Flerov Laboratory of Nuclear Reactions

JOINT INSTITUTE FOR NUCLEAR RESEARCH

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FLNR JINR Accelerator Complex for Applied Physics Researches: State-of-Art and Future

CYC 2019 22-27 SEPTEMBER CAPE TOWN

The 22nd International Conference on Cyclotrons and their Applications 27.09.2019 Cape Town

Outline

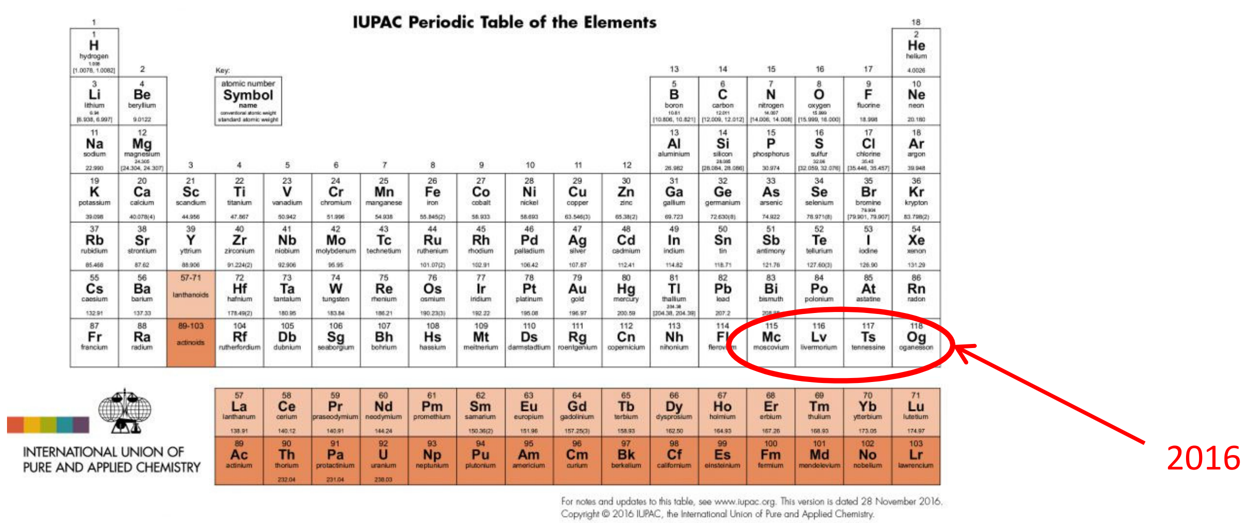
1. FLNR accelerating complex in 2019.
2. Science for life - applied physics researches. Existing and potential applications.
3. Summary: joint needs for future.
4. New dedicated applied science facility at FLNR Accelerator Complex.
5. Road map of the project.
6. Conclusion.

FLNR main activities

*Flerov Laboratory of Nuclear Reactions was founded in the Joint Institute for Nuclear Research in 1957.

FLNR carries out research in the field of heavy ion physics in three main directions:

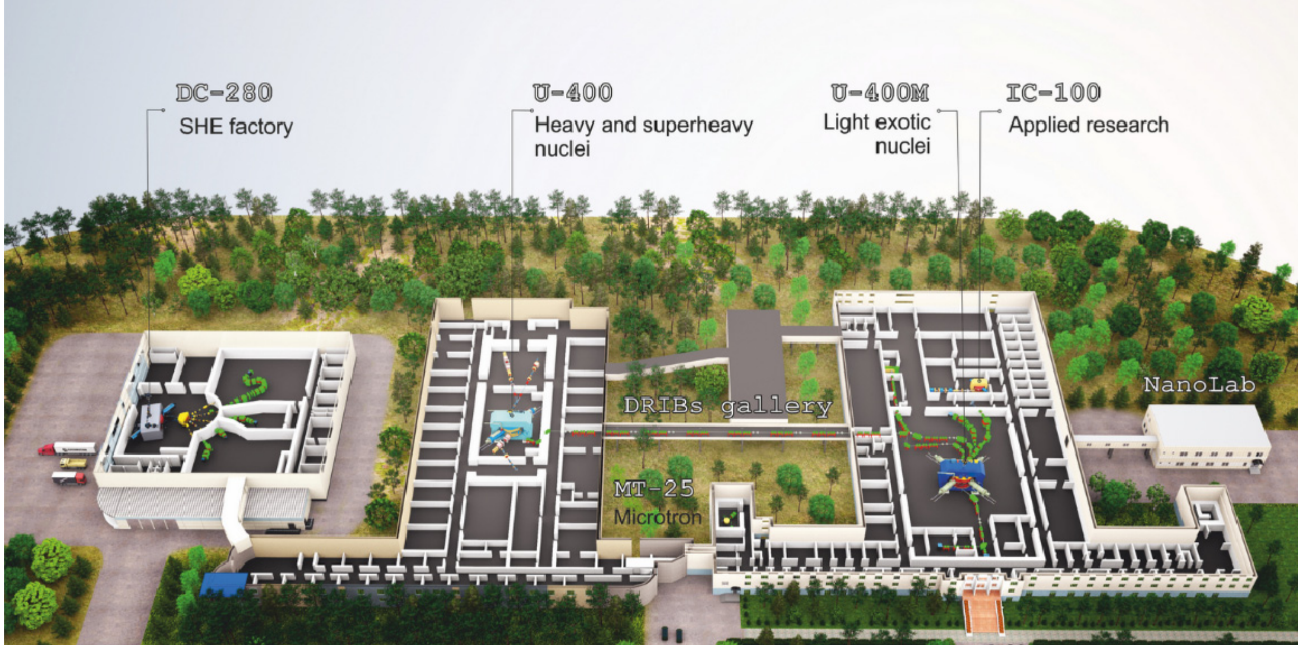
- Synthesis and properties of nuclei at the stability limits
- Accelerator complex of ion beams of stable and radioactive nuclides (DRIBs-III)
- Radiation effects and physical bases of nanotechnology, radioanalytical and radioisotope investigations at the FLNR accelerators



FLNR accelerating complex in 2019.

4 cyclotrons and Microtron

Beam operation time : ~ 7 000 hours/year/per machine of beams **ON** physical targets



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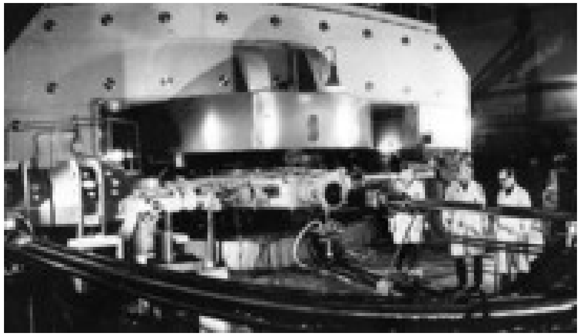
Science for life - applied physics researches

Interactions of accelerated heavy ion beams with matter – projectile + target

Since middle of 1970's track membrane technology based on HIB were realized at U300 in FLNR.



... In 2019

- Creation and development of track membranes (nuclear filters) and the heavy ion induced modification of materials.

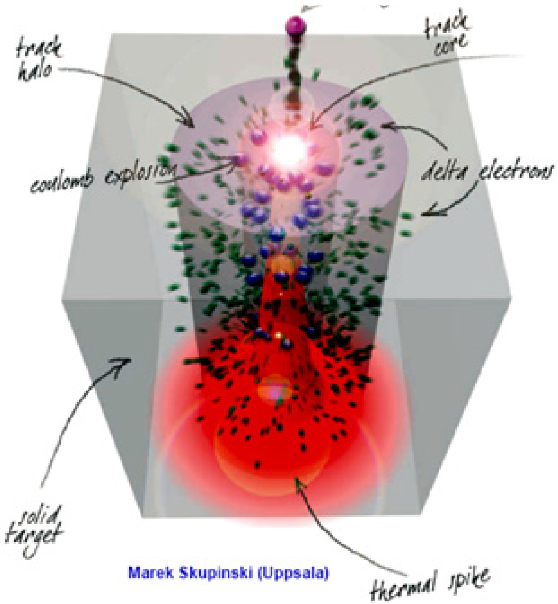
- Activation analysis, applied radiochemistry and production of high purity isotopes.

- Ion-implantation nanotechnology and radiation materials science.

- Testing of electronic components (avionics and space electronics) for radiation hardness.

Ion track etching in polymer foils

Heavy ion



A sequence of physical and chemical events:

1. Ionization of atoms and molecules (knocking out electrons)
2. Rupture of chemical bonds
3. Local heating (thermal spike)
4. Displacements of atoms and disordering crystalline structure (amorphization)
5. Formation of volatile small molecules (CO, CO_2, and others) – in polymers
6. Increase in free volume along the track core (several nanometers in radius)

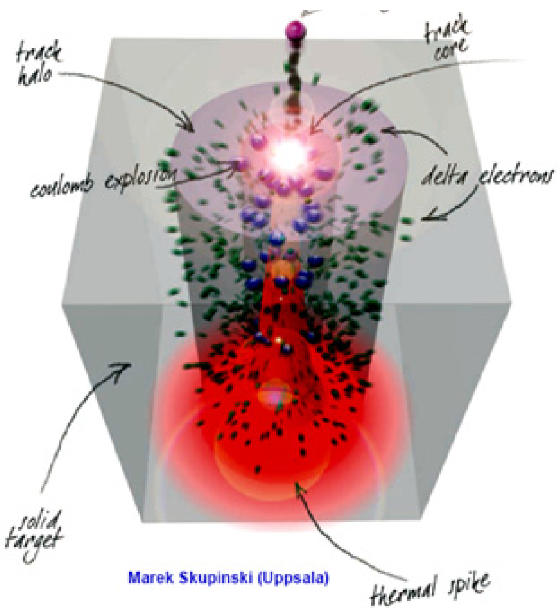
In insulators these phenomena result in the so-called ”etchability of ion tracks”

Irradiation with heavy ions (e.g. Kr, Xe, Au, 1-10 MeV/u) – formation of *latent tracks*

Polymer foil (polycarbonate, polyethylene terephthalate,…)

Ion track etching in polymer foils

Heavy ion



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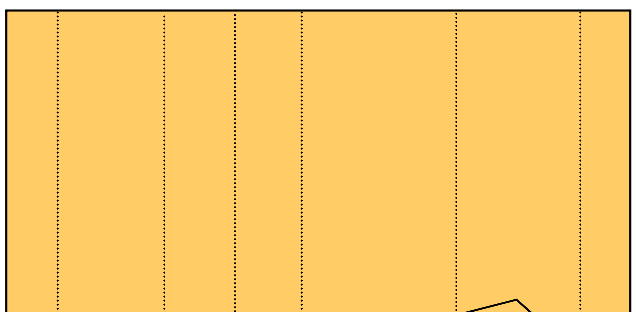

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Ion track etching in polymer foils

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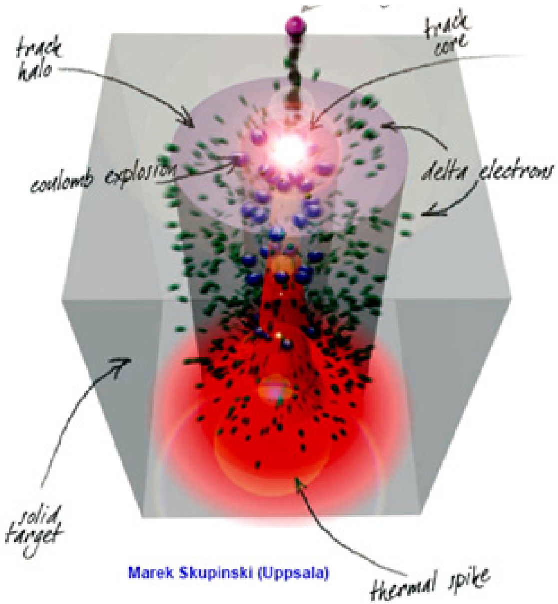

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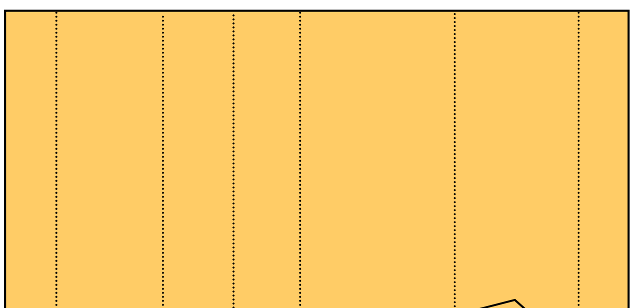

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Irradiation with heavy ions (e.g. Kr, Xe, Au, 1-10 MeV/u) – formation of *latent tracks*

Chemical etching - development of latent tracks and formation of pores

Ion track etching in polymer foils

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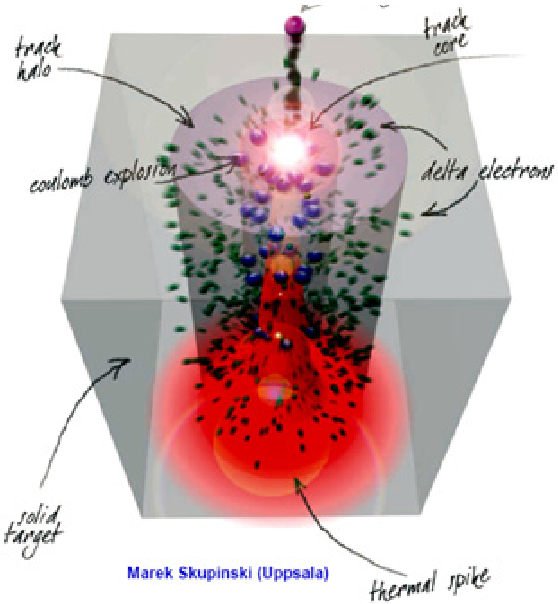

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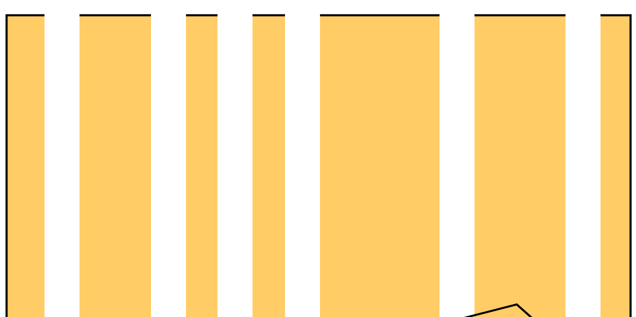


Polymer foil (polycarbonate, polyethylene terephthalate,…)

Irradiation with heavy ions (e.g. Kr, Xe, Au, 1-10 MeV/u) – formation of *latent tracks*

Chemical etching - development of latent tracks and formation of pores

Tailoring the size, shape and surface properties of the pore by chemistry

Diameter of pores: ~ 10 nm ÷ several μm   Number of pores: 1 pore/cm^2 ÷ 10^{10} pores/cm^2

Ion track etching

Heavy ion track etching method allows

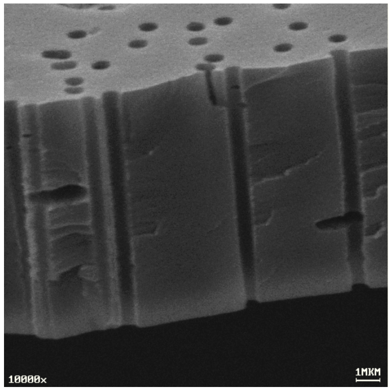
- to vary the pore diameter and pore density independently
- control over the pore orientation (parallel, normal to surface, tilted, non-parallel…)
- to produce either through or non-through pores
- control over the pore shape and thus control over the hydraulic resistance and retention
- product properties of membranes on of both symmetric and asymmetric membranes

⇩

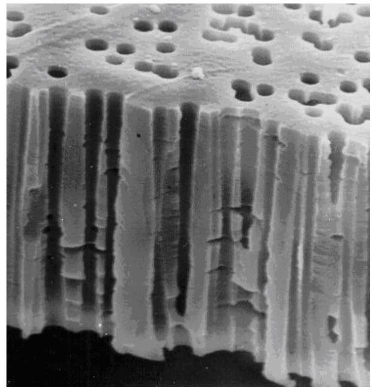
Precise control over structure and transport characteristics

Ion track etching technology

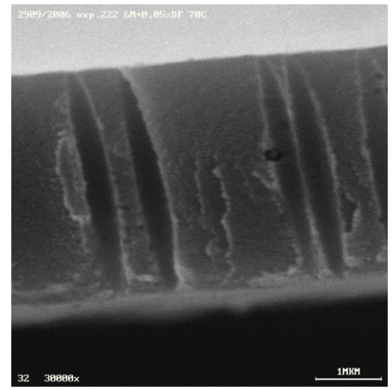
Variety of pore shapes in track-etched membranes



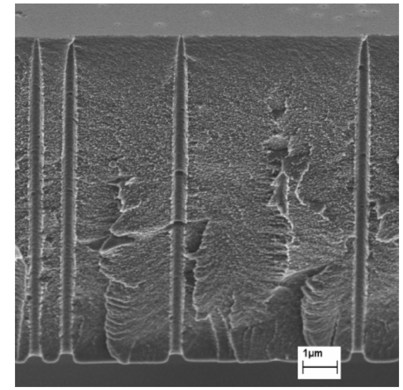
Cylindrical



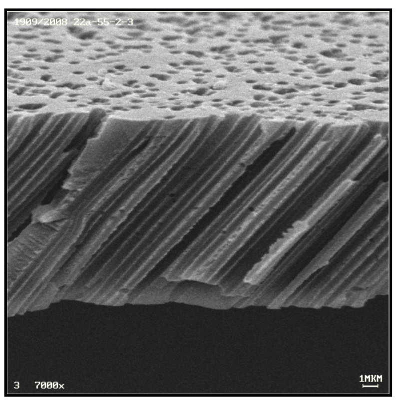
Doubly conical



Cigar-like

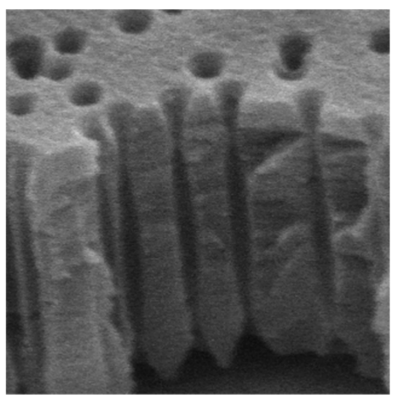


Highly asymmetric with bullet-like tip

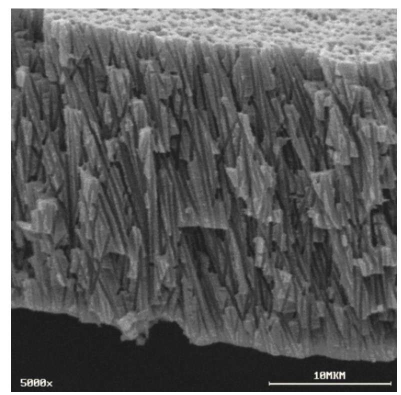


Cylindrical, parallel,

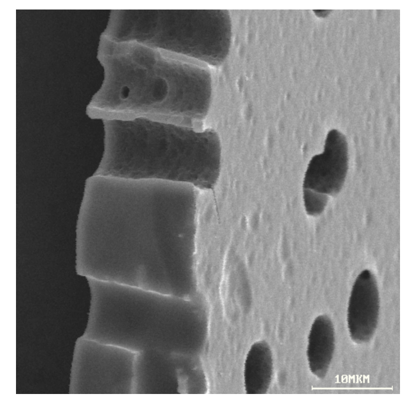
all tilted at an angle of 45°



Bow tie like



Cylindrical, non-parallel (typical commercial TM with small pores)

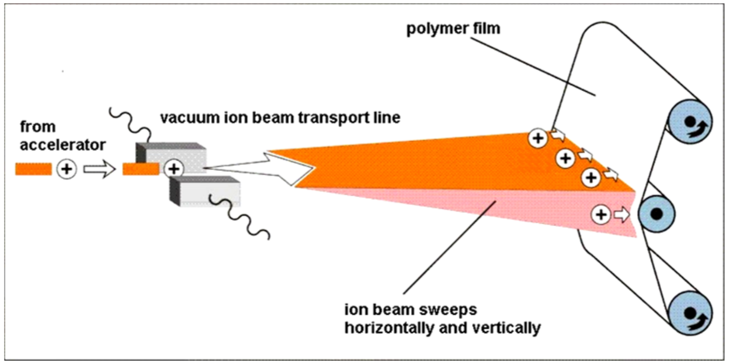


Typical commercial TM with large pores

Ion track etching

Requirements:

•The highest achievable ion current output
•Complex target engineering
•Stability of ion current in time
•Homogeneous ion beam density over the irradiated area
•Controlled impact angle
•Parallel ion beam
•Possibility to bombard with a preset number of ions (e.g. with single ions)

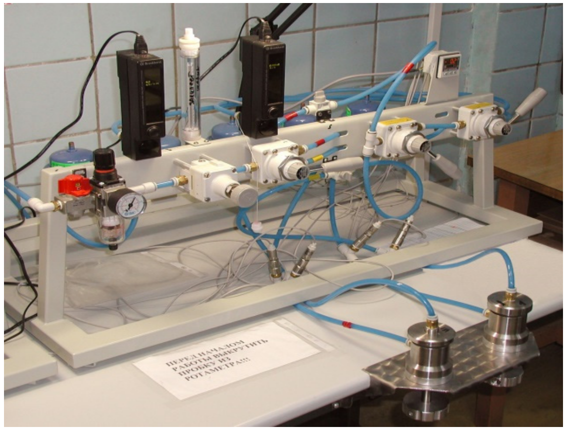


IC-100 dedicated beamline for ion track technology

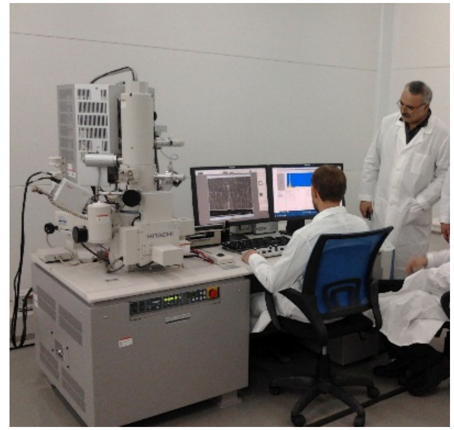
Ion track etching

Quality testing methods

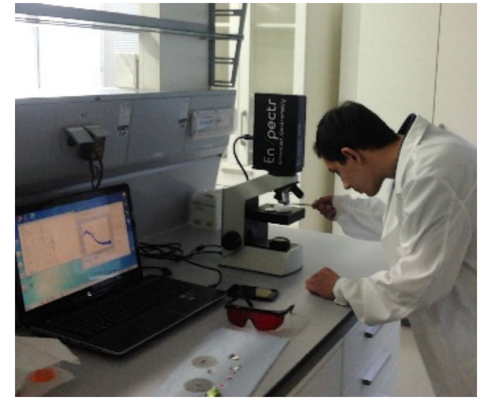
Characterization of track-etched membranes and micro- and nanoporous materials



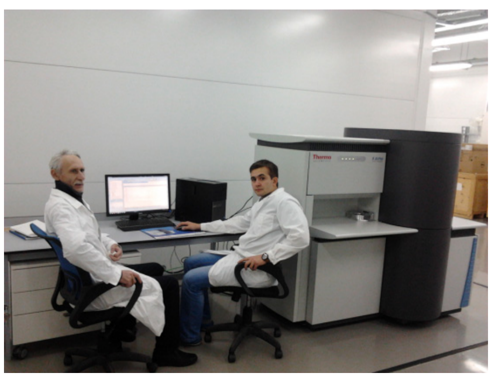
Measurement of gas flow rate and bubble point



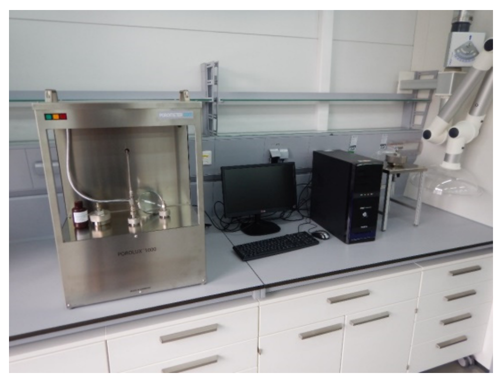
Scanning electron microscope Hitachi SU8020
- determination of pore size, pore shapes, membrane structure



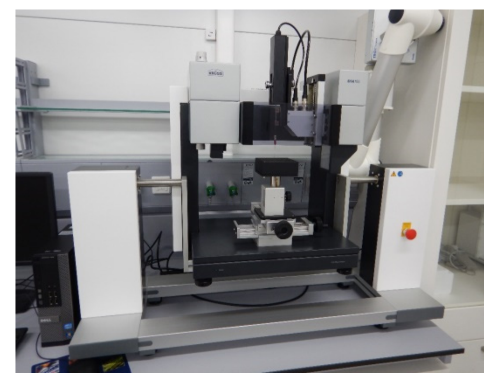
Raman spectrophotometer



X-ray photoelectron spectroscopy K-Alpha – surface analysis



Porometer Porolux 1000 – pore size distribution



KRUESS – contact angle measurements

Ion track etching

Industrial applications of track-etching membranes

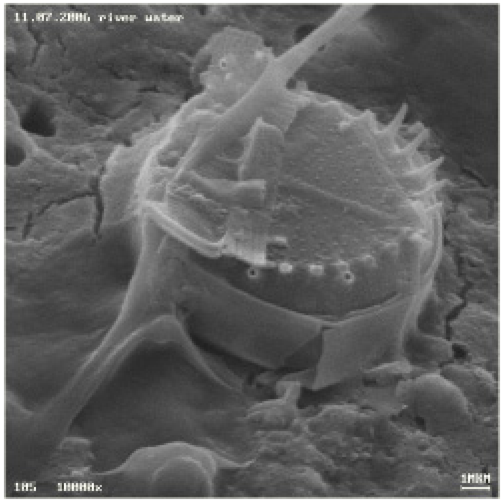
Process filtration
(water, pharmaceuticals, beverages, etc)

Laboratory filtration
(analytical works)

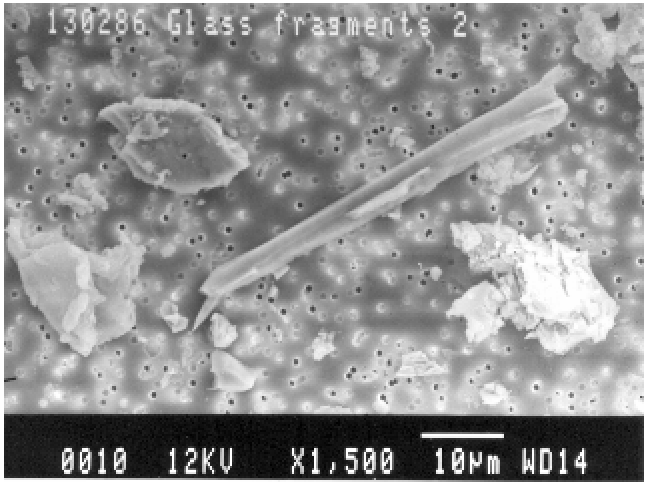
Medicine and pharmaceuticals

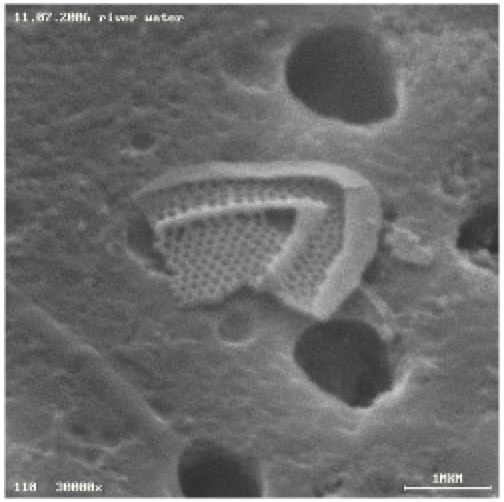
Ion track etching

Application of track-etched membranes in analytical works



- Collecting and fractionation of precipitate particles on membrane surface
- Analysis of the particles using optical or electron microscopy
- Determination of mass of the precipitate
- Element analysis of the precipitate using X-ray fluorescent, {-ray photoelectron spectroscopy, Auger-electron spectroscopy and other methods.
- Dissolution of the precipitate and further analysis in liquid phase

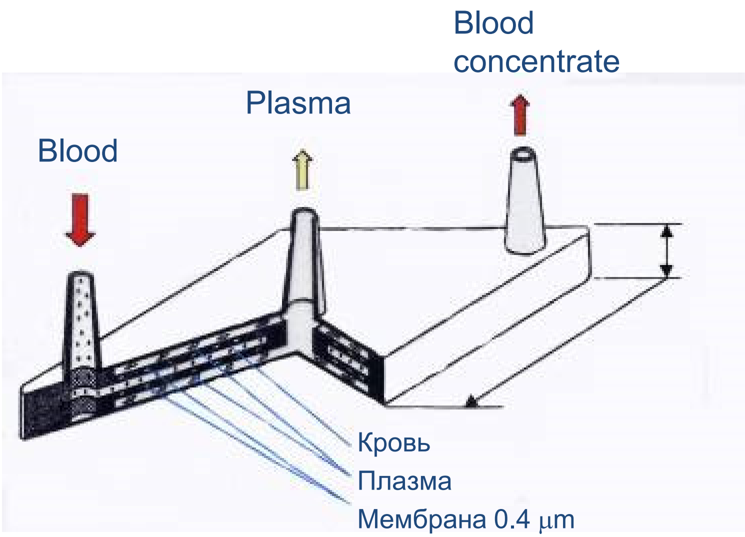




Ion track etching

Track-etched membranes for plasmapheresis

Apparatus for plasmapheresis (TrackPore Technology Company, Russia)



0.1-0.2 м^2 of track-etched membrane in separator «Rosa»

PlasmoFilter Company, SPb, Russia

Ion track etching

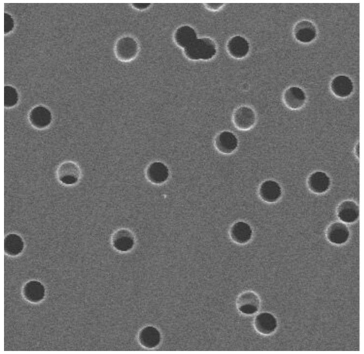
Early cancer diagnostics

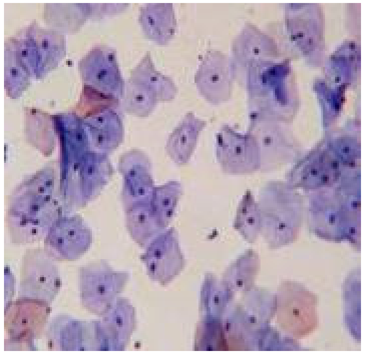
Deformability of erythrocytes

Pore ~4 µm
Erythrocyte ~8 µm
Healthy erythrocytes are able to deform and pass through the pore

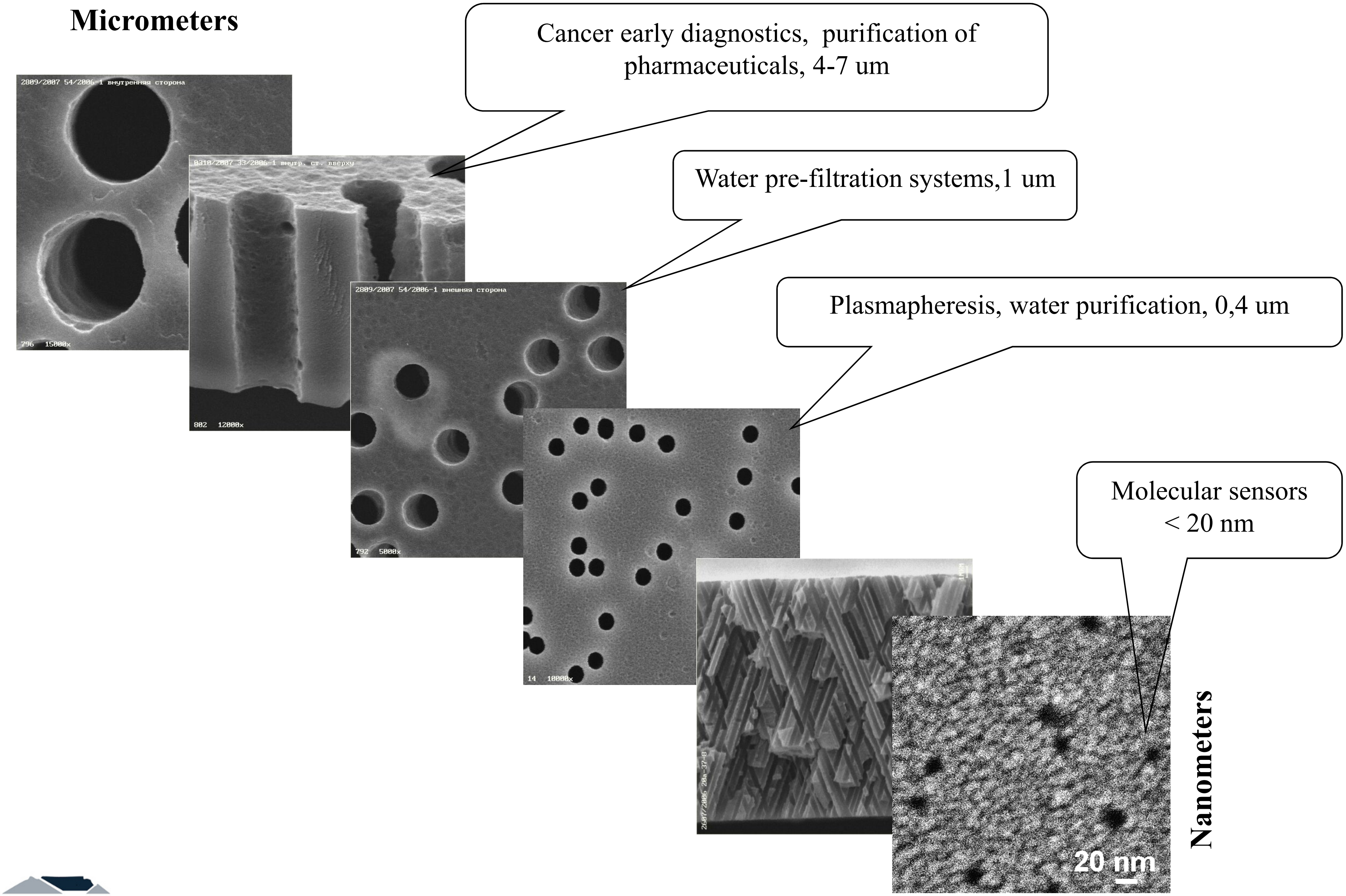
Advanced Pap-rest

The «core» of the method is a track-etched membrane with pore size of 7,2 um. A monolayer of cell is collected on the membrane and analyzed.





Ion track technology



Ion-implantation nanotechnology and radiation materials science.

- Examination of the dense ionization effect in ceramics and oxides with heavy ions of fission fragments energy

The overall intention of this work is to yield sufficient basic data to determine and compare the radiation tolerance of several ceramics and single considered as candidates for inert matrix fuel hosts.

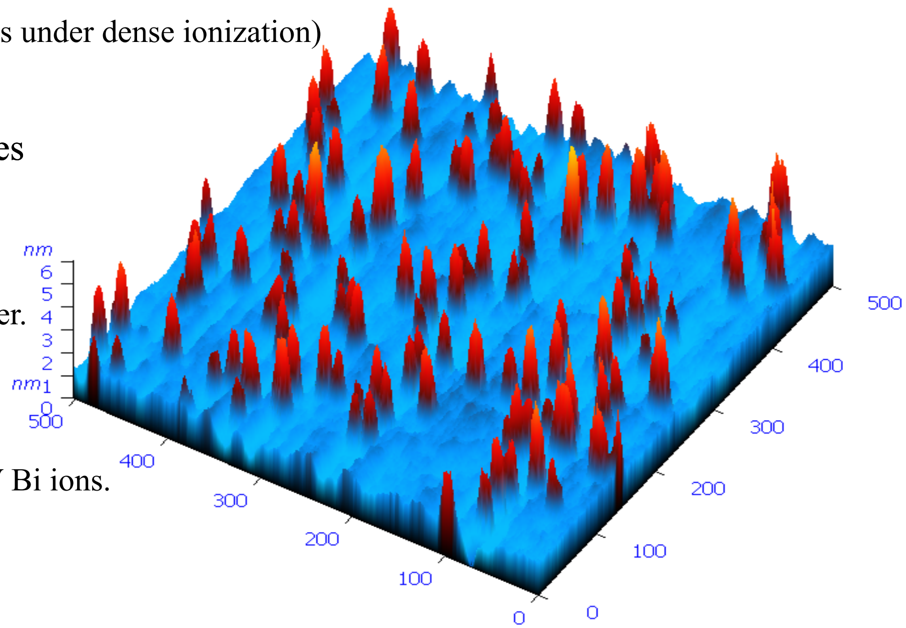
Inert matrices - ceramics with a high melting point and with low neutron absorption cross sections ($MgAl_2O_4$, MgO, Al_2O_3, ZrO_2, SiC, ZrC, ZrN, AlN, Si_3N_4) to be used as hosts for transmutation of actinides via nuclear reactions.

Our central objectives are:

- to study swift heavy ion-induced phase transformations and dense ionization effect on pre-existing defect structure in irradiating materials
- to elucidate the correlation between surface and material bulk radiation damage induced by heavy ions with energies above 1 MeV/amu
- real-time evaluation of mechanical stresses in oxides
- Structural examination and micromechanical testing of ODS (oxide dispersion strengthened steel) irradiated with heavy ions of fission fragments energy (stability of nanoscale oxide particles under dense ionization)

Surface effects of dense ionization in ceramics and oxides

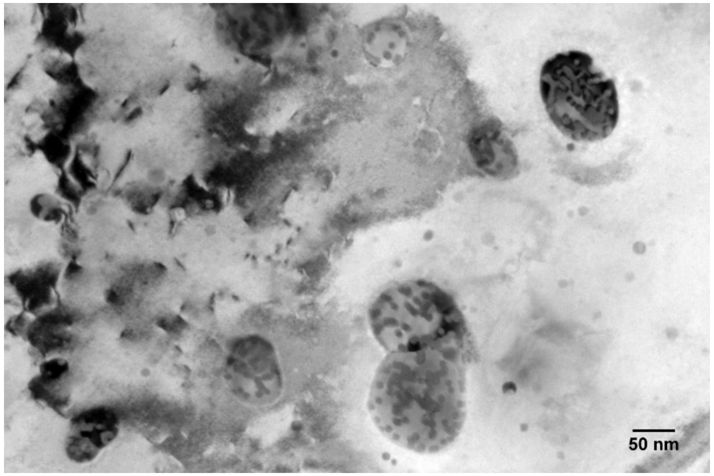
Each Bi ion induces the hillock-like defect.
Overlapping of hillocks leads to amorphization of sub-surface layer.



3D AFM image of $MgAl_2O_4$ surface irradiated with 710 MeV Bi ions.
Ion fluence $5x10^{10}$ cm^{-2}.

Ion-implantation nanotechnology and radiation materials science.

Radiation stability of oxide nanoparticles in ODS alloys against swift heavy ion irradiation simulating fission fragments impact



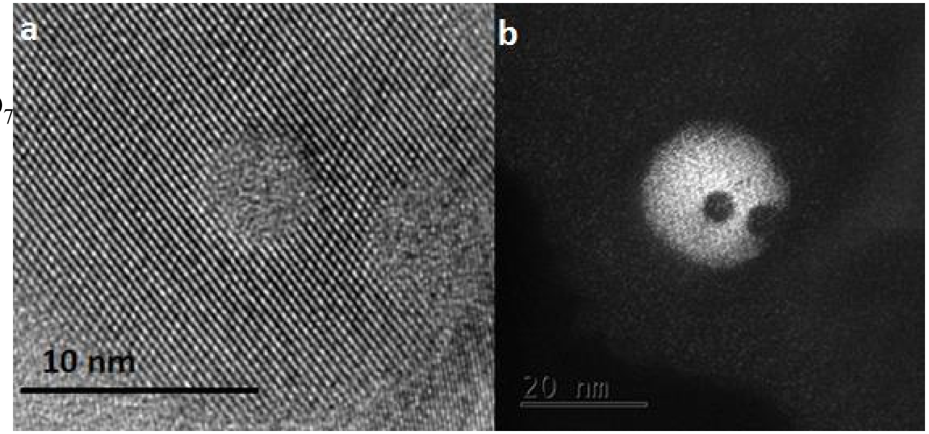
ODS = Oxide Dispersion Strengthened alloys:
Ferritic matrix + 5÷50 nm size thermally stable oxides dispersed within it

Strengthening principle in ODS alloys:
Nanoparticles are obstacles to dislocation glide

ODS steels are promising candidates for fuel cladding

Microstructure of 167 MeV Xe ion irradiated EP450 ODS specimen.
Ion fluence is 10^{12} cm^{-2}.
Dark spots are amorphous latent tracks in $Y_2Ti_2O_7$ nanoparticles.

HRTEM micrograph micrographs of latent tracks in $Y_2Ti_2O_7$ in EP450 ODS steel showing the amorphous nature of ion tracks



Ion-implantation nanotechnology and radiation materials science.

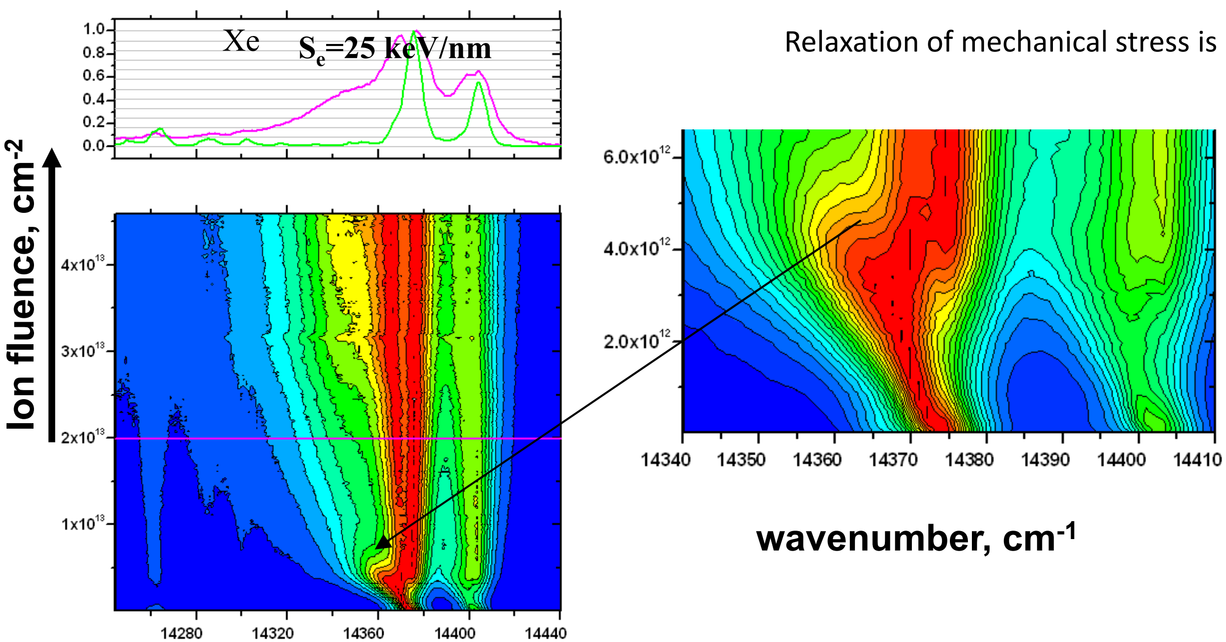
- Accumulation of mechanical stresses under swift heavy ion irradiation

The knowledge about of high energy heavy ion-induced stress is of considerable practical value in view of simulation of fission product impact in radiation resistant oxides and ceramics, considered as candidate materials for nuclear waste management (**inert matrix fuel hosts**)

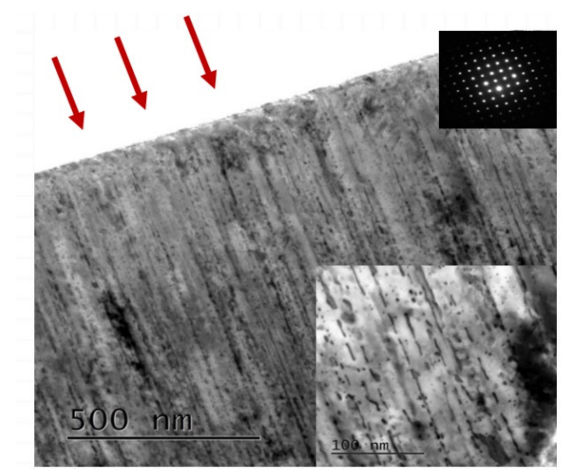
Main questions addressed to real-time measurements:

- Radiation damage and stress accumulation processes before and after ion track region overlapping
- Variation in the stress state under ion irradiation characterized by specific ionizing energy losses higher and lower than the threshold of radiation damage formation via electronic excitations.

STRESS IN Al_2O_3:Cr UNDER SWIFT HEAVY ION IRRADIATION



Relaxation of mechanical stress is due to ion track region overlapping



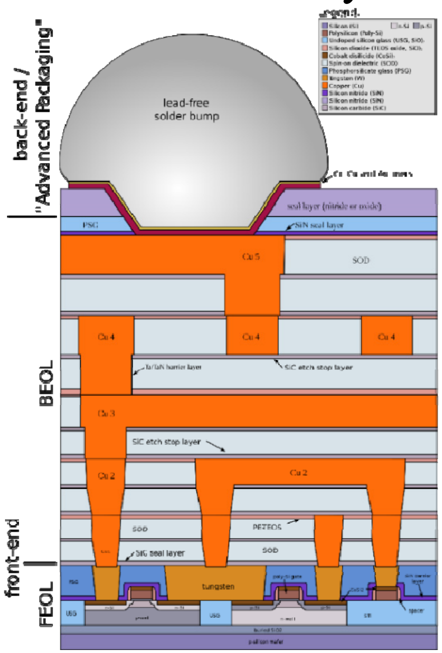
The shift in the wavenumber (frequency, wavelength) is proportional to stress level

Ion-implantation nanotechnology and radiation materials science.

B^{+2}, Ne^{+4}, Ar^{+7}, Kr^{+17}, Xe^{+26} ions with energy ≈ 1.2 MeV/amu

Testing of electronic components (avionics and space electronics) for radiation hardness. (For more details see FRA04 talk)

Question to be answered – what will be if…you have TOO much species in your "sandwich"…. or ONE is already enough ???



*Courtesy to Wiki

- What does it mean for FLNR ??

Using the accelerator complex to irradiate the DUT (Device Under Test) with the heavy ion beams (with well-known characteristics).

- What does it mean for Users ??

To observe response and operate the DUT under exposure online.

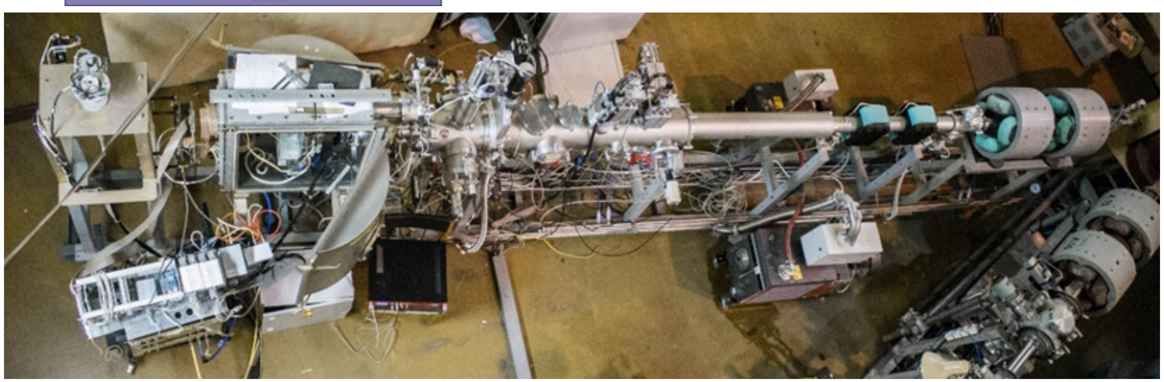
Goal:

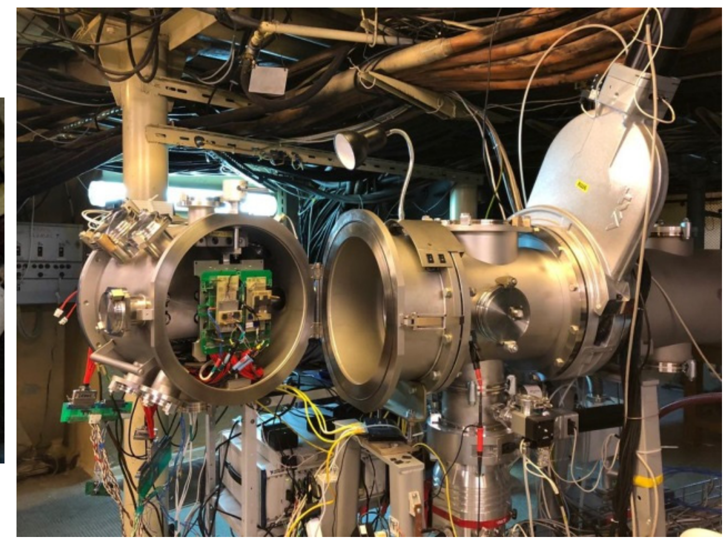
Obtaining experimental data within Earth limits to predict SEE rate in space.

3 dedicated beamlines with E=3÷64 MeV/n.

Since 2010, more then 5000 devices has been tested.

~ 3000 hours per year





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What heavy ion beam parameters do these all-sort practical applications need?

"Shaken, not stirred"

Ion track technology needs:

- energy > **1** MeV per nucleon
- Ions from Ne up to Bi
- Intensity with Xe (as example) $1x10^{12}$ c^{-1}
- Irradiation zone 650*250 mm (1-2 MeV/n) and 325*190mm (4,8 AMeV/n)
- Beam uniformity 5 %
- Casemate - "green area" - people around irradiation chamber
- Oversize irradiation chamber => dedicated beam line

Radiation materials science:

- energy up more than 1 MeV per nucleon
- Ions from Ne up to Bi or U
- Intensity with Xe (as example) $1x10^{12}$ c^{-1}
- Irradiation zone Ø30 mm (1-2 AMeV) and Ø20 mm (4,8 AMeV)
- Dedicated beam line due to specific T° requirements and sample preparation procedure.

Testing of electronic component (SEE testing):

- *Energy, which could provide the ion range in Si around 50 mkm - 4,8 MeV per nucleon*
- Ions from Ne up to Bi (Ne, Ar, Kr, Xe, Au, Bi)
- LET up to 100 MeV/(mg×cm^2)
- Intensity $1x10^5$ c^{-1}×cm^{-2}
- Irradiation zone 200*200 mm at least - *usual user' question is "when we can irradiate the whole device?"*
- Dedicated beam line due to specific requirements and sample preparation procedure.
- *Cocktail beam – quick switching between ion types.*

What we need from cyclotron to fit applied science requirements?

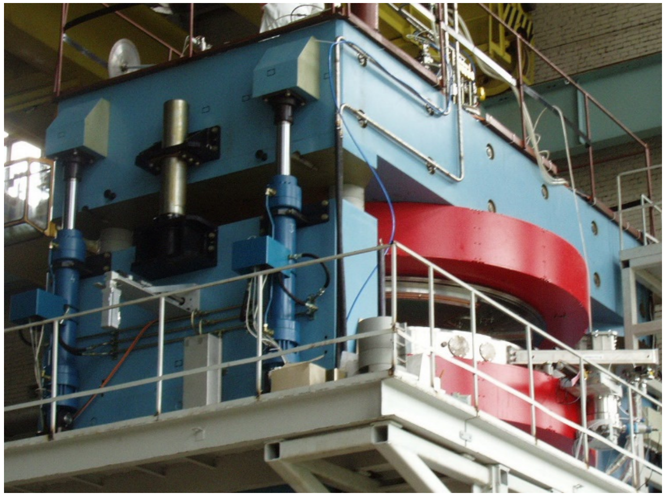
- 24*7*365 ~ 7000 of beam time
- Simplicity of operation
- Time stability
- **Beam cocktail**
- Relatively cheap in use – beam time costs
- Factory approach/routinely use - "turning lathe“
- Economy factor: to use the existing stuff

What we are looking for:

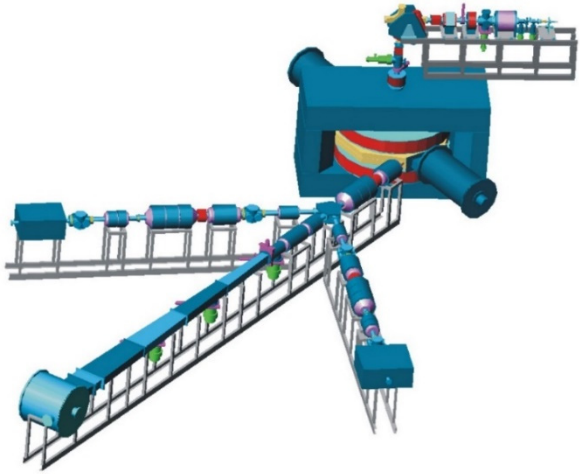
The idea is to modernize/totally upgrade the ~~old U200~~ DC72 machine

DC72 Cyclotron

Cyclotron magnet structure consists of compact E-type magnet yoke, magnet inducing winding and alignment coils. Magnet pole diameter - 2600 mm, number of direct sectors - 4, magnet bore maximum magnetic field - 1.5 T, magnet weight - 320 t, alignment coil maximum power - 53 kW, Overall dimension - 5,6*2,7*3,1 m.
DC-72 cyclotron high-frequency accelerating system consists of two quarter-wave-length resonators, placed upright and downright the cyclotron median plane. Operating frequency range is 17 - 34 MHz. Dees are placed in two opposite valleys, dee maximum amplitude voltage is 60 kV. Ions are accelerated at 2, 3, 4 harmonics of resonance system frequency, dee voltage phasing accuracy is equal to 1. Two high-frequency generators of 35 kW each supply cyclotron accelerating system.



The project of DC-140 cyclotron



Technical characteristics of DC-140:

- range of ions from O to Bi,
  - external beam injection from ECR ion source,
  - ion energies:

2.124 MeV/nucleon (A/Z=7.35 – 8.25). 4.316 MHz

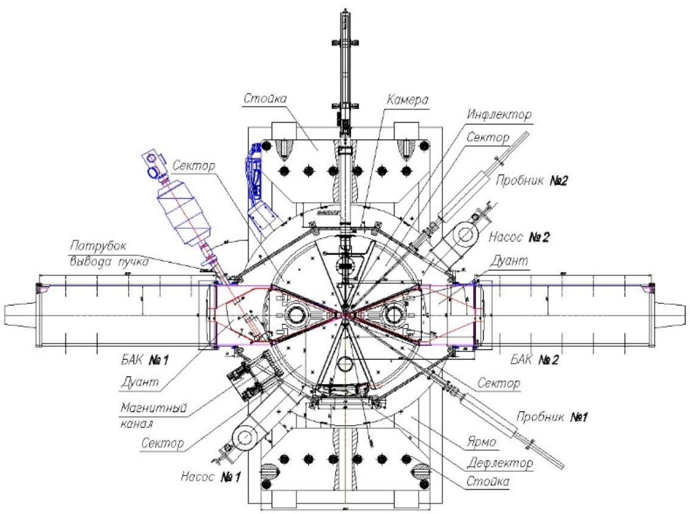
4.8 MeV/nucleon (A/Z=4.9 - 5.5). 2.877 MHz

Physical installations:

- installation for scientific and applied research,
- facility for irradiation of polymer films,
- installation for testing of electronic components.

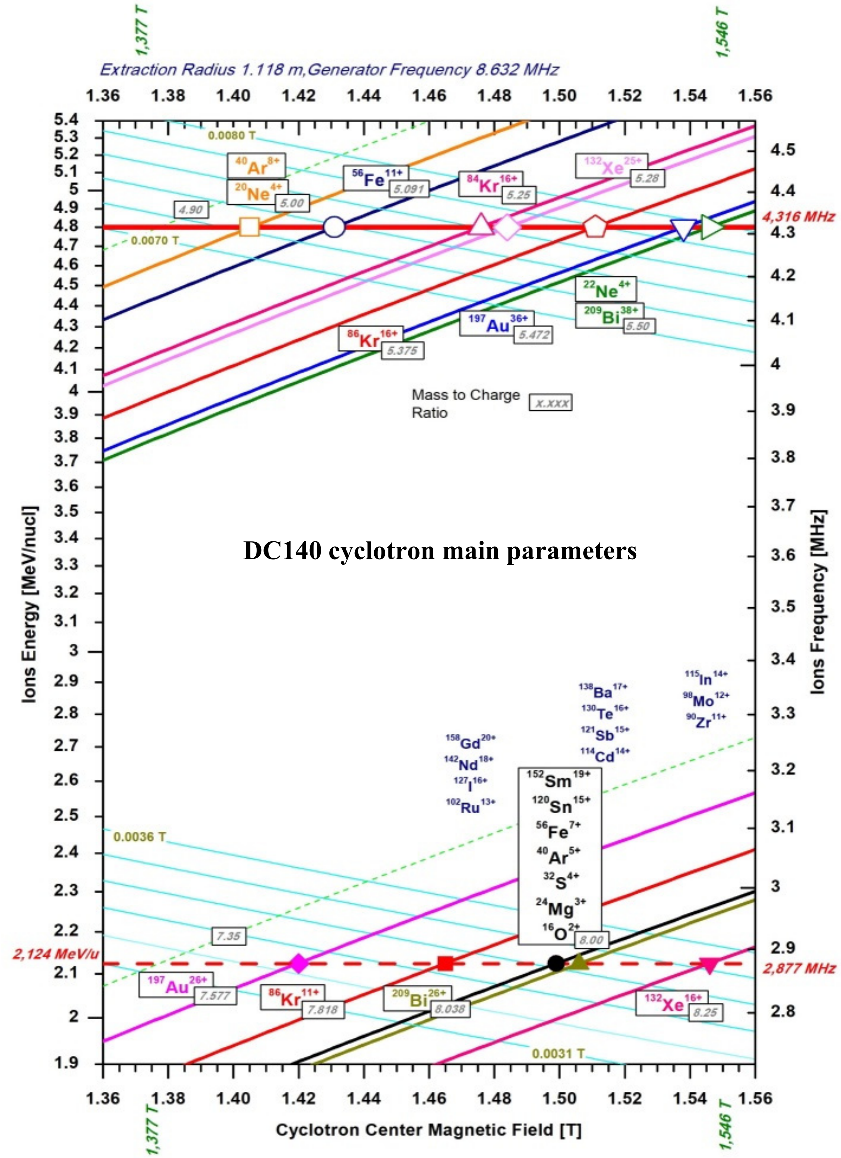
If we will use the main magnet of DC140 of the DC72 cyclotron, that now is waiting for new life, then…

The design should based on **existing** systems of IC100 and DC72 cyclotrons and use only proven technical solutions of DC110.



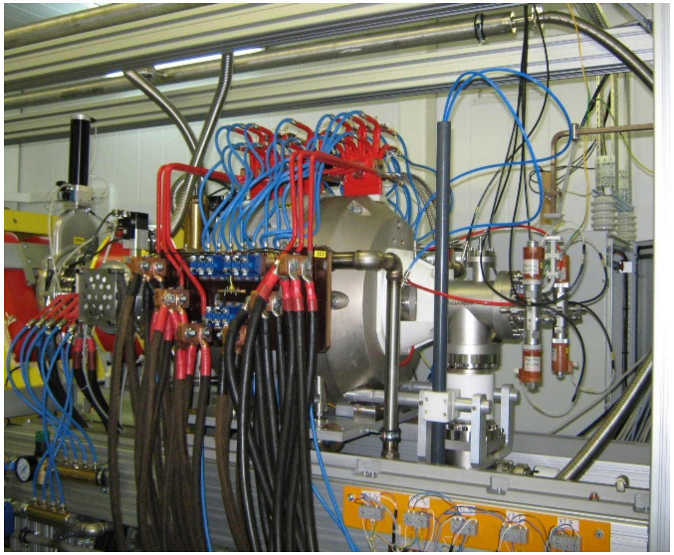
General “draft” layout of the DC140 cyclotron.

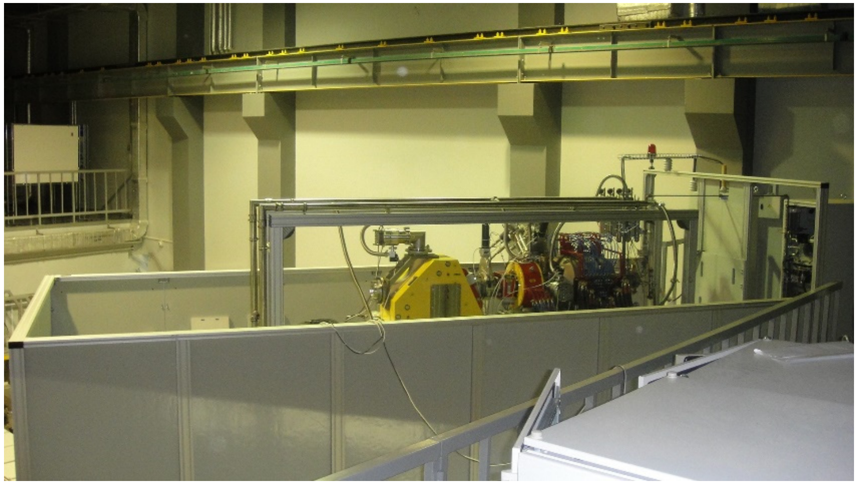
The acceleration of ion beam in the cyclotron will be performed at constant frequency f = 8.632 MHz of the RF-accelerating system for two different harmonic numbers h. The harmonic number h = 2 (f=4.316 MHz) corresponds to the ion beam energy E = 4.8 MeV/u and value h = 3 (f=2.877MHz) corresponds to E = 2.124 Mev/nucleon.



Ion source for the new facility

The 18 GHz DECRIS-5 ion source was developed on the basis of sources of the DECRIS-4 (14 GHz) series with copper windings created at FLNR (JINR, Dubna) by intensifying the magnetic structure and changing to a new type of microwave oscillator. The DECRIS-5 ion source was created for industrial application is characterized by increased reliability. It was already successfully commissioned in the framework of DC110 project (mass production of the track membrane). To ensure the design parameters of the DC-110 project , the ion source should generate intensities of $^{40}Ar^{6+}$, $^{86}Kr^{13+}$ and $^{132}Xe^{20+}$ ion beams of not less than 85µA, 150 µA and 150 µA, respectively. DC110 was successfully commissioned with needed beams intensities in 2012.



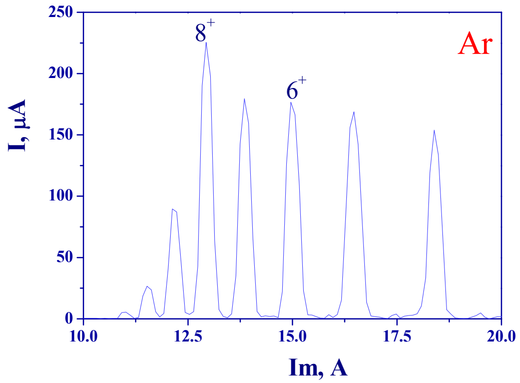


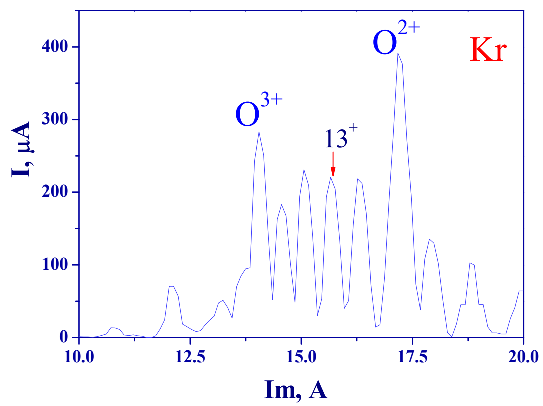
Assembled DECRIS-5 and axial injection system at the DC-110 cyclotron

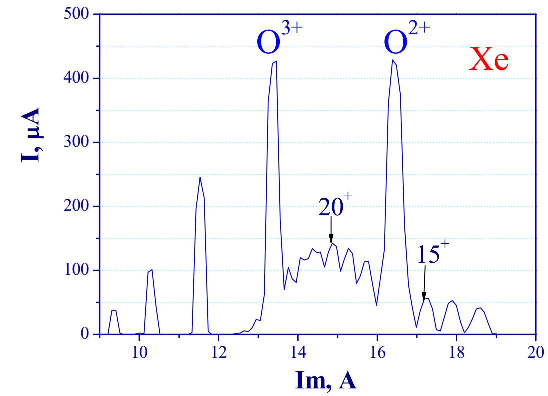
For more details with metallic ion beam see MOP017 poster

Ion source for DC140 project

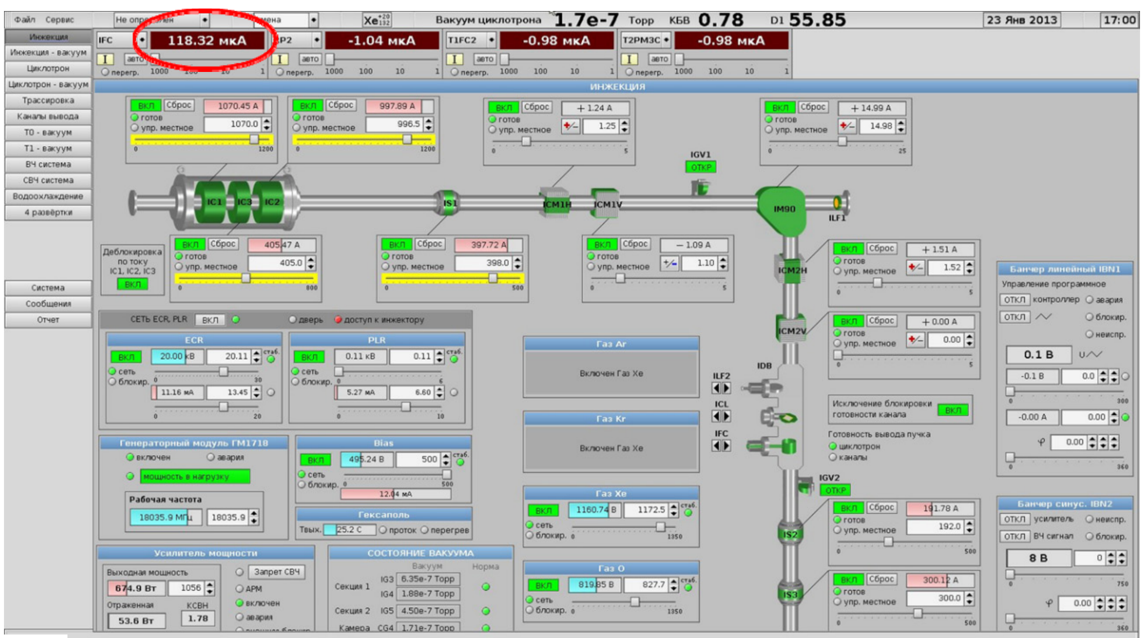
Beams of Ar, Kr, and Xe ions were produced from the source.







DC-110 control panel: Xe is online

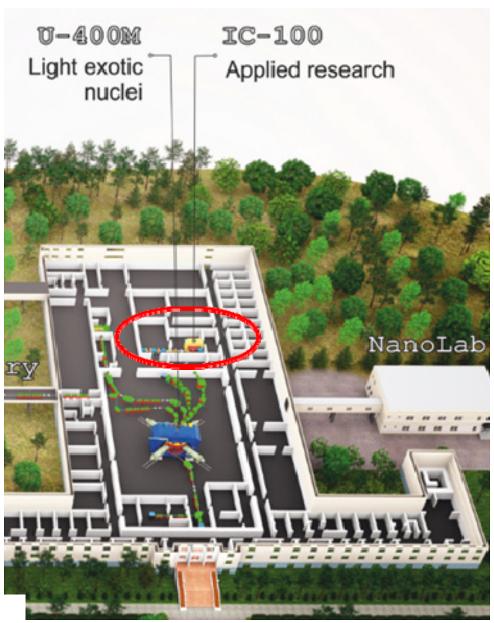


Results of the test

Ion	Current, (eμA)
Ar^{8+}	1200
Ar^{9+}	750
Ar^{11+}	300
Kr^{15+}	325
Kr^{17+}	230
Kr^{18+}	182
Kr^{19+}	120
Kr^{20+}	70
Xe^{20+}	220

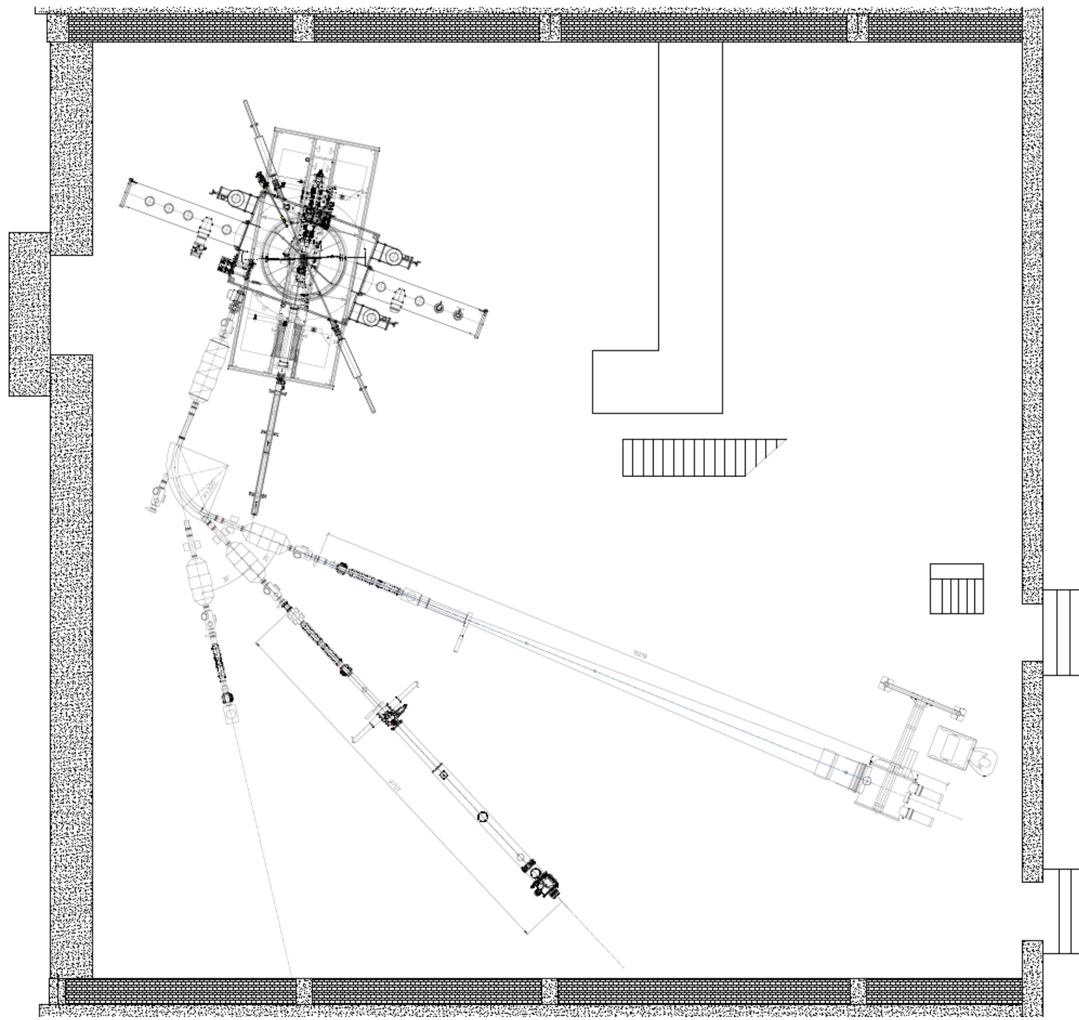
DC140 prelaminar roadmap

What to do:
- Vacuum system + main chamber (new)
- Colling system (new)
- Control system (new)
- Axial injection (partly new) See MOP018 poster
- Beam extraction (new) See MOP020 poster
- Cyclotron magnetic structure (upgrade)
- RF system (upgrade)
- Magnet main coils (new)
- Beamlines (upgrade)
- Safety features (new)
- ………



The Design Study should be finished before the end of 2019.

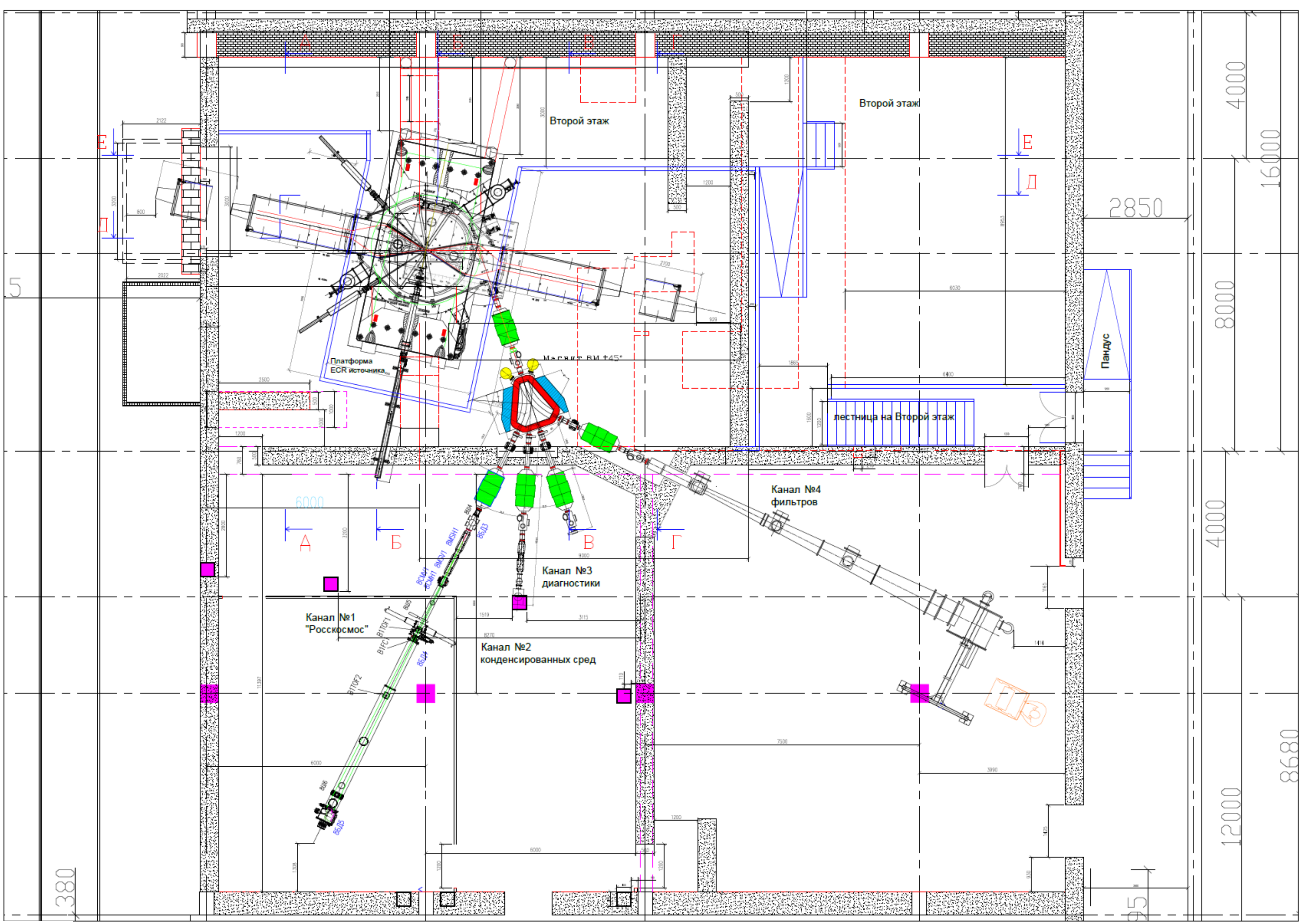
Sketch of 10’2018



DC140 prelaminar roadmap

The Design Study and cost estimation should be finished before the end of 2019.

Планировка DC140 с раздающим магнитом BM ±45° (1:16)



General layout of the DC140 vault 09'2019

DC140 prelaminar roadmap

2018-2019 – Old stuff removing from U200 vault and related casemates

2019 – Design Study

2018-2020 – Building renovation

2019 – 2020 – Equipment accumulation (purchasing)

2020 - 2022 – Assembling

2022 – Start-and-adjustment works*

Conclusion

1. Flerov Laboratory of Nuclear Reaction begun the Design Study of the dedicated applied science facility based on the new DC140 cyclotron.

2. The main characteristics of the new DC 140 cyclotron are defined and fit main user’ requirements well.

3. The detailed project will be ready in December’2019.

4. If everything will go smoothly…… at end of 2022 the facility will be available for users.

FLNR JINR Accelerator Complex for Applied Physics Researches: State-of-Art and Future

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Thank you for your attention!