Hadrontherapy at CNAO, present and future

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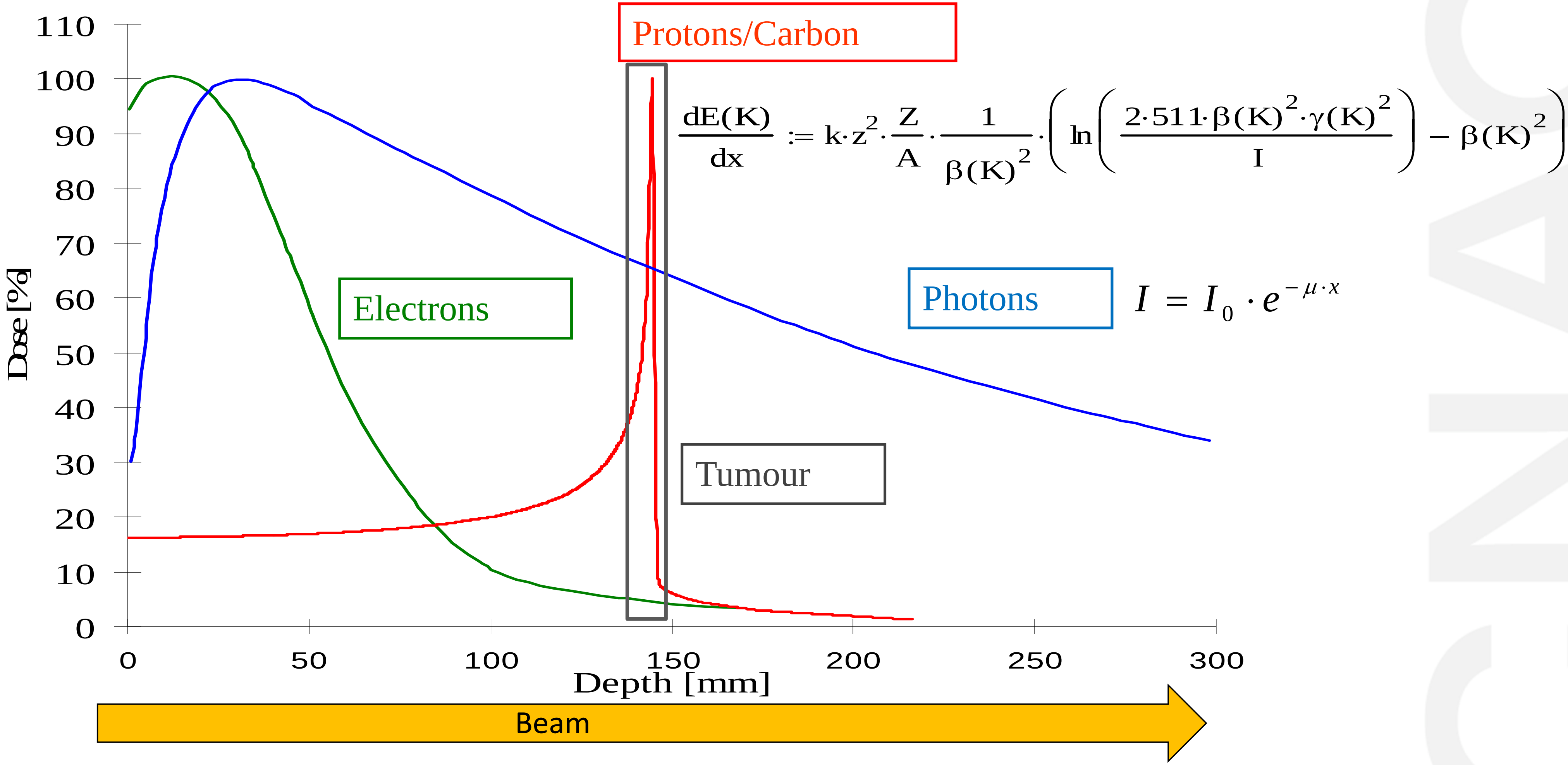
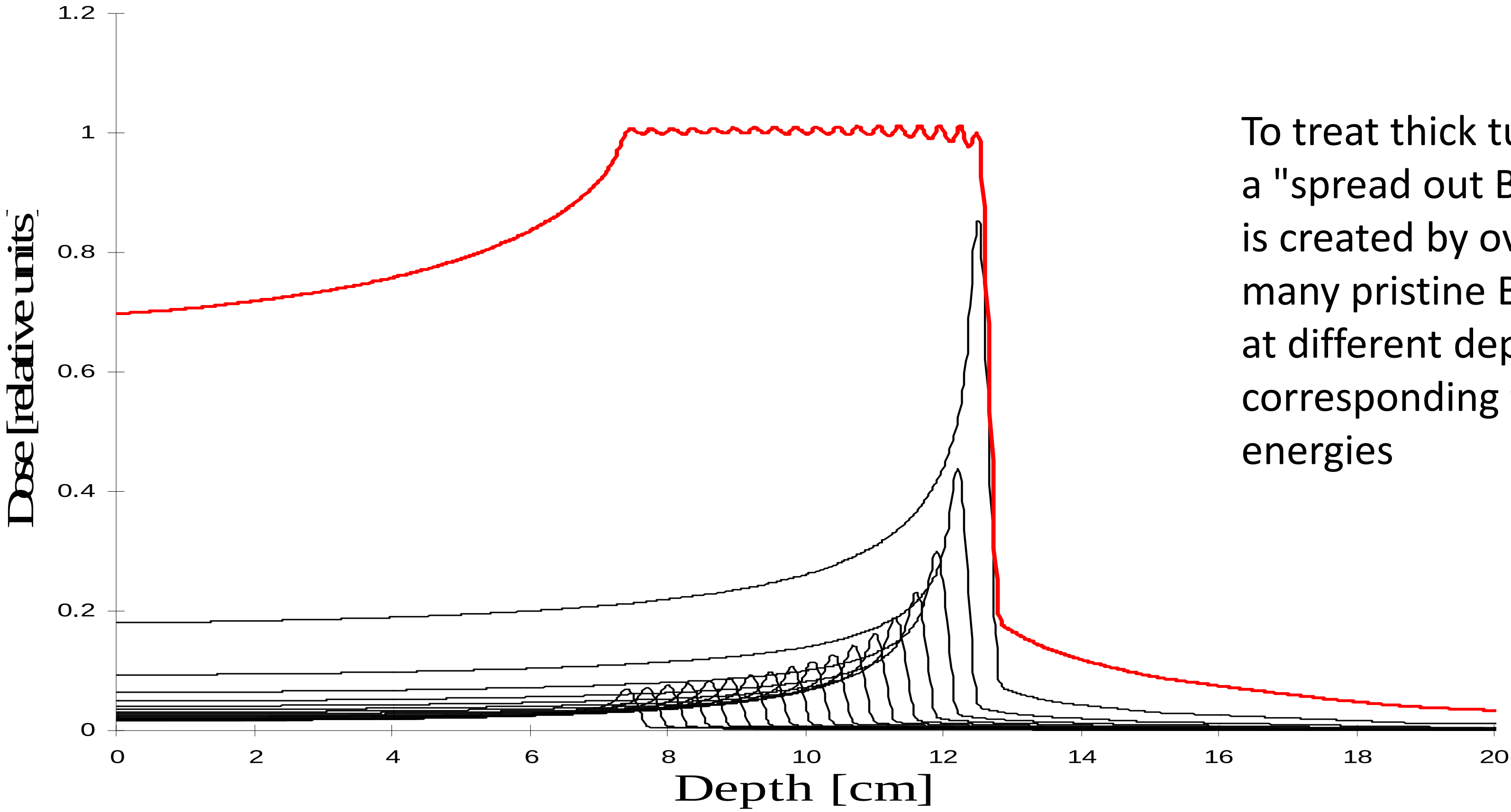
- Introduction to hadrontherapy
- CNAO accelerator overview
- The experimental room
- Developments and upgrades:
  - Third source for new ion beams
  - New proton facility with gantry
  - New facility for BNCT
  - Carbon ion gantry development

Comparison of the depth dose profiles

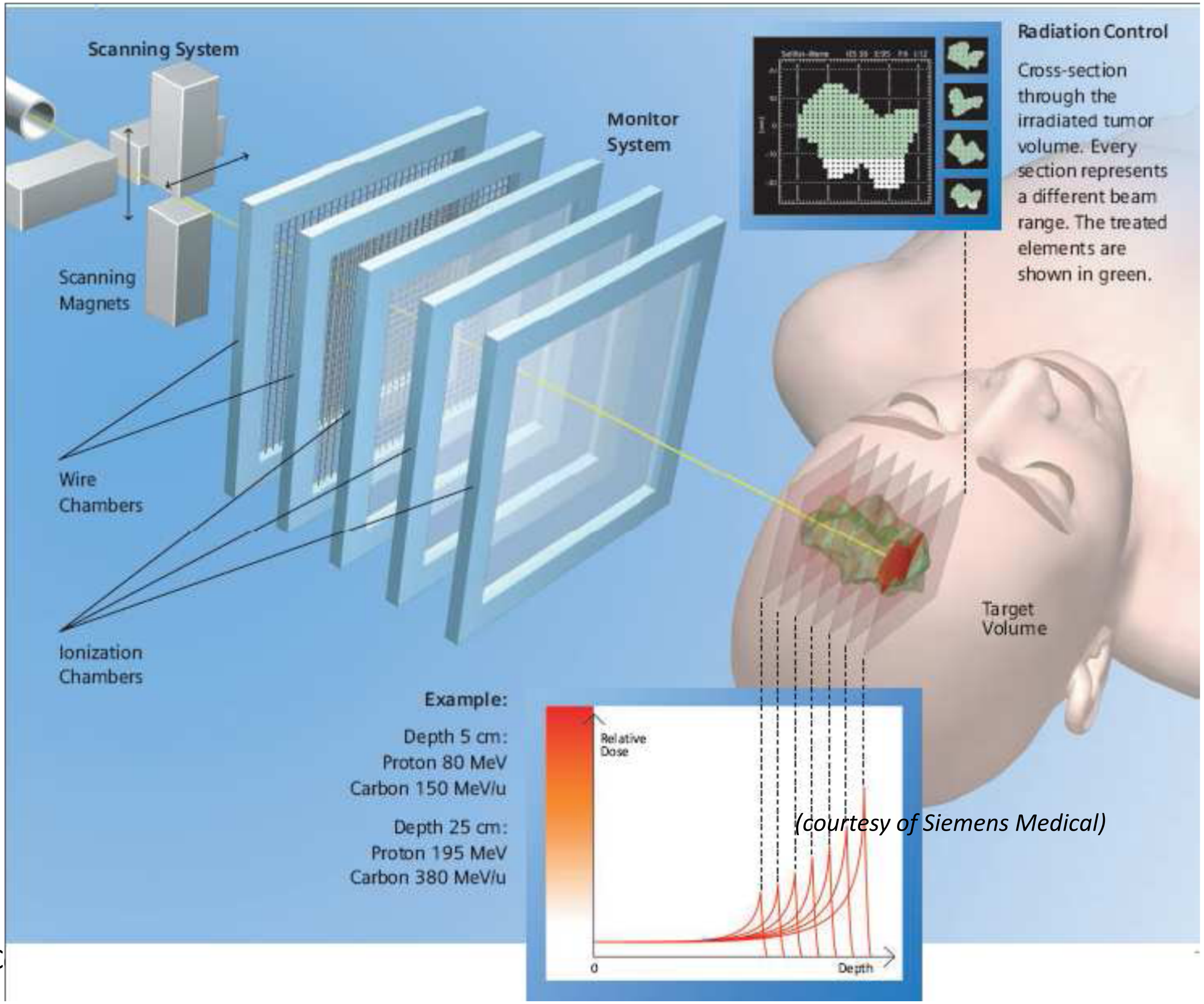


Spread Out Bragg Peak



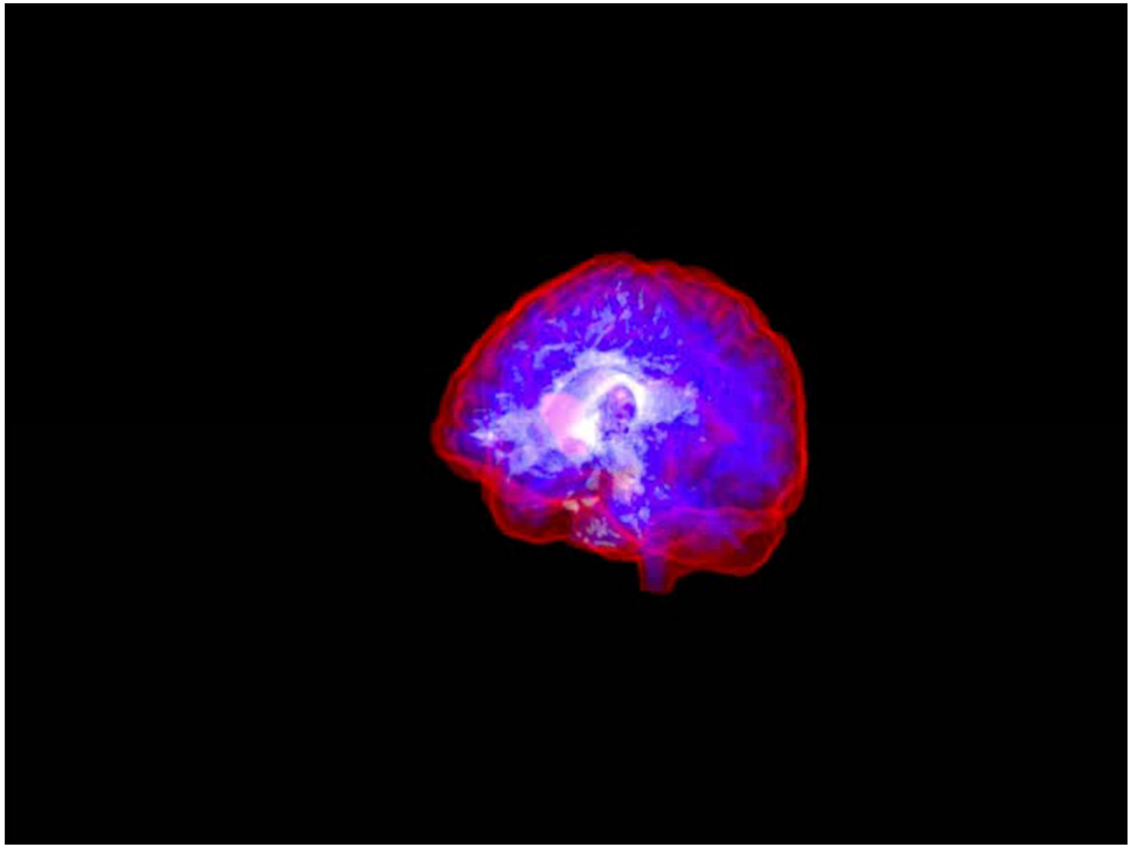
To treat thick tumours a "spread out Bragg peak" is created by overlapping many pristine Bragg peak at different depths, corresponding to different energies

Treatment delivery



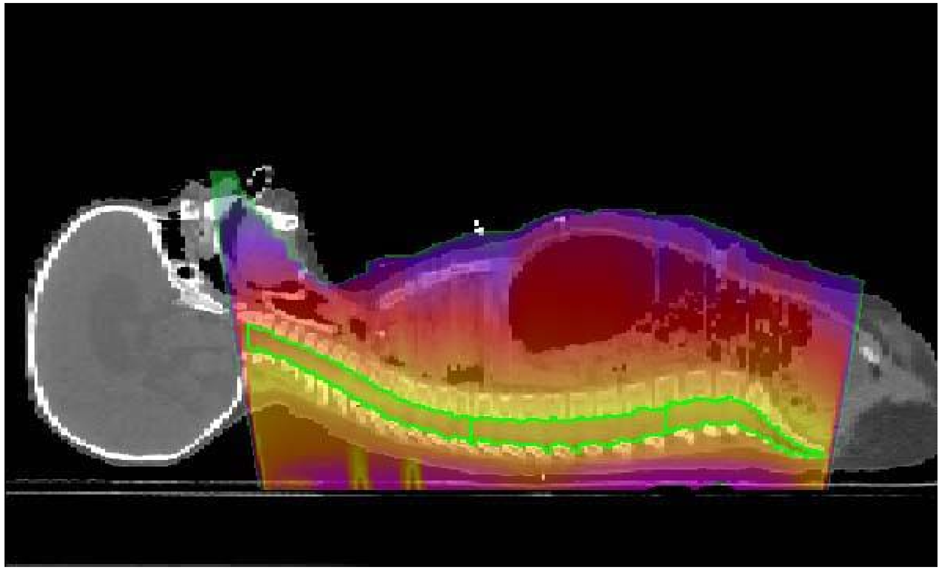
(courtesy of Siemens Medical)

Treatment delivery

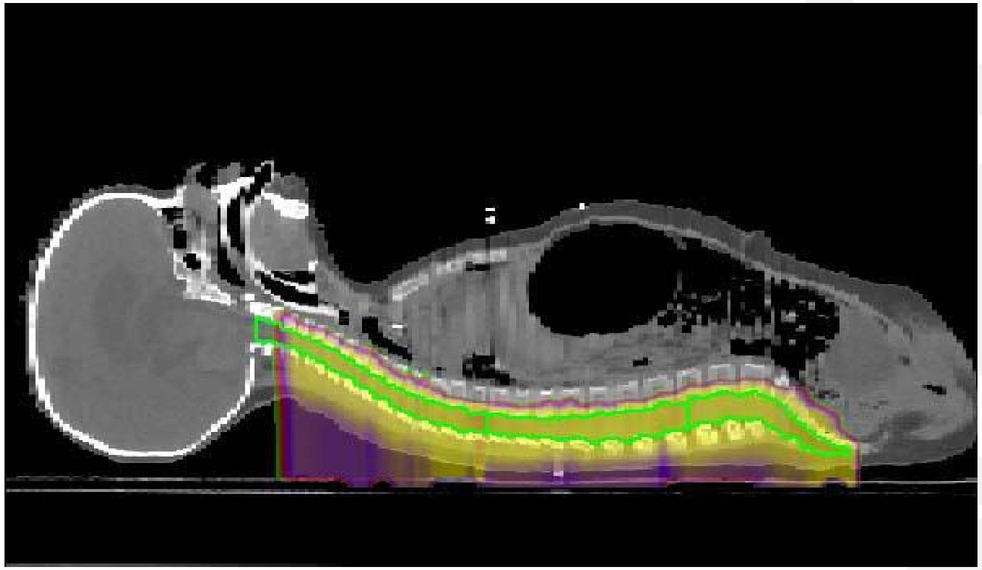


(courtesy of A. Attili)

Geometrical advantage

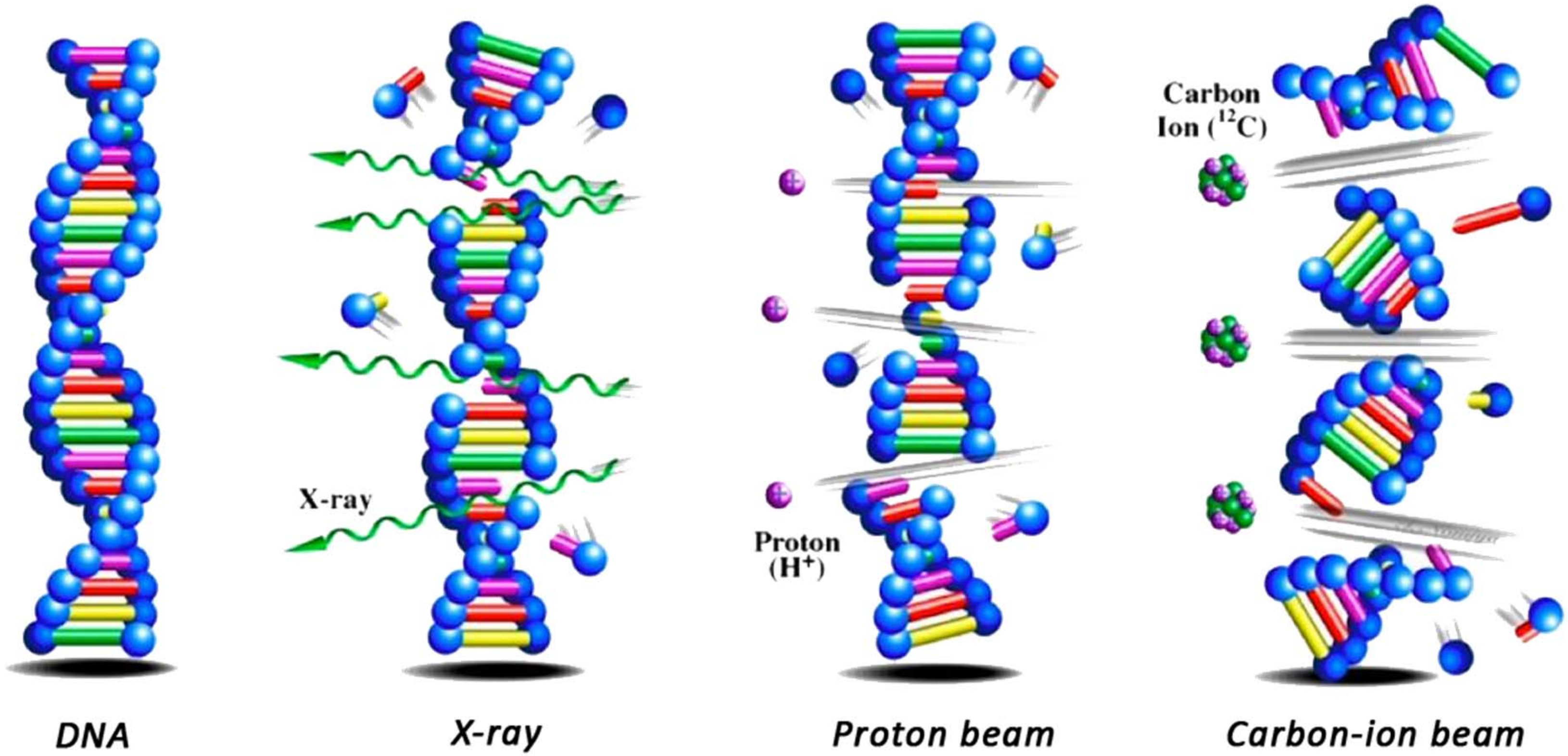


Conventional radiotherapy



Hadrontherapy

Different biological damage (clustered DNA damage)

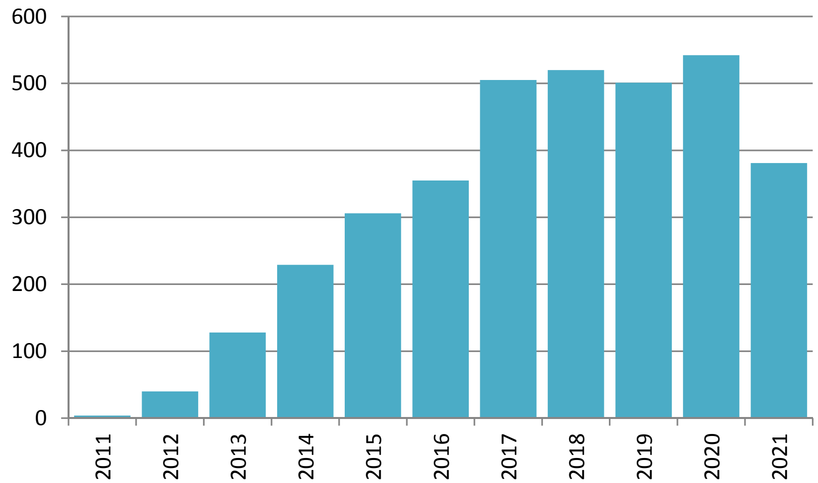


High LET
Multiple strand break

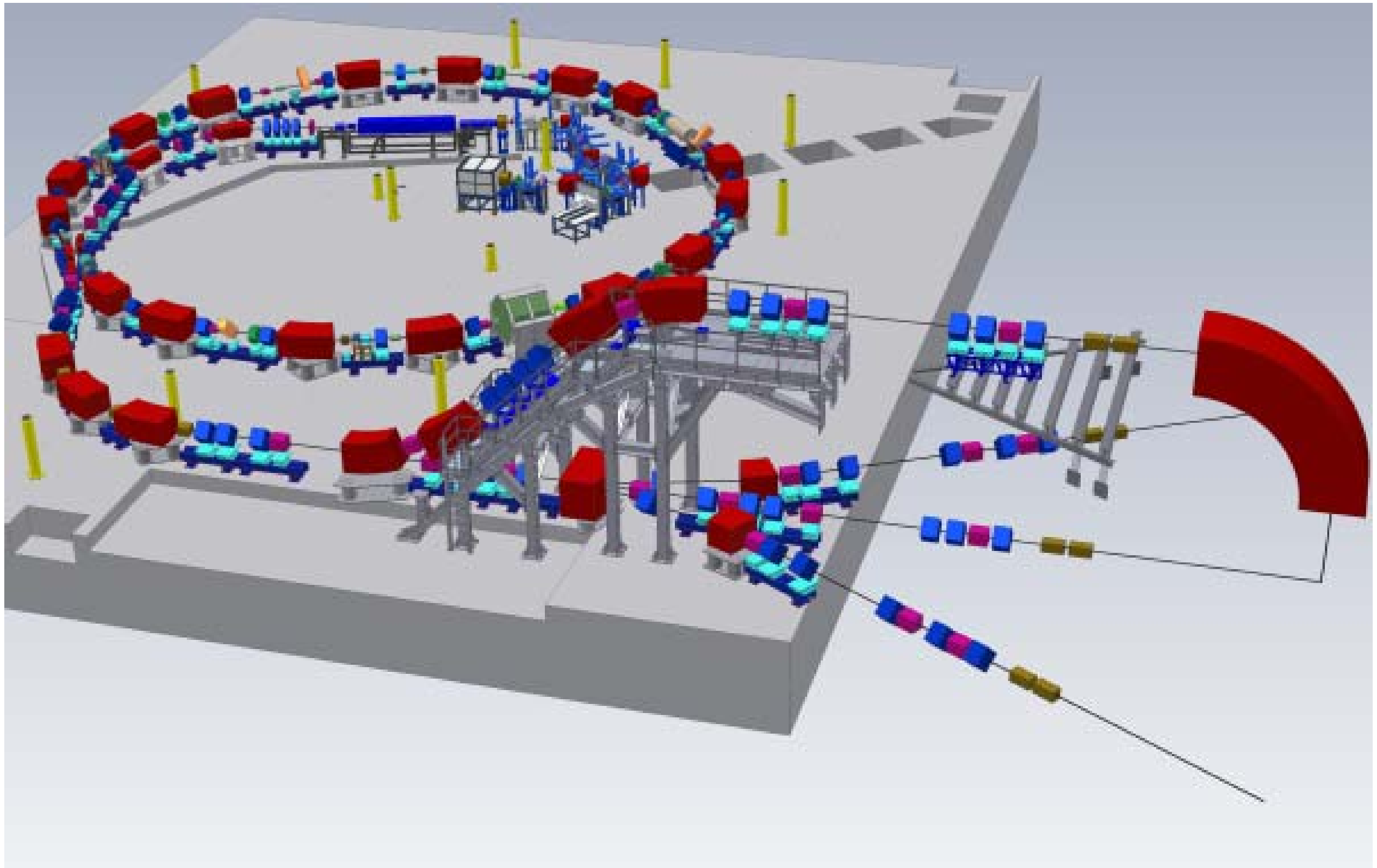
Number of treated patients

More than 3500 patients treated so far

Carbon/protons: 60/40



CNAO dual (multi) particle accelerator system



Design parameters

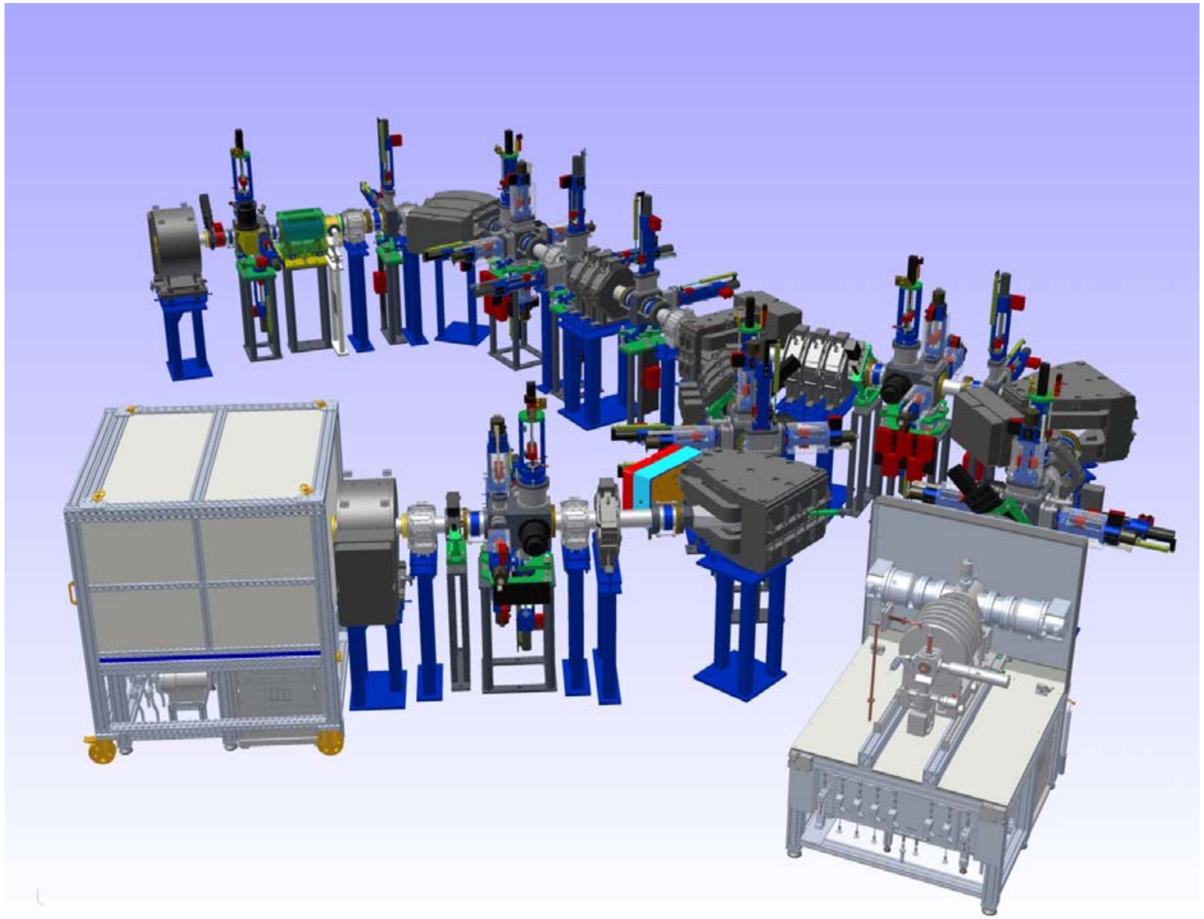
Protons (10^{10}/spill)				
	LEBT (*)	MEBT	SYNC	HEBT
Energy [MeV/u]	0.008	7	7-250	**60-250**
Imax [A]	1.3×10^{-3} (0.65, 0.45)	0.7×10^{-3}	5×10^{-3}	**7×10^{-9}**
Imin [A]	1.3×10^{-3} (0.65, 0.45)	70×10^{-6}	0.12×10^{-3}	17×10^{-12}
$\varepsilon_{rms,geo}$ [π mm mrad]	45	1.9	0.67-4.2	0.67-1.43(V)
$\varepsilon_{90,geo}$ [π mm mrad]	180	9.4	3.34-21.2	3.34-7.14 (V) 5.0 (H)
Magnetic rigidity [T m]	0.013 (0.026)	0.38	0.38-2.43	0.38-2.43
$(\Delta p/p)_{tot}$	±1.0‰	±(1.2-2.2)‰	±(1.2-3.4)‰	±(0.4-0.6)‰

* H^+ (H_2^+, H_3^+)

Design parameters

Carbon ($4\cdot10^8$ C/spill)				
	LEBT (C^{4+})	MEBT	SYNC	HEBT
Energy [MeV/u]	0.008	7	7-400	**120-400**
Imax [A]	0.15×10^{-3}	0.15×10^{-3}	1.5×10^{-3}	$\mathbf{2\times10^{-9}}$
Imin [A]	0.15×10^{-3}	15×10^{-6}	28×10^{-6}	4×10^{-12}
$\varepsilon_{rms,geo}$ [π mm mrad]	45	1.9	0.73-6.1	0.73-1.43(V)
$\varepsilon_{90,geo}$ [π mm mrad]	180	9.4	3.66-30.4	3.66-7.14 (V) 5.0 (H)
Magnetic rigidity [T m]	0.039	0.76	0.76-6.34	3.25-6.34
$(\Delta p/p)_{tot}$	±1.0‰	±(1.2-2.0)‰	±(1.2-2.9)‰	±(0.4-0.6)‰

Sources and LEBT



0.008 MeV/u H_3^+
0.008 MeV/u C^{4+}

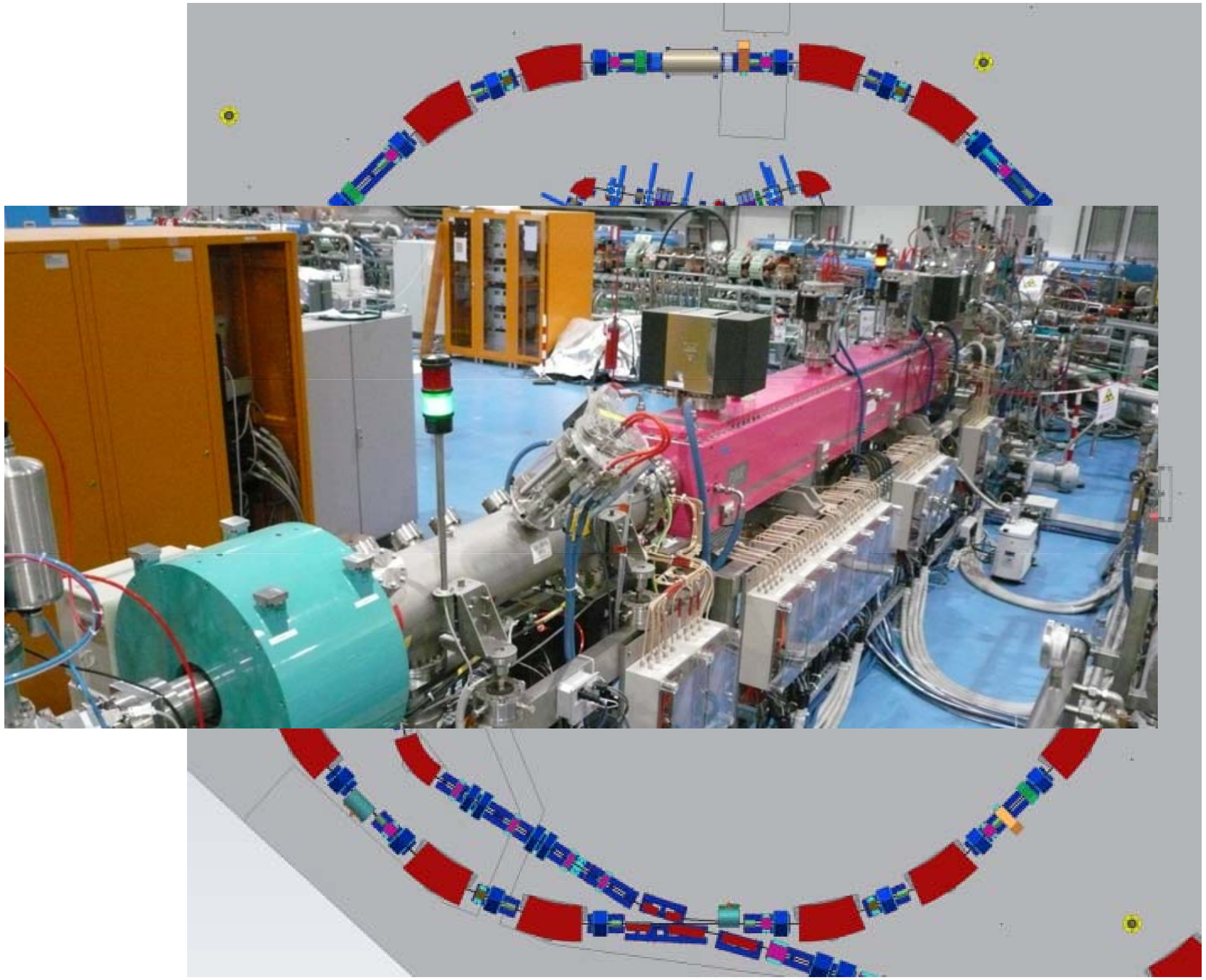
I ~ 0.5 mA (H_3^+)
I ~ 0.15 mA (C^{4+})

Two ECR sources

Continuous beam

LEBT Chopper

LINAC system

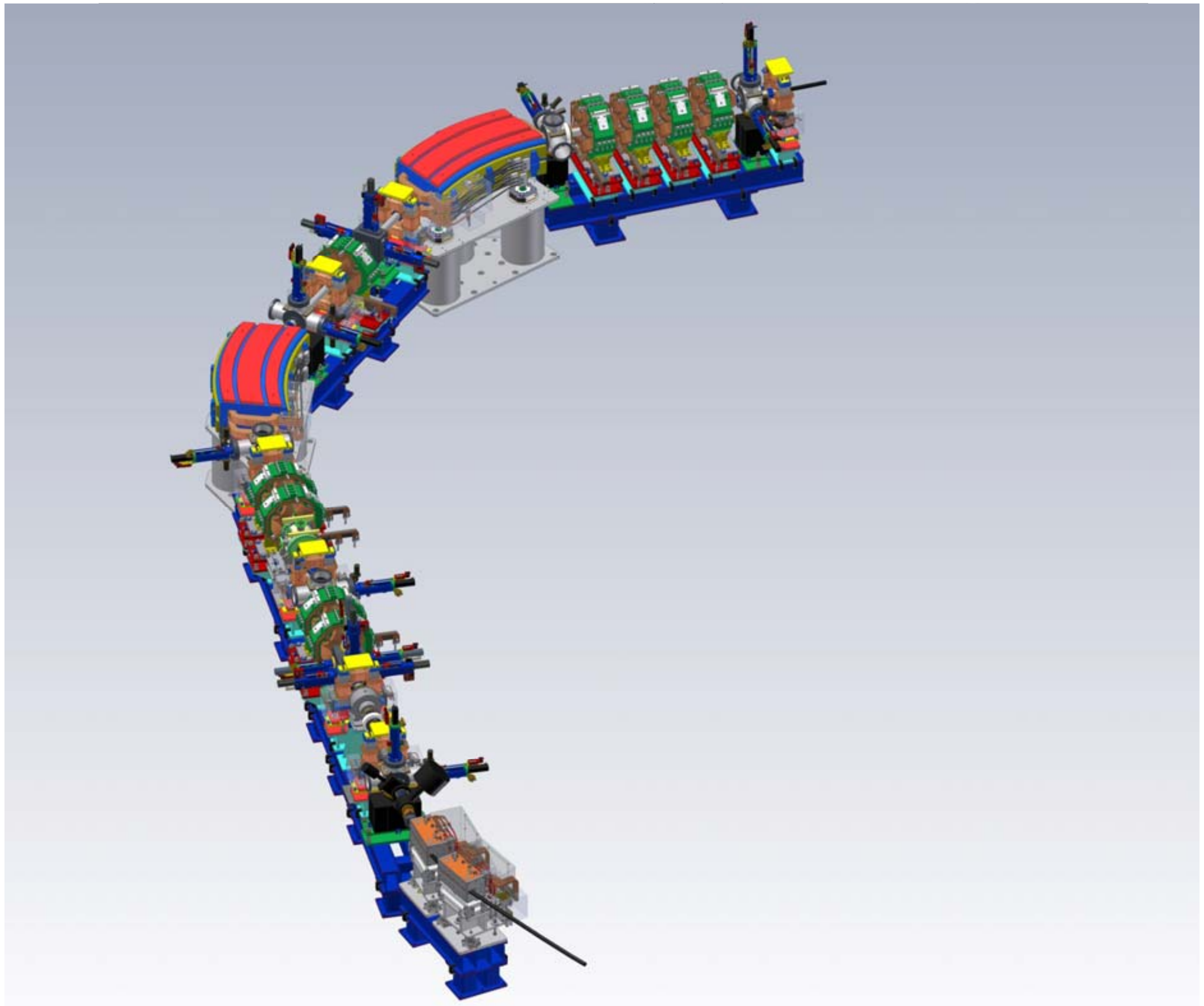


217 MHz

RFQ
0.008-0.4 MeV/u H_3^+
0.008-0.4 MeV/u C^{4+}

IH
0.4-7 MeV/u H_3^+
0.4-7 MeV/u C^{4+}

MEBT Layout



7 MeV p
7 MeV/u C^{6+}

I ~ 0.75 mA (p)
I ~ 0.12 mA (C^{6+})

Stripping foil

[~~Current selection~~]

Debuncher

Emittance dilution

Match betas

$(x,x')_{Inj}$

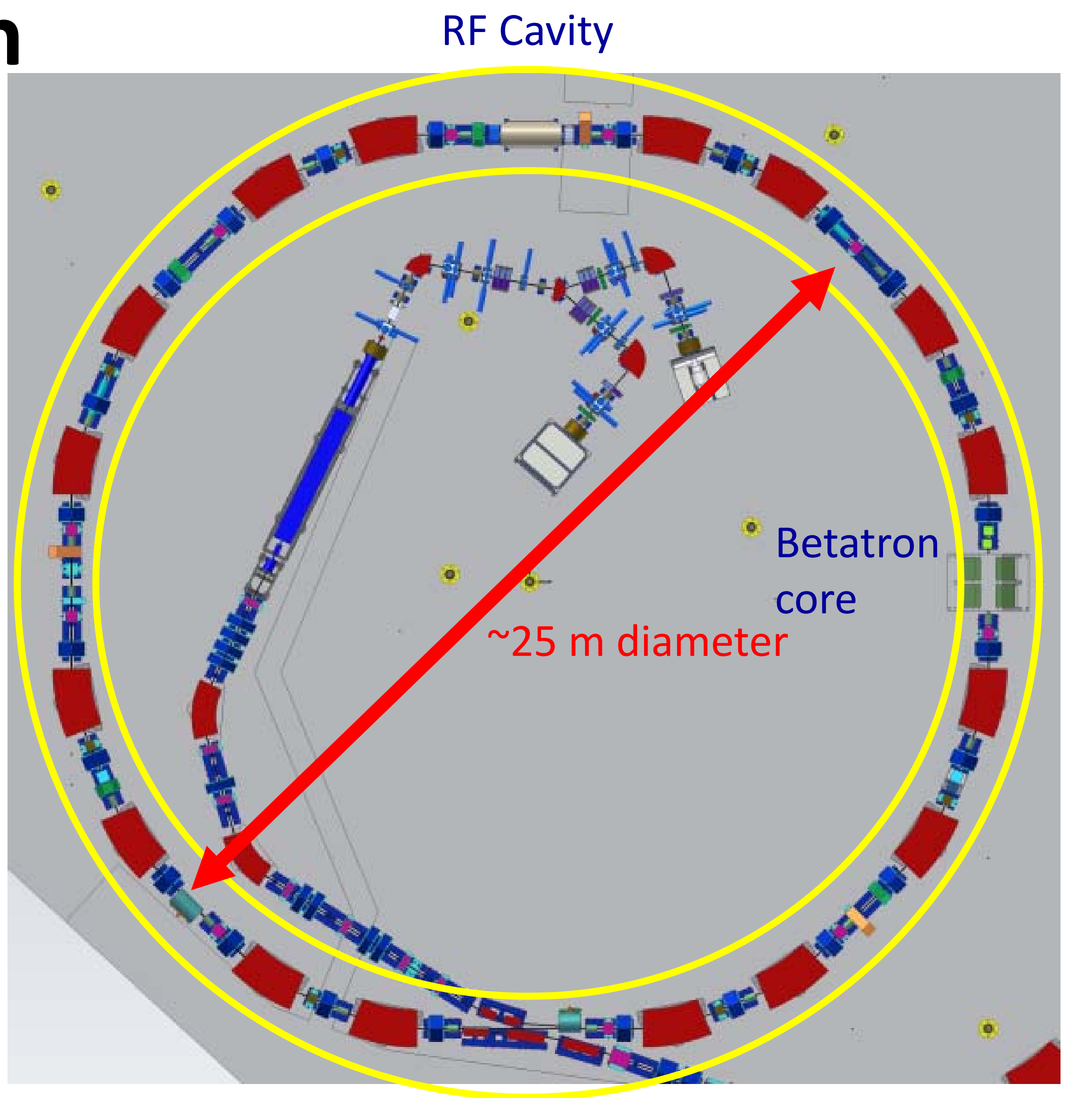
Synchrotron

16 Dipoles in series

24 Quadrupoles
in 3 families

5 Sextupoles
in 3 families

10 Hor corr
8 Ver corr



7-250 MeV p
7-400 MeV/u C

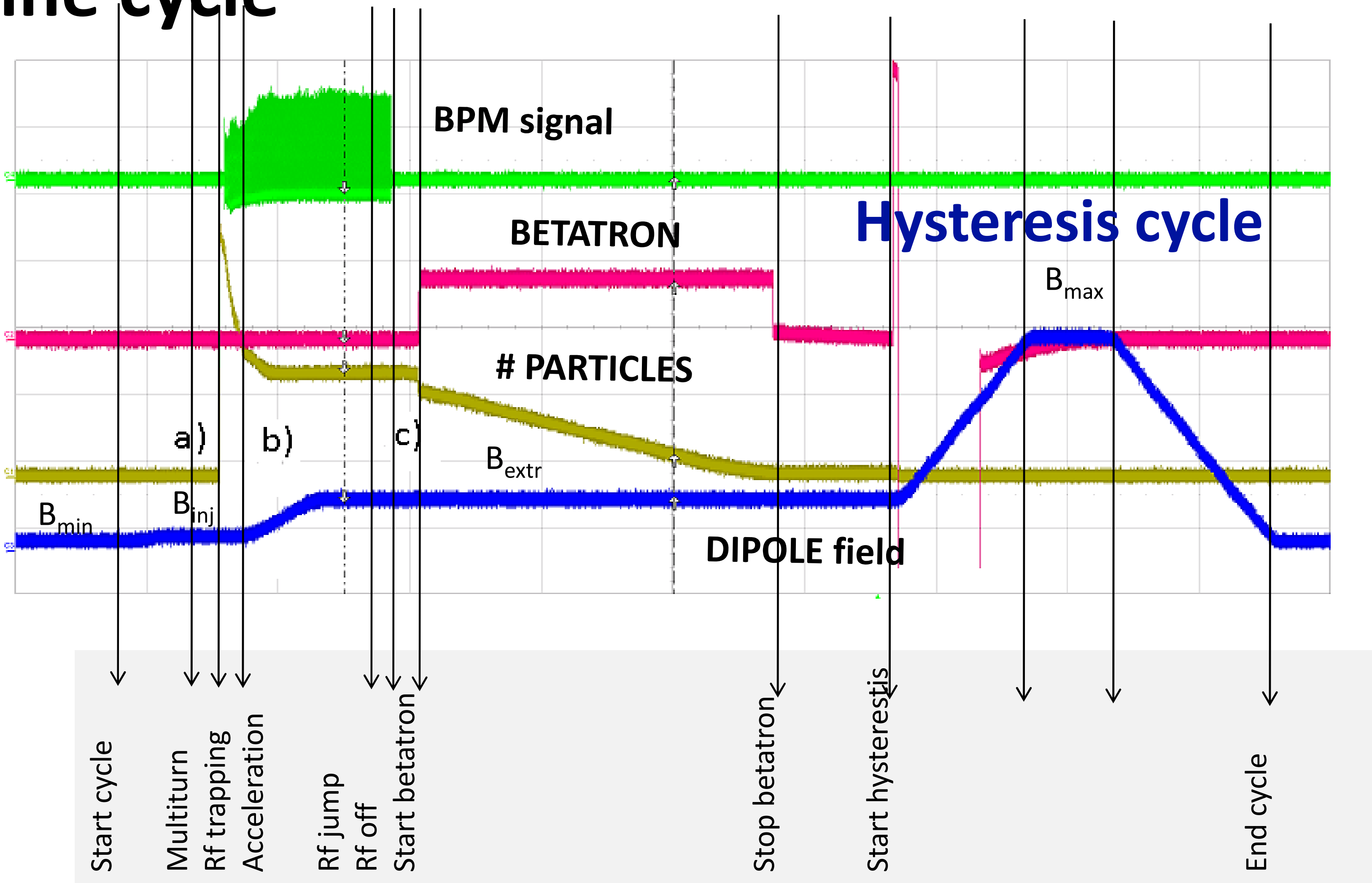
I ~ 0.1-5 mA (p)
I ~ 0.03-1.5 mA (C)

Multi turn injection

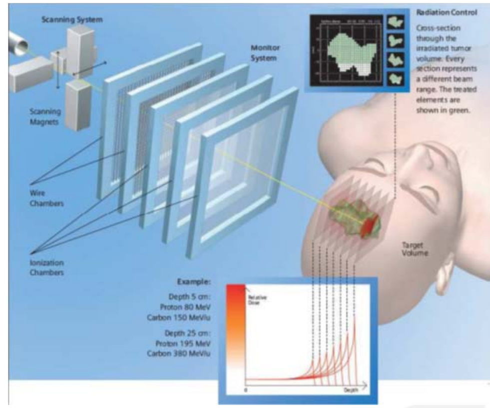
Slow extraction

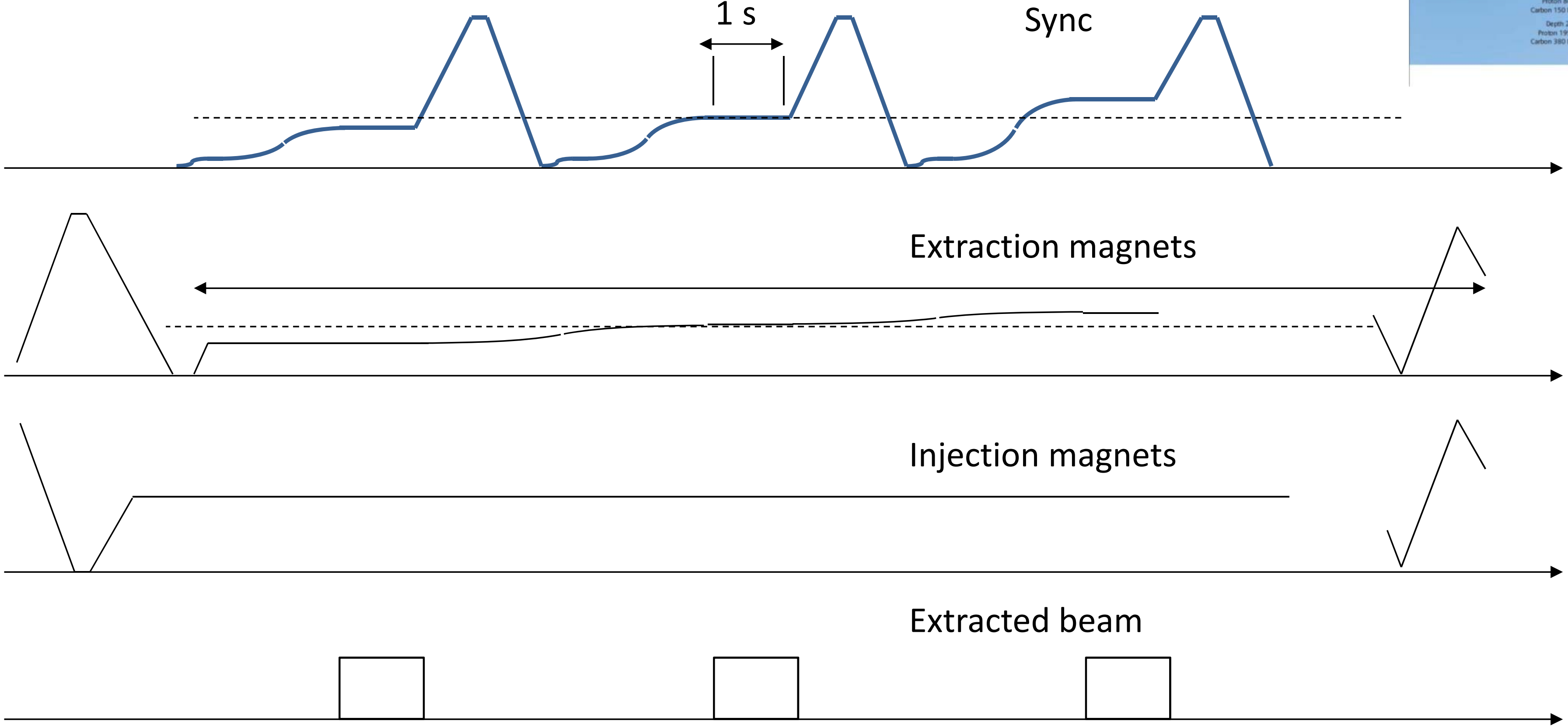
Betatron core
(and RFKO)

Machine cycle



Treatment execution





Extraction at CNAO

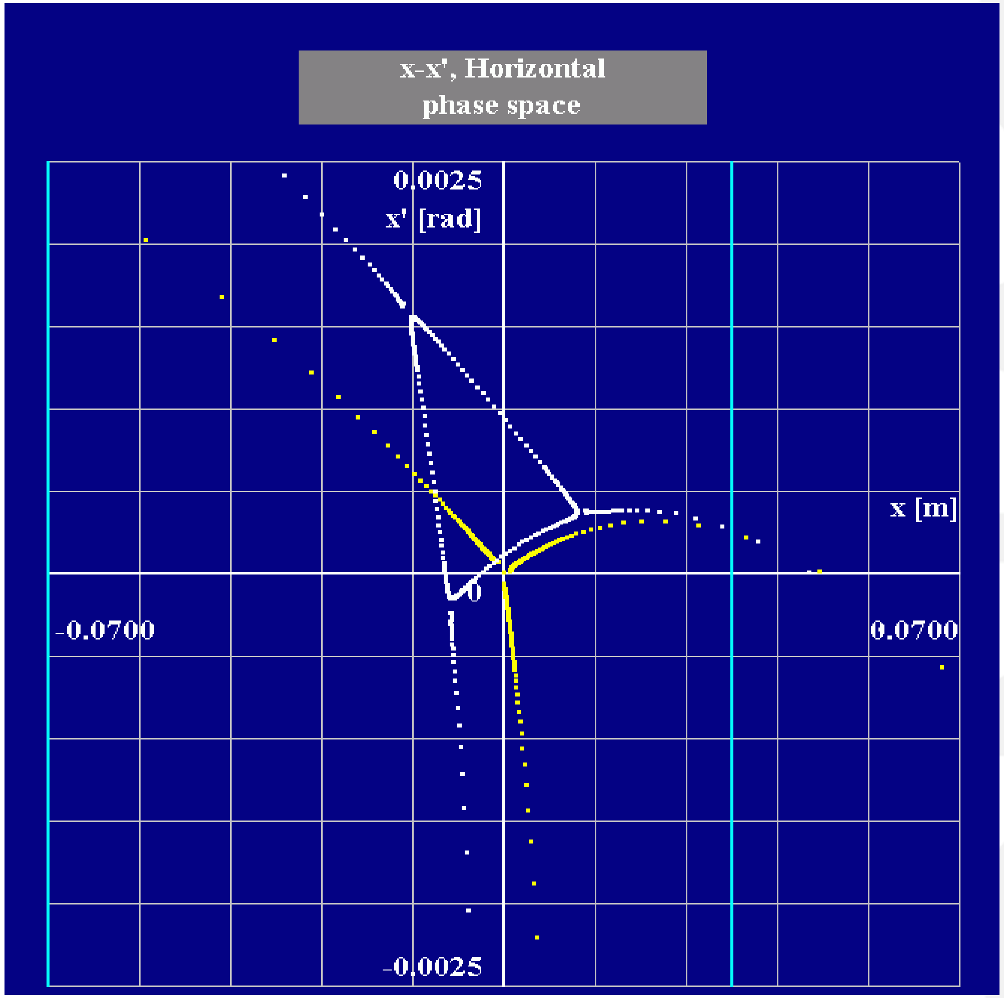
Resonant slow extraction
at Qx=5/3

Betatron core

Empty bucket channelling

Air core quadrupole

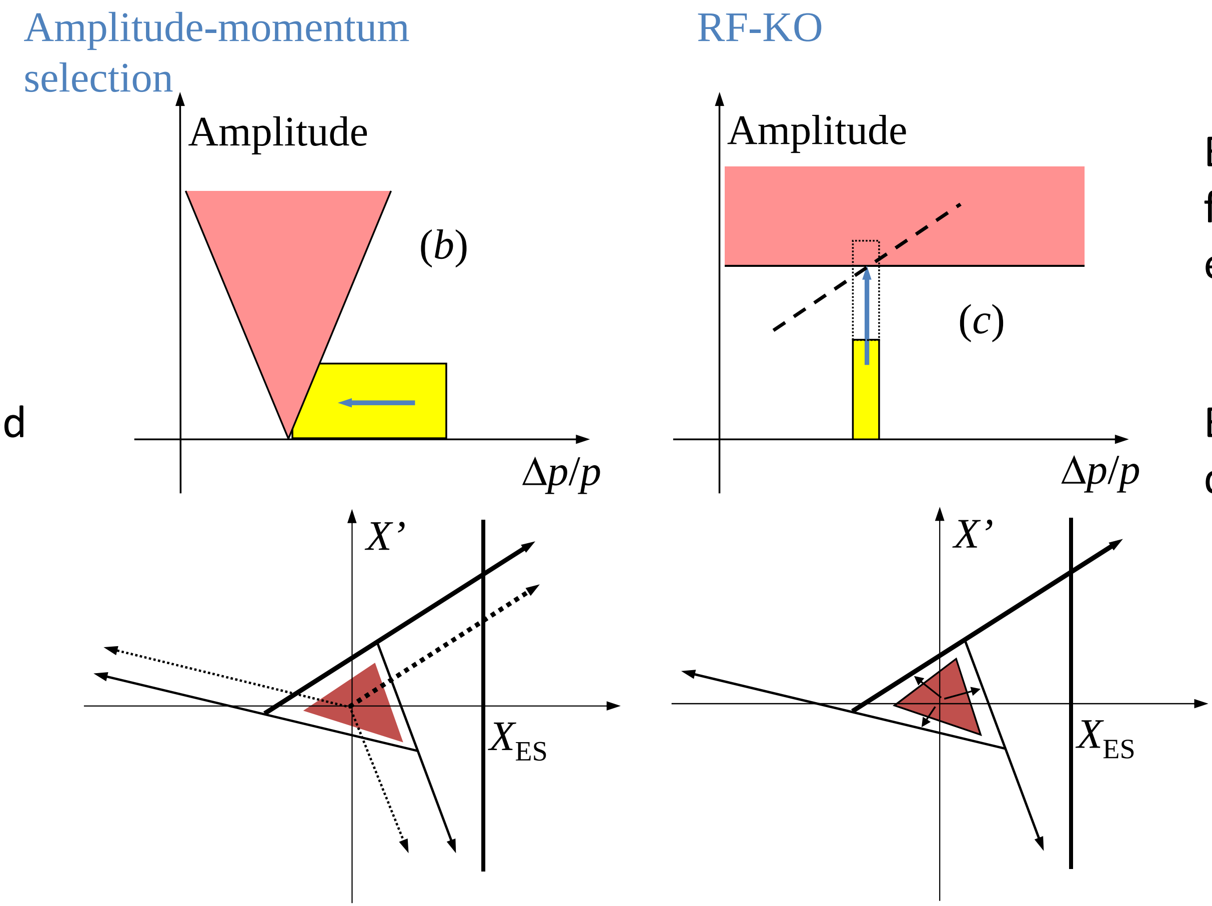
RF-KO in progress



Implementation of RFKO in addition to betatron

Standard method at CNAO

Beam is debunched during extraction

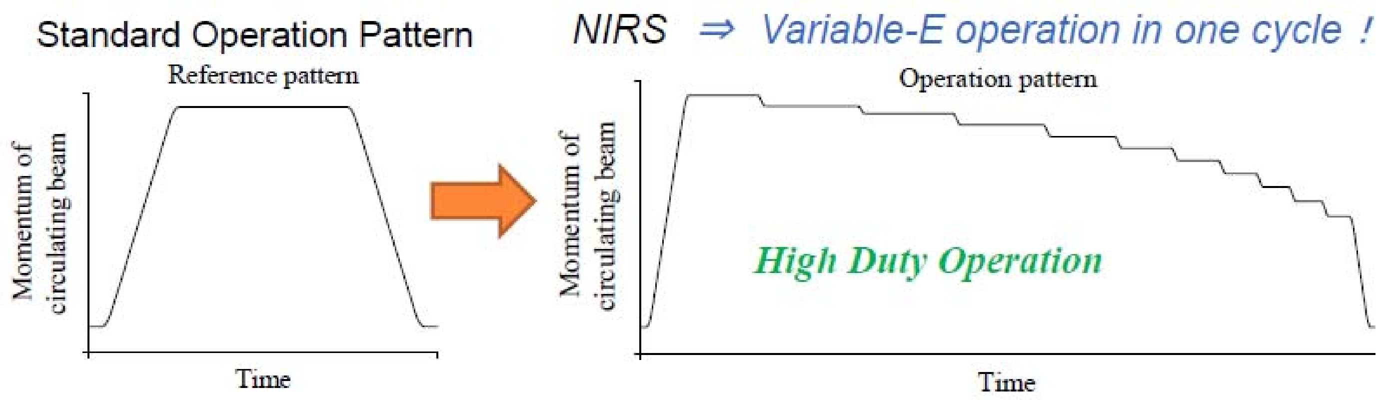


Being implemented for multi energy extraction studies

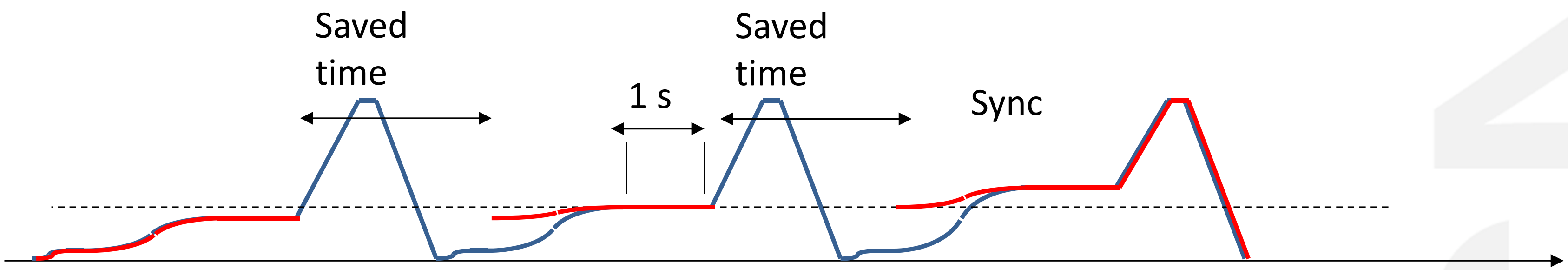
Beam is bunched during extraction

Multi Energy Extraction

Use remaining beam after slice completion



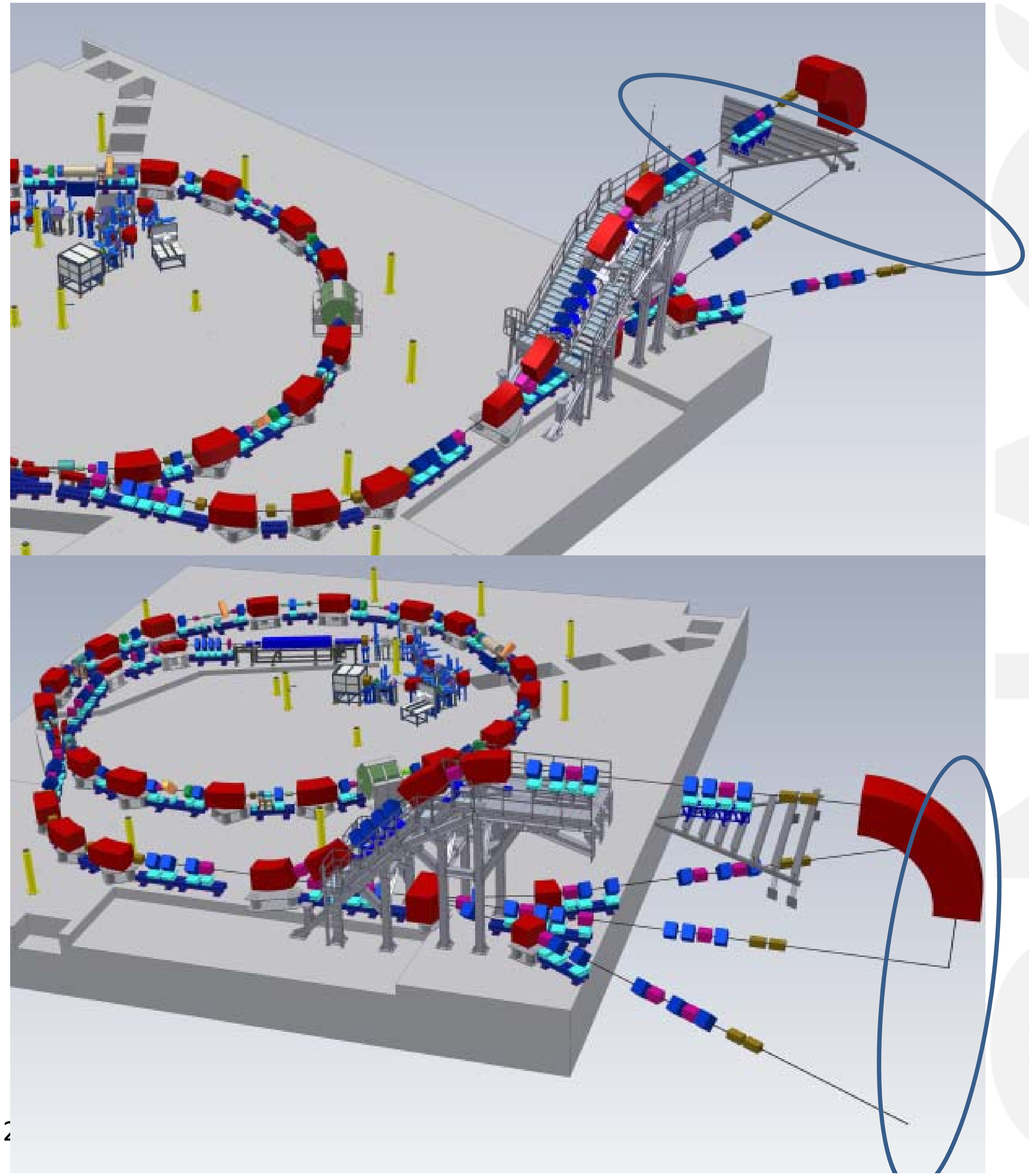
(Courtesy K. Noda – CAS Medical)



HEBT

60-250 MeV p
120-400 MeV/u C
10^{10} p/spill (~2nA)
4 10^{8} C/spill (~0.4nA)

3 Treatment rooms
2 H
1 H+V

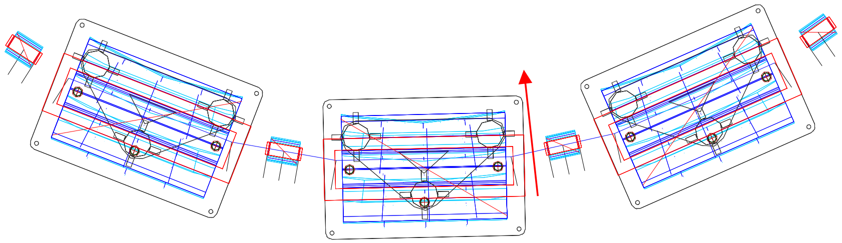


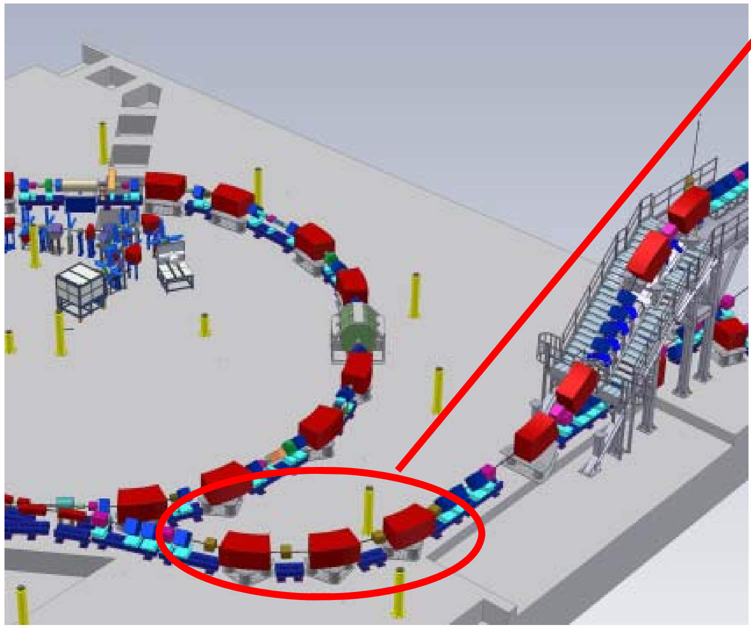
Chopper

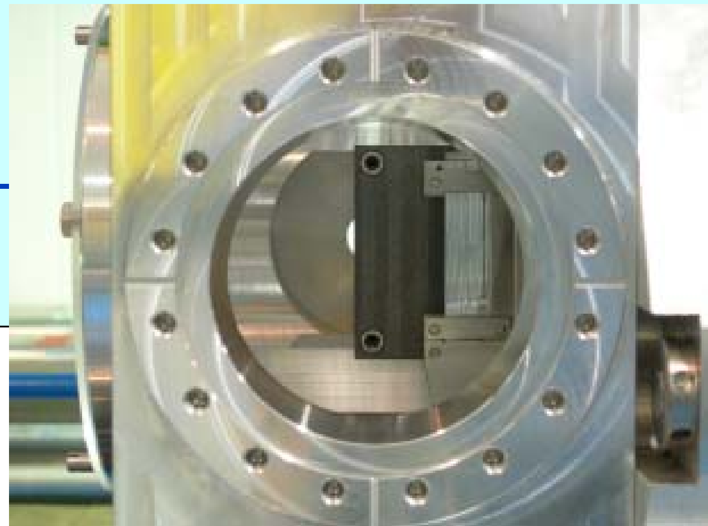
Fast turn on/off for the beam

Intrinsically safe

Allows beam qualification





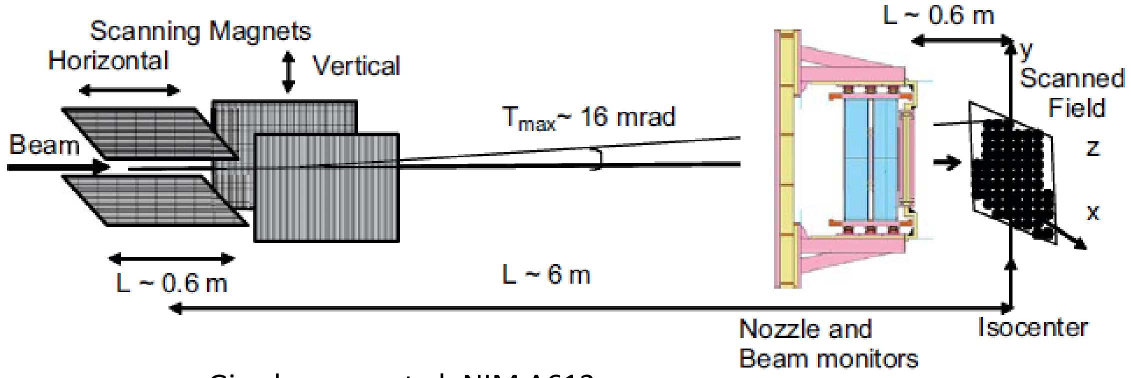


ts

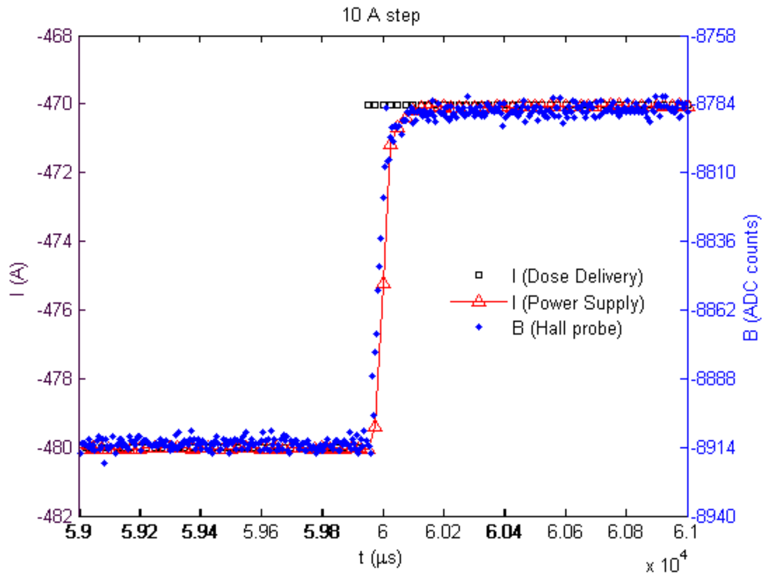
breathing.

Dose delivery

- Dose driven
- Real time measurement
- Feedback on scanning magnets

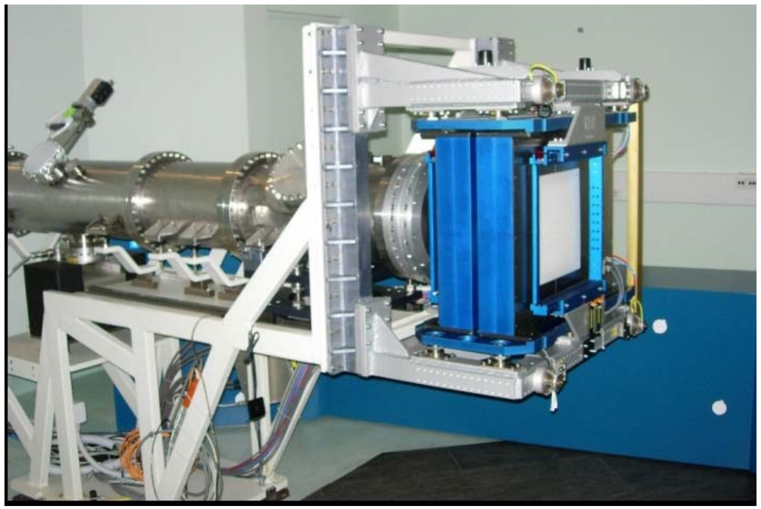


Giordanengo et al.,NIM A613



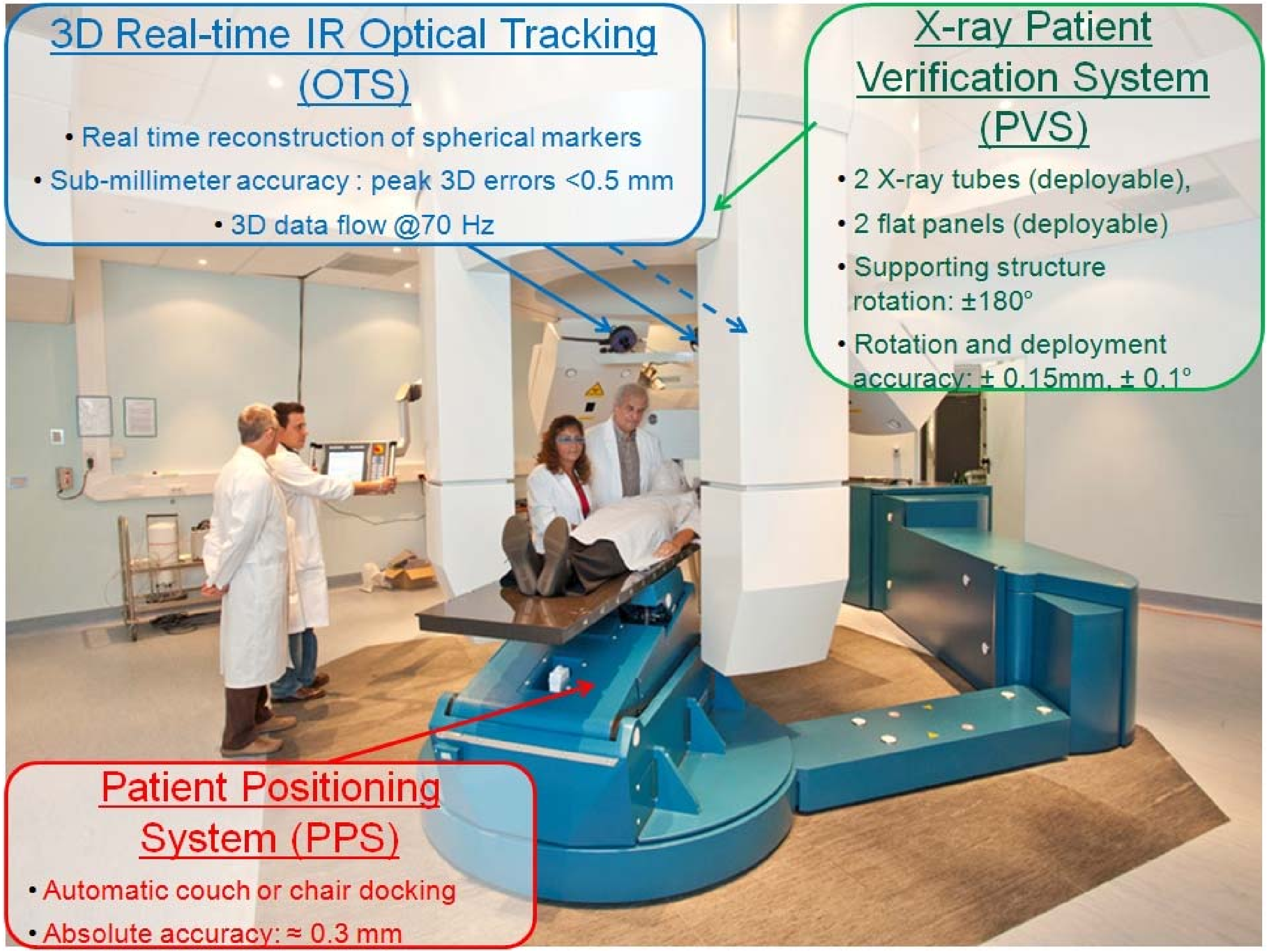
< Δt > = 35.1 ± 3.5 μs between 20% to 80%

ΔI /Δt ~ 170 kA/s or ~ 85 T/sec



In House developed certified medical product

In the treatment room

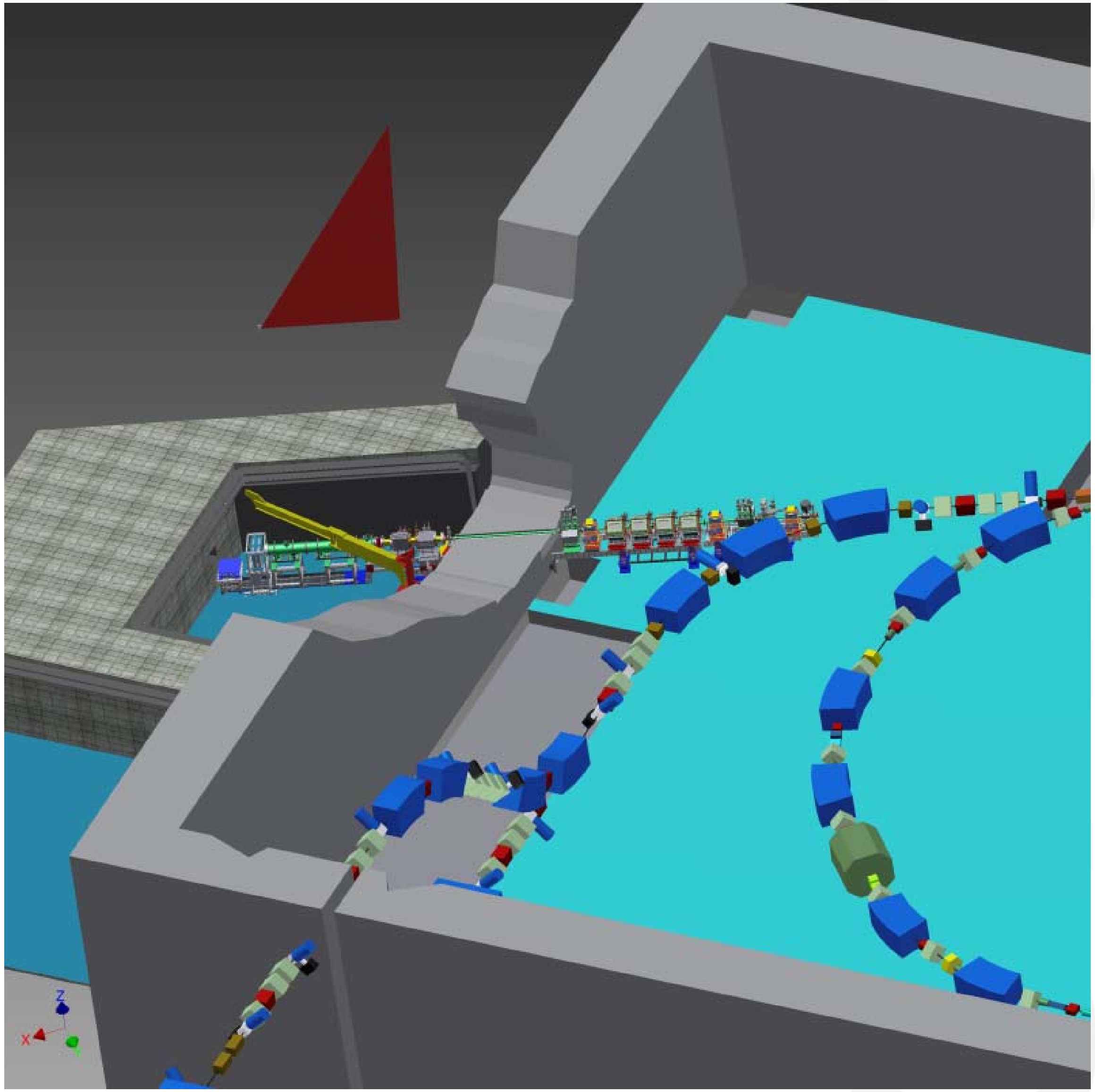


Experimental room

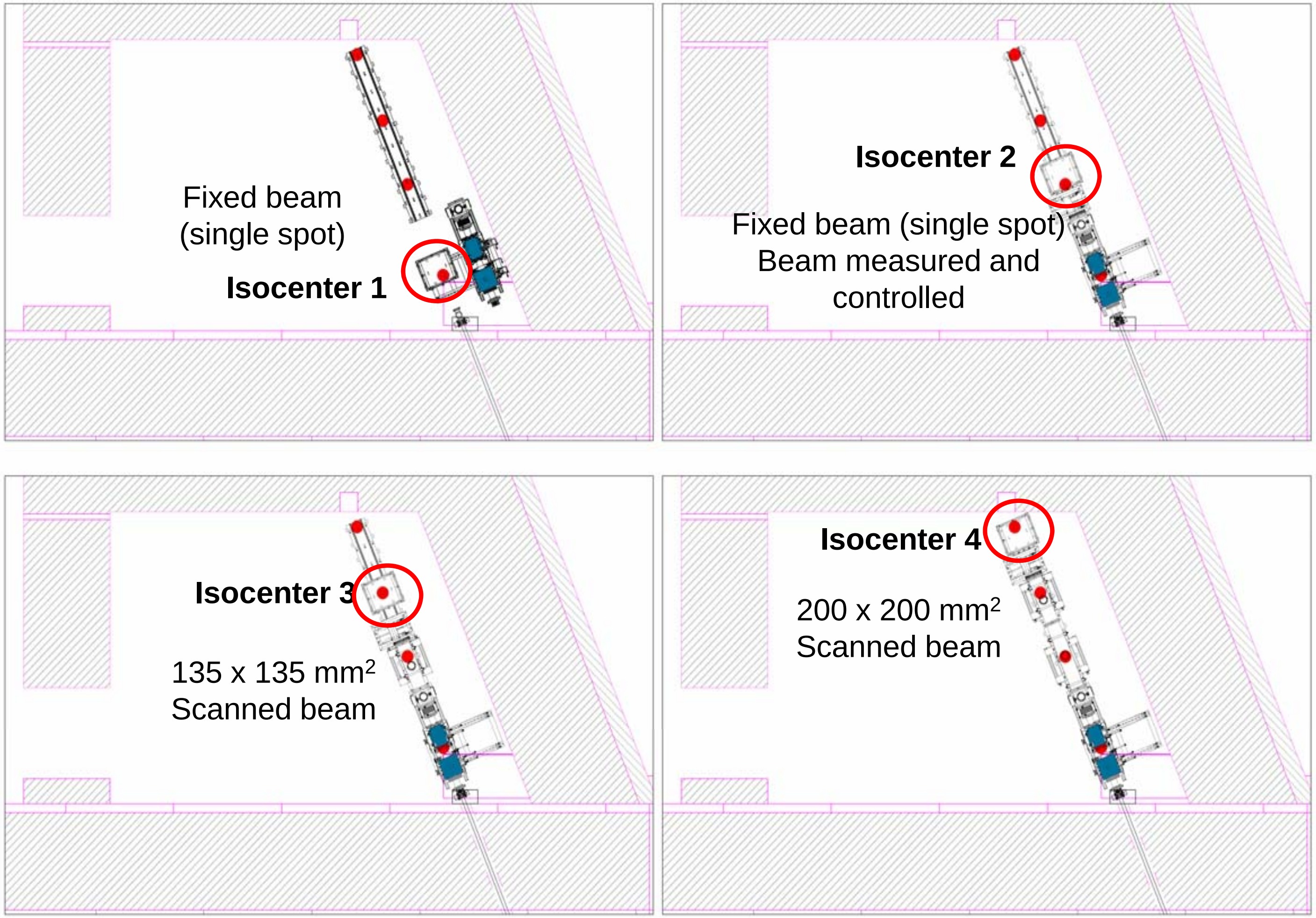
60-250 MeV p
120-400 MeV/u C
10^{10} p/spill (~2nA)
4 10^{8} C/spill (~0.4nA)

3 Treatment rooms
2 H
1 H+V

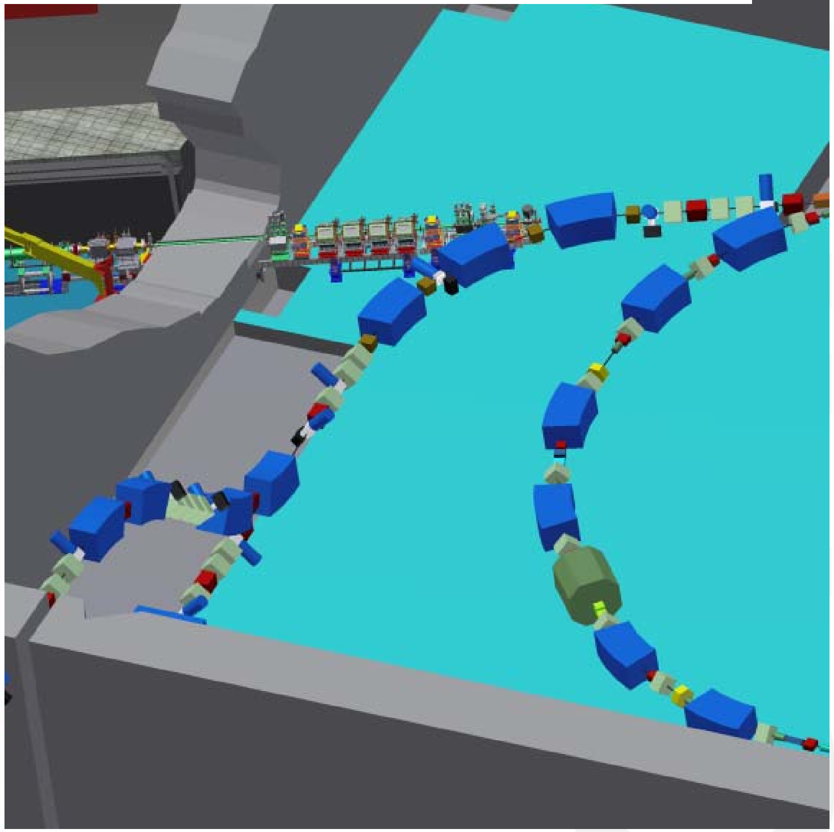
+1 Experimental Room



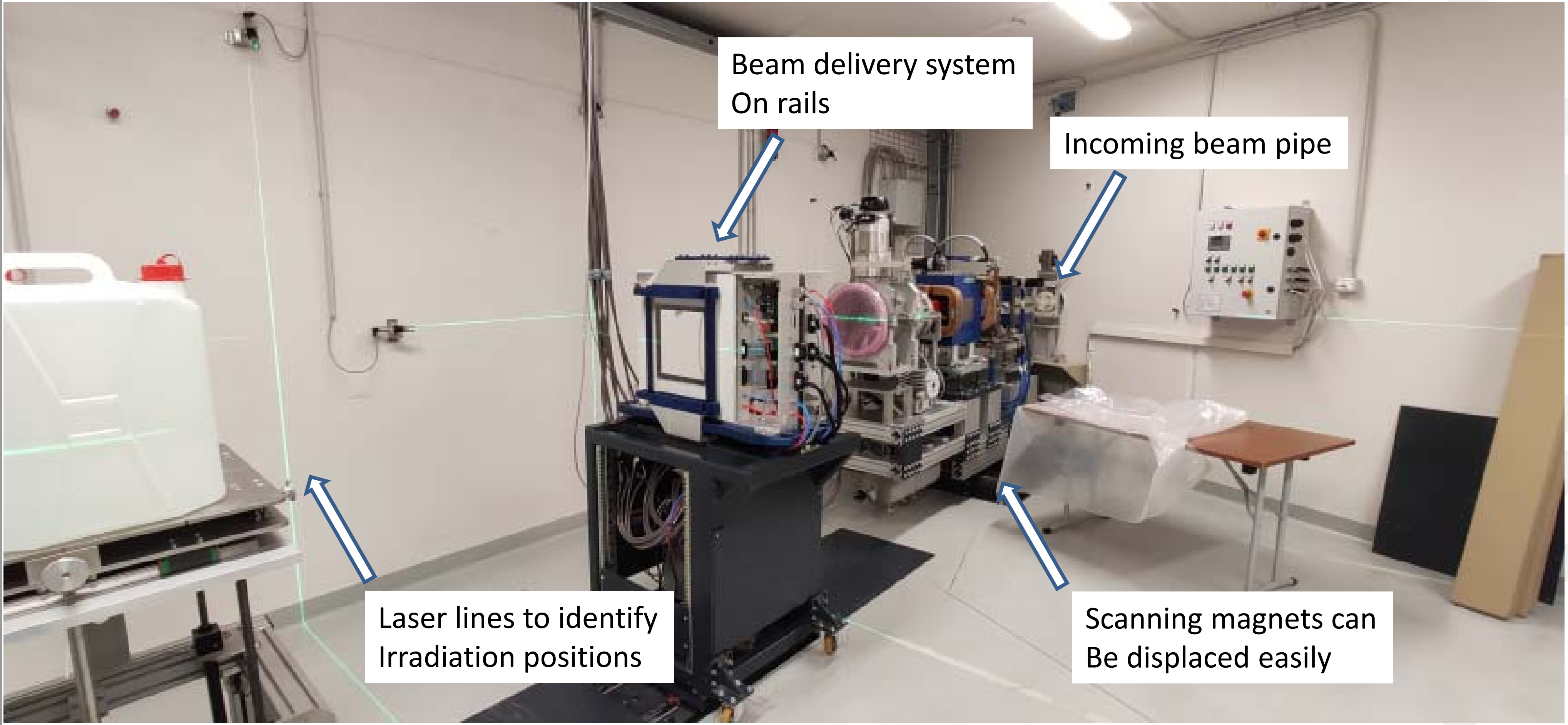
Experimental room



Easily reconfigurable
to suit experimental needs



Reconfigurable irradiation setup



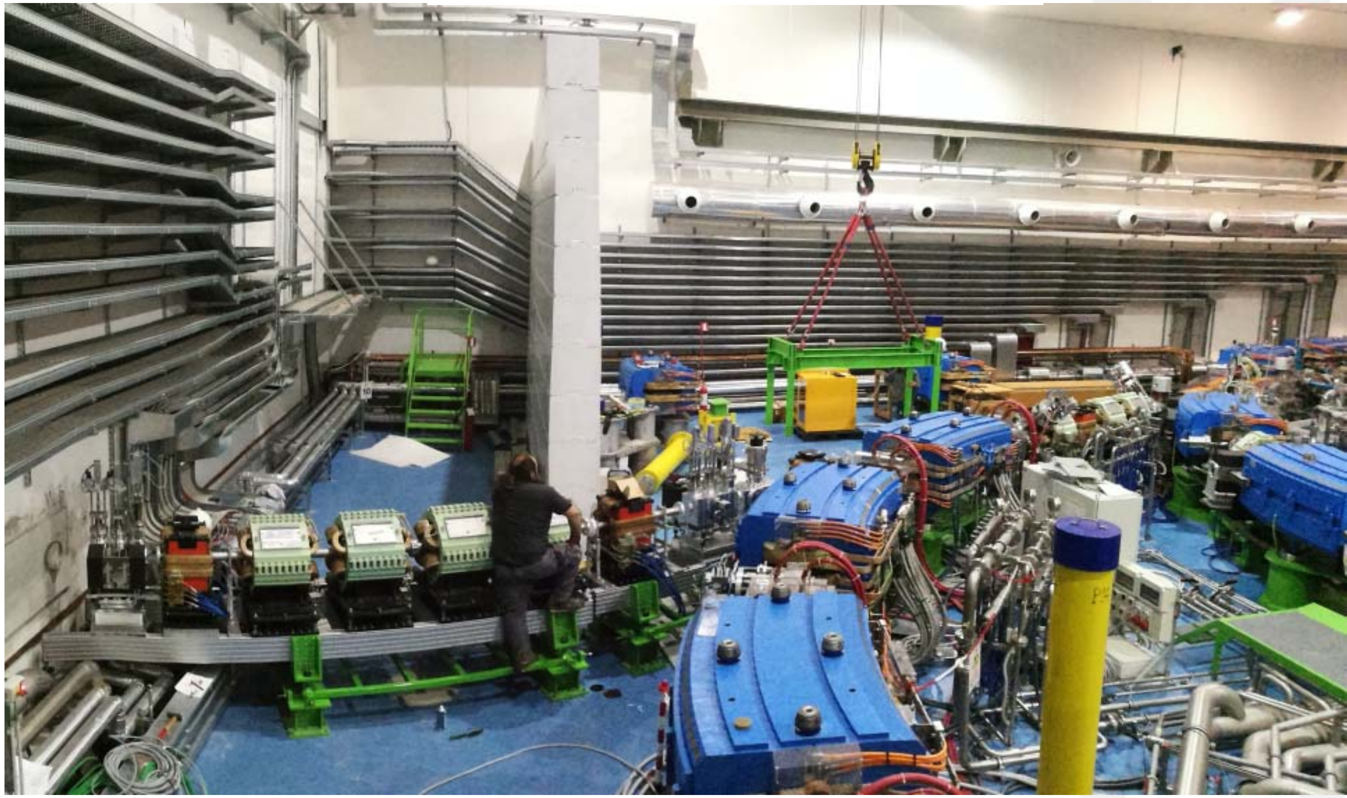
Isocenter 3

The CNAO experimental facility: a unique opportunity to perform research activities at 360°

In collaboration with INFN

CNAO is also a Centre of Research and Development, whose activities range from clinical and radiobiological research to translational research with the objective of providing continual improvements in the capacity to cure.

For researchers a dedicated experimental irradiation room is available, using the CNAO beams, in time slots not impacting on patients treatment, but specifically devoted to research purposes: i.e. some night shifts (22:00 - 4:00) during the week and some full shifts (8h) during weekends.

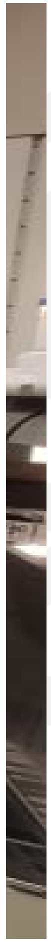


CNAO radiobiology laboratory

Biological laboratory with all the necessary equipment including biological laminar flows, incubators, centrifuges, fluorescence microscope, cell counters is provided. Furthermore, in the next 2 years the research area will be expanded and rooms dedicated to microscopy, cell handling, cytology/histology and small animals preparation will be accessible

Nearby university:

- Animal house
- Centro grandi strumenti

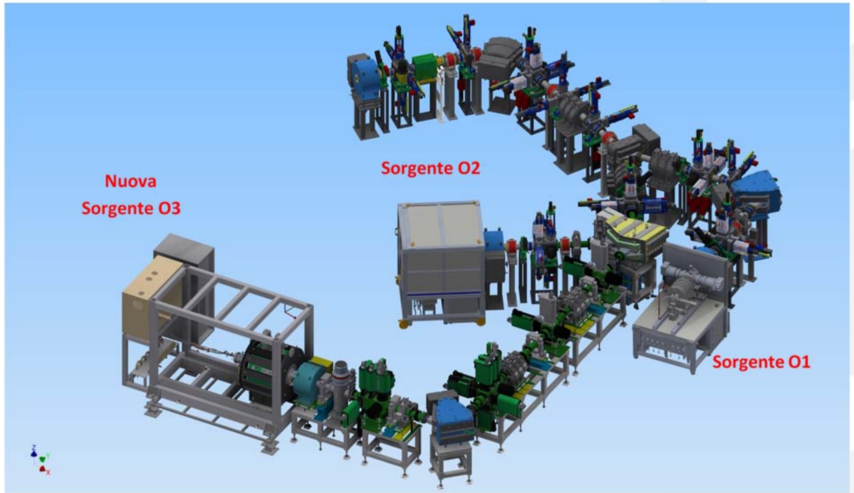


INSpIRIT: new source

Several upgrades to CNAO machine:

- Revamping of critical components in order to speed some normal machine operations
- Revamping of critical components to increase machine reliability
- Upgrade of the radiobiology laboratory
- **New source** for **Helium, Litium, Oxygen and Iron** for new clinical protocols (He, O, Li) and biological or material experiments.

Opens path to
Multi ion treatments, LET painting, killing painting, …

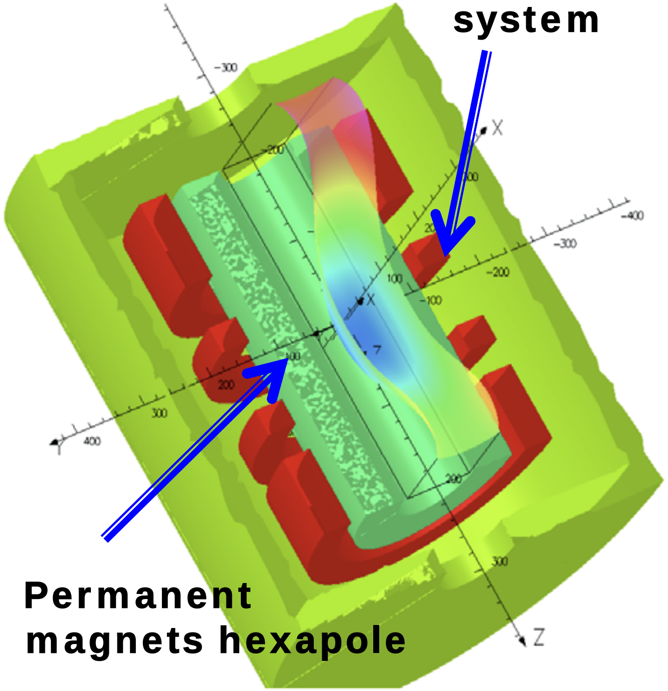


Una facility INnovativa di irraggiamento con Sorgente per Ioni per Ricerca e studi di radiation hardness con applicazioni IndusTriali e cliniche INSpIRIT – ID 1161908

Call HUB ricerca e Innovazione – EU/Regional funds

Sistema Sanitario Regione Lombardia

AISHA Advanced Ion Source for HAdrontherapy



Courtesy of L. Celona

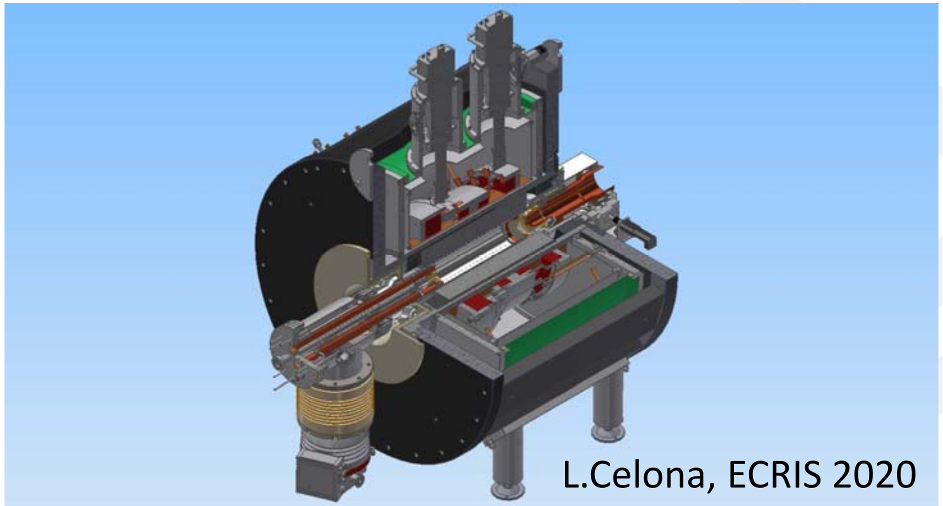
AISHA is a hybrid ECRIS: the radial confining field is obtained by means of a permanent magnet hexapole, while the axial field is obtained with a **Helium-free superconducting system.**

The **operating frequency of 18 GHz will permit** to maximize the plasma density by employing commercial microwave tubes meeting the **needs of the installation in hospital** environments.

Radial field	1.3 T
Axial field	2.7 T - 0.4 T - 1.6 T
Operating frequencies	18 GHz – 21 GHz
Operating power	1.5 + 1.5 kW (max)
Extraction voltage	40 kV (max)
Chamber diameter / length	Ø 92 mm / 360 mm
LHe	Free
Warm bore diameter	274 mm
Source weight	1400 kg

AISHA commissioning at LNS

AISHA: Advanced IonSource for HAdrontherapy



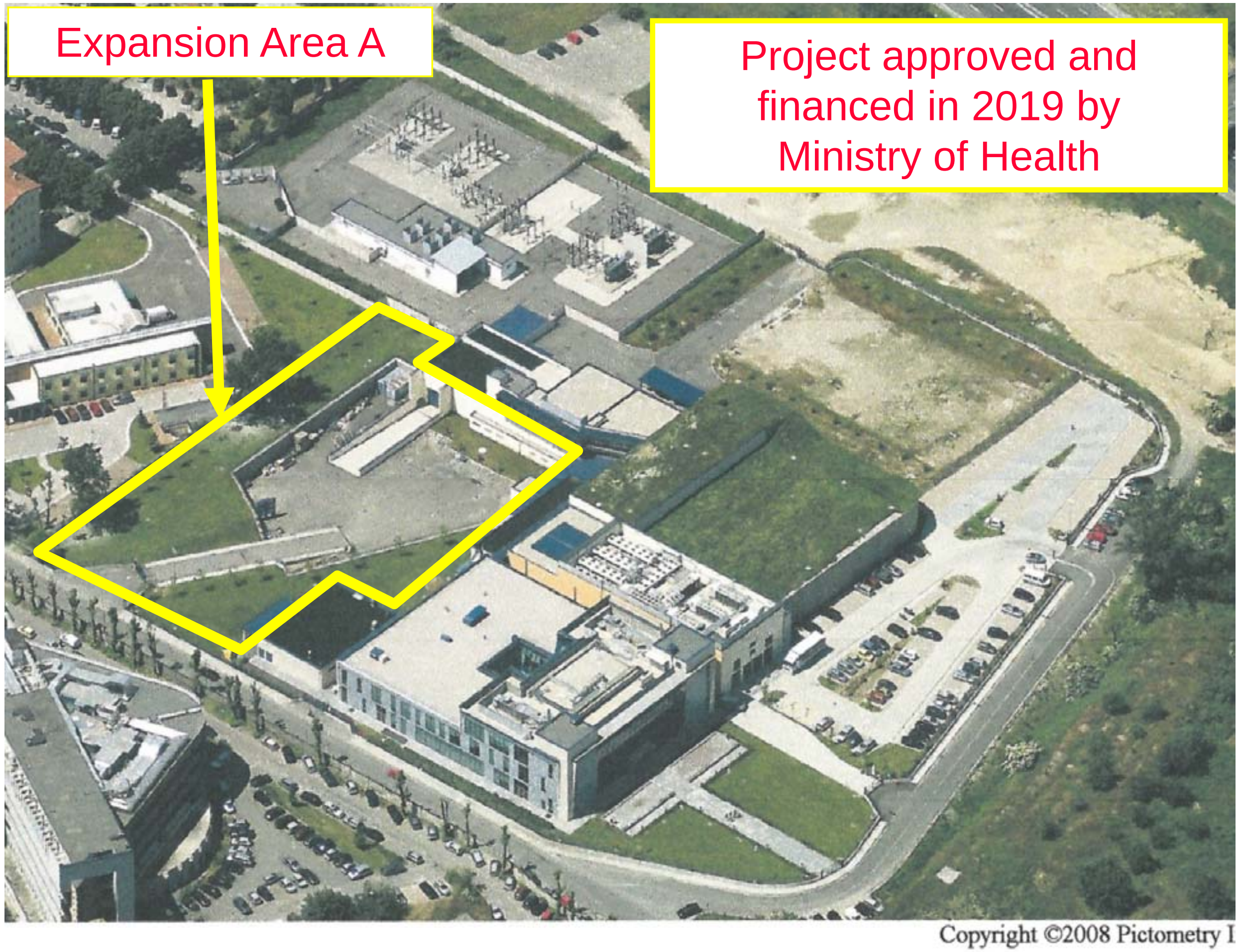
L.Celona, ECRIS 2020

Charge state	Beam intensity [eμA]	$\varepsilon_{rms.norm}$ [$\pi \cdot mm \cdot mrad$]
$^{16}O^{6+}$	1400	0.2198
$^{16}O^{6+}$	225	0.115
$^{16}O^{7+}$	350	0.247
$^{12}C^{4+}$	650	0.272
$^{12}C^{4+}$	150	0.222
$^{12}C^{5+}$	165	---
$^{40}Ar^{11+}$	155	0.201
$^{40}Ar^{12+}$	140	0.201
He^{2+}	5400	0.418
He^{2+}	700	0.245

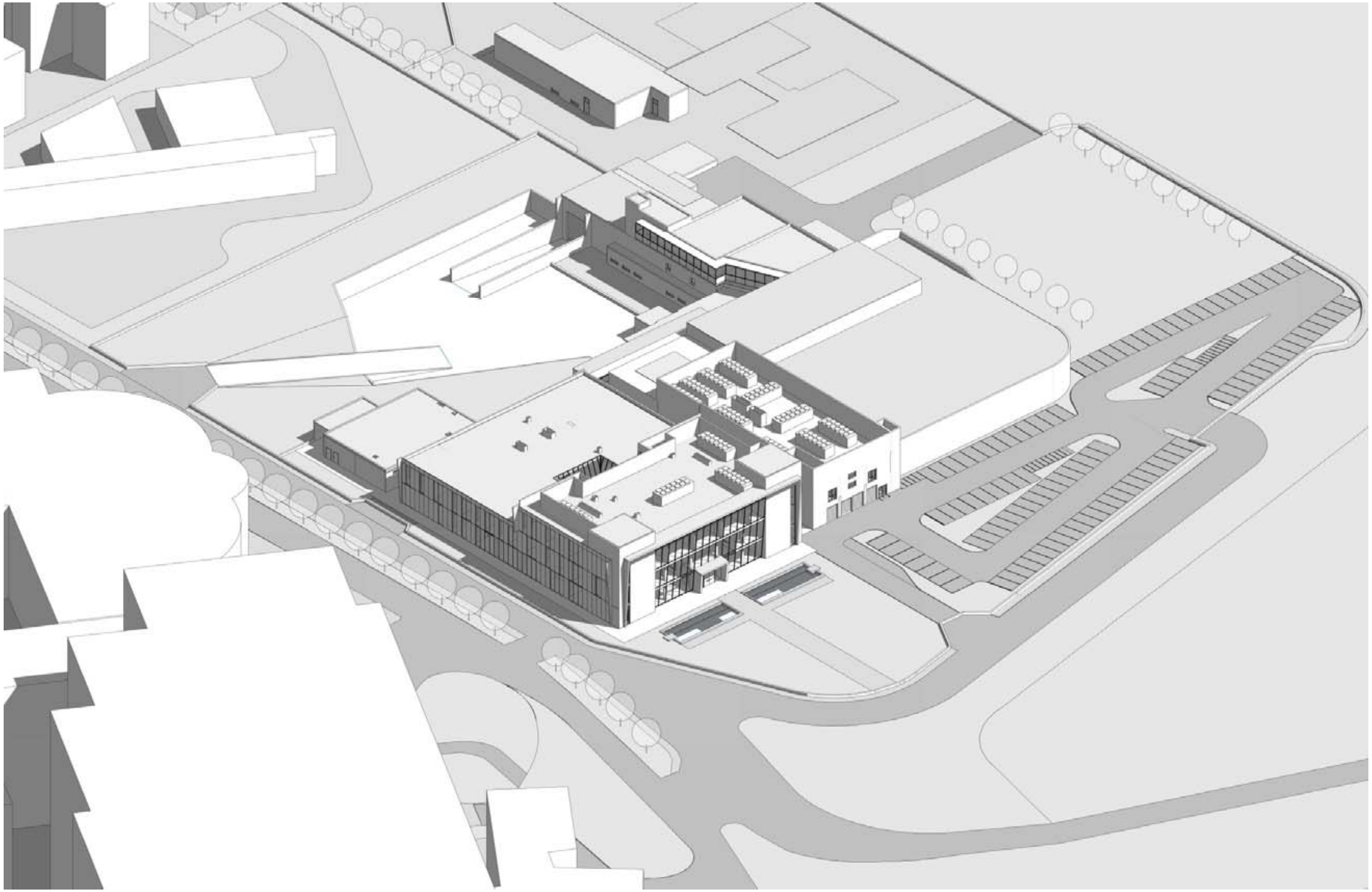
Data analysis in progress

AISHA at CNAO: installation in progress

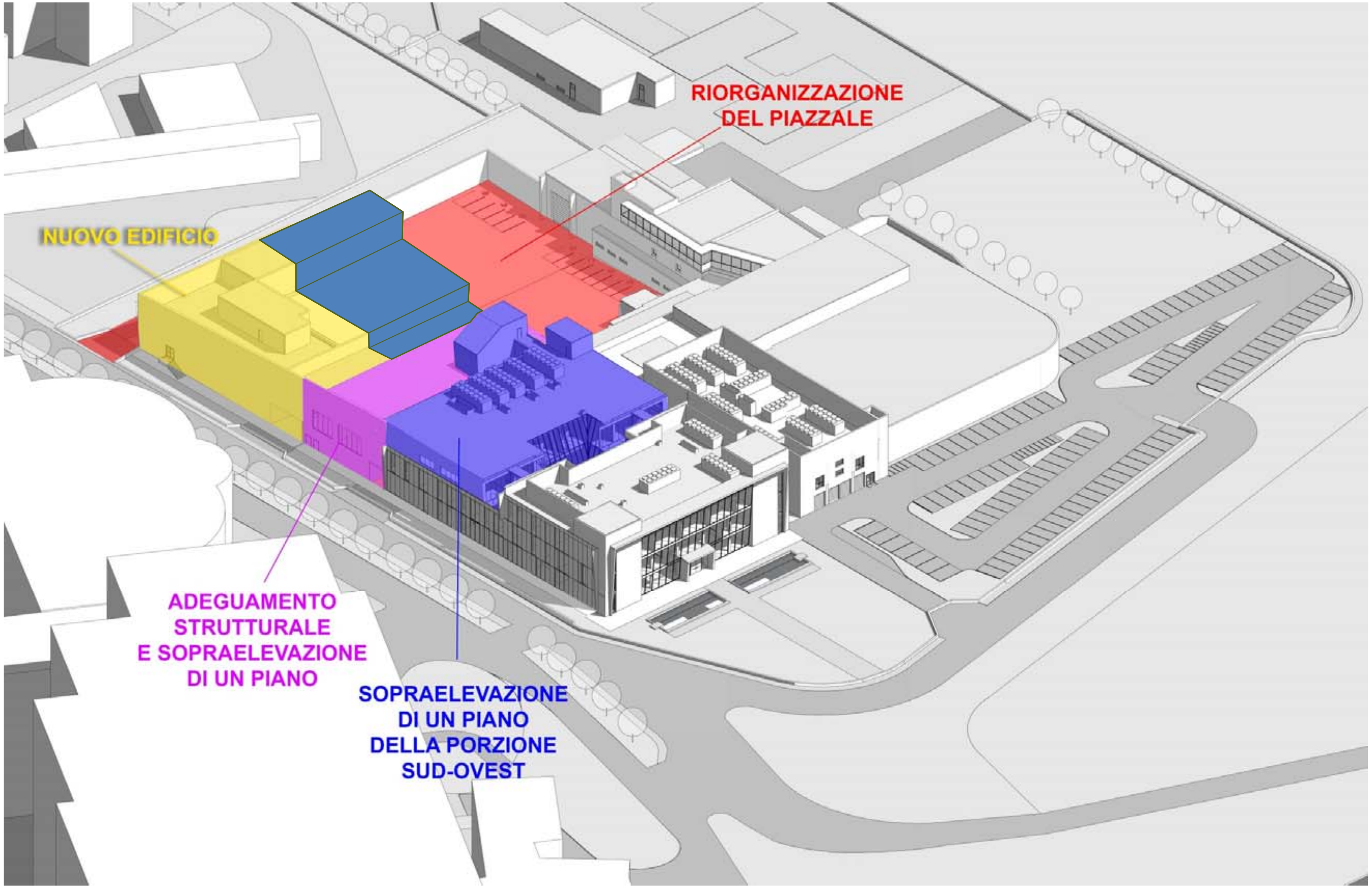
CNAO expansion project

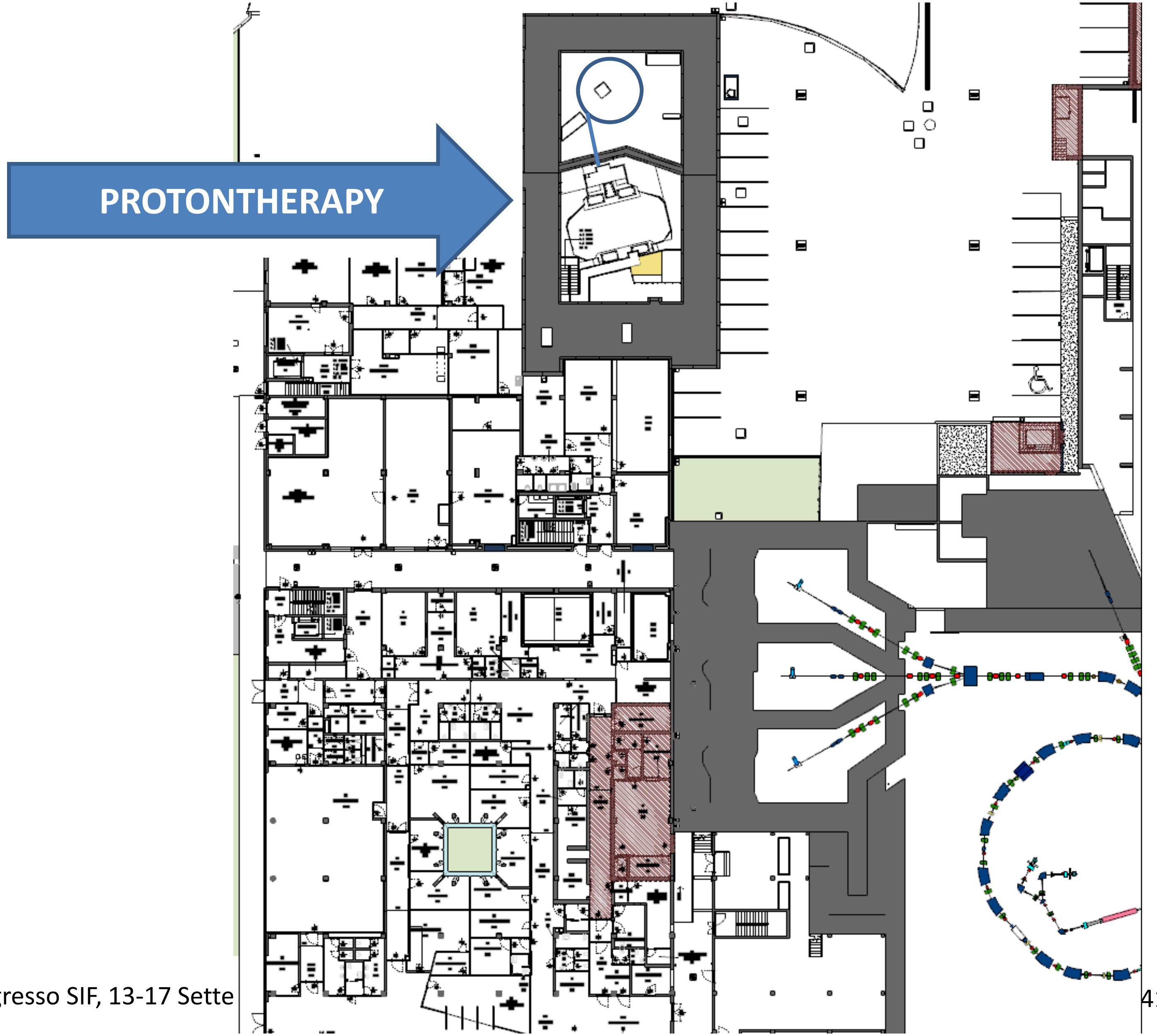


Present

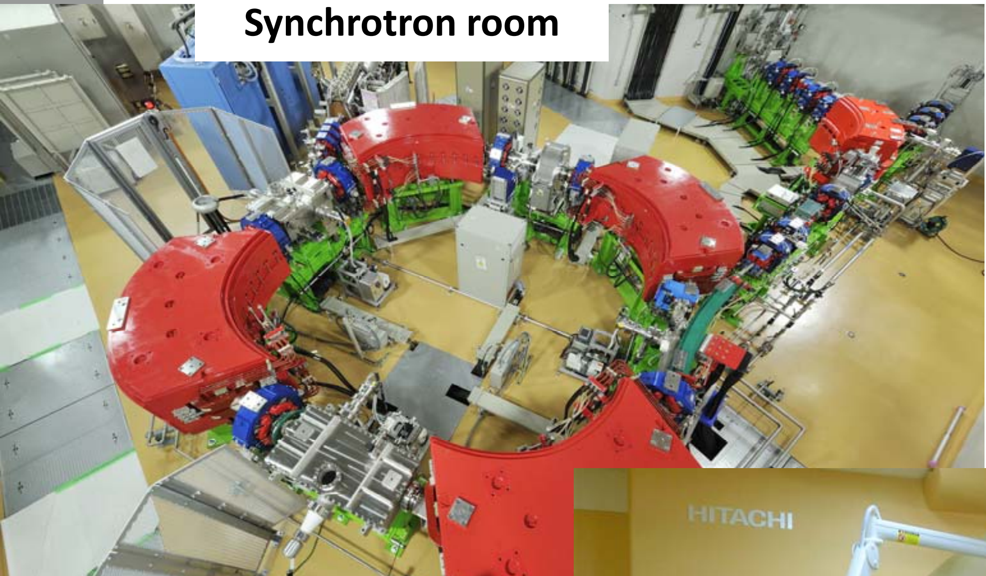


Fully operational end 2023




PROTONTHERAPY

Single room facility with gantry for protons



Synchrotron room

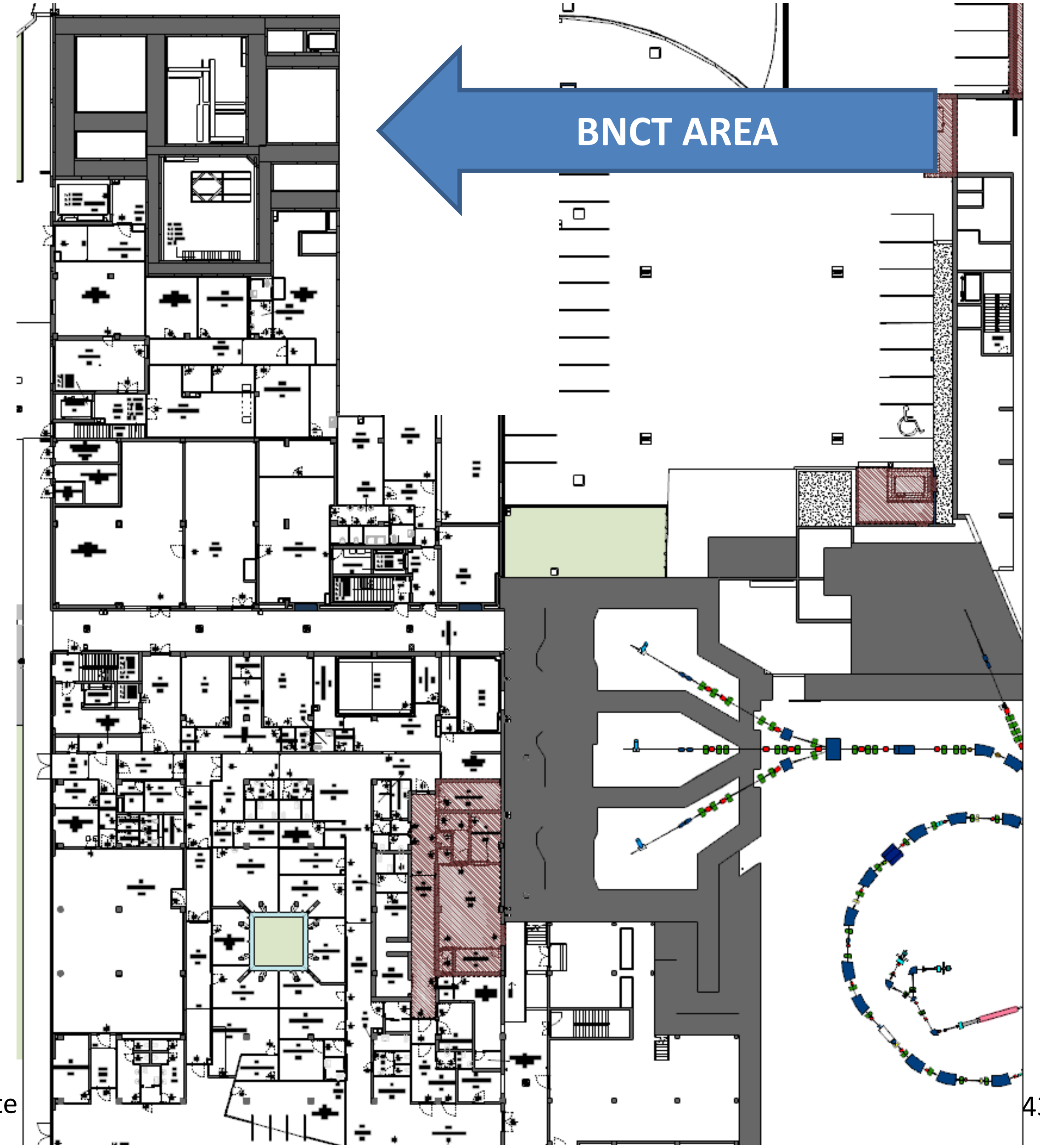
Contract signed with Hitachi:
December 5th, 2019

Operational end 2023

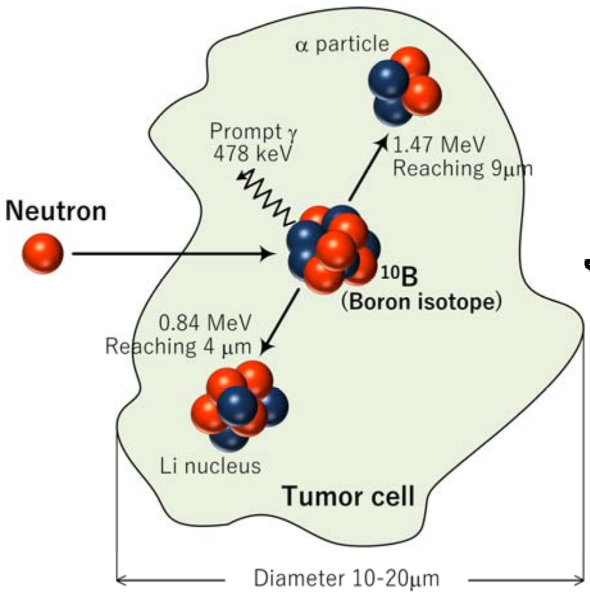
360°isocentric gantry
(Field size: 30x40 cm²)

Treatment room

BNCT



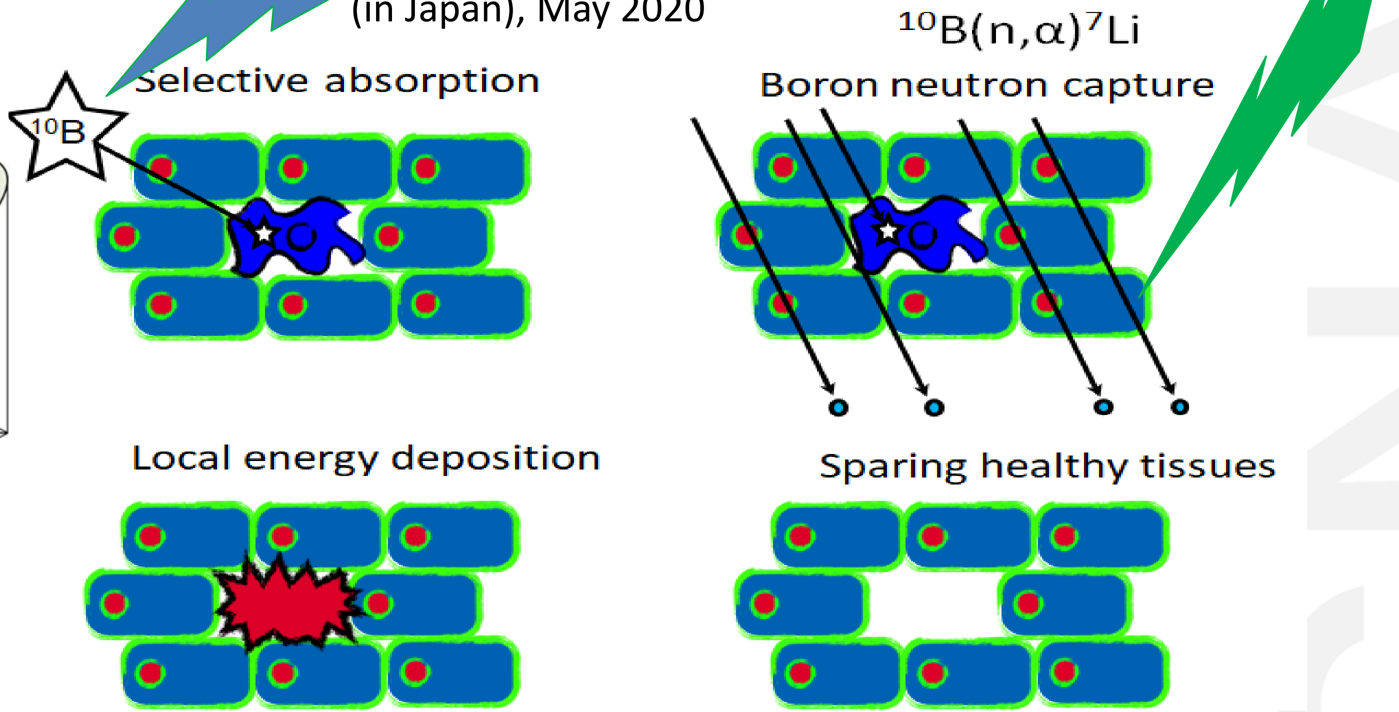
BNCT



Boronated drug that selectively reaches the tumour cells and avoids the healthy tissues

Accelerator driven neutron production

First Approved BNCT Drug (in Japan), May 2020



Accelerator based BNCT

Collaboration agreement signed
September 2020

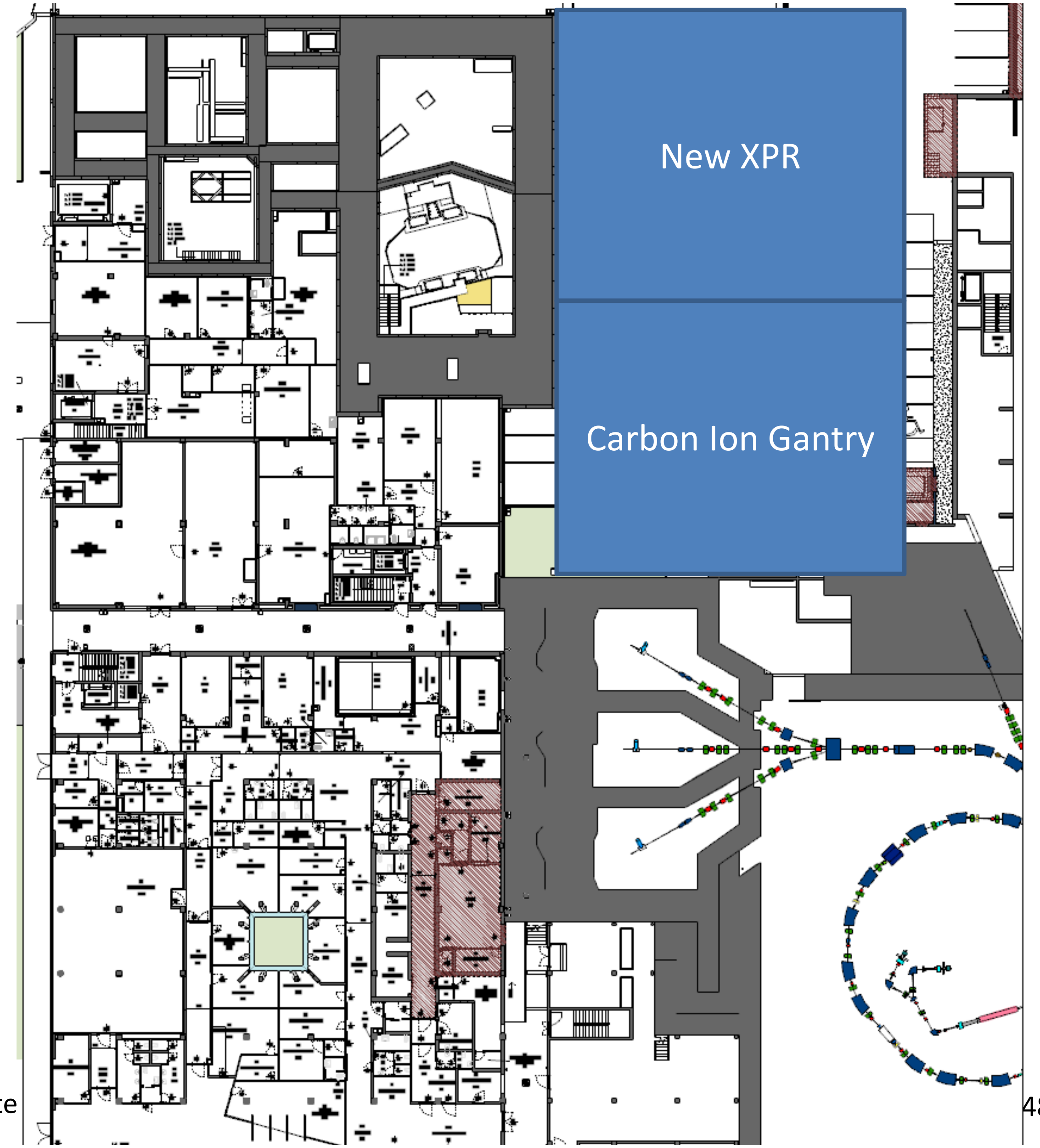
Operational end 2023

Proton energy 2.5 MeV
Intensity 10-15 mA
p-Li reaction

Similar installation, Clinic in Xiamen (Fujian, China)

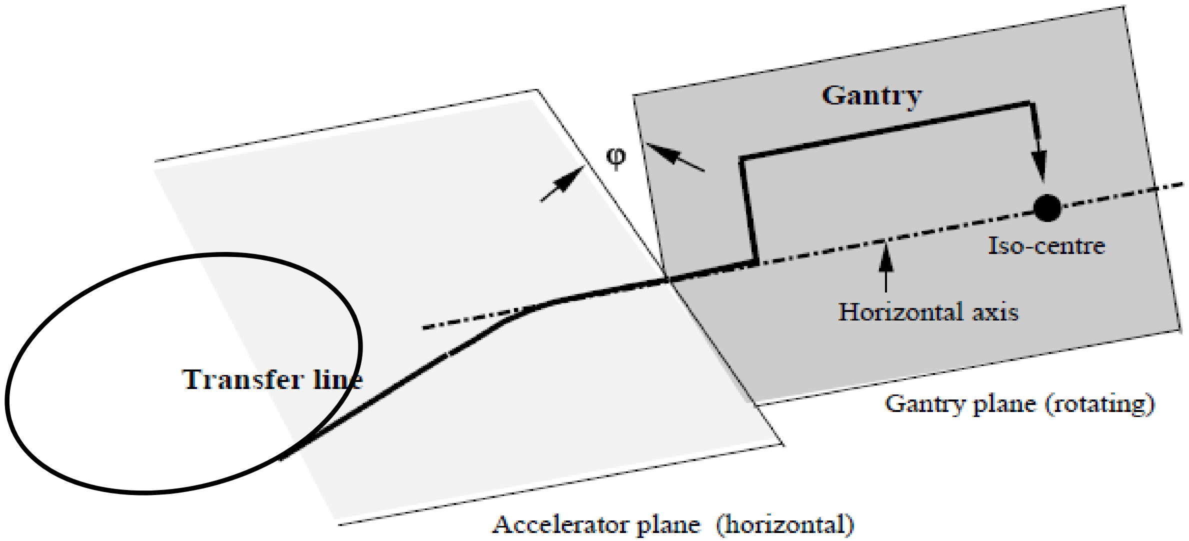
(Sergey Taskaev, Frascati 2019)

Next steps


New XPR
Carbon Ion Gantry

What is a gantry

- A gantry is a section of beamline that can rotate around the isocenter in order to direct the beam onto the patient from any direction

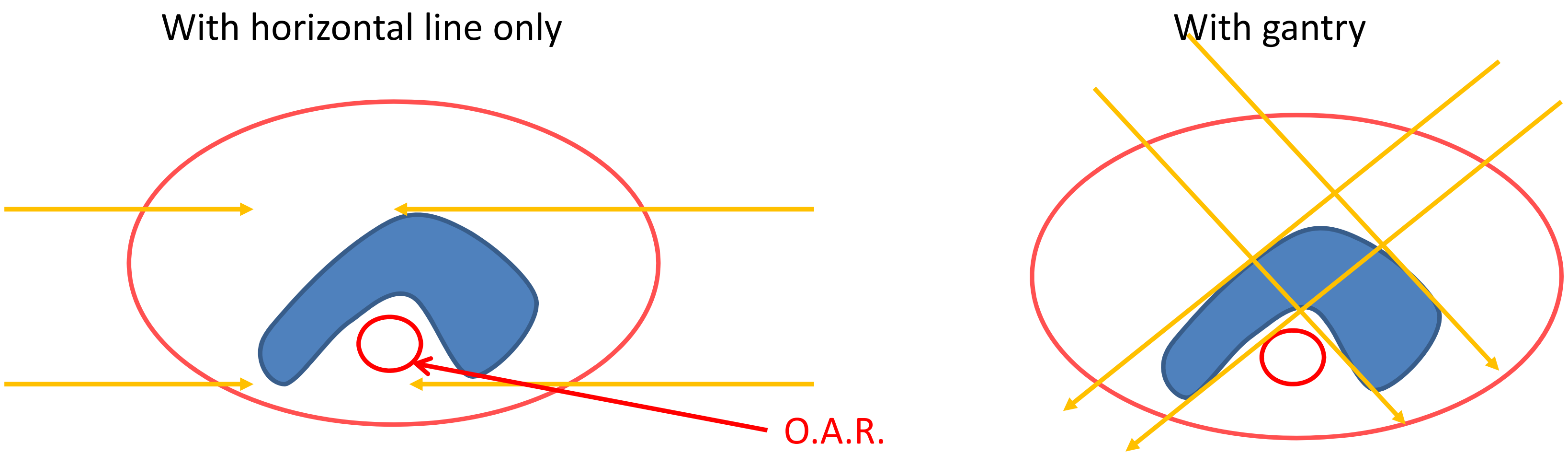


Why a gantry?

- To treat patients in supine position (eventually prone) in the same position in which CT, PET and MRI were acquired. Patient rotation only around gravity to preserve internal organs and soft tissue geometry.
- To provide the maximum flexibility in selecting the irradiation direction when optimising the dose delivery.
- To allow a “robust” treatment planning. Exploiting the sharp distal fall off can be risky in some cases and a gantry helps in avoiding fields directed towards an Organ At Risk (OAR).
- Avoid density heterogeneities
- Minimize SOBP extension (less energies required and better peak to plateau ratio)

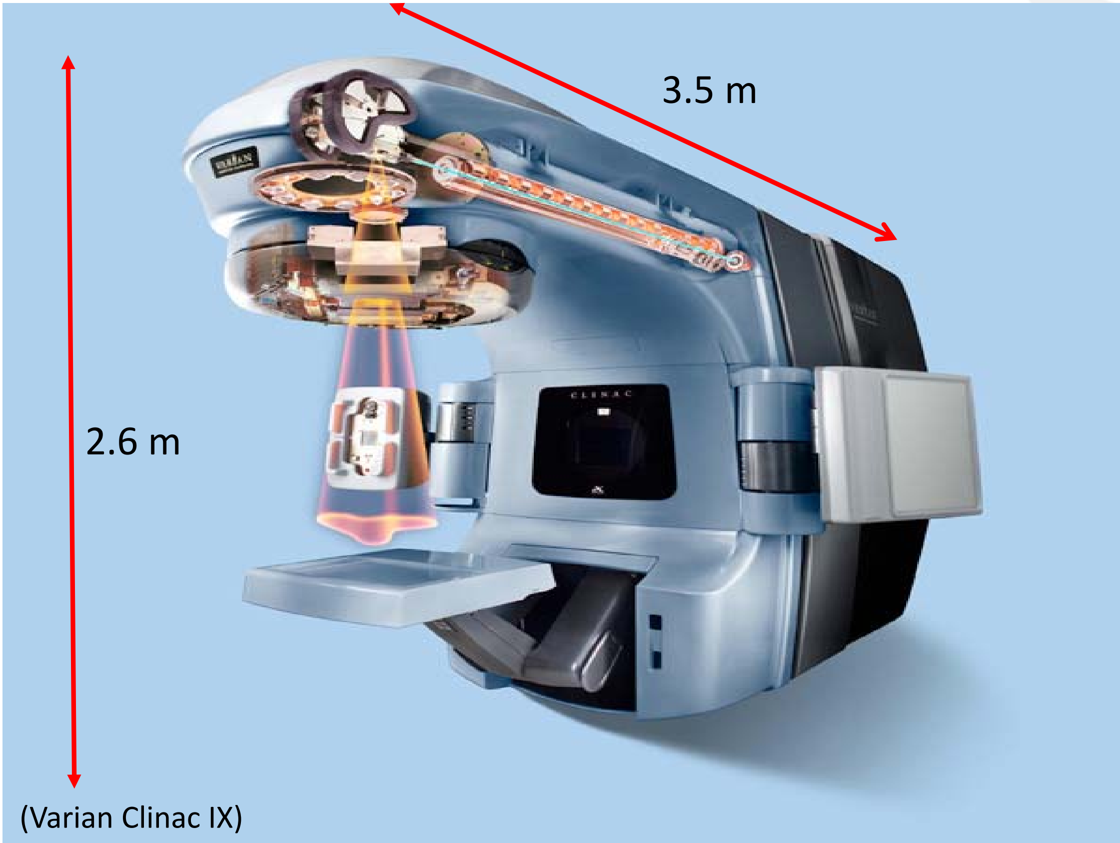
Why a gantry

Allows better, more robust planning:
e.g. minimize fields pointing towards OAR (Organ At Risk)



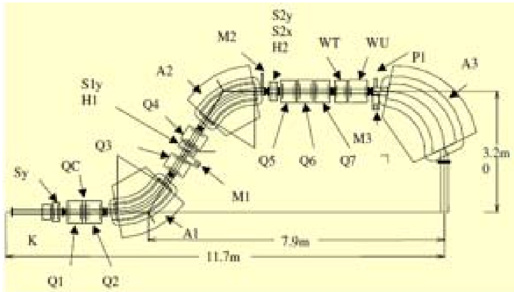
Gantry in conventional radiotherapy

- The whole linac is inside the gantry
- The gantry head can pass between patient and floor for irradiation from below



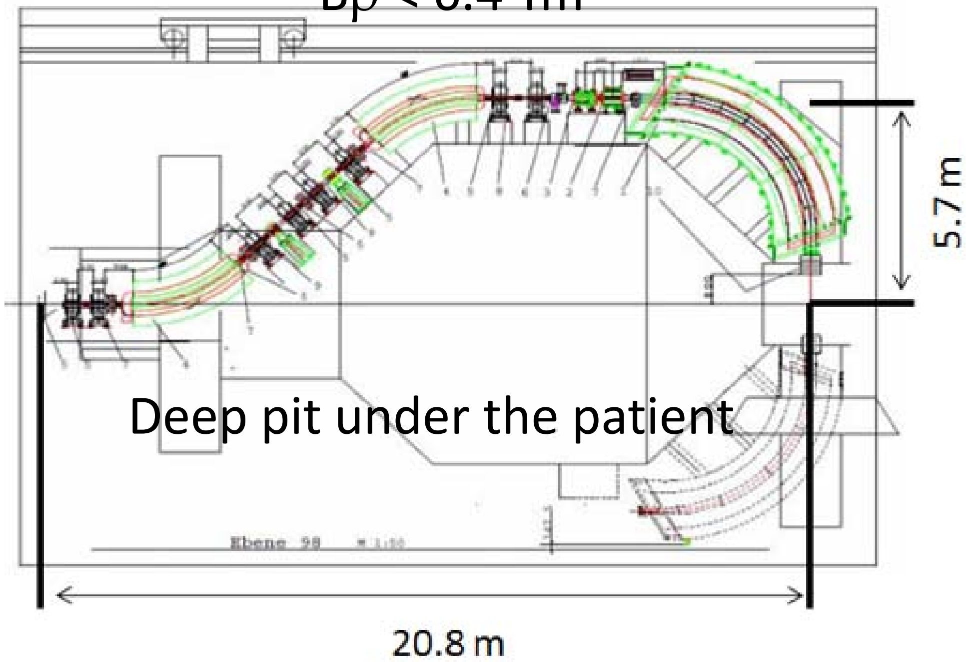
Size and magnetic rigidity

Conventional RT



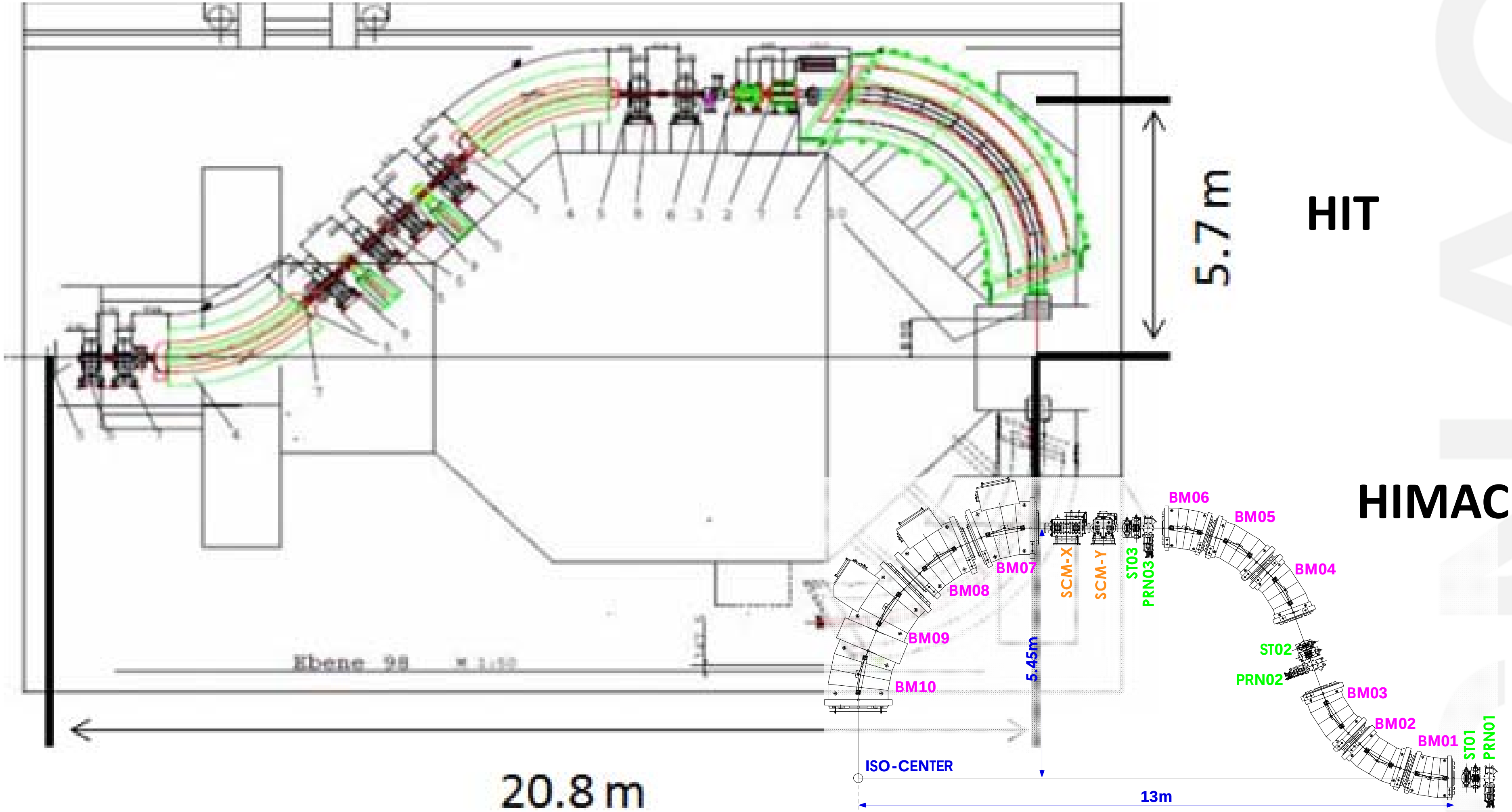
Proton Gantry
Bρ < 2.4 Tm

Carbon Ion Gantry
Bρ < 6.4 Tm



Deep pit under the patient

Only 2 C gantries in clinical operation so far



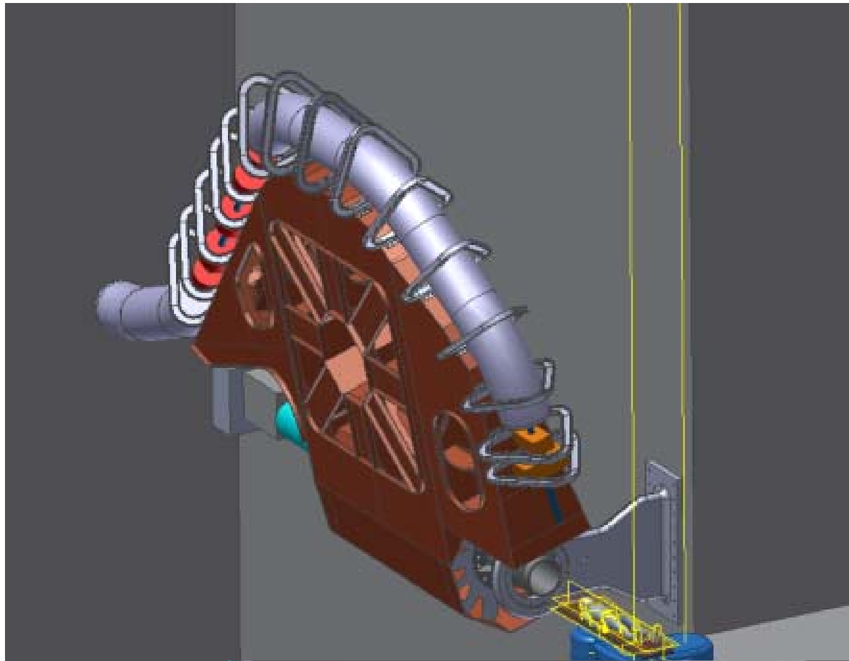
NIRS superconducting rotating gantry

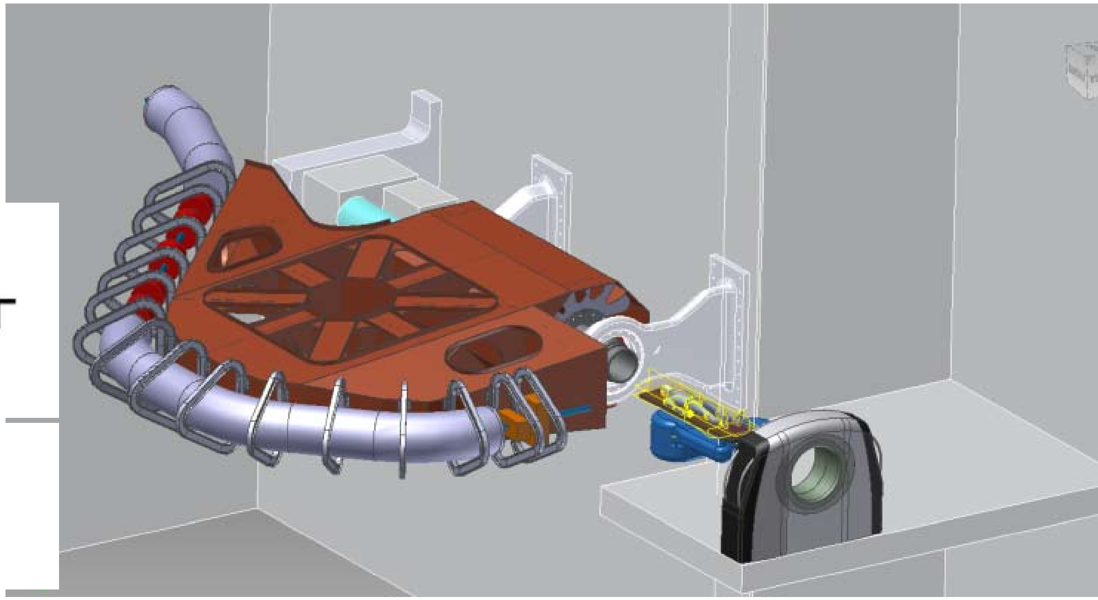
R&D: SC carbon ion gantry

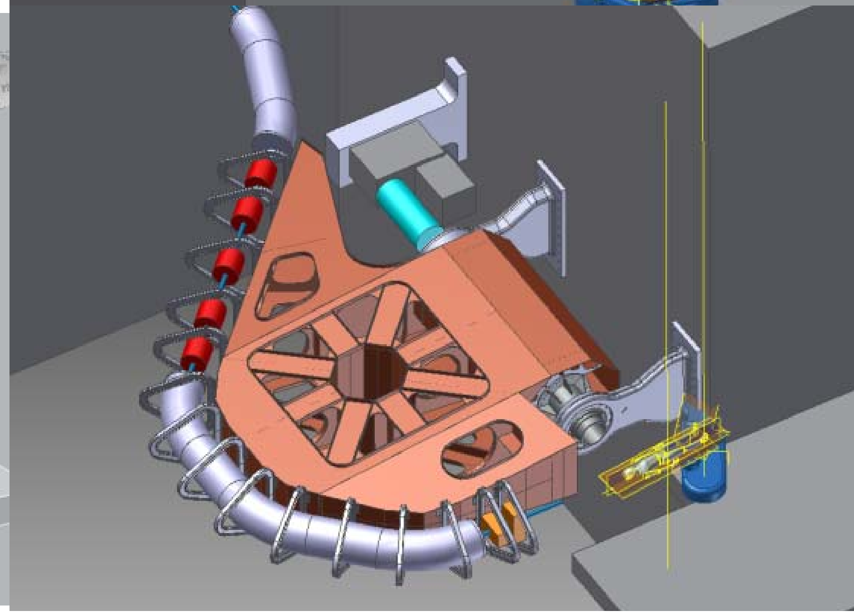
CNAO-INFN-CERN-MedAustron collaboration under discussion.
design start 2021, 4 years duration

Synergies with european projects (IFAST, HITRIPLUS)

Based on the SIGRUM design by TERA Foundation







Research and development are fundamental

- R&D needed to stay at the forefront
- R&D on many subjects
  - Machine operation improvement (e.g. RFKO, MultiEnergy)
  - Improved dose delivery (e.g. organ motion management, 4D DDS)
  - Improved treatment delivery (e.g. new ions, LET painting)
  - Dose delivery and range verification (e.g. Online PET, prompt particles and gamma monitoring, improved beam monitoring)
  - Improved research facility (e.g. XPR, new ions, new lab)
  - Center upgrade (e.g. proton SRF, BNCT, ion gantry)
  - …

"Physics is like sex: sure, it may give some practical results, but that's not why we do it. "

R. Feynmann