Status and prospects of development of the Protvino accelerator complex

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Outlook

- Generalities
- Runs
- Upgrades
- Acceleration of light ions
- Prospects of development
- Conclusion

Accelerator Complex U-70 & synchrotron U-70 per se

“Register of unique nuclear physics facilities ...” approved by the RF Government order issued on December 30, 2009, No. 2125-p
4 machines (since October 2007):
- 2 linacs
- 2 synchrotrons

Experimental Hall, 156 x 96 m²

Modes:
- \( p \) (default, [25] 50-70 GeV)
- light-ion (C, complementary)

Light-ion (C nuclei):
- (very) high energy 24.1-34.1 GeV/u
- intermediate (though high) energy 453-455 MeV/u

URAL-30/U-1.5/U-70
I-100(2 of 3)/U-1.5/U-70

In the SIS-18, SIS-100 name convention:
- LIS-233 [T·m]
- LIS-6.9 [T·m]
Photo album of the machines

RFQ DTL URAL-30
Alvarez DTL I-100
RC PS U-1.5
Main PS U-70
Fixed-target physics and BTL network

Up to 9 HEP experiments (= No of setups) per a run,
Up to 7 beam users per a cycle

Beams of $p, \pi, K, e, \nu, C$

Fields of HEP research:
- $h$ spectroscopy
- spin physics
- rare $K$-decays
- $h$-$A$ interactions
- nuclear physics
- [$\nu$ physics]

Applied research:
- $p$ radiography
- $C$ radiobiology
- …

Collaborators:
IHEP, ITEP, JINR, INR, St.-Pb NPI, BINP, SINP MSU, NRNU MEPHI, CERN, …
VNIIEF, MRRC NMRRC ITEB, IMBP, FMBC…
Goals of activity with accelerators

3 [4] goals:

• Regular runs: stable operation and high \( p \)-beam availability in the 7/24 regime, via proper maintenance
• Improve \( p \)-beam quality (lower \( \varepsilon \), higher \( N \), up to \( 3 \cdot 10^{13} \) ppp), and relevant upgrades
• Implement a complementary light-ion program, \( q/A = 0.4–0.5 \) (carbon nuclei)
• [Assess other diversification and development options ]

U-70 as an universal hadron accelerator complex
• of protons and carbon nuclei
• with high and intermediate energies
• via slow and fast extractions
• for fundamental and applied research in the “fixed target” domain
2 runs (7/24) per year:
- short (XPh 10 days ca) 2 MD(\(p\)) + ions
- long (XPh 30 days ca) 3 MD(\(p\)) + ions

Run 2013-1, SSE out/in 90-94% 1-6.5\(\cdot\)10^{12} ppp

Fractional beam availability for physics = 82.2%

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2014</th>
<th>2014</th>
<th>2015-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>-2</td>
<td>-1</td>
<td>-2</td>
<td>on</td>
</tr>
<tr>
<td>XPh</td>
<td>n/a</td>
<td>n/a</td>
<td>16.2</td>
<td>on</td>
</tr>
</tbody>
</table>

Start point: 12:36:20 17-04-13 II-79 Cycle 365398
End point: 15:58:40 17-04-13 II-79 Cycle 366599

SSE: 0.9\(\cdot\)10^{13} ppp
Extraction (fixed target, multi-user)

Inventory:
- 1-turn/1-bunch FE
- SRE (Q38 & SSE (new))
- IT (secondary's)
- bent Si-CD SE (new)
- flat-bottom (S)SE (new)
- Mt(4-10)FE (new)

Sequential and parallel flattop sharing

1st ½ of a flattop, SSE
2nd ½ of a flattop, IT & CD

![Graph showing current and time]
Slow stochastic extraction

200 MHz RF system
Slow extraction & the OKA experiment

Data: run 2009/1

Data from the OKA facility counters

Technological data from the U70

Spill 1.85 s long
$0.95 \times 10^{13}$ p per a spill
50 GeV

duty factor $\langle \Phi \rangle^2/\langle \Phi^2 \rangle$ to 0.94.
No lines of mains harmonics
Bent-crystal (Si) deflectors

Beam to IHEP-CERN experiment on radiation sustainability of liquid Ar

Run2007: 3 CD(19, 24, 30)
6 experiments

CD19
IT24
IT27
Flat-bottom S(S)E

352 Gs, 1.32 GeV (p, test beam) 455 MeV/u (C)

- Square-wave pulses
- Low spill ripple
- Beam spill duration 0.6-1 sec
- Easier beam sweeping and control over dose delivery to target
- Allows for patient’s breath synchronization

Graphite 32 mm (p 1.32 GeV) Be 4 mm (C 455 MeV/u)

Bragg’s peak
30 cm range in a water phantom
Collimator Ø65 cm

> 95% uniformity
at $R = 3$ cm and less
Longitudinal feedbacks

Accelerating system GRAPHITE, 38 ferrite-loaded 1-gap cavities, RF 5.52–6.06 MHz, 10 kV/gap

6 feedback loops:

<table>
<thead>
<tr>
<th>A (AVC)</th>
<th>T (AFC)</th>
<th>BL</th>
<th>R</th>
<th>P</th>
<th>AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>× 38</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

& dynamic variation of gains in radial (R) and phase (P) loops over acceleration cycle with transition crossing
Beam quality, longitudinally

Peak power 0.4–1 TW
Bunch length 12.2 ns

Momentum spread $\Delta p/p \pm 1 \times 10^{-3}$
Momentum spread $\Delta p/p \pm 4–5 \times 10^{-4}$

without 200 MHz spill cavity below $\gamma_{tr}$

<table>
<thead>
<tr>
<th>@ 50 GeV</th>
<th>≤ 2006</th>
<th>&gt; 2007–8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch length (FW@0.9)</td>
<td>36 ns</td>
<td>12–15 ns</td>
</tr>
<tr>
<td>Momentum spread $\Delta p/p$</td>
<td>$\pm 1 \times 10^{-3}$</td>
<td>$\pm 4–5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
DDS RF master oscillator
Transverse feedback -1

ESK @ SS2 | 0 – 0.2 MHz | ±35.0 kV | PU @ SS2 (+ @SS116)

\[ \text{Im} \delta Q = -2.6 \cdot 10^{-3} \]

3.4 мс
Transverse feedback -2

\[ \text{EMK @ SS90} \quad 0.2 - 15 \text{ MHz} \quad \pm 10.7 \text{ kV} \quad \text{PU @ SS107 + 111} \]

\[ \Theta_\kappa \quad 2\pi(21/120) \quad \Theta_\text{PV} \]

-2

\[ \text{FIR-3 & FIR-4 options} \]

\[ N_z - 10s \]

\[ N_z - 0x0 \]

\[ 10s - 0x0 \]

\[ 20s - 0x0 \]

\[ \text{Out} \]

\[ \text{Inp} \]

\[ W_0 \quad W_1 \quad W_2 \quad W_3 \]

\[ \text{EMK @ SS90} \quad 0.2 - 15 \text{ MHz} \quad \pm 10.7 \text{ kV} \quad \text{PU @ SS107 + 111} \]

\[ \text{Im} \delta Q = -3.9 \cdot 10^{-3} \]

\[ 2.3 \text{ ms} \]

\[ \text{FIR-3 & FIR-4 options} \]

\[ 4 \text{ мс} \]
### Strategy of light ion program

#### Incremental:
- **ion species**
  - $p - d - C$
- **along cascade**
  - $I^{100}$ - BTL - $U^{1.5}$ - BTL - $U^{70}$ flat bottom circulation (DC PSU, RMG) - $U^{70}$ fixed-field variable-RF acceleration - $U^{70}$ transition crossing – $U^{70}$ ramping to flattop field
- **intensity [qpp]**
  - 1 – 1/10 – 1/50 & low-N pilot $p$-beams prior to $d, C$-beams

#### Table: Strategy of light ion program

<table>
<thead>
<tr>
<th>Опорные ионы</th>
<th>$I^{100}$, 2 p-ра из 3</th>
<th>$U^{1.5}$</th>
<th>$U^{70}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q = Z, q/A = 1/2$</td>
<td>IN</td>
<td>OUT</td>
<td>IN</td>
</tr>
<tr>
<td>$p$, pilot beam</td>
<td>$\beta$</td>
<td>0.3724</td>
<td>0.9000</td>
</tr>
<tr>
<td>$B_\rho$, T-m</td>
<td>1.2558</td>
<td>6.8659</td>
<td>233.38</td>
</tr>
<tr>
<td>$T$, MeV</td>
<td>72.71</td>
<td>1323.8</td>
<td>69032</td>
</tr>
<tr>
<td>$d$</td>
<td>$\beta$</td>
<td>0.1862</td>
<td>0.7392</td>
</tr>
<tr>
<td>$B_\rho$, T-m</td>
<td>1.1856</td>
<td>6.8659</td>
<td>233.38</td>
</tr>
<tr>
<td>$T$, MeV/u</td>
<td>16.691</td>
<td>454.56</td>
<td>34057</td>
</tr>
<tr>
<td>$C$</td>
<td>$\beta$</td>
<td>0.1862</td>
<td>0.7414</td>
</tr>
<tr>
<td>$B_\rho$, T-m</td>
<td>1.1776</td>
<td>6.8659</td>
<td>233.38</td>
</tr>
<tr>
<td>$T$, MeV/u</td>
<td>16.678</td>
<td>456.53</td>
<td>34063</td>
</tr>
</tbody>
</table>

- Goal attained

- 50 000
- 23 600
- 34 063
## Light ion program milestones

<table>
<thead>
<tr>
<th></th>
<th>Deuterons $^2\text{H}^+$</th>
<th>Carbon $^{12}\text{C}^6+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1.5</td>
<td>16.7–448.6 MeV/u March 30, 2008</td>
<td>16.7–455.4 MeV/u December 08, 2010</td>
</tr>
<tr>
<td>U70</td>
<td>23.6 GeV/u April 27, 2010</td>
<td>34.1 GeV/u April 24, 2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SE @ 455 MeV/u April 24, 2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.1 GeV/u in BTL#22 &amp; FODS (300 GeV full) April 27, 2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Validation tests of top-energy extractions with ion beam April 24, 2013</td>
</tr>
</tbody>
</table>
April 27, 2012. 1st ever extracted C beam in 190 m BTL#22 = FRS & FODS (a FOcusing Double-arm Spectrometer) experimental facility

24.1 GeV/u or 300 GeV full E

**Hadron calorimeter**

- $^2$D 50 GeV
- $^4$He 100 GeV
- $^{12}$C 300 GeV

**Scintillator counters**

- $q = 1$
- $q = 2$
- $q = 3$
- $q = 6 @ \text{bin #9250}$

BTL#22 50 GeV/c (p), 25 Gev/c/u $q/A=1/2$

BTL#22 60 GeV/c (p) \pm 1% a FRS

25.7 Gev/c/u $q/A=3/7$
BTL #25 and radiobiological bench
Upgrades of the recent years

= PoA = points of attraction
Ion beam therapy center (proposal)

A joint venture by NRC KI – IHEP (Protvino) and NMRRC – MRRC (Obninsk)
Pulsed $n$-source at U-1.5

1.32 GeV at peak fractional yield = 30 n/p/GeV
1-1.5\cdot10^{13} p per pulse (6.5 sec)
29 benches (50-80 nsec) in 2 sec

Optional: 0.3-1.32 GeV (p), d, C @ 455 MeV/u max
The OMEGA project


the extended Lol, 37p, June 2013

445.1 m 0.4-3.5 GeV 25 Hz $7.5 \times 10^{13}$ ppp 1 MW
Conclusion

Accelerator Complex \textit{U-70} of NRC “Kurchatov Institute” – IHEP (Protvino):

- comprises 4 machines (\textit{URAL-30}, \textit{I-100}, \textit{U-1.5}, and \textit{U-70} itself),
- readily ensures running the fixed-target physics program
- is subject to ongoing upgrade program
- has noticeably improved quality of proton beam recently
- ensures a routine acceleration and extraction of light ions to 24-34 GeV per nucleon for high-energy nuclear physics
- now has slow extraction of 455 MeV per nucleon of \(^{12}\text{C}^{6+}\) beam for radiobiology and future prior-to-therapy studies
- \textit{U-1.5} and \textit{U-70} now belong to PS and (L)IS categories
- is open for a few promising options for future development