ITEP-TWAC Status Report

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Содержание доклада

- *Общая характеристика комплекса ИТЭФ-ТВН*
- *Статистика по эксплуатации*
- *Основные направления развития комплекса*
- *Анализ результатов модернизации лазерного ионного источника*
- *Первые эксперименты по ускорению и накоплению ионов железа и алюминия*
- *Перспективы повышения интенсивности и мощности ионных пучков*
- *Заключение*

ITEP Accelerator Facility
(Brief history of construction)

1958-1961 - construction of 7 GeV proton synchrotron U-7 with 5 MeV Van de Graaf (Electrostatic) Injector

1967 - construction of 25 MeV linear injector I-2

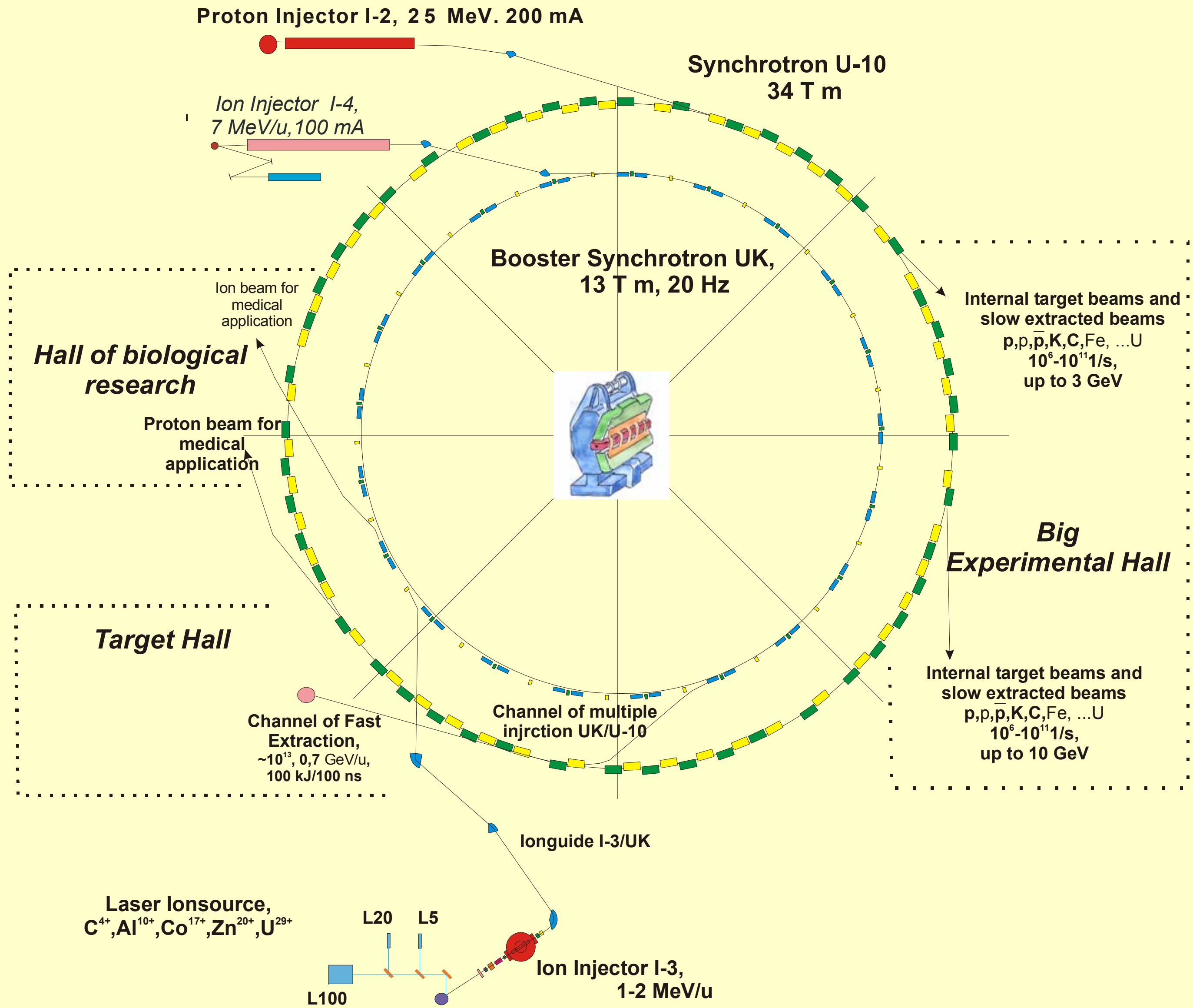
1973 - reconstruction of the U-7 lattice for the machine energy increase up to 10 GeV, accelerator gets hew name U-10

1985 - new project of machine reconstruction was started for heavy ions acceleration, but it was not finished and terminated in 1989

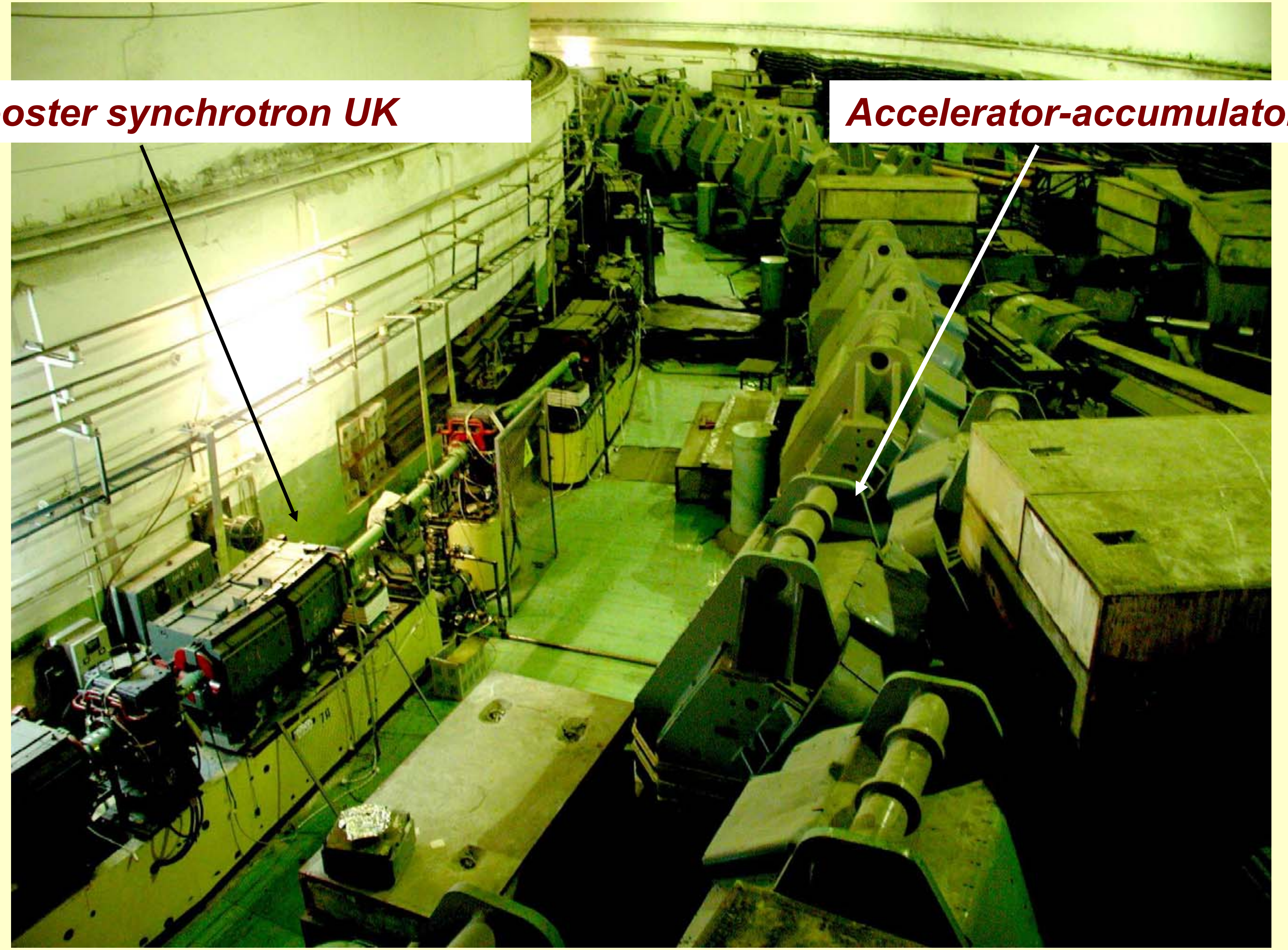
1997-2003 - proton synchrotron U-10 was reconstructed to proton-ion accelerator-accumulator facility ITEP-TWAC

2004-200x – ITEP-TWAC operation for research and applications, optimization of machine parameters, extending of its functional potentialities

ITEP Accelerator Facility



Ring magnets hall of ITEP-TWAC Facility



Booster synchrotron UK

Accelerator-accumulator U-10

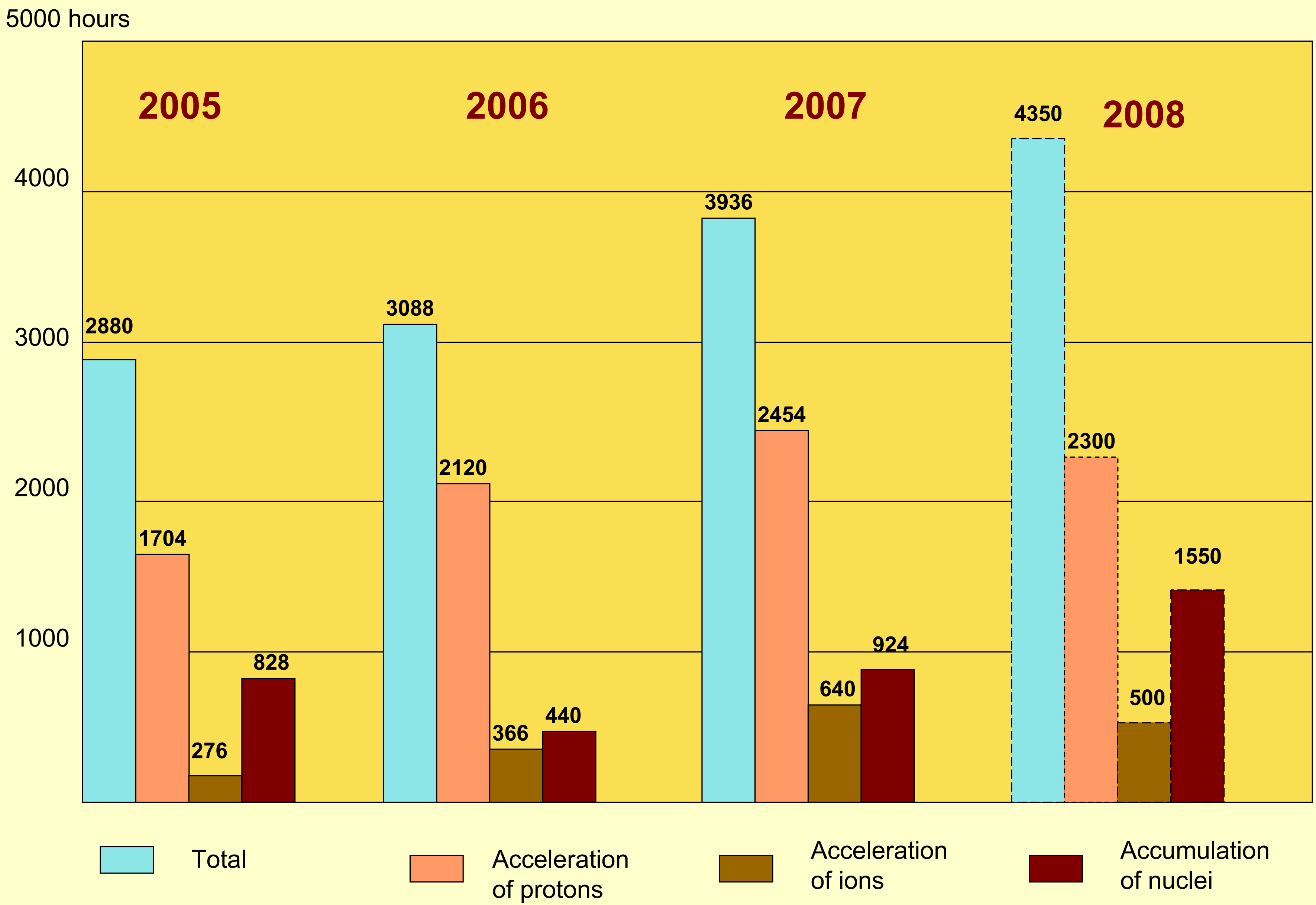
ITEP-TWAC Operation Parameters

Mode of operation	Accelerators	Beam energy, MeV/u	Regime of beam extraction
Proton acceleration	*I-2* *I-2/U-10* *I-2/UK*	25 up to 230 up to 3000 up to 9300 up to 3000 (9300) up to 3000	pulse, 10 μ/s medical extraction, 200 ns, fast extraction, 800 ns, internal target, 1s slow extraction, 1s fast and slow extraction, 0,5s
Ion acceleration, *C, Al, Fe,(Pb,U)*	*I-3/UK* *I-3/UK/U-10*	1,5 – 400 50 - 4000	fast extraction, 800 ns, slow extraction, 0,5s internal target, 1s, slow extraction, 1s
Nuclei accumulation, *C, Al,Fe, (Co,Zn)*	*I-3/UK/U-10*	200-300 700-1000	fast extraction with compression to 150 ns, continue extraction of stacking beam

Operation time of ITEP-TWAC Facility in 2007 is 3936 hours:

2454 h - proton acceleration (at energy of 2,5GeV - 1908 h, at energy 9 GeV - 360 h),
924 h – nuclei accumulation up to the energy of 200-300 MeV/u,
648 h – carbon nuclei acceleration up to the energy of 4 GeV/u.

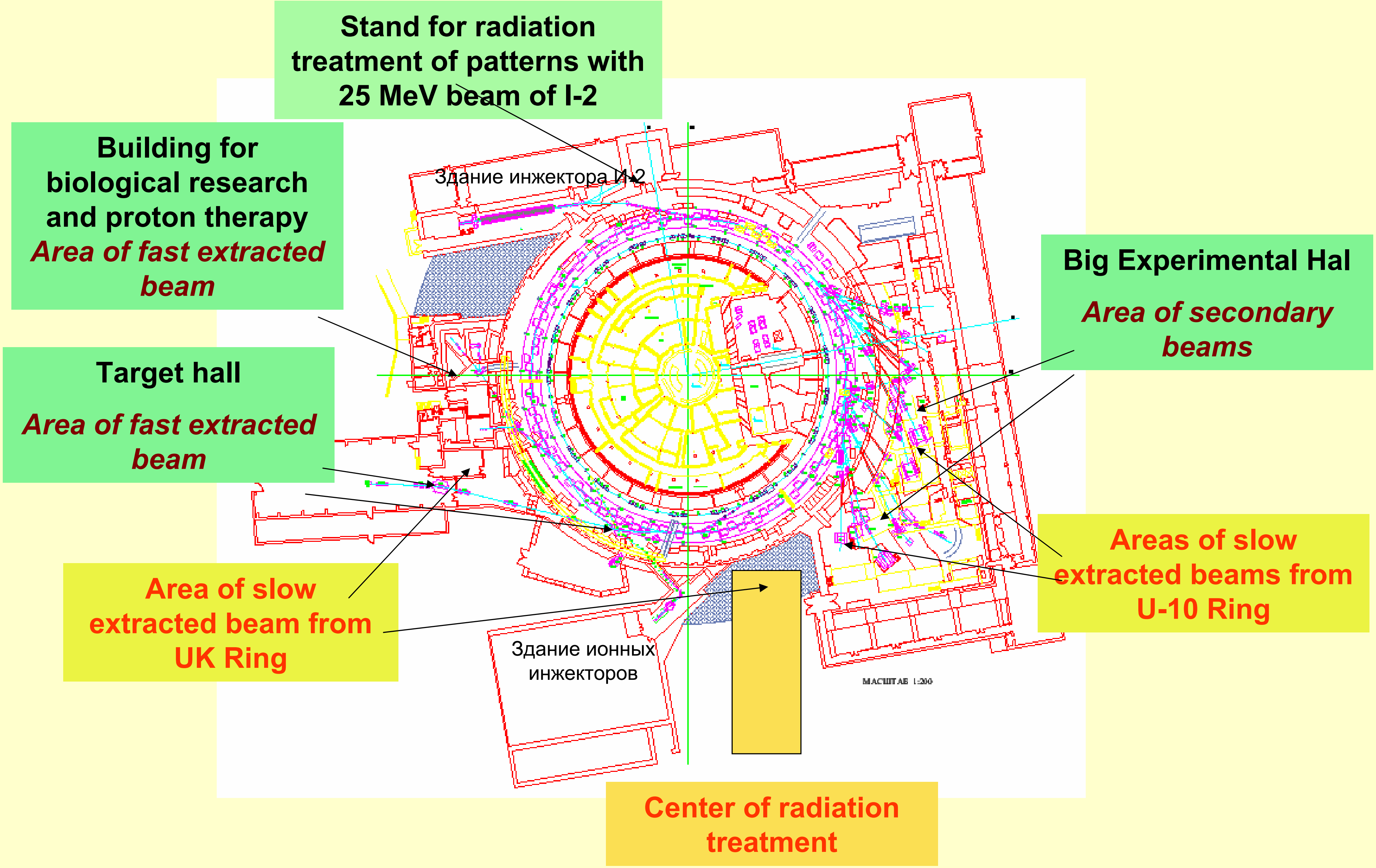
Statistic of ITEP-TWAC operation



Accelerator operation time for different research fields

Research fields with proton and ion beams	Beams	Accelerator operation time, (hours)		
		2007	2008	Require-ments
Relativistic nuclear physics	p (2-9 ГэВ, $10^{11}c^{-1}$) He, C,Al …(4 ГэВ/н, $10^{8}c^{-1}$)	1030	1200	1000
Methodical research	p (1-9 ГэВ, $10^{11}c^{-1}$) C(0,2-4 ГэВ/н, $10^{8}c^{-1}$)	1338	1500	2000
Physics of high density energy in matter	C, Al,Fe…, Zn (300-700 МэВ/н, $4x10^{10}c^{-1}$)	344	350	500
Radiobiology and medical physics	p (250 МэВ, $10^{11}c^{-1}$) C (400-800 МэВ/н, 10^{9} c^{-1})	2520	2350	5000
Proton therapy	p (250 МэВ, $10^{11}c^{-1}$)			
Ion therapy	C (400-800 МэВ/н, 10^{9} c^{-1})	0	0	
Radiation treatment of materials	p (25-800 МэВ, $10^{11}c^{-1}$) Fe, Sn, U (40-200 МэВ/н, 10^{9} c^{-1})	802	1200	>6000
ВСЕГО		6034	6600	>14500

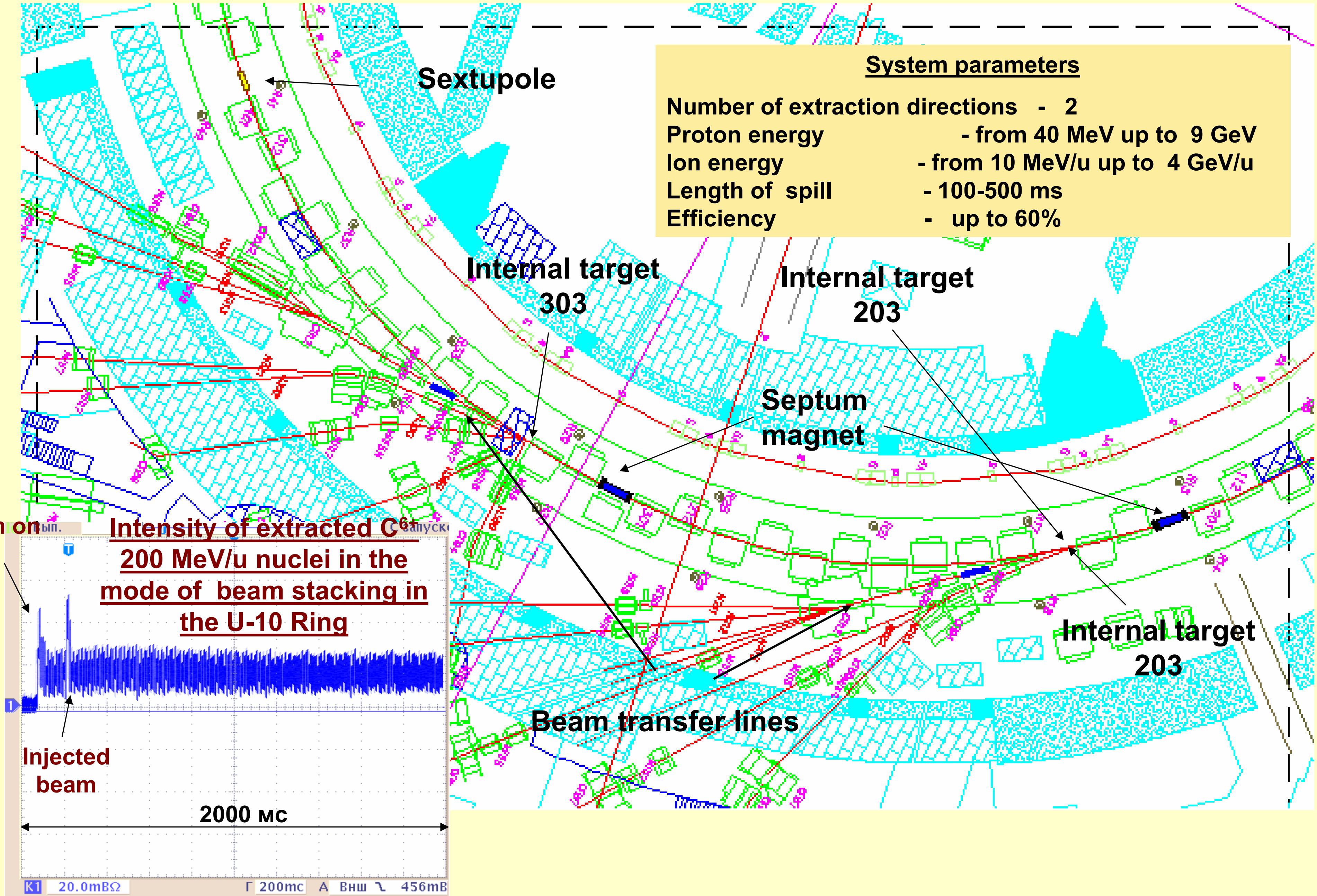
Development of ITEP-TWAC infrastructure



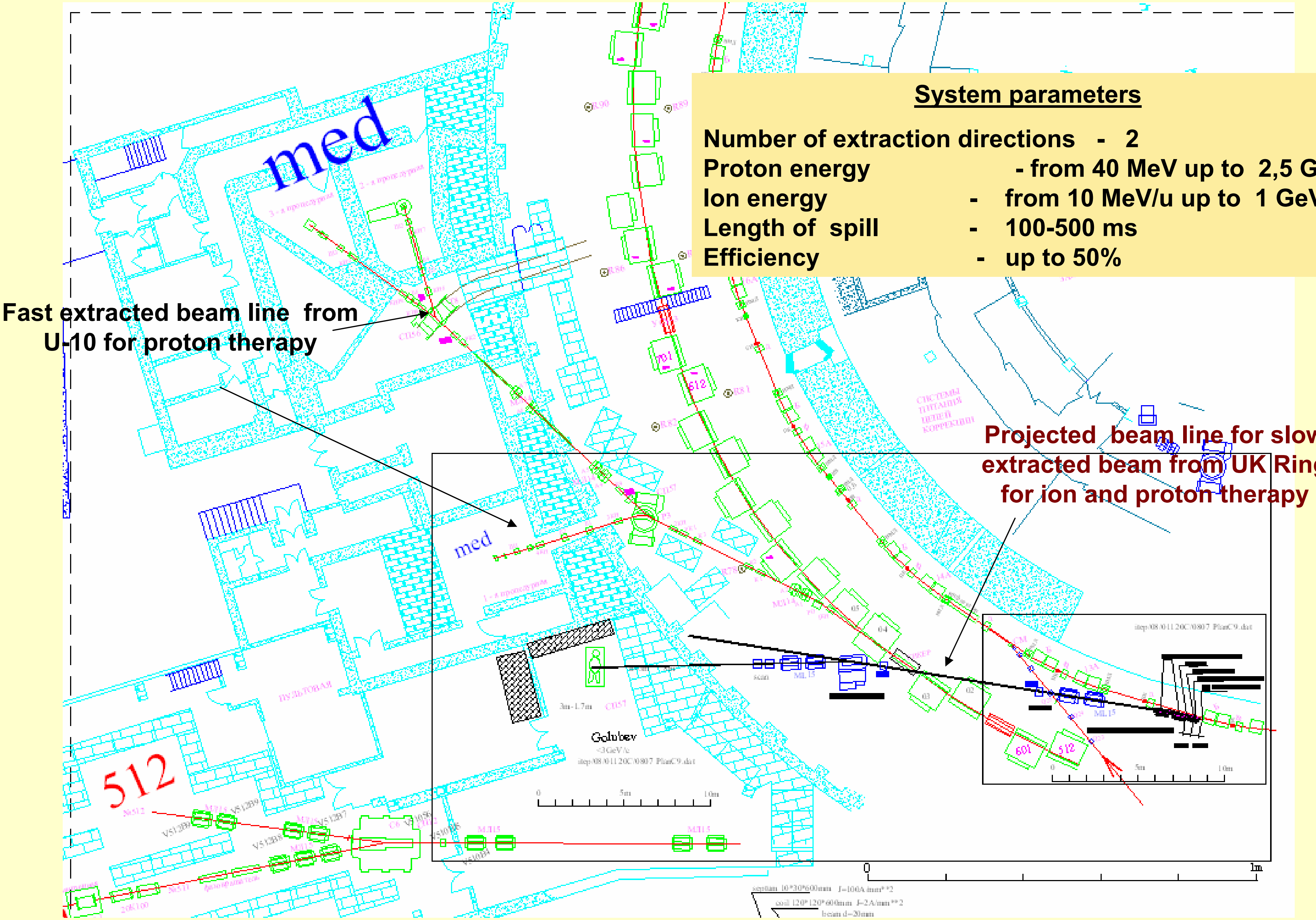
Slow extraction system of U-10 Ring

System parameters

Number of extraction directions - 2
Proton energy - from 40 MeV up to 9 GeV
Ion energy - from 10 MeV/u up to 4 GeV/u
Length of spill - 100-500 ms
Efficiency - up to 60%



Project of slow extraction system for UK Ring



System parameters

Number of extraction directions - 2
Proton energy - from 40 MeV up to 2,5 GeV
Ion energy - from 10 MeV/u up to 1 GeV/u
Length of spill - 100-500 ms
Efficiency - up to 50%

ITEP-TWAC machine development for progress in extreme parameters of beams

Raising of beam intensity and compressed beam power

1) Improvement of Booster synchrotron UK systems:
   - chromaticity correction,
   - increase of acceleration rate,

2) Modernization of beam accumulation technology:
   - improvement of charge exchange injection system,
   - expansion of accumulator ring dynamic aperture
   - increase of beam compression voltage

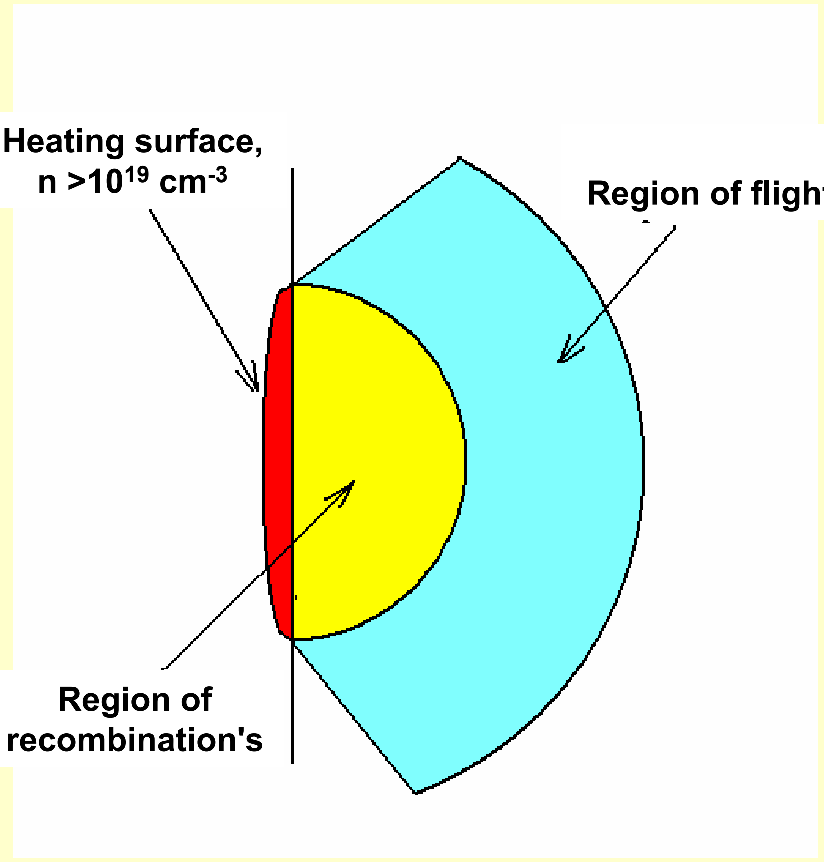
3) Construction of high current ion injector

Extension of accelerated and stacked ion species to heavier one

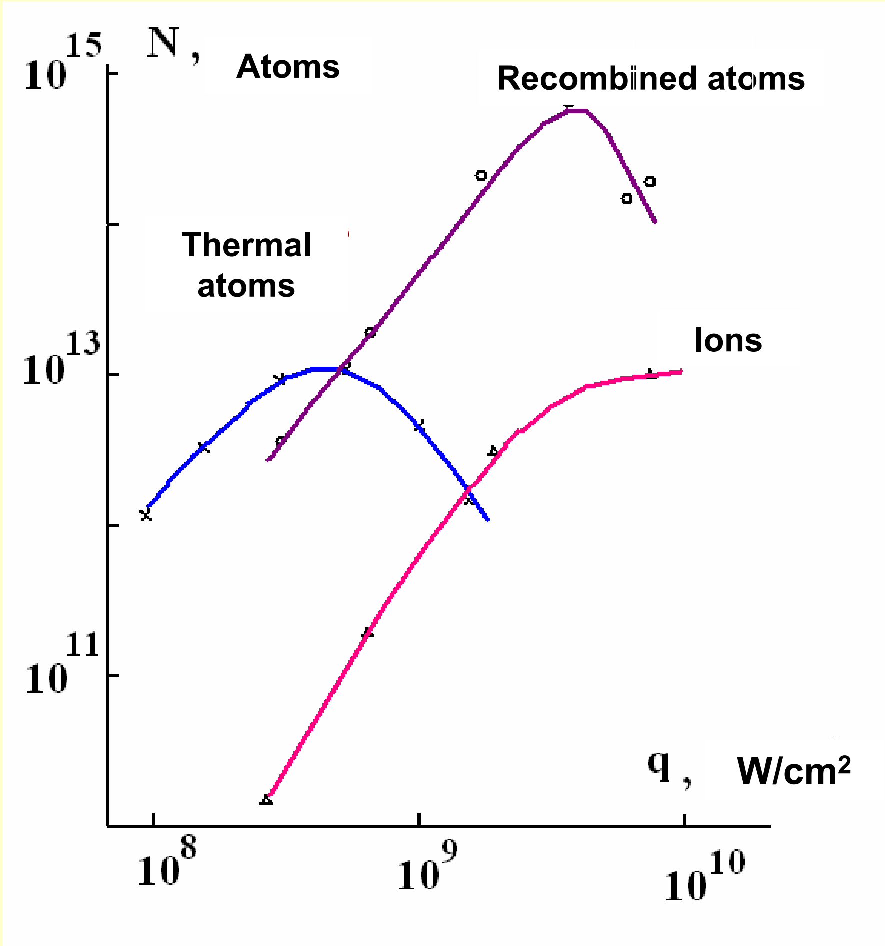
1) Development of laser ion source technology

Development of laser ion source technology

Laser plasma at sharp focusing of radiation on target surface

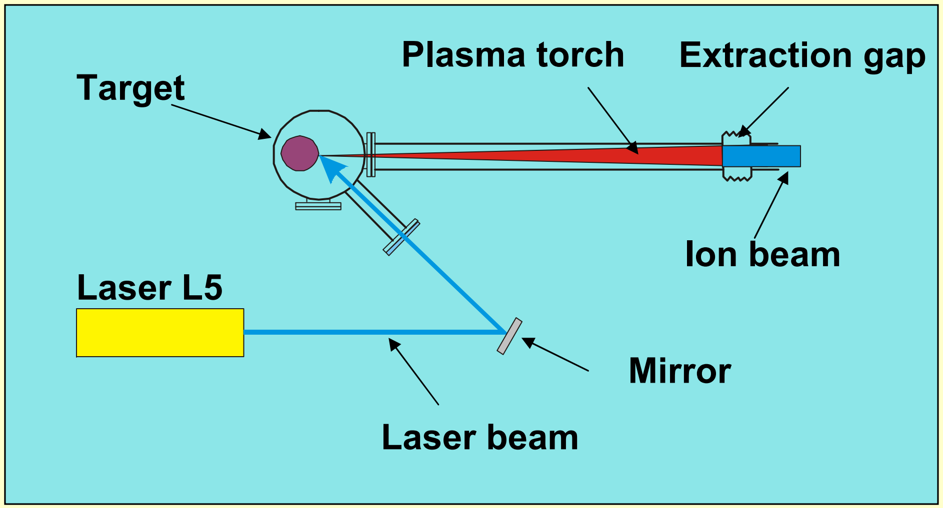


Number of cobalt of atoms and ions as a function of laser radiation density on target surface

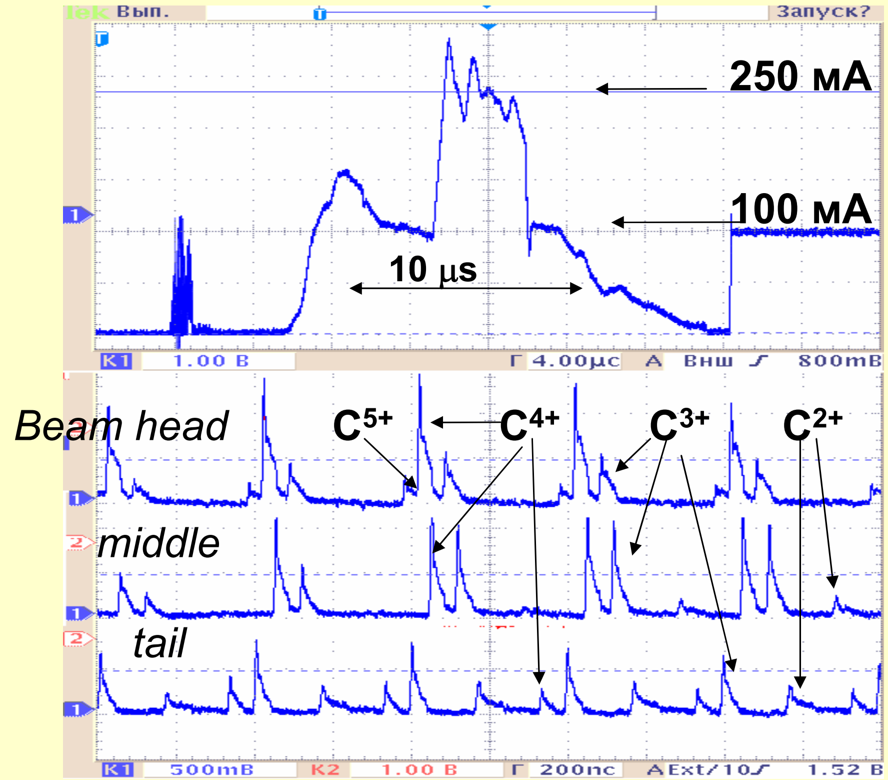


Laser Ion Source with 5J CO_2-laser

Optical scheme



Carbon beam at the output of LIS



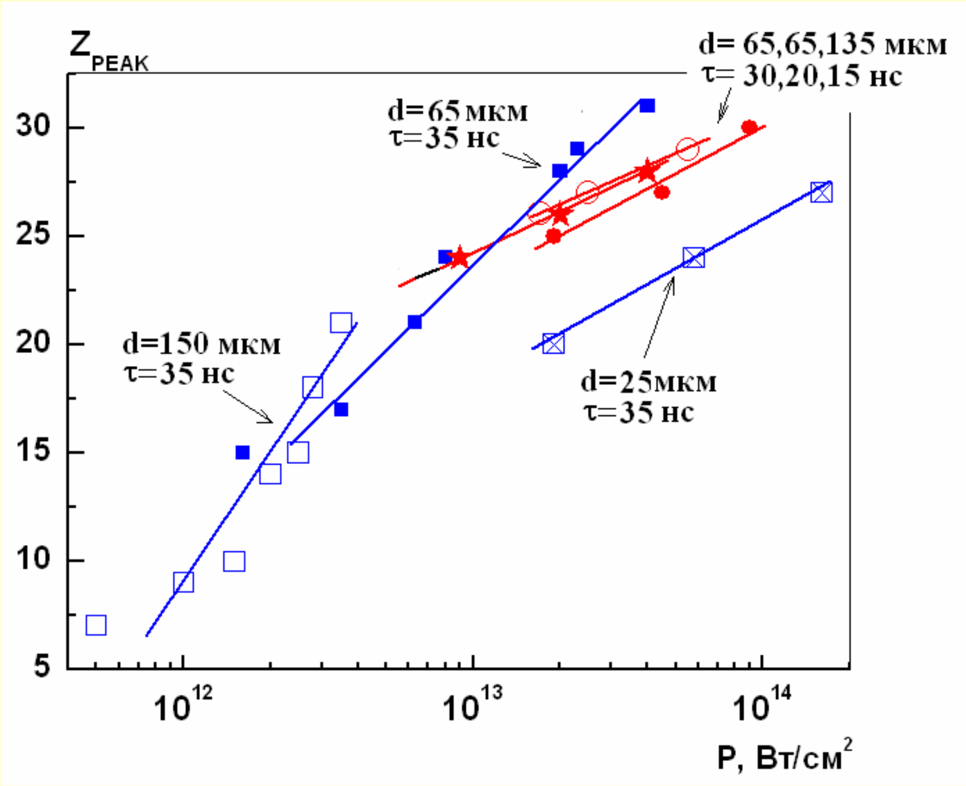
Laser parameters

Wavelength	10,6 μ
Pulse energy	5 J
Pulse duration	100 ns/1,5 μs
Power density at target spot	5x10^{11} W/cm^2
Max. repetition rate	0,5 Гц
Operational resource	~10^6

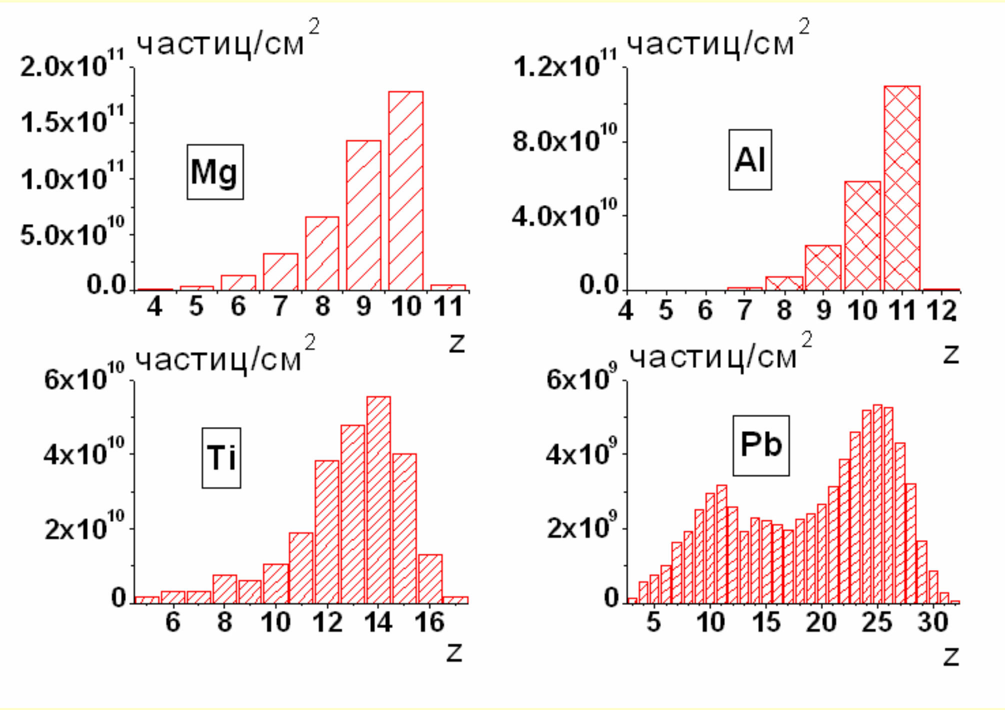
Laser L5

Parameters of LIS with 75J CO_2- laser

Maximal charge state of Pb ions from density of laser radiation power on the target



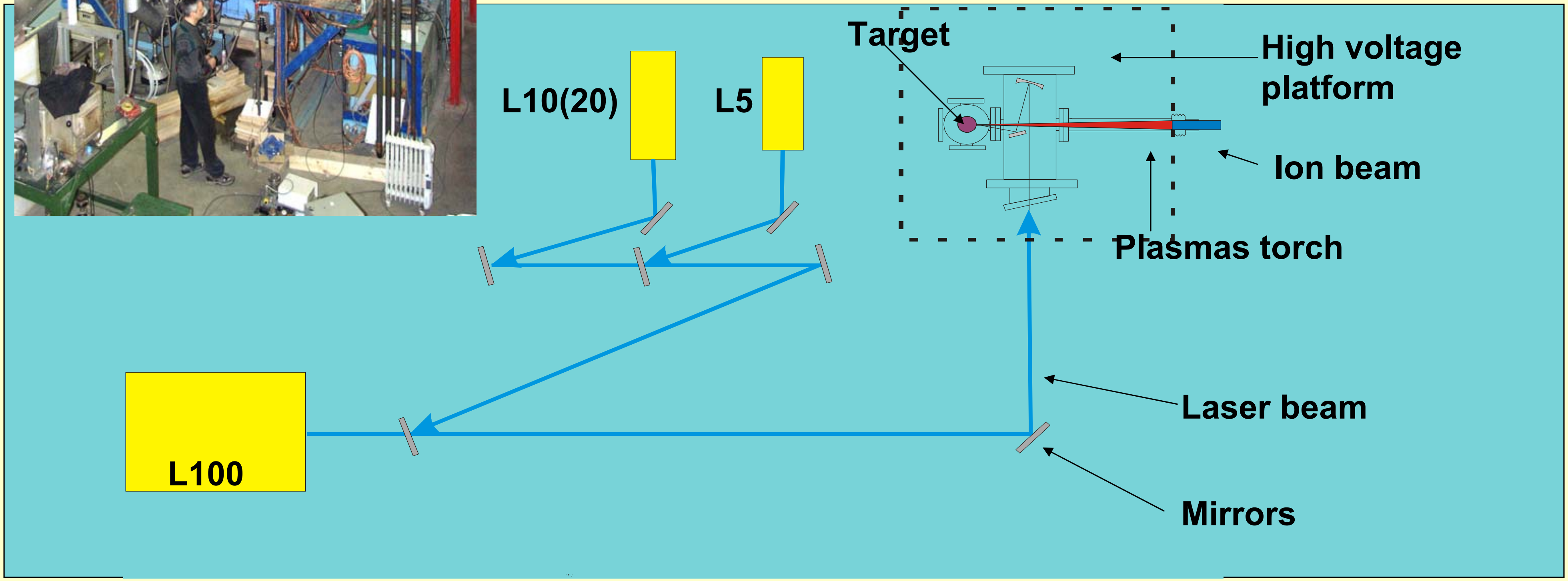
Density of different ions at the distance of 1 m from the target (τ=30 ns, d=65 μ)



New scheme of LIS
with set of lasers L5, L10 and L100

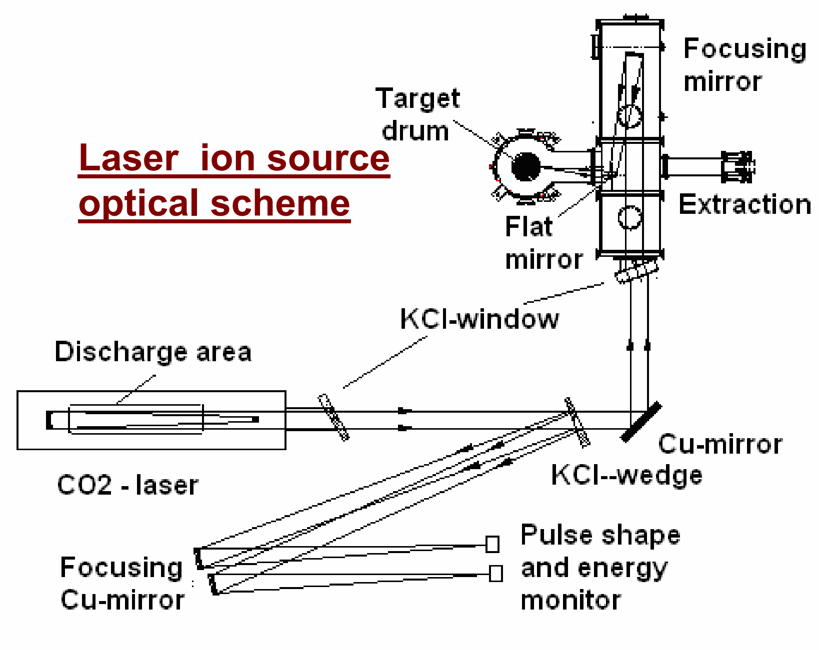
Laser L100

Wavelength, μ	10,6
Pulse energy, J	5/20/100
Pulse duration, ns	100/80/30
Power density at target spot	$5x10^{11}/10^{13}/10^{13}$ W/cm^2
Max. repetition rate, Hz	0,5 /1/1
Operational resource	~10^6



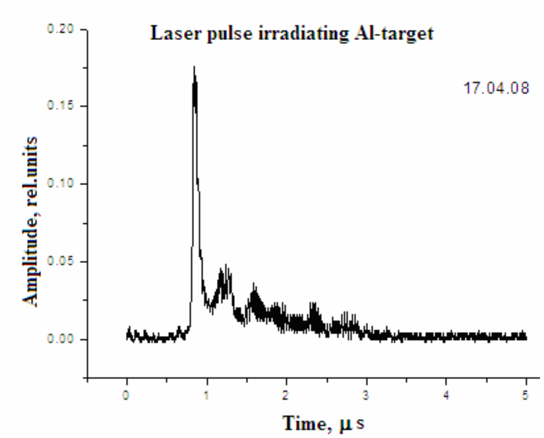
The 100J CO_2-laser running for Fe- ion beam production

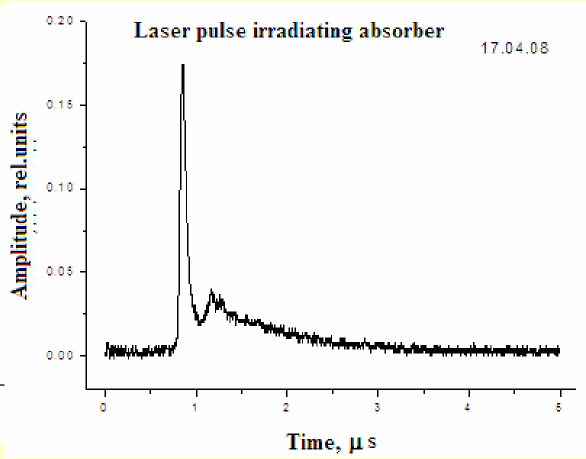
The new LIS simplified optical scheme is shown in Fig.1. The laser radiation is transferred to the target in the optical channel with nine Cu-mirrors at the distance of ~40 m. The length of a drift tube for generated plasma is 1.7 m. The typical laser radiation pulse at the free-running regeme of laser operation is characterized by the sharp spike of 30-250 ns (depending on the resonator active medium parameters) at the pulse front and a long low intensity radiation tail of 1-2 μs duration that contains up to 60% of the total laser pulse energy. Stretching in time the radiation energy investment to the target results in low-charge state ions domination in a generated ion beam and intensive evaporation of a target material.



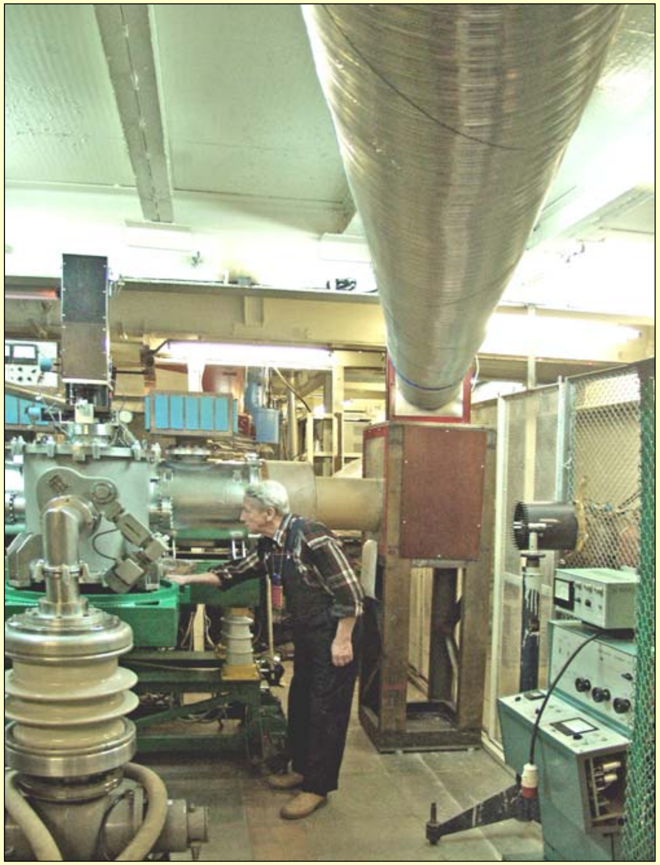
Laser Parameters

Wavelength	**10.6 μm**
Pulse energy	**>100 J**
Pulse duration	**(35-250) ns/(1-2) μs**
Power density at target	**~10^{13} W/cm^2**
Pulse structure	**multimode**
Lasing mixture	**CO_2:N_2:He=2:1:7**
Gas pressure	**1 Barr**
Operation voltage	**500 kV**
Max. repetition rate	**0,25 (1,0) Hz**
Operational resource	**~10^6 pulses**





Laser Ion Source components

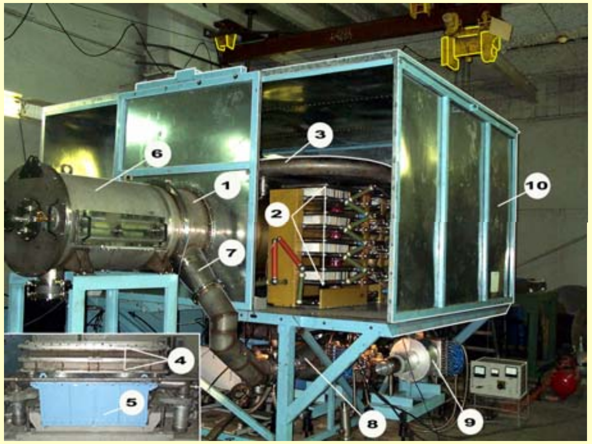


Laser beam transport tube

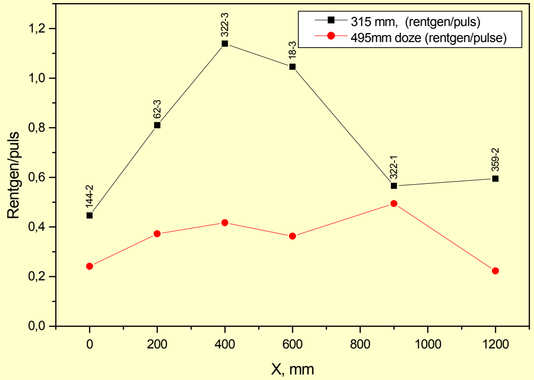
Target station

Beam extraction gap and matching channel

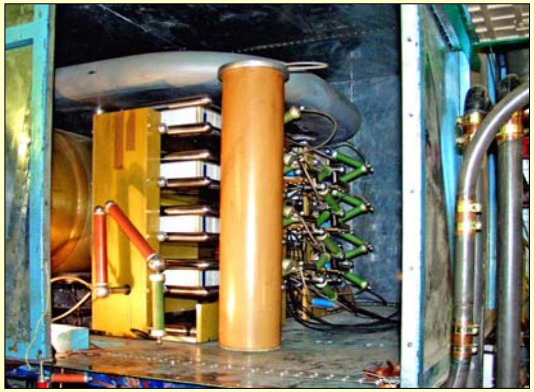
The 100J CO_2-laser adjusting



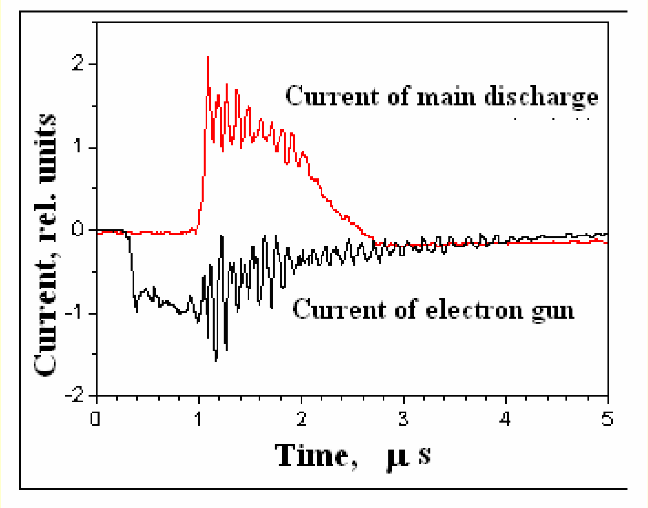
Laser layout



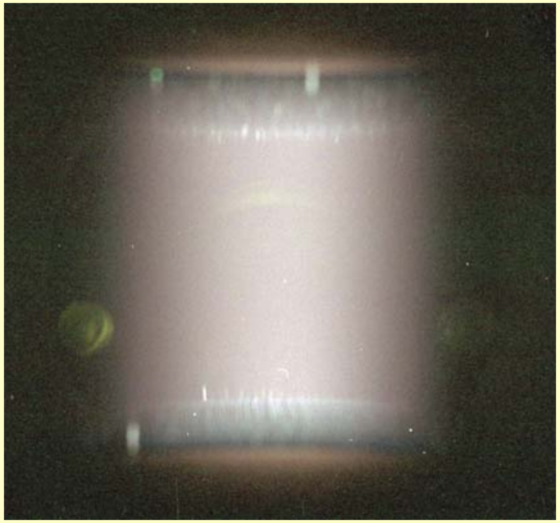
X-radiation distribution along electron gun



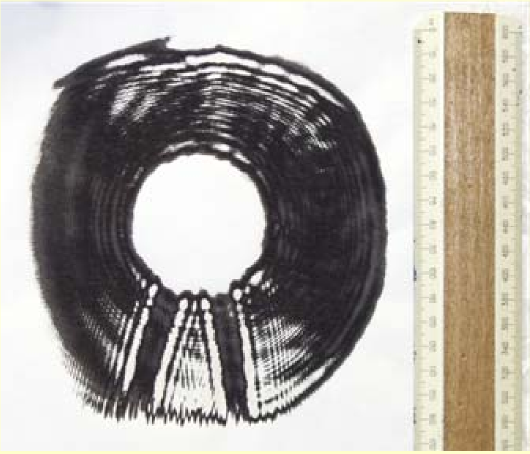
High voltage pulse generator



Shape of laser discharge current pulse



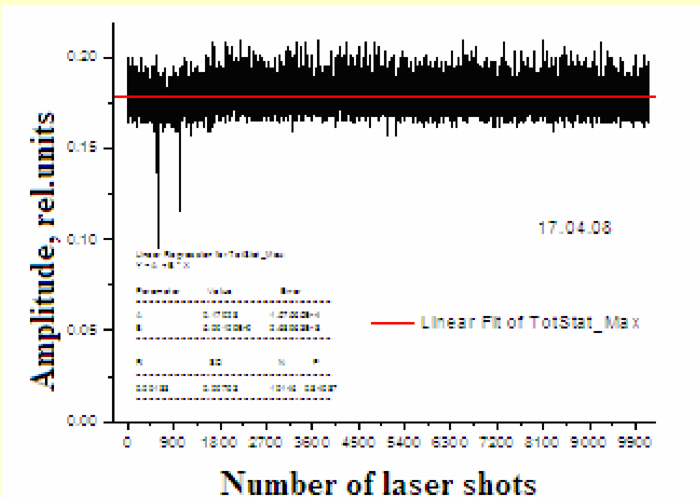
Homogeneous laser discharge
after $5x10^5$ training pulses

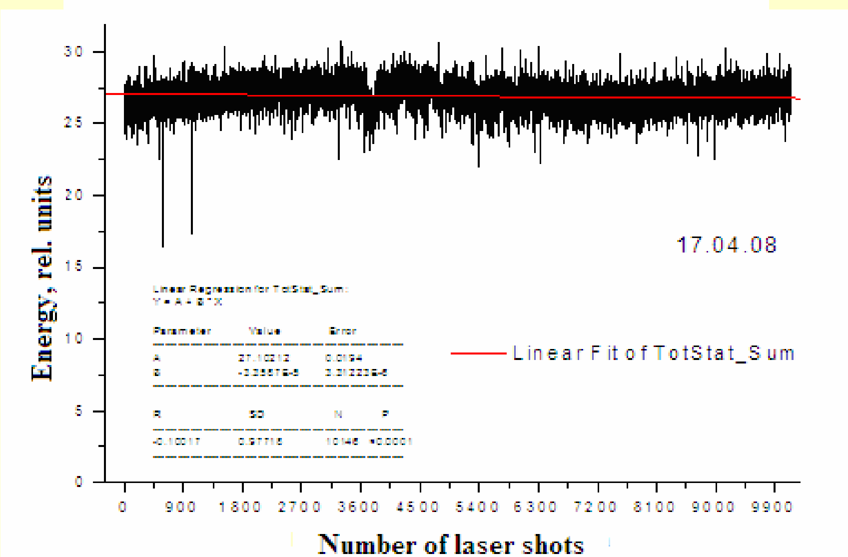


Laser beam portrait
on the photographic paper

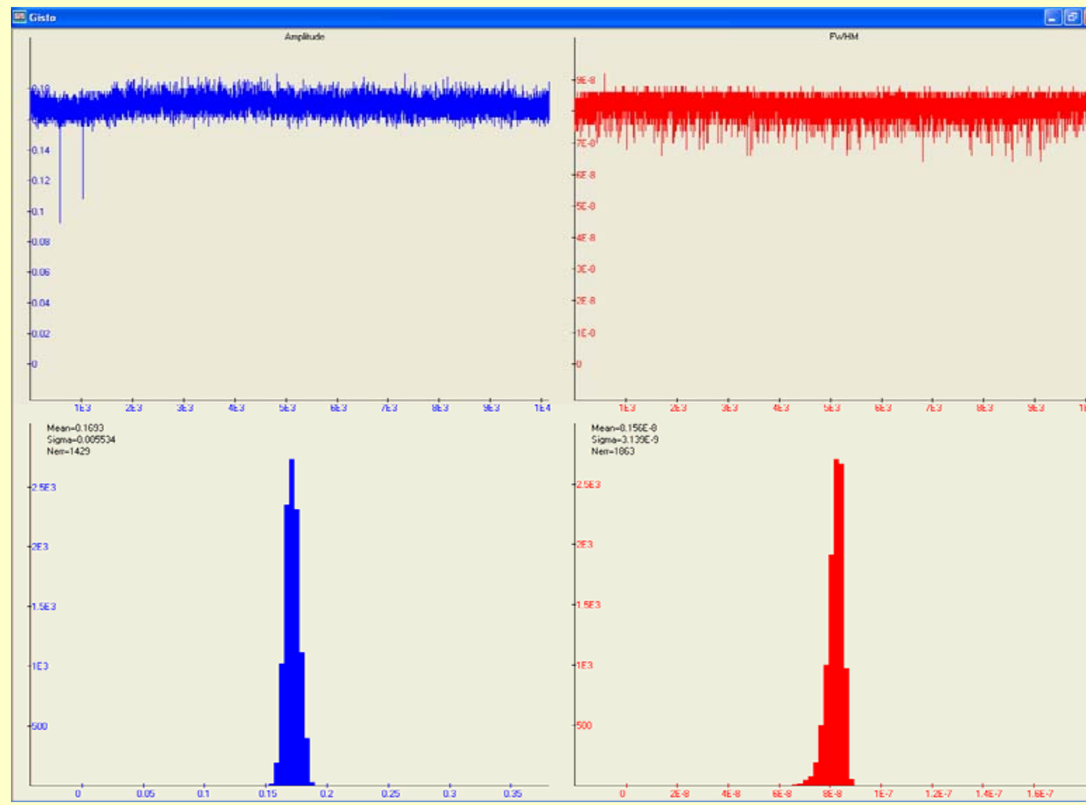
Operation parameters of the 100J CO_2-laser

The first run of the 100J laser for heavy ions generation has been continued three week scheduled by 12 hours per day at repetition rate of 0.25 Hz. Most part of run time has been spent for operation with the Fe-beam and two last days - with Al-beam. The laser has turned out more than 10^5 shots with high enough stability of pulse amplitude and energy distribution.





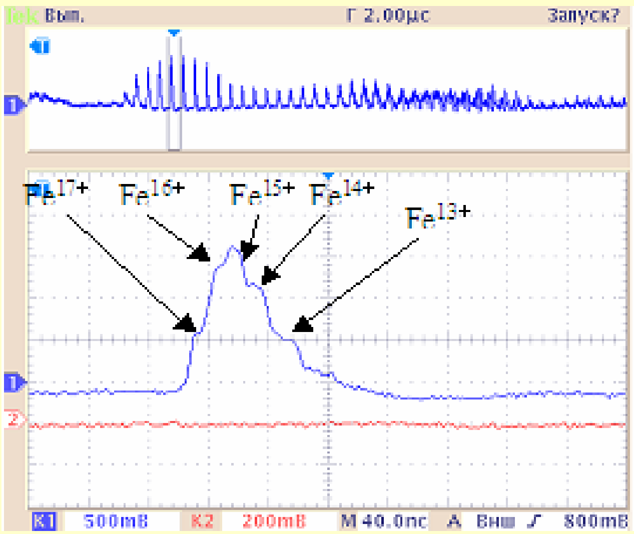
Statistics for 10146 laser pulses



Amplitude of laser pulse spike **FWHM of laser pulse spike**

The Fe^{16+} beam acceleration in injector I-3 and synchrotron UK

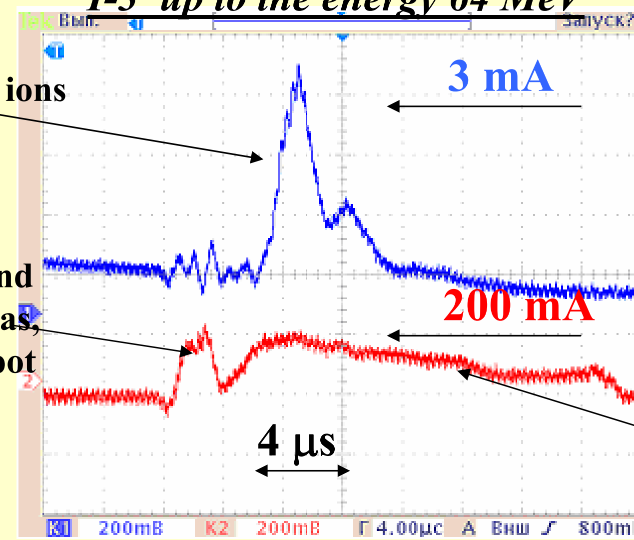
Charge states of Fe-beam at the LIS output



The current of Fe^{16+} beam accelerated in I-3 up to the energy 64 MeV

Current of Fe^{16+} ions

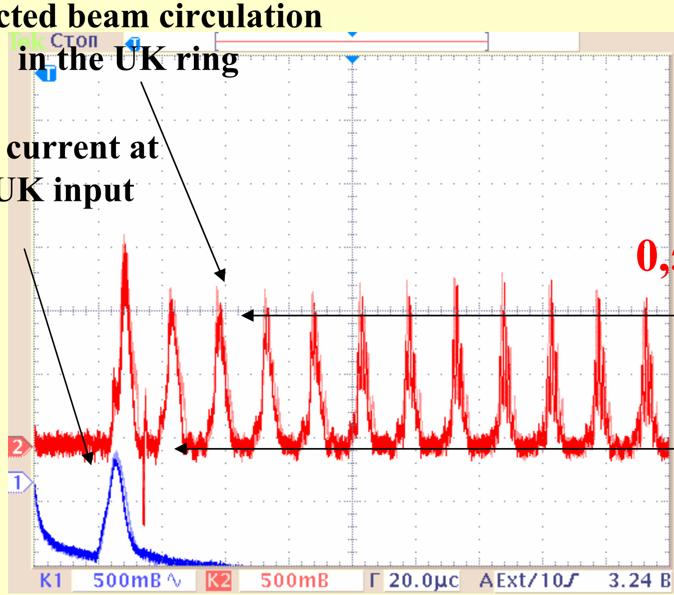
Pulse of electrons and ions from residual gas, initiated by laser spot on the target



Total current of Fe-beam at the LIS output

Injected beam circulation in the UK ring

Beam current at the UK input

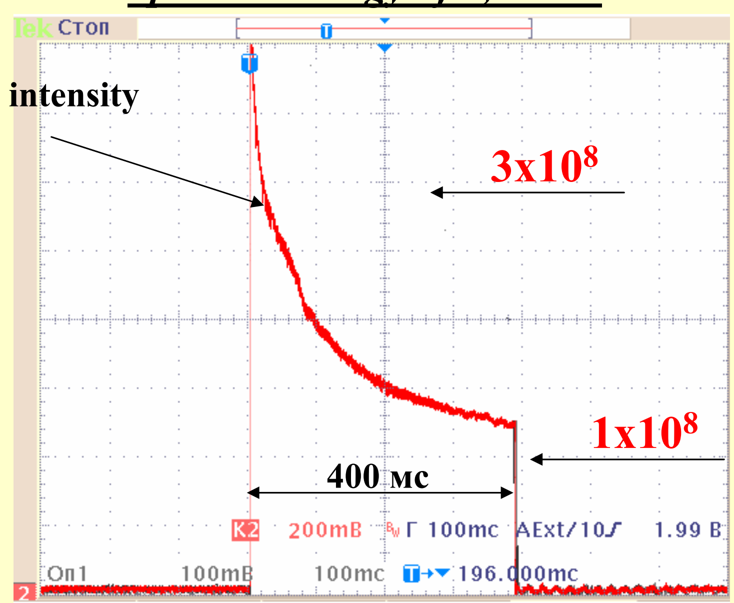


0,5 mA

1mA

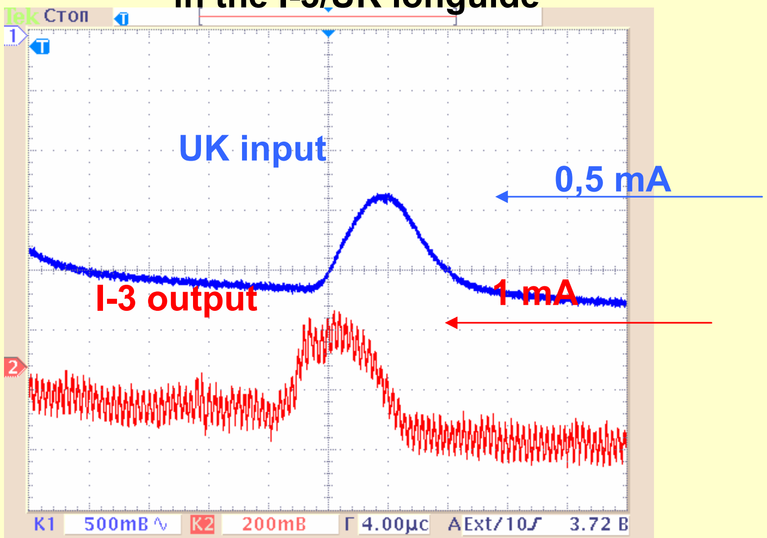
The Fe^{16+} acceleration in synchrotron UK up to the energy of 9,2 GeV

Beam intensity



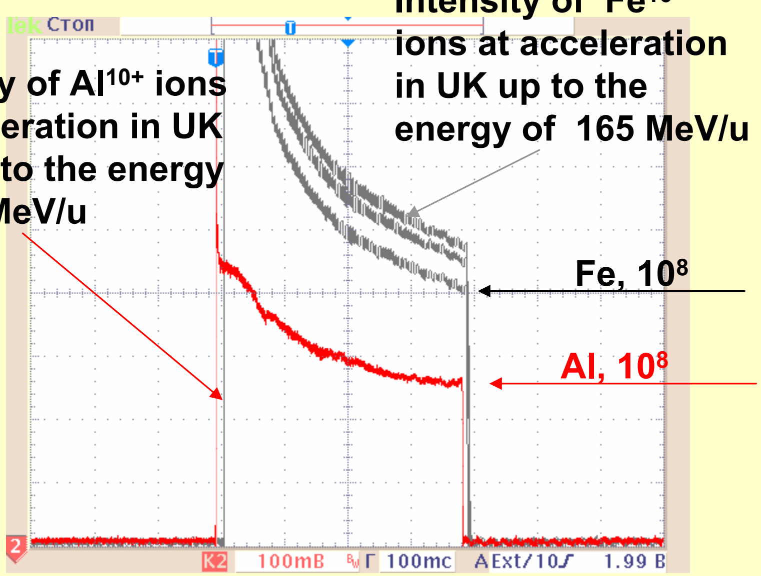
Acceleration of Al^{10+} ions in injector I-3 and synchrotron UK

Current pulses of 40 MeV/u Al^{10+} ions in the I-3/UK ionguide



Intensity of Al^{10+} ions at acceleration in UK ring up to the energy of 265 MeV/u

Intensity of Fe^{16+} ions at acceleration in UK up to the energy of 165 MeV/u

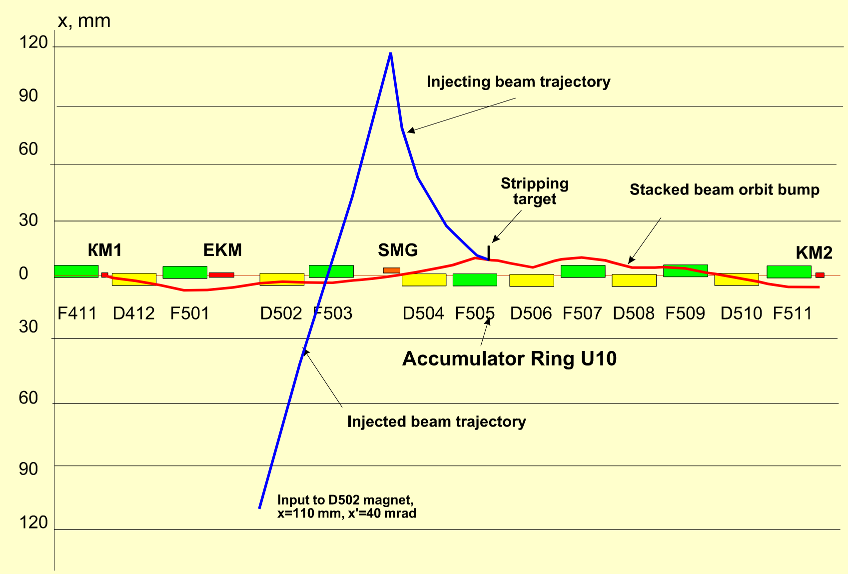


The Ions of C^{4+}, Al^{10+} and Fe^{16+} accelerating in the booster synchrotron UK at similar conditions up to the energy of 165, 200 and 265 MeV/u have been differed by factor of particle losses during acceleration cycle as 2, 1.5 and 3 correspondingly. Those beam losses can't be explained by vacuum which is estimated by value of $1x10^{-9}$ Torr confirmed in experiments for studying of C^{4+}-ions vacuum losses in the UK ring. Taking into account experimental results, the beam loss factor by vacuum can't be more than 10%. The beam loss at acceleration is apparently explained by the great dispersion of particle tune shift which is not corrected in this ring and estimated at the beam injection by the value of $\Delta Q_{x,z}=\pm 0.1$. Different rate of betatron resonance's crossing causes some variation of particles losses for various ion species. Chromaticity correction system for the UK ring is now under construction to solve the problem of beam losses.

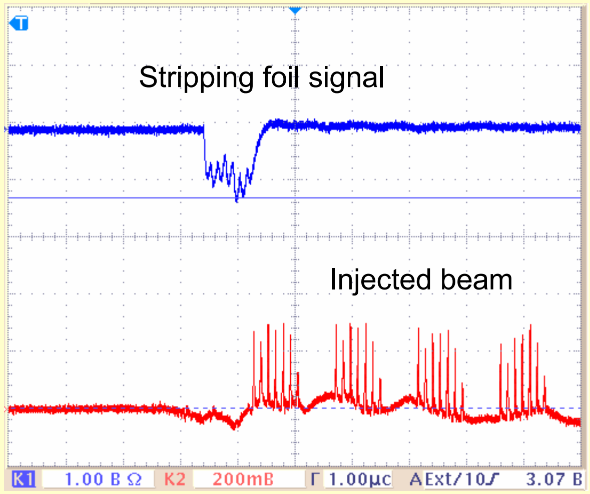
Charge-exchange injection technique

The ion accumulation is based on the charge-exchange injection with using a fast bump system for minimising the stacked beam perturbation over penetrating through the stripping foil material. Schematic layout of the beam trajectory at injection are shown in Fig. The deflection of the beam in the septum magnet SMG at injection is 98 mrad, the maximum field is 1.2 T. This magnet steers the injected beam to the centre of the stripping foil of 5x10 mm size, which is placed in the vacuum chamber of the F505 with a displacement of 20 mm from the ring equilibrium orbit. The fast bump system matching of both injected and circulating beams includes three kicker magnets installed in the short straight sections after of the magnets F411, F511 and F711. The first kicker magnet gives the kick of 3 mrad deflecting the stacked beam to the stripping foil at a moment when the injected beam is passing through the transfer line. The two beams, becoming one after passing through the stripping foil, are set to the ring closed orbit downwards by the kicker magnets in straight sections of F511 and F711. The foil material is mylar with the thickness of 5 mg/cm^2, that yields >90% of bare carbon ions with projectile energy of >50 MeV/amu.

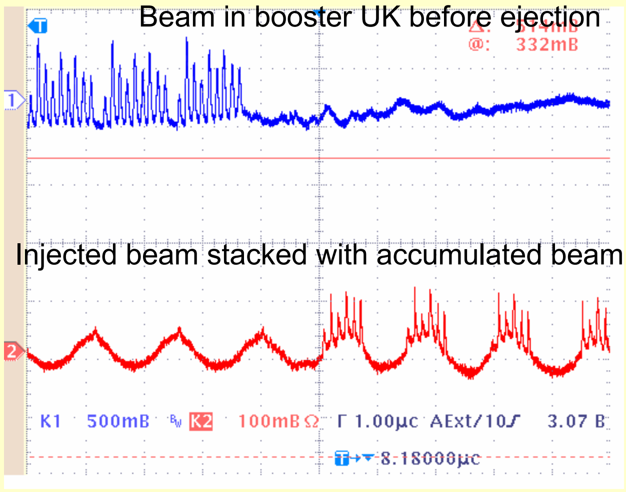
Beams trajectories at injection



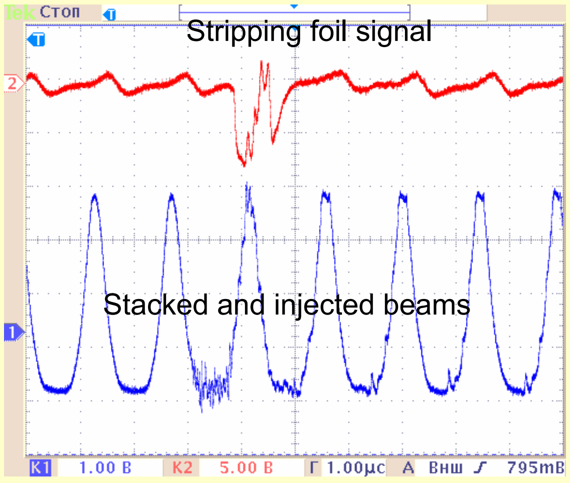
Injecting beam crosses stripping foil



Accelerated and stacked beams



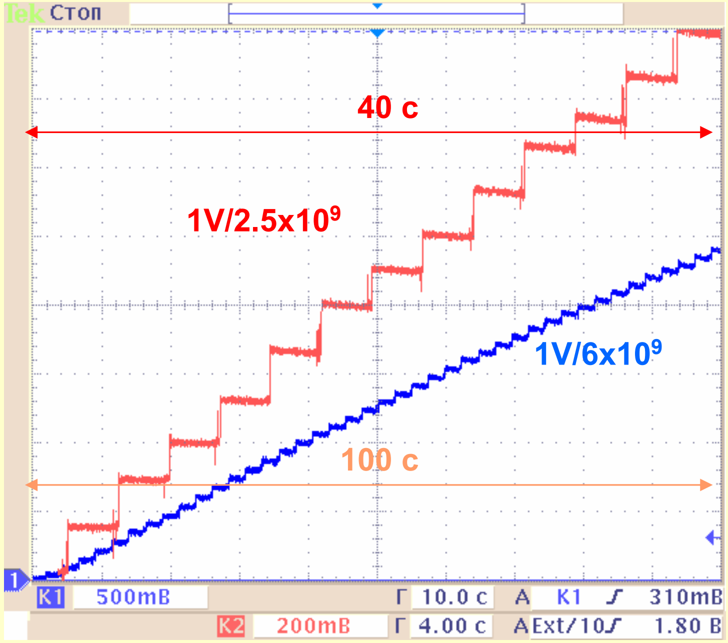
Two beams meeting in stripping foil



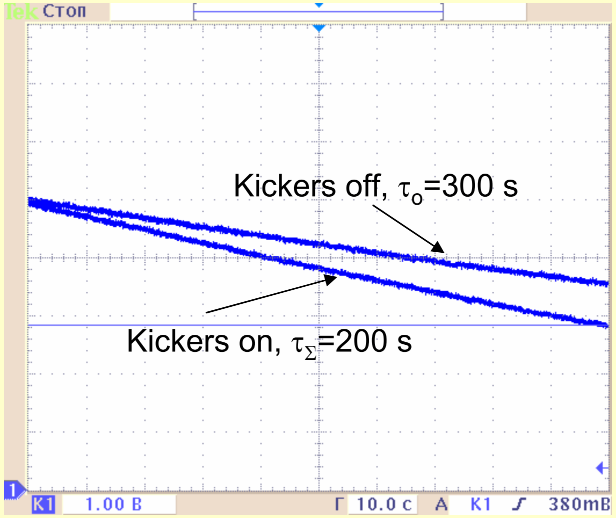
Optimised stacking of C^{4+}=>C^{6+} beam

The injection efficiency is now limited by the rise time of the pulse in the UK ejection kicker magnet and some particle losses (~10%) in beam transfer line between booster and accumulator rings. The efficiency of beam stacking is near to absolute for particles crossing stripping foil. The efficiency of accumulation process is characterized by lifetime of the stacked beam with fast bump system on (τ_Σ) and off (τ_o). Using equality τ_o=25·$A_{x,z}$, we get estimation of the accumulator ring dynamic acceptance as $A_{x,z}$ ~ 12 π mm·mrad. Designating δA as acceptance reduction from the orbit displacement by the fast bump at injection, and considering equality $(\tau_o\tau_\Sigma)/(\tau_o-\tau_\Sigma)=20(A_{x,z}-\delta A)$, it gets estimation of δA ~ 2 π mm·mrad. The factor of stacked beam losses at injection of a new portion of particles is calculated as $\delta=(\tau_o-\tau_\Sigma)/(f_{inj}\tau_o\tau_\Sigma)=0.005$, and the factor of stacking intensity increase is equal to $k_\infty=(f_{inj}\tau_\Sigma)$ ~70.

The stairs of C^{6+}-beam stacking in the U10 ring

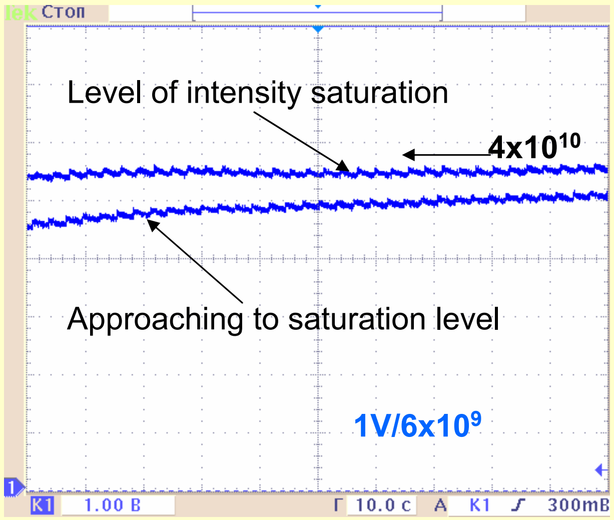


Stacked beam life time in the U-10 Ring

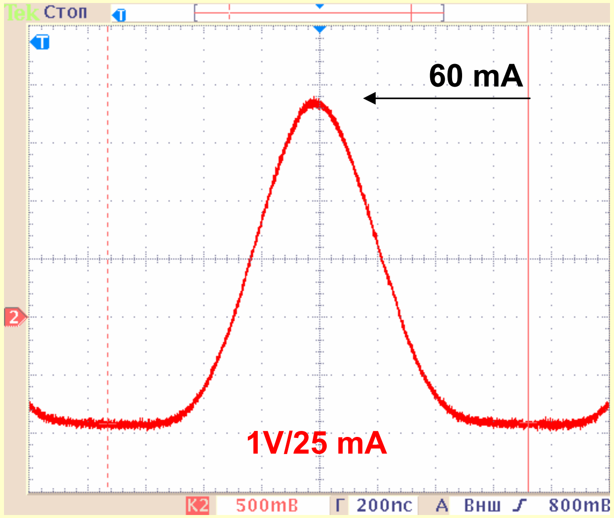


Maximal intensity of stacked beam

k_∞=>70

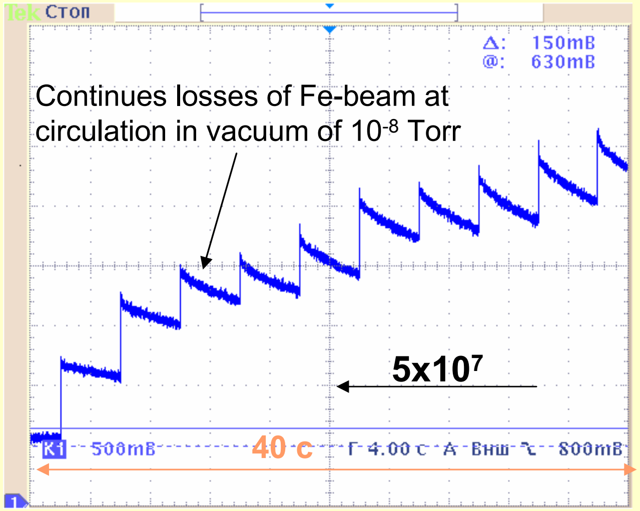


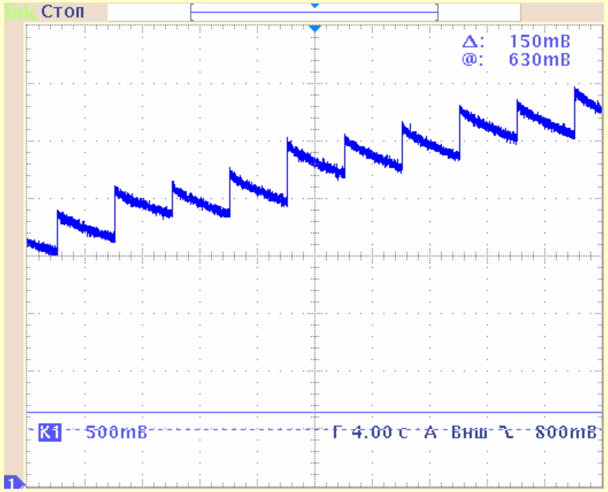
Stacked beam current



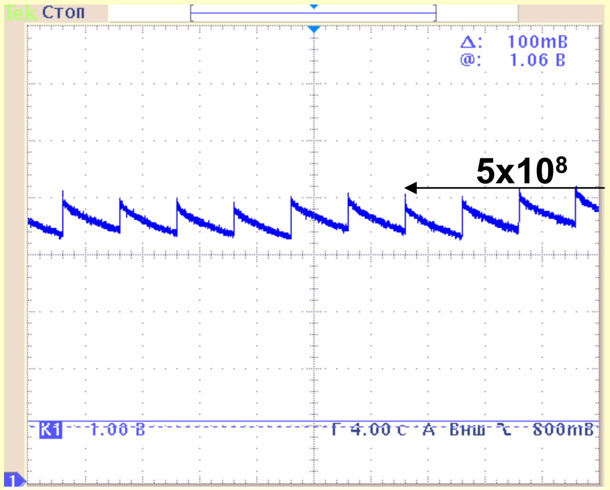
First experience with $Fe^{16+} \Rightarrow Fe^{26+}$ stacking

Stacking of the $Fe^{16+} \Rightarrow Fe^{26+}$ beam in U-10 Ring



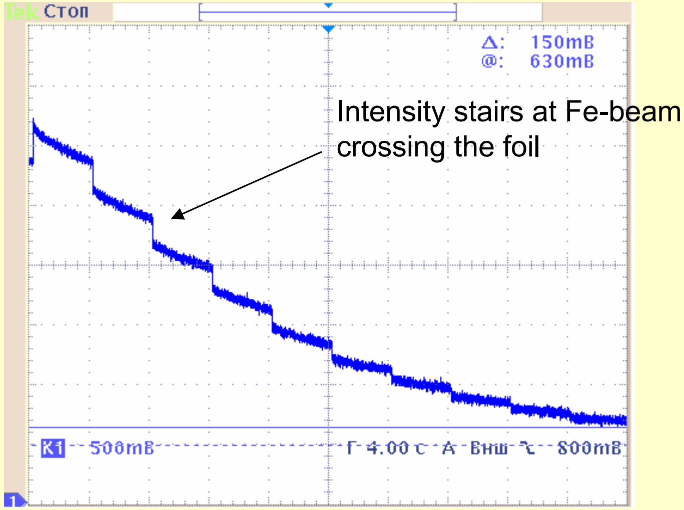


Maximal intensity of Fe^{26+} stacked beam
$k_{\propto} \Rightarrow 10$



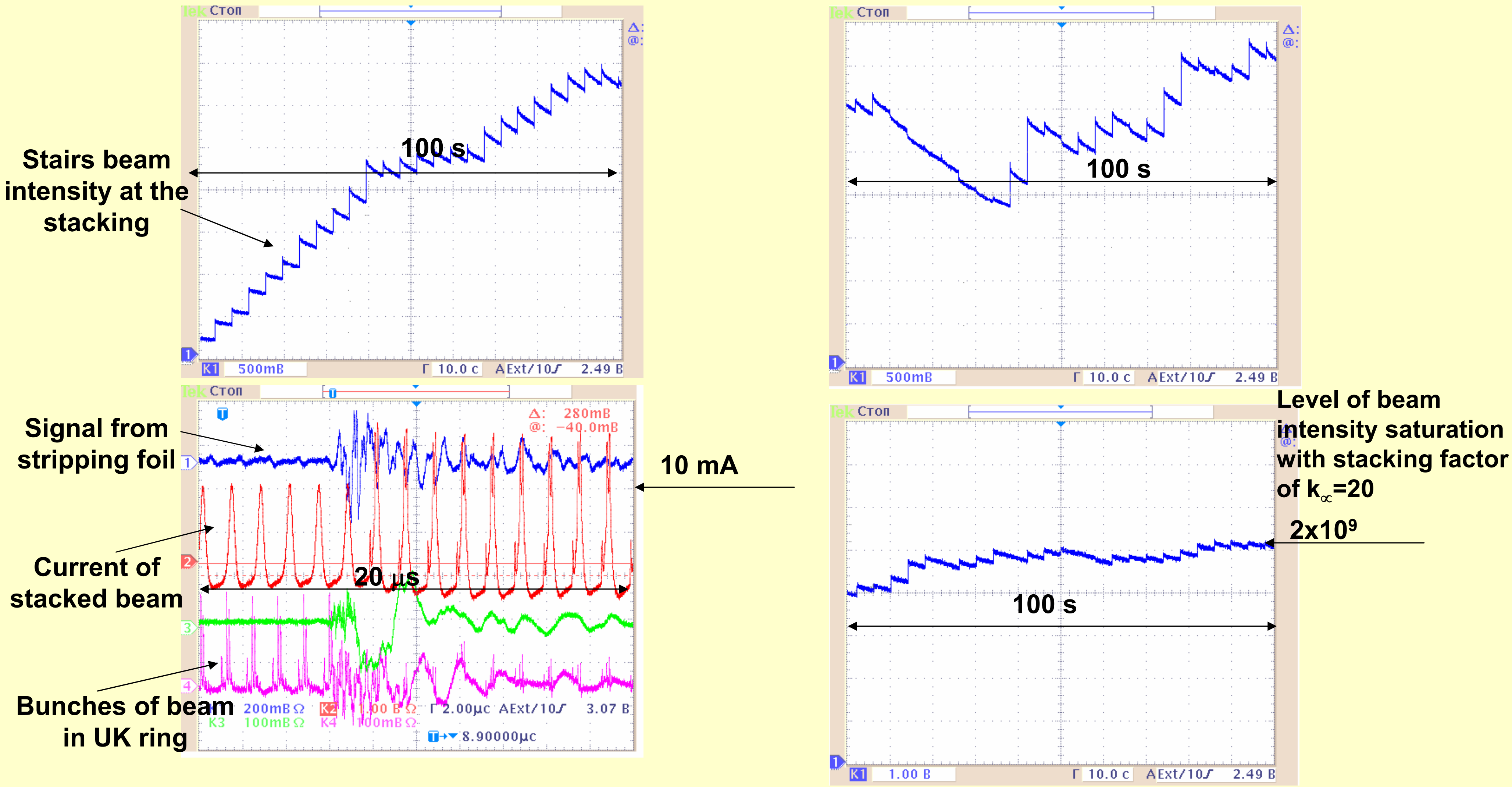
Energy	165 MeV/u
Target material	mylar
Target foil thickness	1,5 mg/cm^2
Foil size	10x20 mm^2
Cross section of ions stripping	~3x10^{-21} cm^2
Cross section of electron pickup	~1x10^{-23} cm^2
Injection repetition rate	0,25 Hz

Stacked beam life time in the U-10 Ring at kickers on, τo=16 s



First stacking of Al^{10+}=>Al^{13+} ions with the energy of 265 MeV/u

The resulting process of Al-nuclei stacking have been as expected little differing from the C-nuclei stacking shown on Fig. The factor of Al-nuclei stacking was limited by the lack of optimisation time and by injected beam instability depending on imperfection of the LIS target station which has to be improved.

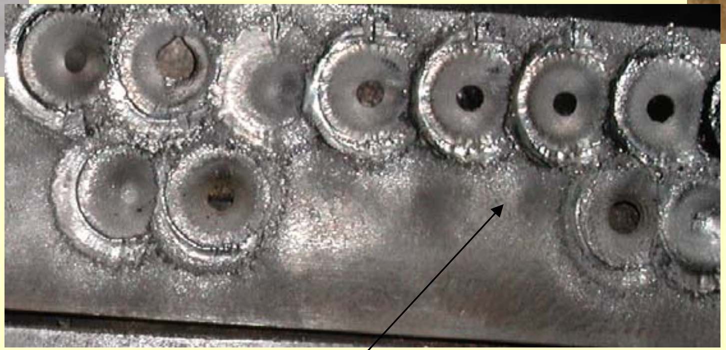


Target of Laser Ion Source irradiated for the ion beams generation

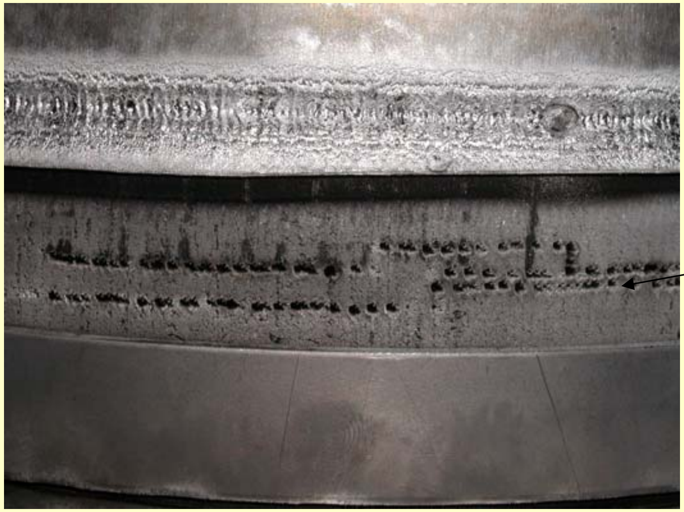
Fe-strip with holes made by laser beam

The surface of Al material is pierced through by ten laser pulses to fixed target

For Fe-beam generation, optimized time of target position changing found to be 40-50 minutes at displacing irradiated point on 5-6 mm.



For Al-beam generation, the target drum has been rotated after any laser shot displacing irradiated point on 0.5 mm.



The Fe-strip pierced through by laser beam

The C-drum with holes at the depth of 5 mm

The surface of Al material is worked out on the depth of ~1 mm at slow motion of irradiating point

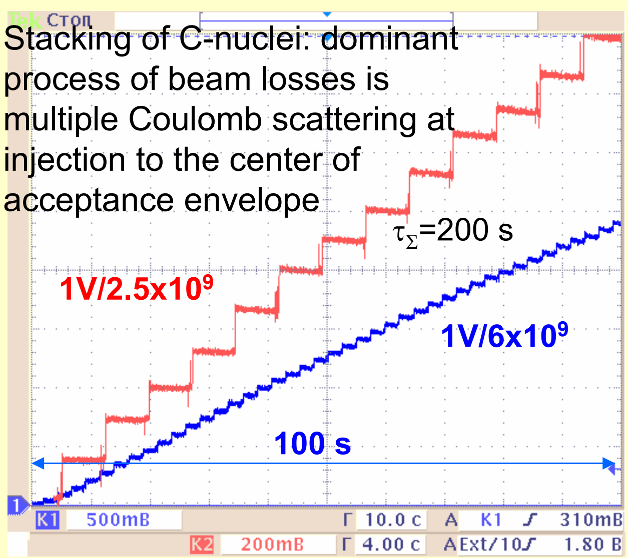
Comparison of stacking parameters for different ions

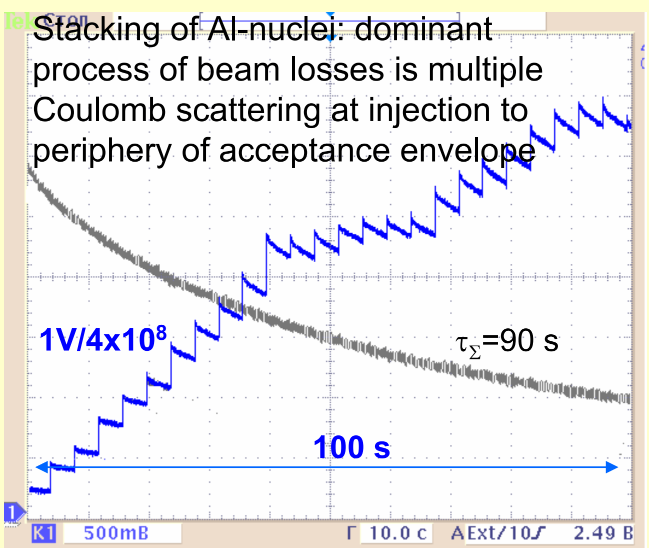
Parameters of stacking beams and injection system are listed in Tab.1. Energy of ions is high enough for its stripping to bare nuclei but the foil thickness provides 99% bare ion yield for C and Al and only 65-70% for Fe. Reduced yield of Fe-nuclei in stripping foil has to be compensated by decreasing multiple Coulomb scattering and electron pickups increasing resulting beam stacking efficiency. It was expected to get at experiments a little less efficiency of stacking for Fe-beam but a little more for Al-beam than it was obtained for C-beam (Fig.6).

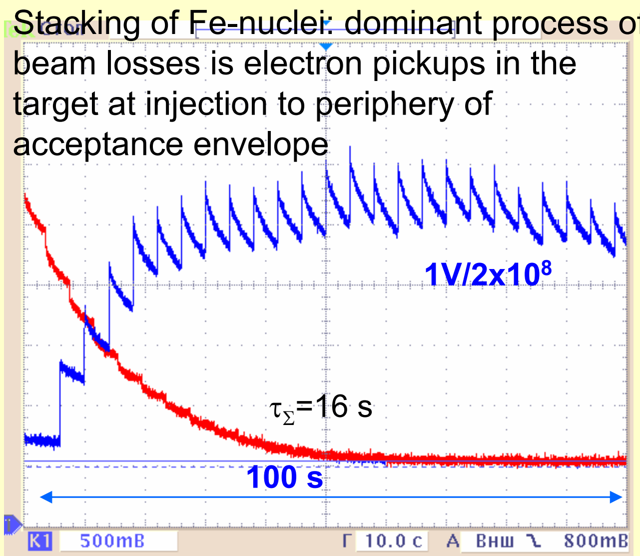
Main experimental results shown in Fig.7 are the following: Fe^{16+}-ions are stripping in the foil with predicted probability, but Fe-nuclei loss rate in the target (Fig.7) is order of magnitude higher than it was predicted by the theory [5-7]. The loss of Fe-nuclei traversing large distance in vacuum of 10^{-8} Torr approximately corresponds to the beam loss in the target. The resulting Fe-nuclei stacking process gives the cross section of particles losses as much as $4\text{x}10^{-21}$ cm^{-2}.

Parameters of stacking beams

Stacking ion	${}_{12}C^{4+=>6+}$	${}_{27}Al^{10+=>13+}$	${}_{56}Fe^{16+=>26+}$
Energy, MeV/u	213	265	165
Charge changing factor	0.67	0.77	0.615
Injection repetition rate,Hz	0.3	0.25	0.25
Stripping foil thickness, mg/cm^2	1.5		
Vacuum in the Ring, Torr	10^{-8}		
Acceptance filling	central	peripheral	peripheral
Injected beam intensity, ppp	~6x10^8	~1x10^8	~5x10^7
Momentum spread, %	±0.04		
Emittance, π mm·mrad	~5		
Stacked beam intensity	>4x10^{10}	>2x10^9	>5x10^8







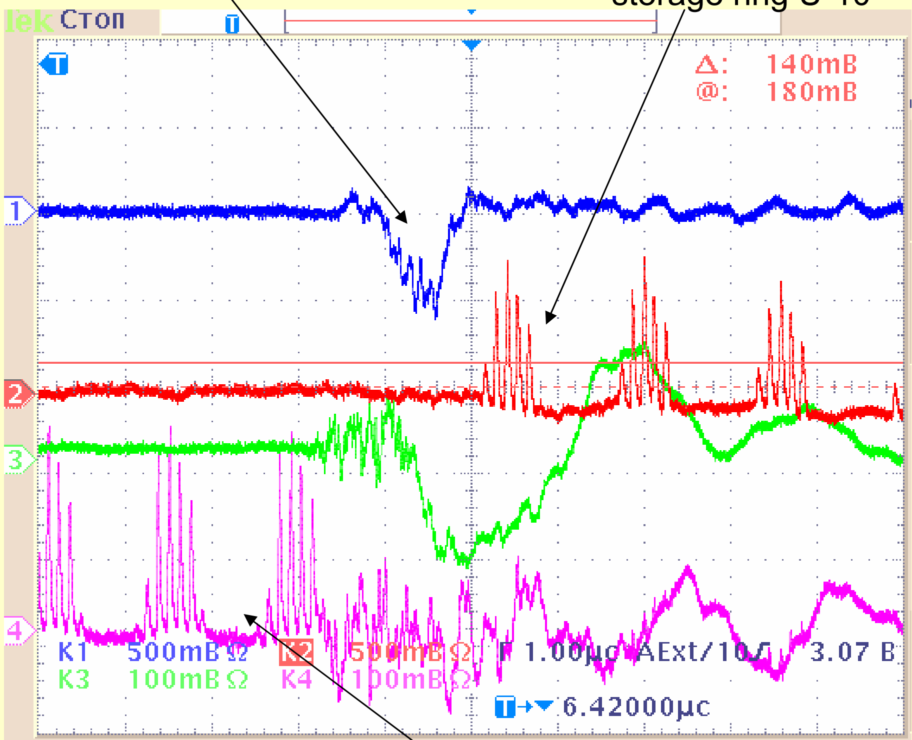
Electrons pickup by Fe-nuclei crossing the target

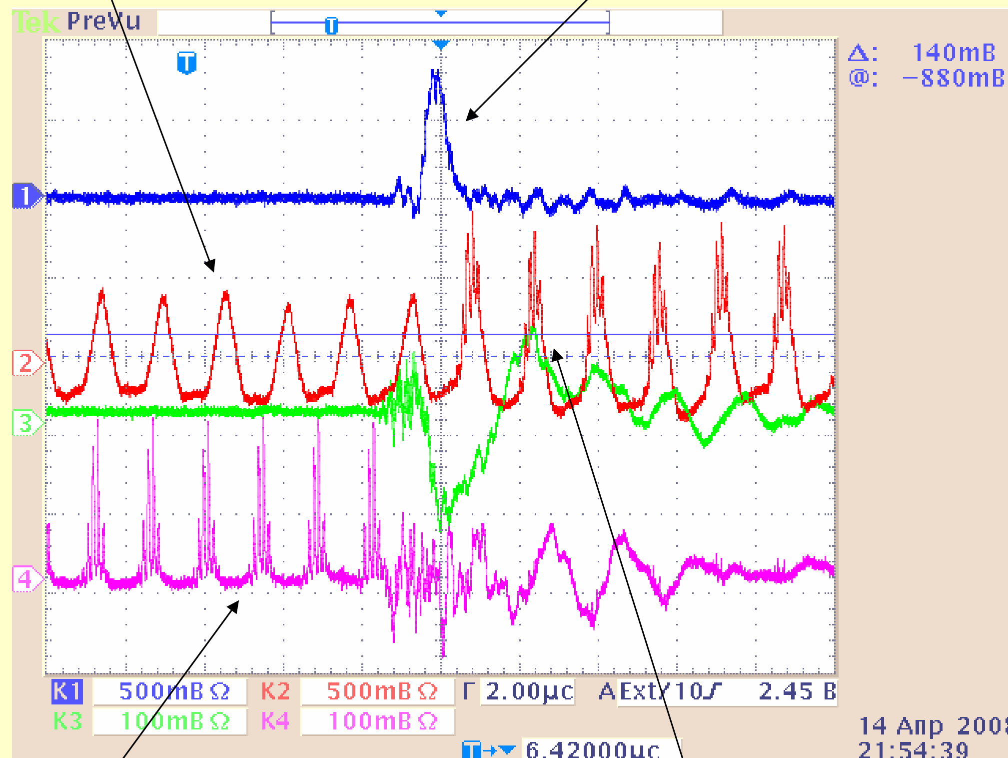
Signal electrons stripped in the target foil

Bunches of beam injected to the storage ring U-10

Bunches of beam stacked in the storage ring U-10

Signal of electrons carried off the target foil by the Fe-nuclei beam





Bunches of beam circulated in booster synchrotron UK before to be extracted for injection to storage ring U-10

Bunches of injected beam stacked with accumulated beam in the storage ring U-10

Progress in ITEP-TWAC beam parameters (2006-2008)

	2006	**Reached to 2008**	**Expected to 2009**	**Remote plans**
Accelerated particles	C^{4+}	Al^{10+}, Fe^{16+}	до U^{29+} **(2009)**	
Stacked particles	C^{6+}	Al^{13+}, Fe^{26+}	до Zn^{30} (**2009**)	
Energy of of beam stacking, MeV/u	300		700 (**2009**)	
Repetition rate, Hz	0.3		1 (**2009**)	
Intensity of UK synchrotron (for C^{4+} ions)	10^9		$3x10^9$	$\sim 10^{10}$ **(2010)**
Beam momentum spread, %	0.04		0.03	<0.03
Efficiency of charge exchange injection, %	~50	~60	~80	~100
Dynamic aperture of U-10 ring, π mm mrad	7	10	15-20	50
Efficiency of beam stacking, %	>90		>95	~100
Life time of stacked beam, c	200		>250	>500
Factor of stacked beam intensity increase	70		100	>100
Intensity of stacked beam (C^{6+})	$3x10^{10}$	$4x10^{10}$	$>10^{11}$	$>10^{12}$ **(2011)** $\sim 10^{13}$ **(2012-13)**
Power of stacked beam, Вт	$1x10^8$	$2x10^8$	$\sim 10^9$	$>10^{10}$ **(2010)** $\sim 10^{12}$ **(2012-13)**

Conclusion

1) The ITEP Accelerator Facility is now successfully in operation by more than 3000 hours yearly accelerating proton and ion beams and stacking carbon nuclei for physics experiments and radiation technologies.

2) The nearest progress in the ITEP-TWAC project depends now on the Laser Ion Source commissioning with the master oscillator mode of the 100J CO_2 laser operation required for a heavier ion beam generation with lionization potential of more than 1 kV. First experiments with Fe- and Al-ions generated in LIS with the laser operated in free-running mode have shown up some shortcomings of target station construction to be eliminated for the high current beam stability increase.

3) Experiments with acceleration of various types of ions in the booster synchrotron UK shows dependence of beam loss at acceleration on the beam tune shift dispersion that will be minimized by chromaticity correction system which is now under construction in the UK ring to reduce beam loss at acceleration by factor of ~2.

4) Experiments with Fe-nuclei stacking at the energy of 165 MeV/u indicates the unexpectedly high cross section of particles losses by electron pickups at the beam crossing the stripping foil and at the stacked beam traversing large distance in vacuum of 10^{-8} Torr. The disagreement of experimental data with calculations may partly be explained by some mismatching in the Fe-beam with the storage ring at the charge exchange injection to periphery of acceptance region so plans are being made to continue experiments and trying the stacking process with Fe-beam of higher and lower energy at different position of stripping foil displacement from the ring equilibrium orbit.

5) Summarizing the current status of the ITEP-TWAC Facility, it should be noted that progress achieved for improvement of the machine parameters in last two years is low than it was expected. The program of LIS modernization is moderated and not yet finished. The problem of the booster synchrotron intensity increase by factor of ten is one of the main one but restrained by deficit of resources for development and construction of required components for its overcoming.