Status of the Nuclotron-M project

MAC meeting, Dubna, 12 Jan’2010

G. Trubnikov
for the project team
Nuclotron provides now performance of experiments on accelerated proton and ion beams (up to Fe^{24+}, A=56) with energies up to 5.7 and 2.2 GeV/n correspondingly (project parameters for ions is 6 GeV/n with Z/A = 0.5).
Optic structure of the Nuclotron: 8 super-periods, each contains 3 regular periods and 1 period, which does not contain dipole magnet. Regular period includes focusing and defocusing quadrupole lenses, 4 dipoles and 2 small straight sections for multipole correctors and diagnostics.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromaticity $Q_x/(p/p)$</td>
<td>7.8</td>
</tr>
<tr>
<td>and $Q_z/(p/p)$</td>
<td>-10.0</td>
</tr>
<tr>
<td>Compaction factor</td>
<td>0.012</td>
</tr>
<tr>
<td>Corrected orbit amplitude</td>
<td>4 mm</td>
</tr>
<tr>
<td>Acceptance horiz/vert [π mm mrad]</td>
<td>40 / 45</td>
</tr>
<tr>
<td>Emittance inj/acc [π mm mrad]</td>
<td>30 / 1.7, and 2.0</td>
</tr>
<tr>
<td>DP/P inj/max/accel</td>
<td>$\pm 10^{-3}$ / 4 $10^{-4}$ / 8 $10^{-3}$</td>
</tr>
</tbody>
</table>
10 stages-subprojects of the Nuclotron-M project

- Modernization of ion source KRION to KRION 6T;
- Improvement of the vacuum in the Nuclotron ring;
- Development of the power supply system, quench detection and energy evacuation system;
- Modernization of the RF system (including trapping & bunching systems, controls and diagnostics);
- Modernization of the slow extraction system for accelerated heavy ions at maximal energies;
- Modernization of automatic control system, diagnostics and beam control system;
- Transportation channel of the extracted beams and radiation safety;
- Improvement of the safety, stability and economical efficiency of the cryogenics;
- Modernization of the injector complex (fore-injector and linac) for acceleration of heavy ions;
- Development and creation of high intensity polarized deutron source

Beam dynamics: minimization of the beam losses at all stages from injection to acceleration and to extraction of the beams (not more then 15-20%, we have about 50-80%).
Heavy Ion Sources KRION-2, KRION-6T (E. Donets)

- We provided series of experiments aimed to get highly-charged Xe ions at the continuous Xe-gas injection into electron string. Ions of Xe\(^{36+}\) at electron energy \(E_{\text{inj}}=3.7\text{kV}\) were obtained.
- It is planned to perform 4 experimental runs (all 4 have been performed) at the existing KRION-2 during 2009 with ions Xe\(^{44+}\) (\(A=124, \frac{Z}{A}=0.35\)).

Progress with new ion source KRION-6T:
- Simulation and design works were successfully performed; prototypes of the electron gun and electron reflector for KRION-6T constructed and tested at KRION-2;
- Manufactured elements of the electron drift tube and ion trap for the structure at 4,2K
- Assembled main elements of the automatic spooling machine for SC solenoid, special software was created.
- Ready all elements of the vacuum vessel for KRION-6T. Vacuum system of the source is assembled.
- Developed and constructed oil-free vacuum pumping system for the KRION-6T.
As LU-20 accepts ions with charge to mass ratio $q/M > 1/3$ one should produce in ion source $^{124}$Xe ion beams with the following charge states: $^{124}$Xe$^{41+}$, $^{124}$Xe$^{42+}$, $^{124}$Xe$^{43+}$, $^{124}$Xe$^{44+}$ This was done in October 2009 run with use of KRION-2T Electron String Ion Source. Highly charged Xe ion beams with charge state Xe$^{42+}$ in the maximum of the charge state spectrum (see picture) has been produced for 780 ms of ionization time. A total pulse ion current for highly charged Xe ions was obtained on a level 130 $\mu$A which contains mixture of Xe$^{40+}$, Xe$^{41+}$, Xe$^{42+}$, Xe$^{43+}$, Xe$^{44+}$ charge states. In terms of the single chosen charge state Xe$^{42+}$ in its maximum the extracted ion beam pulse contained about $3 \times 10^7$ Xe$^{42+}$ particles per pulse. Pure separated isotope $^{84}$Kr was used for calibration of Time-of-Flight analysis.
Assembled vacuum and cryogenic vessels of the new source KRION-6T; New automatic machine tool for solenoid coil spooling.
Injector (LU-20) modernization

It was planned for 2009:

- dismounting of the linac vessel and geodethy of all 59 drift tubes – performed (3 month);

- new power supplies for corrector magnets; commissioning of the new synchronization system for all linac control channels – done;

- exchange of some vacuum chamber parts of the injection channel (new fast vacuum shutters) – done;

Achieved deutron current from laser source >5 mA (before was 3 mA)
- 2-3 dedicated beam runs – 4 done;
Experiments with polarized beams are planned at existing Linac LU-20, and accelerate ions at Nuclotron up to the max. energy. Booster usage in such scheme is inexpedient because it has less periodicity. Protons acceleration for $p \times U$ collisions is also with LU-20.
Nuclotron vacuum system modernization (H.Khodjibagiyian)
Before installation of new pumps av. vacuum at Nuclotron ~ (1-2) * 10^{-8} Torr (2008)
Before modernization of the injection channel ~ 5 * 10^{-7} Torr (2006)

Run 37, circulation of H_2^+ – lifetime 100 msec,
Average vacuum ~ 2 * 10^{-9} Torr (2009)

Crossection decay of H_2^+ ions on Nitrogen at Energy 5 MeV/n ~ 10^{-16} cm^2

Run 37, circulation of H_2^+
Lifetime ~ 10 msec
Works on design of new high voltage power supply for the electro-static septum in the LHEP design bureau were completed in autumn 2008. Prototype of such system was constructed and successfully tested up to 140 kV (existing septum power supply allows up to 110 kV only – it corresponds to 2.3 GeV/n extracted beam).

Now all the elements of new power supply had been manufactured at LHEP workshops and this system is assembled — **03 Jan 2010: tested up to 220 kV**. We plan to install it in the slow extraction sector in order to provide experiments on beam extraction at energy 4 GeV/n during next Nuclotron run.
Modernization of the automation system for control, beam diagnostics and monitoring of parameters of the accelerator complex. (V. Volkov)

- New Control System for the Main Magnet Power Supplies – result of 2-years contract with **Slovakia** – commissioned;
- New diagnostics;
- Full modernization of the inflector system (beam injection) with reserve kit of it for non-stop operation – commissioned;
- New kit of beam-bump power supplies commissioning – done;
- Full scale renewal of the Nuclotron server - Contract with **Romania** (50k$) – equipment delivered to Dubna in May’09, commissioning.
- Commissioning of new power supply for beam orbit correctors, commissioning of 24 supplies in Autumn 2009, commissioning of 25 units more in the middle of 2010. Contract with **Slovakian Institutes** (175 kEuro for 2 years);
- R&D works on design, construction and installation of new elliptical pick-ups;
- continuation of the beam orbit measurement and correction (with **Bulgaria**, **Slovakia**).
New Power supplies for correctors
50 pieces (Slovakia)

Chip for automatic beam orbit system
(30 pieces)

“Glassman” power supplies kit
for beam bump in the b.1
New diagnostics (elliptical pick-up stations)

New (elliptical) pick-up station prototype for Nuclotron (GSI design).

Elliptical pick-up designed and constructed at LHEP workshops ready for cryotraining
Improvement of the power supplies, shielding and energy evacuation system of the magnets and lenses (V. Karpinsky)

**Run 39 (performed):**
Very important stage – increase of the magnetic field in magnets and lenses from 0.9 up to 1.4-1.5T using special prototype of the energy evacuation system;

*Next stage – field increase from 1.4 up to 1.9 - 2T in the beginning of 2010 (with exploitation EES)*

**A lot of other works:**
- Successfully commissioned power supply for current increase in the F-lenses;
- new system for magnet field control;
- beam-bump power supply;
- electric shield of the compressor cascade;
- modernization of main power supply 19TV and 20 TV (6kA, 300V)
- ....
Decrease of the noise with factor of 10–15
Team of creators. EES at b.1A

New commutation schemes
Completed contract with KRIOGENMASH plant aimed on the total modernization of the oil-cleaner unit for liquid Helium at KGU-1600 plant: complicated 13-ton system with cryogenic and high-pressure ingredients. The budget of works is 110k$ and this work was successfully completed during July-November. System had been commissioned in February 2009.
HELIIMASH Chief Engineer and LHEP Chief Engineer

"Wet" turboexpanders (frequency 300000 turns/min)
- 6 units were fixed by now

4-month marathon
Extracted beam transport channels. Radiation shielding
(P. Rukoyatkin, A. Alfeev, A. Kochurov)

- Extracted beam profilometers (first half of extraction channel) were re-designed and reconstructed; diagnostic system for the extracted beam intensity measurement was revised and reconstructed;
- Automatization of control and measurement of the coil current in magnets and lenses of beam transportation channel.
- New automatic system (industrial PC, 32-channel block, active filter modules, cable lines, complex software) for measurement and control of coil current will be commissioned and used by operation personnel during the run. It gives detailed information about unstable work of magnetic optic elements.
- 32 neutron detectors in experimental halls (1 and 205) were totally graduated and metrological attestation was performed for all them.
Development and creation of a high-intensity polarized deuteron source (V. Fimushkin)

We continue collaboration works with INR (Troitsk) on the development of the new high-intensity polarized deuteron source, and signed an addendum for work prolongation in 2009. We plan to complete TDR documentation in this year and start construction of some elements at INR.

Simulation, modeling and design of different elements of the future source are in active phase at LHEP.

Experimental hall for the future test bench with that source is prepared at LHEP building 203A, preparation electrical and water-cooling works were performed.

It is planned to purchase part of necessary vacuum equipment (TMN pumps) for the SPD realization in 2009 – done.
Engineering infrastructure development
We continue geodetical measurements in the Nuclotron tunnel (which we started 1.5 year ago) in order to monitor season alignment of the the ring elements: <0.3 mm/year

- Large volume of infrastructure (fixing and construction works) was performed in 2009

- Water cooling and energetic systems are under modernization (collaboration with Bulgaria on automatization of water systems, reconstruction of power station, etc). Total budget is about 150 k$
Run №39 (June 2009)  
machine development shifts

1. Commissioning of the new system of magnetic field control.

2. Commissioning of the vacuum system automatic control system.

3. Commissioning of the adiabatic capture equipment.

4. Cold tests of the new system for beam orbit diagnostics and correction.

5. Complex tests of the power system and energy evacuation system at 1.5T.

6. Tests of the new system for control of the current at transportation channel’s optic elements.
Run #39: operational field is 1.5T (~3.8 GeV/n)
RUNS № 40 & 41 (PLANNED)

- Start: November 2009 (400-900 hours).
  February-March 2010 (400-900 hours).

- Main accelerator task – project field (1.8 - 1.9T),
  generation and acceleration of heavy ions with
  maximal possible (!) intensity, tests of the beam
  extraction at high energies.

  - Program (Xe, deuterons)
  - Preparation, methodical shifts ~ 200-300 hours;
  - Physics experiments ~ 200-700 hours.
Run 40 (560 hours) 17 Nov - 12 Dec 2009.
main results:

- Staged commissioning of the new power system automatic control equipment
- Commissioned new automatic control system for vacuum equipment of the ring
- Commissioned new digital system of the RF stations frequency control
- commissioned new power supply for Nuclotron corrector
- New methodologies of the losses measurement at extracted beam channels
- commisioned new automatic control system of the beam injection
Power system automatization, magnetic field control

Energy evacuation system prototype is upgraded and tested

Prepared and commissioned the channel for beam injection with ions $Z/A = 1/3$. 
Beam dynamics study and minimization of the particle losses at all the stages of accelerator cycle

The losses can be reduced by a factor of 5-6 due to improvement of RF capture scheme and careful beam dynamics study at the time interval of 100-200 mks after injection.
Commissioned and successfully tested new digital system of the control by RF station frequency towards magnetic field

New equipment of the digital beam orbit measurement successfully tested
25.12.09: Cryogens is prepared for operation (all filters are washed-out, blowed-out, installed by-passes, performed warm blowing of both cryo lines.

23.12.09: We succesfully agreed with HELIIMASH to give the property on screw compressor to JINR (scale of 1ME). We will put into reserve the piston compressors (youngest is made in 1978)

27.12.09: results of the run at LU-20: for the first time at Nuclotron’s linac and injection channel succesfully accelerated ions of $^{+4}\text{C}^{12}$ (0.5 mA). We are ready for ESIS with Xe.
<table>
<thead>
<tr>
<th>Position</th>
<th>Required</th>
<th>Achiev. by 2007</th>
<th>Status by 2009</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion source</td>
<td>124Xe44+ (2T)+new 6T</td>
<td>56Fe28+</td>
<td>84Kr28+ &amp; 124Xe44+</td>
<td>95</td>
</tr>
<tr>
<td>Linac</td>
<td>Vacuum+optimization</td>
<td>No</td>
<td>Ready</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>New modulator and DT</td>
<td>No</td>
<td>Under manufacturing</td>
<td>10</td>
</tr>
<tr>
<td>RF system</td>
<td>Noise reduction</td>
<td>1</td>
<td>1/15</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>Automatization</td>
<td>no</td>
<td>partially</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Adiabatic capture</td>
<td>no</td>
<td>yes</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Feedback with beam</td>
<td>No</td>
<td>No</td>
<td>10</td>
</tr>
<tr>
<td>Ring vacuum, Torr</td>
<td>5*10^-10</td>
<td>5*10^-7</td>
<td>2*10^-9</td>
<td>85</td>
</tr>
<tr>
<td>Field (energy)</td>
<td>2T (6 AGeV)</td>
<td>1T (2.2 AGeV)</td>
<td>1.4 (3.8 AGeV)</td>
<td>70</td>
</tr>
<tr>
<td>Intensity</td>
<td>10^11 (d), 10^8 (i)</td>
<td>2*10^10 (d)</td>
<td>5<em>10^10 (d), 5</em>10^7 (Li)</td>
<td>50</td>
</tr>
<tr>
<td>Power supply</td>
<td>Serial connection of magnets, new EES, MF control</td>
<td>old (&lt; 1Tesla)</td>
<td>Serial connection ESS - 90% ready</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>connection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Gs precision</td>
<td></td>
<td>99</td>
</tr>
<tr>
<td>New quench protection system</td>
<td>200 sensors</td>
<td>200 old</td>
<td>New prototype tested</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30 - for run</td>
<td></td>
</tr>
<tr>
<td>Slow extraction system (efficiency)</td>
<td>Extraction at 6 AGeV</td>
<td>Max energy 2.2 AGeV (95%)</td>
<td>Prototype for 6 AGeV ready (95%)</td>
<td>80</td>
</tr>
<tr>
<td>Control, diagnostics</td>
<td>Beam losses &lt;10%</td>
<td>70-80% losses</td>
<td>30-40% losses</td>
<td>50</td>
</tr>
<tr>
<td>Cryogenics</td>
<td>Safety + stability</td>
<td>Worked-out</td>
<td>Ready</td>
<td>99</td>
</tr>
<tr>
<td>Run stability</td>
<td>6 months/year</td>
<td>3 runs x 1month</td>
<td>2 runs x 1month</td>
<td>70</td>
</tr>
</tbody>
</table>
Development of the KRION ESIS + Injector modernization

Energy evacuation system
Quench protection system
Slow extraction at HE
Vacuum improvement
Control, diagnostics, RF
Cryogenics modernization
Power supply system modernization
Radiation safety

Heavy ions
(A=100-200)

Energy 6 Gev/n
(for Z/A = 1/2)
Field ~ 2T

Intensity >10^7 ppc
(with KRION-2)

Stable, safe, long operation

Nuclotron-M beams in 2010 and further (until NICA commissioning):
- Deutrons, protons – development of existing physics program + appl. research
- Light ions – hypernuclei, applied research (medicine, radiobiology, etc)
- Heavy ions – R&D for detector elements, key accelerator technologies for NICA (stripping, fast injection/extraction, cooling, electron clouds effect, etc)
- Polarized deutrons from new intense source (polarimetry, etc.)
Thank you for your attention!