Maintenance of ITEP-TWAC facility operation and machine capabilities development

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Institute for Theoretical and Experimental Physics

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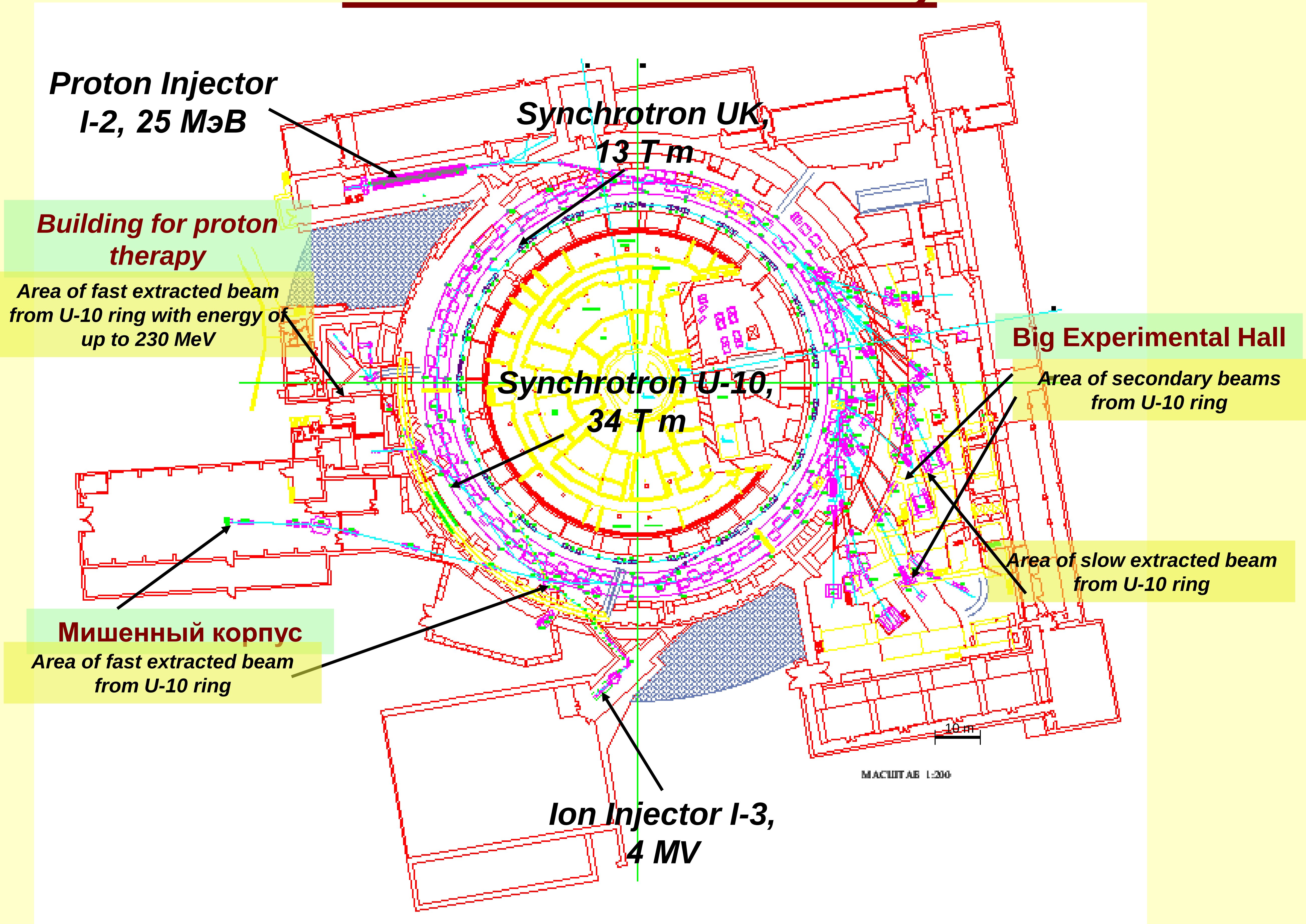
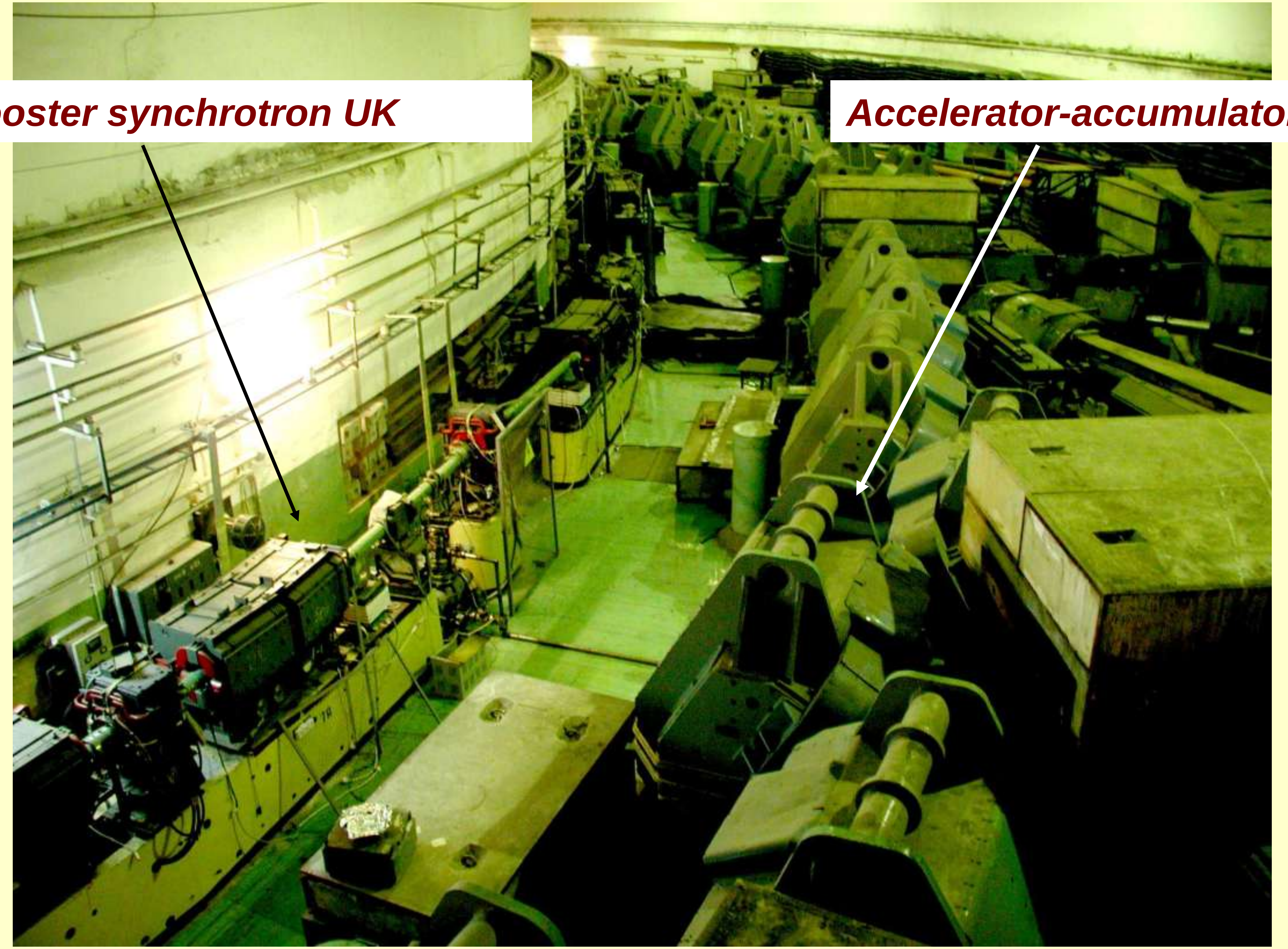
Содержание доклада

- *Общее состояние комплекса ИТЭФ-ТВН*
- *Статистика по эксплуатации*
- *Результаты по ускорению и накоплению тяжелых ионов*
- *Основные направления использования*
- *Опыт эксплуатации и модернизации лазерного ионного источника*
- *Развитие технологии перезарядного накопления ионов*
- *Создание нового ионного инжектора*
- *Проекты расширения инфраструктуры комплекса*
- *Заключение*

ITEP Accelerator Facility



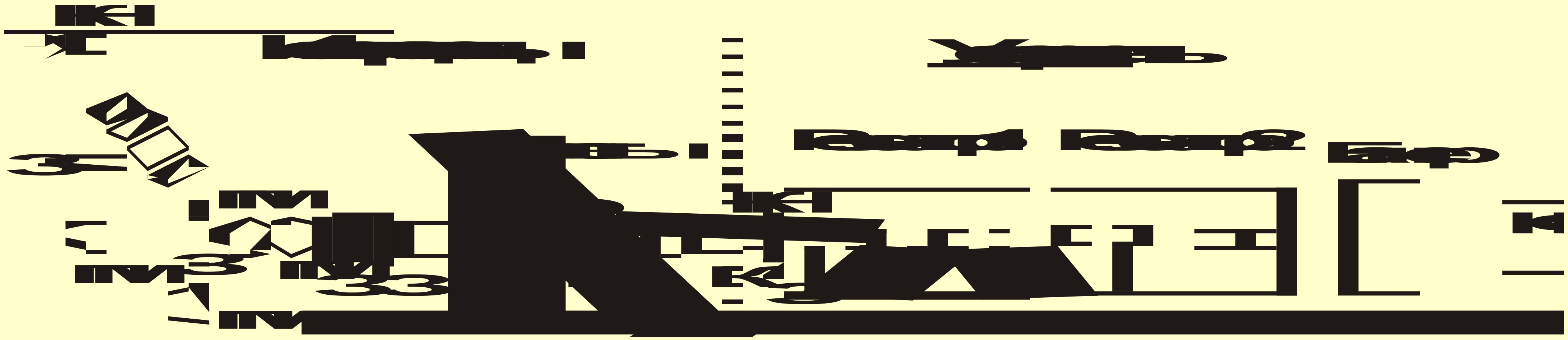
Ring magnets hall of ITEP-TWAC Facility



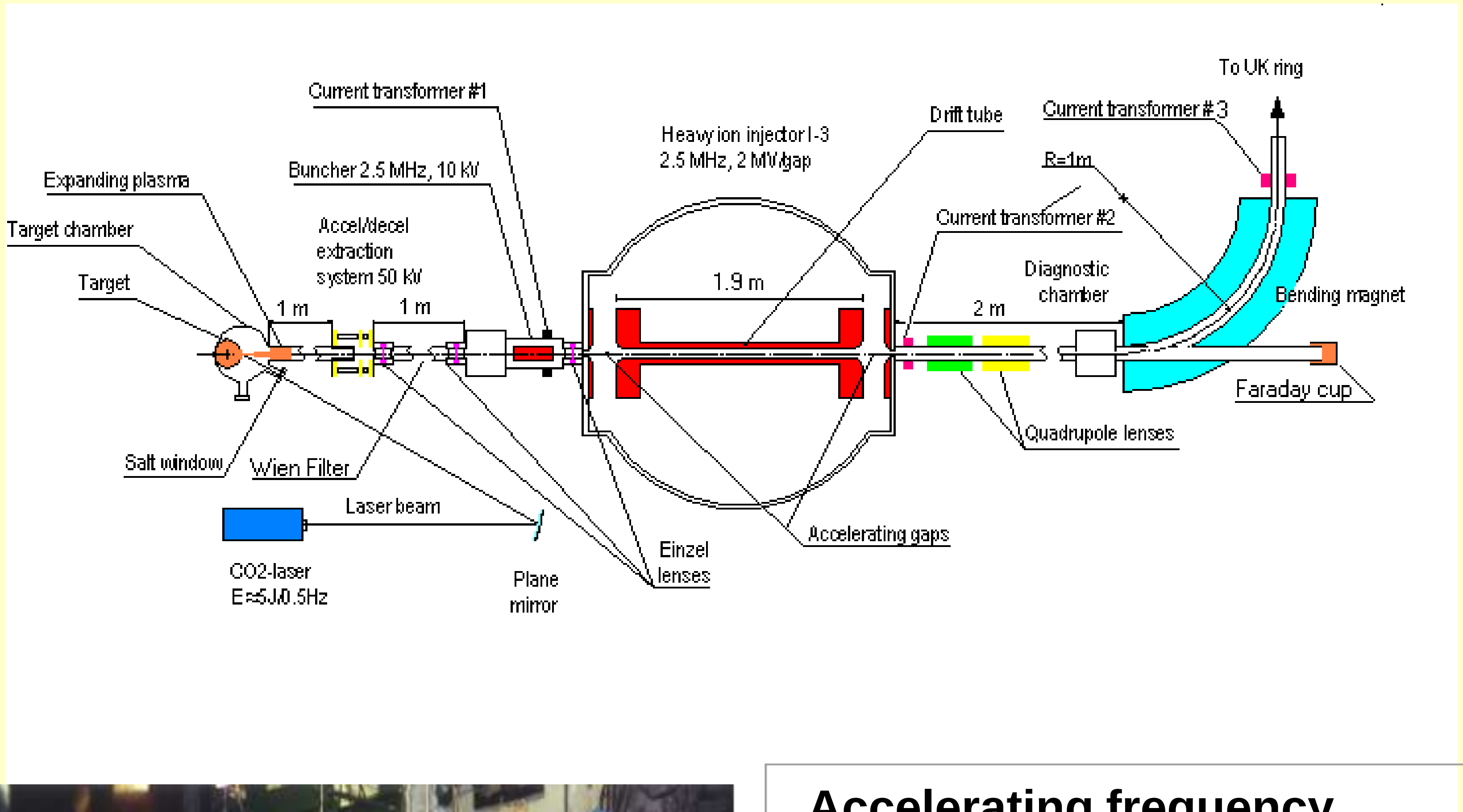
Proton Injector I-2 (1967)

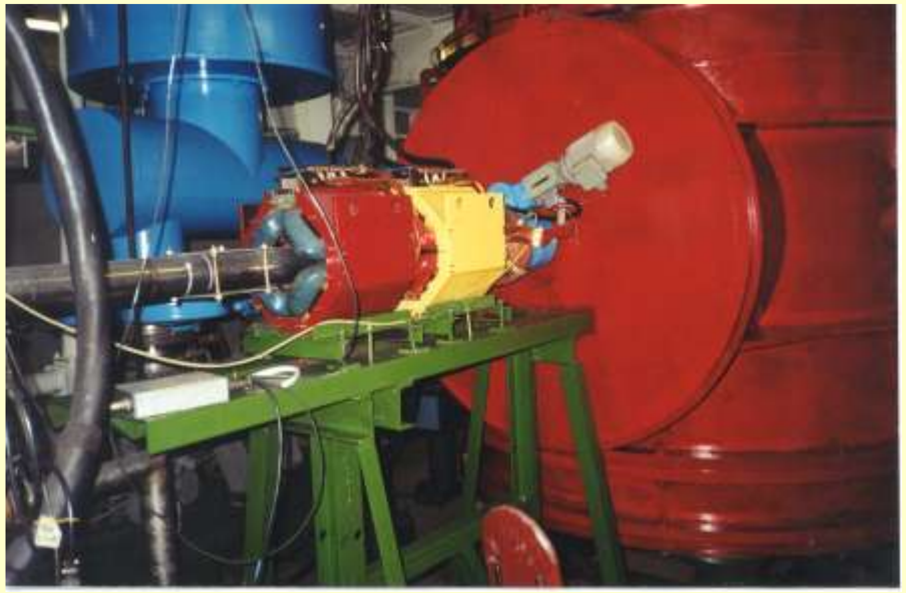
For-Injector (680 kV)

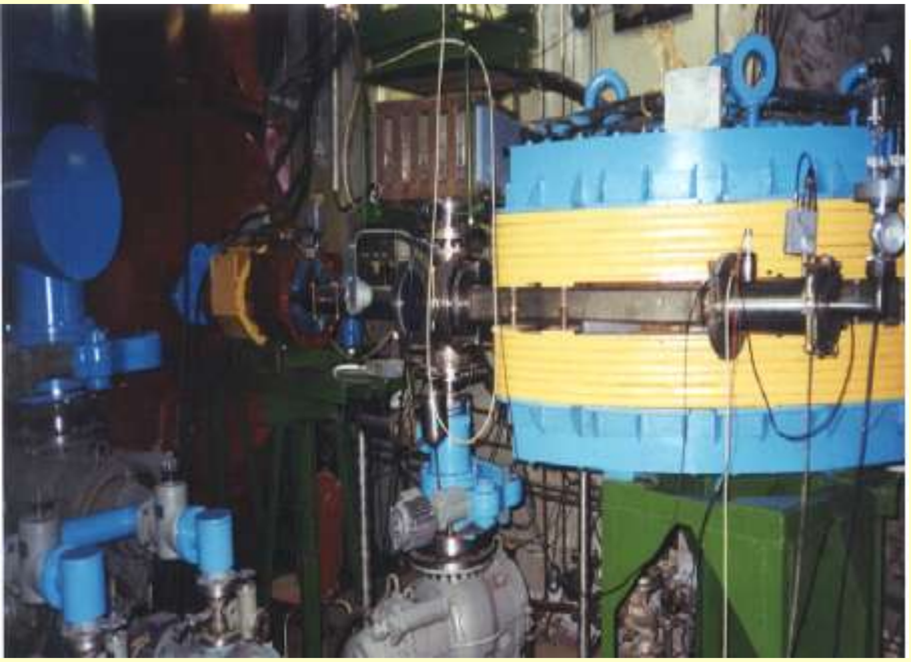
Linac (25MeV/200 mA)



Ion Injector I-3







Accelerating frequency	**2,504 MHz**
Accelerating voltage	**2x2 MV**
Bunching voltage	**up to 10 kV**
Accelerating ions	**any**
Input beam energy	**50 kV**
Ion energy at Z/A=0,2÷0,5	**0,8-1,9 MeV/u**
Transverse acceptance	**2000 π·mm mrad**
Max output beam current	**7 mA (C^{4+})**

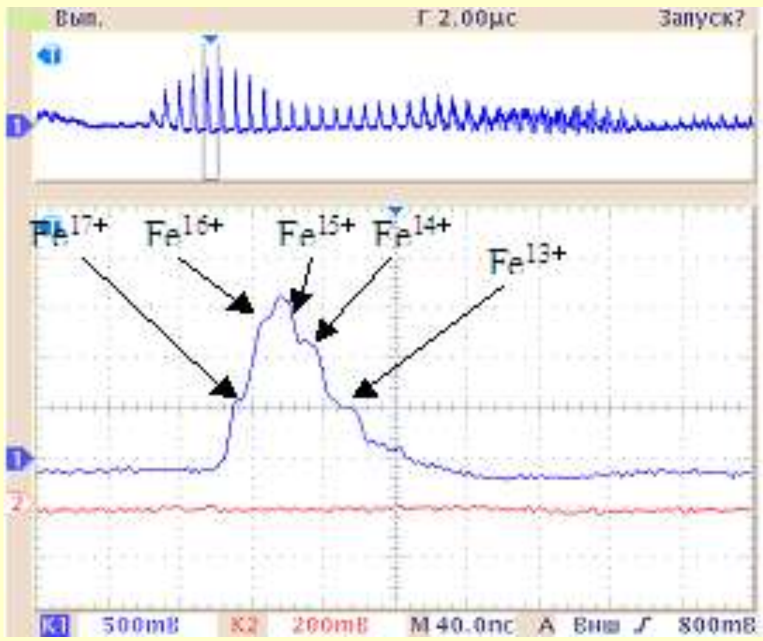
ITEP-TWAC Operation Parameters

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, Ag* *(Si,Ti,V,Cr,Cu,Mo)* *(Pb,Bi,U)*	*I-3/UK* *I-3/UK/U-10*	1,5 – 400 up to 4000	fast extraction, 800 ns, *C(400 MeV/u, 2x10^9), Al (230 MeV/u, 5x10^8), Fe (230 MeV/u, 2.5x10^8), Ag (100 MeV/u, 2x10^7),* internal target, 1s, fast (800 ns, 3 Ge/c) and slow extraction, (1 s, 3 GeV/c) *C(4 GeV/u, 5x10^8), Al (4 GeV/u, 1x10^8), Fe (3.6 GeV/u, 2x10^7),*
Nuclei accumulation, *C, Al,Fe,* *(Si,Ti,V,Cr,Cu)*	*I-3/UK/U-10*	200-300 700-1000	fast extraction with compression to 150 ns, continue extraction of stacking beam

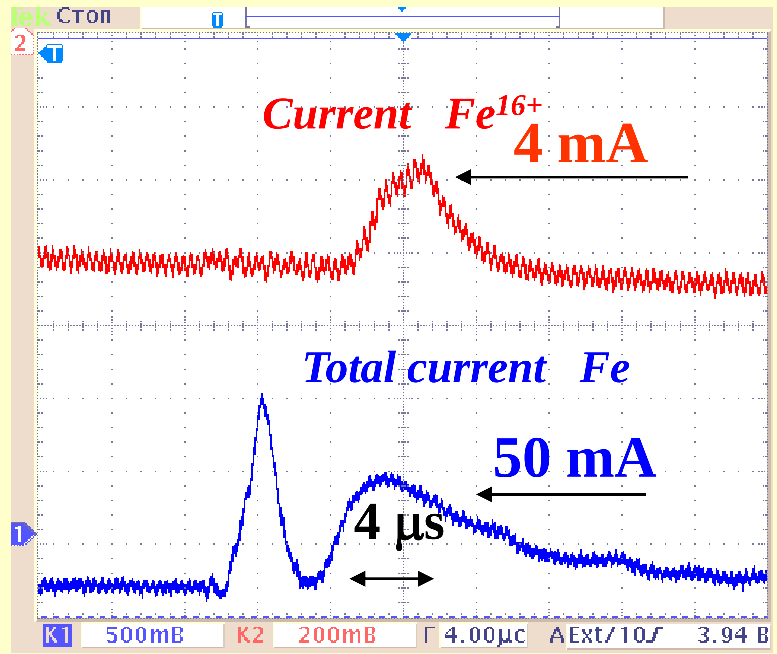
X – in operation, X – near plan, X – future plan

Acceleration of Fe nuclei in I-3/UK/U-10 up to relativistic energy

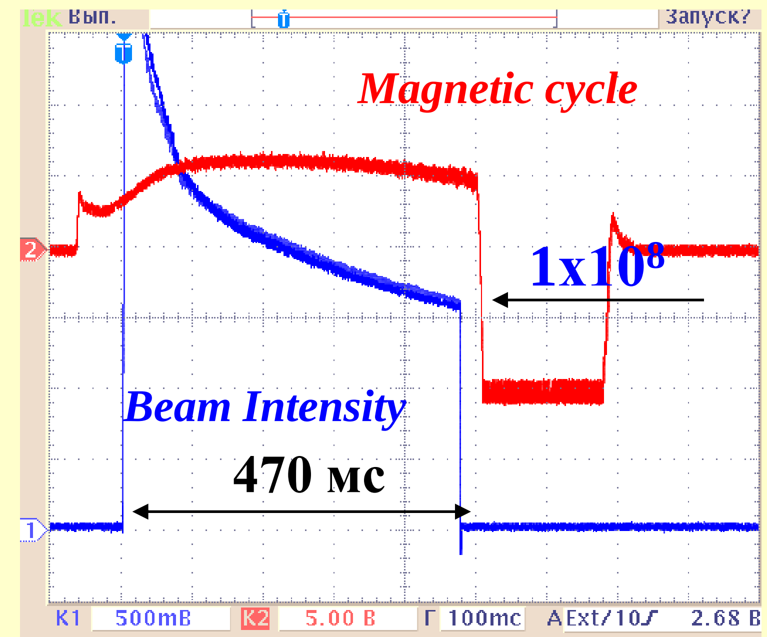
Generation of $_{56}$Fe ion in LIS100



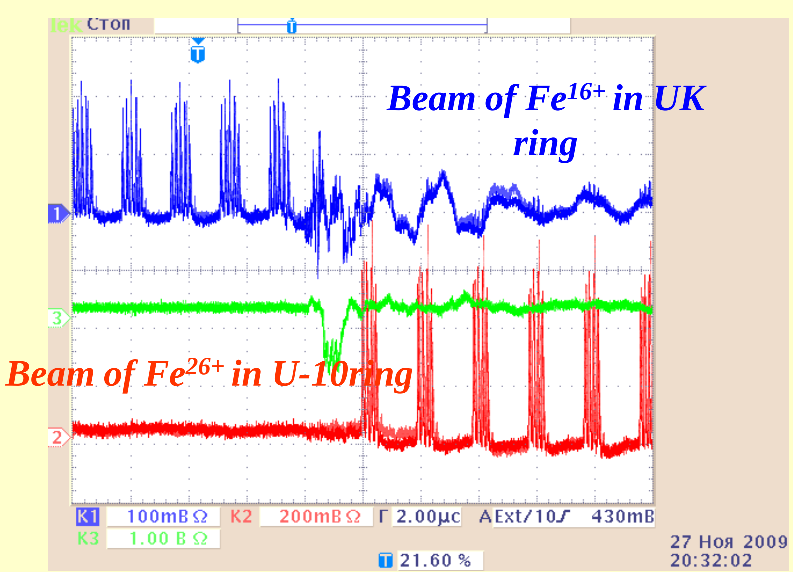
Acceleration of Fe^{16+} в I-3



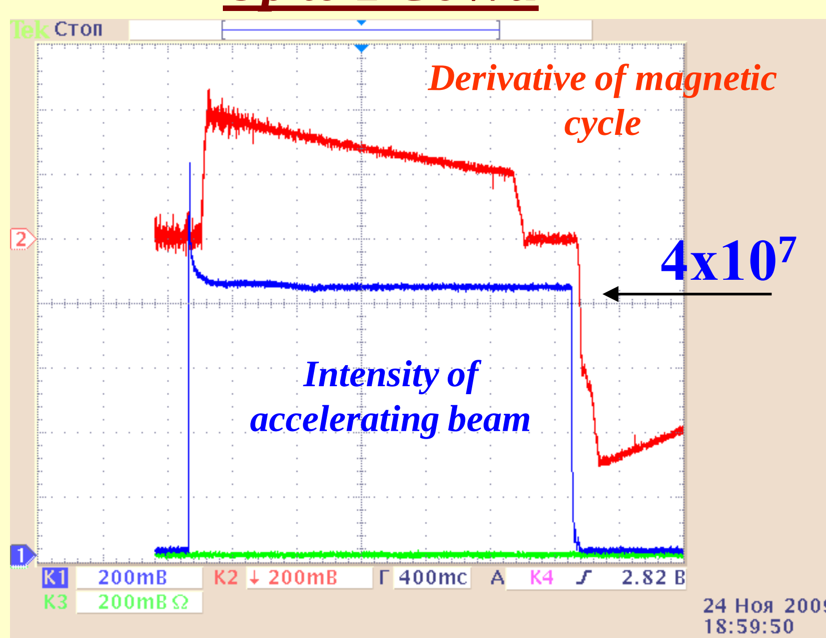
Acceleration of Fe^{16+} up to 12,9 GeV



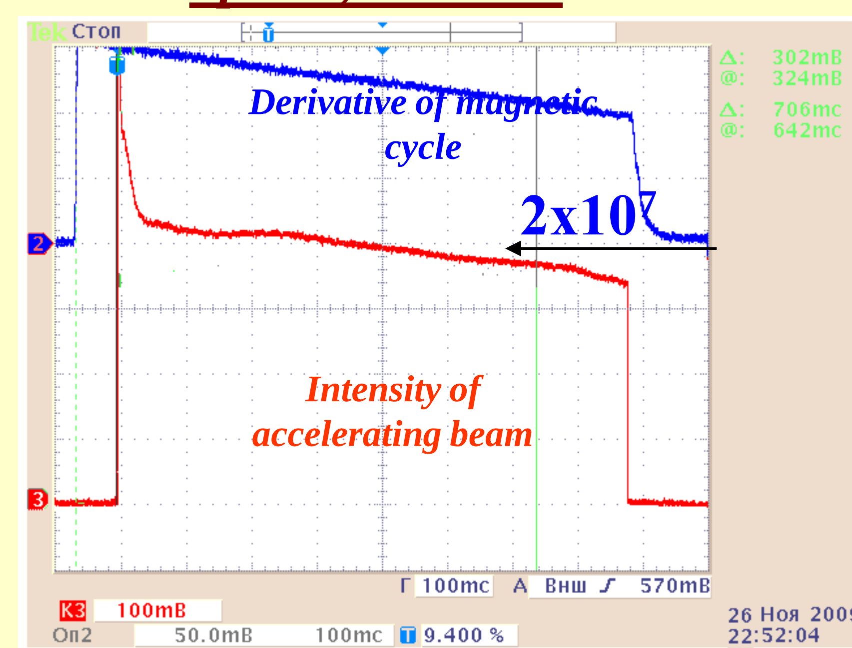
Charge exchange injection of $_{56}$Fe from UK to U-10



Acceleration of Fe^{26+} in U-10 Up to 1 GeV/u

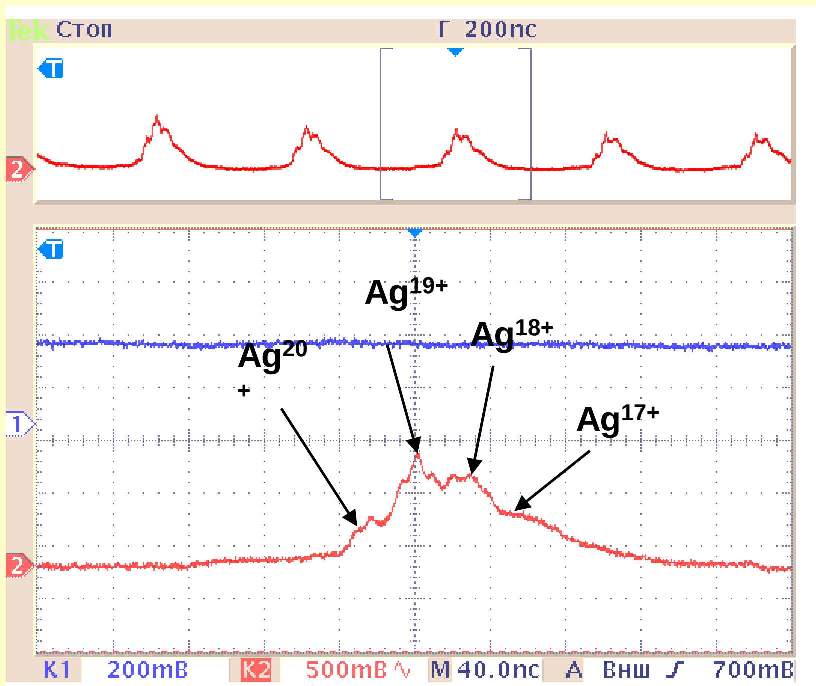


Acceleration of Fe^{26+} in U-10 up to 3,65 GeV/u

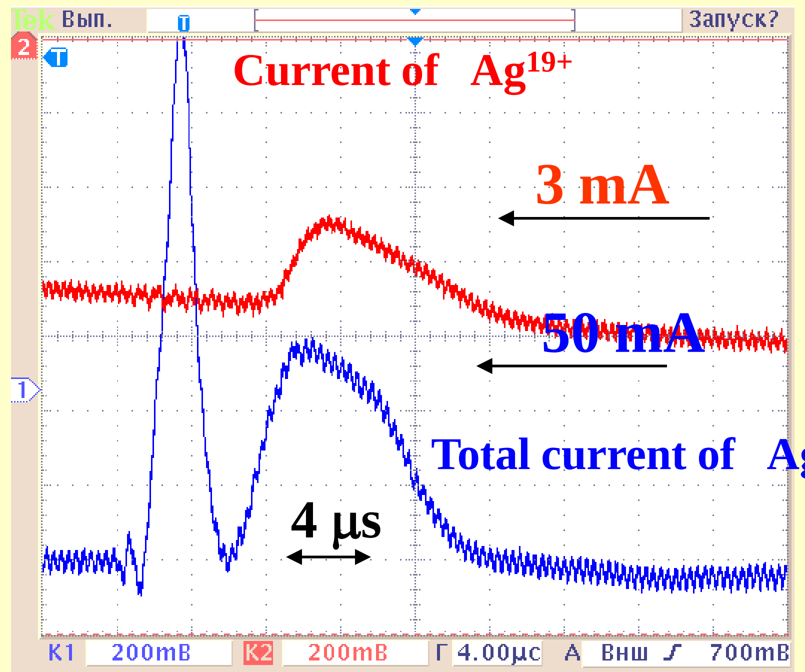


Ag ions acceleration in synchrotron UK

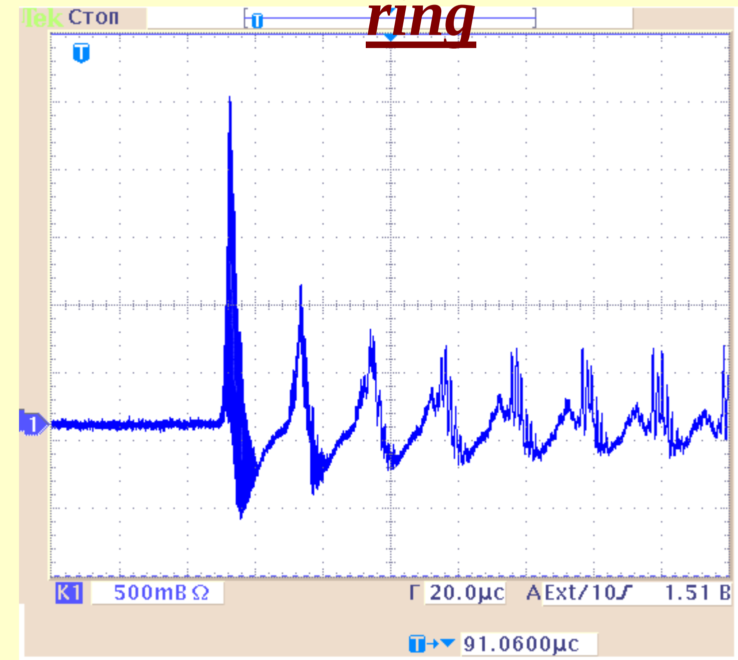
Generation of $_{109}$Ag in L100



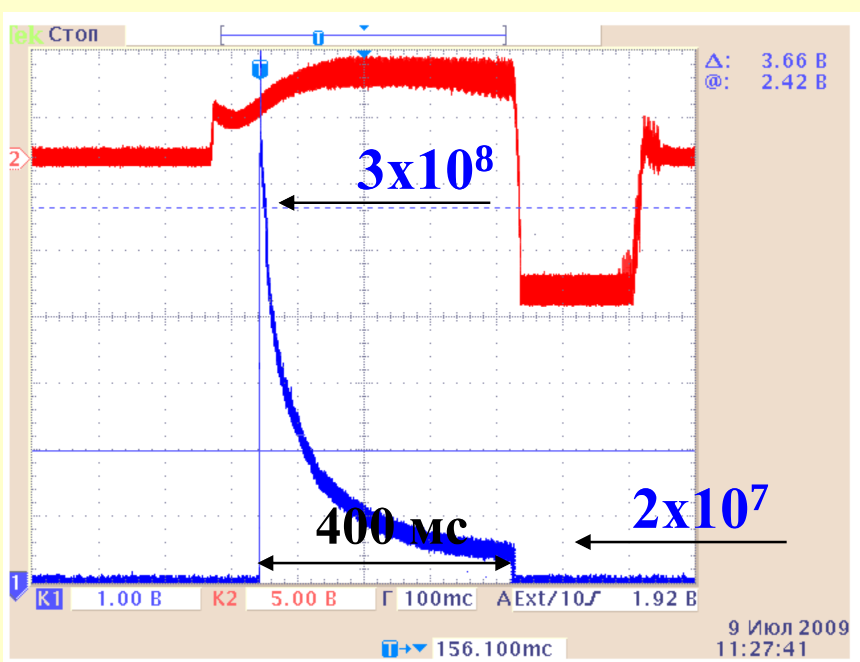
Acceleration of Ag^{19+} in I-3

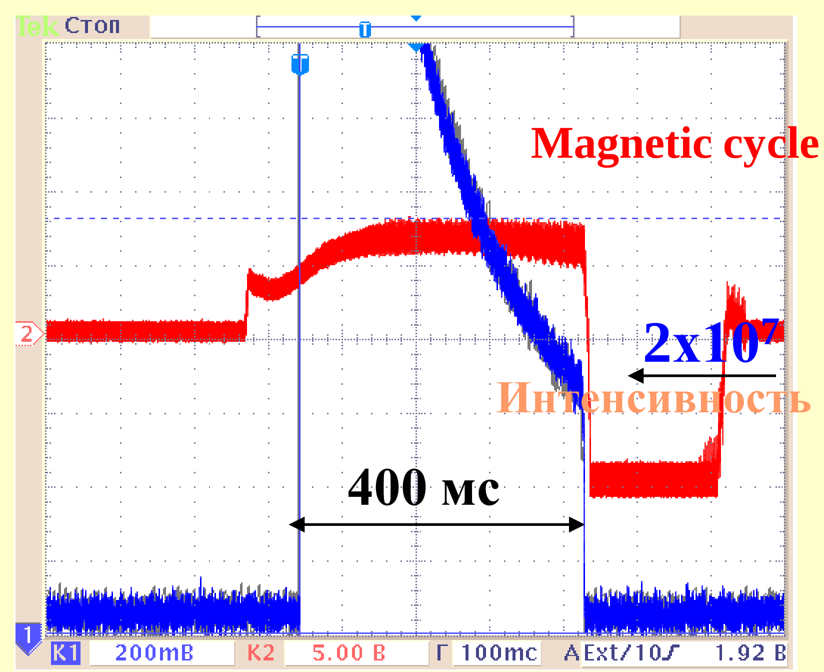


Circulation of Ag^{19+} in UK ring

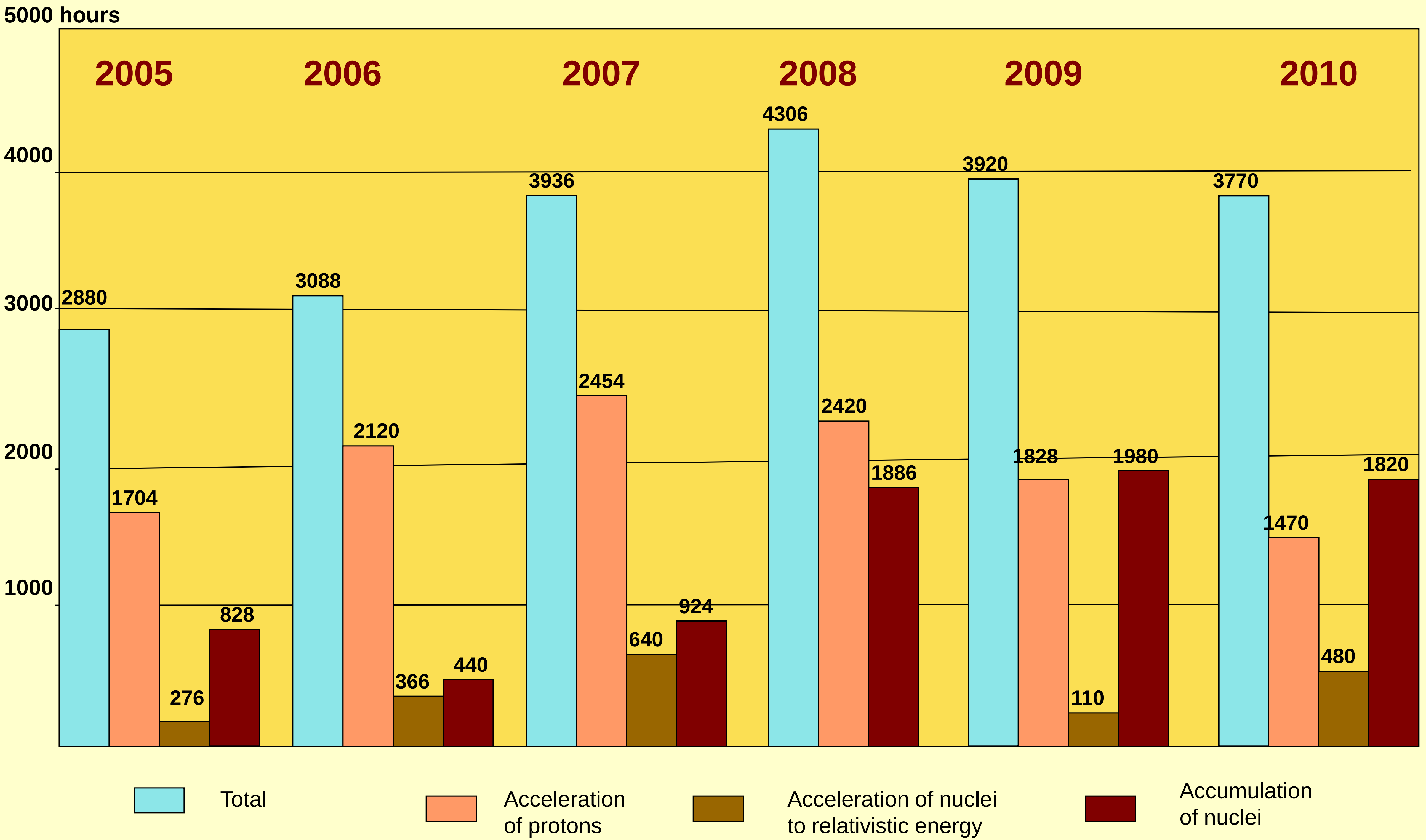


Acceleration of Ag^{19+} in UK ring up to energy of 10,9 GeV (100 MeV/u)





Statistic of ITEP-TWAC operation



Accelerator operation time for different research fields

Research fields with proton and ion beams	*Beams*	*Accelerator operation time, (hours)*		
		2008	*2009*	*Require-ments*
Relativistic nuclear physics	**p (2-9 ГэВ, 10^{11}с$^{-1}$) He, C,Al …(4 ГэВ/н, 10^{8}с$^{-1}$)**	**828**	**1100**	**1500**
Methodical research	**p (1-9 ГэВ, 10^{11}с$^{-1}$) C(0,2-4 ГэВ/н, 10^{8}с$^{-1}$)**	**2432**	**2100**	**2500**
Physics of high density energy in matter	**C, Al,Fe…, Cu (300-700 МэВ/н, 4x10^{10}с$^{-1}$)**	**320**	**350**	**500**
Radiobiology and medical physics	**p (250 МэВ, 10^{11}с$^{-1}$) C (300-800 МэВ/н, 10^{9} с$^{-1}$)**	**2350**	**2150**	**3000**
Proton therapy	**p (250 МэВ, 10^{11}с$^{-1}$)**			
Ion therapy	**C (300-800 МэВ/н, 10^{9} с$^{-1}$)**	**0**	**0**	
Radiation treatment of materials	**p (25-400 МэВ, 10^{11}с$^{-1}$) Fe, Ag, Bi, U (40-200 МэВ/н, 10^{8} с$^{-1}$)**	**858**	**1100**	**>2000**
Total		**6788**	**6800**	**>9500**

X – future plan

Progress in ITEP-TWAC beam parameters (2006-2010)

	2006	**Reached in 2008**	**Expected in 2010**	**Plans**
Accelerated particles	C^{4+}	**Fe^{16+}, Ag^{19+}**	**Si^{12+}, Cu^{19+}**	U^{29+} **(2013)**
Stacked particles	C^{6+}	Al^{13+}, Fe^{26+}	**Si^{14+}, Cu^{19+}**	Cu^{29+} (**2010**)
Repetition rate, Hz	0.3			1 (**2012**)
Energy of beam stacking, MeV/u	200	300	500	700 (**2011**)
Intensity of UK synchrotron (for C^{4+} ions)	10^9	$2x10^9$	$3x10^9$	$>10^{10}$ (**2012**)
Beam momentum spread, %	0.05	0.04	0.03	<0.03
Efficiency of charge exchange injection, %	~50	~60		~100
Dynamic aperture of U10 ring, π mm mrad	7	10		50
Life time of stacked beam, s	200		~250	>500
Factor of stacked beam intensity increase	70		100	200
Intensity of stacked beam	$3x10^{10}$ C^{4+} =>C^{6+}	$4x10^{10}$ (C^{4+} =>C^{6+})	$\sim10^{11}$ (Si^{12+}=> Si^{14+})	$>10^{12}$ (**2012**)
Compressed beam width, ns	150		100	80 **(2011)**
Power of stacked beam, W	$1x10^8$	$3x10^8$	$\sim10^9$	$>10^{10}$ (**2011**) 10^{11} (**2013**)

Accelerator technologies development

1. Development of laser ion source technology

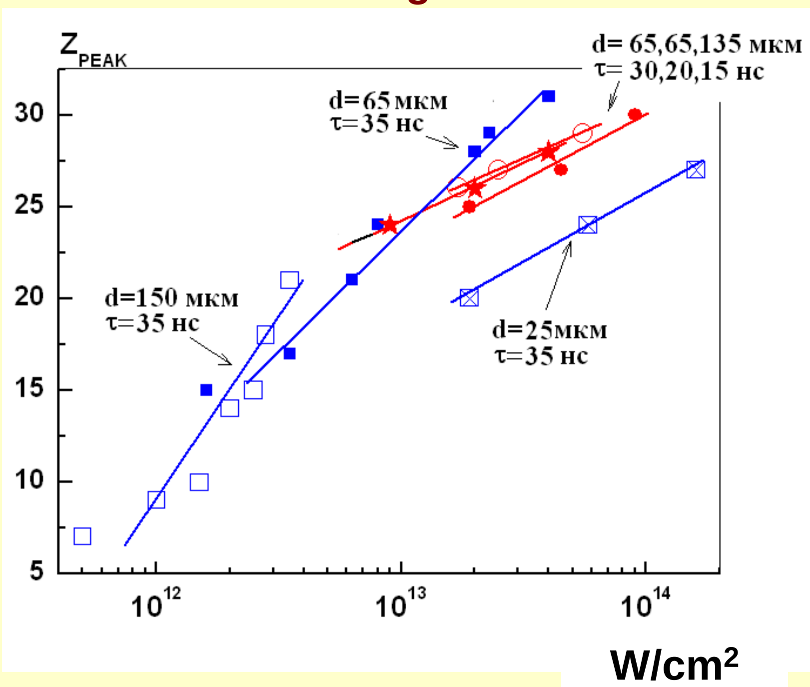
2. Construction of the new ion injector I-4

3. Development of charge exchange injection technique for heavy ions

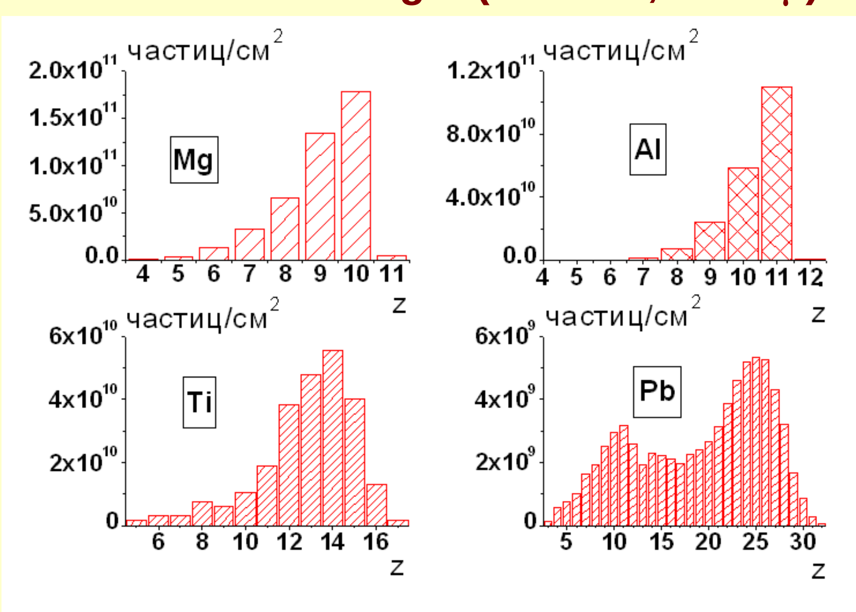
4. Development of ITEP-TWAC facility infrastructure

Generation of high charge state ions in LIS

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)

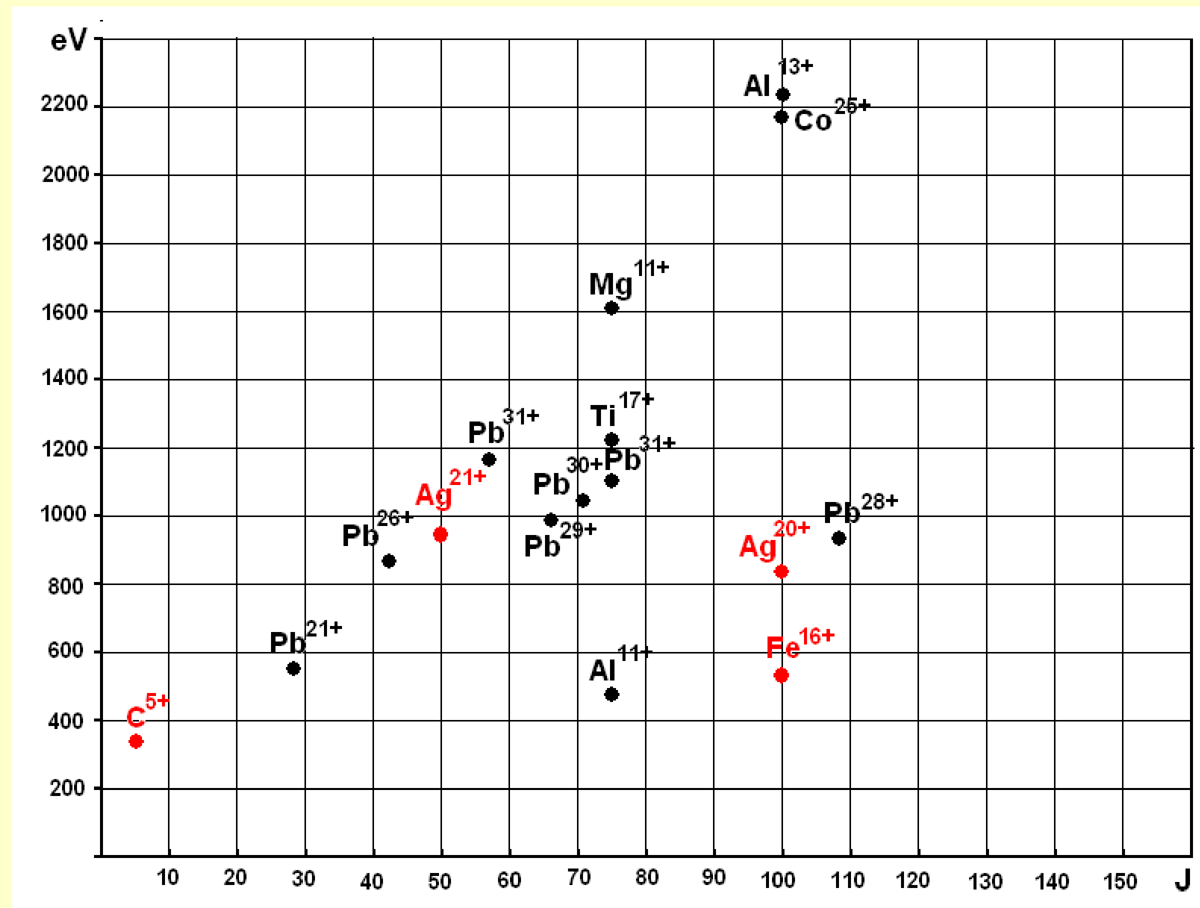


Ionization potential as a function of relevant parameters

I_{ion} =f(λ, E, P, τ , d, q) where

λ – wave length of laser radiation,
E - energy in laser pulse,
P(E, τ) – pick power of laser pulse,
τ - laser pulse width,
d – spot diameter on target surface,
q (P, d) – radiation power density on target surface

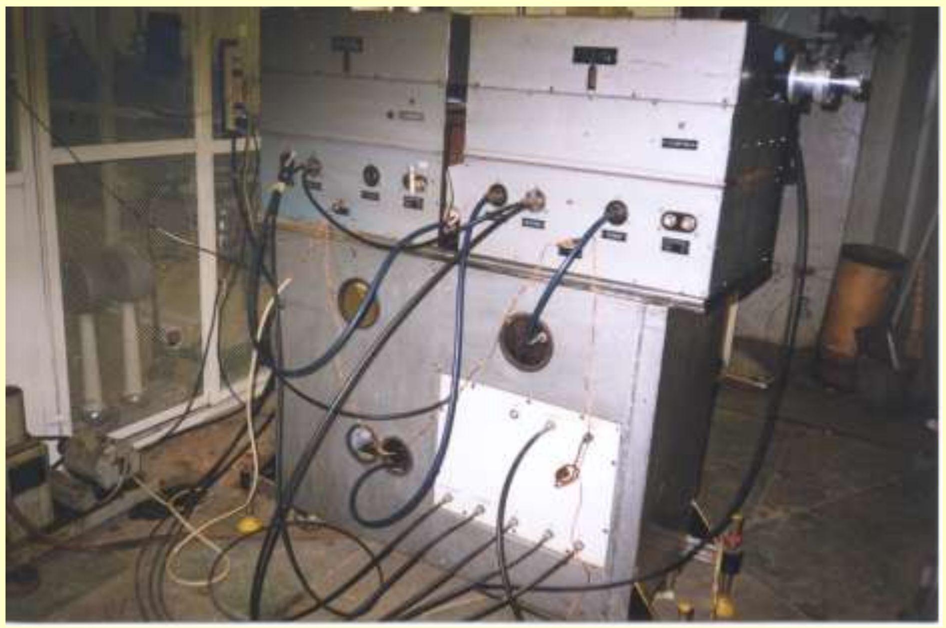
Maximal ionization potential of different ions from energy of laser radiation on the target



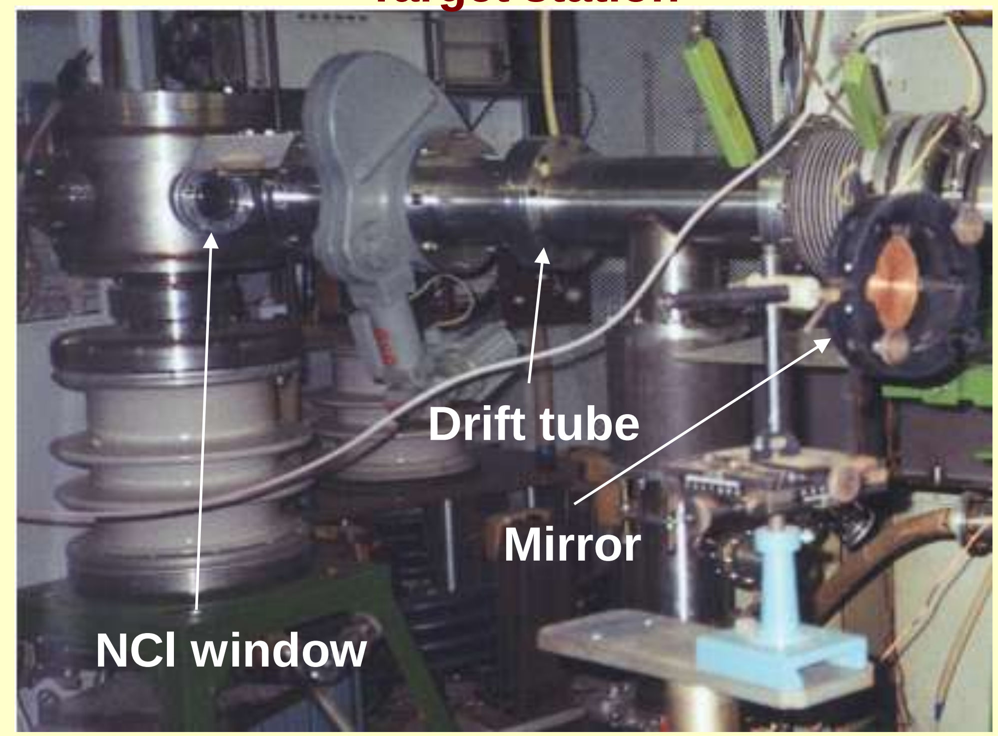
Experience with LIS Operation

First configuration of LIS (1998-2006)

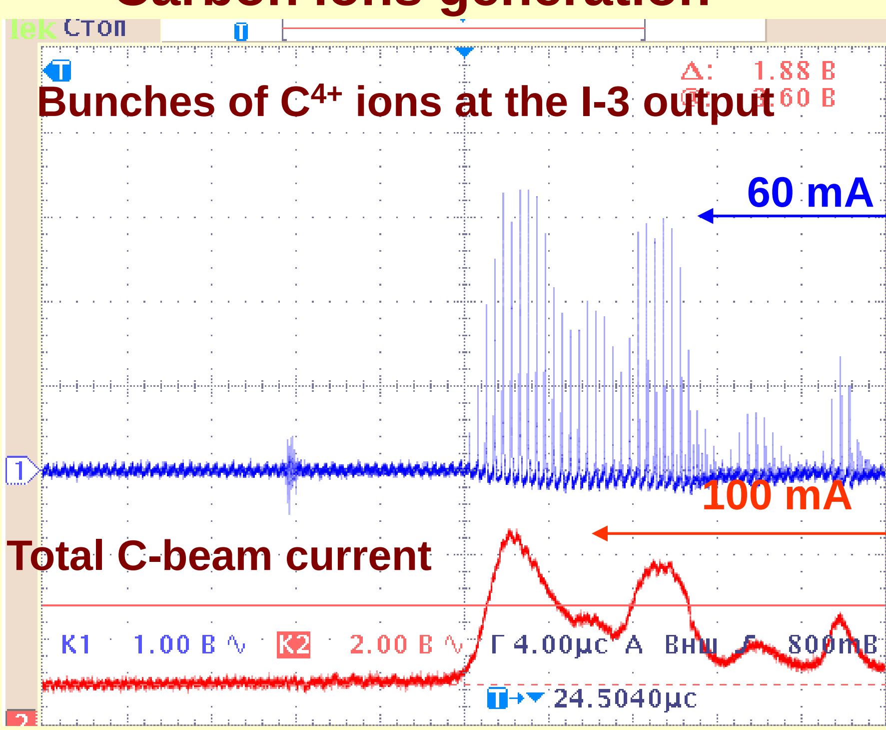
Laser L5



Target station



Carbon ions generation



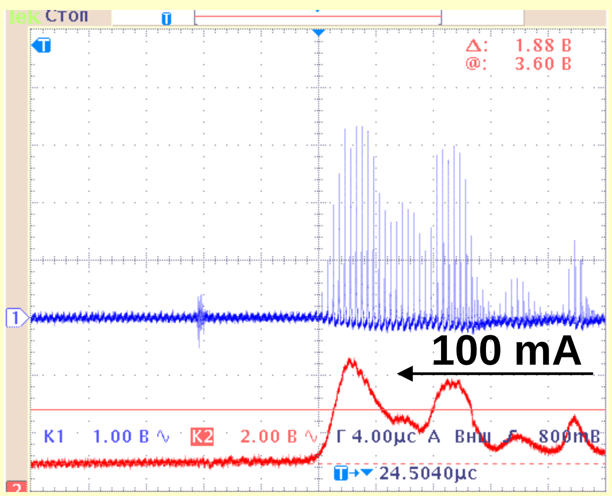
LIS Parameters

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

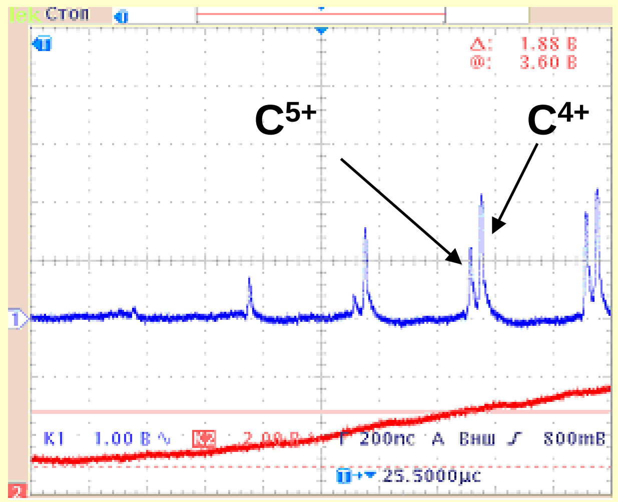
Experience with LIS Operation

Carbon ions generation in LIS with laser L5 (2006)

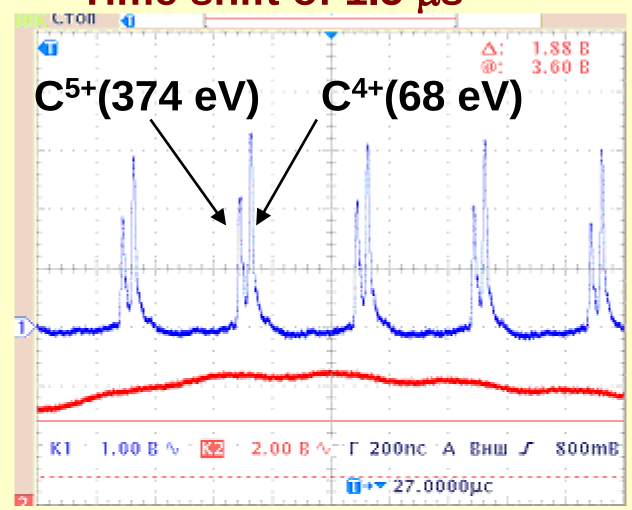
Total beam current



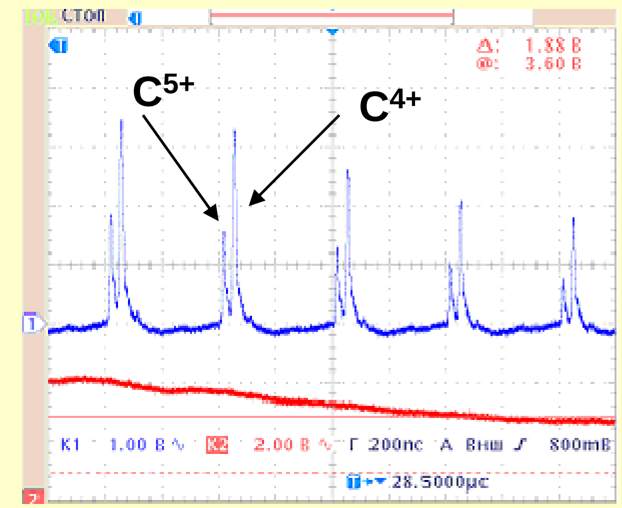
Front of beam



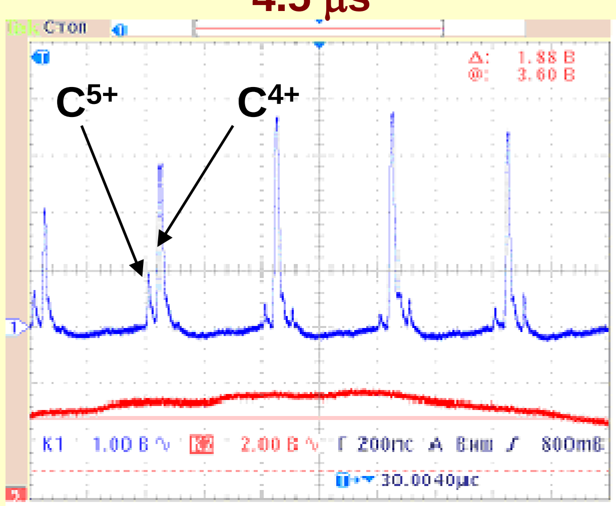
Time shift of 1.5 μs



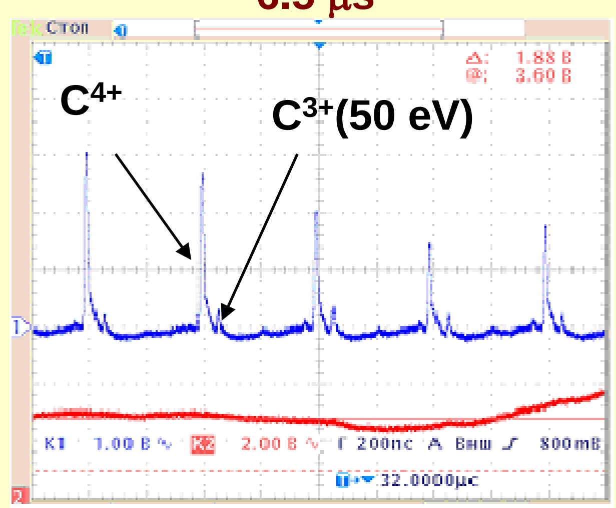
3 μs



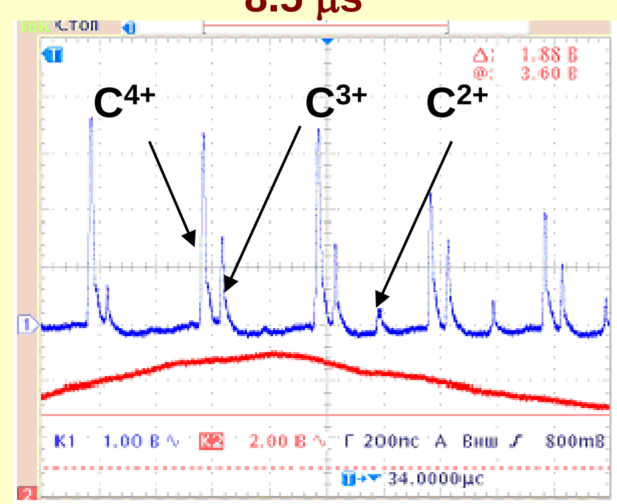
4.5 μs



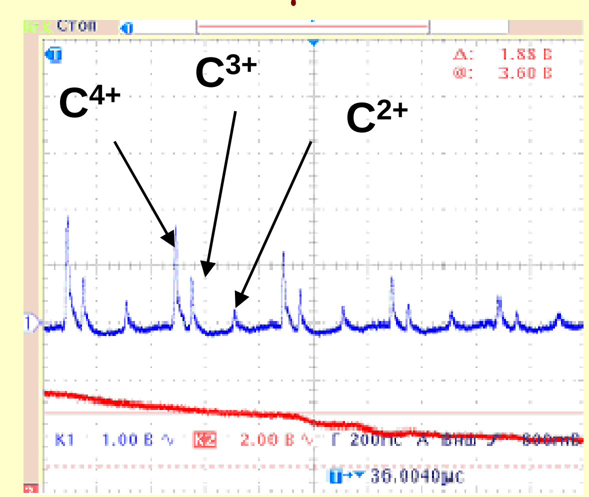
6.5 μs



8.5 μs



10.5 μs

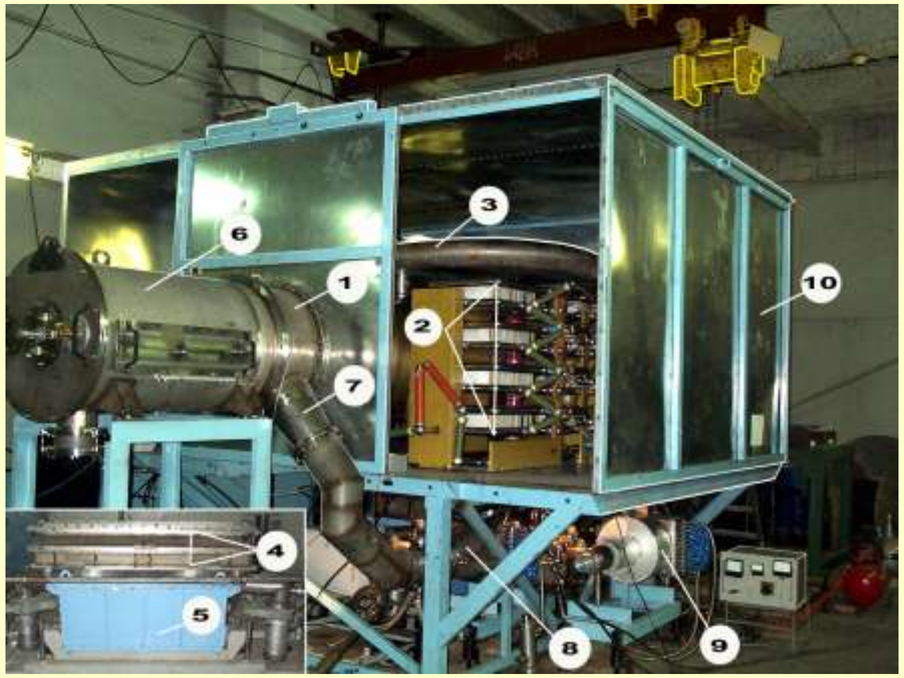


Beam parameters

	C^{5+}	C^{4+}
Pulse width, μs	3.5	10
Number of particles	3×10^{10}	5×10^{11}

New configuration of LIS (2007)

Laser L100 layout



Laser ray transfer line

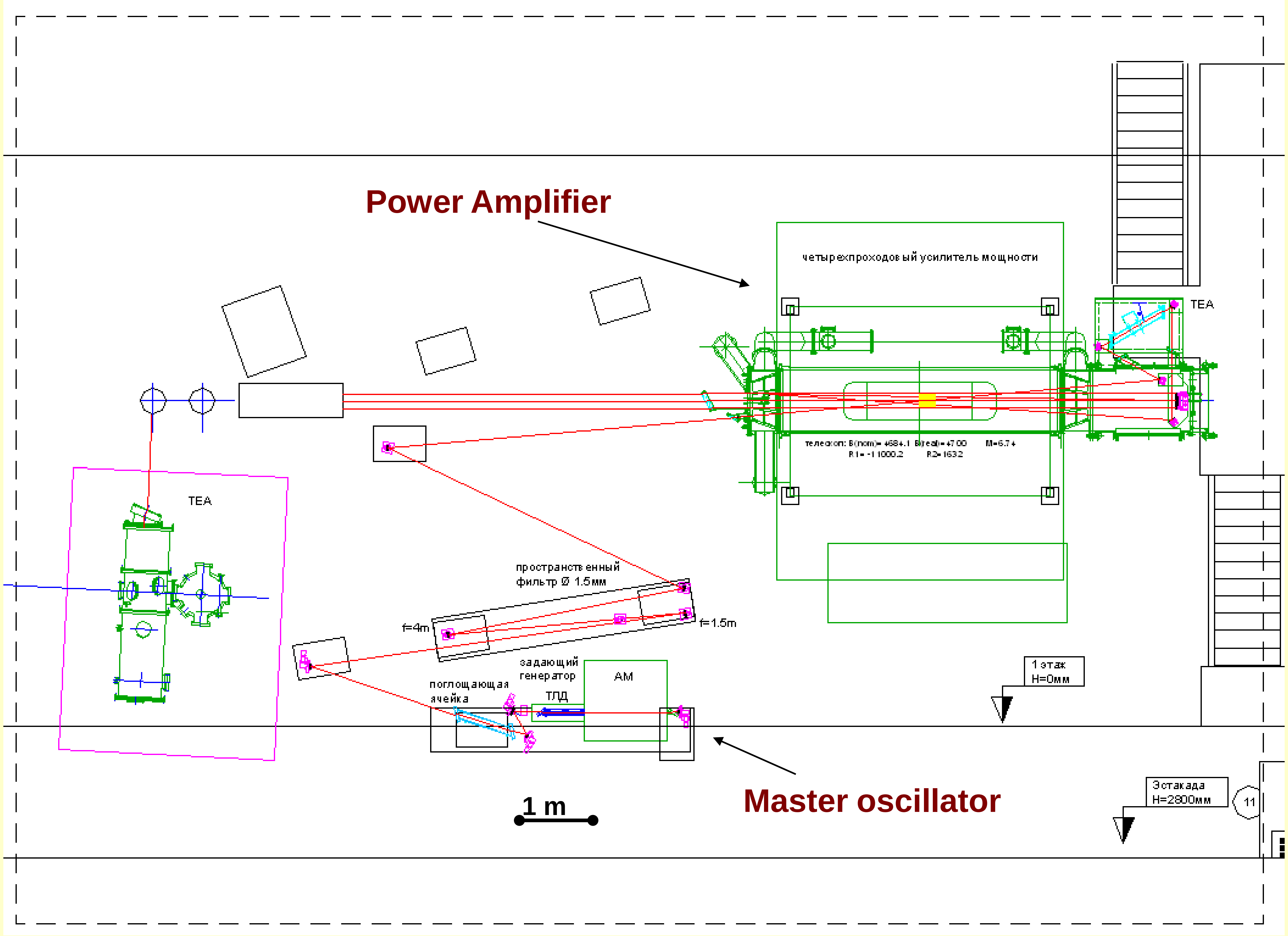
Target station

Laser L100 and output conduit

Expected LIS Parameters

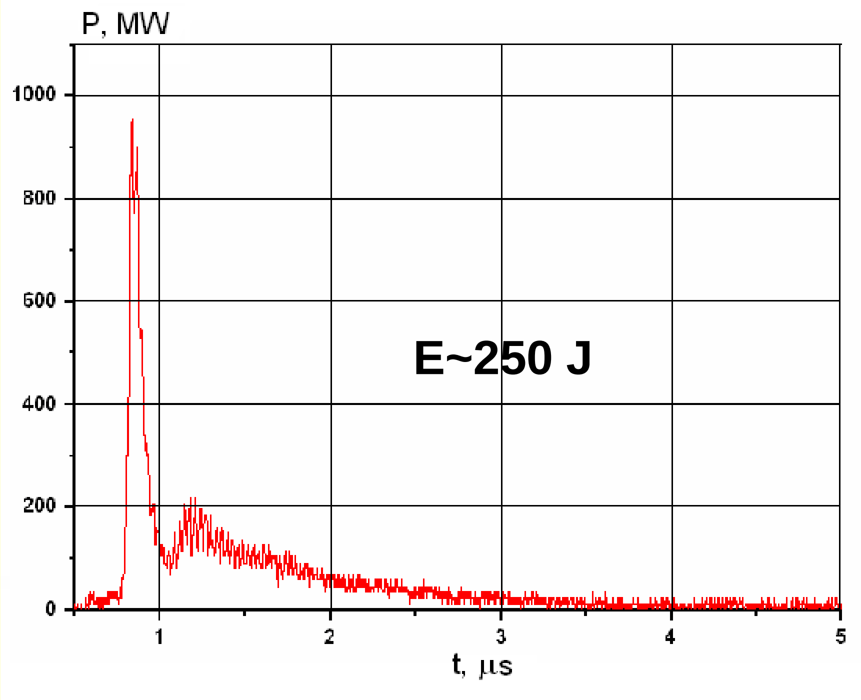
Wavelength, μ	**10,6**
Pulse energy, J	**5/20/100**
Pulse duration, ns	**100/80/30**
Power density at target spot	$2\text{x}10^{11}/10^{12}/10^{13}$ W/cm^2
Max. repetition rate, Hz	**0,5 /1/1**
Operational resource	**~10^6**

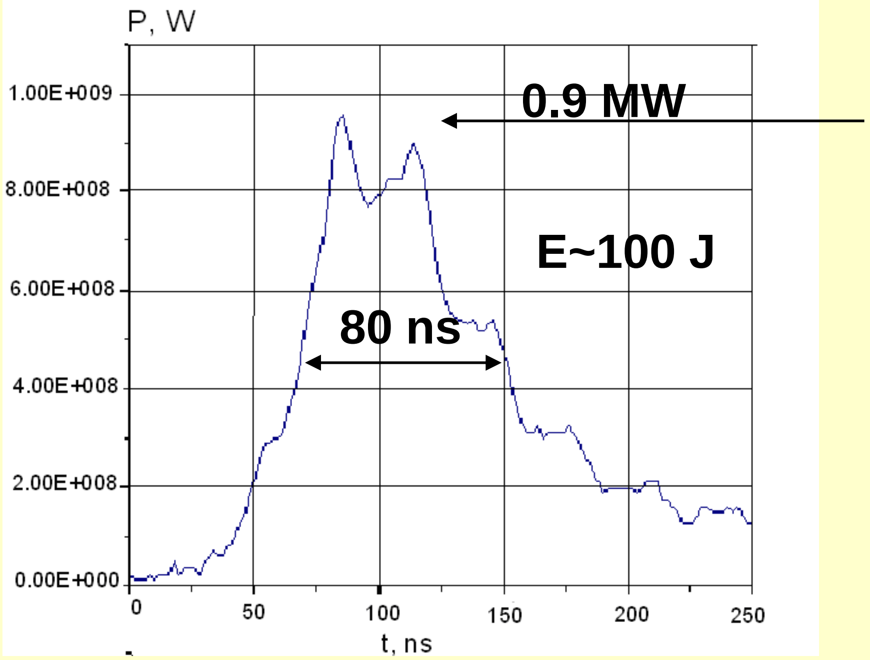
Optical Scheme of 100 J CO_2- Laser L100M



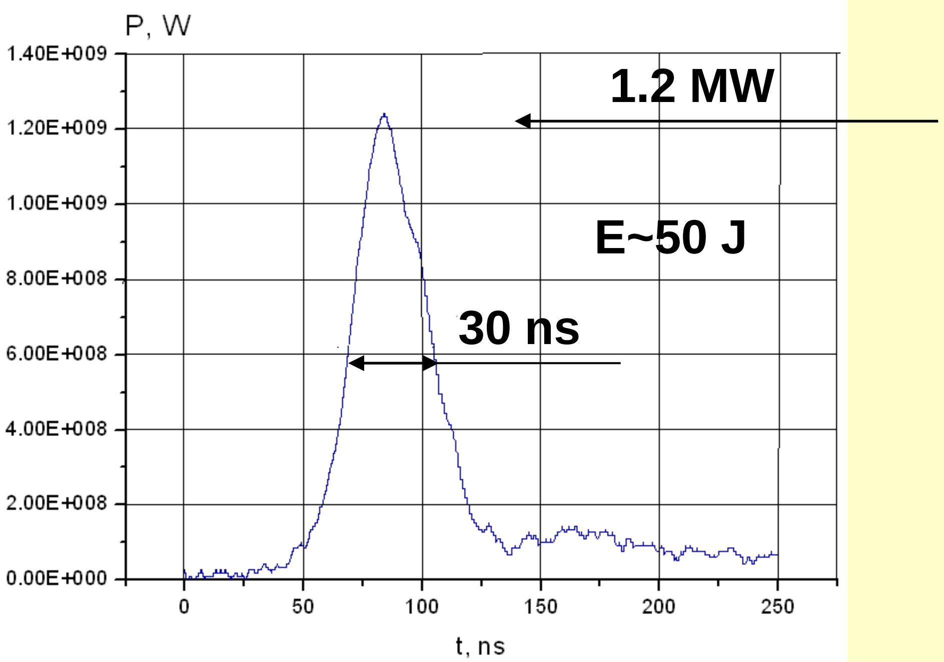
Pulses of L100 and L100M laser configurations

Free generation mode of L100 laser radiation

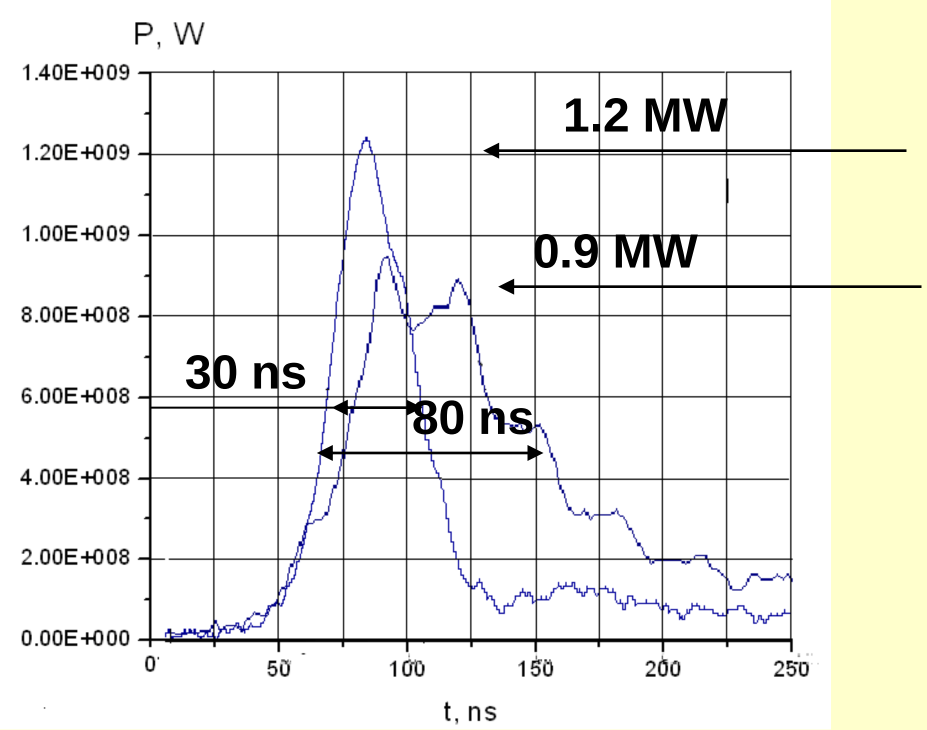




Amplifier mode of L100M laser radiation

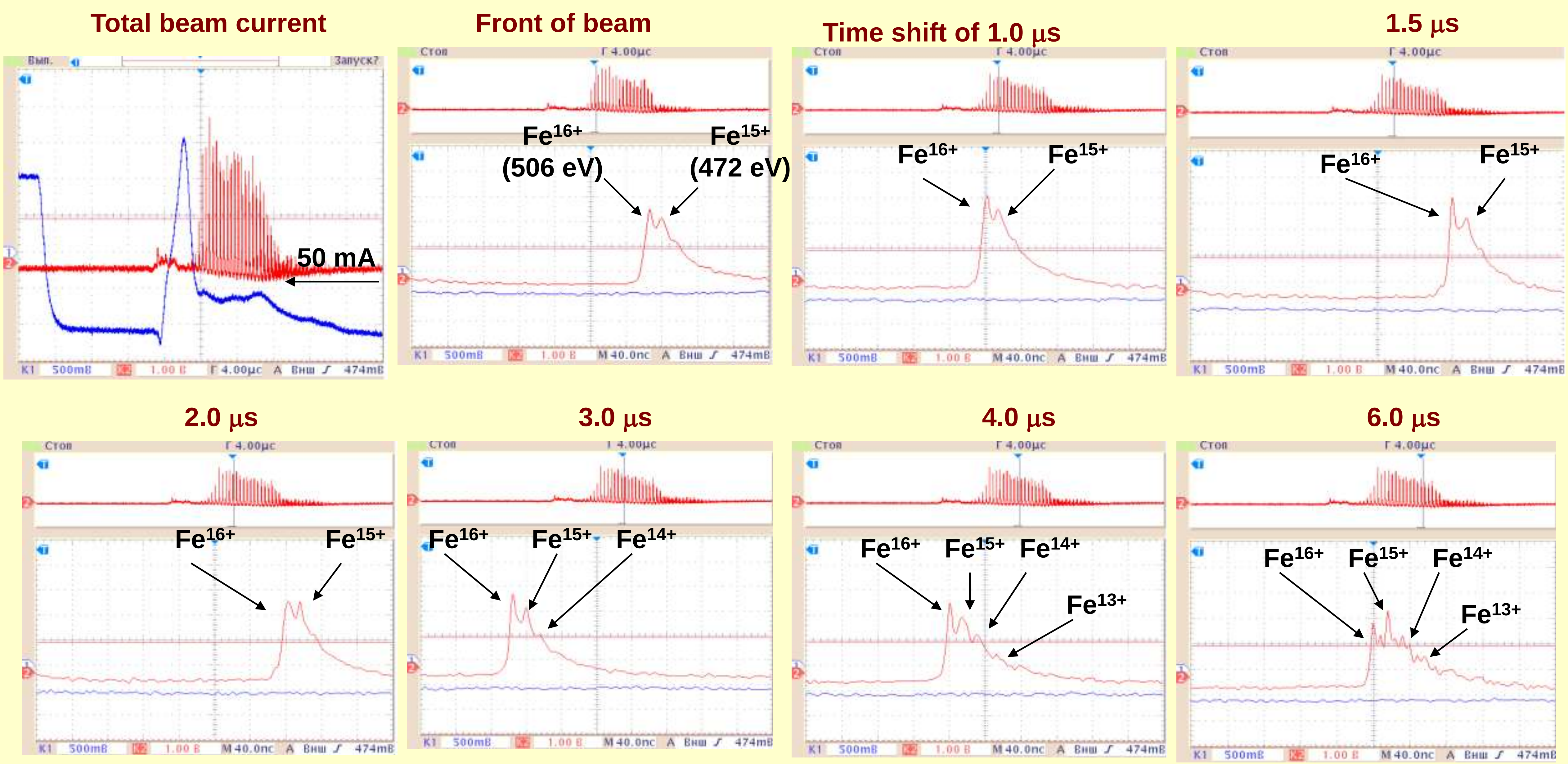


Superposition of L100 and L100M pulses



Fe ions generation

Fe ions generation in LIS with laser L100 (2008)



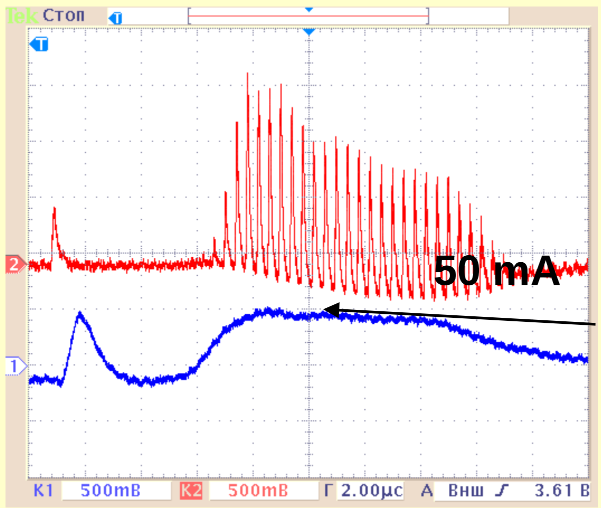
Beam parameters

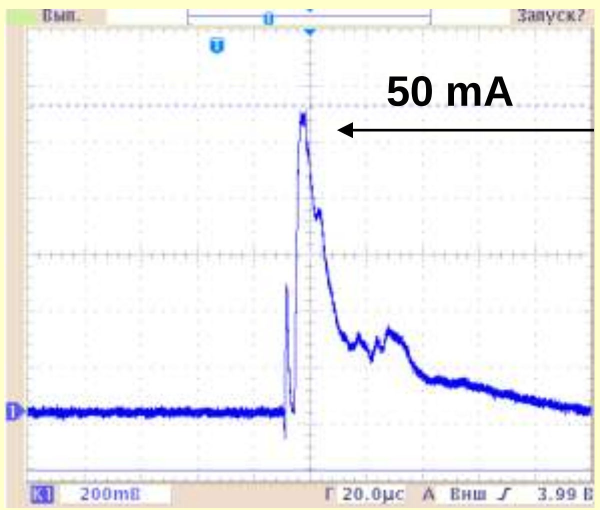
	Fe^{16+}	Fe^{15+}
Pulse width, µs	4.5	5
Number of particles	1×10^{10}	8×10^{9}

Ag ions generation

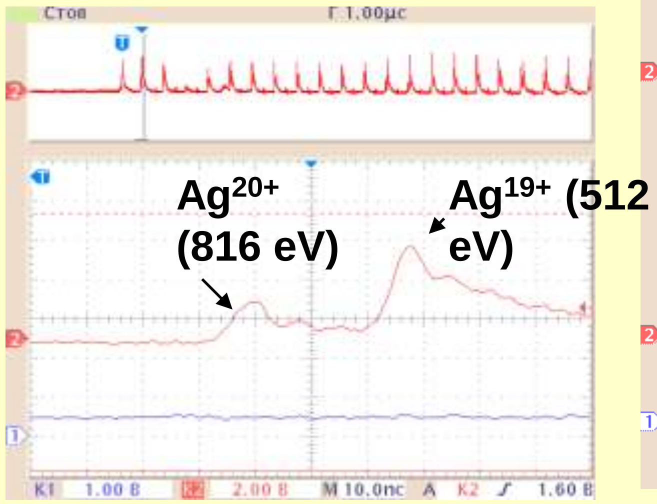
Ag ions generation in LIS with laser L100 (2010)

Total beam current

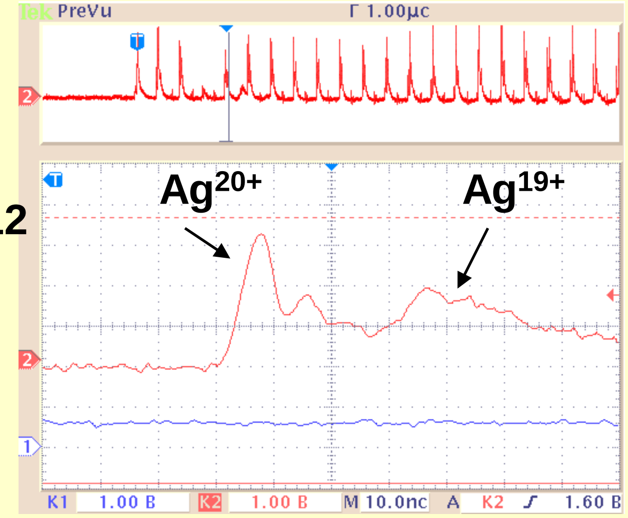




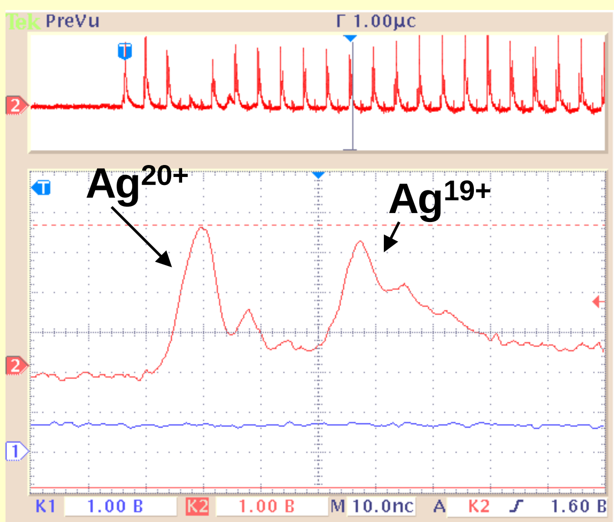
Front of beam



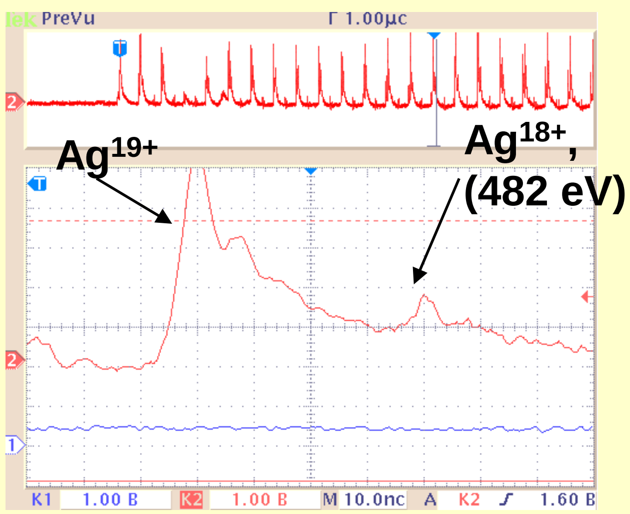
Time shift of 1.5 μs



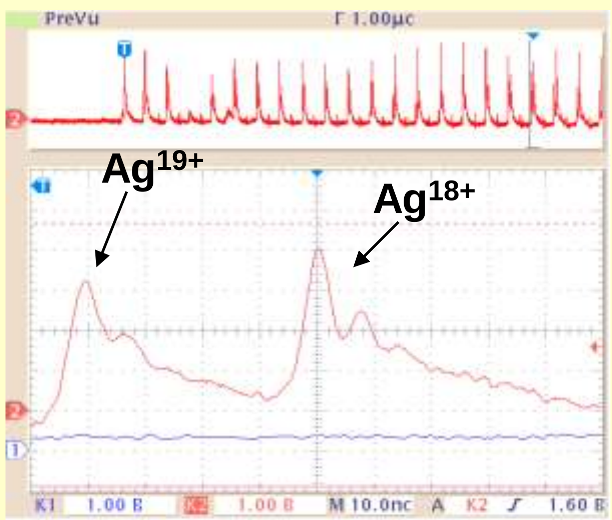
3.0 μs



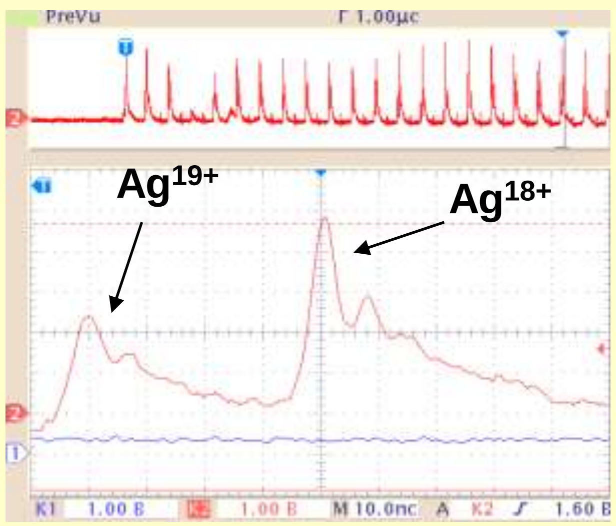
4.5 μs



6.5 μs

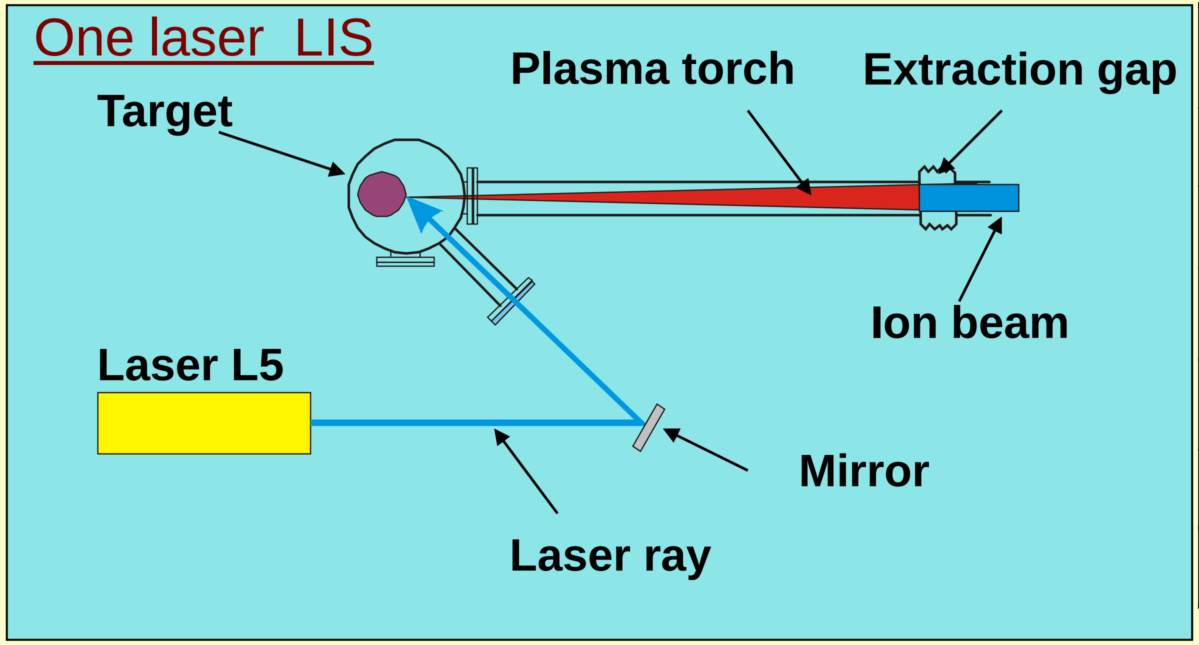


7.5 μs



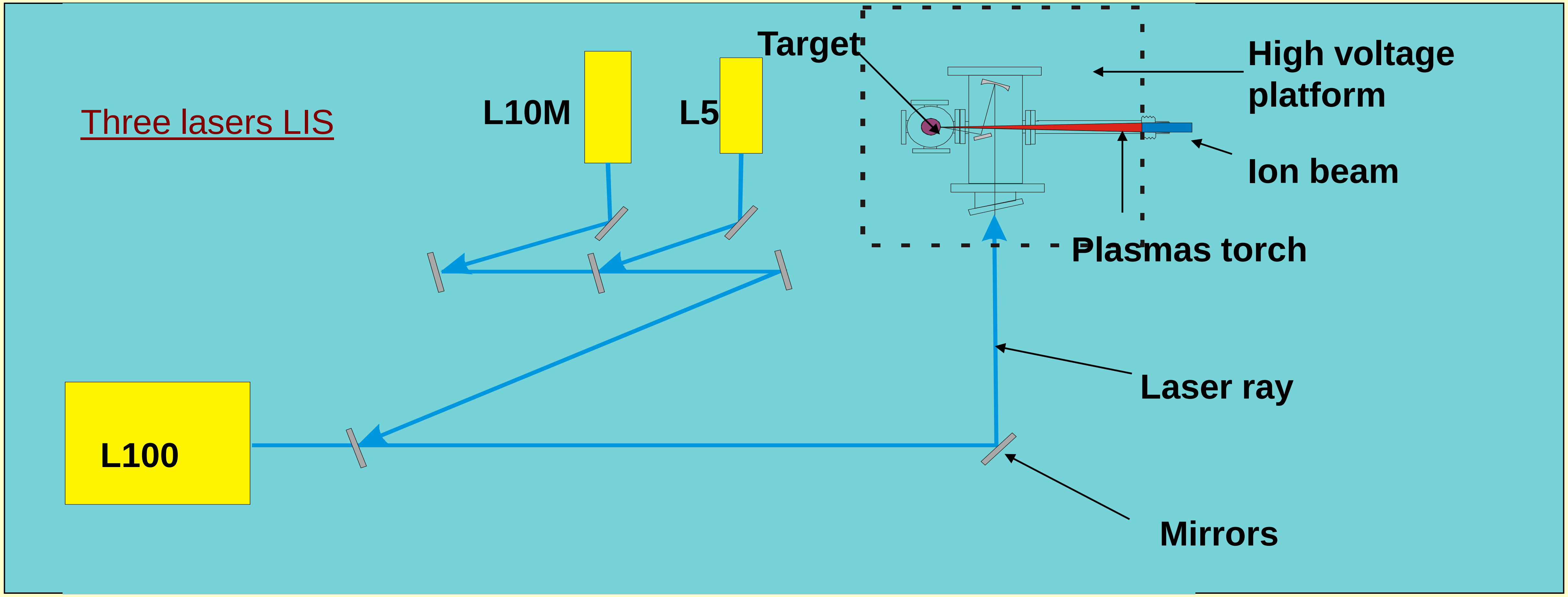
	Ag^{20+}	Ag^{19+}
Pulse width, ms	2.5	6
Number of particles	2×10^9	1×10^{10}

LIS focusing system



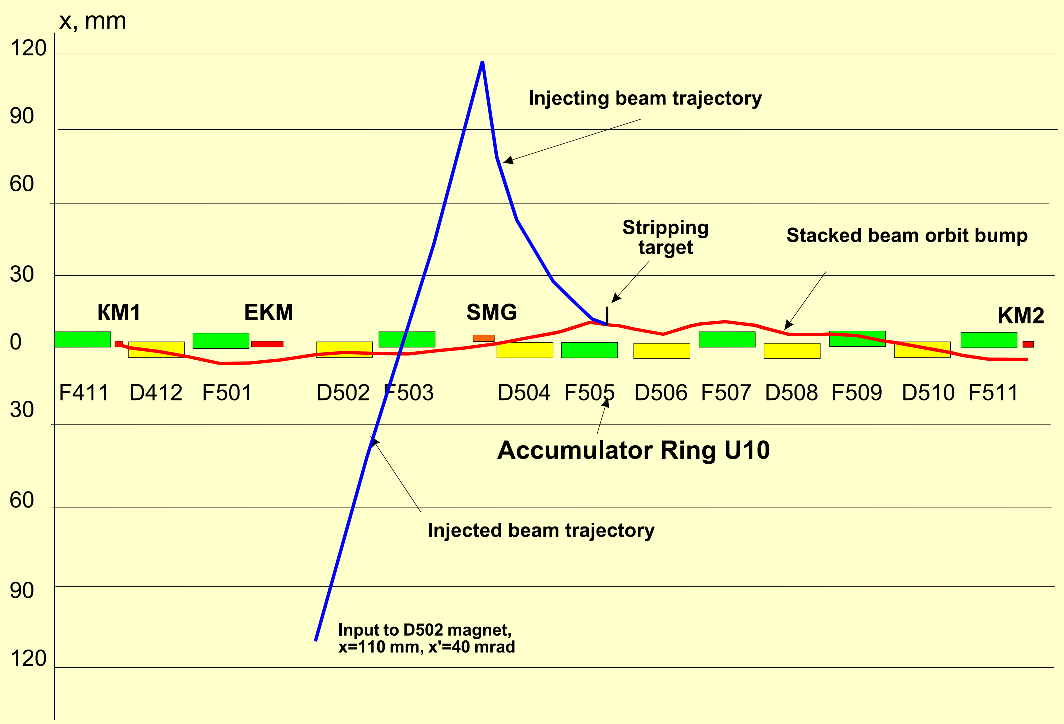
Parameters of old and new LIS configurations

LIS	Old	New
No of mirrors	3	9
Focal length	30	160
Length of laser ray transfer line, m	1.5	30
Ray spot size on focusing lens, mm	30	180
Ray spot size on target, mm	~0.15	~0.5
Power density on the target, W/cm^2	$2x10^{11}$(L5)	$7x10^{11}$(L100)

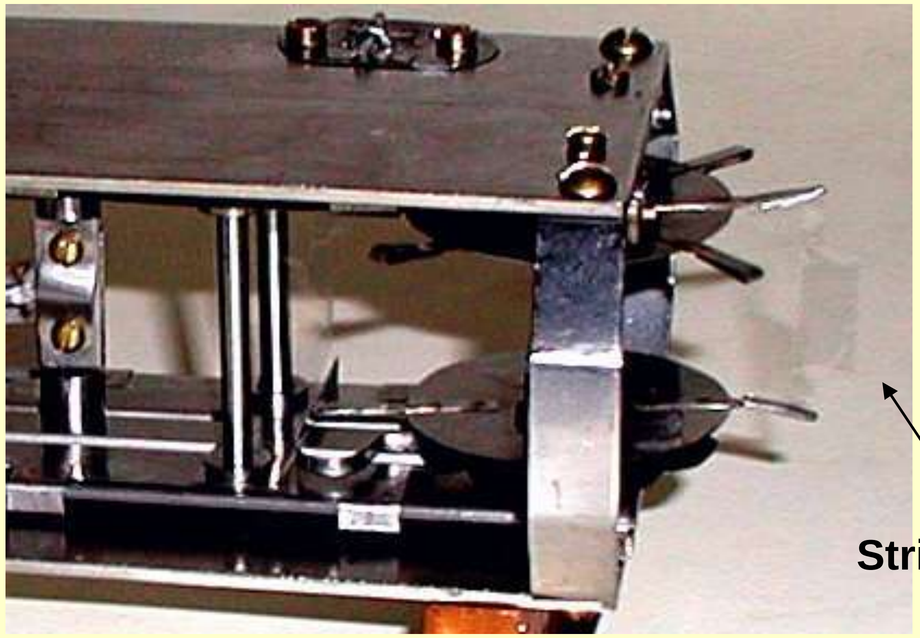


Development of charge-exchange stacking of nuclei

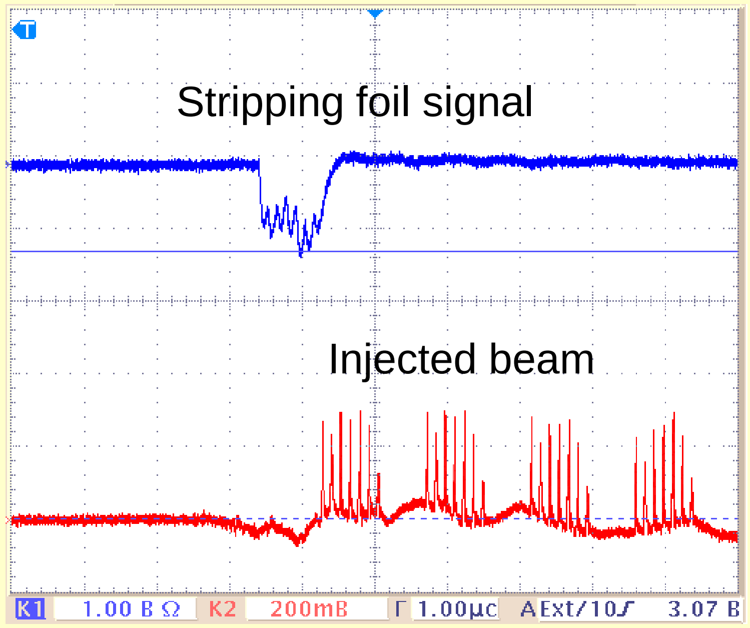
Beams trajectories at injection



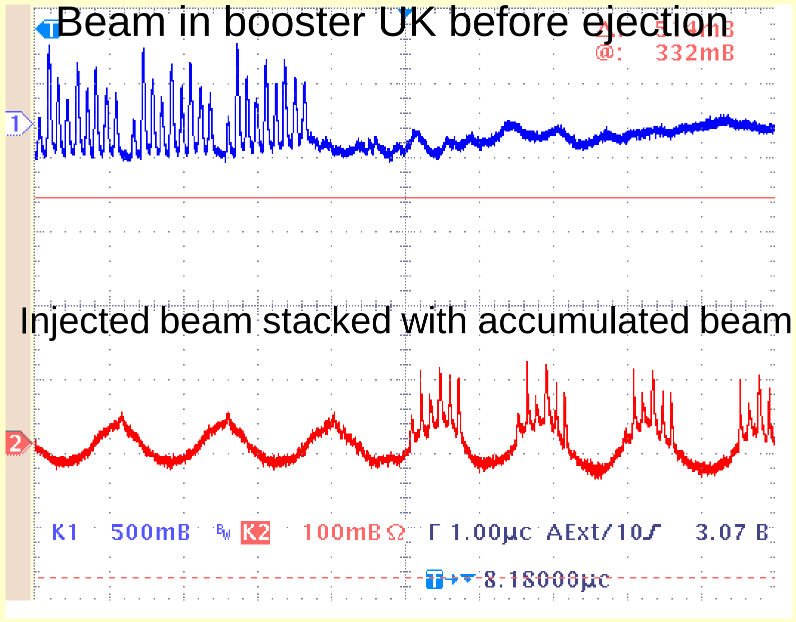
Stripping target cassette



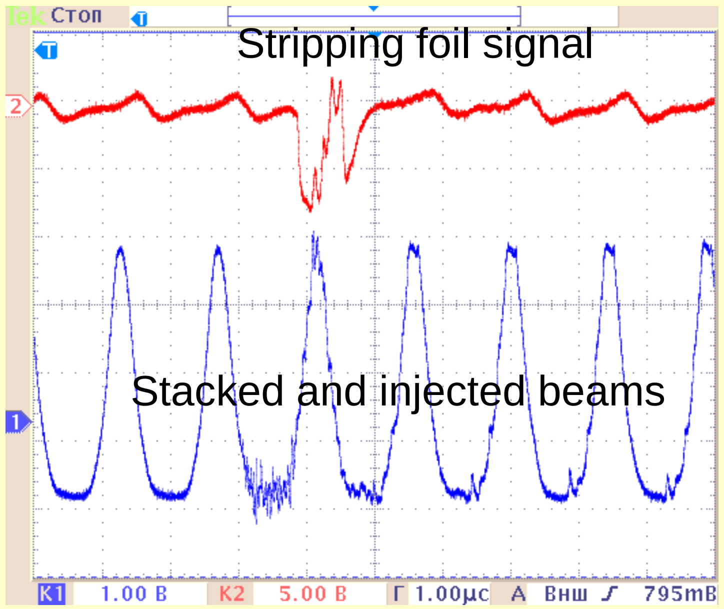
Injecting beam crosses stripping foil



Accelerated and stacked beams



Two beams meeting in stripping foil



Development of charge exchange injection technique for nuclei stacking

Optimization of beam stacking technique:

improvement of power supplies for beam bump system,
modification of injection scheme for high charge state ions,
commissioning of beam compression system at extraction from UK ring

Improvement of storage ring U-10 parameters:

expanding of *dynamic aperture,*
improvement of vacuum,
development of beam diagnostic

Studying of beam dynamics and increase the beam stacking efficiency to maximal value for multiple injection of ions with A<30, as :

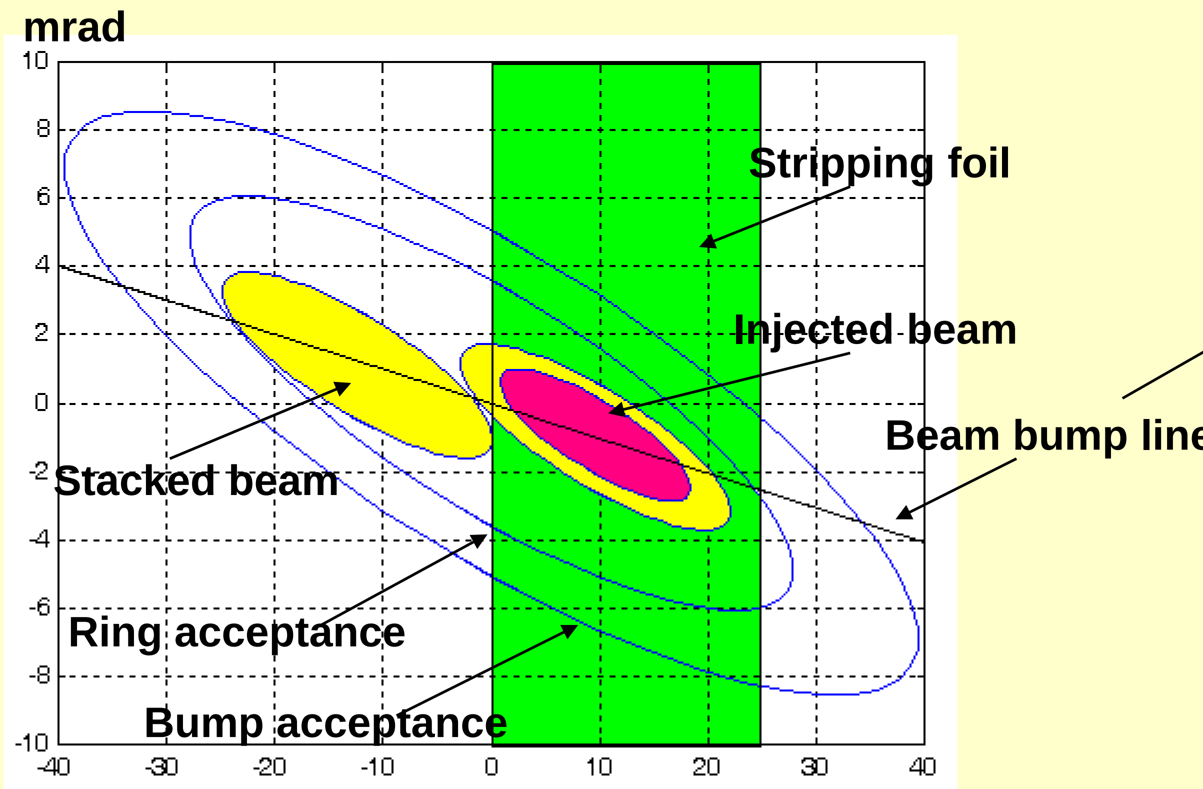
C^{4+} => C^{6+} and Si^{14+} => Si^{16+} at the energy up to 500 MeV/u

Optimization of beam stacking and minimizing stripping foil disturbing effects for ions with A~60, as:

Fe^{24+} => Fe^{26+} and Cu^{27+} => Cu^{29+} at the energy up to 700 MeV/u

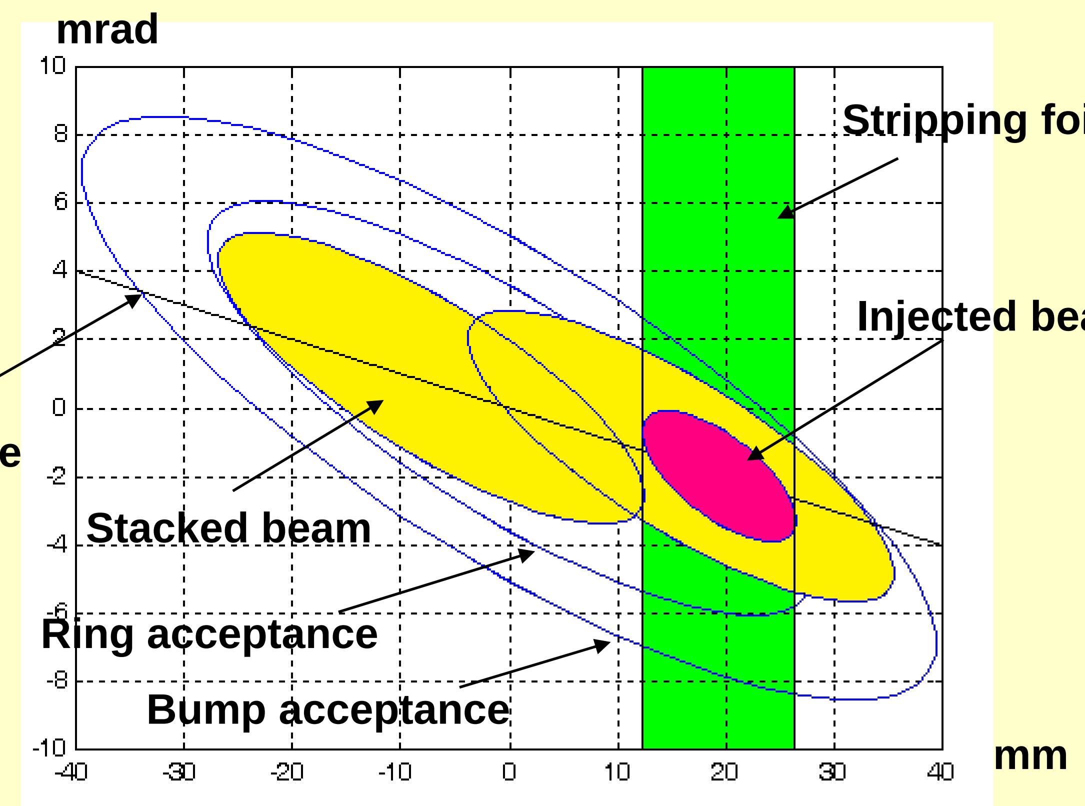
Expanding of ring acceptance

Beam stacking into a_x=20 π mm mrad
at bump acceptance A_x=100 π mm mrad



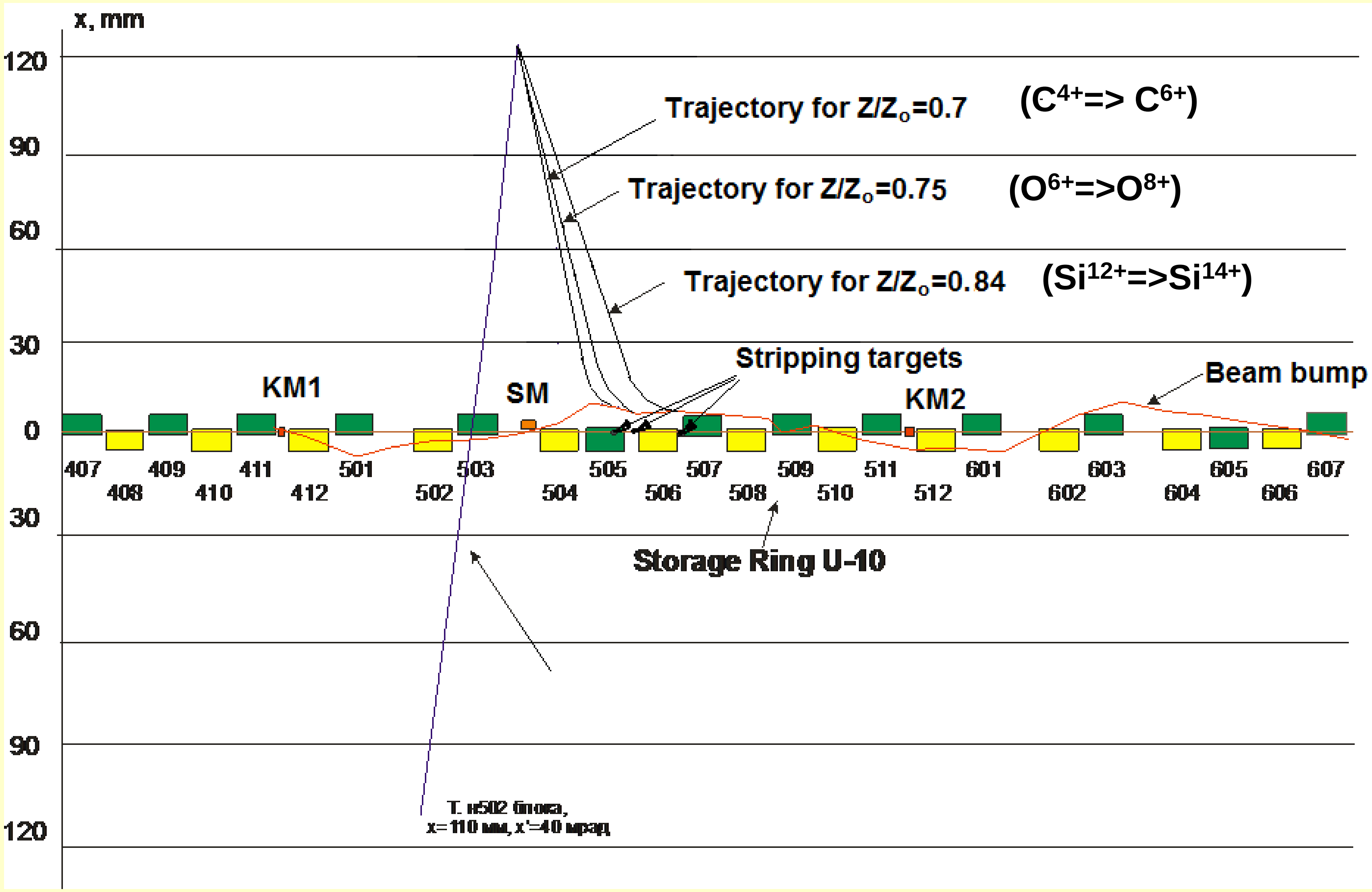
ε_x=10 π mm mrad
a_x=20 π mm mrad
A_x=100 π mm mrad

Beam stacking into a_x=50 π mm mrad
at bump acceptance A_x=200 π mm mrad



ε_x=10 π mm mrad
a_x=50 π mm mrad
A_x=200 π mm mrad

Modification of injection scheme for high charge state ions

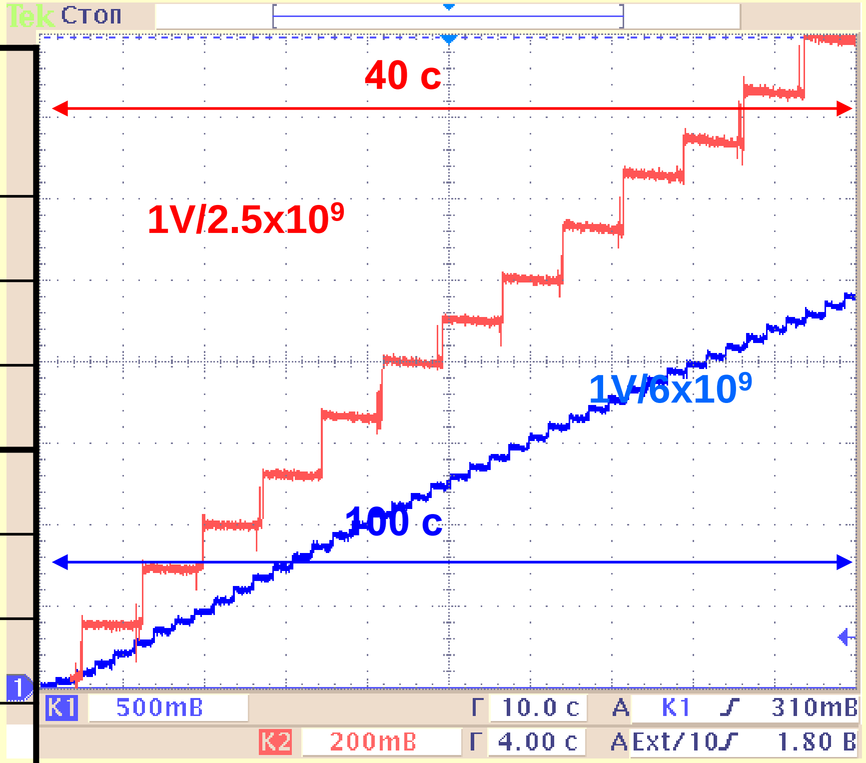


Optimization of beam stacking for ions of A<30

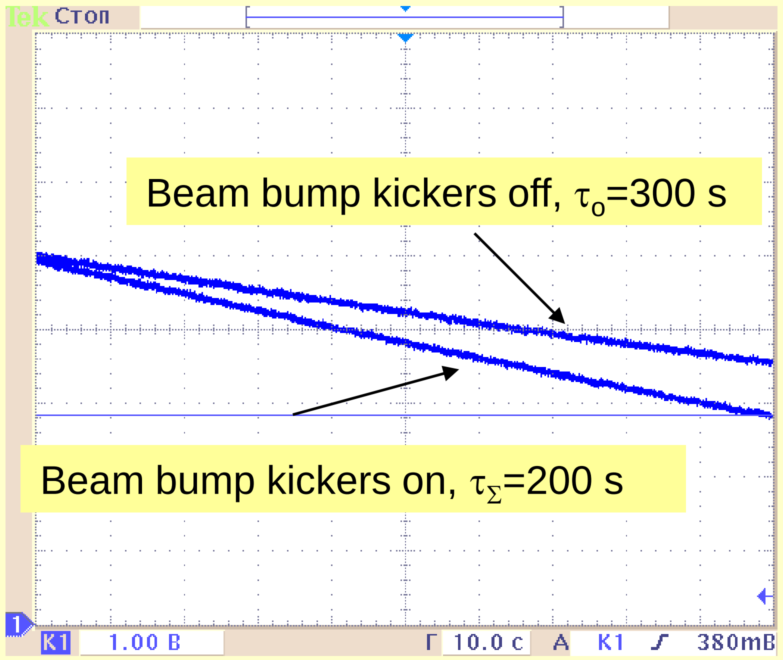
Parameters of beam stacking with laser L5 (L100 for Si) and 4MV injector I-3

Parameters	Reached for C^{4+}=>C^{6+}	Expected for C^{4+} =>C^{6+}	Expected for Si^{12+} =>Si^{14+}
Energy	300 MeV/u	400 MeV/u	650 MeV/u
Injected beam intensity	$6x10^8$	$\sim5x10^9$	$\sim5x10^9$
Cycle time , s	3	2	2
Acceptance, A_x, π mm mrad	10	30-50	30-50
Vacuum, Torr	$\sim1x10^8$	$\sim1x10^9$	$\sim1x10^9$
Stacking factor	~70	~200	~200
Stacked beam intensity	$4x10^{10}$	$\sim10^{12}$	$\sim10^{12}$

The stairs of C^{6+}-beam stacking in the U10 ring (2006)

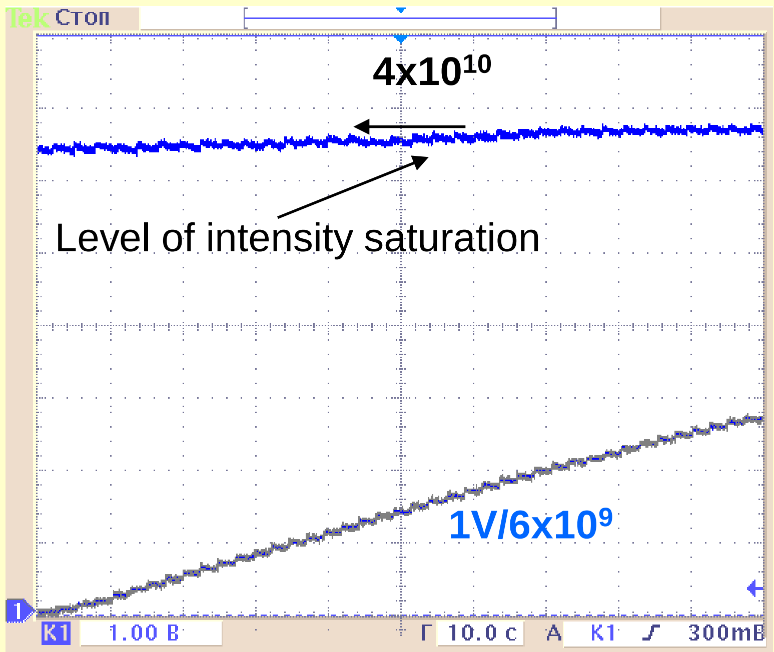


Stacked beam life time in the U-10 Ring

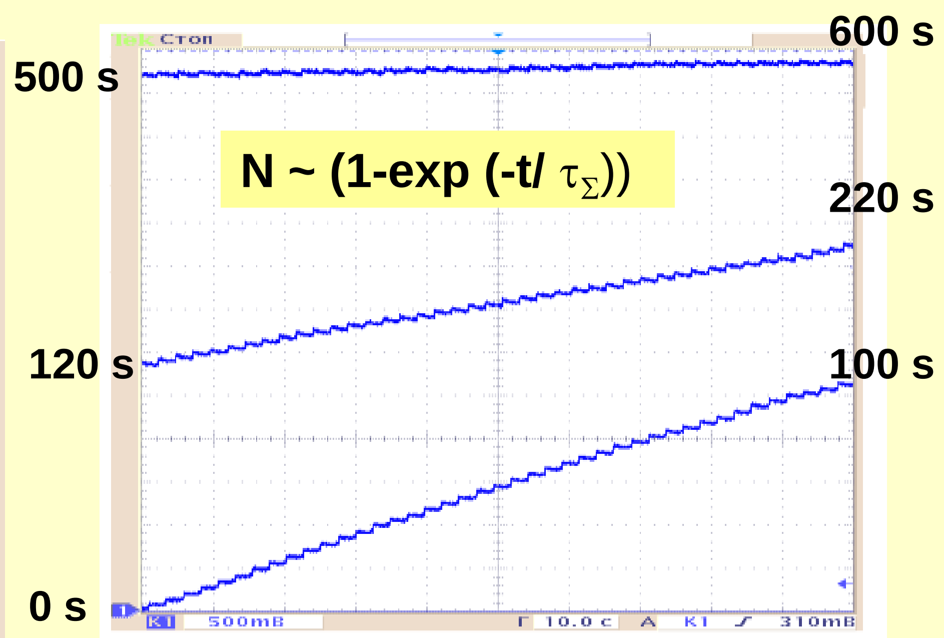


Maximal intensity of stacked beam

$k_{\infty-}$=>70



Intensity increase in time

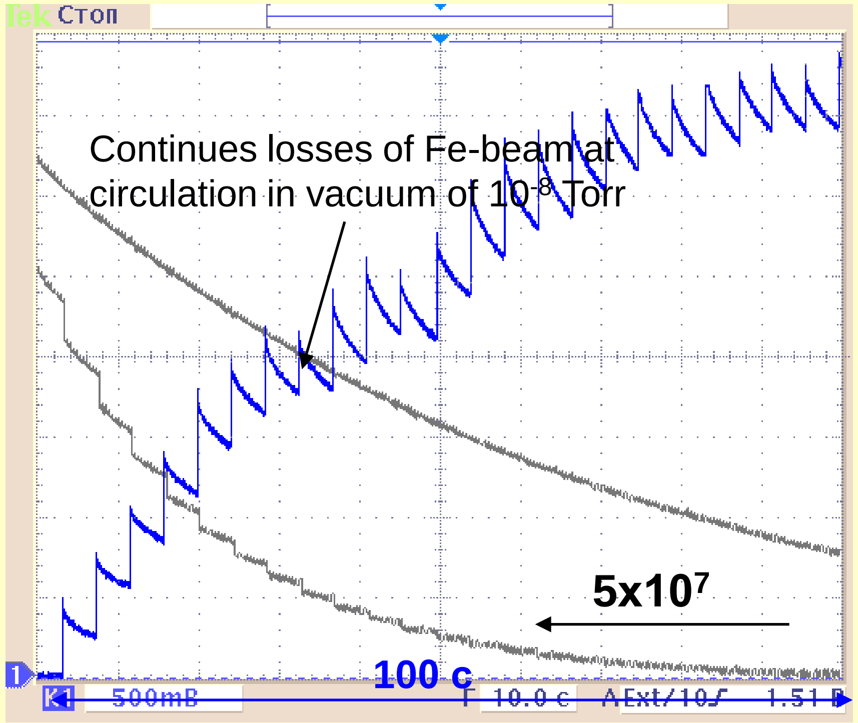


Optimization of beam stacking for ions of A~60

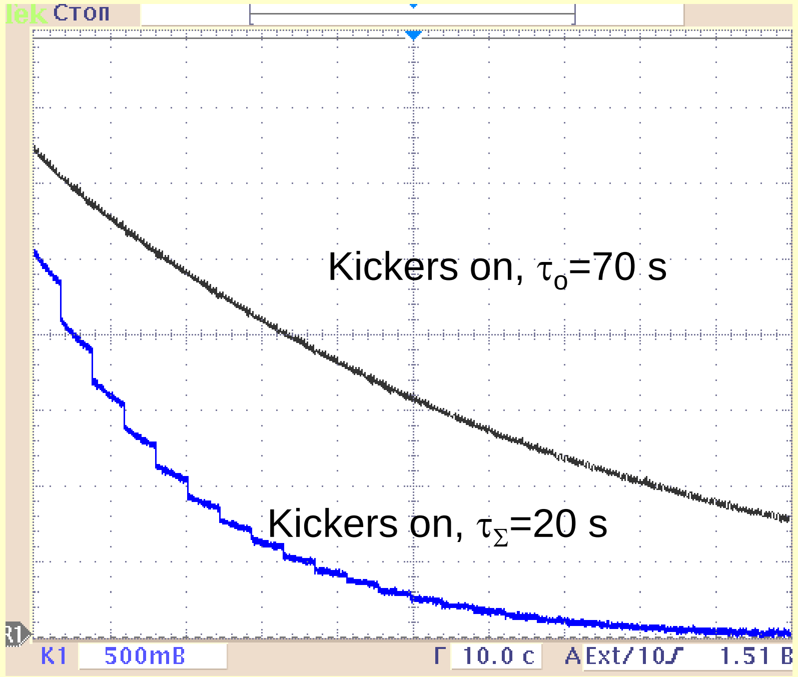
Parameters of beam stacking with laser L100 and 4MV injector I-3

Parameters	Reached for Fe^{16+}=>Fe^{26+}	Expected for Fe^{24+} =>Fe^{26+}
Energy	230 MeV/u	700 MeV/u
Injected beam intensity	$5x10^{7}$	$\sim 5x10^{8}$
Cycle time , s	4	2
Acceptance, A_x, π mm mrad	10	30-50
Vacuum, Torr	$\sim 1x10^{8}$	$\sim 1x10^{9}$
Stacking factor	~10	~100
Stacked beam intensity	$5x10^{8}$	$\sim 5x10^{10}$

The stairs of Fe^{16+} =>Fe^{26+} beam stacking in the U10 ring (2010)



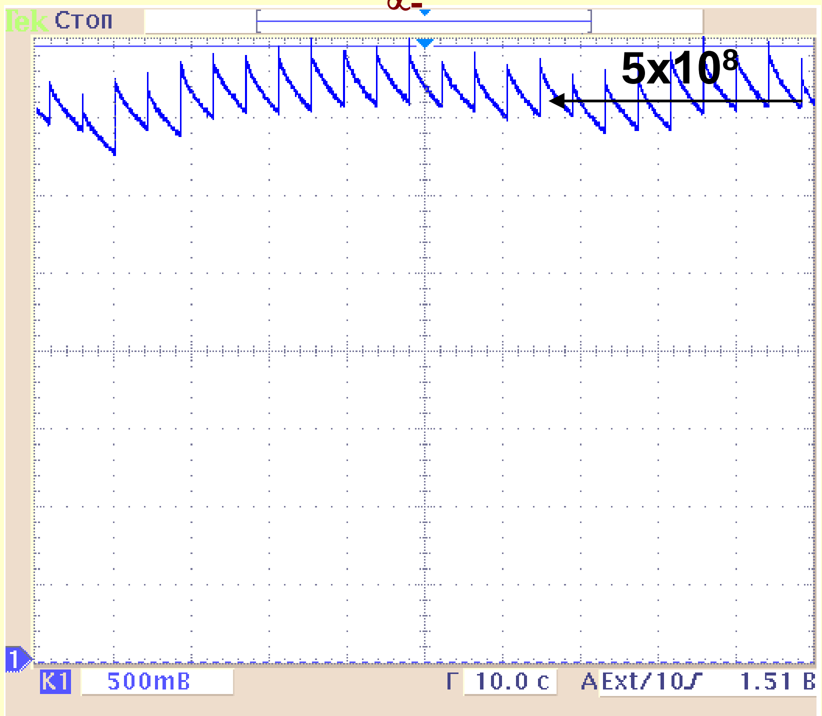
Stacked Fe-beam life time in the U-10 Ring



Maximal intensity of stacked beam

k_{∞}=>10

1V/$6x10^{7}$



Construction of new ion injector I-4 for ITEP-TWAC Facility

The new heavy ion high current injector for ITEP-TWAC Facility is now under construction for acceleration of ions with 1/3 charge to mass ratio up to energy of 7 MeV/u and beam current of 100 mA.

The 81.5 MHz RFQ section based on 4 vane resonator with magnetic coupling windows is constructed for the beam energy of 1.57 MeV/u

The second section of 163 MHz H-type resonator is designed and in progress for construction.

Design of RFQ STRUCTURE

The design of the 81.5 MHz RFQ cavity is based on 4-vane resonator with magnetic coupling windows which was originally developed in ITEP. The windows improve both azimuthal and longitudinal stabilization of the operating mode by increasing the separation operational and parasitic modes. They also significantly reduce the transverse dimensions of the resonator. The windows on adjacent vanes have been displaced with respect each other in order to increase the magnetic coupling among quadrants

Finite elements model of the regular cell.

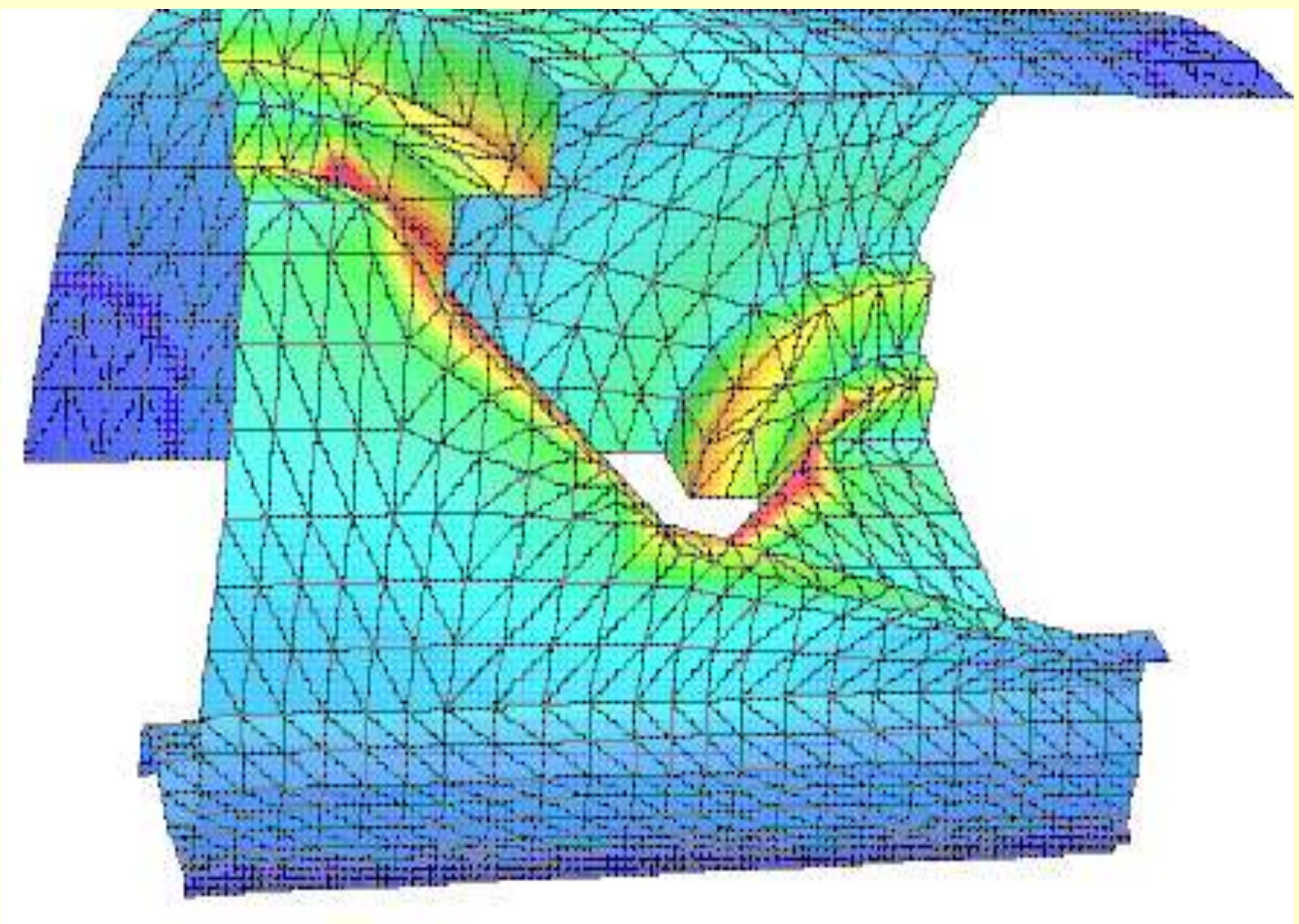
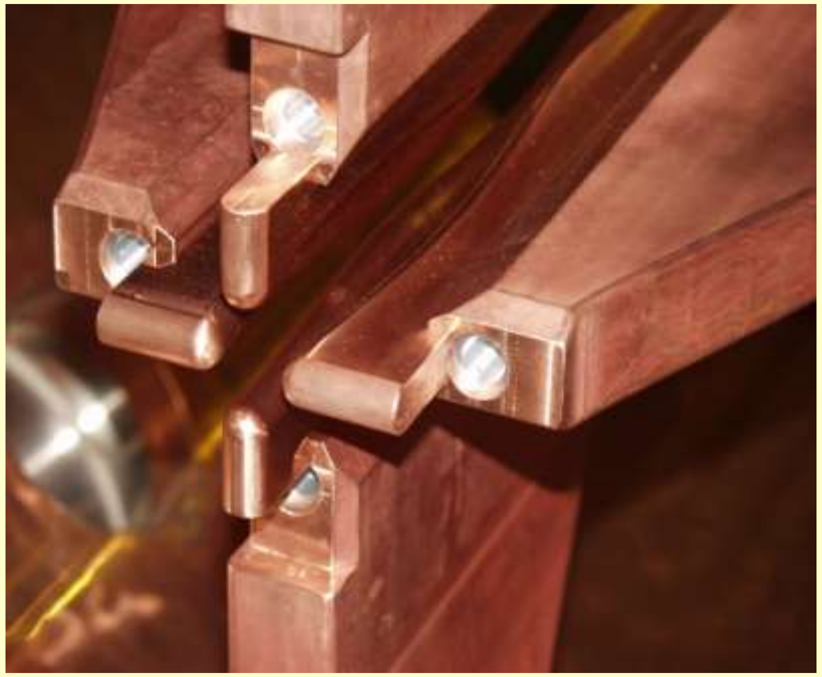


Table 1: Main parameters of RFQ structure

Parameter	Unit	Value
Operating frequency	MHz	81.5
Charge to mass ratio		1/3
Input/output energy	MeV/u	0.02/1.57
Average radius	mm	10
Vane tip radius	mm	7.5
Voltage	kV	182.5
Input emittance (norm)	cm*mrad	0.327
Output emittance (effective)	mm*mrad	2.3*π
Output current	mA	100
Pulse repetition	Hz	1
Pulse duration	μs	100
Output energy spread	keV/u	+/- 20
Length of the RFQ vanes	m	6.258
Inner cavity diameter	m	0.564
Quality factor of the resonator		11000

Construction of RFQ section

View of the RFQ with open outlet flange

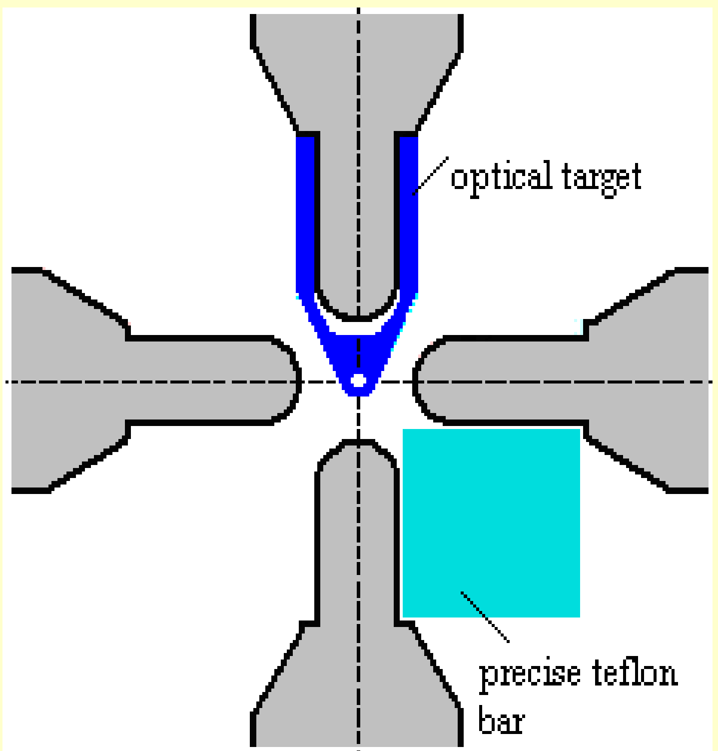


Close view of the RFQ

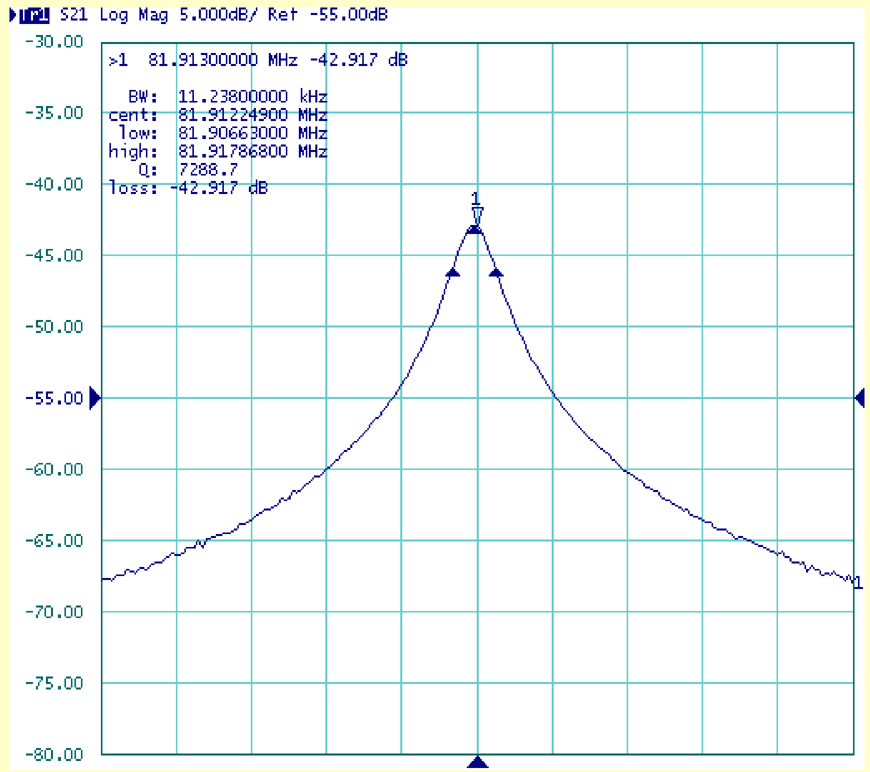
Close view of the vane

Results of RFQ section alignment and tuning

The vanes have been aligned with respect to beam axis by means of telescope and optical target The vanes have a reference edges, manufactured with proper accuracy relatively beam axis. The target has a hole with a cross. The position of each vane was corrected in order to install the cross on the beam axis. Orthogonality of the vanes has been tested by means of precise teflon bar sliding between each pair of the vanes.



Scheme of the alignment



Resonant curve of operational mode

Normalized Inter-electrode voltage along the structure for 4 quadrants of the RFQ

Resonant frequency f_0 after alignment is equal to 81.913 MHz. Nearest parasitic modes (TE211 and TE110) are 85 MHz and 92 MHz respectively. Quality factor of the resonator Q is equal to 7500. The azimuthal voltage unbalance among the four quadrants was measured to be within +/- 1%. The longitudinal inter-electrode voltage distribution has a tilt of about 10%. It may be caused by both increasing average radius of the aperture to the end of the structure and detuning end cells of the resonator.

IH DTL SRUCTURE

The IH-DTL structure is designed for the second acceleration section. Beam dynamics studies and layout of the IH DTL structure were reported in work. The structure is based on separate resonators with KONUS scheme and focusing elements placed between resonators.

The structure layout and transverse beam envelopes at full current of 100 mA.

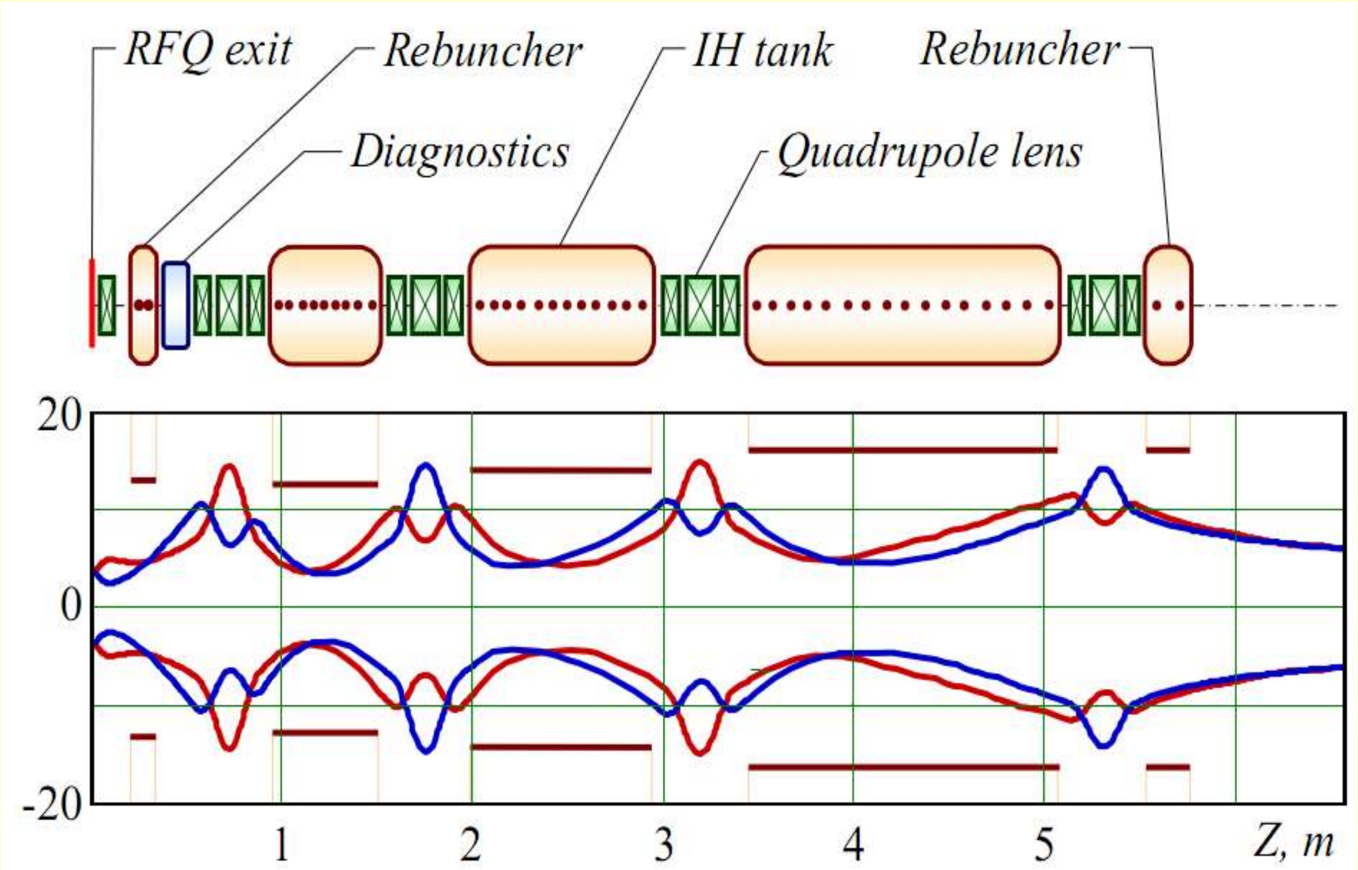


Table 2: General parameters of IH-DTL structure

Operating frequency	MHz	163
Beam current	mA	100
Input/output energy	MeV/u	1.57/7.04
Final energy spread	%	+/- 0.5
Transverse emittance (norm)	mm*mrad	$3*\pi$
Longitudinal emittance (norm)	AkeV*ns	16.2
Transv. Rms emit. Growth	%	40
Long. Rms emit. Growth	%	22
Total length	m	5.75
Number of RF tanks		3
Number of RF bunchers		2
Total gap number		41
Aperture diameter	mm	25-38
Gap / cell ratio		0.48-0.4
Effective gap voltages		370-700
Maximum on-axis field	MV/m	14
Lens aperture diameter	mm	40
Magnetic field gradient	T/m	48

The structure includes three IH tanks, two external rebunchers, diagnostic box, four quadrupole triplet lenses and one small single quadrupole lens directly at the RFQ exit, which provides the space for rebuncher and diagnostic box.

Development of ITEP-TWAC Infrastructure

Preconditions:

1. **Many mode operation of ITEP-TWAC with different types of particles in wide range of energy**

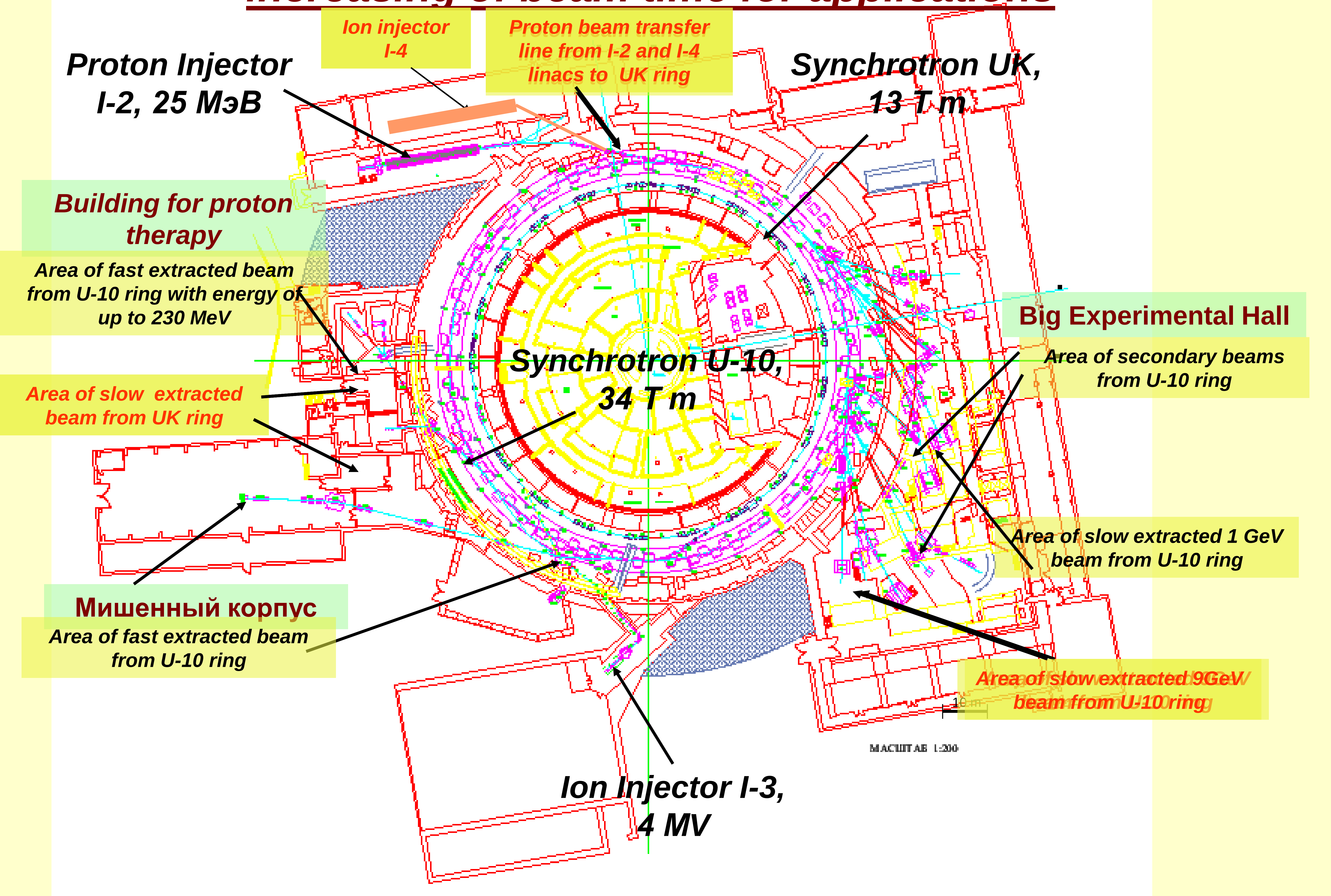
2. **Shortage of beam time for home users**

3. **Tendency to increasing demand from outside users for proton and heavy ion beams for applications**

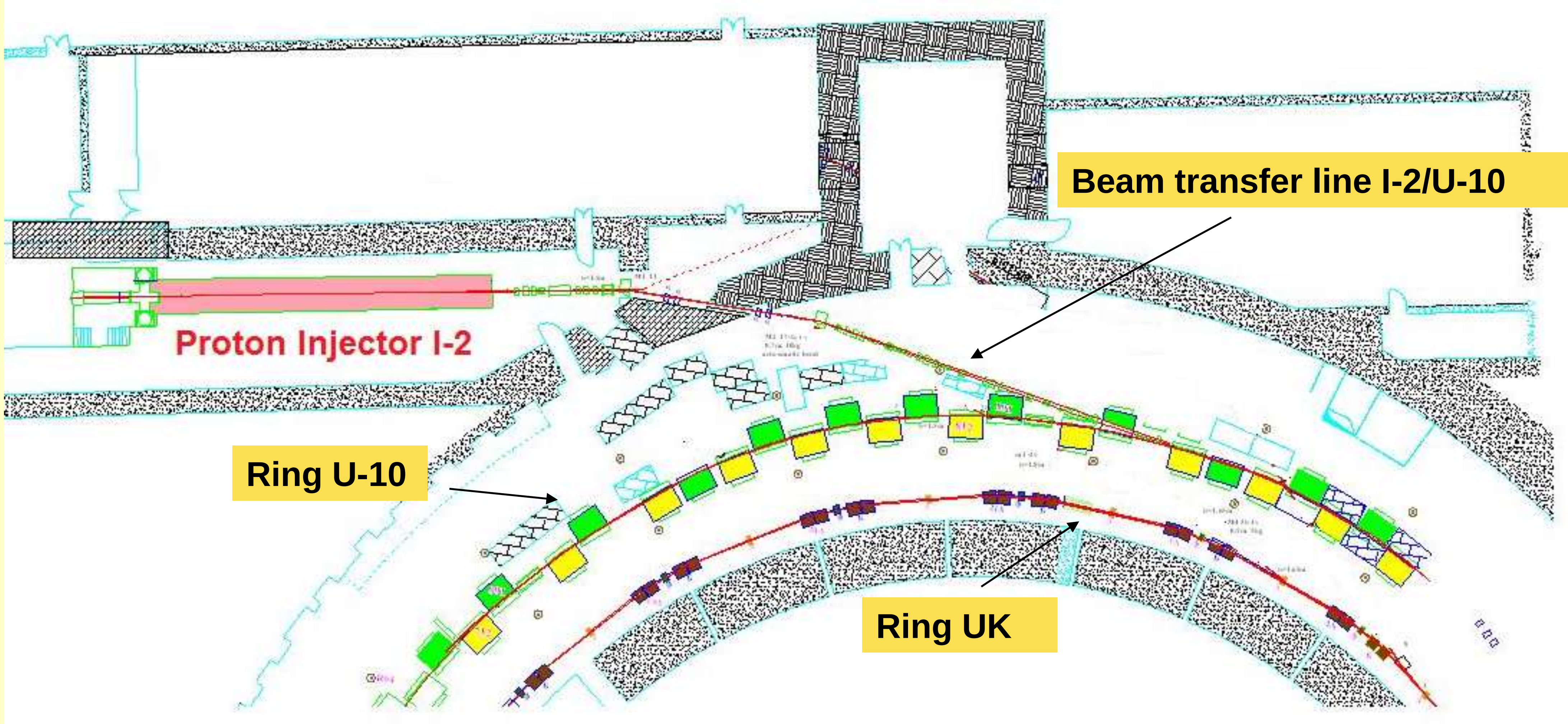
4. **Lack of slow extracted beam for experiments on relativistic nuclear physics**

5 . **Possibility to redouble beam time for physical experiments and applications making operation of U-10 and UK synchrotrons in parallels**

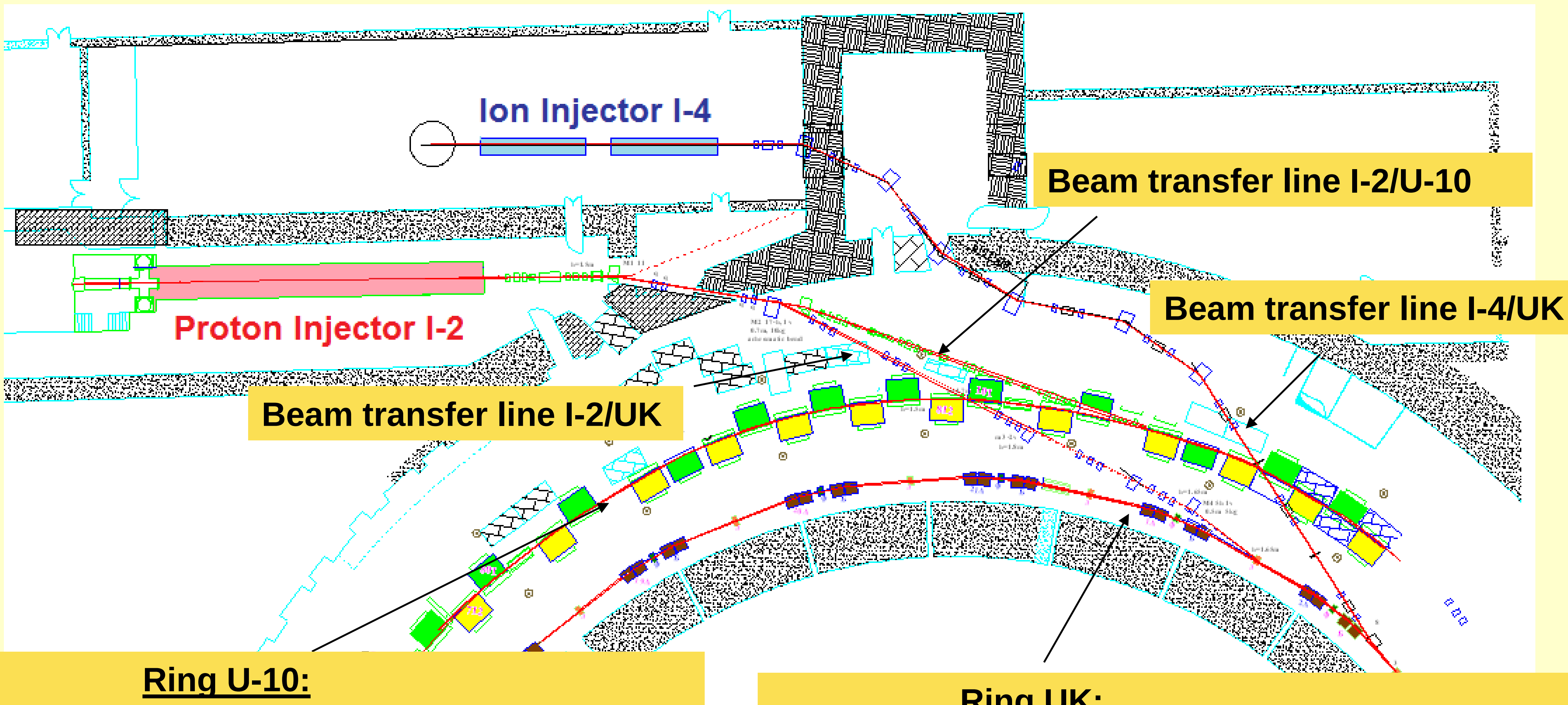
Extending of ITEP-TWAC experimental area for increasing of beam time for applications



Proton Injection to U-10 Ring



Project of new Injection Complex for ITEP-TWAC



Ring U-10:

Acceleration of proton and any ion beams up to the energy of 2.5-9 GeV for protons and 100 MeV/u – 4 GeV/u for ions,

Stacking of nuclei at the energy of 200-700 MeV/u

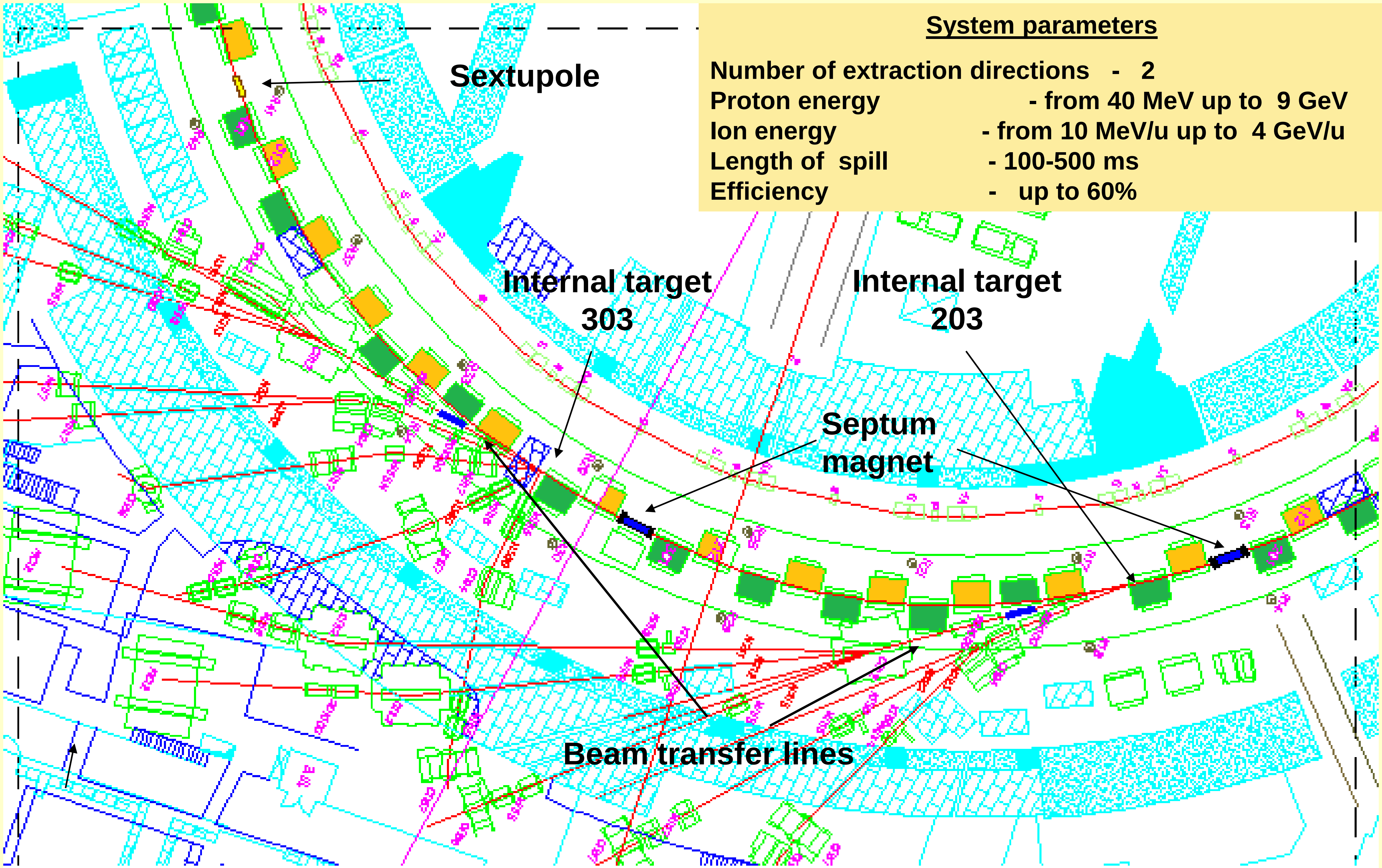
Ring UK:

Acceleration of proton and any ion beams up to the energy of 50 MeV – 2.5 GeV for protons and 10 MeV/u – 700 MeV/u for ions

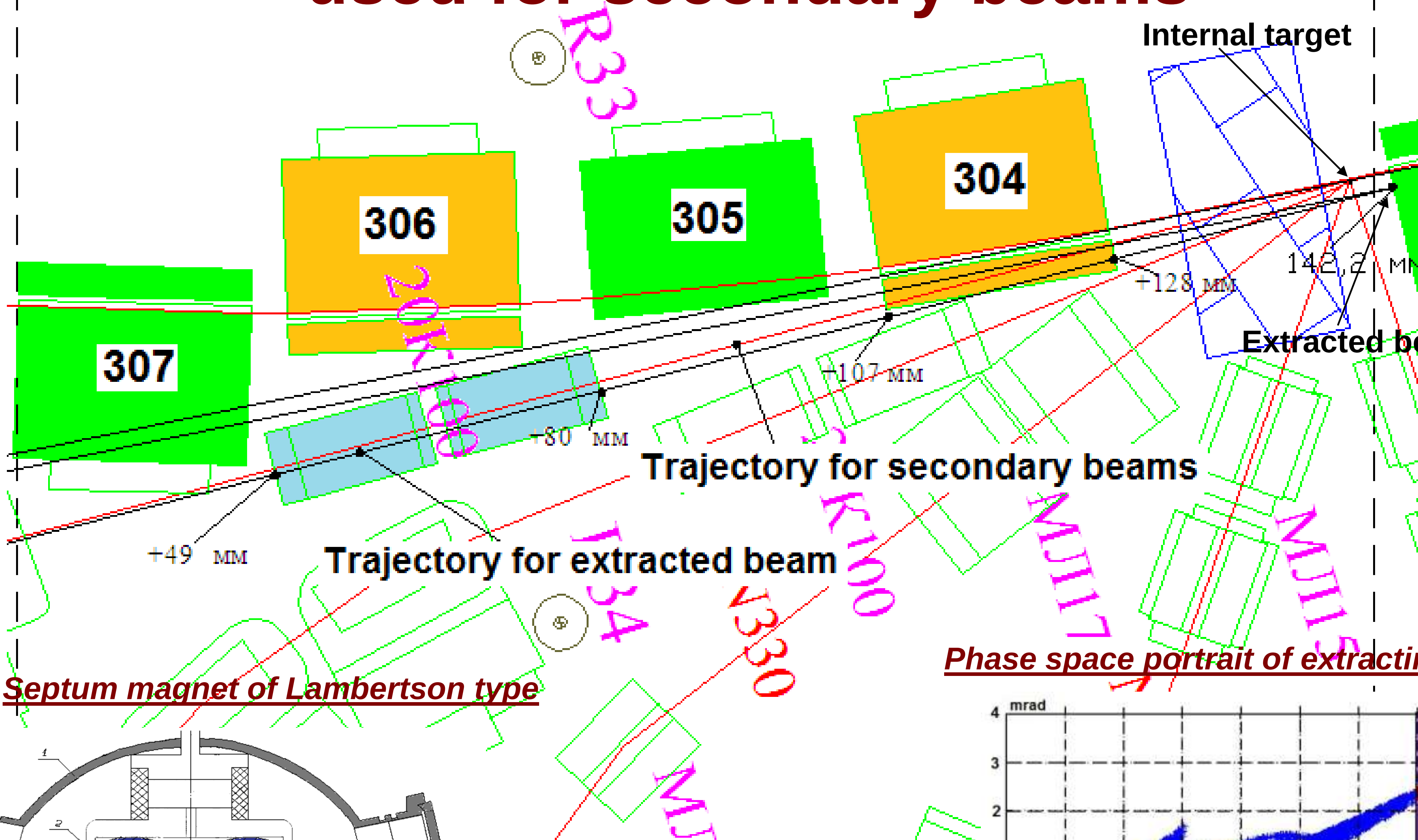
Slow extraction systems of U-10 Ring

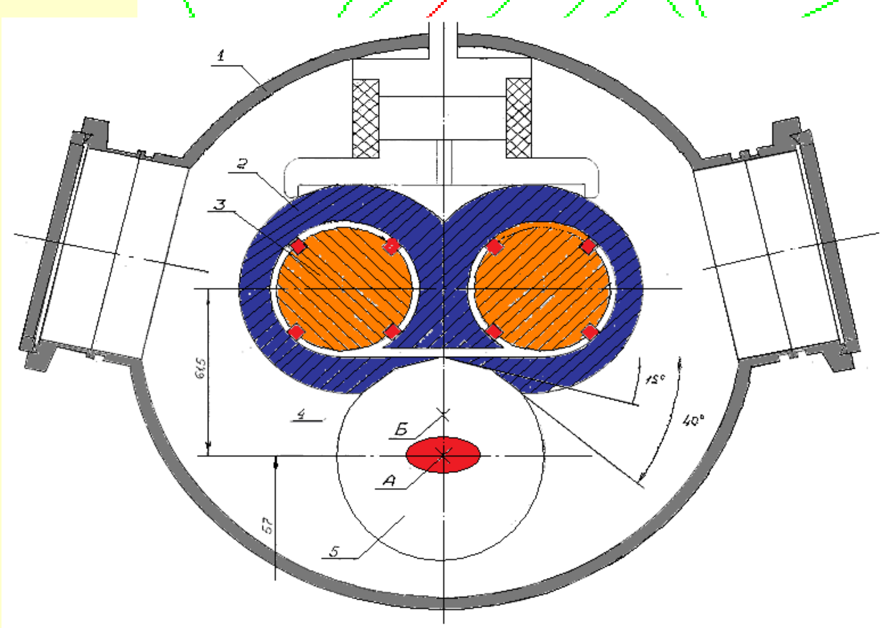
System parameters

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%

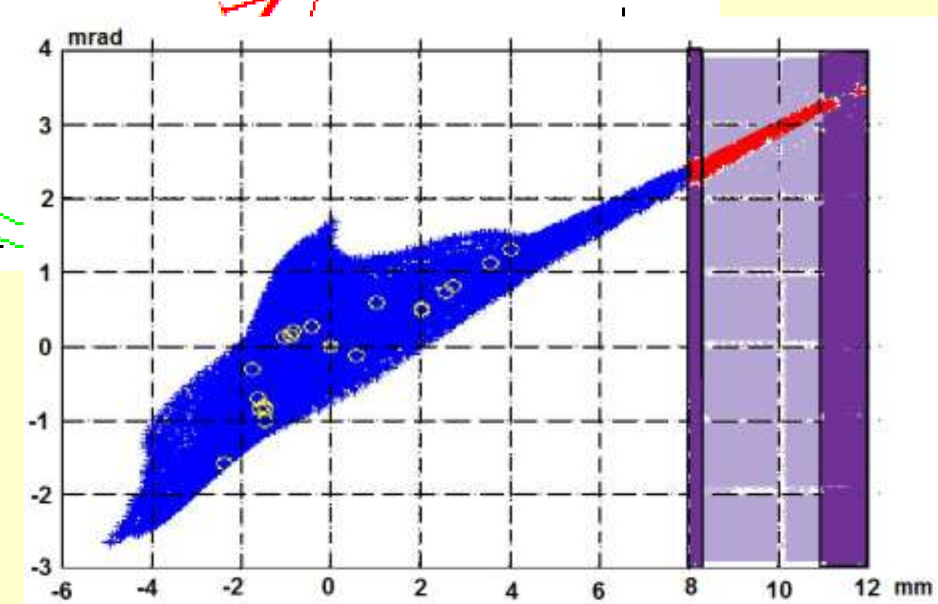


Beam extraction from U-10 Ring to tract used for secondary beams



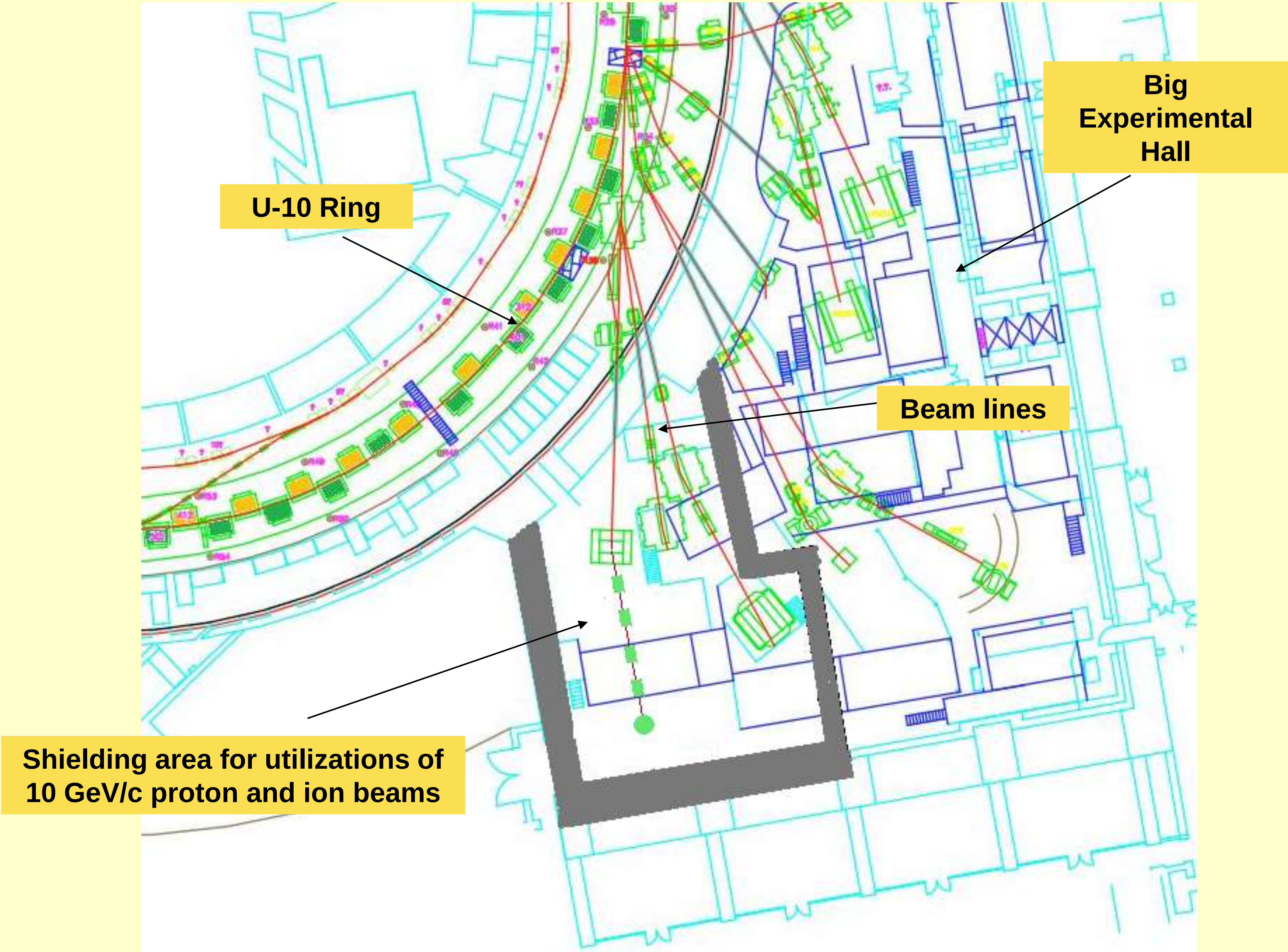


__Septum magnet of Lambertson type__



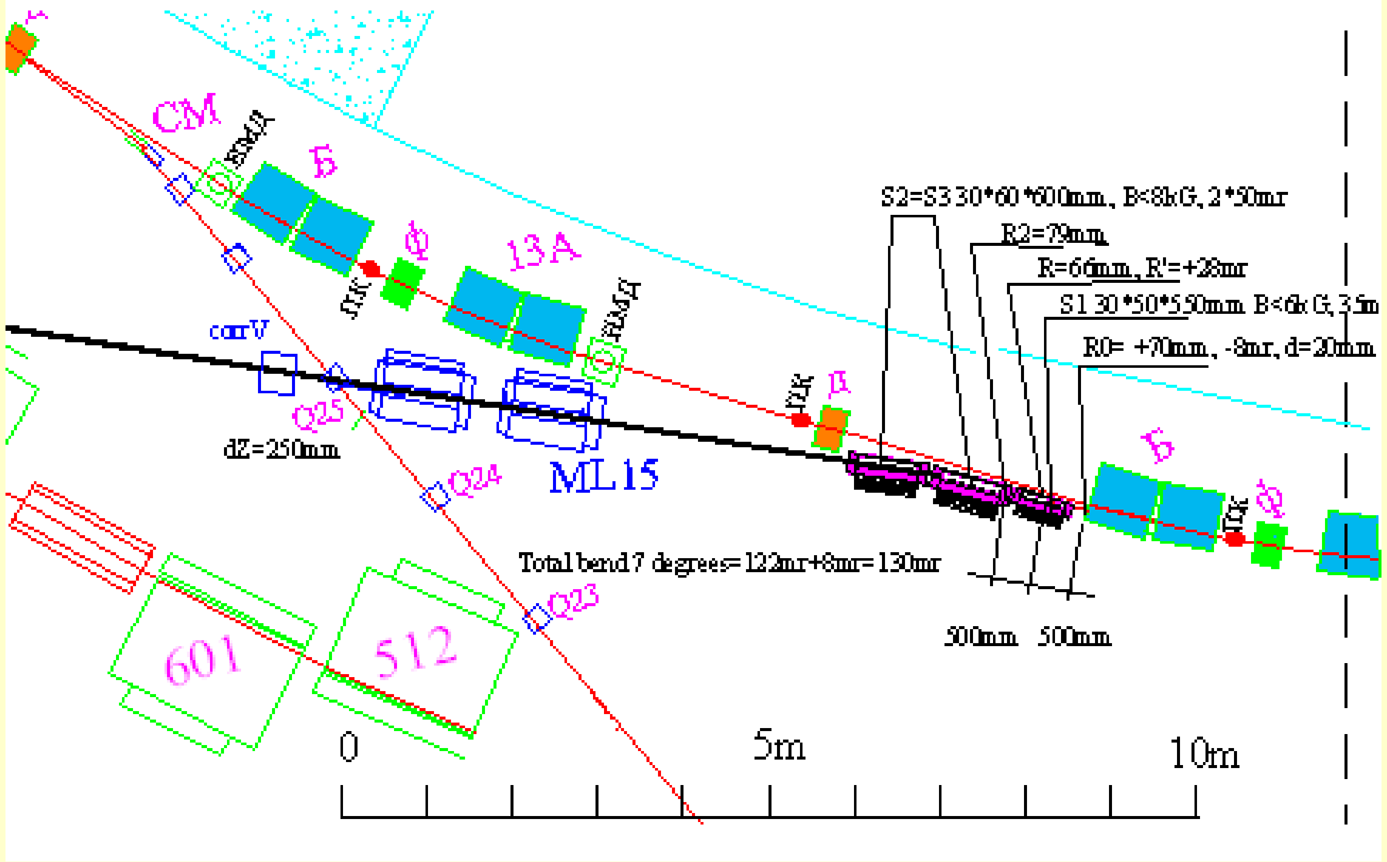
__Phase space portrait of extracting beam__

Extracted 10 GeV/c beam for experiments on nuclear physics and radiography

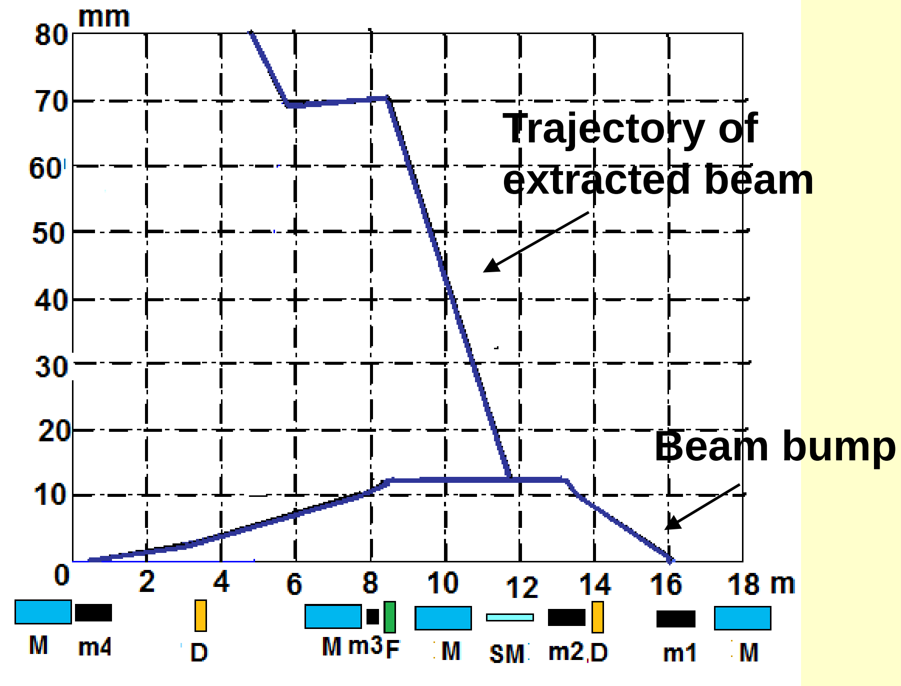


Project of slow extraction system for UK Ring

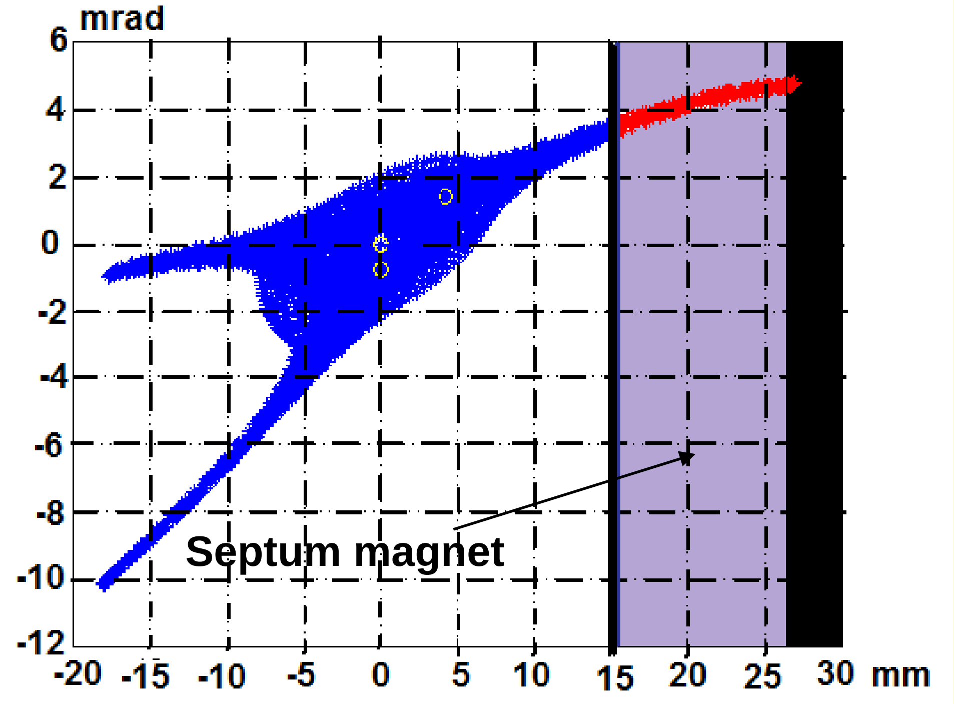
Extracted beam transfer line



Beam kinematics at extraction



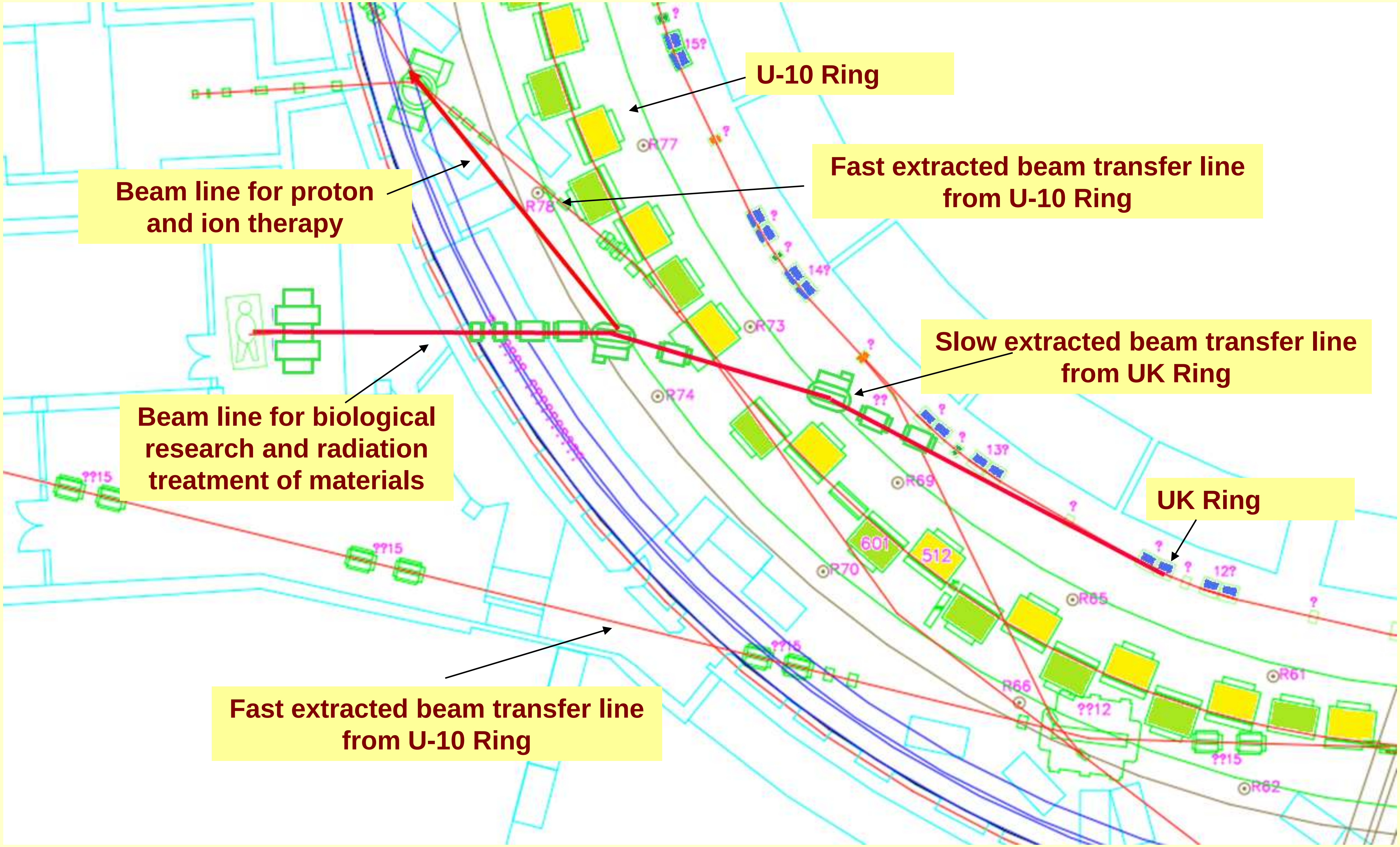
Phase space portrait of extracting beam



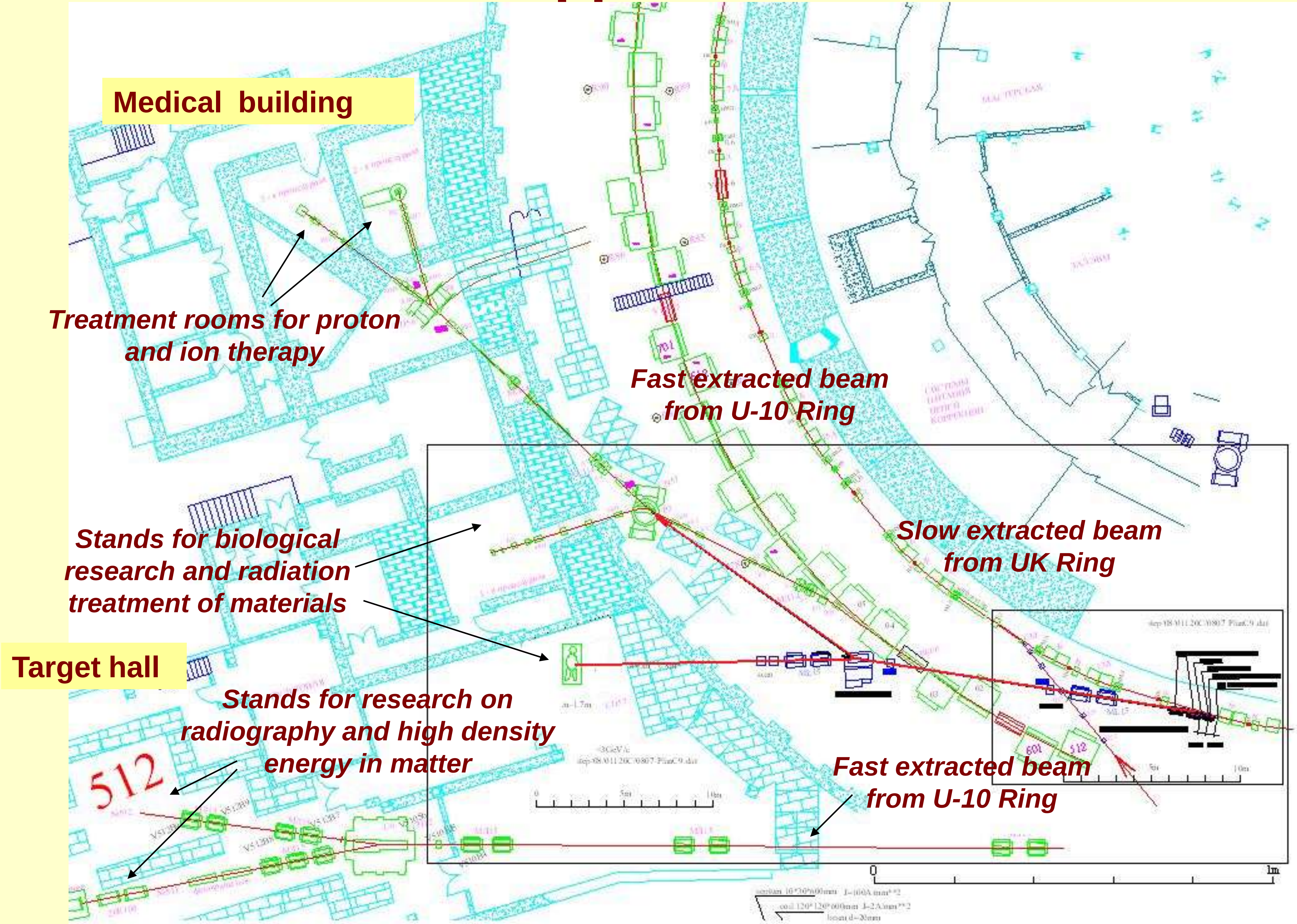
System parameters

Number of extraction directions - 2
Proton energy - from 40 MeV up to 2,2 GeV
Ion energy - from 10 MeV/u up to 1 GeV/u
Length of spill - 100-500 ms
Efficiency - up to 80%

Directions of beam transfer from UK Ring



Layout of expanded experimental area for applied research



Conclusion

1) The ITEP Accelerator Facility is in operation by ~4000 hours yearly accelerating proton and ion beams and stacking nuclei for physics experiments, methodical research and radiation technologies.

2) The progress has been achieved in generation and acceleration of heavy ion: ions of Ag^{19+} have been generated in LIS with 100J CO_2 laser L100 and accelerated in synchrotron UK up to the energy 100 MeV/u with intensity of $2x10^7$; nuclei of Fe^{26+} have been accelerated using three stage scheme I-3/UK/U-10 up to record energy of 3.6 GeV/u or 200 GeV per particle with intensity of $5x10^7$.

3) Experiments on the ion beam generation in LIS with 100J CO_2 laser L100 give evidence of optic used imperfection reducing the laser radiation power density on the target surface by factor of more than ten. New focusing scheme for target station is elaborated on a base of parabolic short focusing mirror to increase the power density by factor of three. Next factor of power density increase will be achieved replacing windows by them of better quality.

4) Construction of the new heavy ion injector I-4 is in progress: the RFQ section for the energy of 1.5 MeV/u of Z/A=0.3 ions is constructed and successfully tested for resonator parameters measuring and RF power loading. Preparations of RFQ section for the beam test is now started to be carried out in the first quarter of next year.

5) The progress in intensity of heavy ion beam stacked in U-10 Ring using multiple charge exchange injection technique is expected in the experiments planned for the end of this year with stacking of ions Si^{12+}=> Si^{14+} at the energy of 500 MeV/u.

6) Development of ITEP-TWAC facility Infrastructure is aimed to redouble beam time for physical experiments and applications making operation of both U-10 and UK synchrotrons in parallels .