Mechanical design of the FCC-ee interaction region (MDI)

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FCC Week 2019 (24 – 28 June 2019) Brussel

IR (MDI) task and systems

Main task of MDI is to provide design (maximum) luminosity and design (minimum) detector background in the whole FCC-ee energy range.

Components:

- Magnet (FF quadrupoles, solenoids, correctors)
- Vacuum (pipes, bellows, pumps, flanges, RVC (Remote Vacuum Connector)-flange)
- Cryogenic (cryostats, pipelines)
- HOM absorbers
- Beam diagnostics (BPMs, luminometer)
- Detector protection shield, SR masks, etc.
- Water cooling pipes
- Geodesic alignment marks
- Mechanical supports: framework, stands, bars, carcass, etc.
- …

Mechanical design tasks and constrains

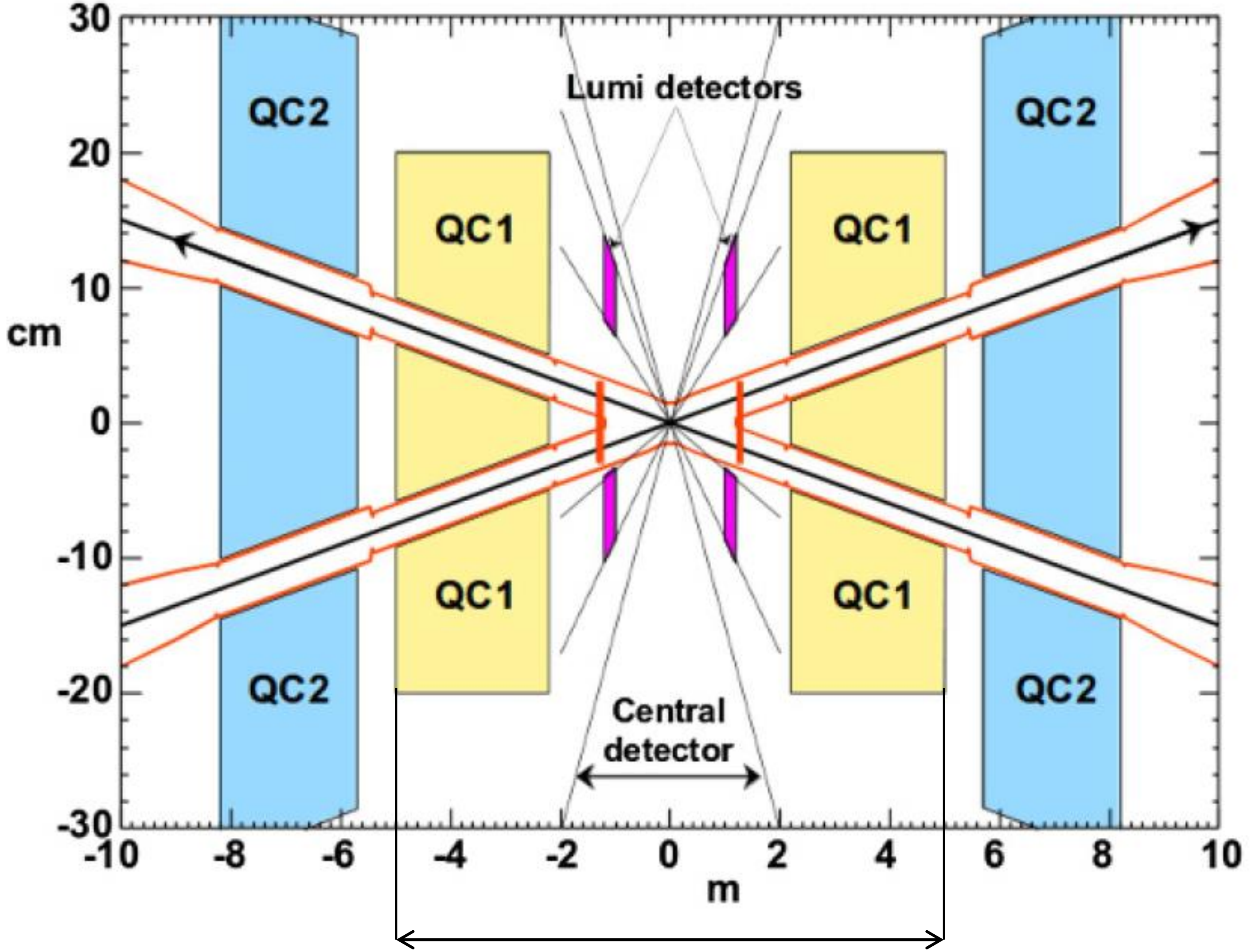
Mechanical system should

- Integrate all accelerator systems in solid block(s) providing required precision of the components (magnets, BPMs, masks, etc.) positioning wrt to the design beam trajectory
- Integrate accelerator block(s) with detector providing required precision of the accelerator components wrt detector
- Allows easy and reliable assembling/disassembling of the accelerator and detector parts preventing equipment damage (power/signal cables and wires, water tubes, cryogenic lines, etc.)
- Withstands dynamical processes (magnets and detector field up/down, quenches, cooling, warming, vibration, etc.) conserving design coordinates of all accelerator elements with required tolerance

Factors influencing MDI design

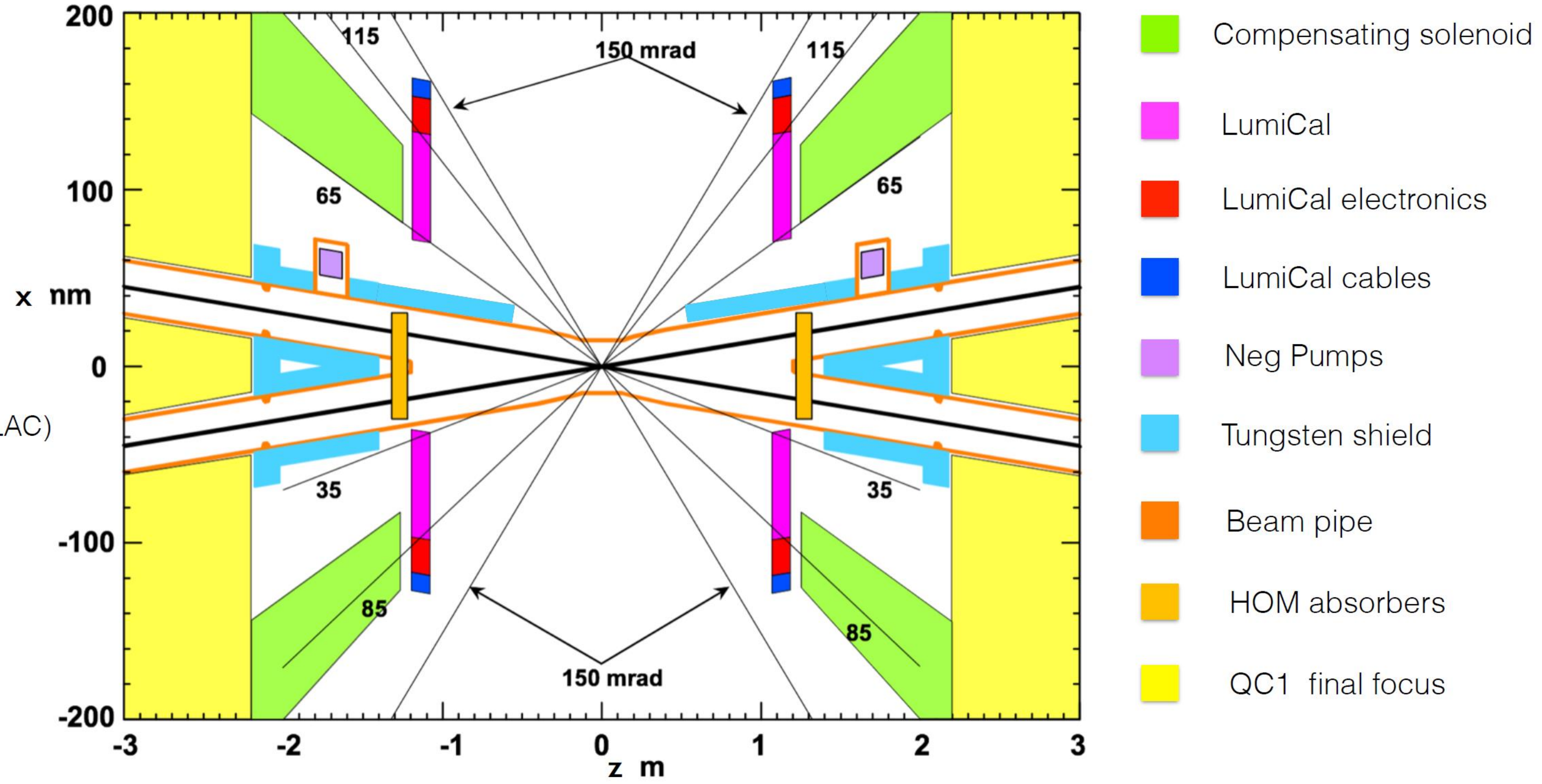
- Very stringent beam parameters (energy, current, beam size, etc.) and their tolerances. Consequently, requirements on the accelerator components tolerances (position accuracy, excitation current accuracy, field quality, etc.) are very tough as well.
- Crab Waist collision method. FF magnets are very close to the IP deep inside the detector and hardly can be inspected, adjusted, repaired etc. during operation without dismounting. All components should be rather compact.
- Strong field (superconducting) FF magnets.
- Strong electromagnet forces between the detector field and FF magnet components.
- Detector background requirements.
- 100 mrad blind detector solid angle.

Baseline MDI schematic view I



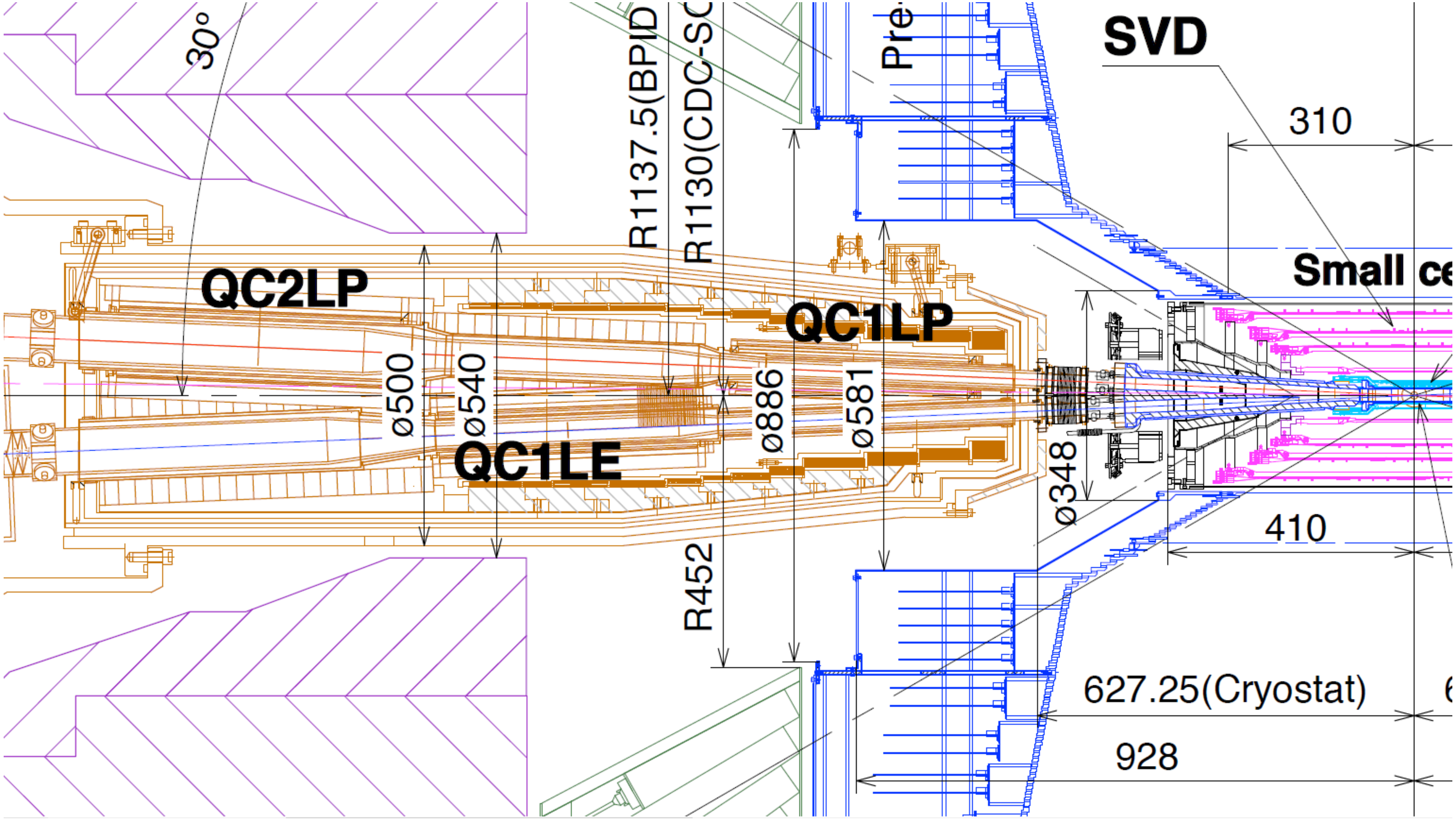
Inside the detector (≈±4.5 m)

Baseline MDI schematic view II



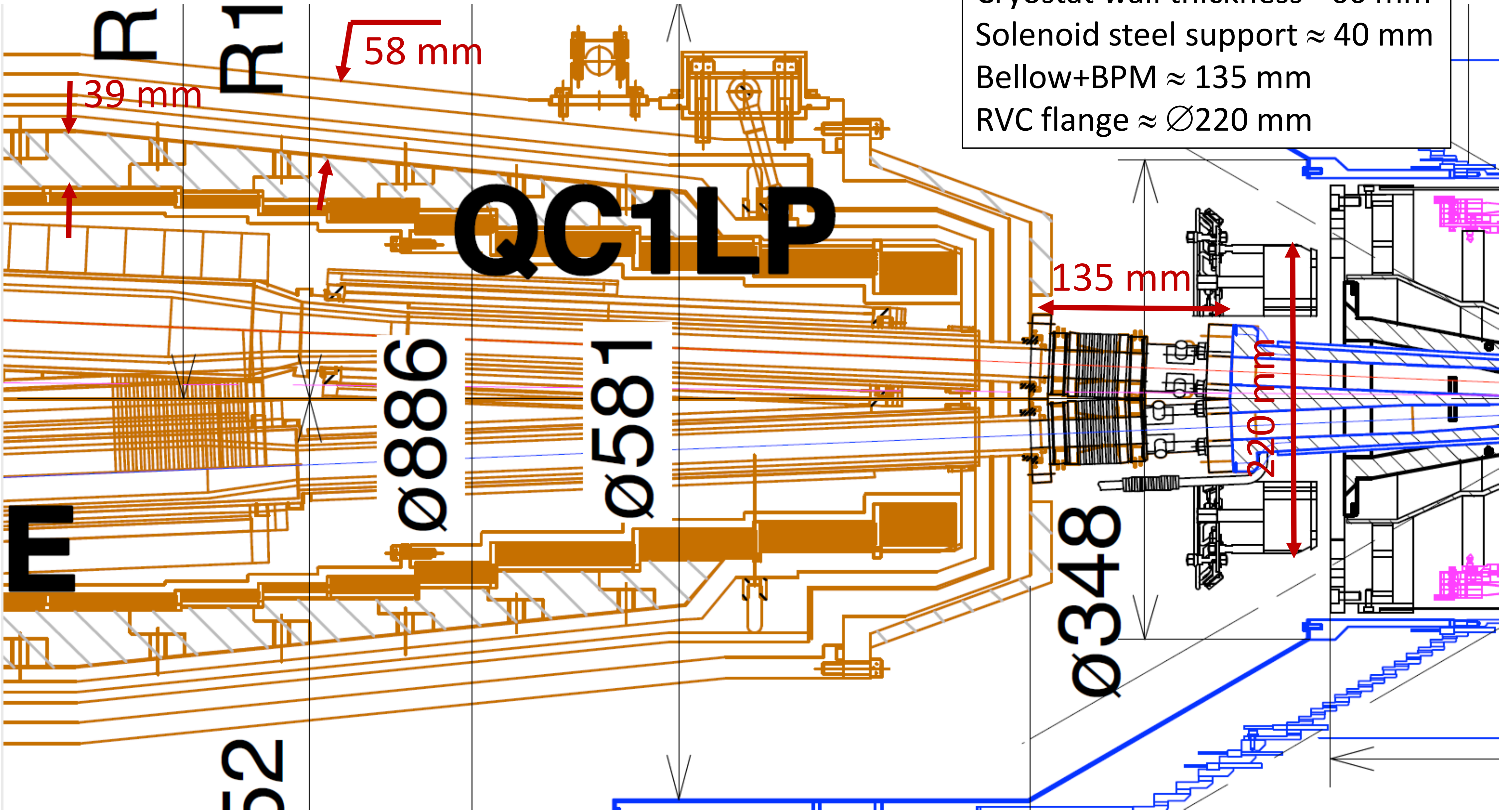
M. Sullivan (SLAC)

Super KEKB MDI example



Super KEKB MDI

Typical dimensions:
Cryostat wall thickness ≈60 mm
Solenoid steel support ≈ 40 mm
Bellow+BPM ≈ 135 mm
RVC flange ≈ ∅220 mm



Beam parameters

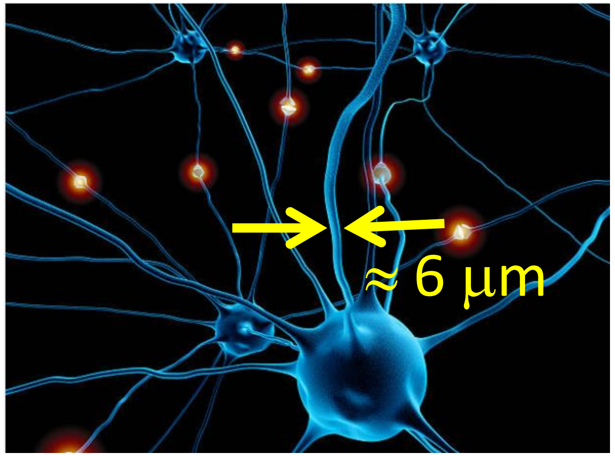
Baseline beam parameters for FCC-ee (FCC CDR v.2, 2019)

Parameters	Z-pole	WW	$H(ZH)$	$t\bar{t}$
Beam Energy [GeV]	45.6	80	120	182.5
ε_x [nm·rad]	0.27	0.28	0.63	1.45
ε_y [pm·rad]	1	1	1.3	2.7
β_x^* [m]	0.15	0.2	0.3	1
β_y^* [mm]	0.8	1	1	1.6
Number of bunches	16640	1300	328	33
$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	230	32	8	1.5

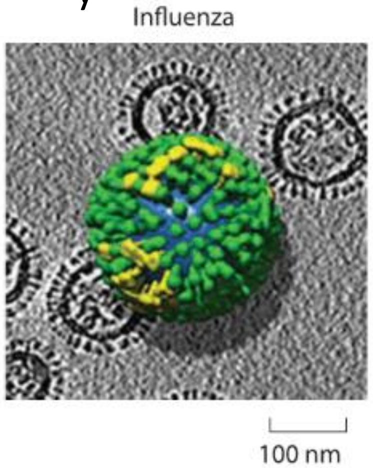
	FCC-ee	SKEKB	ATF2	ILC
E(GeV)	45-182	4/7	1.3	250
ε_y (pm)	1-3	$\approx$ 10	12	0.07
β_y (mm)	0.8-1.6	0.3	0.1	0.48
σ_y (nm)	30-80	55	40	6

IP beam size at Z

σ^*_x = 6.4 μm (neuron width)



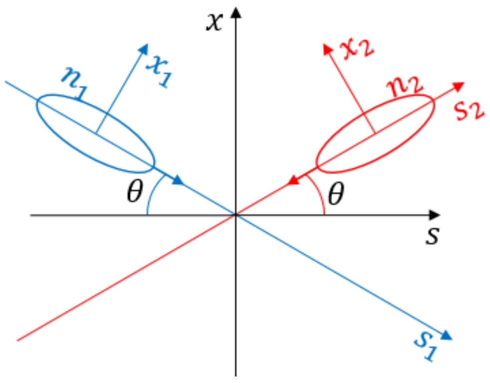
σ^*_y = 28.3 nm

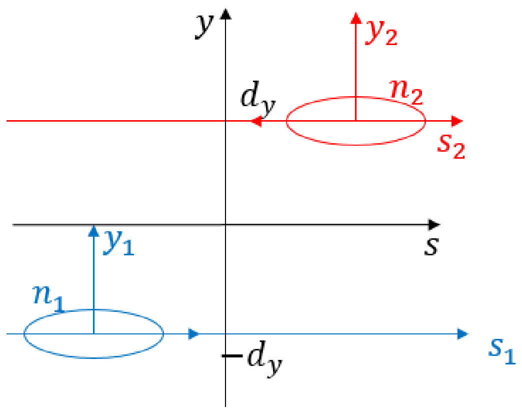


Influenza virus

Luminosity vs vertical beams separation

A.Bogomyagkov





$$\mathcal{L} = \mathcal{L}_0 \exp\left(-\frac{d_y^2}{\sigma_y^2}\right)$$

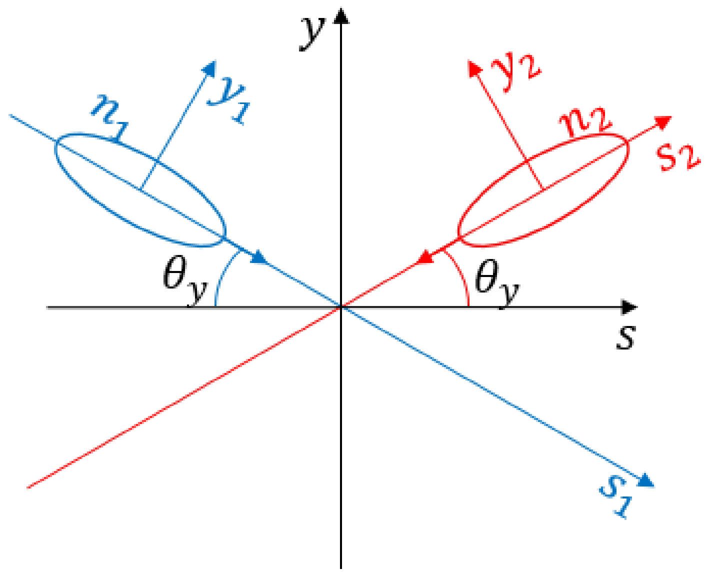
	Z	W	H	tt	ttH
E, GeV	45.6	80	120	175	182.5
$\mathcal{L}_0, 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	230	34	8.5	1.9	1.7
σ_y, nm	28	41	36	76	82
d_y, nm	60	60	60	60	60
$\frac{\Delta\mathcal{L}}{\mathcal{L}_0}$, %	-99	-88	-94	-46	-41

For 10% luminosity loss, the vertical separation at IP should be $d_y < 10$ nm

Active beam adjusting feedback is needed.

Luminosity vs vertical crossing angle

A.Bogomyagkov



$$\mathcal{L} = \mathcal{L}_0 - \mathcal{L}_0 \frac{\sigma_s^2}{8\sigma_y^2(1+\varphi^2)} \frac{3+\cos 4\theta}{(\cos\theta)^4} \theta_y^2$$

For 10% luminosity loss, the vertical crossing angle at the IP $\theta_y < 10\text{-}20$ μrad

	Z	W	H	tt	ttH
E, GeV	45.6	80	120	175	182.5
$\mathcal{L}_0, 10^{34}\text{cm}^{-2}\text{s}^{-1}$	230	34	8.5	1.9	1.7
$\sigma_{py}, \mu\text{rad}$	35	41	36	48	51
$\theta_y, \mu\text{rad}$	25	25	25	25	25
$\frac{\Delta\mathcal{L}}{\mathcal{L}_0}$, %	-7	-14	-20	-23	-20

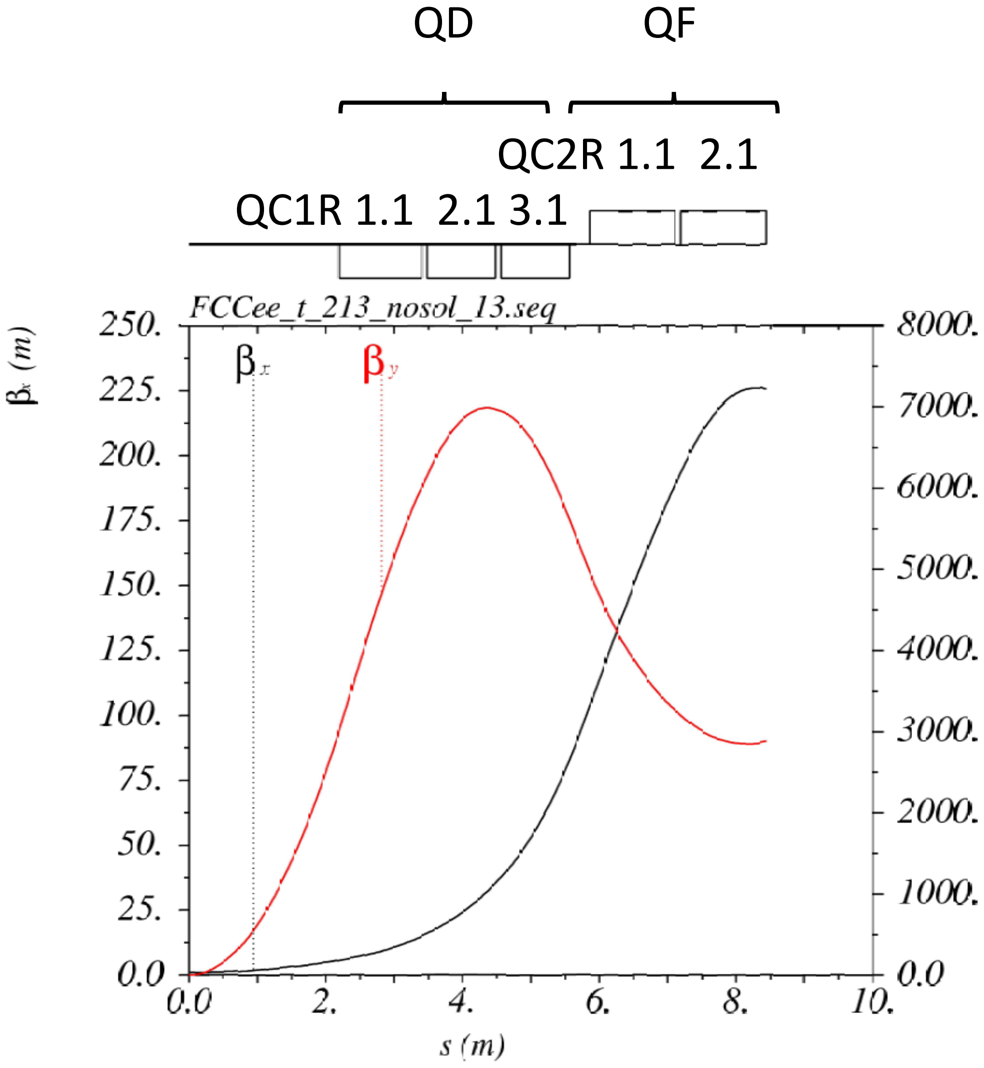
In horizontal plane

$d_x < 20\text{-}60$ μm

$\theta_x < 1\text{-}2$ mrad

But still active beam adjusting feedback is needed.

FF quadrupoles shift



A.Bogomyagkov

E = 182.5 GeV

β_{ymax}= 6960 m β_{yIP}= 1.6 mm

β_{xmax}= 225 m β_{xIP}= 1 m

$\Delta y(QD) = 1\ \mu m \rightarrow \Delta y(IP) \approx -1\ \mu m$

$\Delta x(QF) = 1\ \mu m \rightarrow \Delta x(IP) \approx -6\ \mu m$

CDR requirements

Magnet type	Hor. displacement Δx μm	Vert. displacement Δy μm	Tilt $\Delta\theta$ μrad
Arc quadrupoles	100	100	100
Sextupoles	100	100	0
IP quadrupoles	50	50	50

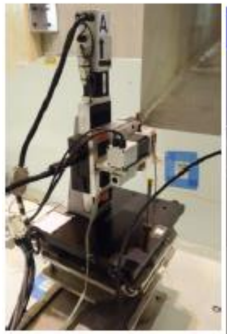
N.Ohuchi
IPAC2018

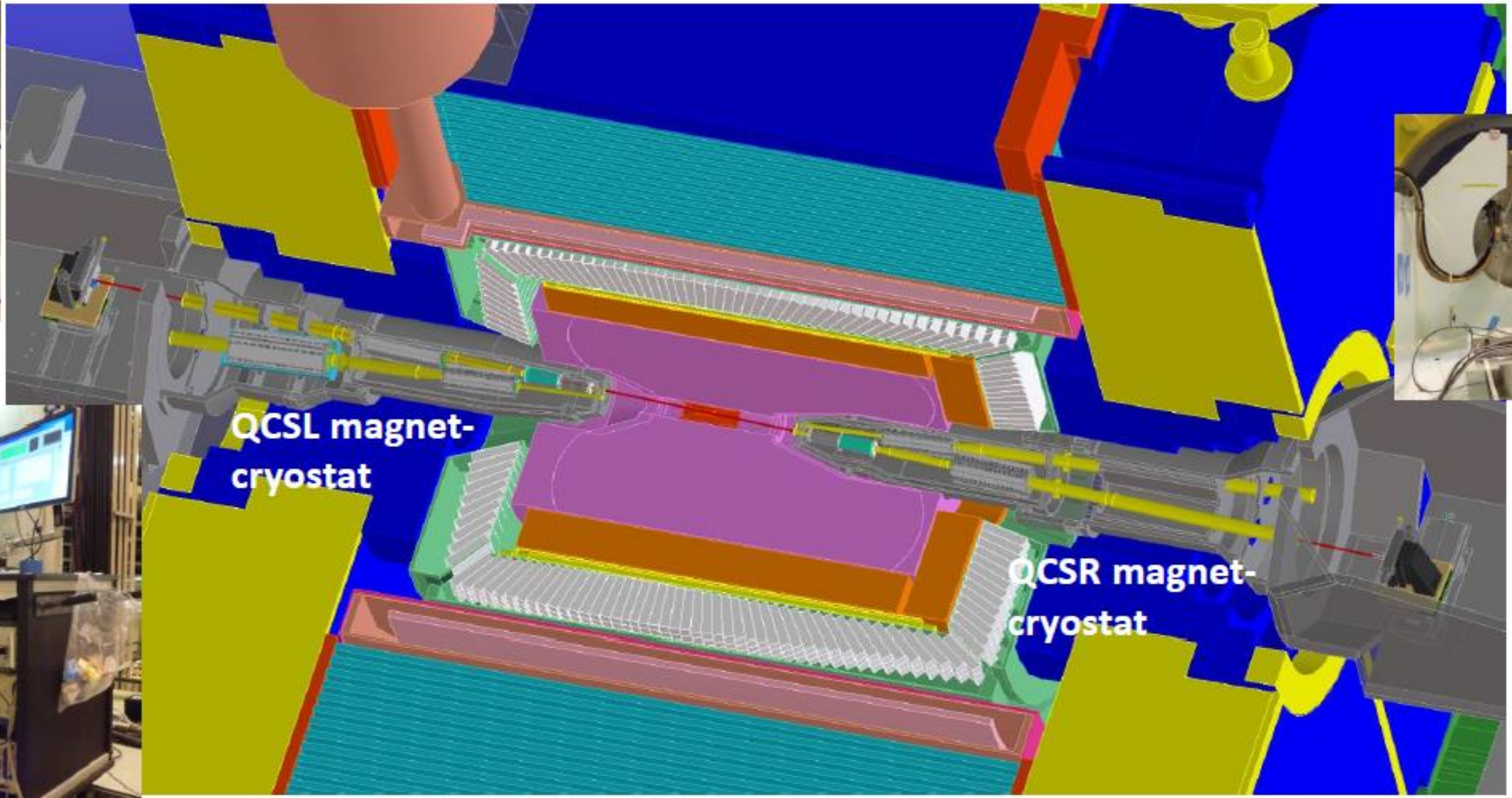
SSW measurement

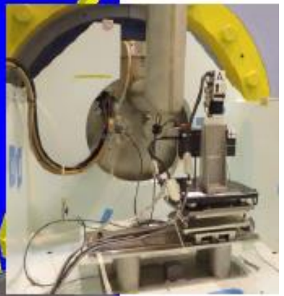
Single Stretched Wire Measuring System

SSW measurement system in the IR

- Two magnet-cryostats of QCSL/R were aligned to the beam lines with the targets of the cryostats.
- A BeCu single wire of ϕ0.1 mm, which was aligned to the design beam line, was stretched through QCSR and QCSL cryostat bores.
- The measurements were performed with operating the Belle SC solenoid at 1.5 T, and ESL and ESR1 solenoids.
  - The measured data include the displacement by the electro-magnetic forces between solenoids and magnetic components in the cryostats.







SSW measurement summary

N.Ohuchi
IPAC2018

- Measured magnetic center shifts to the design values and field angles to the horizontal planes of the 8 main quadrupoles as follows:

	QC1LP	QC2LP	QC1RP	QC2RP
Δx, mm	0.01	-0.34	0.68	0.49
Δy, mm	-0.21	-0.69	-0.30	0.04
$\Delta \theta$, mrad	-1.67	-4.05	2.02	-1.73

	QC1LE	QC2LE	QC1RE	QC2RE
Δx, mm	-0.21	0.13	0.25	0.08
Δy, mm	-0.29	-0.54	-0.37	-0.58
$\Delta \theta$, mrad	-1.60	-1.54	-0.14	-0.73

- Every alignment errors are able to be corrected by the corrector magnets.

Lessons for FCC-ee:

- Proper steering magnets should be placed at proper places.
- MDI symmetrical to the electromagnet forces is preferable to minimize displacement
- Measurement of the components' position inside the detector is needed
- Measurement of the magnet field inside the detector is needed

CDR sketch of MDI

Mike Koratzinos

Very simple, no details

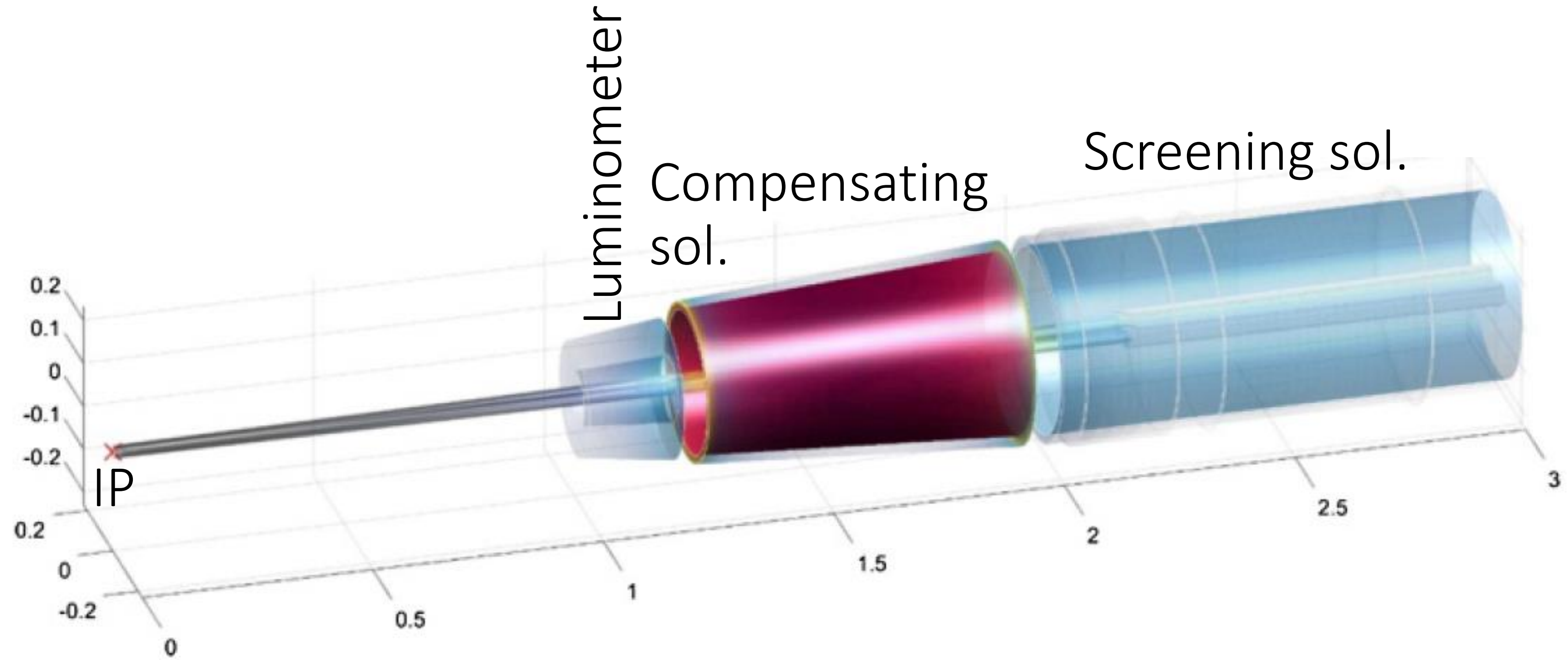
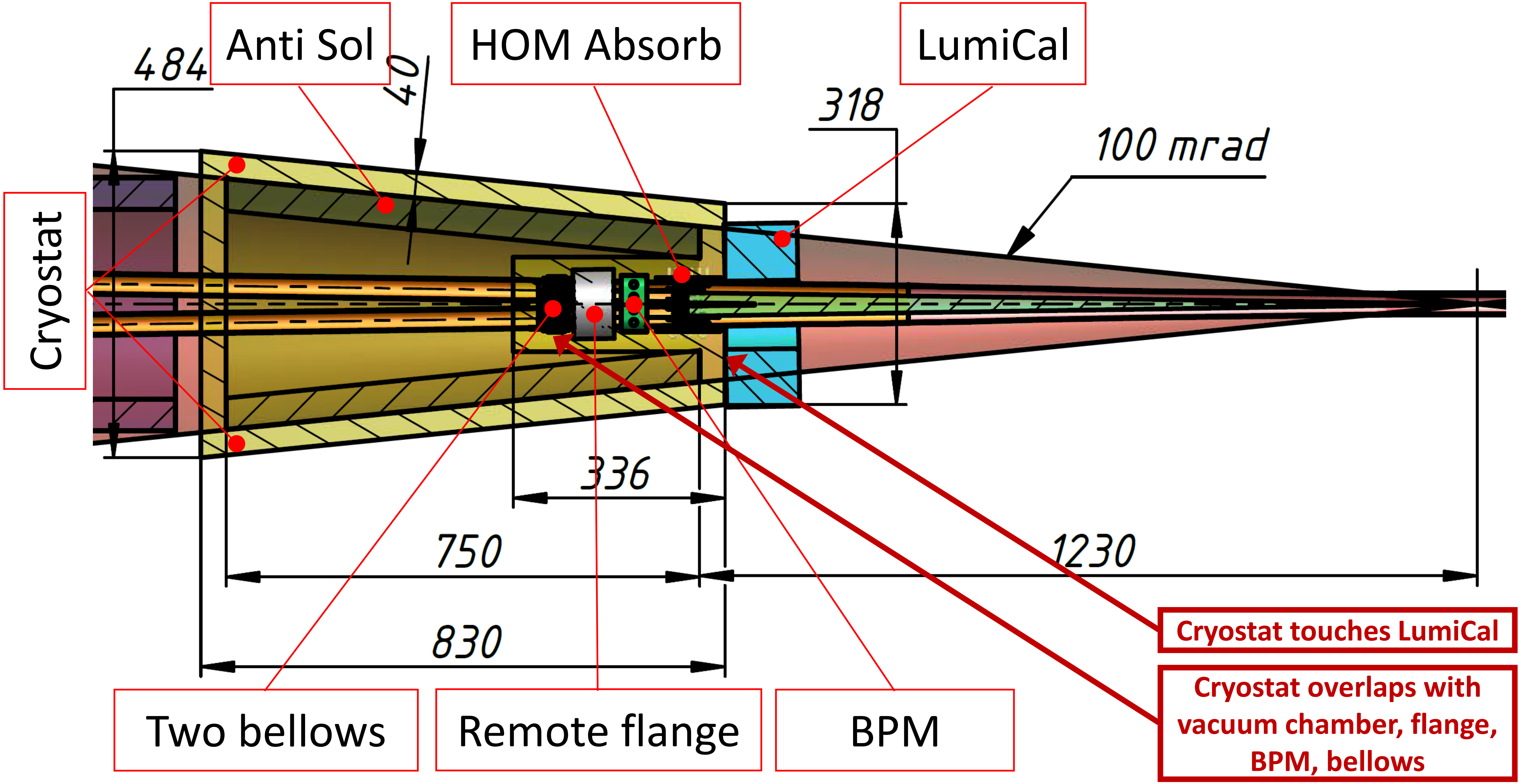
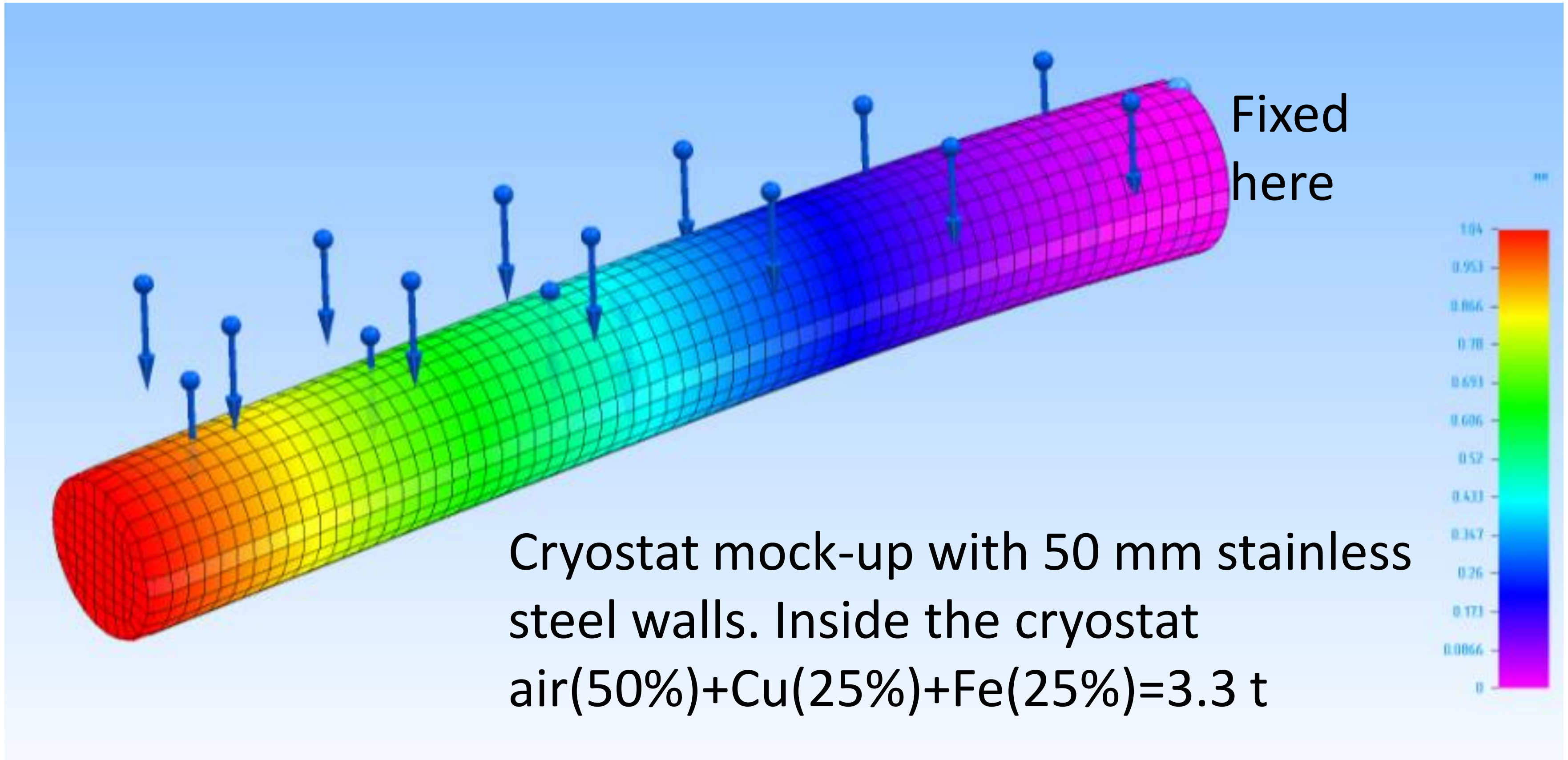


Fig. 2.20. A 3D sketch of the interaction region (IR) magnet system in the first 3 m from the interaction point (IP). Zero in the plot marks the location of the IP).

Attempt to look in detail

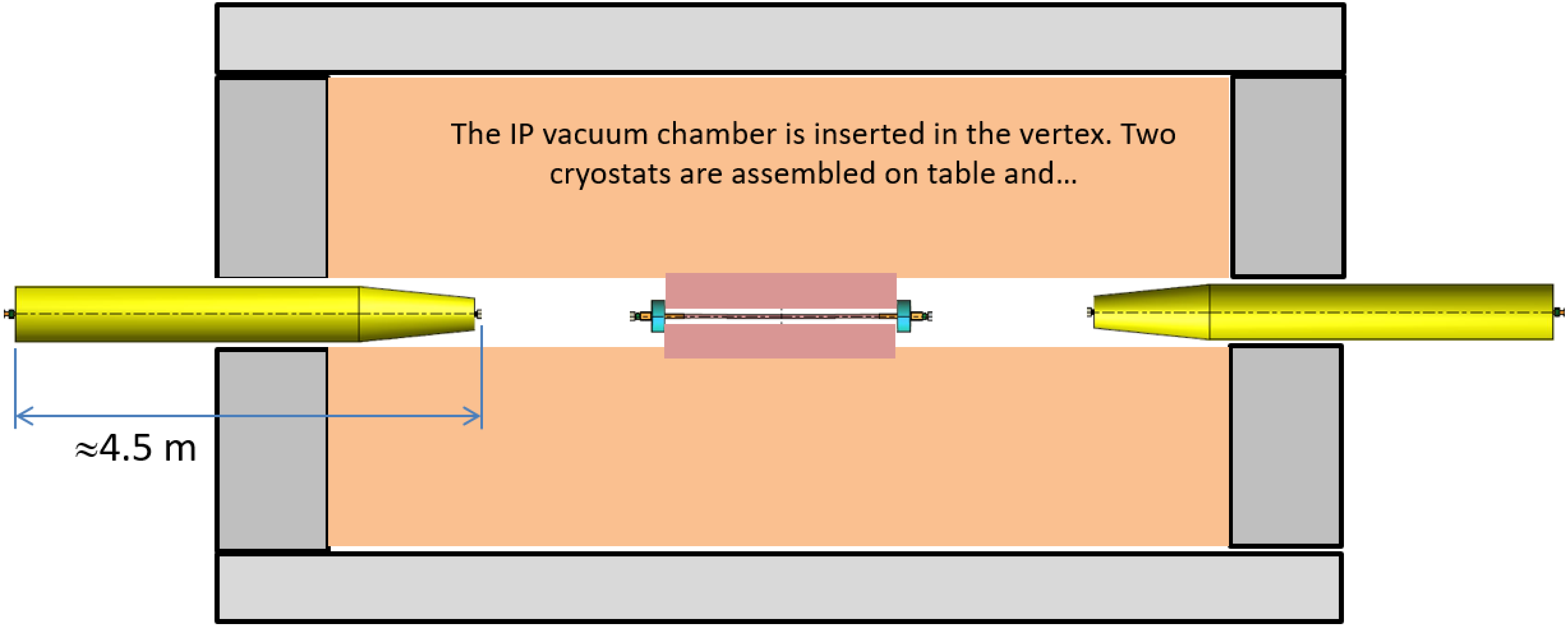


Cryostat bent

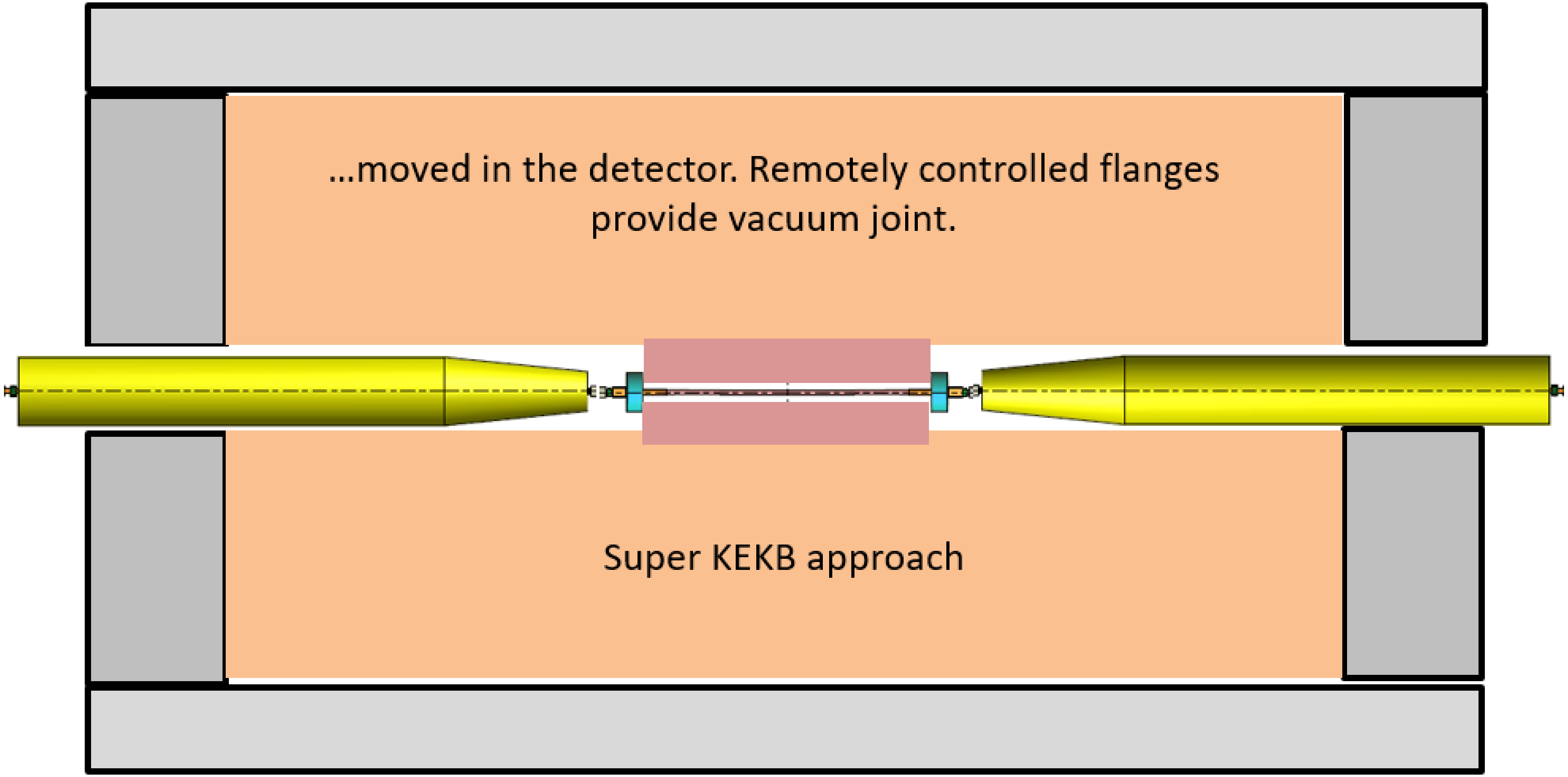


Cryostat bent under the gravity force is 1 mm (3.3 tons components weight+2.5 tons cryostat). We need to support it in several points on the skeleton inside the detector. It should be adjusted to the detector design. Electro-magnetic forces should be taken into account.

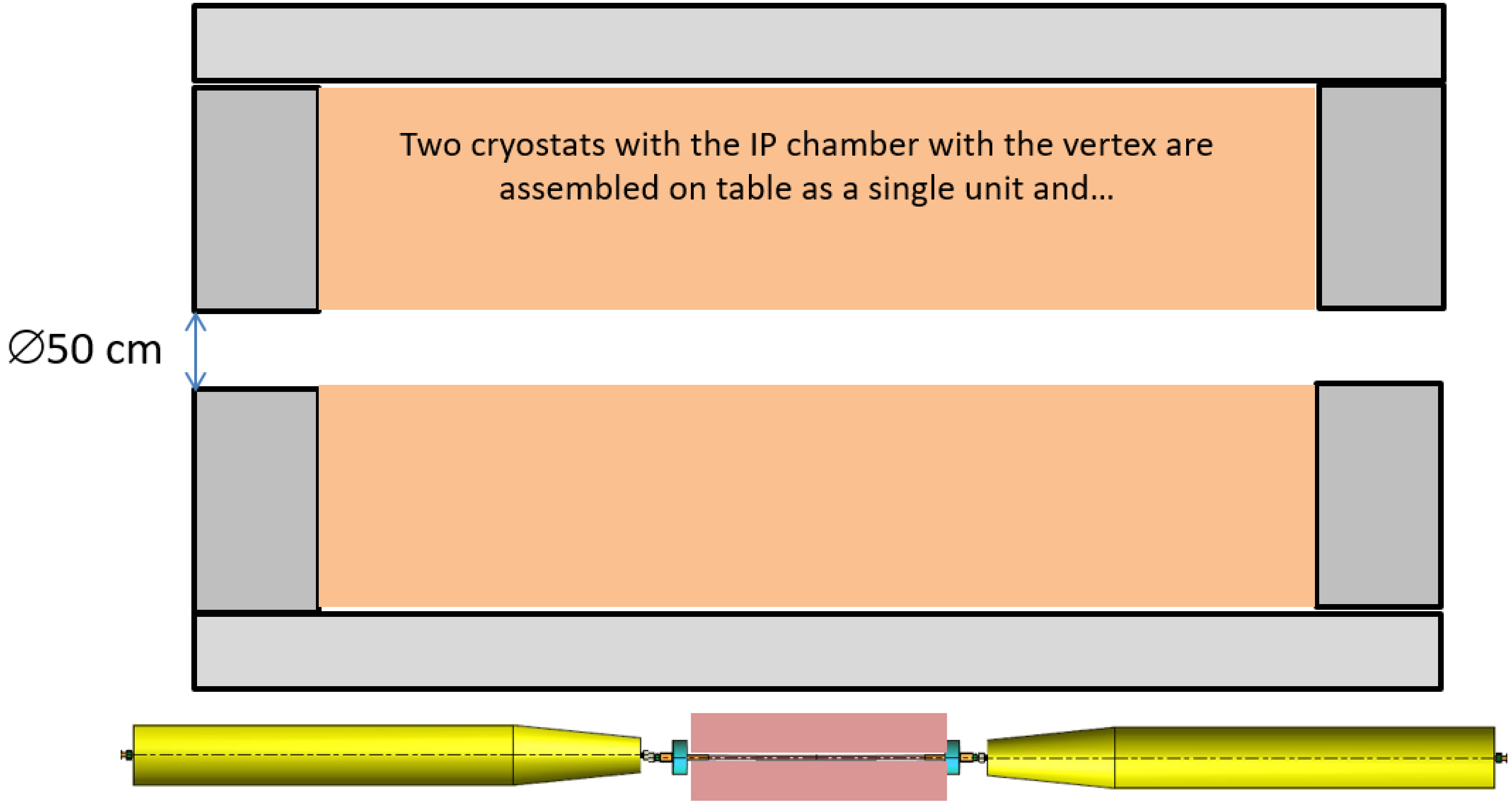
MDI assembling 1-1



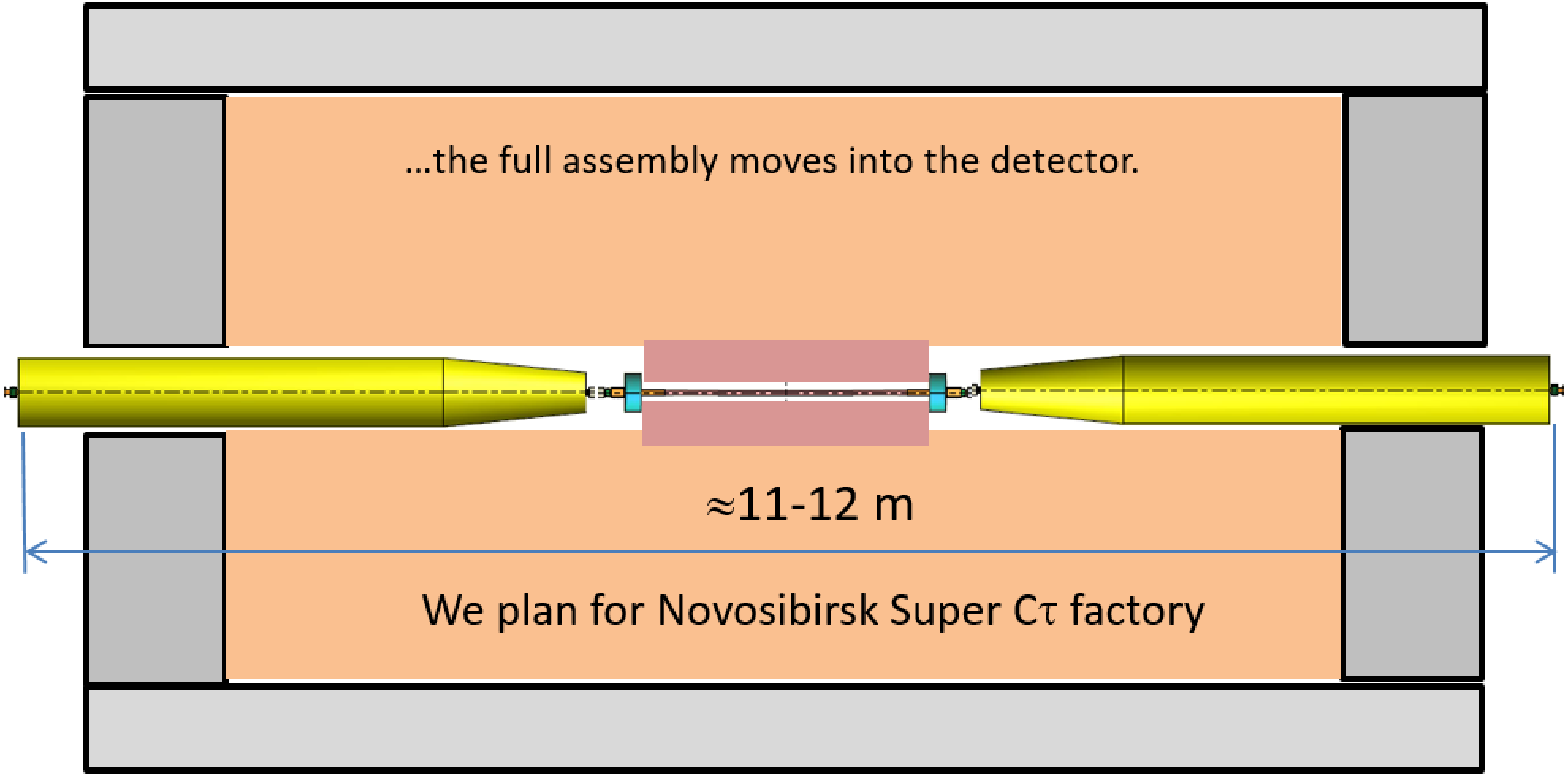
MDI assembling 1-2



MDI assembling 2-1



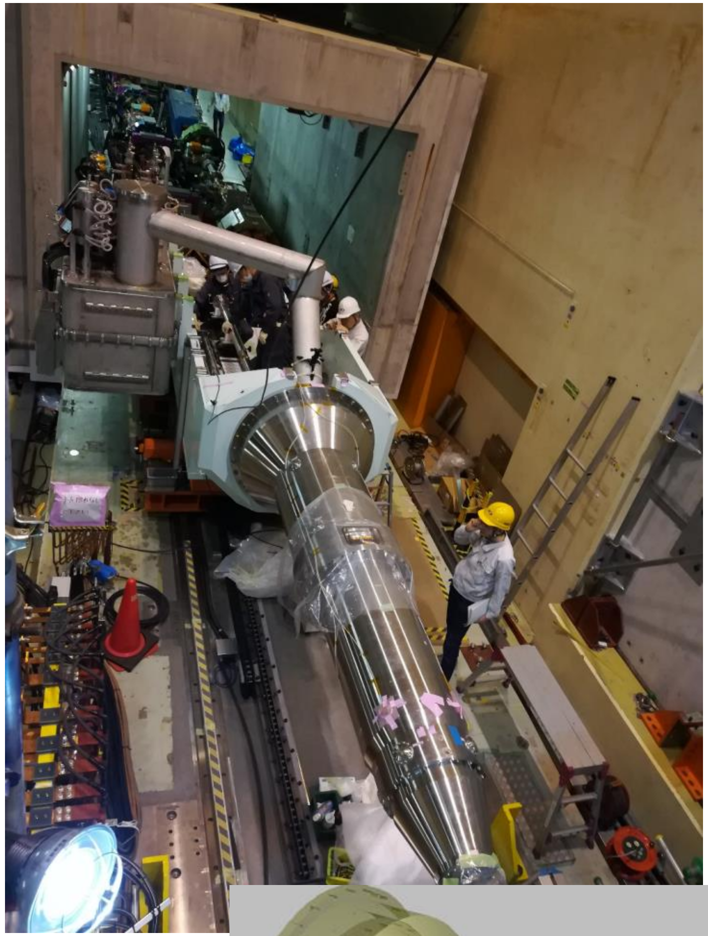
MDI assembling 2-2

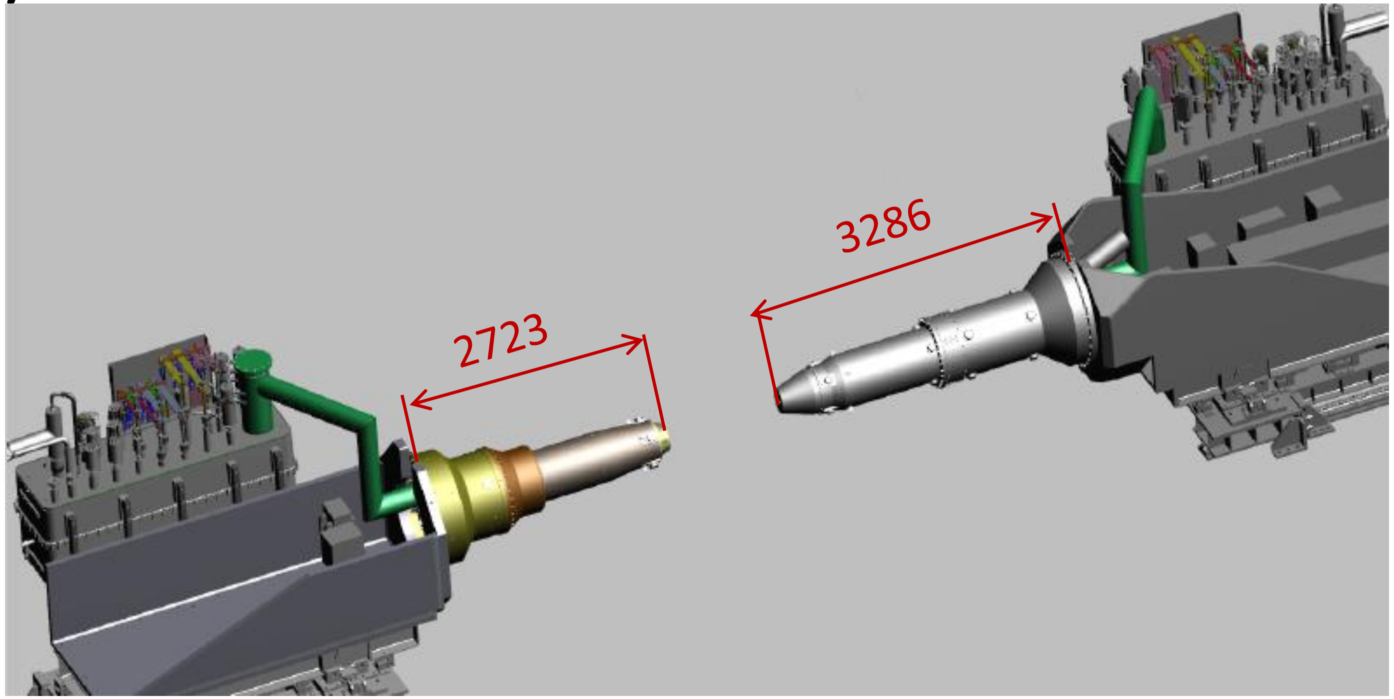


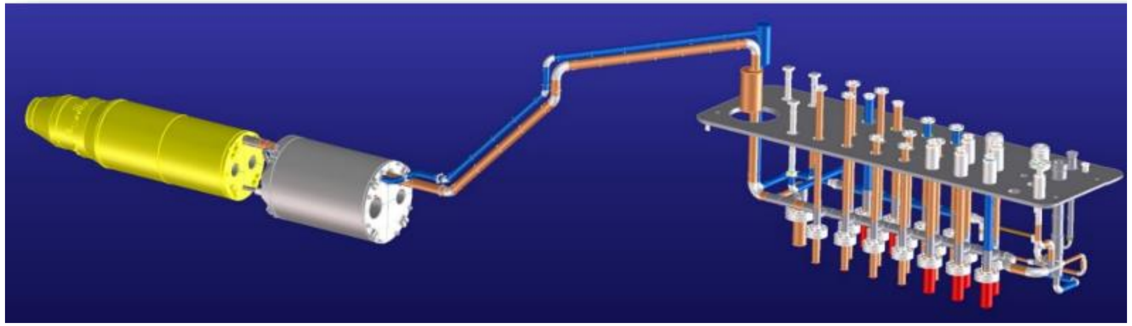
Questions to the CDR baseline design

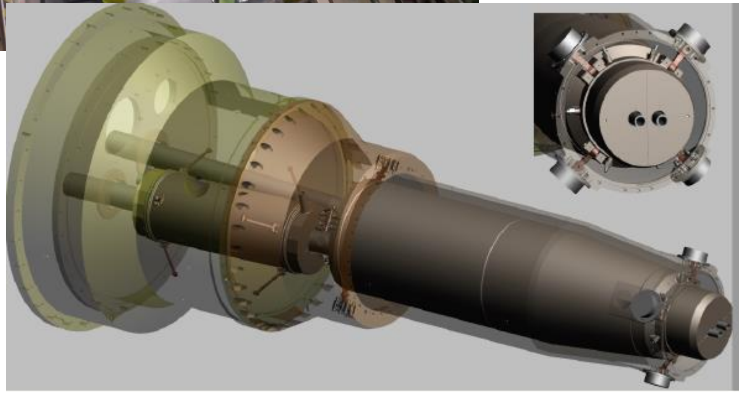
- Is 100 mrad solid angle possible for realistic design (magnets, solenoids, cryostat, etc.)?
- Is it possible to place BMPs, bellows, RVC flange, HOM absorbers, etc. inside the cryostat? How to connect their cables, cooling water tubes? How to connect draw bars to the RVC flange inside?
- Real sizes of the accelerator components inside the cryostat? Real size of the accelerator components outsize the cryostat? Real size of cryostat?
- How to assemble the MDI inside the detector with required accuracy?
- How to provide/control/adjust the components inside the cryostat inside the detector?
- Is there a skeleton inside the detector to support the cryostat(s)?
- Etc.

SKEKB MDI assembly









We need so detailed models/sketches/drawings to answer the questions.

Conclusion

IR/MDI is very critical system for the FCC-ee performance. To be sure in the IR/MDI mechanical design, we need

- 3D magnetic field map
- 3D force map
- Collect requirements for the MDI area from accelerator/detector experts
- Design separately all the systems/components (magnets, vacuum, cryo, …)
- Integrate all the components is the blocks
- Integrate the accelerator blocks in the detector