1/July/2021 FCC WEEK 2021

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INFN
LNF

CERN

FUTURE
CIRCULAR
COLLIDER

OVERVIEW, PLAN, AND OPEN QUESTIONS

Manuela Boscolo
for the MDI group

Outline

The design of the interaction region must comply with various important constraints, imposed by high beam energy, high luminosity, need for polarization, and crossing scheme.

An **overview of the MDI design** with recent results and ongoing studies

- layout and mechanical model
- beam backgrounds study

Plan & Open question

Collision scheme for e^+e^- circular colliders

Crab-waist based on two ingredients:

- concept of **nano-beam scheme** (vertical squeeze of the beam at IP and large horizontal crossing angle, reduced instantanous overlap area, allowing for a smaller β_y^*)
- crab-waist sextupoles

Smaller beams at IP → higher $\mathcal{L}$ & higher backgrounds

(IP bkgs and beam losses in the final focus quads due to the very high β-function)

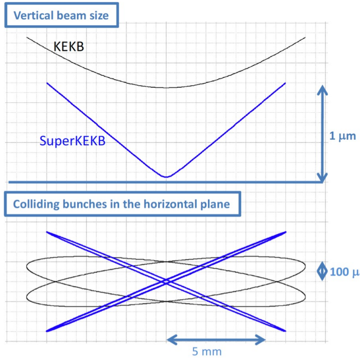


Figure 2: Schematic view of the nanobeam collision scheme.

https://arxiv.org/pdf/1809.01958.pdf

These ingredients determine the complex MDI design

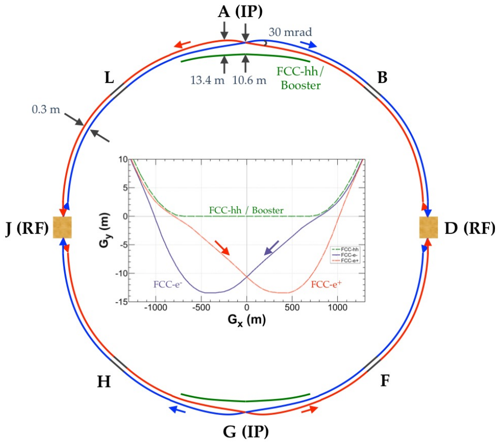
- **Tight and packed interaction region → small L*, QC1 inside detector, mechanical constraints**
- **Beam pipe design, as splitting in two pipes is very close to the IP**
- **Robustness against machine backgrounds (from IP and environment)**
- **Radiation damage and occupancy and fake hits**
- **Higher trigger rate, DAQ and computing**

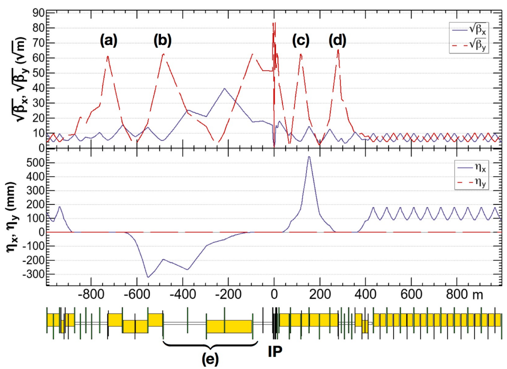
Ref. First Successful validation test performed at DAFNE (2008) link
SuperKEKB successfully implemented the FCC-ee *virtual* crab-waist, i.e. w/o new sextupoles [2020, K. Oide]

FCC-ee IR optics design

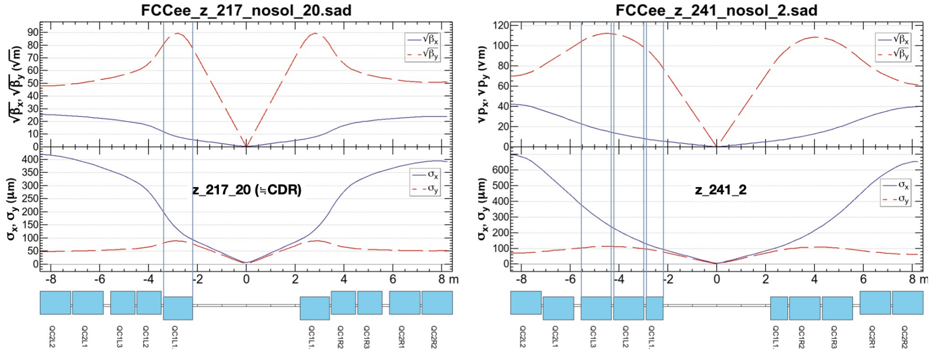
K. Oide

driven by synchrotron radiation:
E_{critical} <100 keV from 450 m from the IP
(from LEP experience)
-> Asymmetric IR optics





IR parameters table		Z	W⁺W⁻	ZH	ttbar	
β_x^*	m	0.15	0.2	0.3	1.0	
β_y^*	mm	0.8	1.0	1.0	1.6	
σ_x^*	µm	6.4	13	13.7	38.2	
σ_y^*	nm	28	41	36	68	
σ_z	mm	12.1	6	5.3	2.54	in collision
z^*_{int}	mm	0.42	0.85	0.9	1.8	interaction length



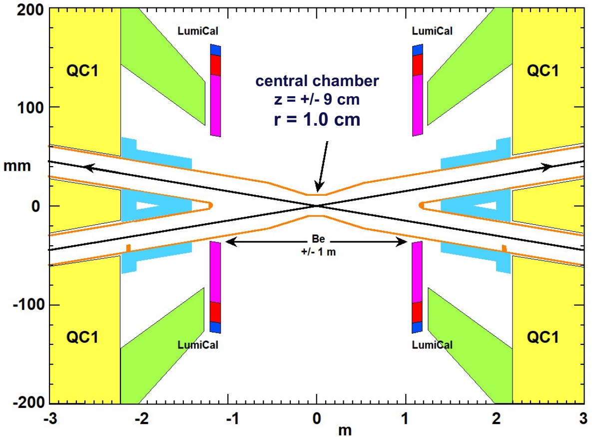
Flexible design with final focus doublet
in slices to adapt for the different beam energies

FCC-ee Interaction Region

[ArXiv:2105.09698]

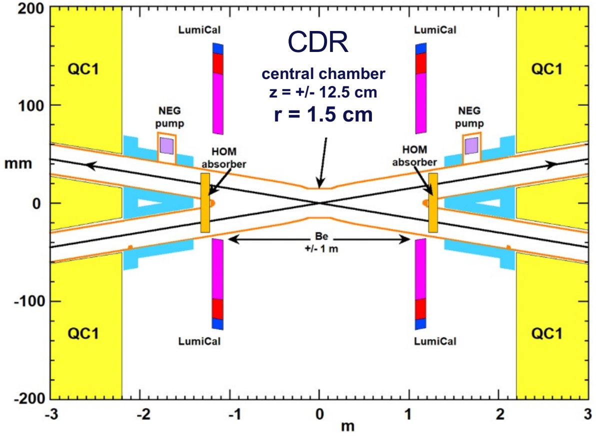
L*=2.2 m
B=2 T

- **Flexible** design, one IR for all energies
- **Compact** design: QC1 and compensation solenoids inside detector
- **Squeezed beams at IP**, tens of nm in σ_y^*
  challenges in several aspects, from magnets to vibrations mitigation, alignment and monitoring system, feedback for beam orbit and luminosity
- **High intensity and high energy beam**



- **Synchrotron radiation**: detector sustainability top priority

- **Solenoid compensation scheme** preserves $\varepsilon_y \approx$ pm
- **Luminosity detector** @Z: absolute meas. to 10^{-4} (low angle Bhabha),
- **Robustness against machine bkgs, occupancy**
- **Optimization of the central beam pipe design, material, thickness**
- Keep **low material budget**: minimise mass of electronics, cables, cooling

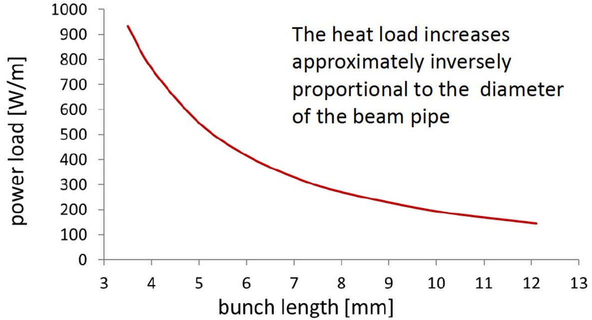


Low impedance central beam pipe

A. Novokhatski

Smaller central pipe 20 mm diameter

The double effect of smoothing the geometry and a smaller central pipe reduces the local heating power by a factor ten wrt the CDR design.

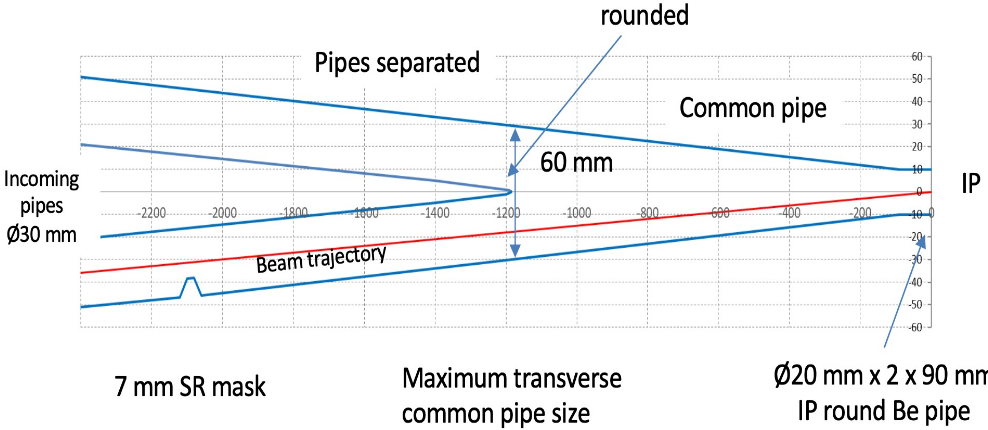


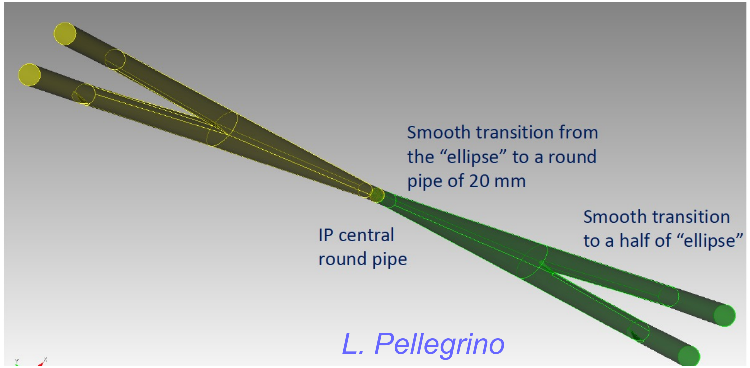
The heat load increases approximately inversely proportional to the diameter of the beam pipe

Heat load due to resistive wakefields vs bunch length for a r=1cm Be central beam pipe.

σ_z=12 mm in collision at Z

Heating power is 260 W for the two beams, most of this power will travel out away from the IP





L. Pellegrino

Low impedance central beam pipe

A. Novokhatski

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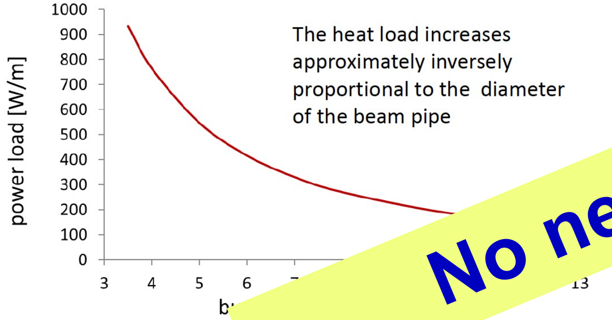


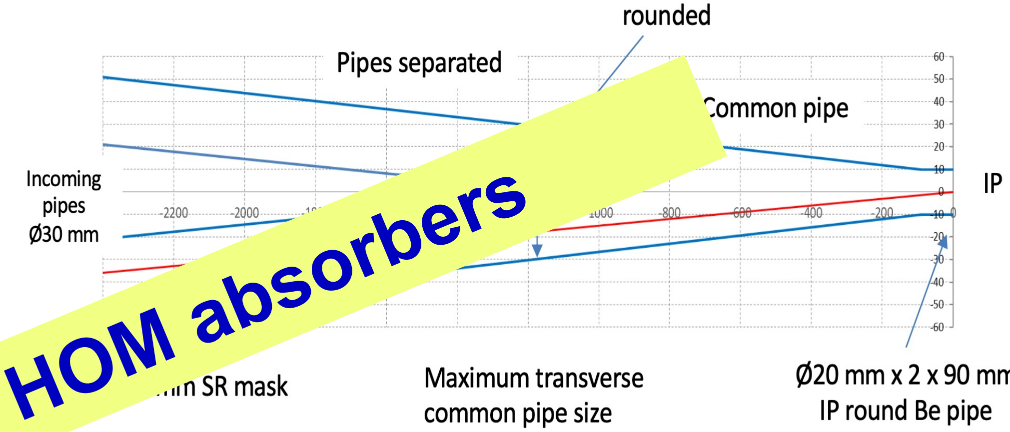
The heat load increases approximately inversely proportional to the diameter of the beam pipe

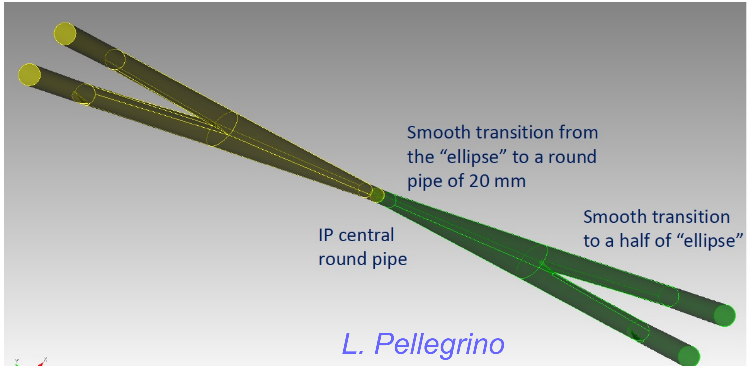
Heat load du[illegible]ve wakefields vs bunch length for a r=[illegible]m Be central beam pipe.

No need of HOM absorbers

σ_z=12 mm in collision at Z

Heating power is 260 W for the two beams, most of this power will travel out away from the IP

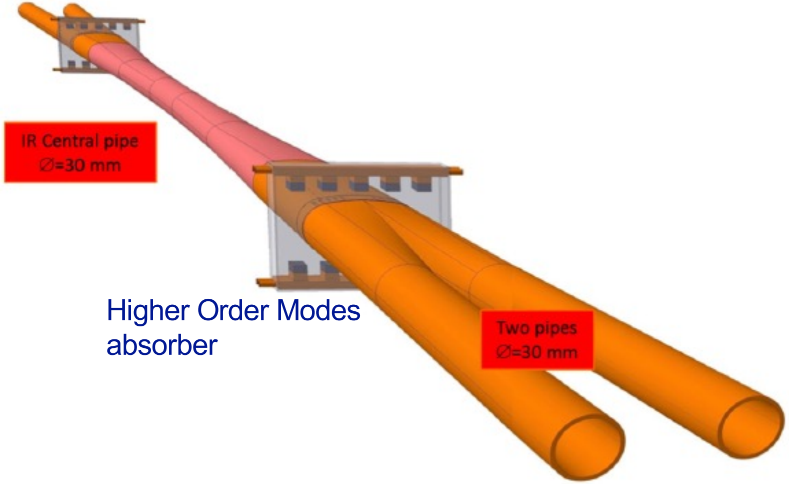




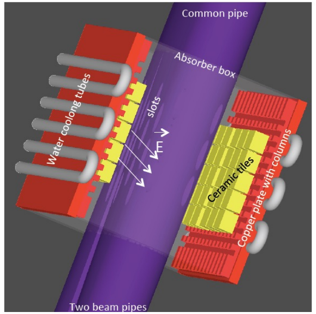
L. Pellegrino

CDR IR pipe model with HOM absorbers

Higher Order Modes absorbers were foreseen in the CDR design to absorb the trapped mode found by CST simulations

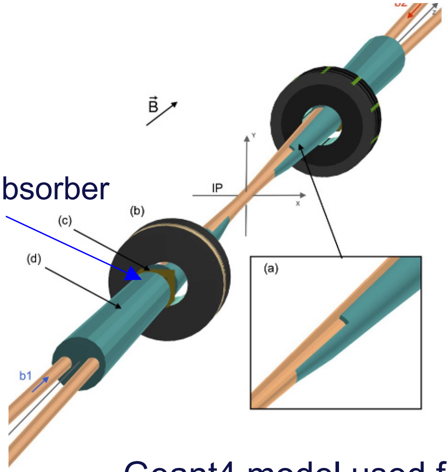


Higher Order Modes absorber



The HOM fields, which are generating by the beam in the Interaction Region pass through the longitudinal slots into the absorber box.

HOM absorber



Geant4 model used for detector background studies (CDR)

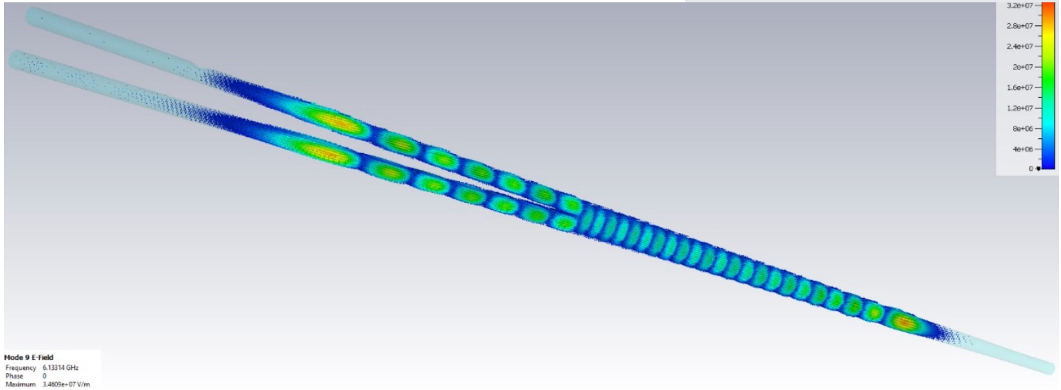
[A. Novokhatski et al. PR-AB 20, 111005 (2017)]

Low impedance central beam pipe

r=10 mm

No need of HOM absorbers

- The distributed trapped modes have very small shunt impedance and even at the resonance they produce **less than 200 W** for the two beams.
- To remove the remaining heat, we will use paraffin as **liquid coolant** that will flow within the room temperature pipe in the central chamber, and water outside.



CST wake field simulation

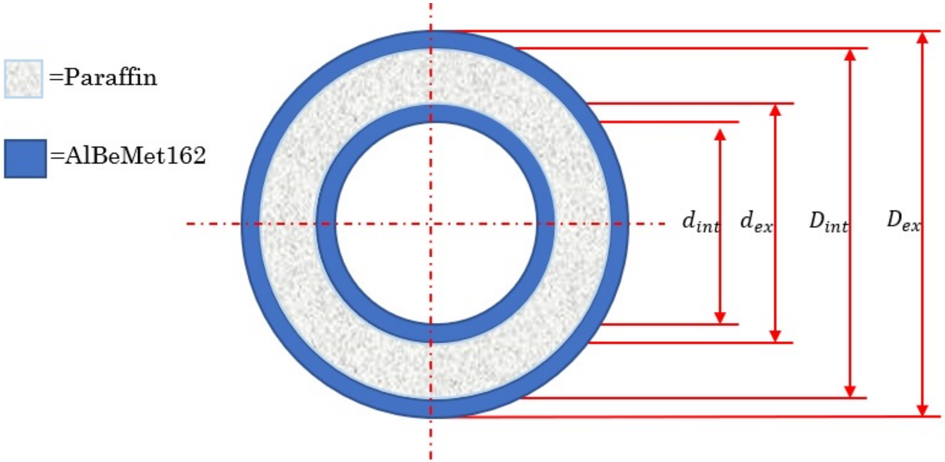
Central pipe composition

[more details by F. Fransesini, this session]

Inner radius **10 mm**

Thickness 1.7mm (**X/X0=0.59%**)

Material	*thickness*
AlBeMet162	**0.35 mm**
Paraffin (PF200)	**1 mm**
AlBeMet162	**0.3 mm**
Au	**5 µm**



AlBeMet162: 62% beryllium and 38% aluminum alloy

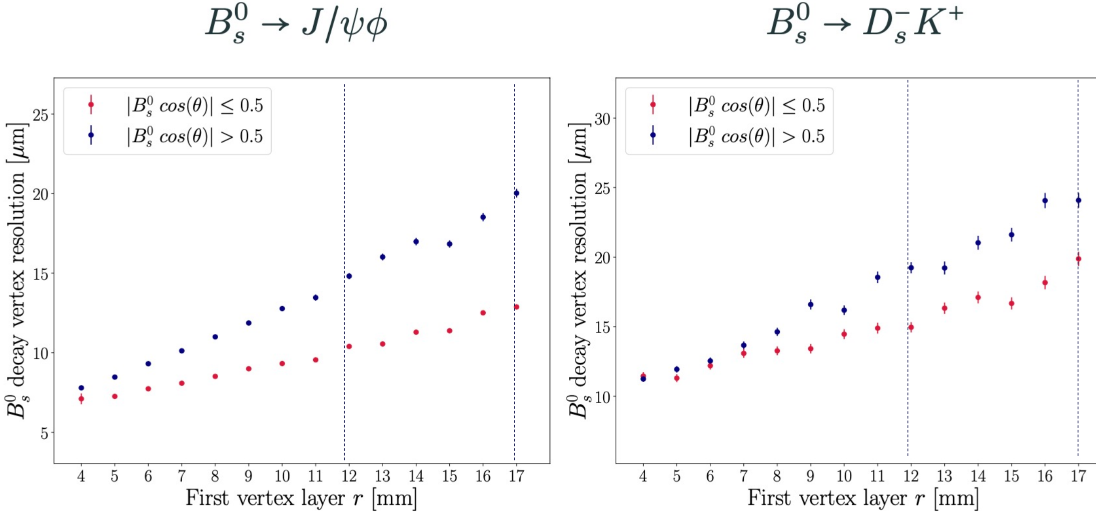
Central pipe CDR values: inner radius 15 mm
1.2 mm Be + 0.5 mm H_2O for X/X0=0.47%

Vertex resolution vs the first vertex layer radius

Donal Hill, MDI meeting #33

Radial distance (r) of the very first vertex layer

- Improvement in the vertex resolution from 17 to 12 mm of about 25%, better especially for central B's.
- Vertex performance mildly dependent on slight variations of X/X0

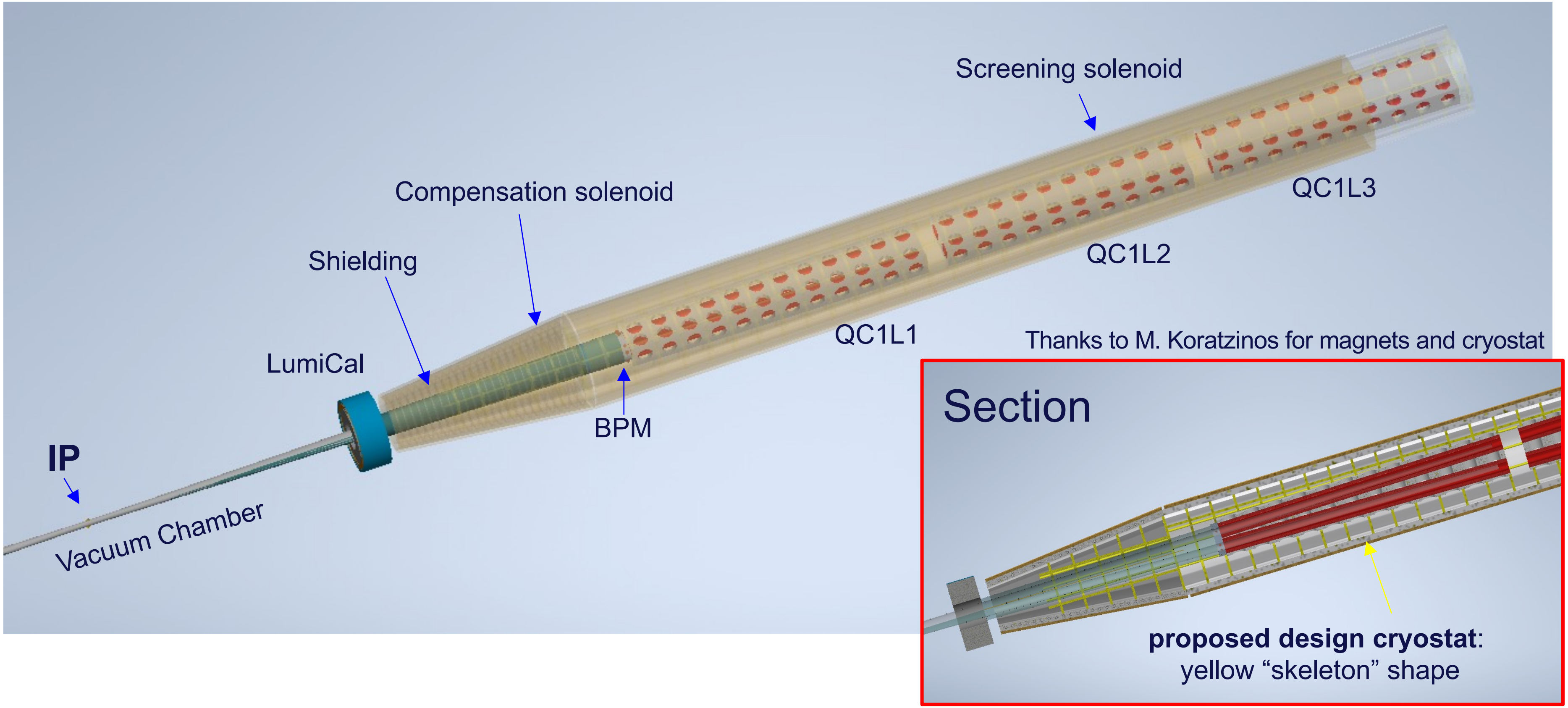


More central B's are shown in red, and more forward B's in blue (defined according to cos(θ) values)

IDEA Delphes configuration

Preliminary assembly of the MDI

[F. Fransesini, this session]



Thanks to M. Koratzinos for magnets and cryostat

proposed design cryostat:
yellow “skeleton” shape

Final Focus quadrupole canted cos-theta design

[M. Koratzinos, this session]

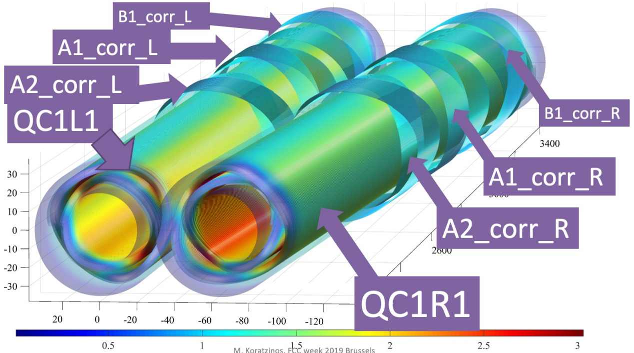
Iron-free design,it can provide an excellent field quality
One prototype designed, manifactured, assembled and tested at warm at CERN

- Conductor technology NbTi
- The maximum field gradient is 100 T/m.
- QC1 inner diameter of beam pipe 30 mm
- (minimum distance between the magnetic centers of e+/e- for QC1L1 is only 66 mm)

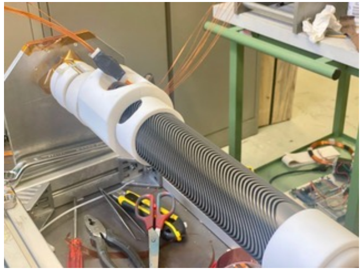
QC1 will be embedded in the screening solenoid and cryostat, all inside the detector

Foreseen next steps:

- Cold test on the prototype
- Cryostat
- Proper shielding to avoid quenches
- Supports for vibration mitigation studies



M. Koratzinos, FCC week 2019 Brussels

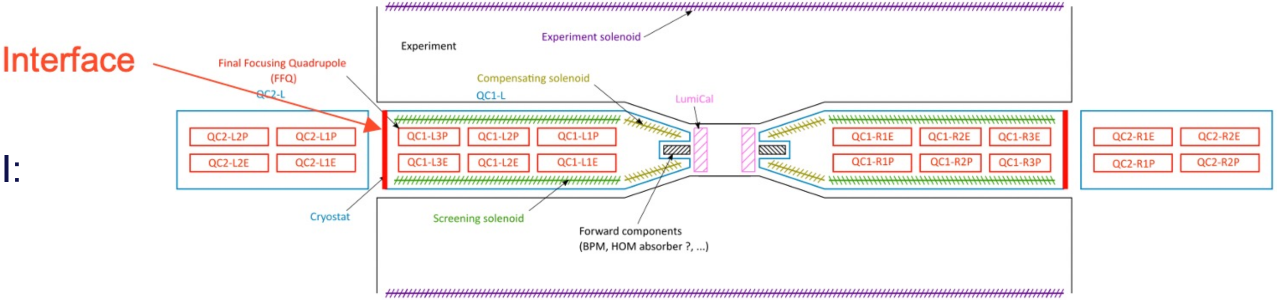


prototype
during construction

Alignment

Léonard Waterlot, this session

Strategy under study



Two systems to monitor the MDI:
- external monitoring system
- Internal monitoring system

The interface would be monitored from the outside of the experiment.
This will allow the alignment of the interfaces of the two sides of the detector.

The interface would serve as a origin to compute the deformations of the cryostat and/or skeleton and the position of the inner elements.

Requirements on distance measurements

- **Lumical** lumical-IP at 50 μm, two faces lumical at 100 μm
- **Final focus quads and sextupoles** radially 75 μm, longitudinally 100 μm
- **BPM** radially 40 μm, relative to quad displacement 100 μm

Beam Background studies

MDI induced detector backgrounds estimation study restarted to deepen the studies presented in the CDR with the following objectives:

- Get full control of the relevant tools for detector background estimation, provide a unified vision and simplified and well documented access.
- Investigate the impact of the debris in the MDI, optimize the shielding in the MDI area
- A complete and flexible description of the geometry of the relevant components (in DD4hep format)
- A solution for interplay with CAD based formats

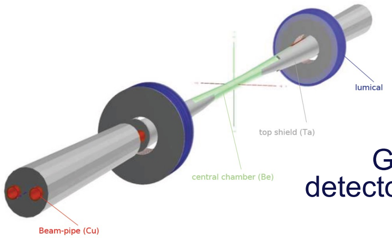
Final goal is to assess the control of detector backgrounds with reliable estimates

in collaboration with the detector group

Collimation scheme to protect detector from sudden beam loss events is also as important

in collaboration with the collimation group

Beam Background studies



Geant4 model for
detector background studies

Synchrotron radiation background

complementary codes (MDISim, Synch_bkg,SYNRAD+)

study in progress to optimise shielding, SR absorbers, vacuum chamber *in collaboration with vacuum group*

and radiation produced at IR also by non gaussian beam tails

Generation and tracking of beam scattered particles

- IP backgrounds
- Single beam backgrounds

(thermal photons, beam-gas studied for the CDR)

restarted after the CDR →

First case-study GuineaPig++ performed integrated in FCCSW key4hep, *goal*: events reconstruction for detector backgrounds sim. study Beamstrahlung photons

Radiative Bhabha BBBrem

tracking spent beam

radiation from radiative Bhabha

A. Ciarma

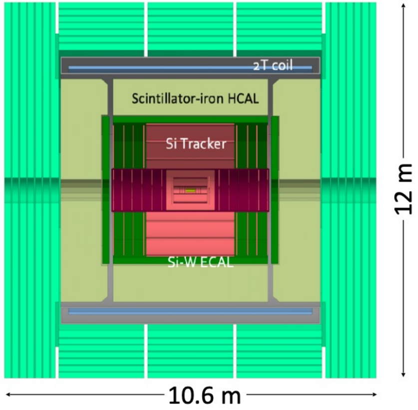
Relevant for MDI are especially IR loss map

Beam tails for lifetime and backgrounds source

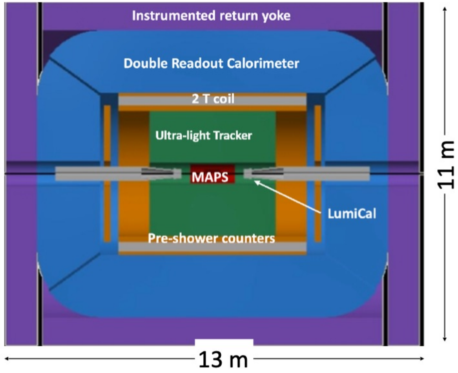
Two Detector concepts

B=2 T

CLD



IDEA



Based on CLIC detector design

- Silicon-based vertex and tracker
- Coil outside calorimeter

New, innovative

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

Synchrotron Radiation with smaller central beam pipe – Z case

M. Sullivan

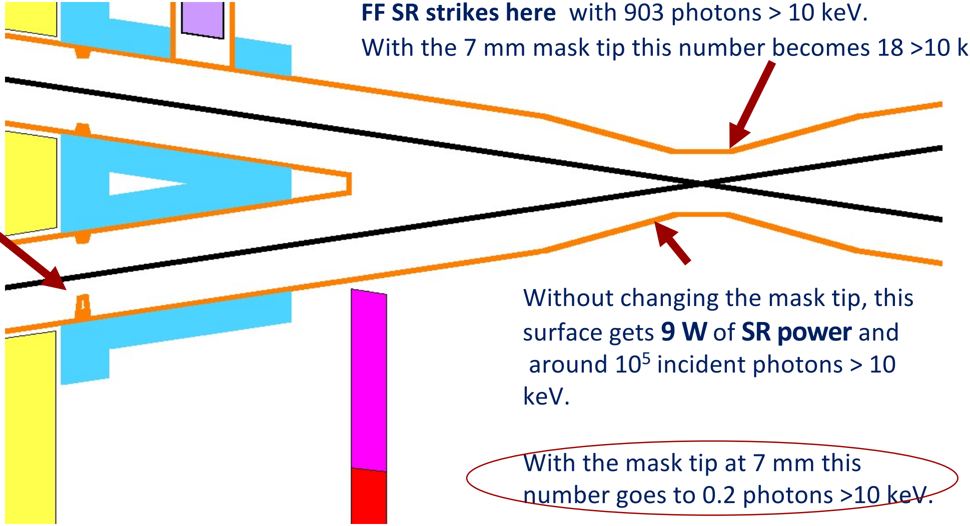
Central pipe with 20 mm diameter and cylindrical length shorten from ±12.5cm to ±9cm

The **mask tip is increased from 10 to 7 mm** to shield the tapered section upstream the IP from the last bend and final focus quadrupole radiation.

On-axis beam, non-Gaussian beam tails to 20 σ_x and 60σ_y have been considered.

The bend radiation can be masked away by reducing the mask radius from 10 mm to 7 mm from the beam line at -2.1 m.

The quadrupole radiation cannot be totally masked away even with a 5 mm radius mask at -2.1 m



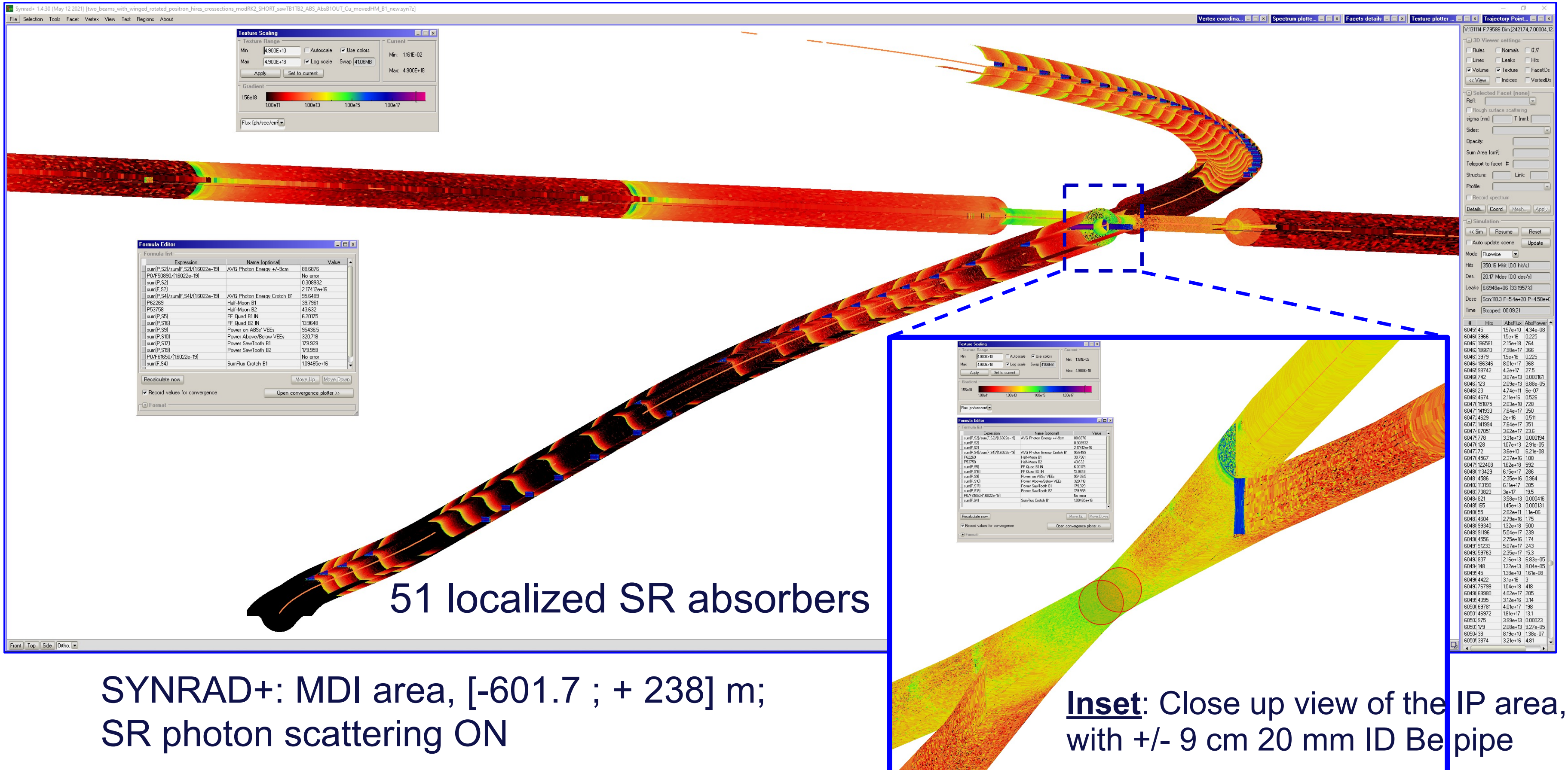
FF SR strikes here with 903 photons > 10 keV.
With the 7 mm mask tip this number becomes 18 >10 keV.

Without changing the mask tip, this surface gets **9 W** of **SR power** and around 10^5 incident photons > 10 keV.

With the 7 mm mask tip at 7 mm this number goes to 0.2 photons >10 keV.

Synchrotron Radiation

courtesy R. Kersevan



Texture Scaling

Texture Range

Min 4.900E+10 ☐ Autoscale ☑ Use colors

Max 4.900E+18 ☑ Log scale Swap 41.06MB

Apply | Set to current

Current

Min: 1.161E-02

Max: 4.900E+18

Gradient

1.56e18 — 1.00e11 1.00e13 1.00e15 1.00e17

Flux (ph/sec/cm²)

Formula Editor

Formula list

Expression	Name (optional)	Value
sum(P,S2)/sum(F,S2)/(1.6022e-19)	AVG Photon Energy +/-9cm	88.6876
P0/F50890/(1.6022e-19)		No error
sum(P,S2)		0.308932
sum(F,S2)		2.17412e+16
sum(P,S4)/sum(F,S4)/(1.6022e-19)	AVG Photon Energy Crotch B1	95.6489
P62269	Half-Moon B1	39.7961
P53758	Half-Moon B2	43.632
sum(P,S5)	FF Quad B1 IN	6.20175
sum(P,S16)	FF Quad B2 IN	13.9648
sum(P,S9)	Power on ABSs' VEEs	95436.5
sum(P,S10)	Power Above/Below VEEs	320.718
sum(P,S17)	Power SawTooth B1	179.929
sum(P,S19)	Power SawTooth B2	179.959
P0/F61650/(1.6022e-19)		No error
sum(F,S4)	SumFlux Crotch B1	1.09465e+16

Recalculate now | Move Up | Move Down

☑ Record values for convergence | Open convergence plotter >>

⊞ Format

V:131114 F:79586 Dim:(2421.74,7.00004,12

3D Viewer settings

☐ Rules ☐ Normals ☐ $\vec{u},\vec{v}$

☐ Lines ☐ Leaks ☐ Hits

☑ Volume ☑ Texture ☐ FacetIDs

<< View ☐ Indices ☐ VertexIDs

Selected Facet (none)

Refl:

☐ Rough surface scattering

sigma (nm): T (nm):

Sides:

Opacity:

Sum Area (cm²):

Teleport to facet #

Structure: Link:

Profile:

☐ Record spectrum

Details... | Coord. | Mesh... | Apply

Simulation

<< Sim | Resume | Reset

☐ Auto update scene | Update

Mode: Fluxwise

Hits: 350.16 Mhit (0.0 hit/s)

Des.: 20.17 Mdes (0.0 des/s)

Leaks: 6.6948e+06 (33.1957%)

Dose: Scn:118.3 F=5.4e+20 P=4.58e+0

Time: Stopped: 00:09:21

#	Hits	AbsFlux	AbsPower
6045	45	1.57e+10	4.34e-08
6046	3966	1.5e+16	0.225
6046	196581	2.15e+18	764
6046	186610	7.98e+17	366
6046	3979	1.5e+16	0.225
6046	186346	8.01e+17	368
6046	98742	4.2e+17	27.5
6046	742	3.07e+13	0.000161
6046	123	2.09e+13	8.88e-05
6046	23	4.74e+11	6e-07
6046	4674	2.11e+16	0.526
6047	151875	2.03e+18	728
6047	141933	7.64e+17	350
6047	4629	2e+16	0.511
6047	141994	7.64e+17	351
6047	87051	3.62e+17	23.6
6047	778	3.31e+13	0.000194
6047	128	1.07e+13	2.91e-05
6047	72	3.6e+10	6.21e-08
6047	4567	2.37e+16	1.08
6047	122408	1.62e+18	592
6048	113429	6.15e+17	286
6048	4586	2.35e+16	0.964
6048	113198	6.11e+17	285
6048	73823	3e+17	19.5
6048	821	3.58e+13	0.000416
6048	165	1.45e+13	0.000131
6048	55	2.82e+11	1.1e-06
6048	4604	2.79e+16	1.75
6048	99340	1.32e+18	500
6048	91196	5.04e+17	239
6049	4556	2.75e+16	1.74
6049	91233	5.07e+17	243
6049	59763	2.35e+17	15.3
6049	837	2.16e+13	6.83e-05
6049	148	1.32e+13	8.04e-05
6049	45	1.38e+10	1.61e-08
6049	4422	3.1e+16	3
6049	76799	1.04e+18	418
6049	69980	4.02e+17	205
6049	4395	3.12e+16	3.14
6050	69781	4.01e+17	198
6050	46972	1.81e+17	13.1
6050	975	3.99e+13	0.00023
6050	179	2.08e+13	9.27e-05
6050	38	8.19e+10	1.38e-07
6050	3874	3.21e+16	4.81

51 localized SR absorbers

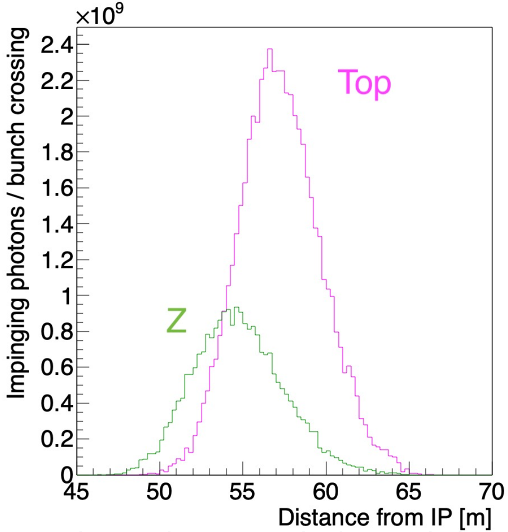
Inset: Close up view of the IP area, with +/- 9 cm 20 mm ID Be pipe

SYNRAD+: MDI area, [-601.7 ; + 238] m;
SR photon scattering ON

Beamstrahlung Radiation generated at the IP

[GuineaPig++]

- A significant flux of photons is generated at the IP in the very forward direction by Beamstrahlung, radiative Bhabha, and solenoidal and quadrupolar magnetic fields.
- **Beamstrahlung** interactions produce an **intense source of locally lost beam power**
- The impinging angle of the **Beamstrahlung** photons with the pipe is about 1 mrad for both beam energies.



Beamstrahlung photons tracked up to their loss points, at about 50-60 m after the IP

	Beam energy	Beamstrahlung Radiation power
<Eγ> = 2 MeV	45.6 GeV	387 kW
<Eγ>=67 MeV	182.5 GeV	89 kW

Fluka or Geant4 simulation to design the proper shielding for this radiation is necessary.

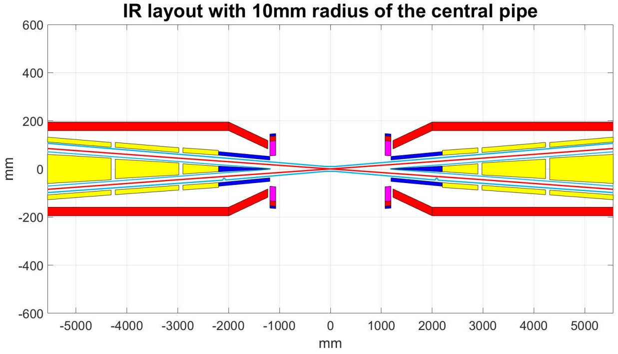
Open questions for mechanical model

Conceptual design of IR elements/systems:
some are under study, others require optimisation,
others are yet missing

- **Progress with the mechanical assembly** adding all the main components as they will be provided by the experts of the different systems. →
- Introduce the weight of the components to design the **supports** and start with the structural studies. This will allow the optimization of the different options of different configurations of supports for **vibration** mitigation, in collaboration with LAPP.
- Space for the **alignment system** to fulfill the stringent requirements.
- **Thermal and mechanical simulations** Just started, with preliminary studies (cooling of central pipe, strength of simplified X pipe to vacuum load at several thicknesses)
- We will define the **strategy for the integration.**

Cryostat design
IR beam diagnostic devices
IR corrector magnets
Shielding
Vacuum system
Remote vacuum connection

Vertex detector (& other IP detectors)



Background control, beam loss and radiation

Ongoing studies

- Synchrotron Radiation background: extensively studied, but still ongoing and planned refined studies
  - induced by non gaussian tails
  - backscattering photons
  - vacuum pipe modeling to absorb and intercept the SR photons, SR absorbers
  - induced in the IR by solenoidal fringing fields and FF quads
- Collimation strategy, and to provide for a safe machine and detector protection
- Beam losses from collisions processes: beamstrahlung, luminosity, including spent beam tracking, shielding optimization and evaluation of effect in detector

collaboration with collimation team

Some open questions

- Top-up injection background
- Neutron radiation in the IR area
- Tail collimation
- Beam abort system

Conclusion

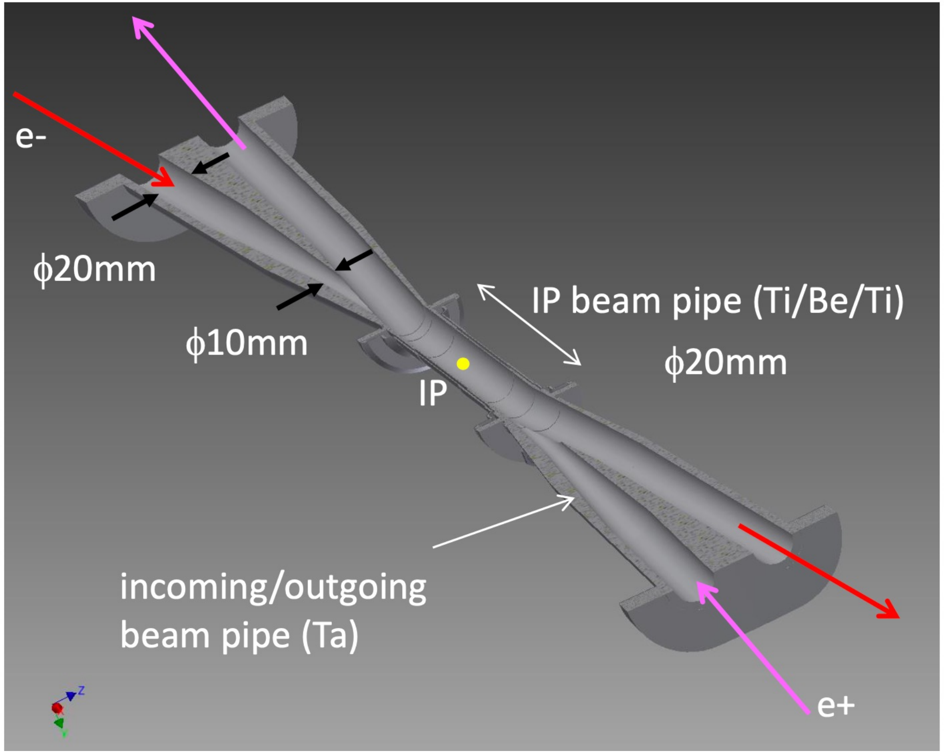
- The Machine Detector Interface study is a key topic for the success of FCC-ee
- Many exciting challenges for the design with state-of-the art technologies and experience on past and present colliders
- A lot of work has been done and ongoing.
- Interesting years ahead of us in the next years!

Thank you
for your attention.

IR future colliders Parameter Table

particle		e^+e^-				**pp**			e^- - ion	
type		**circular**		**linear**		**circular**			**circular/ ERL**	
collider name		**SuperkekB**	**FCC-ee**	**ILC**	**CLIC**	**LHC**	**HL-LHC**	**FCC-hh**	**EIC**	**LHeC**
Beam Energy	GeV	**LER (e+) 4 HER (e-) 7**	**45.6, 120,182.5**	**125, 250**	**190 / 1500**	**7000**	**7000**	**50000**	(e-) 10 (h) 275	(e-) 49.19 (p) 7000
$\mathcal{L}$ (peak)	$10^{34}cm^{-2}s^{-1}$	**80**	**230, 8.5, 1.6**	**1.4, 1.8**	**1.5, 6**	**2.1**	**5**	**5-30**	**1**	**23**
crossing angle	mrad	**83**	**30**	**14**	**16.5, 20**	**0.26**	**0.5**		**25**	**0**
Bunch spacing	ns	**4**	**20**	**554, 5Hz train**	**0.5, 50Hz 312 train**	**25**	**25**	**25**	**10**	**50**
L* (free region)	m	**L 0.77 H 1.22**	**2.2**	**4.1**	**6**	**23**	**23**	**40**	**4.5**	**10**
β_x*	cm	**L 3.2 H 2.5**	**15,30, 100**	**1.3, 2.2**	**80 / 70**	**25**	**15**	**110-30**	**45 80**	(e-) 6.45 (p) 10
β_y*	mm	**L 0.27 H 0.3**	**0.8, 1, 1.6**	**0.41, 0.8**	**0.1 / 0.12**	**250**	**150**	**1100-300**	**56 72**	(e-) 64.5 (p) 100
Normalised emittance x	μm	**L 25 H 63**	**24, 148, 479**	**5, 10**	**0.95/ 0.66**	**3.5**	**2.5**	**2**	(e-) 391 (h) 3.3	(e-) 50 (p) 2.5
Normalised emittance y	nm	**L 68 H 177**	**89, 235, 1000**	**35, 35**	**30/20**	**3500**	**2500**	**2000**	(e-) 25400 (h) 290	(e-) 50000 (p) 2500
B_{det}	T	**1.5**	**2**	**5 (SiD)**	**3.5-5**	**Atlas 2T, CMS 4T**			**1.4**	**3.5**
central pipe radius	cm	**1**	**1.5 (1)**	**1**	**3**	**2.35 Atlas, 2.1 CMS**	**2.35 Atlas, 2.1 CMS**	**2.5**	**elliptical**	**elliptical**

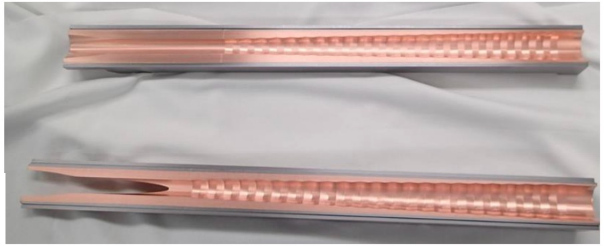
SuperKEKB beam pipe & synchrotron radiation



- ϕ20mm→ϕ10mm collimation on incoming beam pipes (no collimation on outgoing pipes, HOM can escape from outgoing beam pipe)

- Most of SR photons are stopped by the collimation on incoming pipe.
- Direct hits on IP beam pipe is negligible

- To hide IP beam pipe from reflected SR, "ridge" structure on inner surface of collimation part.

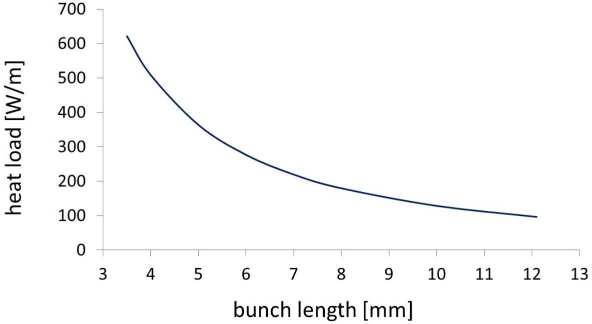


Inner surface of Be pipe are coated with **Au layer (10 μm)** to protect detectors from SR

Heat load for 30 mm beam pipe

bunch length [mm]	HEAT LOAD Two beams [W/m]				current [A]	Bunch spacing [ns]	
					2 x 1.39	19.50	
12.10	63.45	69.18	81.68	96.57	125.23	349.64	1473.91
Material	Cu	Au	Al	Be	Ni	SS	NEG

- Beryllium pipe takes **100 W/m for a 12 mm bunch** but **strongly increasing with shortening the bunch length**.
- **A gold coating can decrease the heat load by 30%**



A. Novokhatski

Beamstrahlung

- SR in field of opposing beam, estimated at the Z with **Guinea-Pig**
- The IR will generate **a very significant flux and power of hard X-rays lost mostly in the first downstream bend** (49-55 m from IP)

Classical SR and Guinea-Pig	<Nγ>	<Eγ> keV	Power KW
IP magnets (quad, solenoid)	1.3	24	43 kW
Beamstrahlung	0.15	2000	**417 kW**

(also without collisions)

photon energies extend into the GDR region

- **~460 kW hitting in a narrow ~5 m wide region**
- wall power / length of order 100 kW/m

some MW / IP with spectrum extending into tenths of MeV

strongly varying with bb-parameters and residual separation

H. Burkhardt