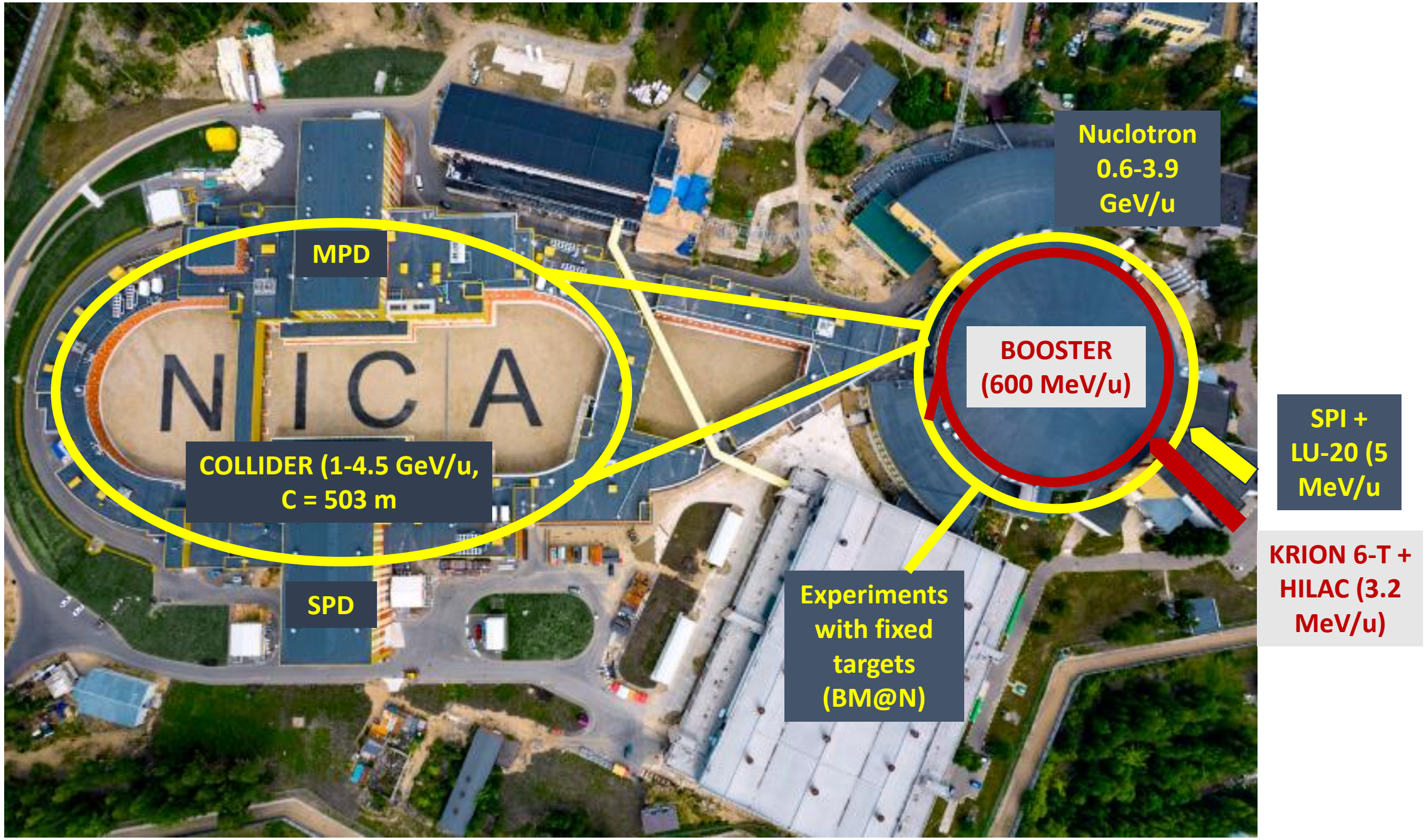
Multiple heavy ion injection into NICA Booster

Andrei Martynov

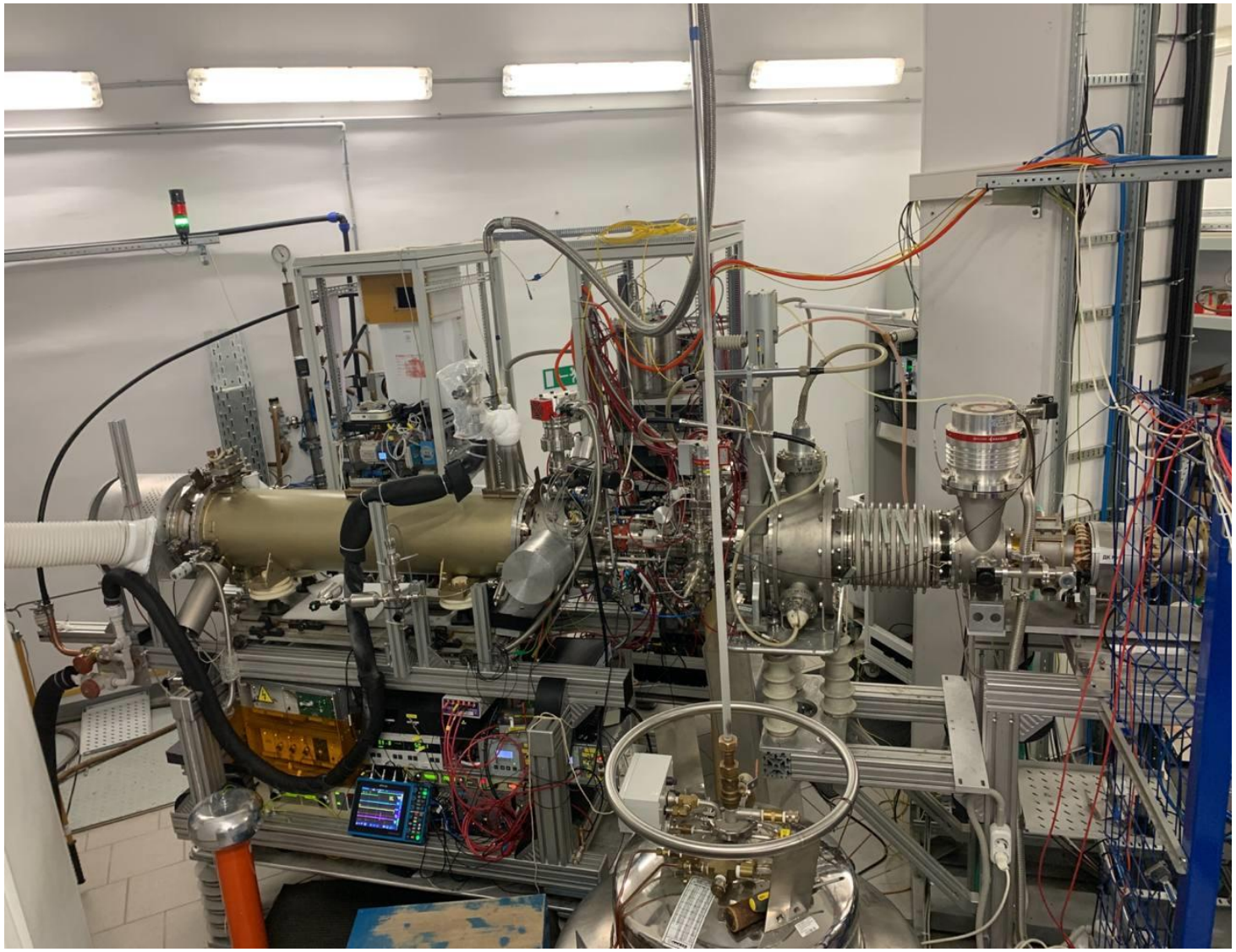
Dubna, 2024

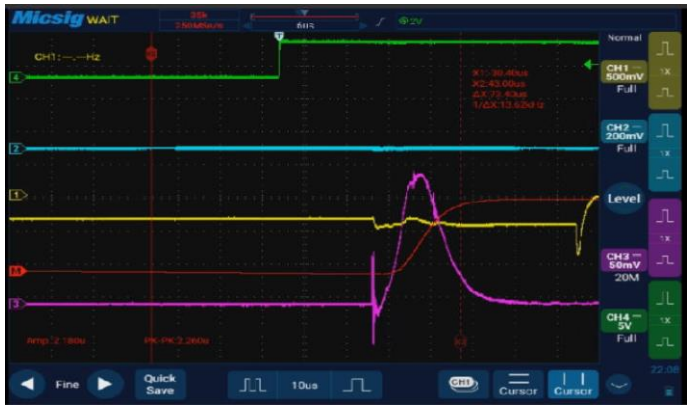

SPD
(Detector)
BM@N (Detector)
Extracted beam
Heavy Ion
Linac
Collider
MPD
(Detector)
E-cooling
LU-20
Nuclotron
Booster
NICA


NICA


Nuclotron
0.6-3.9
GeV/u
MPD
NICA
BOOSTER
(600 MeV/u)
SPI +
LU-20 (5
MeV/u
COLLIDER (1-4.5 GeV/u,
C = 503 m
KRION 6-T +
HILAC (3.2
MeV/u)
SPD
Experiments
with fixed
targets
(BM@N)

KRION – 6T Electron String Ion Source

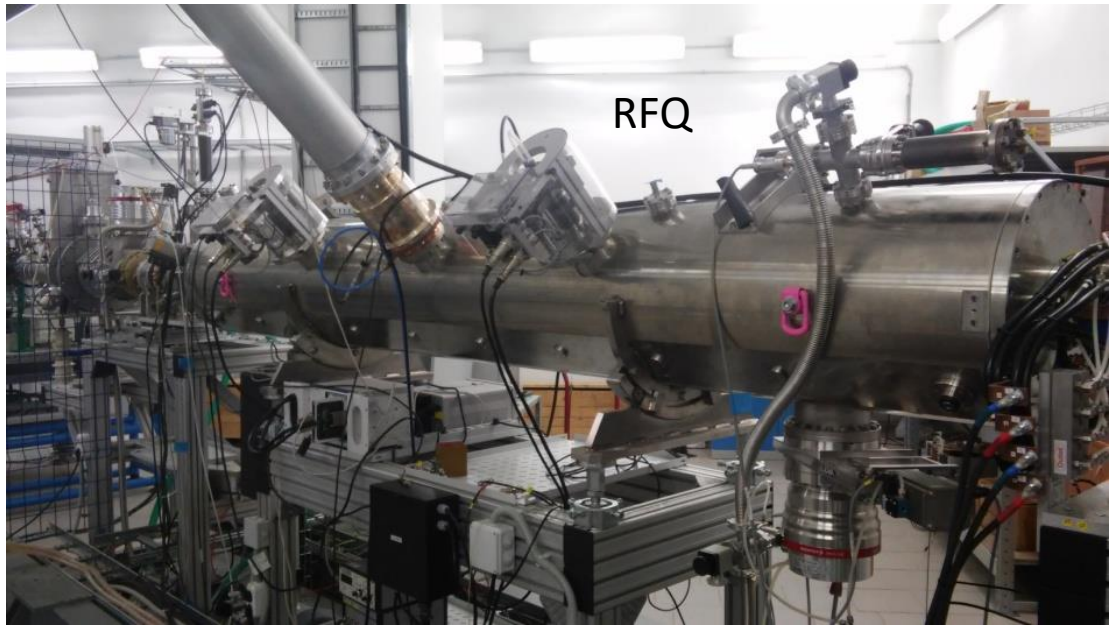


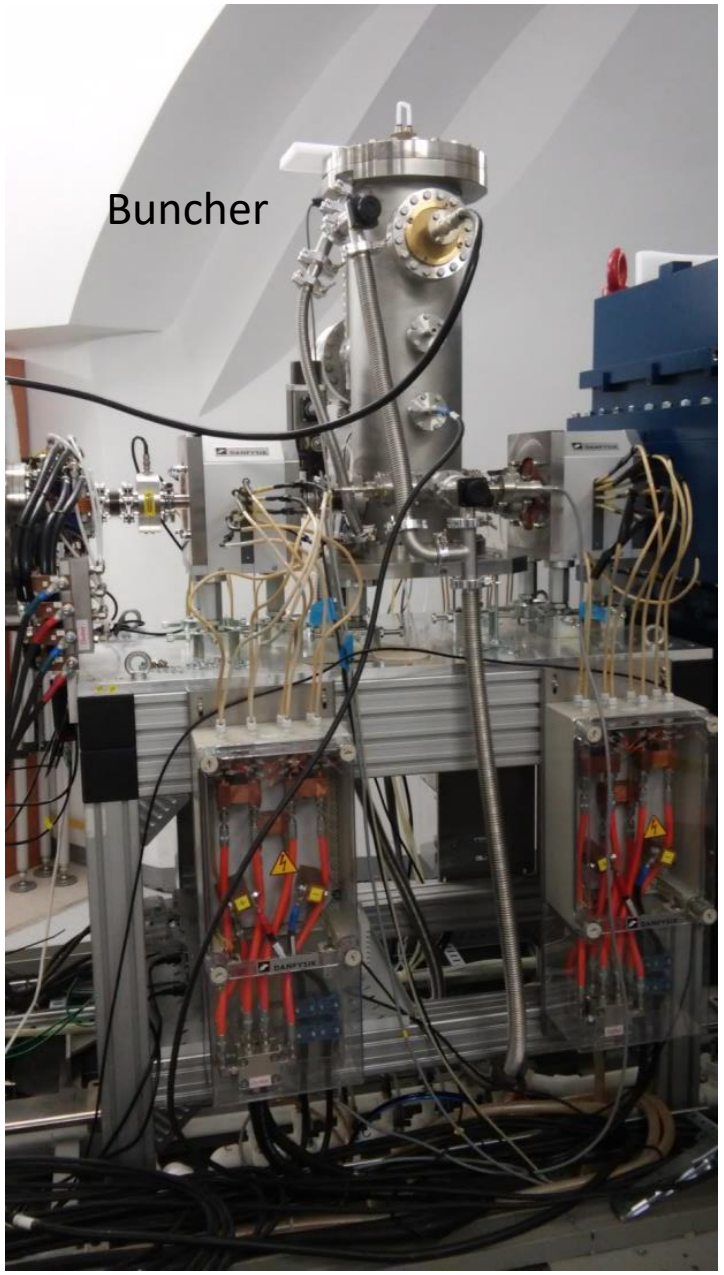


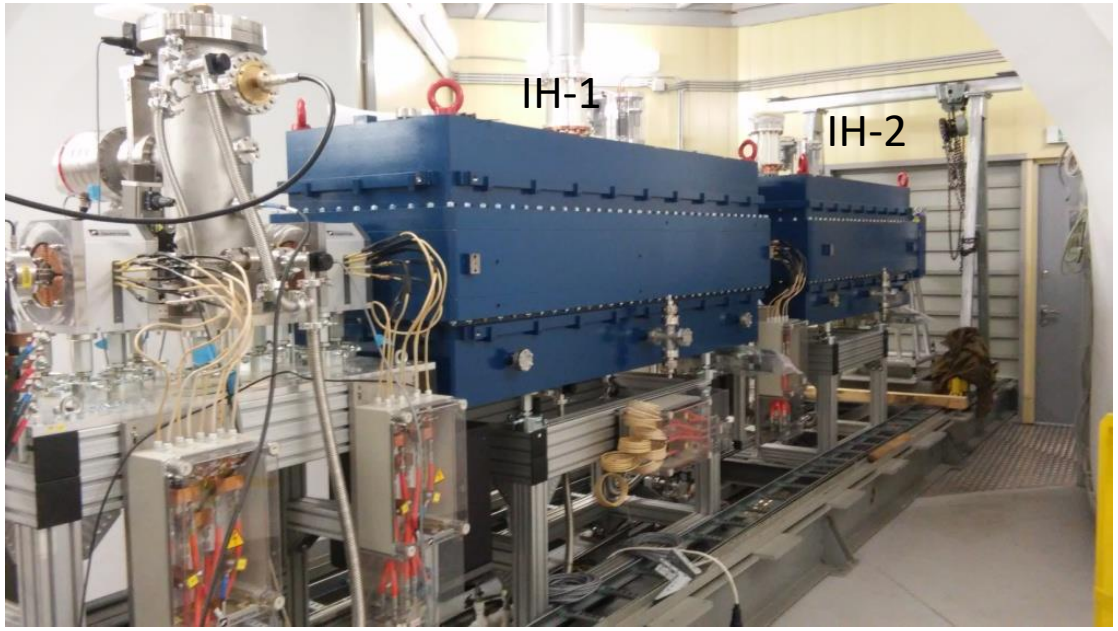
^{124}Xe Q=2,18 nK, I= 200 μA, t= 25 μs

Source type	Electron string (ESIS)
Ion type	^{124}Xe28+
Magnetic field in the trap	5T
Magnetic field at the cathode	0.25 T
Effective cathode voltage	6 kV
Cathode diameter	1.2 mm
Electron beam current	4-6 mA
Ion trap length	70 cm
Total ion charge	2.3 nC
Number of target ions at source exit	10^8

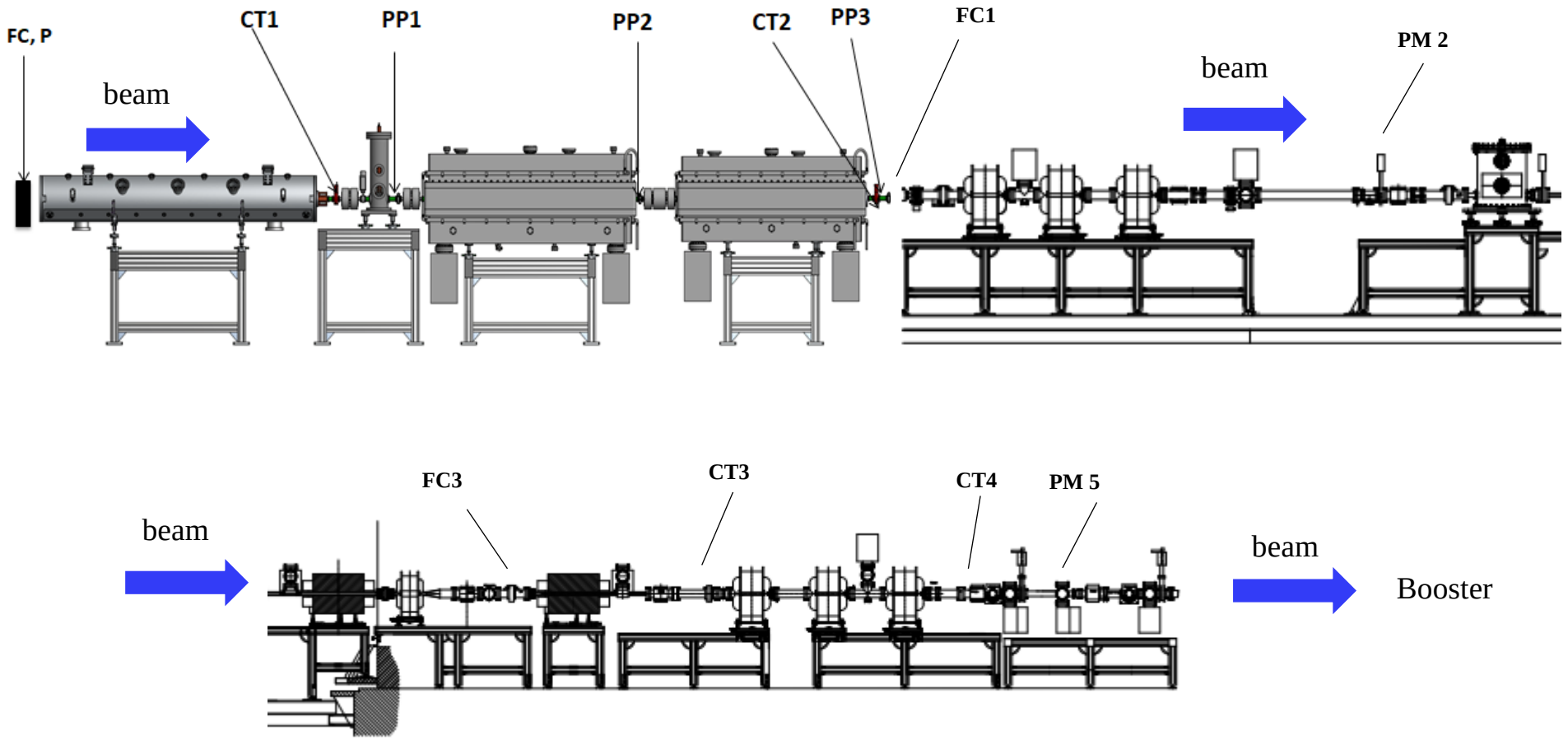
HEAVY ION LINEAR ACCELERATOR (HILAC)







Auxillary diagnostic equipment along the injector



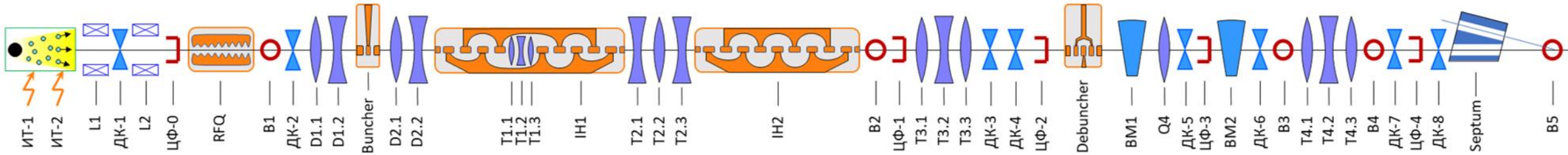
CT – Current transformer, FC – Faraday Cup, PM- Profilometer, PP- Phase Probe)фазовый датчик)

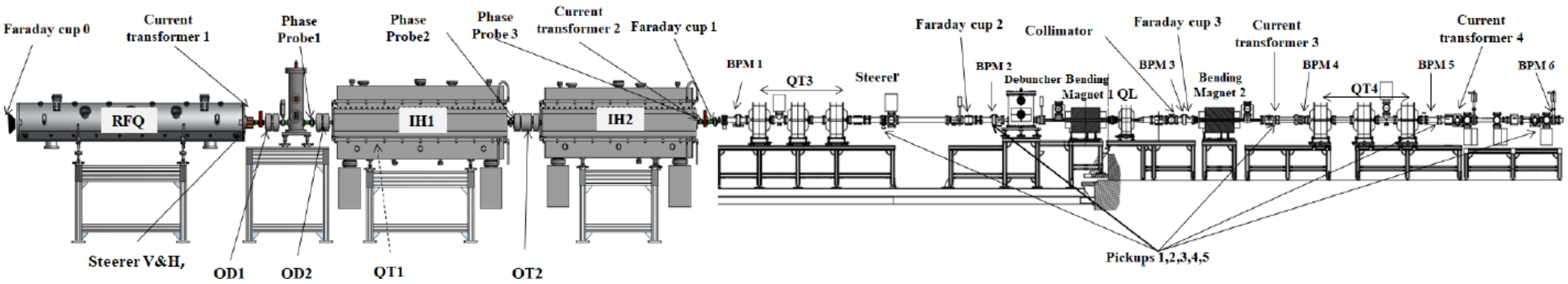
Injection line into Booster

Heavy Ion linac consists of:

- Electron String Heavy ion source (ESIS) KRION-6T, 6T conducting solenoid of 1.2m length, extraction voltage up to 25.0 kV;
- Low energy beam transport channel LEBT, E_{out} = 17 keV/n;
- Heavy ion LINAC: 4-rod RFQ is followed by two IH DTL section with the KONUS accelerating structure, accelerates ions with Charge-to-mass ratio of q/A = 6.25, E_{in} = 17 keV/n, E_{out} = 3.2 MeV/u;

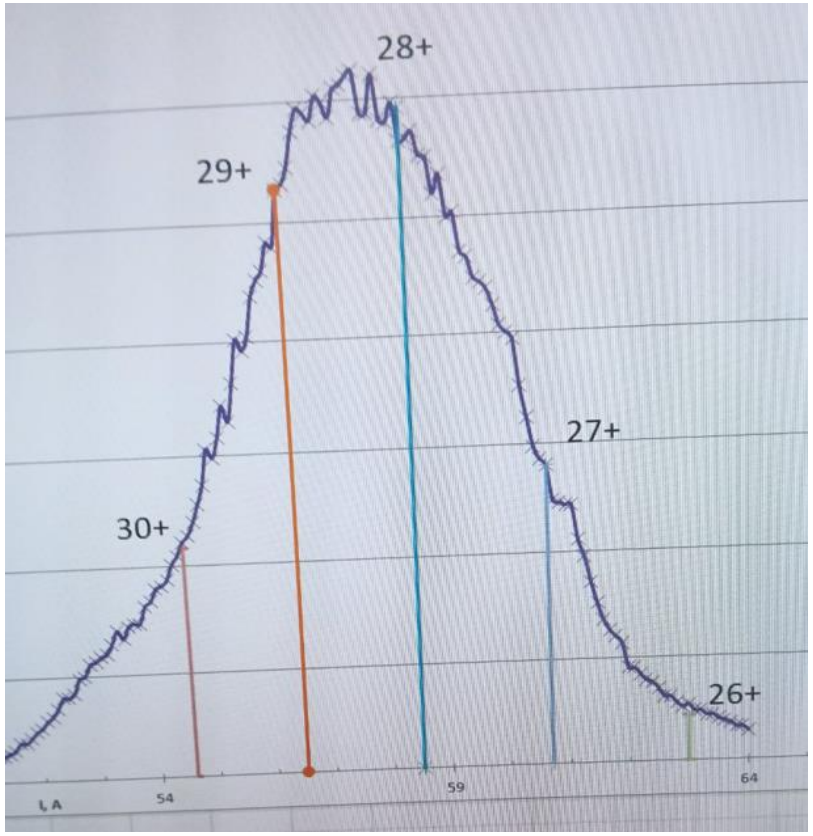
-High energy beam transport channel (HILAC – BOOSTER)





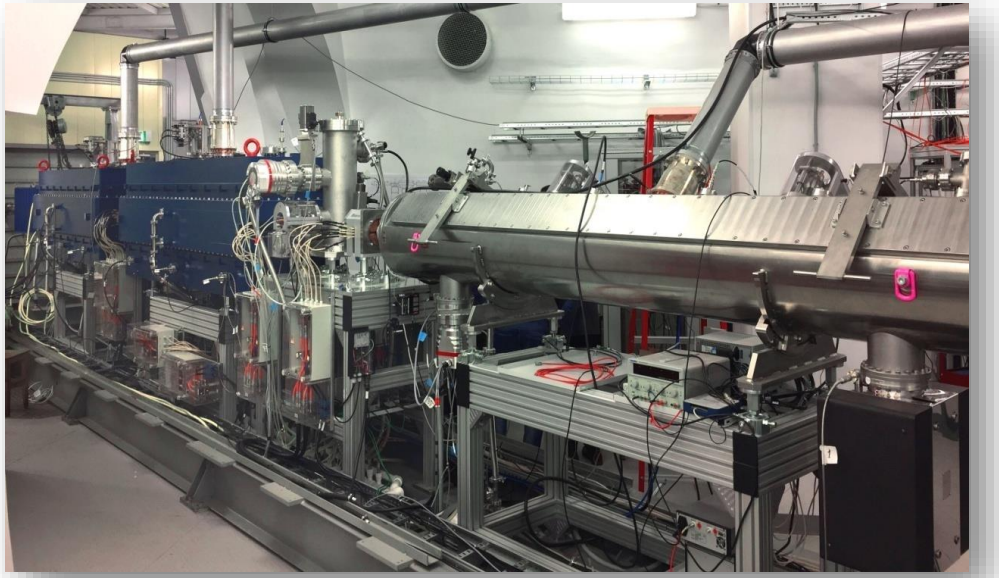
Ion Source Main Parameters for the Run 4

Source type	Electron string (ESIS)
Ion type	$^{124}Xe28+$
Magnetic field in the trap	5T
Magnetic field at the cathode	0.25 T
Effective cathode voltage	6 kV
Cathode diameter	1.2 mm
Electron beam current	4-6 mA
Ion trap length	70 cm
Total ion charge	2.3 nC
Number of target ions at source exit	10^8



<u>Ion composition at the linac end:</u>
Ionization time – 18 ms;
Target charge 28+ ~20-25%
(% is close to SBSIM calculations, 23%)

Stable and safe HILAC operation with Ar^{13+} and Xe^{28+} beams



At RFQ exit I=100 μA (yellow line). At HILAC exit I=65 μA at ion pulse duration 22 μs (red line), about 70% at this pulse of target ions $^{124}Xe^{28+}$.

Number of ions accelerated in HILAC at energy 3,2 MeV/n is about 1×10^{8}.

Project HILAC intensity $^{209}Bi^{35+}$ at energy 3,2 MeV/n is about 1.8×10^{9} per pulse.

Realization of multi cycle injection and upgrade of KRION-6T

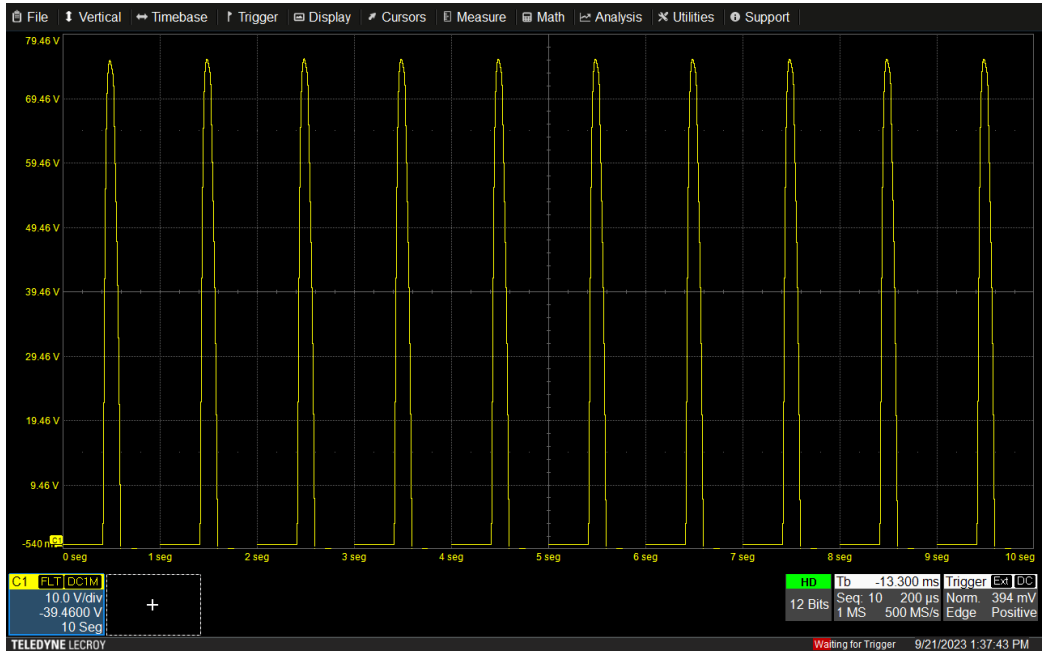
HILAC status

Preparation for multi-injection.

Includes system check-ups:

- power supply for platforms with pulse injection voltage
- Solenoid focusing
- Quadrupole focusing
- RF power supply
- System of synchronisation

Injection voltage pulses, 75 kV



Voltage pulses (top) and injection current (bottom) in quadrupole doublets for A/Z= 6.25

HILAC STATUS

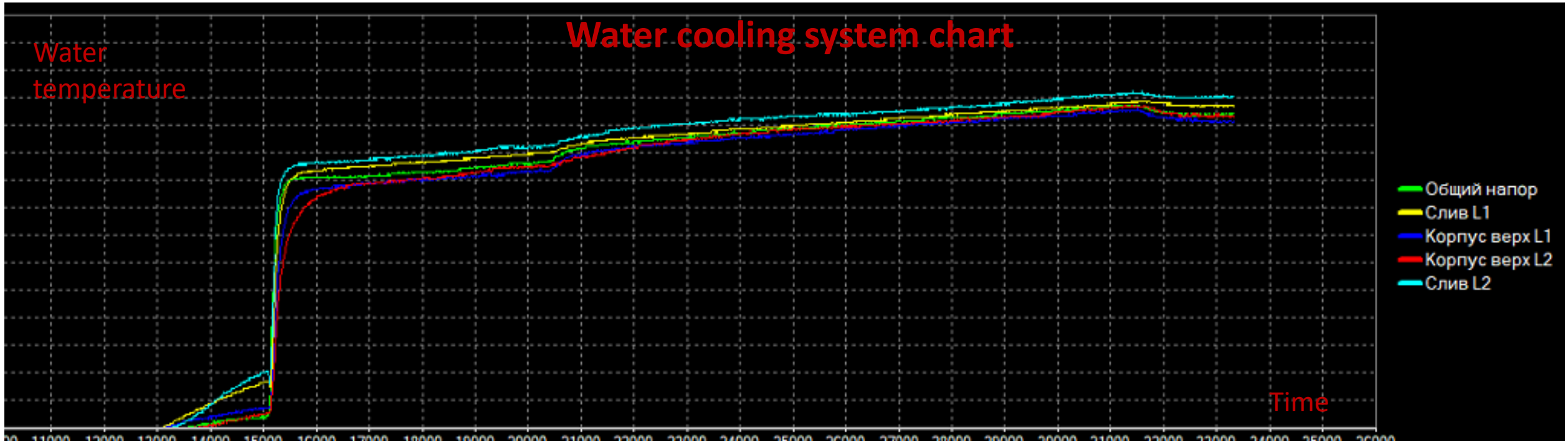
Preparation for multi-injection cycle

RF system

Pickup signals from RFQ, IH1, IH2, Buncher

Signals obtained by ion hits on the Faraday Cup at HILAC output (FC-3, red) and phase probes(green and blue).

Water cooling system chart

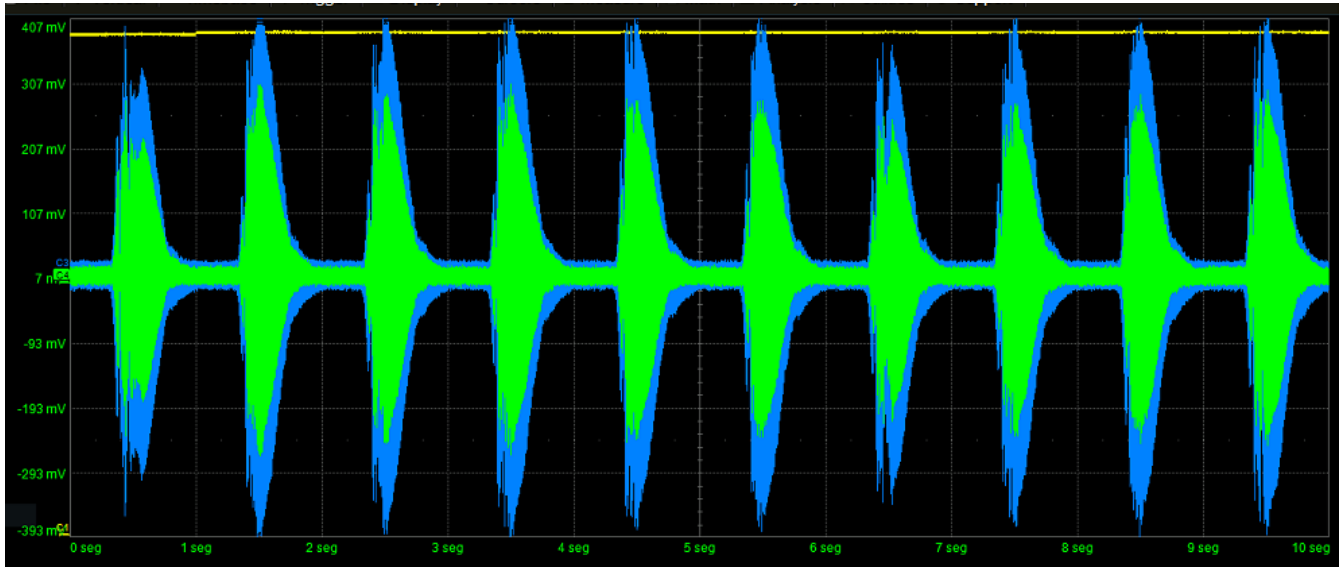


Termometr 1-Wire

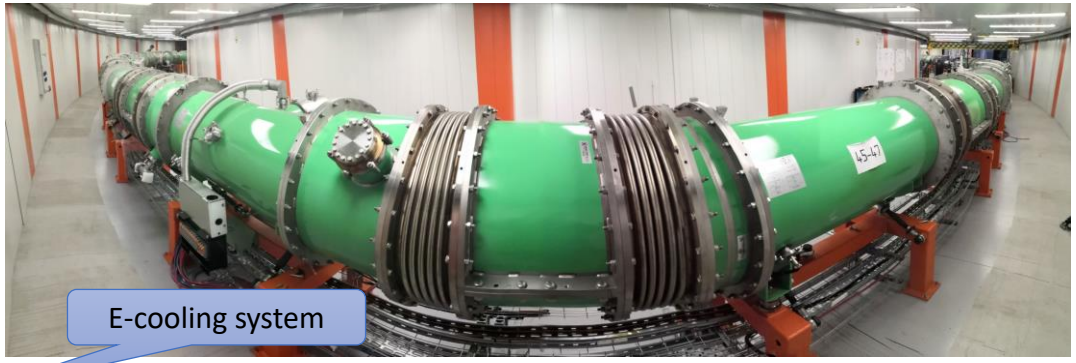
Tx = 105144: Err = 0: ID = 1: F = 04: SR = 10000ms

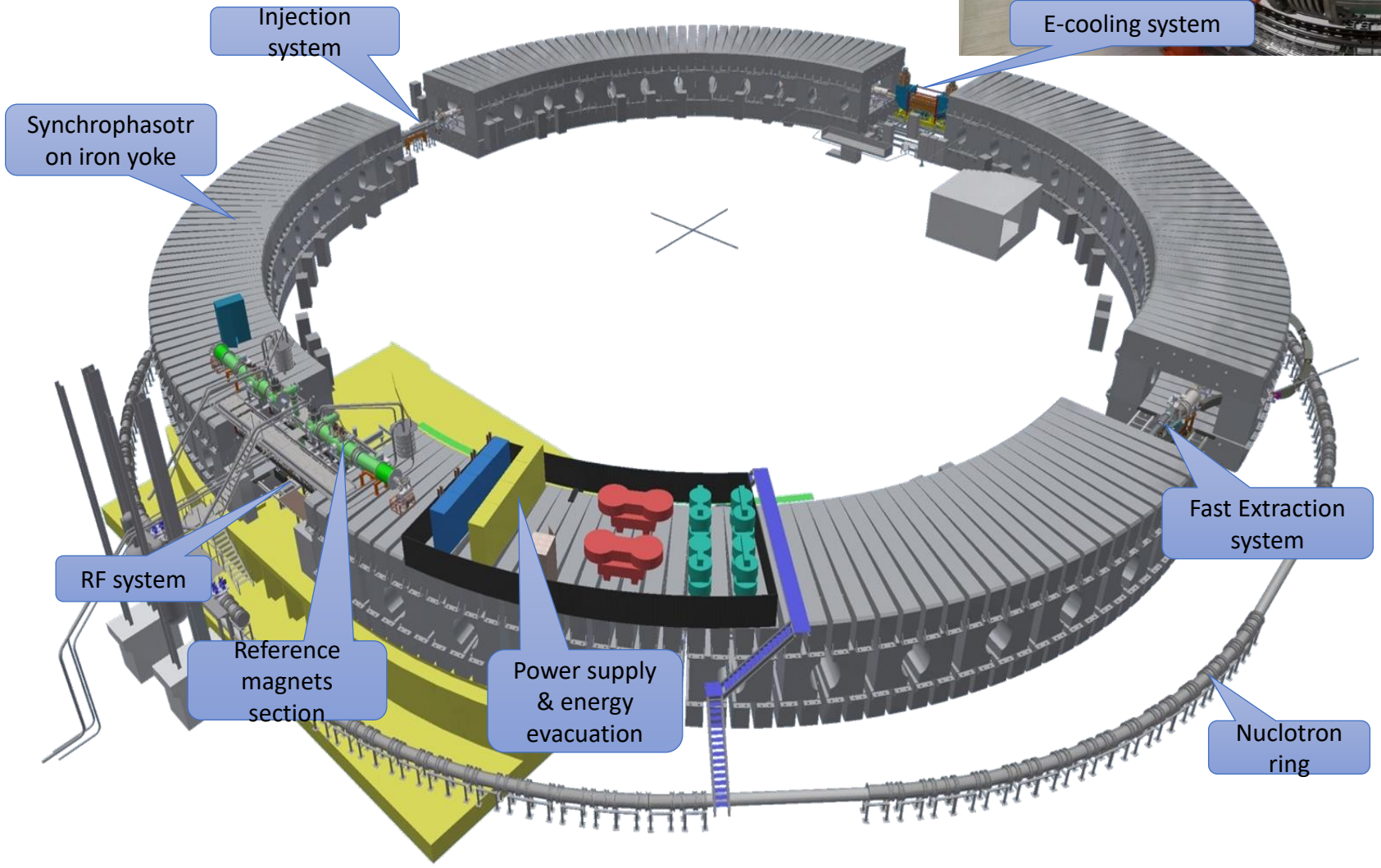
	Name	00010
0	1 - Общий напор	31,44
1	2 - Слив L1	31,75
2	3 - Корпус верх L1	31,13
3	4 - Корпус верх L2	31,38
4	5 - Слив L2	32,06
5	Статус	0
6		
7		
8		
9		

Beam signal from phase probe (10x injection)

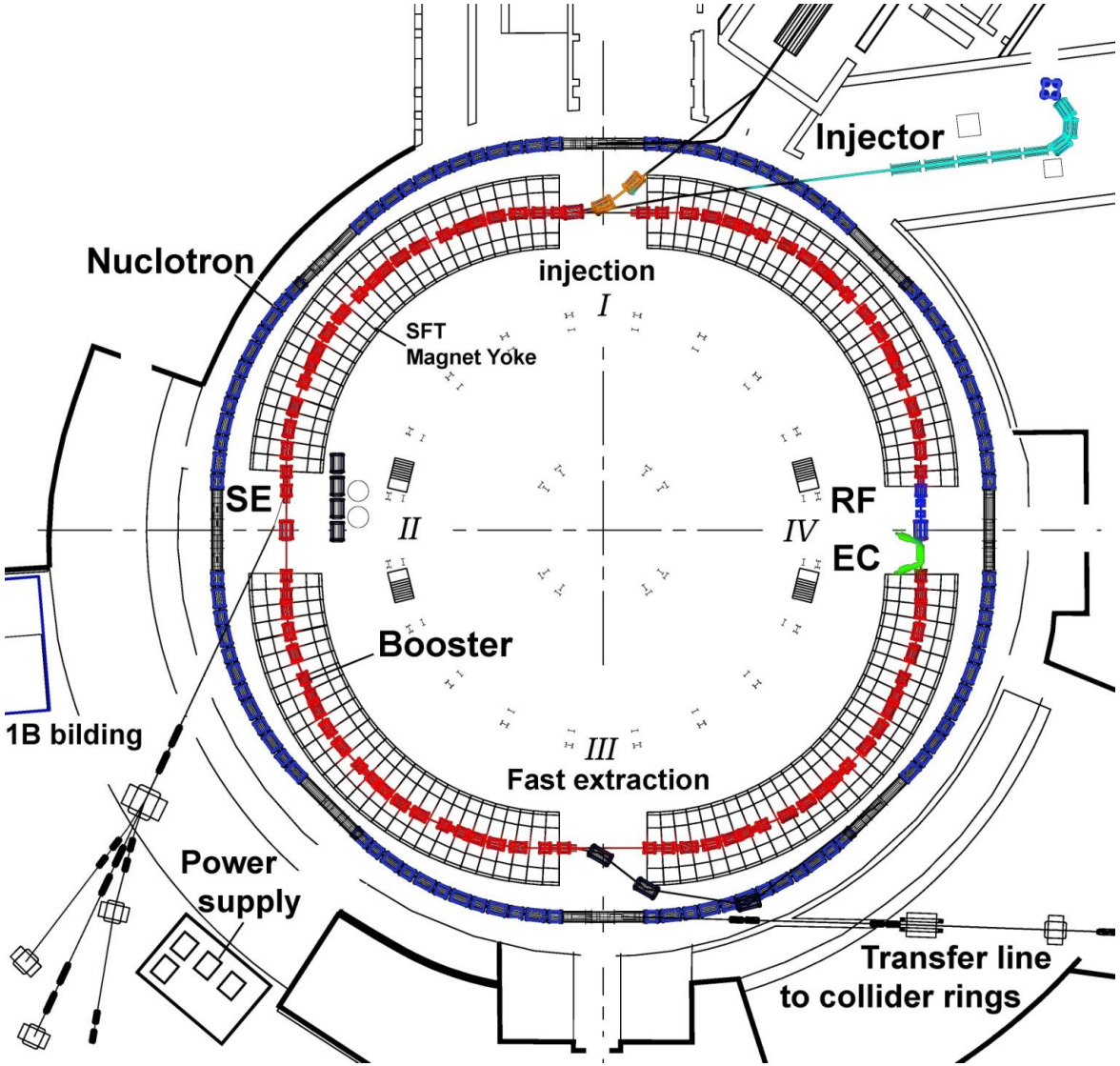


Booster ring layout



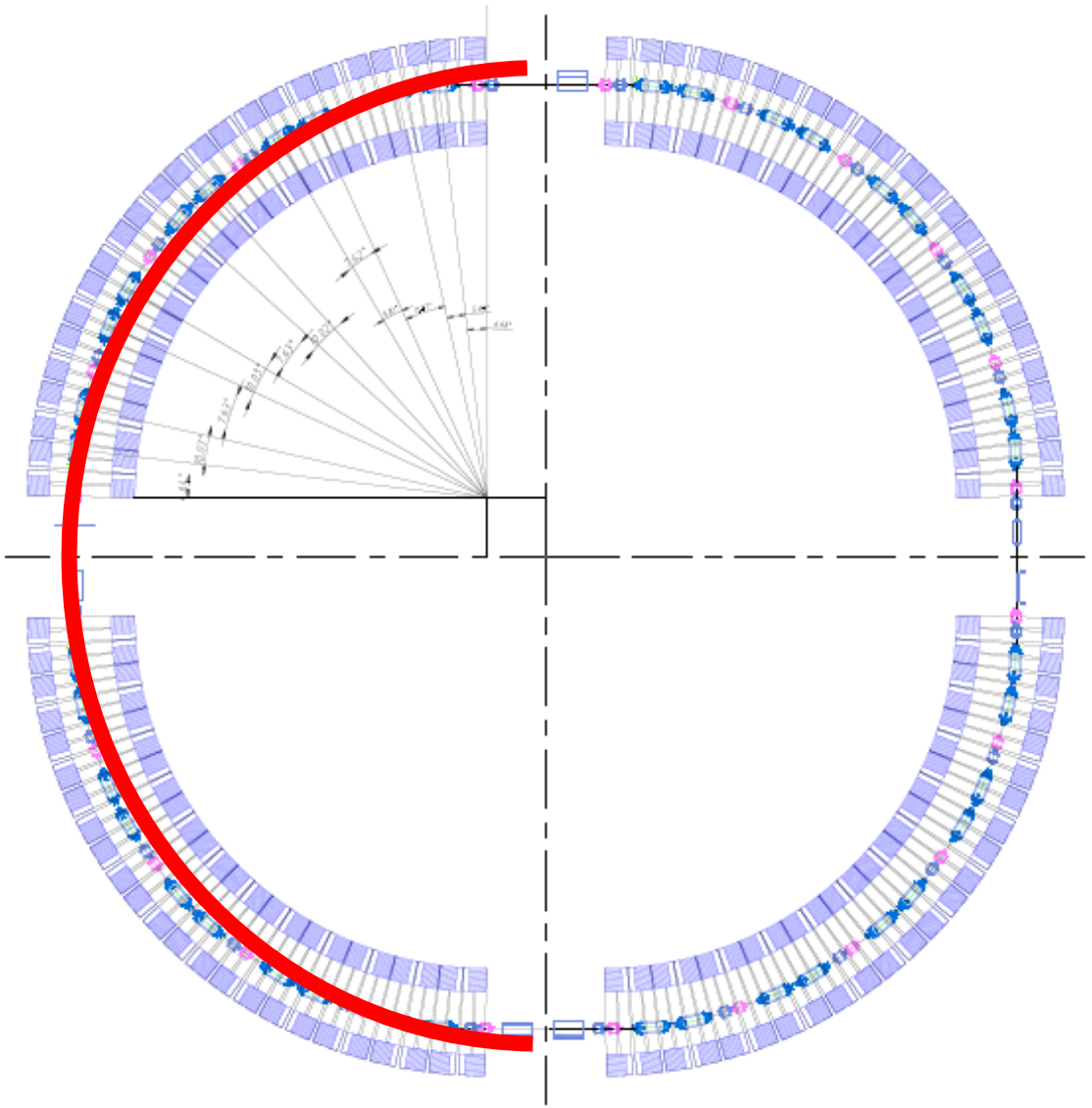


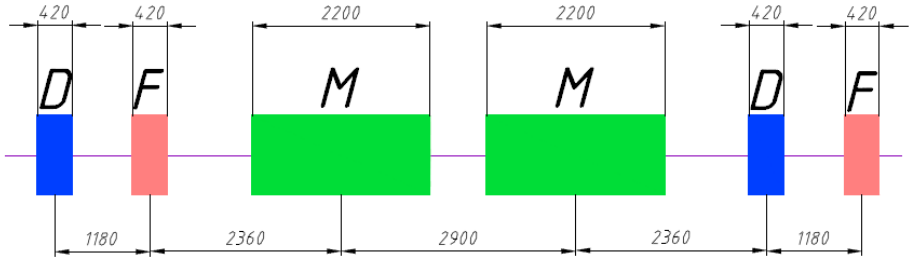
NICA Booster



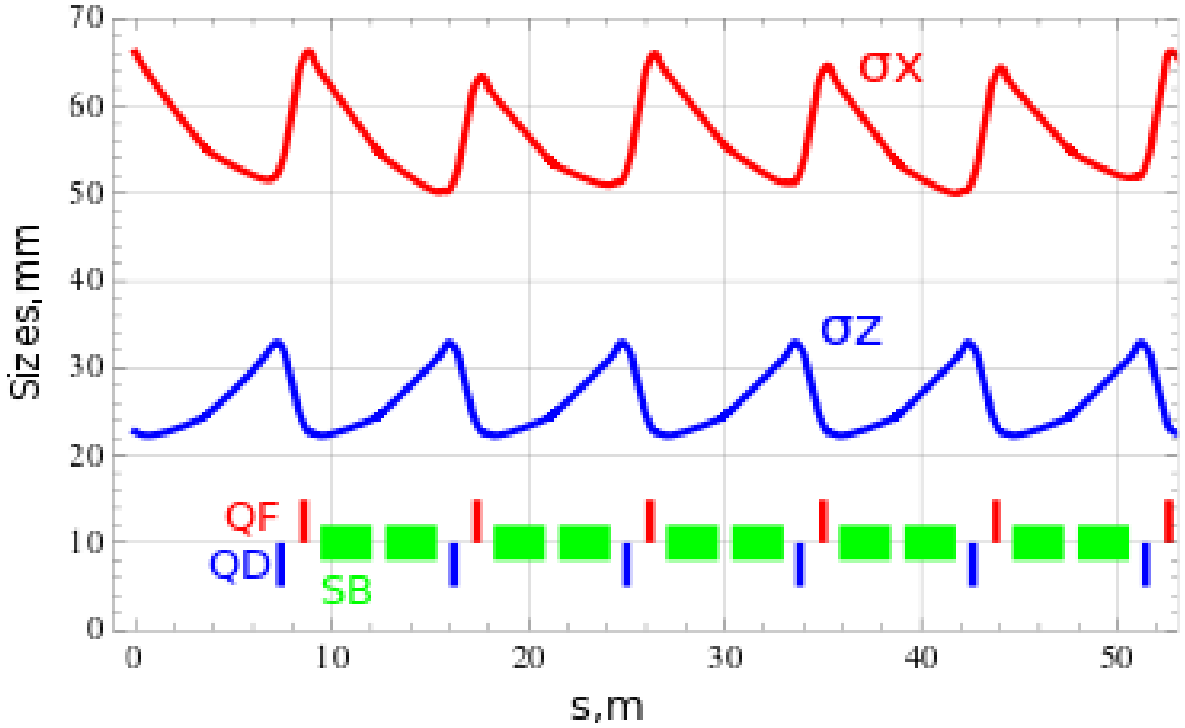
	Booster
Magnetic rigidity, T/m	25
Radius, meters	211
Beam intensity, particles per pulse	2-6x10^9
Max. energy	600 MeV/u

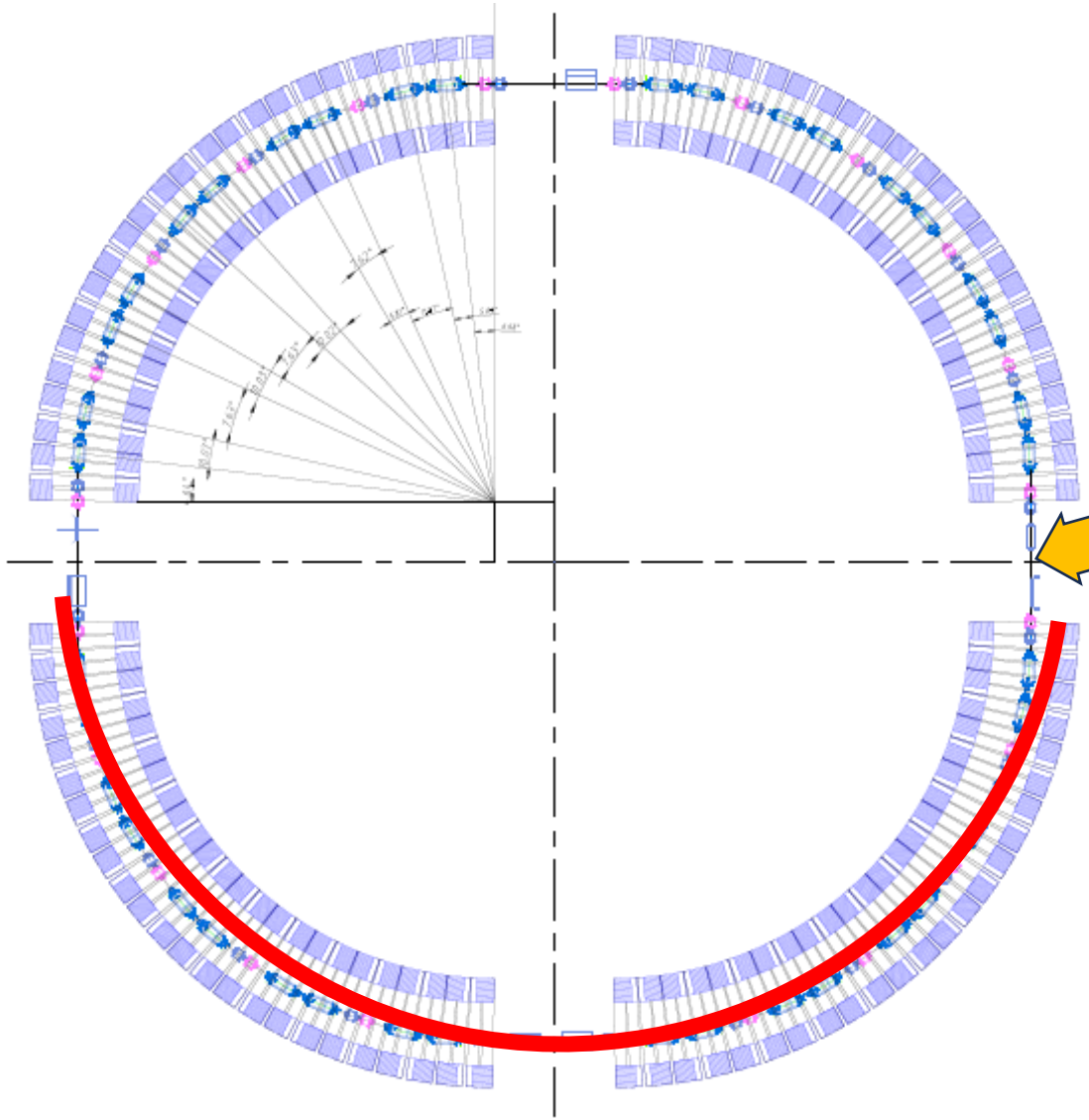
Dipoles	
Number of dipoles	40
Maximum magnetic field, T	1.8
Effective field length, m	2.2
Bending angle, deg	9.0
Curvature radius, m	14.09
Vacuum chamber, mm^2	128x64
Quadrupoles	
Number of quadrupoles	48
Field gradient, T/m	19.7/-20.3
Effective field length, m	0.4

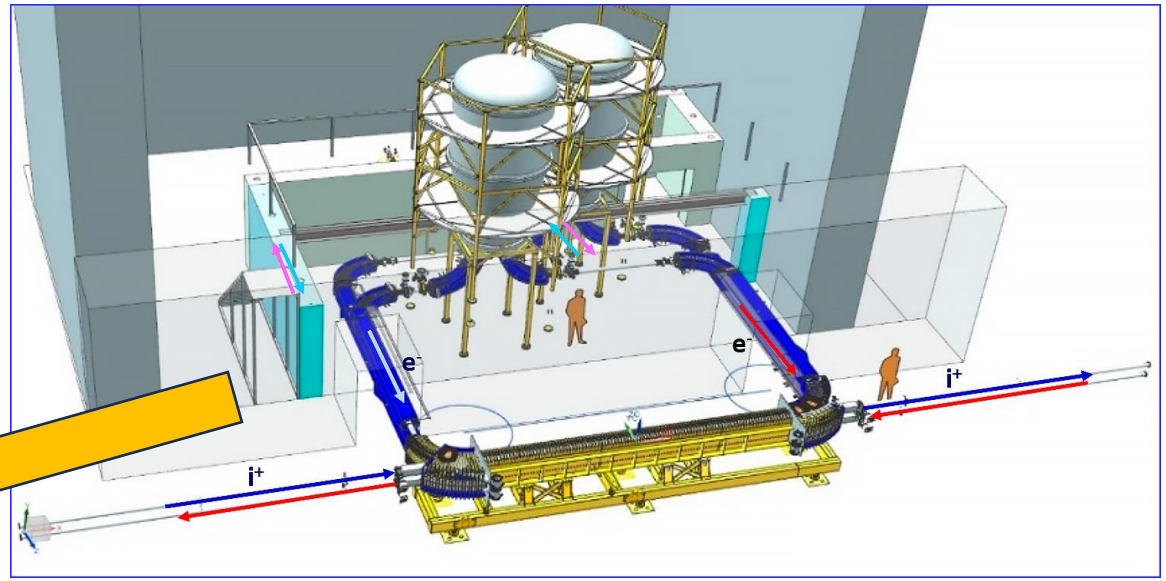


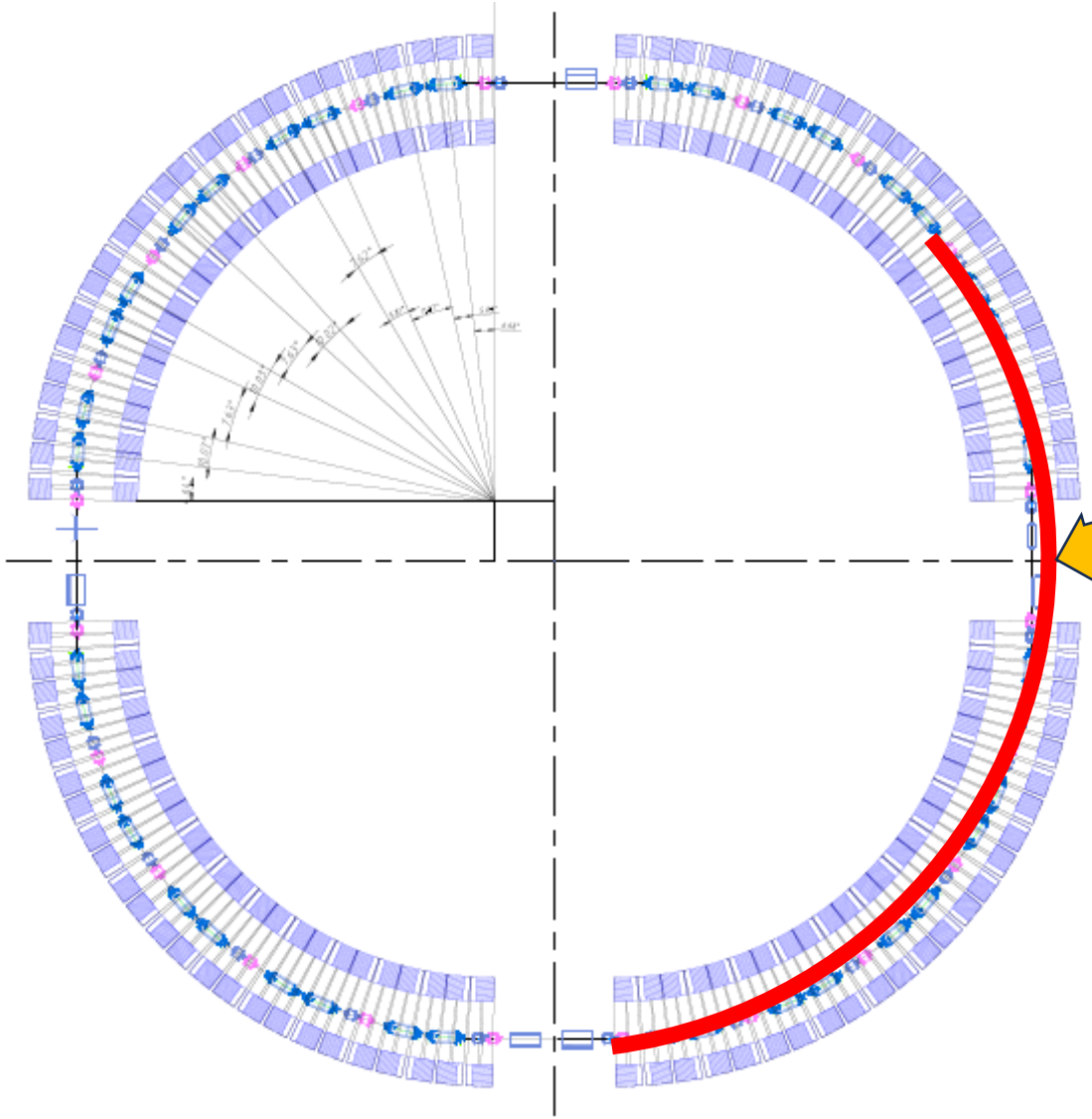

420
420
2200
2200
420
420
D
F
M
M
D
F
1180
2360
2900
2360
1180

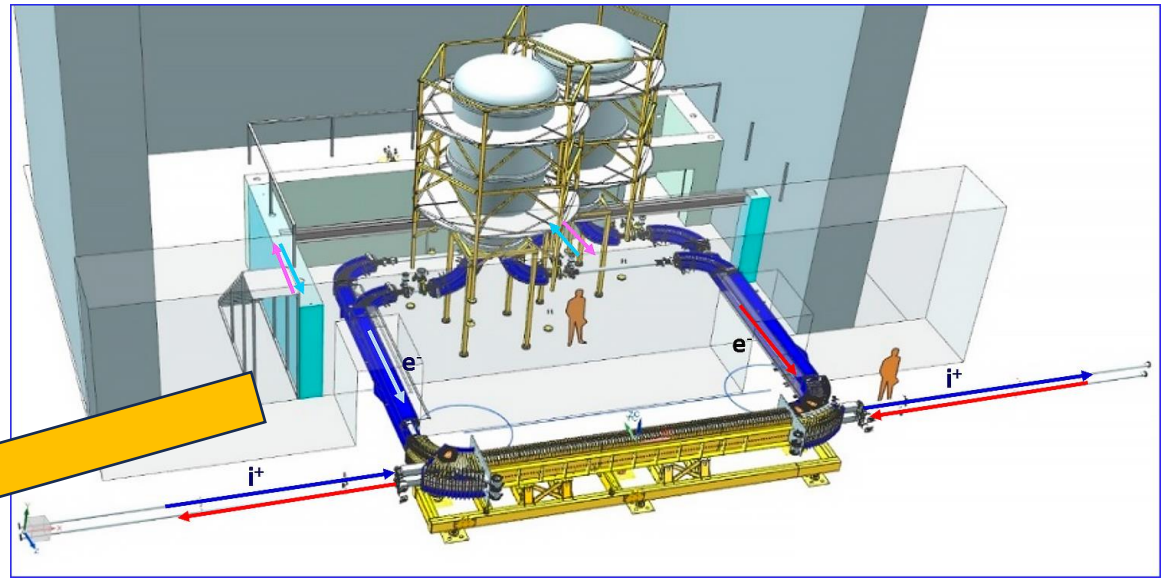

420
420
F
D

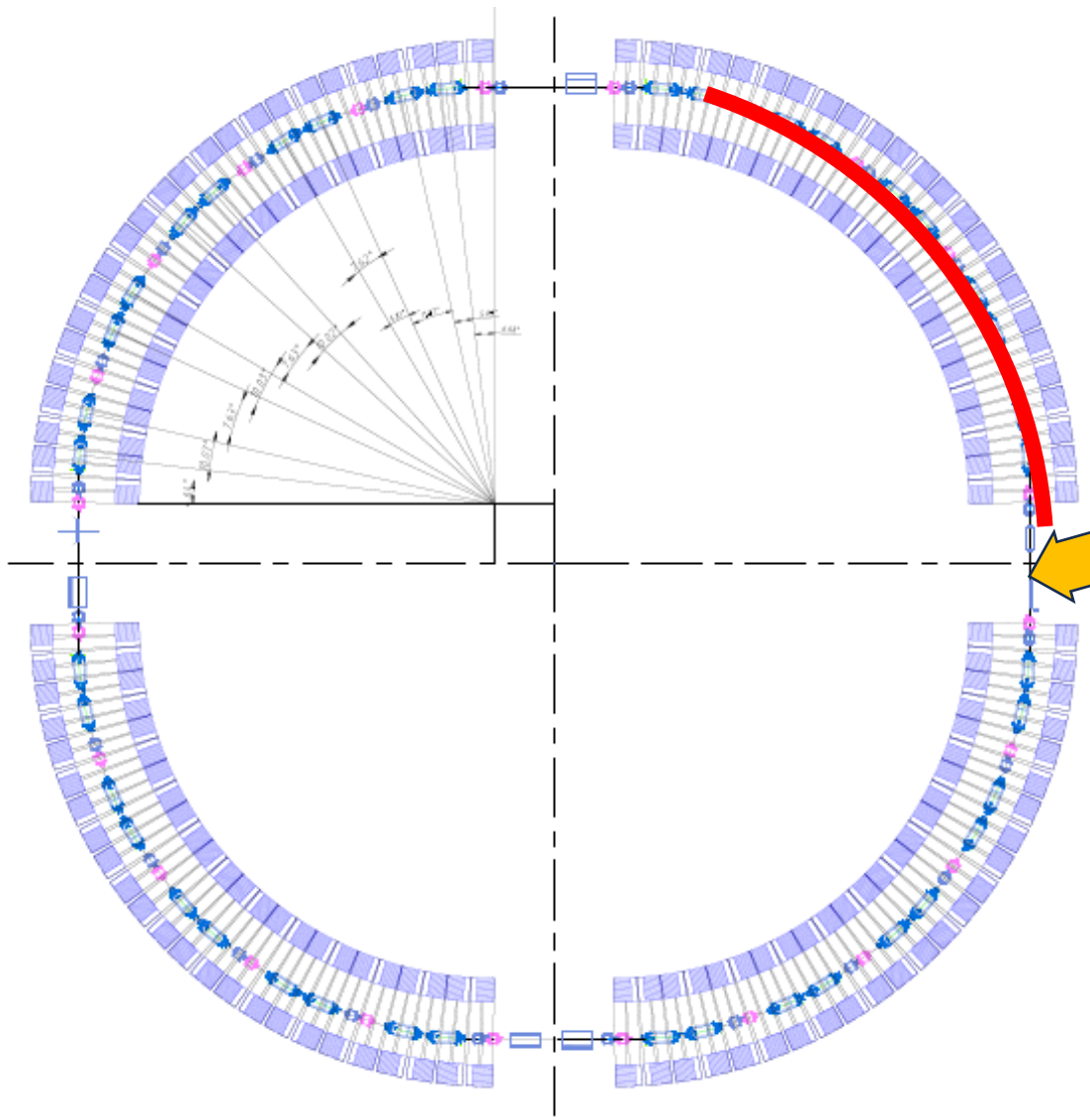

70
60
50
40
30
20
10
0
Sizes, mm
σx
σz
QF
QD
SB
0
10
20
30
40
50
s, m

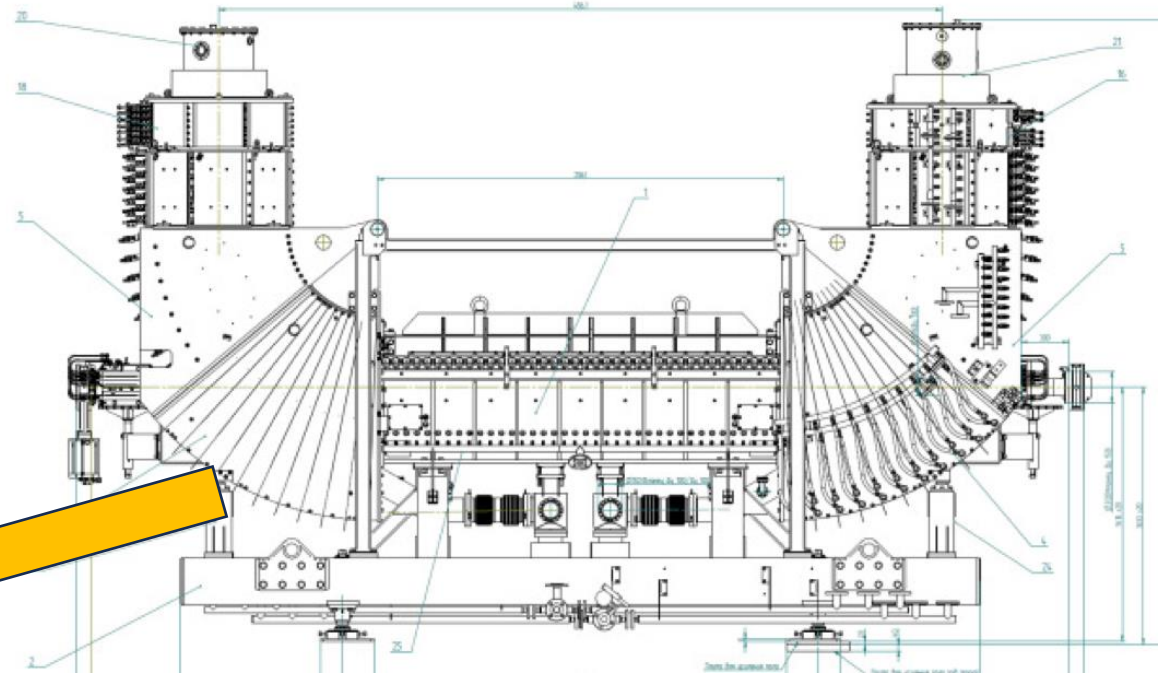


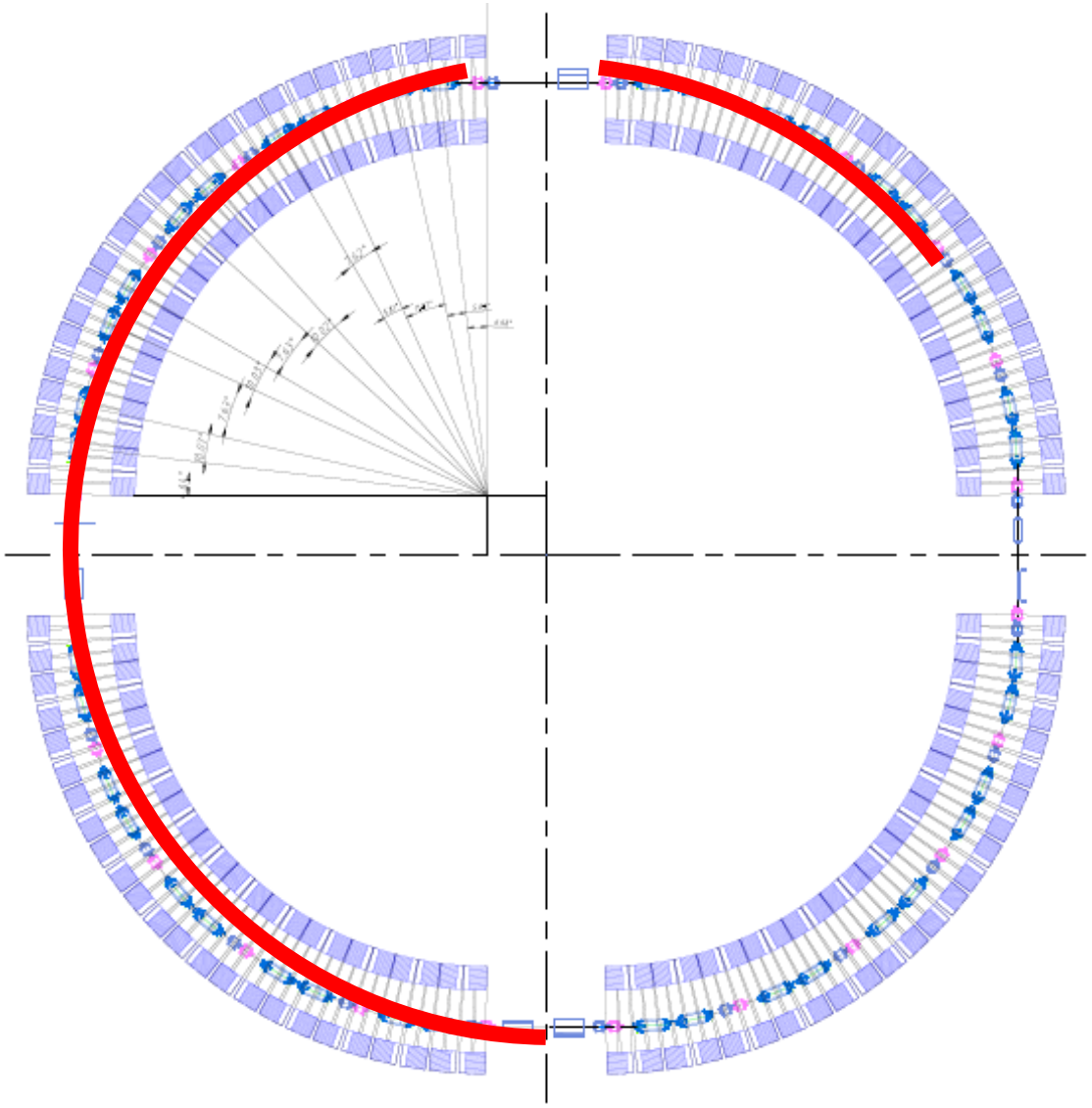

e⁻
e⁻
i⁺
i⁺



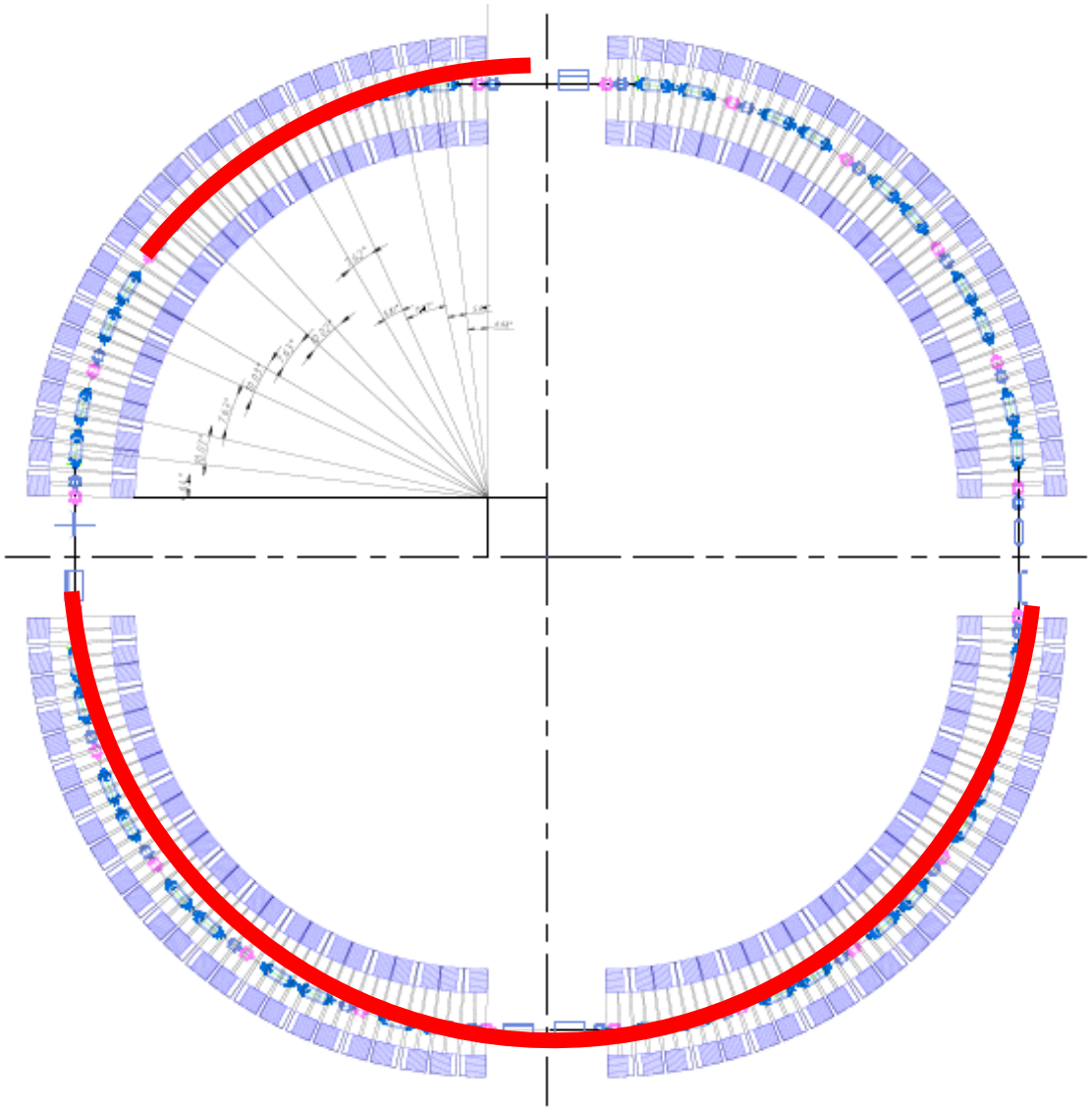

e⁻
e⁻
i⁺
i⁺



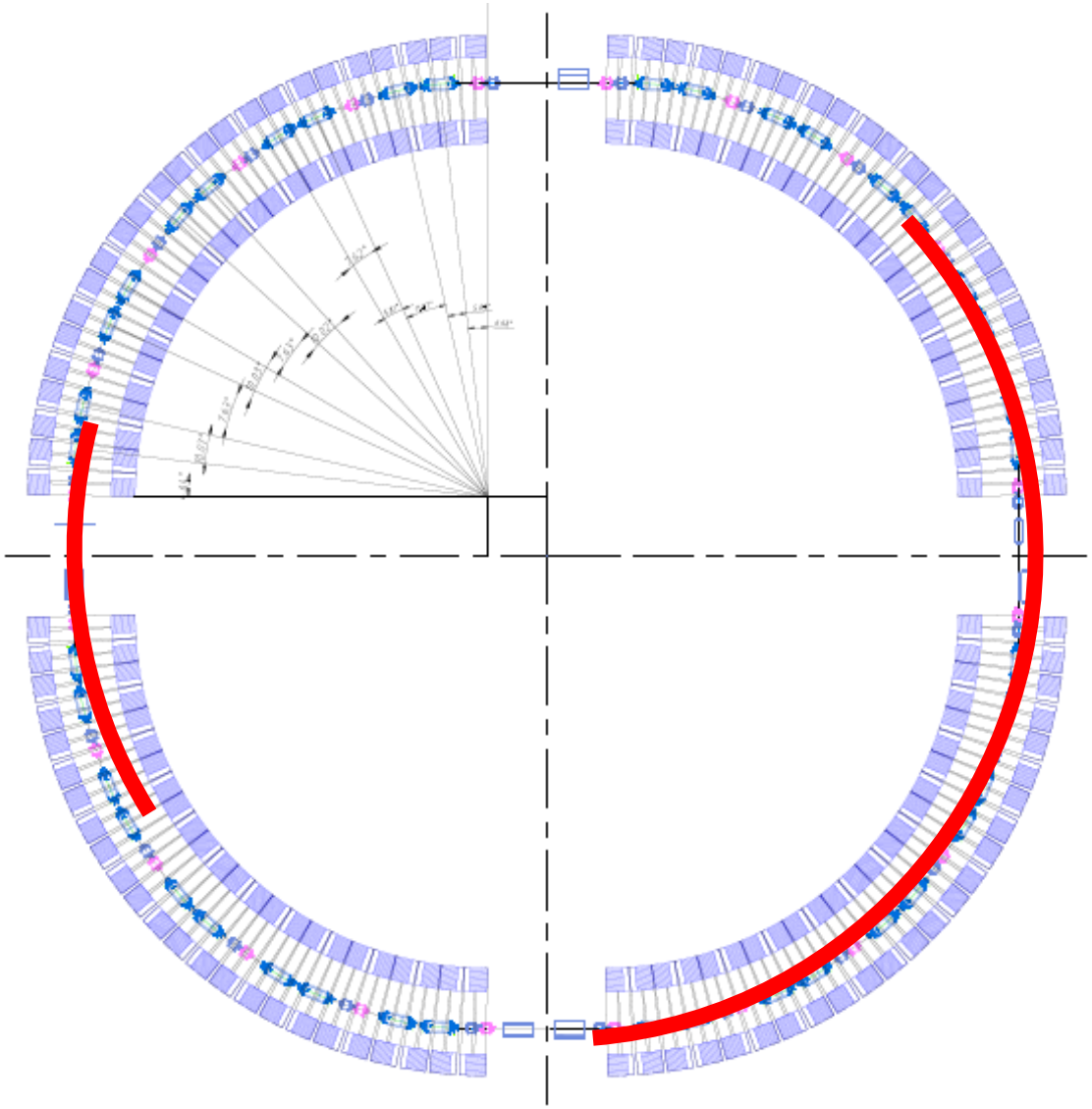




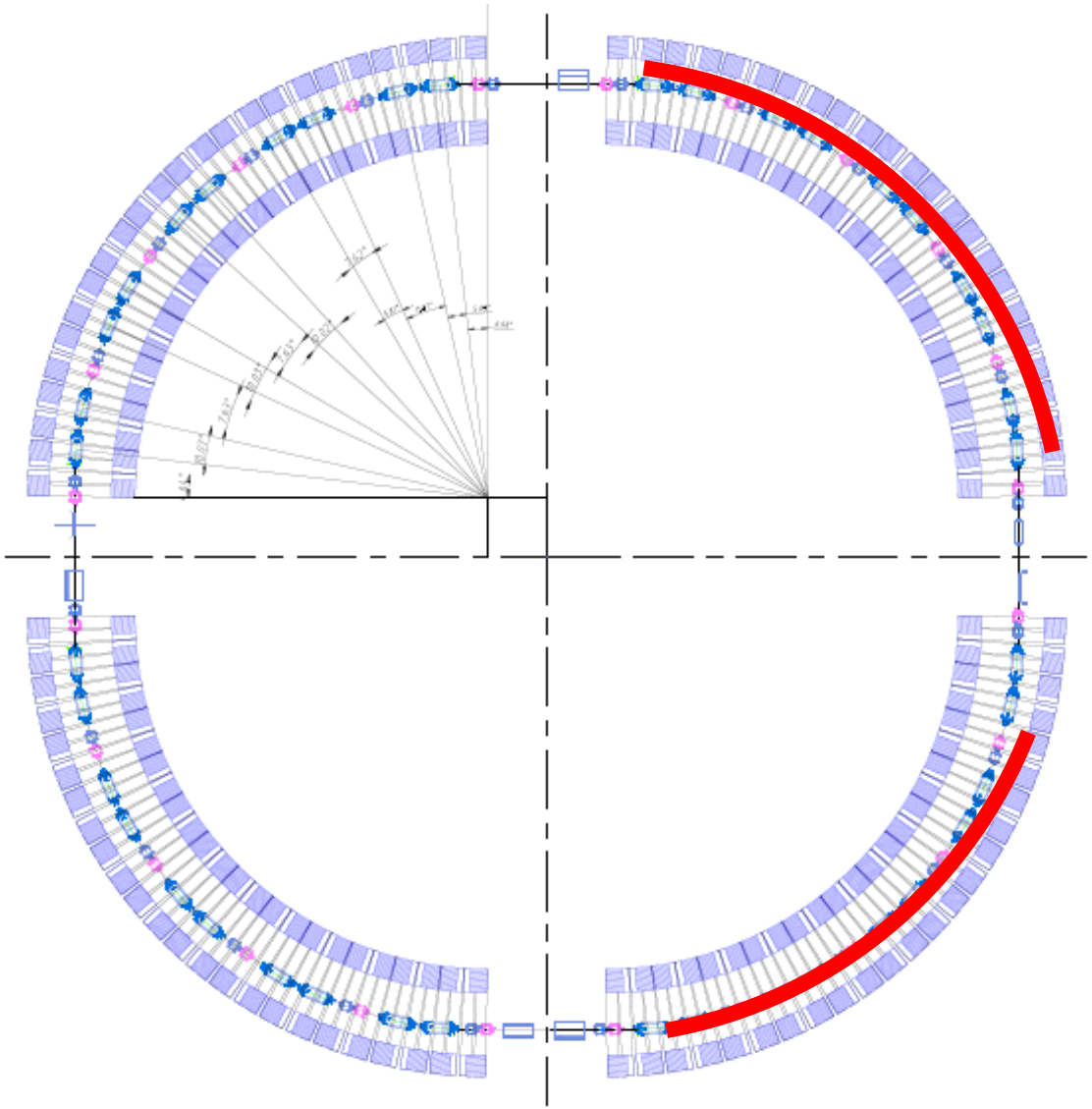
Parameter	Value
Electron energy E, keV	≤ 1
Accuracy of energy adjustment and its stability, $\Delta E/E$	$\leq 1 \cdot 10^{-5}$
Beam current stability, $\Delta I/I$	$\leq 1 \cdot 10^{-4}$
Electron beam loss current, $\delta I/I$	$\leq 3 \cdot 10^{-5}$
The strength of the ECS longitudinal magnetic field, kGs	1 – 2
Permissible inhomogeneity of the longitudinal magnetic field in the cooling area, $\Delta B/B$	$\leq 3 \cdot 10$-5 on the length 15 cm
Transverse temperature of electrons in the cooling section (in the particle system), eV	≤ 0.3
Correction of the ion orbit at the input and output of ECS	offset, mm $\leq 1,0$ angular deviation, mrad $\leq 1,0$



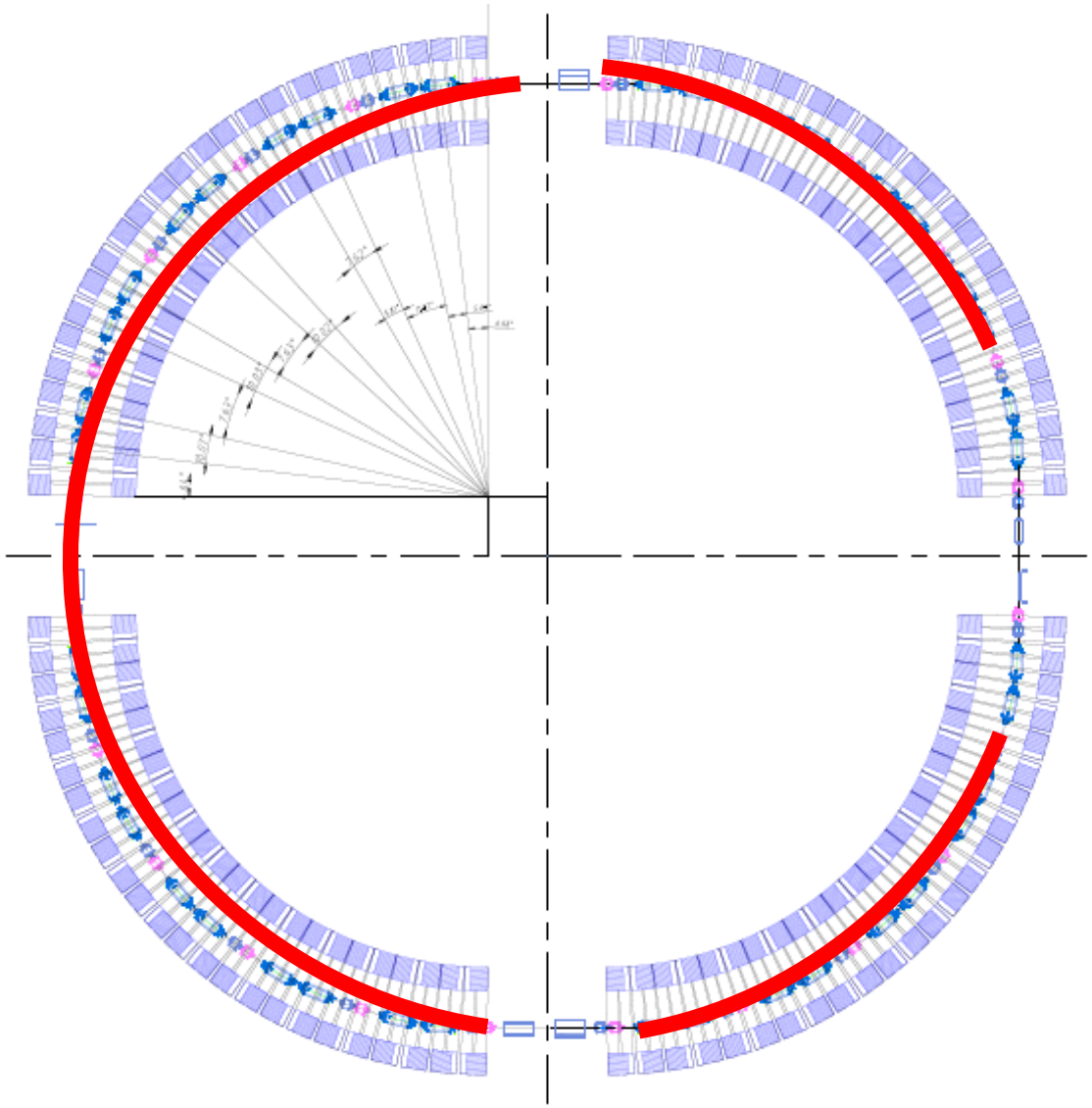
Parameter	Value
Electron energy E, keV	≤ 1
Accuracy of energy adjustment and its stability, ΔE/E	≤ $1 \cdot 10^{-5}$
Beam current stability, ΔI/I	≤ $1 \cdot 10^{-4}$
Electron beam loss current, δI/I	≤ $3 \cdot 10^{-5}$
The strength of the ECS longitudinal magnetic field, kGs	1 – 2
Permissible inhomogeneity of the longitudinal magnetic field in the cooling area, ΔB/B	≤ 3·10-5 on the length 15 cm
Transverse temperature of electrons in the cooling section (in the particle system), eV	≤ 0.3
Correction of the ion orbit at the input and output of ECS	offset, mm ≤ 1,0 angular deviation, mrad ≤ 1,0

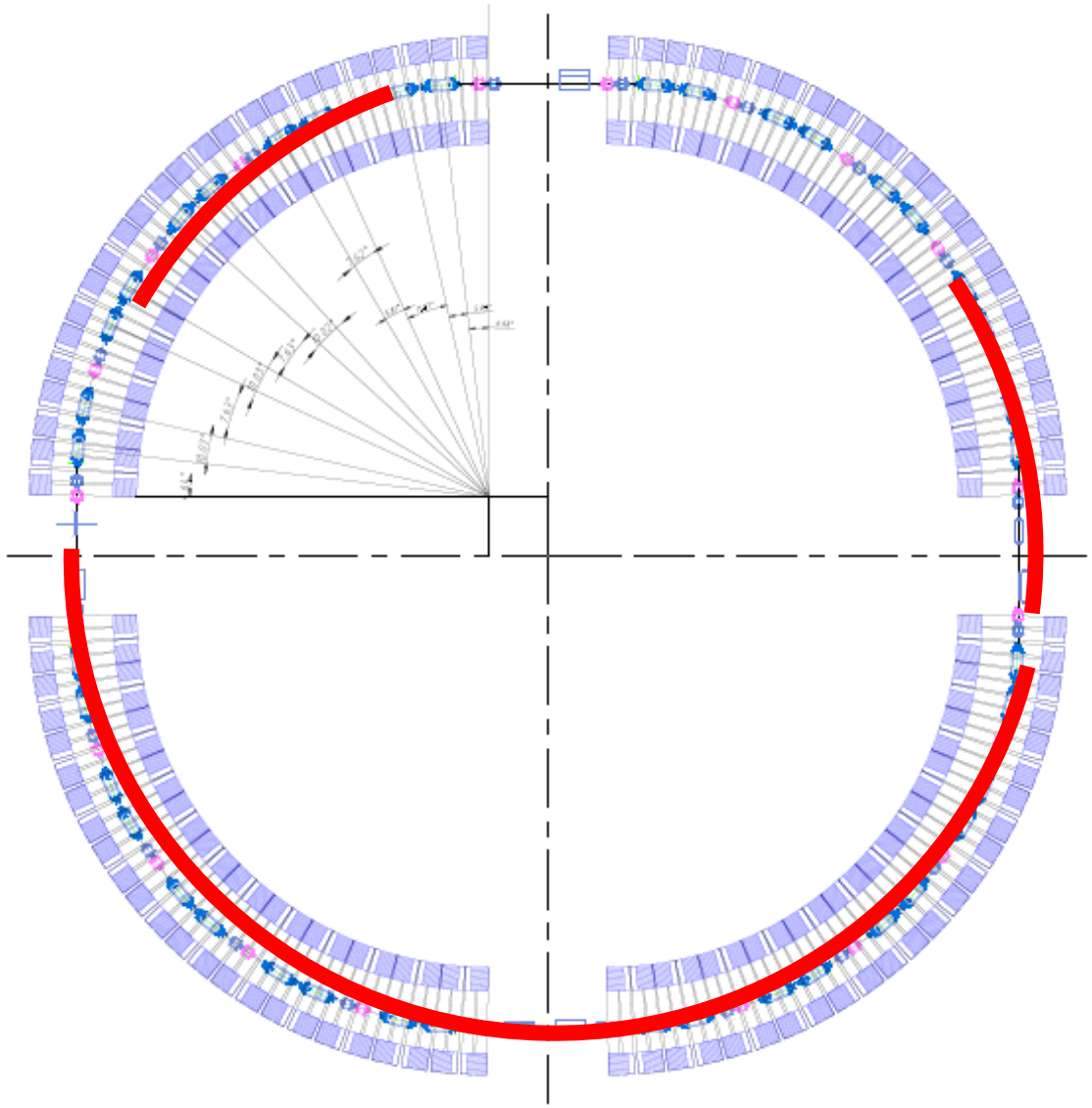


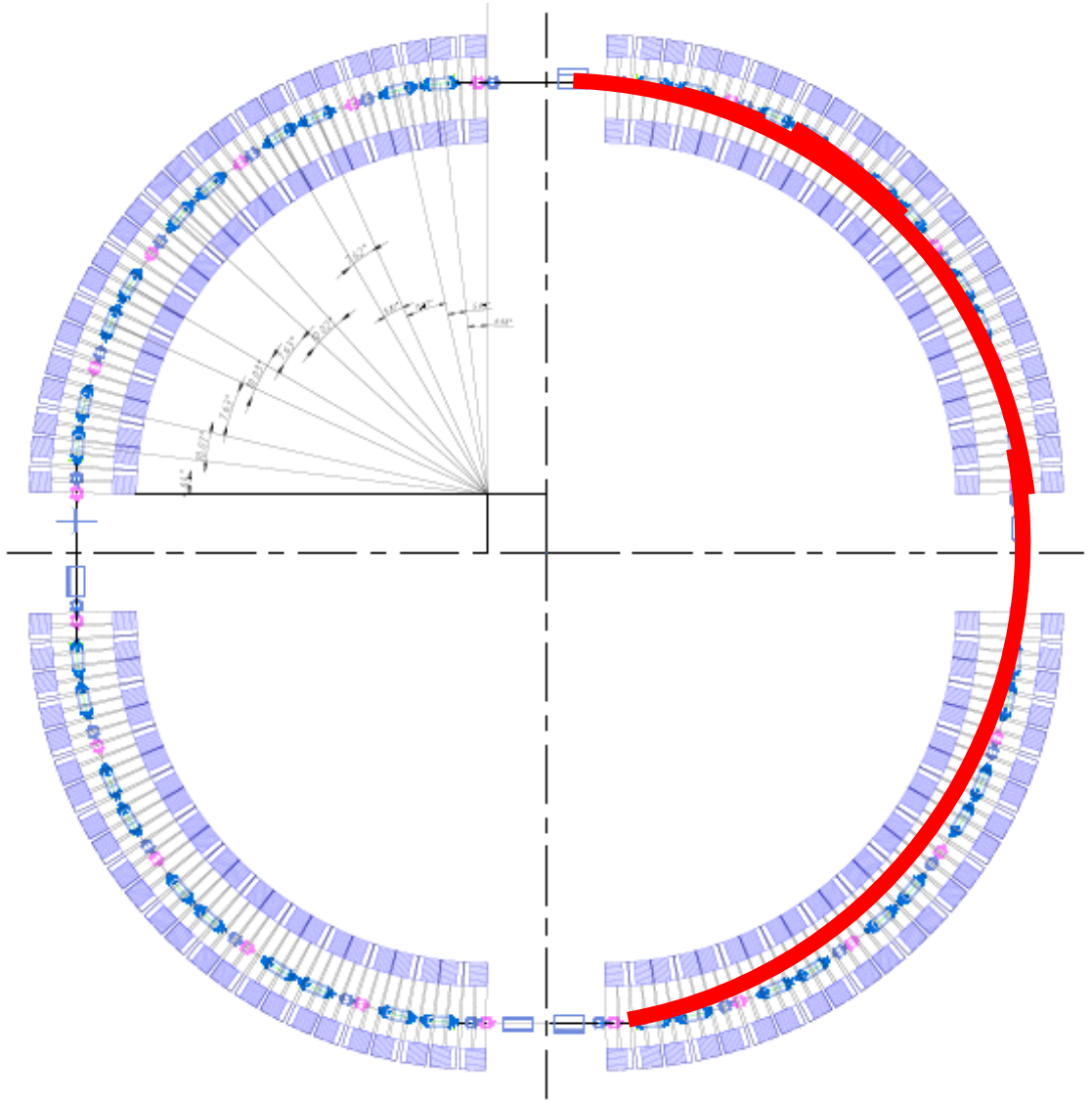
Parameter	Value
Electron energy E, keV	≤ 1
Accuracy of energy adjustment and its stability, $\Delta E/E$	$\leq 1 \cdot 10^{-5}$
Beam current stability, $\Delta I/I$	$\leq 1 \cdot 10^{-4}$
Electron beam loss current, $\delta I/I$	$\leq 3 \cdot 10^{-5}$
The strength of the ECS longitudinal magnetic field, kGs	1 – 2
Permissible inhomogeneity of the longitudinal magnetic field in the cooling area, $\Delta B/B$	$\leq 3 \cdot 10$-5 on the length 15 cm
Transverse temperature of electrons in the cooling section (in the particle system), eV	≤ 0.3
Correction of the ion orbit at the input and output of ECS	offset, mm $\leq 1,0$ angular deviation, mrad $\leq 1,0$

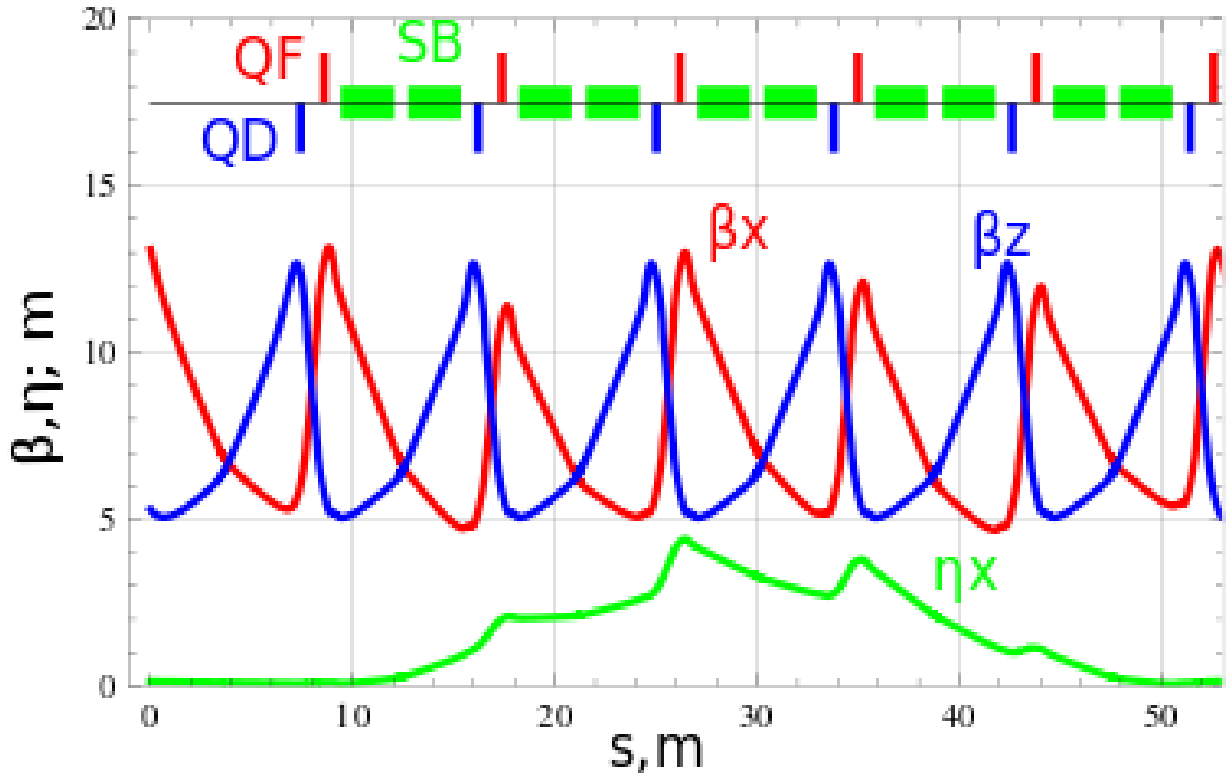


Parameter	Value
Electron energy E, keV	≤ 1
Accuracy of energy adjustment and its stability, ΔE/E	≤ $1 \cdot 10^{-5}$
Beam current stability, ΔI/I	≤ $1 \cdot 10^{-4}$
Electron beam loss current, δI/I	≤ $3 \cdot 10^{-5}$
The strength of the ECS longitudinal magnetic field, kGs	1 – 2
Permissible inhomogeneity of the longitudinal magnetic field in the cooling area, ΔB/B	≤ 3·10-5 on the length 15 cm
Transverse temperature of electrons in the cooling section (in the particle system), eV	≤ 0.3
Correction of the ion orbit at the input and output of ECS	offset, mm ≤ 1,0 angular deviation, mrad ≤ 1,0

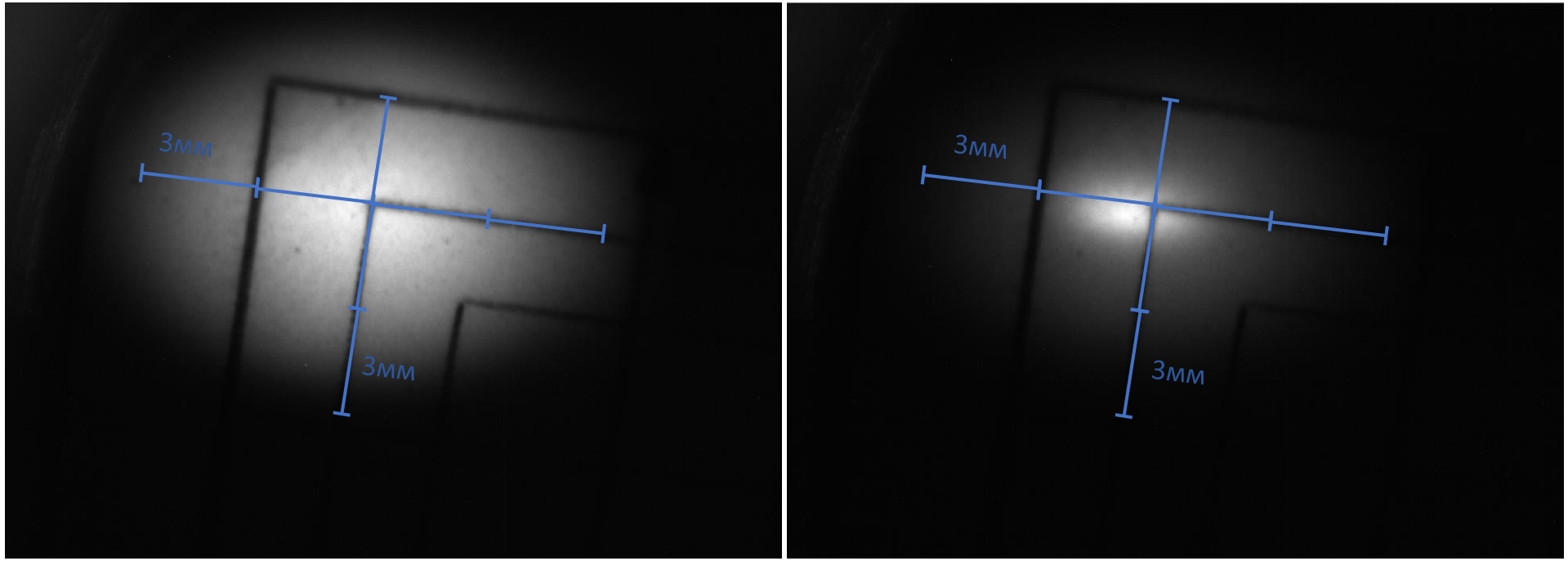







QF
SB
QD
βx
βz
ηx
β,η; m
s,m
0
5
10
15
20
0
10
20
30
40
50

Cooling of the $^{124}Xe28+$ ion beam by electron beam with 50mA current at the energy of 1,830 keV

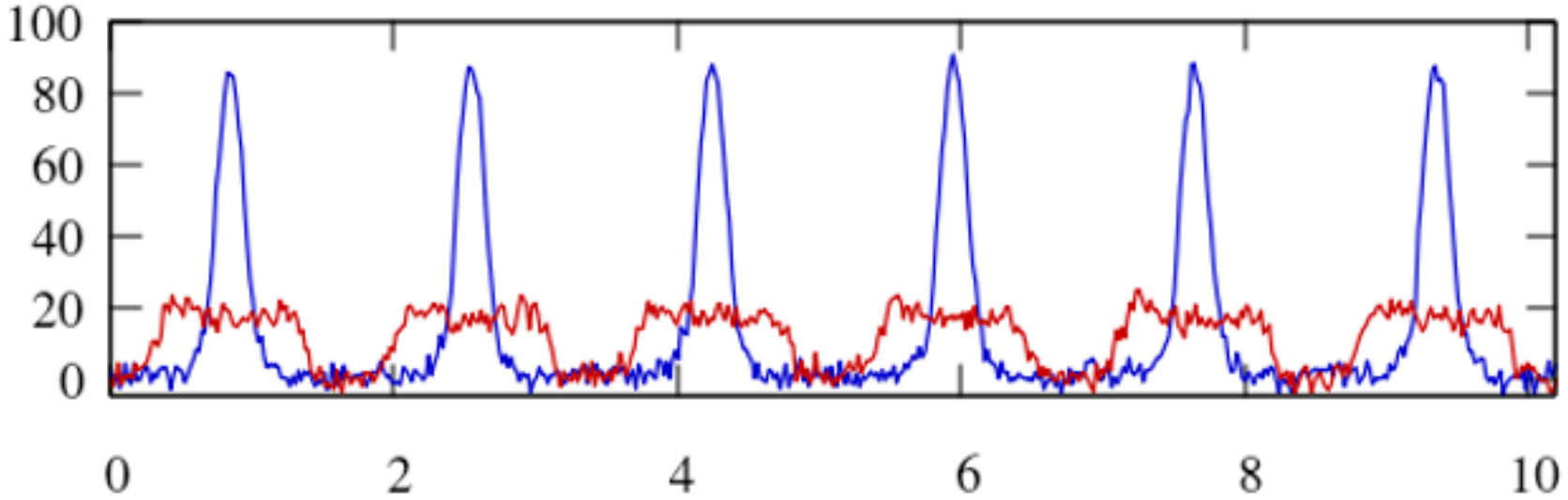


The uncooled and cooled ion beams.

При работе с пучком ионов, охлаждённых и ускоренных в Бустере, полностью «ободранных» на выходе из Бустера, доускоренных в Нуклотроне и выведенных на детектор BM@N, его *скорость счёта возросла в два раза*.

Electron Cooling in Booster

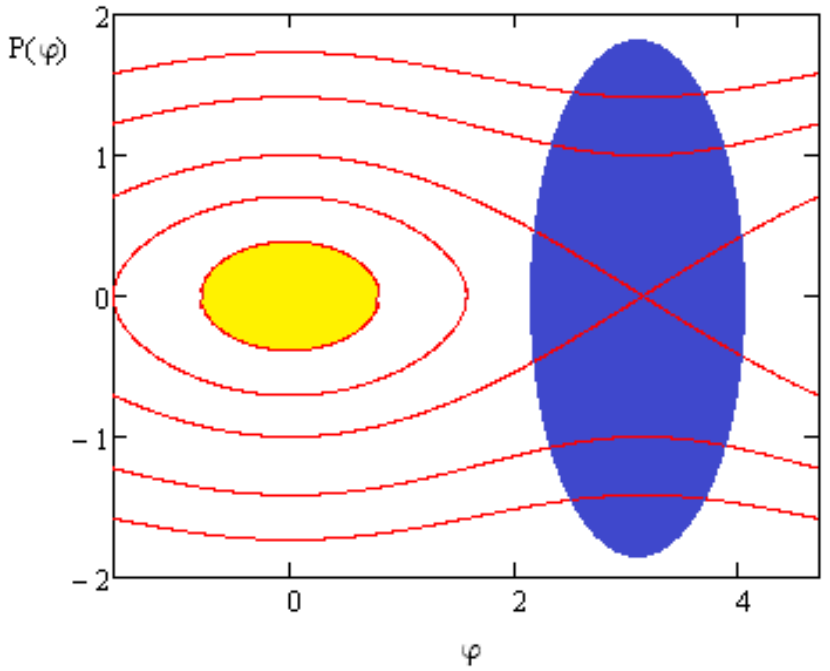
- Electron cooling was demonstrated with the RF voltage present as it is required for beam accumulation
- Measurements support the accumulation rate of about 10 Hz



Beam current dependence on time with and without electron cooling. Rf harmonic number – 5. Cooling cycle duration - 200 ms. Electron beam current 50 mA. Electron beam voltage 1.83 keV

Beam Accumulation at electron cooling

- Beam accumulation happens in the longitudinal plane at Booster injection
  - 4 μs bunch – 8 μs revolution time
- Each new injection happens after the previous one is cooled to the core
  - Expected injection rate – 10 Hz
  - 10 – 15 injections will require
  - Total cycle duration ~5 s
- The permanently present 1st RF harmonic weakly affects large amplitude particles
- For small amplitude particles the cooling force will be intentionally reduced to avoid overcooling



- To avoid anticoolig we need to match well the injection magnetic field and e-beam energy
  - It happens since for large $\Delta p/p$, dF/dt changes sign after reaching the peak

An increase of ion accumulation intensity by a factor of 5 is planned. However application of electron cooling is restricted by ion bunch space charge effects at a level of $\cdot 10^9$ ions of Bi^{35+}

CONCLUSION

The HILAC is modified for multi-injection and successfully tested (Summer 2024)

New power supplies for solenoids are developed, installed and proved their reliability under a long-duration operation,

New water-cooling system for lenses is ready and tested

The beam transportation channel is capable to transfer the beam of increased intensity to the Booster (Summer 2024)

The Booster Run with multi-injection is scheduled for the Winter 2024-2025

Thank you for attention!

Список научных работ

(данные на 16.12.2024)

Публикации в рецензируемых журналах (зарубежные):

1. The New Light-Ion Linac for the NICA Collider
Alexander M. Bazanov, Andrey V. Butenko, Boris V. Golovenskiy, Denis E. Donets, Valeriy V. Kobets, Alexander D. Kovalenko, Alexander I. Govorov, Konstantin A. Levterov, Dmitriy A. и др., AIP Conference Proceedings, ISSN:0094-243X, eISSN:1551-7616, Изд:American Institute of Physics, 2019

2. Laser Ion source in injection facility of NICA project
A M Bazanov, A V Butenko, A I Govorov, B V Golovenskiy1, H Holtermann, D E Donets, V V Kobets, A D Kovalenko, B Koubek, K A Levterov, D A Liakin, D A Luyosev, A A Martynov, V V Mia и др., Physica Scripta, ISSN:0031-8949, eISSN:1402–4896, Изд:Royal Swedish Academy of Sciences IOP Publishing Limited, 95, 5, 2020

3. Laser ion source in injection facility of NICA project
A M Bazanov, A V Butenko, A I Govorov, B V Golovenskiy, H Holtermann, D E Donets, V V Kobets, A D Kovalenko, B Koubek, K A Levterov, D A Liakin, D A Luyosev, A A Martynov, V V Mial и др., Physica Scripta, ISSN:0031-8949, eISSN:1402–4896, Изд:Royal Swedish Academy of Sciences IOP Publishing Limited, 95, 055307, 1-7, 2020

Публикации в рецензируемых журналах (российские):

1. Research and design of a new RFQ injector for modernization of the LU-20 drift-tube linac
M. A. Gusarova, V. S. Dyubkov, S. M. Polozov, A. V. Samoshin, T. V. Kulevoy, A. A. Martynov, A. S. Plastun, V. A. Andreev, S. V. Barabin, A. V. Kozlov, V. A. Koshelev, G. N. Kropac и др., Physics of Particles and Nuclei Letters, ISSN:1547-4771, eISSN:1531-8567, Изд:MAIK Nauka/Interperiodica distributed exclusively by Springer Science+Business Media LLC., 13, 7, 915–918, 2016

2. Проектирование и создание нового инжектора с пространственно-однородной квадрупольной фокусировкой для модернизации ЛУ-20
M. A. Gusarova, V. S. Dyubkov, S. M. Polozov, A. V. Samoshin, T. V. Kulevoy, A. A. Martynov, A. S. Plastun, V. A. Andreev, S. V. Barabin, A. V. Kozlov, V. A. Koshelev, G. N. Kropac и др., Письма в ЭЧАЯ, ISSN:1814-5957, eISSN:1814-5973, Изд:ОИЯИ, 13, 7(205), 1425-1431, 2016

3. Injection of Polarized Protons and Light Ions in the Nuclotron Superconducting Synchrotron
S.V. Barabin, A.M. Bazanov, A.S. Belov, A.V. Butenko, A.I. Govorov, B.V. Golovenskiy, D.E. Donets, E.M. Syresin, V.V. Fimushkin, V.V. Kobets, A.D. Kovalenko, A.V. Kozlov, G.N. Krop и др., Physics of Particles and Nuclei Letters, ISSN:1547-4771, eISSN:1531-8567, Изд:MAIK Nauka/Interperiodica distributed exclusively by Springer Science+Business Media LLC., 7, 15, 827–830, 2018

4. Light-Ion Linear Accelerator for the NICA Project
M. Bazanov, A. V. Butenko, B. V. Golovenskiy, D. E. Donets, V. V. Kobets, A. D. Kovalenko, A. I. Govorov, K. A. Levterov, D. A. Lyuosev, A. A. Martynov, V. A. Monchinskiy, V. V. Mi и др., Physics of Particles and Nuclei Letters, ISSN:1547-4771, eISSN:1531-8567, Изд:MAIK Nauka/Interperiodica distributed exclusively by Springer Science+Business Media LLC., 17, 4, 481-487, 2020

Материалы научных мероприятий (международные, устный доклад):

1. RuPAC 2016, , St. Petersburg, Russia
COMMISSIONING OF NEW LIGHT ION RFQ LINAC AND FIRST NUCLOTRON RUN WITH NEW INJECTOR, A.M. Bazanov, A.V. Butenko, A.I. Govorov, B.V. Golovenskiy, D.E. Donets, V.V. Fimushkin, V.V. Kobets, A.D. Kovalenko, K.A. Levterov, D.A. Lyuosev, A.A. Martynov, V.V. Mialkovsky, V.A. Monchinskiy, D.O. Ponkin, R.G. Pushkar, V.V. Seleznev, K.V. Shevchenko и др., 153-155, 2016

2. RuPAC 2016, , St. Petersburg, Russia
COMMISSIONING OF THE NEW HEAVY ION LINAC AT THE NICA PROJECT, A.M. Bazanov, A.V.Butenko, B.V.Golovenskiy, D.E. Donets, V.V. Kobets, A.D. Kovalenko, K.A. Levterov, D.A. Lyuosev, A.A. Martynov, V.A. Monchinskiy, D.O. Ponkin, K.V. Shevchenko, A.O. Sidorin, I.V. Shirikov, A.V. Smirnov, G.V. Trubnikov, D.A. Liakin, H.H& и др., 156-159, 2016

3. VIIIth International Particle Accelerator Conference (IPAC 2017), , Copenhagen, Denmark
Commissioning of New Light Ion RFQ Linac and First Nuclotron Run with New Injector, Andrey Butenko, Sergey Barabin, Alexander Bazanov, Aleksandr Belov, Denis Donets, V. Fimushkin, Boris Golovenskiy, Alexander Govorov, Valery Kobets, Alexander Kovalenko Aleksander Kozlov, Gennady Kropachev, Timur Kulevoy, Viktor Kuzmichev, Konstantin Levte и др., 2017

4. VIIIth International Particle Accelerator Conference (IPAC 2017), , Copenhagen, Denmark
COMMISSIONING OF THE NEW HEAVY ION LINAC AT THE NICA PROJECT, A.M. Bazanov, A.V. Butenko, B.V. Golovenskiy, D.E. Donets, V.V. Kobets, A.D. Kovalenko, K.A. Levterov, D.A. Lyuosev, A.A. Martynov, V.A. Monchinskiy, D.O. Ponkin, K.V. Shevchenko, A.O. Sidorin, I.V. Shirikov, A.V. Smirnov, H.H?ltermann, U.Ratzinger, A.Sche и др., 2362-2365, 2017

5. XXVI Russian Particle Accelerator Conference RuPAC2018, , Protvino, Russia
PROGRESS OF THE NICA COMPLEX INJECTION FACILITY DEVELOPMENT, A.V. Butenko, A.I. Govorov, B.V. Golovenskiy, D.E. Donets, A.D. Kovalenko, K.A. Levterov, D.A. Lyuosev, A.A. Martynov, V.V. Mialkovsky, V.A. Monchinskiy , D.O. Ponkin, K.V., Shevchenko, A.O. Sidorin, I.V. Shirikov, A.V. Smirnov, G.V. Trubnikov, T.V. Kulevo и др., 75-77, 2018

6. XXVI Russian Particle Accelerator Conference RuPAC2018, , Protvino, Russia
LIGHT ION LINEAR ACCELERATOR UP TO 7 AMEV FOR NICA, A. M. Bazanov, A. V. Butenko, A. I.Govorov, B. V. Golovenskiy, D.E. Donets, V. V. Kobets, A. D. Kovalenko, K. A. Levterov, D. A. Lyuosev, A. A. Martynov, V. A. Monchinskiy, D. O. Ponkin, K.V. Shevchenko, A. O. Sidorin, I. V. Shirikov, E. M. Syresin, H. H и др., 68-71, 2018

7. LINAC2018, , Beijing, China
INJECTION COMPLEX DEVELOPMENT FOR THE NICA PROJECT, A.V. Butenko, A.I. Govorov, B.V. Golovenskiy, D.E. Donets, A.D. Kovalenko, K.A. Levterov, D.A. Lyuosev, A.A. Martynov, V.V. Mialkovsky, V.A. Monchinskiy, D.O. Ponkin, K.V., Shevchenko, A.O. Sidorin, I.V. Shirikov, A.V. Smirnov, G.V. Trubnikov, T.V. Kulevoy и др., 663-665, JACoW Publishing, 2018

8. 12th International Particle Accelerator Conference (IPAC2021), Brazilian Center for Research in Energy and Materials (CNPEM), Campinas, SP, Brazil
ACCELERATION OF He+ BEAMS FOR INJECTION INTO NICA BOOSTER DURING ITS FIRST RUN, V. Akimov, A. Bazanov, A. Butenko, A. Galimov, A. Govorov, B. Golovenskiy, D. Donets, D. Egorov, V. Kobets, A. Kovalenko, K. Levterov, D. Letkin, D. Leushin, D. Lyuosev, A. Martynov, V. Mialkovsky, V. Monchinskiy , D. Ponkin, A. Sidorin, E. Syresin, I. Shi и др., 3016-3019, JACoW Publishing, JACoW Publishing, Geneva, Switzerland, 2673-5490, 2021

9. XXVII Russian Particle Accelerator Conference (RuPAC-2021), Scientific Council of RAS on Charged Particle Accelerators, Joint institute for nuclear research, Alushta, Russia
Acceleration the Beams of He+ and Fe14+ Ions by HILAC and its Injection into NICA Booster in its Second Run, K.A. Levterov, V.P. Akimov, A.M. Bazanov, A.V. Butenko, D.E. Donets, D.S. Letkin, D.O. Leushin, D.A. Lyuosev, A.A. Martynov, V.V. Mialkovskiy, D.O. Ponkin, I.V. Shirikov, A.O. Sidorin, A. Tuzikov, D. Egorov, A.R. Galimov, B.V. Golovenskiy, A. Govorov, V.V. и др., 2021

Материалы научных мероприятий (международные, стендовый доклад):

1. IPAC'16, the Seventh International Particle Accelerator Conference, Pohang Accelerator Laboratory, Korea, Korea
COMMISSIONING OF NEW PROTON AND LIGHT ION INJECTOR FOR NUCLOTRON-NICA, V.S. Aleksandrov, A.V. Butenko, B.V. Golovenski y, A.I. Govorov, V.V. Kobets, A.D. Kovalenko, K.A. Levterov, V.A. Monchinsky, V.V. Seleznev, A.O. Sidorin, G.V. Trubnikov, et.al., 941-943, 2016

2. LINAC2018, , Beijing, China
THE NEW LIGHT ION INJECTOR FOR NICA, B. Koubek, M. Basten, H. Hoeltermann, H. Podlech, U. Ratzinger, A. Schempp, R. Tiede, A. Butenko, A. Govorov, B. Golovenskiy, D. Donets, K. Levterov, D. Lyuosev, A. Martynov, V. Monchinskiy, D. Ponkin, K. Shevchenko, I. Shirikov, E. Syresin, C. Kampmeyer, и др., 362-365, JACoW Publishing, 2018

Электронные публикации:

1. NICA ION COLLIDER AT JINR
Syresin E., Agapov N. N., Alfeev A. V., Andreev V., Baldin A. A., Bazanov A. M., Brovko O. I., Bugaev V. V., Butenko A. V., Donets D. E., Donets E. D., Donets E. E., Eliseev A. V., Filatov G. A., Fimushkin V. V., Galimov A. R., Golovenskiy B. V., Gorbachev E. V., Govorov A., Grebentsov A. Yu., Ivanov E. V., Karpinsky V., Kekelidze V., Khodzhibagiyan H. G., Kirichenko A., Kobets A. G., Kobets V. V., Korovkin S. A., Kostromin S. A., Kozlov O. S., Levterov K. A., Lyuosev D. A., Malyshev A. M., Martynov A. A., и др., Joint Accelerator Conferences and Website (JACoW), 2021