Preparation of the Strategic plan
for long-term development of JINR

NUCLEAR PHYSICS
AT LOW AND INTERMEDIATE ENERGIES

Alexander Karpov

JINR Scientific Council meeting, September 19-20, 2019

Sub-group

Nuclear physics of low and intermediate energies including atomic physics, nuclear chemistry, and astrophysics

- Synthesis and properties of superheavy elements
- Study of exotic nuclei
- Nuclear reactions induced by heavy ions

Local working group

	Name	Institution
1.	Alexander Karpov	JINR
2.	Sergey Sidorchuk	JINR
3.	Sergey Dmitriev	JINR
4.	Vladimir Utyonkov	JINR
4.	Alexander Eremin	JINR
5.	Nikolay Aksenov	JINR
6.	Alexander Rodin	JINR
7.	Yuri Penionzhkevich	JINR
8.	Andrey Fomichev	JINR
9.	Leonid Grigirenko	JINR
10.	Vladimir Rachkov	JINR

Group of experts

	Name	Institution
1.	Robert Eichler	PSI
2.	Emanuele Vardaci	INFN
3.	Gottfried Münzenberg	GSI
4.	Ephraim Eliav	School of Chem., Tel Aviv Uni.
5.	Mikhail Onegin	NRC KI, Petersburg
6.	James Roberto	ORNL
7.	Joseph Hamilton	Vanderbilt University
8.	Marek Pfützner	Warsaw University

Meetings on heavy and superheavy elements research

- **3rd International Symposium on Super-Heavy Elements**
  "Challenges in the studies of super-heavy nuclei and atoms"

Kazimierz Dolny, Poland September 10-14, 2017

- **3 meetings**
  "Super-heavy atoms & chemistry of Super-heavy elements",

JINR, Dubna, Russia December 7-8, 2017, October 24-25, 2018, June 1, 2019

- **ECT* Workshop**
  "Spontaneous and induced fission of very heavy and super-heavy nuclei",

Trento, Italy April 9-13, 2018

- **Meetings of the RAS Council on Heavy-Ion Physics**
  "Future of SHE research at Dubna",

JINR, Dubna, Russia October 26-27, 2018

- **International Symposium**
  "The present and the future of the Periodic table of chemical elements"

JINR, Dubna, Russia May 30-31, 2019

- **4th International Symposium**
  "Super-Heavy Elements"

Hakone, Japan December 1-5, 2019

Meetings on light exotic nuclei research

- **Meetings of the RAS Council on Heavy-Ion Physics**
  "Future of RIBs research at Dubna",

JINR, Dubna, Russia December 1-2, 2017

- **ECT* Workshop**
  "Probing exotic structure of short-lived nuclei by electron scattering"

Trento, Italy July 16 – 20, 2018

- **ECPM 2018**
  "41st European Cyclotron Progress Meeting",

JINR, Dubna, Russia September 3 – 5, 2018

- **EXON 2018**
  "IX International Symposium on EXOtic Nuclei",

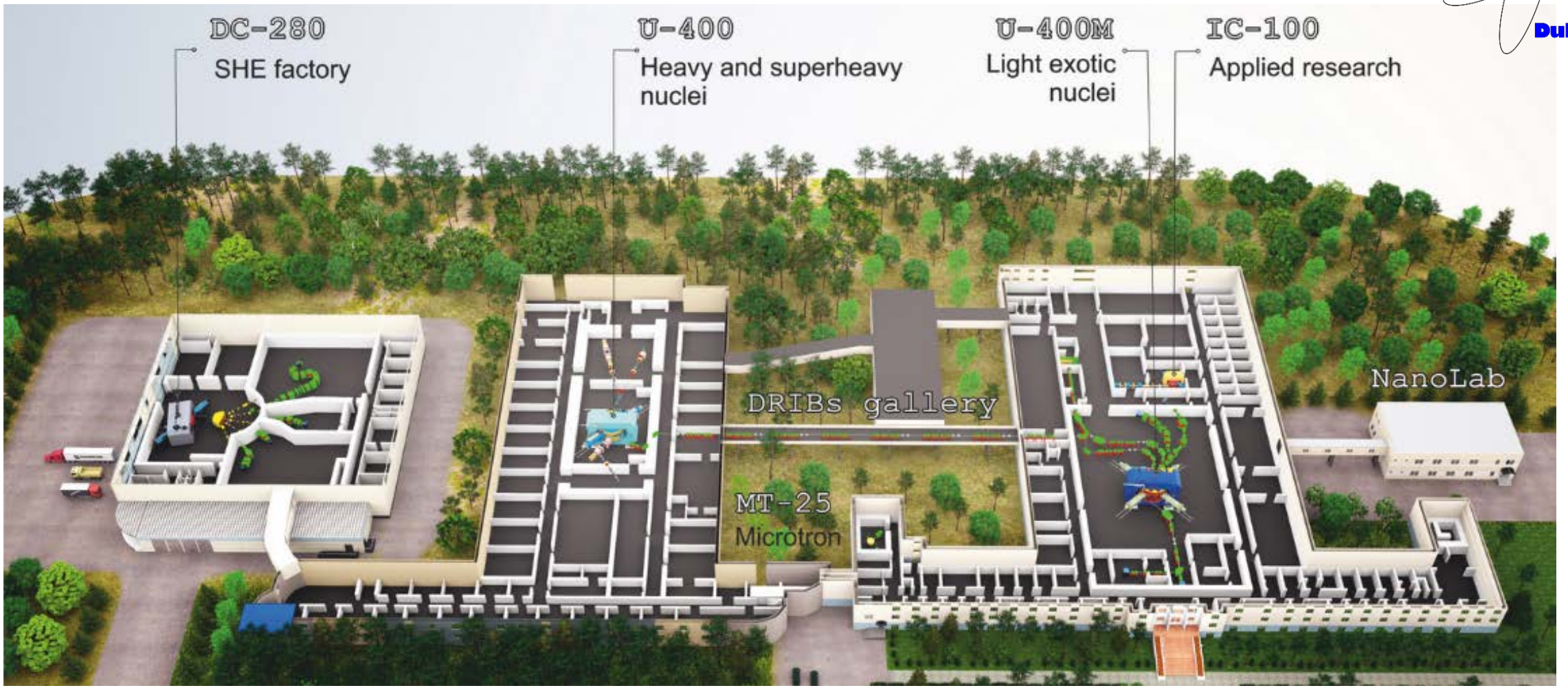
Petrozavodsk, Russia September 10 – 14, 2018

- **Workshop in frames of**
  "the 8th International Conference on New Frontiers in Physics"

Crete, Greece August 21-25, 2019

DRIBS-III ACCELERATOR COMPLEX

FLEROV LABORATORY OF NUCLEAR REACTIONS



FLNR's basic directions of research:

- Heavy and superheavy nuclei
- Light exotic nuclei
- Radiation effects and physical groundwork of nanotechnology
- Accelerator technologies

FLNR main tasks for 2017–2023

Commissioning and development of "SHE Factory" based on DC280 cyclotron:

- *smoothly variable energy;*
- *beam intensity ~10 pμA for nuclei with A~50;*
- *new set-ups;*
- *infrastructure for accommodation of user setups.*

Modernization of the U400M cyclotron (2020-2021):

- *new main magnet coils, vacuum, diagnostics and radiation safety control systems;*
- *increasing beam intensities and energies.*

Reconstruction of the U400 to U400R cyclotron complex (2020-2023):

- *new experimental hall;*
- *accelerated ions from helium to uranium;*
- *smoothly variable energy within a wide range 0.8–25 MeV·A;*
- *decrease the cyclotron power consumption.*

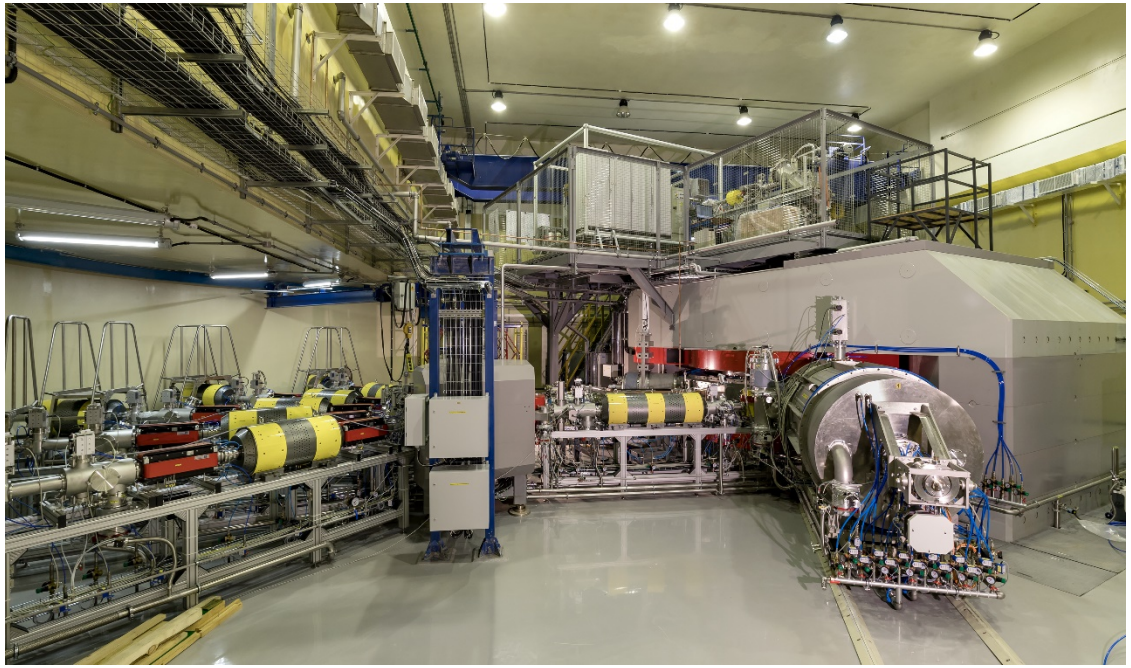
Development of long-running experimental set-ups

Heavy and superheavy elements

basic facility: DC-280 @ SHE Factory

DC-280 ACCELERATOR COMPLEX

SUPERHEAVY ELEMENTS FACTORY



Commissioned: 2018-2019

Beams (examples)		
Ion	Ion energy [MeV/A]	Estimated output intensity [pps]
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	6	6×10^{13}
^{48}Ca	6	$(6\text{-}12)\times10^{13}$
^{54}Cr	6	2×10^{13}
^{58}Fe	6	1×10^{13}
^{124}Sn	6	2×10^{12}
^{136}Xe	6	1×10^{14}
^{238}U	7	5×10^{10}

Main parameters	
Range of energies	4÷8 MeV/A
K factor max.	280
Pole diameter	4 m
Magnet weight	1000 t
Magnet power	300 kW
Vacuum	10^{-7} Torr

Tasks:

Experiments at the extremely low (σ<100 fb) cross sections:

- Synthesis of new SHE in reactions with ^{50}Ti, ^{54}Cr ...;
- Synthesis of new isotopes of SHE;
- Search for rare decay modes of SHE;
- Study of excitation functions.

Experiments requiring high statistics:

- Nuclear spectroscopy of SHE;
- Precise mass measurements;
- Study of chemical properties of SHE.

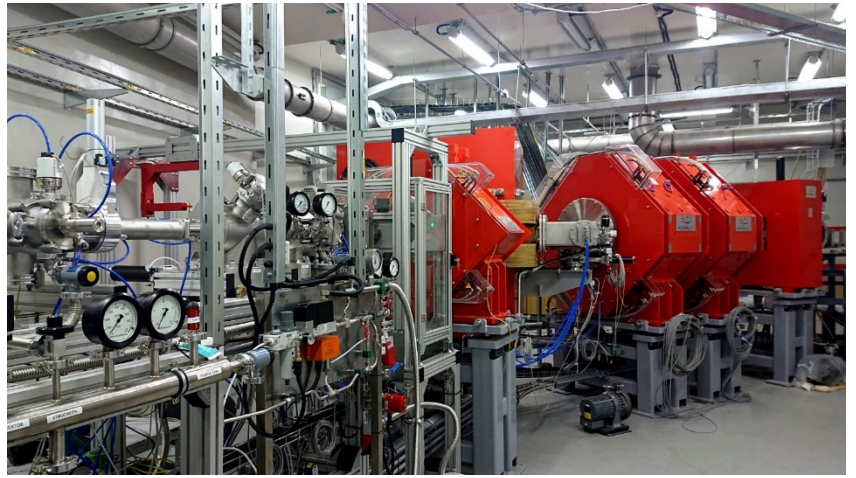
Main setups:

- Gas-filled recoil separator (DGFRS-II);
- Gas-filled recoil separator (DGFRS-III) for spectroscopy and chemical studies;
- *Mass Analyzer of SuperHeavy Atoms (MASHA) – from U-400M*
- Channels reserved for external users

SuperHeavy Element Factory

- **GFRS-2**

status: commissioned;
tests and tuning are in progress
purpose: synthesis of new SHE,
new isotopes of SHE, decay modes, excitation functions, etc.



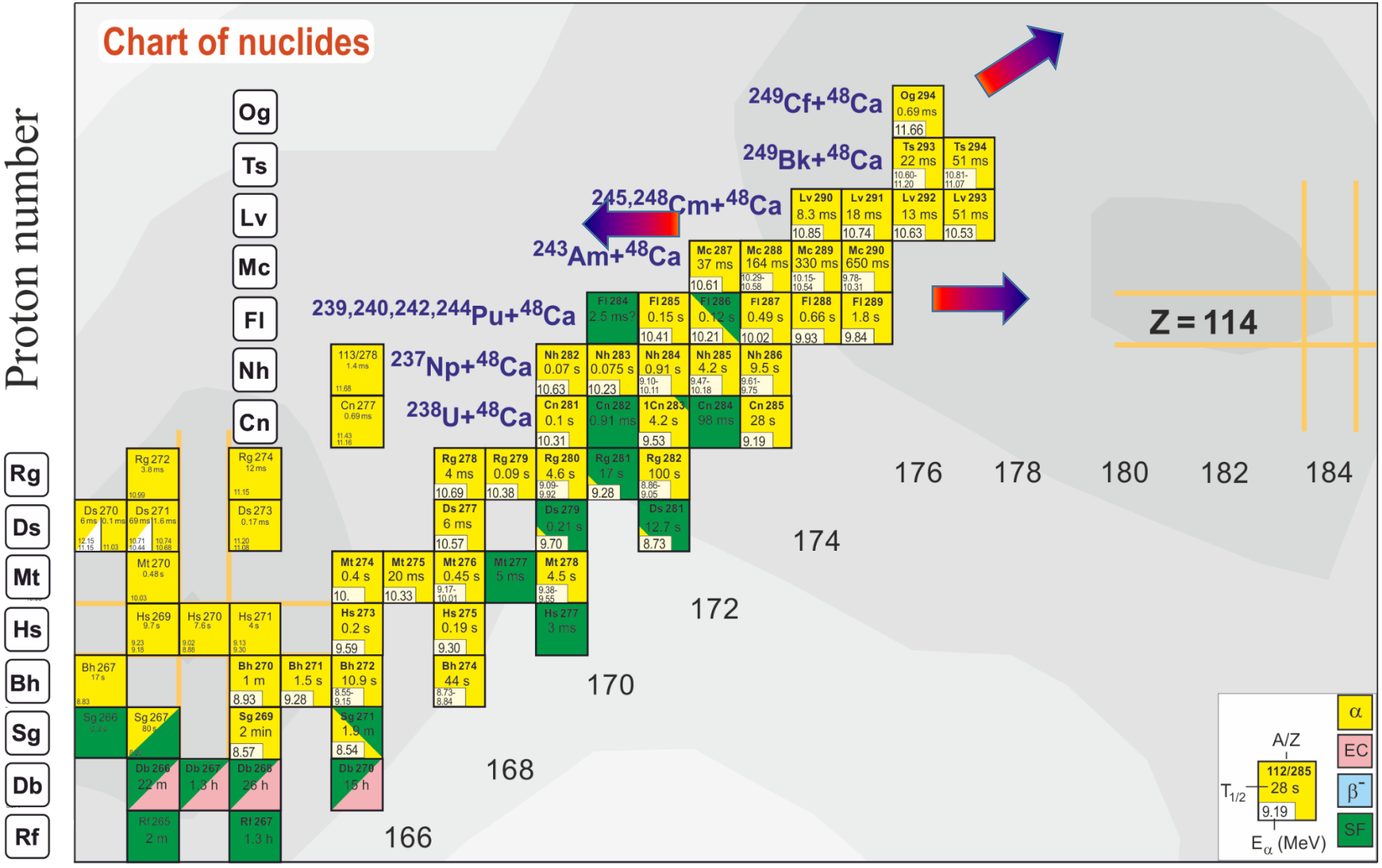
- **GFRS-3**

status: manufactured,
delivery to Dubna is expected by the end of 2019;
assembling - 2020
purpose: decay spectroscopy; chemistry of SHE

Long-term plans:

- **Specialized radiochemical complex of the 1st class**
- **ECR ion source on 28 GHz**
- **Development of experimental set-ups**

Fusion reactions: *left, right or up?*

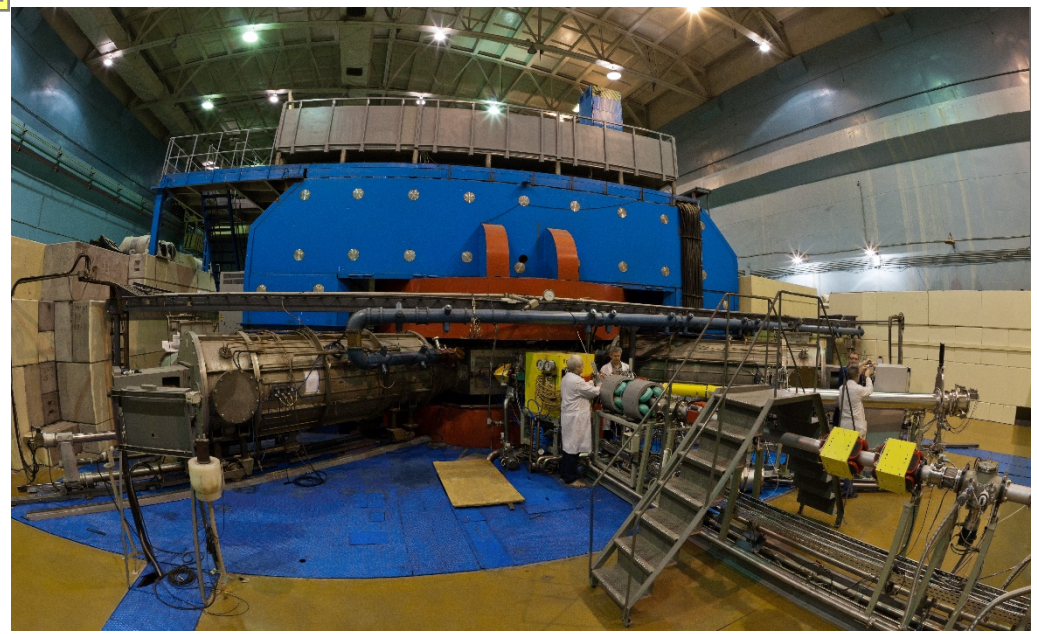


Light exotic nuclei

basic facility: modernized U-400M

U-400M ACCELERATOR COMPLEX

EXPERIMENTS WITH RADIOACTIVE ION BEAMS



Commissioned: 1991
Modernized: 1996
Reconstruction: 2020-2021 (plan)

Beams (examples)		
Ion	Ion energies [MeV/A]	Output intensity [pps]
^{6}Li	46	5×10^{13}
^{7}Li	35	6×10^{13}
^{11}B	32	3×10^{13}
^{12}C	47	2×10^{13}
^{15}N	50	1×10^{13}
^{18}O	33	1×10^{13}
^{20}Ne	53	2×10^{12}
^{32}S	53	1×10^{12}
^{40}Ar	40	1×10^{12}
^{84}Kr	27	2×10^{10}
^{132}Xe	25	1×10^{9}

Main parameters	
Energy range	5÷10 & 25÷55 MeV/A
K factor max.	550
Pole diameter	4 m
Magnet weight	2300 t
Magnet power	1000 kW
Vacuum	10^{-7} Torr

Tasks:

Stand-alone mode:

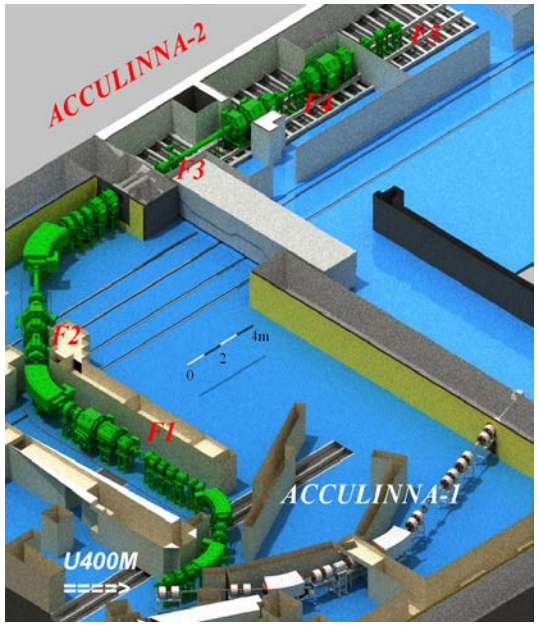
- Properties and structure of light exotic nuclei
- Reactions with exotic nuclei
- Decay properties of nuclei at drip lines
- Mass & laser spectroscopy of heavy nuclei
- Applied research

Driving accelerator mode:

- Production of beams of radioactive nuclei (U-400M → U-400)

FRAGMENT SEPARATOR ACCULINNA-II

Experiments with radioactive beams



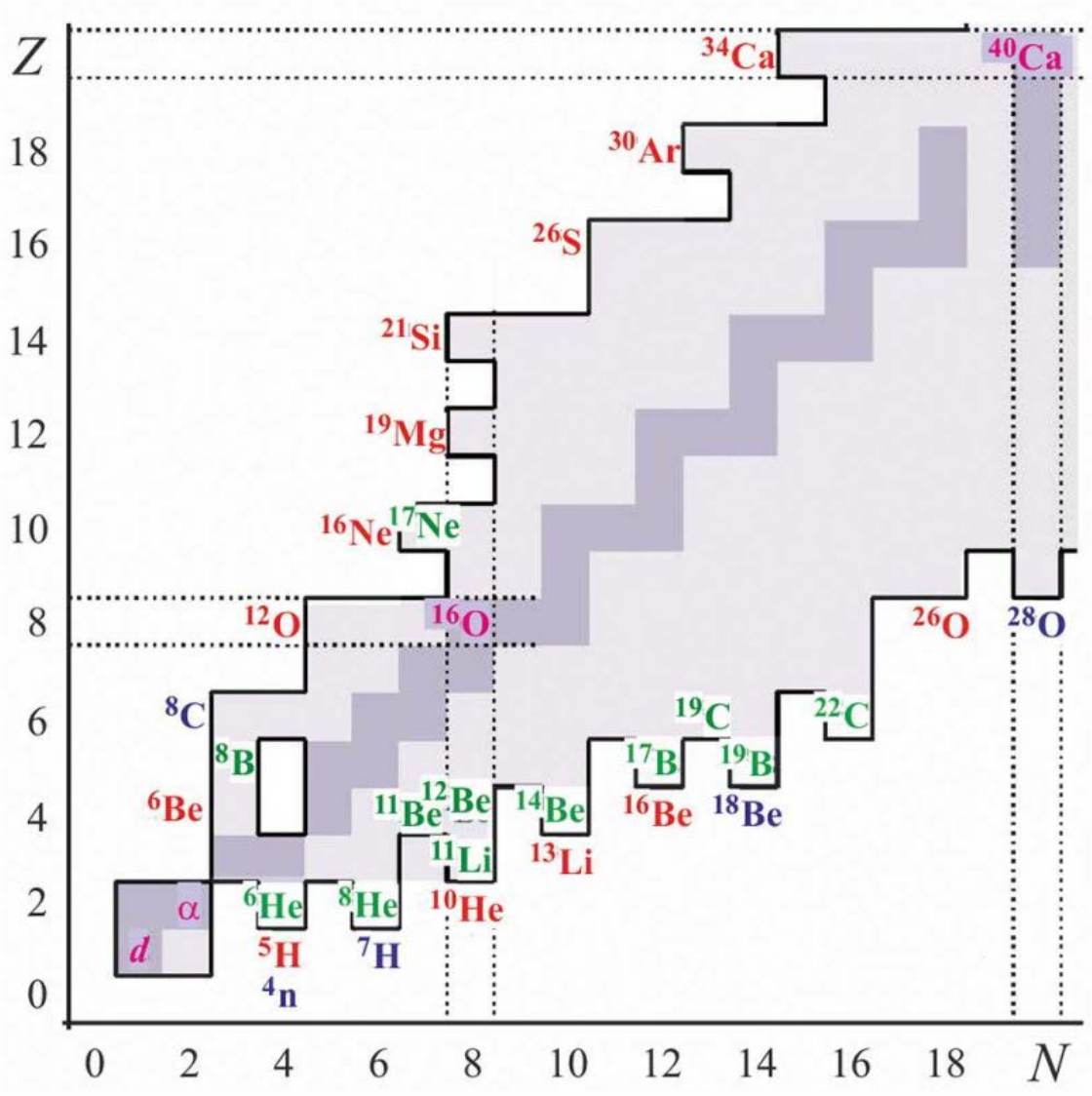
RIB*	Intensity, pps (at 1 pμA)	Energy, MeV/A
^{6}He	4x10^{7}	22
^{6}He	1x10^{7}	13
^{8}He	8x10^{4}	23
^{11}Li	7x10^{3}	33
^{14}Be	2x10^{3}	35
^{15}B	4x10^{5}	32
^{16}C	2x10^{7}	29
^{18}C	1x10^{4}	25
^{24}O	2x10^{3}	23
^{8}B	2x10^{6}	16
^{13}O	1x10^{6}	24
^{17}Ne	2x10^{6}	30
^{24}Si	7x10^{3}	12
^{28}S	1x10^{3}	38

http://aculina.jinr.ru/acc-2.php

2019: RF kicker
2021: Cryogenic target system (hydrogen, tritium, deuterium): under development (Sarov)
2021: Completion of modernization of the U-400M cyclotron
Continuously: Development of detectors for charged and neutral particles (optical TPC, neutron wall, scintillator arrays, Si-telescopes, active target, HPGe array)

Experimental program with exotic nuclei (2019-2030)

- Nucleon halo, neutron skin
- Exotic decays: β-delayed, 2p, 2n radioactivity, etc.
- Soft excitation mode
- New magic numbers and intruder states
- Spectroscopy of exotic nuclei
- Cluster states
- Reactions with RIBs
- Astrophysical applications



Possible future of the RIBs research at FLNR

- Substitution of the driving accelerator U-400M with a new one.
- Superconducting LINAC-100 is under consideration. Goals:

  - **Beams**: up to Uranium
  - **Energy**: ~100 MeV/nucleon
  - **Intensities**: maximal possible

A new project entitled “Construction of a prototype of the initial section of the high-current heavy-ion linear accelerator for the production of intense radioactive ion beams for basic research” was proposed and considered by JINR PAC on Nuclear Physics.

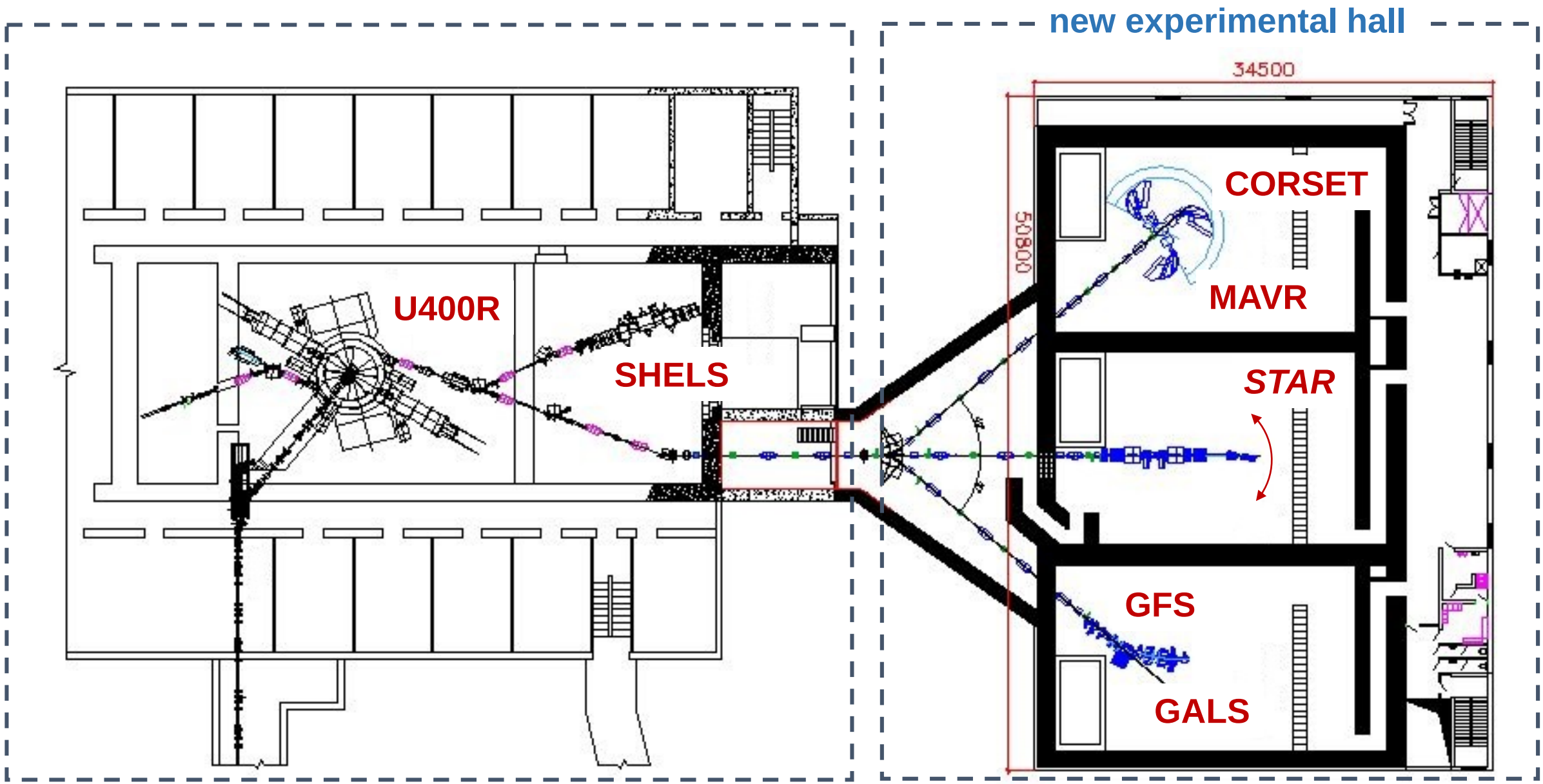
The project is a supplement to the physical program of the project “Development of the FLNR accelerator complex and experimental setups (DRIBs-III)” (theme: 03-0-1129-2017/21).

The works within this project should demonstrate the feasibility of the LINAC-100 plus new fragment separator facility and prepare the basic technical documentation (TDR).

Nuclear reaction studies

basic facility: reconstructed U-400R

U400R: facility for nuclear reaction studies



Summary

HEAVY AND SUPERHEAVY ELEMENTS

- Development of experimental set-ups @ the SHE Factory.
- Realization of the experimental program in the area of SHE research.
- Construction a specialized radiochemical complex of the 1st class.
- Development of ECR ion source on 28 GHz for acceleration of ions up to Uranium.
- Upgrade the U-400 (U-400R) accelerator, construction of the new experimental hall and equipping it with existing and new set-ups intended mainly for the study of nuclear reactions.

Summary

LIGHT EXOTIC NUCLEI

- Continuation of experimental program on light exotic nuclei at the modernized U-400M cyclotron with the use of the ACCULINNA-2 fragment separator.
- Consideration of a feasibility of construction of a new driving accelerator for the radioactive beam research.

Summary

- Total available beam time of three FLNR's cyclotrons (DC-280, U-400R, and U-400M) is expected to be of about 18 000 hours annually. This will allow us to formulate a user policy and open the FLNR facilities for external users.

Summary

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