Experiment to Demonstrate a Possibility of Creation of the Tensor Polarized Heavy Ion Beam in the NICA Injection Complex

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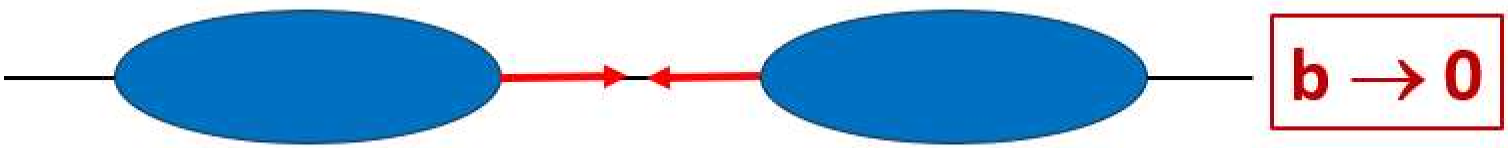
Objectives

- Study of collisions of polarized protons and deuterons create an insight into their structure, and in particular their spin structure
  - It is important part of NICA collider program (SPD detector)
- Polarization o heavy ions creates another degree of freedom in collisions of heavy ions
  - Shell structure



How to get the "clean" data for such studies? - Collide polarized beams!

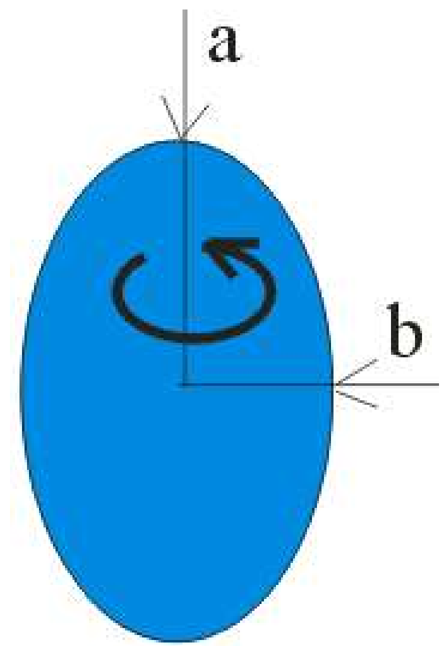
«…We benchmark this method in collisions of … uranium-238 nuclei, known for their elongated, … shape. Our findings show a large deformation with a slight deviation from axial symmetry in the nuclear ground state, … **This approach offers a new method for imaging nuclear shapes, enhances our understanding of the initial conditions in high-energy collisions and addresses the important issue of nuclear structure evolution across energy scales**.» [1]

  - Does nuclear spin contribute to magnetic field of magnetars [2]

[1] Nature, vol. 635, pages 67–72 (2024) STAR Collaboration
[2] e-Print: **2408.05281** [astro-ph.HE]

How to get Polarized Heavy Ions

- To support collider operation the intensity of NICA injection complex has to be increased by ~2 orders of magnitude relative to the intensity achieved in Run IV (Oct. 2022 – Feb. 2023)
  - Required intensity is ~(2–10)·10^8 heavy ions in ~6 s accel. cycle
  - It will be achieved by reduction of beam loss in the course of beam acceleration and the beam accumulation in Booster
- Such intensity increase creates a possibility to make tensor-polarized heavy ions if these ions have large quadrupole moment aligned with spin
  - Quadrupole deformation is described by β_2:



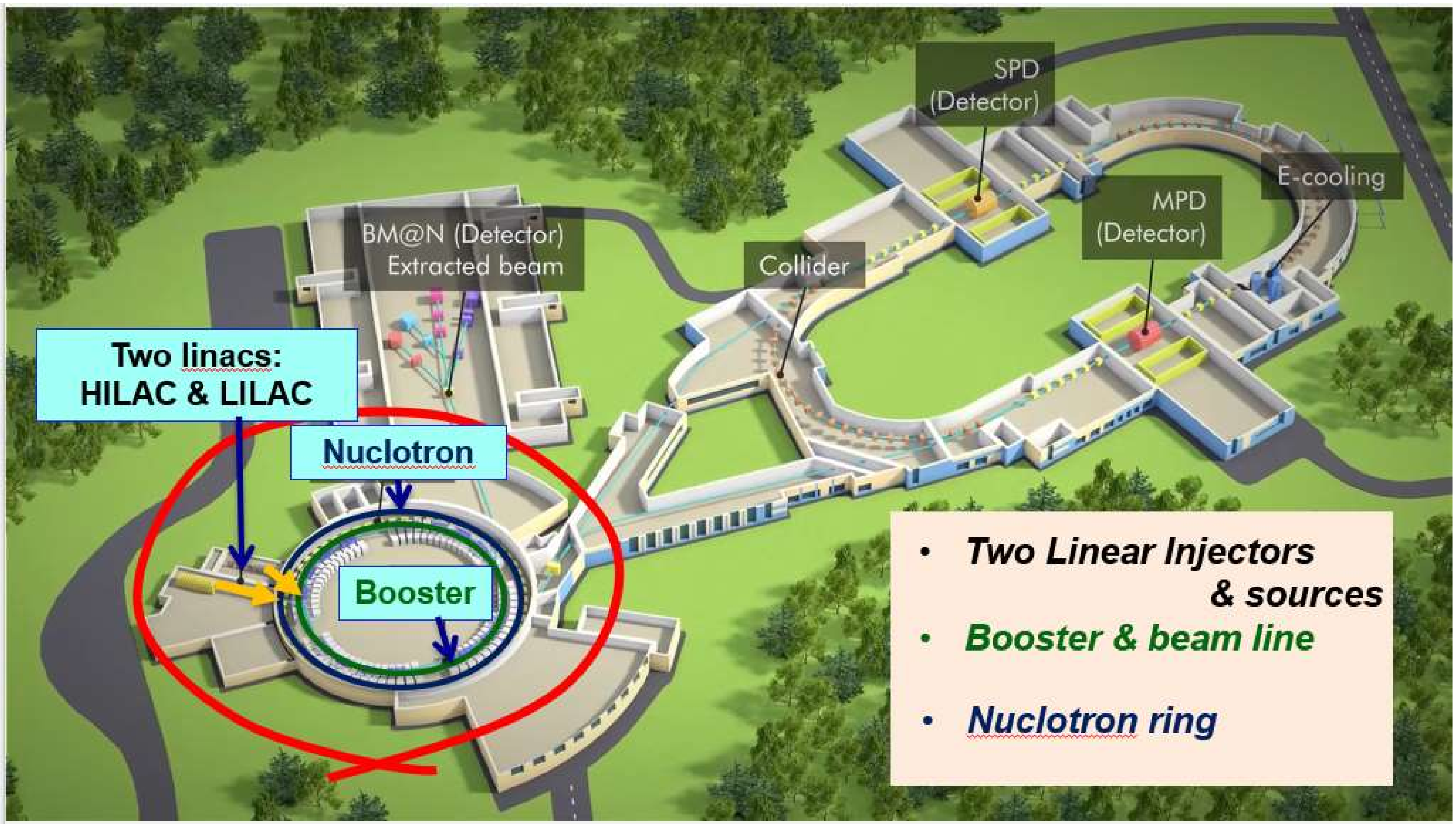
$$R \equiv \frac{a}{b} = \frac{1+\sqrt{5/4\pi}\,\beta_2}{1-\sqrt{5/4\pi}\,\beta_2}$$

$$\sigma_{\parallel} = \pi a^2$$

$$\sigma_{\perp} = \pi ab$$

⇨ Beam obtains tensor polarization after passing few nuclear lengths

NICA Collider Complex Layout



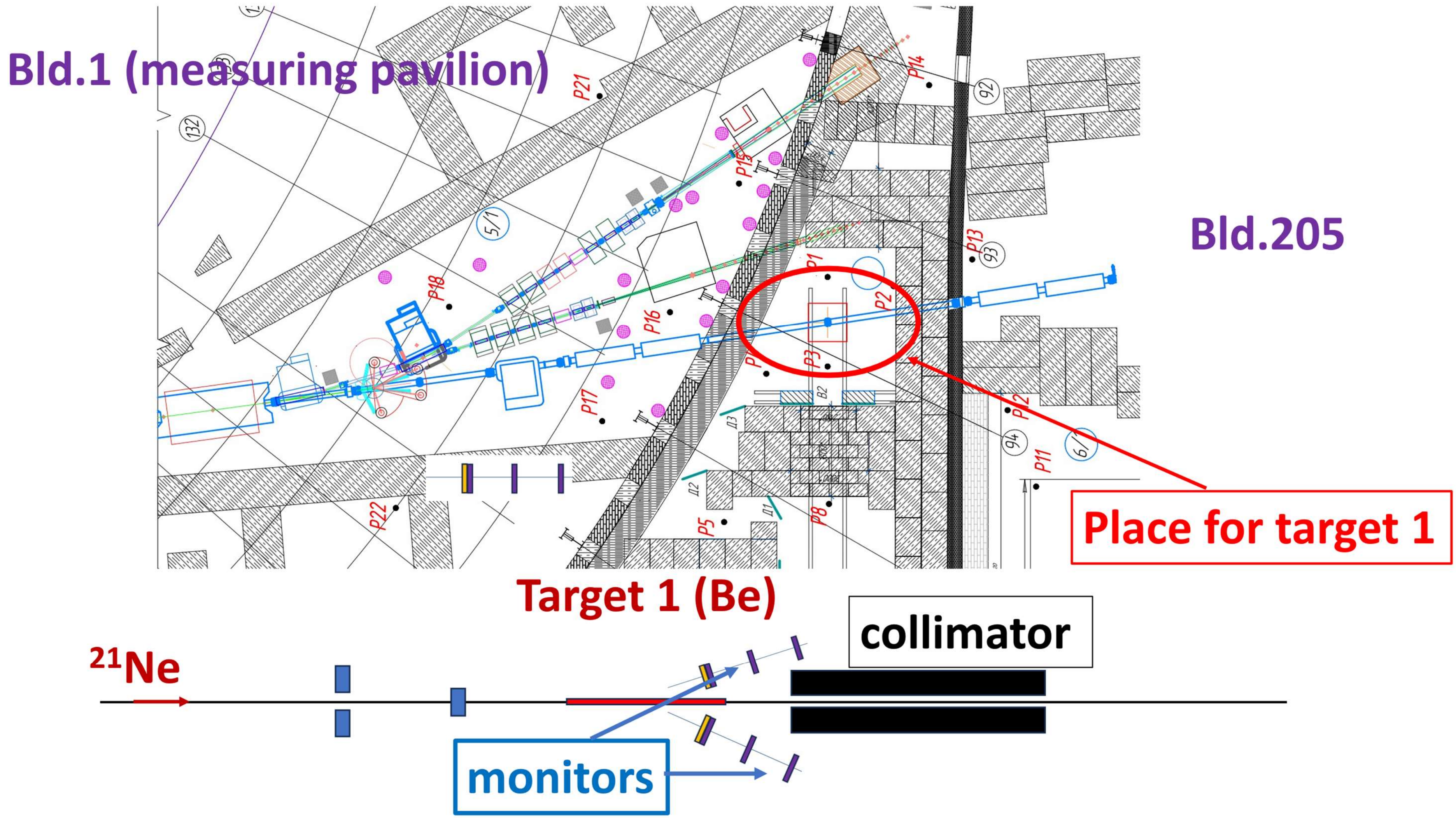
- Injection complex is already in commissioning for few years
  - Previous Run achievement (Feb.2023): $(5\text{-}8)\cdot 10^{6}$ fully stripped Xe ions at the top Nuclotron energy of 3.9 GeV/u was achieved
  - Demonstrated accumulation of five pulses at 200 ms resulting $6\cdot 10^{7}$
  - Collider operation needs: $(2\text{-}10)\cdot 10^{8}$

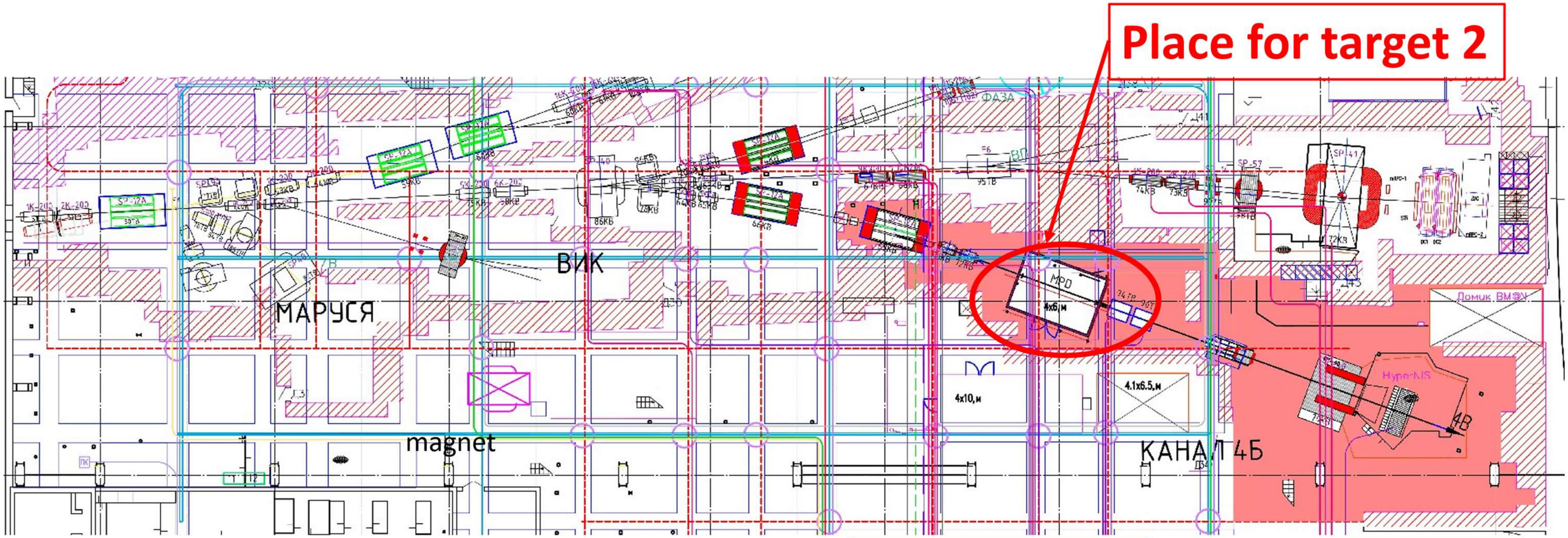
Short Experiment Description

- Send ^{21}Ne beam on the target
  - Use slow extraction
  - Focus the beam into small spot to reduce effect of multiple scattering in the target
  - Obtain tensor polarized beam at the exit after loss of >90% beam
- 1st stage collimation reduces radiation induced by fragments
- 2nd stage collimation
  - Bending magnets span particles in the momentum
  - Collimator removes off momentum particles
- Beam comes to the second target surrounded by detectors
  - Counts number of interacting particles. That enables to measure cross section – i.e. polarization

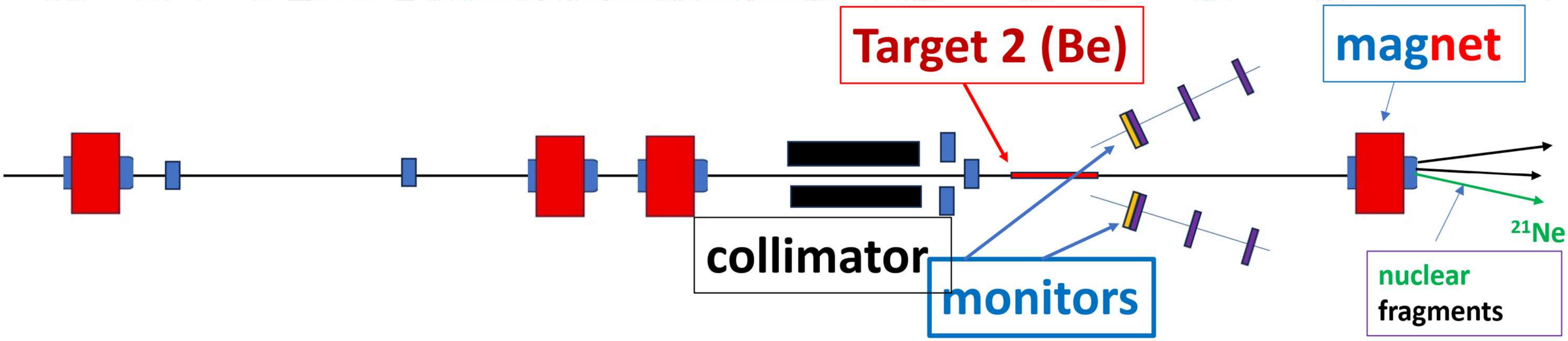
- Measurement of the interaction cross section in the absence of the first target yields effect of the polarization on the cross section

Experiment Layout



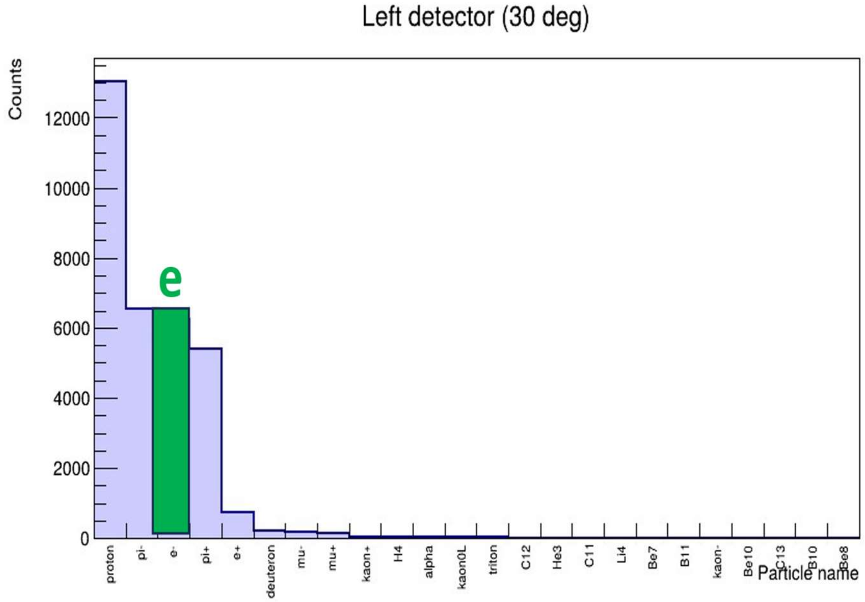


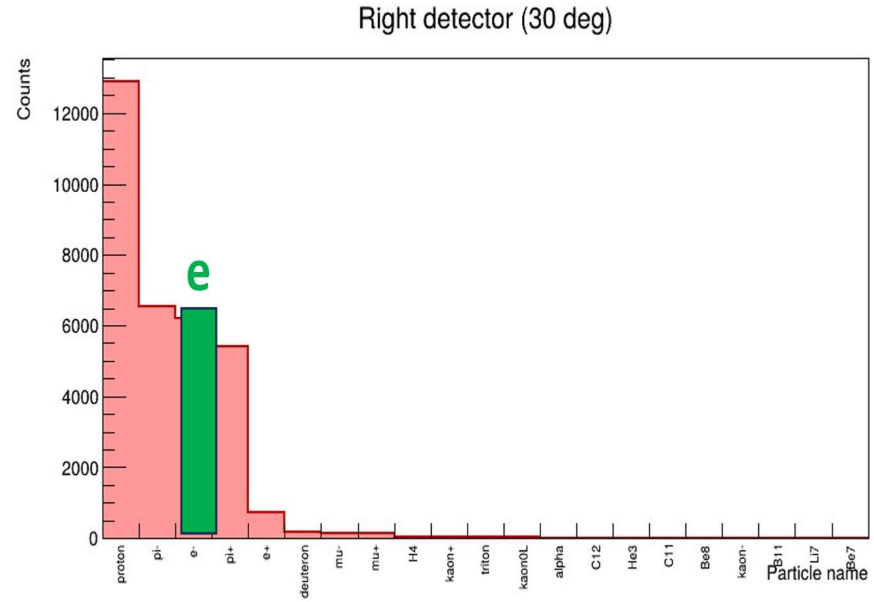
Place for target 2
ВИК
МАРУСЯ
magnet
КАНАЛ 4Б
MPD
4x10,м
4.1x6.5,м
HyperNIS

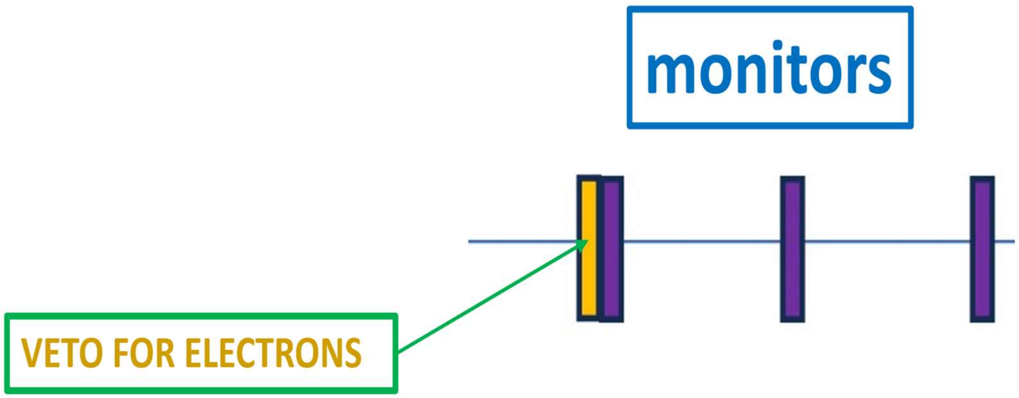


Target 2 (Be)
magnet
collimator
monitors
21Ne
nuclear
fragments

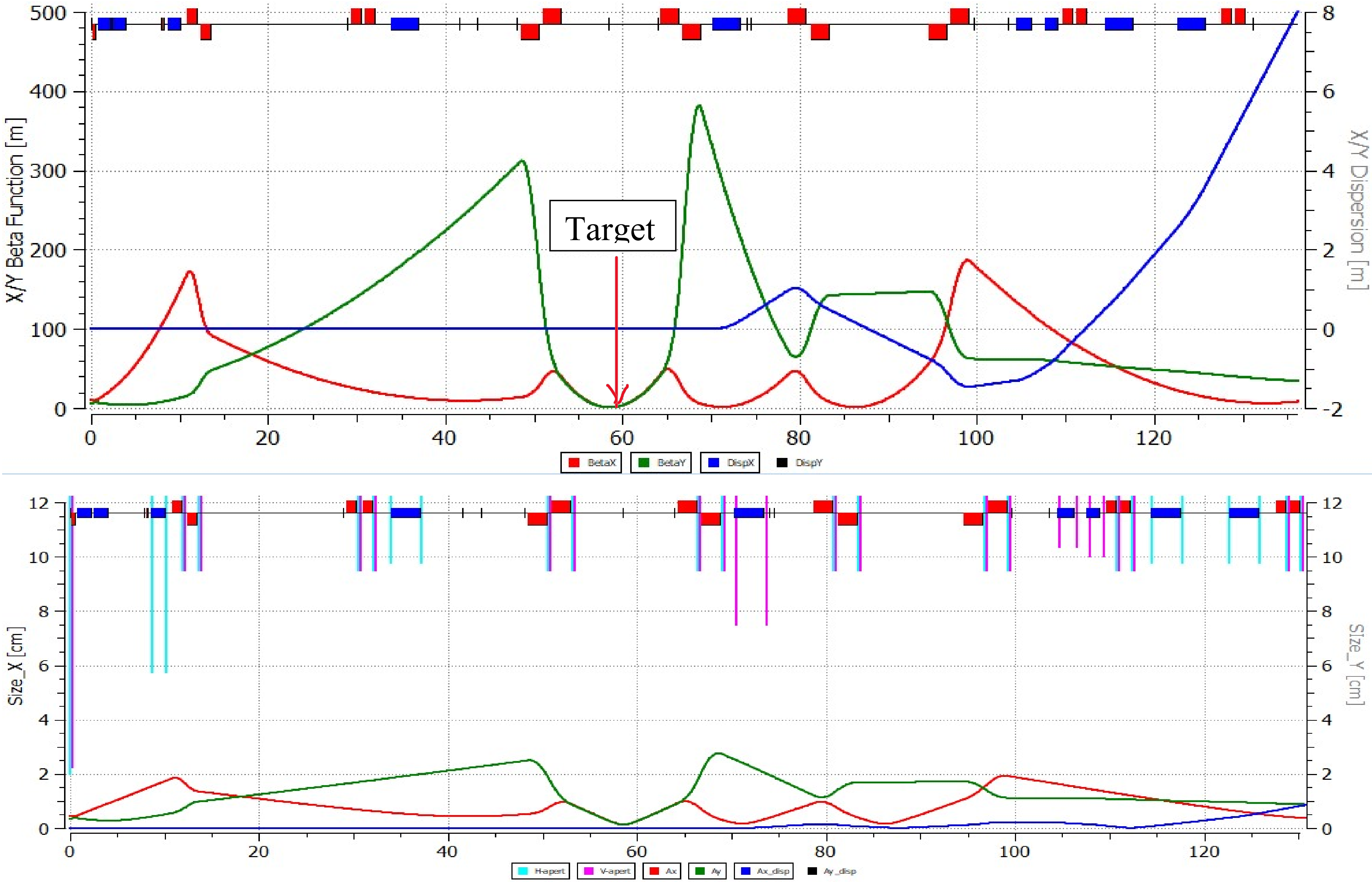
ELECTRONS IN MONITORS





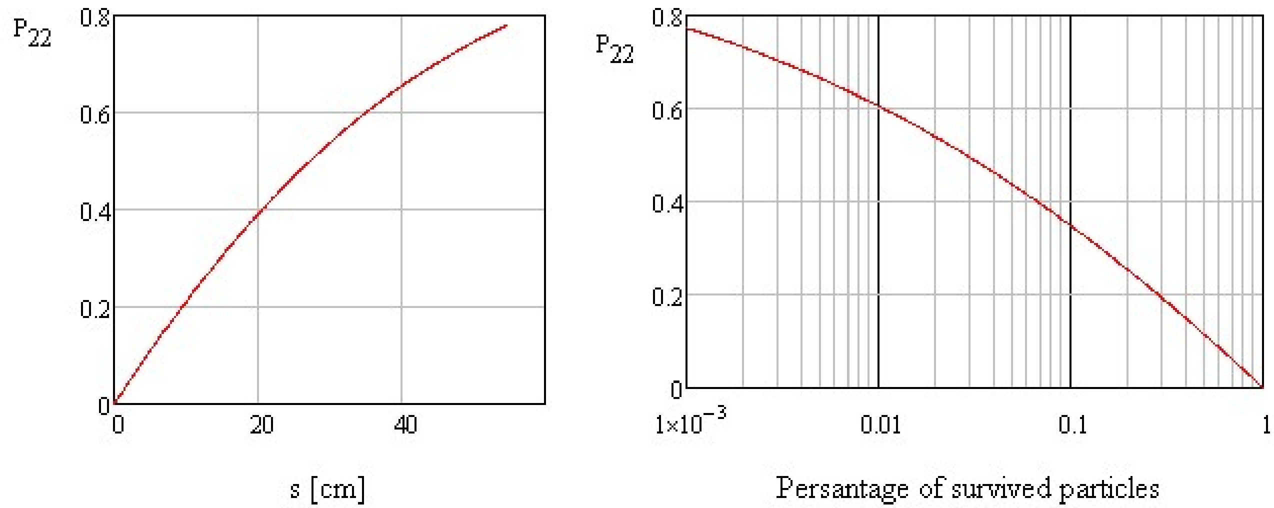


Beam Optics

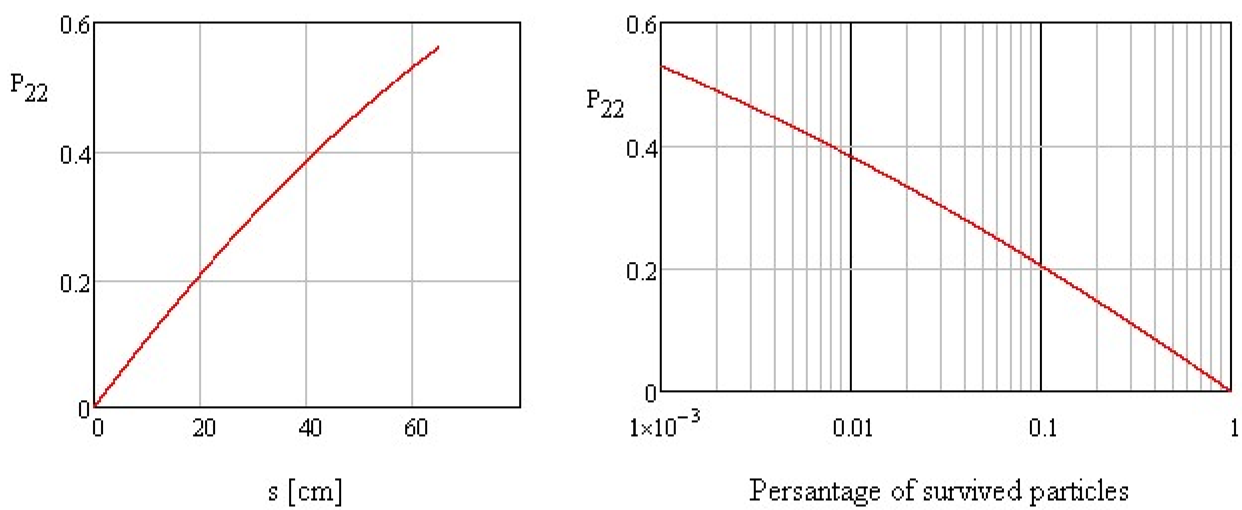


β-functions and rms sizes in the beam-line (Nuclotron extraction to final collimator);β*=80 cm

Value of the Polarization



Dependence of tensor polarization for ^{21}Ne beam on the target thickness (left) and on the percentage of survived particles (left) for beryllium target



Same as above but for the lead target

Candidates for Demonstration Experiment

- There are large number of nuclei which can be used
- We choose [21]Ne for the demonstration experiment
  - Straightforward to use it in the KRION ion source
  - β_2=0.463 (a/b=1.52)
  - S=3/2
  - G=-1.463

	0	1	2	3	4	5
0	"#Z"	"A"	"Name"	"beta_2"	"S,P"	"mu"
1	1	1	"H"	0	"1/2+"	2.79
2	1	2	"D"	0	"1+"	0.857
3	2	3	"He"	0	"1/2+"	-2.13
4	10	21	"Ne"	0.463	"3/2+"	-0.662
5	12	24	"Mg"	0.393	"2+"	1.02
6	12	25	"Mg"	0.346	"5/2+"	-0.855
7	12	26	"Mg"	-0.351	"2+"	1
8	14	28	"Si"	-0.36	"2+"	1.1
9	42	100	"Mo"	0.25	"2+"	0.7
10	46	110	"Pd"	0.24	"2+"	0.62
11	63	153	"Eu"	0.486	"5/2+"	1.532
12	64	158	"Gd"	0.28	"2+"	0.78
13	64	160	"Gd"	0.28	"2+"	0.72
14	65	159	"Tb"	0.31	"3/2+"	2.014
15	67	165	"Ho"	0.284	"7/2-"	4.177
16	70	173	"Yb"	0.313	"5/2-"	-0.648
17	71	175	"Lu"	0.29	"7/2+"	2.23
18	71	176	"Lu"	0.29	"7-"	3.17
19	72	176	"Hf"	0.278	"2+"	0.63
20	72	177	"Hf"	0.277	"7/2-"	0.793
21	72	179	"Hf"	0.267	"9/2+"	-0.641
22	73	181	"Ta"	0.255	"7/2+"	2.37
23	74	184	"W"	0.23	"2+"	0.578
24	79	197	"Au"	0.089	"3/2+"	0.146
25	83	209	"Bi"	-0.042	"9/2-"	4.11
26	90	232	"Th"	0.2	"-"	0
27	92	235	"U"	0.215	"7/2-"	-0.38
28	92	238	"U"	0.236	"-"	0
29	93	237	"Np"	0.226	"5/2+"	...

a_b =

	0
0	0
1	1
2	1
3	1
4	1.513
5	1.424
6	1.367
7	0.701
8	0.694
9	1.257
10	1.246
11	1.543
12	1.291
13	1.291
14	1.325
15	1.295
16	1.329
17	1.302
18	1.302
19	1.288
20	1.287
21	1.276
22	1.262
23	1.235
24	1.087
25	0.961
26	1.202
27	1.218
28	1.241
29	1.23

g =

	0
0	0
1	5.58
2	0.857
3	-4.26
4	-0.441
5	0.51
6	-0.342
7	0.5
8	0.55
9	0.35
10	0.31
11	0.613
12	0.39
13	0.36
14	1.343
15	1.193
16	-0.259
17	0.637
18	0.453
19	0.315
20	0.227
21	-0.142
22	0.677
23	0.289
24	0.097
25	0.913
26	0
27	-0.109
28	0
29	1.256

G =

	0
0	0
1	1.79
2	-0.143
3	-4.195
4	-1.463
5	-0.49
6	-1.356
7	-0.458
8	-0.45
9	-0.583
10	-0.629
11	-0.256
12	-0.519
13	-0.55
14	0.642
15	0.47
16	-1.32
17	-0.215
18	-0.439
19	-0.615
20	-0.722
21	-1.177
22	-0.161
23	-0.641
24	-0.879
25	0.15
26	-1
27	-1.139
28	-1
29	0.6

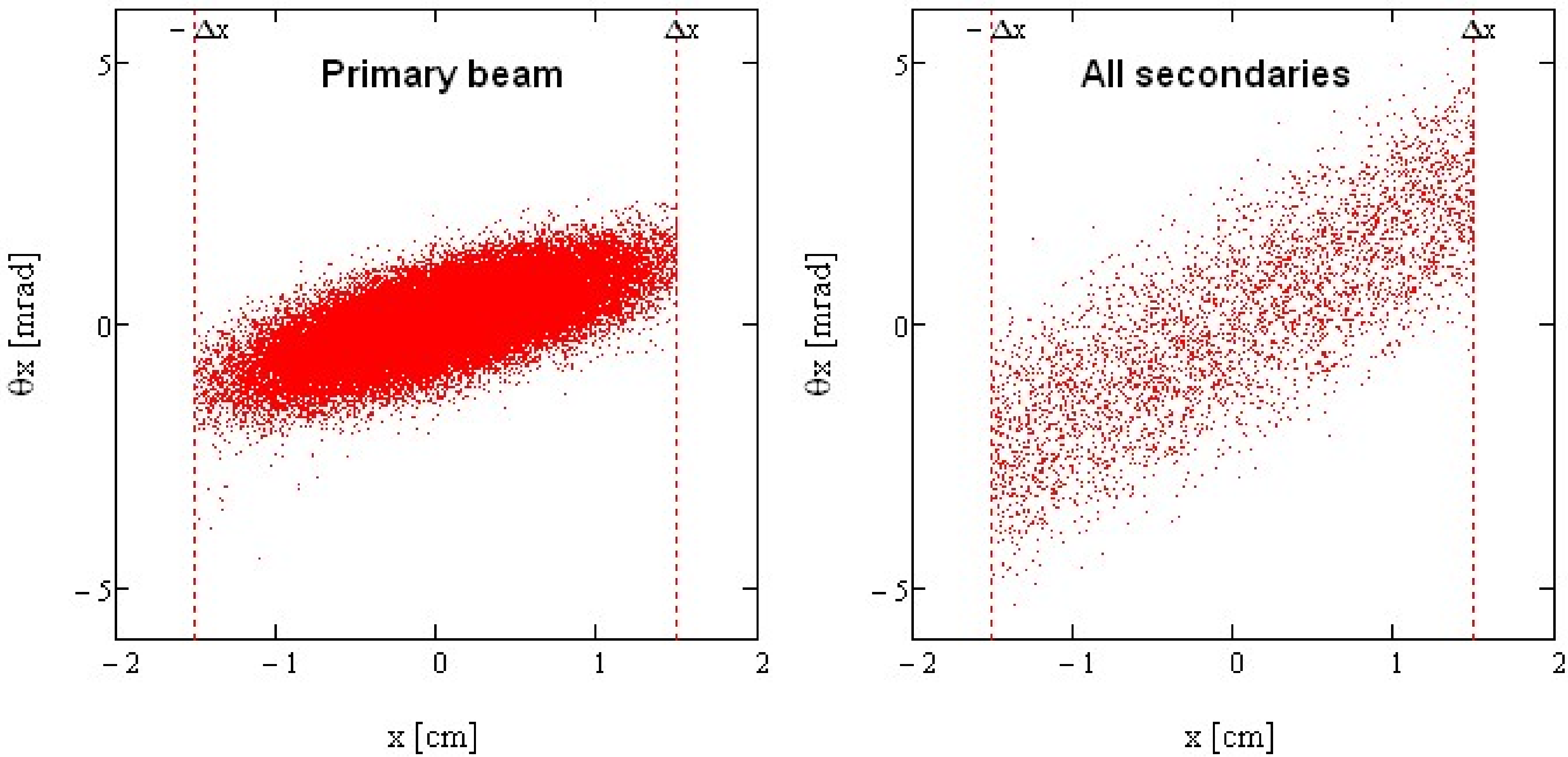
Choice of Parameters

- Sufficiently large energy of the primary ions
  - Reduction of ionization loss on energy of exiting ions (>3 GeV/n)
  - Reduction of multiple scattering
- Low Z target!!!
  - Smaller multiple scattering
  - Larger difference between $\sigma_{||}$ and $\sigma_{\perp}$

	LH	Li	Be	Graphite
Nuclear collision length for ^{21}Ne, λ [cm]	34	20	7.1	7.3
Multiple scattering angle for d=3λ [mrad]	0.43	0.83	1.05	1.47
Momentum change due to ionization loss, $\Delta p/p$ [%]	3.1	5.6	6.6	8.8
$\sigma_{\perp} / \sigma_{\|\|}$	1.36	1.28	1.27	1.26

- Beryllium target of 3λ length is chosen, (20 cm)
  - Compromise between contractionary requirement
- Beta-function in the target center – 80 cm
  - Beam rms angular spread – 1.6 mrad (multiple scattering – 0.9 mrad)
  - Beam rms beam size – 1.3 mm

Particles Coming out of the Target

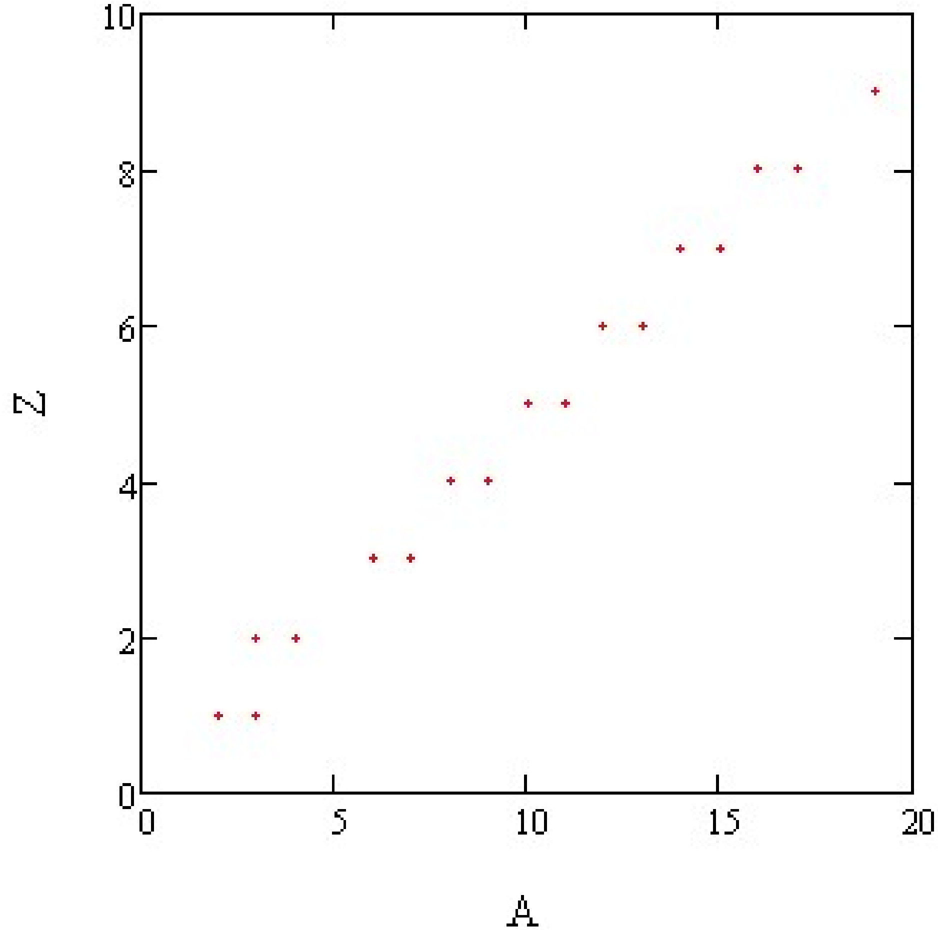


Particle distribution in horizontal plane: left – primary beam, right – secondaries.

Collimator width – 3 cm.

Background

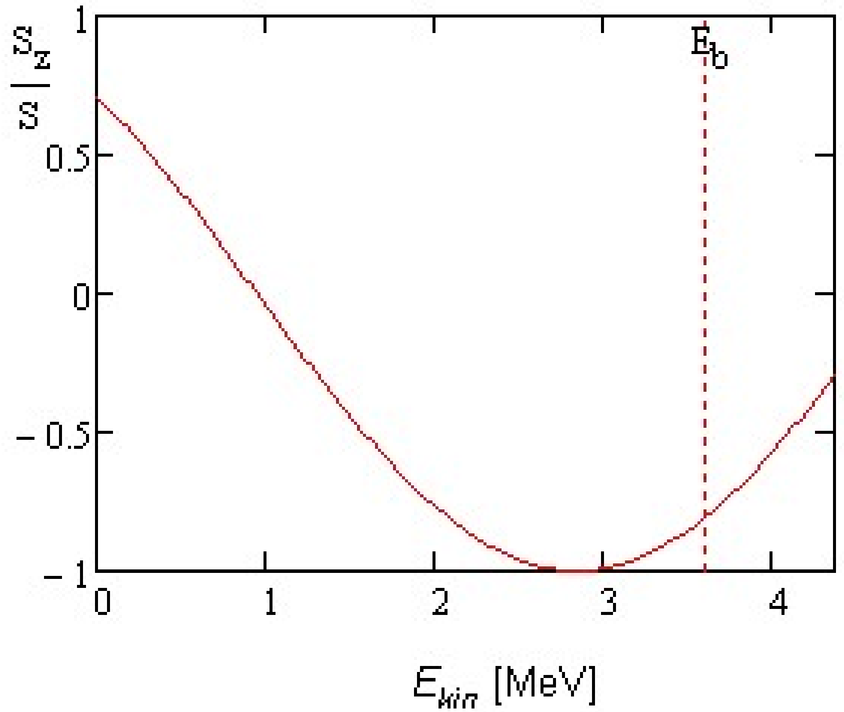
- Bending field after the target removes major fraction of secondaries leaving only particles with the same momentum per unit charge
  - Major species left after collimator are: ^{4}He – 34%, 19F – 29%, ^{2}H – 12%



Mass and charge of ions passed through collimator

Rotation of Polarization

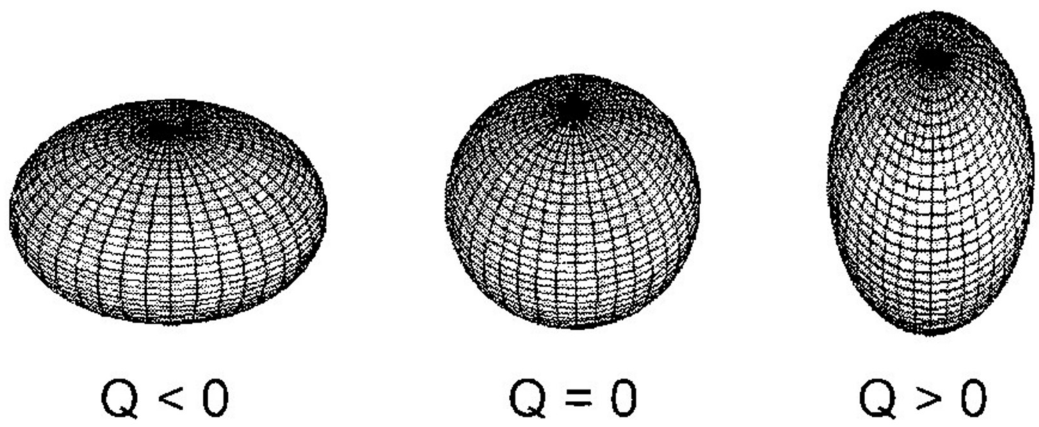
- Bending field is required to remove secondaries but it results in rotation of polarization relative to the beam direction
  - For chosen parameters spin precession results in rotation of about 180 deg.; *i.e.* it does not change the tensor polarization



Conclusions

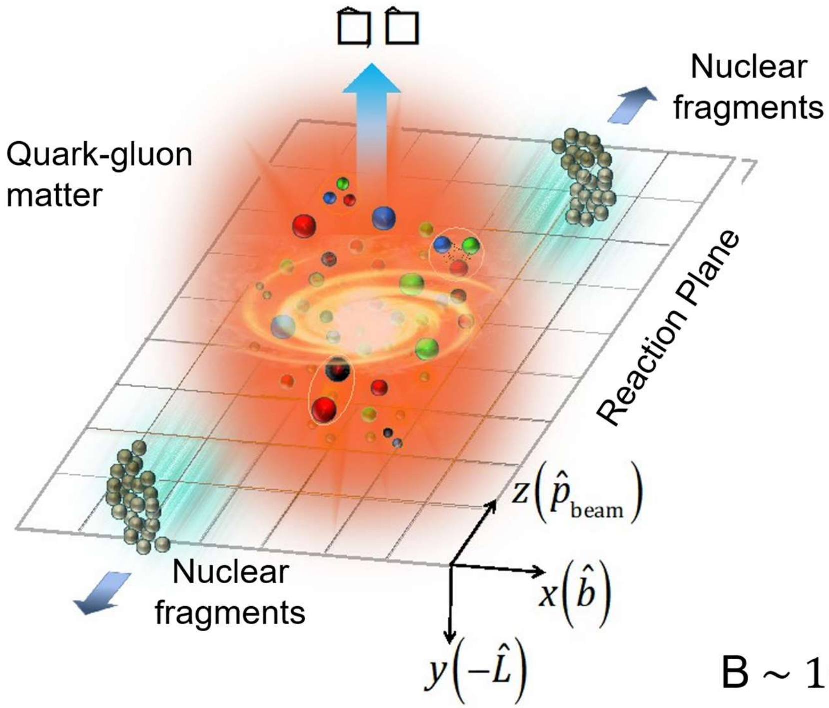
- Experiments with polarized heavy ions open another view on the structure of the ions and their interactions
- We are looking into a possibility to carry out a demonstration experiment to validate the method

Backup Slides



Nuclear shapes and the corresponding electric quadrupole moments.

QGP Under Rotation



$B \sim 10^{18}$ Gauss

$L \sim 10^{3} - 10^{7}\hbar$

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1]

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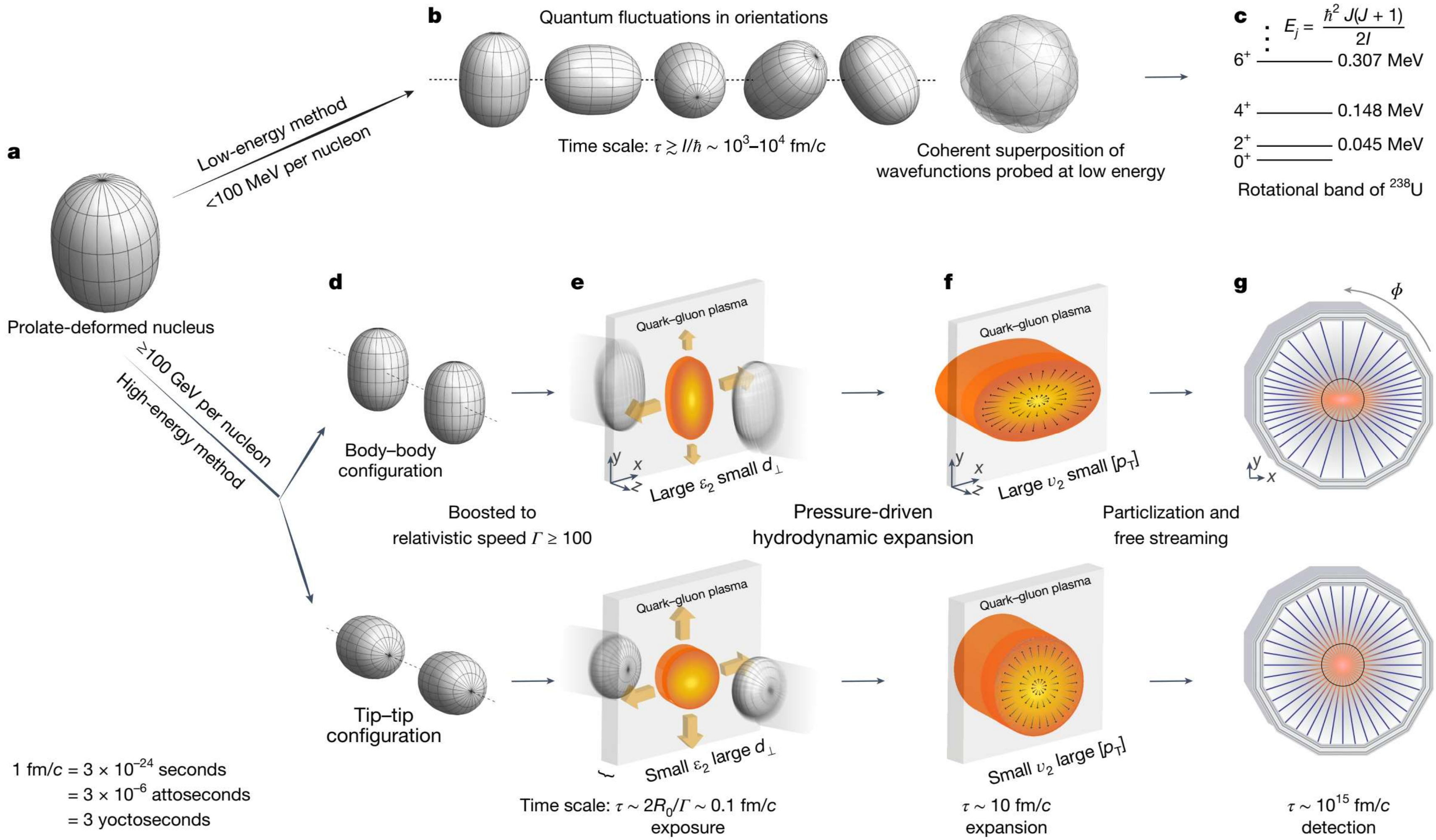
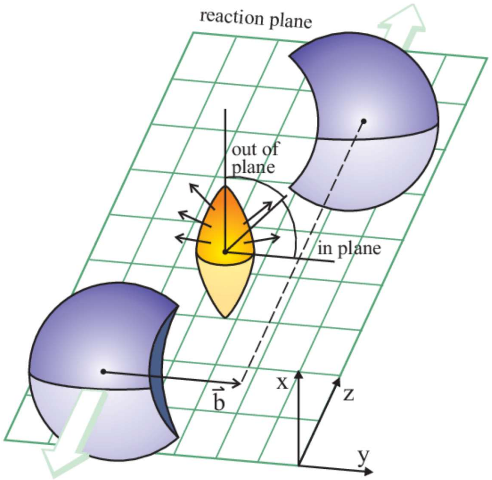
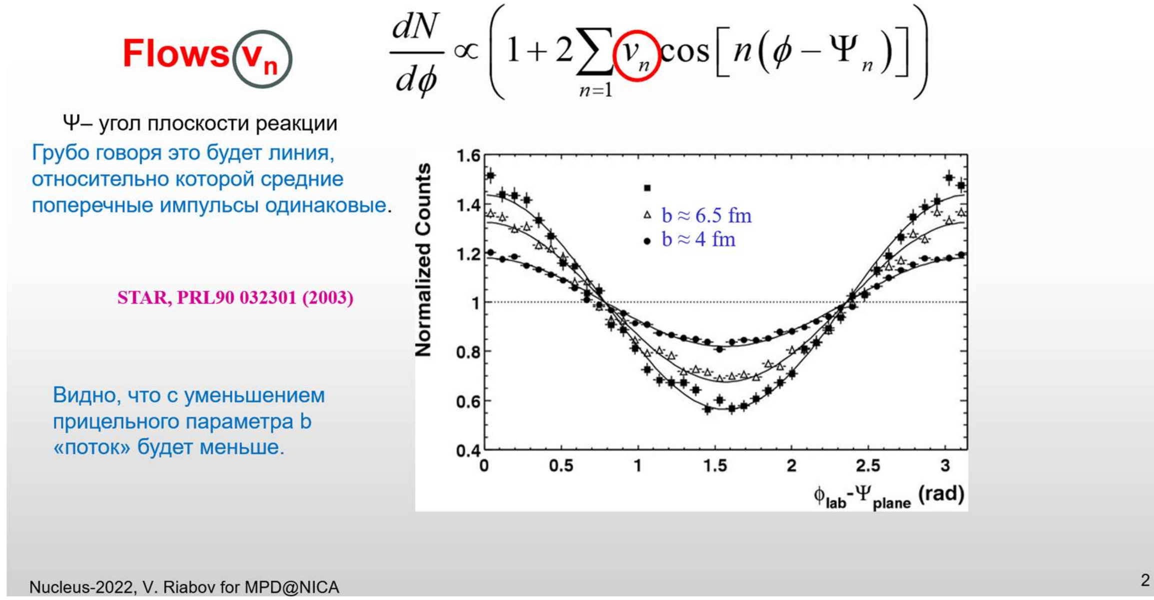


Fig. 1 | Methods for determining the nuclear shape in low and high energies. **a**, Cartoon of a well-deformed prolate-shaped nucleus. **b**, Quantum fluctuations over Euler angles for this nucleus and associated overall timescale. **c**, Quantum mechanical manifestation of the deformation in terms of the first rotational band of ^{238}U. **d**, Aligning the two nuclei in the head-on body–body configuration (top) and tip–tip configuration (bottom). **e**, High-energy collision of two Lorentz-contracted nuclei and resulting 3D profile of the initially produced quark–gluon plasma (QGP), in which the arrows indicate the pressure gradients. **f**, The 3D profile of the QGP at the end of the hydrodynamic expansion before it freezes out into particles, in which the arrows indicate the velocities of fluid cells. **g**, Charged particle tracks measured in the detector. The timescales shown are in units of fm/c—the time for light to travel 1 femtometre. The body–body configuration has large eccentricity ε_2 and small gradient $d_\perp$, leading to large elliptic flow v_2 and smaller average transverse momentum $[p_T]$ and vice versa for tip–tip configuration (see main text).


reaction plane
out of plane
in plane
x
z
y
$\vec{b}$


Flows v_n
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]\right)$$
Ψ– угол плоскости реакции
Грубо говоря это будет линия, относительно которой средние поперечные импульсы одинаковые.
STAR, PRL90 032301 (2003)
Видно, что с уменьшением прицельного параметра b «поток» будет меньше.
Normalized Counts
b ≈ 6.5 fm
b ≈ 4 fm
$\phi_{lab}-\Psi_{plane}$ (rad)
Nucleus-2022, V. Riabov for MPD@NICA
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