Development of BIOMAT researches at NICA facility

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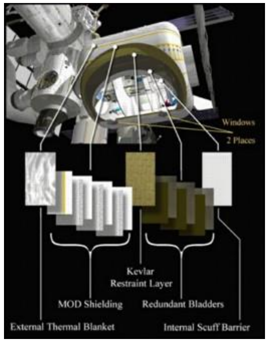
Outline

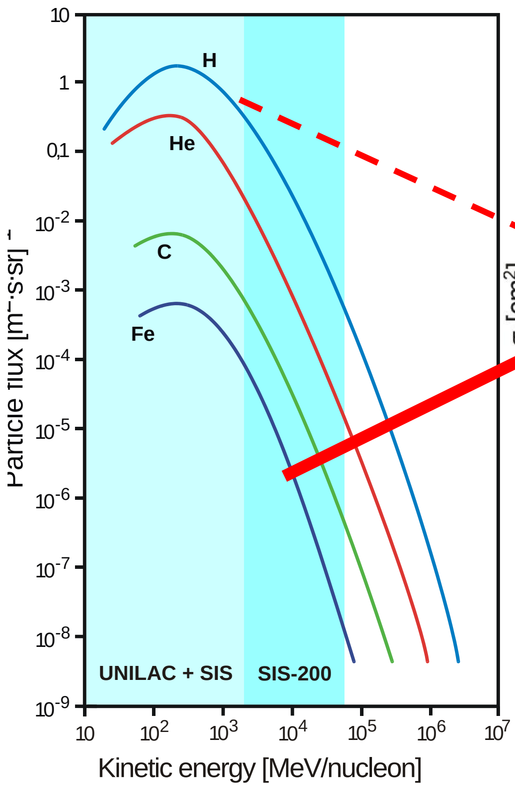
- Motivation and view on applied research development in the material science and radiobiology at NICA
- The draft of the first stage of the experimental setup BIOMAT@NICA:
  - to direct research of influence of a high energy protons and heavy ions with energy up to 0.8 GeV/n on the electronic equipment used in special equipment and space devices
  - to research on impact of protons and heavy ions on a biological objects and materials

BIOMAT - Space Research

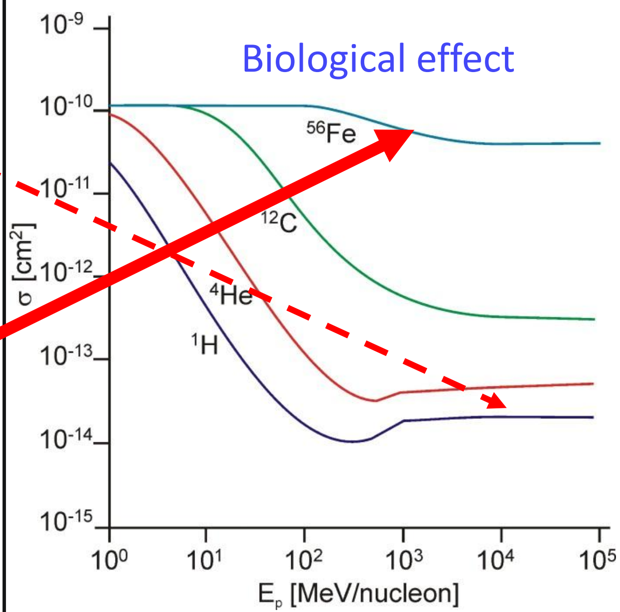
Solar and galactic particle radiation consists primarily of protons and helium ions, but the relatively small number of heavier ions in the galactic cosmic radiation (GCR) can significantly contribute to radiation dose due to their high ionization energy loss.

- In humans - genetic alterations, cancer, cataracts, cognitive abilities and so on
- In space instrumentation - as the high charge locally deposited by energetic heavy ions can produce changes in electronic devices

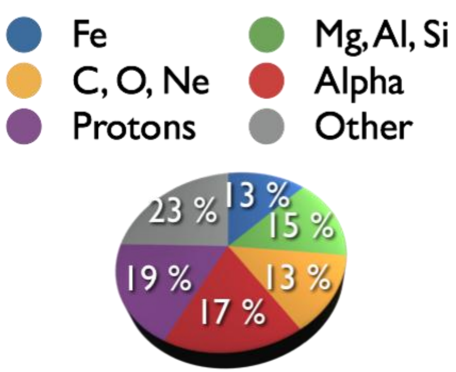




Particle spectrum Galactic Cosmic particles



Contribution to a dose for GCR particle

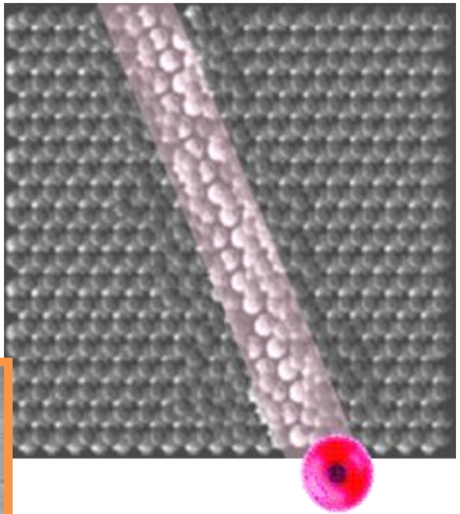


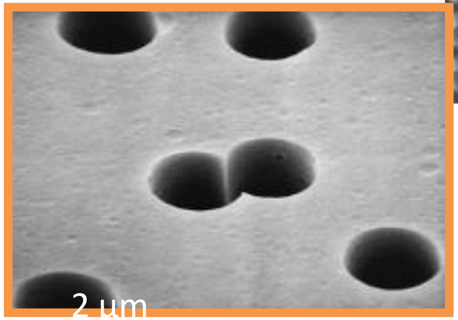
Task: simulation of cosmic particle radiation using high-energy accelerators

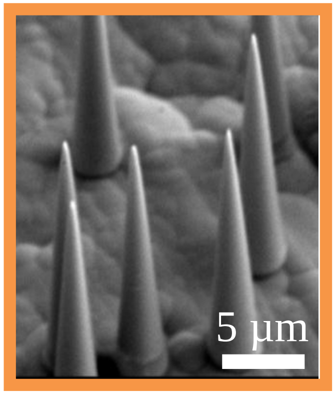
- Test and calibration of space flight instruments
- Radiation hardness tests
- Radiobiological risk assessment for manned space missions

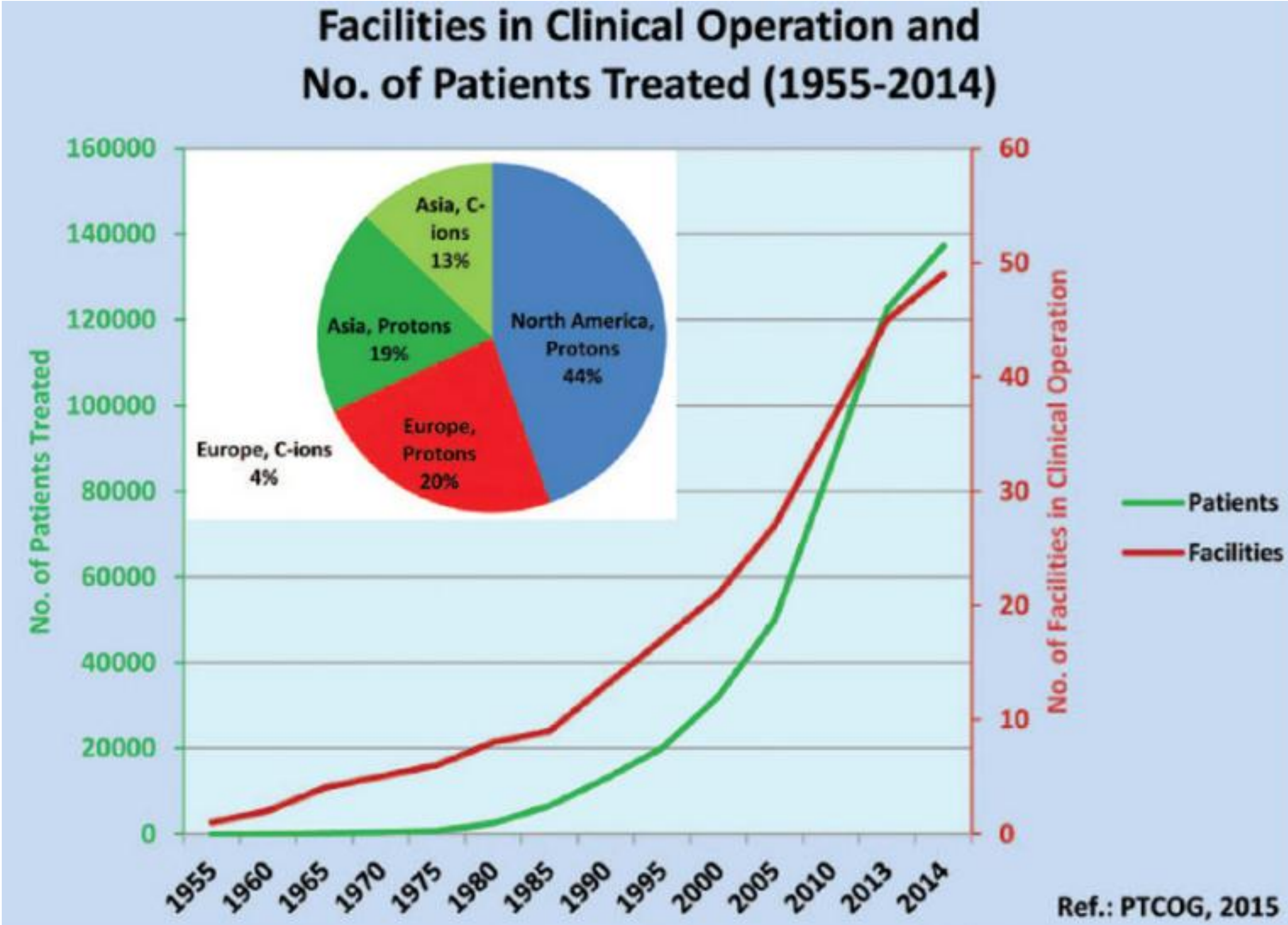
BIOMAT - Materials Research and Nanotechnology with High Energy Ion Beams

- **Ion - Solid interaction processes**
  - Materials response in extreme environments
  - Ion beam induced modifications
  - Radiation damage in various materials
  - Materials under extreme conditions
- **Ion-Track Nanotechnology**
  - Nanopores
  - Nanowires









Charged particle therapy facilities in operation and patients treated with charged particles from 1955 to 2014. In the pie chart, the distribution of the patients treated only in 2014 with charged particles in different continents is provided. The total number of patients treated with particles is 137 000, with 15000 treated in 2014 only. Data from PTCOG website (www.ptcog.ch), charts reproduced with permission from Jermann (2015). CC BY 4.0.

Marco Durante and Harald Paganetti, Rep. Prog. Phys. 79 (2016) 096702 (59pp)

BIOMAT- radiobiology @ charge particles beam therapy

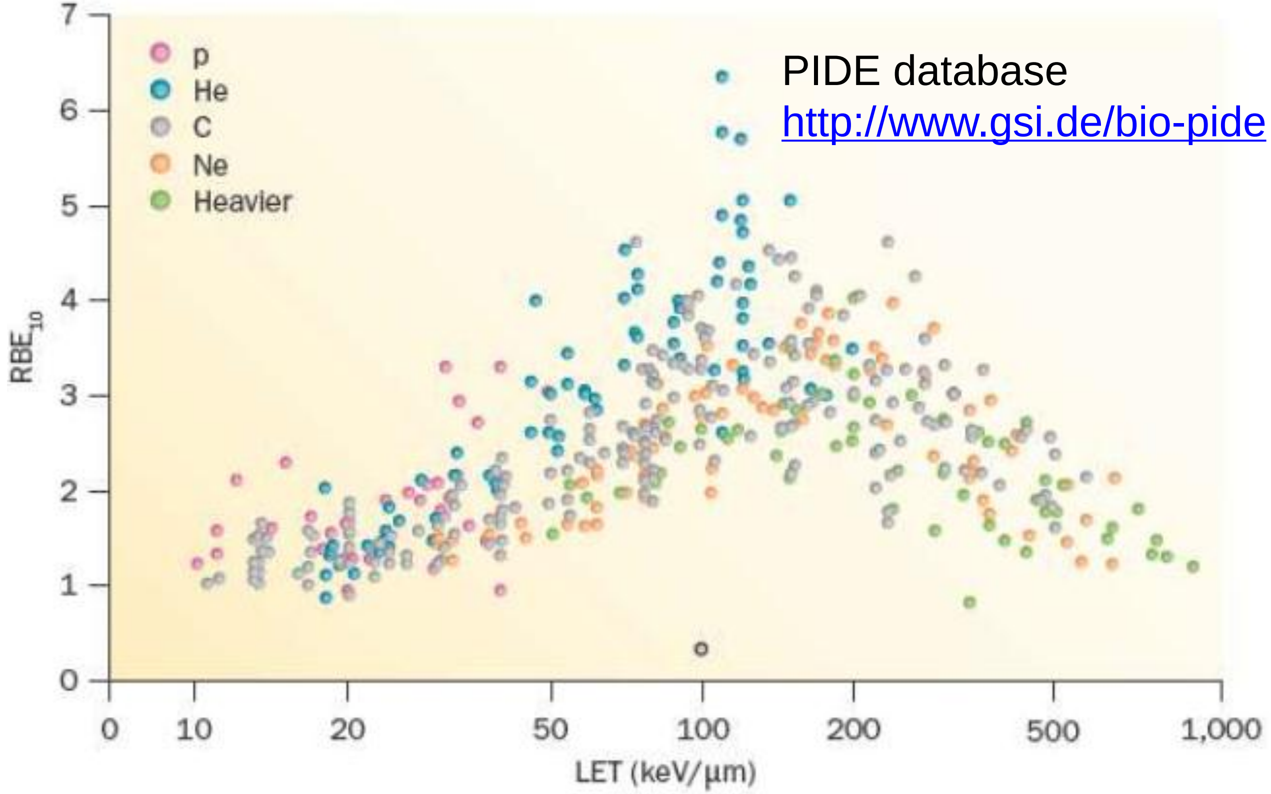
Main tasks:

- Irradiation of moving tumors
- Decrease of RBE uncertainty;
- Risk of development of secondary cancer
- Hypofractionating;
- Uses of other ions, for example oxygen ions;
- ……

BIOMAT- radiobiology @ charge particles beam therapy

Decrease of RBE uncertainty

Dependence of RBE on LET (these more than 800 experiments)



RBE compared with LET from published experiments on *in vitro* cell lines. RBE is calculated at 10% survival, LET values are given is keV/μm in water. Different colours indicate different ions, from protons to heavy ions. Data points are extracted from the particle radiation data ensemble (PIDE) database (Friedrich *et al* 2013), which currently includes 855 survival curves for cells exposed to photons (α/β ratio ranging 1–30) and ions. PIDE is available online at www.gsi.de/bio-pide. Figure from Loeffler and Durante (2013)

Beam requirements for BIOMAT research

- Since the relevant energy spectra of solar and galactic cosmic rays cover a broad range, it is of utmost importance to offer a wide range of energies at the BIOMAT installation.

  Energy - up to 10 GeV/u, Type of ions -- p – U, (the required range of LET values in Si – 120MeVcm2/mg), Slow extraction beam: - ≥ 1 s.

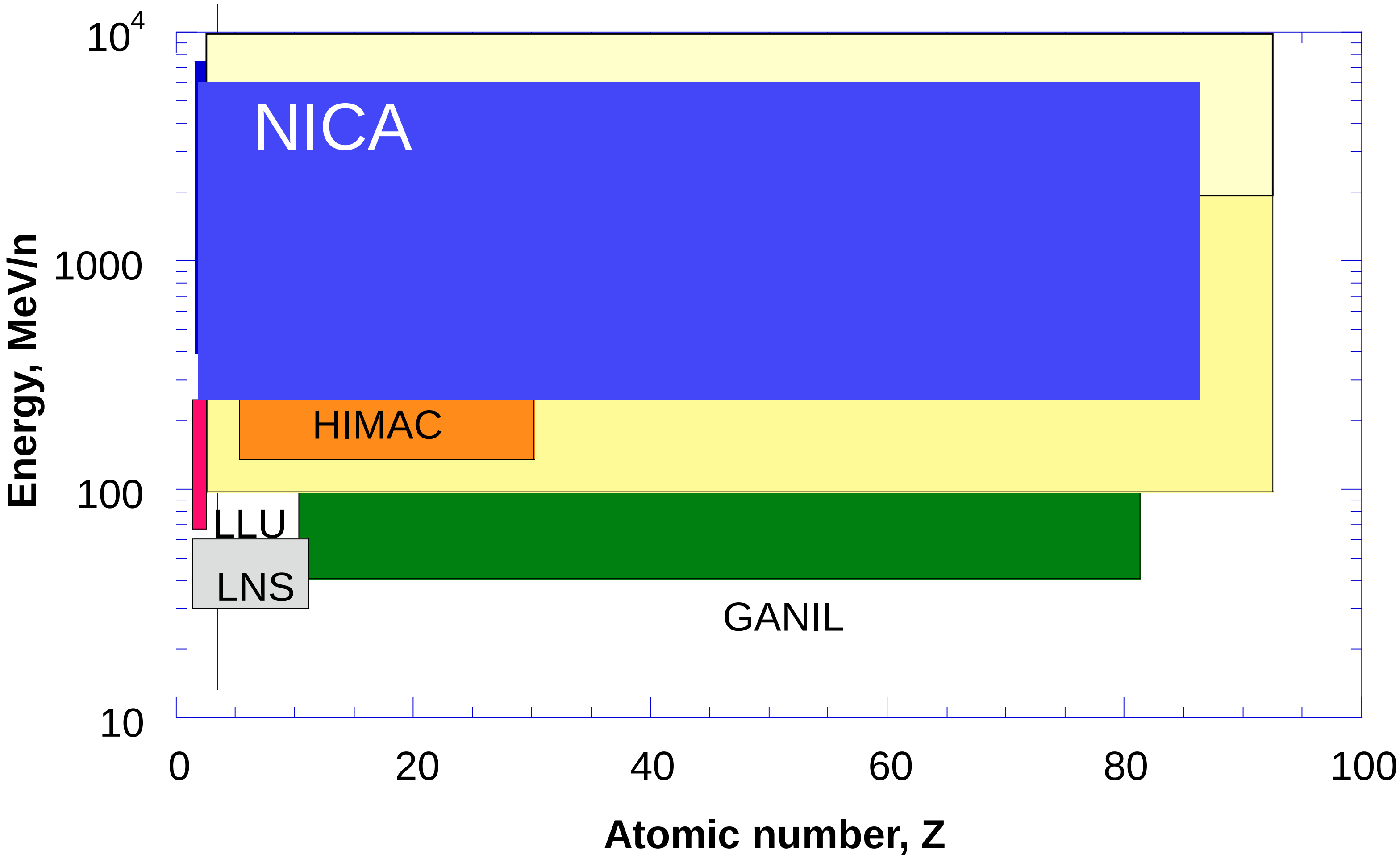
  Intensity: For the heavier ions the maximum intensities are defined by tolerable flux and fluency requirements of the materials research program in combination with reasonable exposure times. 10E3 - 10E9 ion/sm2 s.

  For space research experiments (e.g. space flight instrument calibration or radiation hardness tests of electronic components) need a very low intensities of the order of 10E3 - 10E6 ion/sm2 s.

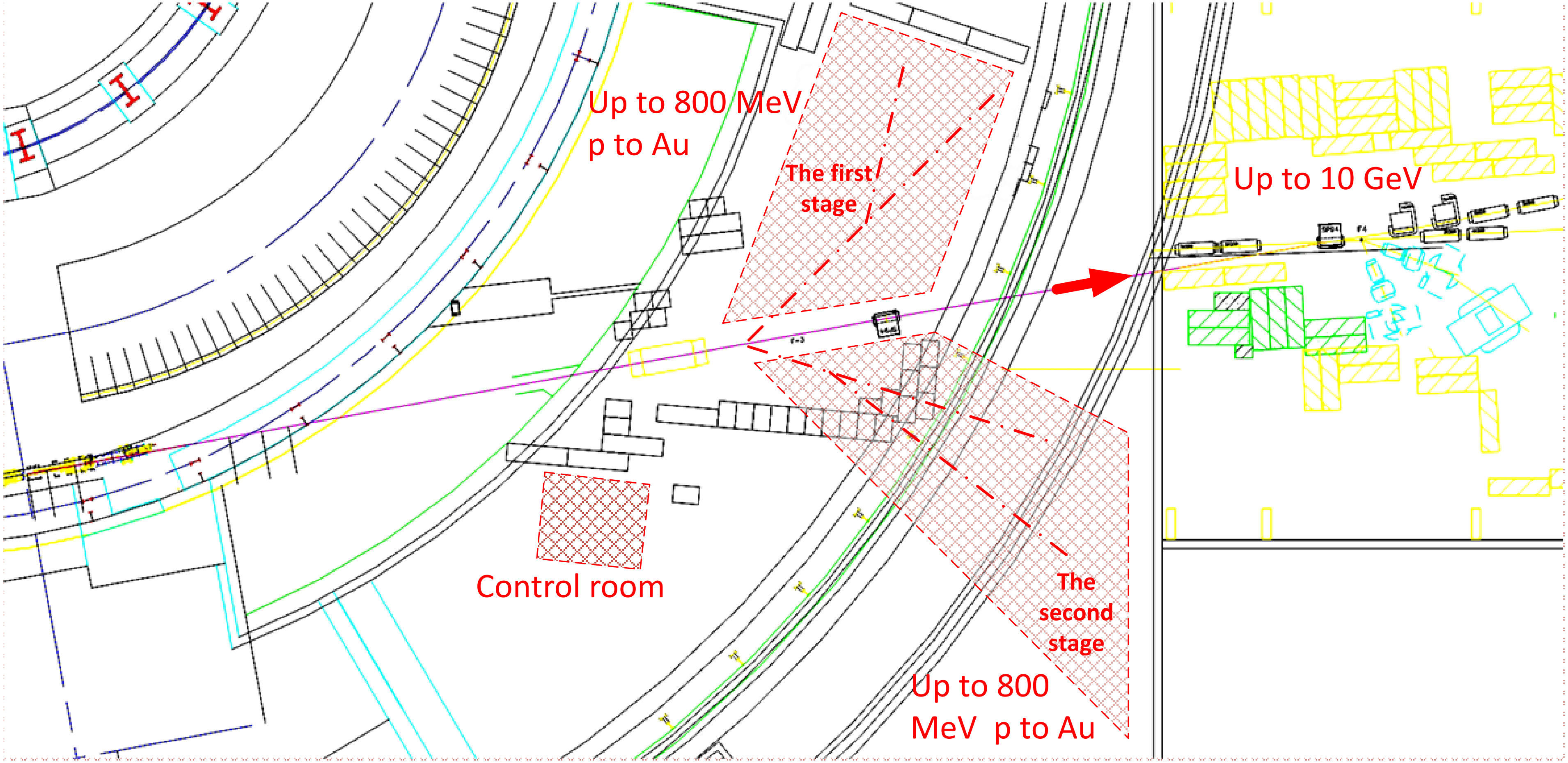
- Biophysics and materials research experiments require a representative set of beams ranging from protons to uranium. The maximum required beam intensities for ion species correspond to the delivery of a homogeneous dose of 10 Gy to a target area of 100 cm2 in about 1 min. With such a dose rate acceptable irradiation times are reached. This is very important for the irradiation of sensitive biological samples (e.g. cell cultures) which need to be kept in a growth medium

Final decisions concerning highest beam intensities require more detailed calculations of radiation exposure outside the cave of experimental area and need to be discussed with the radiation protection group.

Heavy-ion accelerator facilities



Experimental areas for BIOMAT research



The first – the experimental setup at the gallery for the irradiation of electronics for space equipment's, materials and biological objects

The second - the radiobiology research to application of carbon therapy including of proton microscope for visualization of area irradiation

The third – the radiobiology researches on influence the high energy up to 10 GeV/u of protons and heavy ions on biological samples

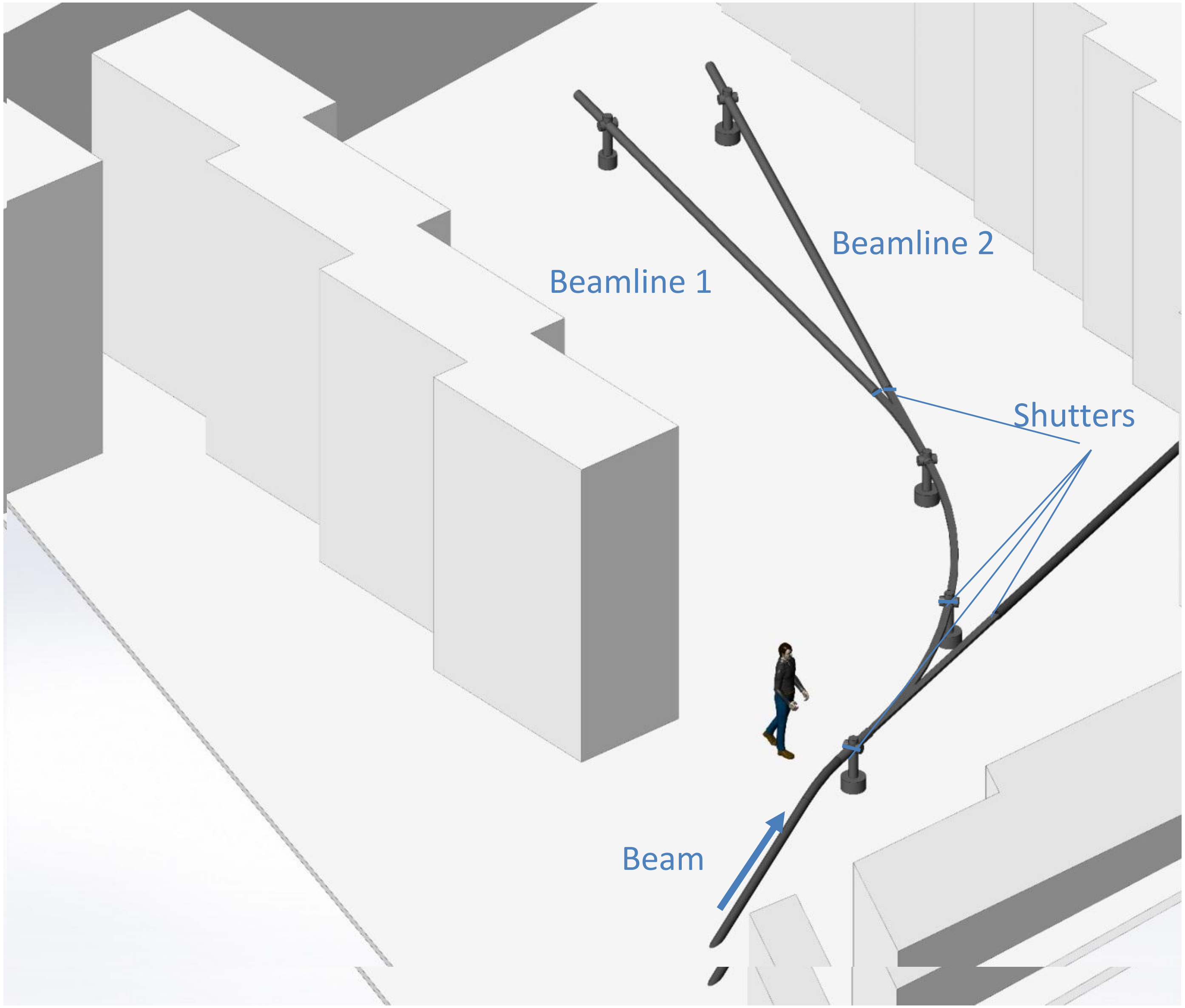
Components of the irradiation facility

- beamline with vacuum pumping
- ion-optical system
- beam diagnostics
- target station with target handling systems
- beam monitors at target position
- radiation shielding
- beam dump
- control room and laboratory rooms
- auxiliary equipment (e.g. positioning lasers, TV-cameras)

The installation will be used by many different groups for the irradiation of electronics for space equipment's, materials and biological objects. This requires a flexible target area and a variety of target handling systems which should meet the requirements of typical irradiation experiments. In this way, it was decision to develop two beam lines with a target stations.

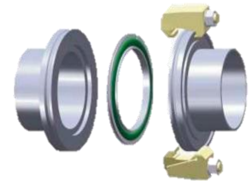
Beamline and vacuum system

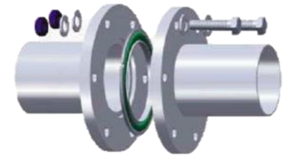
System Requirements:
Vacuum range:
10^{-7} - 10^{-8} torr
Two independent beamlines
Thin vacuum windows for beam output



Vacuum pumping system

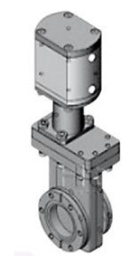
- **Standard fitting type ISO/CF - 160:**
  Tube size Ø152mm, vacuum range up to 10^{-8} torr , material - steel ANSI 304/L, gasket material – FKM(Viton)



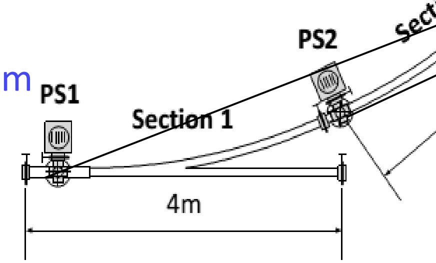
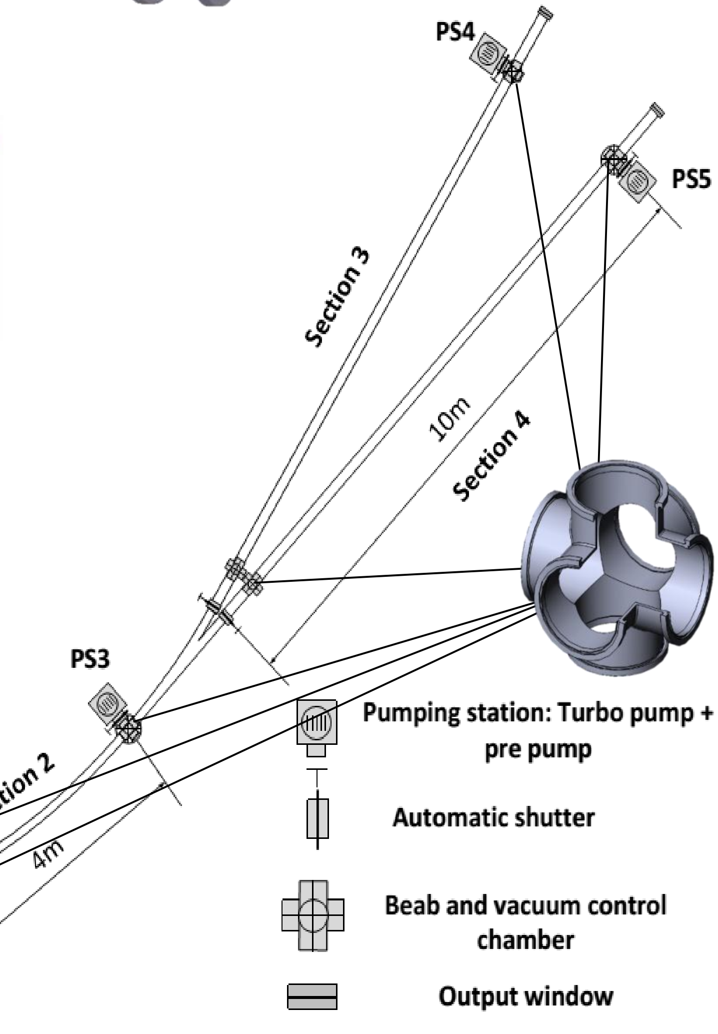


- **5 independent pumping stations**
  High rate turbomolecular pump 1000-1500 l/s rate with pre pump 500 – 1000 l/min (e.g. Shimazu TMP + IVATA ISP, or Pfeiffer HiCube)

- **Pneumatic shutters and manipulators operation system**
  Common gas infrastructure (50-150 psi) for all devices

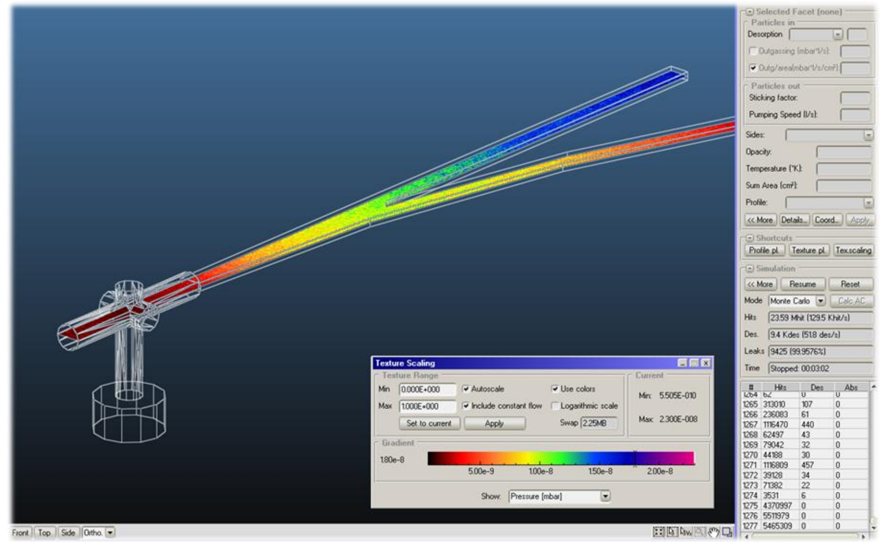


- **Automatic pressure measurement and control system**
  Full-range pressure gauges
  (e.g. Pfeiffer PKR 251/360)
  in connection with shutter operation system

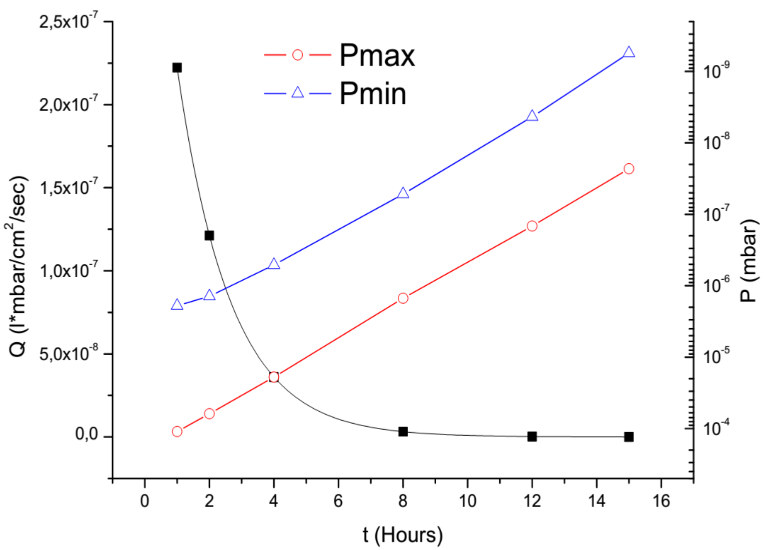
Example of vacuum calculations

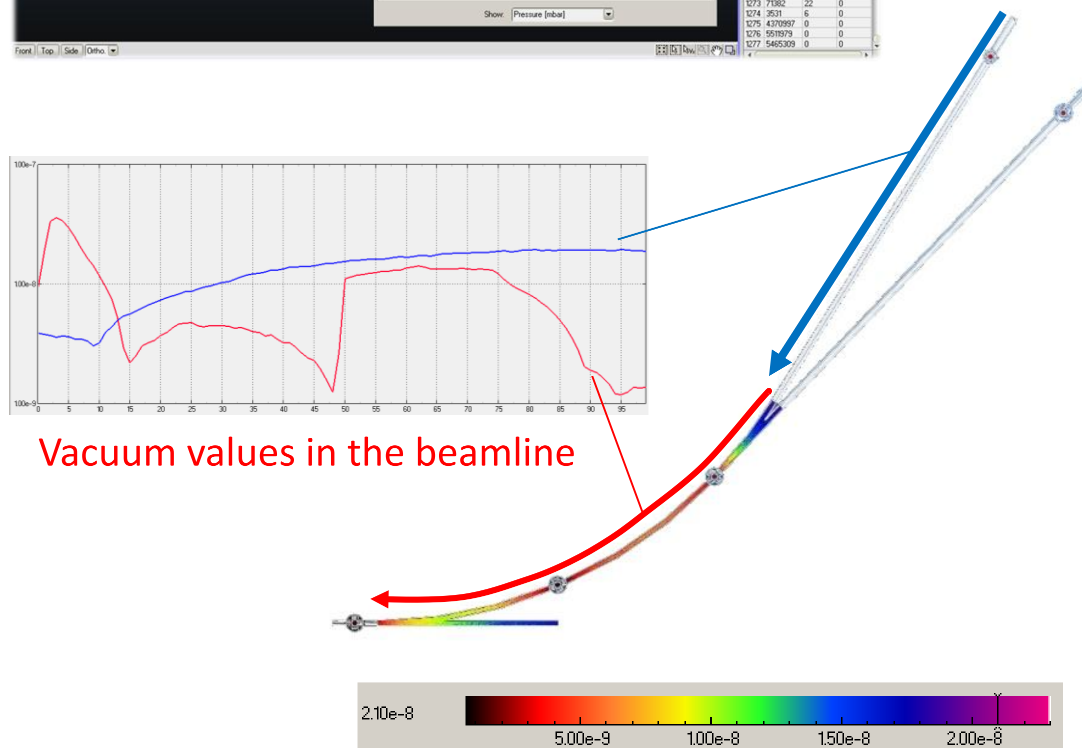
MolFlow+ is opensource software for vacuum Monte-Carlo simulation. It was developed in CERN (molflow.web.cern.ch) and allow to simulate gas flow in current CAD geometry



Beamline simulation parameters:
Material: ANSI 304 (GOST 1X18H10T),
Turbo pump rate: 1000l/s, 5 Pumps geometry.

The range of vacuum values (max and min) in the beamline in depends on time





Vacuum values in the beamline

Beamline: Ion-optical system

Most experiments in radiation biology or space-related radiation tests require irradiations with a beam in air using uniform beam fluxes over rectangular areas of typically 100 -150 mm size at target position. For beam enlargement different methods can be applied:

a. ion-optical techniques

b. active beam scanning

c. passive scattering techniques

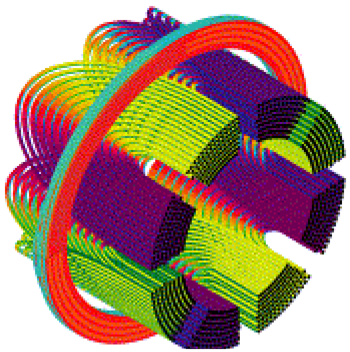
Passive scattering of the beam provides a simultaneous irradiation of the whole object using thin foils at a large distance upstream from the target position results in enlarged beam spots with Gaussian profiles, but can be very effective in combination with ion-optical elements.

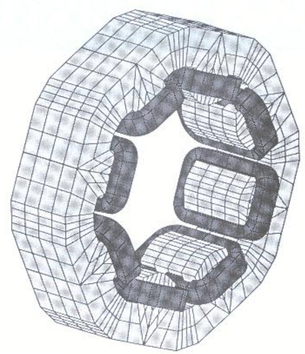
Intensity-controlled beam scanning systems offer highly homogeneous particle fluency's over large areas, which is a big advantage for most irradiation experiments. In addition, the scanned beam is not contaminated with secondary fragments. Scanning systems, however, require sophisticated control systems and the operation is more complex compared to passive systems.

Beamline: Ion-optical system

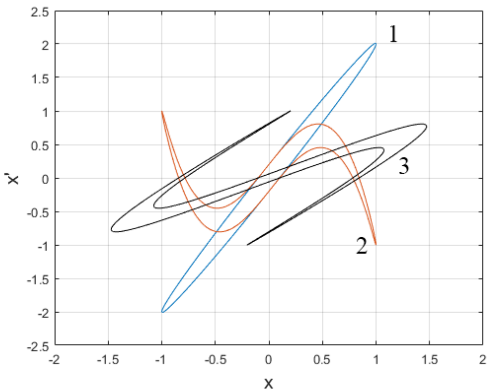
Use of nonlinear optics

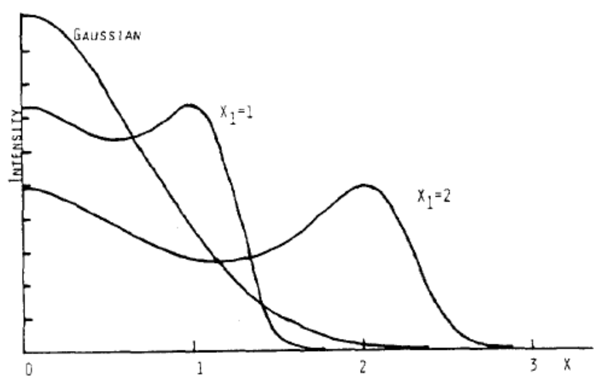
One of ways of formation of uniform distribution of density of a beam on a target is the method of application of nonlinear ion optics.





Several magnetic octupoles installed along an beamline allow to distort a phase volume of a beam in such a way that in the target plane distribution of density of a beam instead of normal Gaussian becomes similar on rectangular





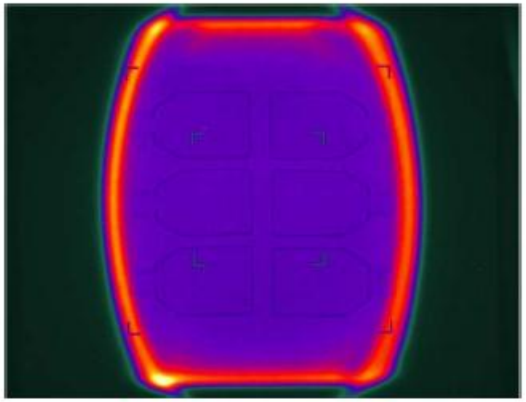
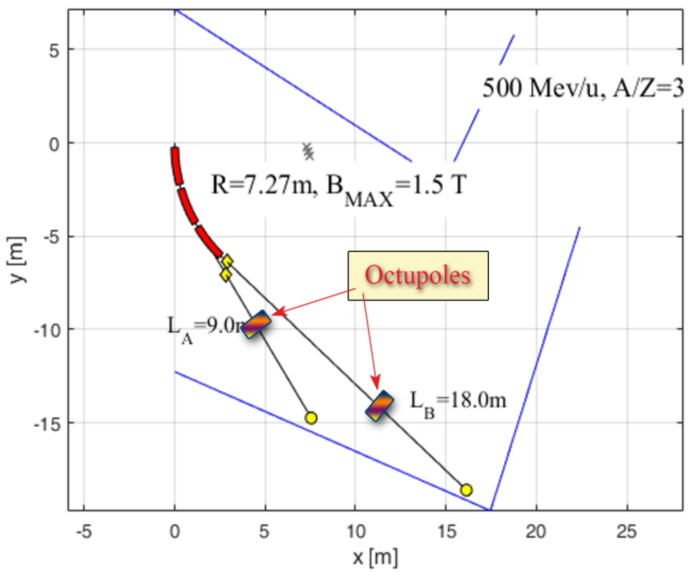
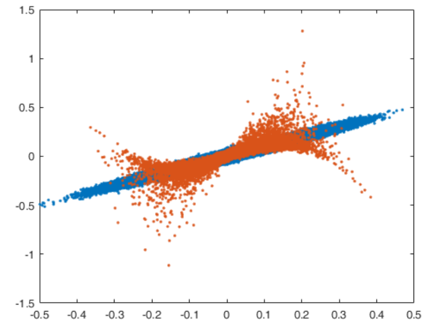


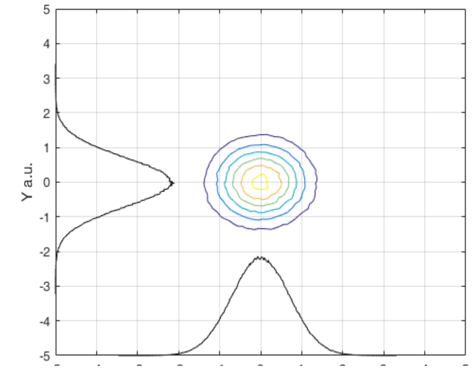
Fig. shows process of formation of a 'rectangular' beam. At correctly picked up initial provision of a beam (a curve 1) and the corresponding magnetic field octupole the phase portrait of a beam is distorted that 2 drawings are shown to a curve. The subsequent drift interval linearly shifts the turned-out distribution so that to receive the most flat area in the center of a beam. Increasing quantity of nonlinear elements it is possible to reach unevenness of distribution of density in borders of several percent at high coefficient of utilization of the accelerated beam. Example of such system created by NASA Space Radiation Laboratory at BNL present.

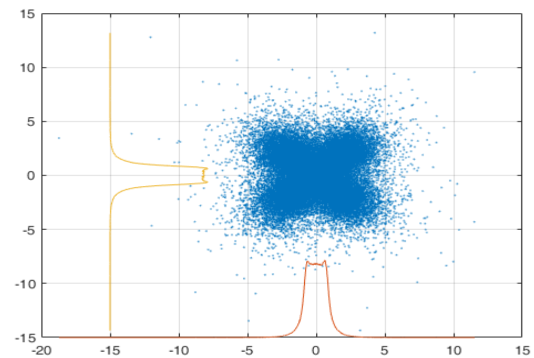
Beamline: Ion-optical system

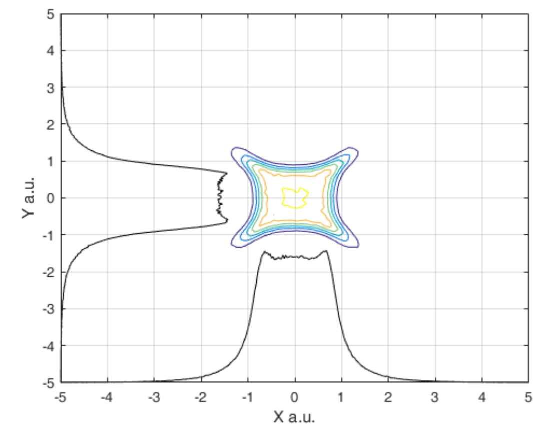
The first version of the uniform field formation of radiation for beam in the Biomat experimental area with one octupole magnet on each of beamlines.







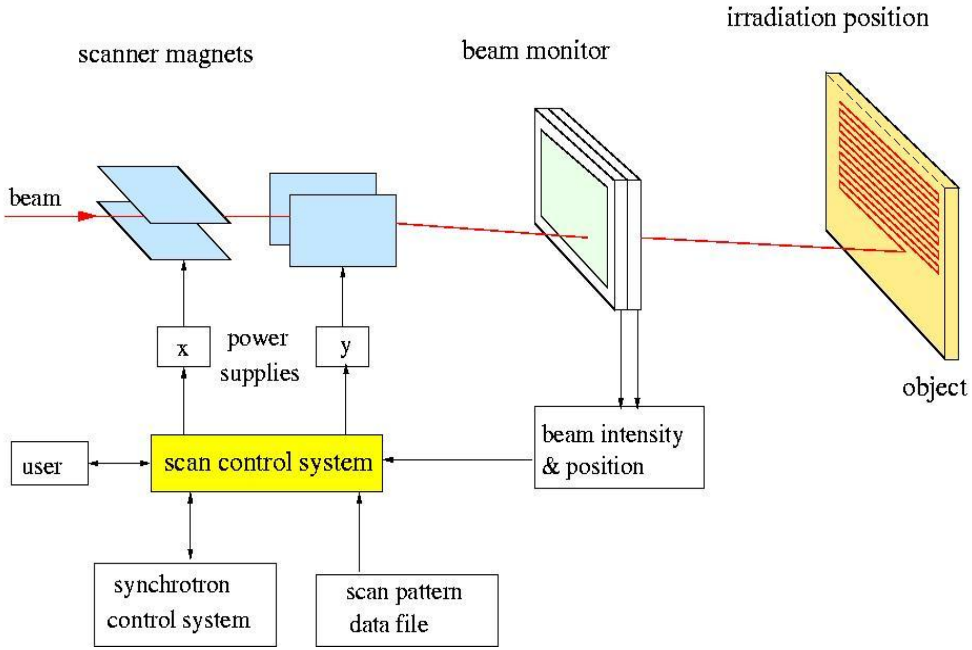


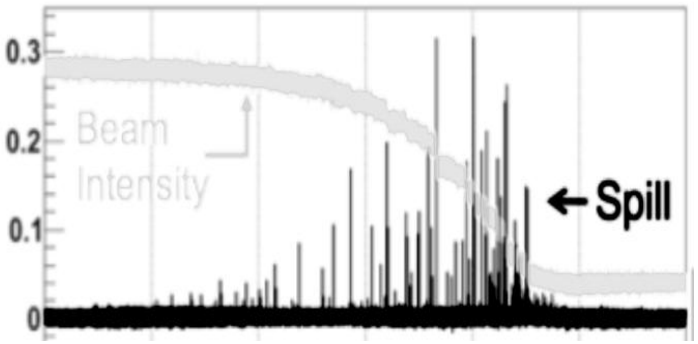


The mechanism of formation of the required ions distribution of a beam demands at least six meters of space of drift between octupole and a target. Besides the ionic optics has to prepare a beam so that on an entrance in octupole beam parameters (the size and divergence) corresponded to certain vales. The fig. show the phase portrait of the beam on an entrance (blue color) and an exit from an octupole magnet. The result of work of ionic optics is shown in Fig, so that in principle it is possible to receive the required uniformity of ions density involving 70-90% of the accelerated particles.

Beamline: Ion-optical system

Scanning system





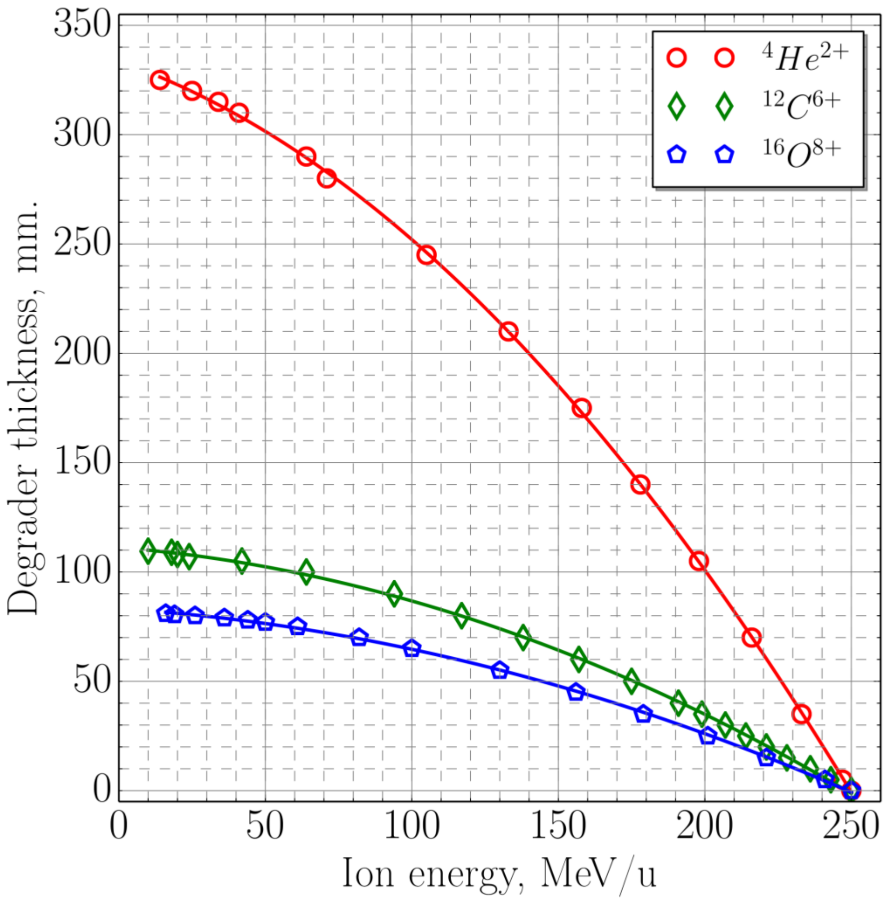
It is necessary to recognize that a scanning of a target surface as the most flexible and effective way of formation of the uniform field of target radiation. Rather small cross size of a beam guarantees localization of radiation without activation of the other equipment. The principle of the intensity-controlled raster scan techniques [Haberer et al., NIMA330, 296 (1993)] is shown in Fig. From the fig see that the ion optics is supplemented with two deflecting magnets determining the law of movement of a beam on a target. Shortcomings of the scanning system are defined by considerable heterogeneity of intensity of current of a beam during the pulse that results in need to control integrated current of a beam for each his situation on a target.

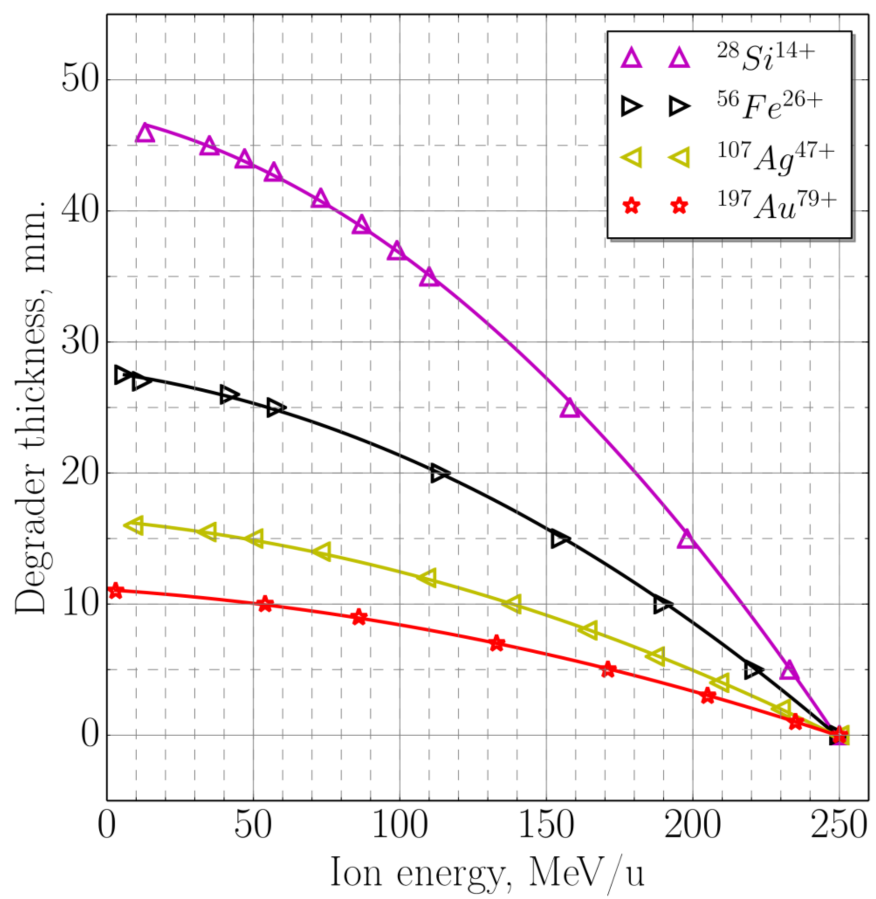
Degrader for low energy beam

Beam energy: 250 → 10 MeV/u

Degrader material: PMMA, density 1.20 g/cm3

Degrader geometry: 150x150 mm plates of various thickness (0.1, 0.5, 1, 5, 10 mm)





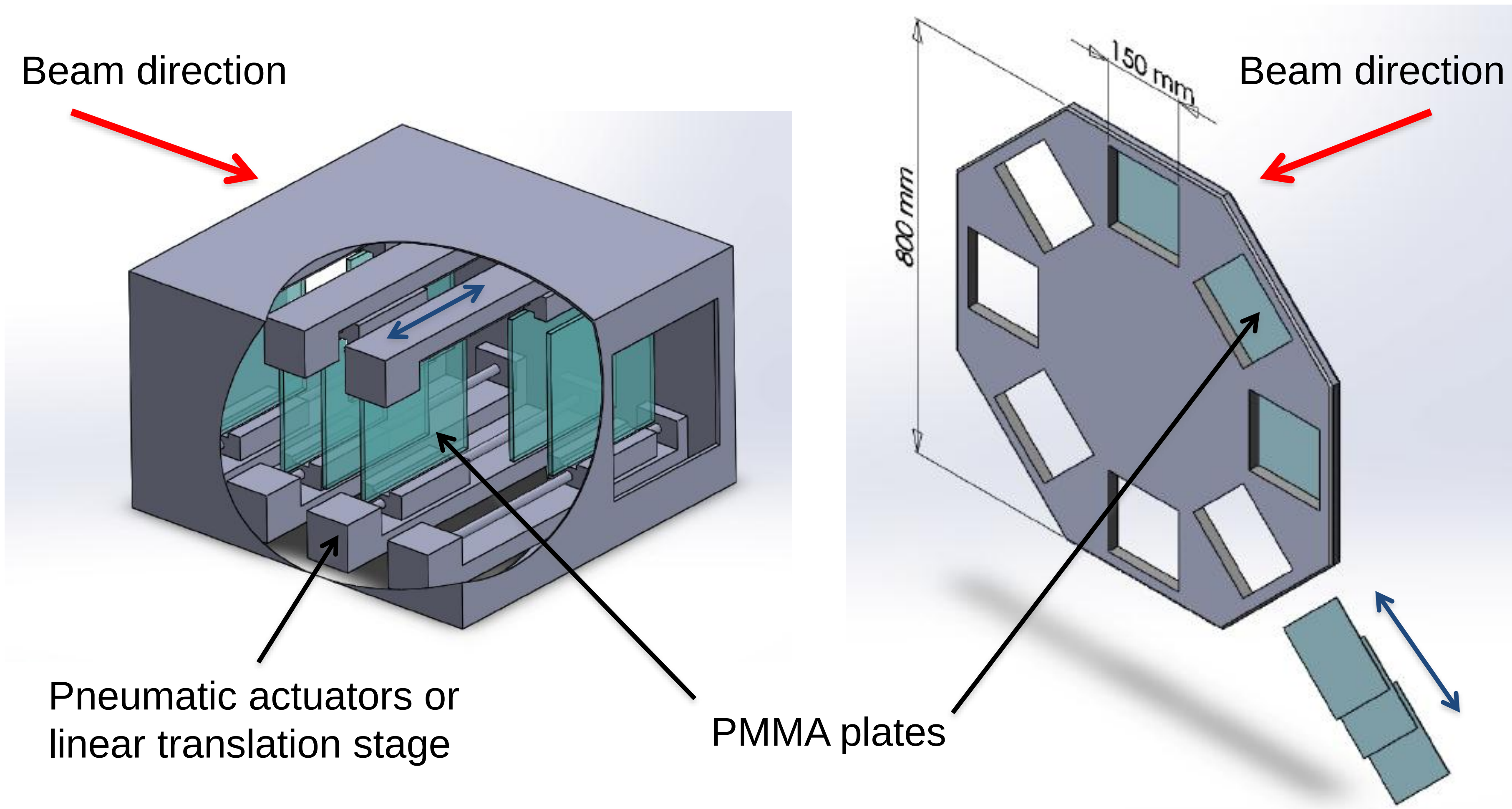
Degrader design

Automatic mode

- Set of PMMA plates with various thickness;
- Required thickness is set automatically;
- Large dimensions (more then 500 mm)

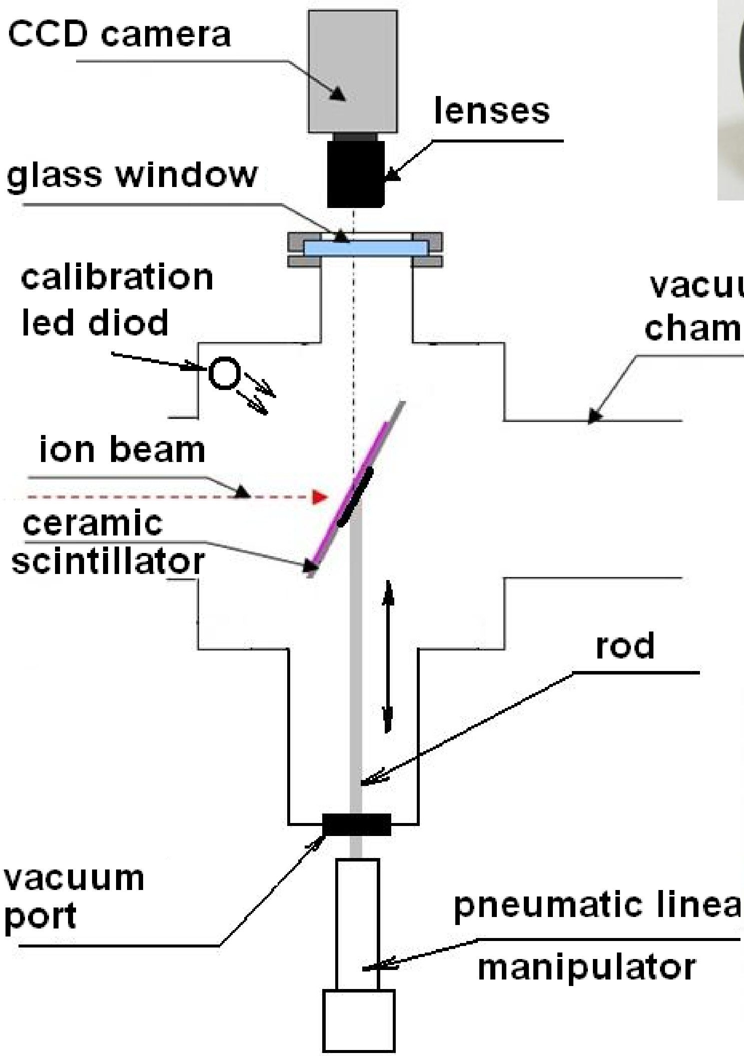
Manual mode

- PMMA plates are loaded manually;
- Required thickness is set automatically;
- Slow operation speed;

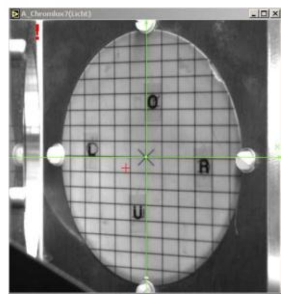


Beam diagnostic: beam profile measurement

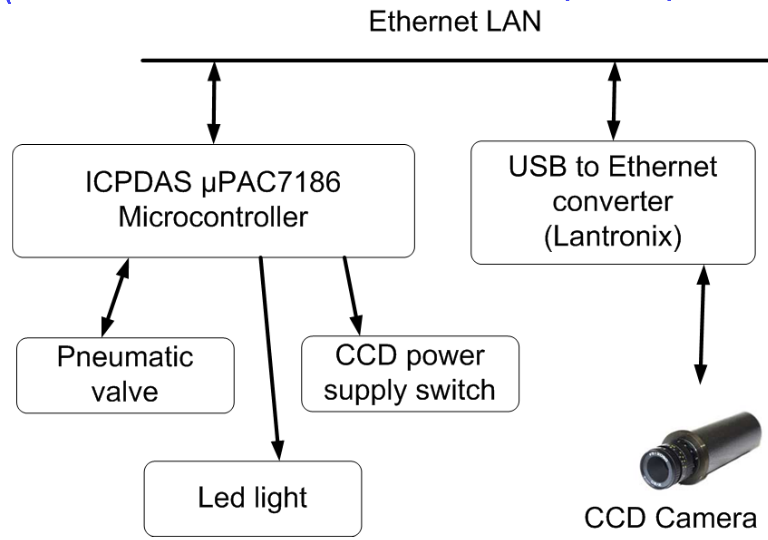
Beam diagnostic vacuum box (ceramic – http://www.polikor.net)



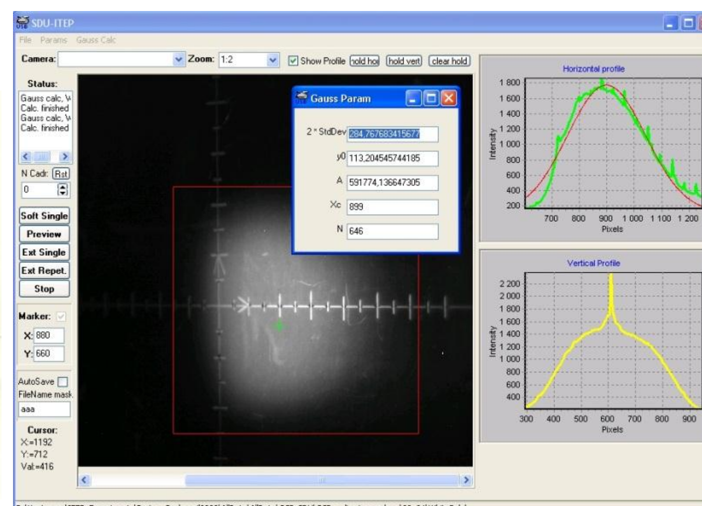
SDU-415
CCD digital camera



Beam diagnostic subsystem
(one channel of multi channels system)

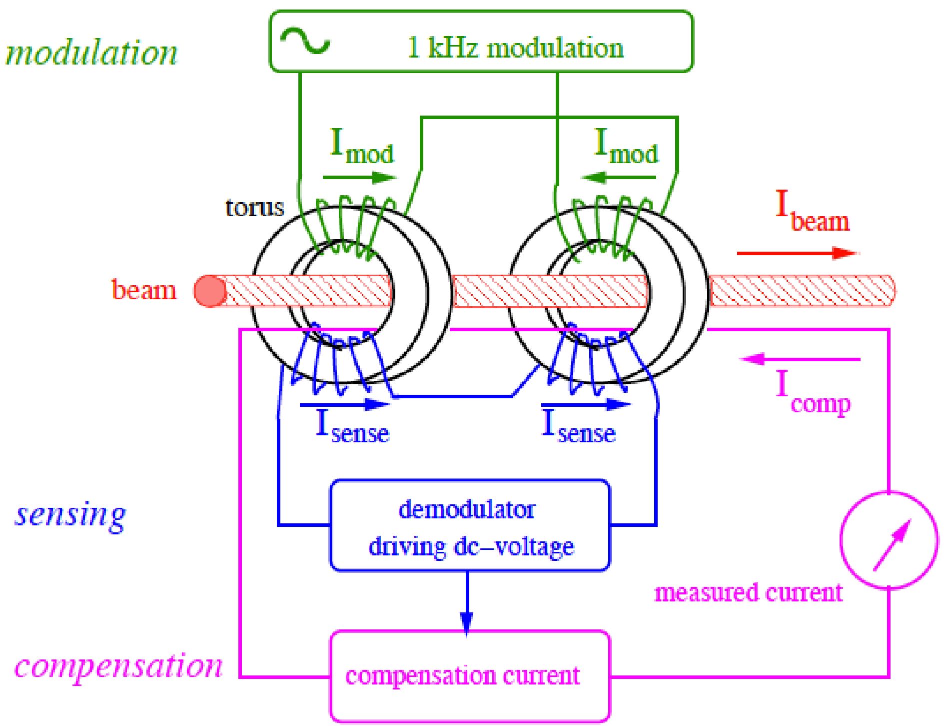


SDU-ITEP profile measurement software



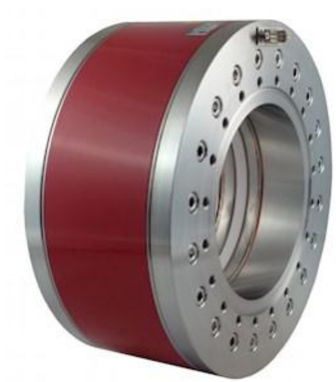
Beam diagnostic: Current transformer

1. Fast CT (passive ac-trans.): beam pulse length from 1 ns to 10 μs.
2. Integrating CT (active ac-trans.): beam pulse length from 1 μs to 10 ms.
3. Parametric CT (dc-trans.): beam pulse length from from seconds to days!



- Torus saturation due modulation;
- I_{sense} in secondary windings cancel each other;
- With I_{beam} saturation is shifted and I_{sense} is not zero;
- Adjust compensation current until I_{sense} is zero once again.

Minimum detected beam current ~10^{-4} A



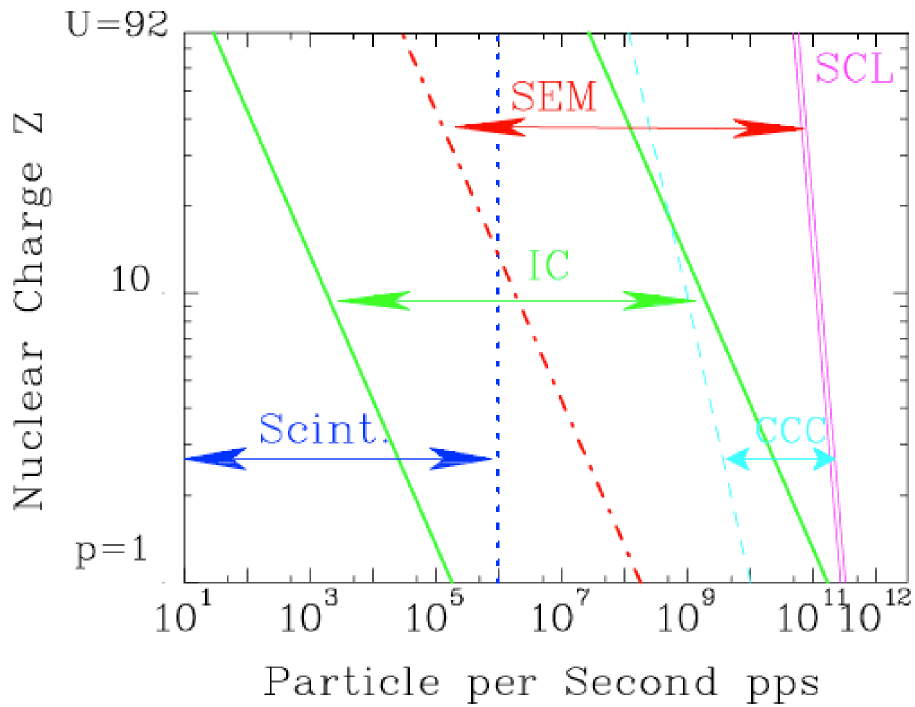
NPCT-E electronics with power supplies and In-flange NPCT sensor and from Bergoz

Low beam intensity

Typical condition for slow extraction mode:

Beam current from 10^3 up to 10^{12} particles per second (pps) → Detector current from 10^{-15} up to 10^{-6} A

- For the current below 10^6 pps - scintillators with CCD or by photo-multiplier;
- For the medium range from about 10^4 to 10^9 pps - ionization chamber;
- For the higher range from about 10^8 pps detectors based on secondary electrons emission from a metal.



Beam Instrumentation and Diagnostics By Peter Forck (GSI)

Beam diagnostic: Ionization chambers

- 25 cm x 25 cm sensitive area;
- plane readout for dosimetry and 128 by 128 strip readout for position and shape tracking;
- Minimum scattering due to thin films of low-Z material;
- Small insertion length;
- Atmospheric pressure air or flow-through gas;
- Integrated temperature, pressure and humidity sensing;
- Energy range 30 MeV/u to 500 MeV/u;
- Beam current density range up to 30 nA cm^{-2} (proton particle current ~ $2x10^{10}$ pps)
- High voltage bias up to 2000 V

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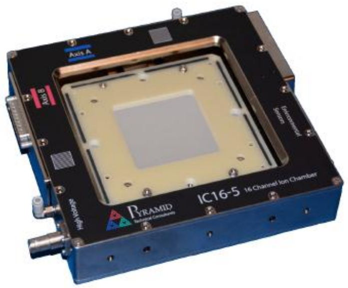
Beam diagnostic: Ionization chambers

Compact Position Sensing Transmission Ionization Chamber

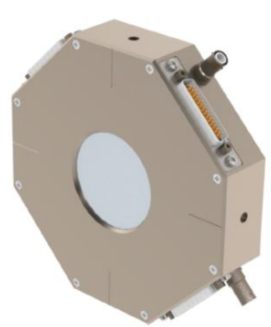


- 48 mm x 48 mm sensitive area
- 16 x16 strip readout for position and shape monitoring
- Energy range 30 MeV/n to 500 MeV/n
- Beam current density up to 20 nA cm^{-2} (particle current)
- High voltage 500-1000 V, max. 1500 V

Dosimetry and Position Sensing Ionization Chamber for Ion Beam Tracking

- 16 cm x 16 cm sensitive area
- 64 x164 strip readout for position and shape monitoring
- Energy range 30 MeV/n to 500 MeV/n
- Beam current density up to 20 nA cm^{-2} (particle current)
- High voltage 2000 V, max. 3000 V

Pixelated 2D-Sensing Ionization Chamber



- 42 mm diameter sensitive area
- 120 pixel readout for position and shape monitoring
- Energy range 30 MeV/n to 500 MeV/n
- Beam current density up to 20 nA cm^{-2} (particle current)
- High voltage 500-1000 V, max. 1500 V

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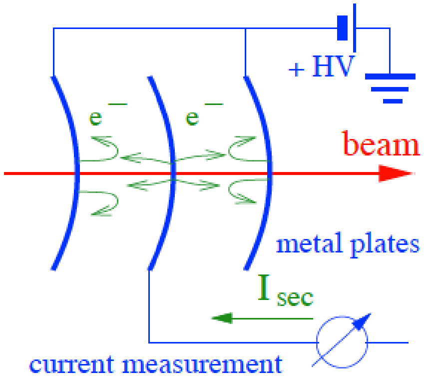
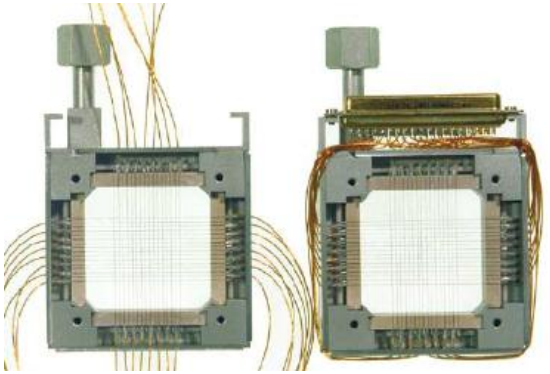
Beam diagnostic: Secondary electron emission

Secondary electron monitor

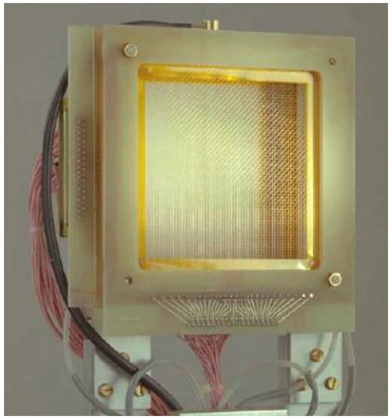
Material: pure Al (≃99.5%)
Thickness: 100 µm
Number of electrodes: 3
Active surface: 80 × 80 mm2
Distance between electrode: 5 mm
Voltage: 100 V





Secondary electron emission (SEM) grid

Wires diameter: 0.05 to 0.5 mm
Spacing: 0.5 to 2 mm
Material: W or W-Re alloy
Number of wires: 10 to 100



Multi-wire proportional chamber MWPC

Similar as SEM-grid, but with additional amplification (factor of 10^4) due to the gas

Such detectors aren't commercially available!!!

Beam Instrumentation and Diagnostics
By Peter Forck (GSI)

Dose measurements

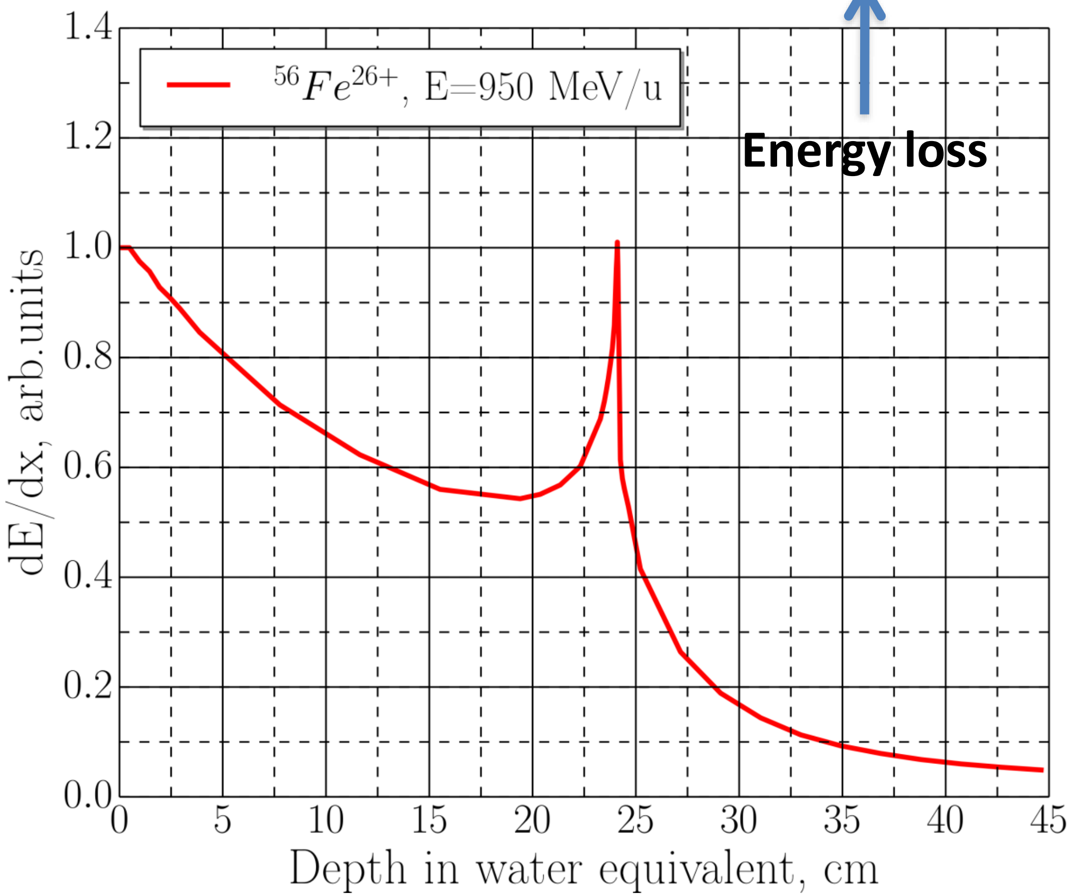
Fluence based approach

$$D[Gy] = 1.602 \cdot 10^{-9} \times \frac{dE}{dx}\left[\frac{keV}{\mu m}\right] \times \frac{N}{S}\left[\frac{1}{cm^2}\right] \times \frac{1}{\rho}\left[\frac{cm^3}{g}\right]$$

Energy loss

Particle fluence

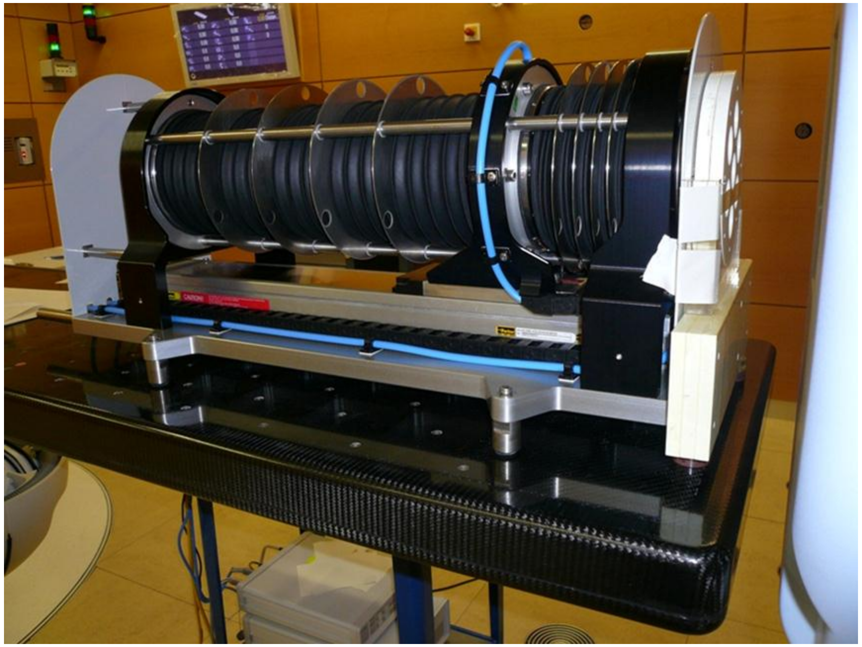
Material density



Data from NASA Space Radiation Laboratory website

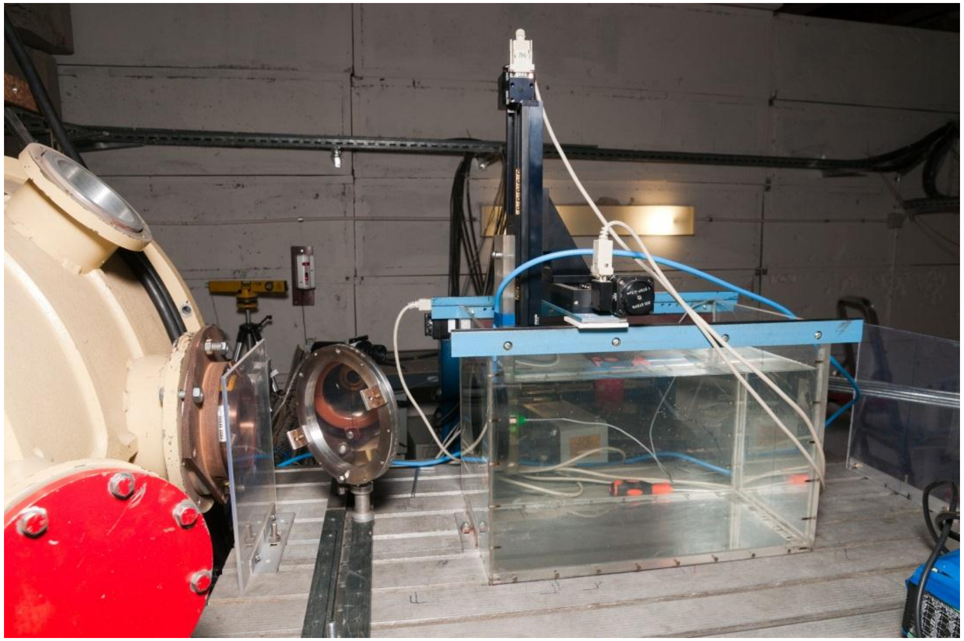
Depth - dose measurements

PEAKFINDER from PTW (Germany)



- Equipped with two plate-parallel IC
- Designed for therapeutic beam;
- Easy in operation;
- Range up to 350 mm;
- Limited beam energy.

“Home-made” water phantom

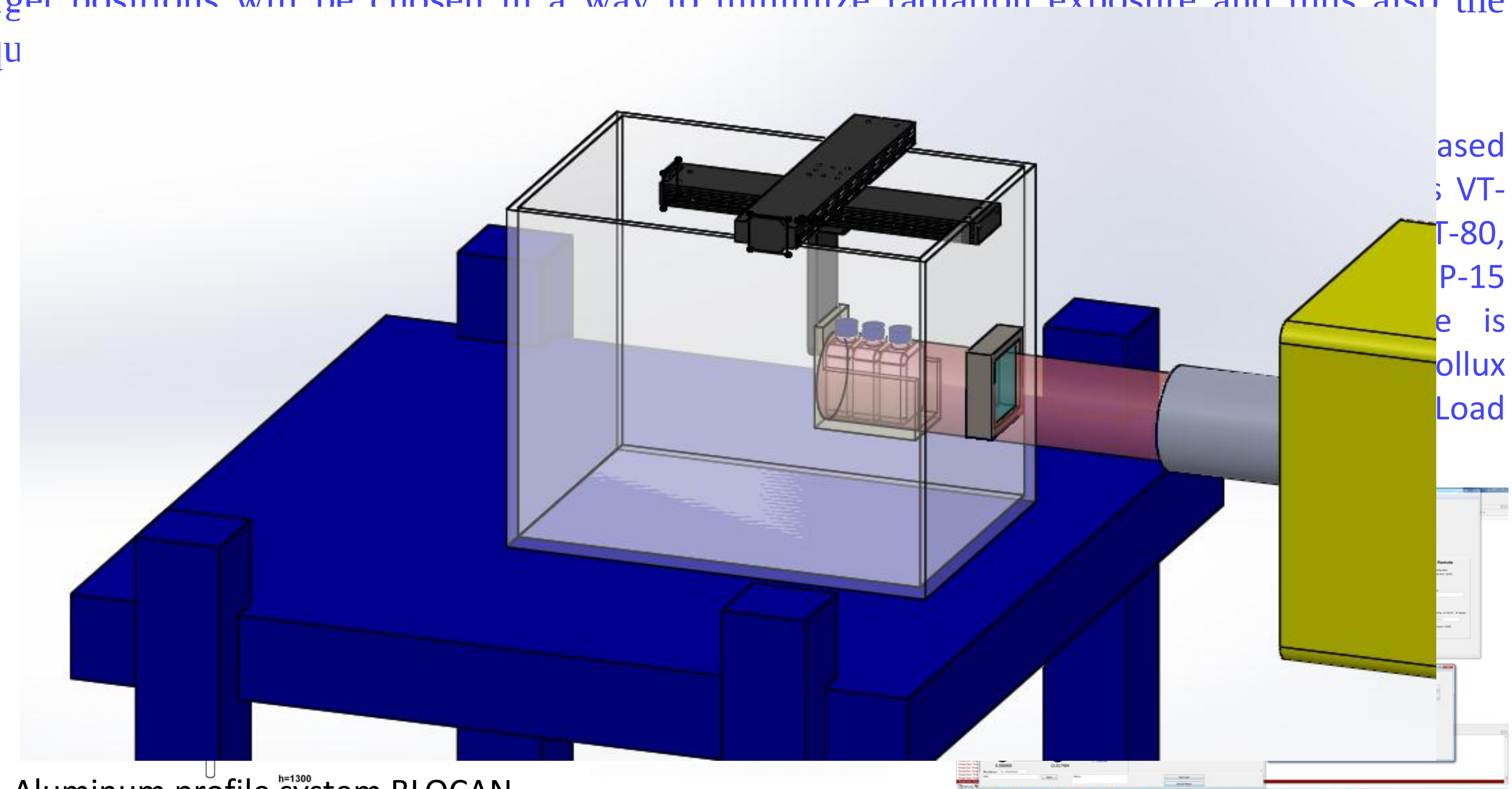


- Measurement's volume more than 500x500x500 mm;
- Detectors of any type and size (water protection is required)
- Water utilization system is needed.

Target stations

The target area will include different beam-monitoring systems and different systems for manual or automatic sample positioning of the irradiation targets. The choice of the beam-monitoring system will depend on the particular experimental conditions like e.g. beam-shaping method (active scanning vs. passive scattering), ion species, energy and particle fluence. The choice of the target position system will depend on target size, target type, etc. Target positions will be chosen in a way to minimize radiation exposure and thus also the requ

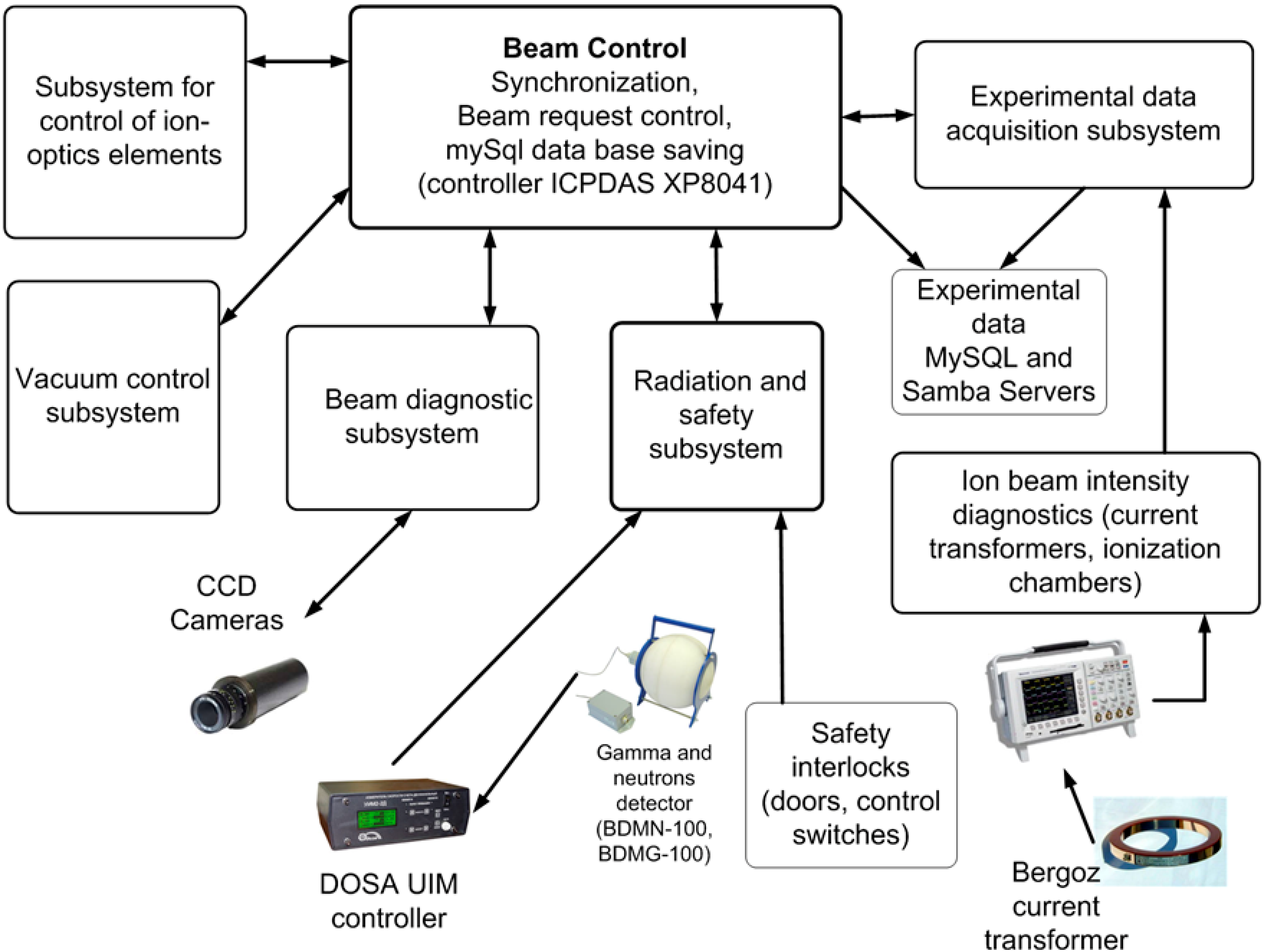
ased
VT-
T-80,
P-15
e is
ollux
Load



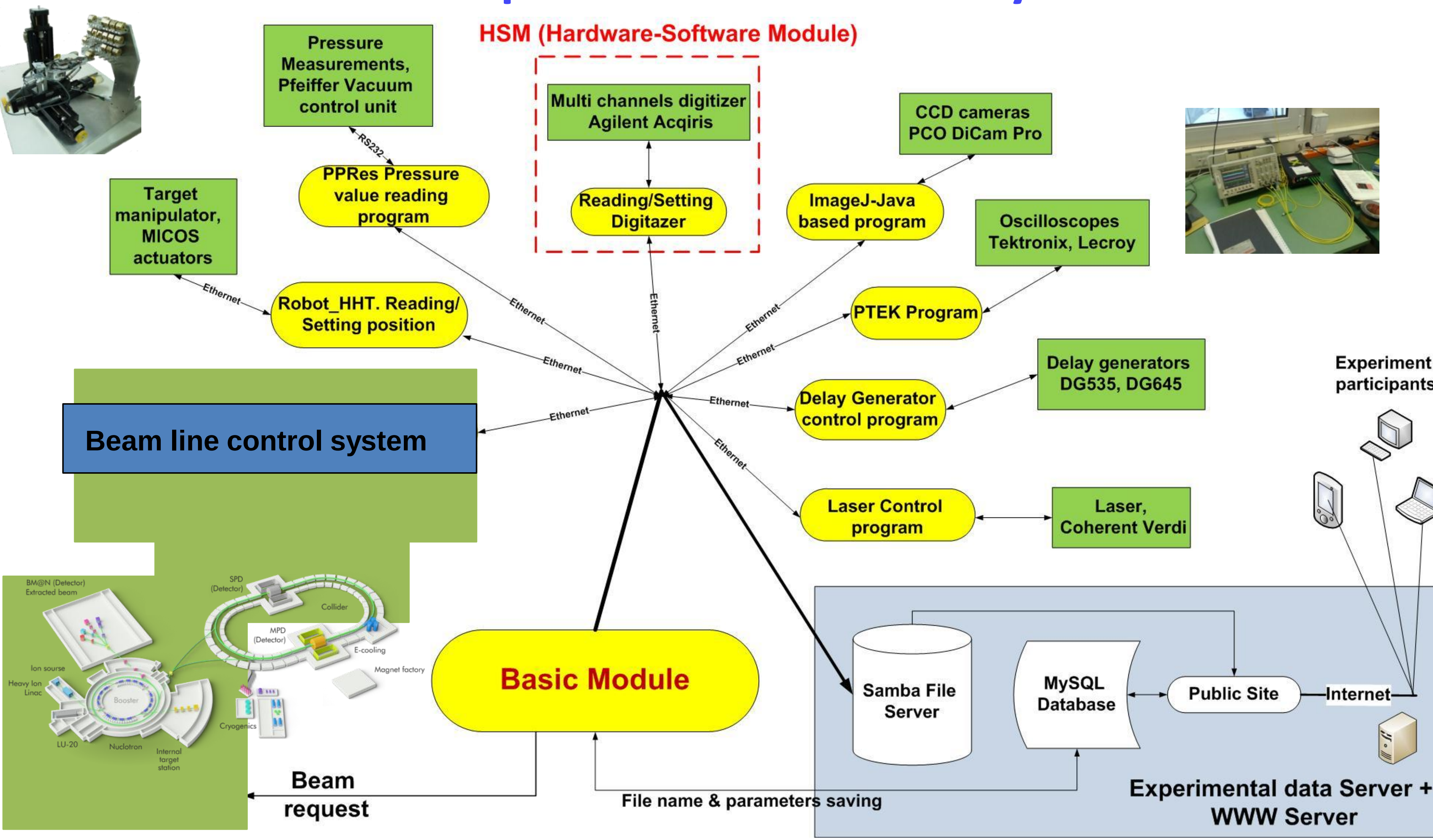
Aluminum profile system BLOCAN (http://rk-russia.ru/)

Software (Delphi XE2)

Data acquisition and control system



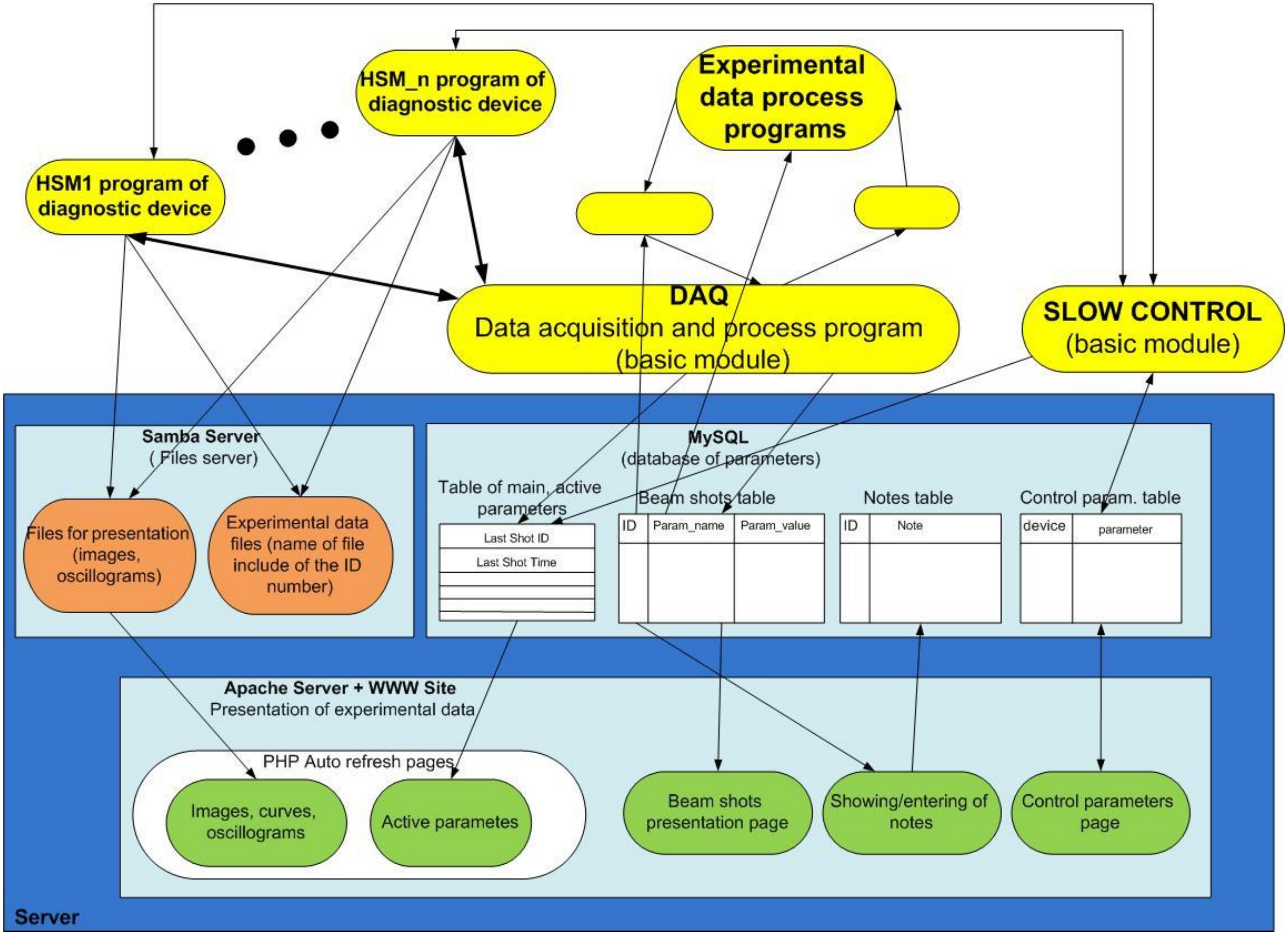
Data acquisition and control system



Data acquisition and control system for experiments consists of a set of hardware–software modules (HSMs), each of which includes one measuring, diagnostic, or actuating device and the relevant program for acquisition or processing of experimental data. The HSM programs reside in several personal computers integrated into a local Ethernet network. Data communication between the HSM programs has been organized **via the TCP/IP socket** interface.

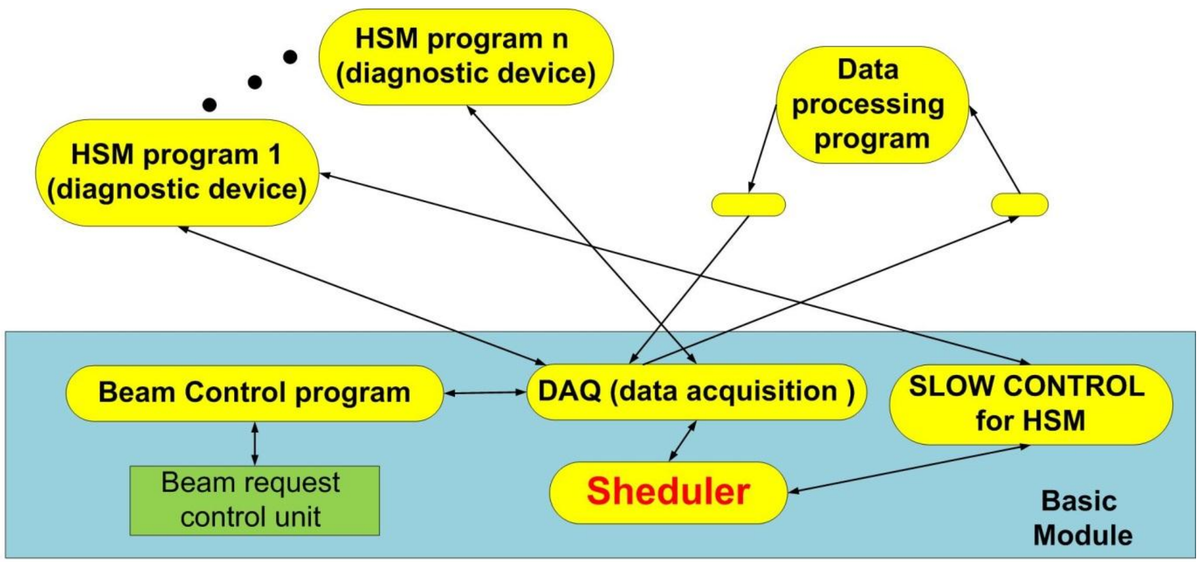
Data acquisition and control system

Principal schematic of data saving, processing and presenting

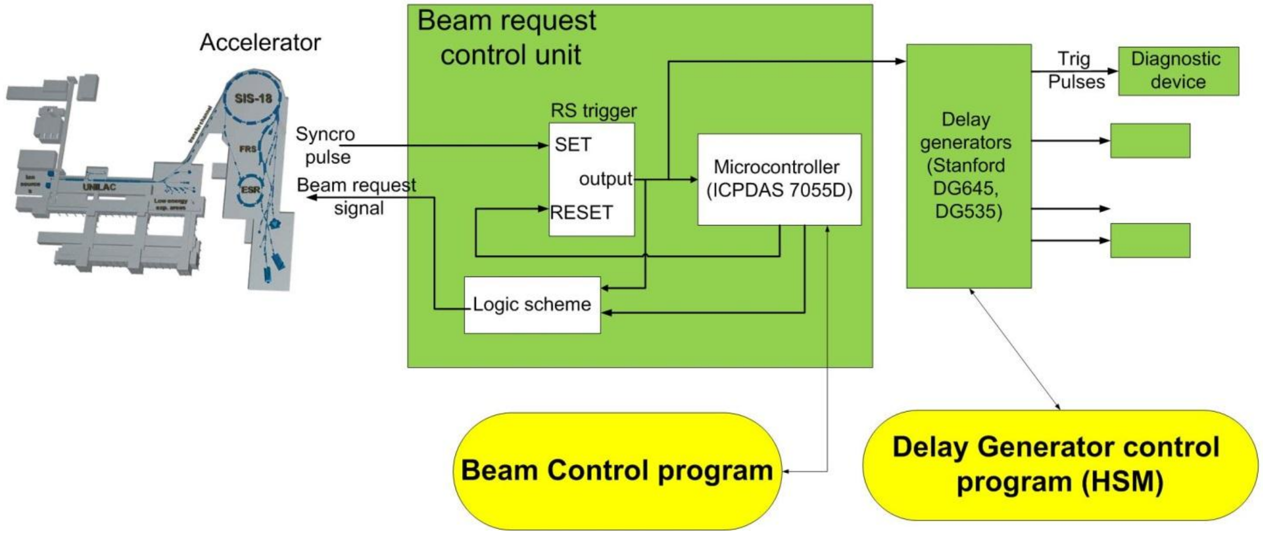


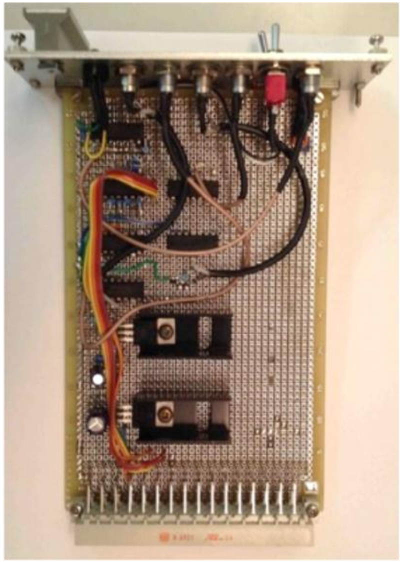
Data acquisition and control system

Basic HSM module +Synchronizing of devices.

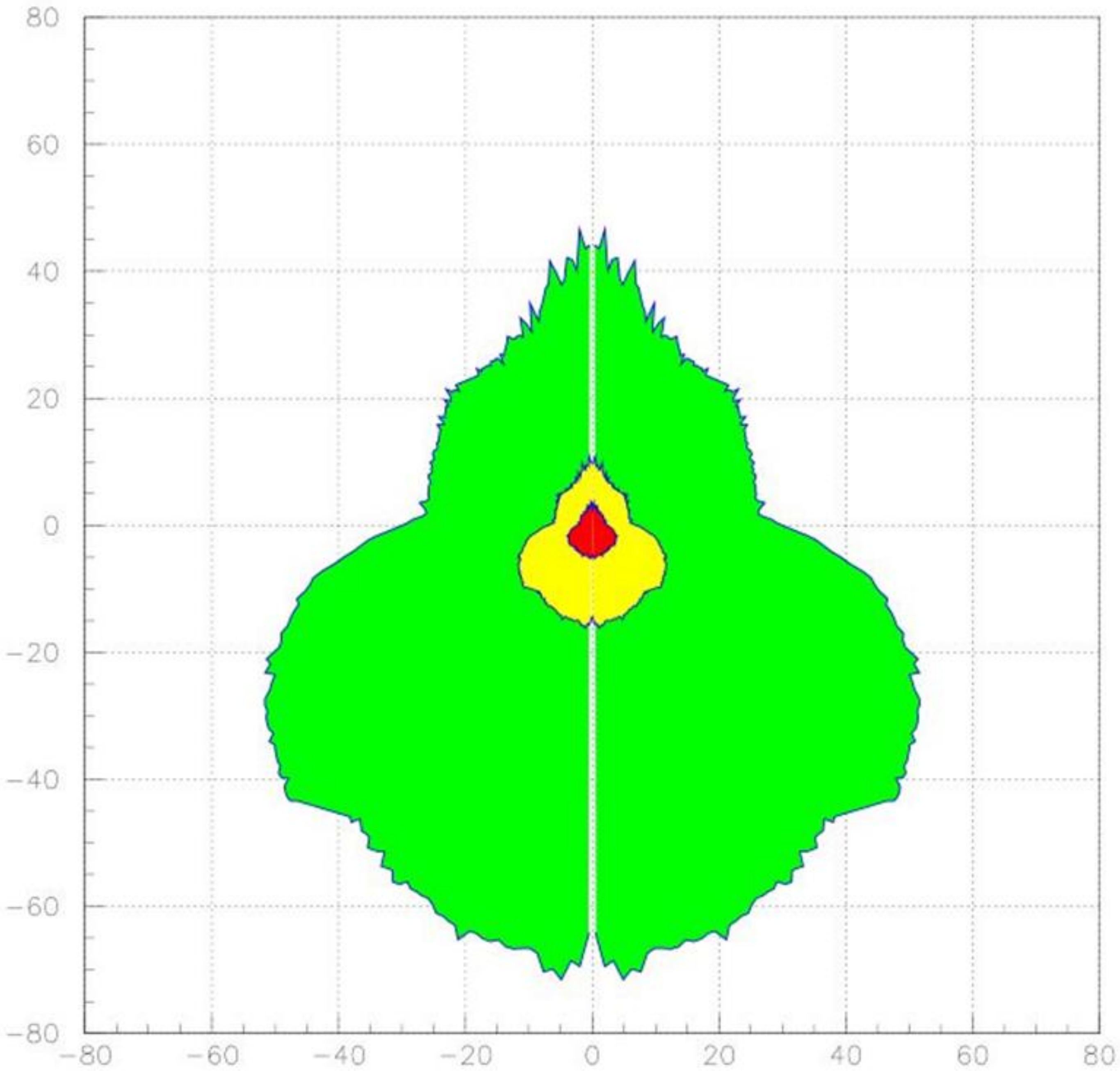


Prototype of beam request and synchronization control unit. Accuracy – 1 ns

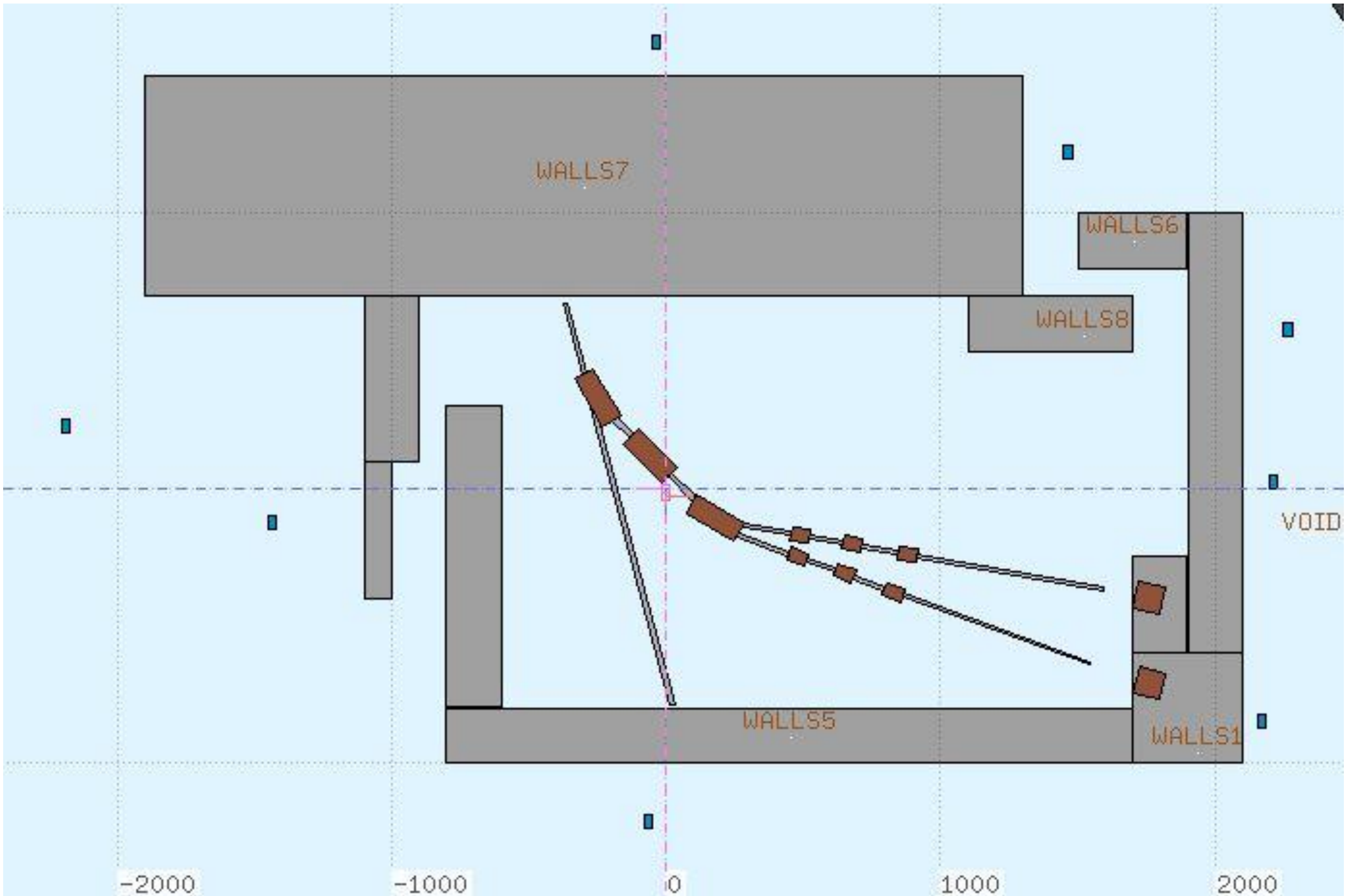


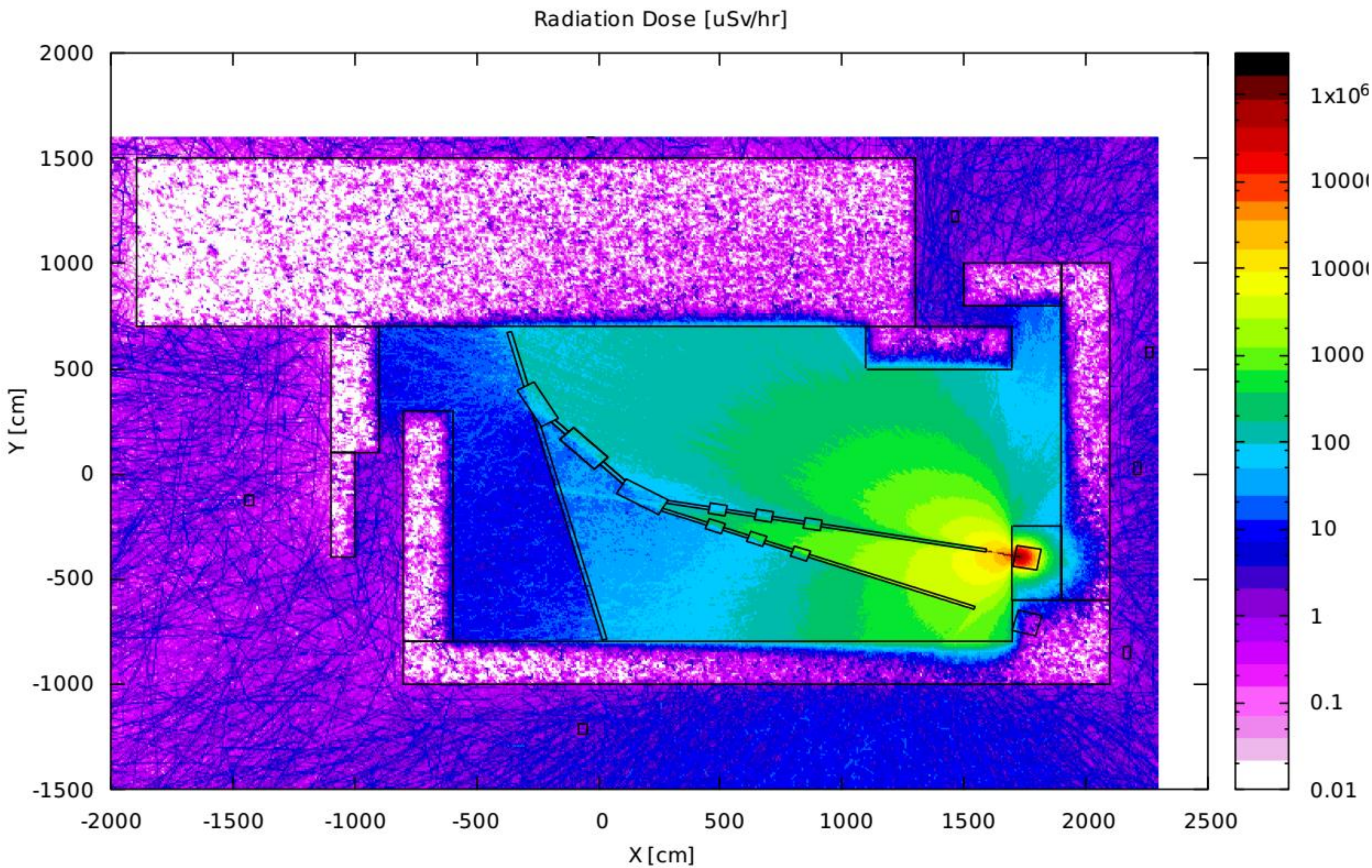


Beam
Protor
Beam
Shield



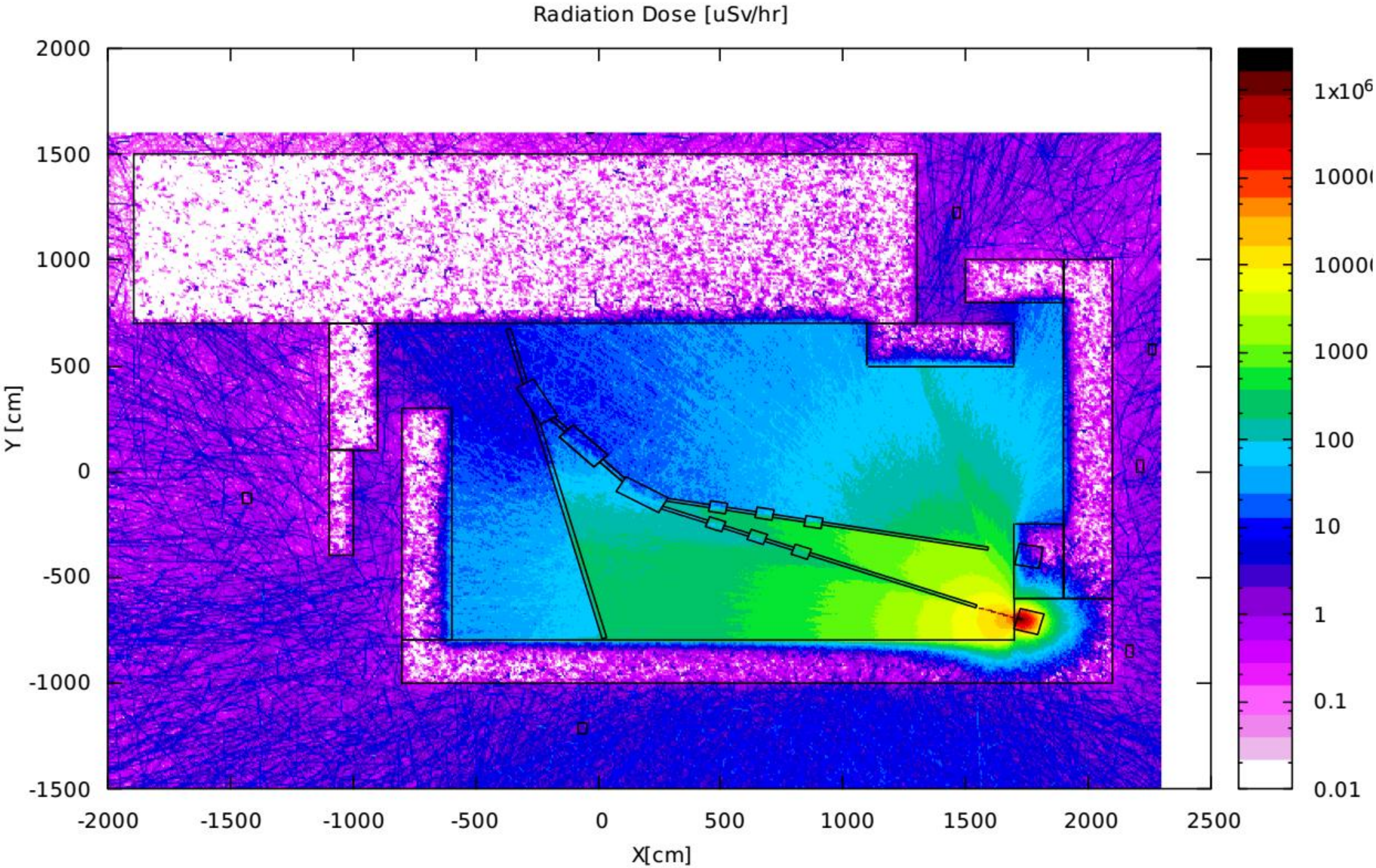
Modeling of the cave (Fluka)



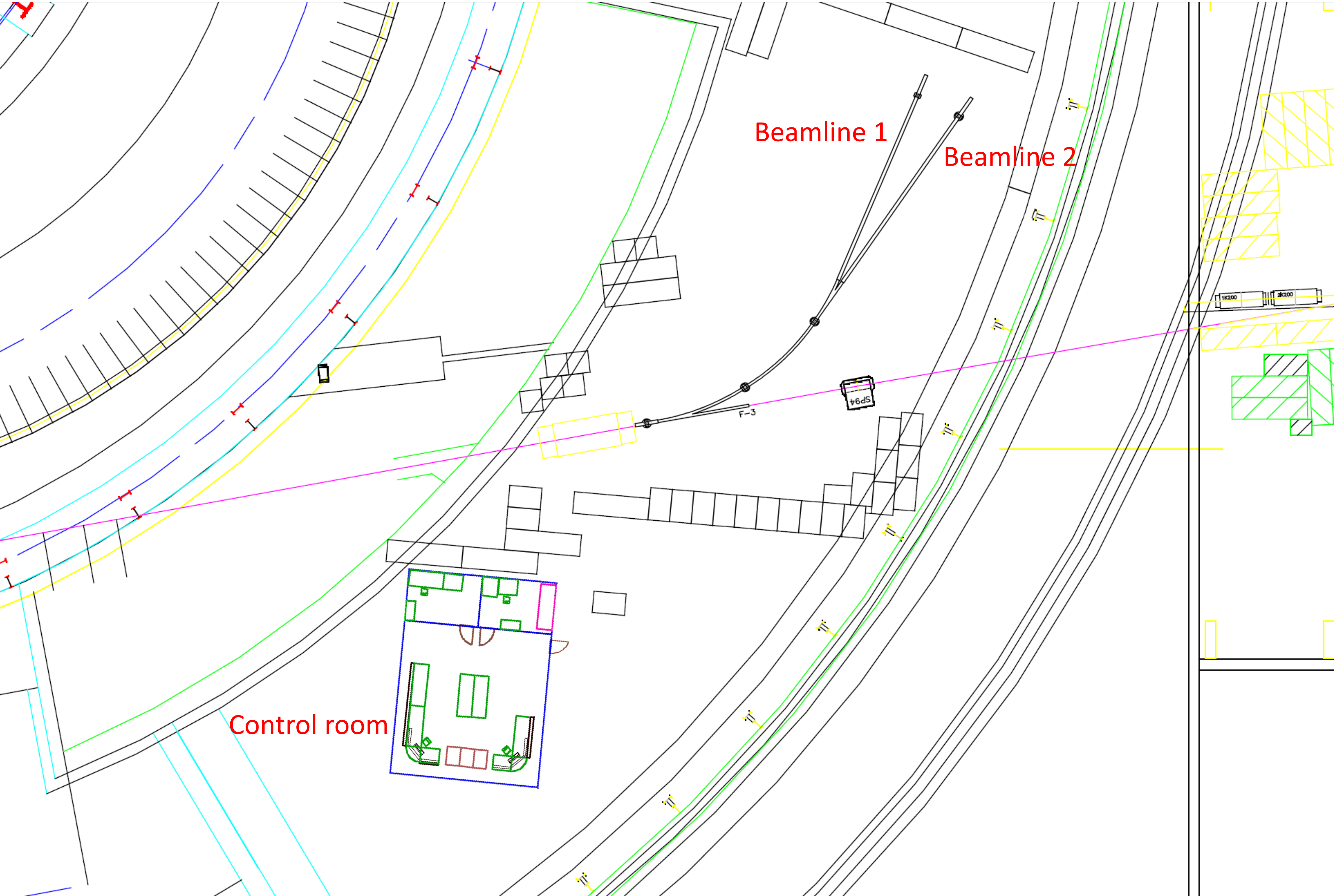


Radiation Dose [uSv/hr]
Y [cm]
X [cm]
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-1500
-1000
-500
0
500
1000
1500
2000
2500
1x10^6
10000
10000
1000
100
10
1
0.1
0.01

$9 * 10^{11}$


Radiation Dose [uSv/hr]
Y [cm]
X[cm]
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-1500
-1000
-500
0
500
1000
1500
2000
2500
1x10^6
10000
10000
1000
100
10
1
0.1
0.01

Control room and beamlines (main view)

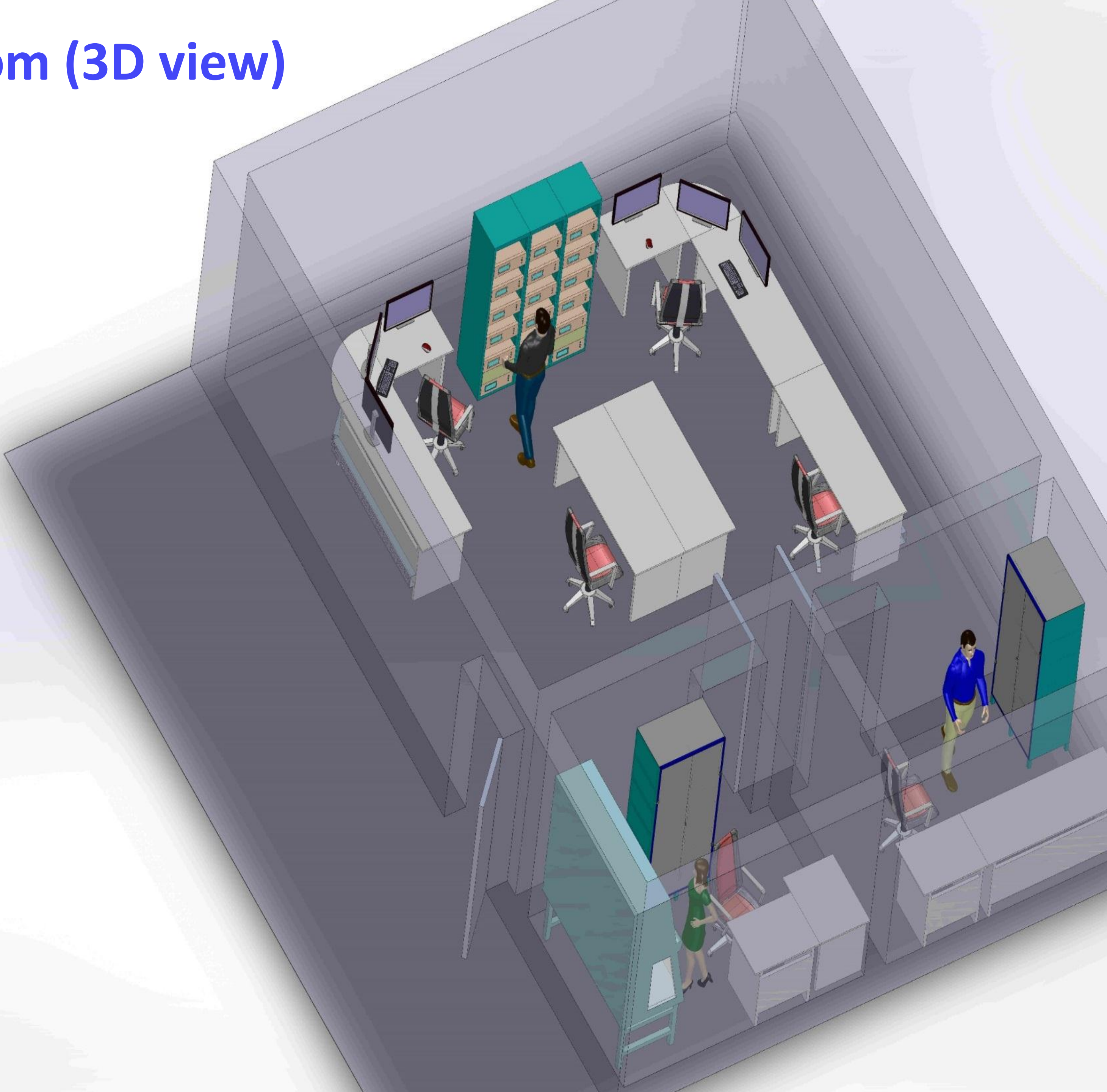


Control Room Scheme and Basic Dimensions

Inside dimensions (m)	Control room (main room)	Target lab	Bio Target lab
Length	7.0	3.1	3.
Width	7.7	3.35	3.35

Control room (main room)	Target lab	Target Bio lab
Beam extraction control system (3)	Workplace (2-3 persons)	Workplace (2-3 persons)
Control system for target positioning and diagnostics (1)		Laminar flow bench (LFb)
Control system for target positioning and diagnostics (2)		
Electric raceway (4)		
Workplaces (app. 12 persons)		

Control room (3D view)



Conclusion

The experimental setup for BIOMAT research at NICA are on the phase of beginning and any suggestion, comments are welcome!

Thank you for your attention