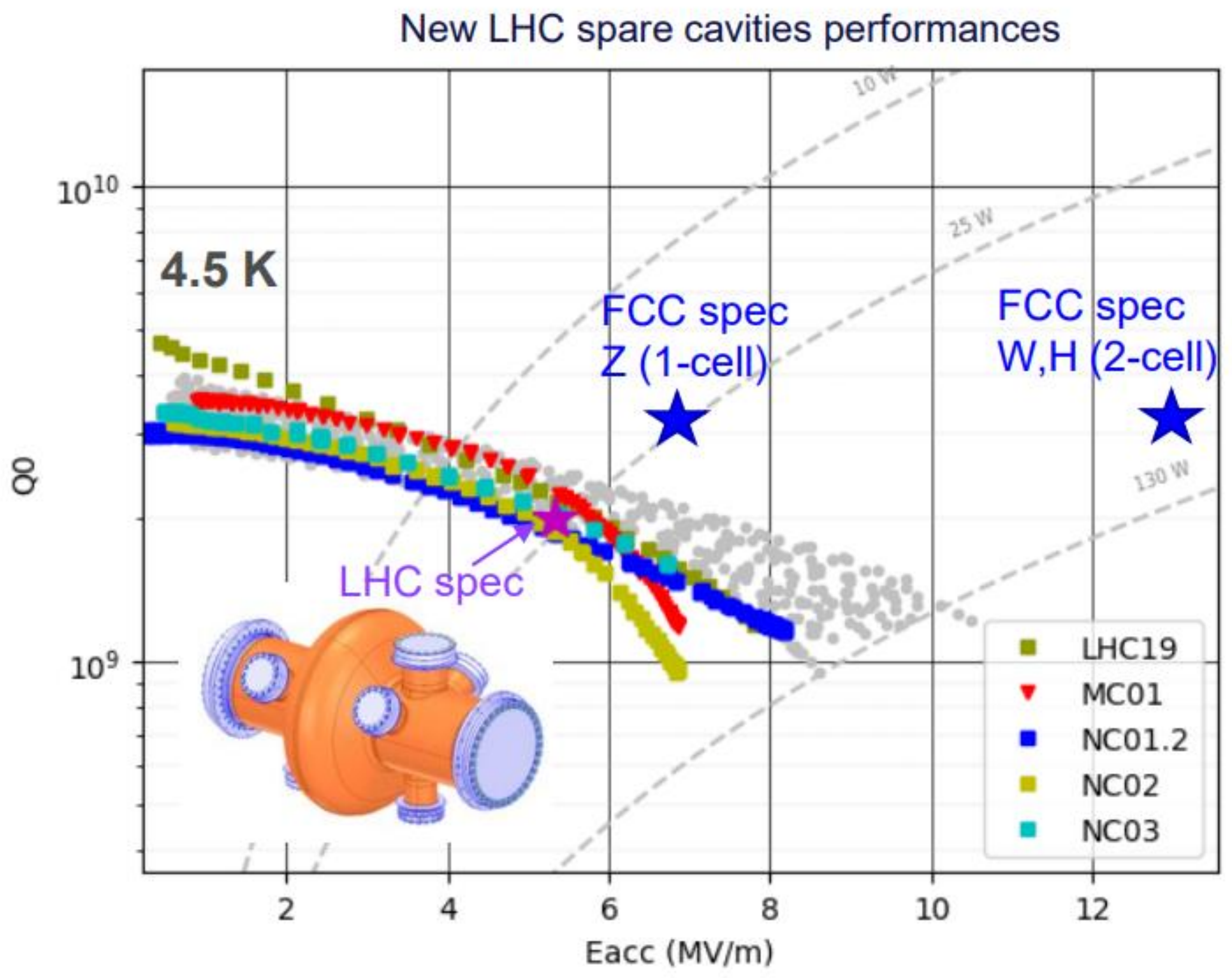
Compared to LHC cavities, significant **improvement of Eacc** and **reduction Q0 slope** shall be achieved for FCCee cavities. New technological process are being developed:

→ **Internal welding** of copper hall cells or **seamless** cavity

→ **Electropolishing** of the copper cavity

→ Highly performant niobium coating :**HiPIMS**
Magnetron Sputtering with a high voltage pulsed power source

→ Application of modern surface preparation and clean room procedures to reach high gradients



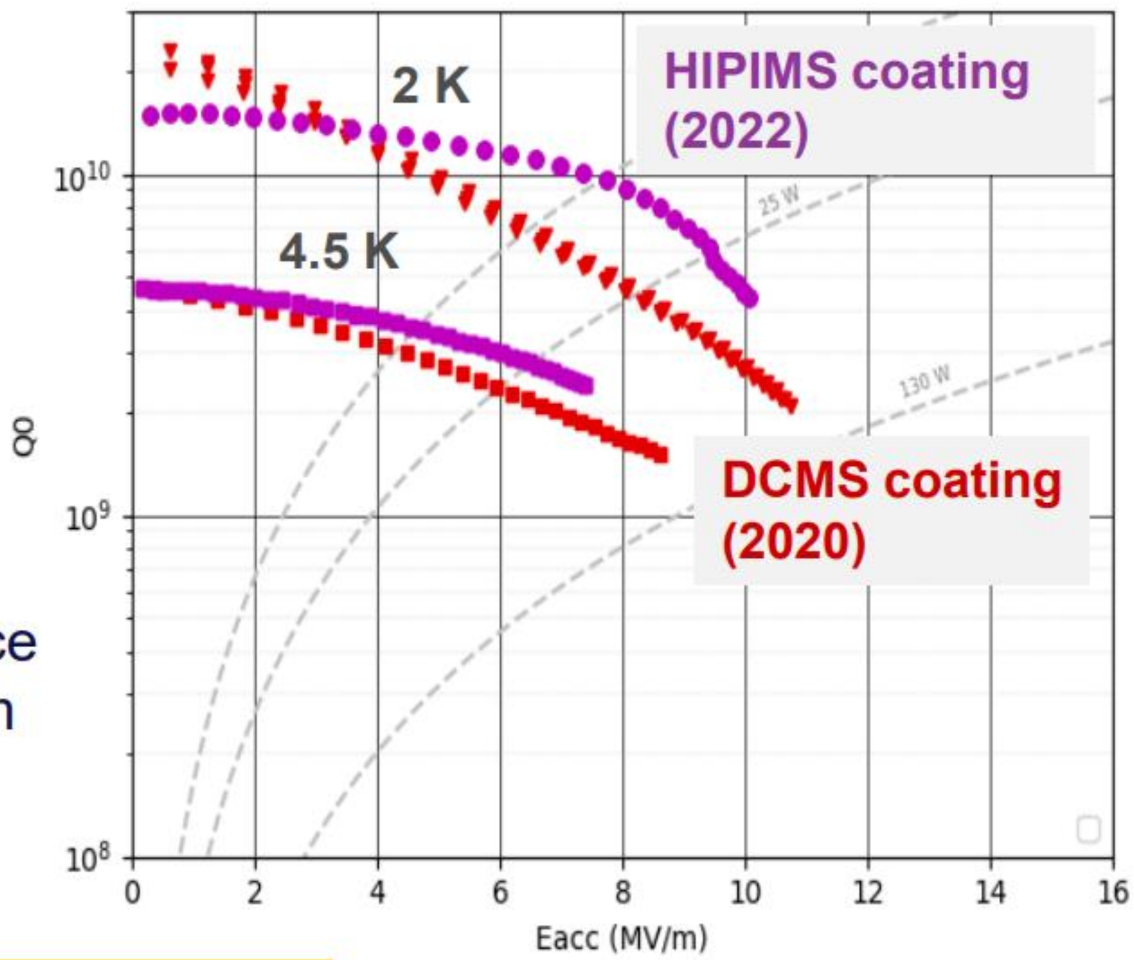
400 MHz Nb/Cu

First attempt of HiPIMS coating on a 400 MHz cavity

Reduction Q_0 slope is confirmed

Encouraging result obtained without electropolishing

Test limited by field emission → a new surface preparation in clean room is planned in Q12023 (with niobium coated flanges and HPR)



G. Rosaz, J. Walker, Y. Cuvet, G. Pechaud

PC04 cavity on vertical insert in SM18

Franck Peauger

alternative 600 MHz scenario

SRF cavities and power RF sources specification at 600 MHz

→ only two types of SRF cavities and one type of high efficiency klystron to develop

07-Dec-22	Bare cavity in vertical test stand		Jacketed cavity with HOM couplers in vertical test stand		Cryomodule (with FPC) in horizontal test stand		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
2-cell 600 MHz	13.2	3.3E+09	12.6	3.15E+09	12	3.0E+09	10.8	2.7E+09
5-cell 600 MHz	27.6	3.3E+10	26.3	3.15E+10	25	3.0E+10	22.5	2.7E+10

07-Dec-22	Z		W		H		ttbar2		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF source type	600 MHz 600 kW klystron	600 MHz 600 kW klystron	600 MHz 600 kW klystron	600 MHz 600 kW klystron	600 MHz 600 kW klystron	600 MHz 65 kW solid state amplifier	600 MHz 65 kW solid state amplifier	600 MHz 600 kW klystron	600 MHz 50 kW solid state amplifier
Frequency [MHz]	600	600	600	600	600	600	600	600	600
Pcav [kW]	547.4	410.6	251.1	123.1	251.5	64.9	43.9	252.4	12.2
Prf conditioning [kW]	136.9	102.6	62.8	30.8	62.9	16.2	11.0	63.1	3.1
# cavities / RF sources	1	1	2	4	2	1	1	2	4
# RF sources	180	12	196	10	196	76	392	164	101

SuperKEKB-type fast beam losses in FCC-ee

- **Start with the worst-case losses and apply directly to FCC-ee (80% over 2 turns)**
- **Not trivial to blow up the beam this quickly**
  - LHC-like transverse damper (ADT) excitation probably not suitable:
    - Random dipole kicks take longer to blow up the beam
    - Resonant kicks will make the loss location dependent on the phase advance from the ADT
  - Longitudinal excitation via RF frequency shift is also not suitable
- **Custom synthetic simulation setup as a first step:**
  - Add 18 'beam heater' elements that give uniform random per-particle kicks
  - The beam centroid should remain relatively unaffected
  - Adjust the maximum amplitude of the kicks to achieve the loss rate
    - $3.5\ \sigma_{xp}$ per excitation for horizontal blow-up
    - $25\ \sigma_{yp}$ per excitation for vertical blow-up

```
dist:
  start_element: 'ip.1'
  source: 'internal'
  parameters:
    type: 'matched_beam'
    sigma_z: 0

insert_element:
  -
    name: 'crazybeam'
    at_s: [5e3, 10e3, 15e3, 20e3, 25e3,
           30e3, 35e3, 40e3, 45e3, 50e3,
           55e3, 60e3, 65e3, 70e3, 75e3,
           80e3, 85e3, 90e3]
    type: 'BeamHeater'
    parameters:
      name: 'crazybeam'
      max_kick_x: 0
      max_kick_y: 0

dynamic_change:
  element:
    -
      element_regex: 'crazybeam.*'
      parameter: 'max_kick_x'
      change_function: 'sigx * 0.02'
```

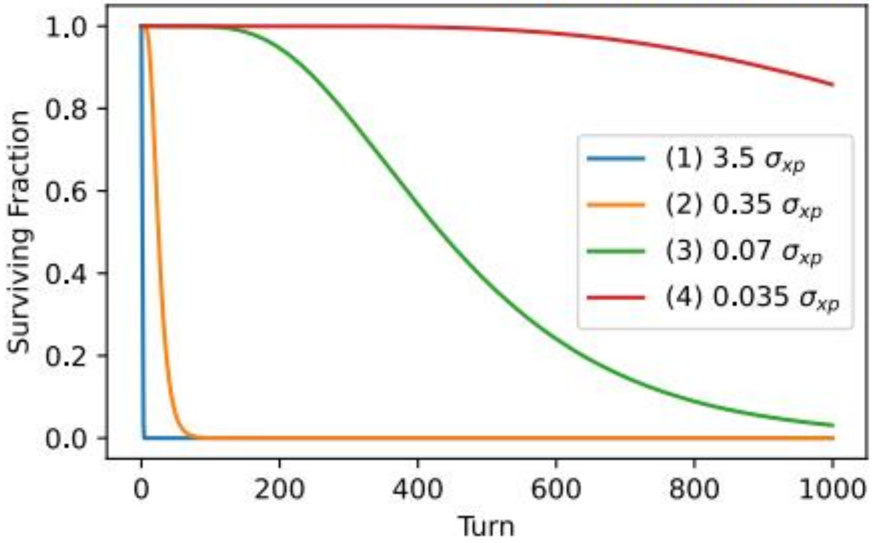
Z-mode fast losses

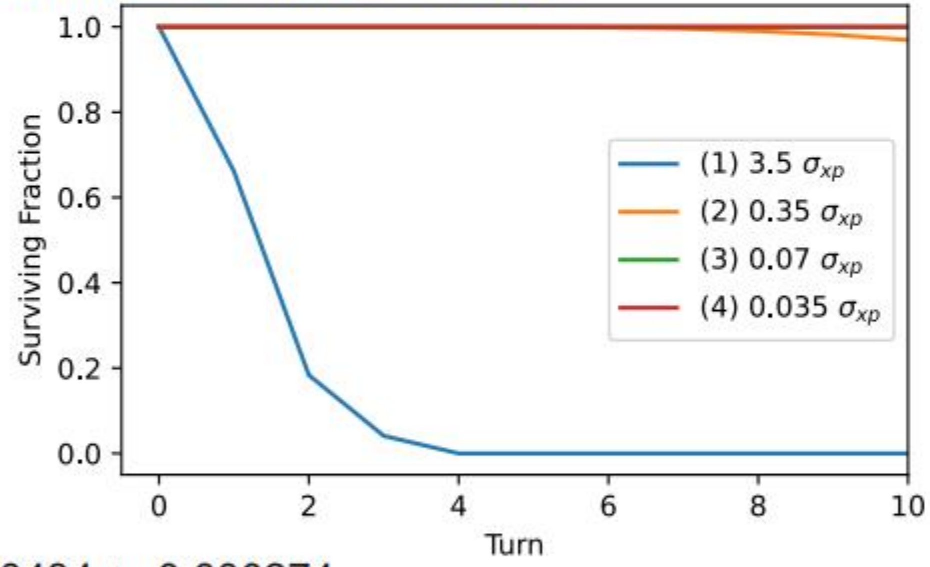
- **Huge losses observed in the simulation scenario**
  - Cleaning inefficiency of up to **0.1 m^{-1}** in the horizontal and **0.5 m^{-1}** in the vertical around the IPs
  - Translates to losses of up to **MJ / m** in the superconducting final focus quadrupoles
  - This loss energy is likely destructive for the final focus doublets, detectors, and / or the tungsten SR collimators there (not included)
  - **Due to the large excitation amplitude, primary particles impact the aperture bottlenecks directly, before being intercepted by the collimation system in PF** (may not be the same for other types of excitation)
- **Mitigation**
  - This loss scenario (**80% intensity loss over 2 turns**) is likely not tolerable without additional collimators close to and in-phase with the aperture bottlenecks, like the LHC tertiary collimators
  - **The decision whether to protect against this extreme case will have a profound impact on the design**
  - The loss scenario must be defined better for the FCC-ee
    - **Time-scale and percentage intensity loss**
    - **Driving process (location, transverse vs. longitudinal, etc.)**
    - **Specification of what losses the collimation system must handle**

Z-mode fast losses – additional investigation

- **It is possible in simulations to adjust the excitation intensity**
  - Invert the problem – what is the minimum lifetime tolerable before damage limits are exceeded
  - Need damage limits for the collimators, the halo and SR ones, and the IR magnets
  - Investigate other approaches of modelling the losses – **single kick, resonant kick, others**

Using different excitation amplitude for the B1H setup





(1) lifetime [s]: 0.000434 +- 0.000274
(2) lifetime [s]: 0.008514 +- 0.007099
(3) lifetime [s]: 0.163935 +- 0.140128
(4) lifetime [s]: 4.047940 +- 4.559846

Beam lifetime from exponential fit

Andrea Ciarma

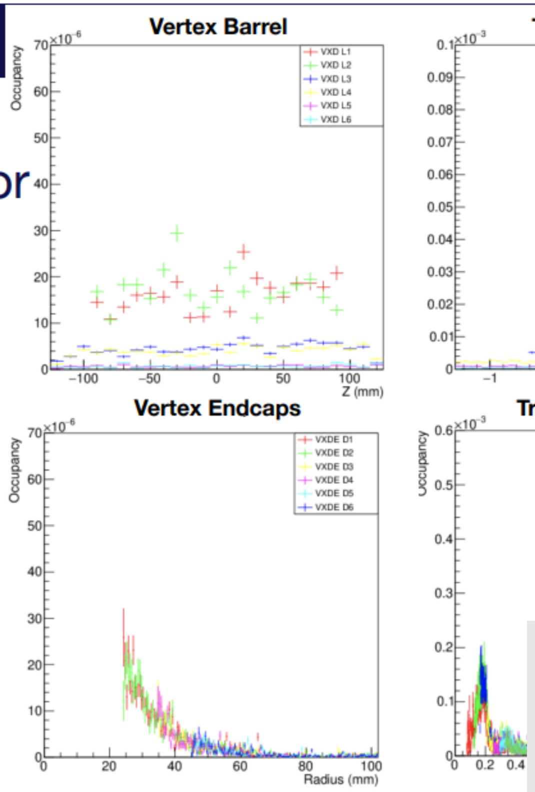
Background @Z
Horizontal Primary collimator

Beam losses coming from the **halo particles** intercepted by the horizontal primary collimator.

The losses happen few meters upstream the IP, so the most interested detectors will be the **tracker endcaps**.

For the Z working point, the maximum occupancy registered is **well below the 1%** in all the subtedectors

	Losses per second (10^9)	Highest occupancy
IPA	0.26	0.02% (ITE)
IPD	0.14	< 0.01% (ITE)
IPG	0.12	< 0.01% (ITE)
IPJ	0.39	0.11% (ITE)



Occupancy at IPA for Z worki

detector occupancy
for 5 min lifetime

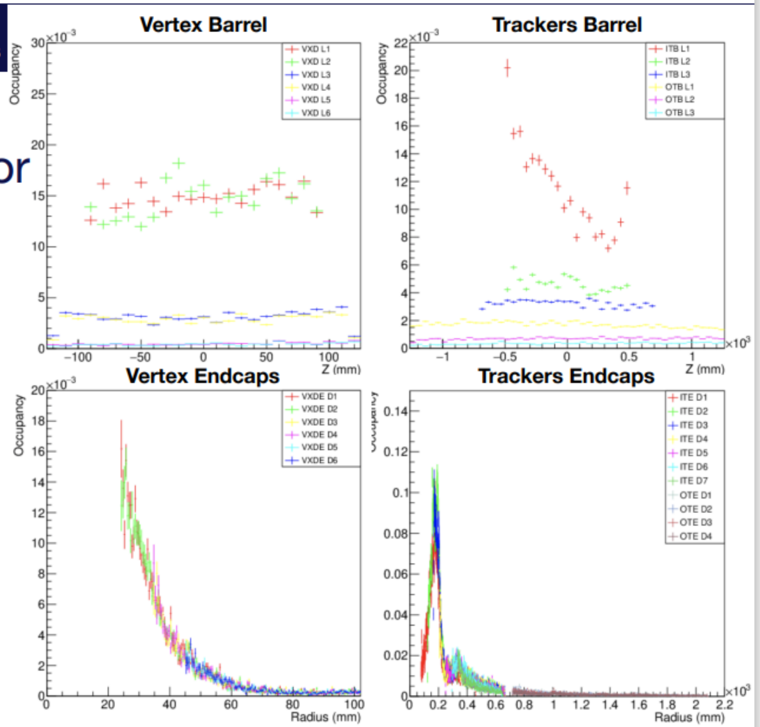
FCC FCCIS Workshop 2022 - CERN - 07/12/2022
Andrea Ciarma Failure Scenario Beam Losses

Background @Top
Horizontal Primary collimator

Going to the Top working point, the **induced background increases** a lot, reaching **several percents** in the inner tracker endcap, but also in the innermost layers of the other subdetectors.

This is due to the fact that, despite the losses per second are of the same order, the **number of bunches** is much lower now (40 vs 10'000), therefore the occupancy increases. A secondary factor is due to the particles **higher energy**.

	Losses per second (10^9)	Highest occupancy
IPA	0.15	10.95% (ITE)
IPD	0.11	7.78% (ITE)
IPG	0.10	6.41% (ITE)
IPJ	0.16	12.62% (ITE)



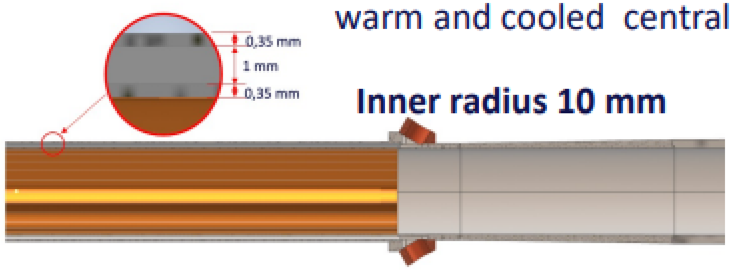
Occupancy at IPA for Top working point

IR mock-up

Manuela Boscolo

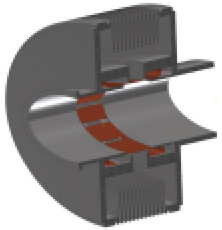
Main Prototypes Phase 1

warm and cooled central beam pipe



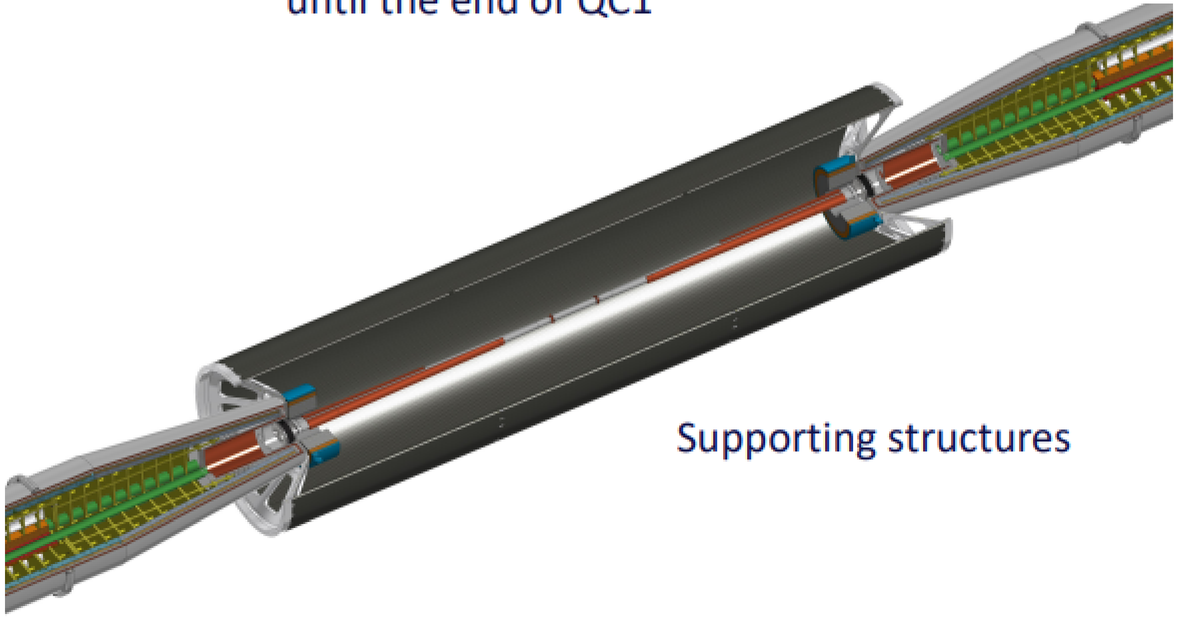
Inner radius 10 mm

Central chamber in AlBeMet162 with with
a double layer for the liquid coolant.



Bellow

Vacuum chamber with cooling system
until the end of QC1



Supporting structures

And:
- Remote flange
- 3D printed mock-ups of non-critical elements for this phase, but essential critical for phase 2
- Remote vacuum connection concept and prototype in collaboration with TE-VSC

IR mechanical model

Open questions (1)

Francesco Fransesini

- **Services** (cables and cooling) should be carefully taken into account
- **Detector design** is still preliminary, and some parts are represented only by an **envelope**, we will integrate further **details** when-available
- **LumiCal** should be split in **two halves** in order to be assembled, therefore it is necessary to **check the feasibility** and **study an alternative solution:**
  - ➢ Modify the geometry of the bellows to decrease the external diameter to fit in to the internal diameter of the LumiCal
  - ➢ Modify the geometry of the bellows to increase the internal space, adopting a conical shape (discussed during the FCC EIC joint meeting 10/2022

Clearance on internal surface for routing cables (drawing not in scale)

- It is necessary to study **how** and **where cylinder** can be **supported** inside the main detector

Beam tracking studies: preliminary results (1)

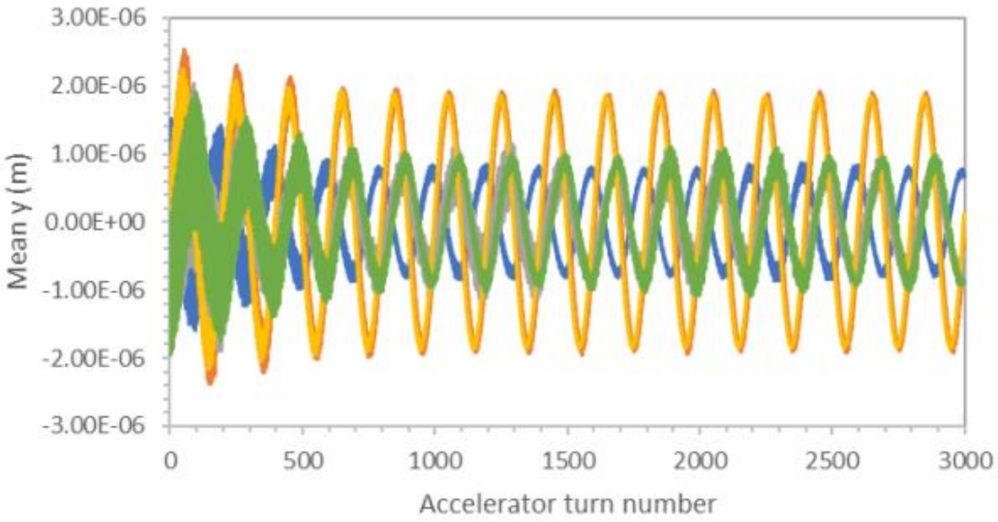
Eva Montbarbon,
Stanislas Grabon

First studies:

- Bunch of 200 electrons, gaussian beam
- Tracking study over 3000 turns (⇔ 1s beam time)

- *Sinusoidal vibration of all FFS quadrupoles:*
  - Frequency: 15 Hz
  - Amplitude: 1 μm
  - Random phase advance between all quadrupoles, fixed at the first turn

⇨ Simulation of 5 seeds to efficiently compare results



Observations:

- 15 Hz pattern noticed in each seed
- Amplitude of y mean and phasing between the seeds very different

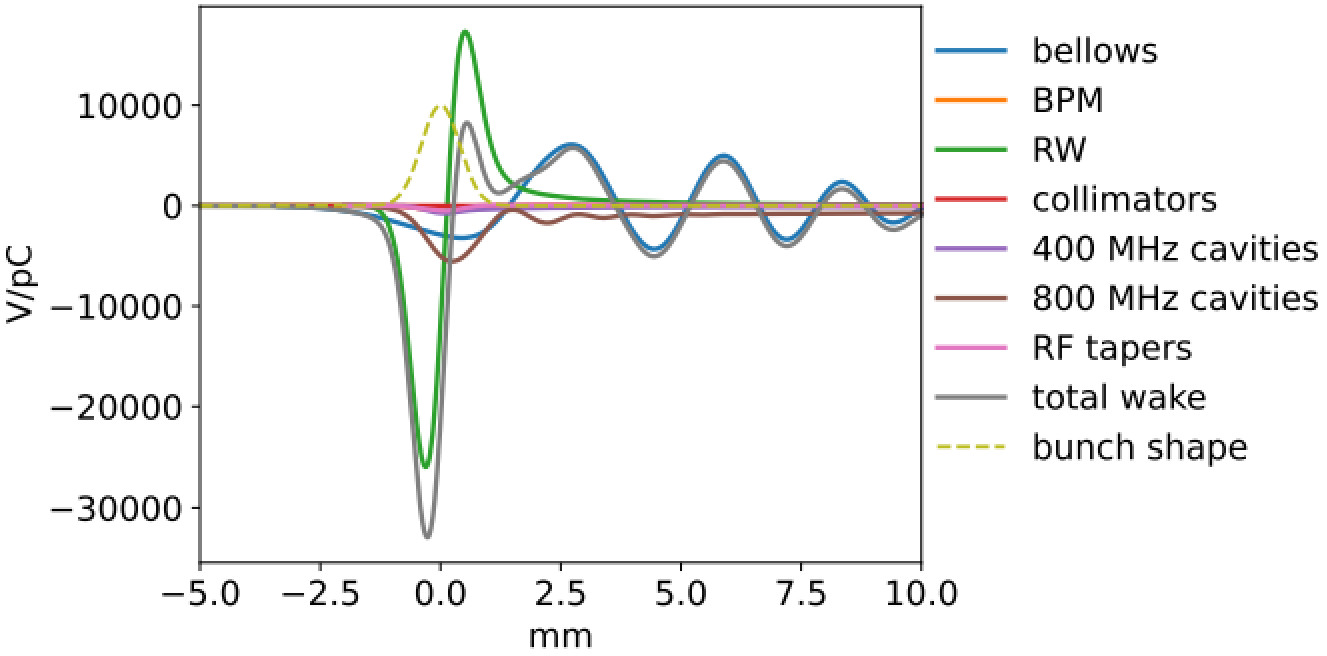
Question: what are the contributions of each FFS quadrupole?

longitudinal impedance

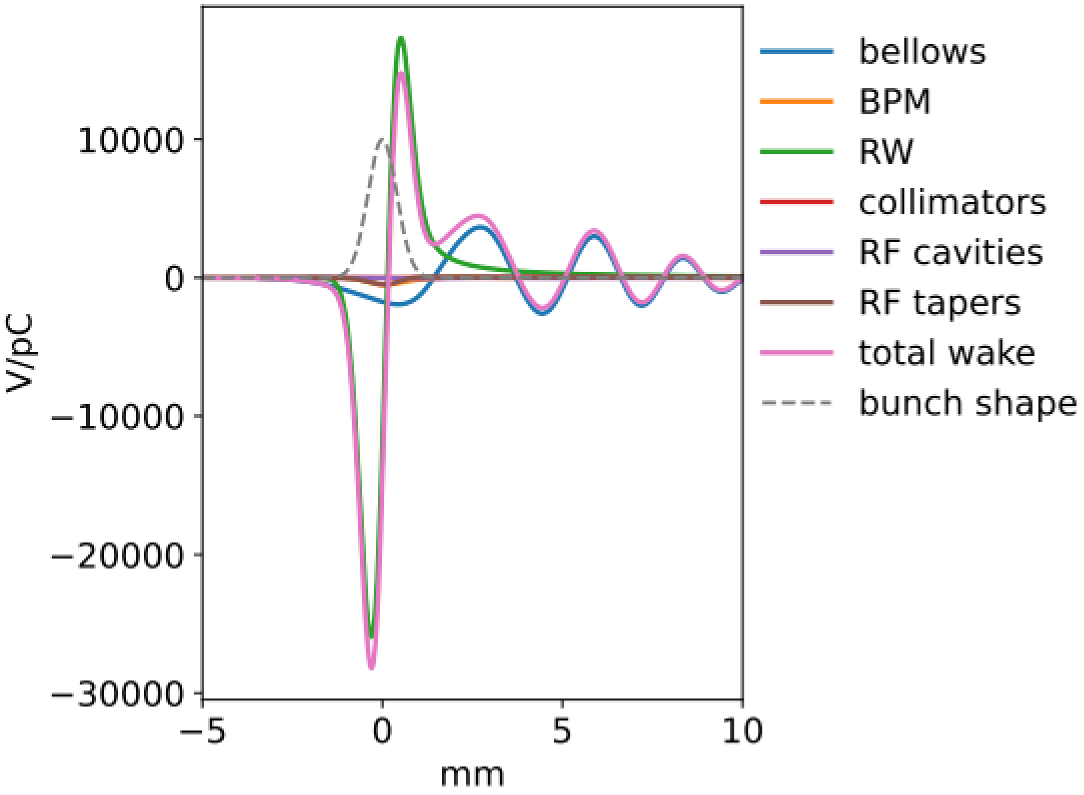
Mauro Migliorati

Z-pole with ttbar RF system

New wake (longitudinal)



Standard Z-pole wake (longitudinal)

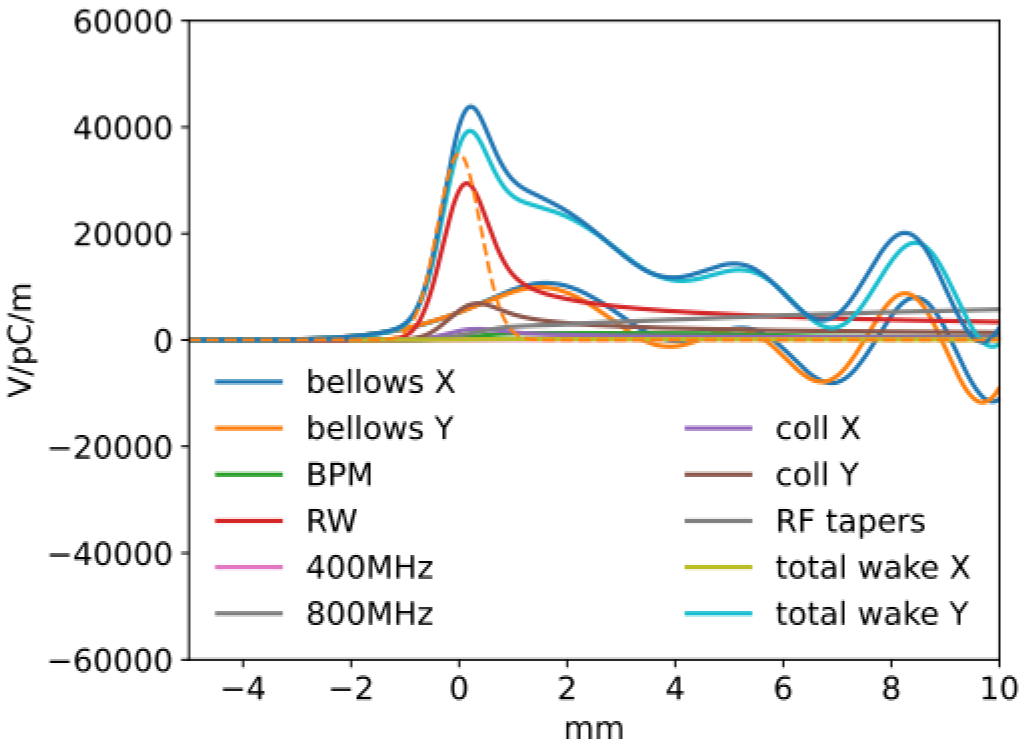


Mauro Migliorati

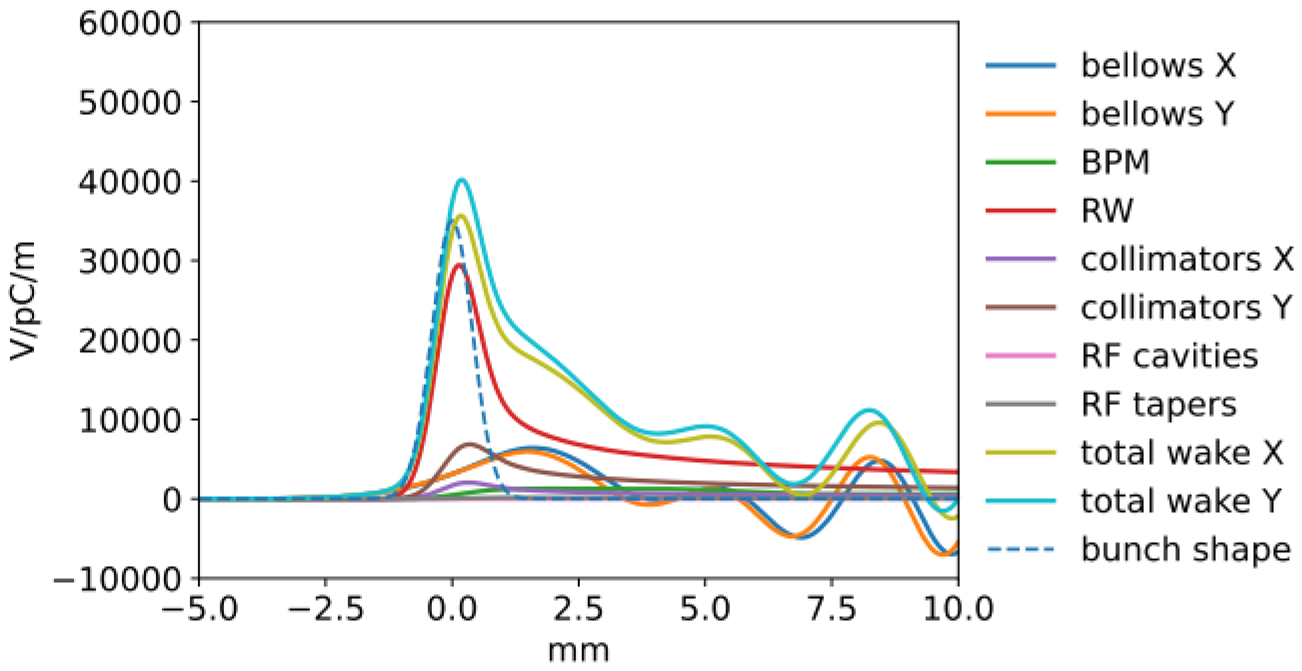
transverse impedance

Z-pole with ttbar RF system

New wake (transverse dipolar)



Standard Z-pole wake (transverse dipolar)

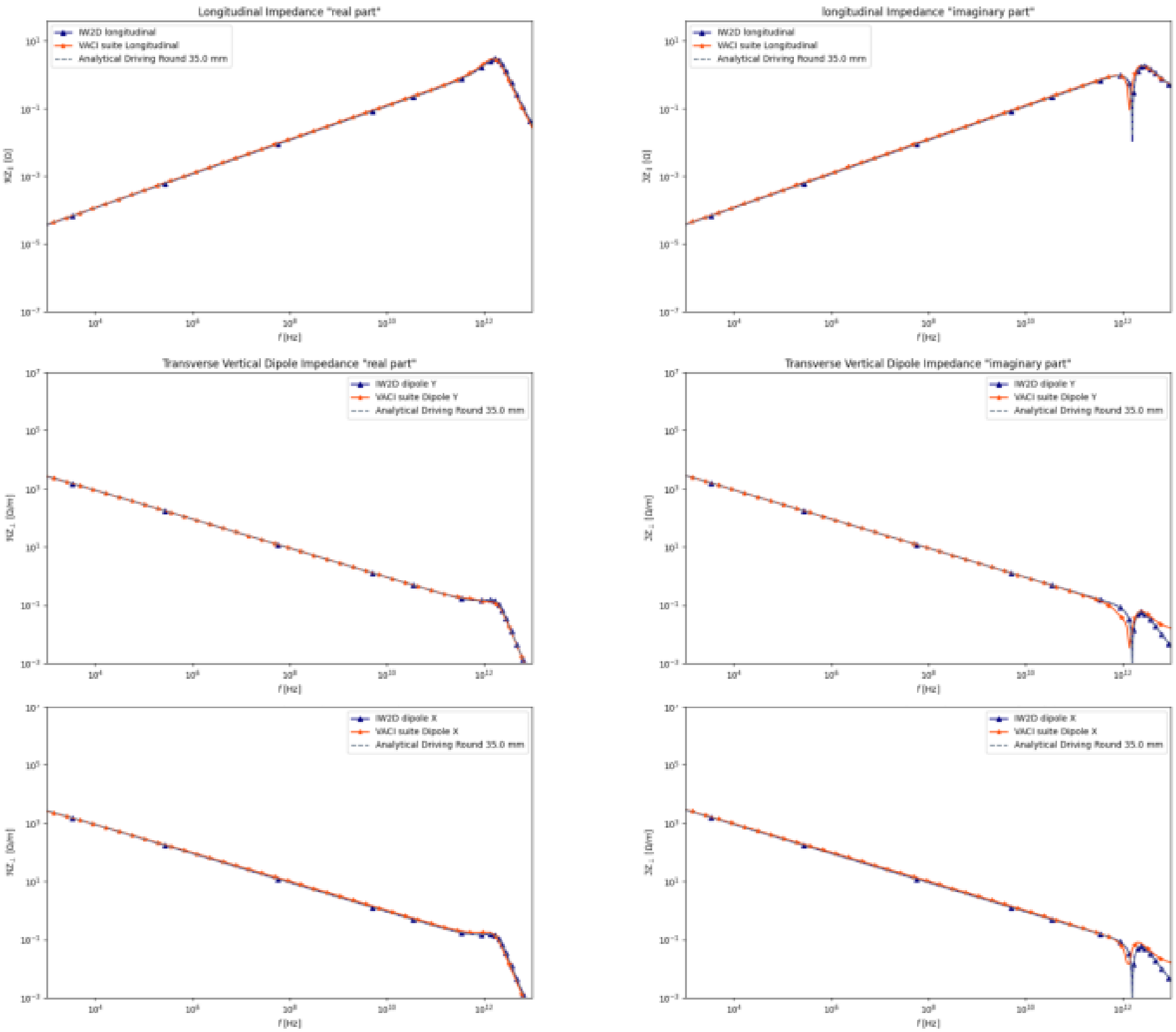


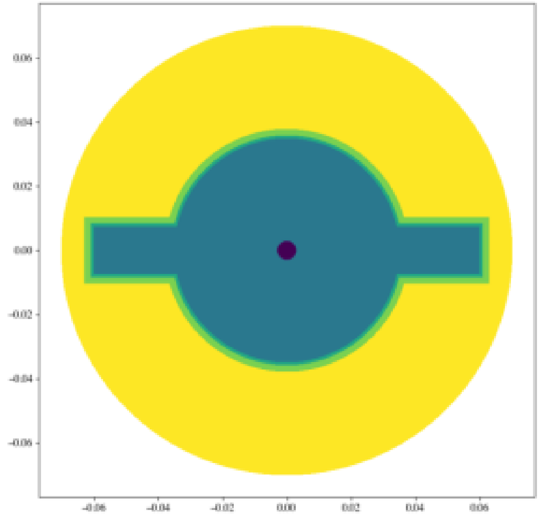
Ali Rajabi

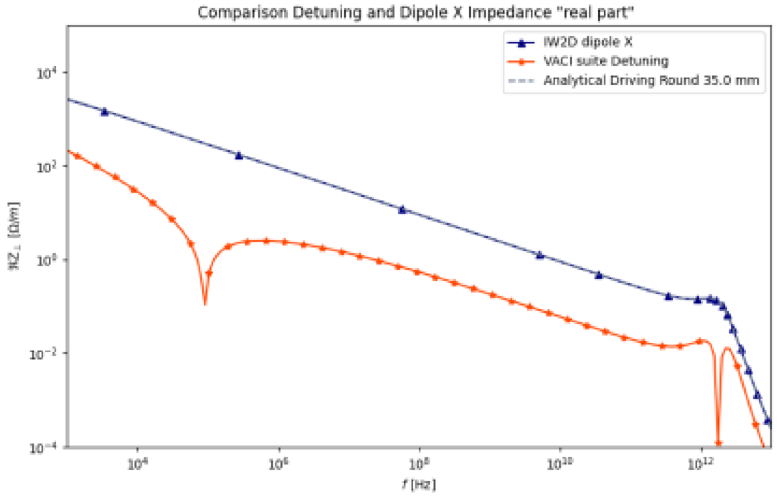
VACI results for FCC main ring

RW impedance

Copper Vacuum chamber
Length: 1m
No NEG considered.

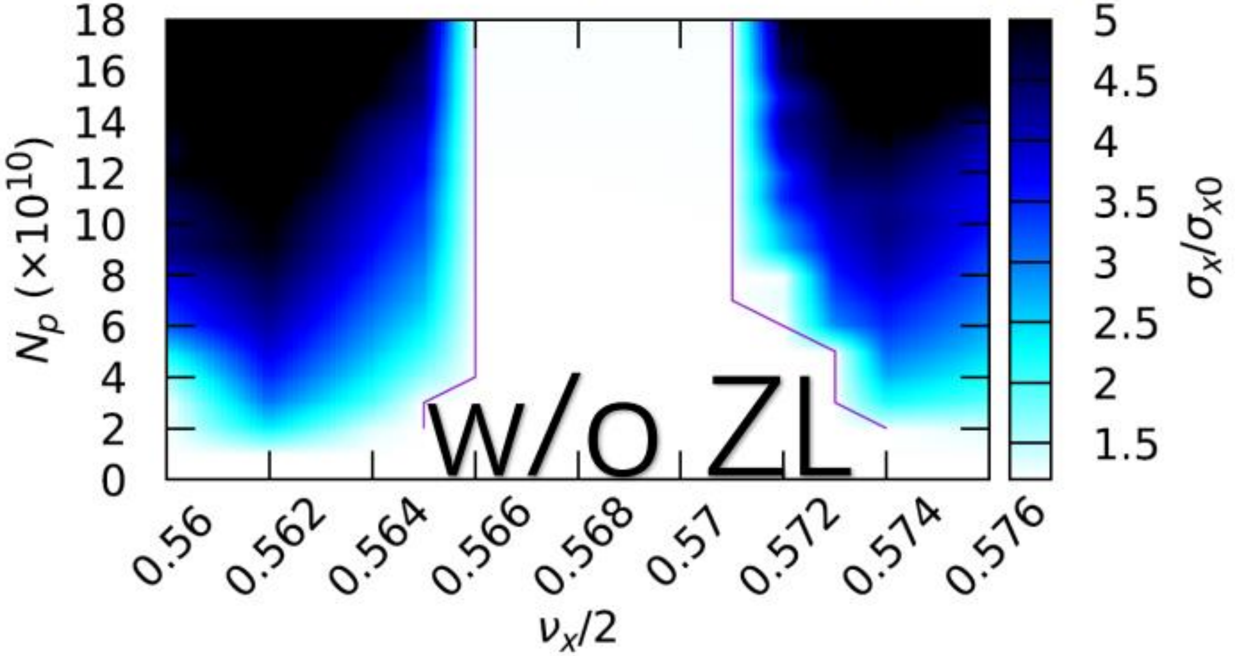


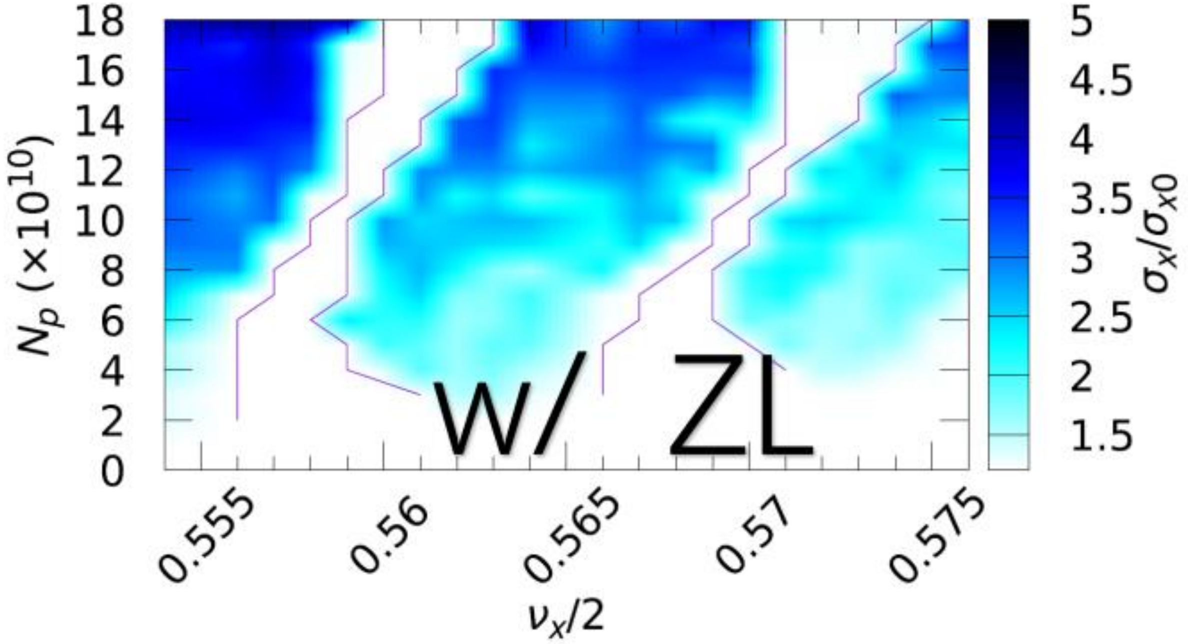




effect of longitudinal impedance

Eur. Phys. J. Plus (2021) 136:1190





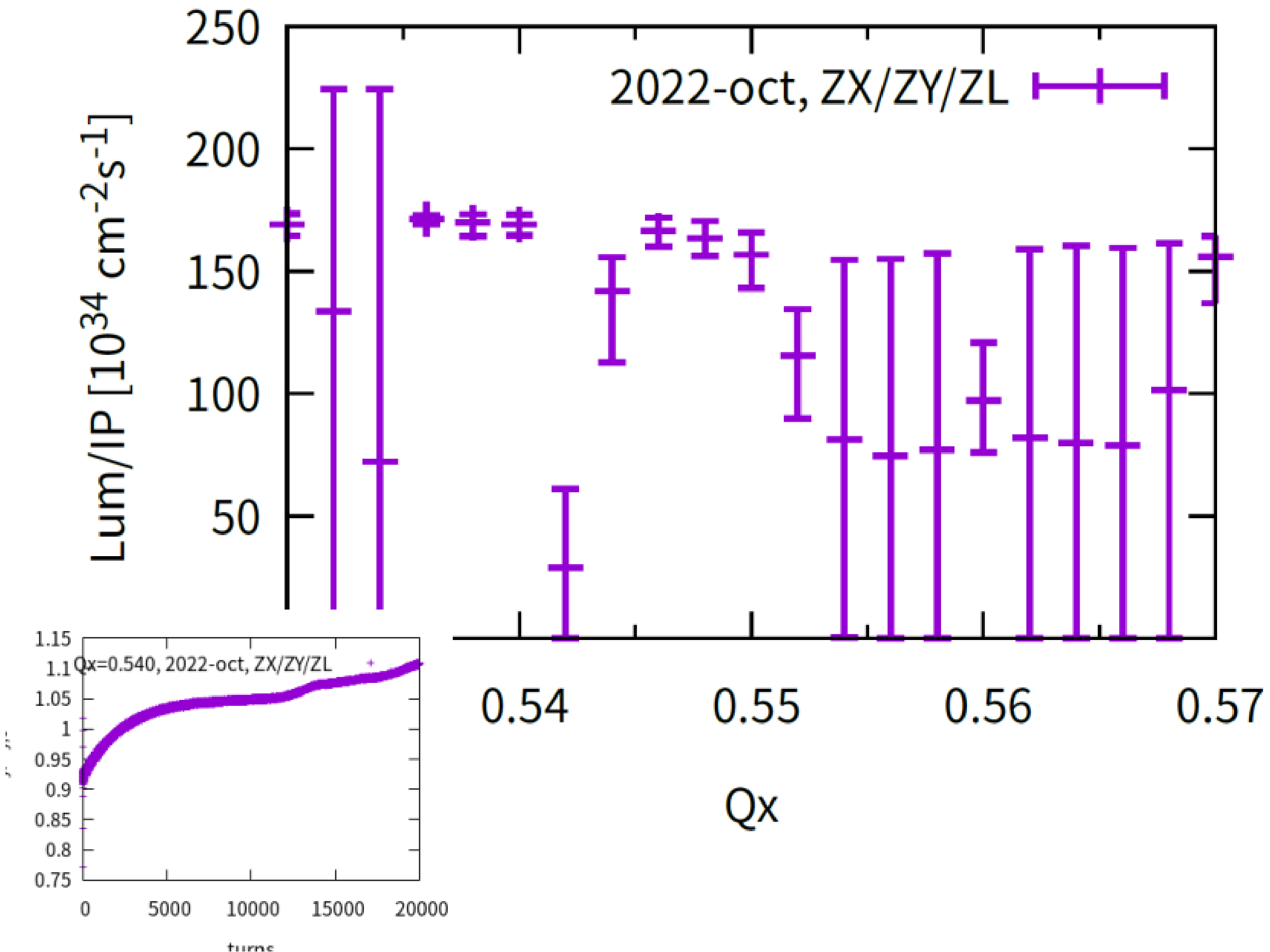
Yuan Zhang

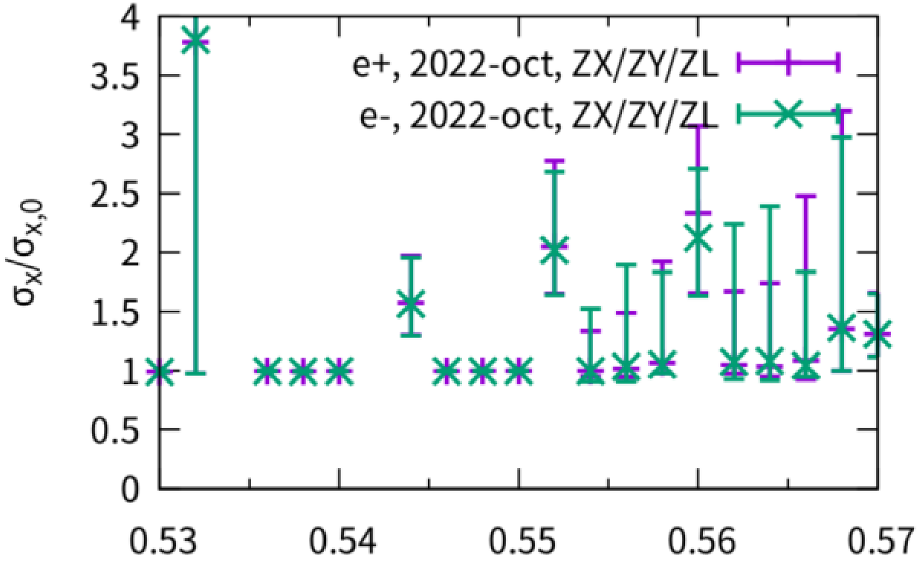
beam-beam with longit. & transv. impedance

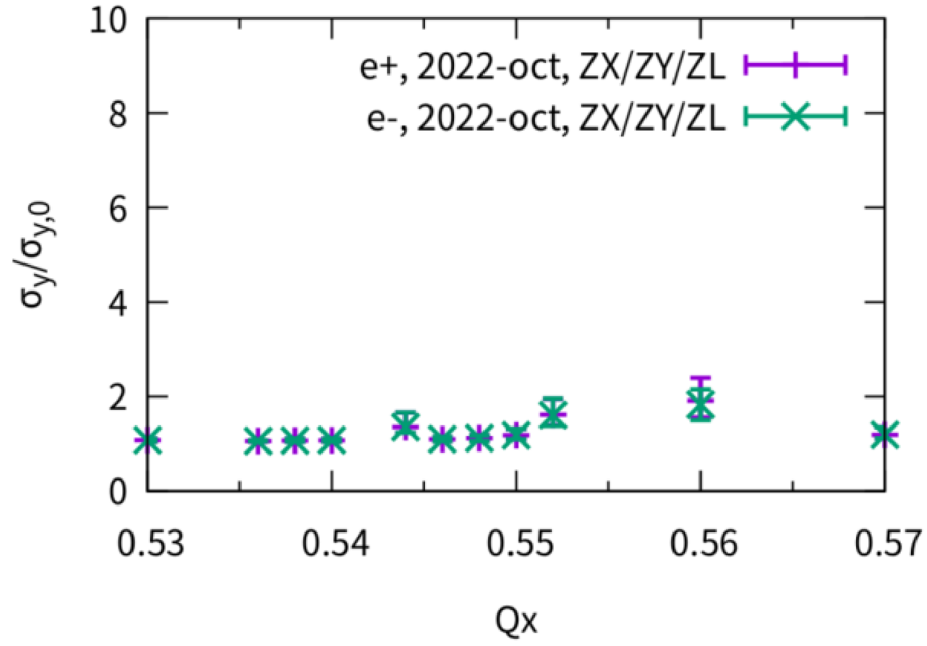
Yuan Zhang

Qy=0.600

Horizontal tune scan



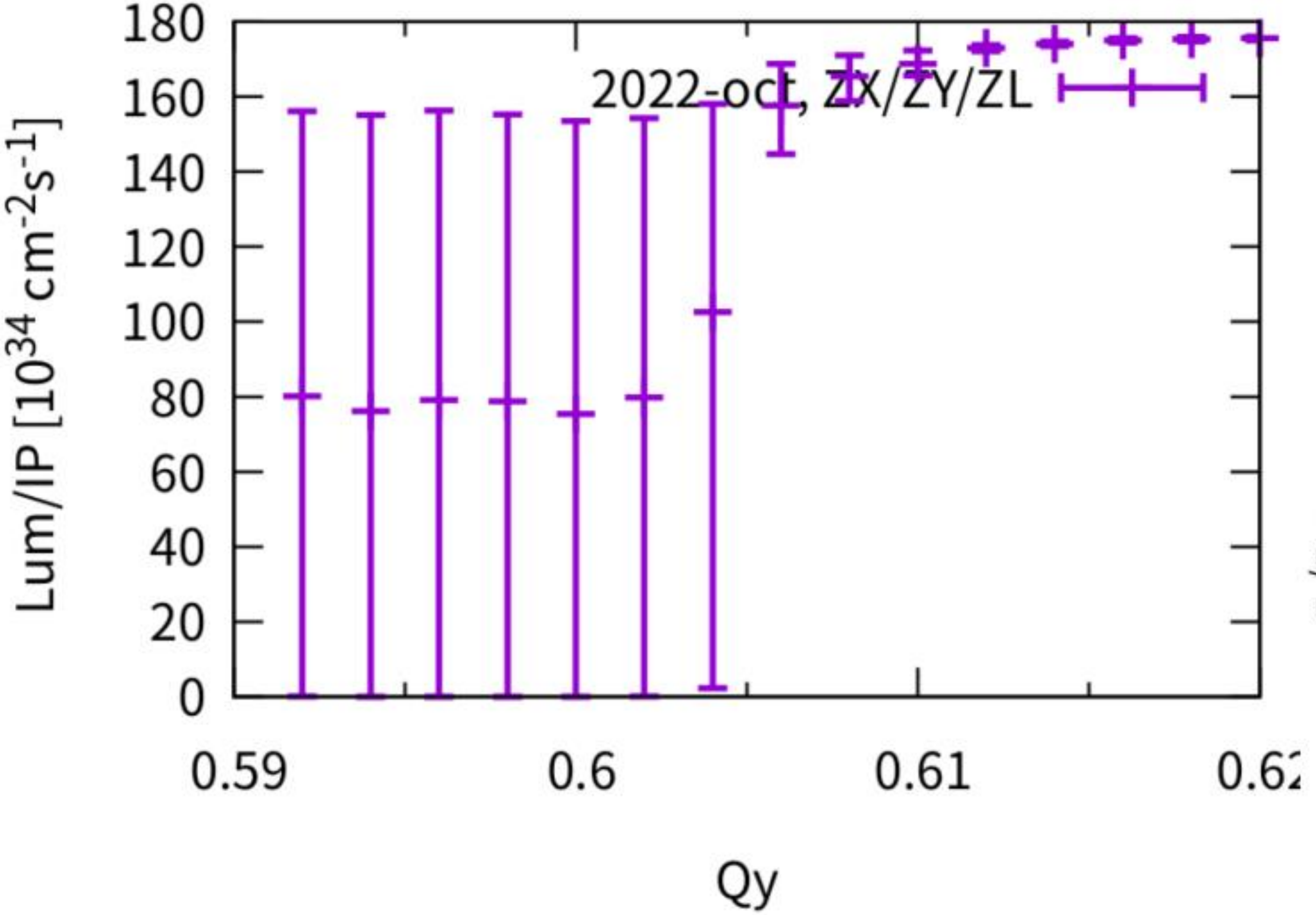


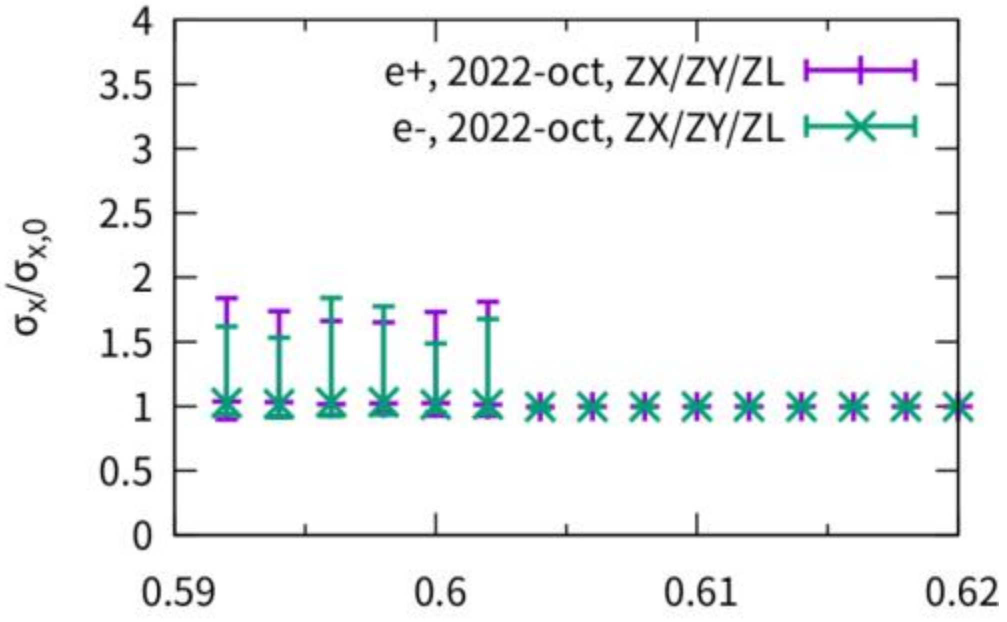


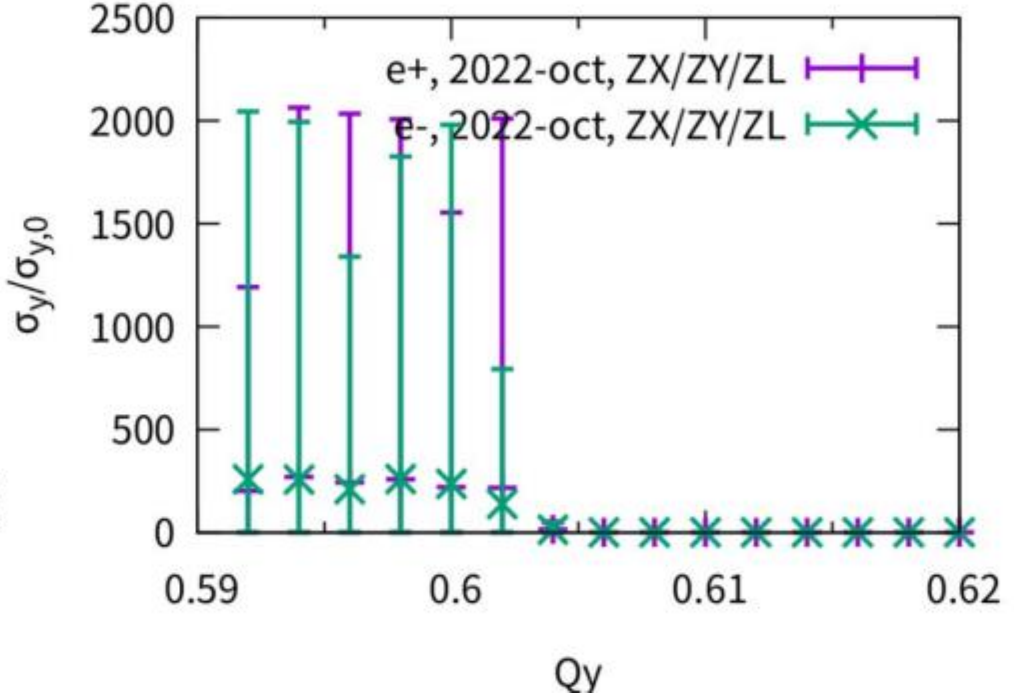
Yuan Zhang

Qx=0.556

Vertical tune scan

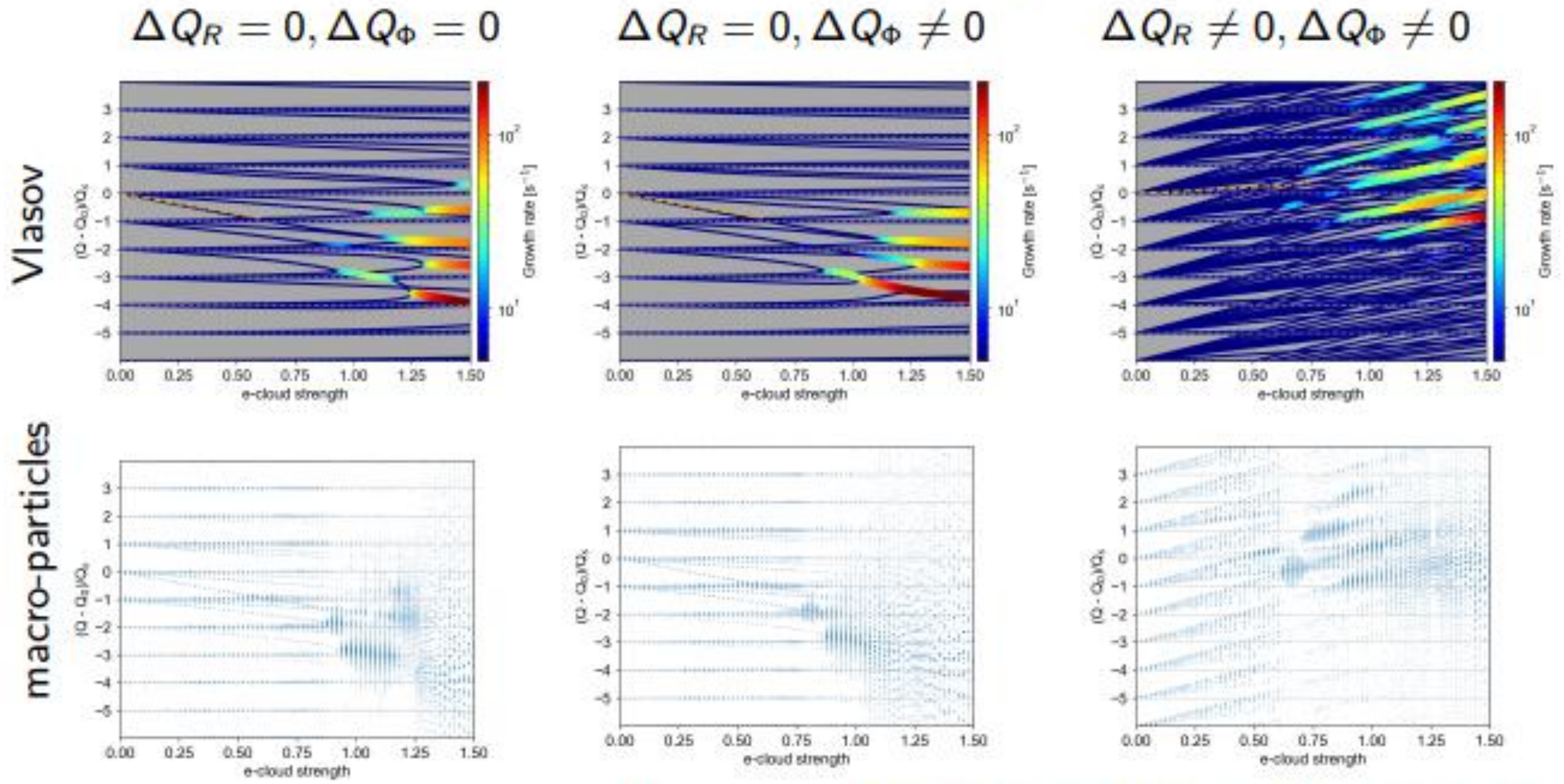






Sofia Carolina Johannesson

Results with zero chromaticity - Phase Shift



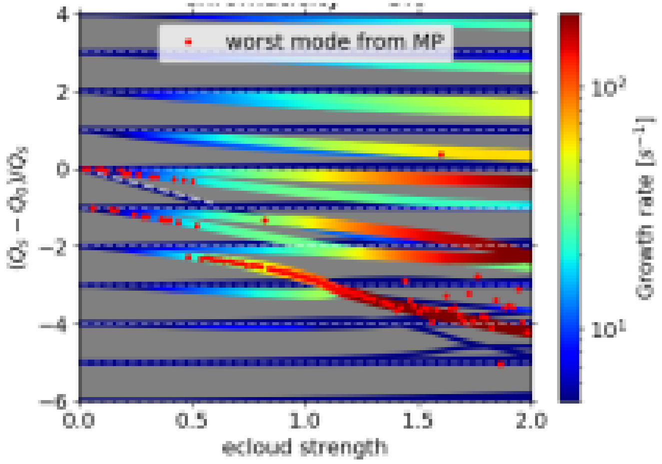
Include also detuning with longitudinal amplitude.

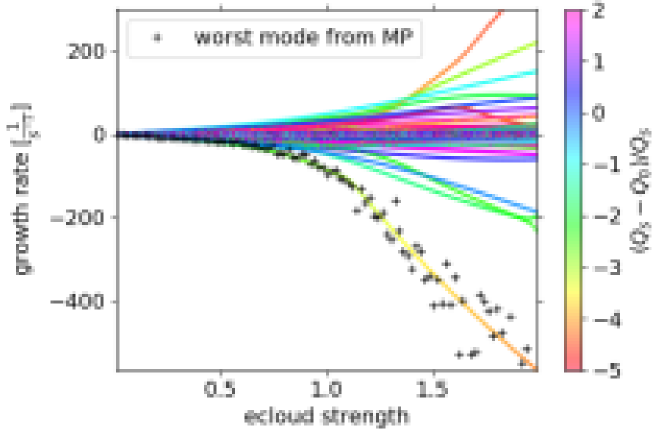
Modes agree when full detuning from e-cloud are included!

Sofia Carolina Johannesson

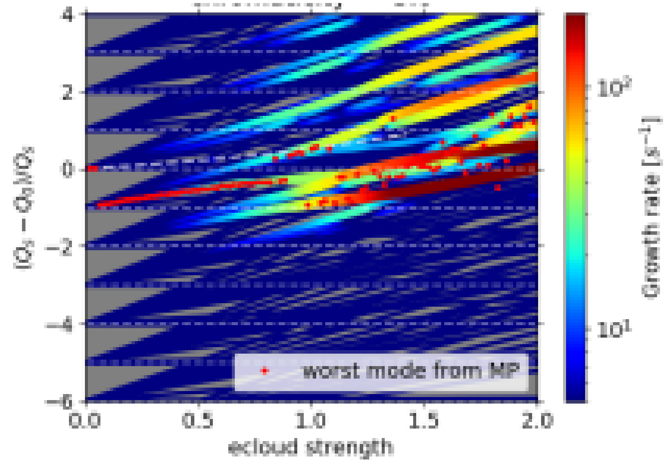
Chromaticity = -5

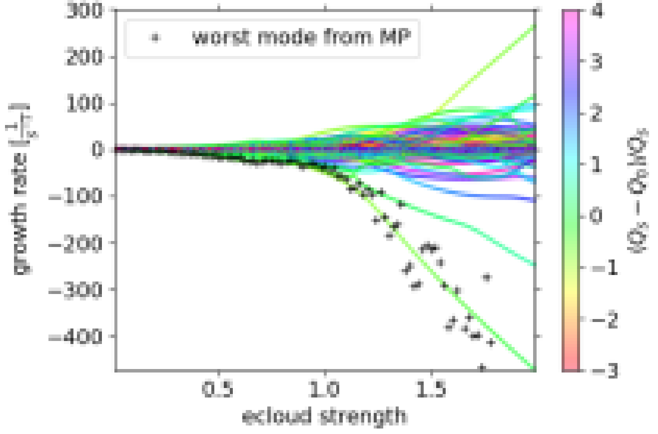
$\Delta Q_R = 0, \Delta Q_\Phi = 0$





$\Delta Q_R \neq 0, \Delta Q_\Phi \neq 0$



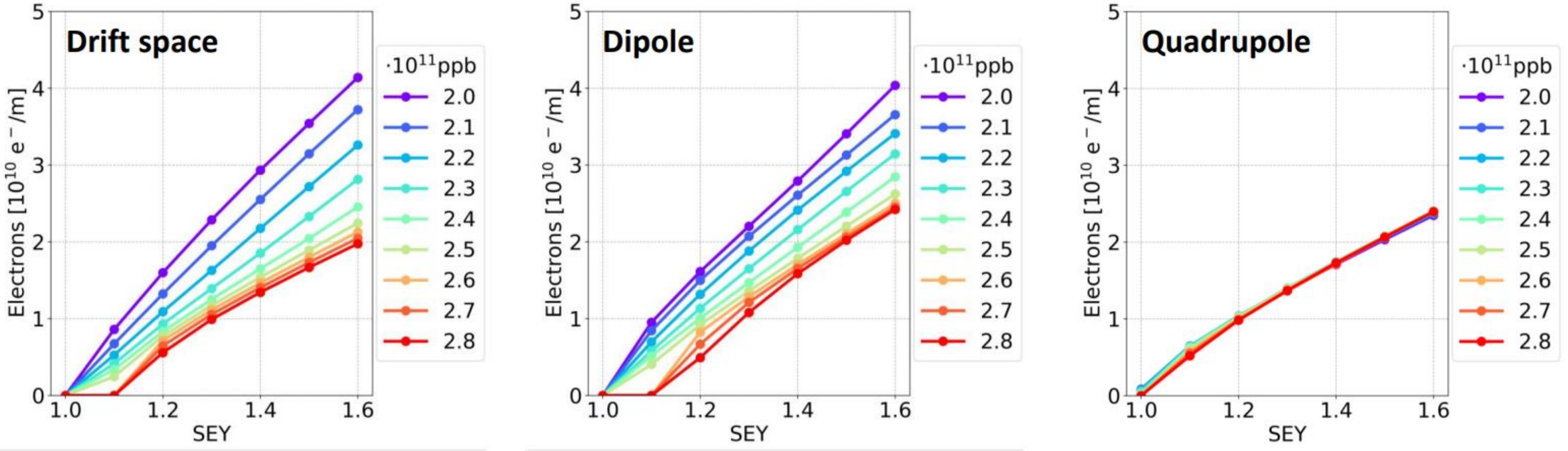


The macro-particle simulation results follow the behaviour of the worst mode from Vlasov.

Dependence on the elements and bunch spacing

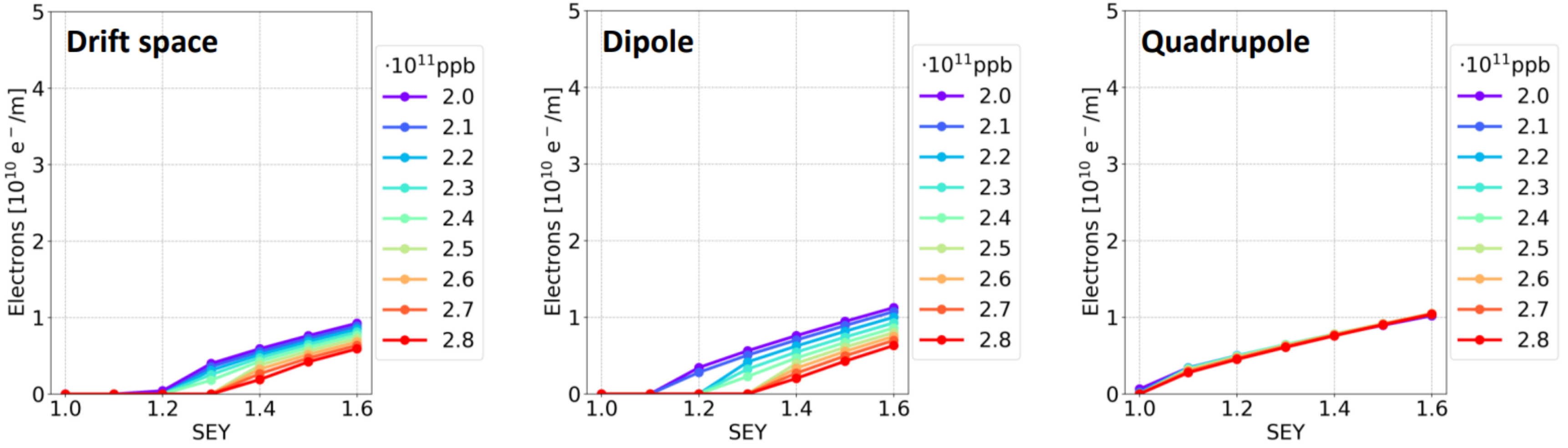
Luca Sabato

positrons, bunch spacing 10 ns



Dependence on the elements and bunch spacing

positrons, bunch spacing 20 ns

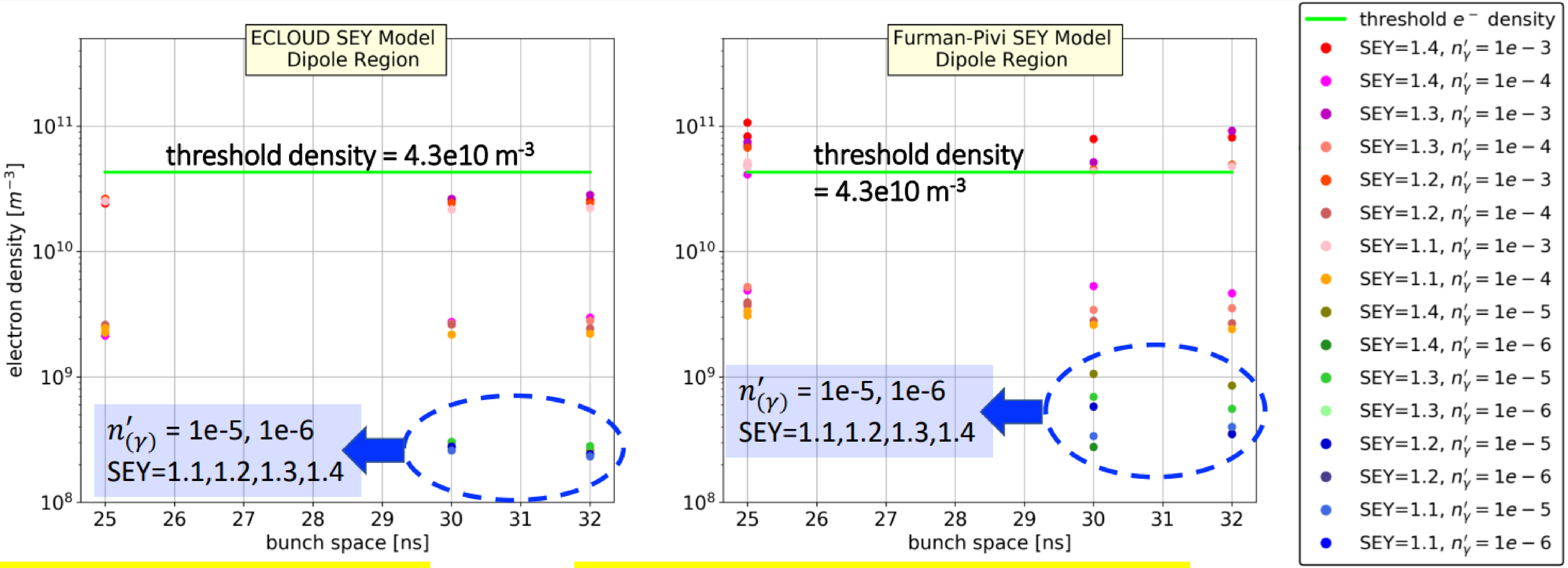


Larger bunch charge & larger spacing reduce cloud density

Behavior during injection?

Dipole Region

Fatih Yaman



SEY=1.4 still OK

Can we achieve $n_\gamma' < 10^{-3}$ / e+/m?

ECLOUD Model, $n'_{(\gamma)}$ = (1e-3, 1e-4, 1e-5, 1e-6)m^{-1}, r = (30, 35)mm, BS=(25, 30, 32)ns, SEY=(1.1,1.2,1.3,1.4) ☺

Furman-Pivi Model, $n'_{(\gamma)}$ < 1e-3 m^{-1}, r = (30, 35)mm, BS=(25, 30, 32)ns, SEY=(1.1,1.2,1.3,1.4) ☺

Furman-Pivi Model, $n'_{(\gamma)}$ = 1e-3 m^{-1}, r = (30, 35)mm, BS=(25, 30, 32)ns, SEY=(1.1,1.2,1.3,1.4) ☹

16:30 → 18:00 **WP2 - Collider design**

31/3-004 - IT Amphitheatre (C...

Join

Convener: Andrey Abramov (CERN)

16:30 **Arcs and Straight sections: beam dynamics studies and optimization** 30m

Speaker: Dr Pantaleo Raimondi (SLAC National Accelerator Laboratory (US))

Arcs and straight se... | Arcs and straight se...

17:00 **Final Focus design with local compensation of geometric and chromatic aberrations** 30m

Speaker: Dr Pantaleo Raimondi (SLAC National Accelerator Laboratory (US))

Final Focus beam d... | Final Focus beam d...

17:30 **Optic subsystems integration and general considerations** 30m

Speaker: Dr Pantaleo Raimondi (SLAC National Accelerator Laboratory (US))

Optics subsystems i... | Optics subsystems i...

~2 hours with complete solution

Premise

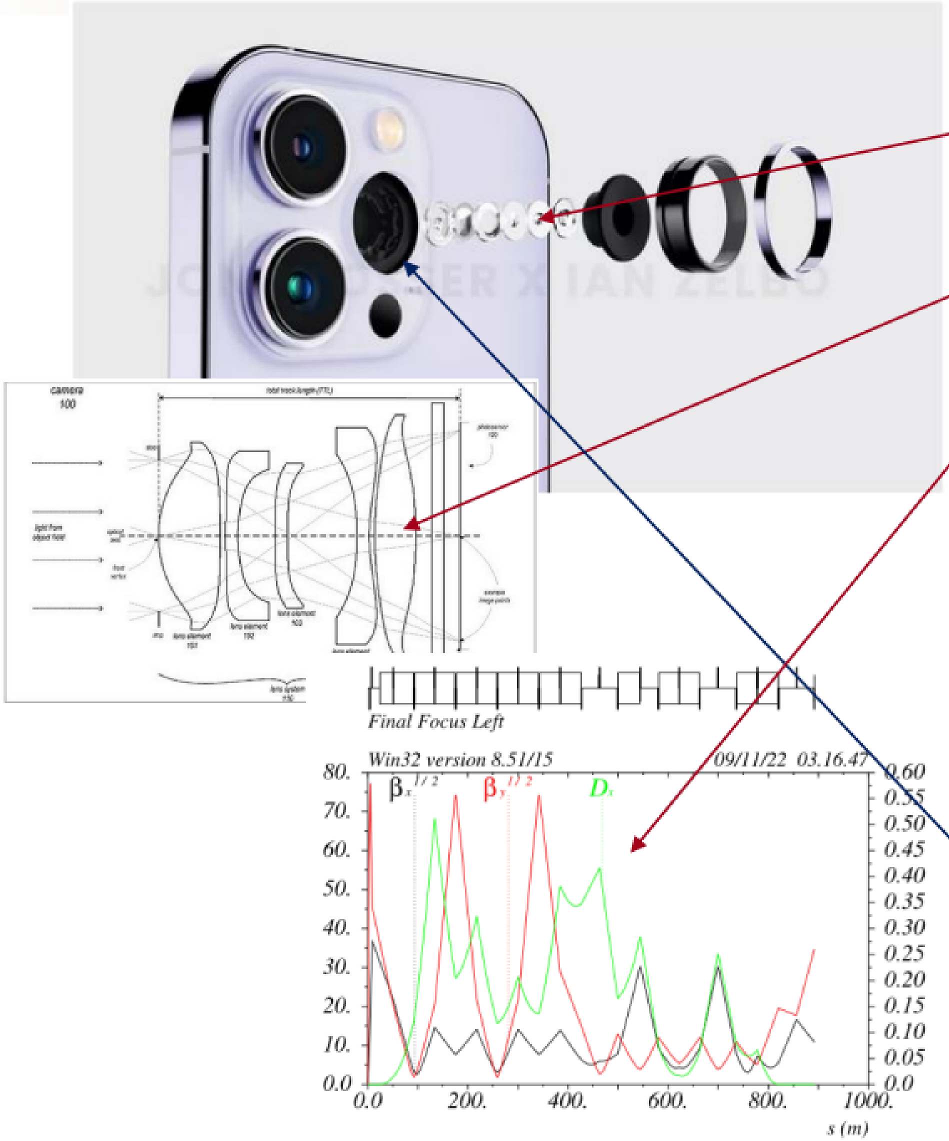
SLAC

This work has been triggered by M Benedikt and F Zimmermann, they did ask me to investigate the possibility of relaxing tolerances on machine errors, specifically alignment requirements.

About 3 presentations (minimum) are required to explain in a reasonably analytical/exhaustive way the proposed solution to this not trivial problem.

Pantaleo Raimondi

Can we beat the competition?



- Iphone camera system “industrial grade” is extremely compact efficient and cheap.
- **9 lenses** (many are special) are all what is needed to make a nearly chromatic and aberrations free telescope.

- I thought that accelerator optics could never match this, but I am not so sure anymore

The FF has 24 lenses.
It can be assumed the sextupoles+nearby_quadrupoles to be single anamorphic lens (as the “special” iphone lenses)

Considering that for simplecticity reasons two independent systems are needed for X and Y plane, the FF is made of:

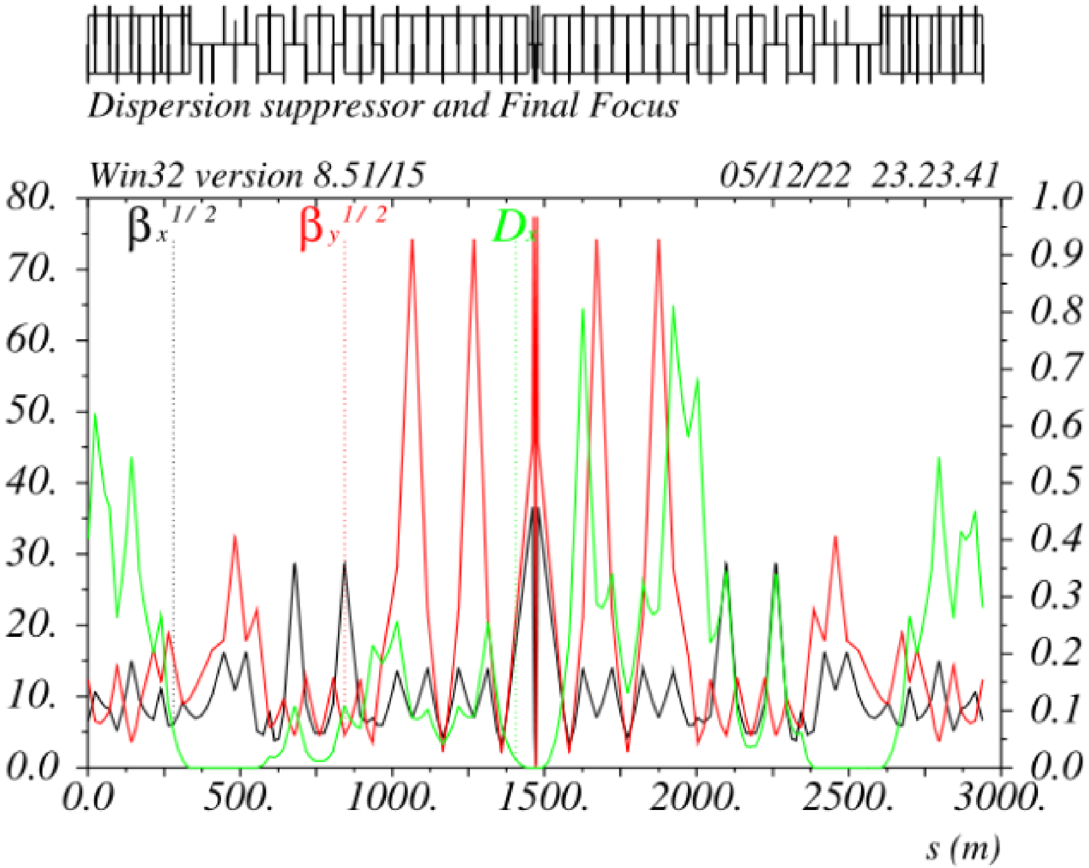
12 lenses/plane => not that far from the Iphone-FF !!!!

Iphone camera system resolution is further improved (~factor two) with computational power reprocessing the CCD image.

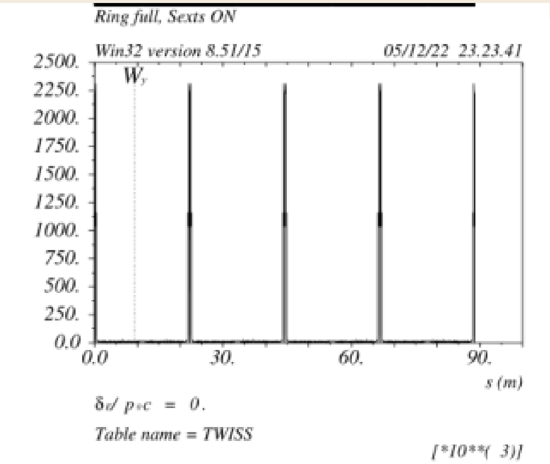
FF aberrations can be further reduced by further global optimization of FF+ARCs sextupoles

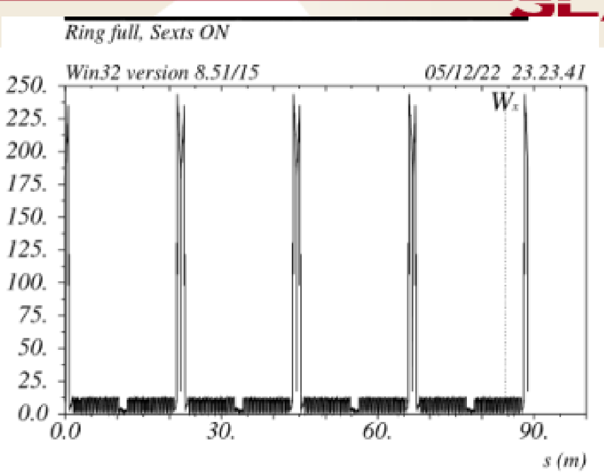
This new FCC FF optics as good as the iPhone !

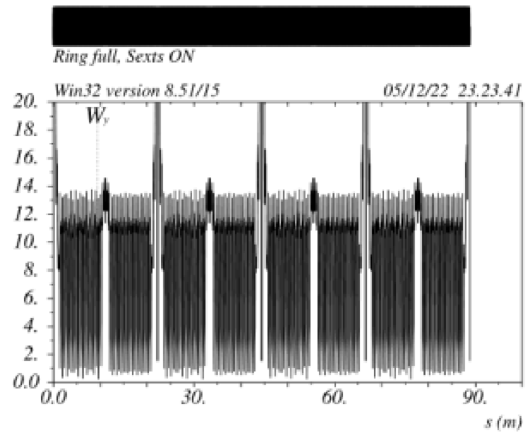
FFLR optics and chromatic properties of the complete ring v_34a1

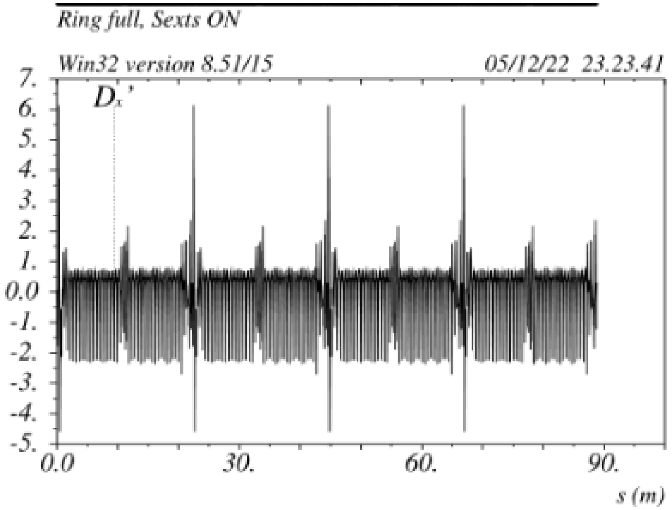


Matching sections optics is left-right symmetric as well









Ring chromatic functions are unaffected by inserting the FFs
ARC sextupoles are not changed as well

ARC sextupoles alignment tolerances

Pantaleo Raimondi

SLAC

- ARC sextupole alignment tolerances are relaxed at least proportionally to the reduction in their strength.

  This is effectively true for the Long-FODO9090 case that has similar betas and dispersion across the sextupoles..

  Tolerances should be further relaxed because the non-linear dynamics across the sextupoles is improved: dynamic betas are nearly identical to on-energy&on-axis ones. The fact that ARC sextupoles do not contribute (significatively) to the FF chromatic correction helps as well.

- Supposing that the present lattice requires 10um alignment tolerances (on both ends), HFD+LCCFF would most likely require 100-200um (on both ends) tolerances

  Alignment requirements on relative quad-nearby_sext positioning can be of the order of 50-100um.

  BBA can be performed (as for current machines) on the nearby quad, this will ensure that the absolute orbit on the sextupoles will not exceed the quad-sext positioning error and tolerances will be kept.

Implementation for FCC

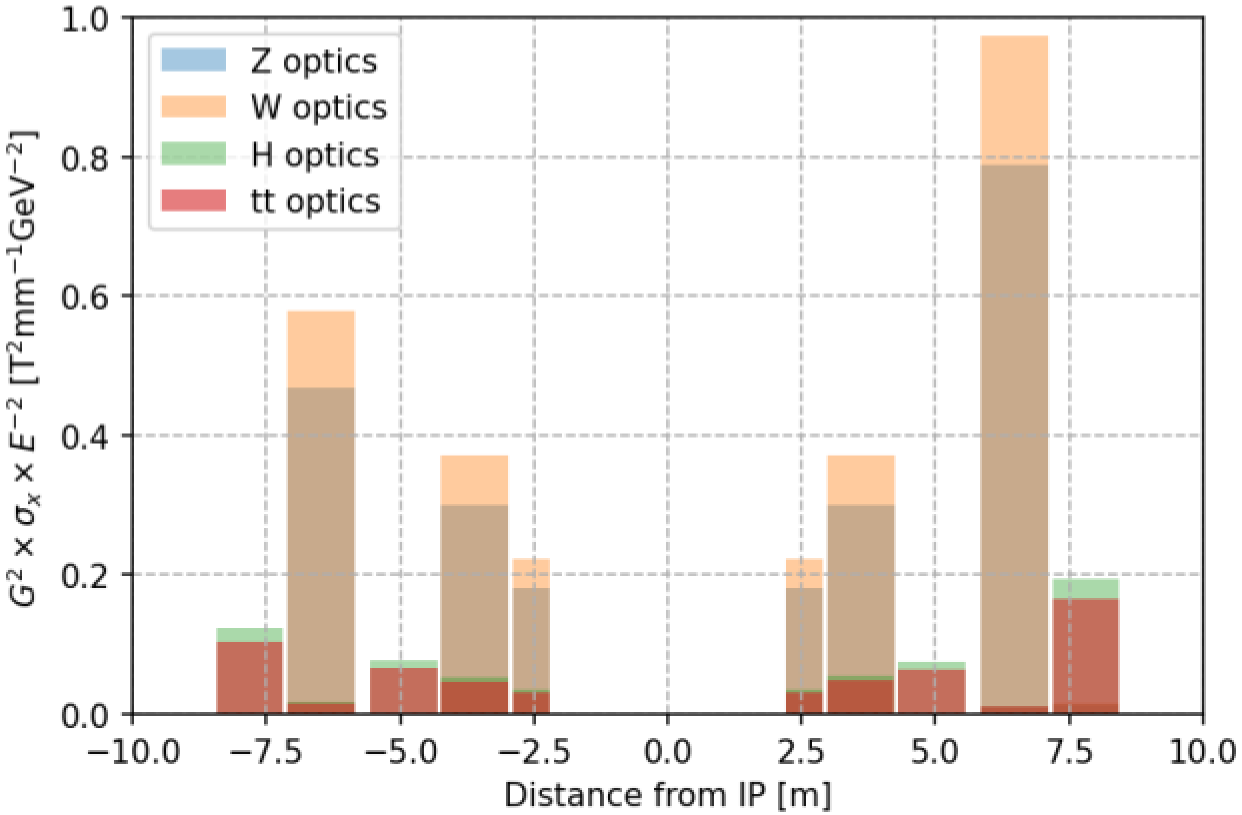
Solution for SuperKEKB ?

Kevin Andre

Figure of merit, synchrotron radiation from FF quadrupoles

N. Bernard analytical estimate from SR in quads [ref]

$$P = P_0 I_0 G^2 \left[\varepsilon_x \int_0^L \beta_x(s) ds + \varepsilon_y \int_0^L \beta_y(s) ds \right]$$



The function $G^2\sigma_x E^{-2}(s)$ represents a figure of merit to estimate SR from quadrupoles. As the beam current is scaled according to E^4 for the various operation modes of FCC-ee.

The amount of synchrotron radiation emitted in the FF quadrupoles strongly depends on the optics designs and quadrupole gradients.

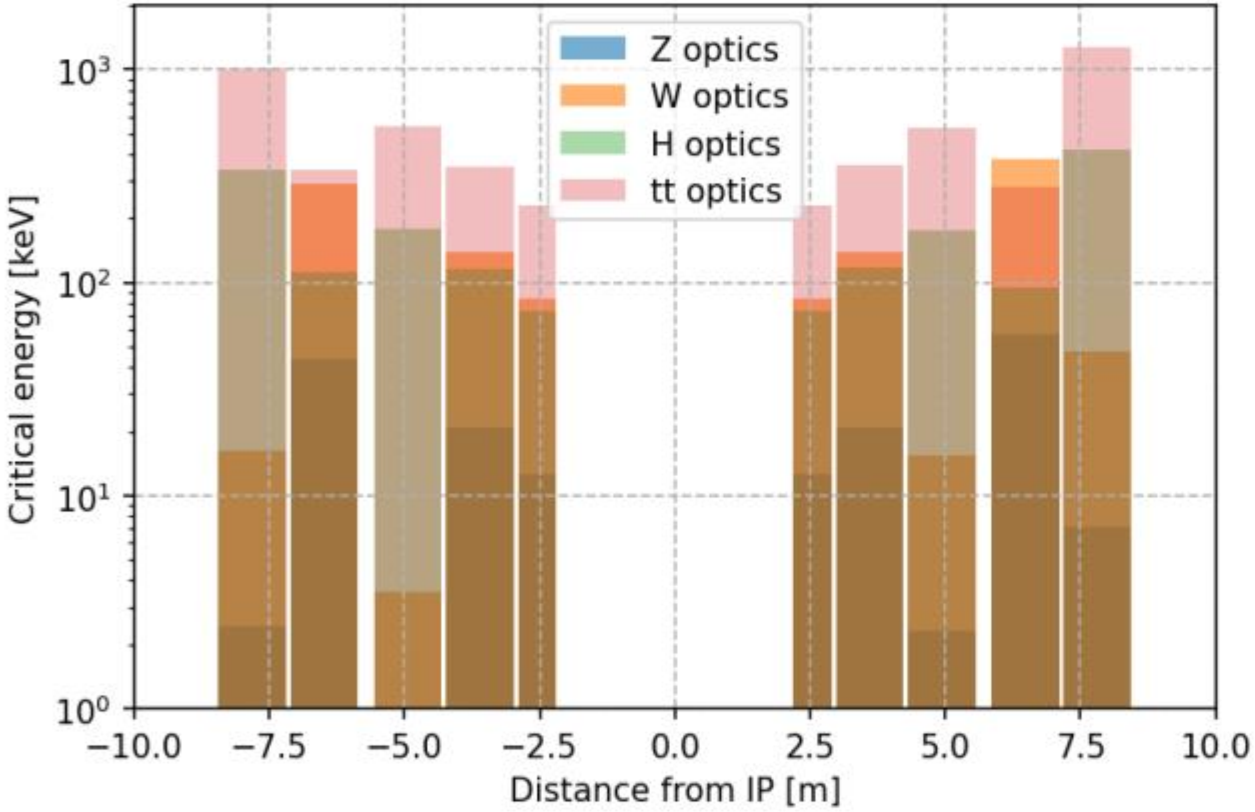
	P /W	P /W	P /W	P /W
Mode	Z	W	H	tt
QC2L2	13	20	742	547
QC2L1	**4101**	**6266**	86	65
QC1L3	1	1	249	204
QC1L2	**1125**	**1812**	124	116
QC1L1	242	410	32	33
QC1R1	242	410	32	33
QC1R2	**1127**	**1815**	129	120
QC1R3	12	19	243	199
QC2R1	**6939**	**10599**	60	45
QC2R2	111	169	**1176**	866

Kevin Andre

Figure of merit, synchrotron radiation from FF quadrupoles

Critical energy analytical estimate from SR in quads:

$$E_{crit} = \frac{3\hbar c E^3}{2(m_e c^2)^3} \frac{G}{B\rho} \sqrt{\left[\varepsilon_x \int_0^L \beta_x(s)ds + \varepsilon_y \int_0^L \beta_y(s)ds\right]}$$



The function $G\sigma_x E^2(s)$ represents a figure of merit to estimate the critical energy from quadrupoles. It does not depend on the beam current and scales with E^3.

The different operation modes will produce different photon energies with the higher beam energy producing higher photon energies.

	E/ keV	E/ keV	E/ keV	E/ keV
Mode	Z	W	H	tt
QC2L2	3	18	**373**	**1127**
QC2L1	48	**321**	**128**	**389**
QC1L3	1	4	**219**	**695**
QC1L2	26	**179**	**154**	**523**
QC1L1	12	83	78	**278**
QC1R1	12	83	78	**278**
QC1R2	26	**176**	**157**	**533**
QC1R3	3	18	**216**	**687**
QC2R1	62	**417**	**107**	**325**
QC2R2	8	53	**470**	**1417**

Kevin Andre

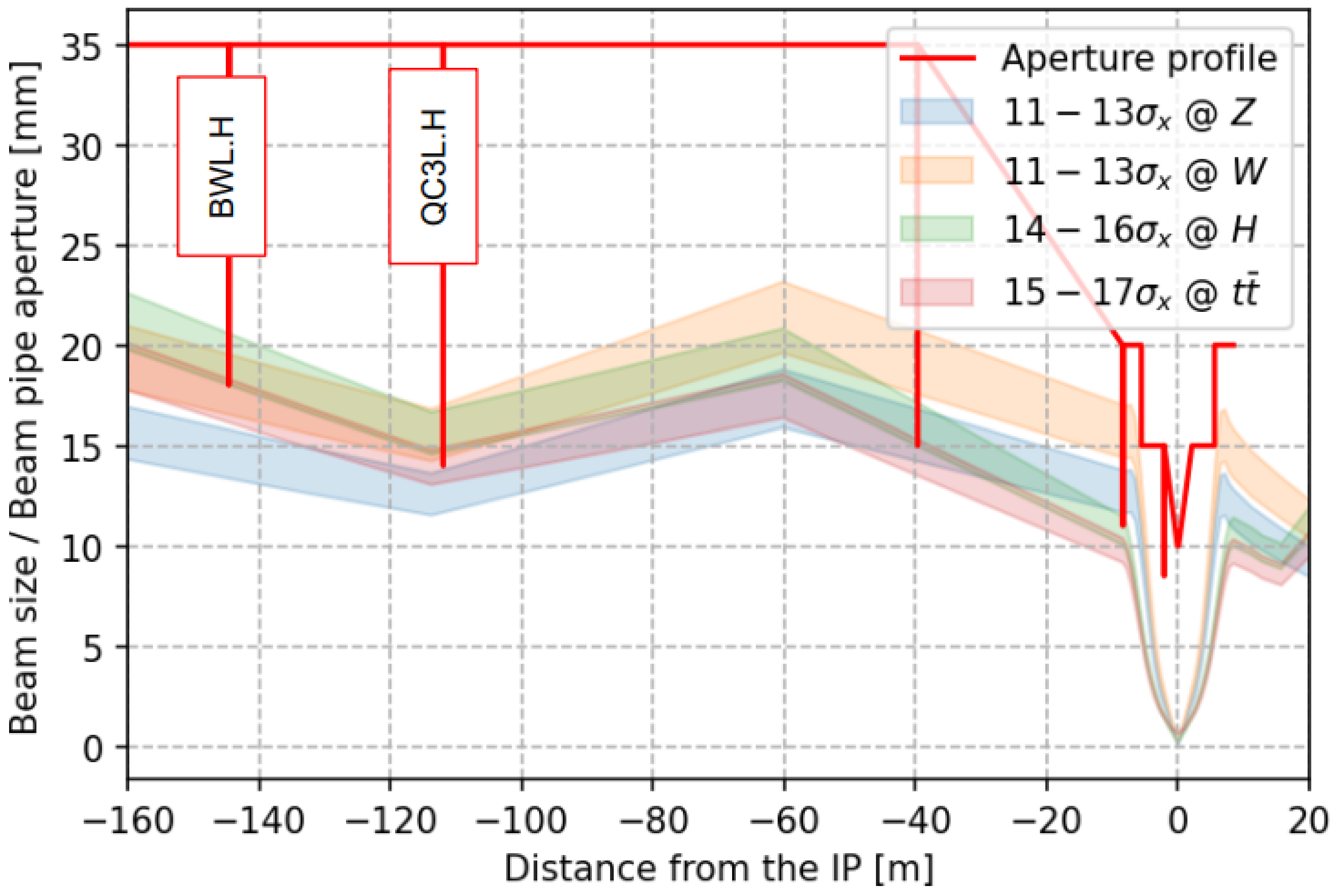
Synchrotron radiation collimation scheme

BWL: might be a problem @ H, but can be re-optimised once BWL dipole will be split. *Not critical*.

QC3L: Ok @ Z and tt, but difficult @ W and H. Could be more opened but more SR power would be deposited in the beam pipe. *Not critical*.

QT1L: Ok @ tt, *difficult for Z, W and H.* Can be opened more but more SR will propagate to PQC2LE and will represent an issue for Z and W modes.

PQC2LE: Ok @ H and tt, but requires more opening @ Z and W. Less protection of QC2L and may require to close MSK.QC2L further (radial mask).



The primary and secondary collimator settings for **W** and **H** are speculative. There are no issues in the vertical plane.

IR collimators sometimes closer to beam than primary or secondary collimators

booster design

Antoine Chancé

larger dipole field errors?

Orbit sawtooth effect on the ramp and at top energy

minimum injection energy?

DA at injection (20 GeV) with multipole errors

FUTURE CIRCULAR COLLIDER

Static dipole field errors of the CT dipole design at 56Gs considered + 10% random part

Dynamic field effect not taken into account in this simulations: dipole and multipole reproducibility expected to be $\leq$ **5×10^-4**

Dynamic Aperture defined as
Stable initial amplitude @ 4500 turns (~15% tx 20 GeV)

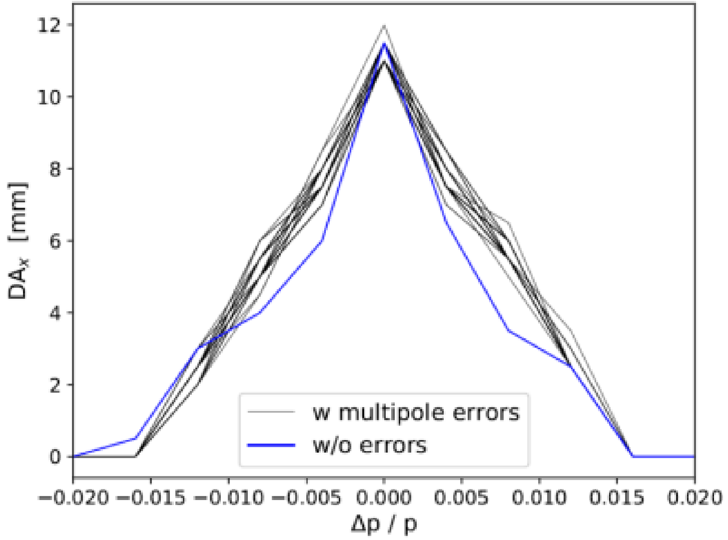
Courtesy of F. Zimmermann and Jie Gao

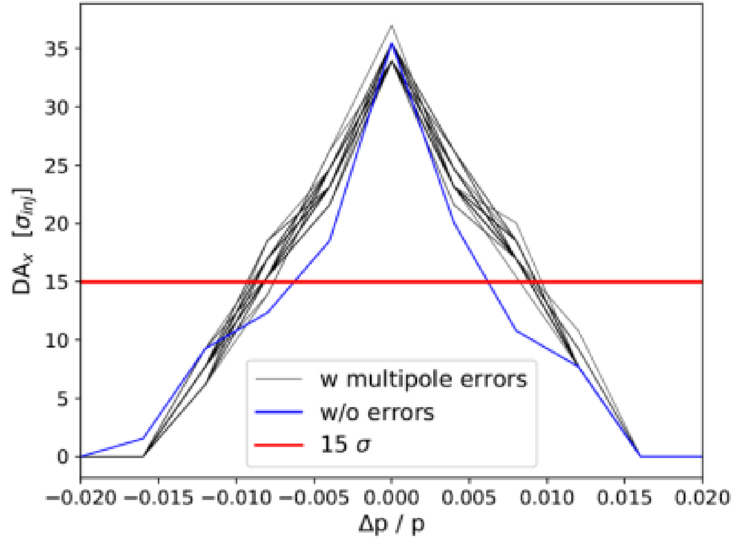
	CT dipole		Iron-core dipole	
GFR=R26	28Gs	56Gs	28Gs	56Gs
B1/B0	-5.20E-04	-1.04E-04	-1.56E-03	-2.60E-04
B2/B0	4.73E-04	5.41E-04	-2.03E-03	-2.03E-04
B3/B0	-7.03E-06	1.05E-04	3.52E-04	1.76E-04
B4/B0	-9.14E-04	-3.66E-04	4.57E-04	-1.83E-04
B5/B0	3.56E-05	-2.38E-05	-2.38E-05	-3.56E-05
B6/B0	6.18E-04	2.16E-04	-3.09E-04	9.27E-05

relative values @ R = 26 mm

91km 60°/60° optics

$\beta_x = 83.2$ m $\beta_y = 32.2$ m $D_x = 0$ m
Geometric emittance injected 1.27 nm



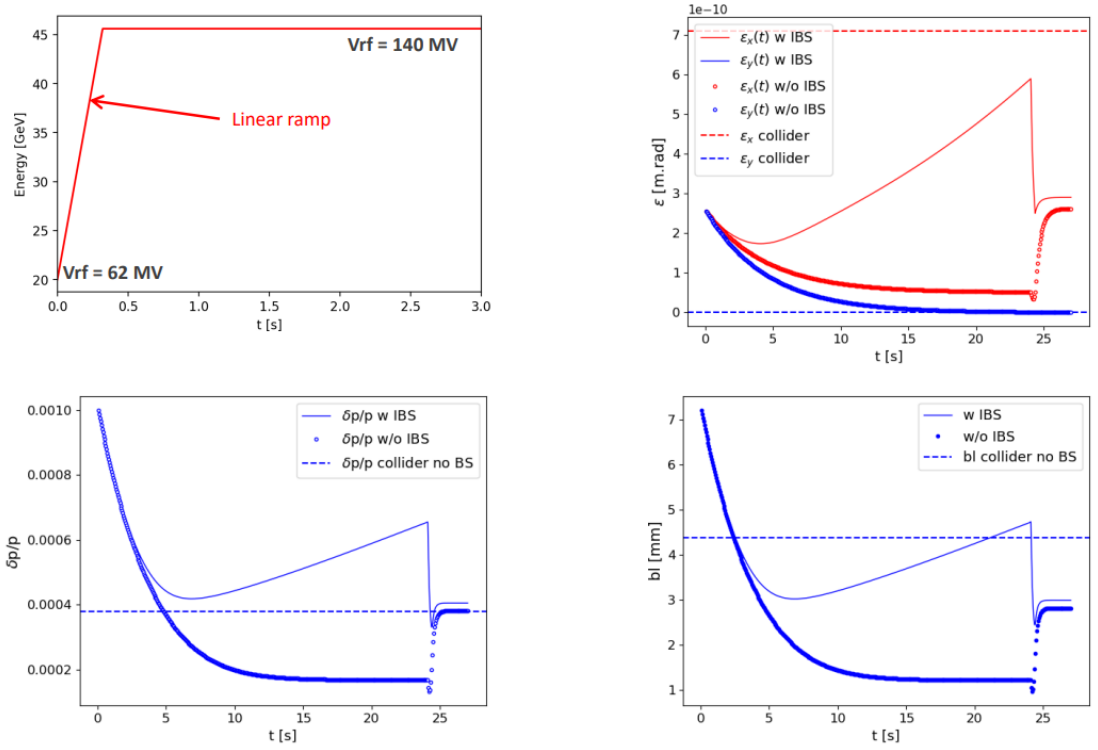


preliminary

DA of 91km **90°/90° optics** is ~ **5mm** (due to strong sextupoles)

booster cycle

Emittance: accumulation + ramp
10μm x 10μm; 0.1%

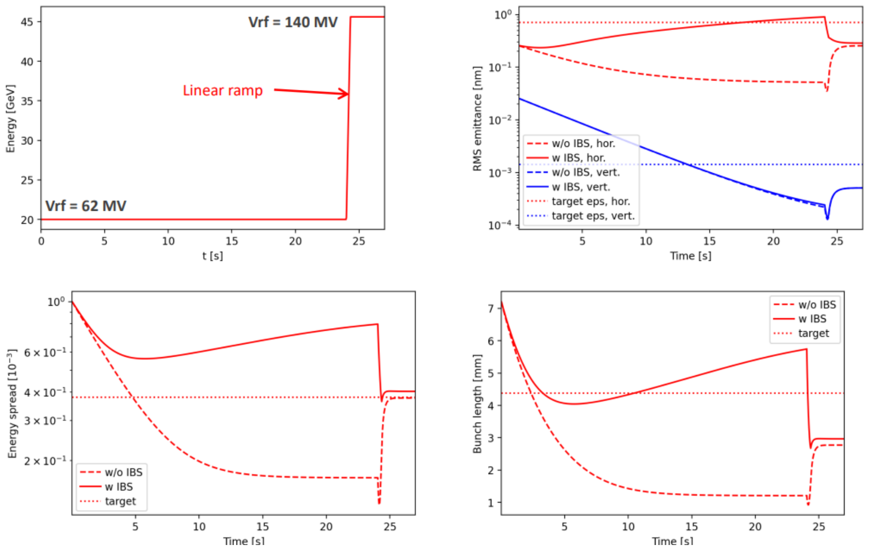


Antoine Chancé

Parameter variation during the cycling

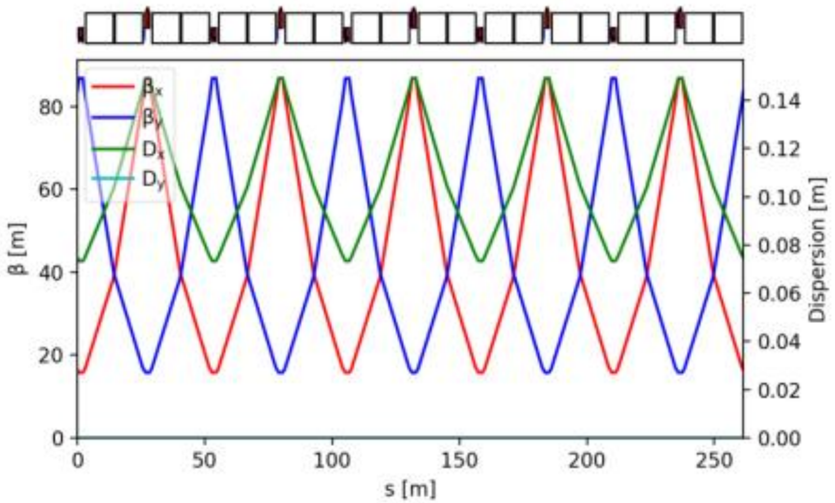
- **During the accumulation process,**
  - IBS processes drive the emittance evolution.
  - The bunch parameters (length, emittance, size) vary from a bunch to another bunch. Energy spread doesn't reach equilibrium emittance at injection.
- If we do not modify the I2 function (with different dipole families), **we should have a flat top of at least 2 seconds to damp the beam** with an initial round normalized emittance of 10 µm**.**
- The duration of the flat top depends on the initial emittances **1-3 s** for **1-50 µm.**
- **We have assumed that the beam is matched at the entrance.** An initial energy spread of 0.1% gives a bunch length of 7.2 mm. We could reduce a bit the initial bunch length by increasing the initial RF voltage but we are quickly limited by the maximum total RF voltage.

Emittance: accumulation + ramp
10μm x 1.0μm; 0.1%

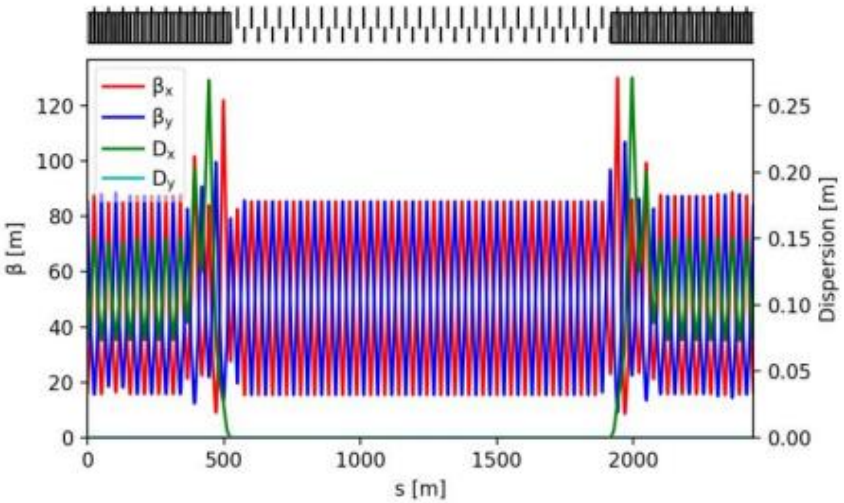


Alternative optics: reference

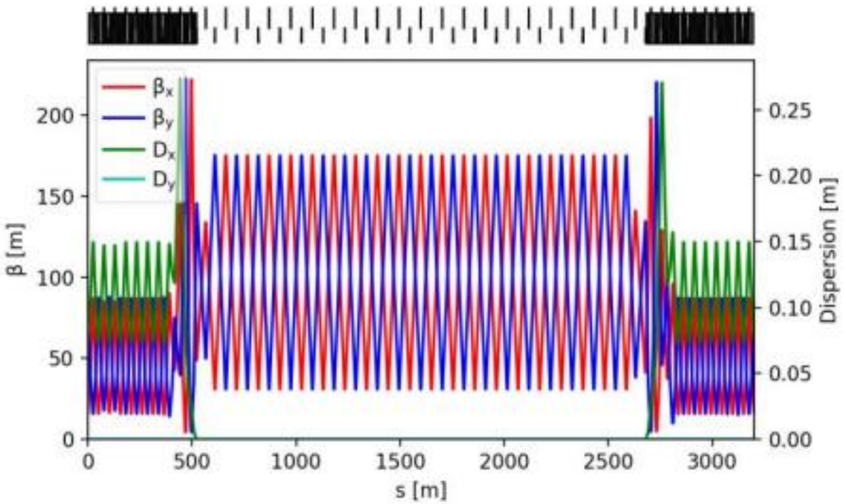
Arc cell



Section 1



Section 2



Momentum compaction:

$$\alpha = 0.73 \times 10^{-5}$$

Synchrotron integrate I5:

$$I_5 = 0.179 \times 10^{-12}$$

90 degrees FODO cells

Antoine Chancé

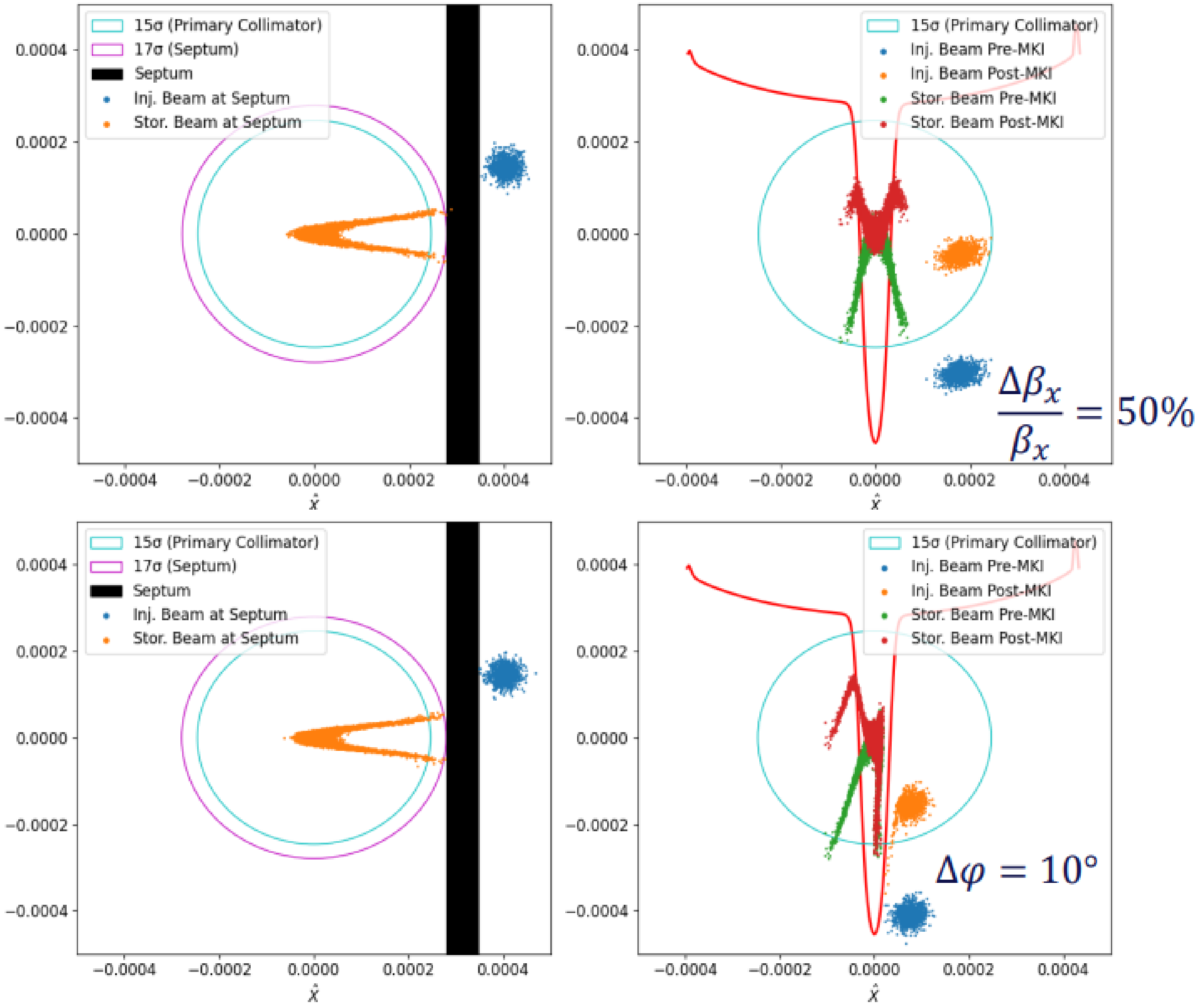
Michael Hofer

Multipole kicker injection

Impact of optics errors

- Similarly, optics errors resulting in distortion of stored beam and reduced injection efficiency

- Tolerable distortions to be studied with tracking studies, including beam-beam



At Septum

At MKI

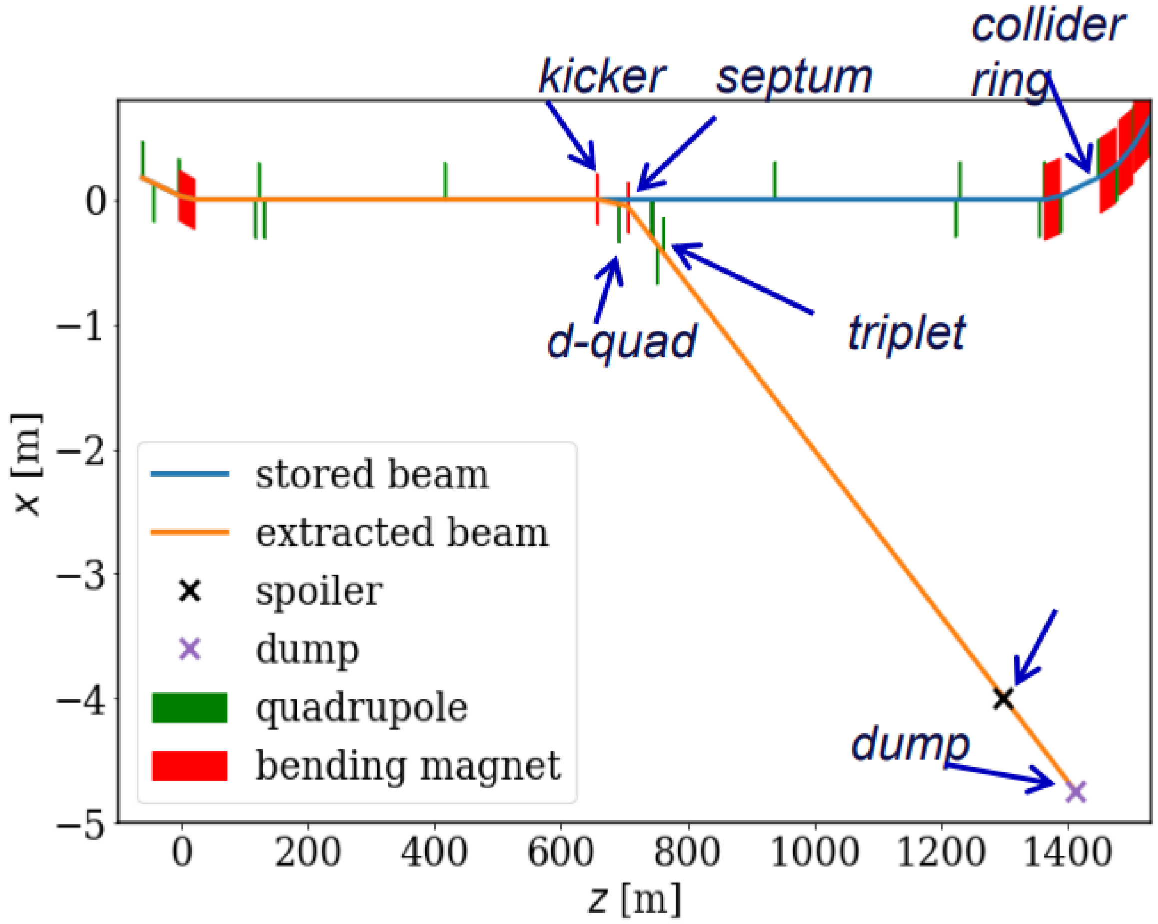
Extraction

- First study on layout of extraction and requirements presented last workshop [ref]

- After extraction, defocusing triplet to blow up beamsize, propagating for ~700m
  before hitting spoilers and finally beam dump

- Hardware parameter achievable
  - Kicker: $1\ mrad$ deflection, $3\ \mu s$ rise time, $300\ \mu s$ flat top
  - Septum: $5\ mrad$ deflection, $5\ cm$ separation

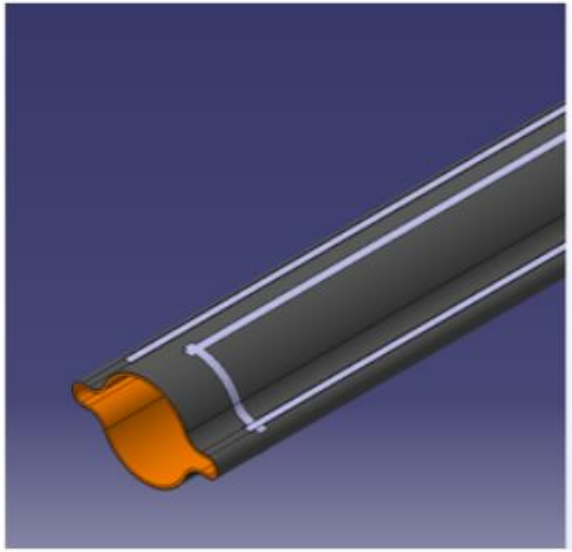
- Based on SKEKB experience with "crazy beam", proposal to install extraction upstream of each IP



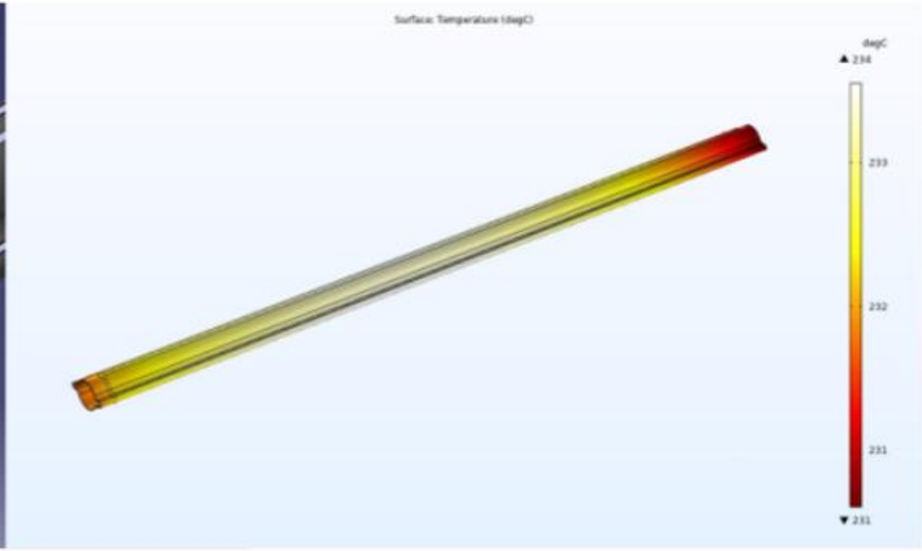
machine protection concern (kicker failure modes), impact on experiments; how fast can the beam be extracted?

Roberto Kersevan

Development of cold-sprayed titanium tracks for ~250 °C bake-out



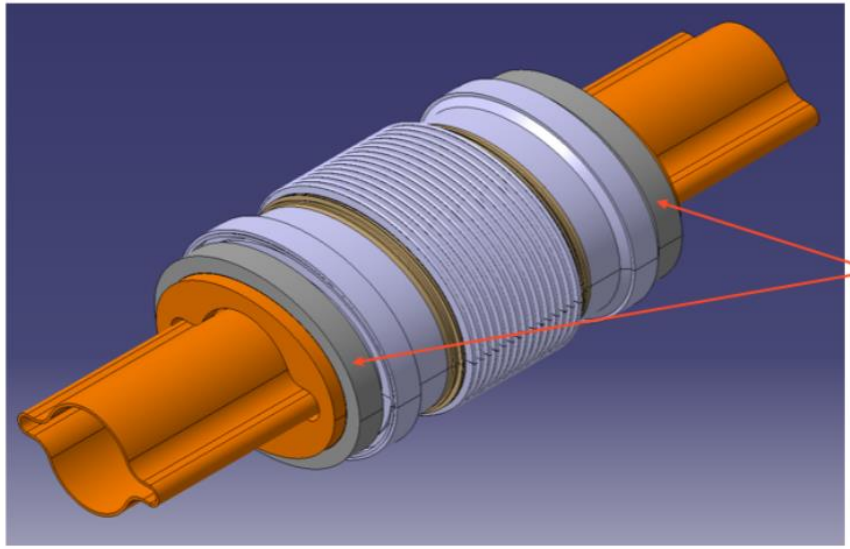
Development of cold-spray titanium tracks for FCC-ee vacuum chamber
Courtesy S. Rorison, CERN



Thermal testing of design suitable for prototyping;
Rather uniform temperature profile

Vacuum system
- bake-out, bellows

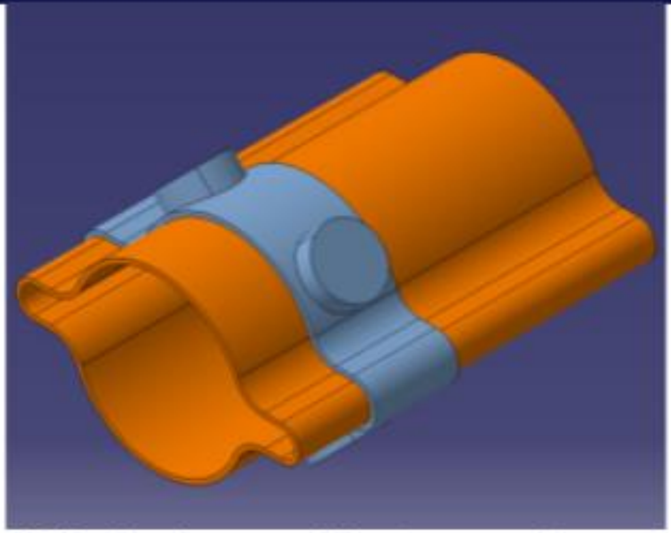
Development of RF contact fingers and bellows



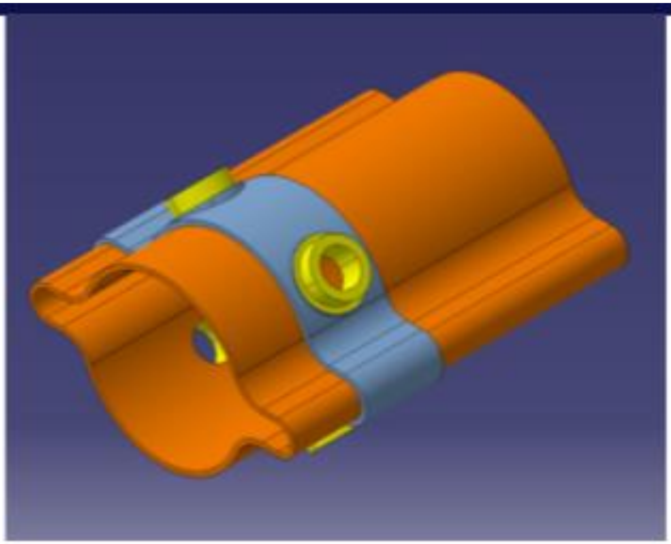
Version with contact-less RF fingers, derived from HL-LHC triplet area

Elliptical flanges with Shape-Memory Alloy rings

Vacuum system - BPMs

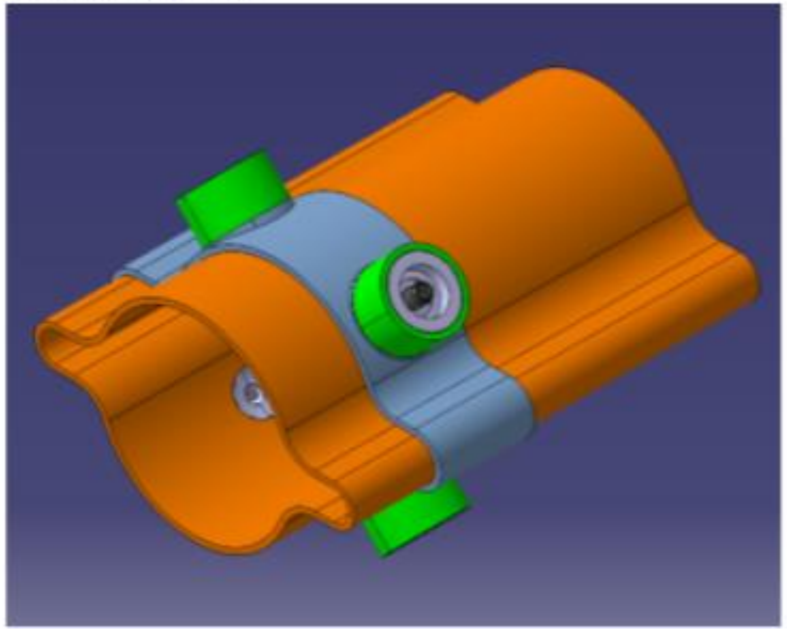


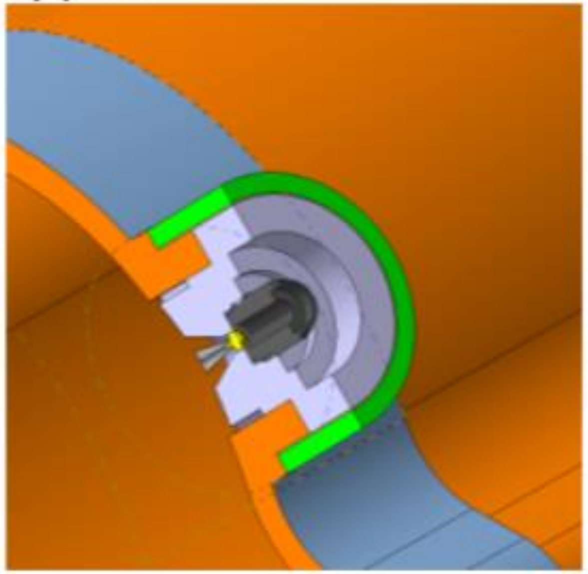
BPM – blue is pre-machining 'as-sprayed' cold-spray deposit.



x4 extruded bosses are machined (yellow areas) to accommodate SMA connectors and BPM equipment

Design of BPM blocks: additive manufacturing (cold spray technol.)





Assembly and cross-sectional view of BPM equipment and SMA mini connector

Further work to design mechanical alignment with magnet system on-going

Working in close contact with BPM people (M. Wendt)

Vacuum system – status

Roberto Kersevan

1. The vacuum system for the FCC-ee arc sections has been under study since many years; we look with interest the progress on **SUPEKEKB vacuum commissioning** and troubleshooting, and **CEPC design** as well
2. We have come to the conclusion that the aggressive experimental program with large integrated luminosity values within a rather short amount of time (4 yrs for the Z-pole starting from an unconditioned machine) require two things:
   i. **NEG-coating of the chamber**
   ii. **Localized ("lumped") SR absorbers**
3. We have generated several pumping configuration scenarios, changing the number of additional pumps and the partial saturation of the NEG-coating
4. A series of prototypes are under advanced design and prototyping; we **have received** a copper extrusion for the chamber which is weld-free and straight, with winglets; **we have put ease of fabrication at industrial scale and cost-saving at the forefront of our design**; **next step is metrology, to check its straightness and surface conditions**
5. Tests on various welding techniques for connecting flanges (e.g. **stir-friction weld**.) and also of **additive manufacturing techniques** (e.g. **3D laser** and **cold-spray**) are being pursued for the flanges, BPM blocks, and SR absorbers
6. 2m-long prototype is going to be designed and will be possibly tested with **SR irradiation** at a SR light source (BESTEX test bench at KARA/KIT?); tests will be also carried out on potential **e-cloud mitigation** techniques and **impedance** issues; **Installation foreseen on BESTEX/KARA at KIT in H1 2023.**
7. ~~Design of **NEG-coating horizontal benches** capable to deposit the required thin-film along ~12m-long chambers is pursued (capitalizing on technology developed for HL-LHC);~~ **Tunnel integration** under study as well (dedicated working group)

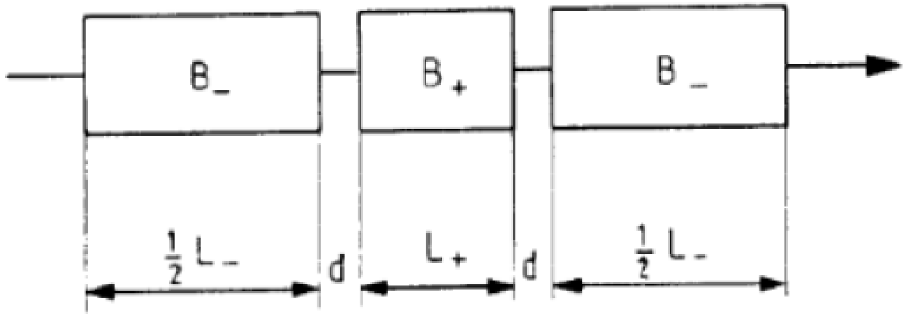
Jacqueline Keintzel

Wigglers I

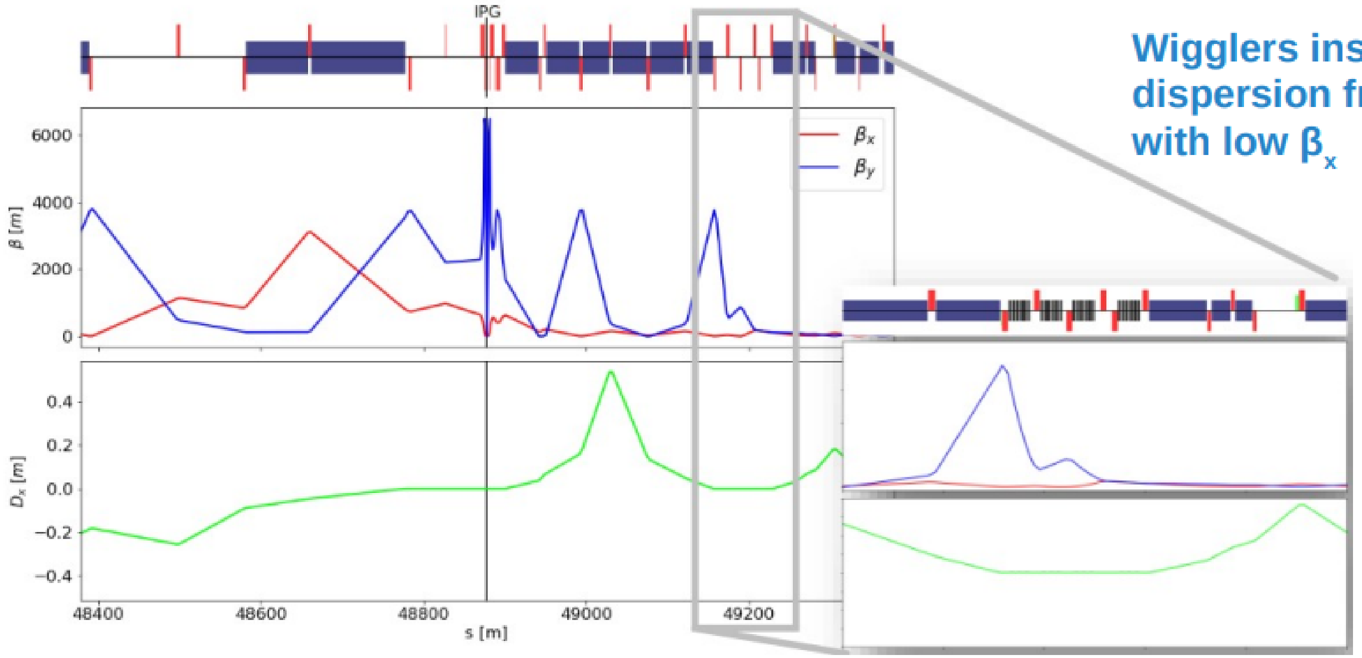
- Very long polarization time in FCC-ee at Z-pole
- Wigglers improve polarization time significantly

$$\left(\frac{\sigma_E}{E}\right)^2 \propto \frac{E^4}{\gamma^3 \tau_p \Delta E_{loss}} \qquad r = \frac{B_+}{B_-} = \frac{L_-}{L_+}$$

Follow 3 three-block design from LEP



Parameter	FCC-ee	LEP
Number of units per beam	24	8
B_+ [T]	0.7	1.0
L_+ [mm]	430	760
r	6	2.5
d [mm]	250	200
Crit. Energy of SR photons [keV]	968	1350



Wigglers installed in dispersion free section with low β_x

For Z-pole:
Polarization time decreases from 248 h to 12 h
Energy spread increases from 17 MeV to 64 MeV

M. Hofer: indico.cern.ch/event/1080577/

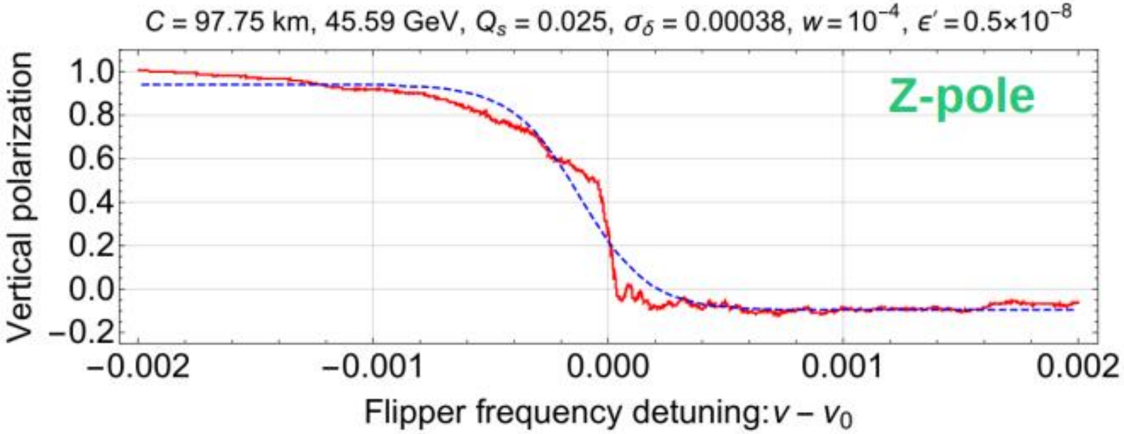
I. Koop, S. Nikitin, I. Nikolaev

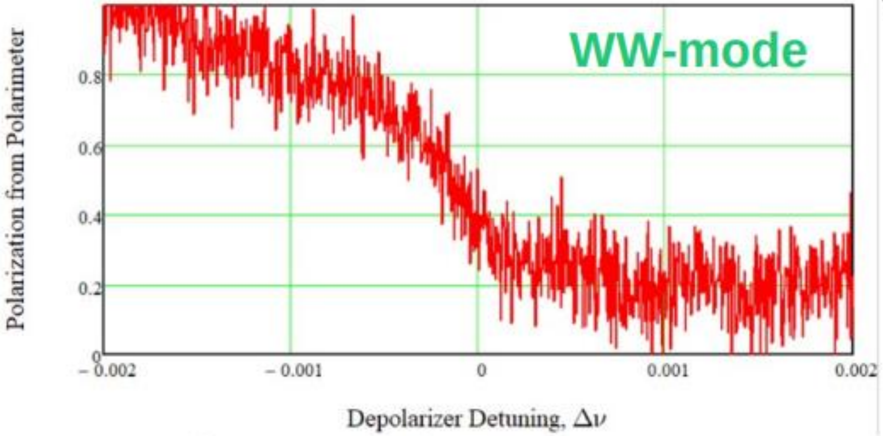
Resonant Depolarization

- Continous resonant depolarization (RDP) proceedure foreseen at the Z- and the WW- mode
- Depolarizer sweeps through frequencies ω_d
- Resonant condition $\Omega = n\omega_0 \pm \omega_d$
- Depolarization for dertimination of spin tune

ω_0 … revolution frequency
aγ … ~ spin tune

$$\Omega = \omega_0 \left(1 + a\gamma \right)$$





New approach compared to LEP at W-energy

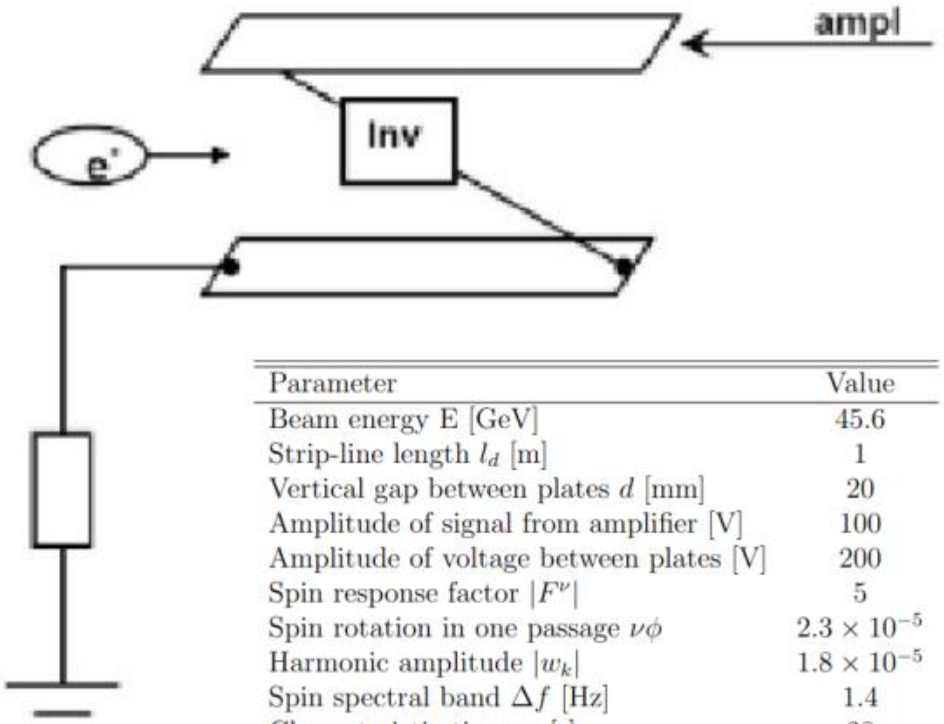
Natural width of spine line due to radiative diffusion much larger than desired level of precision
(Z: 200 keV and W: 1.4 MeV)

Solution: Use of **2 selective kickers simultaneously acting on 2 pilot** bunches and scanning in opposite directions
→ accuracy better than 10 keV

I. Koop, S. Nikitin, I. Nikolaev, J. Wenninger

Jacqueline Keintzel

Depolarizer II



Parameter	Value
Beam energy E [GeV]	45.6
Strip-line length l_d [m]	1
Vertical gap between plates d [mm]	20
Amplitude of signal from amplifier [V]	100
Amplitude of voltage between plates [V]	200
Spin response factor $\lvert F^\nu \rvert$	5
Spin rotation in one passage $\nu\phi$	2.3×10^{-5}
Harmonic amplitude $\lvert w_k \rvert$	1.8×10^{-5}
Spin spectral band Δf [Hz]	1.4
Characteristic time τ_d [s]	38

LHC transverse feedback system would provide adequate strength and bandwidth even with ¼ of LHC strength

- Implemented as stripline that creates TEM wave propagating towards the beam
- Harmonic amplitude created by depolarizer

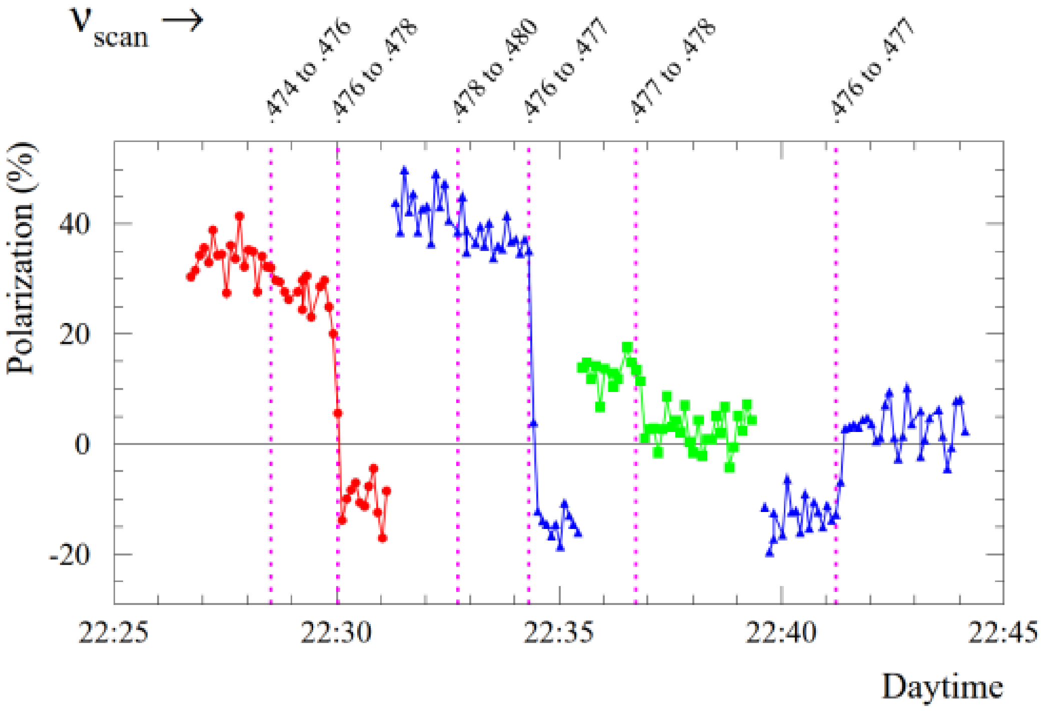
$$|w_k| = \frac{\nu B l}{2\pi B\rho}|F^\nu| = |F^\nu|\frac{\nu\phi}{2\pi} \propto \frac{\nu U l_d |F^\nu|}{Ed}$$

- Scan rate 1 keV/s or 0.007 Hz/s
- About 20 mins required for frequency sweep with $\mathbf{w_k \sim 10^{-5}}$ (rather weak)
- Alternatively with stronger, $\mathbf{w_k \sim 10^{-4}}$, leads to adiabatic spin fip and resonance search time < 1 min; requires e.g. 3 times longer plates

Discussion at the FCC-ee Polarization Workshop

- **LEP:** Energy calibration at the end of fills with non-colliding beams
- **FCC-ee:** Continuous energy measurements using non-colliding pilot bunches

  → But: Polarization time of 240 h



*The colors refers to different bunches, in one case (**blue**) the polarization is flipped, and flipped polarization is used to re-depolarize a second time .*

1 point every ~ 8 seconds.

J. Wenninger: FCC EPOL Workshop

- Measurements at LEP indicated polarization flip instead of depolarization

  → **Can the polarization be flipped back?**

Special diagnostics at KARA

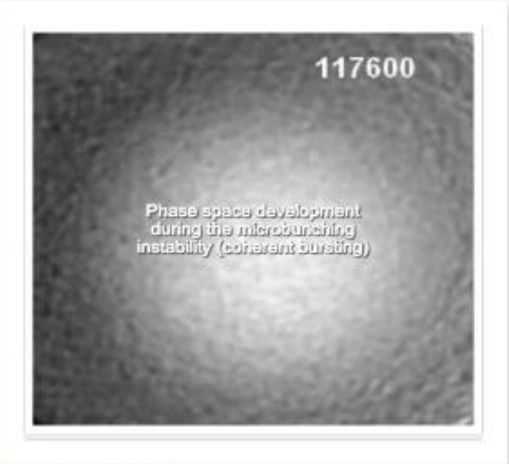
Karlsruhe Institute of Technology

- Measurements of resonant spin depolarization

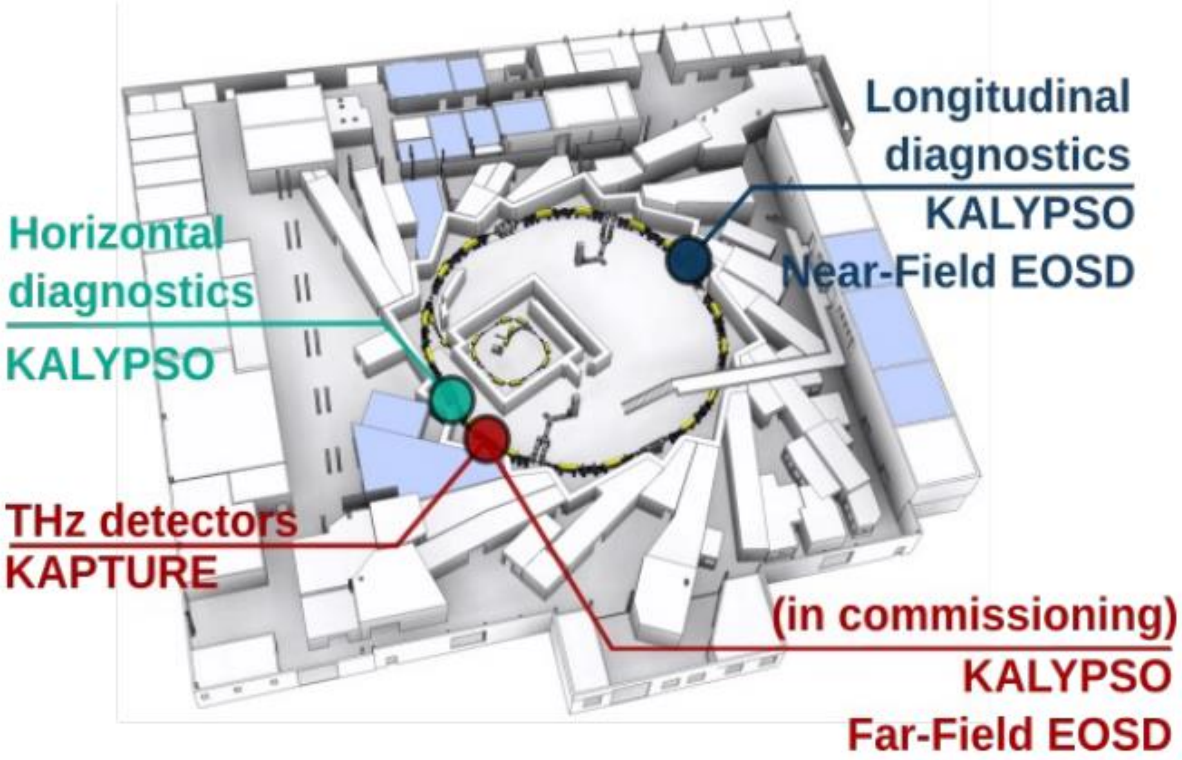
- Turn-by-turn and bunch-by-bunch diagnostics @KARA

phase space tomography

- Complete phase space image reconstructed from time interval of 61 µs
- “Randon morphing“ between independent measurement



S. Funkner et al. arXiv preprint, arXiv:1912.01323



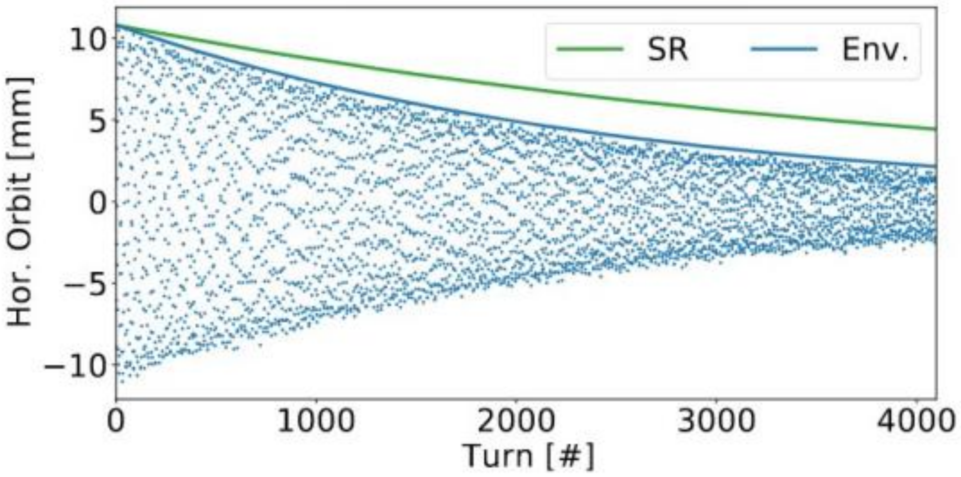
Get in touch with us! ☺
bastian.haerer@kit.edu

Jacqueline Keintzel

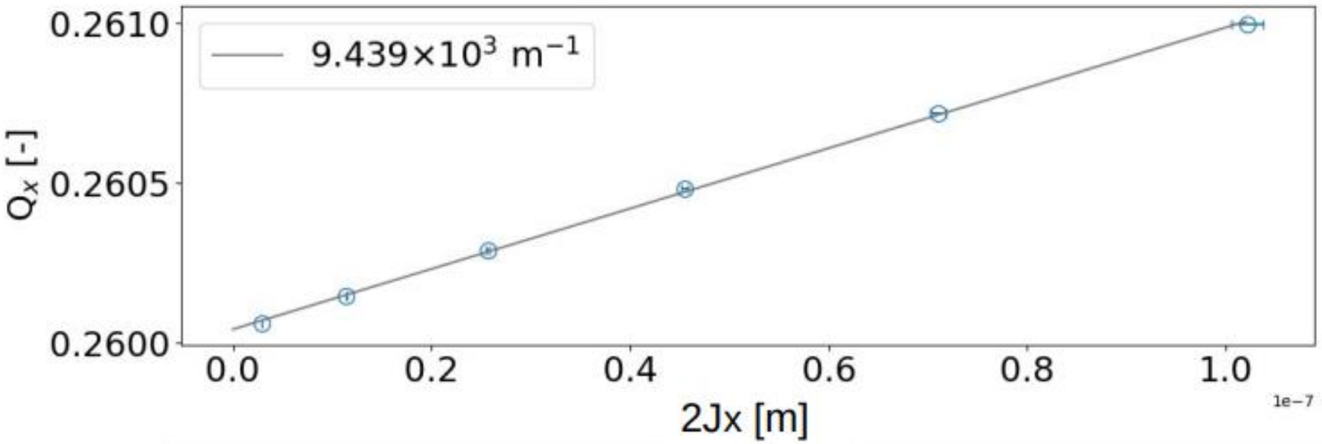
Single Kicks in Measurements

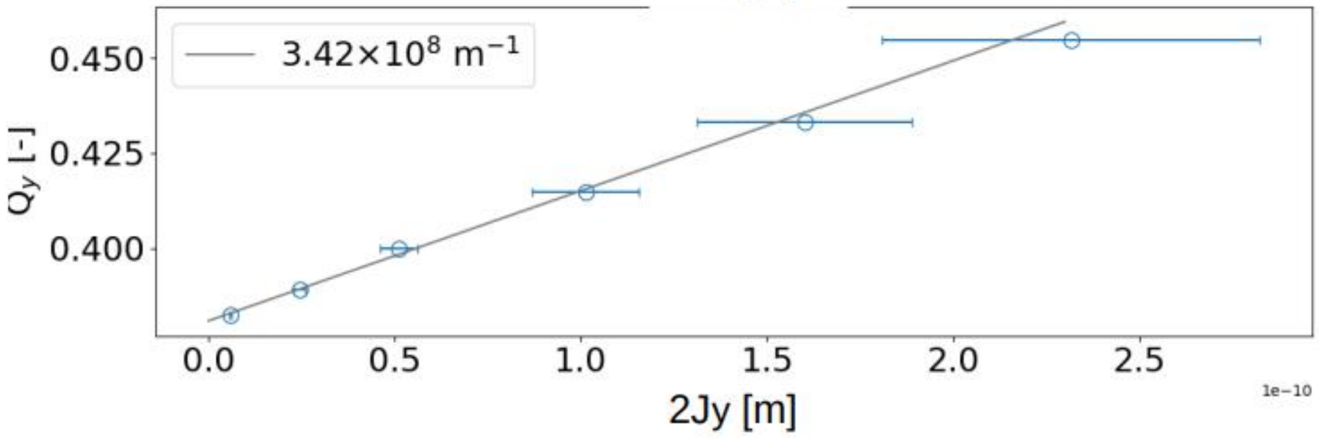
- After kick is applied, orbit is affected by
  - Synchrotron radiation (SR)
  - Decoherence from amplitude detuning
  - Head-tail effect and impedance
- Detailed analysis of SKEKB TbT data

Qx' = 1.70 ± 0.04 , Qx'' = -22 ± 18



Amplitude detuning for FCC-ee Z-mode also needs to be considered in addition to SR



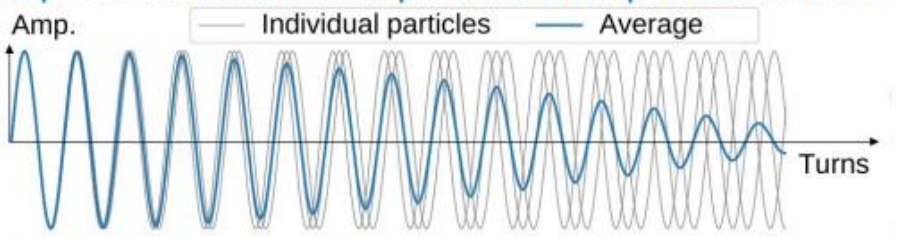


Jacqueline Keintzel

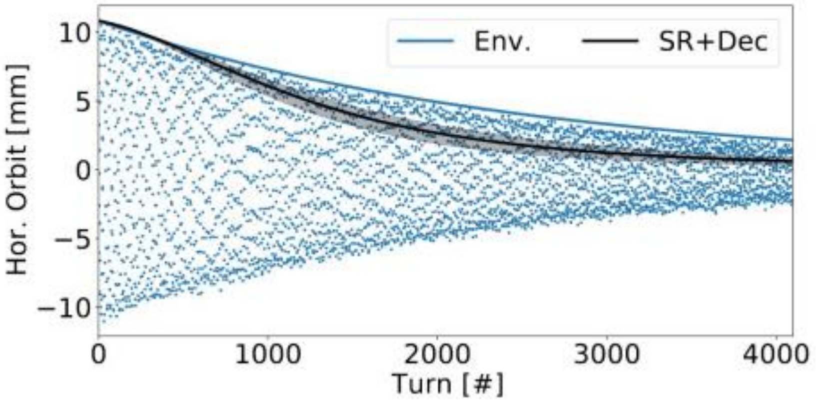
Lepton Decoherence

- Decoherence from amplitude detuning enhances damping of center-of-charge
- Only pseudo-damping → amplitude of individual particles not affected by decoherence

Decoherence illustrated for 3 hadrons
Leptons: individual amplitudes damp over time too



Synchrotron radiation and decoherence over-estimate damping → growth contributions



Damping explained by synchrotron radiation and decoherence
→ TbT orbit data scaled to reproduce radiation damping
→ Measure tune for various actions and fit gives amplitude detuning
Method applicable for all lepton storage rings such as FCC-ee

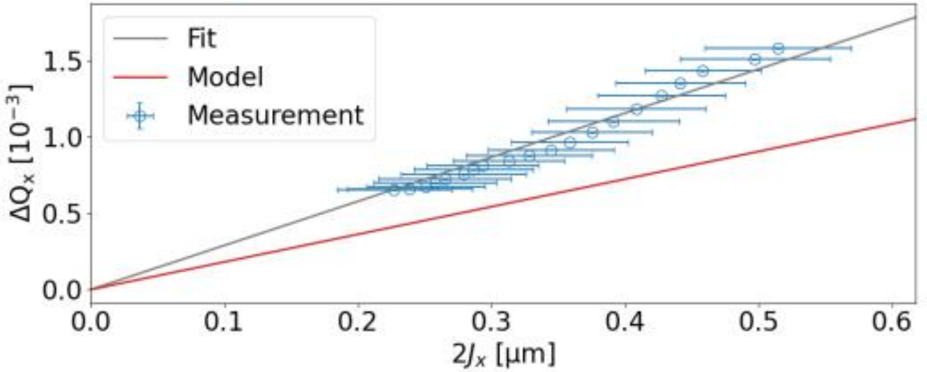
Existing theory for hadrons: μ … Amplitude detuning N … Turns
Z … Kick strength

$$A_{\mathrm{Dec}} = \frac{1}{1+\theta^2}\exp\left\{-\frac{Z^2}{2}\frac{\theta^2}{1+\theta^2}\right\} \quad \theta = 4\pi\mu N$$

Here extended for leptons:

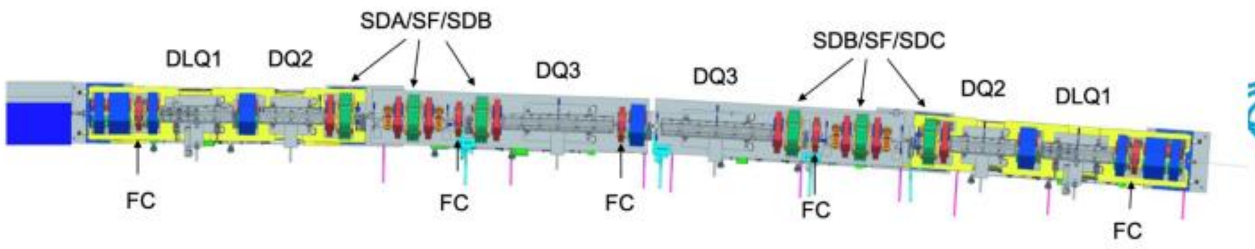
$$\boxed{\theta = 2\pi\mu\,\tau_{\mathrm{SR}}\left(1-e^{-2N/\tau_{\mathrm{SR}}}\right)}$$

SuperKEKB LER amplitude detuning measurement

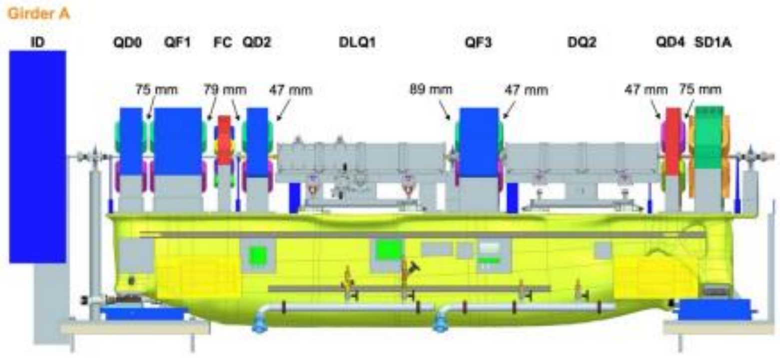


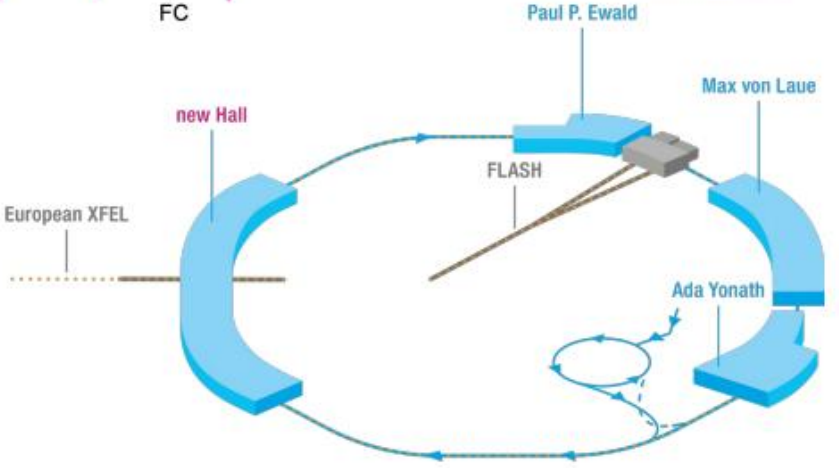
PETRA IV

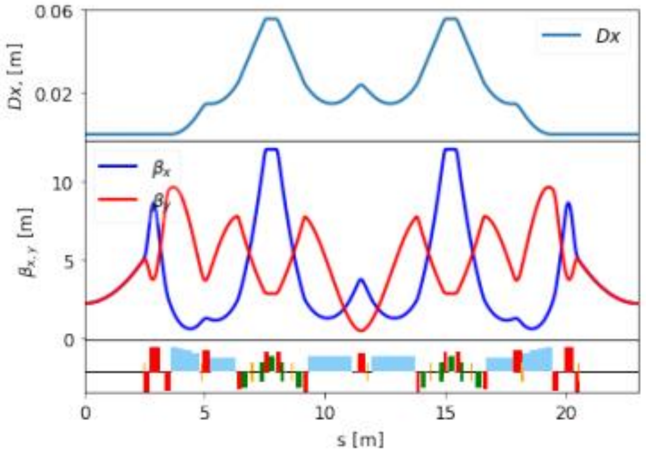
I. Agapov

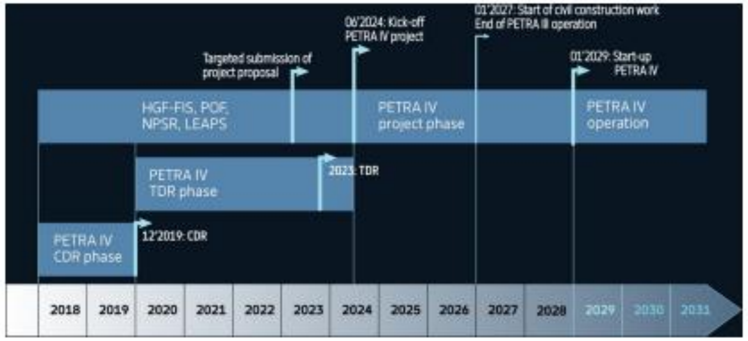


- Upgrade of PETRA III
- 6 bend achromat optics



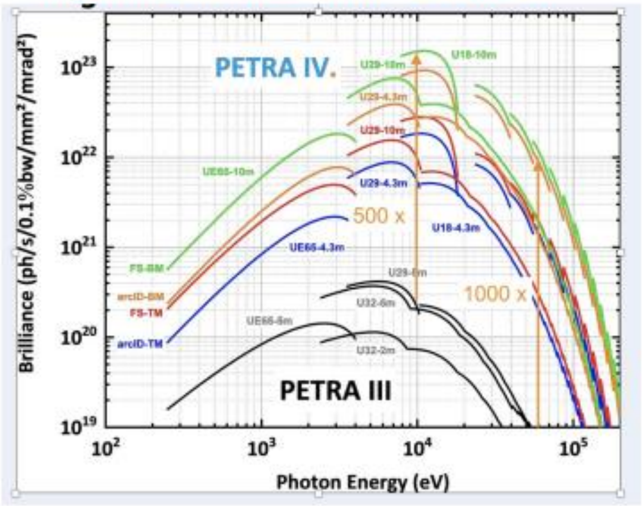






	H6BA Lattice		PETRA III	
Parameter	brightness mode	timing mode	continuous	timing mode
Number of Bunches	1600 - 1920	80 (40)	480 - 960	40
Total current / mA Bunch current / mA	200 0.125	80 (80) 1.0 (2.0)	120 0.25 - 0.125	100 2.5
Arc ID β_x/β_y / m long ID β_x/β_y / m	2.2 / 2.2 4.0 / 4.0		high β: 20.0 / 4.0 low β: 1.4 / 4.0	
Hor. Emittance ε_x / pmrad Vert. Emittance ε_y / pmrad	20 5	35 (38) 7 (8)	1300 10	
Bunch length σ_z / ps Bunch separation / ns	30 4	65 (75) 96 (192)	40 16 - 8	43 192
Energy spread σ_ε / 10^{-3} Touschek lifetime τ / h	0.9 > 10	1.2 (1.5) > 5	1.3 9 - 13	1.3 1.5
Number of beamlines	33 — 35 + 1 VUV		26 + 1 VUV	

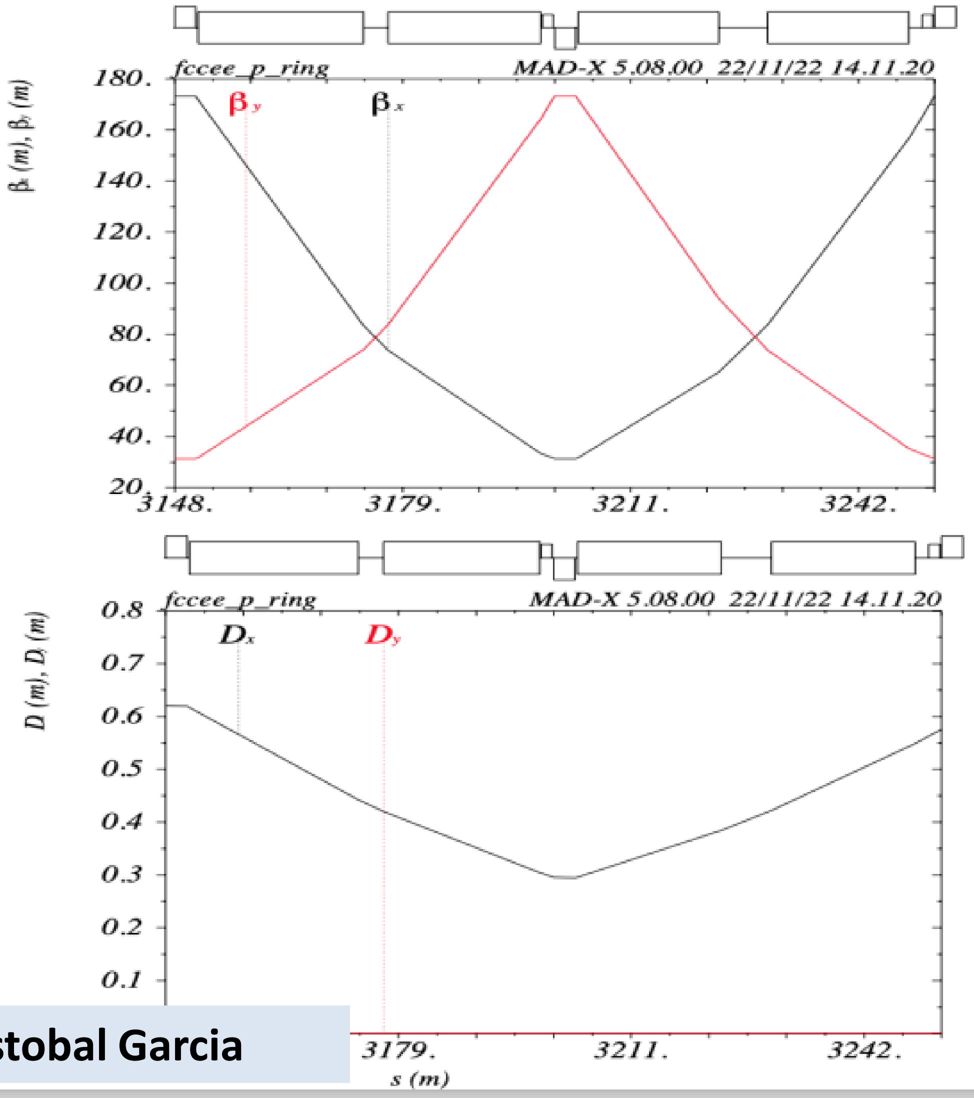
Higher brillance than PETRA III

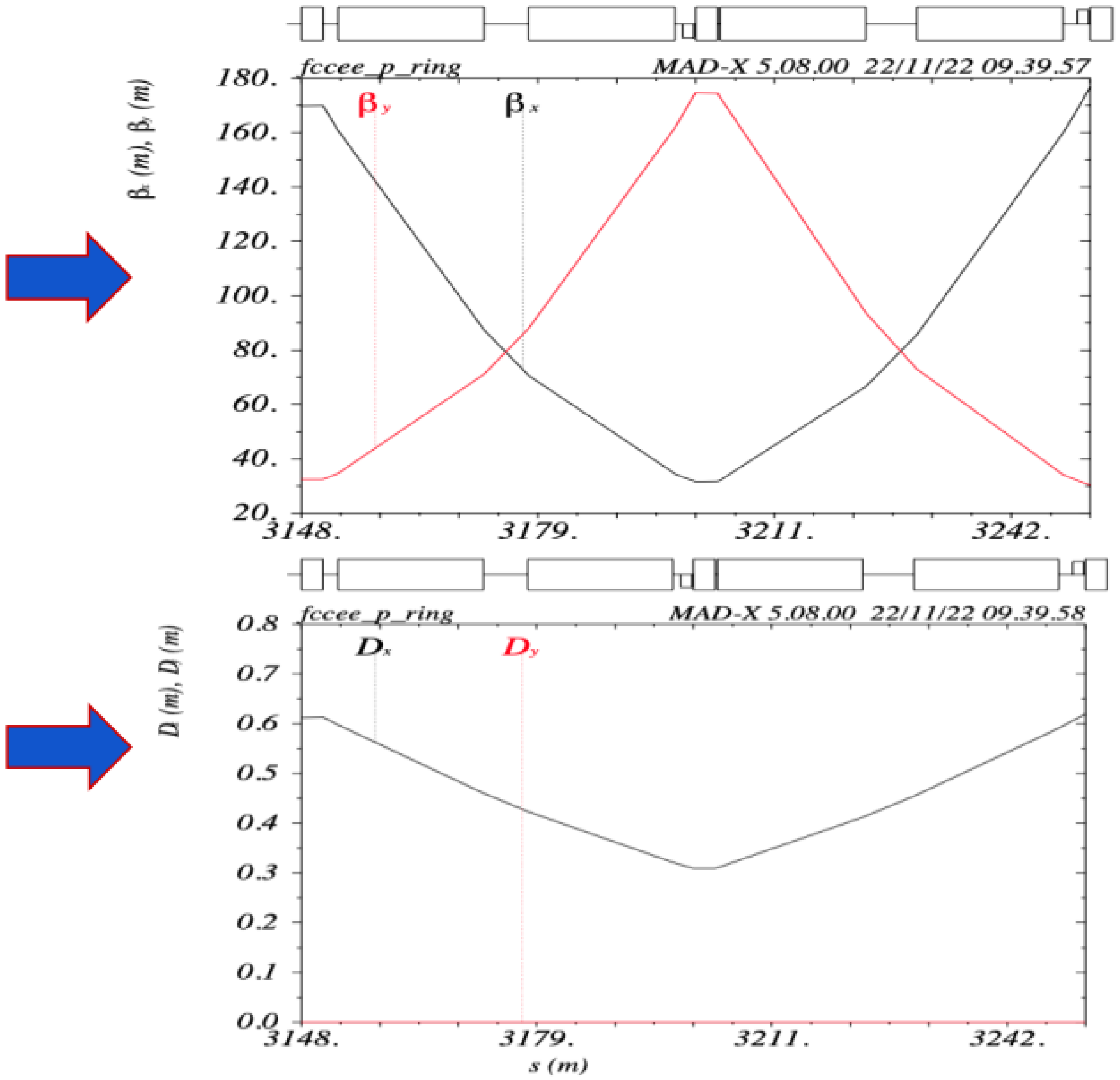


Jacqueline Keintzel

New Lattice with Combined Functions Magnets

→ Option 1) Quadrupoles are replaced by elements with a quadrupole and dipole component in the same object. In this way we have a combined function magnet effect for the simulations:





Cristobal Garcia

Emittance with Combined Function Magnets

	Baseline	Option 1	Option 1 (modified)
Horizontal tune	214.260	214.260	214.260
Vertical tune	214.380	214.380	214.380
Horizontal Chromaticity	-1.165	-1.165	-1.165
Vertical Chromaticity	-1.911	-1.911	-1.911
Dispersion_{max} [m]	0.624	0.634	0.634
Emittances [pi micro m]	0.33E-06	-0.36E-06	0.10E-04
J_x, J_y, J_E	0.999&1.00 2.00	-0.866&1.00 3.86	0.031& 0.999 2.968
I4 / I2	0/0.00064	0.00110/0.00060	0.00058/0.00061

- Obtain unphysical "negative" emittances with this new lattice using EMIT module
- Due to negative horizontal partition number (no damping)

$$\epsilon_u = C_q \frac{\gamma^2}{J_u} \frac{\mathcal{I}_{5u}}{\mathcal{I}_2},$$

  - Large I4 integral due to quadrupole field overlapping with dipole

$$J_u = 1 - \frac{I_4}{I_2}$$

$$I_4 = \oint \frac{D}{\rho}\left(2k + \frac{1}{\rho^2}\right) ds$$

- Need to develop strategies improve partition number
  - E.g by changing bending radius in CF magnets
    - First iteration performed

Cristobal Garcia

thank you !