# FCC-ee Arc Half-Cell Configuration Project & Mock-up

F. Carra (CERN)

*On behalf of the Arc Half-Cell Configuration Project, with inputs from many FCC WG and colleagues*

# Outline

- Aim of the project
- Project organization & timeline
- Arc cell configuration(s)
- Main studies
  - Integration layout & booster placement
  - Arc systems interfaces & inter-beam distance
  - Accelerators supporting systems & SSS girders
- Arc half-cell mock-up & Novel concepts
- Conclusions

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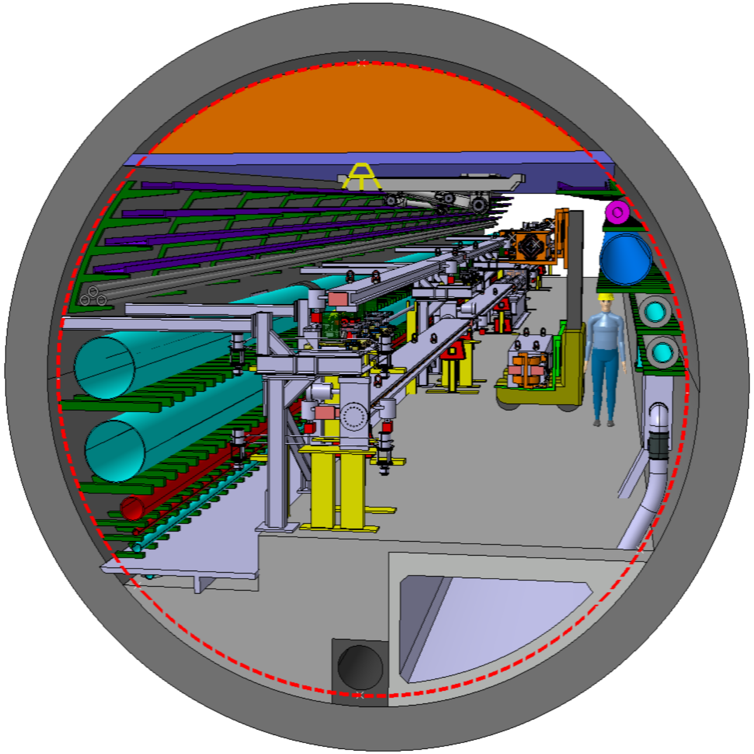
# Aim of the project

- **Arc half-cell**: most recurrent assembly of mechanical hardware in the accelerator (~1500 similar FODO cells in the FCC-ee)
- Building a mock-up allows optimizing and testing **fabrication, integration, assembly, transport, installation, alignment, maintenance**
- Working with demonstrators of the different equipment, and/or structures with equivalent volumes, weights, stiffness
- ***First proposal*** *later in this presentation!*



*Arc perspective view, F. Valchkova-Georgieva*

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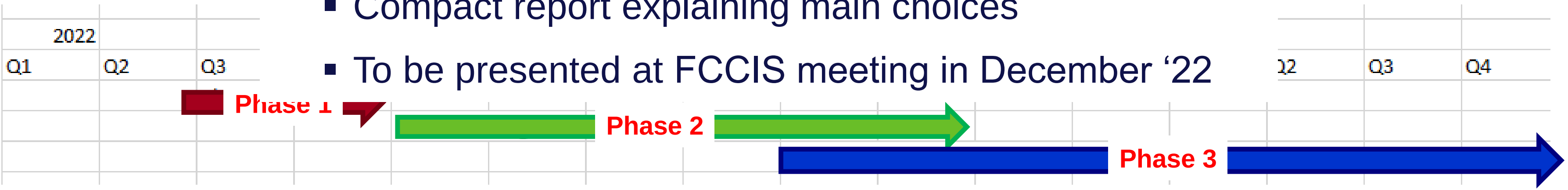
# Timeline

- **Phase I 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




- **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).

# Phase I setup

- **Dedicated working group representing all domains involved**
  - PL: Federico Carra (overall mechanical concept)
  - Scientific secretary & Calculations: L. Baudin
  - FCC Integration (enlarged) F. Valtchkova, J. P. Corso, S. Grillot, J. Etheridge, S. Chemli
  - Design & Stabilization: M. Timmins, C. Tetrault, K. Artoos, O. Capatina, M. Guinchard, L. Baudin
  - Alignment: H. Mainaud-Durand;
  - Beam Instrumentation: M. Wendt
  - Accelerator hardware aspects: via R. Losito as coordinator for Technology R&D
  - RF: O. Brunner
  - Technical infrastructure: via K. Hanke as coordinator of Technical Infrastructure Pillar
  - CE tunnel: J. Osborne
  - Accelerator design: K. Oide (FCCee) and A. Chance (Booster)
  - + additional team members, full list in e-group: fcc-ee-arc-cell-mockup-project (FCC-ee arc-cell mock-up meeting members);
- **Oversight directly by Accelerator Pillar Coordinators (T. Raubenheimer, F. Zimmermann)**
- **Regular meetings with Senior Advisors Panel** to report on status, collect feedback & proposed actions (A. Bertarelli, F. Bertinelli, P. Fessia, F. Lackner, J.P. Tock, J. Wickstrom, P. Raimondi with M. Benedikt, T. Raubenheimer & F. Zimmermann)

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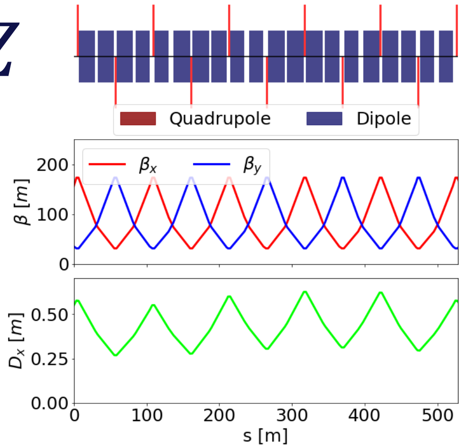
# Arc cell configuration(s)

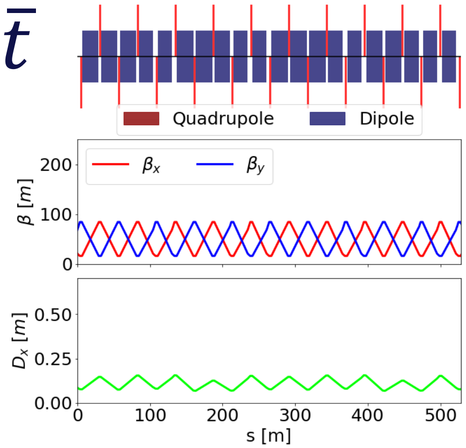
*T. Raubenheimer, "Accelerator Overview", FCC week, 30th May 2022.*

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

$Z$




$t\bar{t}$

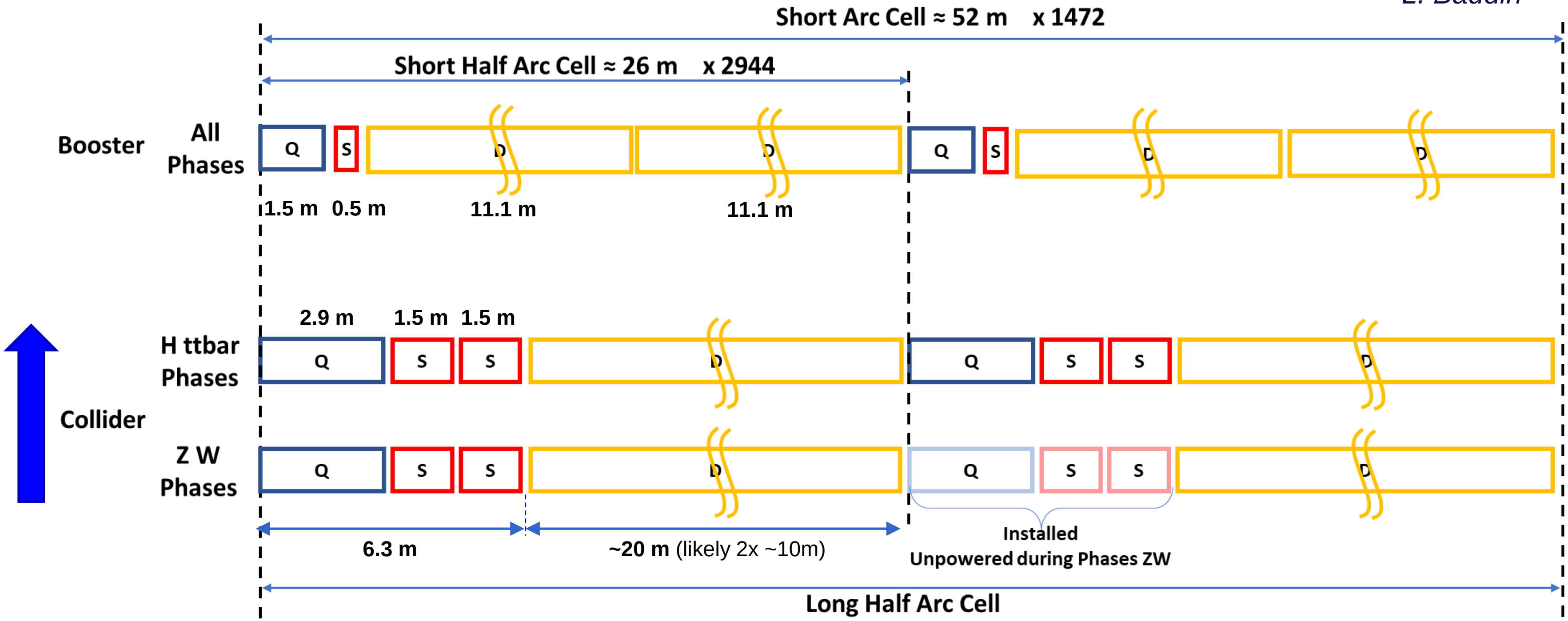



- New configuration for arc optics with long ~100 m FODO cells at Z & W and short ~50 m cells at Zh and $t\bar{t}$ (more details in Katsunobu's talk this morning)
- Total arc length 9.6 x 8 ~ 77 km

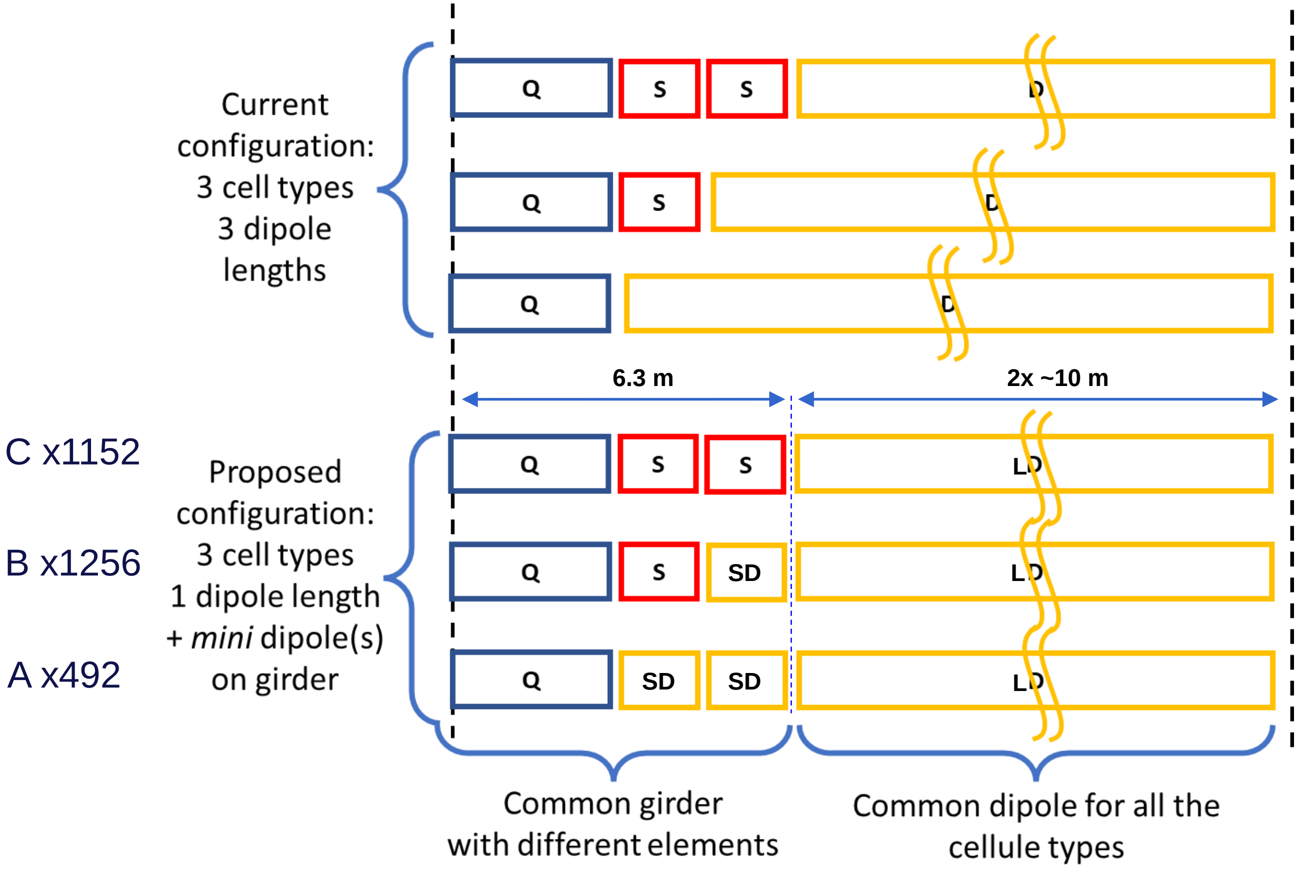
- FCC arcs are constructed from roughly 750 long cells or 1500 short cells
- Integration study (Phase I): to give also inputs on how to best **evolve from long cell (low energy) to short cell**

# Arc cell configuration: from low to high energy

*L. Baudin*



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




*L. Baudin, J. Bauche*

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

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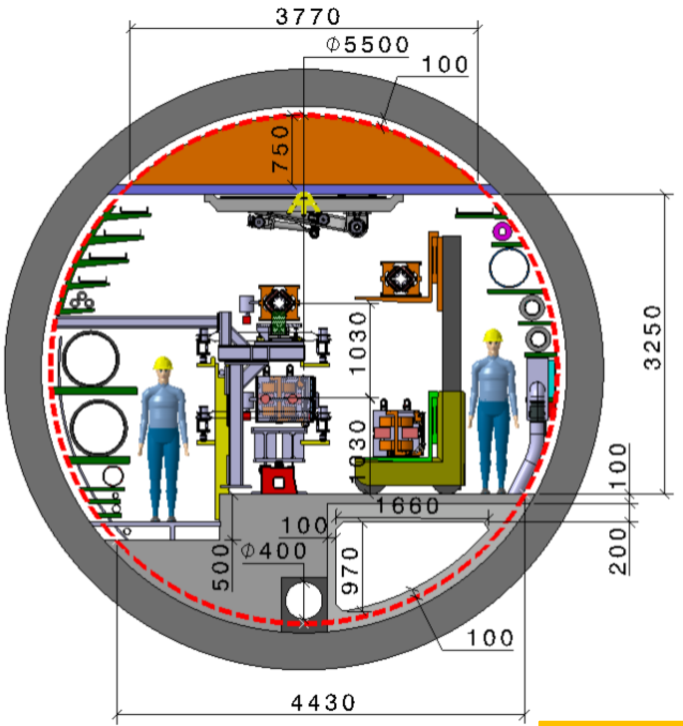
# Tunnel Layout – Vertical placement booster to collider

*F. Valchkova-Georgieva*

**Machine tunnel 5.5m in diameter**

- Main cross section as for **FCC-hh**
- Main ring below of booster ring
- Main ring and booster ring 1.03 m distant
- Demineralized water circuit decreased to DN550 *(can possibly be less, requirement update exercise triggered with G. Peon and equipment owners)*



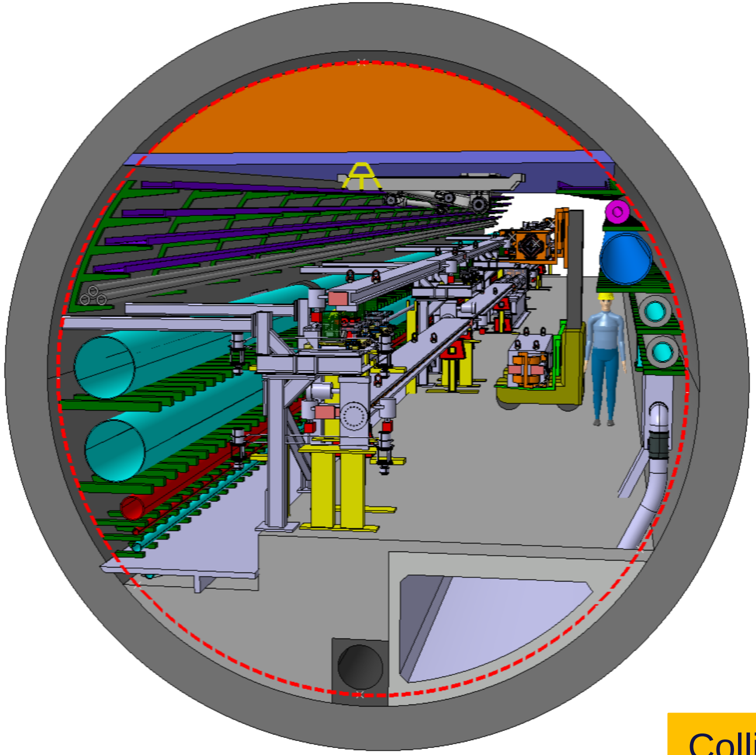

Collider Center

# Tunnel Layout – Vertical placement booster to collider

*F. Valchkova-Georgieva*

Machine tunnel 5.5m in diameter

**Perspective view**



Collider Center

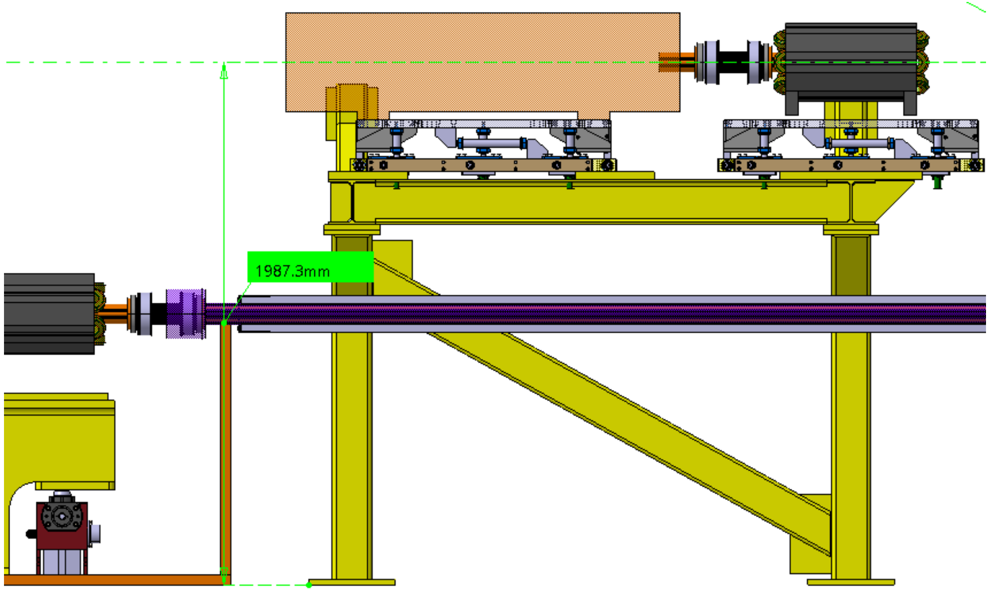
# Tunnel Layout – Vertical placement booster to collider

C. Tetrault

Vertical placement considers that:

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

- *Proposed and approved at 159th FCC-ee Optics Design Meeting*



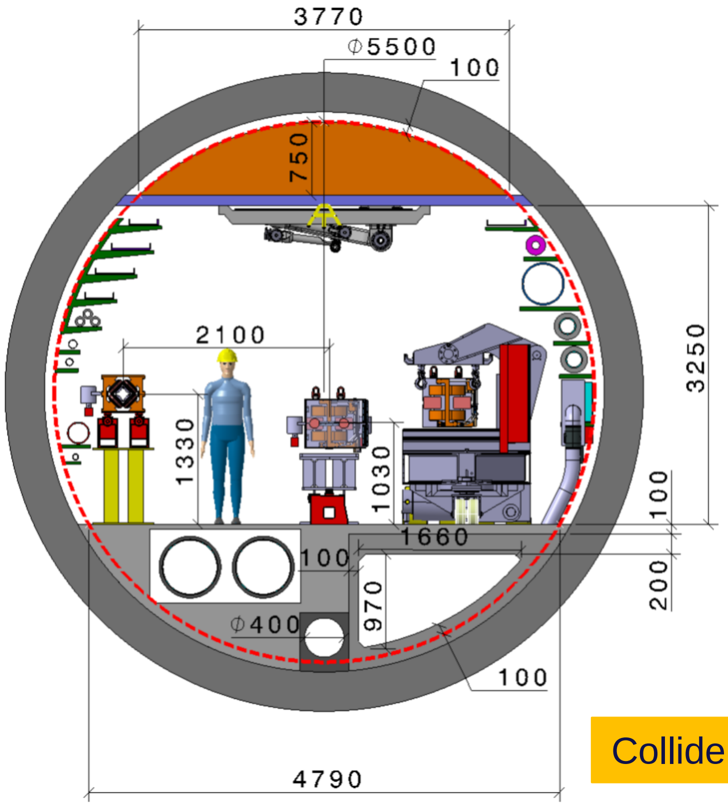

*Booster SSS on top of collider dipoles*

# Tunnel Layout – Horizontal placement booster to collider

*F. Valchkova-Georgieva*

<u>Machine tunnel 5.5m in diameter</u>

- Main ring and booster ring 2.1 m distant
- Demineralized water circuit DN550 in a trench



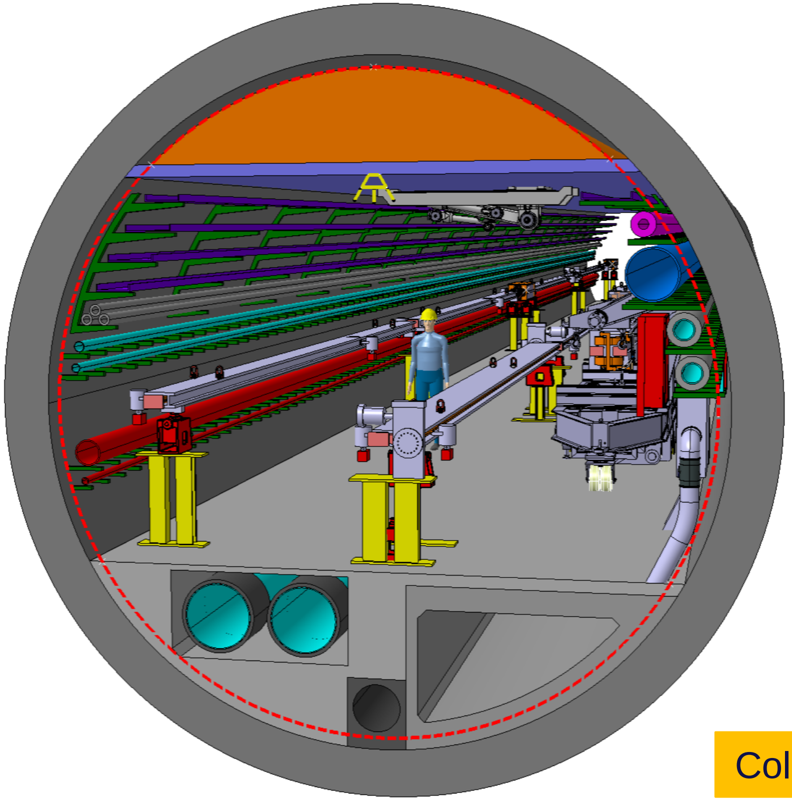

Collider Center

# Tunnel Layout – Horizontal placement booster to collider

*F. Valchkova-Georgieva*

Machine tunnel 5.5m in diameter

**Perspective view**



Collider Center

# Booster-Collider positioning – Inspiration from the past

**Hera DESY**

6.3 km Lepton-Proton rings

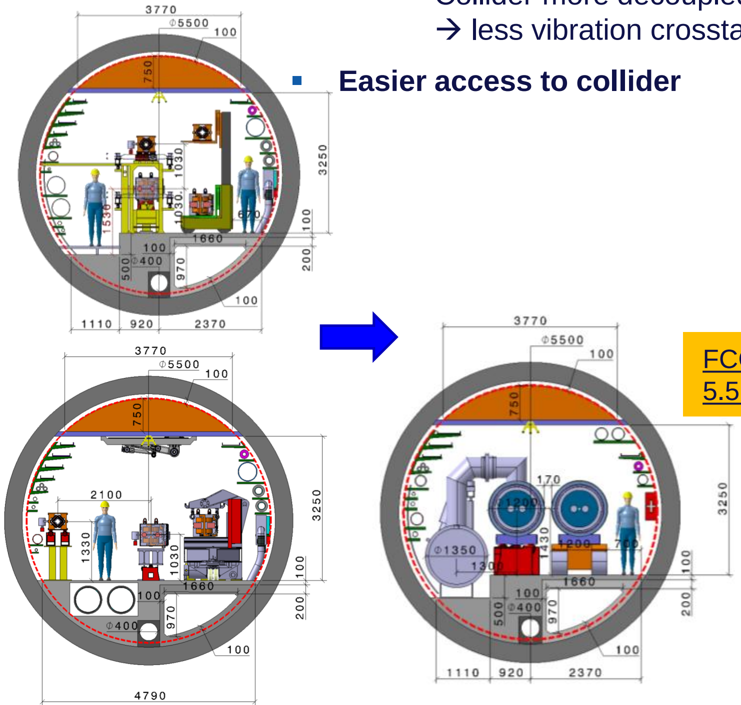
**KEKB, SuperKEKB**

3 km Electron-Positron rings

# Horizontal (wrt Vertical) configuration

## Pros

- **Overall better stability**
  - Less vibrations to the booster
  - Collider more decoupled from the booster → less vibration crosstalk
- **Easier access to collider**



FCC-hh: Machine tunnel 5.5m in diameter

Collider Center

## Cons

- Demineralized **water circuit in trenches** presents complications:
  - Water-induced vibrations to accelerators
  - Lower stiffness of ground close to accelerators
  - Difficult access to valves and connection water pipes DN80 (every some tens of meters)
- **Complex integration of alignment system**, with reduced space for maintenance
- **Imposes larger diameters** to other tunnel regions than arcs (*e.g.* RF 6.8m points L/H vs. 5.5-6.3/6.3m L/H; IP…)
- EN-HE perspective: **more problematic transport and maintenance**.
  - To remove outer ring magnets, necessary to remove inner ring ones, beampipe and survey equipment to gain access
  - Slightly less space for the passage of vehicles
- **Ground adaptation required when moving to FCC-hh**

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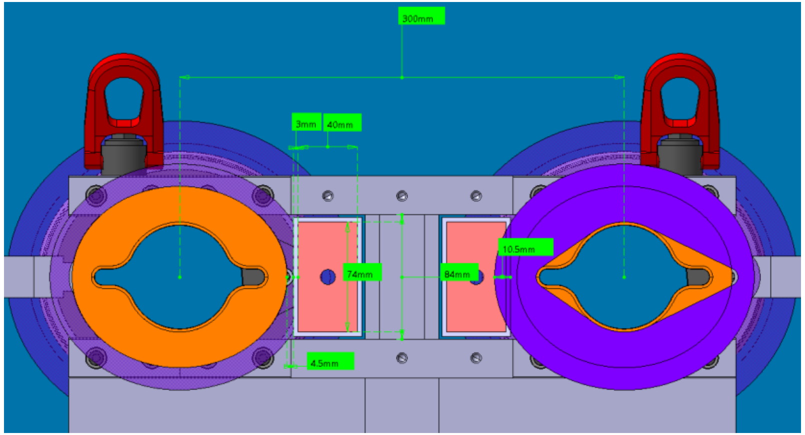
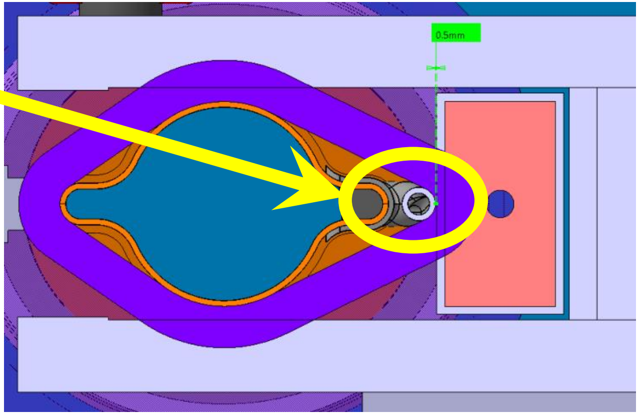
# Collider: e+e- interbeam distance

- Mechanical design study of magnetic & vacuum system and interfaces of collider
  - **Larger space required for SR absorbers** *(water cooling piping and fittings; safety distance to busbar wrt voltage)*
  - Proposed to **increase the inter-beam distance from 300 to 350 mm**



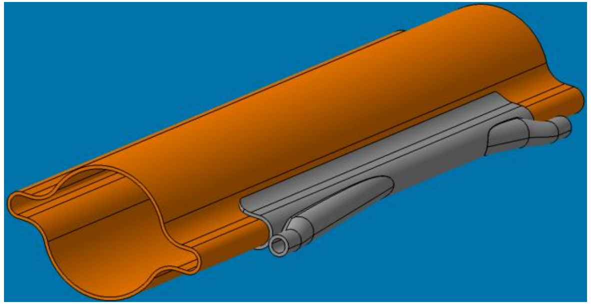

*Dipole cross-section with SMA flanges*

*<u>Conflict</u>:*
*SR absorber - busbar*




*SR absorber integration in dipole*

*Discussed and approved at <u>160th FCC-ee Optics Design Meeting</u>*



*SR absorber*

*C. Tetrault*

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# Short Straight Sections configuration

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

**Collider SSS:**

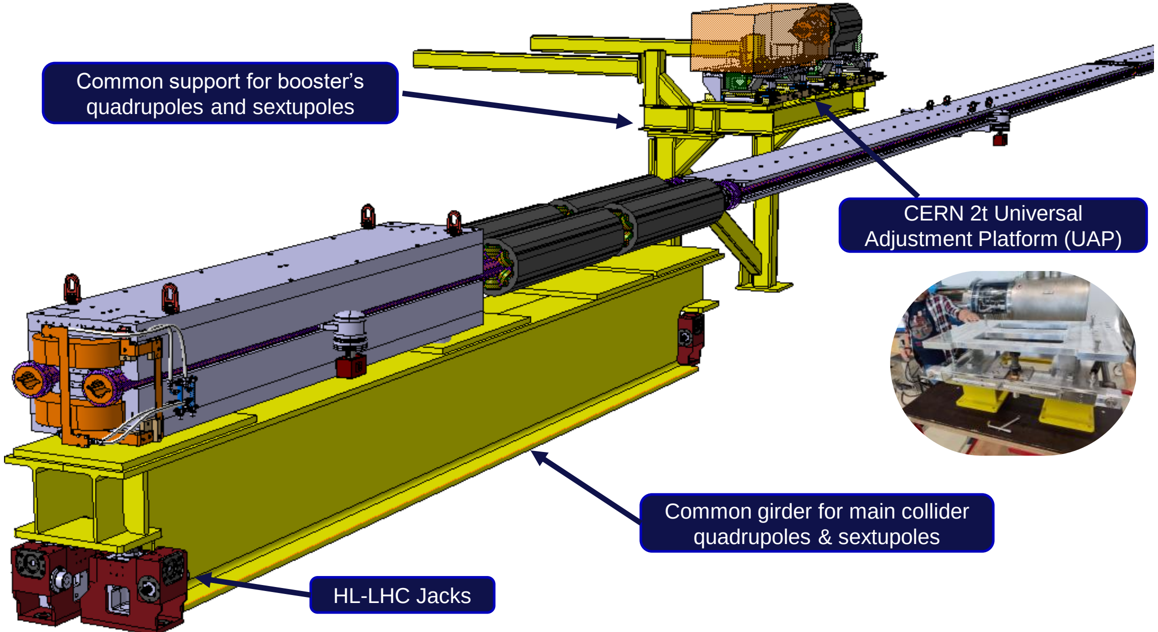
Quadrupole weight: ~5300 Kg.

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

Total: ~8020 Kg

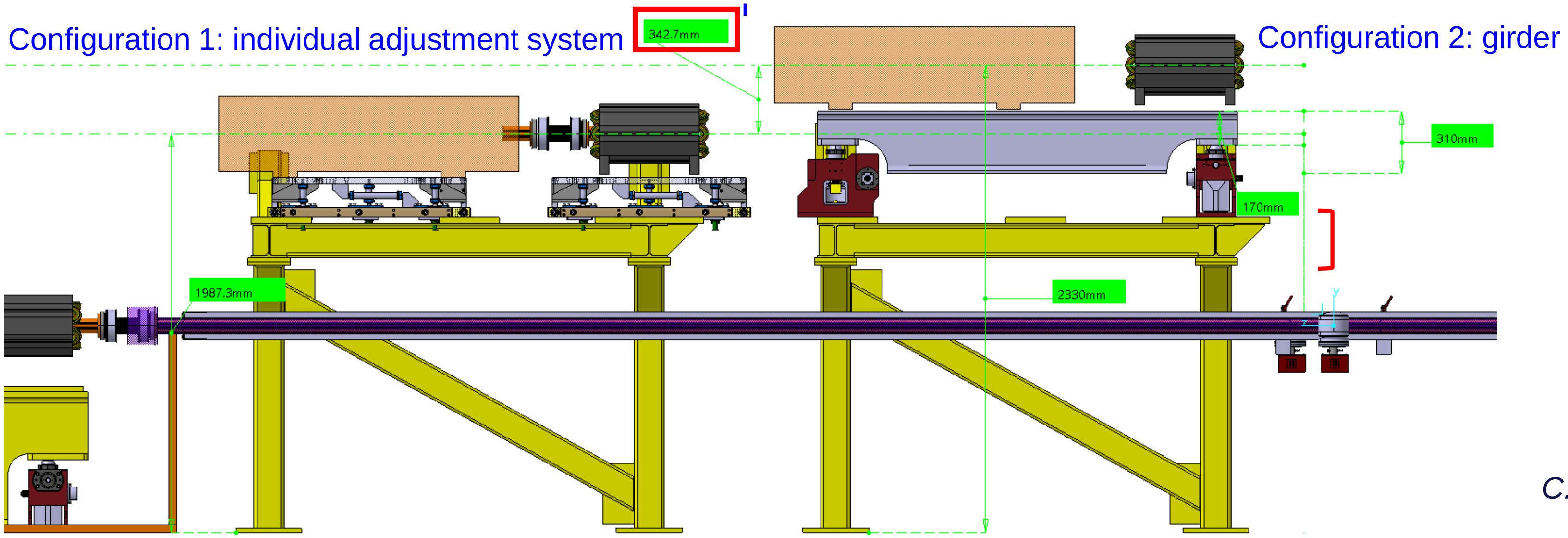
Preliminary girder weight: ~3000 Kg
Girder: 650 mm x 720 mm x 6500 mm

*C. Tetrault*



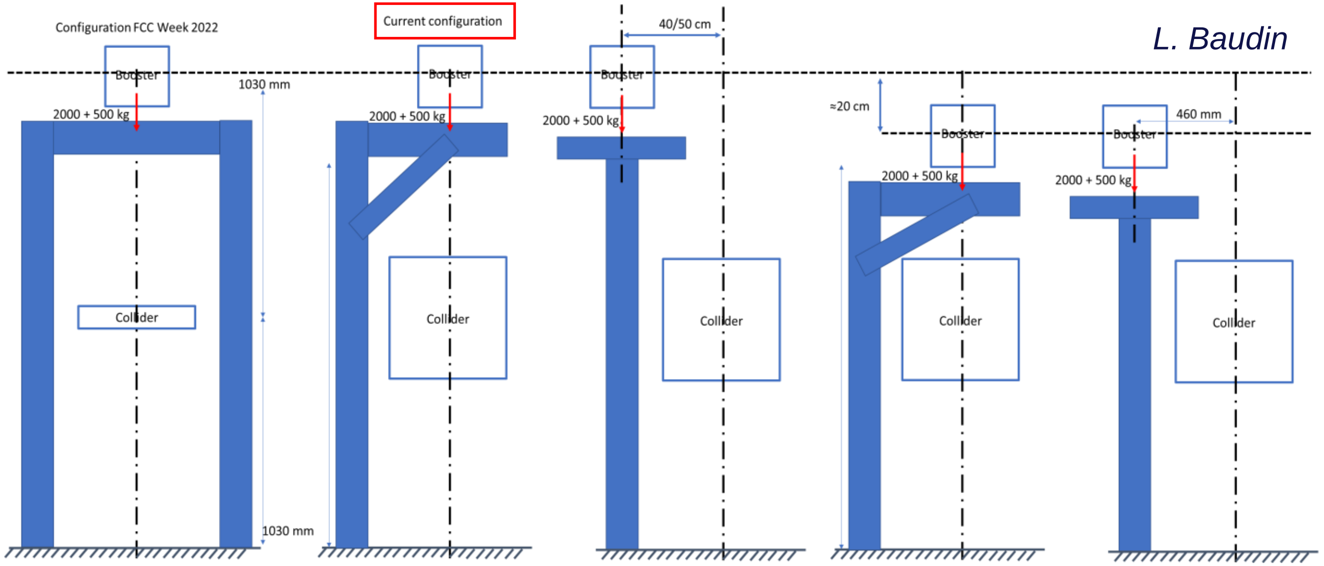
# Short Straight Sections configuration

- Booster SSS supports, two preliminary configurations:




C. Tetrault

# Booster support – design iterations



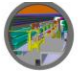

Collider Center

- Proposals to allow compacting/stiffening the booster to collider placement discussed and approved at the Arc Half-Cell mock-up meeting, at the Accelerator Pillar meeting and at the FCC-ee Optics Design Meeting

# Booster (and collider) stability: functional spec

- Draft version collecting outcome of several discussions with Tor, Frank, Katsunobu, Antoine, Barbara, Michael G., etc. link

FCC



## ARC HALF-CELL

## SPEC & REQUIREMENTS

F. Carra, L. Baudin *with inputs from the Arc half-cell project members, Accelerators & Technical Infrastructures Pillars*



## Alignment & Stability – Collider Regular Arcs

| Type | ΔX (μm) | ΔY (μm) | ΔPSI (μrad) | ΔS (μm) | ΔDTHETA (μrad) | ΔDPHI (μrad) | Field Errors |
|---|---|---|---|---|---|---|---|
| Arc quadrupole* | 50 | 50 | 300 | 150 | 100 | 100 | $\Delta k/k = 2\times10^{-4}$ |
| Arc sextupoles* | 50 | 50 | 300 | 150 | 100 | 100 | $\Delta k/k = 2\times10^{-4}$ |
| Dipoles | 1000 | 1000 | 300 | 1000 | 0 | 0 | $\Delta B/B = 1\times10^{-4}$ |
| Girders | 150 | 150 | - | 1000 | - | - | - |
| IR quadrupole | 100 | 100 | 250 | 250 | 100 | 100 | $\Delta k/k = 2\times10^{-4}$ |
| IR sextupoles | 100 | 100 | 250 | 250 | 100 | 100 | $\Delta k/k = 2\times10^{-4}$ |

* misalignment relative to girder placement [1]T. Charles, Optics Correction Studies, FCC week 2022.

Translate to **alignment spec**, considering the case of SSS on girders [2]
- Mechanical alignment
  - Girder elements → 20 μm
  - Girders over 200 m → 200 μm
- Beam-based alignment
  - Girders relative positioning → 10 μm

**Stability spec** [3]
- Maximum allowed magnetic centre motion
  - Integrated RMS → 10 nm
  - Ground motion → start with LHC reference EDMS 1399820 [4]
- Relevant frequency range
  - 10 ÷ 100 Hz
  - Orbit feedback, oscillation suppression up to 10 Hz



## References for alignment & stability assumptions


1. *T. Charles, "Optics Correction Studies", FCC week 2022, https://indico.cern.ch/event/1064327/contributions/4887402/*
2. *Preliminary discussions between T. Raubenheimer, H. Mainaud-Durand, L. Baudin, F. Carra, "ArcHalfCellMock-up Meeting - Alignment and girder", 26th October 2022, https://indico.cern.ch/event/1213083/*
3. *K. Oide, "Tolerances for vibration", FCCIS 2021, https://indico.cern.ch/event/1085318/*
4. *M. Guinchard, "Ground motion measurements in LHC accelerator on both sides of CMS experiment - Coherence length measurements", EDMS 1399820, https://edms.cern.ch/document/1399820*
5. *B. Dalena, "Overview on the High Energy Booster", ArcHalfCellMock-up Meeting - Booster #1, 2nd November 2022, https://indico.cern.ch/event/1213096/*
6. *Preliminary discussions L. Baudin and F. Carra with B. Dalena and T. Raubenheimer*




## Alignment & Stability – Booster Regular Arcs

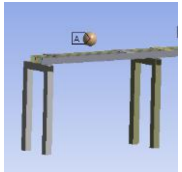
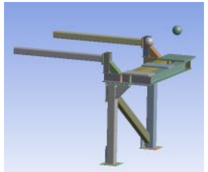
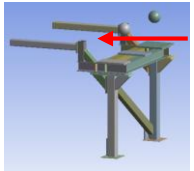
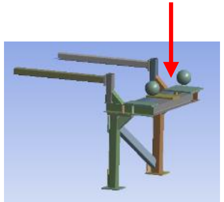
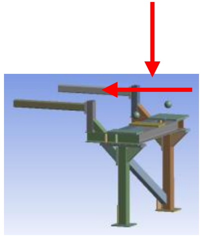
Translate to **alignment spec**, considering the case of SSS on girders [5]
- Similar order of magnitude for mechanical alignment as for collider
- Mechanical alignment
  - Girder elements → 50 μm
  - Girders over 200 m → 150 μm

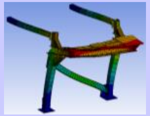
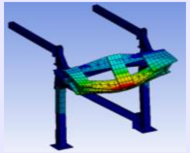
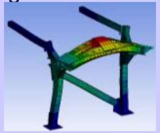
**Stability spec**
- *More relaxed than collider, but not by an order of magnitude (possibly factor 2)* [6]
- Maximum allowed magnetic centre motion
  - Integrated RMS → 20 nm
  - Ground motion → start with LHC reference EDMS 1399820
- Relevant frequency range
  - 10 ÷ 100 Hz
  - Orbit feedback, oscillation suppression up to 10 Hz

*Comment: with booster vertically placed on collider, similar spec in terms of vibration is very challenging!*

# Booster supports – calculations

*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)
- Some room for further improvement but **already a reasonably robust result**
  - PETRA IV girder 46 Hz
  - PSB LIU girder 29 Hz

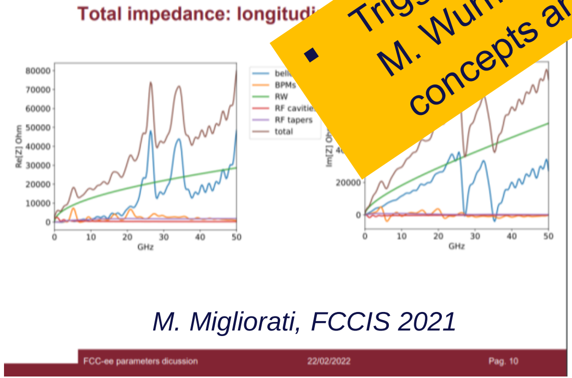
**Next steps**

- 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**

# Recap of girder concept for SSS, pros’ and cons’

## Pros

1. **Pre-assembly and pre-alignment on the surface** leaving in-tunnel connections with bellows at ends: better tools, more space, clean environment
2. **Reduced time** for installation and alignment in the machine
3. **Less bellows**: easier azimuthal integration, important gain in impedance
4. **Single chamber** for elements in the SSS
5. Reduced need for sextupole **beam-based alignment** (weak trims, less BPMs, …)
6. **Easier maintenance of faulty elements** (b on girders)




*M. Migliorati, FCCIS 2021*

## Cons

1. Require **design/mate al/supporting optimization** to prevent higher vibrations, but sol xist:
   - Biologi uctures *à la* PETRA IV (topology optimization Ma ness/mass ratio (*e.g.* polymer concrete)
   - of feet (4-6), alignment with wedges
2. **hardware cost** (collider: ~2000 girders, 15 allpark → 30 MCHF), but to be weighed against:
   - a costs of bellows, flanges and alternative supporting system
   - Possibly shorter (cheaper) overall assembling and alignment time

- Triggered discussions with PSI (J. Wickstrom, M. Wurm) around collaboration on girder/jacks concepts and design

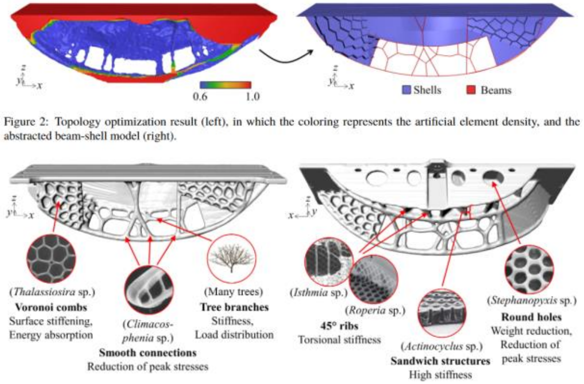



Figure 2: Topology optimization result (left), in which the coloring represents the artificial element density, and the abstracted beam-shell model (right).

*S. Andresen et al., “Innovative and biologically inspired PETRA IV girder design”, MEDSI2020*

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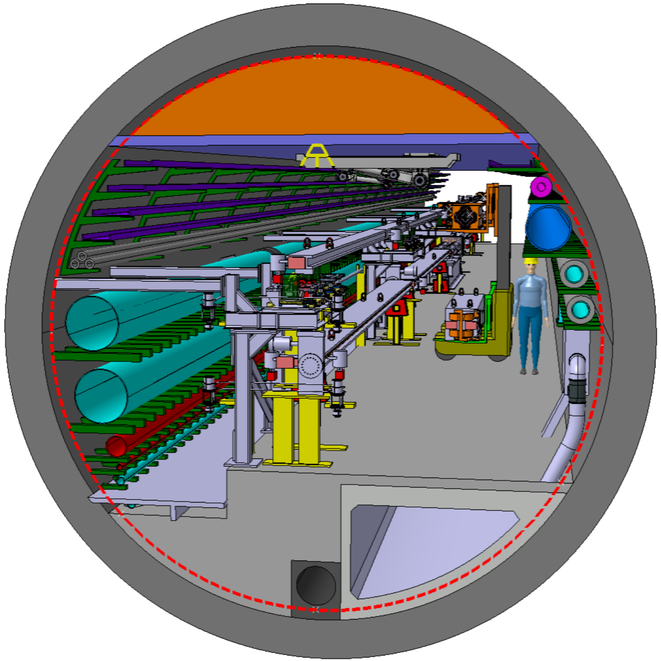
# Arc half-cell mock-up: 1st proposal

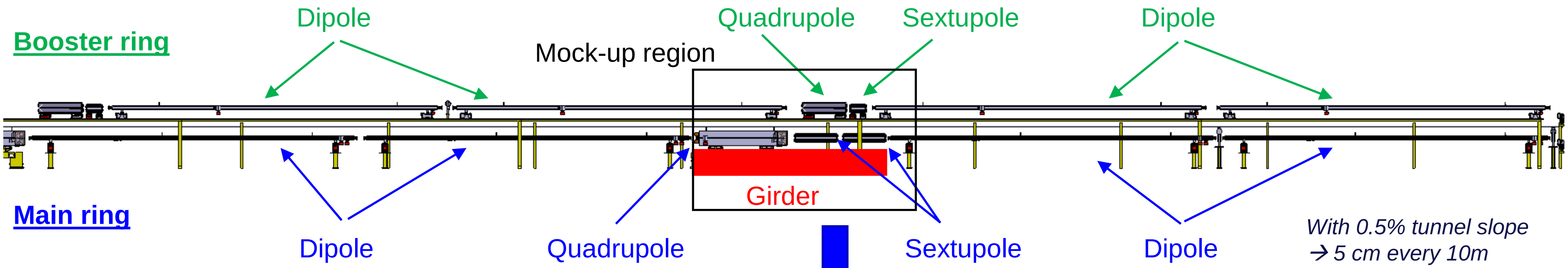
**Objectives**:

- Test different **integration options** in terms of element positioning & supporting
- Test **accessibility to equipment, handling, logistic**
- Test **safety** aspects & procedures
- Test **interfaces and connections** between systems, **mechanical alignment of SSS**
- Benchmark numerical simulations in terms of **rigidity, stability of supporting systems (girder, jacks) and magnets**
- Test **instrumentation systems** (“standard” DAQ, Digital Twins, …)
- Host **prototypes of the main systems** under responsibility of equipment groups
- Better estimation of **costs and technological feasibility** of systems
- Having a **visual and clear representation of a region characteristic of ~90% of the FCC tunnel, in view of the next update of the ESPP**



# Arc half-cell mock-up: 1$^{st}$ proposal

*(example for booster / collider vertical placement)*



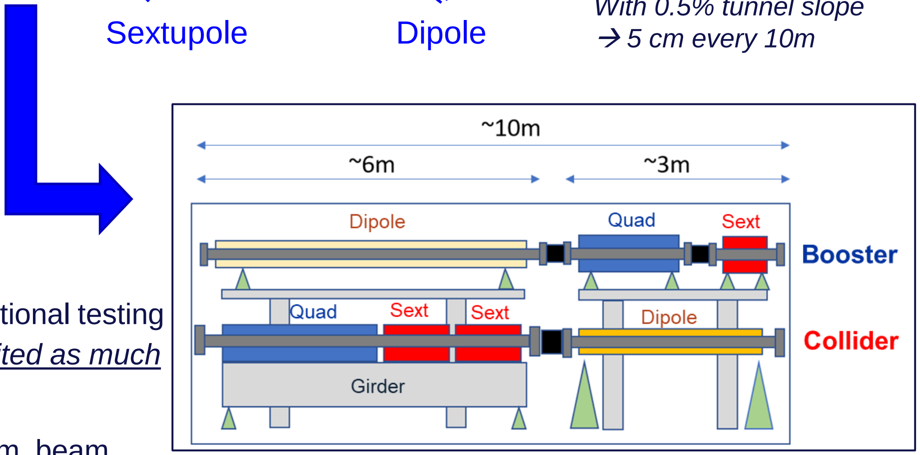

*With 0.5% tunnel slope*
*→ 5 cm every 10m*

**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*

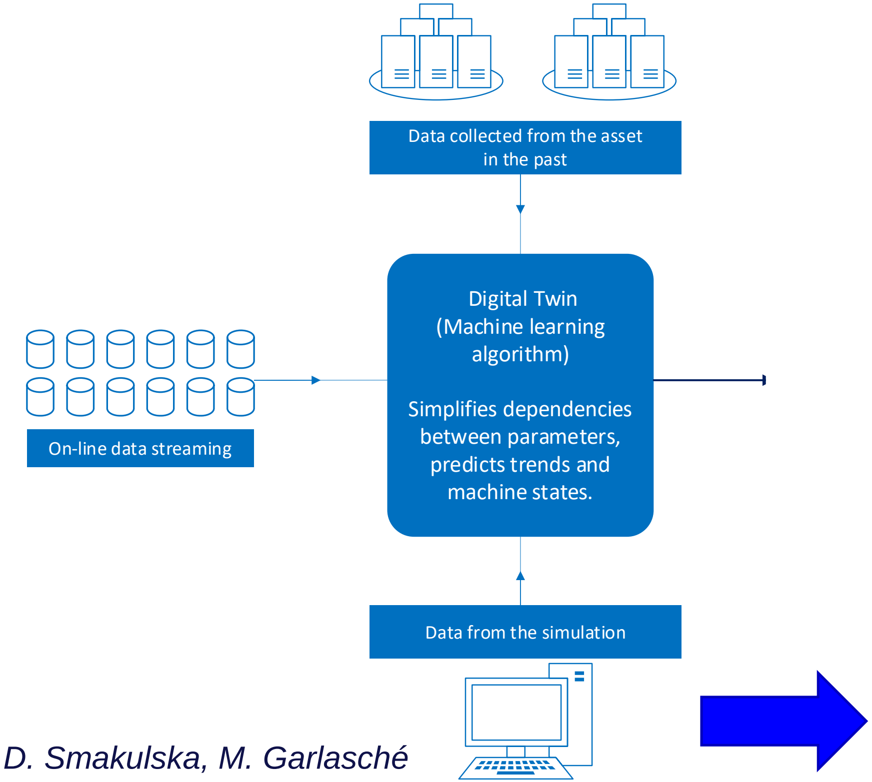
# Novel concepts: Digital Twins

## 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




*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.

# Outline

- Aim of the project
- Project organization & timeline
- Arc cell configuration(s)
- Phase I main studies
  - Integration layout & booster placement
  - Arc systems interfaces & inter-beam distance
  - Accelerators supporting systems & SSS girders
- Arc half-cell mock-up & Novel concepts
- Conclusions

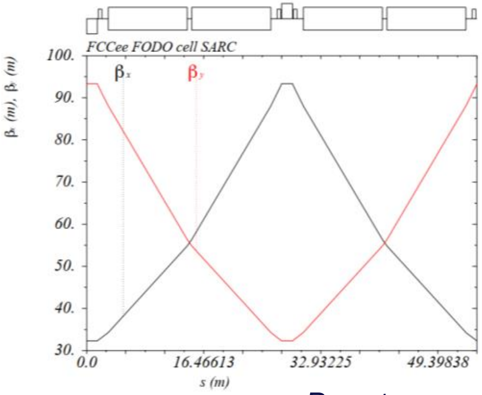
# Conclusions

- 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) focused 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
- **The Phase I, under conclusion, led to important results**, including (but not limited to):
  - Definition of inter-beam distance
  - Design study of magnet and vacuum systems interfaces
  - Optimization of booster and collider supporting frames
  - Study and recommendations on booster-to-collider placement and integration, as well as of supporting concepts for the SSS
  - Proposals for the standardization of the equipment and for the switch from low to high energy
- **Concise summary report** will be prepared in January to document the study
- **A preliminary proposal for a mock-up was discussed**, and will be refined (and costed) once the Phase II is approved
- Discussions for **collaborations** on different tasks are ongoing with University La Sapienza (Rome), University of Malta, PSI, …

# Thank you for your attention.

# Arc cell configuration(s)

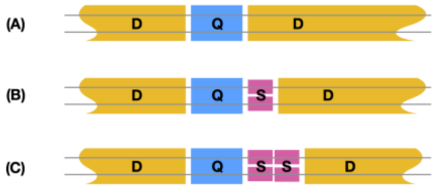
- **Arc half-cell**
  - 1 **Quadrupole**
  - 0, 1, 2 **Sextupoles**
  - Up to ~24 m **Dipoles** (segmented, variable length)




*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*