Results of operation of the test accelerator facility for SKIF linear accelerator

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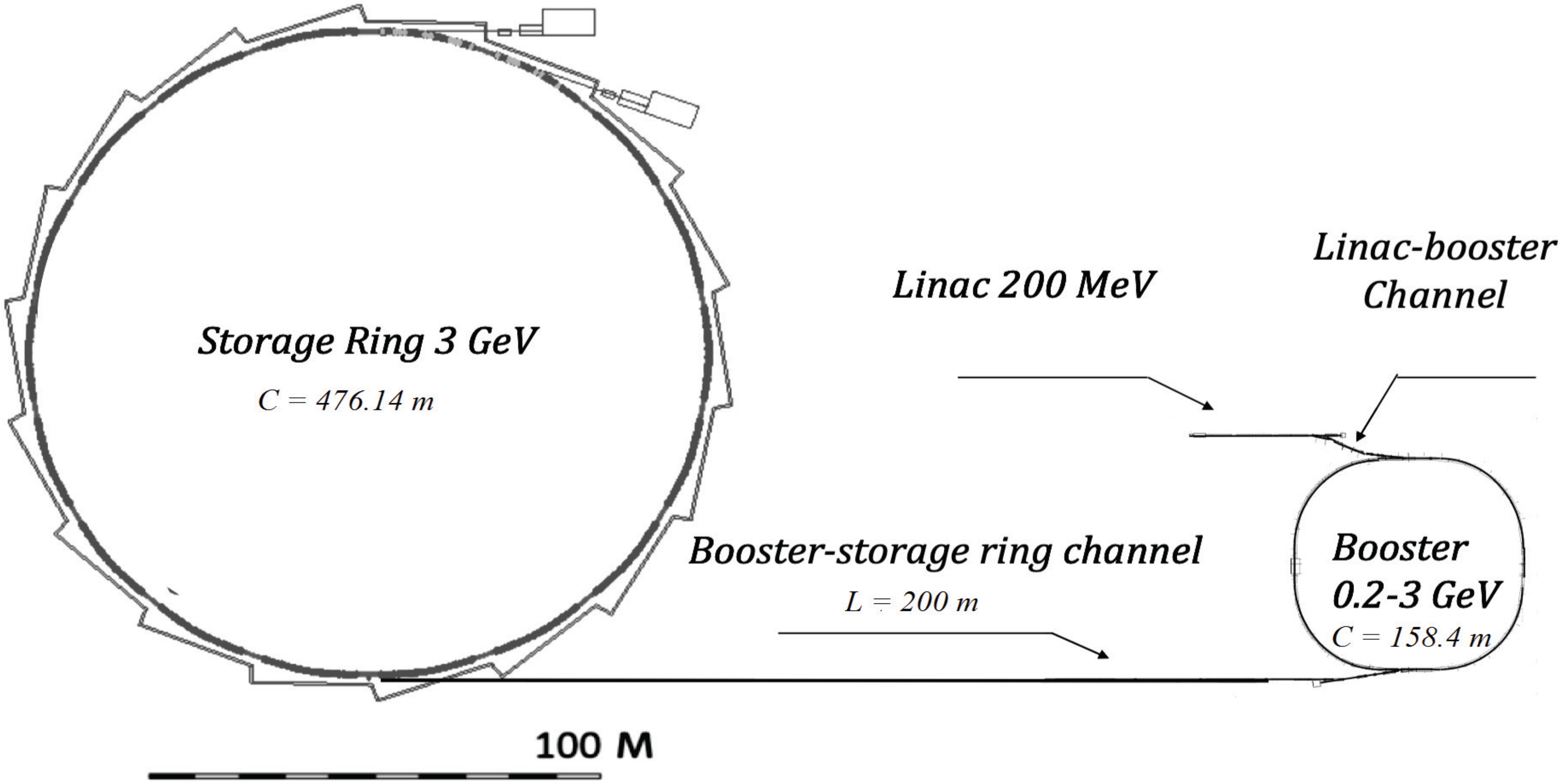
СКИФ
СИБИРСКИЙ КОЛЬЦЕВОЙ ИСТОЧНИК ФОТОНОВ

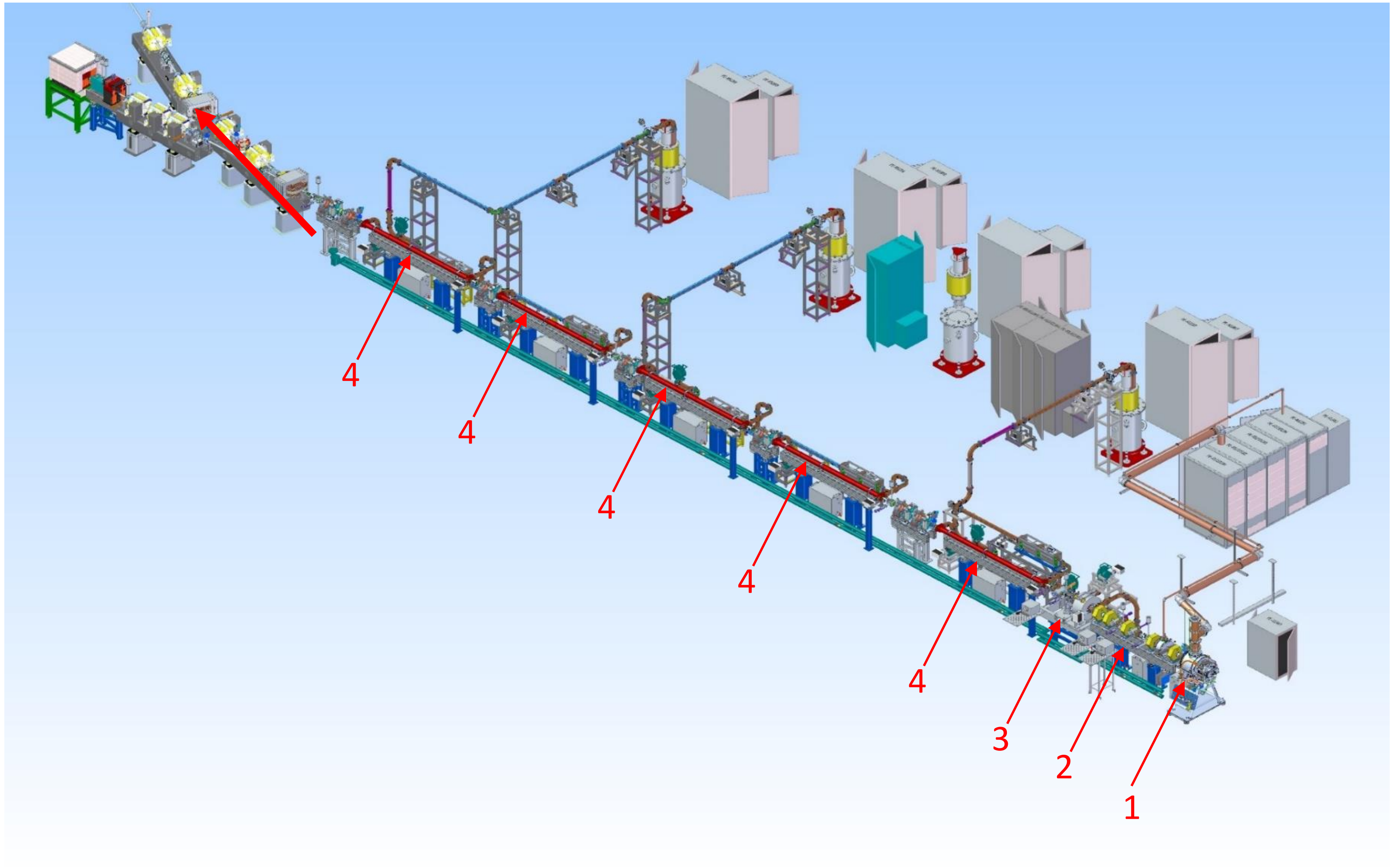
RuPAC’23, Novosibirsk

Институт ядерной физики имени Г.И. Будкера СО РАН

Synchrotron radiation facility SKIF



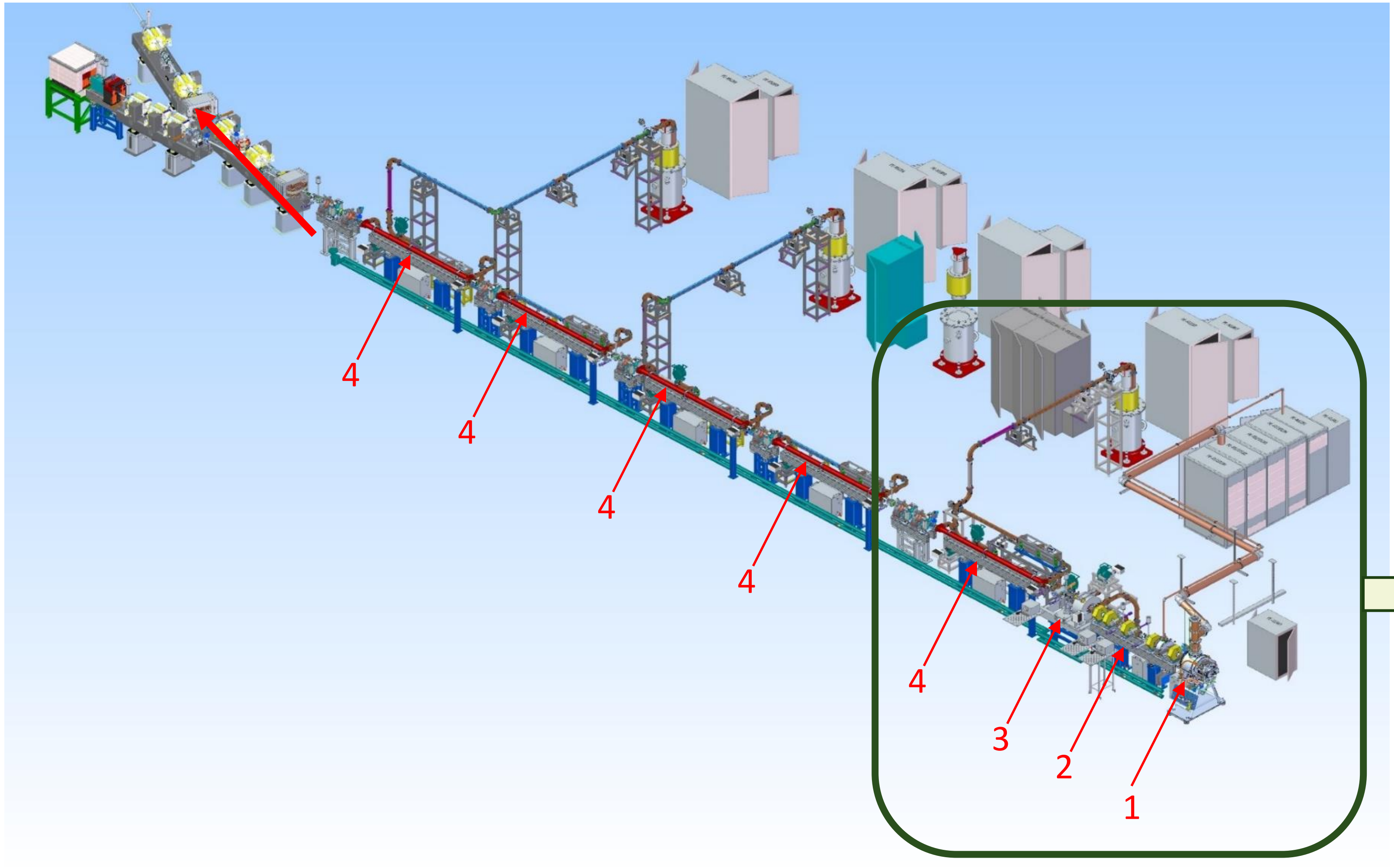
Linear accelerator



1 – Electron source (RF gun)
2 – Bunching cavity
3 – Preaccelerator
4 – Accelerating structures (5 pcs)

Energy	200 MeV
Energy spread (RMS)	1%
Repetition rate	1 Hz
Bunch period	5.6 ns
Number of bunches in the beam	55
Single bunch charge	0.3 nC
Horizontal emittance at 200 MeV	150 nm

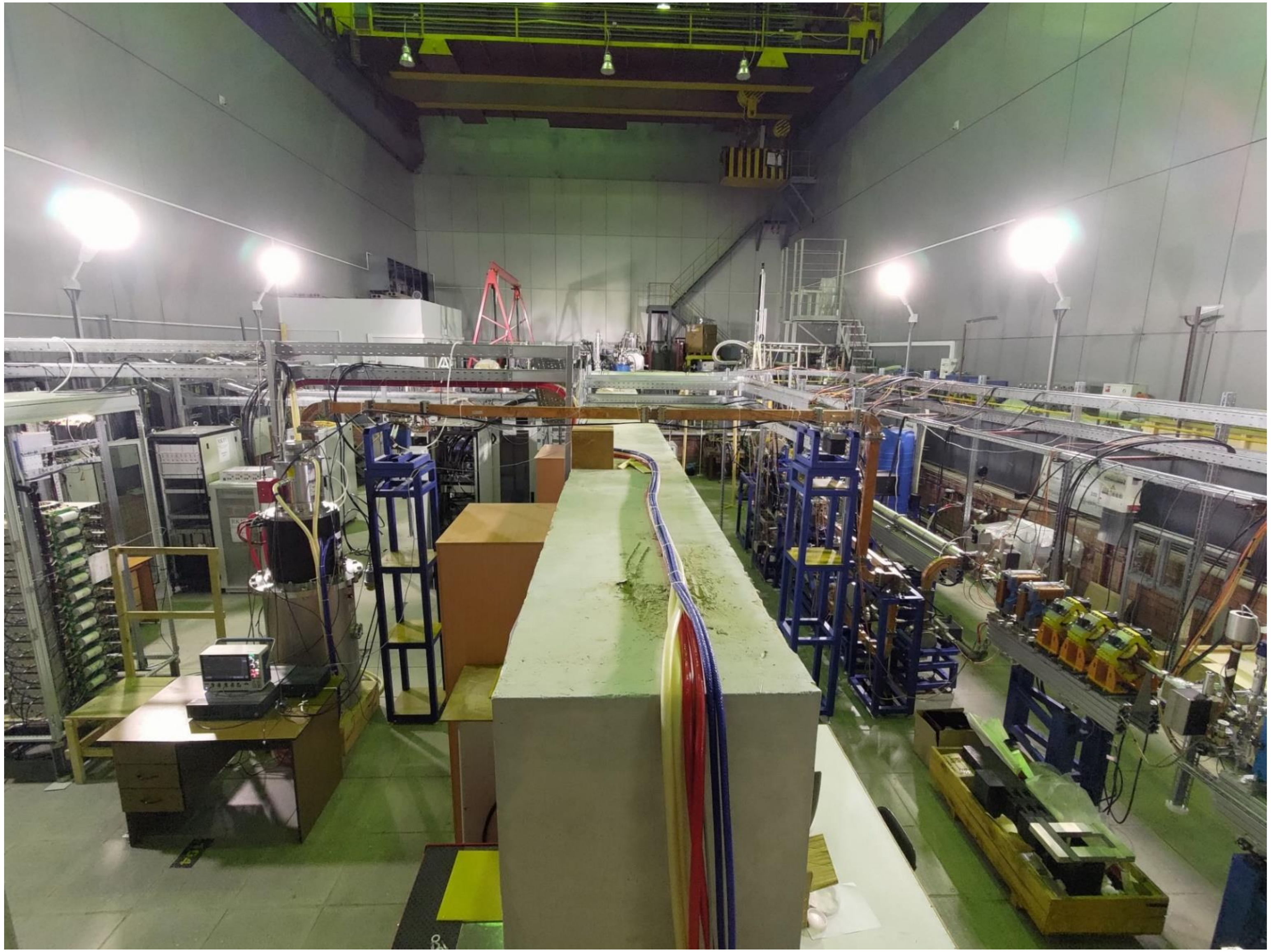
Linear accelerator



1 – Electron source (RF gun)
2 – Bunching cavity
3 – Preaccelerator
~~4 – Accelerating structures (5 pcs)~~
4 – Accelerating structure (1 pc)

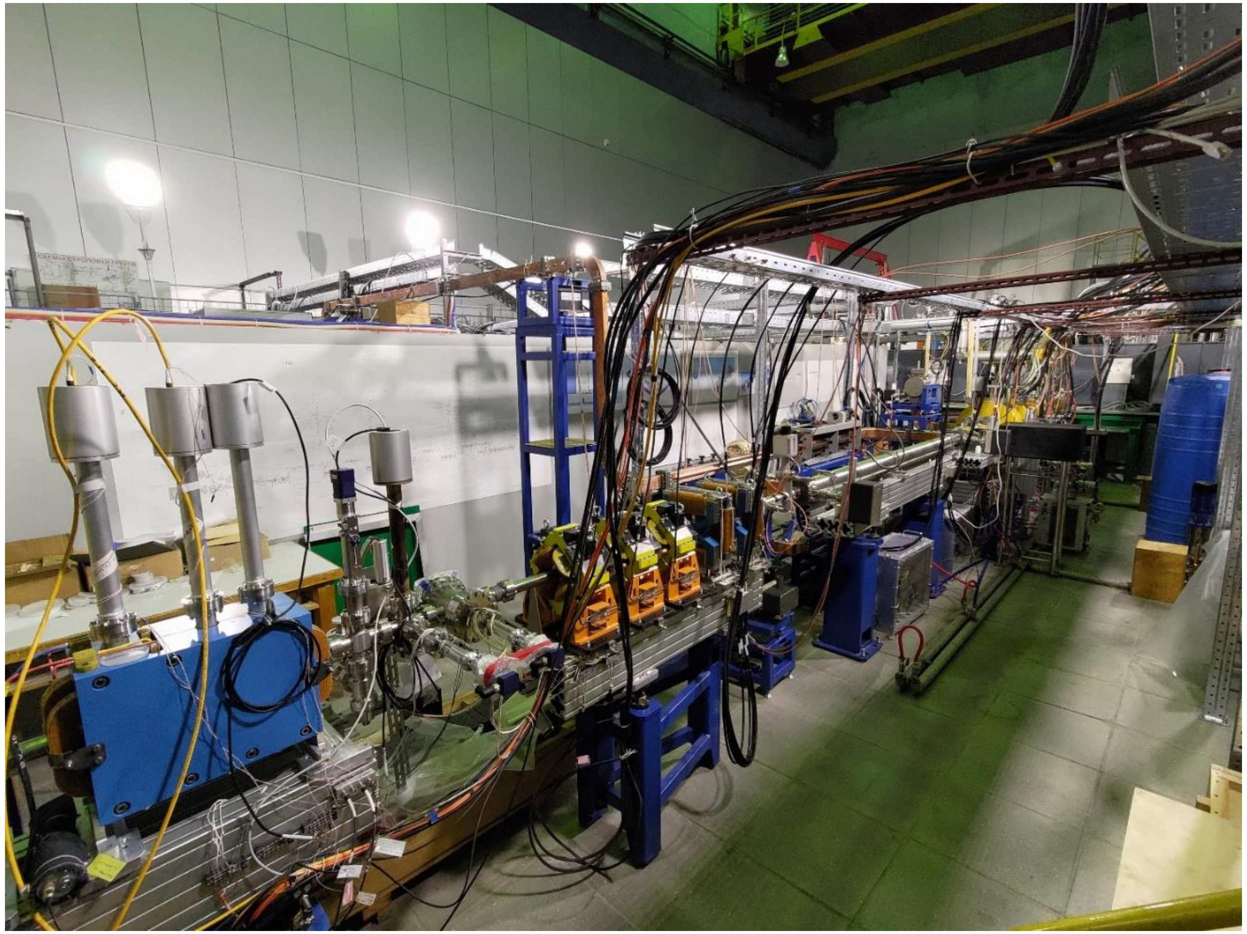
Test facility
Linac-20

Assembled test facility Linac-20

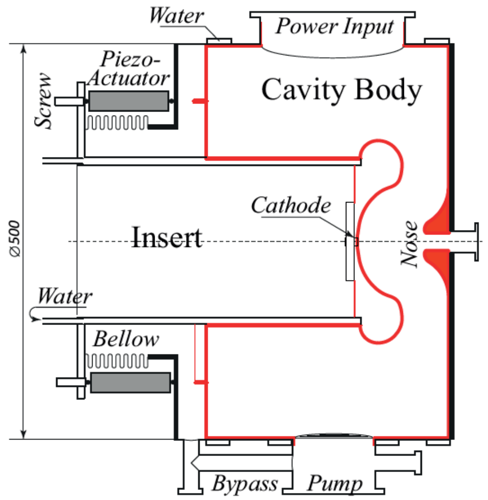


2019 – beginning of linac element development
End 2021 – beginning of the room preparation
October 2022 – first beam from the RF gun
February 2023-now – work with the accelerated beam

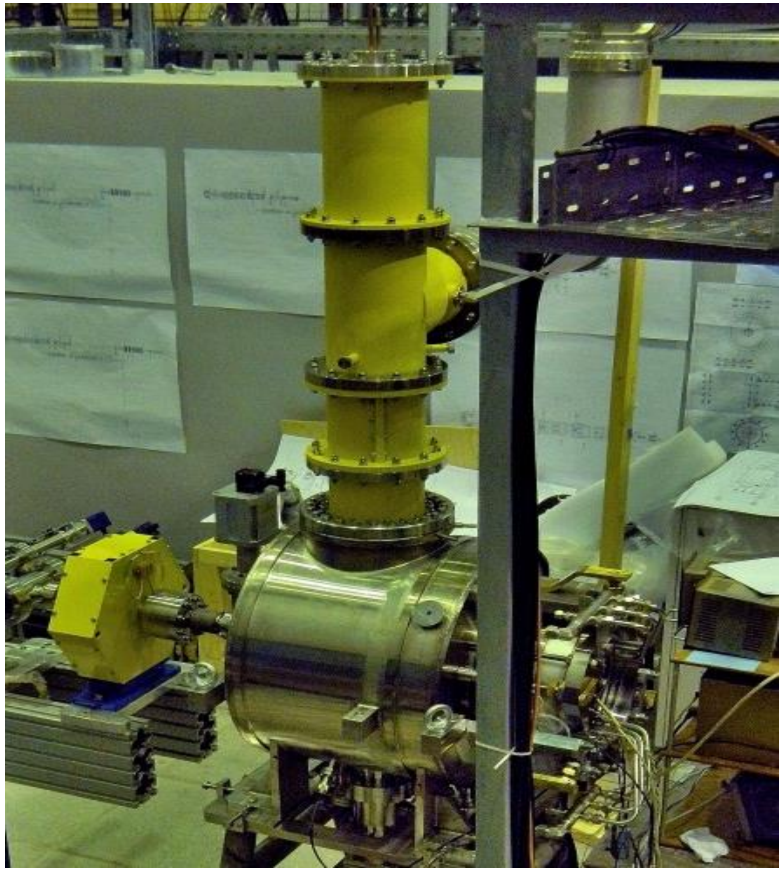
Assembled test facility Linac-20



RF gun 178.5 MHz



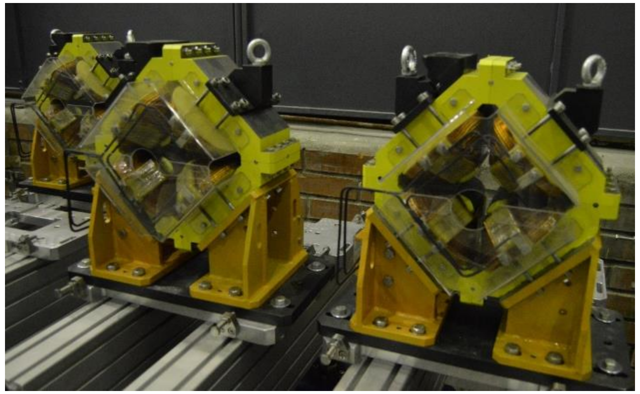
Operating frequency	178.5 MHz
Input power	Up to 700 kW
Input pulse length	100 us
Max. repetition rate	10 Hz
Bunch energy	0.7 MeV
Bunch charge	Up to 1 nC

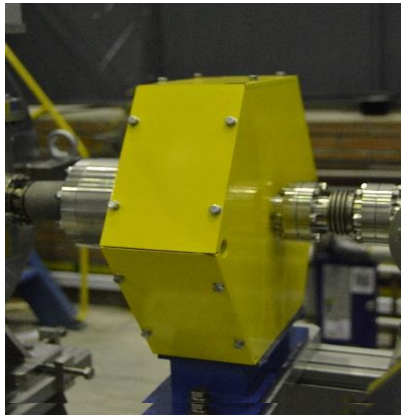


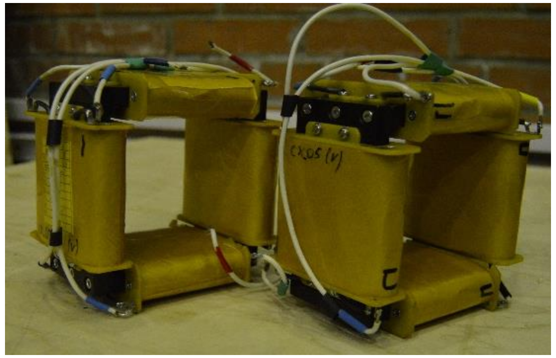
RF gun at the test stand facility

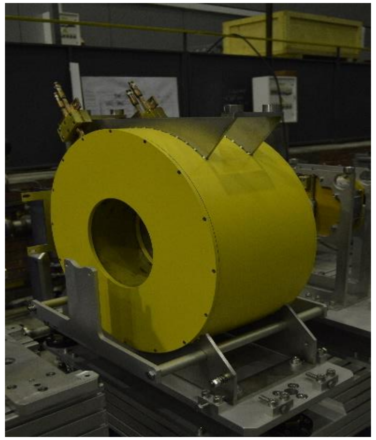
Magnet system

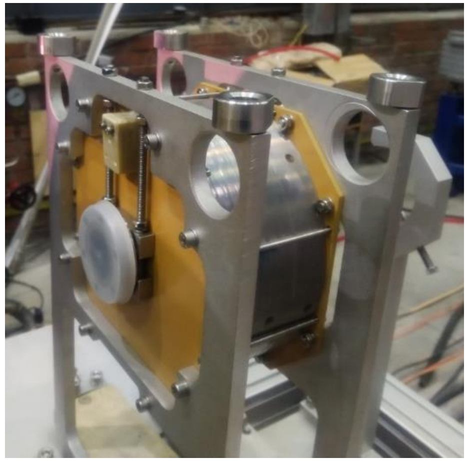
Magnet	Number	Field magnitude, kGs	Current, A
Solenoids of the bunching channel	5	0.858	6
Preaccelerator solenoids	2	2.3	200
Matching solenoid	1	0.98	3
Correctors of the bunching channel	8	0.019	3
Quadruple lenses after the AS	3	6 (integral)	6
Correctors after the AS	3	0.47	6

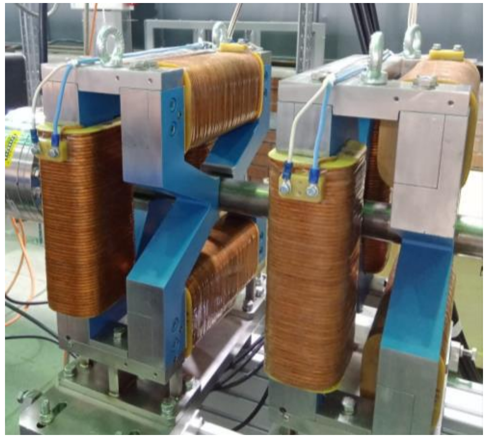

Linac quadruple lenses


Solenoid of the bunching channel

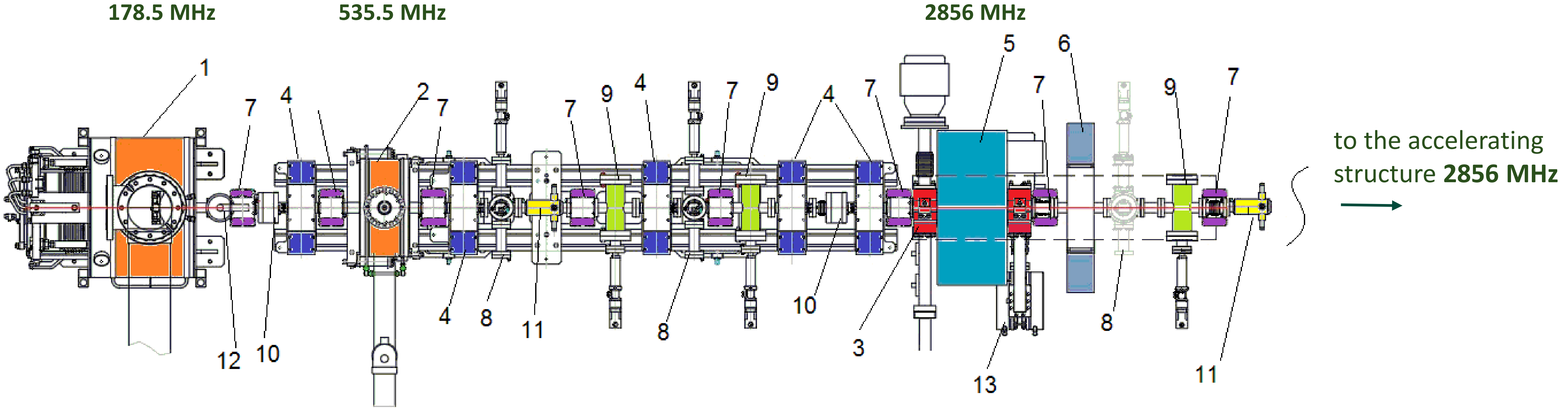

Correctors of the bunching channel


Solenoid of the preaccelerator


Matching solenoid

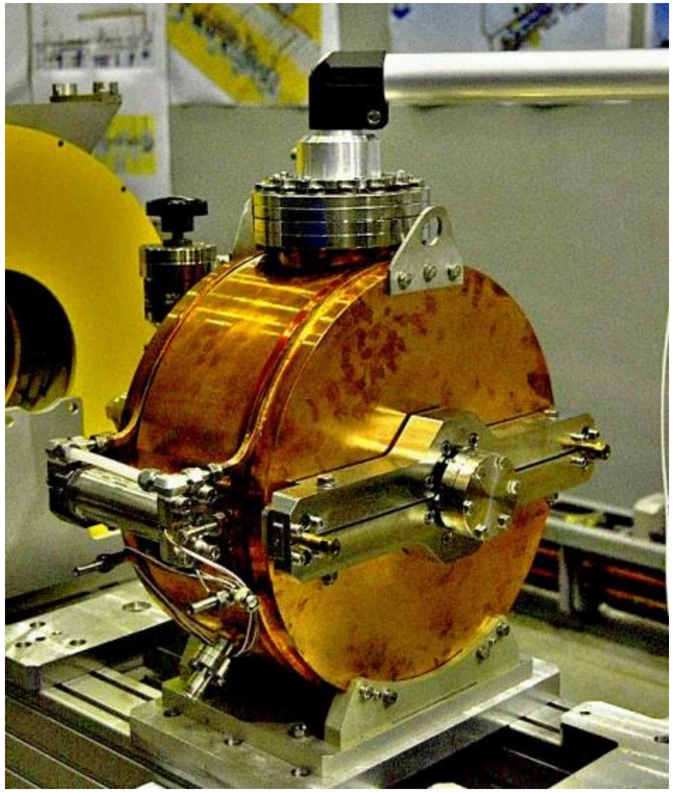

Correctors of the linac

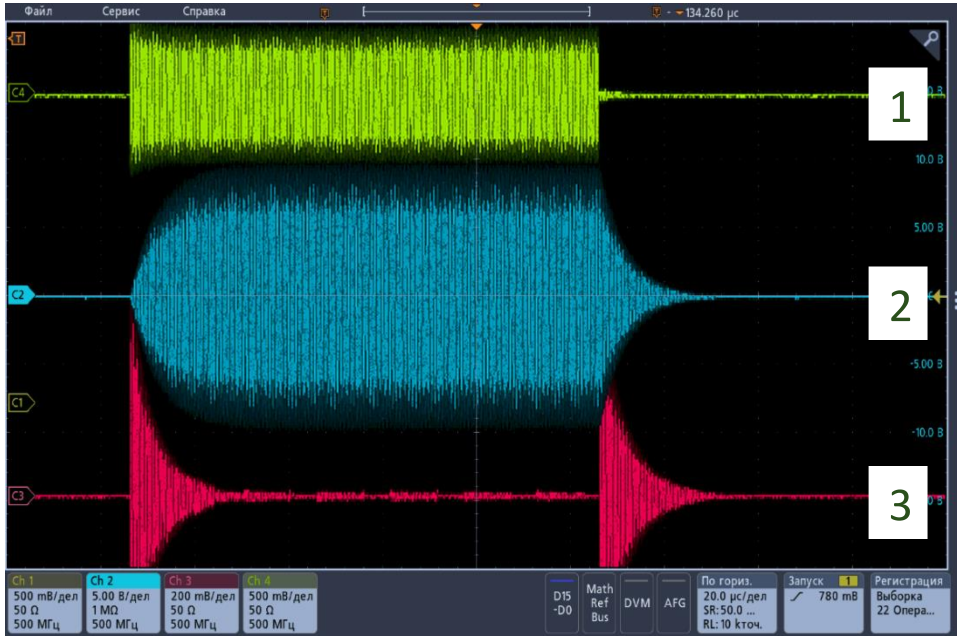
Bunching channel



1 – RF gun, 2 – third harmonic bunching cavity, 3 – preaccelerator structure, 4 – drift gap solenoids (5 pcs), 5 – PB solenoids (2 pcs), 6 – matching solenoid, 7 - correctors (8 pcs), 8 – scintillator screens (3 pcs), 9 – Cherenkov censor (3 pcs), 10 - FCT (2 pcs), 11 - BPM (2 pcs) , 12 - automatic vacuum gate, 13 - waveguide RF load

Bunching cavity 535.5 MHz





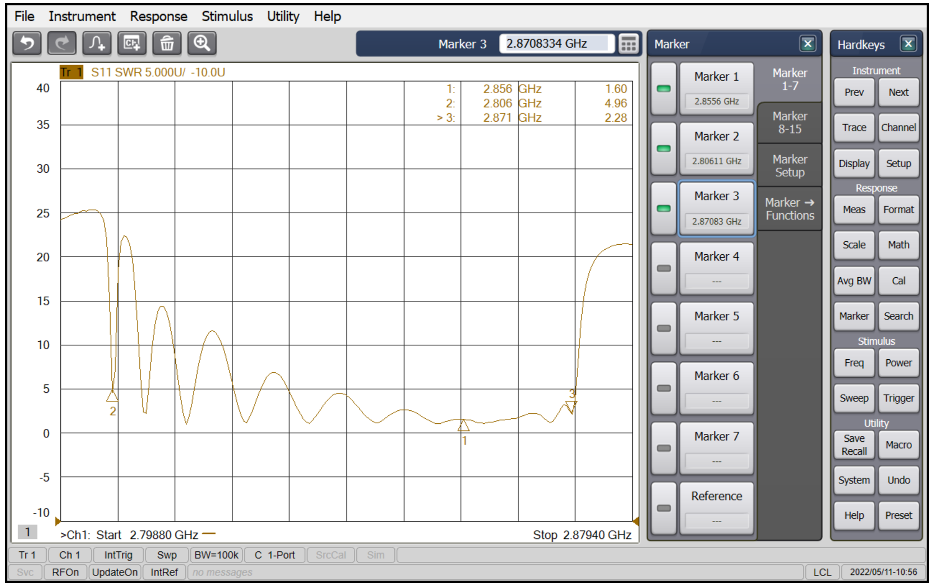
RF waveforms:
1 – input signal
2 – cavity loop signal
3 – reflected signal

Cavity parameter	Value
Operating frequency	535.5 MHz
Input power	10 kW
Quality factor	21000
Coupling factor	1

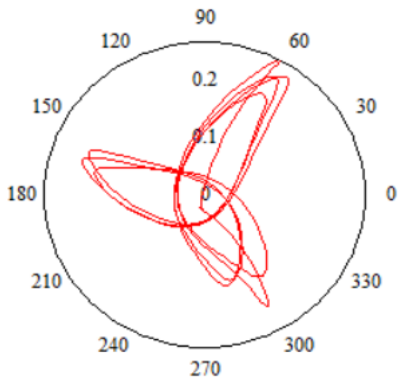
Preaccelerator 2856 MHz

Preaccelerator inside the solenoid

Operating frequency in vacuum and at T=25 C^0	2856.3 MHz
Operating mode	$2\pi/3$
Total phase error per structure	2^0
RMS phase deviation per accelerating cell	$\pm 3^0$
Q-factor	$1.2{\cdot}10^4$
SWR	1.5

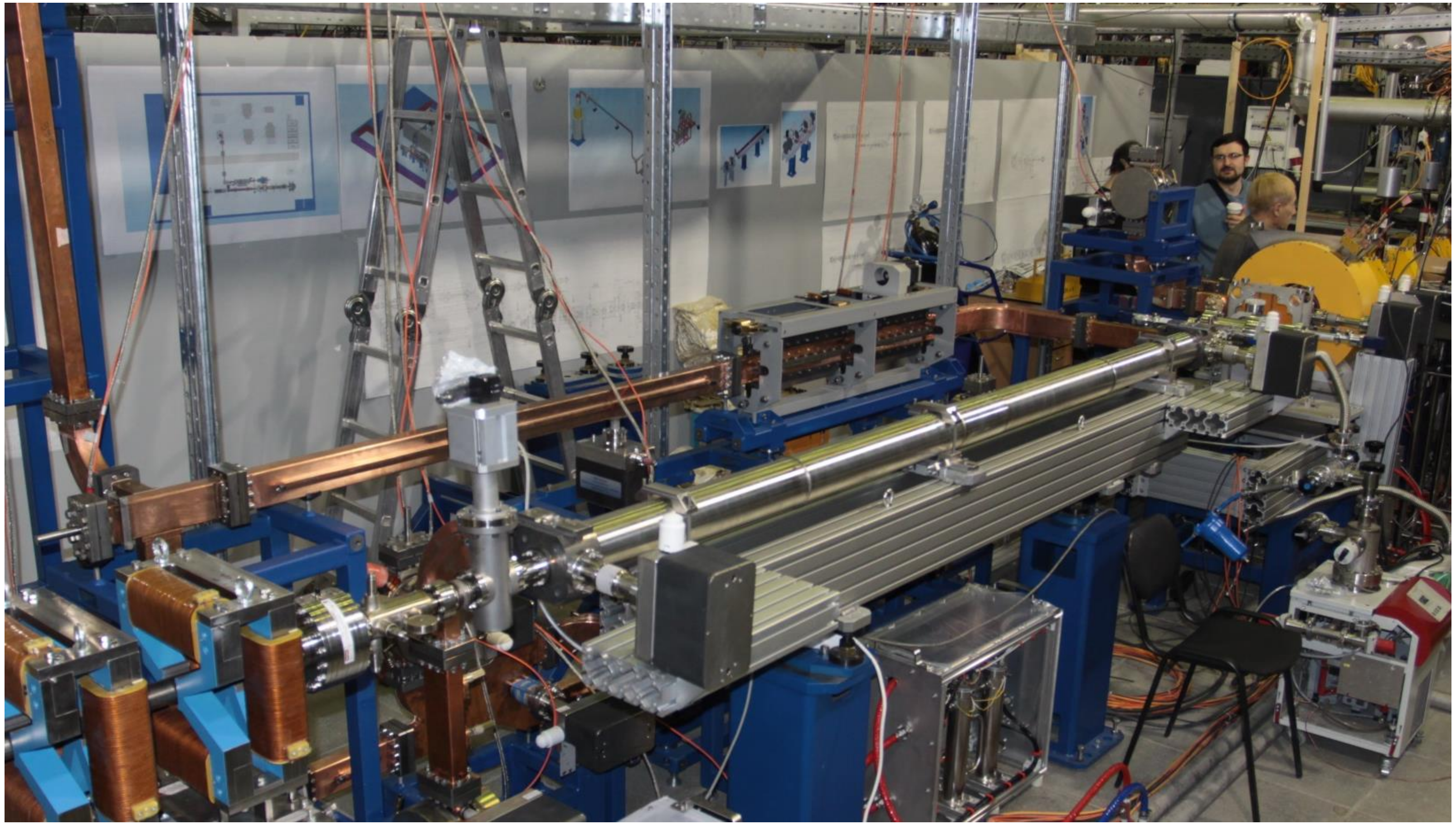


Frequency band of the preaccelerator



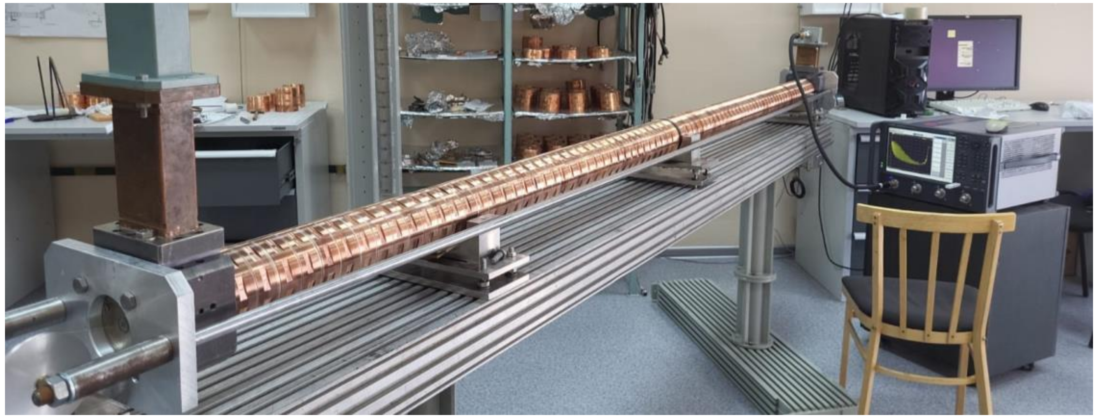
Preaccelerator phase measurements

Accelerating structure 2856 MHz



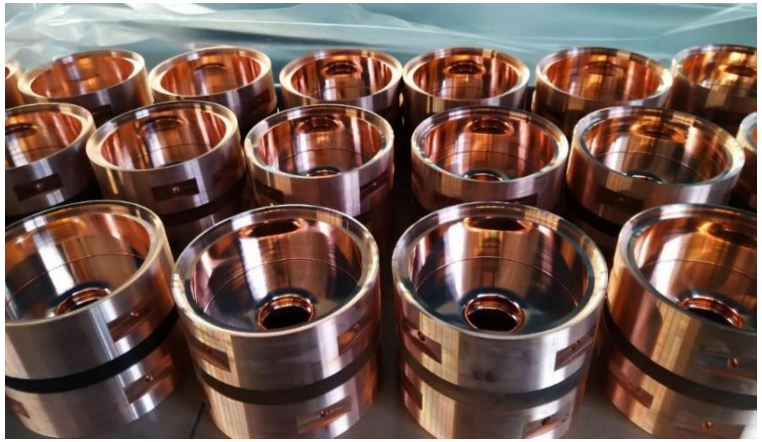
Accelerating structure at the test facility Linac-20

Accelerating structure 2856 MHz

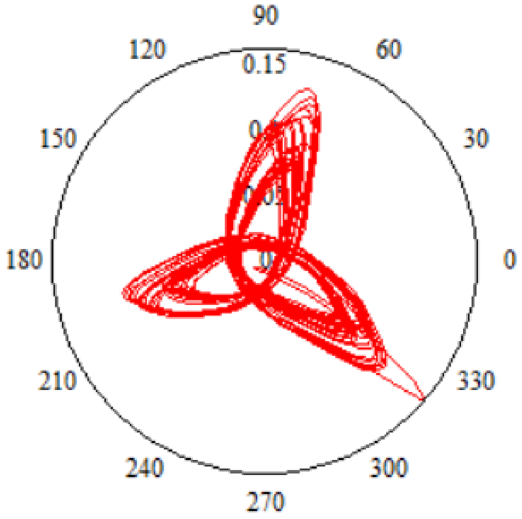


Accelerating structure during the measurements

Operating frequency in vacuum at T=25 C^0	2856.6 MHz
Operating mode	$2\pi/3$
Total phase error per structure	0.8^0
RMS phase deviation per accelerating cell	$\pm1.2^0$
Q-factor	$1.35\cdot10^4$
SWR	1.4



Cells of the accelerating structure



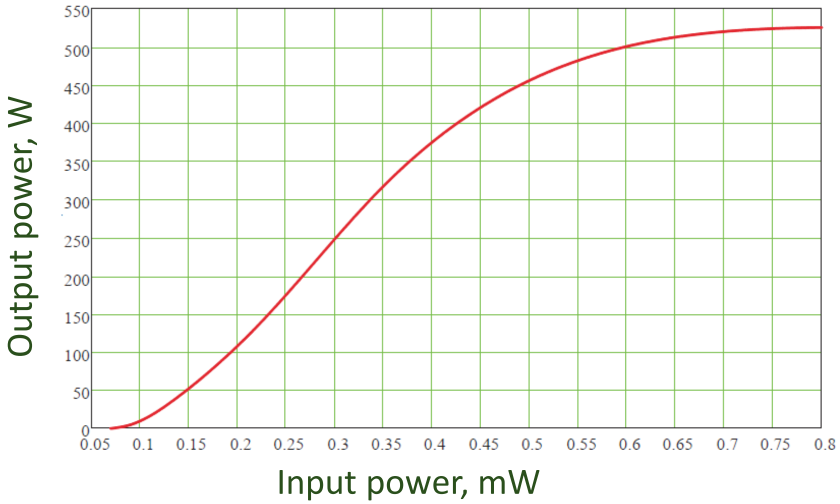
Phase measurements of the accelerating structure

Klystron

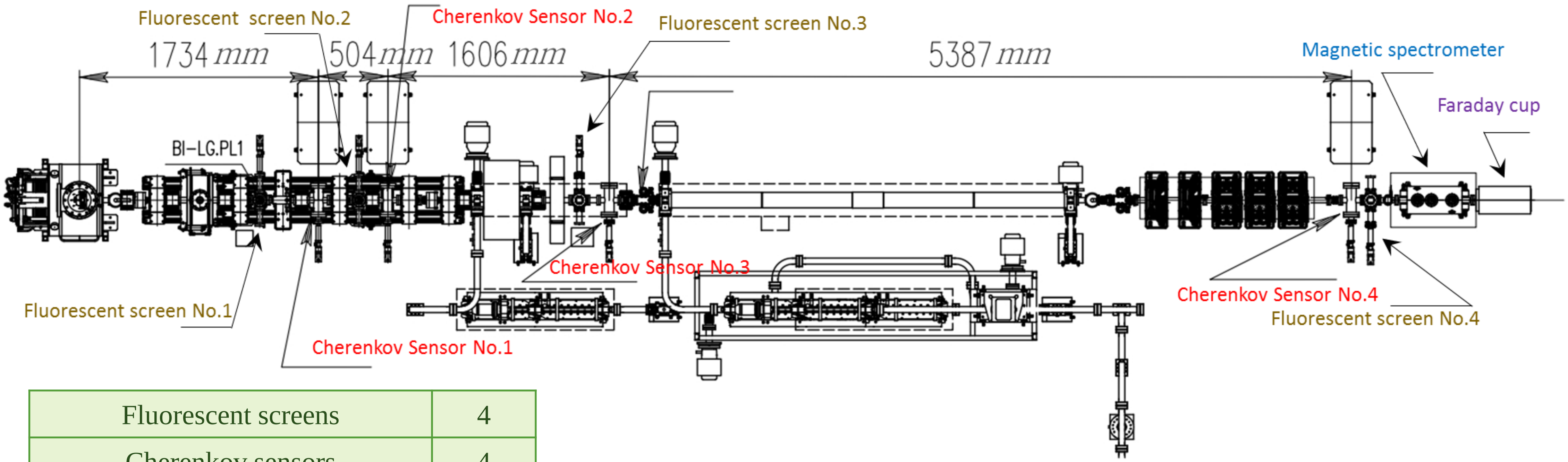
Klystron Canon E3730A

Klystron parameter	Value
Frequency	2856 MHz
Voltage	325 kV
Current	400 A
Input power	500 W
Output power	≥ 50 MW
Average power	5÷10 kW
RF pulse length	≥4 μs

Semiconductor preamplifier 500 W



Beam diagnostics

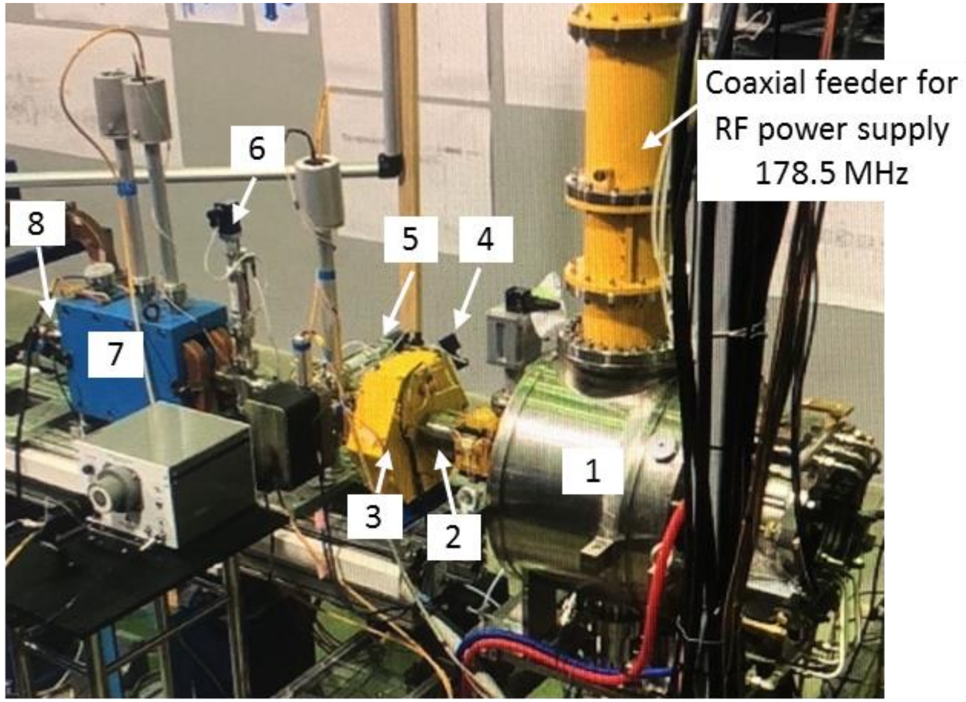


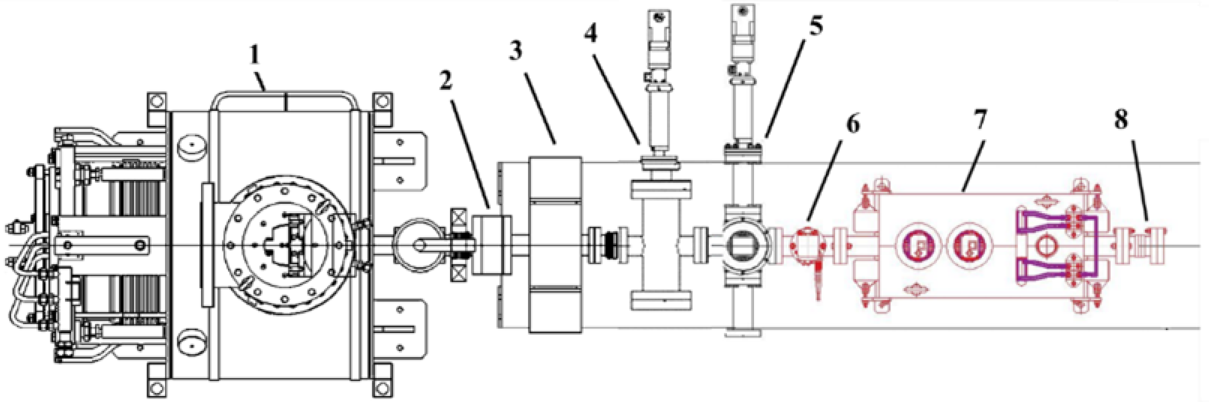
Fluorescent screens	4
Cherenkov sensors	4
Magnetic spectrometer	1
Faraday cup	1
Beam position monitors (BPM)	3
Fast Current Transformers (FCT)	3

First beam: (only) after the RF gun

October-November 2022

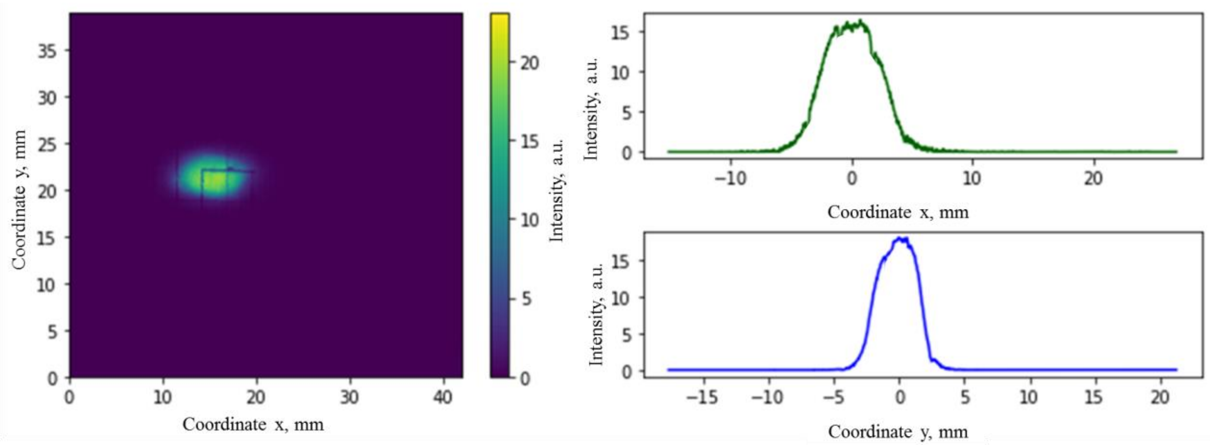
Channel with the RF gun





Scheme for measuring the beam parameters after the gun: 1 - RF gun, 2 - FCT, 3 - solenoid, 4 - Cherenkov sensor, 5 - fluorescent screen, 6 - collimator, 7 - spectrometer, 8 - Faraday cup

Beam parameters after the RF gun



Typical beam image at the fluorescent screen after the gun, $E_b \approx 0.5$ MeV

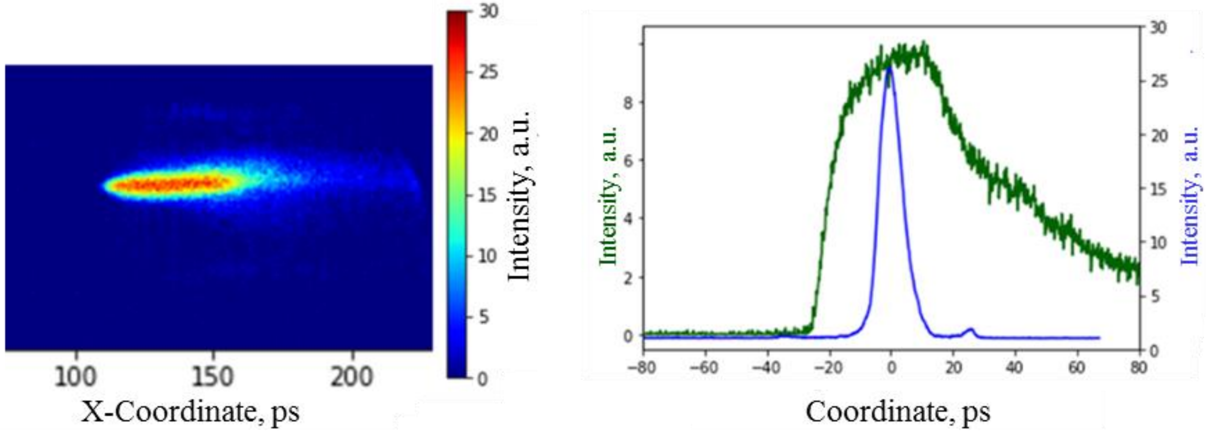
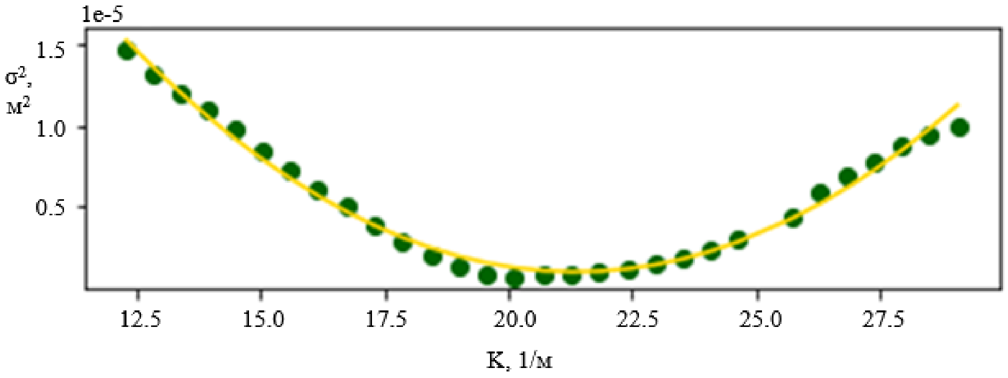
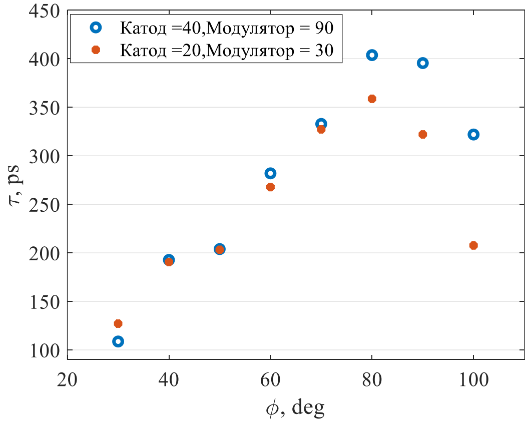


Image and longitudinal beam distribution at the c Cherenkov screen at the modulator voltage U_m = 70 V

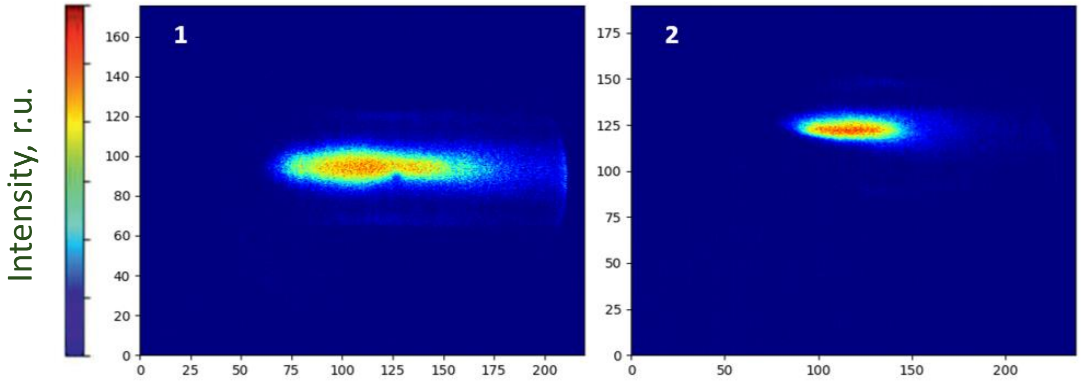


Solenoid scan: normalized emittance of 20 um

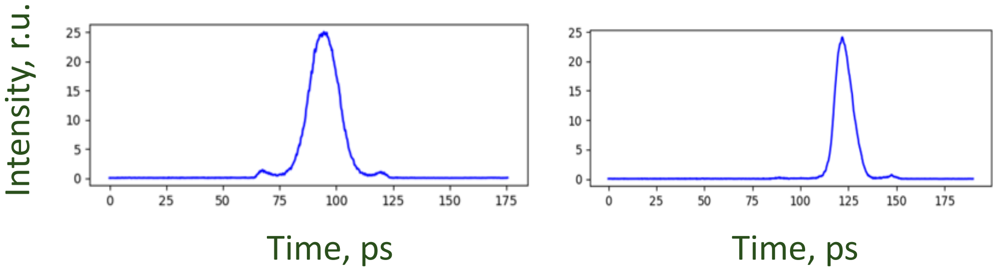


Beam duration (FWHM) vs injection phase

Beam bunching



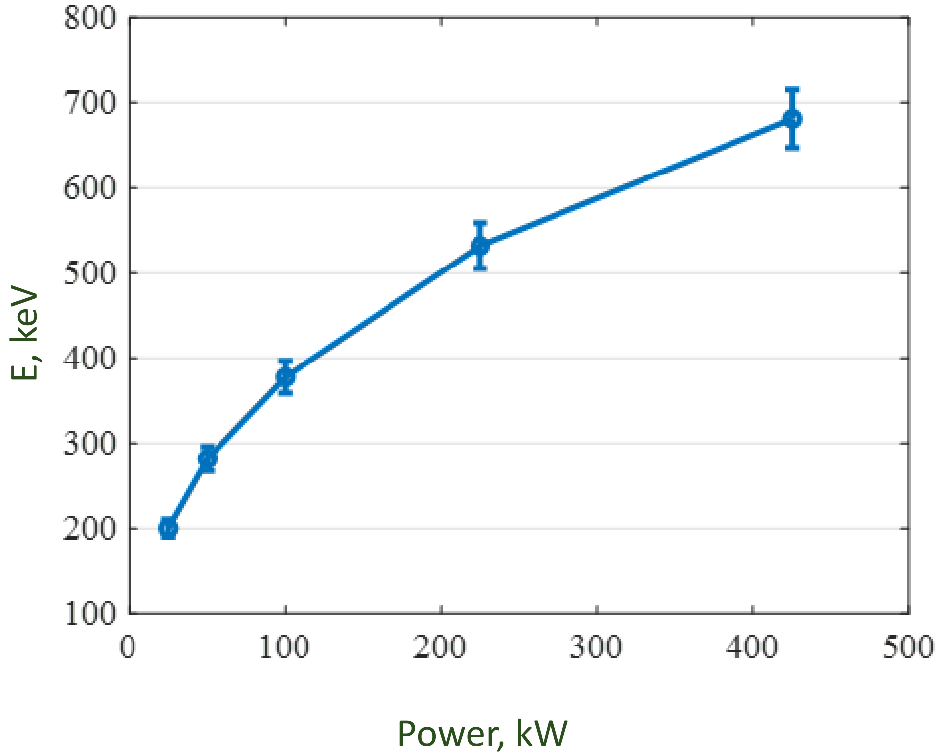
Beam image at Cherenkov screens in the bunching channel:
1 – at 1st screen (at 1.7 m from the cathode)
2 – at 2nd screen (at 2.2 m from the cathode)



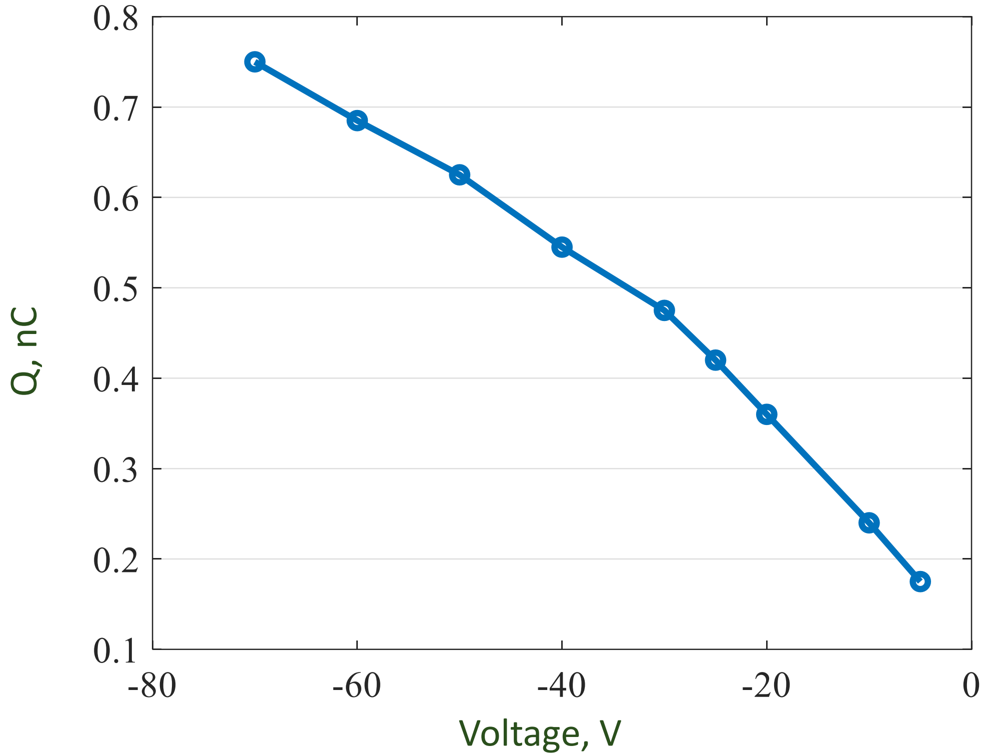
$\tau_{FWHM} = 85\,ps$ $\tau_{FWHM} = 48\,ps$

Longitudinal beam profile at the bunching channel:
1 – at 1st screen (at 1.7 m from the cathode)
2 – at 2nd screen (at 2.2 m from the cathode)

Beam parameters after the RF gun



Measured beam energy as a function of RF power in the gun

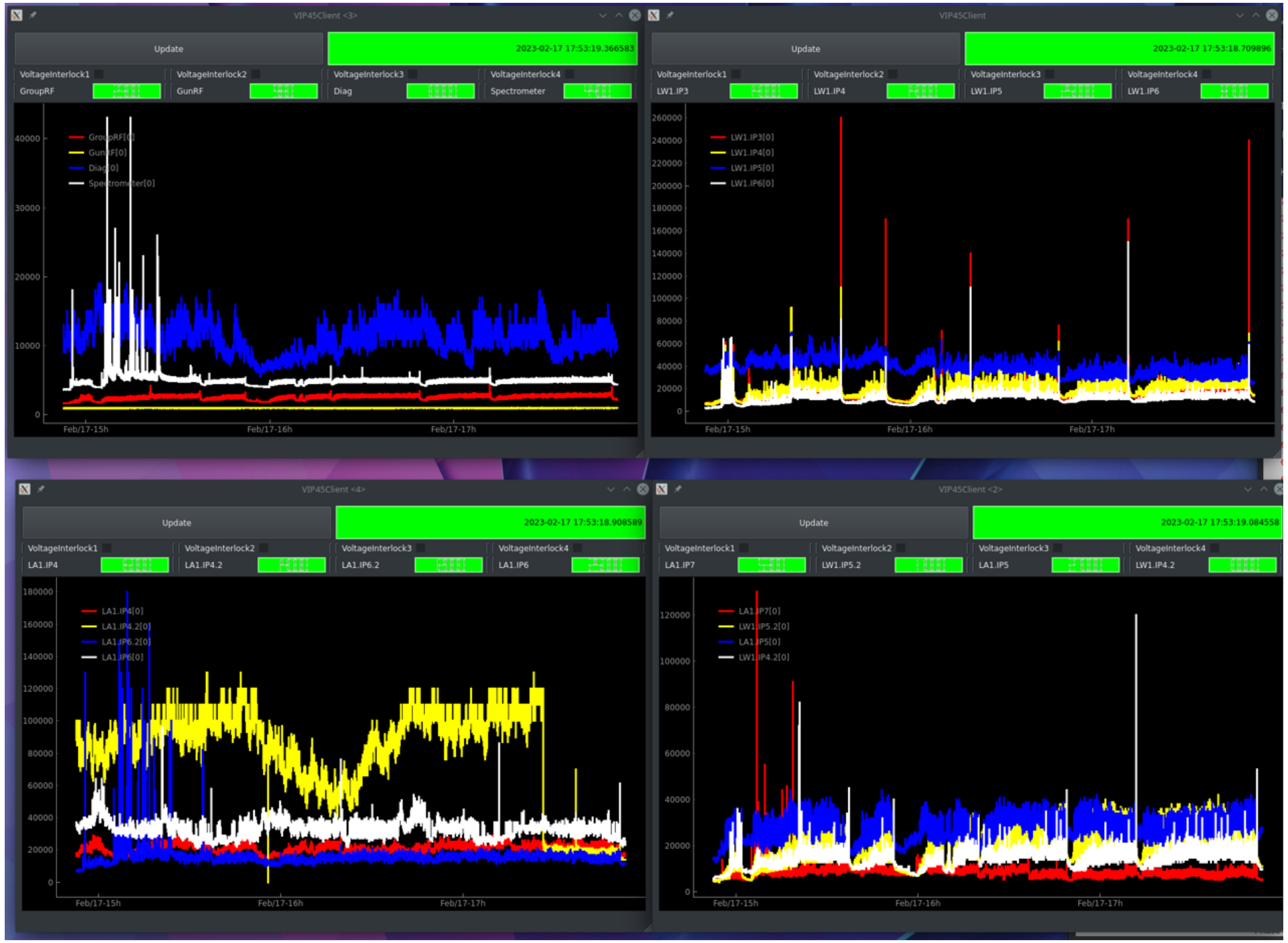


Dependence of the RF gun beam charge on the voltage of the modulating pulse

Work with the beam at the fully assembled linac

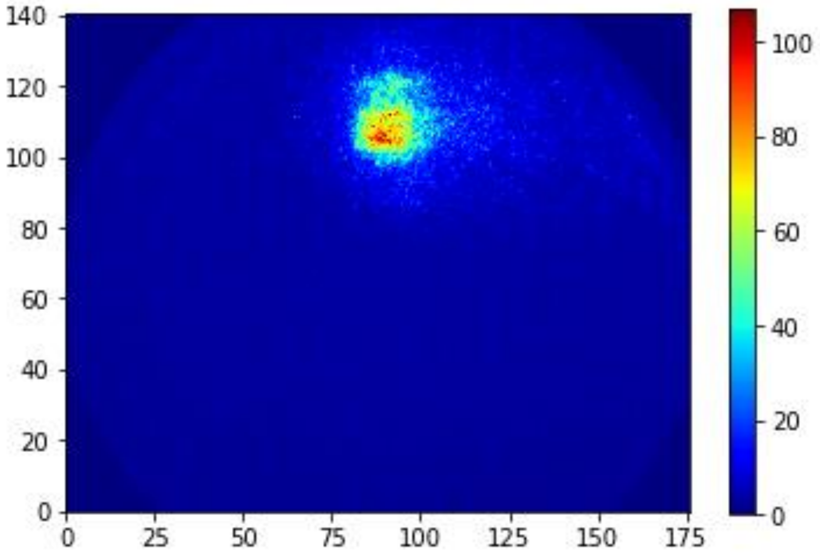
December 2022 - …

Waveguide system training

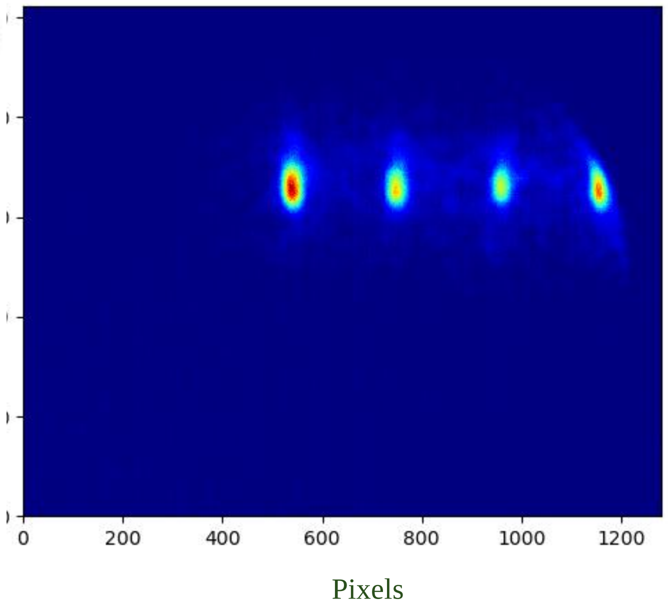


Vacuum measurements during the training

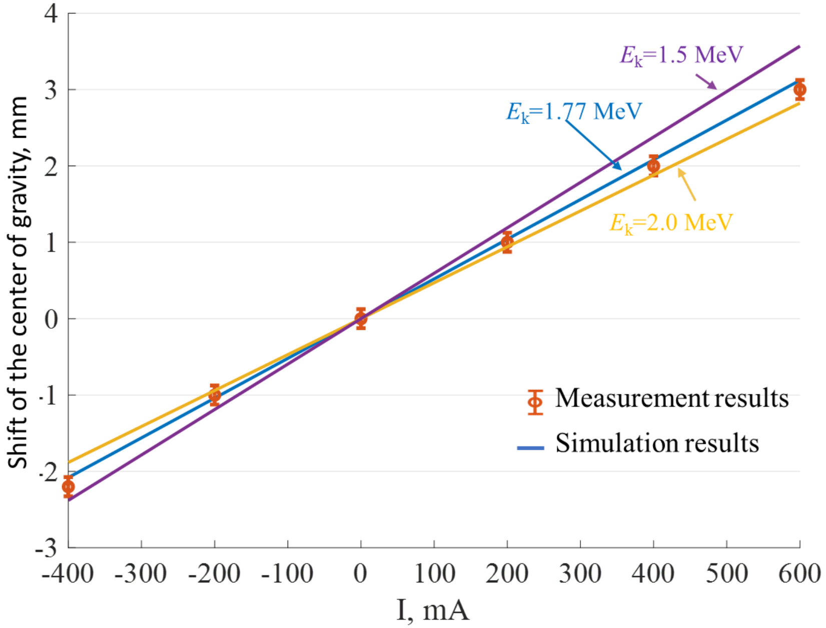
Beam after the preaccelerator (before AS)



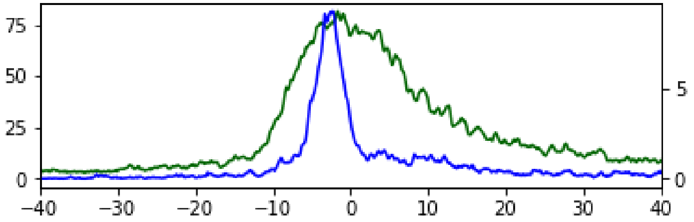
Beam image at the Cherenkov sensor: single bunch



Bunch train with the 5.6 ns period



Beam energy measurements at the klystron power of 19 MW: E = 1.77 MeV

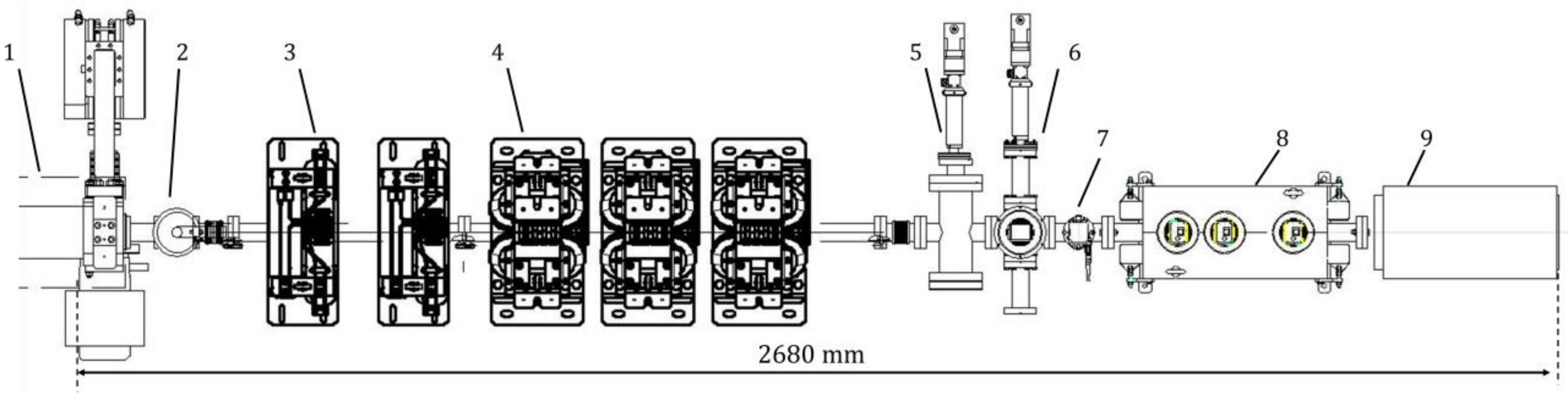


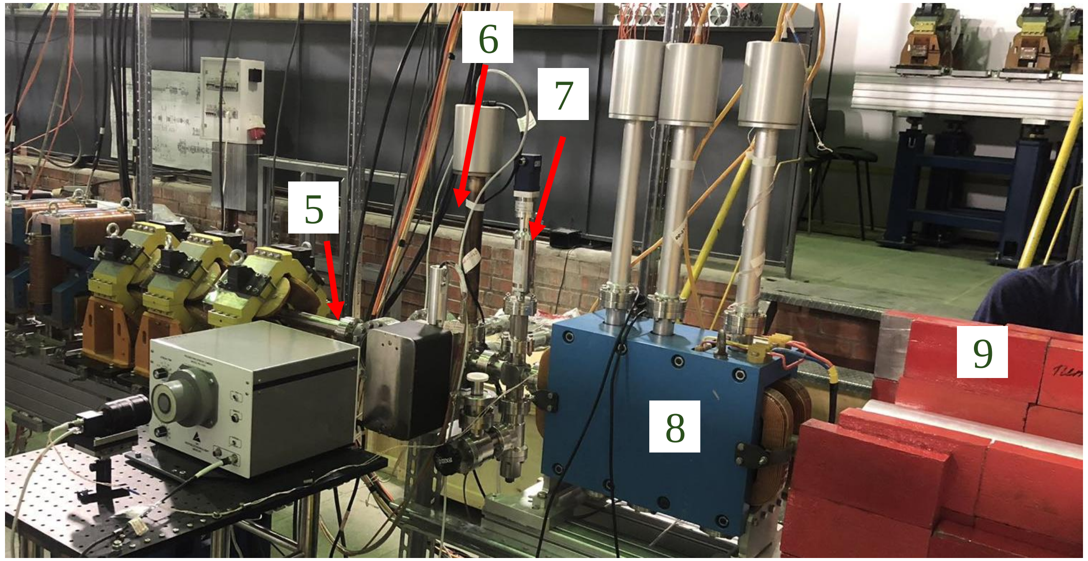
FWHM = 17.7 ps

~~Input power of 10 MW provides the beam energy of 3 MeV~~

Input power of 2 MW provides the beam energy of 1.7 MeV

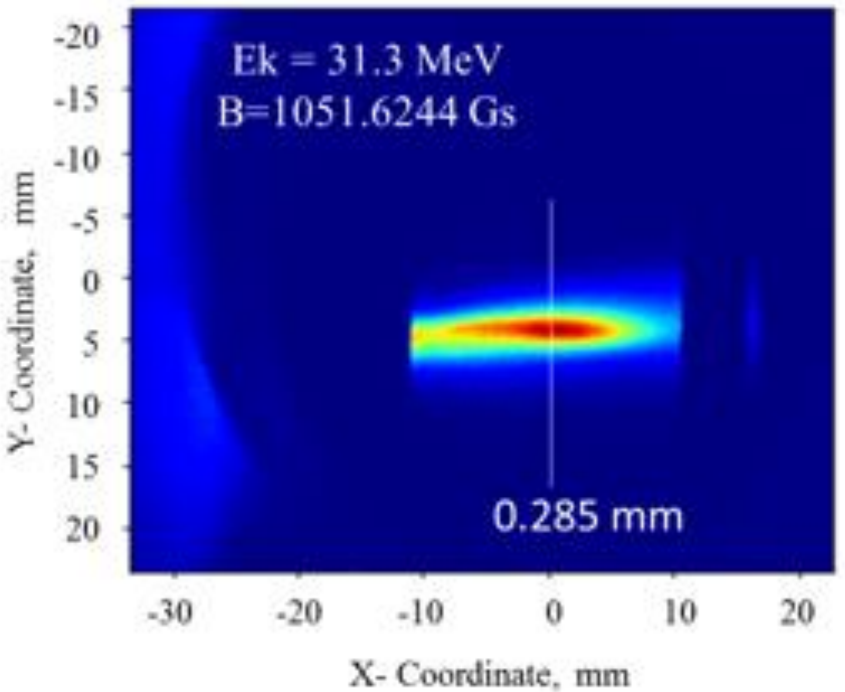
Diagnostics at the end of linac





1	Accelerating structure
2	Gate valve
3	Dipole correctors
4	Quadruples
5	Cherenkov sensor
6	Fluorescent screen
7	Collimator
8	Spectrometer
9	Damp with Faraday cup

First beam at the end of linac

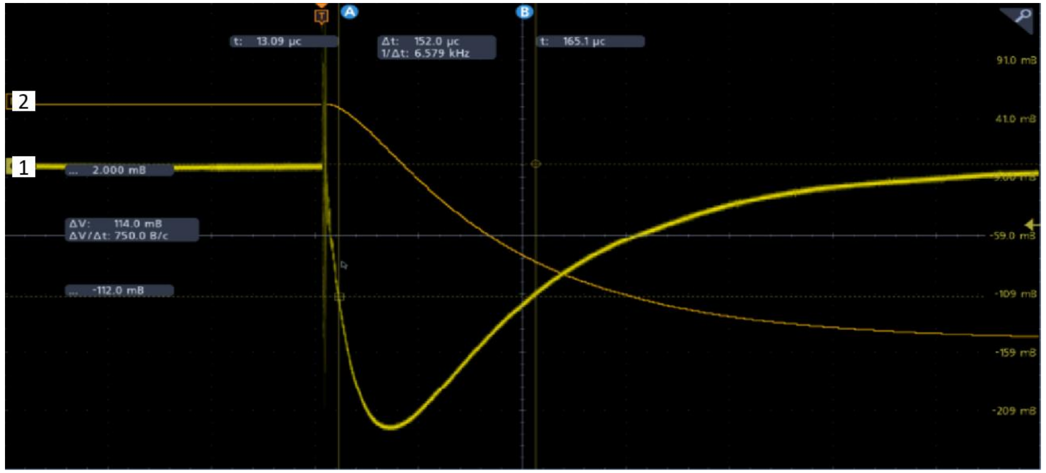


Beam image at the spectrometer screen

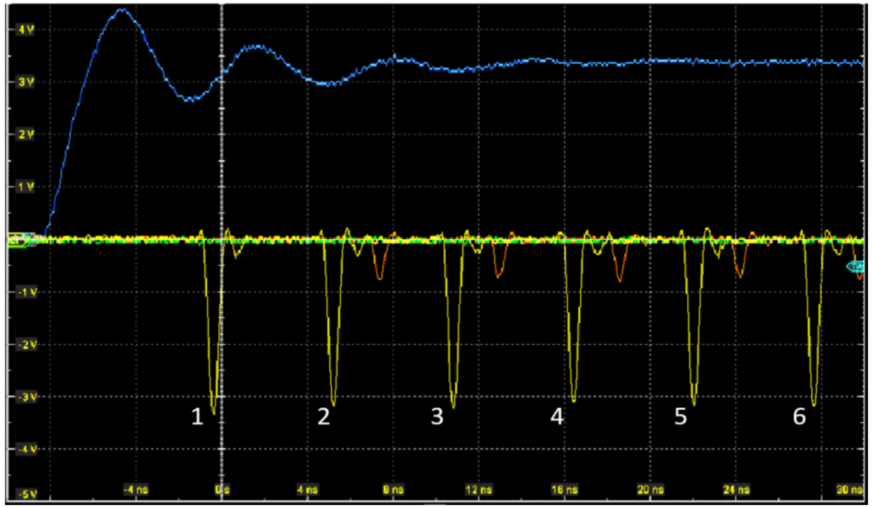
FCT signals: 1 – after the RF gun, 2 – before the preaccelerator, 3 – after the accelerating structure

13.02.2023 – first beam after the accelerating structure, $P_{kl} = 17\ MW$
14.02.2023 – measured energy of 20 MeV
20.02.2023 – measured energy of 30 MeV, 70 % passage
06.06.2023 – 100 % passage, 34 MeV, charge >0.3 nC in the bunched beam (klystron power of 20 MW)

Beam charge



Faraday cup signal, q = 0.3 nC

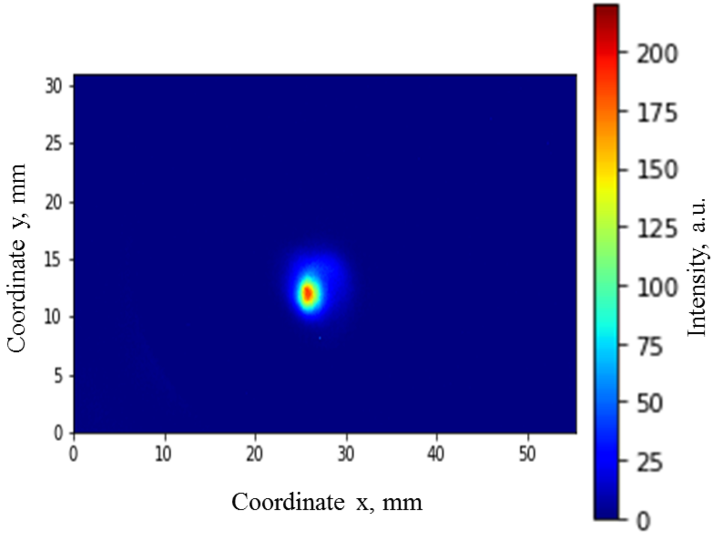


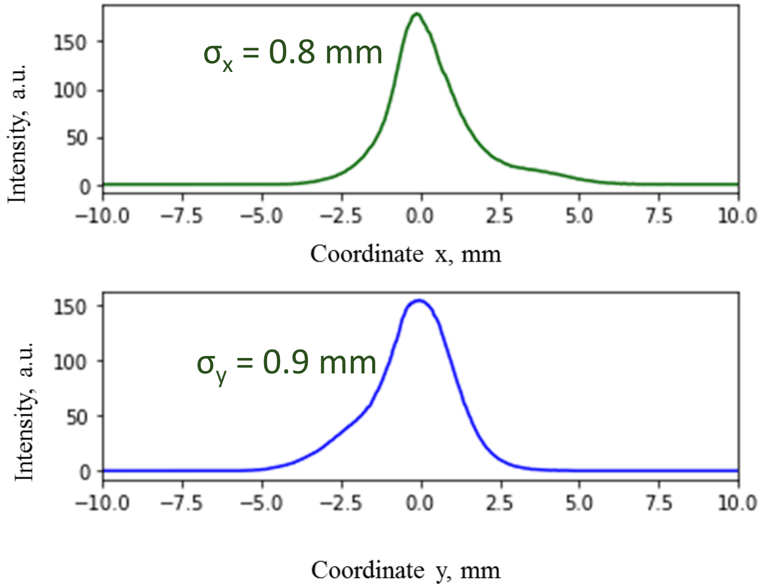
FCT signal after the RF gun
in the multibunch mode

FCT signal in the single bunch mode

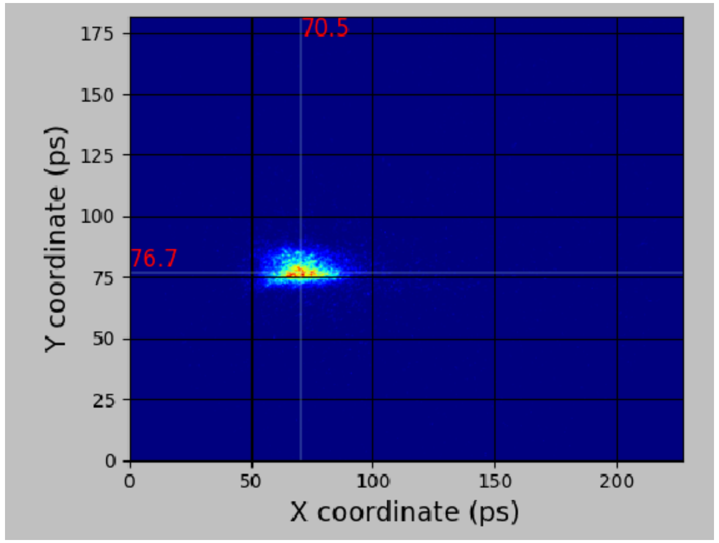
Optimized beam at the end of linac

Beam charge 0.3 nC



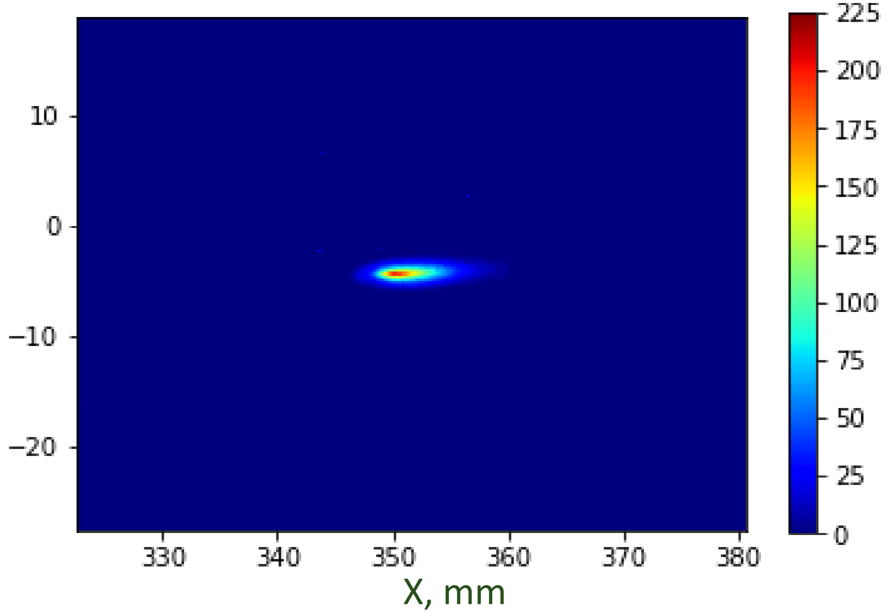


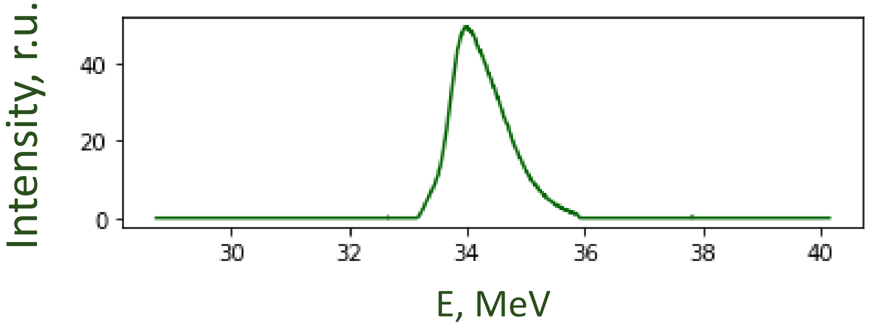
Beam image at the fluorescent screen at the linac end



Beam image at the Cherenkov screen at the linac end, FWHM=19 ps

Beam energy, energy spread





Beam image at the spectrometer screen with the collimator

In the 0.3 nC mode:
E=34 MeV
ΔE = 0.98 MeV (FWHM)

Conclusions

Done:

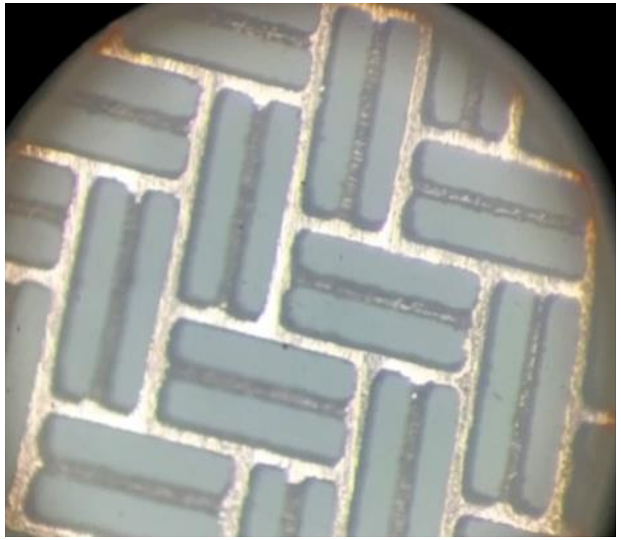
- Achieved stable work with the beam at the fully assembled linac, 100% beam passage
- Beam parameters correspond to the simulations results
- A number of improvements noticed for the full linac version

To be done:

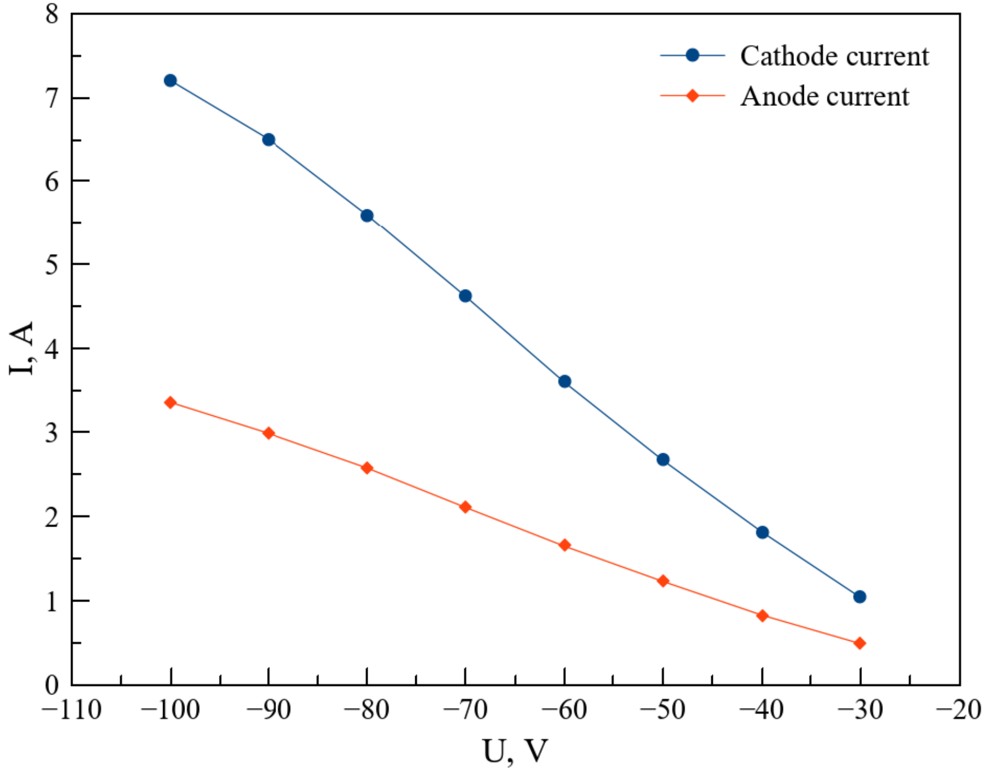
- Clarify emittance measurements
- Attempt to increase RF power in the accelerating structures → get closer to required parameters up to the technical specifications
- Work in the multibunch mode

Cathode assembly

Cathode-grid assembly (NPO Toriy)

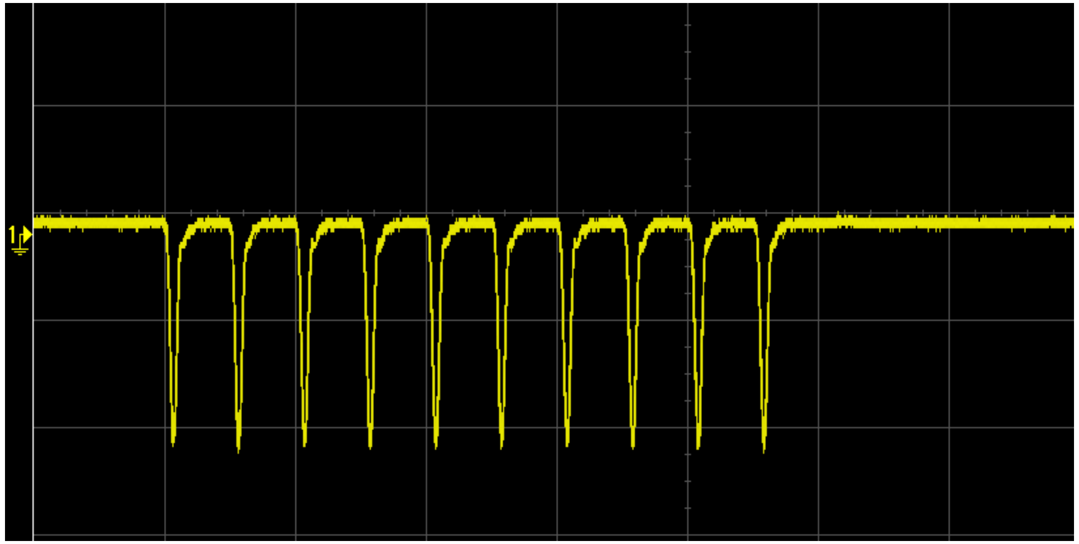


Parquet grid



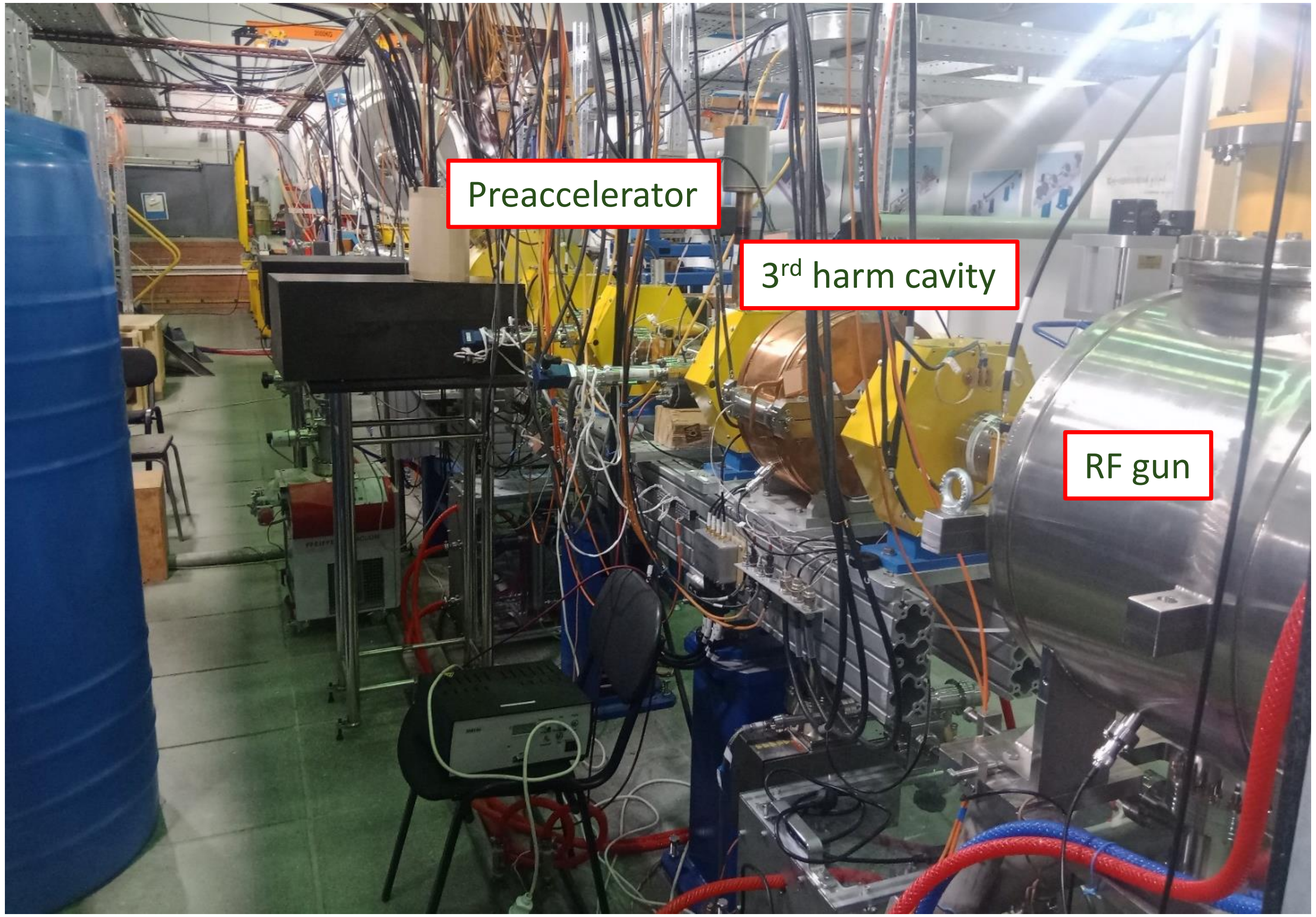
Beam current modulator

Modulator



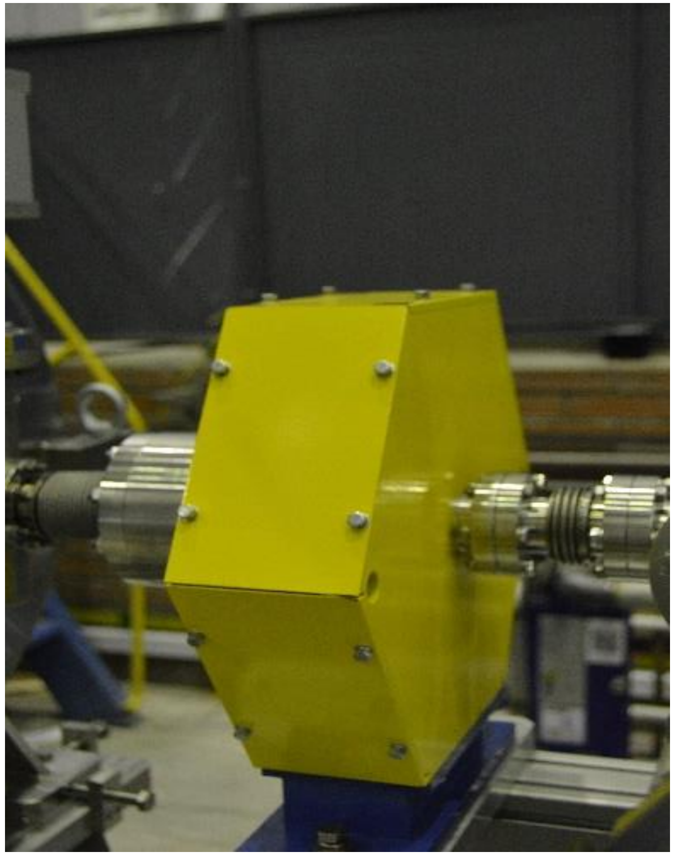
10 modulator pulses with the frequency of 178.5 MHz and duration of 1 ns, voltage -120 V

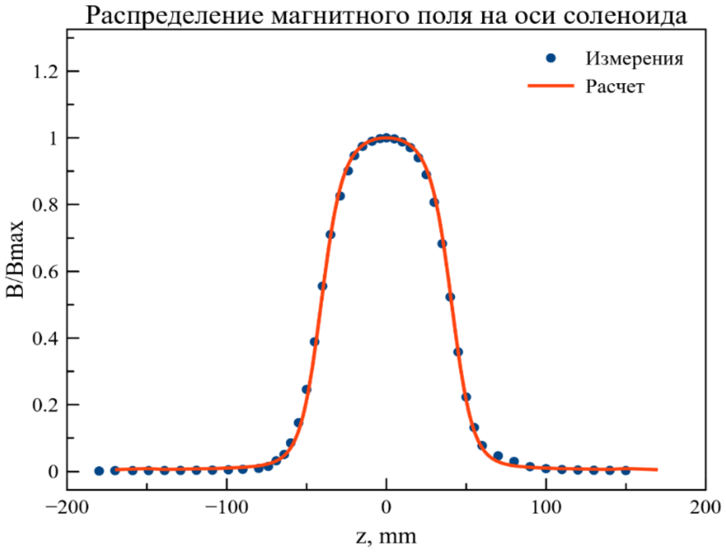
Bunching channel

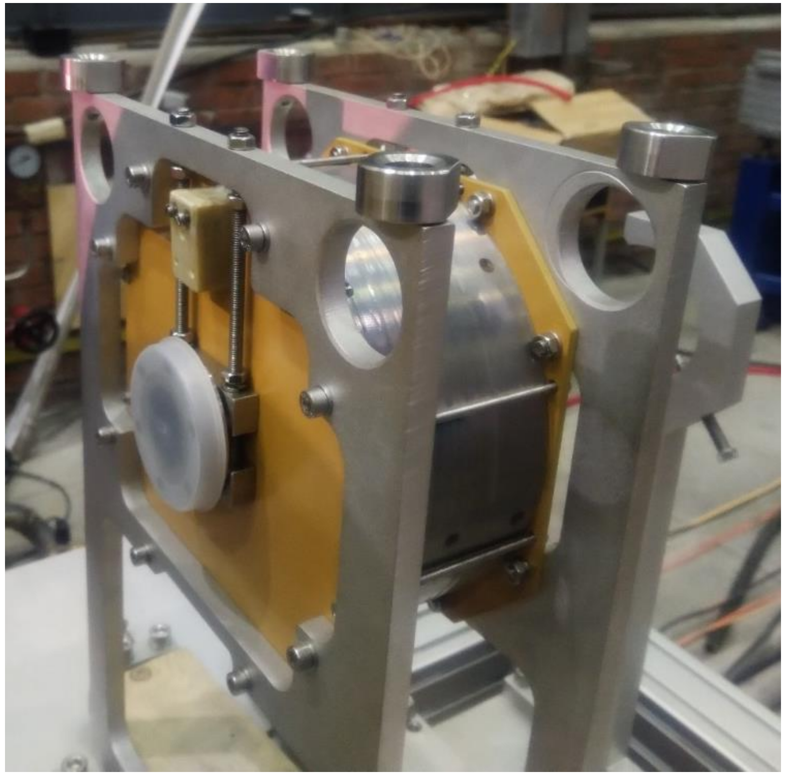


Magnet system

Solenoid of the bunching channel

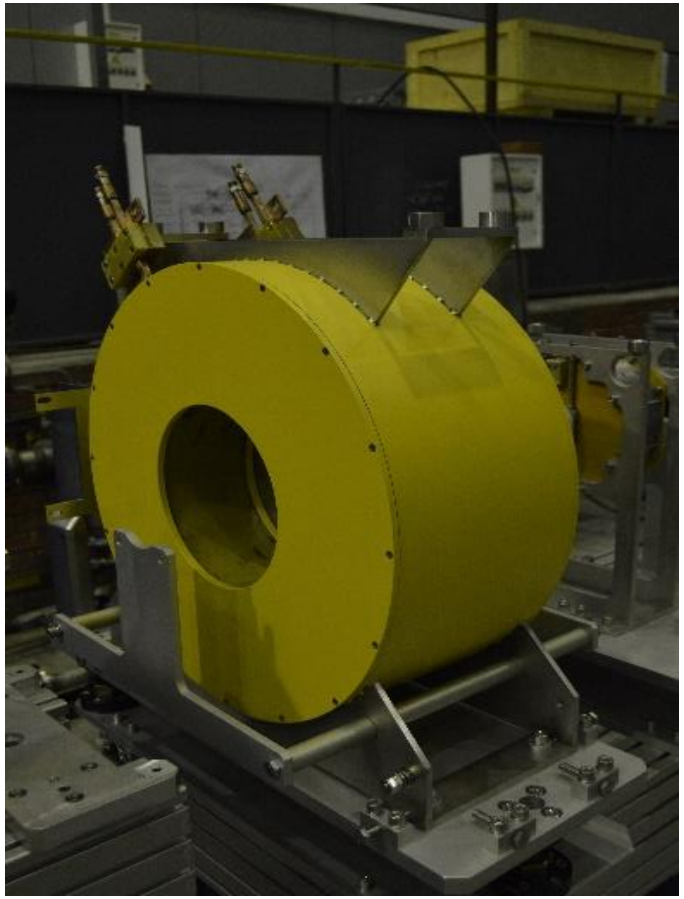






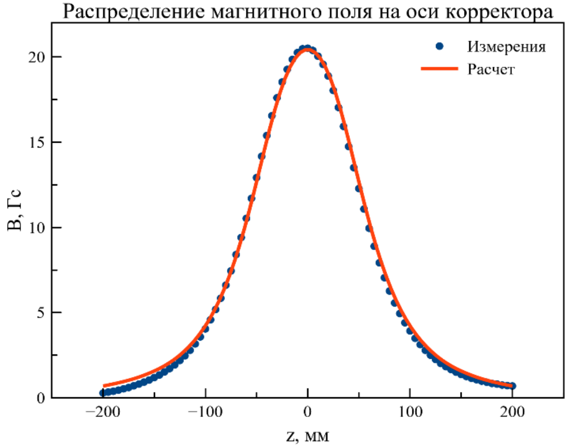
Matching solenoid

Magnet system

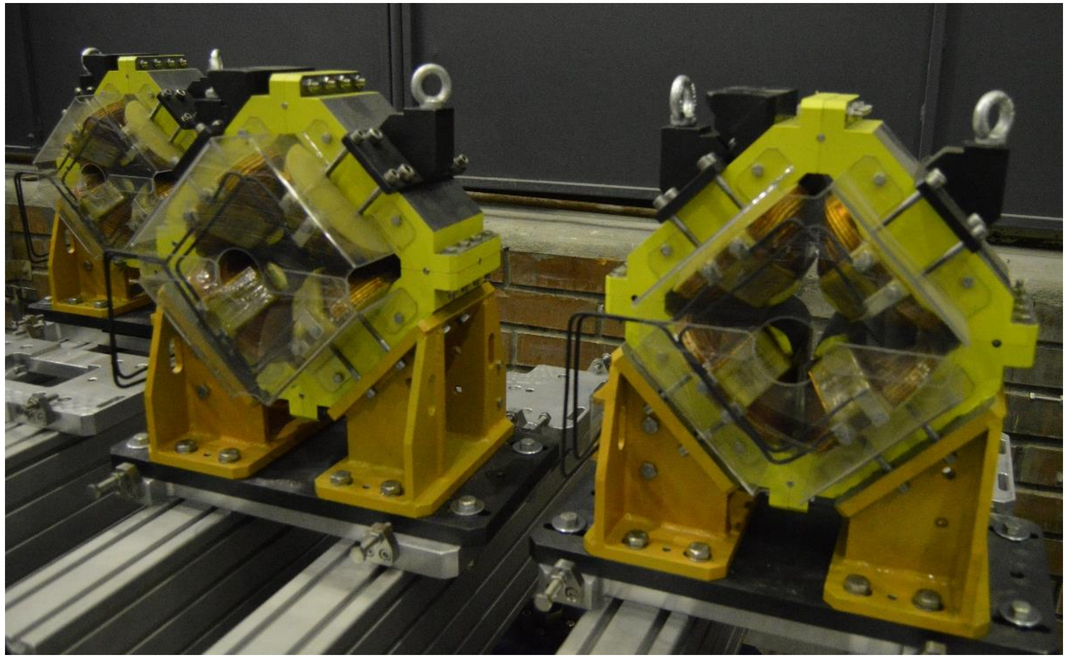


Preaccelerator solenoid

Corrector of the bunching channel

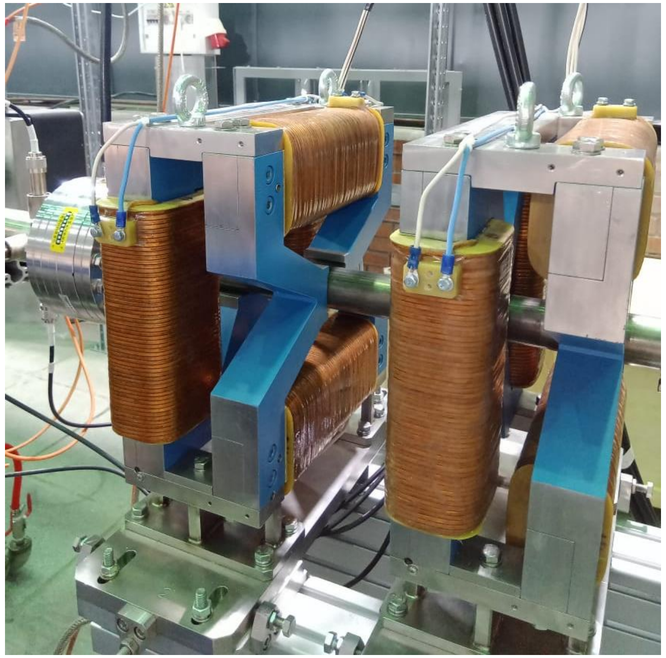


Magnets after the AS



Quadruple lenses after the accelerating structure

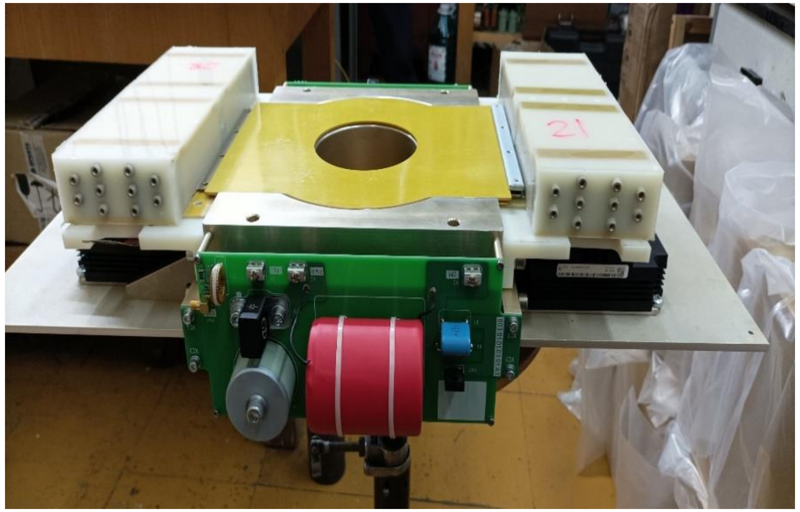
Number	Measured field integral, T	Current, A
3	0.6083	6



Dipole correctors after the accelerating structure

Type	Number	Field, Gs
Corrector	2	470

Klystron modulator



Single inductor of the modulator

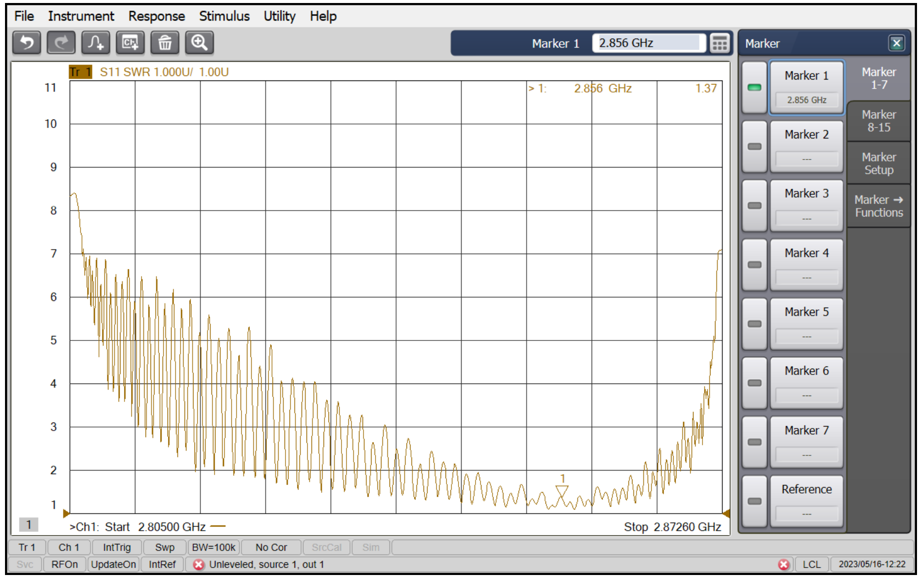
Klystron parameter	Value
Frequency	2856 MHz
Voltage	325 kV
Current	400 A
Input power	500 W
Output power	≥ 50 MW
Average power	5÷10 kW
RF pulse length	≥4 μs

Klystron modulator

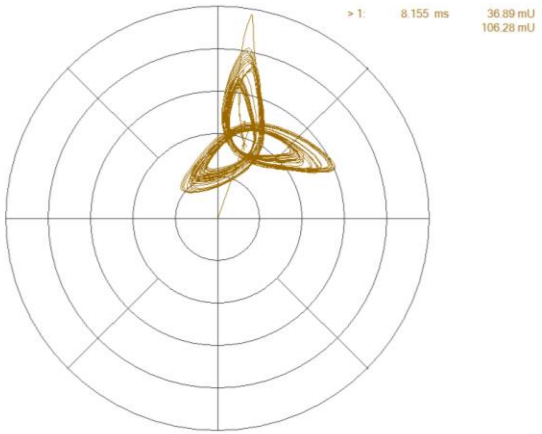
СКИФ

ИЯФ СО РАН

Other accelerating structures



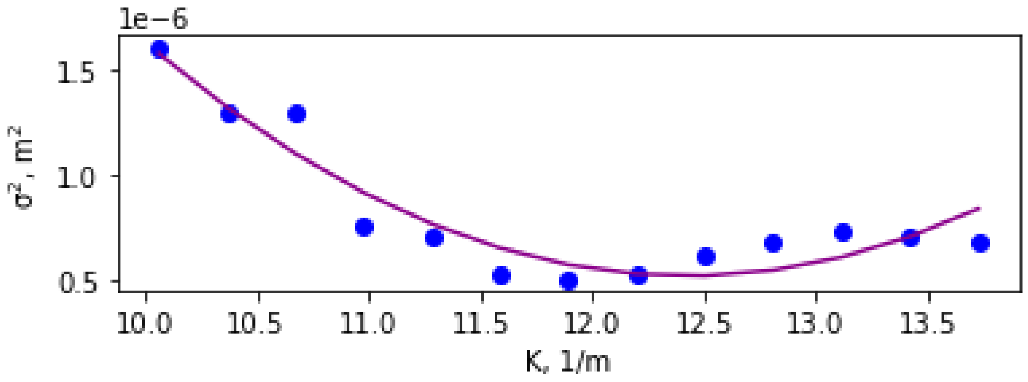
SWR of the accelerating structure



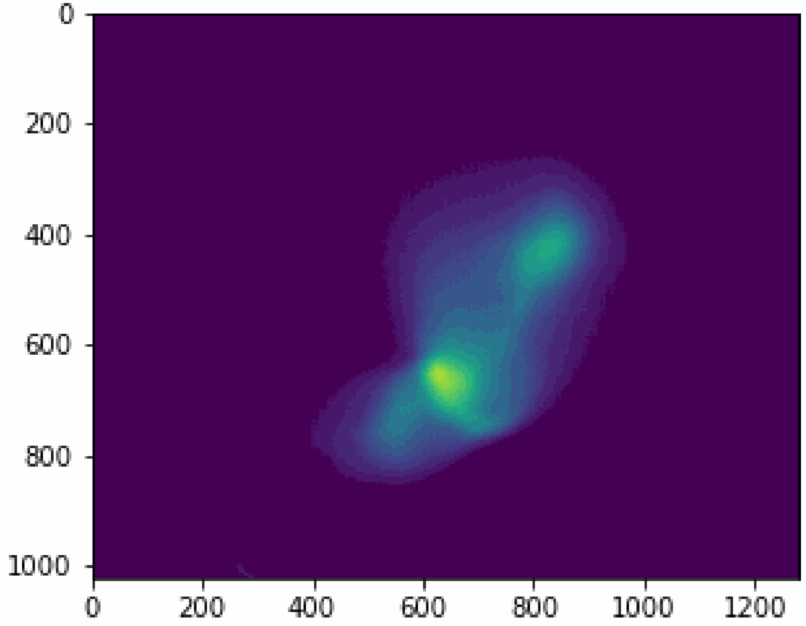
Phase measurements of the next accelerating structure

Manufactured accelerating structures 2-4

Beam after the preaccelerator

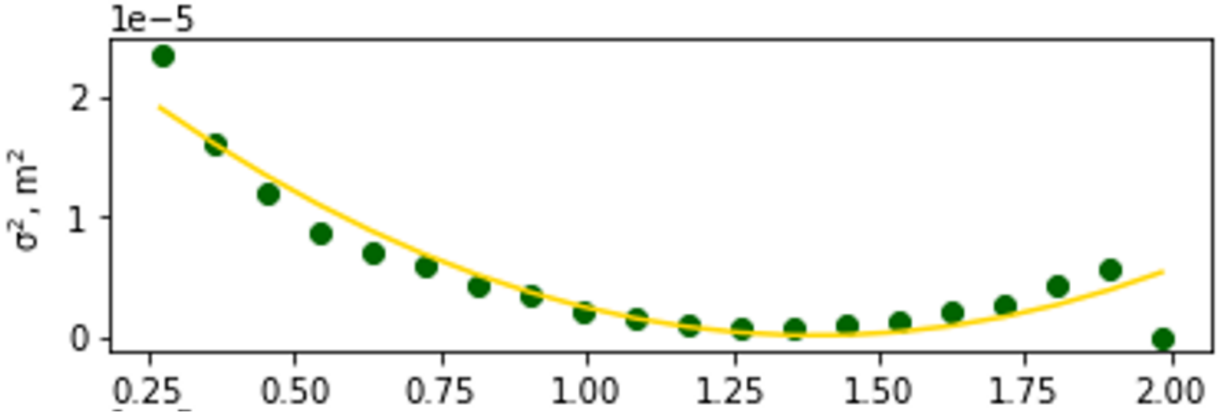


Normalized emittance of 50 mm*mrad

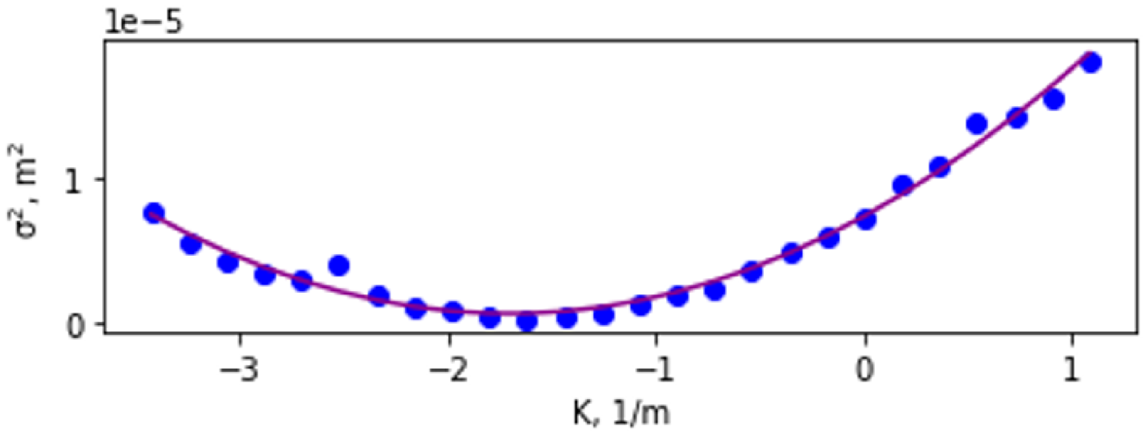


Beam at the fluorescent screen after the detuned preaccelerator at different phases

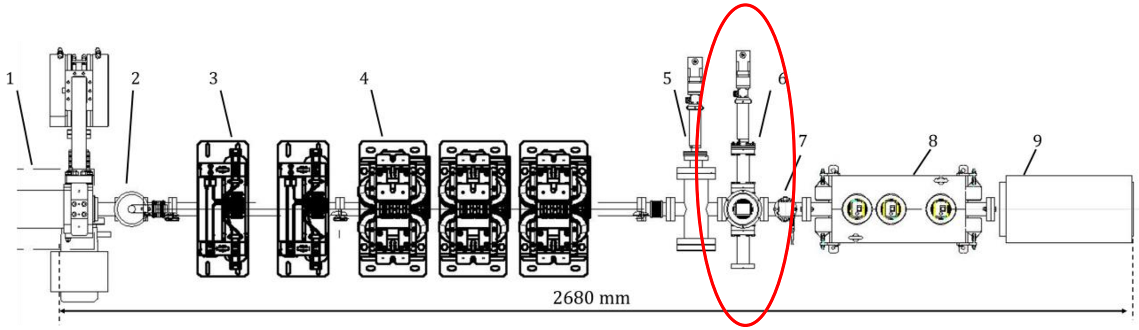
Beam emittance

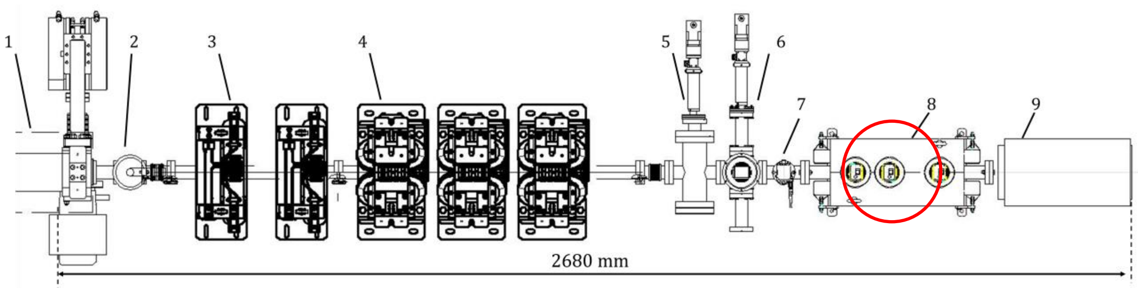


Нормализованный эмиттанс 100 мм мрад после ускоряющей структуры (энергия 34 МэВ). Сканирование после квадруполя на люминофоре. Заряд 0.3 нКл



Нормализованный эмиттанс 40 мм мрад после ускоряющей структуры (энергия 34 МэВ). Сканирование после квадруполя на люминофоре спектрометра. Заряд 0.6 нКл



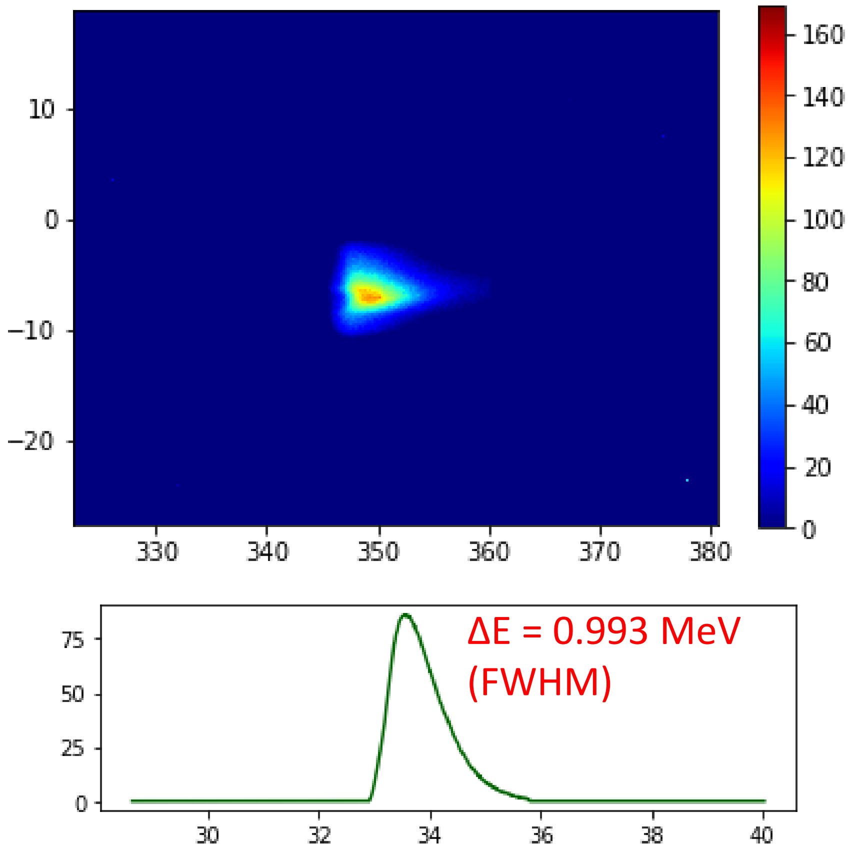


На данный момент есть несоответствие эмиттанса с расчетом, а также разные его значения являются самой нерешенной задачей. Значения эмиттансов:

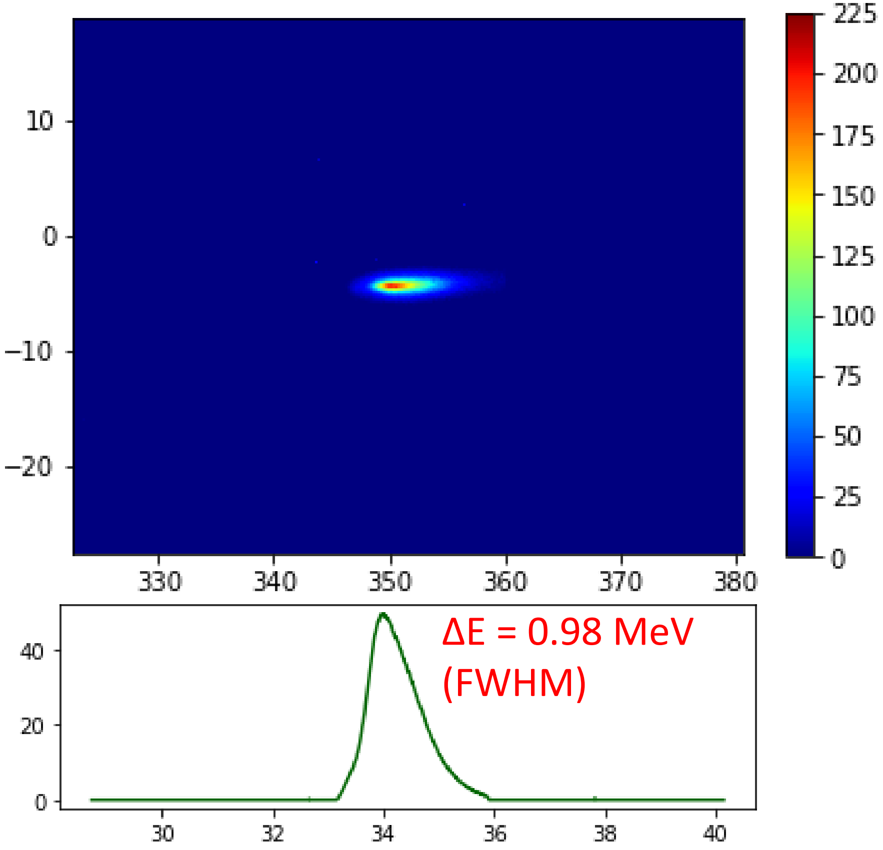
После пушки 20 мм мрад
После предускорителя 50 мм мрад
После УС на люминофоре 100 мм мрад
После УС на спектрометре 40 мм мрад

?

Beam energy spread



Beam charge of 0.6 nC

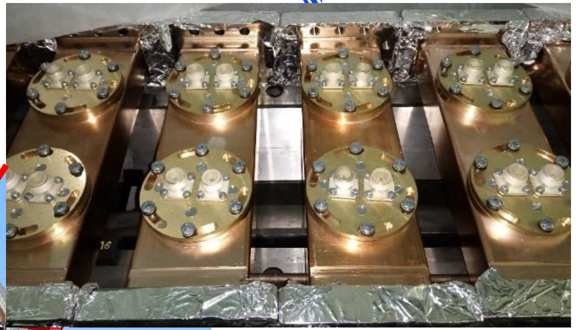


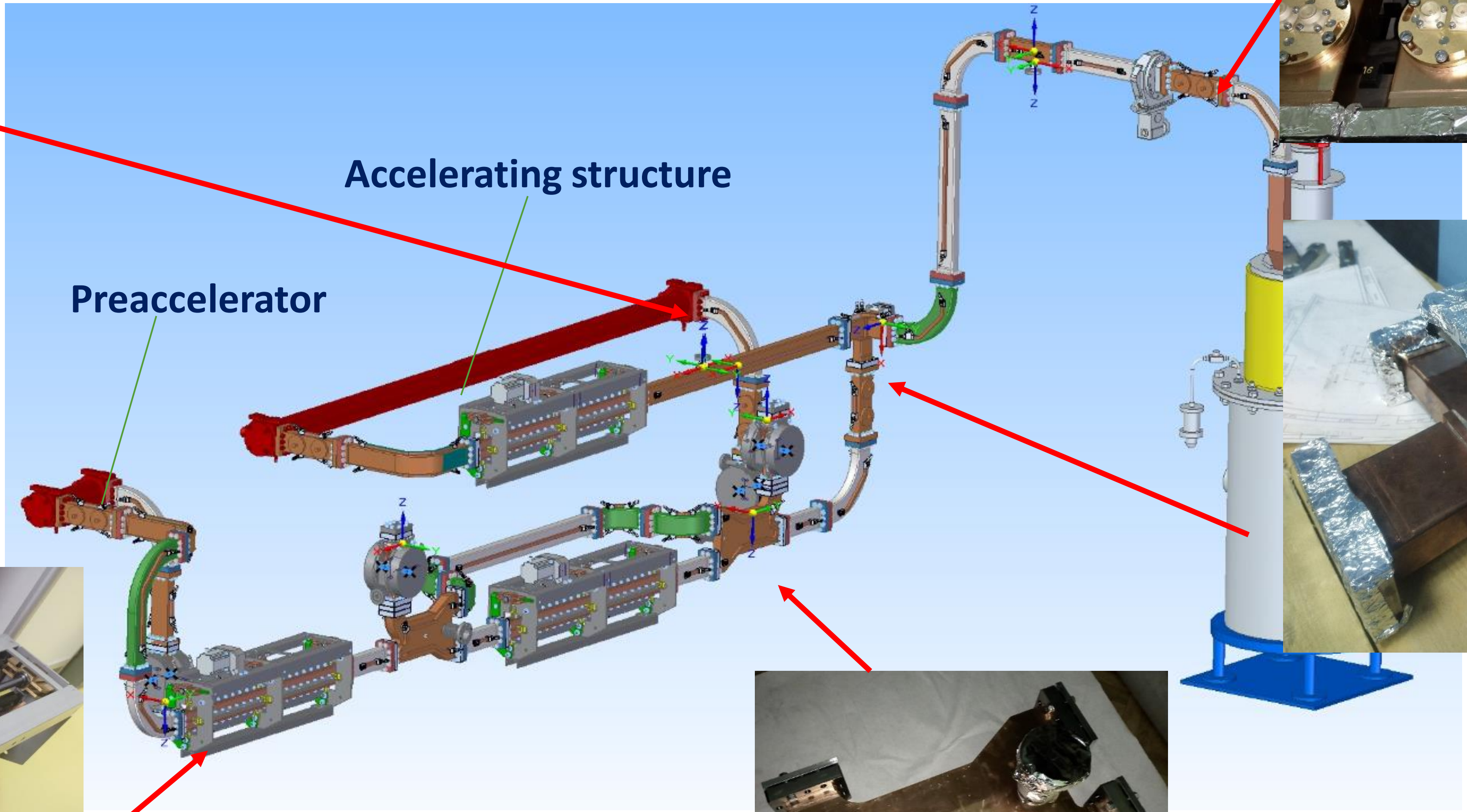
Beam charge of 0.3 nC

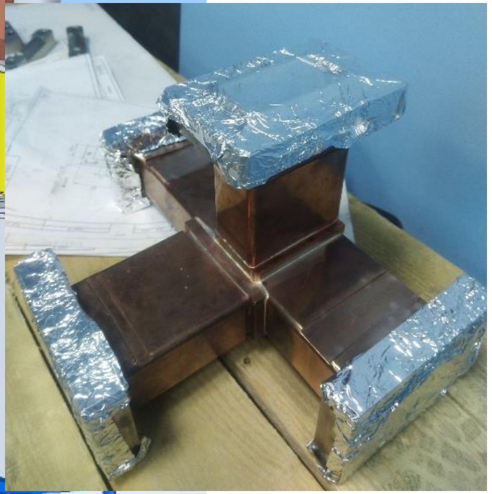
Waveguide system

RF loads

Meas. couplers





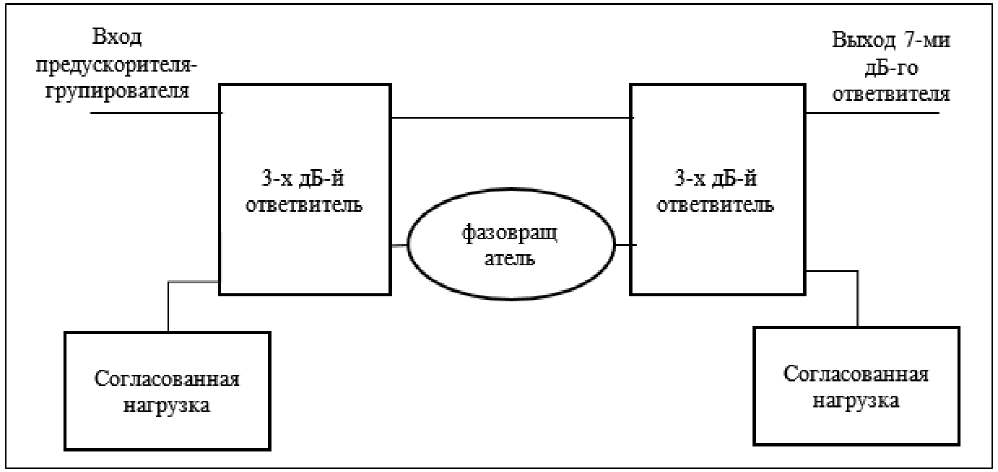


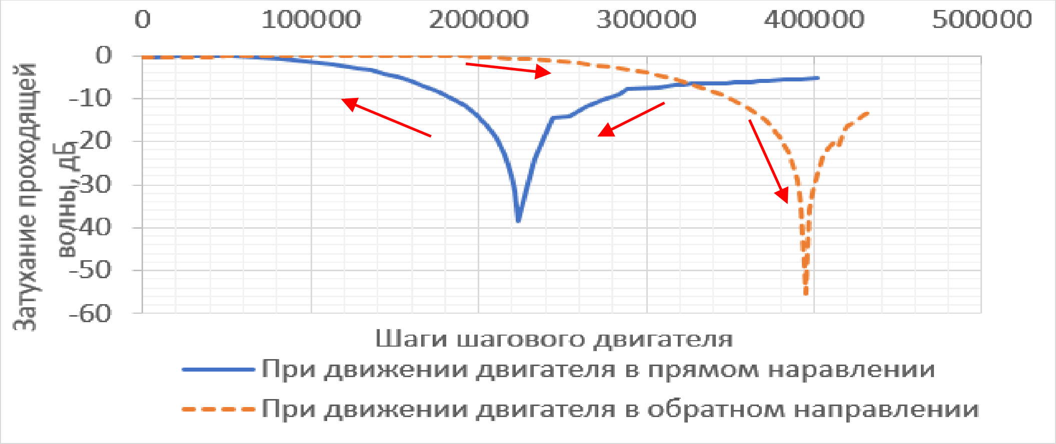
7dB coupler

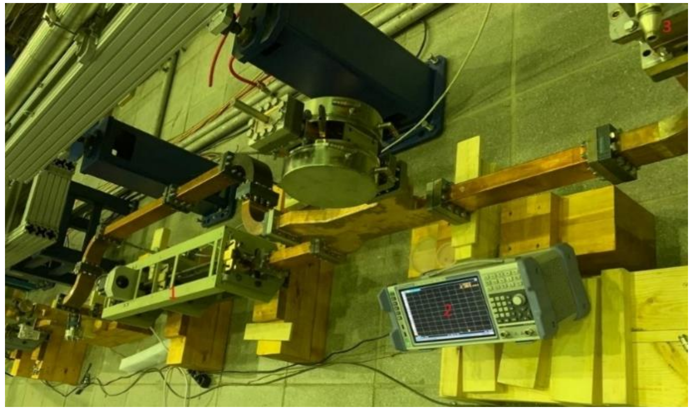
Phase shifter

3 dB coupler

Attenuator and 7 dB coupler



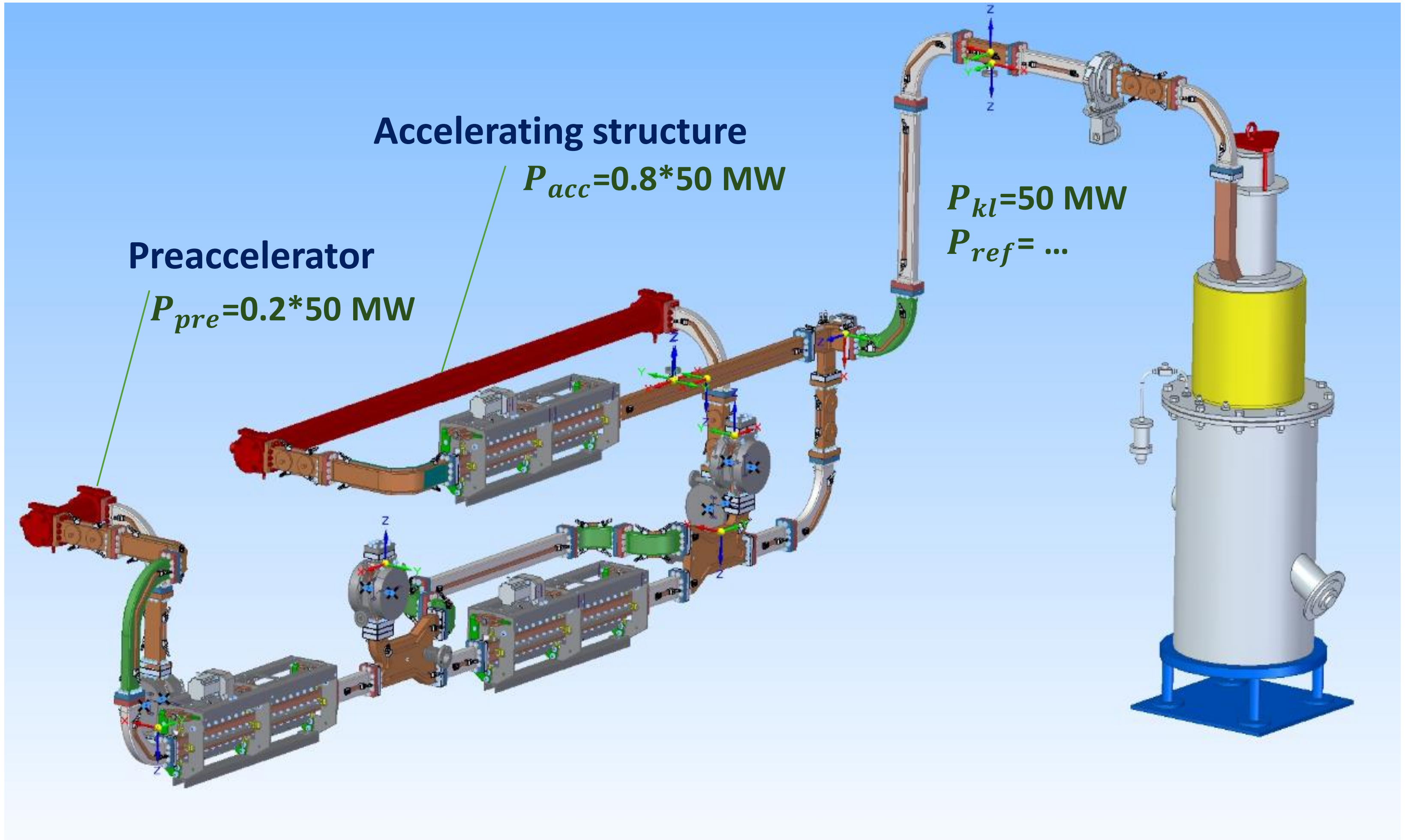




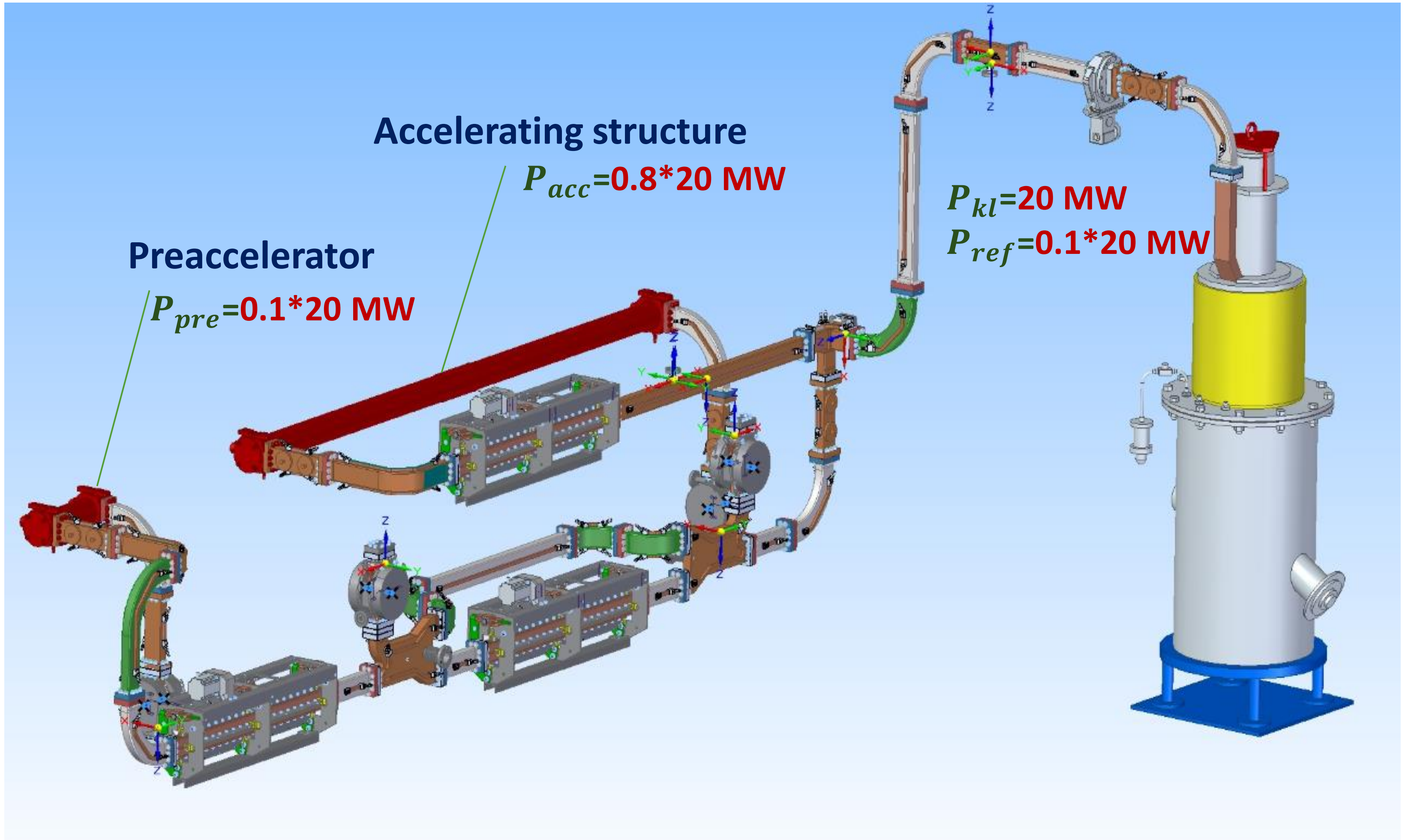
Attenuator for the preaccelerator

7 dB coupler during the measurements

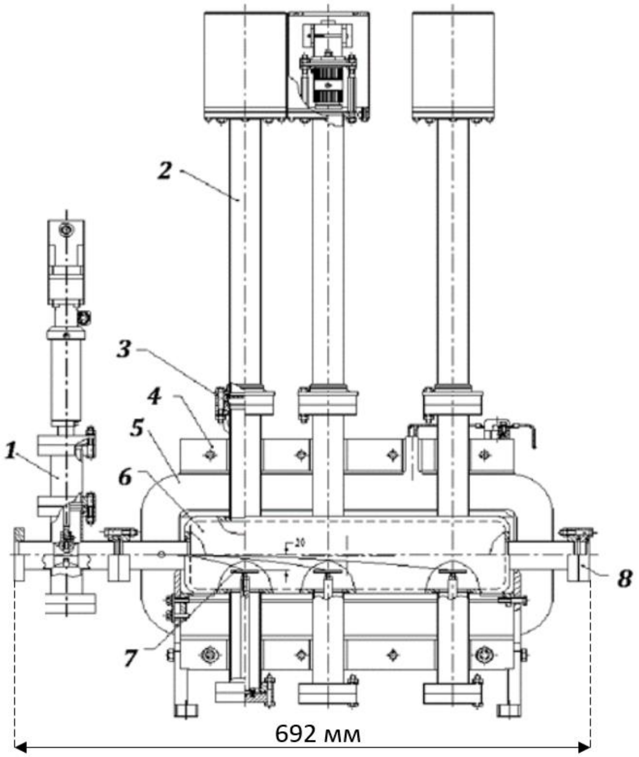
Power balance – planned

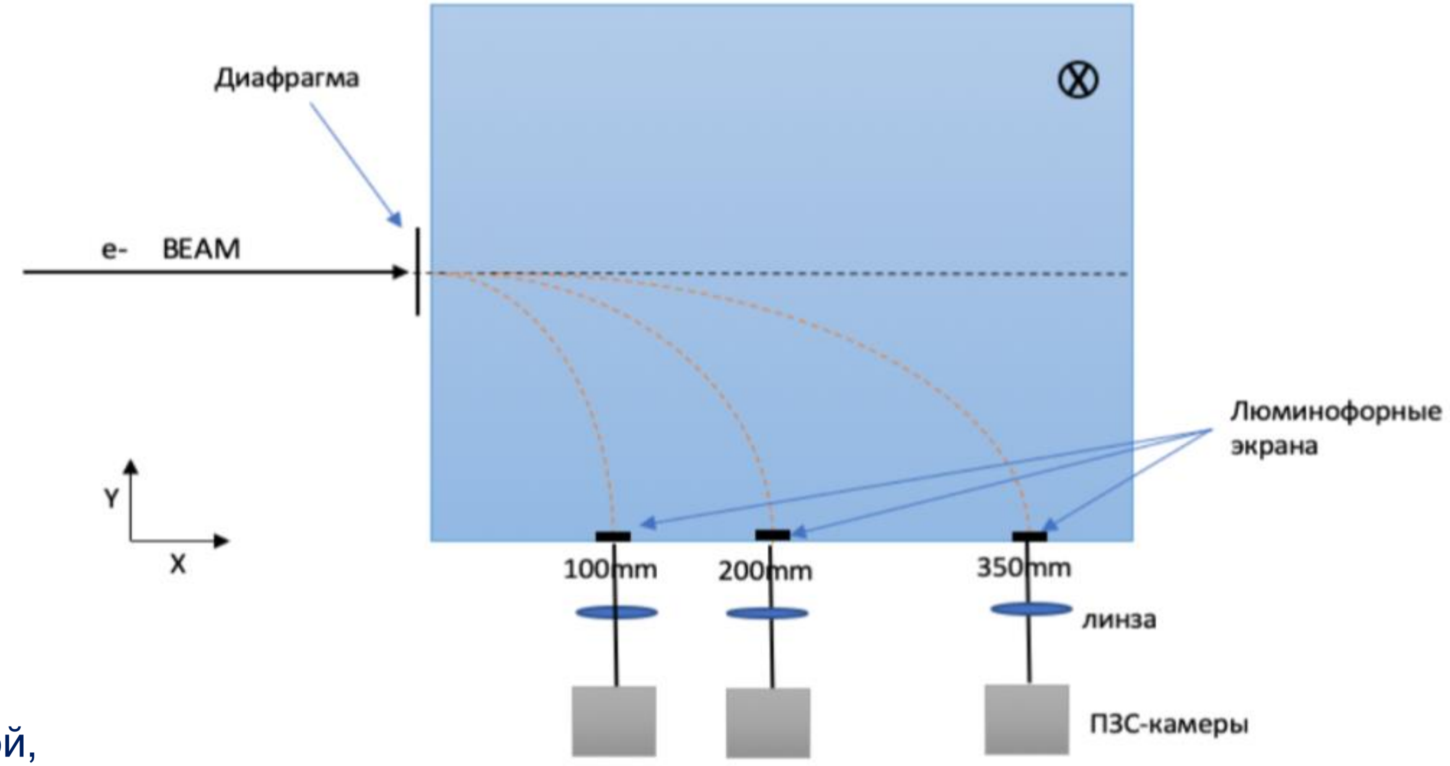


Power balance – reality



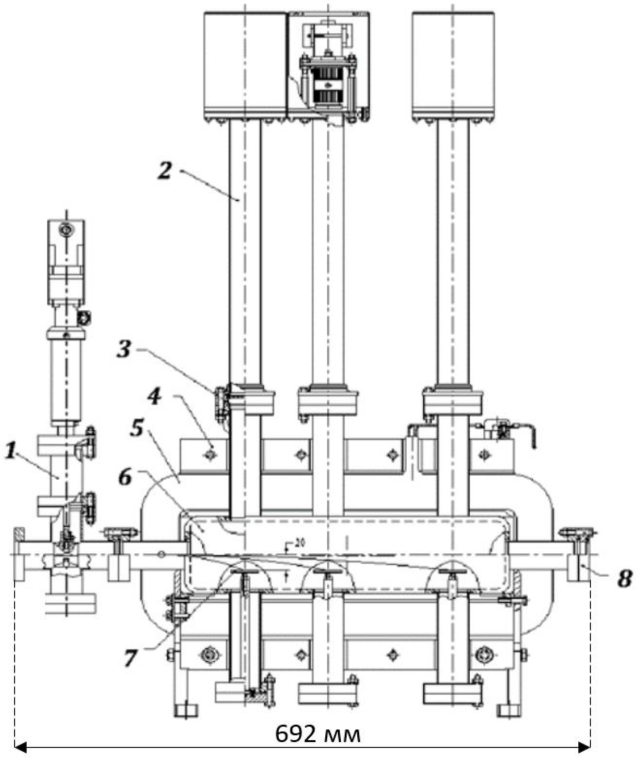
Dipole spectrometer





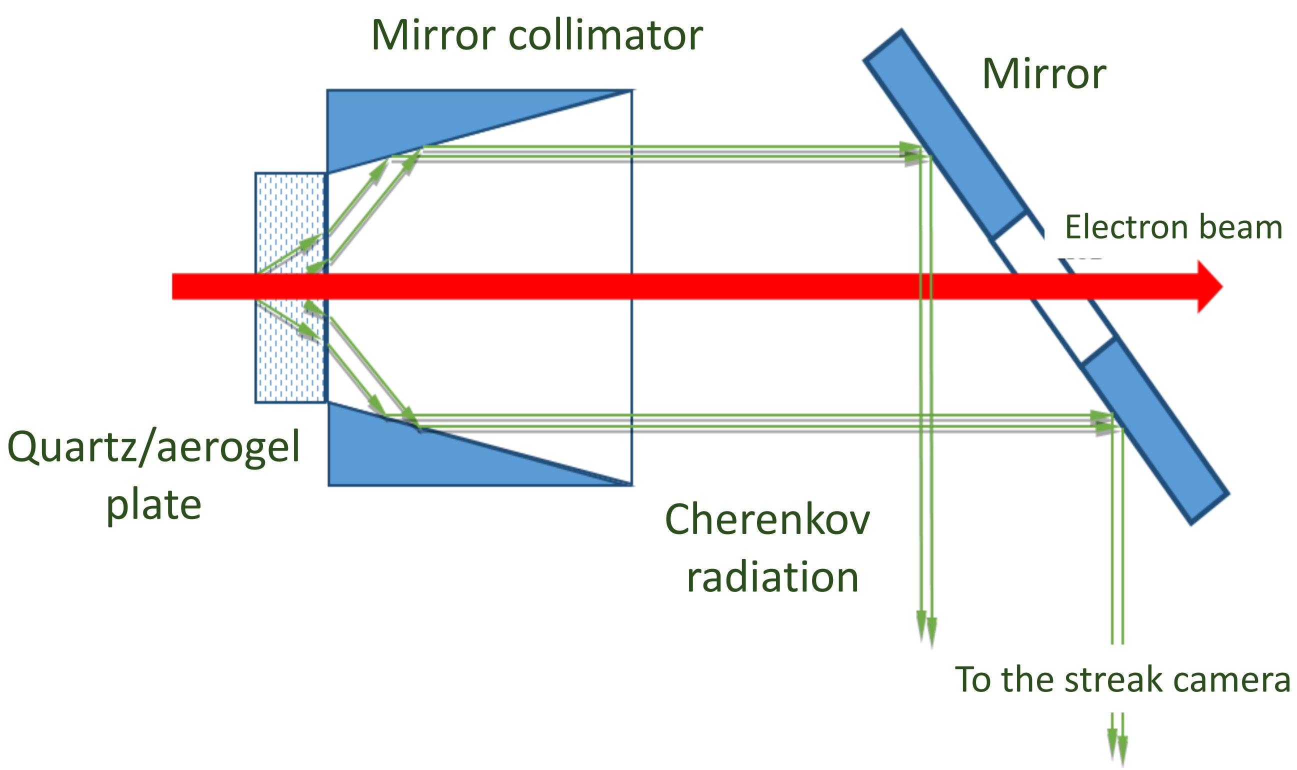
1) коллиматор, 2) сборка с цифровой камерой,
3) вакуумное окно, 4) ярмо магнита, 5) обмотки,
6) вакуумная камера, 7) люминофоры,
8) титановое выпускное окно.

Dipole spectrometer



1) коллиматор, 2) сборка с цифровой камерой,
3) вакуумное окно, 4) ярмо магнита, 5) обмотки,
6) вакуумная камера, 7) люминофоры,
8) титановое выпускное окно.

Cherenkov screens

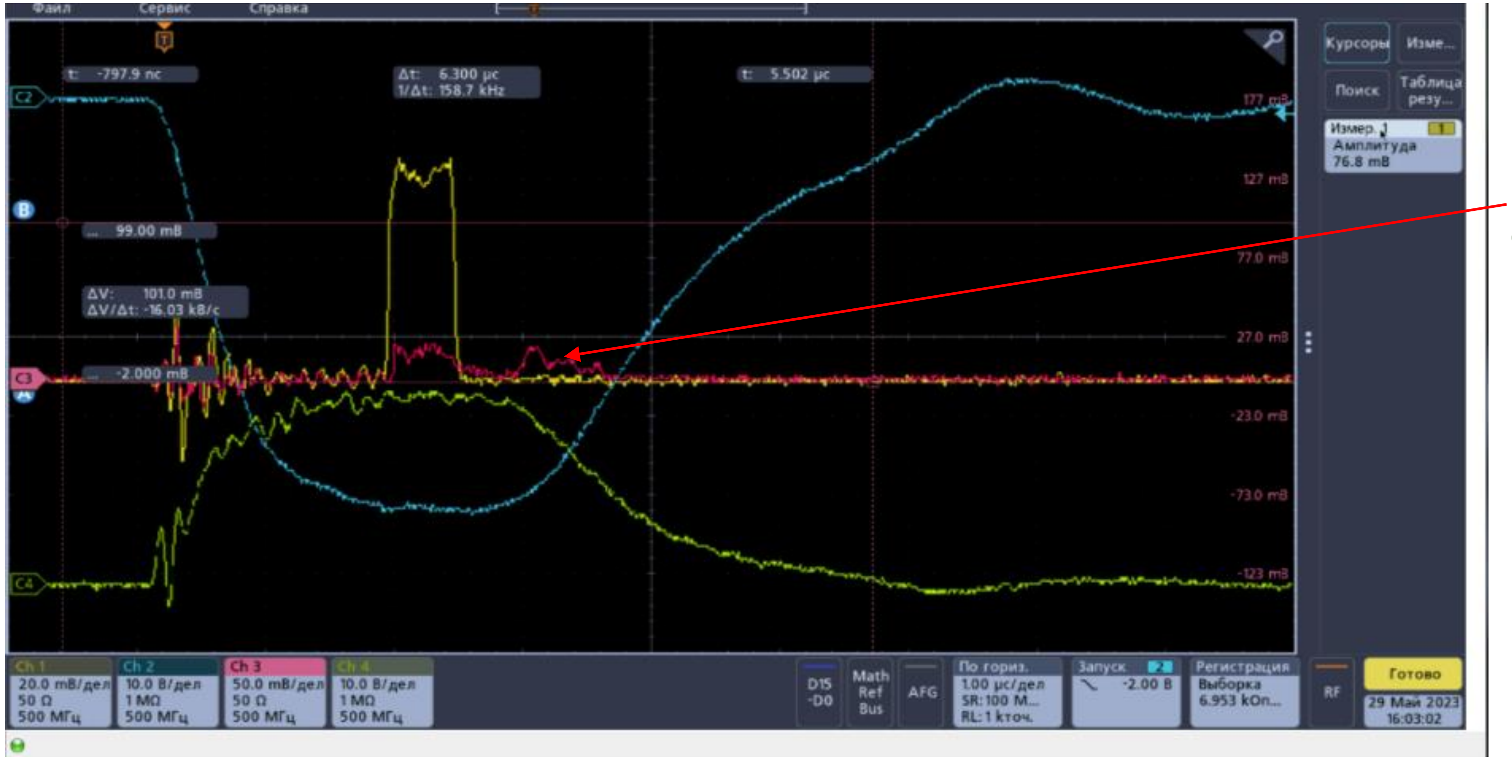


Размер пучка, мм	Коэф.преломления вещества радиатора	Врем.разрешение, пс
1	1.46	3
3	1.46	9
5	1.46	15
7	1.46	21
1	1.05	1
3	1.05	3
5	1.05	5
7	1.05	7

Waveguide system training – stable mode

Power signals in the stable mode after the long-lasting trainings

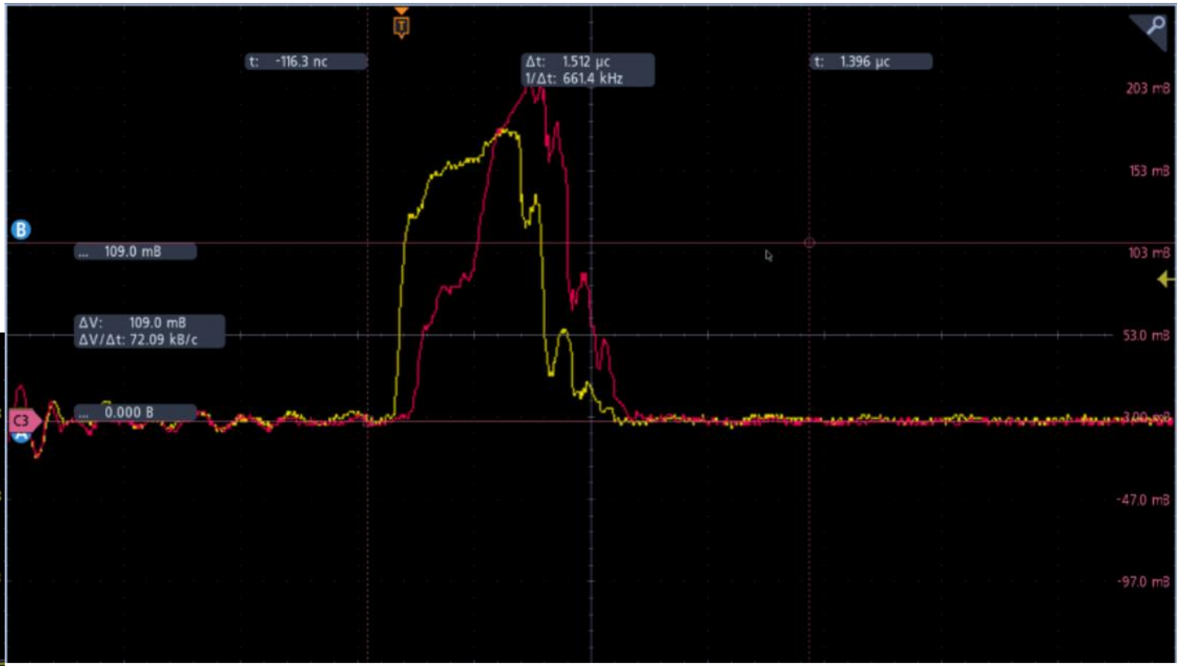
Waveguide system training – to be studied

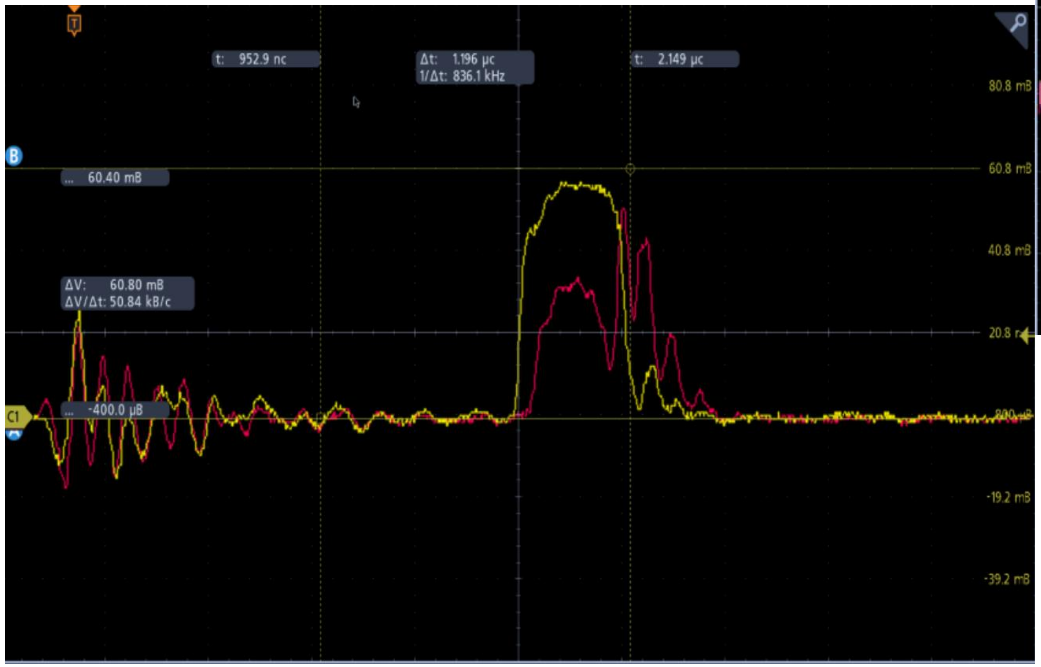


Significant reduce of the reflected power

During the work with the phase shifter we found the mode with the reduced reflected signal. Possibly, in this phase mode we can increase the klystron power from 20 MW without damaging the klystron window.
The effect is now being analyzed.

Waveguide system training





Power signals after the klystron:
Yellow – klystron output power
Red – reflected to the klystron power