MDI challenges toward the TDR

Manuela Boscolo
for the MDI team

10 November 2020
FCC November Week 2020

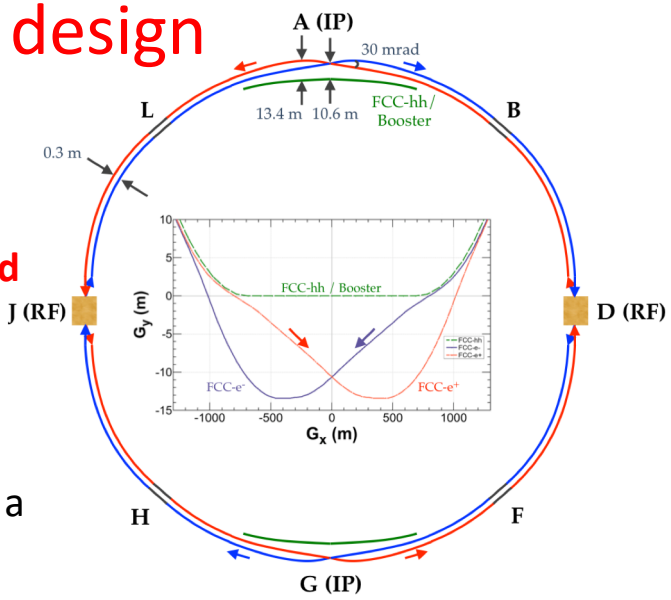
The Future Circular Collider Innovation Study (FCCIS) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 951754

Outline

- Present status of the FCC-ee MDI study
- Beam backgrounds studies and mitigation remedies
  - Synchrotron radiation, masks, shieldings and collimators
  - Beam induced effects, loss maps and collimation
  - Impact on detectors background
- Engineering effort
- Conclusion with some key issues that require further studies

Key parameters for FCC-ee MDI design

- **Double ring** e^+e^- collider, **100 km**
- FCC-ee follows the footprint of FCC-hh, except for around the IPs
- **2IPs** with **crab-waist scheme ->** large horiz. crossing angle: **30 mrad**
- Crab-waist has large impact in the design: separated tunnels around the IR for +/- 1.3 km needed



- **Flexible optics design: common lattice for all energies,** except for a small rearrangement in the RF section

- **Large energy acceptance required (>2.8 %)** at high energy, required by the strong beamstrahlung

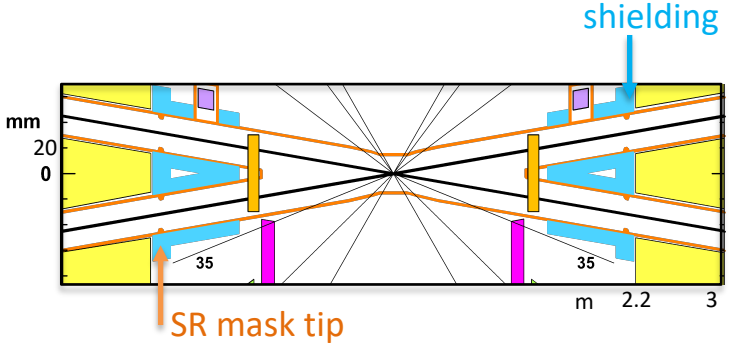
- **Synchrotron radiation** is one of the main drivers for the FCC-ee MDI design

  first requirement: $E_{critical}$ < 100 keV for incoming beam to IP from 500 m (based on LEP experience)

  possibly keep $E_{critical} \lesssim 1$ MeV in the whole ring, to minimize n-production (LEP2 0.72 MeV)

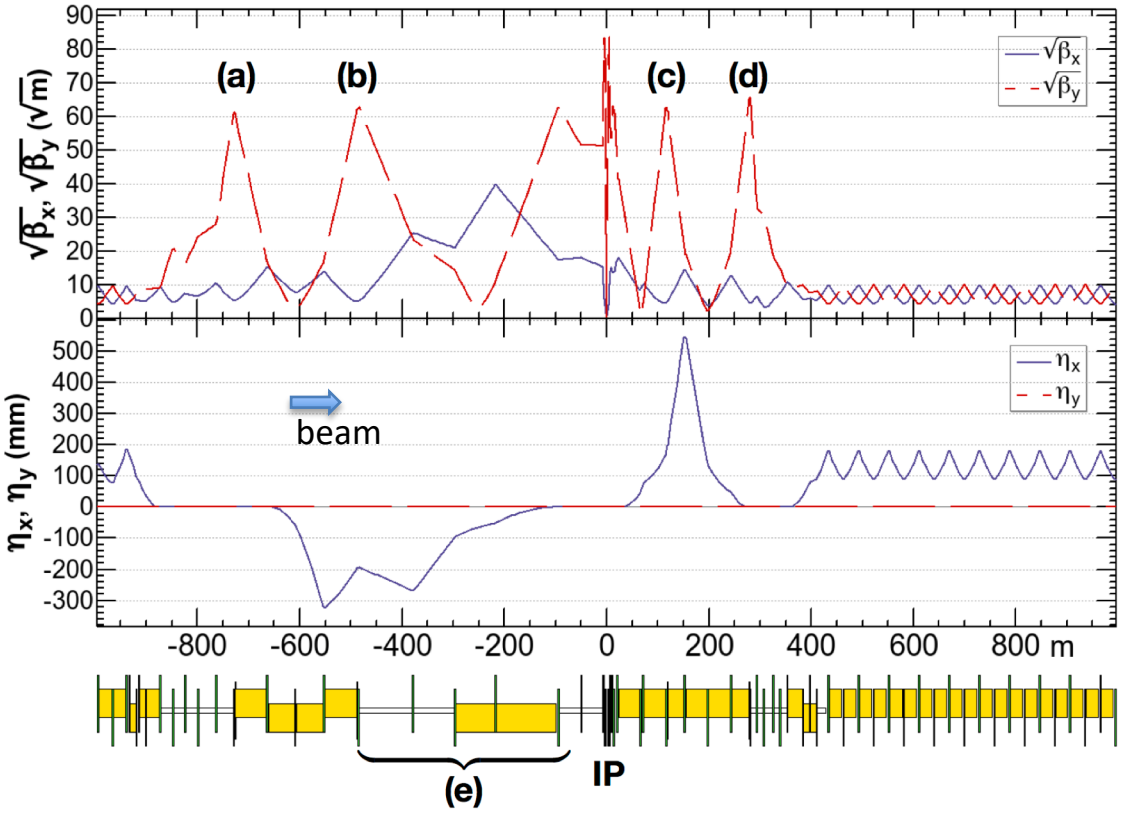
  countermeasures:

  - ✓ Optics with asymmetric dipoles in the IR
  - ✓ SR mask tips to intercept SR photon fans
  - ✓ high-Z shielding outside vacuum chamber
  - ✓ sawtooth ridged chamber inside FF quads
  - ✓ SR collimators



Asymmetric Interaction Region optics

ttbar 182.5 GeV



K. Oide

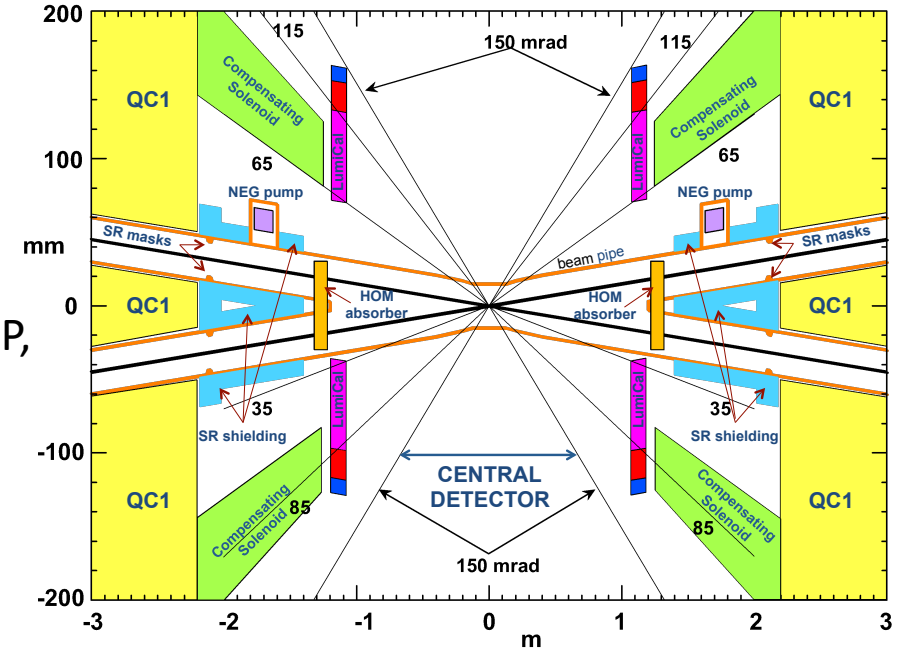
yellow boxes: dipole magnets

- Asymmetric optics suppresses SR toward the IP, $E_{critical}$ <100 keV from 450 m from the IP
- Local chromaticity correction scheme for y-plane (a-d), incorporated with crab sextupoles (a,d), needed for energy acceptance requirement (up to 2.8%)

FCC-ee collider, some challenges for the IR design

to provide and maintain high Luminosity: challenge for the accelerator & engineering design

Complicated IR with large crossing angle
the beam pipes separate already at ~1.2m from IP,
tight space constraints with compensating and screening solenoid inside the detector solenoid

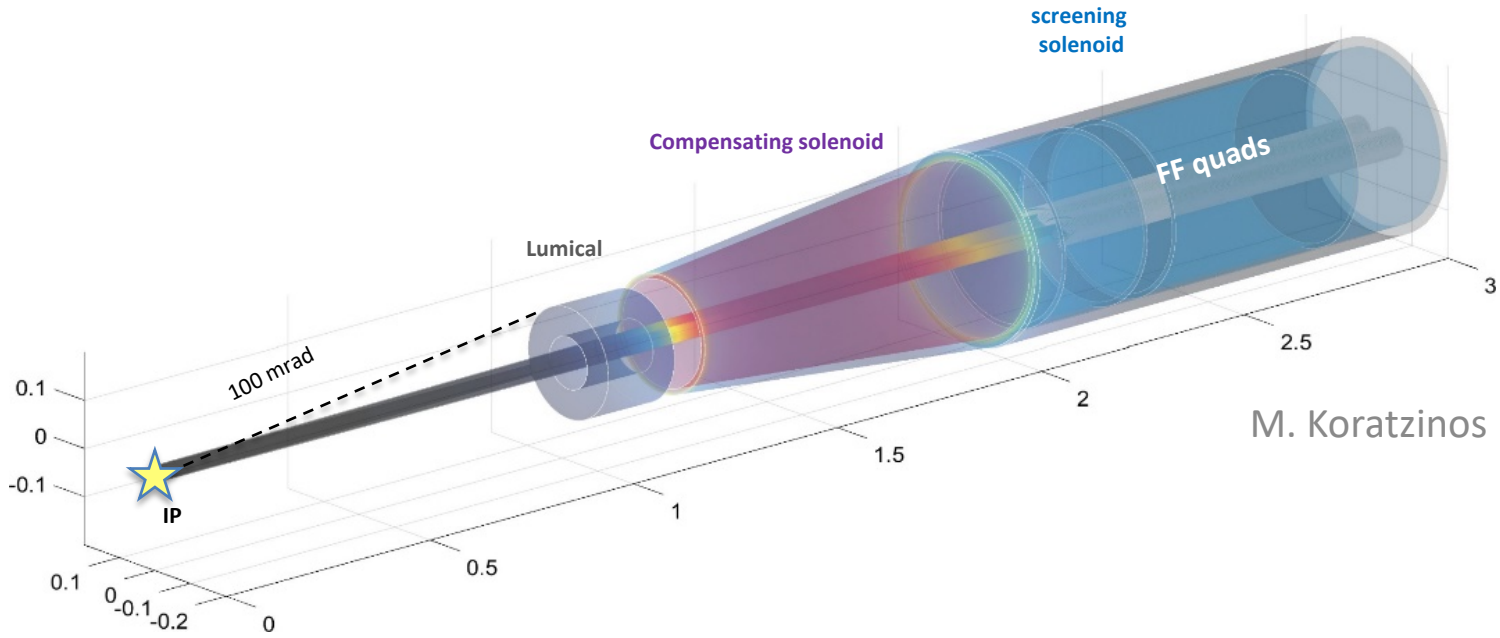


- **high chromatic effects by FF quads**
- **solenoidal fringe fields**
- **Stringent beam coupling factor (~$2 \cdot 10^{-3}$) and vertical emittance growth ($\lesssim$ 30% nominal value)**
- **Tight tolerances for alignment of magnets, very good orbit stability and vibrations control**

- Very significant **Beamstrahlung**, large sigmaz variations for collective effects, beam-beam stability, induced background in sorrounding components and detector
- **Synchrotron Radiation**: at **top** energy high energy photons, at **Z** intense flux
- **Top-up injection**, injection backgrounds (SuperKEKB experience important)

Baseline for FCC-ee Solenoid Compensation Scheme

All machine elements, including the compensating solenoid, are kept inside a cone with an opening angle of 100 mrad around the z axis as required by the physics.



- **screening solenoid** that shields the detector field inside the quads
- **compensating solenoid** in front of the first quad, as close as possible, to reduce the ε_y blow-up

about 0.3 pm is the overall ε_y blow-up for 2IPs @Z

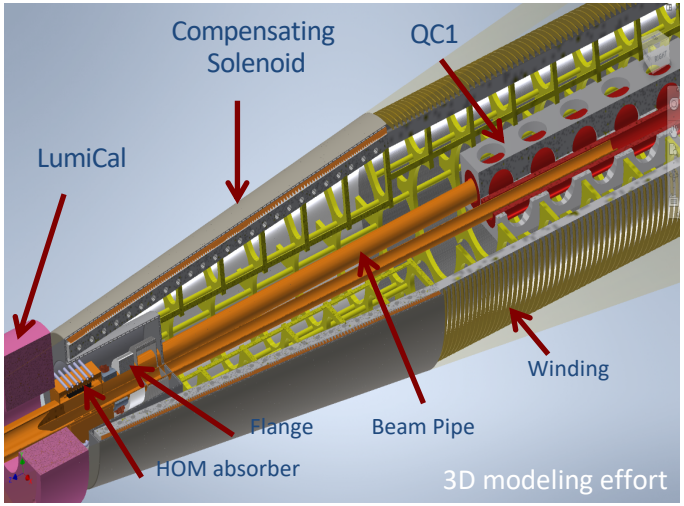
Plans for FCC-ee MDI design and optimization

Within the FCCIS project our goal is to demonstrate the feasibility of the FCC-ee interaction region also providing the related engineered design that meets

- mechanical requirements in terms of integration, assembly, and stability
- optics, beam dynamics and high current requirements
- tolerable radiation and sustainable backgrounds

Main MDI areas of study:

- Beam physics (optics, beam dynamics, collective effects)
- Beam induced backgrounds
- Development and update of new simulation tools
- Experimental environment
- Luminosity measurement
- Mechanical design and integration study
- Engineering sub-systems, like:
  - thermal power budget
  - dimensioning of cooling systems
  - vacuum system
  - alignment/surveying space requirements

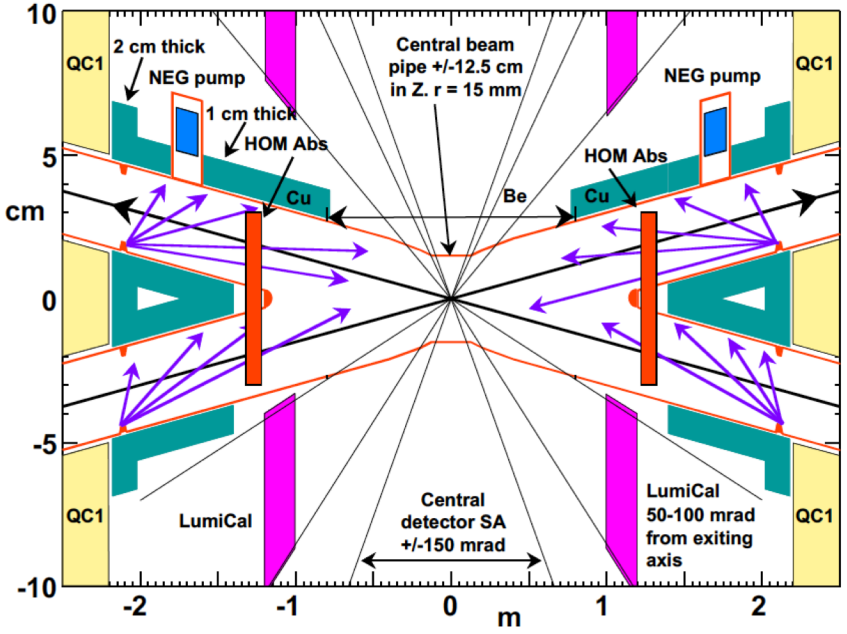


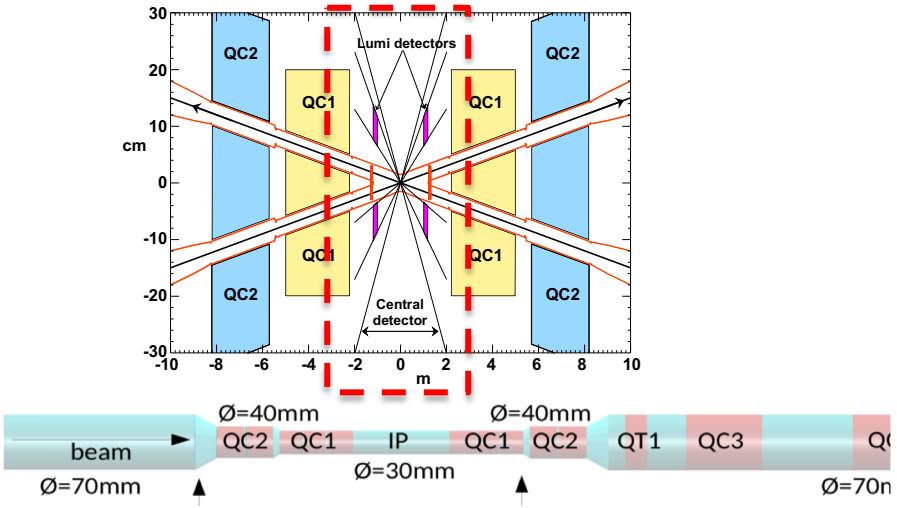
MDI sessions this FCC WEEK 2020

Tuesday 10	WP2 Collider Design: Joint FCC-ee Accelerator and Experiments session	
13:30:14:00	MDI challenges toward the TDR	Manuela Boscolo
14:00-14:20	SuperKEKB experience on MDI design and beam background	Hiroyuki Nakayama
14:20-14:40	Vibration/stabilization: from SuperKEKB to FCC-ee	Laurent Brunetti
14:40-15:00	Possible contributions to MDI	Ralph Assmann

Wednesday 11	Joint Accel. and Exper. session: MDI,Polarization, monochromatization	
14:00-14:20	Design of the FCC-ee Beam Polarimeter	Nickolai Muchnoi
14:20-14:40	Monochromatization schemes and beamstrahlung	M. Alan Valdivia
14:40-15:00	Monochromatization and large crossing angle	Anton Bogomyagkov
15:00-15:20	Mechanical IR design	Luigi Pellegrino
16:00-16:20	Final Focus magnets	Mike Koratzinos
16:20-16:40	Beam backgrounds impact on detectors	Georgios Voutsinas
16:40-17:00	SR collimation in the MDI area	Marian Luckhof
17:00-17:20	SR backgrounds including the effect for a 1 cm radius beam pipe	Michael Sullivan
17:20-17:40	A new low impedance IR FCC-ee beam chamber	Alexander Novokhatski

Interaction Region Layout as in CDR



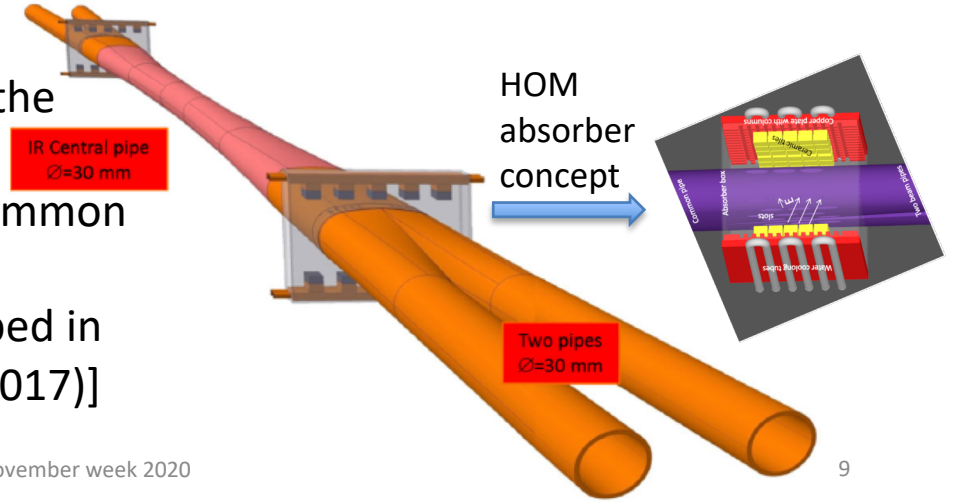


beam pipe length z ± 125 mm, diameter 30 mm

The incoming pipes and the central pipe have the same diameter of 30 mm

Special transition from two beam pipes to a common central pipe.

HOM absorbers are necessary, concept described in Ref. [A. Novokhatski et al. PR-AB 20, 111005 (2017)]



The concept of the HOM absorber

Based on the property of the trapped mode we have designed a special HOM absorber.

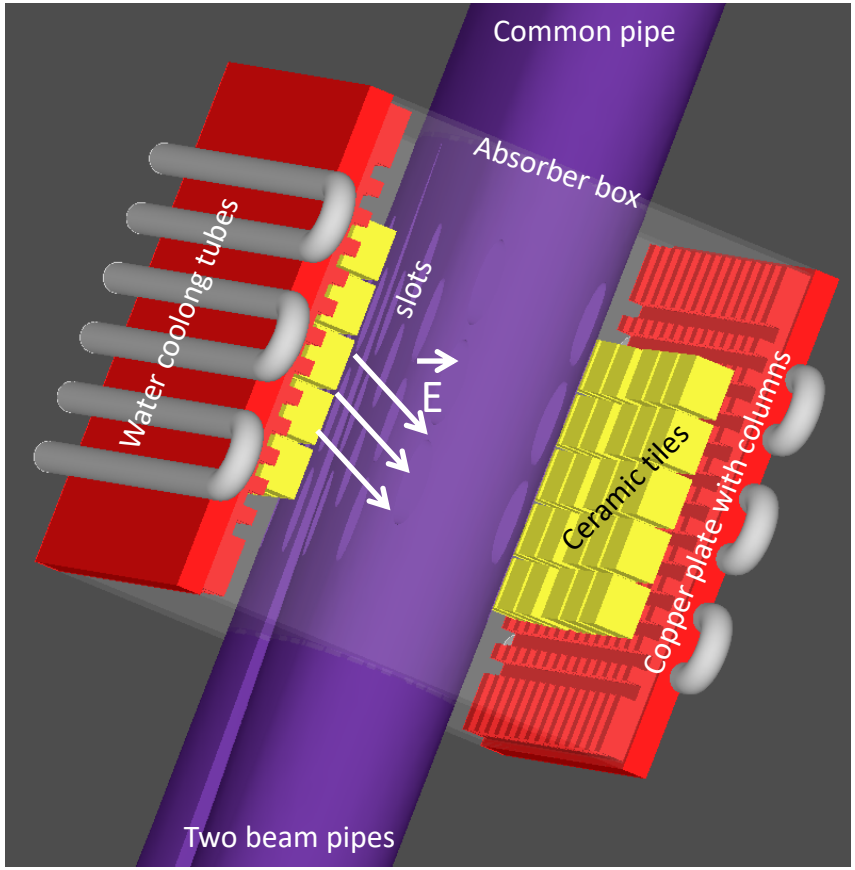
The absorber vacuum box is placed around the beam pipe connection. Inside the box we have ceramic absorbing tiles and copper corrugated plates .

The beam pipe in this place has **longitudinal slots**, which connect the beam pipe and the absorber box. Outside the box we have stainless steel water-cooling tubes, braised to the copper plates.

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

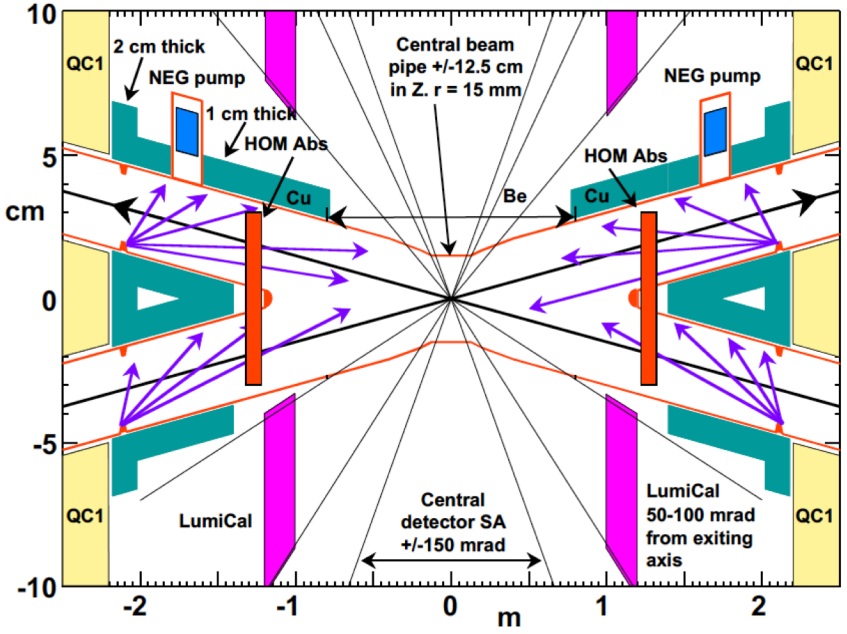
Inside the absorber box these fields are **absorbed by ceramic tiles**, because they have high value of the loss tangent.

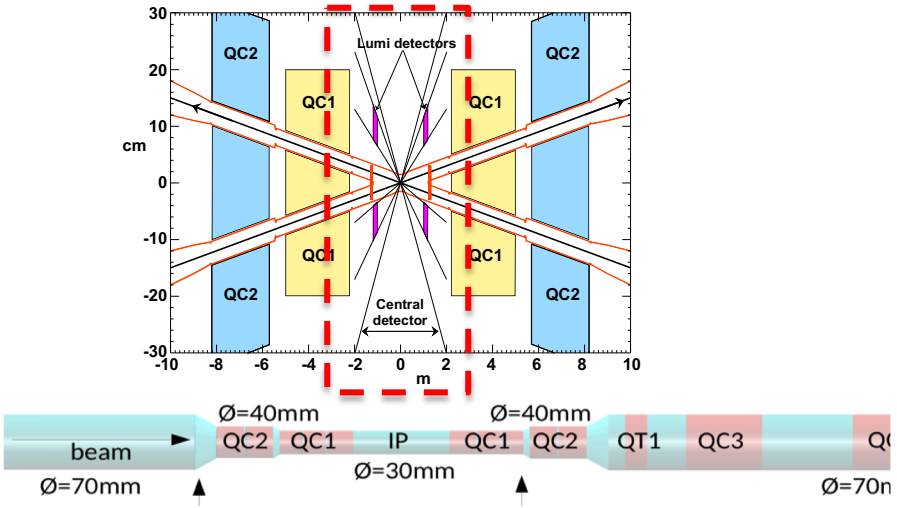
The **heat from ceramic tiles** is transported through the copper plates **to water cooling tubes**.



A. Novokhatski

Interaction Region Layout as in CDR





beam pipe length z ± 125 mm, diameter 30 mm

After the CDR

In 2019 it was suggested to **decrease the size of the central beryllium pipe**:

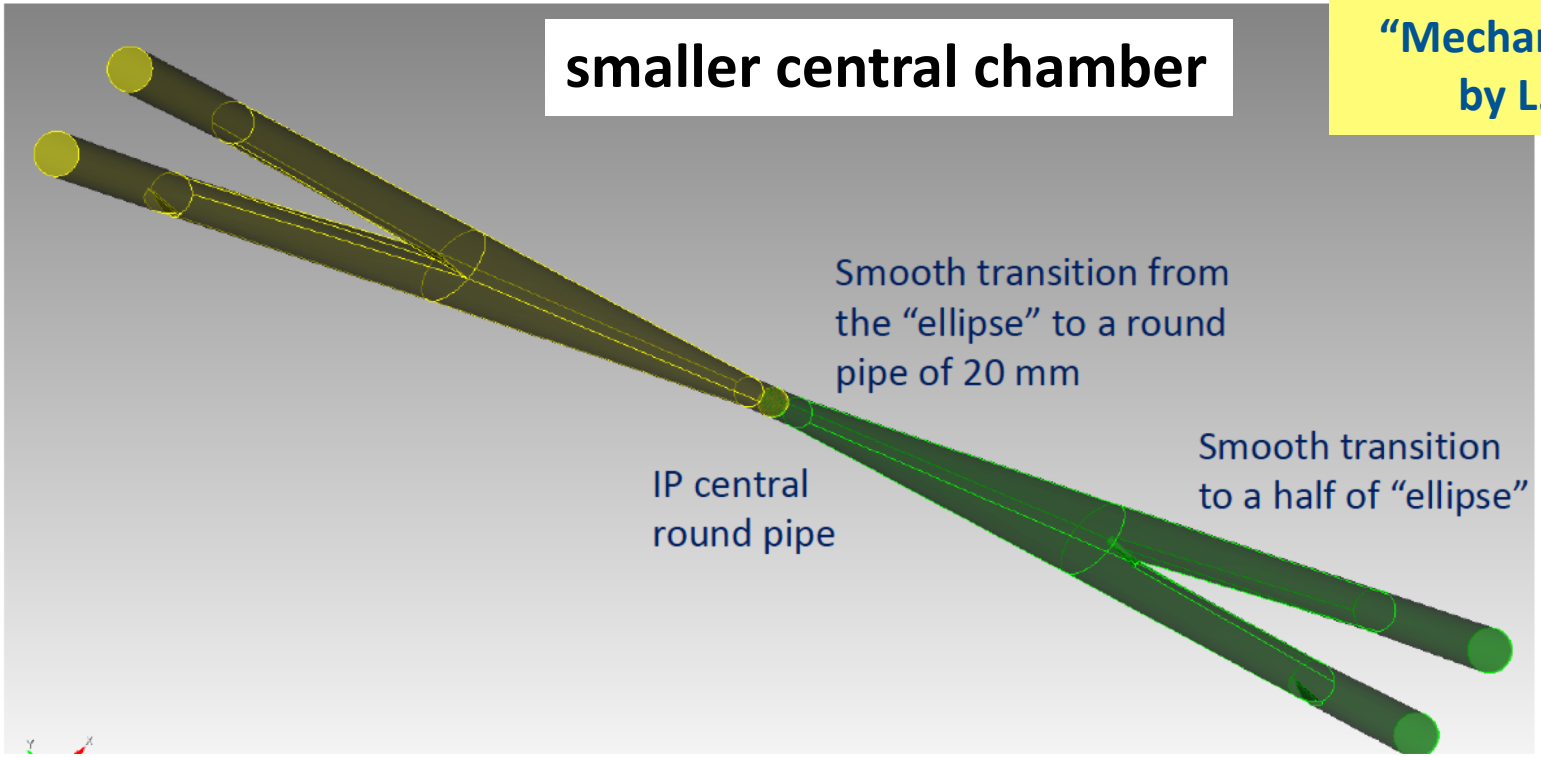
diameter 20 mm and beam pipe length z ± 90 mm

- This modification gives a considerable improvement of the tracking efficiency

  (E. Leogrande FCC WEEK2019)
- Impact on heat load, wake fields and synchrotron radiation was studied

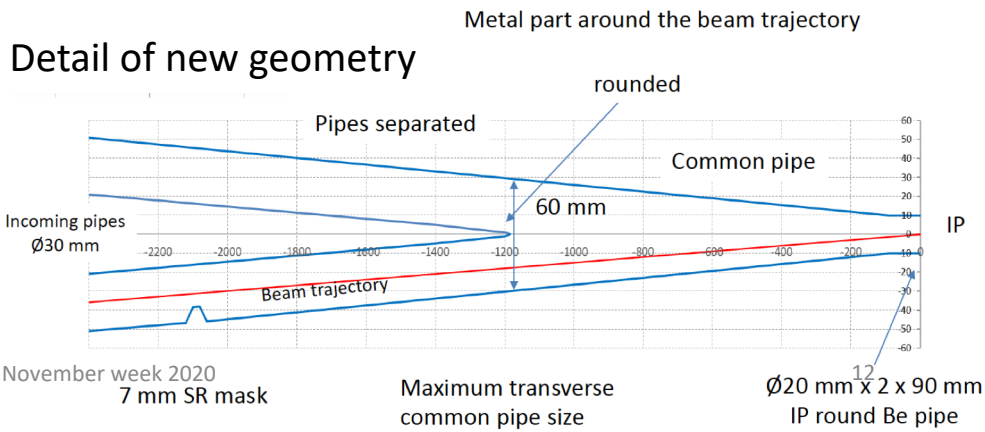
New beam pipe design

more details in talk on "Mechanical IR design" by L. Pellegrino



- Model has been used for wake field calculations
- Work on CAD design started for a feasible and realistic design

Detail of new geometry



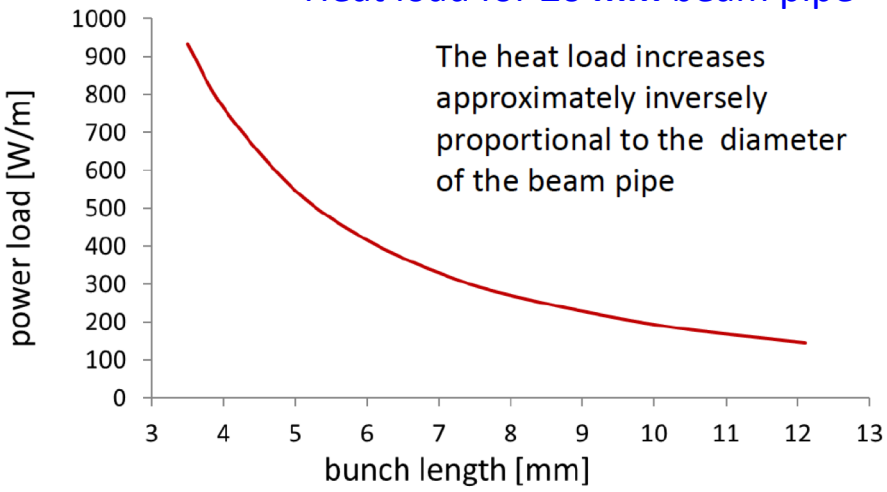
New beam pipe with low impedance

All details in talk by A. Novokhatski

- **NO HOM ABSORBERS** required
- Gain space in the crowed area very close to the IP
- Only **cooling of beam pipe needed, including in the central Be chamber**

- Power 133 W that will mostly go away from IP
- Very small shunt impedance
- A gold coating can decrease the heat load by 30%

Heat load for **20 mm** beam pipe



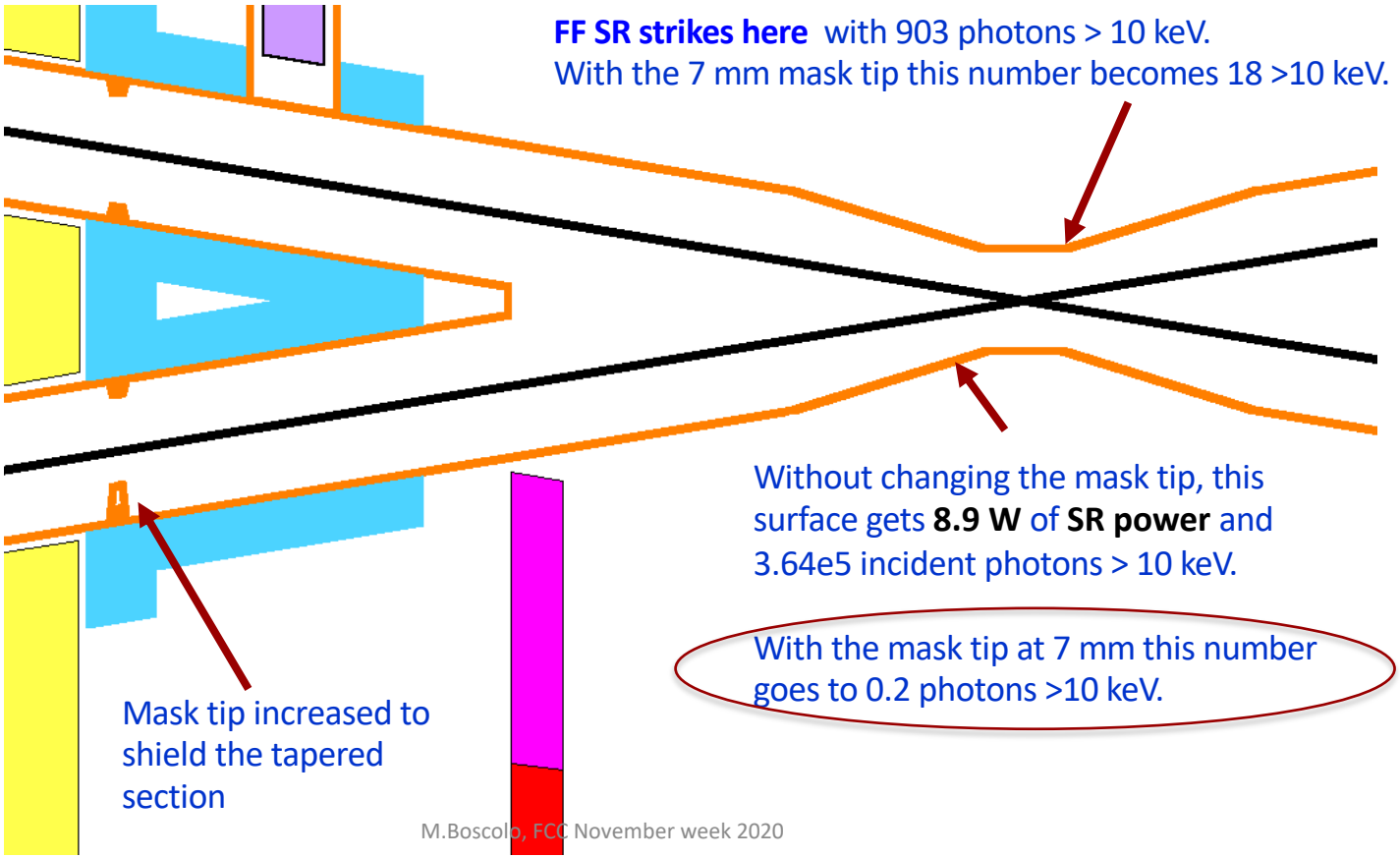
Synchrotron Radiation with smaller central beam pipe – Z case

All details in talk by M. Sullivan

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

- The bend radiation can be masked away by reducing the mask radius at -2.1 m from 10 mm to 7 mm from the beam line.
- The quadrupole radiation cannot be totally masked away even with a 5 mm radius mask at -2.1 m

On-axis beam, non-Gaussian beam tails to 20 σ_x and 60σ_y



Background studies

Effort in developing and updating software tools

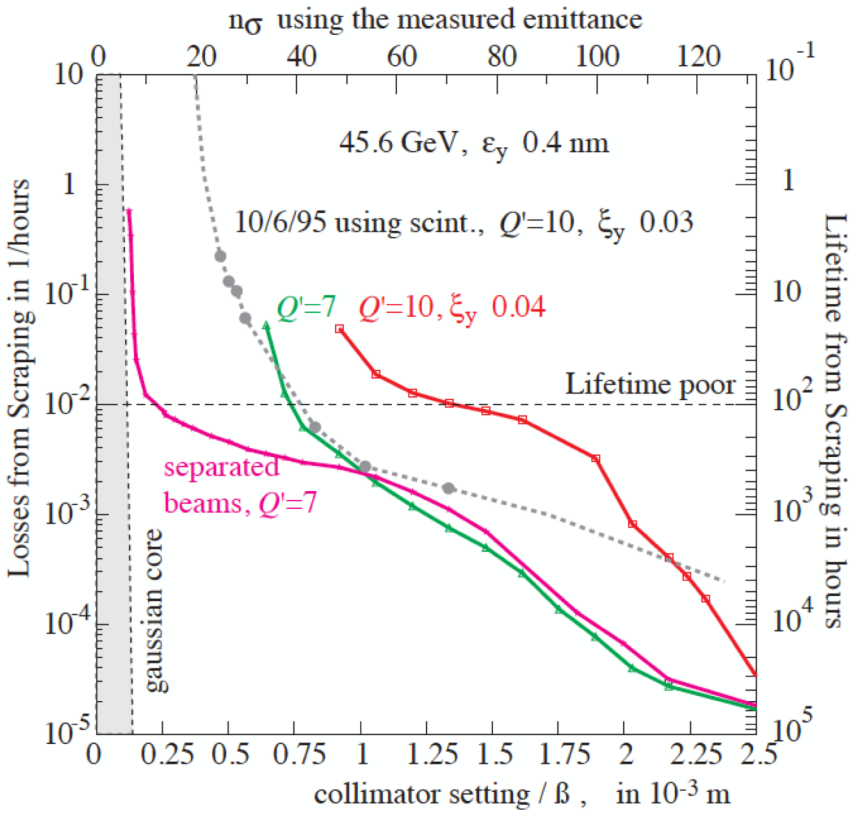
- **Synchrotron radiation background**
  - different codes used on the accelerator side for collimation and masking (MDISim, Synch_bkg, SynRad+) and impact on detector investigated (Geant4)
- **Generation of background sources**
  - IP backgrounds
  - Single beam backgrounds:
- **Tracking beam scattered particles**
  - **to produce IR loss map → and track into detectors** (CLD and IDEA)
  - **to produce loss maps around the ring → for collimation study**
  - Multiturn tracking for IP and single beam bkgs to be continued and strenghtened with more details, especially with non-ideal lattice (energy tapering with radiation, imperfections)
  - Collimation scheme
  - Beam tail

Non-Gaussian tails, LEP

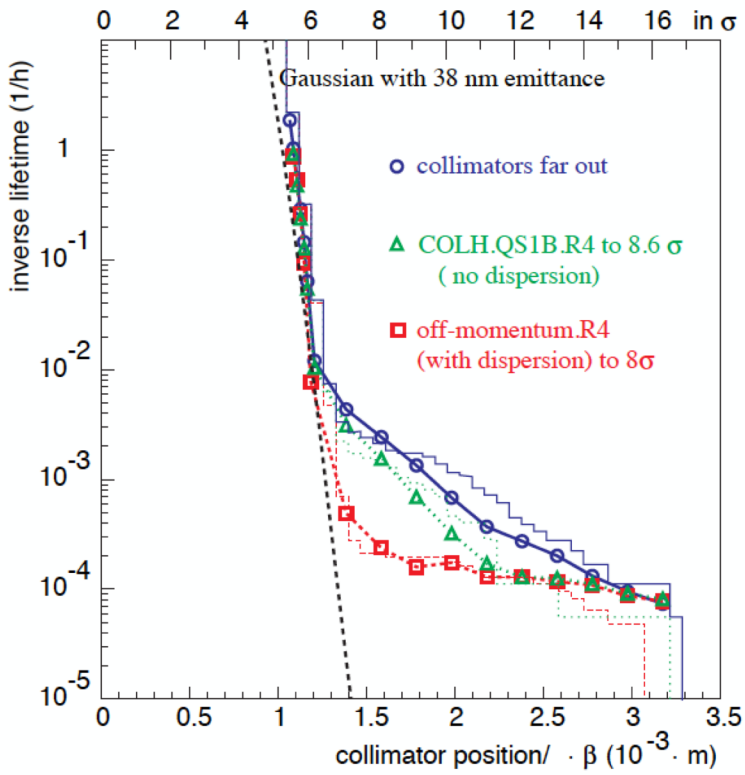
H. Burkhardt

Measured by scraping with loss monitors

Vertical plane, Colliding beams



horizontal plane
Reproduced by simulation



Tails from : beam-beam, high chromaticity, particle scattering

Background spikes, enhanced synchrotron radiation from quadruples

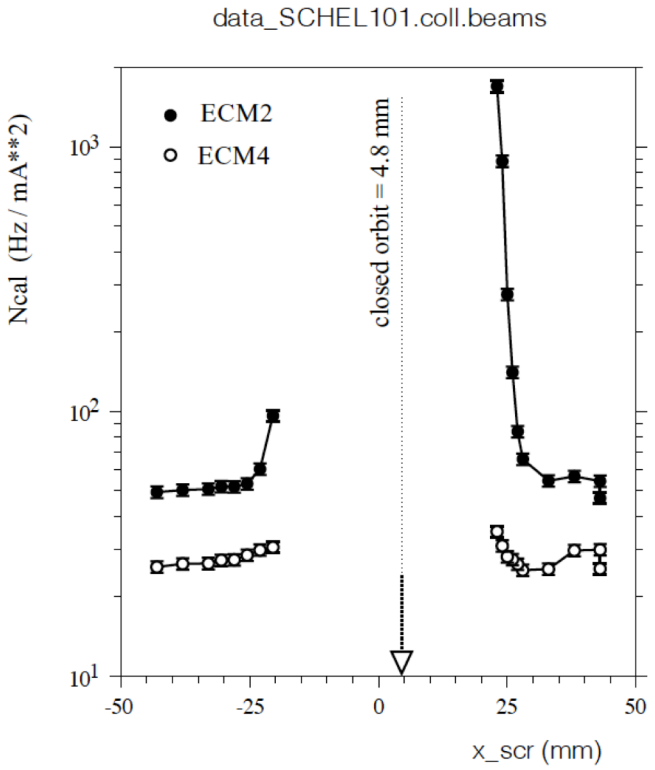
H. Burkhardt, "BEAM LIFETIME AND BEAM TAILS IN LEP." CERN-SL-99-061-AP and Proc. e+ e+ Factories 1999, KEK, Tsukuba 1999
Transverse beam tails due to inelastic scattering, Phys. Rev. ST Accel. Beams 3, 091001 (2000)

Non-Gaussian tails, DAFNE

Touschek dominated machine

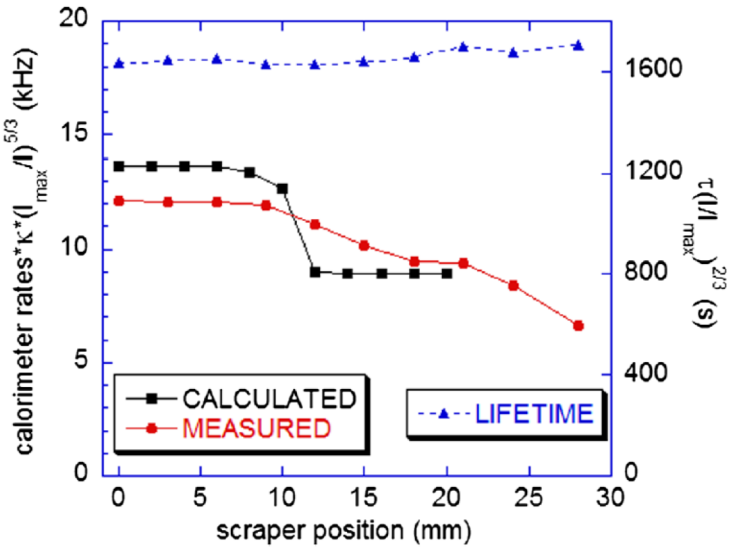
Measured by scraping with KLOE sectors endcaps calorimeter

Horizontal plane, single beams



M. Boscolo, G. von Holtey, et al.
DAFNE Techn.NOTE IR-9, 13/10/2000

Fully dominated by Touschek scattering, as expected by simulations



Ref. [M. Boscolo and P. Raimondi, PRST-AB 15, 104201 (2012)]

Background studies: generators and tools

IP

Background source	generator	tracking code for loss map
Beamstrahlung	*GuineaPig , BBWS*	*SAD, MADX*
Radiative Bhabha	*GuineaPig, BBBrem*	*SAD, MADX*
Pair production (incoherent dominant)	*GuineaPig*	*Geant4*
$\gamma\gamma$ to hadrons (small effect)	combination of *GuineaPig and Phythia*	*Geant4*

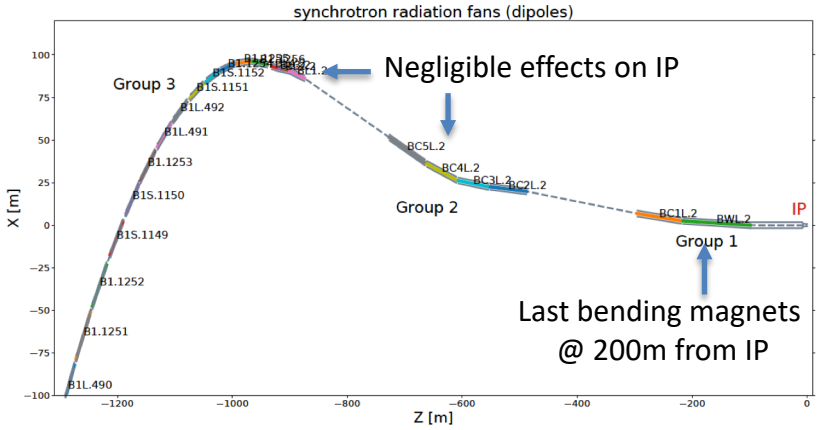
Single beam

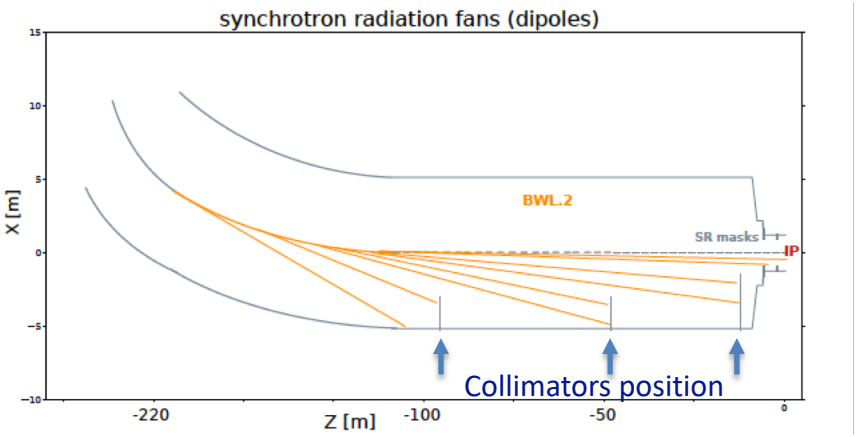
Synchrotron Radiation	*Geant4, SYNRAD+, BKG_SYNC*	*MDISim / G4*
Thermal photons	*MC (H. Burkhardt) MC (A. Ciarma)*	*MADX*
Beam-Gas Bremstrahlung (BGBrem)	*Geant4, MC (A. Ciarma)*	*MDISim MADX*
Touschek	*MC (A. Ciarma) (in progress)*	*MADX*

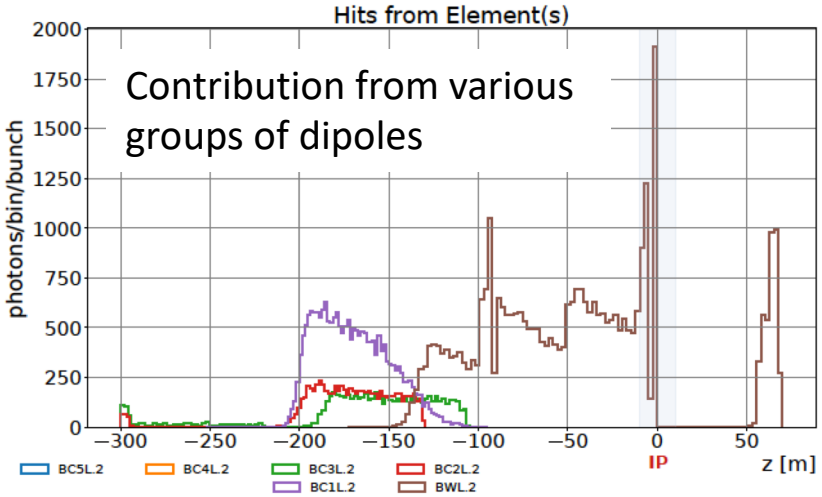
Synchrotron Radiation control in the MDI upstream the IR

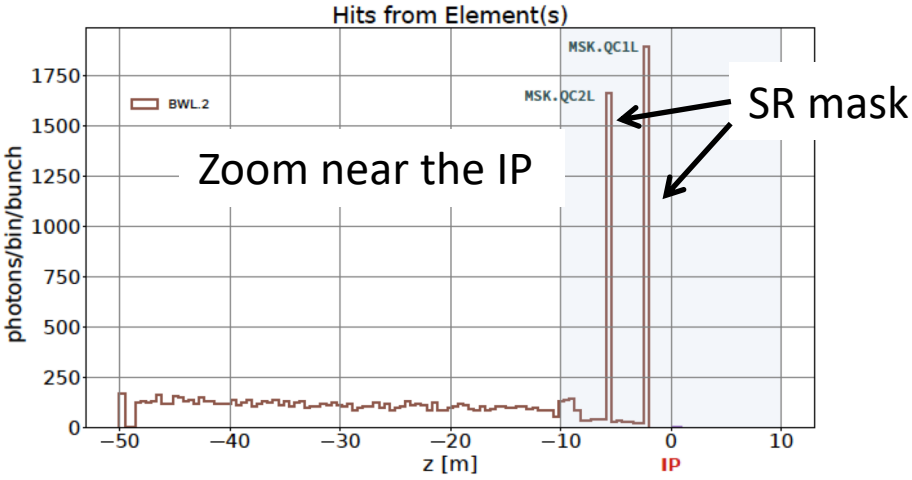
Ref. MDISim

Details in talk by M. Luckof









- Around the IR, Synchrotron Radiation is dominated by fans coming from the last bending @200m from IP
- Most of it is intercepted by masks the last of which is places 2.2m from the IP
- High Z shielding around the beam pipe (where possible and non detrimental for the LumiCal) further decreases the amount of SR reaching the Vertex detector
- Currently studying specific collimators in order to further reduce the SR impact on the IR

Status and plan for further studies on Synchrotron Radiation at the IR

- We plan to **refine simulations** with improvements on the simulation level:
  - tracking in IR with beams tilted in solenoid
  - fringe fields overlapping with quads
  - X-ray reflection not yet included in Geant4 (and check for giant dipole resonance)
- Primaries are under control, **secondary sources** to be simulated carefully also with the output from MDISim
- **SR collimators** study has been performed with MDISim, it will be updated with the new small central chamber and optimized masks
- **Interaction region optimization and shielding of the hard synchrotron radiation** including radiation from the final quadrupoles (especially for top energy).

- First handle to control SR is OPTICS (Lattice/Layout)
- SR studied with **SYNC_BKG, MDISim** (MADX/ROOT/Geant4) and **SYNRAD+**

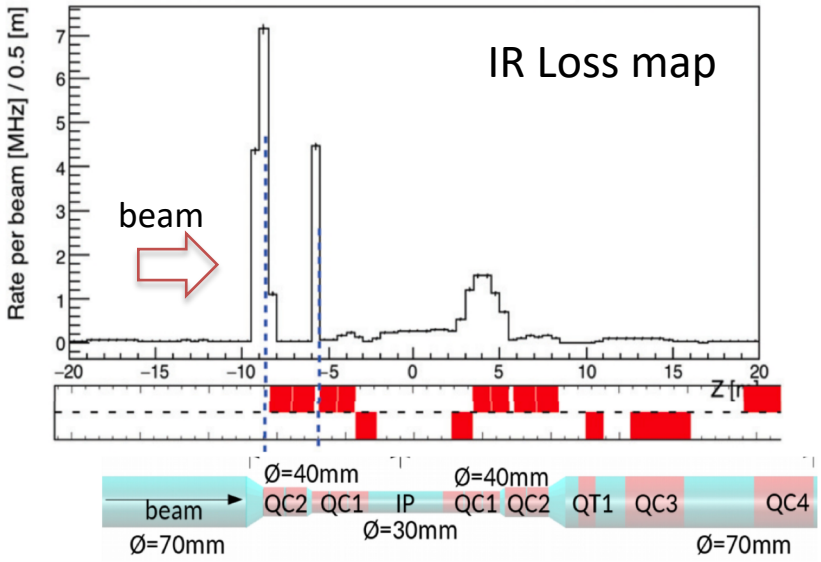
Inelastic Beam-gas scattering

more details in talk by A.Ciarma, acceler. code development session

New beam background tracking tool under development

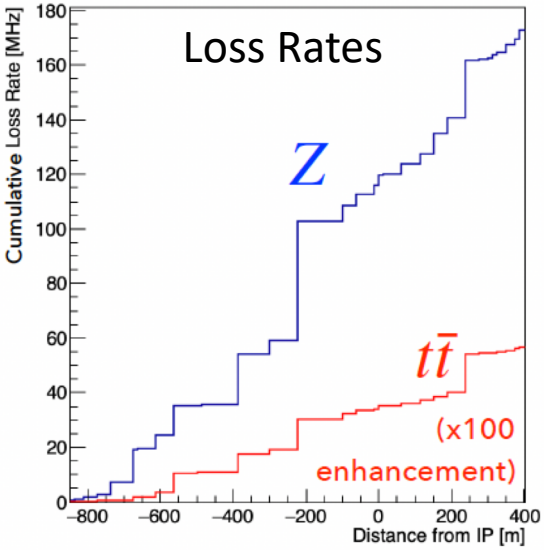
Benchmark with MDISim showed excellent agreement

MOPMF085, IPAC18

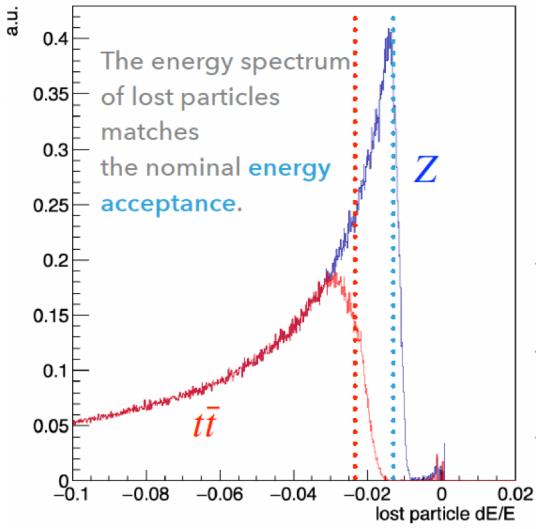


Main IR losses coincide with beam aperture limitations

Assumed 10^{-9} mbar residual gas pressure



More relevant at Z energy due to highest beam current

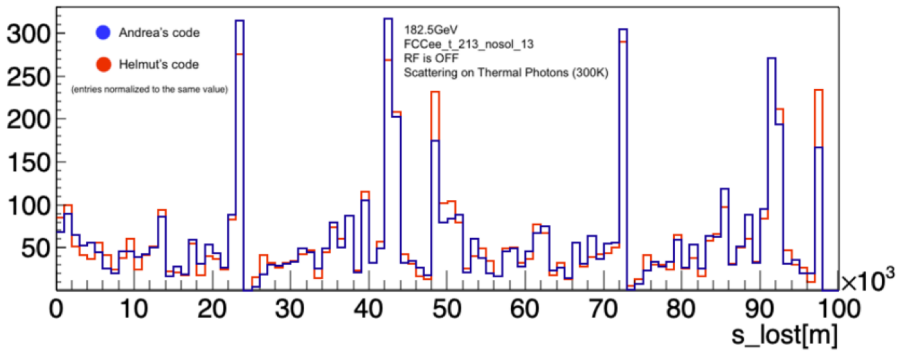


Thermal photons scattering- beam losses

more details in talk by A.Ciarma, acceler. code development session

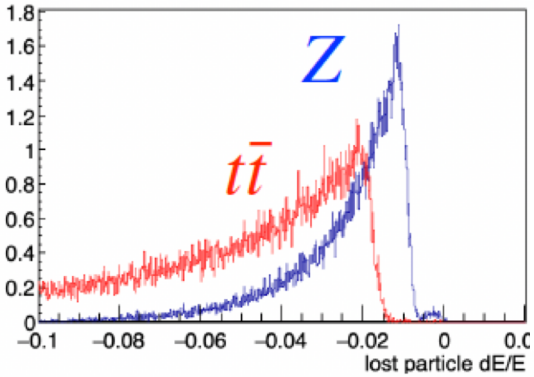
First described in 1987 by V. Telnov , main single beam lifetime limitation in LEP, well measured and simulated using the algorithm described in SL/Note 93-73

Loss map@ttbar

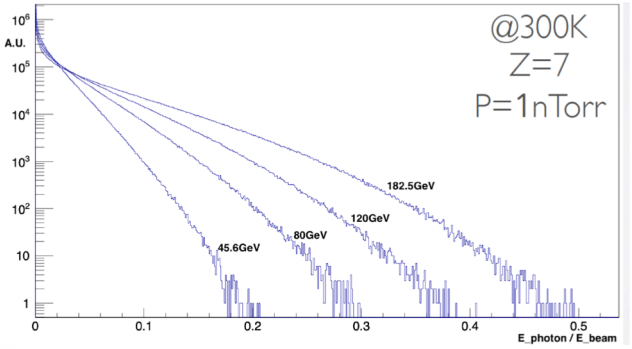


New beam background tracking tool under development, benchmarking with other codes done [H. Burkhardt, FCC WEEK2019]

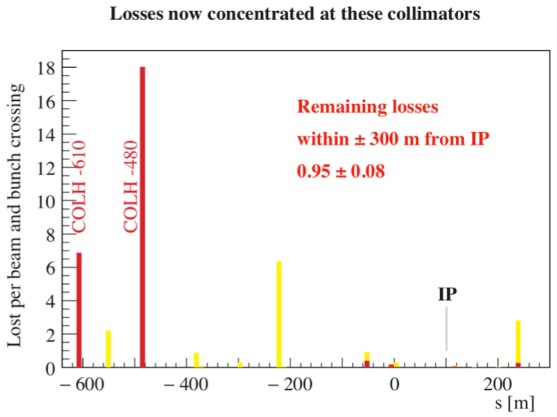
mitigation by off-momentum collimators



lost particles energy spectrum

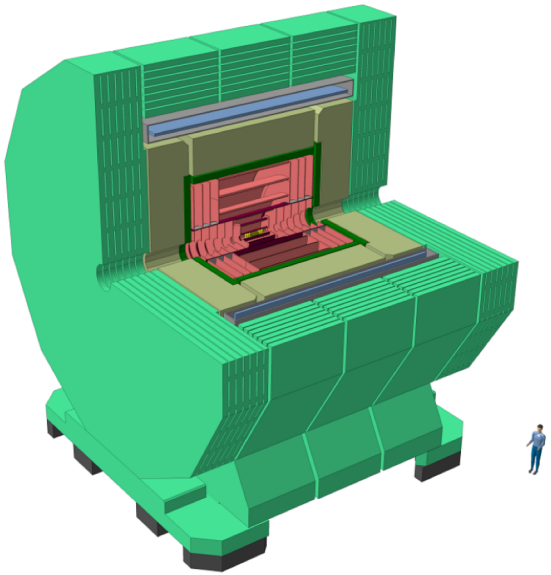


Photon energy spectrum distribution



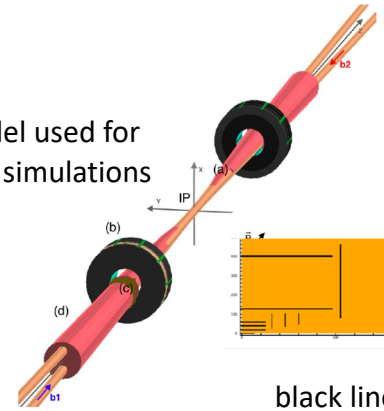
Thermal γ 31.2 ± 0.5 $|s|<1.5$ km from IP lost/beam/crossing
of which 11.1 ± 0.3 $|s|< 300$ m

CLD Detector

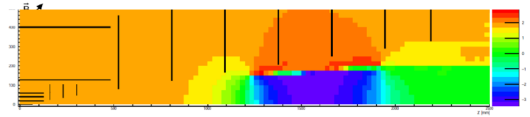


- adaptation of the CLIC detector model (2T)
- Silicon-based vertex and tracking detectors
- ILCSoft

Geant4 model used for backgrounds simulations



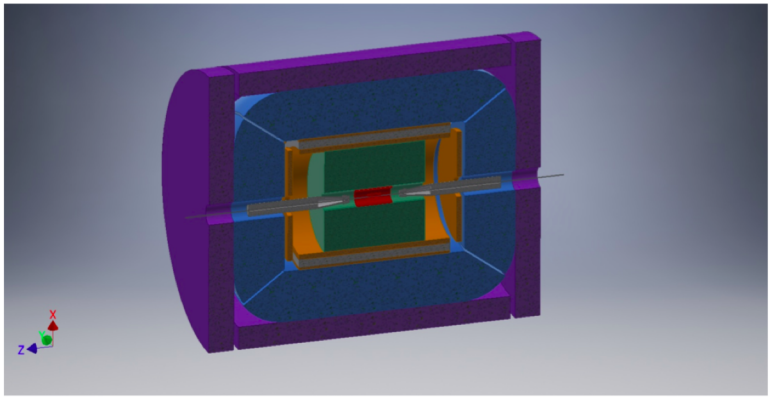
Field map x-z

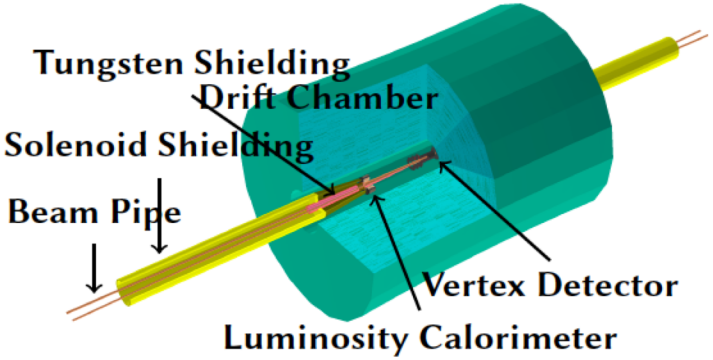


B field map: Rz slice

black lines are VXD/tracker layers

IDEA detector





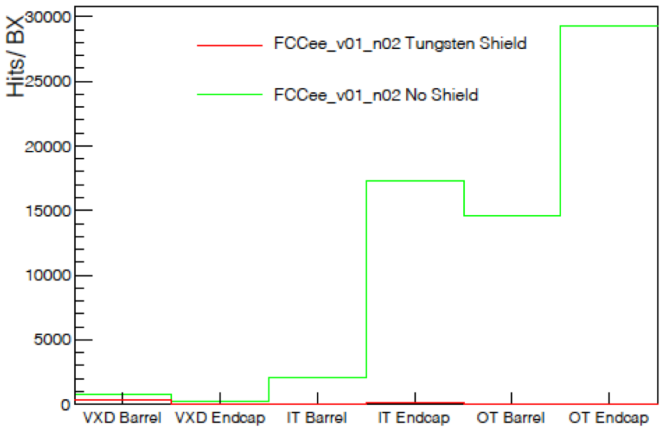
IDEA DCH

- Material budget $\sim 1.6\% X_0$
- Resolution $\sigma_{xy} < 100\mu m$, $\sigma_z < 1$mm
- $\sim 100\ ns$ integration time
- dE/dX $\sim$ 4%, dN/dX $\sim$ 2%
- Implemented in DD4hep
  - Analysis performed with FCC software

Simulation studies of the impact of backgrounds on detectors and on LumiCal

details in talk by G. Voutsinas

- Impact of SR: proper shielding reduces it to negligible levels
- Beamstrahlung
- Incoherent Pair Production at CLD
- $\gamma\gamma$ to hadrons
- Radiative bhabhas
- Beam-gas



Impact of backgrounds found to be manageable, as documented in the CDR
Further studies are needed as more realistic and detailed simulations are performed

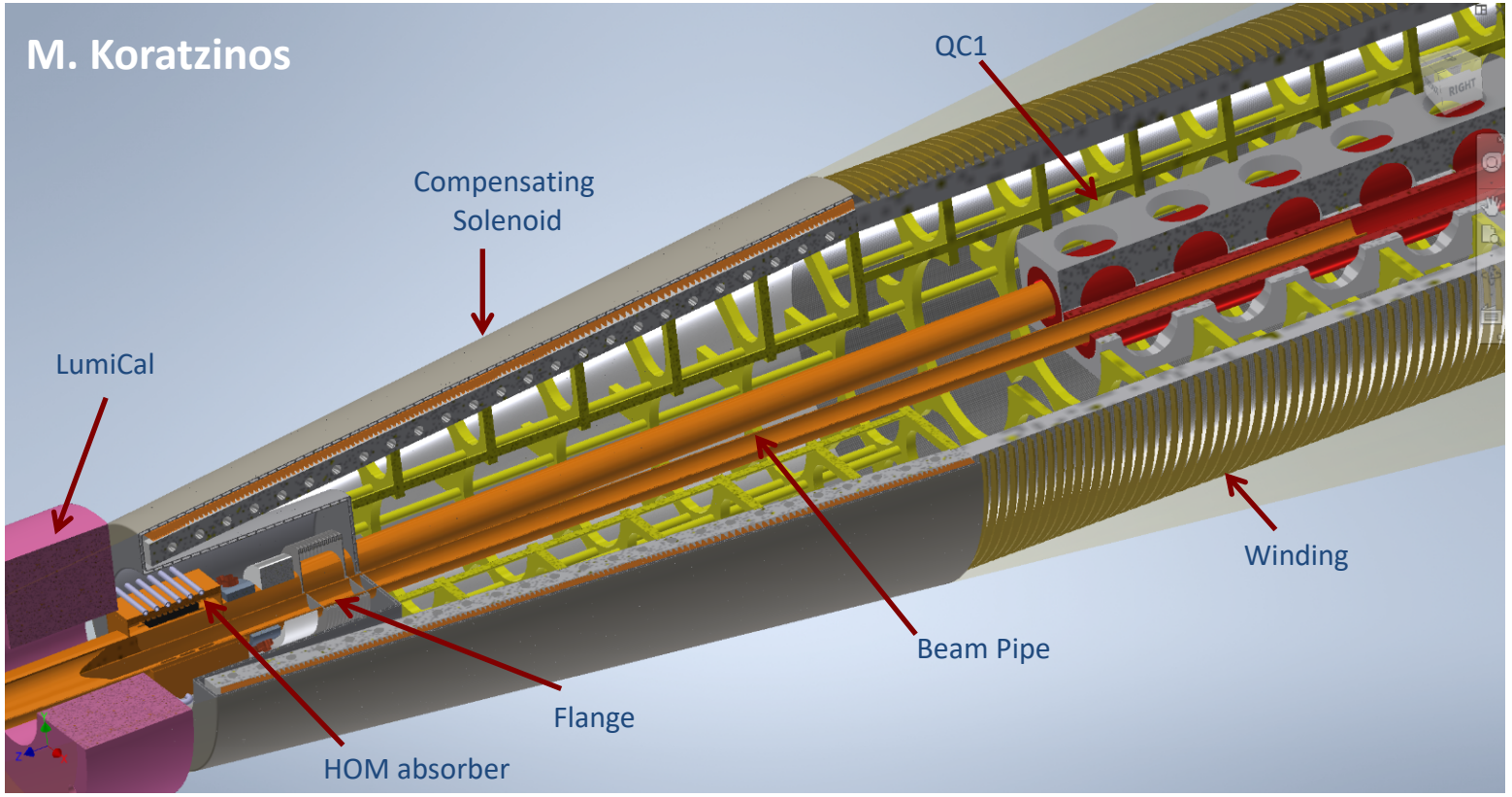
Mechanical Design
Ingredients for a 3D IR model

- realistic CAD IR beam pipe model
- magnets
- masks
- draft cryostat design
- weight of elements
- electromagnetic static forces from magnet interaction
- assembly concept (one side, two side, auxiliary equipment)
    → pre-dimensioning support structure
        → input to stability/vibration analysis
- thermal power budget
    - synchrotron radiation, resistive wall, HOM
    - local heat loads from beamstrahlung, radiative Bhabha scattering
- pre-dimensioning of cooling systems
- vacuum chamber details, vacuum pumping, gauges, remote flanges if needed (prototyping?)
- pre-dimensioning of cabling & alignment/surveying space requirements
- verification of MDI space allocation
- magnet quench management (forces, gas venting)

3D modeling

more details in talk on "Mechanical IR design" by L. Pellegrino

A CAD for an engineered design started

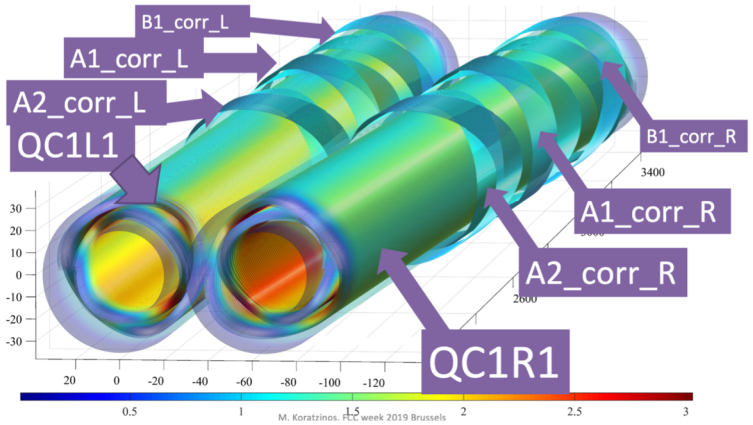


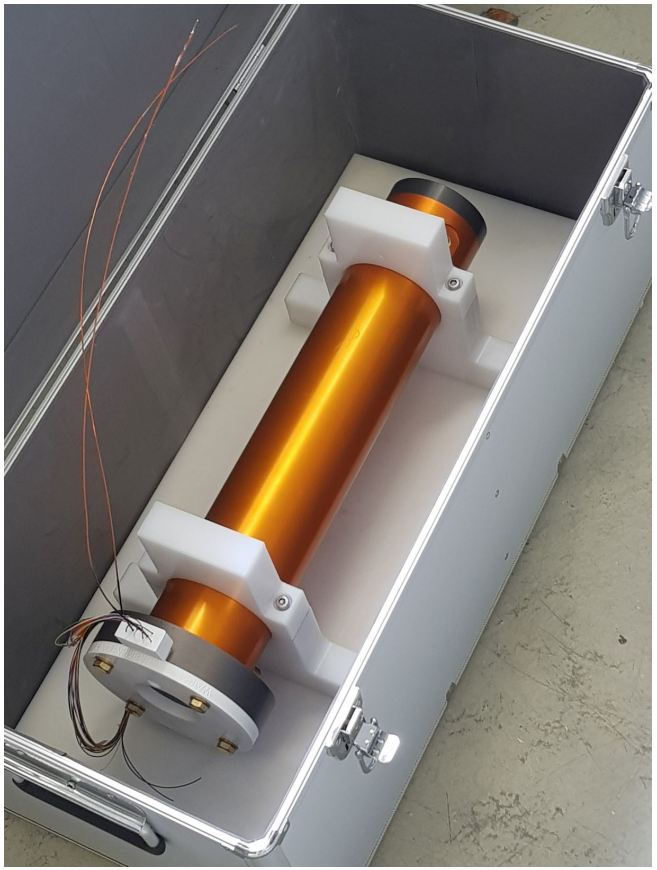
Final Focus Quadrupole

details in talk by M. Koratzinos

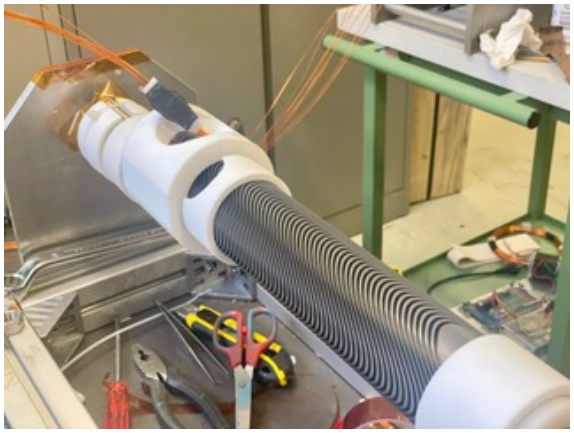
CCT (canted cosine theta) concept

No iron





First prototype FF quad is ready for warm testing by the TE-MSC-MM team



prototype during construction

FCC-ee Position Monitoring & Alignment

- On-going activity to define **alignment concept for FCC-ee**

- Alignment precision requirements in the MDI area are being worked out
- Details on the supports of the magnets will come with the mechanical design

- The application, adaptation, and integration of alignment and internal metrology components into a single system needs to be studied

Experience based on HL-LHC, CLIC and ILC development work
Few tents of microns relative alignment of FF quads possible

- Concept based on design for CLIC
  - Full Remote Position Monitoring and Alignment System
  - Wire Position sensors
  - Hydrostatic Levelling sensors
  - Motorised positioning system

continuous position and orientation determination

M. Jones, L. Watrelot

Vibrations and stabilisation concept at the FCC-ee IR

Details in talk by L. Brunetti

- LAPP will contribute with its experience (SuperKEKB, ATF2) in the design of the stabilisation and positioning system for the interaction region elements.
- **Important step: is determine the specifications needed at the IP**
- **Mechanical simulations of magnets, supports, cryostat, luminometer, heavy shielding essential to define the stabilisation strategy.**
- **Stabilisation strategy:** active and/or passive control, IP feedback with frequency range of interest, development of needed controls.

- R&D on vibration sensors, if needed.
- Prototypes to test dynamical aspects.

Conclusion

FCCIS project focuses its priority on demonstrating the key issues feasibility of FCC-ee, MDI being one of the main ones.

Main MDI topics in FCCIS

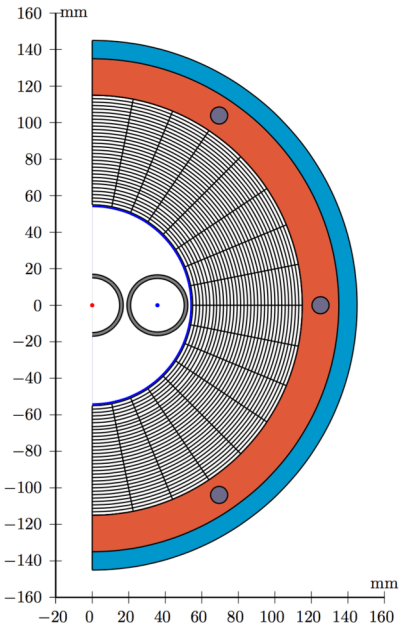
- **Engineered design** of IR and MDI layout with integration concept
- **IR magnets**
- Attainable **vertical emittance** in presence of various errors and with colliding beams, and further luminosity optimization. **Alignment** tolerances and alignment system.
- Vibration and **stabilisation** system.
- Refined studies to control the effect of **SR** and beam **backgrounds** in the MDI area, surroundings and detector, including masks and collimators. Beam-tail collimation for background control. **Interaction region optimization** and **shielding** of the hard synchrotron radiation including radiation from the final quadrupoles. Link common software framework FCCSW and MDI codes.
- **Collimation** / masking and machine protection strategy. Injection background.

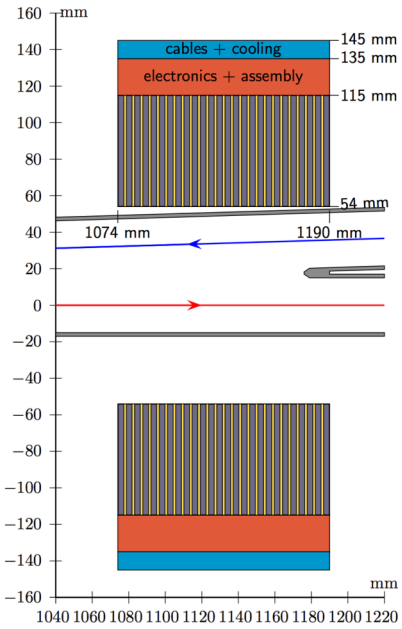
- Start to envisage studies on the expected backgrounds during commissioning .

Back-up

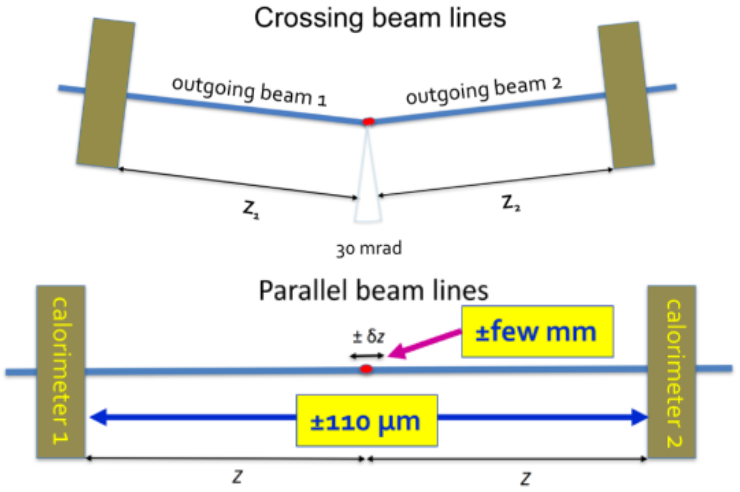
LumiCal

- **Goal: absolute luminosity measurement to 10^{-4} at the Z**
- The luminosity calorimeter is a key device in the MDI area: space and alignments requirements, as well as backgrounds tolerances limit





- Bhabha cross section 12 nb at Z-pole with acceptance 65-85 mrad
- The LumiCals are centered on the outgoing beamlines with their faces perpendicular to the beamlines



- **Conclusion**: Optimal situation is if interaction point is centered wrt LumiCal coordinate system within the following tolerances:
  - Few hundred microns in radial direction
  - Few mm in longitudinal direction

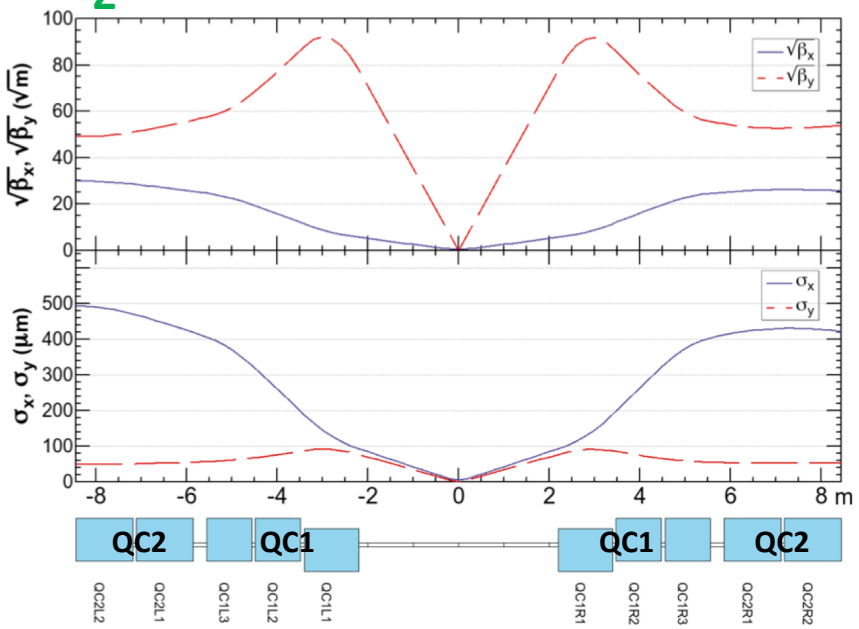
M. Dam

Final Focus optics

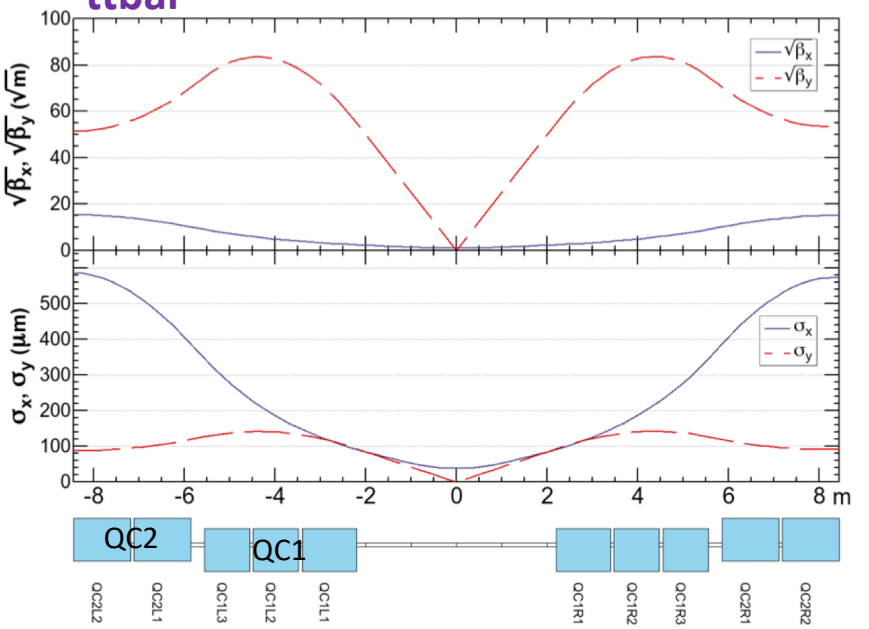
One of the design requirements for the IR optics was flexibility to have a single IR at all energies

Flexible optics design obtained with FF quads longitudinally split into three slices

Z



ttbar



K. Oide

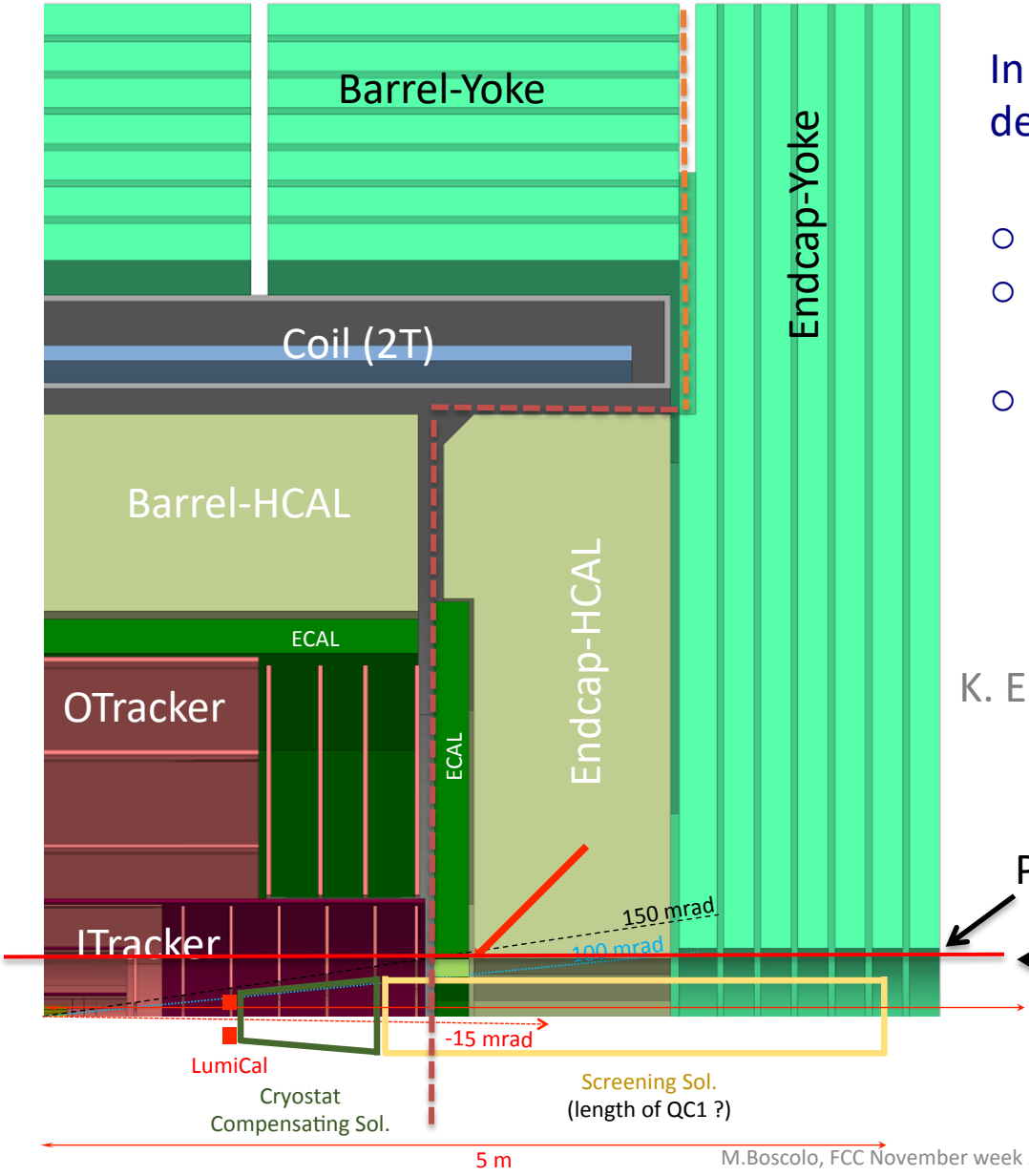
		Z	W^+W^-	ZH	ttbar
β_x^*	m	0.15	0.2	0.3	1.0
β_y^*	mm	0.8	1.0	1.0	1.6

values optimized:

- ✓ to mitigate the coherent beam-beam instability also at $W^{\pm}$, ZH
- ✓ to mitigate 3D flip-flop

At the Z chromaticity is reduced with a smaller β^*, smaller beam size

IR and its mechanical interface with detector (CLD)



In case of a cylindrical IR + Inner detector assembly:

- Inner tracker to be re-designed
- Close the gap between 100mrad and 150mrad?
- Boundary between endcap and barrel to be re-optimized ?

K. Elsener

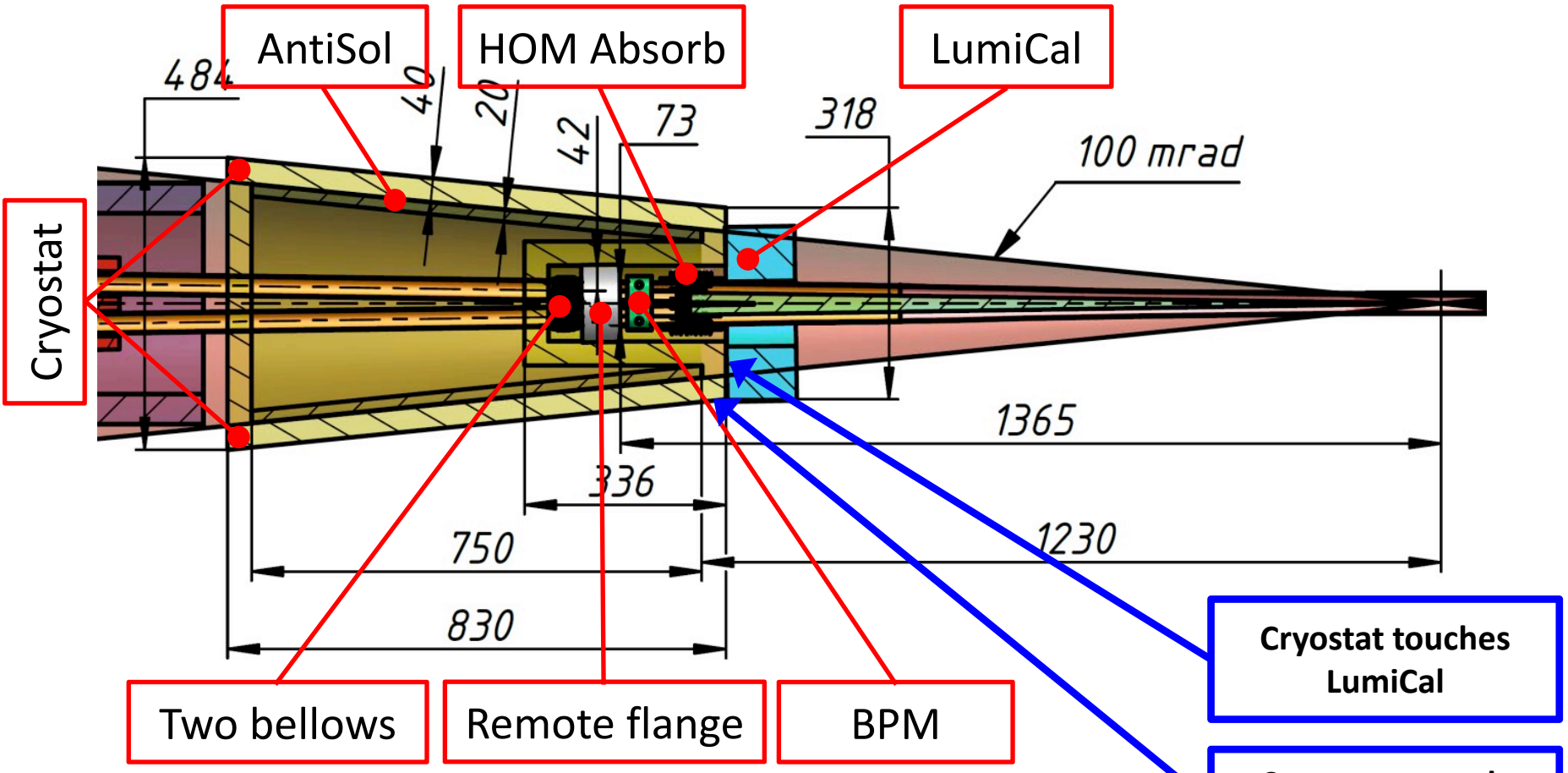
Possible inner bore opening ?

Necessary gap for:

1. mechanical supports
2. Clearances
3. All services of IR+inner detectors

Baseline design

Space constraint

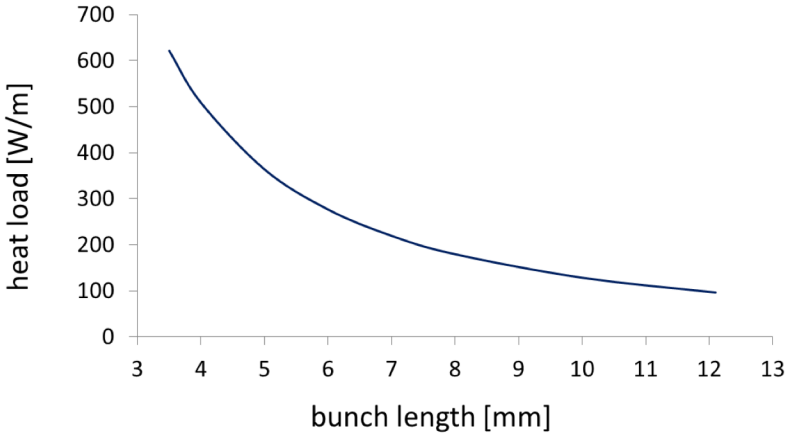


A. Bogomyagkov

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%**

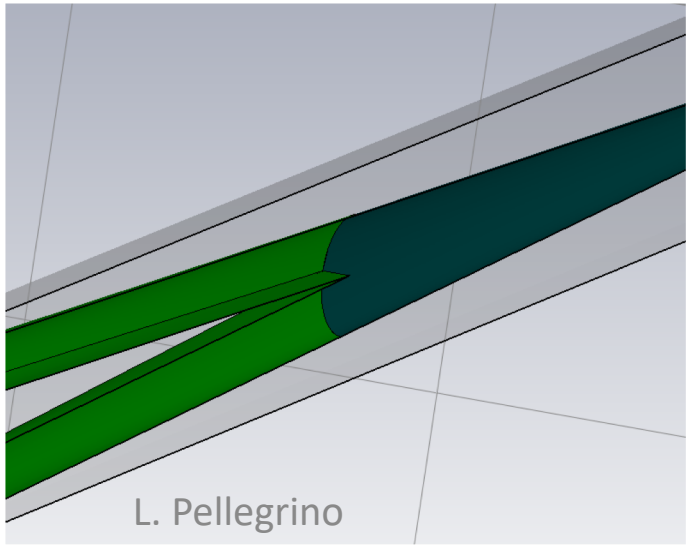


A. Novokhatski

Comparison of resistive heat loads (Be pipe) and temperatures

Beam pipe diameter [mm]	Heat load [W/m]	Max Temp. [K] without cooling
30	97	88
20	145	198
10	290	792

The central Beryllium tube requires an increasing cooling liquid as the beam pipe diameter decreases.
First estimates show that this problem can be technically solved.



Max temperature
was calculated by formula:

$$\Delta T_{[K^\circ]} = \frac{P_{[W]} * L_{[m]}}{\kappa_{[W/(K^\circ m)]} * 2\pi R_{[m]} \Delta r_{[m]}}$$

For the pipe length L of 125 mm
(half of the Be pipe)
with **thickness** Δr of **1 mm** and
Be thermo- conductivity of 182 W/m/K

Radiative Bhabha

- BBBrem has been implemented in **SAD**
- Beam loss due to radiative Bhabha for FCC-ee at the Z:
  - **4 kW** by **400 m downstream** the **IP**
  - **150 W** within the first quad **QC1**
- The effect of beam-beam is about 20% on the loss at QC1.
- The result is neither sensitive to the misalignment of aperture at QC1, nor to the IP solenoid field.

- The tolerance of the final quadrupole for such amount of beam loss must be examined.
- Cross check with other method is necessary and in progress.

K. Oide

Beamstrahlung

H. Burkhardt

- 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

Beamstrahlung

- well cooled absorbers in the critical region
- study impact of radiation: neutron flux (GDR), activation

- understanding / tools to deal with the beam dynamics in the FCC-ee with SR by the combined effect of
  - detailed IR fields with solenoid, fringe, overlap
  - beam distribution with realistic tails & crab-waist
  - em-fields of colliding beams

FCC-ee parameters

CDR parameters

FCC-ee parameters		Z	W^+W^-	ZH	ttbar
Beam energy	**GeV**	**45.6**	**80**	**120**	**182.5**
Luminosity / IP	**10^{34} cm^{-2} s^{-1}**	**230**	**28**	**8.5**	**1.55**
Beam current	mA	1390	147	29	5.4
Bunches per beam	#	16640	2000	328	48
Average bunch spacing	ns	19.6	163	994	3396
Bunch population	10^{11}	1.7	1.5	1.8	2.3
Horizontal emittance ε_x Vertical emittance ε_y	nm pm	0.27 1.0	0.84 1.7	0.63 1.3	1.46 2.9
β_x^* / β_y^*	**m / mm**	**0.15 / 0.8**	**0.2 / 1.0**	**0.3 / 1.0**	**1.0 / 1.6**
beam size at IP: σ_x^* / σ_y^*	**µm / nm**	**6.4 / 28**	13 / 41	13.7 / 36	38.2/68
Energy spread: SR / total (w BS)	%	0.038 / 0.132	0.066 / 0.131	0.099 / 0.165	0.15 / 0.192
Bunch length: SR / total	mm	3.5 / 12.1	3 / 6.0	3.15 / 5.3	1.97 / 2.54
Energy loss per turn	**GeV**	**0.036**	**0.34**	**1.72**	**9.2**
RF Voltage /station	GV	0.1	0.75	2.0	4/6.9
Longitudinal damping time	turns	1273	236	70.3	20.4
Acceptance RF / energy (DA)	%	1.9 / ±1.3	2.3 / ±1.3	2.3 / ±1.7	3.36 / (-2.8; +2.4)
Rad. Bhabha/ actual **Beamstr. Lifetime**	min	**68 / > 200**	**59 / >200**	**38 / 18**	**40 / 18**
Beam-beam parameter ξ_x / ξ_y		0.004 / 0.133	0.01 / 0.141	0.016 / 0.118	0.099 / 0.126
Interaction region length	mm	0.42	0.85	0.9	1.8

IP backgrounds

Radiative Bhabha *BBBrem/GuineaPig & SAD/MADX*

- beam loss map through the ring
- characterization of photons produced at IP

Beamstrahlung *GuineaPig /BBWS & SAD/MADX*

- beam loss map through the ring
- characterization of photons produced at IP

e^+e^- pairs *GuineaPig, G4 into detector*

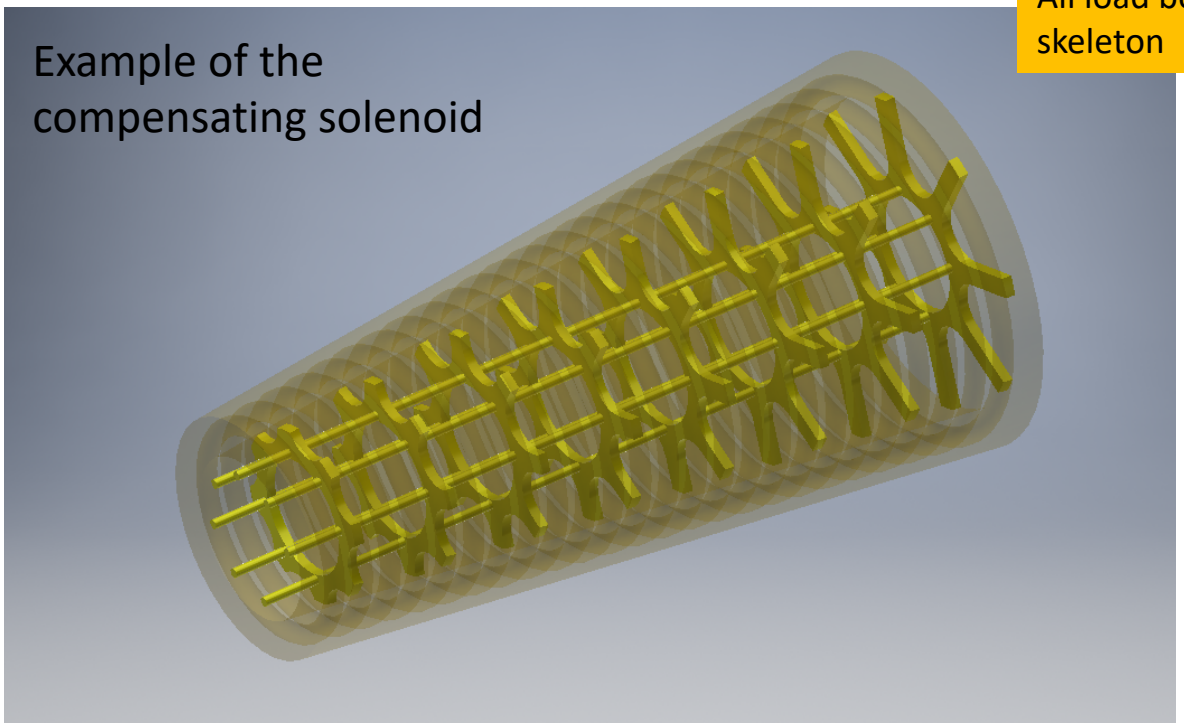
- **Coherent** Pairs Creation: **Negligible**
  Photon interaction with the collective field of the opposite bunch, strongly focused on the forward direction
- **Incoherent** Pairs Creation**: Dominant** (real or virtual photon scattering)

$\gamma\gamma$ to hadrons combination of *GuineaPig and Phythia, G4*

- **Small effect**
- Direct production of hadrons, or indirect, where one or both photons interact hadronically

Perhaps we can reduce the space for the solenoids by rely on a stiff internal skeleton

The idea is to use a stiff skeleton which will replace the very heavy cryostat.
All load bearing capability will rely on this skeleton



- Forces: 30 tons on compensating solenoid, 8 tons on screening solenoid
- Torque: 1000 Nm on screening solenoid

- Forces and twists of the magnet system have been calculated
- A (possible) mechanical design using an (endo)skeleton has been presented

M. Koratzinos