FCC-ee Arc Half-Cell Configuration and Mock-up

F. Carra (CERN)

On behalf of the FCC-ee Arc Half Cell Mock-up Project team

Outline

- Arc half-cell mock-up project
- Phase I main results
- Update on stability studies
- Proposed experimental campaign
- Conclusions

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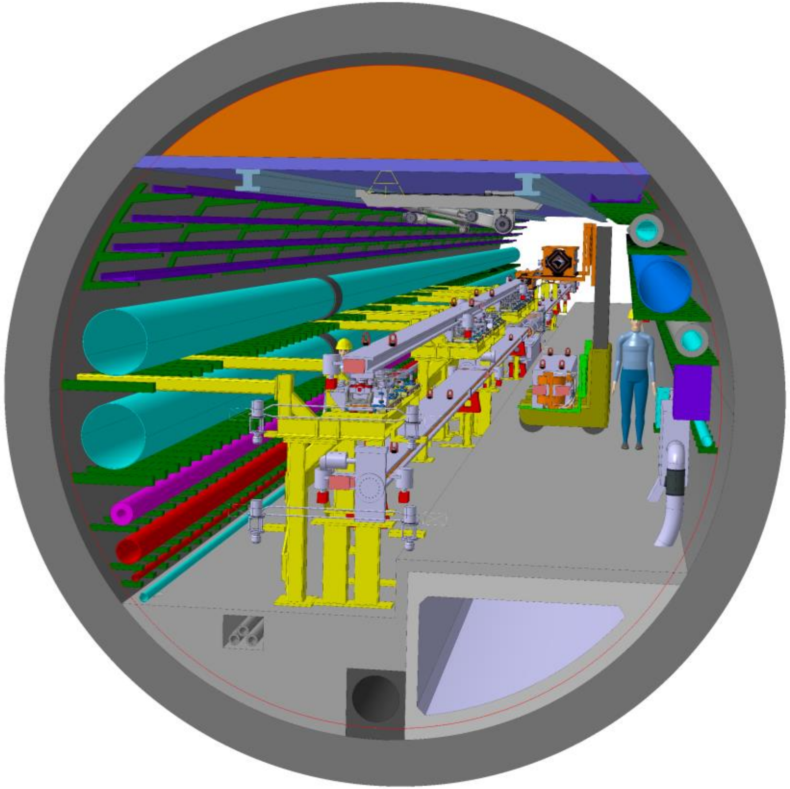
Aim of the project

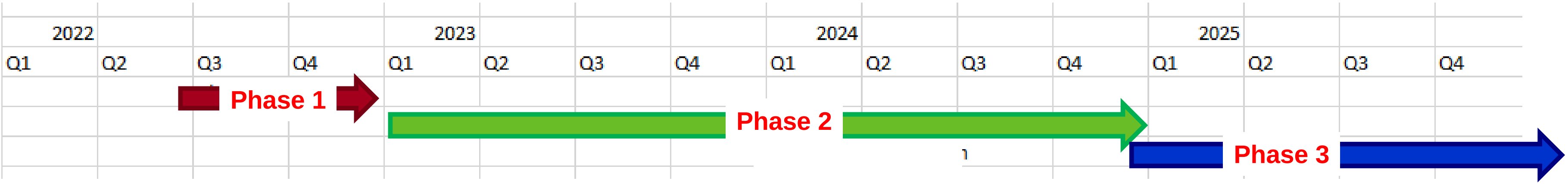
- **Arc half-cell**: most recurrent assembly of mechanical hardware in the accelerator (~1500 similar FODO cells in the FCC-ee)
- **Mock-up** → Functional prototype(s) → Pre-series → Series
- Building a mock-up allows optimizing and testing **fabrication, integration, installation, assembly, transport, maintenance, robotics**
- Working with demonstrators of the different equipment, and/or structures with equivalent volumes, weights, stiffness



Arc perspective view, F. Valchkova-Georgieva

Timeline

T. Raubenheimer



- **Phase 1: Concept development** → functional spec + integration studies. Develop 3D model for 'representative' arc half-cell.
- **Phase 2: Engineering design** of half-cell mock-up systems and delivery of 2D functional and fabrication drawings.
- **Phase 3**: **Fabrication** of half-cell mock-up with tunnel boundary with representative components and systems (non-operational).

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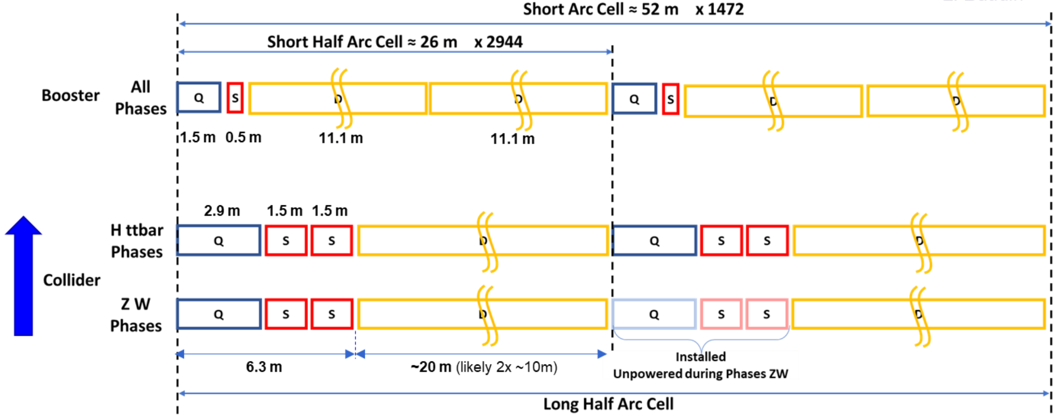
Phase I main results

- Booster/collider placement
- Configuration of Short Straight Sections
- Stability studies
- Mock-up proposal

- ***"FCC-ee Arc Half-Cell Mock-up Project – Phase 1 Summary Report"****, CERN EDMS document n.* *2817139*
- ***"FCC-ee Arc Half-Cell: Preliminary Design and Integration Studies, with Ideas for a Mock-up"****,* *Proc. of IPAC'23* *and accepted for publication on IOP special issue*
- ***"First Considerations on the Supporting Structures of FCC-ee Booster and Collider in the Arc Regions"****, accepted for publication on* *JINST special issue*
- ***Dedicated section in FCC FS Mid-Term Review Report***

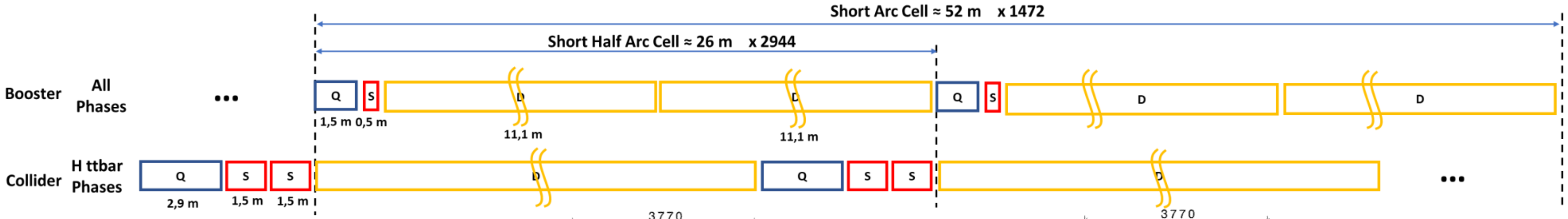
L. Baudin



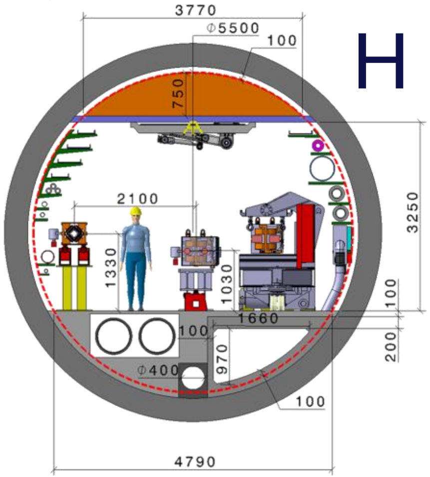
"FCC-ee Arc Half-Cell Configuration Project & Mock-up"*, presented at* *the FCCIS 2022**.*

Phase I main results: booster/collider placement

- **Azimuthal**: shift of SSS by maintaining periodicity → more compact, gain of space vertically



- **Radial & Vertical**: study of best configuration together with FCCIS TI pillar, compared by ranking relevant KPIs



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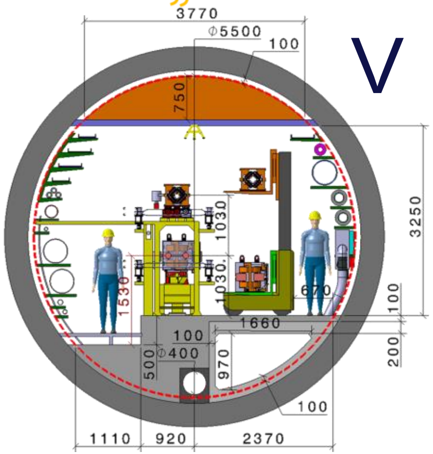
vs.



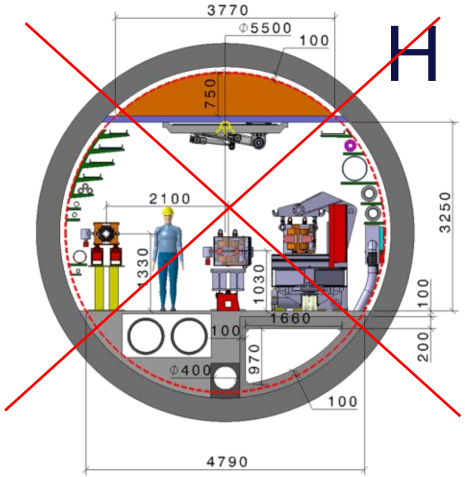
V

Phase I main results: booster/collider placement

Technical KPI	Horizontal	Vertical
Integration in Ø5.5m tunnel	1	3
Interface with other tunnel regions	2	3
Maintenance	2	2
Transport	2	3
Stability	3	2
Radiation	1	2
Compatibility with FCC-hh	2	3

1 = poor 2 = average 3 = good

- **Radial & Vertical**: study of best configuration together with FCCIS TI pillar, compared by ranking relevant KPIs



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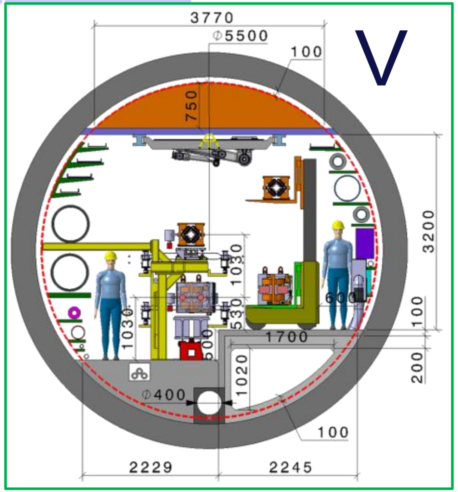
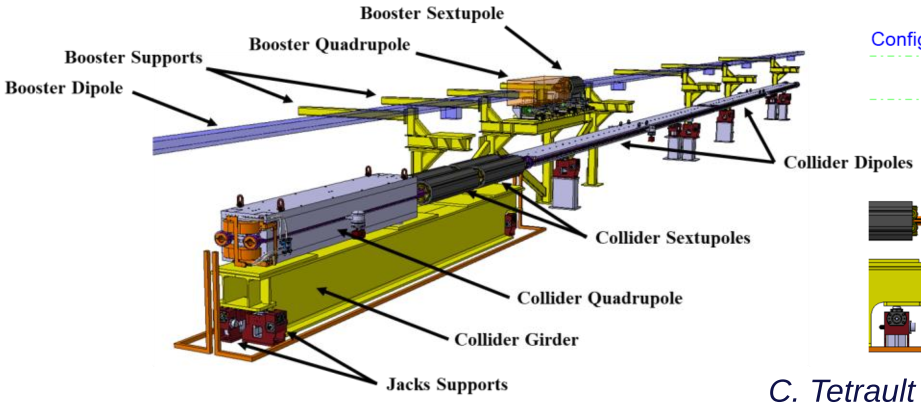
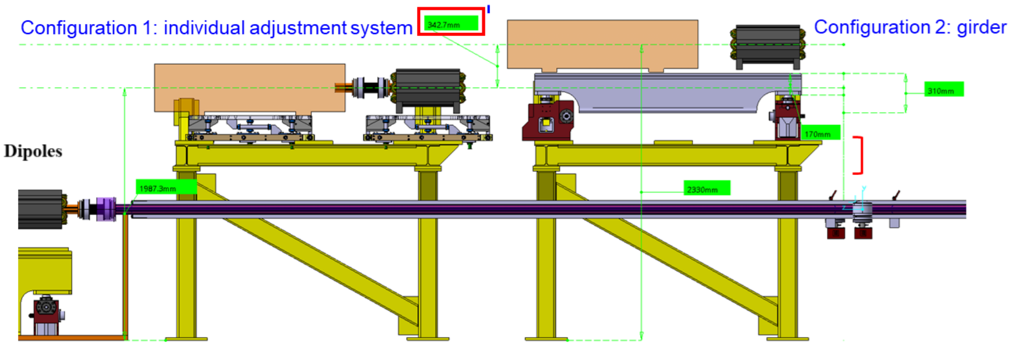


Phase I main results: configuration of the SSS

- **Preliminary mechanical design of SSS supporting system, using common girders** to pre-align magnets with common vacuum chamber in a proper surface facility.
- Clean environment, less in-tunnel work, less transports, less bellows, easy replacement / spare management.

***Senior Advisors Committee**: "Using girders can be an efficient way to install a machine. Pre-assembly can be prepared ahead, with better tools, in a more convenient environment and with more space. Girders allow for reduced installation time and reduced alignment effort in tunnel, since only girder to girder alignment is necessary vs. alignment of each machine component".*





C. Tetrault

Phase I main results: configuration of the SSS

- **Preliminary mechanical design of SSS supporting system, using common girders** to pre-align magnets with common vacuum chamber in a proper surface facility
- Clean environment, less in-tunnel work, less transports, less bellows, easy replacement / spare management.

Optimizing ***quality-to-cost in collaboration*** *with PSI (J. Wickstroem, M. Wurm) and industry*

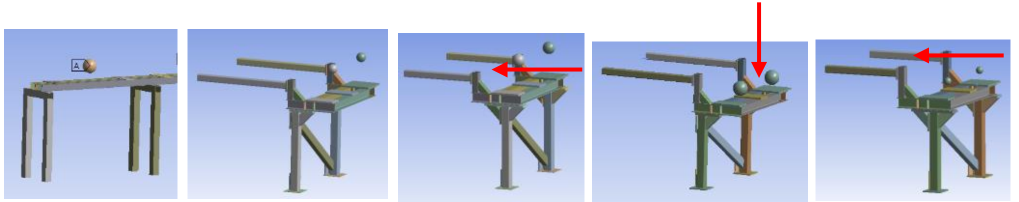
Granite girder for SwissFEL, courtesy J. Wickstroem

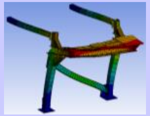
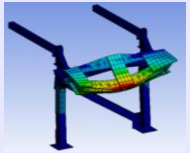
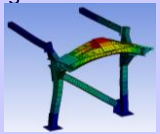
Steel girder for SLS, courtesy M. Wurm

Cast girder for PETRA IV, courtesy R. Losito

Phase I main results: stability studies

L. Baudin



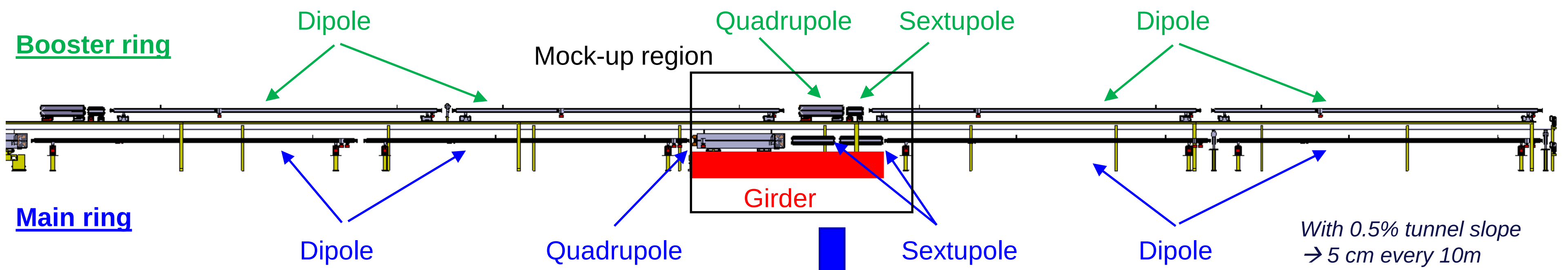
Mode Shape	**FCC Week '22** Frequency [Hz]	**First Iteration** Frequency [Hz]	**Shifted Horizontally** Frequency [Hz]	**Shifted Vertically** Frequency [Hz]	**Shifted Vertically & Horizontally** Frequency [Hz]
Longitudinal 	*7*	*18*	*24*	*21*	***29***
Bending Cantilever Arms/ Torsion Horizontal Beam 	7	19	23	29	**29**
Bending Horizontal Beam 	14	36	41	40	**54**

- Optimization leading **x15 higher stiffness and x4 higher natural frequencies**
- Likely conservative (2.5t total magnet weight, 50% less seems feasible)
- **Reasonably robust result**
  - PETRA IV girder 46 Hz
  - PSB LIU girder 29 Hz

Next steps (see slides on 2022 news)

- Add ground motion & harmonic response to evaluate **expected vibration amplitude**, compare with specs (20 nm @10-100 Hz)
- Add collider to the model, to evaluate **vibrations crosstalk**

Phase I main results: mock-up proposal

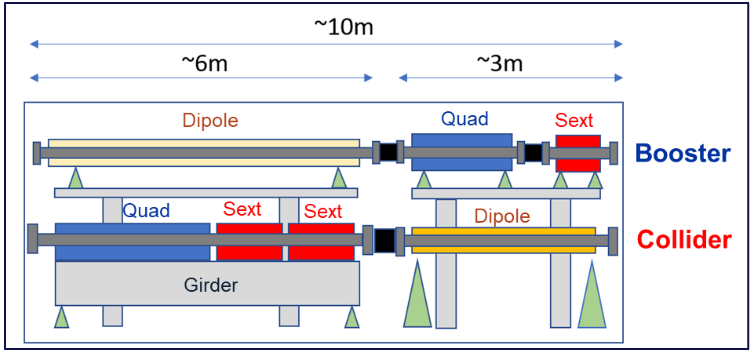


Characteristic size:

- **Section**: 5.5m diameter tube
- **Length:** ~10m

Functional elements:

1. **Ideally**: build magnet/vacuum system prototypes and mock-up as a functional testing platform *(last Senior Advisors Panel: technical potential should be exploited as much as possible, F. Lackner)*. Including alcoves, fire compartmentation?
2. **Lower-budget option**: cost-effective solution combining magnet, vacuum, beam instrumentation prototypes and cheap "maquettes" (dipole extra-length, C&V systems, shelves, etc.)



M. Timmins

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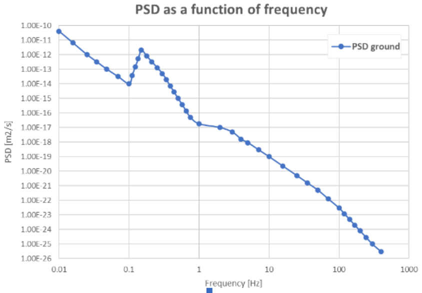
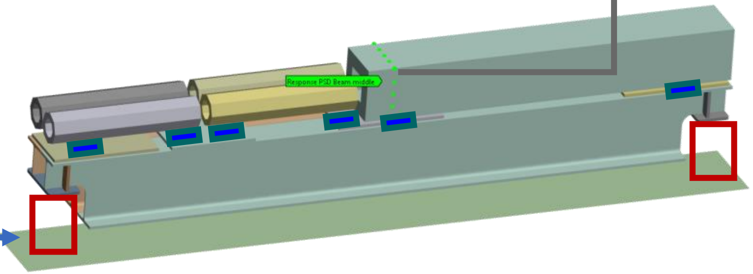
Update on stability studies: collider's SSS, method

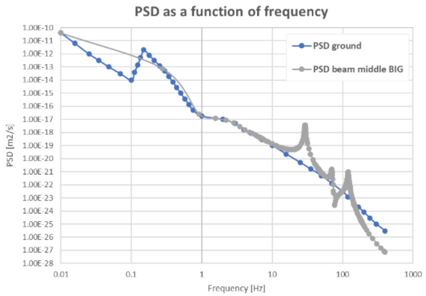
PSD of the ground motion



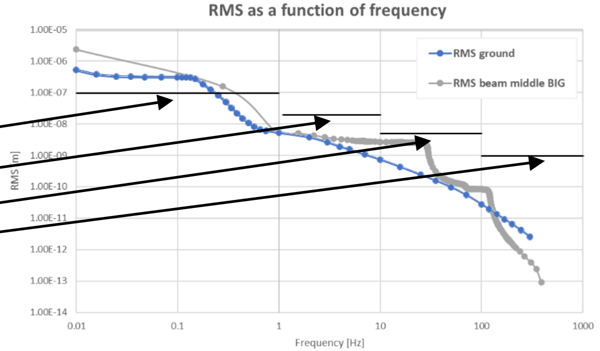
A. Piccini with L. Baudin & M. Guinchard



PSD at the level of the beamline



RMS of the ground and the beam



Assumptions:

→ *Beams model magnets*
→ *Connection between girder and magnets*
→ *Value of the stiffness of the jacks*
→ *Damping of material = 2%*
→ *PSD input = envelop of measurement graphs (LHC tunnel measurements)*
→ *Extrapolated ground motion above 100 Hz*

PSD = *Power Spectral Density*
RMS = *Root Mean Squared*

Specifications:

Frequencies	Tolerance
1 > f > 0.01 Hz	100 nm
10 > f > 1 Hz	20 nm
100 > f > 10 Hz	5 nm
f > 100 Hz	1 nm

Courtesy T. Raubenheimer, FCCIS workshop

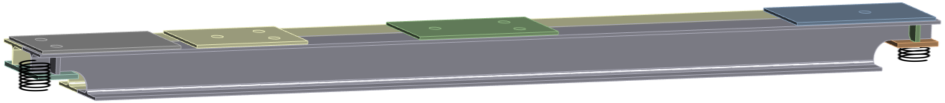
Update on stability studies: collider's SSS, results

Collider beamline = 1030mm

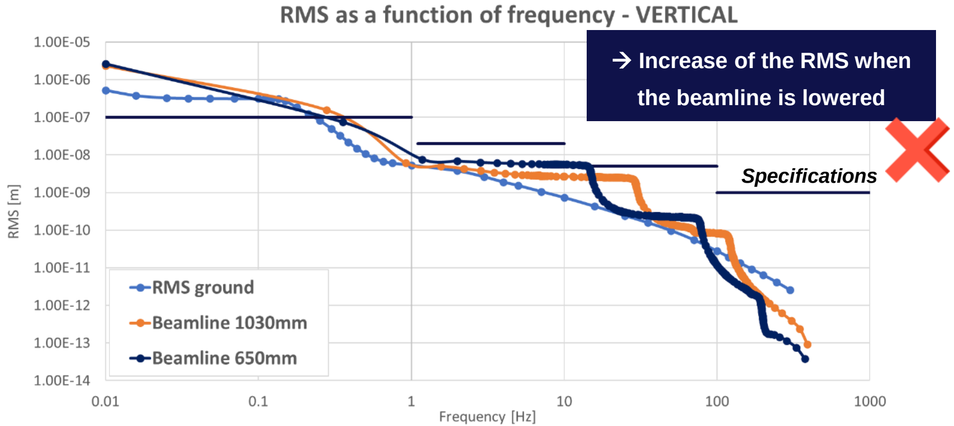
Height of the girder	720mm
Height of jacks	360mm
Stiffness of jacks	800kN/mm *(vert.)* 40kN/mm *(long. and trans.)*

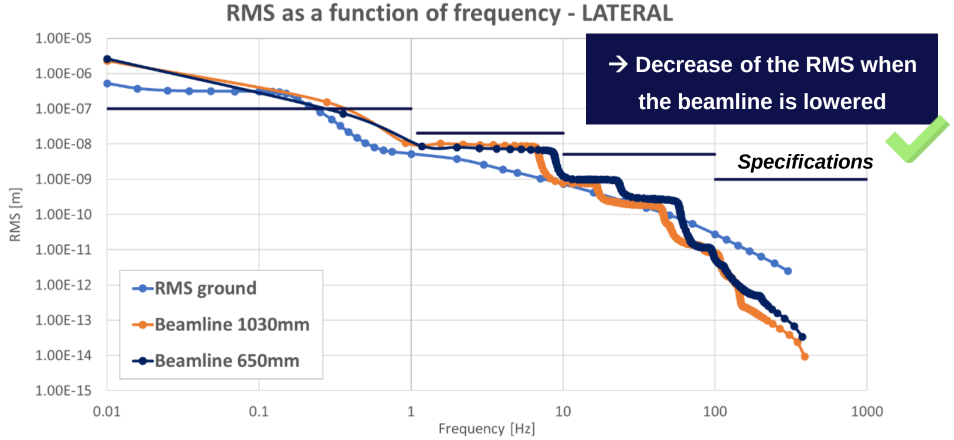
A. Piccini with L. Baudin & M. Guinchard

Collider beamline = 650mm



Height of the girder	340mm
Height of jacks	150mm
Stiffness of jacks	1600kN/mm *(vert.)* 320kN/mm *(long. and trans.)*





Update on stability studies: booster supports, method

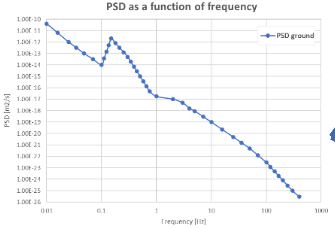
Quadrupole:
Mass = 2000kg
Envelop = 500x500mm
Length = 1500mm

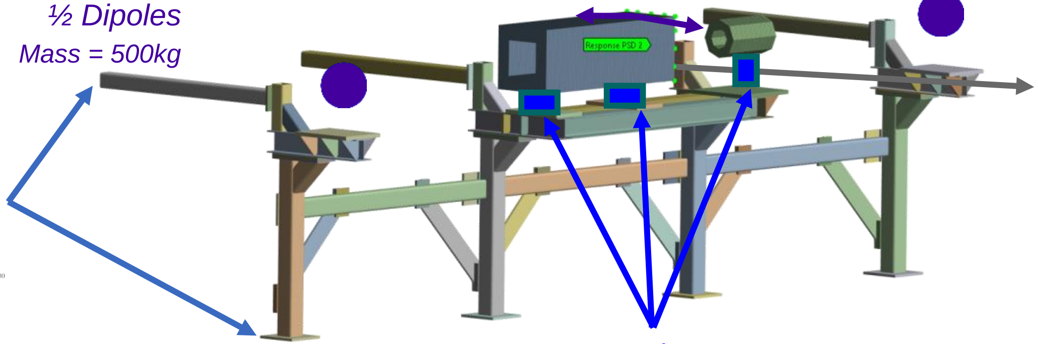
Magnets modeled by beams and point mass

Sextupole
Mass = 200kg
Envelop = Ø300mm
Length = 500mm

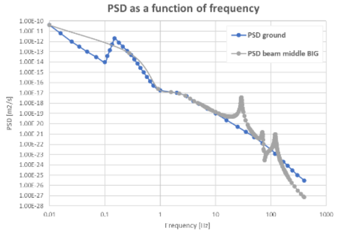
½ Dipoles
Mass = 500kg

PSD of the ground



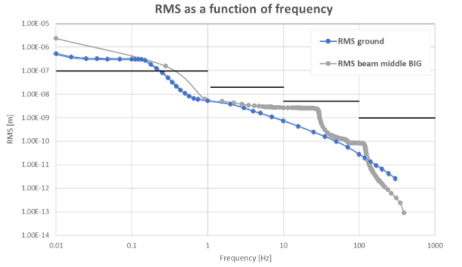


PSD at the level of the beamline



Contacts between magnets and the girder → Fixed

RMS of the ground and the beam

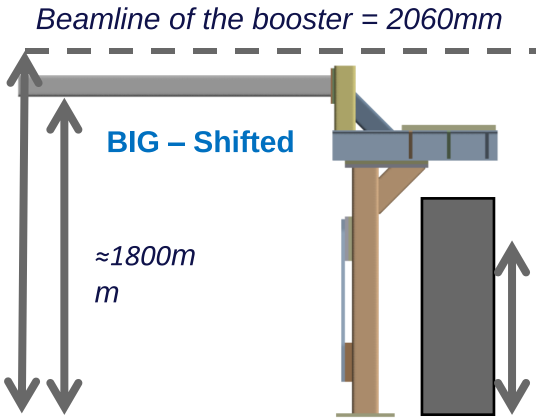


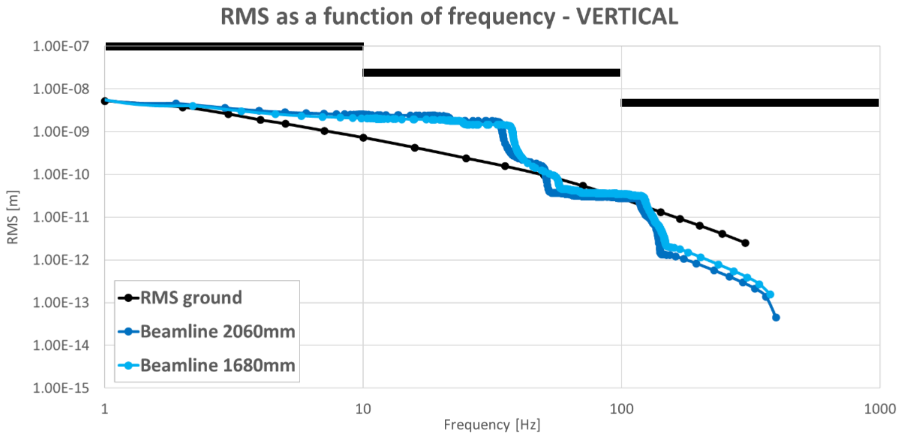
Assumptions:

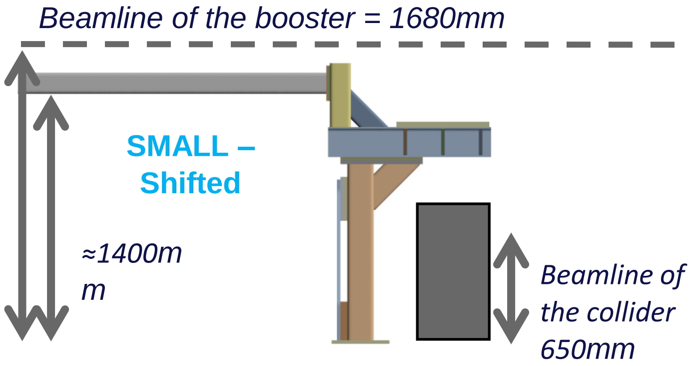
→ *Beams model magnets*
→ *Connection between girder and magnets*
→ *Damping of material = 1%*
→ *PSD input = envelop of measurement graphs (LHC tunnel measurements)*
→ *Extrapolated ground motion above 100 Hz*

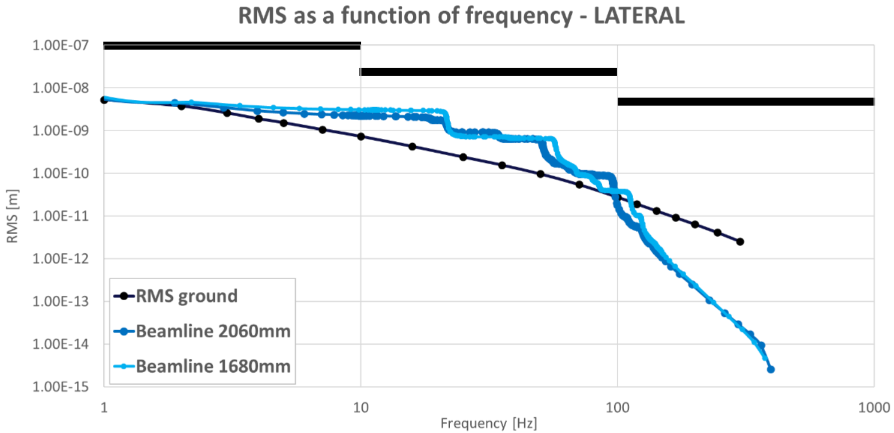
A. Piccini with L. Baudin & M. Guinchard

Update on stability studies: booster supports, results









Update on stability studies: (intermediate) conclusions

- First time performing **vibration simulations** on the current supporting system for booster and collider SSS in the arcs → **results look promising** (order of magnitude)**, however…**
- **…flexibility / transfer function of several links of the chain to be added** (will worsen the stability results):

Yellow: average uncertainty
Red: strong uncertainty

+ booster / collider vibrational crosstalk!

1. Ground → 2. Jacks → 3. Girder → 4. Individual adjustment system → 5. Magnet → 6. Magnet mech. axis to beam axis

- 1. Ground: LHC ground footprint…
- 2. Jacks: HL-LHC jacks…
- 3. Girder: Assumptions on damping ratio…
- 4. Individual adjustment system: Not modelled, shims assumed so far…
- 5. Magnet: Dummy geometry…
- 6. Magnet mech. axis to beam axis: Not considered so far…

- **Measurement campaign proposed to improve the stability model and refine preliminary results** (addressing «red» items first) → iterations and design work in the next months/years!

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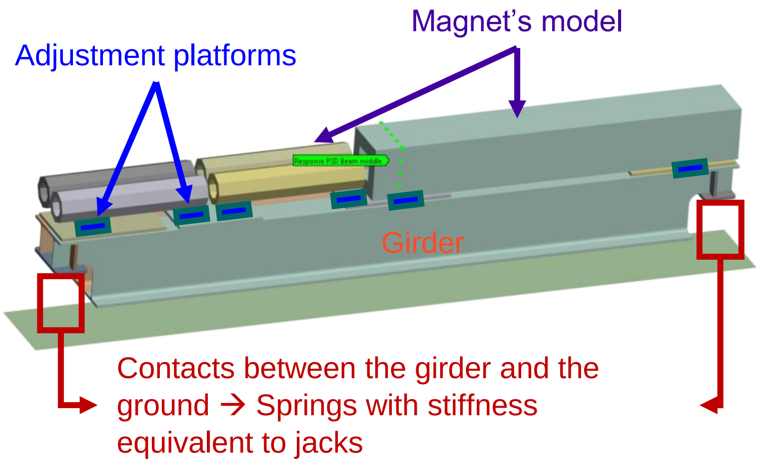
Proposed experimental campaign

- **Goal:** determine stability and stiffness of the different «links of the chain» from ground to magnetic axis.
- **Identification of weakest link** → *i.e. where to invest most of the efforts!*
- Improvement / validation of the **system stability model and architecture**.

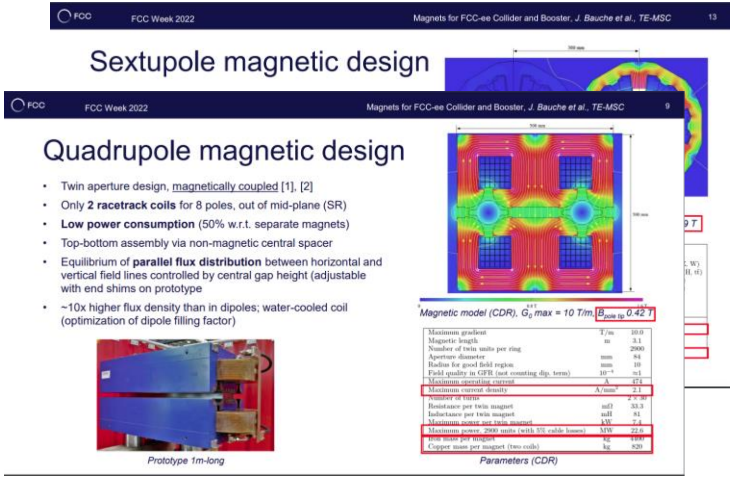


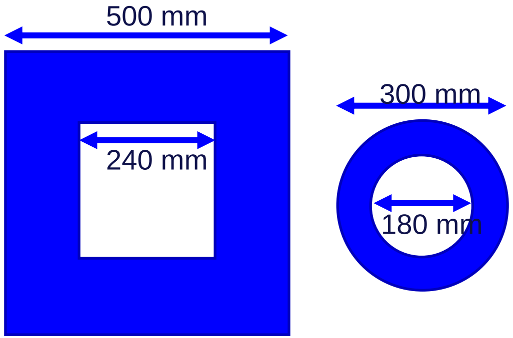
Proposed experimental campaign program:

Step	Timeline
Quadrupole prototype characterisation	2023 Q3
Adjustment platform characterisation	2023 Q4
Characterisation of a simplified collider Short Straight Section	2024 S1
Characterisation of a simplified booster Short Straight Section	2024 S2

Proposed experimental campaign: Step 1

- **Goal:** Quadrupole prototype characterization (2023 Q3)
- 1m-long Quadrupole Prototype already existing at CERN, built by TE-MSC based on design parameters of CDR (1.5 t)
- **How:**
  1. Instrument it and perform **experimental modal analysis**
  2. Comparison with **numerical simulations**
  3. Definition of **simplified model with response equivalent to that measured**, for use in global stability model

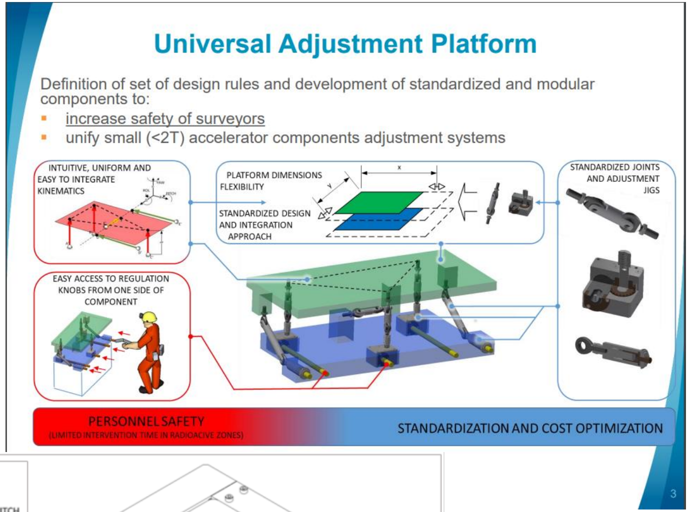




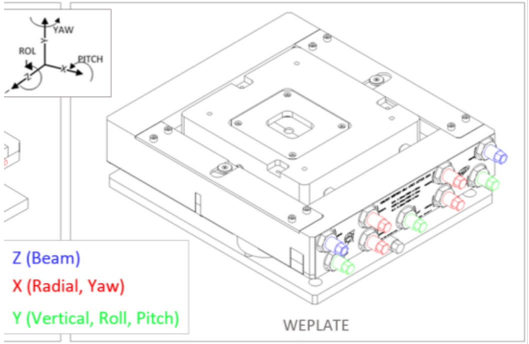
Cross section of the stainless steel beams used as models of the SSS magnets in current studies, A. Piccini

Proposed experimental campaign: Step 2

- **Goal:** Adjustment platform characterization (2023 Q4)
- WEPLATE and BIG UAP are existing adjustment platforms developed at CERN BE-GM, BE-EA
- BIG UAP is compatible with Quadrupole Prototype of FCC-ee (< 2t); WEPLATE possibly as adjustment system for a dummy sextupole (500 kg max)
- Ideally test existing equipment
- **How:**
  1. Instrument them and perform **experimental transfer function measurements**
  2. *Comparison with **numerical simulations???***
  3. Definition of **simplified model with response equivalent to that measured**, for use in global stability model



5DOF/6DOF Platform



WEPLATE

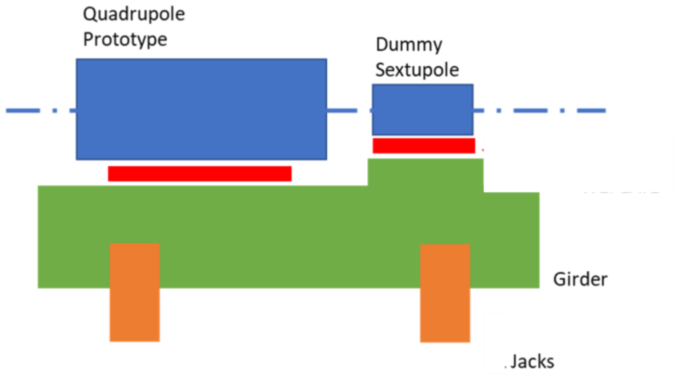
Courtesy M. Sosin, F. Sanchez Galan and A. Piccini

Proposed experimental campaign: Step 3

- **Goal:** characterization of simplified collider SSS (2024 S1)
- Construction of cheap 2m dummy girders (steel, mineral cast, hybrid)
- Existing HL-LHC jacks or production of SwissFEL PSI – like jacks
- Adjustment Platforms or shims (existing UAP and WEPLATE)
- Quadrupole Prototype (existing) + dummy Sextupole
- **How:**
  1. Measure dynamic response progressively at different assembling steps *(i.e. first jacks + marble, then girder on ground, then girder on jacks, etc.)*
  2. Compare with numerical model, built also through Steps 1 and 2
  3. **Extrapolate numerically to a longer SSS (2m to 6.5m)**

Courtesy A. Piccini

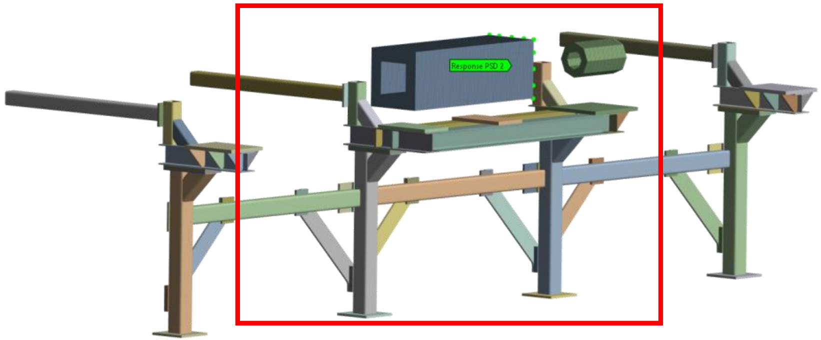
Preliminary 2m-long collider SSS prototype



Proposed experimental campaign: Step 4

- **Goal:** characterization of simplified booster SSS (2024 S2)
- Re-use of elements of Step 3 + construction of booster support
- Maybe booster prototype magnets available? If not, dummy magnets
- **How:**
  - Same as step 3, except that here we don't need to extrapolate, **since real booster SSS is of the same length (2m)**
  - This structure could also eventually be **direct part of the final arc mock-up**… if behaviour satisfactory!

Preliminary 2m-long booster SSS prototype



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Conclusions

- The **Phase I** of the Arc Half-Cell Integration & Mock-up project has been succesfully **completed in 2022** and results reported in a number of documents and papers.
- **Phase II** has started in 2023, initially focusing on the **validation of the supporting system** proposed for the Short-Straight Sections of the arcs.
- **Preliminary vibrations results** have been presented; however, **experimental tests** are needed to evaluate the dynamic behaviour of several of the elements from the ground to the magnet axis. These will be launched in the second half of 2023.
- The working group also collected the information needed to allow a **cost estimation of the current support and girder system**, providing inputs to the mid-term review (M. Timmins).
- **Several collaborations** have been defined or are under definition: LAPP (FR), PSI (CH), University of Malta (MA) and University of La Sapienza - DIMA (IT).

Thank you
for your attention.

Status

- **Arc configuration**: CDR (2019) + updates during FCC feasibility study
- **Conceptual design to fabrication**
  1. Confirmation/update of the functional specifications
  2. Arc integration study
  3. Engineering design of systems and interfaces
- For **collider AND booster**

Table 2: RMS magnet misalignment values. (The definition of the misalignment parameters are defined in Fig. 1.

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)
Arc quadrupole*	50	50	~~400~~ 300	150
Arc sextupoles*	50	50	~~400~~	150
Dipoles	1000	1000	~~400~~	1000
Girders	150	150	-	1000
IR quadrupole	100	100	250	250
IR sextupoles	100	100	250	250
BPM**	40	40	100	-

* misalignments relative to girder placement
** misalignments relative to quadruple placement

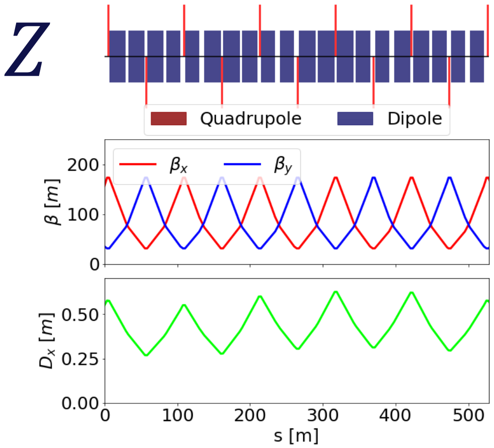
T. Charles et al., "Update on the Low Emittance Tuning Of the e+/e- Future Circular Collider," IPAC'21

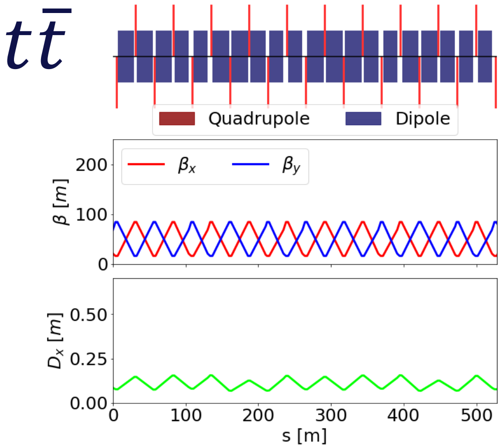
T. Charles, "Optics correction studies", FCC week, 31st May 2022.

Arc cell configuration(s)

T. Raubenheimer, "Accelerator Overview", FCC week, 30th May 2022.

M. Hofer, "Baseline optics and layout of the FCC-ee collider ring", FCC week, 31st May 2022.





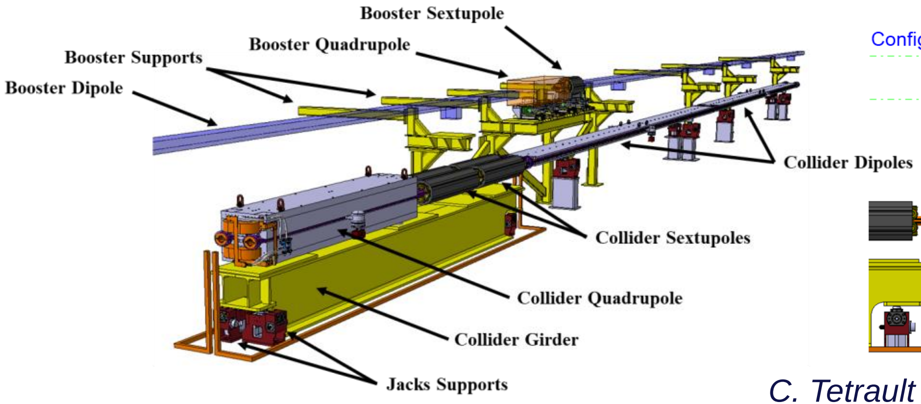
- New configuration for arc optics with long ~100 m FODO cells at Z & W and short ~50 m cells at Zh and $t\bar{t}$ (more details in Tor's talk earlier this week)
- Total arc length 9.6 x 8 ~ 77 km

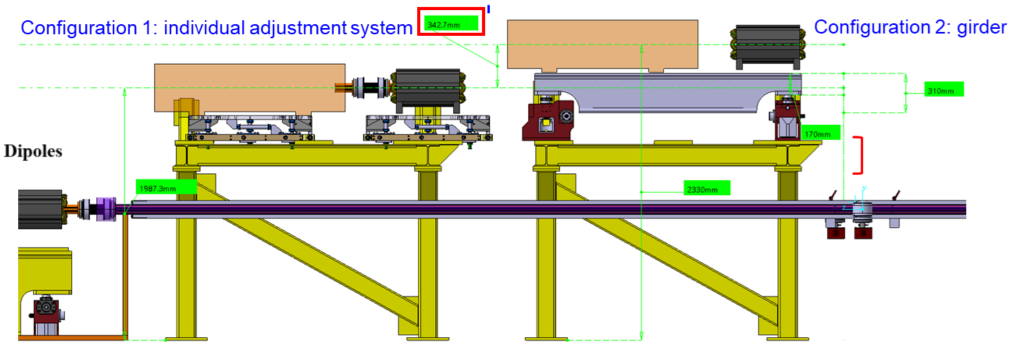
- FCC arcs are constructed from roughly 750 long cells or 1500 short cells
- Integration study (Phase I): to give also inputs on how to best **evolve from long cell (low energy) to short cell**

Phase I main results: configuration of the SSS

- **Preliminary mechanical design of SSS supporting system, using common girders** to pre-align magnets with common vacuum chamber in a proper surface facility.
- Clean environment, less in-tunnel work, less transports, less bellows, easy replacement / spare management.

> ***Senior Advisors Committee****: "Using girders can be an efficient way to install a machine. Pre-assembly can be prepared ahead, with better tools, in a more convenient environment and with more space. Girders allow for reduced installation time and reduced alignment effort in tunnel, since only girder to girder alignment is necessary vs. alignment of each machine component".*

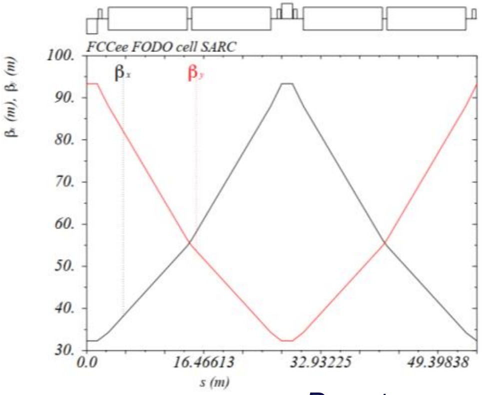




C. Tetrault

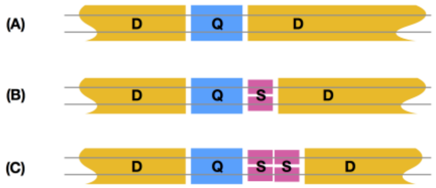
Arc cell configuration(s)

- **Arc half-cell**
  - 1 **Quadrupole**
  - 0, 1, 2 **Sextupoles**
  - Up to ~24 m **Dipoles** (segmented, variable length)



Booster

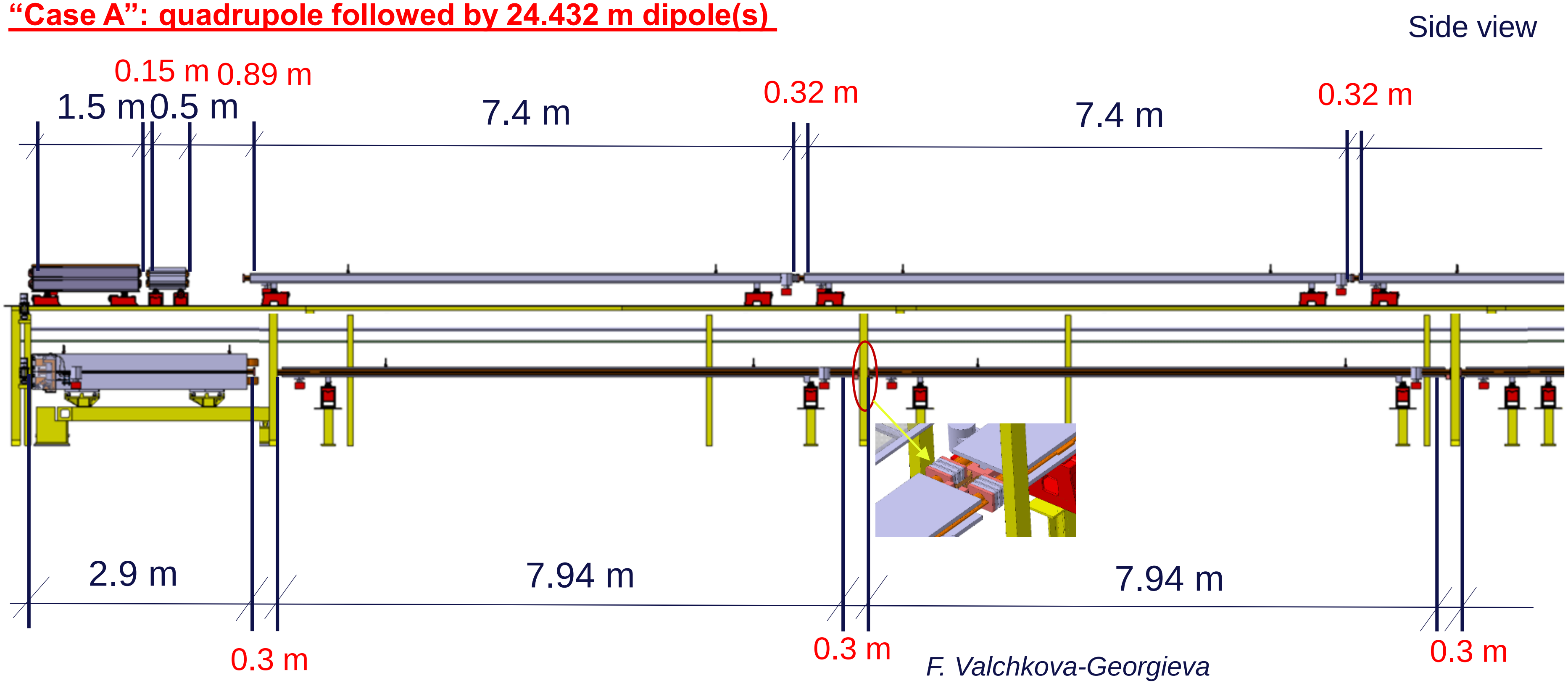
D: dipole, Q: quadrupole, S: sextupole		
Spacing between magnets (m)		
D-Q	0.3	
Q-S	0.3	
S-S	0.1	
S-D	0.3	
Case	Arrange	Length of D
(A)	Q-D	24.432
(B)	Q-S-D	22.732
(C)	Q-S-S-D	21.232
Length (m)		
Q	2.9	twin aperture
S	1.4	single aperture



F. Valchkova-Georgieva

Arc cell configuration(s)

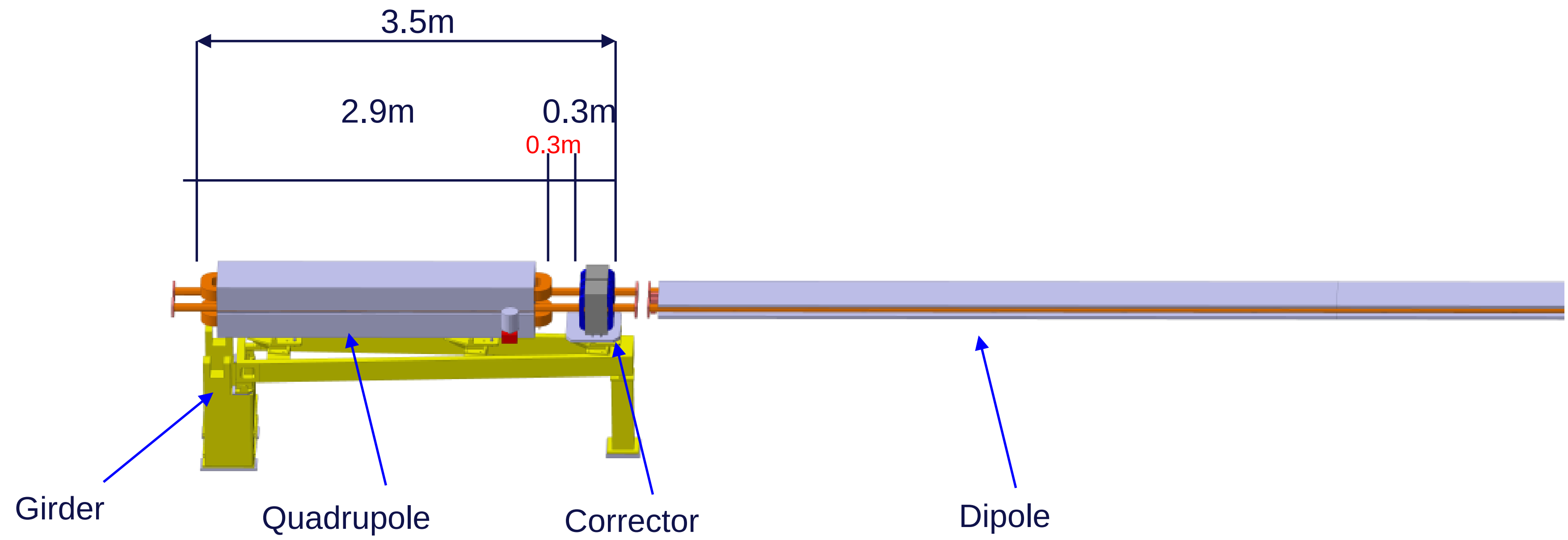
“Case A”: quadrupole followed by 24.432 m dipole(s)



F. Valchkova-Georgieva

Arc cell configuration(s)

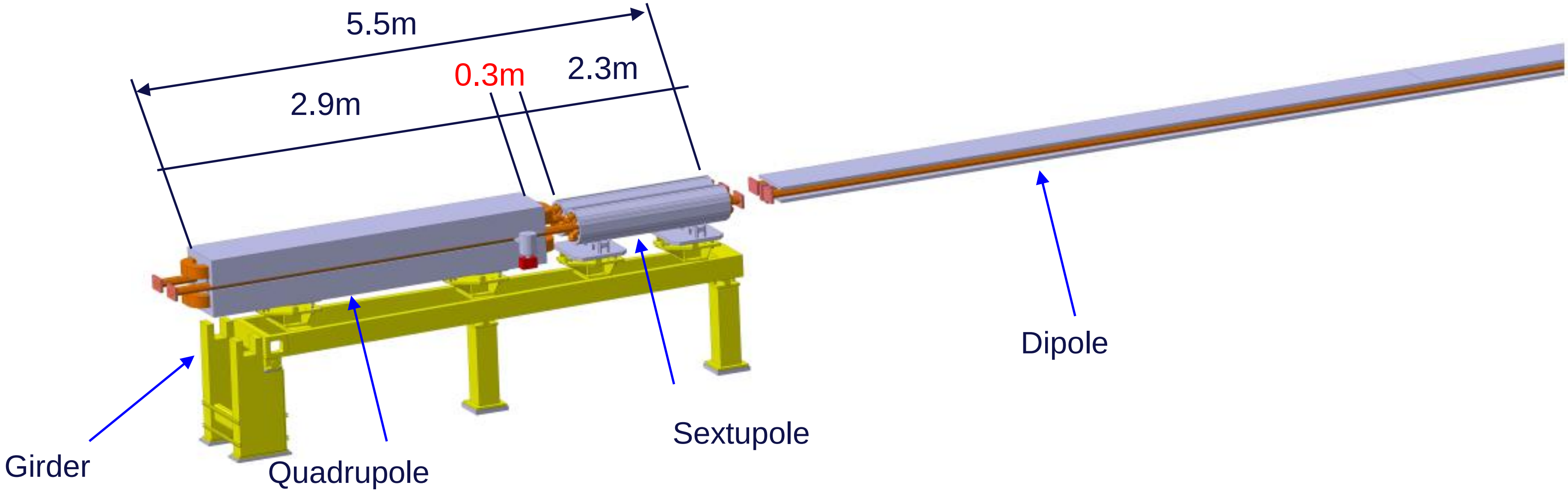
“Case A”: 1 quadrupole followed by dipole(s)



F. Valchkova-Georgieva

Arc cell configuration(s)

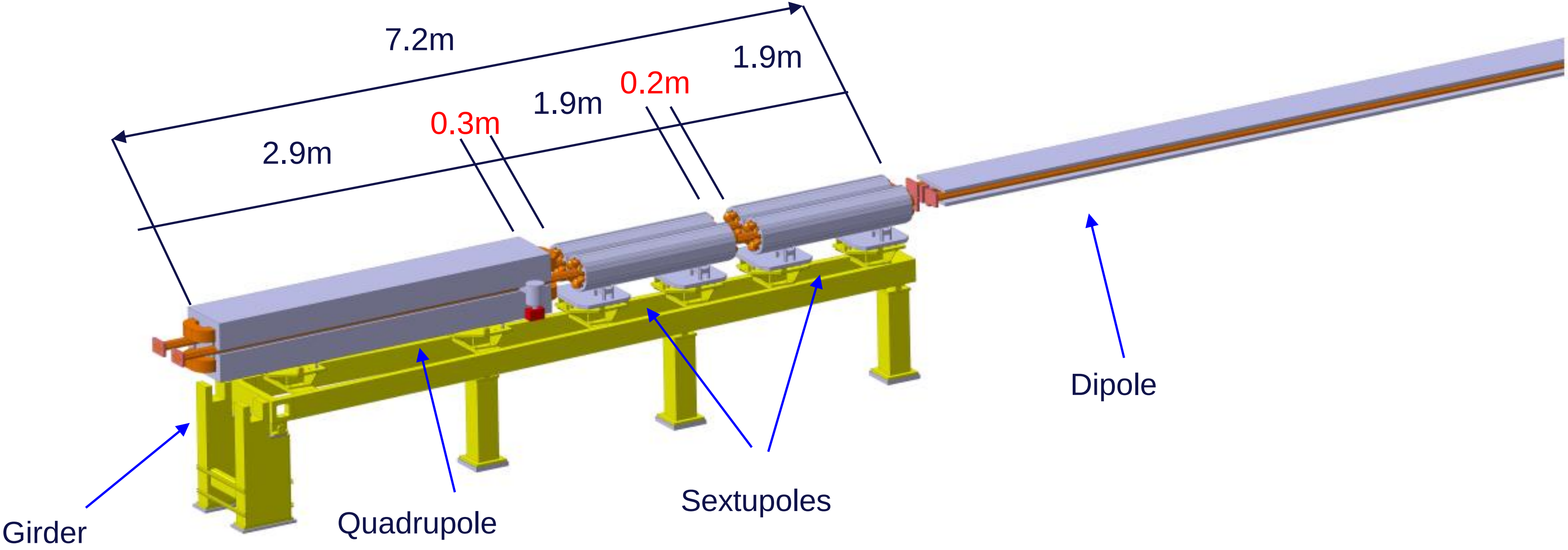
"Case B": 1 quadrupole + 1 sextupole, followed by dipole(s)



F. Valchkova-Georgieva

Arc cell configuration(s)

“Case C”: 1 quadrupole + 2 sextupoles, followed by dipole(s)

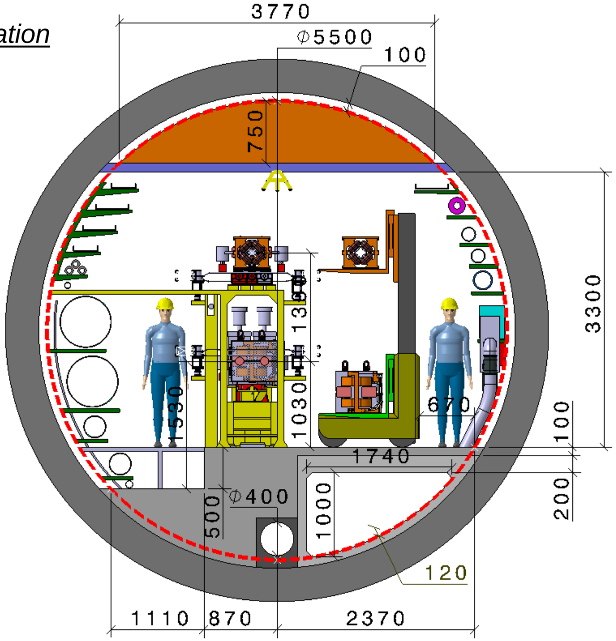


F. Valchkova-Georgieva

Arc Half-Cell Mock-up Project (Phase I)

** Extract from T. Raubenheimer's presentation at the Arc Half-Cell Mock-up kickoff*

- **Mandate***
  - *Develop an optimal integrated solution for the mechanical layout of an Arc Half-Cell considering machine performance, installation, operation, and maintenance, as well as necessary technical infrastructure in the tunnel.*
  - *Identify the components of a representative Arc Half-Cell that will verify the key challenges.*
- **Main deliverables**
  - 3D model + 2D cross-section drawings of arc region
  - Compact report explaining main choices
  - To be presented at FCCIS meeting in December '22

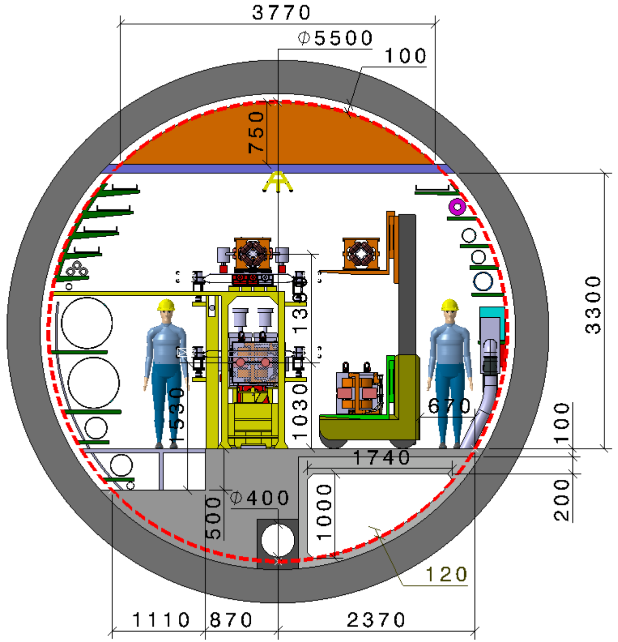


F. Valchkova-Georgieva

Collider Center

Needed studies and challenges (Phase I)

- **Needed studies & challenges***
  - Horizontal separation of the e+ and e- rings in the arcs
  - Vertical placement / separation between collider and booster *(and: is vertical superposition the only solution?)*

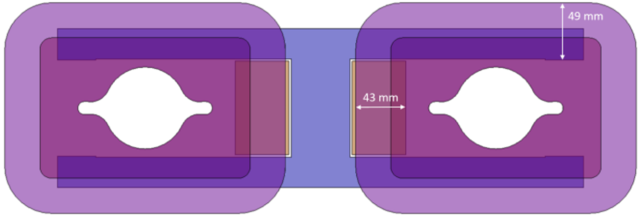


** More detailed list & Project structure in T. Raubenheimer's presentation at the Arc Half-Cell Mock-up kickoff*

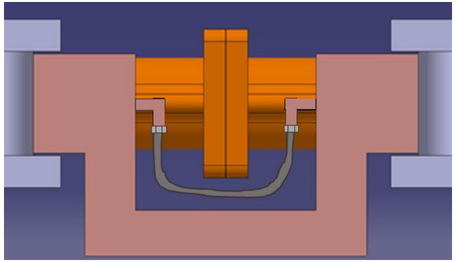
Needed studies and challenges (Phase I)

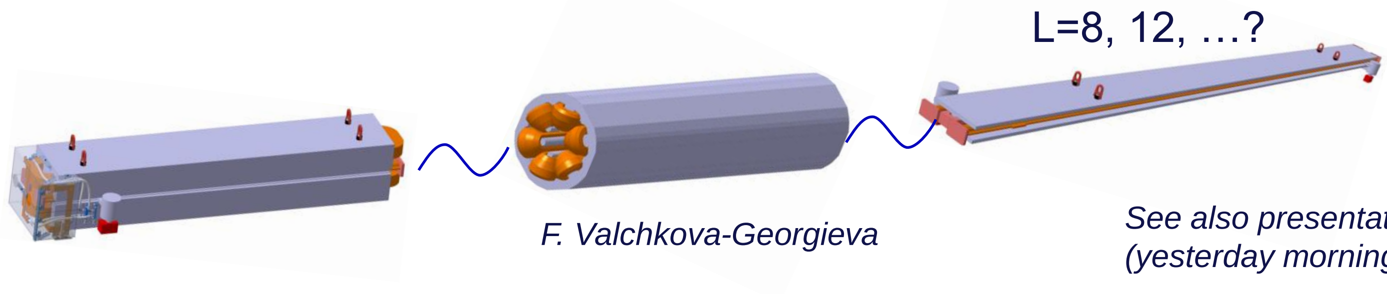
- **Needed studies & challenges***
  - Horizontal separation of the e+ and e- rings in the arcs
  - Vertical placement / separation between collider and booster *(and: is vertical superposition the only solution?)*
  - Define preferred dipole length (*and: continuity or separation between dipoles/busbars?*)
  - Design interfaces between magnet and vacuum systems

Dipole / Vacuum flange



D-D interface





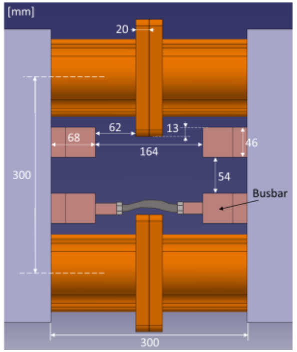
F. Valchkova-Georgieva

See also presentations from J. Bauche, C. Garion (yesterday morning, Technology R&D session)

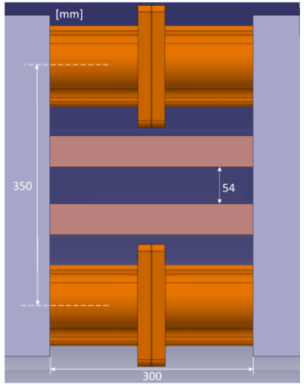
Needed studies and challenges (Phase I)

J. Bauche, C. Eriksson

- **Needed studies & challenges***
  - Horizontal separation of the e+ and e- rings in the arcs
  - Vertical placement / separation between collider and booster *(and: is vertical superposition the only solution?)*
  - Define preferred dipole length (*and: continuity or separation between dipoles/busbars?*)
  - Design interfaces between magnet and vacuum systems (*and: integration of correctors, beam instrumentation, …*)
  - Optimize the power & cooling connections for the magnets, vacuum, and beam diagnostics
  - Develop supporting system in line with installation and alignment procedures (*w. girder*)
  - **And… booster elements!!!**



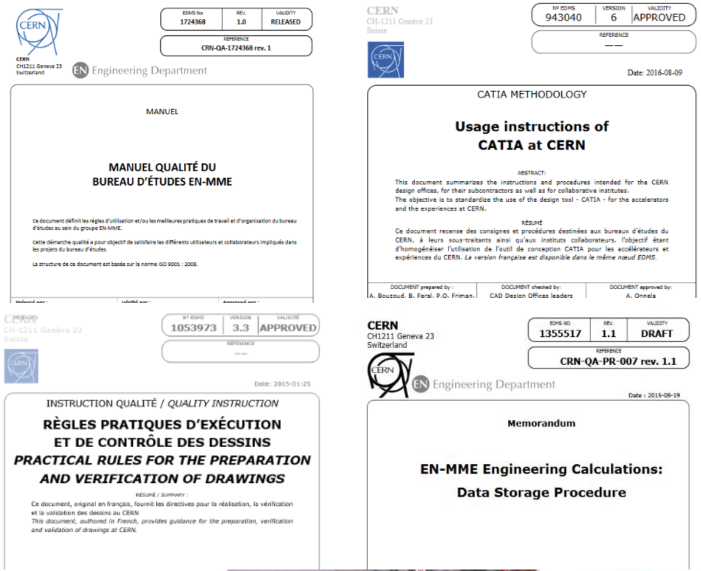
300 mm beam separation



350 mm beam separation

Design standards

D. Perini



- **Quality standards** for the design of components must be used at the earliest stage
- *EN-MME quality manual* available (EDMS 1724368)
- To be linked/integrated with **guidelines for robot-friendly design** *(from Remote maintenance code of practice*)*

**see M. Di Castro, "Code of practice for robotic-friendly design", 2nd Coordination of FCC Technology R&D programme meeting.*

M. Di Castro

Novel concepts: Digital Twins

What is a Digital Twin?

Virtual representation of a system (or an asset)

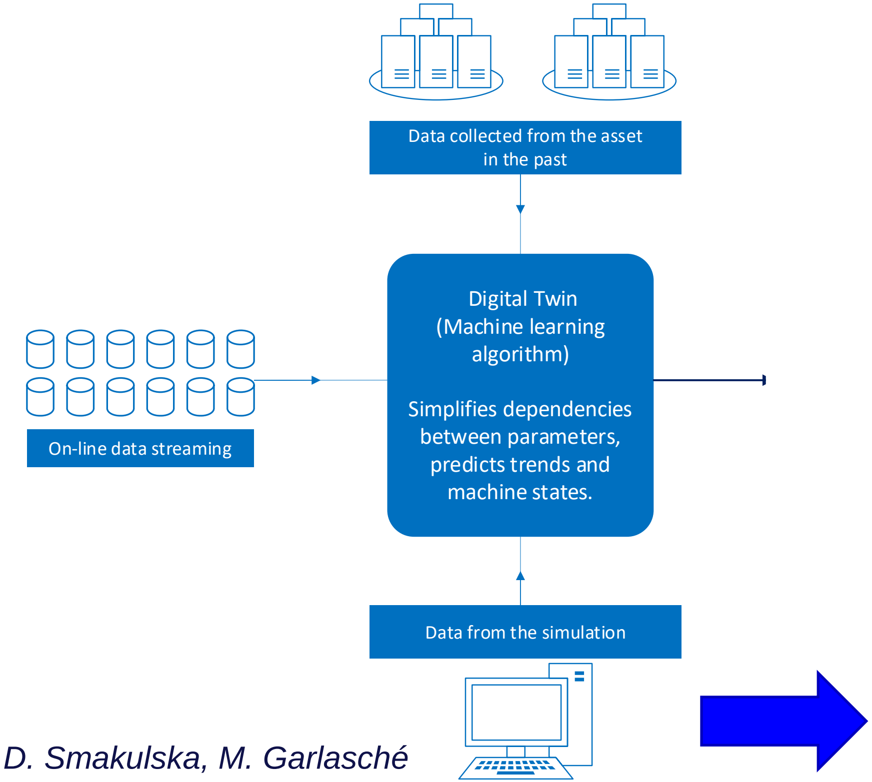
Calculates present system states, through integrated models and data in real-time.

Predicts future system states…real-time

D. Smakulska, M. Garlasché

Novel concepts: Digital Twins

See also the interesting presentations from yesterday afternoon on alignment, vibrations (FCC-ee afternoon session)



D. Smakulska, M. Garlasché

Digital Twin IS MORE than just
- data acquisition & monitoring
- a set of simulations
- experience from historical

OUTPUT

Normal Operation:
- Determine system state through data acquisition
- Real time, ALSO for parameters not directly acquired

Failure:
- Forecast system state, real time interpretation
- Repair scenarios: real time analysis, system-wide

Complexity of the system is tailored to the specific needs

To be considered for mock-up girder and magnets: displacements, vibrations, strains, temperature, etc.

Conclusions

- The design and construction of a **mock-up of an arc half-cell** of the FCC-ee is proposed, in order to investigate aspects such as fabrication techniques, integration, installation, assembly, transport, maintenance.
- The project is divided into **three phases**:
  - **Phase I** (end of 2022) focuses on the integration studies of the arc configuration and the interfaces between its systems
  - **Phase II** (2023-2024) will tackle the engineering design of each element
  - **Phase III** (2024-2025) will involve fabrication and assembling steps
- Concepts such as **robot-friendly systems** and **digital twins** must be taken into consideration already during the early stage of the design.
- **Strong interaction and feedback** from Accelerator and Infrastructure Pillars, and in particular with Integration, Technology R&D, Collider Ring Optics, Booster Ring, Geodesy and Survey, will be key
- Phase I has started, and a platform for discussion has been set (https://indico.cern.ch/category/15513/)
  → **contact us to discuss inputs and ideas!**