“DERICA – prospective accelerator and storage ring facility for radioactive ion beam research”

ECT* workshop on “Probing exotic structure of short-lived nuclei by electron scattering”, July 16-20, 2018

http://aculina.jinr.ru/derica.php
Few-body dynamics in continuum of clusterized exotic (dripline) nuclei

Long-range character of three-body Coulomb continuum problem by example of $^{16}$Ne

K. Brown et al., PRL 113 (2014) 232501

Democratic 2p $\leftrightarrow$ Sequential 2p

Democratic

$E_r : \Gamma(E_r) \sim (0.2 \div 0.3)E_r$

True 2p $\leftrightarrow$ Sequential 2p

T.A. Golubkova et al., PLB 762 (2016) 263
Scientific program of DERICA – prospective accelerator and storage ring facility for radioactive ion beam research


Abstract. Studies of radioactive ions (RI) is the most intensively developing field of the low-energy nuclear physics. In this paper the concept and the scientific agenda of prospective accelerator and storage ring facility for the RI beam (RIB) research are proposed for the large-scale international project based at the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research. The motivation for the new facility is discussed and its characteristics are briefly presented, showing to be comparable to those of the advanced world centers, the so-called “RIB factories”. In the project the emphasis is made on the studies with the short-lived RIBs in storage rings. A unique feature of the project is the possibility to study the electron-RI interactions in the collider experiment for determination of fundamental properties of the nuclear matter, in particular, electromagnetic form-factors of exotic nuclei.

http://aculina.jinr.ru/derica.php

April 26, 2018. The is project is submitted to Russian Ministery of Education and Science on the call for «Proposals to build “megascience”-class facilities on the territory of Russian Federation»
Radioactive Ion Beam (RIB) physics – “highway” of modern low-energy nuclear science

The map of nuclides
- 254 stable nuclides,
- 339 can be found in nature
- Around 3100 RI are known
- Around 2500 to be discovered

Proton dripline:
Achieved and studied for Z<32

Neutron dripline:
Achieved and studied for N<20

“Isle of stability” for superheavies:
We just “touched” a bit of its “shore”...

Limits of nuclear structure existence:
Are known only for the lightest nuclei

Exotic structure of exotic nuclides:
- Neutron/proton halo
- Neutron skin
- “Soft” excitation modes
- Breakdown of shell structure
- New “magic numbers”
What we already have at Flerov lab

Elements 102 - 108 and 113 - 118 were synthesized at FLNR JINR

Superheavy “isle of stability” discovered

New elements
- $^{114}_{48}$Fl Flerovium
- $^{116}_{50}$Lv Livermorium
- $^{113}_{49}$Nh Nihonium
- $^{115}_{48}$Mc Moscovium
- $^{117}_{50}$Ts Tennessine
- $^{118}_{50}$Og Oganesson recognized recently

Fragment-separator ACCULINNA: Studies of the light RIBs

The only facility for RIB studies in Russia, CIS, and Eastern Europe

U-400M accelerator

U-400 accelerator
March 30 2018 – The Lomonosov great gold medal is awarded to Yuri Oganessian and Bjorn Jonson

Yu.Ts. Oganessian – synthesis of superheavy elements

B. Jonson – contribution of studies of exotic nuclei (ISOL method and nucleon halo)
7-year planning prospects

“Factory of superheavy elements”
Stage: mounting of equipment
Investment: ~55 M€

Near future

Facility based on upgraded U-400M + ACCULINNA-2
Stage: first experiments in the fall of 2017
Investment: ~10 M€

Long-time prospects

Near future
New facilities at FLNR

“Factory of superheavy elements”

ACCULINNA-2 fragment-separator
To limit universality

To go to underdeveloped fields

Huge increase in the scale of modern and prospective RIB facilities:
Price tag 1-2 G€

Scale increase – (i) RIB production increase and (ii) universality of RIB facility

Is it possible to have world competitive RIB program with modest investment scale?
Empty “ecological niche”

Underdeveloped field: storage ring physics with RIBs

Empty field: studies of RIBs in electron-RIB collider

Isochronous mass spectrometry

Precision reaction studies on internal gas jet target

RIB storage ring

Studies of electromagnetic formfactors of exotic nuclei in e-RIB collider

electron storage ring

Atomic physics studies with striped ions

Radioactivity studies with striped ions

Etc....
Electron scattering

After masses, the radial properties are the most important characteristics of nuclei

- First Born approximation, fast electrons, relatively light nuclei

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\text{PWBA}} = \frac{\sigma_M}{1 + (2E/M_A) \sin^2(\theta/2)} |F_{\text{ch}}(q)|^2
\]

\[
\sigma_M = \left( \frac{e^4}{4E^2} \right) \cos^2(\theta/2) \sin^{-4}(\theta/2)
\]

\[
q = 2k \sin(\theta/2)
\]

- Charge formfactor, charge radius

\[
F_{\text{ch}}(q) = 4\pi \int_0^\infty dr r^2 j_0(qr) \rho_{\text{ch}}(r)
\]

\[
F_{\text{ch}}(q)/Z = 1 - \frac{q^2}{6} \langle r_{\text{ch}}^2 \rangle + \ldots
\]

Robert Hofstadter 1915-1990, 1961 Nobel Prize "for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons."

Electromagnetic probe is the most reliably studied
- Electron scattering
  - Experiments in traps – “static” EM characteristics \( \rightarrow \) derivation of \( r_{\text{ch}} \)
  - Electron scattering – differential characteristics
Status of charge radii studies – broad field for exploration

900 measured for 3100 known nuclear-stable isotopes

Some isotopic chains are well studied – some not at all

Somewhere driplines is nearly achieved – somewhere very far

Systematics demonstrate complicated dynamical effects in the isotopic chains, especially near the driplines

900 measured for 3100 known nuclear-stable isotopes

Some isotopic chains are well studied – some not at all

Somewhere driplines is nearly achieved – somewhere very far

Systematics demonstrate complicated dynamical effects in the isotopic chains, especially near the driplines
Luminosity requirements for e-RIB collider studies

Realistic setup 10 days of measurements

Limiting cases of charge distributions

$^{40}$Ca and $^{48}$Ca realistic 2 parameter density

1% precision charge radius
$L = 10^{26}$-$10^{27}$ cm$^{-2}$ s$^{-1}$

$T = 10$ days
$L = 7 \times 10^{27}$ cm$^{-2}$ s$^{-1}$

$2\sigma$ (95% confidence)
The electron–ion scattering experiment ELISe at the International Facility for Antiproton and Ion Research (FAIR)—A conceptual design study

A lot of ring projects – serious interest to the topic
- All the ring projects with e-collider abilities were cancelled or indefinitely postponed
A lot of ring projects – serious interest to the topic

All the ring projects with e-RIB-collider abilities were cancelled or indefinitely postponed

Attack at this problem requires record intensities of RIBs with $T_{1/2} > 100$ ms
DERICA

Dubna Electron-Radioactive Isotope Collider Facility

According to different sources “Derica” is female name of German origin with meaning “beloved leader, ruler of the people”
DERICA stages 0 - 1

- Continuity of scientific program
- Minimization of technological risks

Stopped RIB – decay spectroscopy and studies in traps

Experimental hall EH-A for Ion trap studies
DERICA stages 0 -1

Continuity of scientific program

Minimization of technological risks

Reactions with reaccelerated RIBs around Coulomb barrier energy (5-7 AMeV)

Experimental hall EH-A for Ion trap studies

Experimental hall EH-B for Coulomb barrier reaction studies 5-10 AMeV
DERICA stages 0 - 1

Continuity of scientific program

Minimization of technological risks

Direct reactions with reaccelerated RIBs at intermediate energies (20-30 AMeV)

Experimental hall EH-C for intermediate energy high-precision reaction studies 20-30 AMeV

Experimental hall EH-A for Ion trap studies

Experimental hall EH-B for Coulomb barrier reaction studies 5-10 AMeV

U-400M → ACCULINNA-2 Experimental hall → LINAC-30 5-10 AMeV

F5 → F6: Reaction setup → Gas cell → Ion trap → Ion source
DERICA stages 2 - 4

New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects

Direct reactions with in-flight RIBs at intermediate energies (30-80 AMeV)

World-leading intensities are expected for this energy range

Experimental hall EH-1: Application science

DERICA Fragment Separator DFS

Velocity filter

LINAC-100 ($E_{HI}: 100$ AMeV)

Ion Sources

Possible DERICA location 460x230 m$^2$

U400 + SHE

SHE factory construction

Stage 1 location at ACCULINNA-2

U400M + ACCULINNA-2

FLNR

MINIR
DERICA stages 2 - 4

New experimental opportunities on each stage

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Good upgrade prospects

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Experimental hall EH-1: Application science

DERICA Fragment Separator DFS

Velocity filter

- Gas cell - Ion trap
- Charge breeder

LINAC-30 ($E_{\text{RIB}}$: 30 AMeV)

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LINAC-100 ($E_{\text{HI}}$: 100 AMeV)

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Stopped RIB – decay spectroscopy and studies in traps

Reactions with reaccelerated RIBs around Coulomb barrier energy (5-7 AMeV)

Direct reactions with reaccelerated RIBs at intermediate energies (20-30 AMeV)

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Experimental hall EH-2: RIBs 15–70 AMeV

Experimental hall EH-3: reaccelerated RIBs 5 – 300 AMeV

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Ion Sources

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Stage 1 location at ACCULINNA-2

Possible DERICA location 140x230 m²

NIIR node

FLNR

U400+SHG

SHE factory construction
DERICA stages 2 - 4

New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects

Low-energy storage ring experiments

Direct reactions with reaccelerated RIBs at “high” energies (30-300 AMeV)

Experimental hall EH-1: Application science

Experimental hall EH-2: RIBs 15–70 AMeV

LINAC-30 ($E_{RIB}$: 30 AMeV)

DERICA Fragment Separator DFS

Velocity filter

- Gas cell
- Ion trap
- Charge breeder

LINAC-100 ($E_{HI}$)

Fast Ramping Ring Synchrotron FRR: $E_{RIB} \leq 300$ AMeV

Experimental hall EH-3: reaccelerated RIBs 5–300 AMeV

Ion Sources

Stage 1 location at ACCULINNA-2

Possible DERICA location 140x230 m²

U400+ SHE

SHE factory construction

Possible reaction with reaccelerated RIBs at “high” energies (30-300 AMeV)
DERICA stages 2 - 4

New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects

Storage ring experiments

Experimental hall EH-1: Application science

Experimental hall EH-2: RIBs 15-70 AMeV

LINAC-30 ($E_{\text{RIB}}: 30$ AMeV)

Fast Ramping Ring Synchrotron FRR: $E_{\text{RIB}} \leq 300$ AMeV

Velocit filter

DERICA Fragment Separator DFS

- Gas cell - ion trap
- Charge breeder

LINAC-100 ($E_{\text{HI}}: 100$ AMeV)

Gas jet target $p,d,^{3,4}\text{He}$

Electron cooler

Collector Ring CR: $E_{\text{RIB}} \leq 300$ AMeV

Neutron source $\geq 10^8$ n/cm²

Experimental hall EH-3: reaccelerated RIBs 5 - 300 AMeV

Stage 2: Buildings, LINAC-100, DFS, EH-1, EH-2
Stage 3: LINAC-30 relocation, FRR, EH-3
Stage 4: CR, e-RIB collider, ring experiments
DERICA stages 2 - 4

New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects

Experimental hall EH-1: Application science

DERICA Fragment Separator DFS

Velocity filter

- Gas cell - ion trap
- Charge breeder

LINAC–30 ($E_{\text{RIB}}: 30$ AMeV)

Fast Ramping Ring Synchrotron FRR: $E_{\text{RIB}} \leq 300$ AMeV

Gas jet target $p,d,^{3,4}\text{He}$

Electron cooler

Collector Ring CR: $E_{\text{RIB}} \leq 300$ AMeV

Neutron source $\geq 10^8$ n/cm$^2$

Experimental hall EH-3: reaccelerated RIBs 5 – 300 AMeV

Stage 2: Buildings, LINAC–100, DFS, EH-1, EH-2

Stage 3: LINAC–30 relocation, FRR, EH-3

Stage 4: CR, e-RIB collider, ring experiments

e-RIB collider experiments

e-LINAC ($E_e: 500$ MeV)

e-RIB collider

Stage 1 location at ACCULINNA-2

Possible DERICA location 1400 x 2300 m$^2$
### DERICA timeline and opportunities for modern research

<table>
<thead>
<tr>
<th>Research Area</th>
<th>Timeframe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopped RIB – decay spectroscopy and studies in traps</td>
<td>beginning stage 1</td>
</tr>
<tr>
<td>Reactions with reaccelerated RIBs around Coulomb barrier energy (5-7 AMeV)</td>
<td>stages 3-4</td>
</tr>
<tr>
<td>Direct reactions with reaccelerated RIBs at intermediate energies (20-30 AMeV)</td>
<td>stage 1</td>
</tr>
<tr>
<td>Direct reactions with reaccelerated RIBs at “high” energies (30-300 AMeV)</td>
<td>stages 3-4</td>
</tr>
<tr>
<td>Direct reactions with in-flight RIBs at intermediate energies (30-80 AMeV)</td>
<td>end stage 1</td>
</tr>
<tr>
<td>Storage ring experiments</td>
<td>stages 3-4</td>
</tr>
<tr>
<td>e-RIB collider experiments</td>
<td>end stage 3</td>
</tr>
<tr>
<td>Most (many?) important fields of modern RIB research are covered</td>
<td>end stage 4</td>
</tr>
</tbody>
</table>

No wait to construction completion. New research opportunities arise each 3-6 years.
Advantages of the proposed facility

Unusual facility layout

Ordinary approach 1:
ISOL RIB production -> problem to reaccelerate RIBs

Ordinary approach 2:
In-flight RIB production -> Problem to stop/cool RIBs

DERICA approach:
In-flight RIB production + RIB “cooling” in gas cell + reaccelerated RIBs up to 300 AMeV

Staged development
- Continuity and flexibility of the research program
- Low technological risks
- Highly upgradable facility design

Unique opportunities
- World most intense RIBs with intermediate energy (20-70 AMeV) for reaction studies
- Reaccelerated RIBs up to 300 AMeV
- e-RIB collider experiment
**Pro et contra for reaccelerated beams**

**Contra**
- Lifetime limit $T_{1/2} > 10$-$100$ ms (compared to $T_{1/2} > 100$ ns for I-F)
- Factor 5-20 intensity loss at \{gas cell-ion source\} system
- Around $5\times10^8$ pps intensity limit of existing gas cells
- Bunched operation 1-20 Hz - specific DAC requirements

**Pro**
- Choice of secondary beam energy in a broad range
- High quality secondary beams: monochromatic, “zero emittance”
- For intense secondary beams overcome $10^5$ pps limitation of event-by-event operation at in-fight facilities

Re-accelerated beams become **acceptable** for reaction studies RIB production $I>10^4$ pps, and become **preferable** for $I>10^6$ pps
Table 4. Estimates of luminosity in various experimental scenarios in units of \(\text{cm}^{-2}\text{sec}^{-1}\). \(J\) - the flux of RI produced in the fragment separator, \(N_{\text{stor}}(1)\) and \(N_{\text{stor}}(2)\) numbers of RI accumulated CR after acceleration in LINAC-30 and FRR, respectively. \(L_1\) is the luminosity of the experiment in the experimental hall EH-3 for the fixed gas target \(5\times 10^{20}\) \(\text{cm}^{-2}\) thickness. \(L_2\) is the luminosity in the CR ring in the jet gas target \(10^{15}\) \(\text{cm}^{-2}\) thick at the energy 7 MeV/nucleon. \(L_3\) and \(L_4\) are the luminosities in the CR ring in the jet gas target \(5\times 10^{15}\) \(\text{cm}^{-2}\) thick at the energies 30 and 300 MeV/nucleon. \(L_5\) is the luminosity of the collider experiment in the CR ring at the energy 300 MeV/nucleon. Primary beams for the Be, C, Ar and S isotopes are \(^{13}\text{N}, ^{22}\text{Ne}, ^{40}\text{Ca}\) and \(^{48}\text{Ca}\), respectively.

<table>
<thead>
<tr>
<th>Ion</th>
<th>(T_{1/2}) (s)</th>
<th>(J) (s(^{-1}))</th>
<th>(L_1)</th>
<th>(N_{\text{stor}}(1))</th>
<th>(L_2)</th>
<th>(L_3)</th>
<th>(N_{\text{stor}}(2))</th>
<th>(L_4)</th>
<th>(L_5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{11}\text{Be})</td>
<td>13.7</td>
<td>5.0E9(^*)</td>
<td>3.7E29</td>
<td>1.5E10</td>
<td>2.4E28</td>
<td>2.5E31</td>
<td>1.5E10</td>
<td>6.5E31</td>
<td>1.4E29**</td>
</tr>
<tr>
<td>(^{12}\text{Be})</td>
<td>0.02</td>
<td>1.0E9(^*)</td>
<td>1.1E28</td>
<td>6.2E5</td>
<td>1.0E24</td>
<td>1.1E27</td>
<td>2.5E5</td>
<td>1.1E27</td>
<td></td>
</tr>
<tr>
<td>(^{16}\text{C})</td>
<td>0.7</td>
<td>1.5E9(^*)</td>
<td>1.0E29</td>
<td>2.1E8</td>
<td>3.4E26</td>
<td>3.5E29</td>
<td>1.8E8</td>
<td>8.0E29</td>
<td></td>
</tr>
<tr>
<td>(^{17}\text{C})</td>
<td>0.19</td>
<td>2.5E8</td>
<td>1.3E28</td>
<td>7.3E6</td>
<td>1.2E25</td>
<td>1.2E28</td>
<td>4.7E6</td>
<td>2.1E28</td>
<td></td>
</tr>
<tr>
<td>(^{18}\text{C})</td>
<td>0.09</td>
<td>3.0E7</td>
<td>1.1E27</td>
<td>3.0E5</td>
<td>4.9E23</td>
<td>5.0E26</td>
<td>1.5E5</td>
<td>6.6E26</td>
<td></td>
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<tr>
<td>(^{19}\text{C})</td>
<td>0.05</td>
<td>3.8E6</td>
<td>9.6E25</td>
<td>1.4E4</td>
<td>2.3E22</td>
<td>2.3E25</td>
<td>6.0E3</td>
<td>2.6E25</td>
<td></td>
</tr>
<tr>
<td>(^{32}\text{Ar})</td>
<td>0.098</td>
<td>2.0E6</td>
<td>8.0E25</td>
<td>2.3E4</td>
<td>3.8E22</td>
<td>3.8E25</td>
<td>1.2E4</td>
<td>5.2E25</td>
<td></td>
</tr>
<tr>
<td>(^{33}\text{Ar})</td>
<td>0.17</td>
<td>4.0E7</td>
<td>2.1E27</td>
<td>1.0E6</td>
<td>1.7E24</td>
<td>1.7E27</td>
<td>6.3E5</td>
<td>2.8E27</td>
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<tr>
<td>(^{34}\text{Ar})</td>
<td>0.84</td>
<td>2.0E9(^*)</td>
<td>1.4E29</td>
<td>3.4E8</td>
<td>5.5E26</td>
<td>5.6E29</td>
<td>3.0E8</td>
<td>1.3E30</td>
<td>2.8E28**</td>
</tr>
<tr>
<td>(^{35}\text{Ar})</td>
<td>1.77</td>
<td>1.0E10(^*)</td>
<td>7.2E29</td>
<td>3.7E9</td>
<td>6.1E27</td>
<td>6.2E30</td>
<td>3.5E9</td>
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<tr>
<td>(^{40}\text{S})</td>
<td>8.8</td>
<td>2.0E9(^*)</td>
<td>1.5E29</td>
<td>3.8E9</td>
<td>6.3E27</td>
<td>6.4E30</td>
<td>3.7E9</td>
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<tr>
<td>(^{41}\text{S})</td>
<td>2.0</td>
<td>7.0E8(^*)</td>
<td>5.1E28</td>
<td>2.9E8</td>
<td>4.8E26</td>
<td>4.9E29</td>
<td>2.8E8</td>
<td>1.2E30</td>
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<tr>
<td>(^{42}\text{S})</td>
<td>1.0</td>
<td>2.0E8</td>
<td>1.4E28</td>
<td>4.0E7</td>
<td>6.7E25</td>
<td>6.8E28</td>
<td>3.7E7</td>
<td>1.6E29</td>
<td></td>
</tr>
<tr>
<td>(^{43}\text{S})</td>
<td>0.265</td>
<td>6.0E7</td>
<td>3.5E27</td>
<td>2.7E6</td>
<td>4.4E24</td>
<td>4.5E27</td>
<td>1.9E6</td>
<td>8.5E27</td>
<td></td>
</tr>
</tbody>
</table>

Limit of luminosity

1E23 1E23 1E23 1E25 1E25

\(^*\) Productivity of modern gas cells (the stage of the RI stop in gas) is limited by the value \(5\times 10^8\) ions/sec.

\(^{**}\) Corresponding luminosities for \(^{11}\text{Be}\) and \(^{35}\text{Ar}\) in the ELISE project [3] are \(2.4\times 10^{29}\) and \(1.7\times 10^{27}\) \(\text{cm}^{-2}\text{sec}^{-1}\).
Major bottlenecks

- LINAC-100
- Gas cell
- Ring branch layout and measurement strategy
4 new high-current HI LINACs are in construction.

To recover high-frequency superconductivity technology in Russia and built most intense HI LINAC 100 AMeV (with possibility of upgrade) based on the gained experience in the world.

- SPIRAL-2 CW-LINAC ~7 AMeV
- GSI/FAIR UNILAC replacement, pulsed ~17 AMeV
- MSU/FRIB CW-LINAC ~240 AMeV
- HIAF pulsed LINAC ~17 AMeV
- Korea - ???

First version of DERICA’s driver LINAC-100 general layout

- RFQ 81 or 162 MHz
- NC cavities 162 MHz
- QWR/HWR or CH 162/325 MHz
- CH or Spoke 325 MHz

0.7-0.75 keV/u
2 MeV/u
~30 MeV/u
100 MeV/u
Basic considerations: LINAC-100 in trench several meters underground. U-turn for opportunity of linac main section upgrade. Beam dump for charge state separator after stripper. Two experimental halls. First DFS acromat (few meters underground), horizontal total turn angle around 45 dgr. Second DFS acromat brings the beam to the ground level experimental hall horizontally.
Major bottlenecks

Gas cell

Ring branch layout and measurement strategy
Major bottlenecks

Ring branch layout and measurement strategy
Outlook

Development of the large-scale accelerator and storage ring RIB facility based at FLNR JINR is proposed. The project is focused on the storage-ring studies of RIBs. World unique feature of the project is proposed studies of the electromagnetic formfactors of RI electron-RIB collider experiment.

- Important expertise in RF
  but
- Never build without world expertise involved

- Comparatively cheap (~ 300 M€)
  but
- World unique research opportunities

- Relatively small weight of concrete shielding
  but
- Relatively large weight of hi-tech devices

- Long list of challenges for Russian scientific and engineering community
  but
- Seem to be no crucial technological bottlenecks
К концу декабря 2015 г. Прохоров стал единоличным владельцем команды "Бруклин Нетс", поскольку купил долю, которая принадлежала девелоперу Брюсу Ратнеру. В общей сложности российский бизнесмен потратил на команду $825 млн, включая долговые обязательства.

Вклад России в ценах 2005 года – 178.05 М€, что соответствует 17.4% от стоимости проекта ФАИР. Ожидается что ежегодный вклад на эксплуатацию составит порядка 30 М€.

Оценка стоимости проекта DERICA – около 270 М€ - сущие копейки...

http://aculina.jinr.ru/derica.php
Reserve
Reserve
Big, bigger, the biggest

**Huge increase in the scale of modern and prospective RIB facilities:** Price tag 1-2 G€

**Scale increase – (i) RIB production increase and (ii) universality of RIB facility**

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Is it possible to have world competitive RIB program with modest investment scale?
Motivation – Applications to astrophysics (nucleosynthesis)

- Hydrostatic burning – slow process
- Explosive burning – rapid processes
- Where does it take place?
- Every day observed violent events in space are produced by rp-processes
- Element abundance in space is connected with r-processes
- No quantitative understanding until the driplines are studied in details
Motivation – Applications to neutron stars

Equation of state for ideal gas. What about nuclear matter?

Known nuclei: practically symmetric nuclear matter

Moving towards the driplines we get experimental knowledge about more and more asymmetric nuclear matter

All the heavy elements in the Universe are produced in explosive nucleosynthesis

Supernovae explosions. How we get from neutron star to Supernova?

Neutron star: very large nucleus with absolutely asymmetric nuclear matter

\[ PV = (m/\mu) RT \]

Equation of state for ideal gas. What about nuclear matter?
What we already have at Flerov lab

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New elements
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- $^{113}$Nh Nihonium
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Cyclotron U-400: The only facility for RIB studies in Russia, CIS, and Eastern Europe

Fragment-separator ACCULINNA: Studies of the light RIBs
Challenges: rings

CR Collector Ring
- Versatile design with 3 major experimental areas

FRR Fast Ramping Ring Synchrotron
- $\Delta E \sim 30 - 300$ AMeV
- Fastest possible operation time (< 0.5 s - ?) to enhance research opportunities with short-lived nuclides

CE Electron Ring
- $E \sim 500$ MeV
- Highest possible bunched beam intensity for collider operation
Challenges: LINACs

LINAC-100
- Universal heavy-ion accelerator
- Good for RI production nuclides from B to U
- Up to 100 AMeV for B, 60 AMeV for U
- Up to 10 pμA for light ions DC operation

LINAC-30
- Universal heavy-ion accelerator
- ALL CHART OF NUCLIDES
- Up to 30 AMeV, 10^{10} pps
- Pulses < 50 ms, < 20 Hz

e-LINAC
- 500 MeV electrons
- Pulses of highest possible intensity

Luminosity is our absolute aim
Challenges: other important devices

**DFS fragment-separator**
- Unusual design with very large aperture for gas cell mode operation
- Double achromatic or velocity filter?

**Ion sources**
- ECR for LINAC-100 with highest charges/intensities
- EBIS for LINAC-30 with highest charges/shortest operation time

**Gas jet target at CR**
- Operation modes for maximum luminosity ($\sim 5 \times 10^{15}$ thickness) and precision experiments ($\sim 5 \times 10^{13}$ thickness)

**Gas Cell**
- For high intensity RIBs from DFS this is a bottleneck technology
- Modern limitation $10^8$ pps – what about $10^{10}$?

**Neutron "target" at CR**
- Neutron-RI collision can be studied only on "neutron target" in ring

**Electron cooler at CR**
- Sufficient performance for "crystallized beam" CR mode for low-intensity RIBs
Предыстория. K4-K10.

Yu.Ts. Oganessian et. al.,

Инжекция от циклотрона U-400M

Кольцо K4 (Магнитное поле 4 Tm)
- Накопление
- Охлаждение
- Формирование банчей
- Ускорение

Канал сепарации (фрагмент-сепаратор)

Кольцо K10 (Магнитное поле 10 Tm)
- Спектрометр сверхвысокого разрешения
- Реакции на внутренней мишени

Электрон-ионный коллайдер
Currently realized RIB studies strategies

**Ordinary approach 1: ISOL RIB production + reaccelerated RIBs up to 10 AMeV**

**Driver:** high-current p or d from 30 to 1000 AMeV

- U production target + noble gas transport
- A, Z separator
- Decay spectroscopy or Penning trap studies
- LINAC ~10 AMeV
- Reactions

**Ordinary approach 2: In-flight RIB production**

**Driver:** high-current HI accelerator 40 to 1800 AMeV

- Light production target
- In-flight fragment separator
- Relativistic reactions
- Gas cell
- RIB cooling in ring
- LINAC ~10 AMeV
- Storage ring studies
- MSU, GSI, GANIL, etc
- FRIB
- MUSES, ELISE@NESR
e-RIB colliders: Evolution of RIKEN

RID-Ring: isochronous mass spectroscopy for very rare events

- e-RIB collider MUSES

SCRTT: separate-standing ISOL facility for e-RIB collision studies in trap

 Planned

Built

RARF

RIBF RI beam generator featuring superconducting ring cyclotron (SRC) and projectile fragment separator (BigRIPS) will be commissioned late in 2006.

RIBF RI beam experiments will be started in 2007, with colored experimental installations.
**e-RIB colliders: Evolution of FAIR.**

**Planned**

**FAIR “Ring Branch”:**
- Storage ring CR
- Experimental ring NESR

**NESR@FAIR:**
- e-RIB collider ELISE
- experiments on the internal gas target EXL

**Decision postponed to 2026 (?)**

**Низкоэнергетическая программа: переезд CRYRING из Швеции**

**Возможность включить ESR в FAIR:**
Пучковая линия от SuperFRS ??? Л ~ 200 м !!!
Storage rings. China

HIRFL-CSR@Lanzhou
- Weak “driver”
- Not much space for driver upgrade

HIAF:
- 2 storage rings
- 1-st – main function spectrometer
- 2-nd – reactions with “merging beams”
New facilities at FLNR

“Factory of superheavy elements”

ACCULINNA-2 fragment-separator
History of U-150 vs U-400M

- Underdeveloped field: storage ring physics with RIBs
- Empty field: studies of RIBs in electron-RIB collider
- Isochronous mass spectrometry
- Precision reaction studies on internal gas jet target
- Atomic physics studies with striped ions
- Radioactivity studies with striped ions
- Etc....