Accelerator facility for SEEIST

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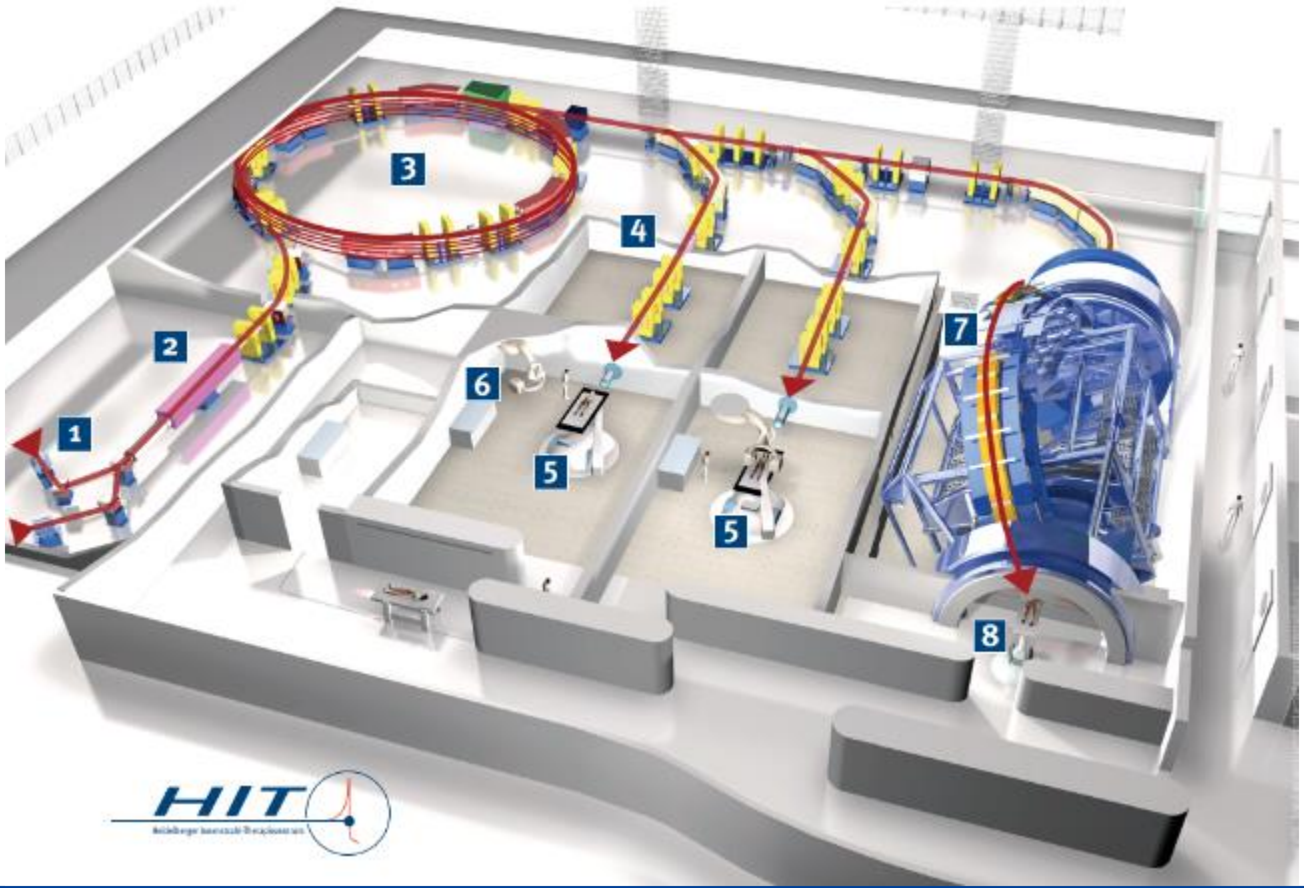
with contributions from S. Sheehy, X. Zhang, (Univ. of Melbourne)

The key element: the accelerator

The new facility will place research and therapy at its focal point - but the particle accelerator remains the key component in terms of cost and performance.



The accelerator system (ion source[1], injector[2], particle accelerator[3], beam lines[4] , gantry[7]) represents **more than 75%** of the construction and operation costs of the facility.

View of the accelerator system of the Heidelberg Ion Therapy center (left) and of its gantry (right)

A new accelerator design, not a copy

Requirements of the ion therapy community, expressed at the Archamps Workshop, June 2018

1. Concentrate on heavy ions (Carbon but also Helium, Oxygen, etc.) because proton therapy is now commercial (4 companies offer turn-key facilities) while ions have higher potential for treatment but lower diffusion.

2. A next generation ion research and therapy accelerator must have:

- ❑ Lower cost, compared to present;
- ❑ Reduced footprint;
- ❑ Lower running costs;
- ❑ Faster dose delivery with higher beam intensity or pulse rate;
- ❑ A rotating ion gantry;
- ❑ Operation with multiple ions (for therapy and research).

An innovative design:

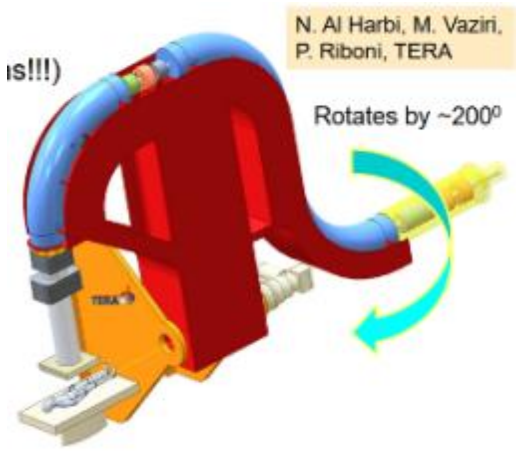
- Can attract a wide support from the scientific community;
- Can increase the exchange SEE-WE and inside SEE thanks to stronger collaboration on scientific and technical issues;
- Can bring modern high technology to the region, with new opportunities for local industry and scientific institutions.

+ Specific requirements for SEEIIST:

- ❑ Easy Industrialization
- ❑ Reliability
- ❑ Simple operation
- ❑ Reduced risk
- ❑ Acceptable time to development

New technologies for future ion therapy accelerators

1. **Improved multiturn injection for higher intensity** 2 x 10^{10} ppc, 20 times higher than HIT or CNAO.
2. **New linac injector design** at higher intensity, higher energy (10 MeV/u) and higher frequency (325 MHz).
3. **New lattice** with intermediate number of magnets between CNAO (16) and HIT (6).
4. **Combined slow and fast extraction** to test new treatment modalities and to extend the experimental programme.
5. **Superconducting gantry -** different options to be compared for a modern superconducting gantry.
6. **Superconducting accelerator magnets** can bring smaller dimensions and lower cost.



TERA superconducting gantry proposal

CERN LHC superconducting magnet

The SEEIIST innovation path

Timing strategy:

- Innovations require time to development and present risks.
- SEEIIST must be ready to start construction at any moment and operate reliably.

Solution: Start from a conservative PIMMS-type design, progressively update to more sophisticated designs

	2020	2021	2022	2023	2024
Injection	DLR Ph1				
Linac		HITRIplus			
Lattice		DLR Ph2			
Extraction	DLR Ph1				
SC gantry		CERN/CNAO coll., HITRIplus			
SC magnets			HITRIplus		ARIES

Pre-TDR

TDR

Updated TDR

* Decision on technology (warm/cold)

DLR Ph.1: SEEIIST EC support contract 1

DLR Ph.2: SEEIIST EC support contract 2

HITRIplus: EC Integrating Activity for ion therapy

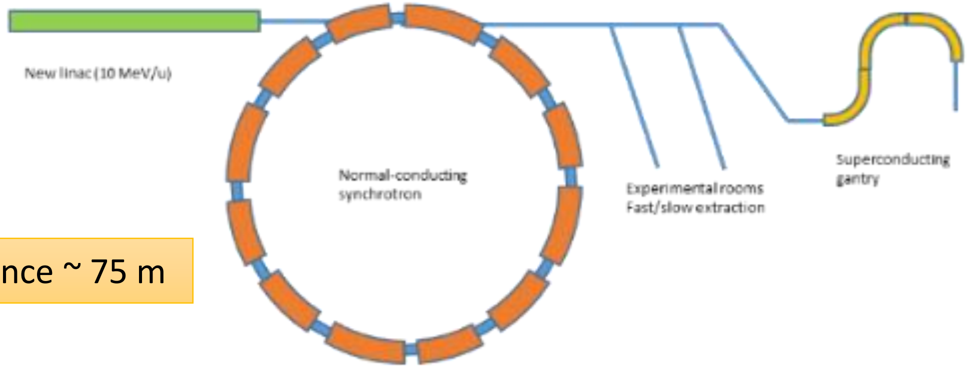
CERN/CNAO/MEDA/INFN gantry collaboration

ARIES: EC Innovation Pilot for accelerator technologies

A Strategy for SEEIIST

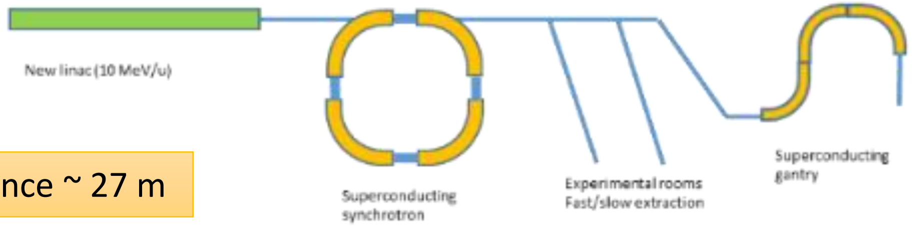
A two-stage approach: develop an innovative synchrotron design employing standard magnets, and develop superconducting magnets that could replace the standard ones

Phase 1
(TDR in 2021)



Ring circumference ~ 75 m

Phase 2
(TDR in 2023)



Ring circumference ~ 27 m

Innovations

- 2 x 10^{10} carbon ions per pulse
- Fast / slow extraction
- New linac at 10 MeV/u
- Superconducting gantry
- Multiple ion operation

As above, plus

- Superconducting magnets for the synchrotron

Additional features:

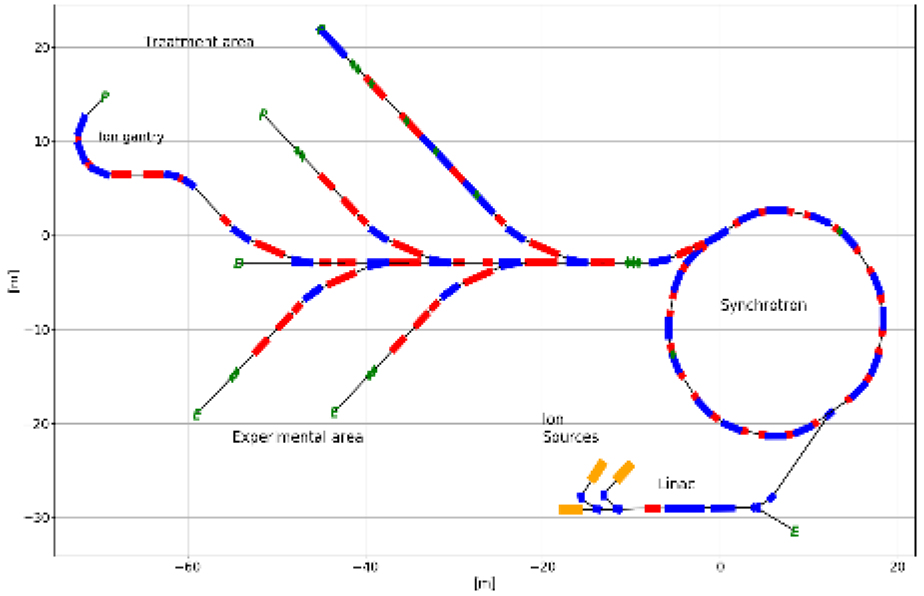
- Upgradability
- Flexibility
- Industrialization

Synchrotron parameters

Particle after stripping		p	$^{4}He^{2+}$	$^{12}C^{6+}$	$^{16}O^{8+}$	$^{36}Ar^{16+}$ (*)
Energy	MeV/u			7		
Magnetic rigidity at injection	Tm	0.456	0.91	0.91	0.91	1.03
Extraction energy range (**)	MeV/u	60 – 250 (1000)	60 – 250 (430)	100 - 430	100 - 430	200 – 350
Magnetic rigidity at highest energy (for therapy)	Tm	2.42	4.85	6.62	6.62	6.62
Maximum nominal field	T			1.5		
Maximum number of particles per cycle		$2.6 \cdot 10^{11}$	$8.2 \cdot 10^{10}$	$2 \cdot 10^{10}$	$1.4 \cdot 10^{10}$	$5 \cdot 10^{9}$
Ramp rate	Tm/s			<10		
Ramp-down time of magnets	s			<1		
Spill ripple, intensity ratio I_{max}/I_{mean} (average on 1 ms)				< 1.5		
Slow extraction spill duration with multi-energy operation	s			0.1 – 60		
Fast extraction	s			10^{-6}		

5 ions (p, He, C, O, Ar only for research)

Intensities scaled for same dose deposition in 1 liter



Superconducting Gantry options

3 options, with increasing complexity in magnet and optics design.

A **collaboration CERN/CNAO/MEDA/INFN** is setting up a committee to analyse the 3T and toroidal options and agree on a common roadmap towards a European gantry design for CNAO, MEDA and possibly SEEIIST.

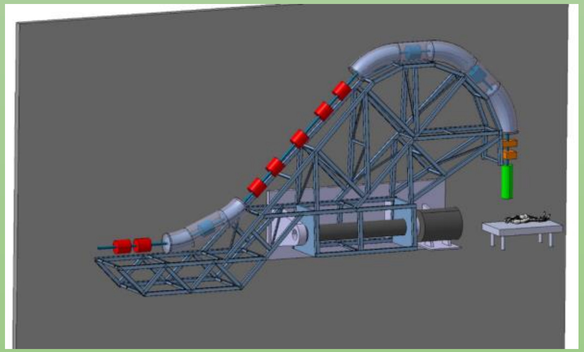
SEEIST is aiming to contribute, and has taken the 3T more conservative options in its baseline design.

3T costheta magnets

200^0 rotation, weight < 30 tons

radius 6.4 m

Mech. concept P. Riboni (TERA), magnet design D. Tommasini, M. Karpinen (CERN), optics E. Benedetto (TERA/CERN/SEEIIST), mechanical design D. Perini, L. Gentini (CERN)



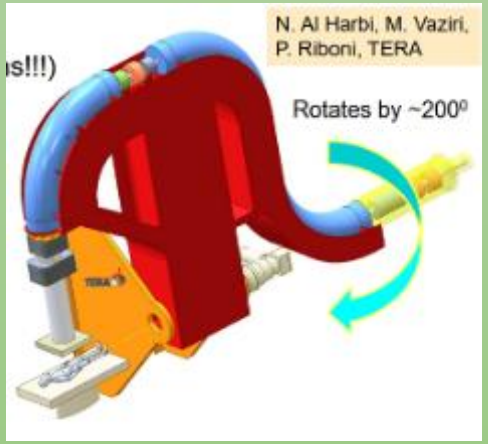
magnets designed, start prototyping

5T CCT magnets

200^0 rotation, weight ~ 40 tons

radius 5 m

Proposed by TERA, requires CCT magnet design and prototyping



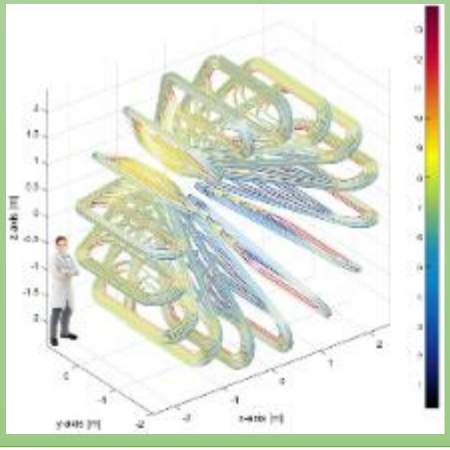
Toroidal

no rotating parts

radius 5 m weight ~ 50 tons

(GaToroid, L. Bottura, CERN)

Requires beam optics design and prototyping



Superconducting magnets

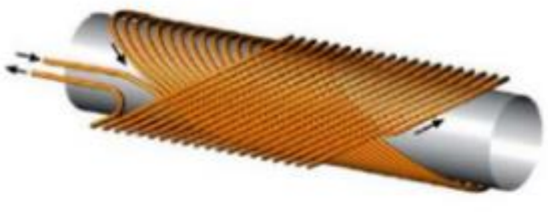
Lucio Rossi, one of the main European experts in superconducting magnets and former project leader of LHC magnet construction and LHC luminosity upgrade, will leave CERN in September and start a new programme for development of high-field pulsed superconducting magnets for medical accelerators at INFN Milano (LASA).

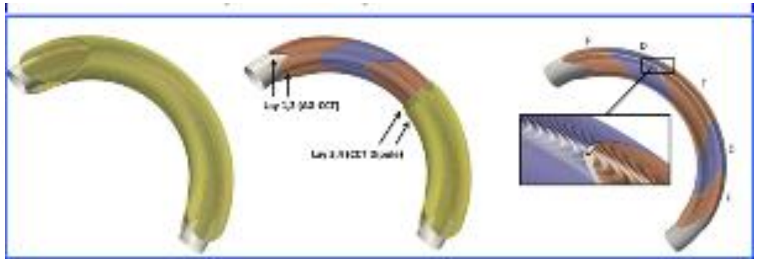
Superconductivity is the key to the progress of accelerators

Eliminates power loss and allows reaching higher fields and smaller dimensions. Now a standard industrial technology with decreasing costs and low risk. New conductors possible, including High Temperature HTS.

Technological roadmap towards new magnet design and prototyping to be developed inside EC funded projects

Canted Cosine Theta (CCT) type magnets, similar to those used in many laboratories, with nested quadrupoles.





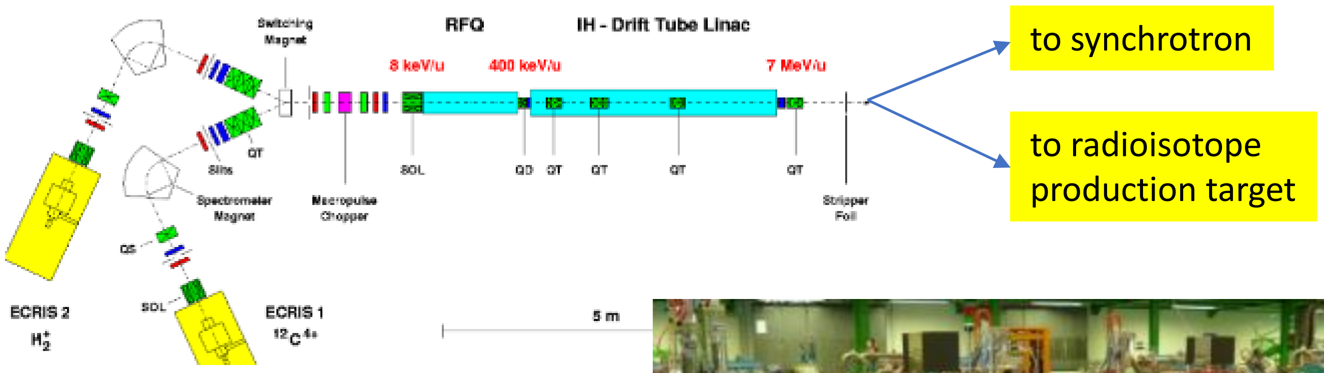
Parameter	Synchrotron HITRI2	Magnet I.FAST (develop.)
Bρ (Tm)	6.6	=
B_0 dipole (T)	3.0	4-5
Coil apert. (mm)	70-90	60-90
Curvature radius (m)	2.2	2.2 , ∞
Ramp Rate (T/s)	1	0.15-1
Field Quality (10^{-4})	1-2	10-20
Deflecting angle	90°	0 - 45°
Alternating-Gradient, fed independently	yes –probably a triplet	N/A
Quad gradient (T/m)	40	40
$B_{quad\ peak}$ (T)	1.54- 1.98	1.2
$B_{peak\ coil}$ (T)	4.6 - 5	5.6-7
Operating current (kA)	< 6	< 5
Type of Superconductor	Nb-Ti (Nb_3Sn)	Nb-Ti (curved), HTS (straight)
Operating temperature K)	[illegible]	[illegible]

Preliminary parameter list – courtesy of L. Rossi

Production of medical radioisotopes at SEEIIST

The SEEIIST facility will have a **new injector linear accelerator** (linac) designed for higher energy (10 MeV/u), with lower cost, higher efficiency and higher intensity.

With a minor additional investment, the linac could have 2 modes of operation: for injection in the synchrotron, and for sending the beam to a target for production of medical radioisotopes.



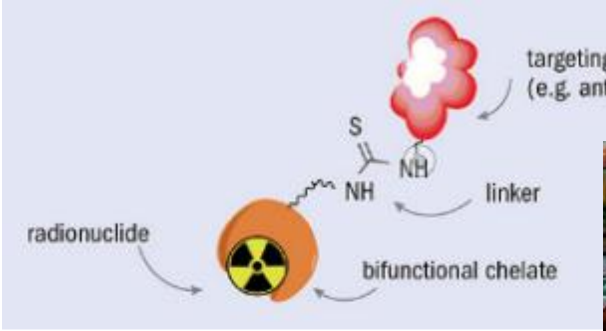
An example: **Targeted Alpha Therapy**

Alpha-emitting therapeutic isotopes: charged atomic nuclei emitting α particles (2 protons+2 neutrons), produced by bombardment of nuclei with an α beam.

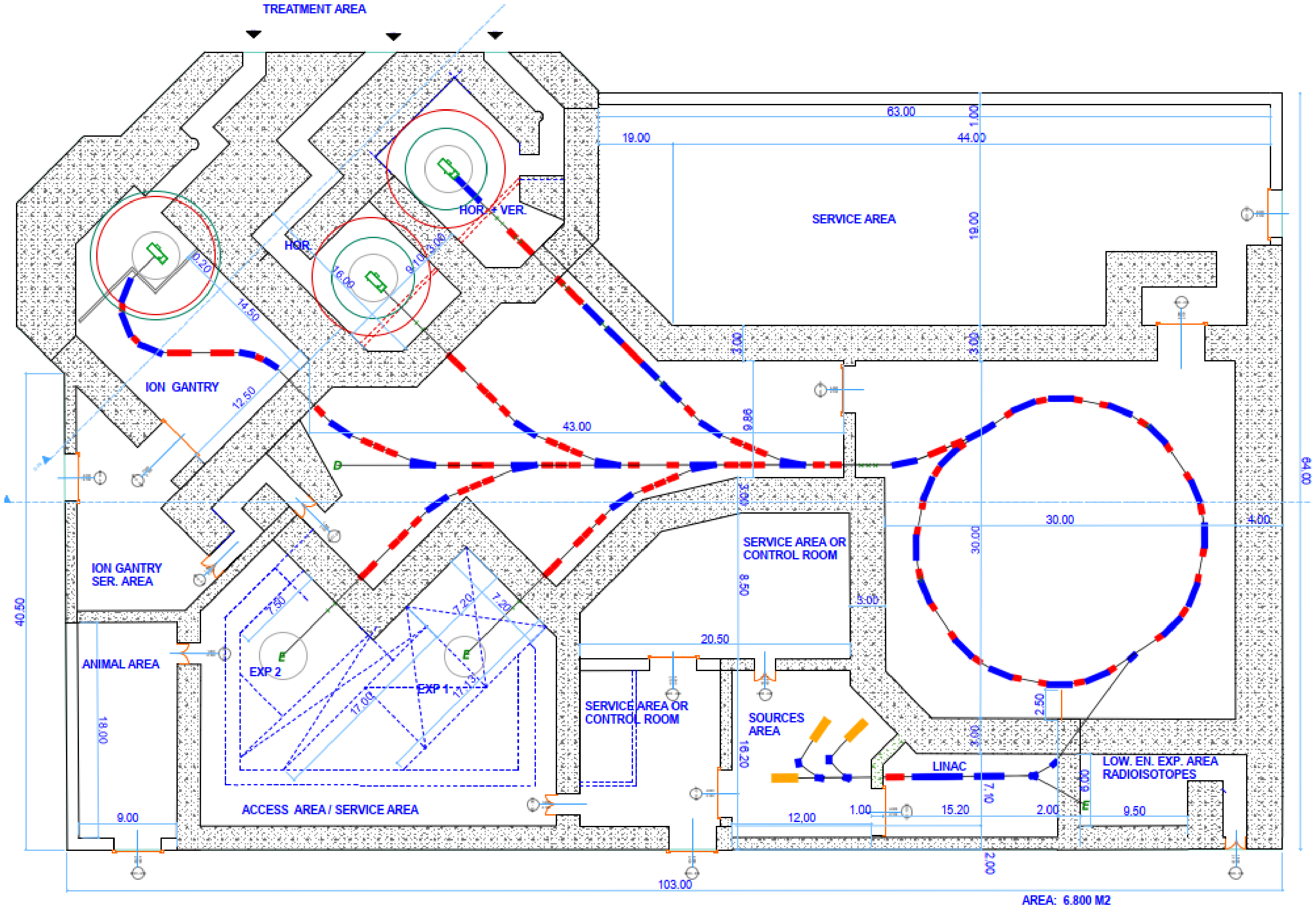
Attached to antibodies and injected to the patient: accumulate in cancer tissues and selectively deliver their dose.

Advanced experimentation going on in several medical centres, very promising for solid or diffused cancers (leukaemia). Potential to become a powerful and selective tool for personalised cancer treatment.

If the radioisotope is also a gamma or beta emitter, can be coupled to diagnostics tools to optimise the dose (theragnostic)



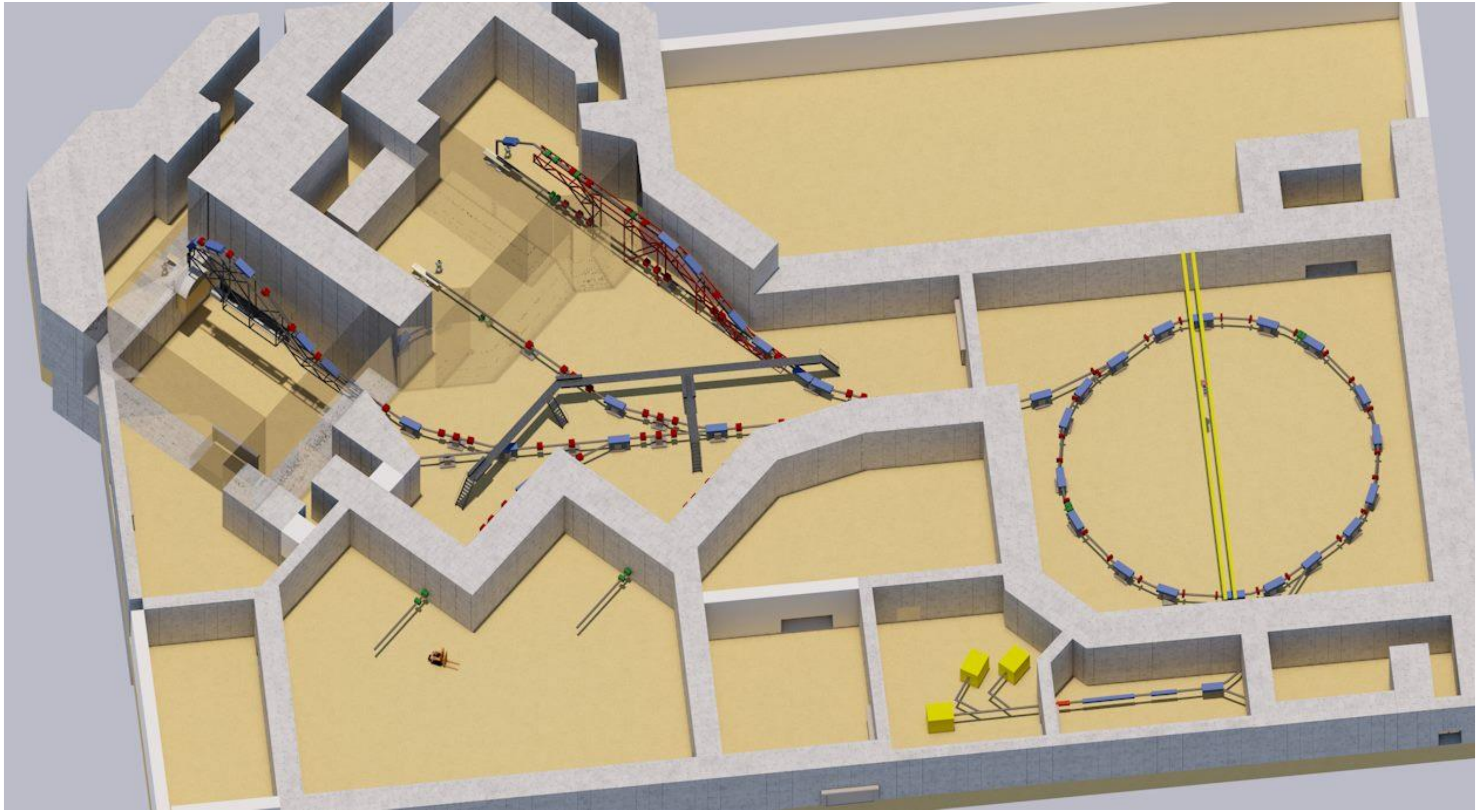
Baseline Layout (warm magnet synchrotron, here PIMMS)



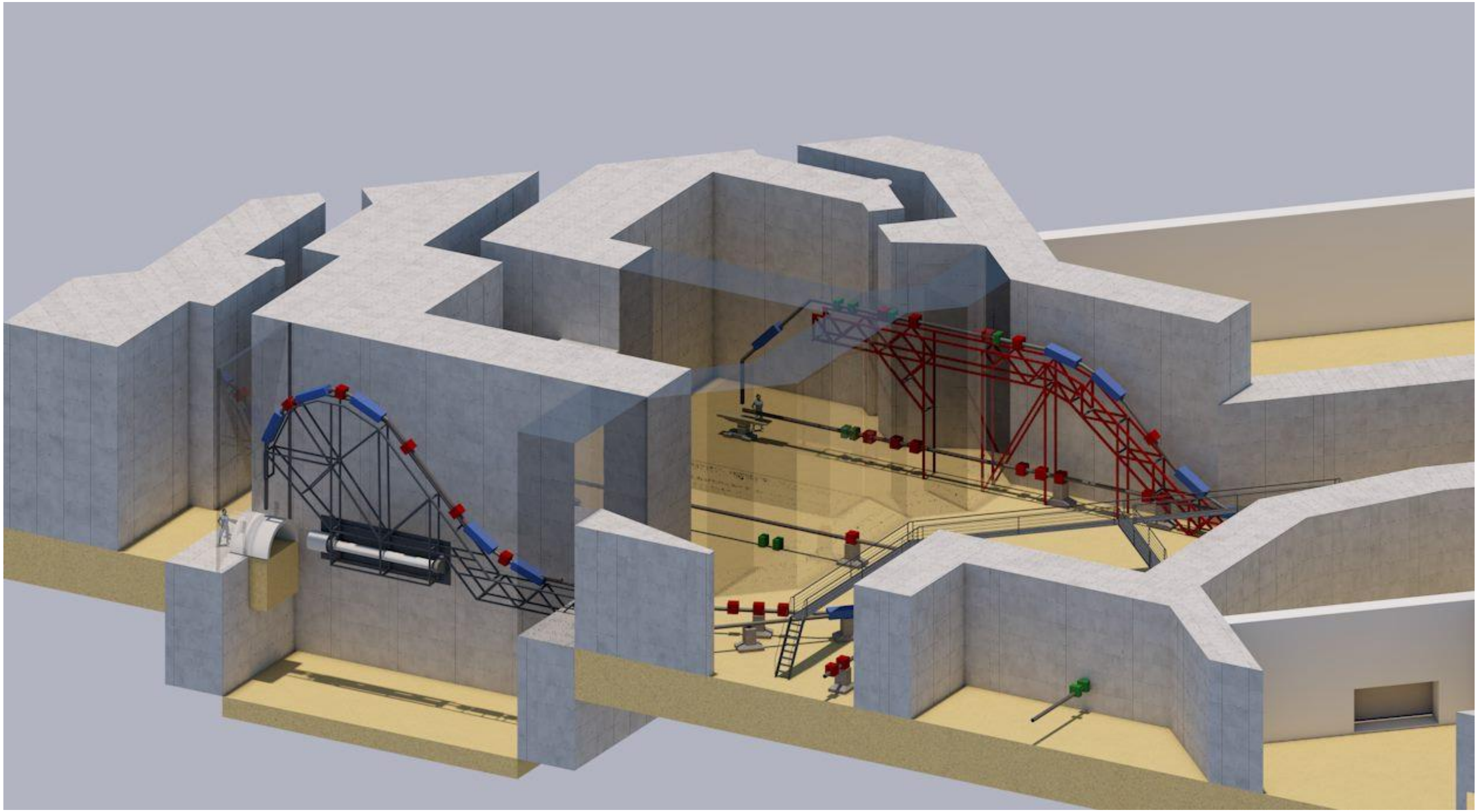
- **Compact layout** (6,800 m2 including service area).
- **Full separation between treatment and experimental area** with separate access: 3 treatment rooms (H, H+V, gantry) on top, 2 experimental rooms at bottom.
- **Reconfigurable experimental rooms** with separate animal area, to accommodate any type of experiment.
- **Low energy area** for experiments and/or production of radioisotopes.
- **Superconducting gantry room** for a 200^0 3T magnet gantry.
- **Configured as a unit** to be integrated into any building design or configuration.

Shielding scaled from existing facilities, precise calculations to be started soon.

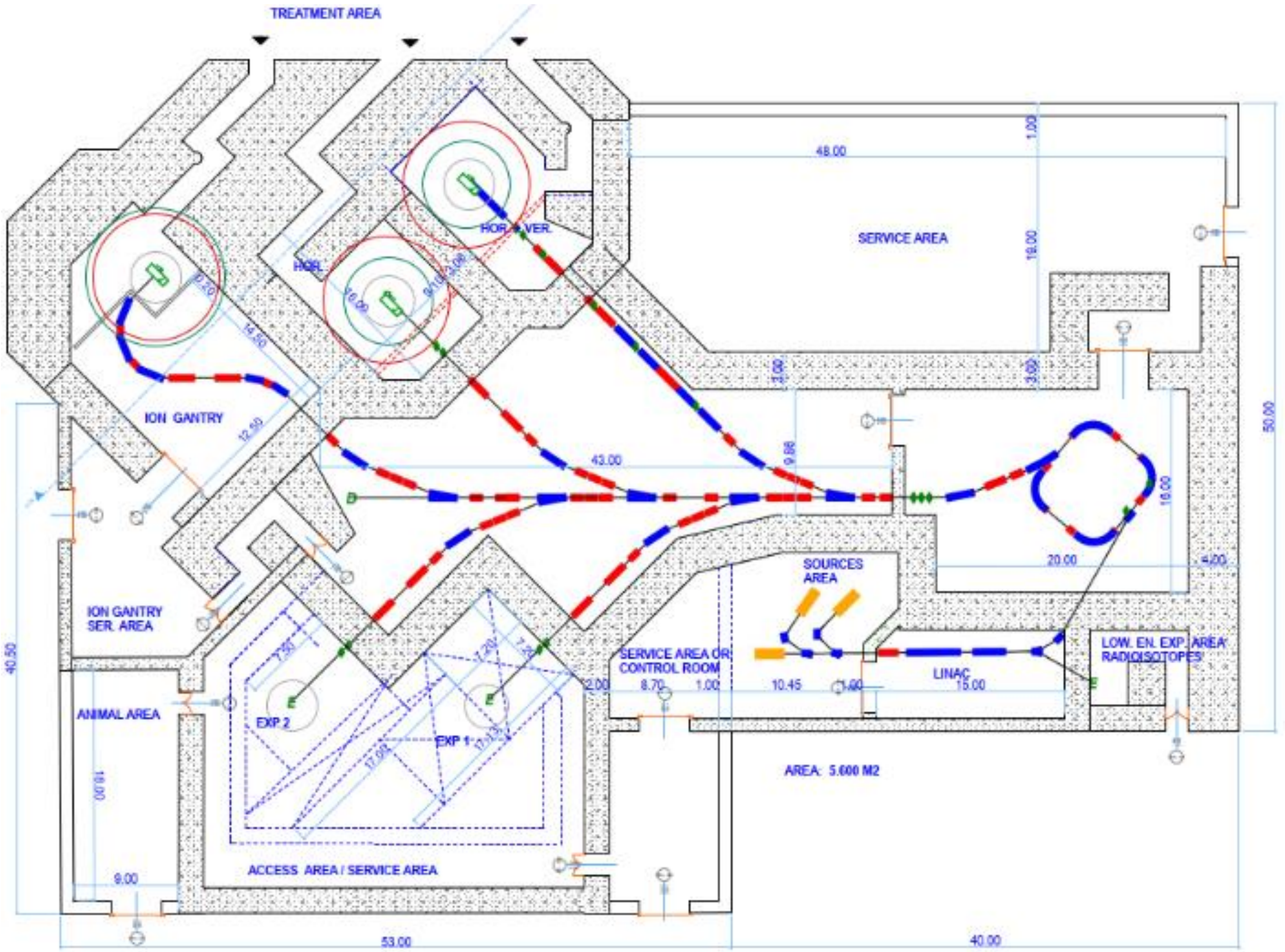
Some more views (from D. Kaprinis, architect)




FUTURE TREATMENT ROOMS

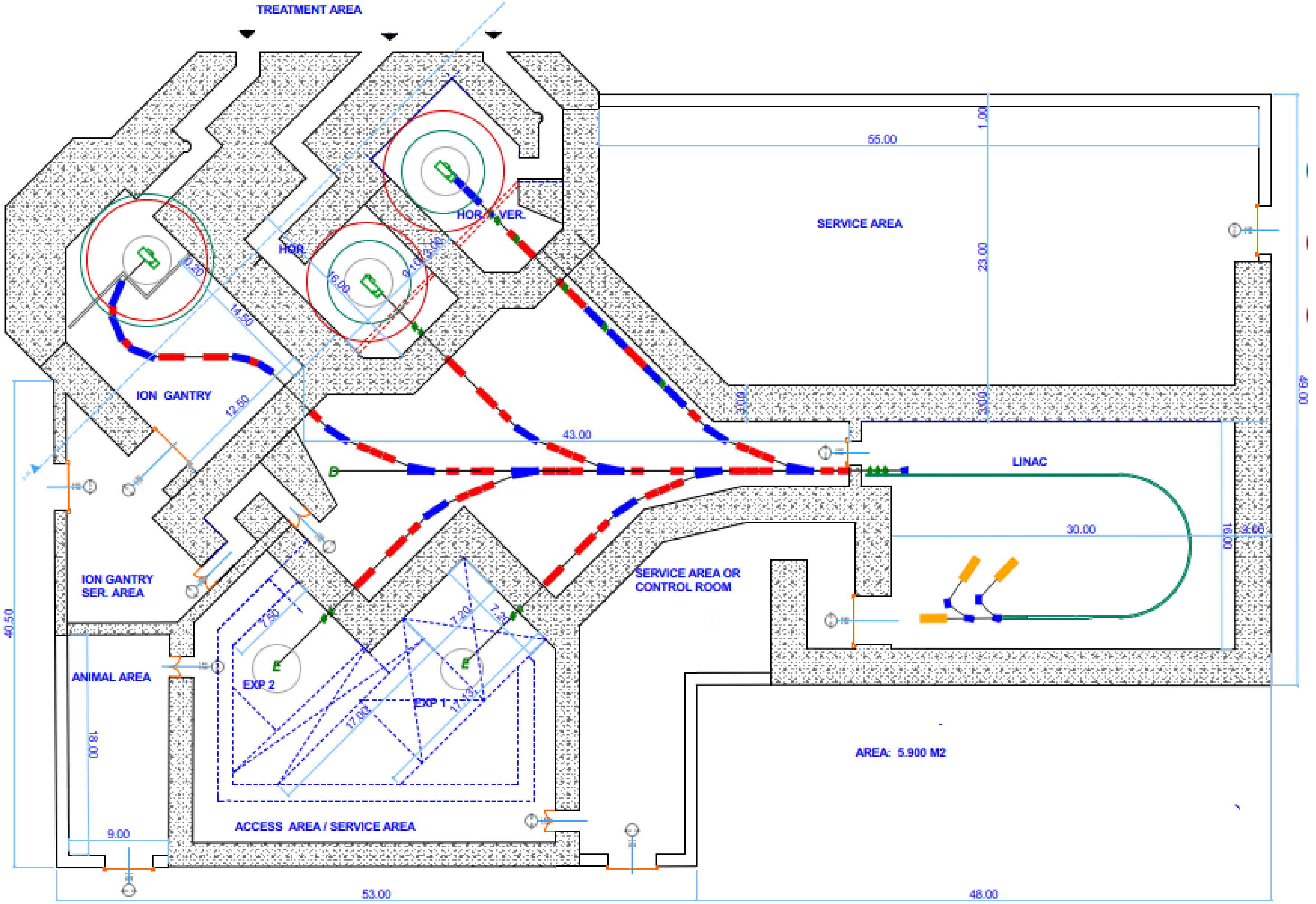


Superconducting option Layout



- **Surface** 5,600 m2 including service area.
- **Reduction of ~ 20 % in overall surface** even though most of surface goes to treatment and experimental rooms and to beam distribution.

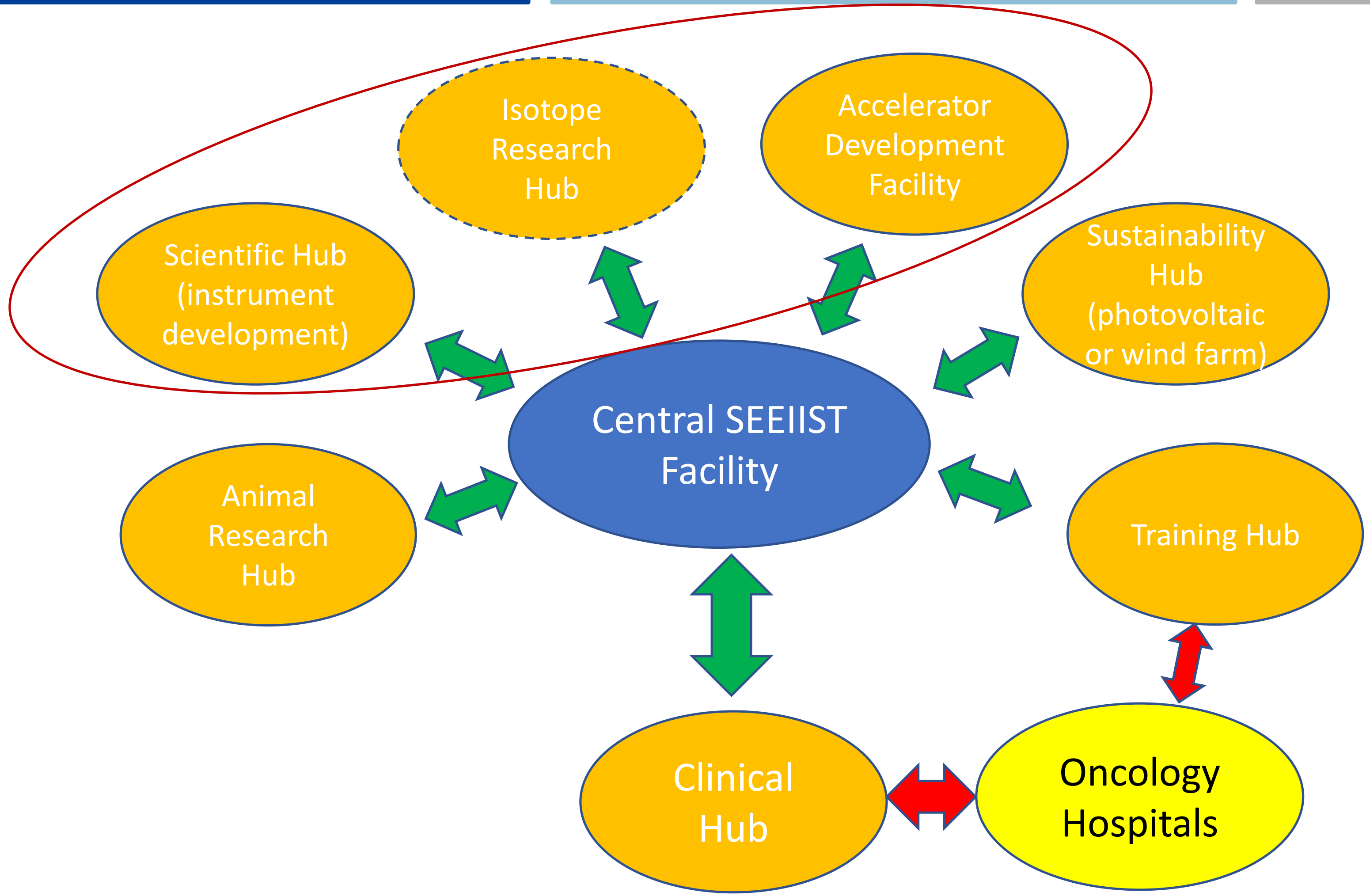
Full linac option Layout



For comparison, an option with a bent 3 GHz linear accelerator going to full energy

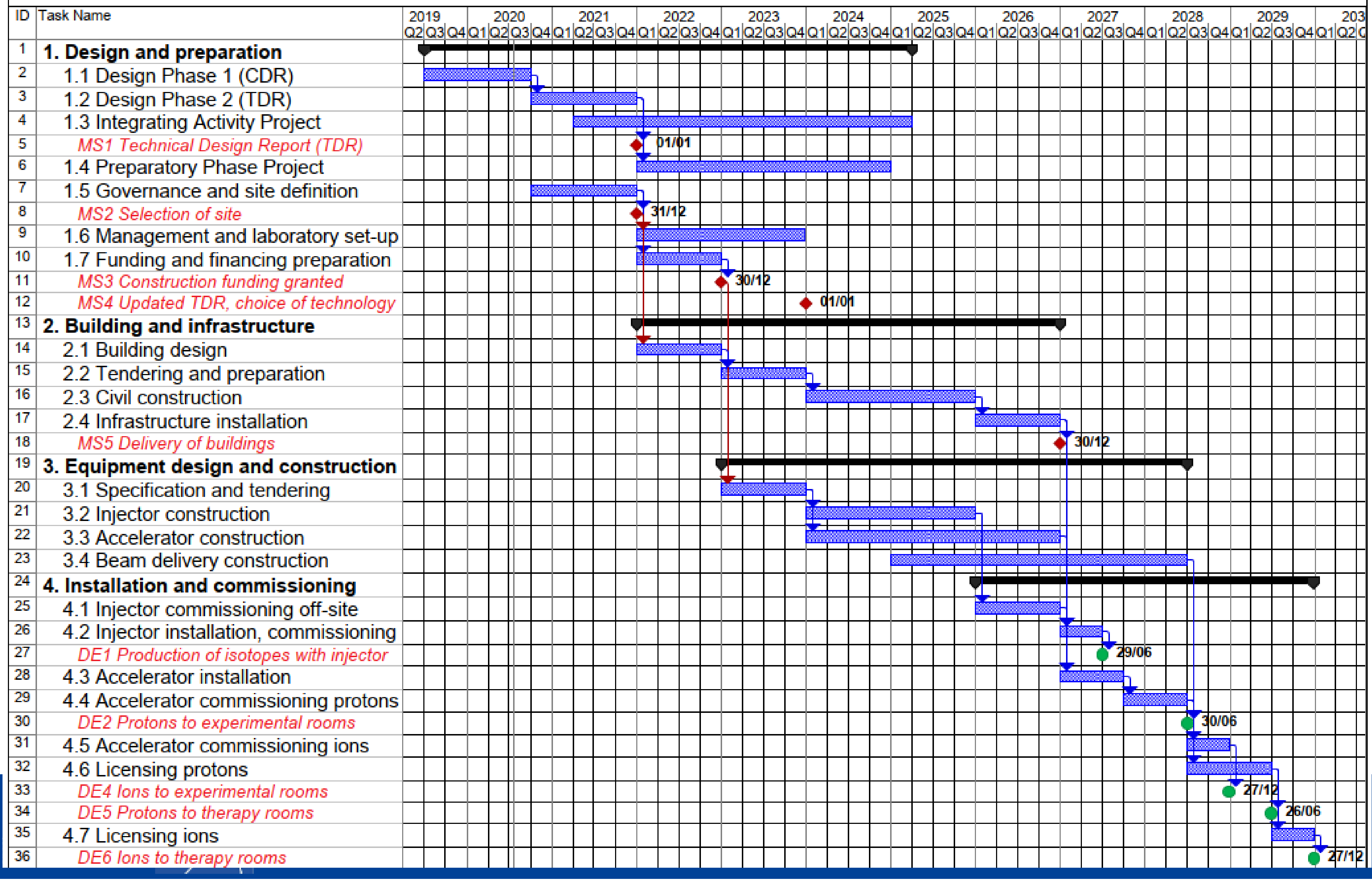
- **Surface** 5,900 m2 including service area.
- **Similar surface reduction** as the superconducting option.
- No access to ion sources during operation, low energy radioisotope area not yet included.

Accelerator as part of the SEEIST distributed facility



7 ancillary facilities, all connected to the main site, can be placed in different countries

Accelerator design integrated in SEEIIST Master Plan



Present plan for ESFRI proposal:

- Accelerator development 2020-2024
- Accelerator construction 2023-2028
- Start of the facility 2027-2029

Conclusions and Outlook

Our goal is to create a community around/for SEEIIST, not only to design an accelerator: develop an ecosystem that will support SEEIIST construction and build in the SEE region the competencies required to construct and operate the facility, involving local capacity at the earliest possible stage.

We are already integrating **SEE students** in our team and we plan to start soon contacting industry.

Priority:
define a flexible and innovative accelerator design strategy, to support the SEEIIST objectives

SEEIIST at the centre of a cooperation network between European accelerator centers, universities and industry.

SEEIIST meets industry Workshop in Sarajevo was unfortunately delayed because of Covid but remains in our agenda.