Laboratory of Physics
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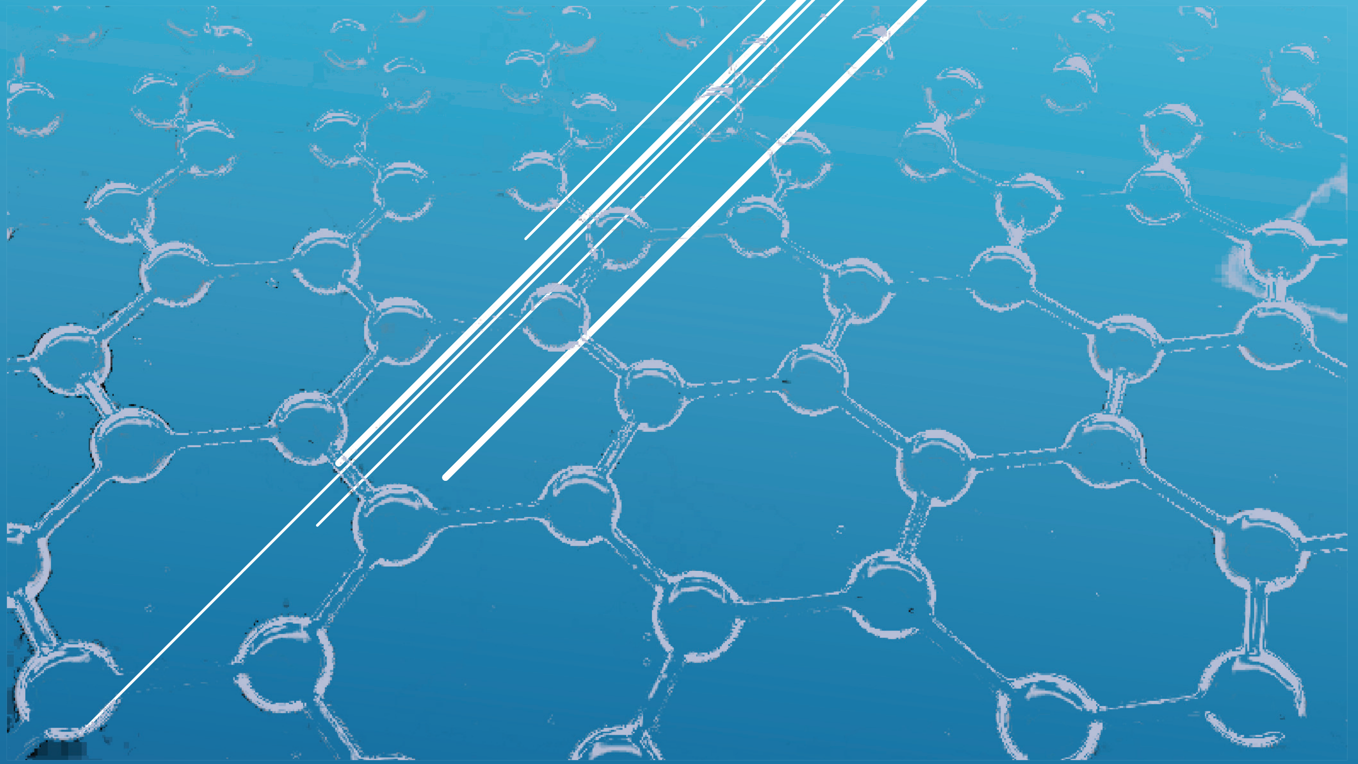
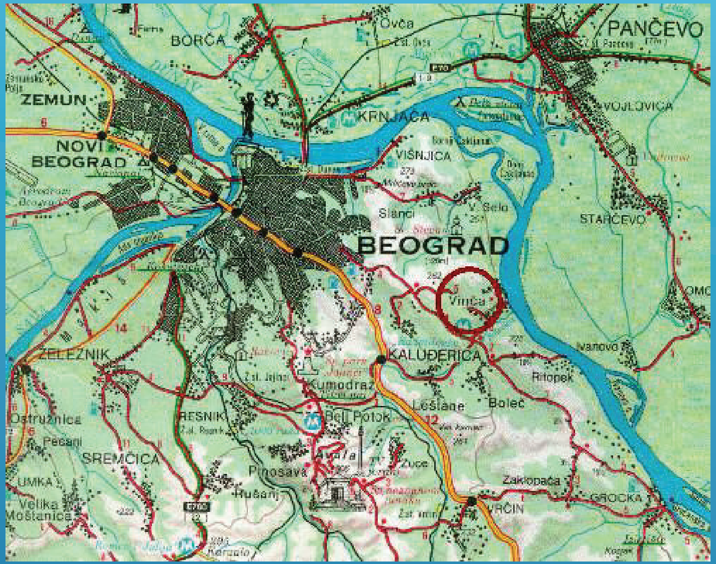
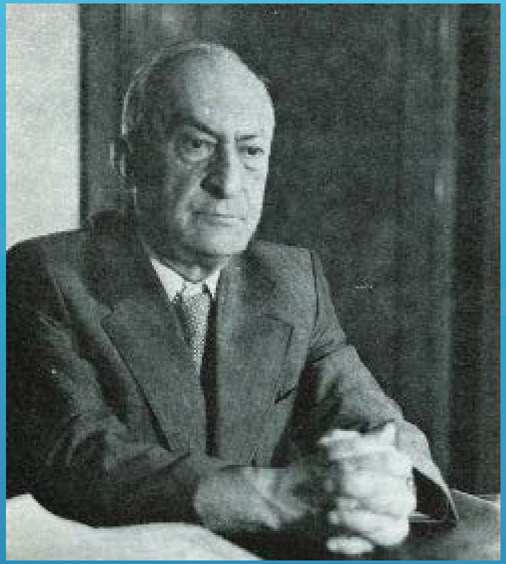
TRANSMISSION STUDIES WITH ION BEAMS WITHIN FAMA

Zoran Jovanović



VINČA INSTITUTE OF NUCLEAR SCIENCES





- Vinča Institute of Nuclear Sciences is founded in 1948 as a research institute in the field of natural sciences – physics, chemistry, biology

- In august 1989 the government of Serbia has decided to build accelerator installation TESLA (AIT), a large infrastructure for production, acceleration and use of ion beam in science, technology and medicine in VINS.

Scientific programs of VINS (until 2030)

- New materials and nanosciences
- Energy and energy efficiency
- Environment and health
- Nuclear, particle physics and theory of gravity
- Science with accelerators and accelerator technologies

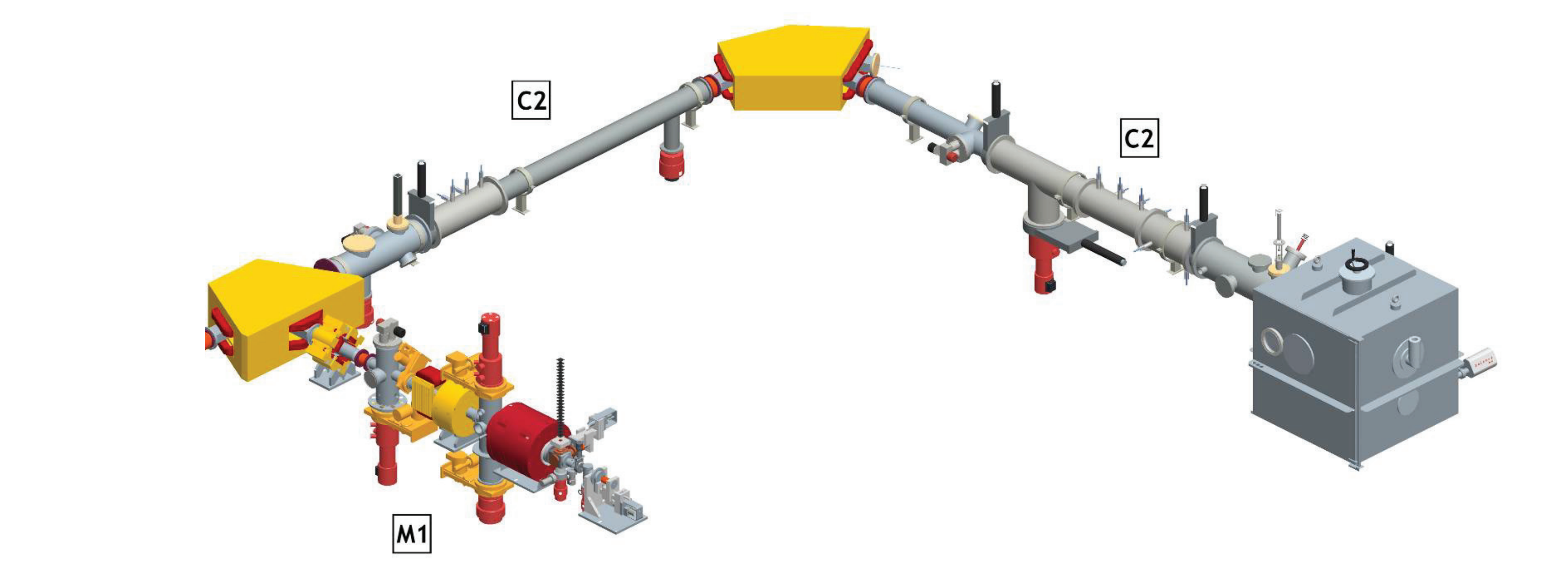
Laboratory of physics at VINS

FAMA – FACILITY FOR MODIFICATION AND ANALYSIS OF MATERIALS WITH ION BEAMS

EARLY FAMA

- Commissioned in May 1998.
- It then comprised:

  - heavy ion source, M1 machine;
  - channel for modification of materials, C2;
  - light ion source, M2 machine;



A three-dimensional scheme of the M1 machine and C2 channel

EARLY FAMA

The M1 machine.

- The M1 machine was commissioned in May 1998.
- It was constructed by the Joint Institute for Nuclear Research, Dubna, Russia, in close collaboration with the Vinča Institute.
- It was an example of successful combining of the Russian engineering and western technologies.

EARLY FAMA

The C2 channel

- The C2 channel was also commissioned in May 1998. It was constructed by Danfysik, Jyllinge, Denmark.
- The M1 machine and C2 channel are used jointly for modification of materials with heavy ions.
- Various metal, semiconductor, carbon, polymer and ceramic targets are bombarded with heavy ions obtained from various gaseous and solid substances.

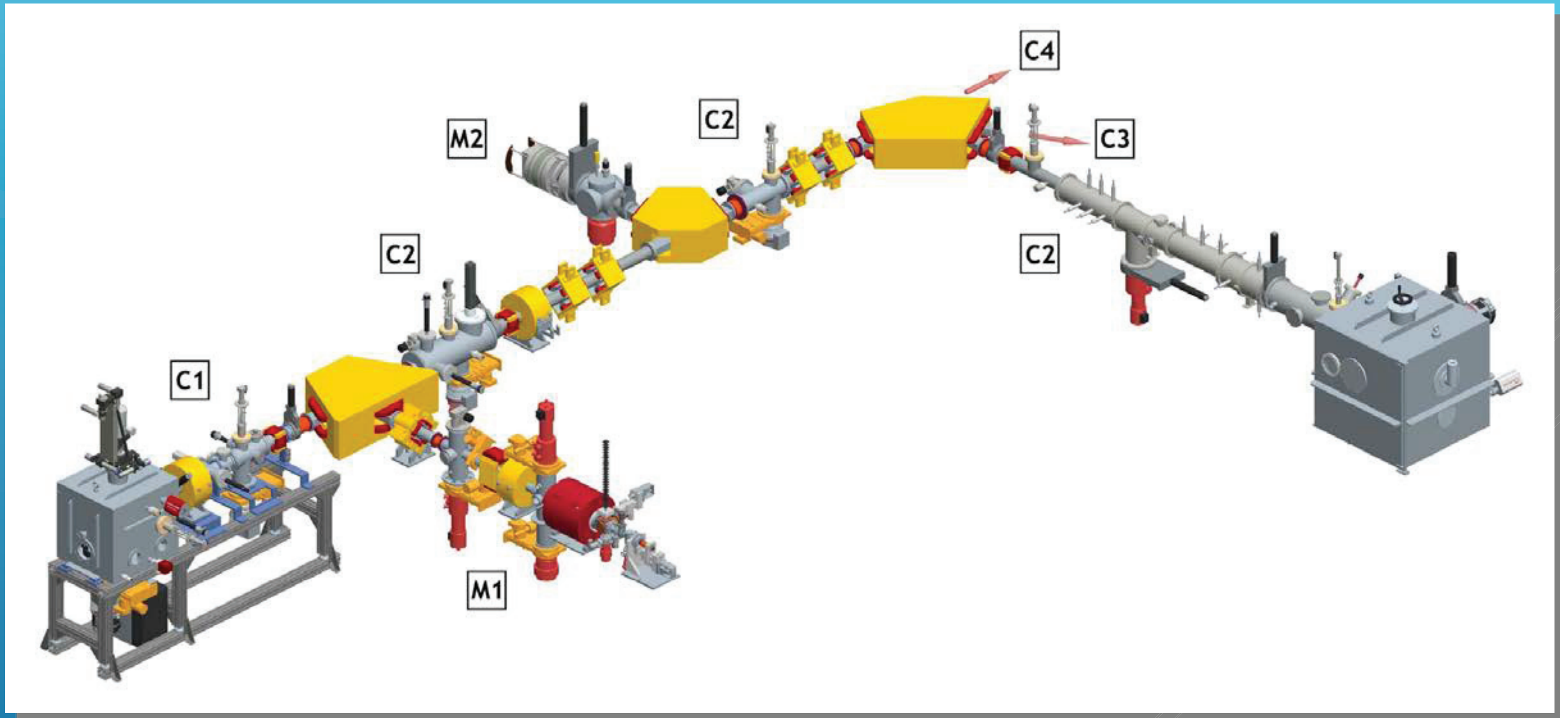
EARLY FAMA

The M2 machine.

- The M2 machine was commissioned in July 1997, as the light ion source of the VINCY Cyclotron.
- It was constructed by AEA Technology, Abingdon, Great Britain.
- From January 1998, the machine has been being used for surface modification of materials with light ion beams.

UPGRADE(ABLE) FAMA

- ❑ In June 2010 the upgrading of FAMA began.
- ❑ This included:
- ➢ refurbishment of the original FAMA
- ➢ construction of C1 channel, for channeling implantation
- ➢ Construction of small cyclotron complex, the M3 machine
- ➢ Constructions of channels for analysis of materials in vacuum and air, the C5 and C6 channels



A three-dimensional scheme of the M1 and M2 machines and the C1 and C2 channels after the refurbishment .

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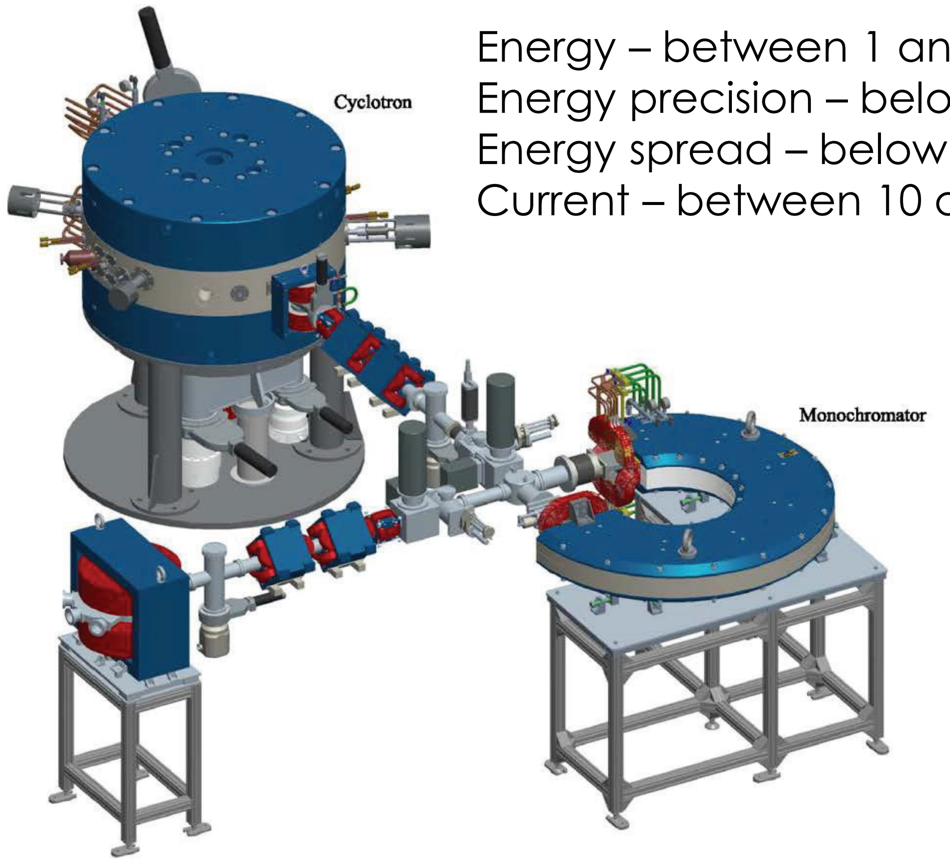
Energy – between 1 and 3 MeV
Energy precision – below 1 keV
Energy spread – below 0.1 %
Current – between 10 and 100 nA



A three-dimensional scheme of the M3 machine.

UPGRADE(ABLE) FAMA

M3 machine – a small proton cyclotron complex.

UPGRADE(ABLE) FAMA

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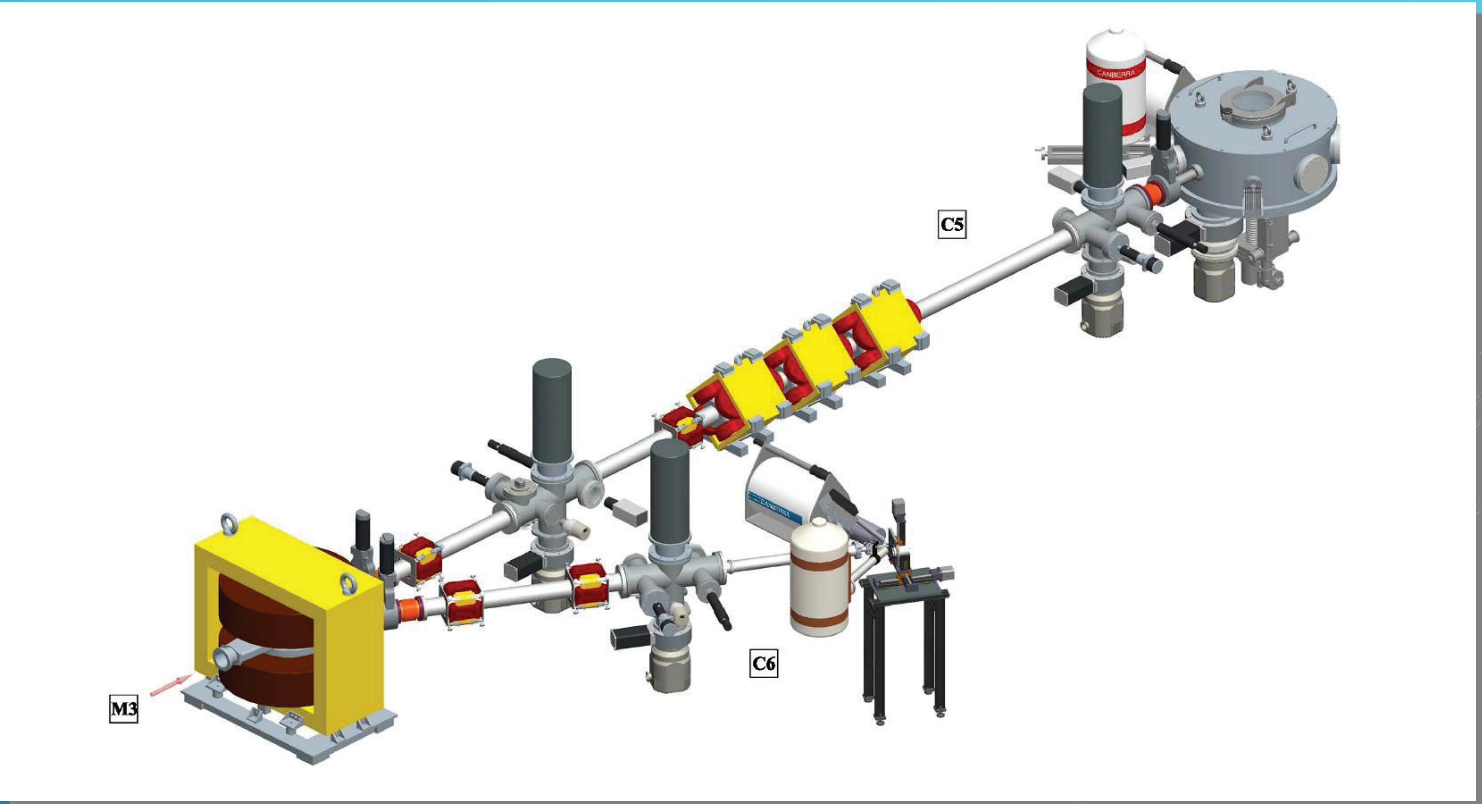
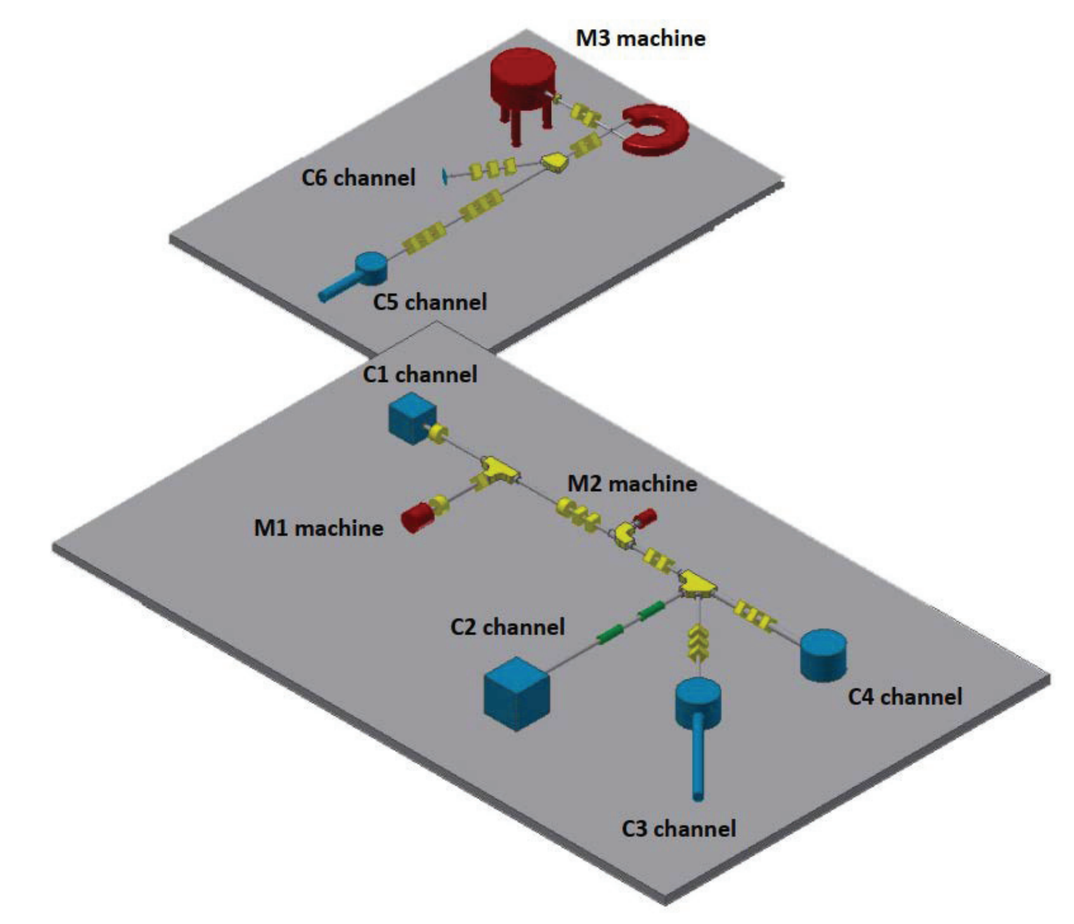


A three-dimensional scheme of the C5 and C6 channels.

UPGRADE(ABLE) FAMA

- ❑ In march 2020 a plan for additional upgrade of FAMA was made
- ❑ This should include:
- ➢ refurbishment of the original FAMA
- ➢ construction of C3 channel, for transmission studies
- ➢ Construction of C4 channel, for surface physics
- ➢ Further upgrade of C5 and C6 channels



A three-dimensional scheme of future FAMA

ION TRANSMISSION STUDIES WITH VERY THIN ELECTROSTATIC LENSES

ION TRANSMISSION THROUGH VERY THIN ELECTROSTATIC LENSES

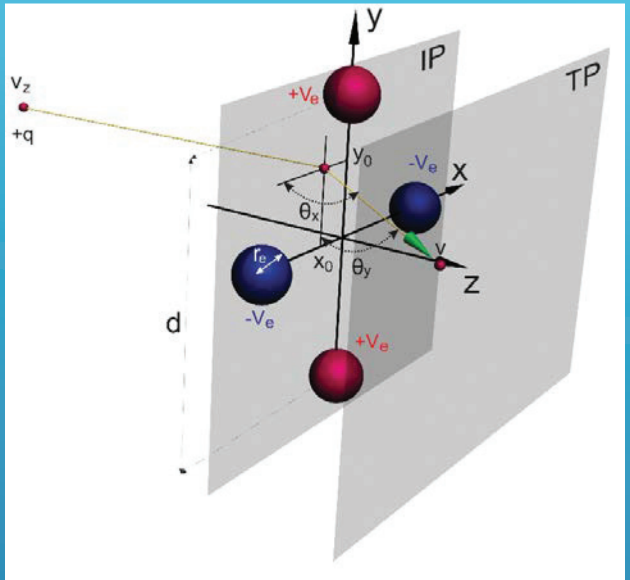


Illustration of ion trajectory solved in ***momentum approximation*** *in quadrupole* ***VTEL-s*** *field*. In **IP** for Z=0 every ion has starting x_0 and y_0 position. Dimension of quadrupole is r_e = 1mm and d = 1cm and DC voltage is V_e **=1kV**. ***q* = *e*** is the ion charge. Ion ienergy **E = 10 keV**.

If lens is sufficiently thin then ion trajectory can be approximated by a straight line. Thus, we can apply the **momentum approximation.** Transmission angles, are:

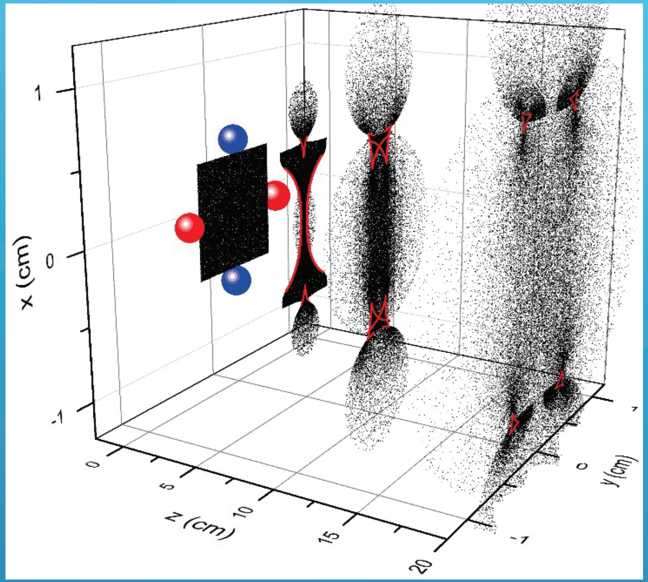
$$\theta_x = -\frac{1}{2E}\int_{-\infty}^{\infty}\partial_x U dz \quad \text{and} \quad \theta_y = -\frac{1}{2E}\int_{-\infty}^{\infty}\partial_y U dz$$

The position ion determined by the equations : $x = x_0 + \theta_x$ and $y = y_0 + \theta_y$. The interaction potential is:

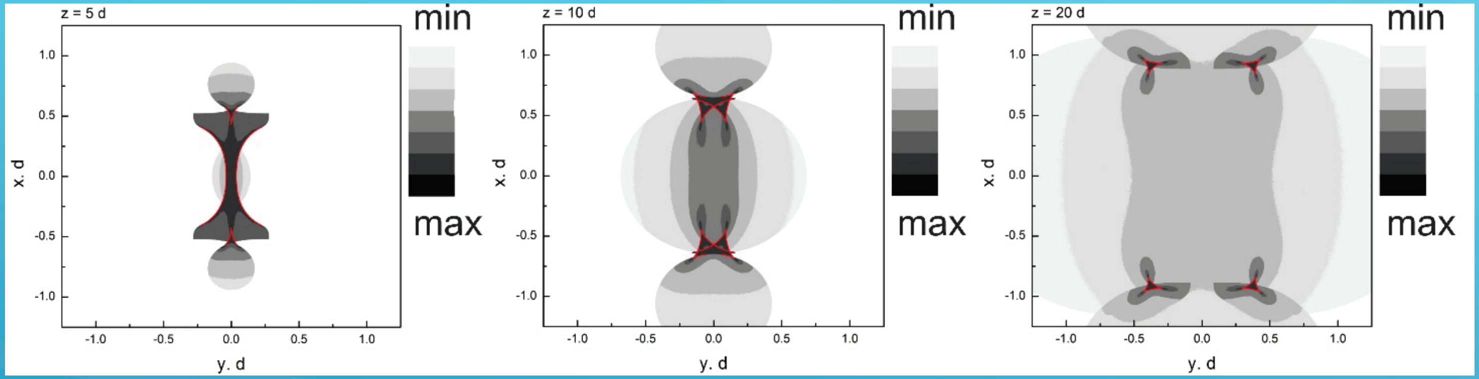
$$U = -\sum_{i=1}^{4}\frac{V_e r_e}{\sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2 + z^2}}$$

x_i and y_i are the vertical and horizontal positions of the i-th electrode. Equation $J_\rho = 0$ defines the spatial rainbow lines in the IP plane. Their image in transversal plain xy form lines called **transversal spatial rainbows** or caustic. Equations $\partial_x J_\rho = 0$ and $\partial_y J_\rho = 0$ define the points in the IP plane at which J_ρ is extremal.

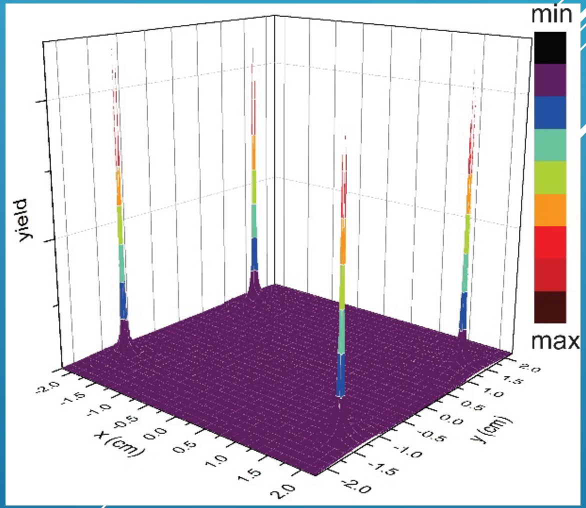
ION TRANSMISSION THROUGH VERY THIN ELECTROSTATIC LENSES



Ion beam in IP and TP plain of quadrupole VTEL-s. The red lines are the images in the TP plane of the fragments of the rainbow patterns in the IP plane lying inside the square aperture.

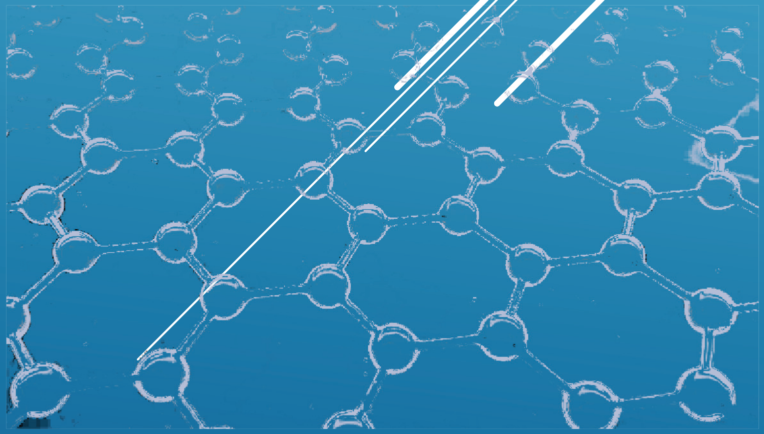


Two-dimensional spatial distribution of transmitted ions. The ion yield scale is 2^n with the yield marked by white up to black colors in 7 steps.

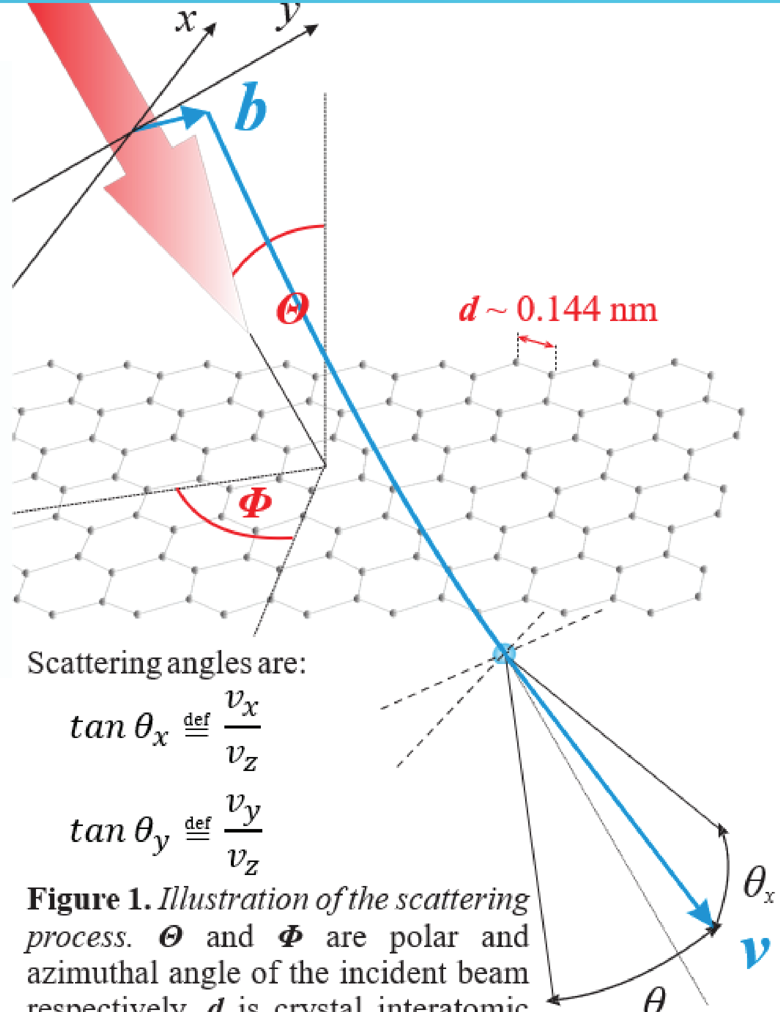


Three-dimensional distribution of transmitted ions after quadrupole VTEL-s in TP plain for z = 50*d*.

ION TRANSMISSION THROUGH TWO-DIMENSIONAL MATERIALS



ION TRANSMISSION THROUGH TWO-DIMENSIONAL MATERIALS



Scattering angles are:

$$\tan\theta_x \stackrel{\text{def}}{=} \frac{v_x}{v_z}$$

$$\tan\theta_y \stackrel{\text{def}}{=} \frac{v_y}{v_z}$$

Figure 1. *Illustration of the scattering process.* ***Θ*** and ***Φ*** are polar and azimuthal angle of the incident beam respectively. ***d*** is crystal interatomic distance. ***v*** is proton velocity in the final state. ***b*** = (***x₀***,***y₀***) is proton impact parameter.

The morphological analysis of graphene

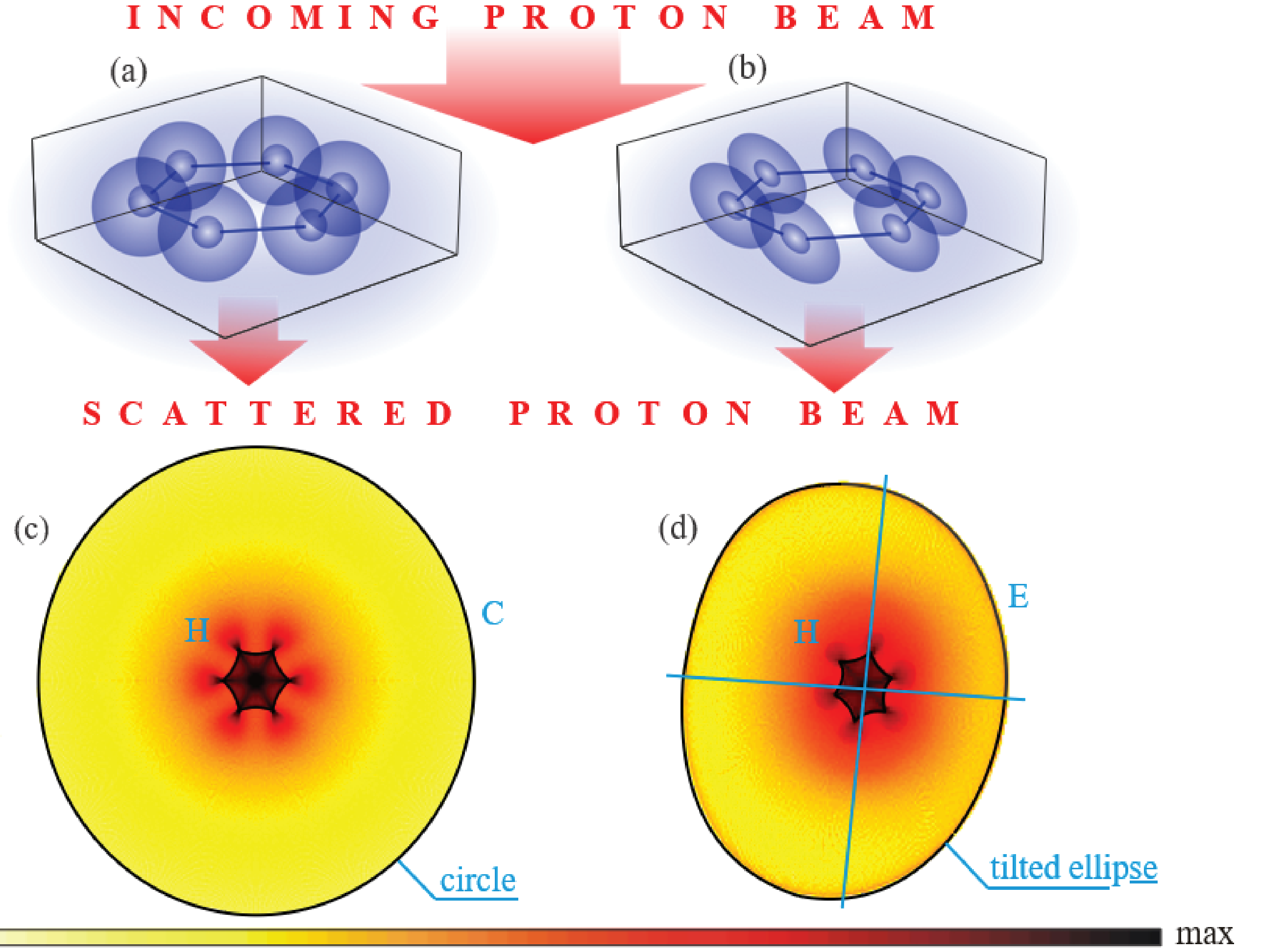
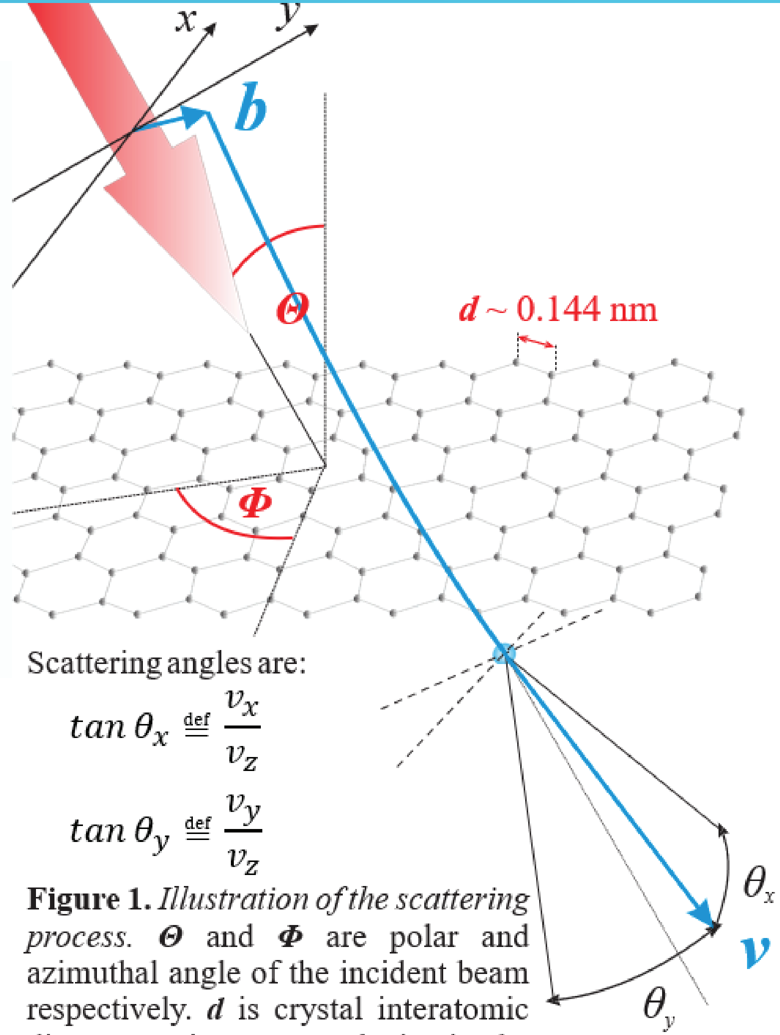


Figure 1. (a) and (b) Graphene hexagons in the case of isotropic and anisotropic thermal vibrations.(c) and (d) angular rainbow lines (black) and corresponding angular proton yields in the logarithmic scale. Rainbows C and E provide information about thermal vibrations.

ION TRANSMISSION THROUGH TWO-DIMENSIONAL MATERIALS



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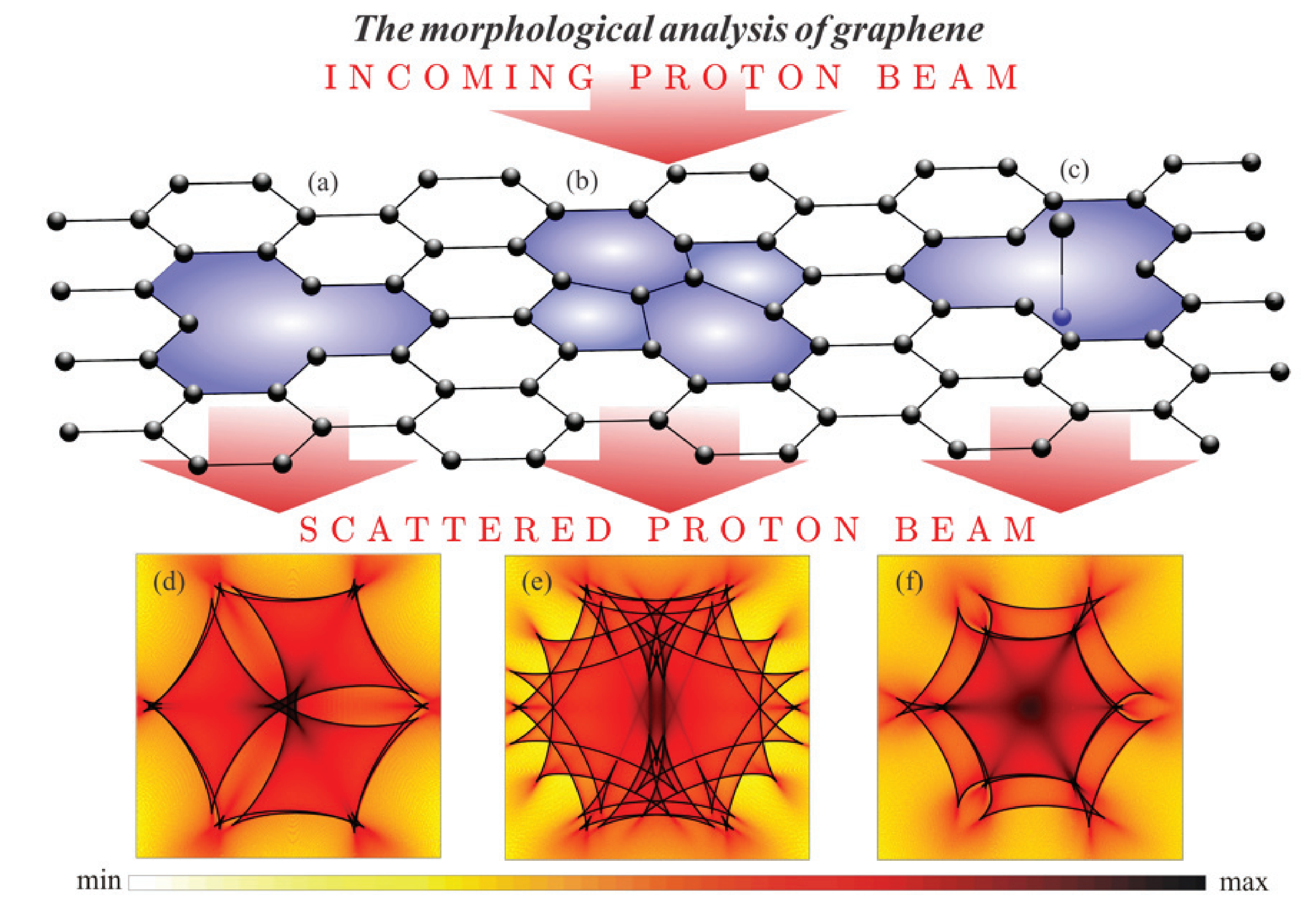
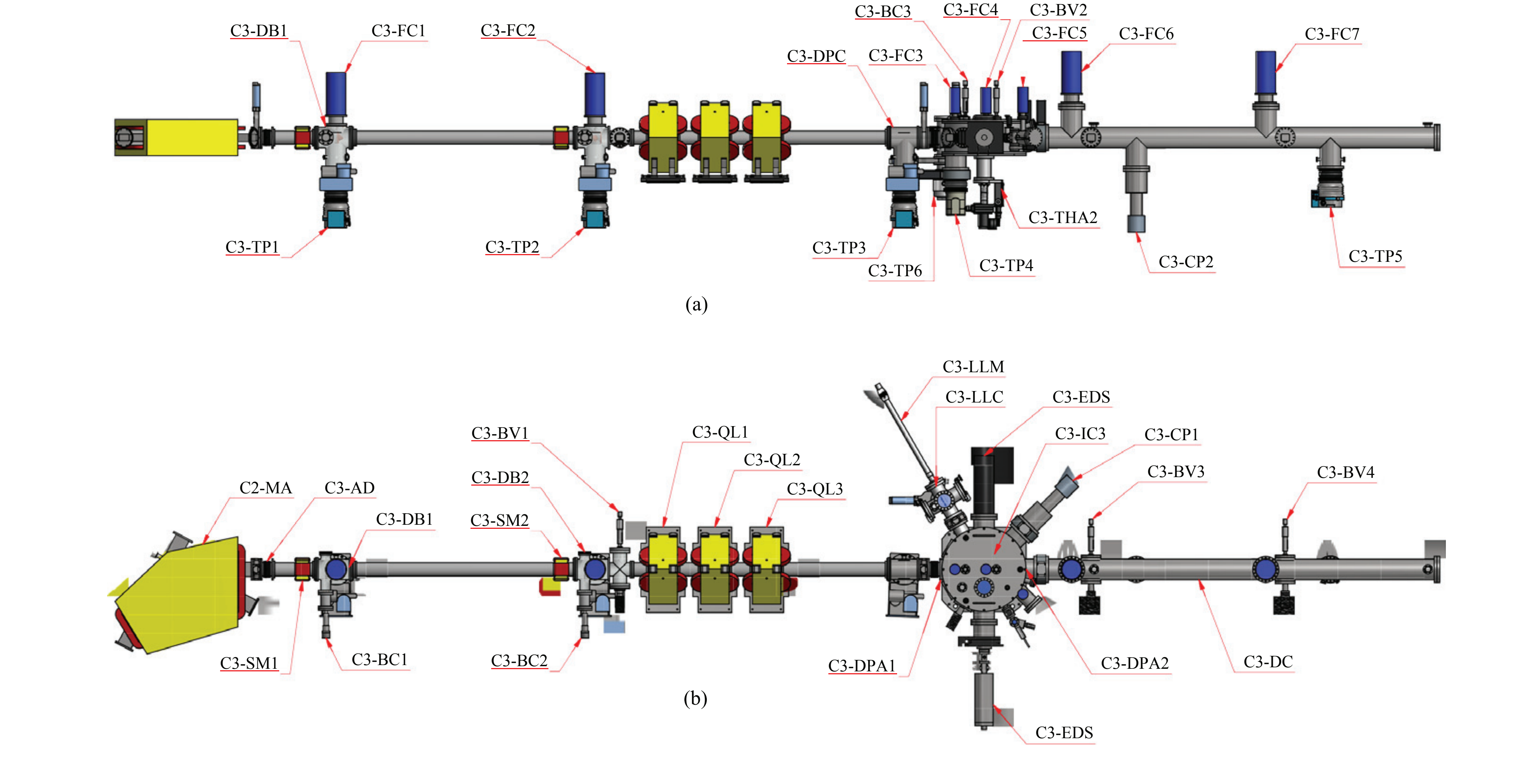


Figure 2. (a), (b) and (c) Graphene with vacancies, Stone-Wales topological defects and carbon adatoms, respectively. (d), (e) and (f) corresponding angular yields of transmitted protons in logarithmic scale.

C3 CHANNEL FOR TRANSMISSION STUDIES AT FAMA

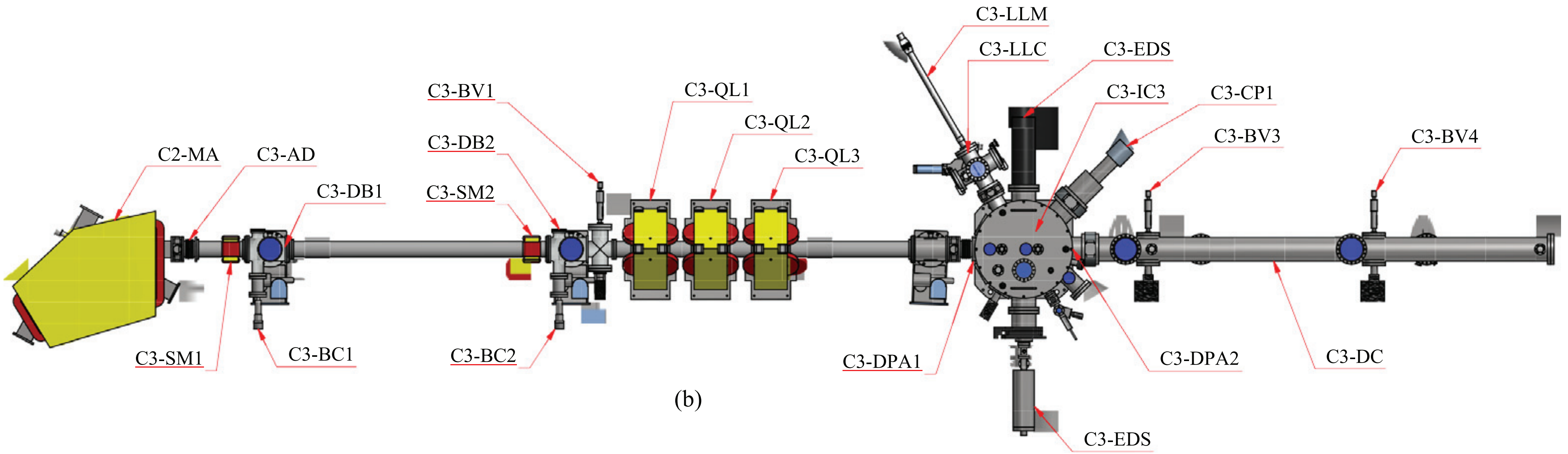
CONCEPTUAL DESIGN OF C3 CHANNEL



- ❑ Transport line
- ❑ Interaction chamber
- ❑ Detection chamber
- ❑ Vacuum system
- ❑ Safety and control

Vertical and horizontal projections of a scheme of the C3 channel – (a) and (b), respectively.

MAIN COMPONENTS OF THE C3 CHANNEL



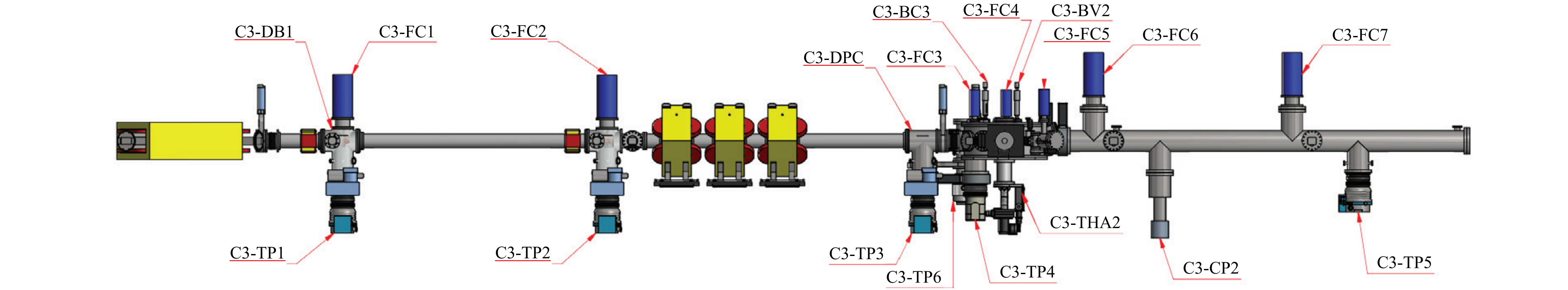
(b)

Main components of transport line:

- two steering magnets
- three magnetic quadrupole lenses
- Two diagnostic boxes
  - a variable circular ion beam collimator
  - a Faraday cup
  - a beam viewer

- Collimators – 5 mm for VTELS and 2 mm for 2D materials
- The transport line is terminated with a differential pumping chamber

MAIN COMPONENTS OF THE C3 CHANNEL



Main components of vacuum and control and safety system:

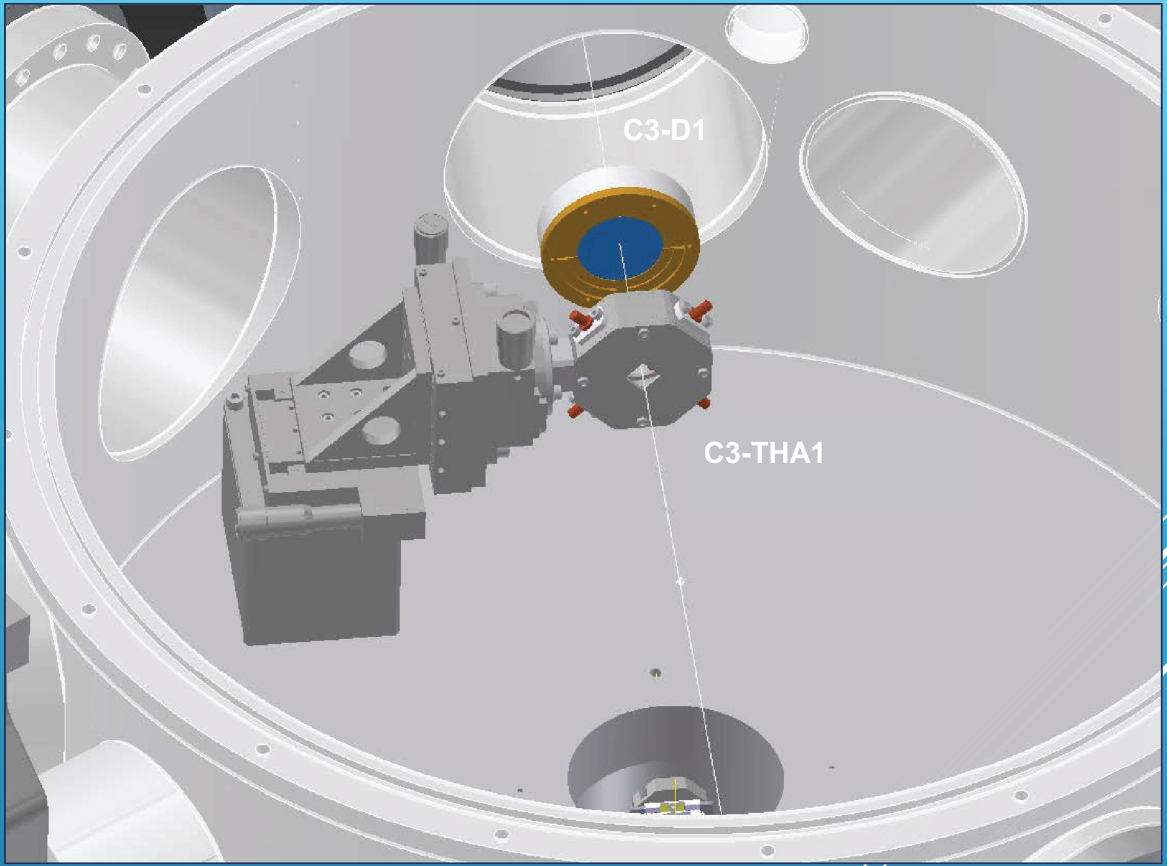
- 5 TP (700 l/s), 1 TP (300 l/s), and 2 CP (1,200 l/s).
- The aim is to ensure the pressure of 5×10^{-8} and 5×10^{-10} mbar in the interaction chamber in the experiments with VTLs and 2D materials, respectively.

- The control and safety system of the C3 channel will be composed of the Group 3 Control hardware and the WonderWare In Touch software.

INTERACTION CHAMBER OF THE C3 CHANNEL

The interaction chamber of the C3 channel

- Inner diameter of 580 mm and height of 250 mm
- UHV, $<5\times10^{-10}$ mbar
- Two target holder assemblies (THAs) - for VTELs and 2D materials
- An electrostatic deflector
- Two position sensitive detectors (PSD) to record the angular distribution of ions.
- The reflection high energy electron diffraction (RHEED) system for monitoring the crystal structure of the chosen 2D material

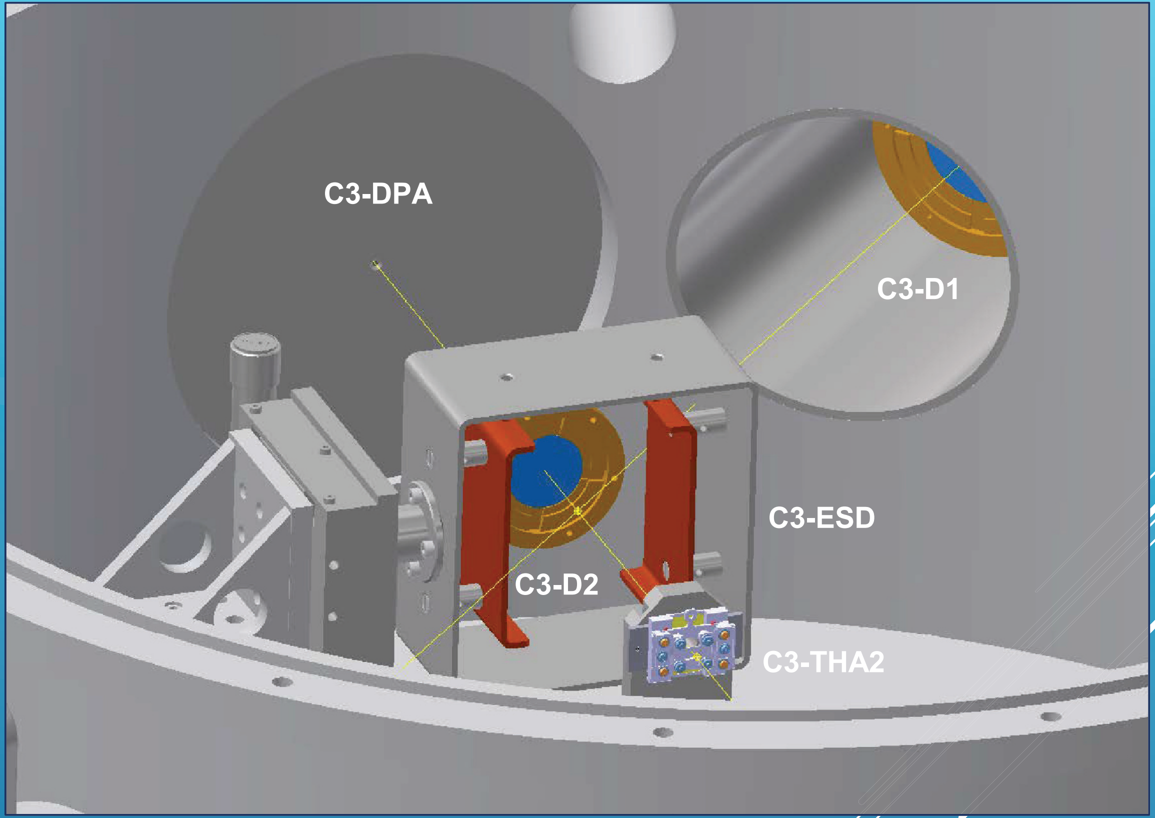


In measurements with VTELs: the target holder assembly – C3-THA1; the target is a very thin quadrupole or square rainbow lens; and C3-D1 – the larger 2D detector.

INTERACTION CHAMBER OF THE C3 CHANNEL

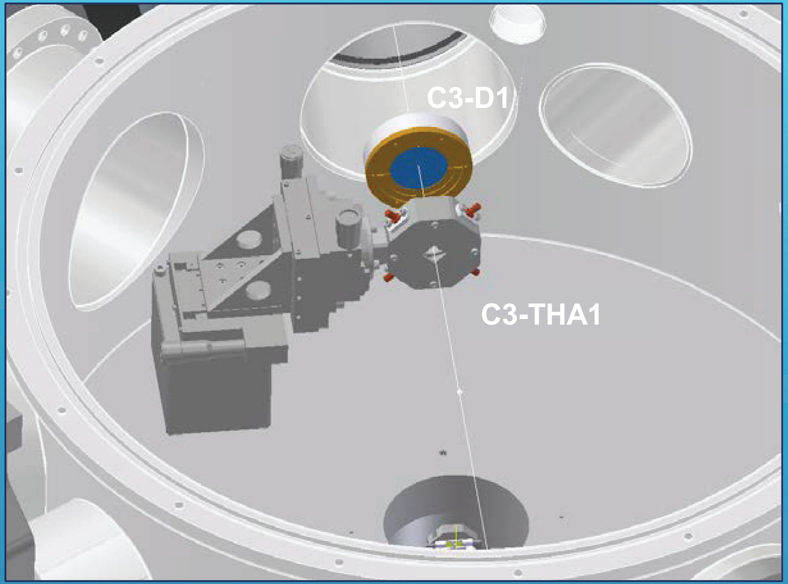
The interaction chamber of the C3 channel

- Inner diameter of 580 mm and height of 250 mm
- UHV, 5×10^{-10} mbar
- Two target holder assemblies (THAs) - for VTELs and 2D materials
- An electrostatic deflector is placed immediately after the target holder assembly for 2D materials
- Two position sensitive detectors (PSD) to record the angular distribution of ions.
- The reflection high energy electron diffraction (RHEED) system for monitoring the crystal structure of the chosen 2D material



In measurements with 2D materials: the target holder assembly – C3-THA2; C3-ESD – the electrostatic deflector, C3-D2 – the smaller 2D detector; and C3-D1 – the larger 2D detector.

INTERACTION CHAMBER OF THE C3 CHANNEL



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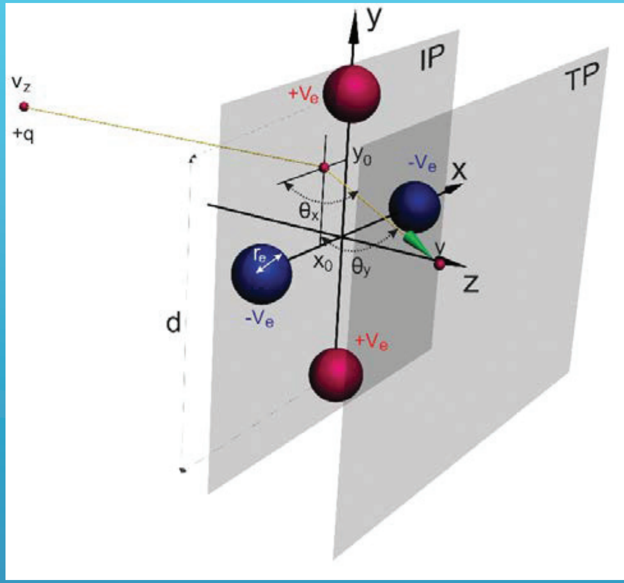
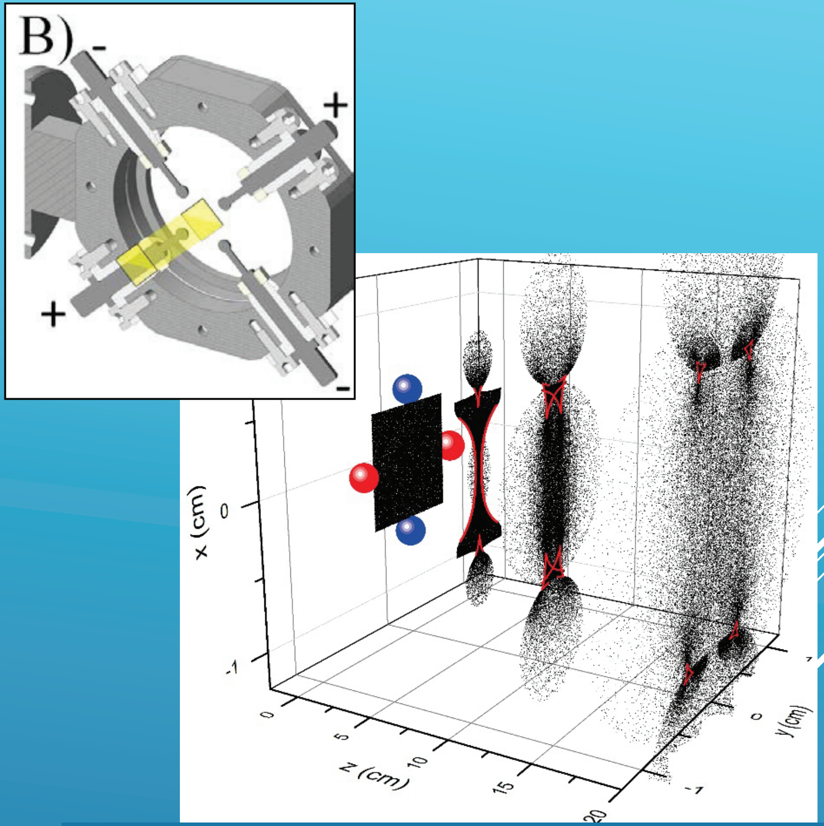
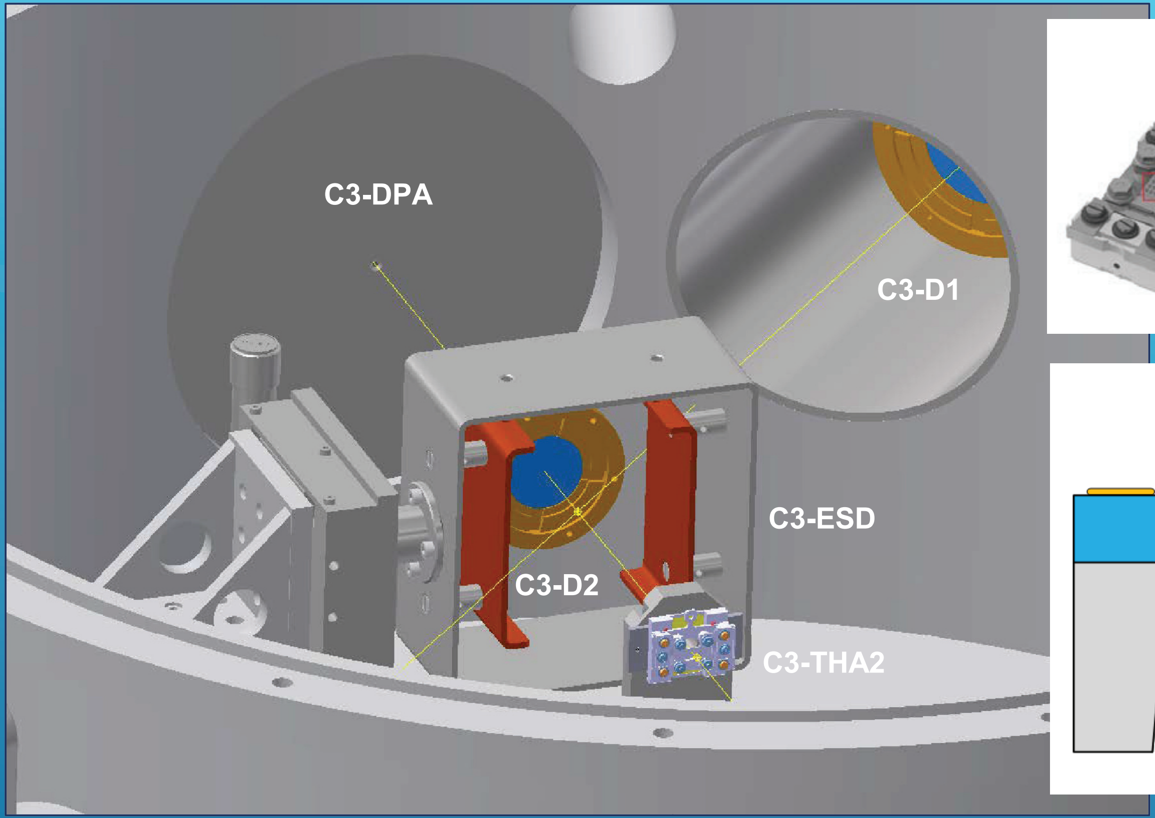


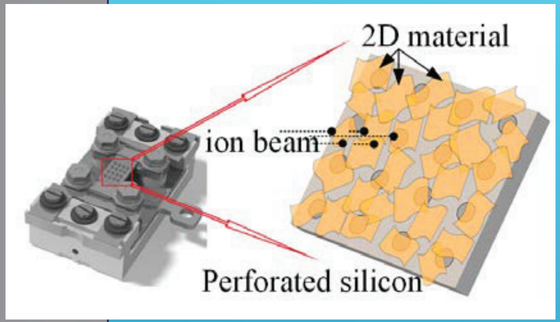
Illustration of ion trajectory solved in ***momentum approximation*** *in quadrupole* ***VTEL-s*** *field*. In **IP** for Z=0 every ion has starting x_0 and y_0 position. Dimension of quadrupole is r_e = 1mm and d = 1cm and DC voltage is $\boldsymbol{V_e}$ **=1kV**. ***q*** **= e** is the ion charge. Ion ienergy **E = 10 keV**.

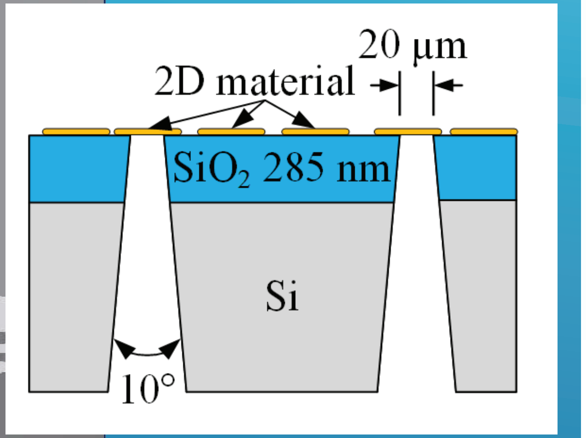


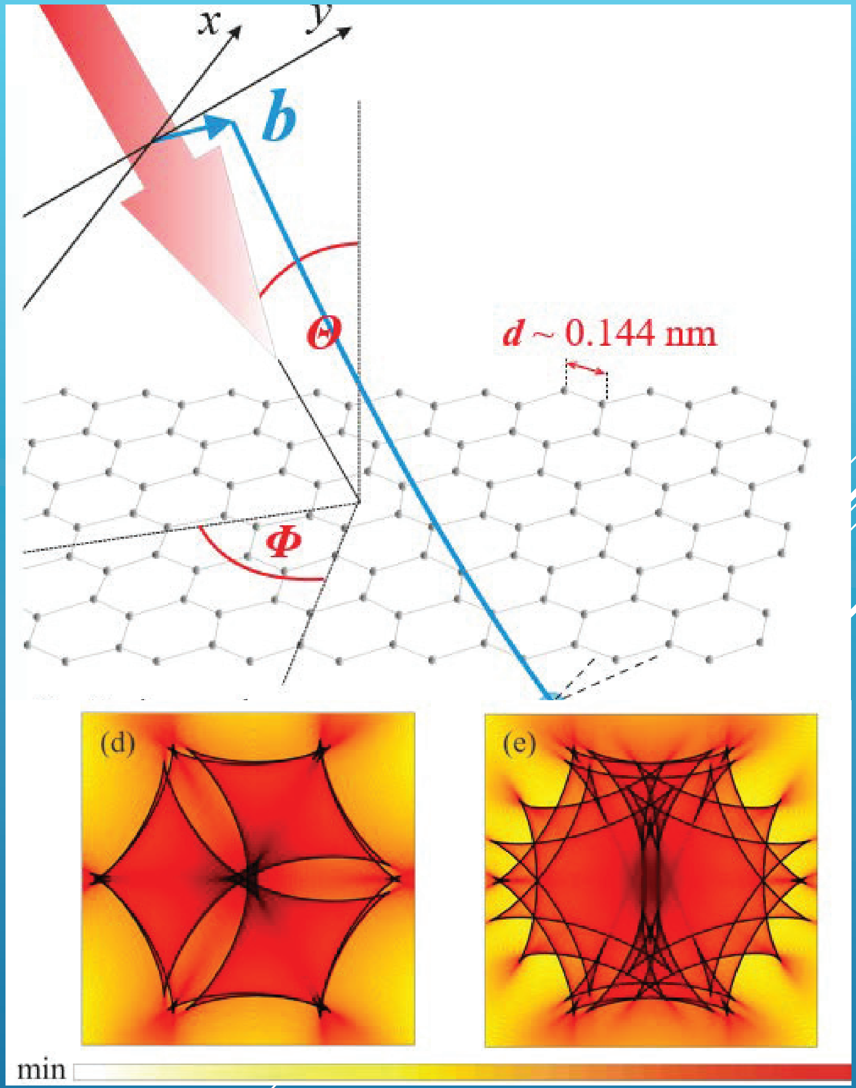
The radius of electrodes will be 1.5 mm, the distance between positively or negatively charged electrodes, d, will be 15 mm, the voltages of the lens electrodes will be +3 keV and -3 keV

INTERACTION CHAMBER OF THE C3 CHANNEL



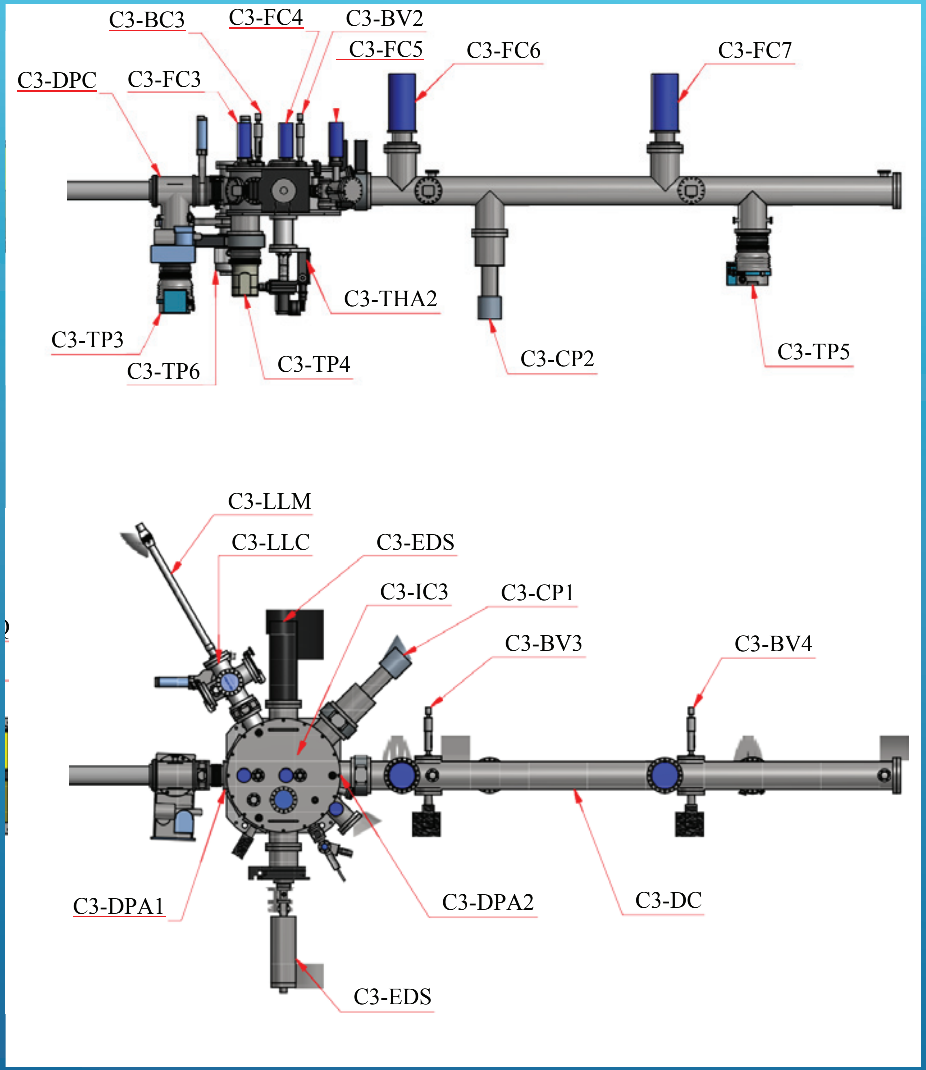






A scheme of the experimental arrangement in measurements with 2D materials: the target holder assembly – C3-THA2; C3-ESD – the electrostatic deflector, C3-D2 – the smaller 2D detector; and C3-D1 – the larger 2D detector.

DETECTION CHAMBER OF THE C3 CHANNEL



The C3 channel also contains:

- a load lock chamber (LLC)
- a detector chamber (C3-DC)

- In C3-DC there will be two 2D position-sensitive detectors. The larger detector, with the diameter of 40 mm, will be used for measuring the spatial distributions of ions transmitted through the chosen VTL at different distances from it while the smaller detector, with the diameter is 25 mm, will be employed for recording different parts of the angular distribution of ions transmitted through the chosen 2D material.
- The larger detector, placed in the interaction chamber, will be also used to measure the charge state distribution of transmitted ions.

Vertical and horizontal projections of a scheme of the C3 channel – (a) and (b), respectively.

TECHNOLOGICAL CHALLENGES OF C3 CHANNEL

- production and diagnostics of the closely parallel ion beams to be directed to VTELs and 2D materials

- Ion beam of a low current, < 1000 ions/s
- Divergence ~0.3-0.5 mrad
- Pepper-pot, small apertures, alignment
- Selection and design of diagnostic elements

- registration of the transmitted ion beams with 2D detectors

- Calibration (sensitivity, linearity, etc.)
- Differentiation between single and multilayers
- Time-frame to record spectra vs. radiation damage vs. impurity build-up

TECHNOLOGICAL CHALLENGES OF C3 CHANNEL

- preparation of 2D materials and maintaining their cleanliness during the measurements

- high quality (similar to HOPG)
- High lateral sizes, > 30 µm
- Preparation, size-selection and assembly procedures

- providing the ultra-high vacuum conditions in measurements with 2D materials.

- *In operando*, 5×10^{-10} mbar or better
- Calculation of vacuum in different compartments
- Selection of vacuum elements and their distribution
- Bake-out approaches and procedures

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- FAMA team
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- Serbia – JINR collaboration

Thank you for your attention!