Can the development from Dubna be applied for an effective high energy high current charge breeder ?

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for the JINR ESIS group

HIE-EBIS Workshop
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B = 3.3 T Q^- = 10 nC,   E_e=8 KeV; J_e=300 A/cm^2; (Krion-2)

B = 6.0 T Q^- = 50 nC   E_e=25 KeV, J_e=2000 A/cm^2

(expected Krion-6T)

= 3.0 10^{11} e.ch.

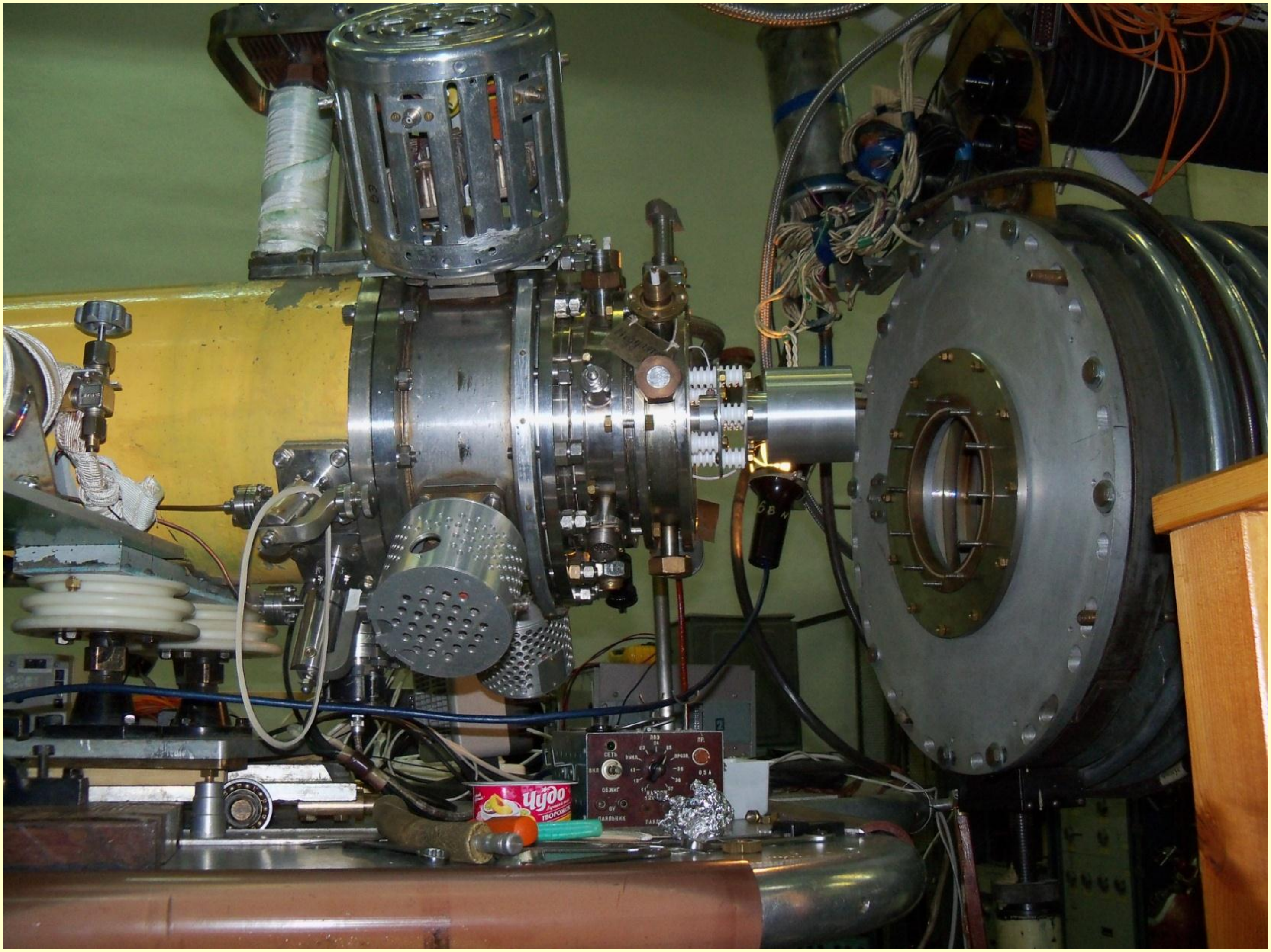
B = 9.0 T Q^- = 150 nC   E_e=70 KeV, J_e=12000 A/cm^2 ????

.

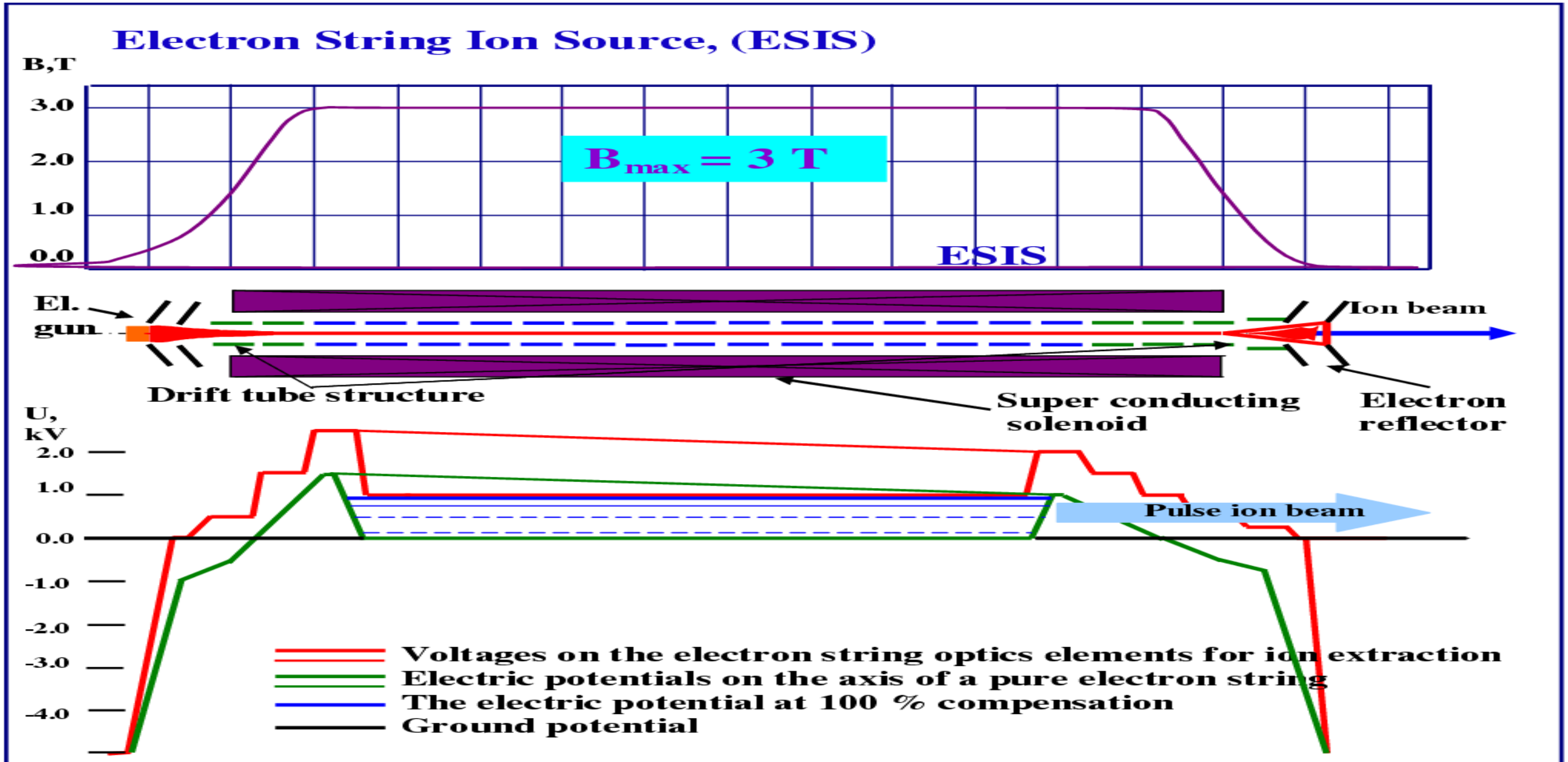
«Krion-2» ESIS: B≤ 3.3 T, electron injection energy $E_e \leq 6.5$ keV.

	Fe^{24+} Nuclotron run, 2003	Au^{32+} (stand)	Au^{51+} (stand, ion-ion cooling is applied, 2007)	Au^{54+}, Xe^{42+} (stand, Nuclotron run 2010 with Xe^{42+}
Binding energy E_b	2.05 keV	1.21 keV	2.96 keV	5.32 keV, 3.07 keV
Electron injection energy	4.0 keV	4.0 keV	5.0 keV	6.5 keV
Ionization time, τ Repetition rate	1.5 s 0.5 Hz	2×10^{-2} s 40 Hz	1.0 s 1.0 Hz;	1.5 s 0.67 Hz
Extraction time, t	8×10^{-6} s	8×10^{-6} s	8×10^{-6} s	8×10^{-6} s
N_i per pulse	1×10^{8}	5×10^{8}	1×10^{8}	$1x10^{7}$ $3x10^{7}$

JINR



Krion-2 installation on HV terminal of LU-20 (Nuclotron run 2010



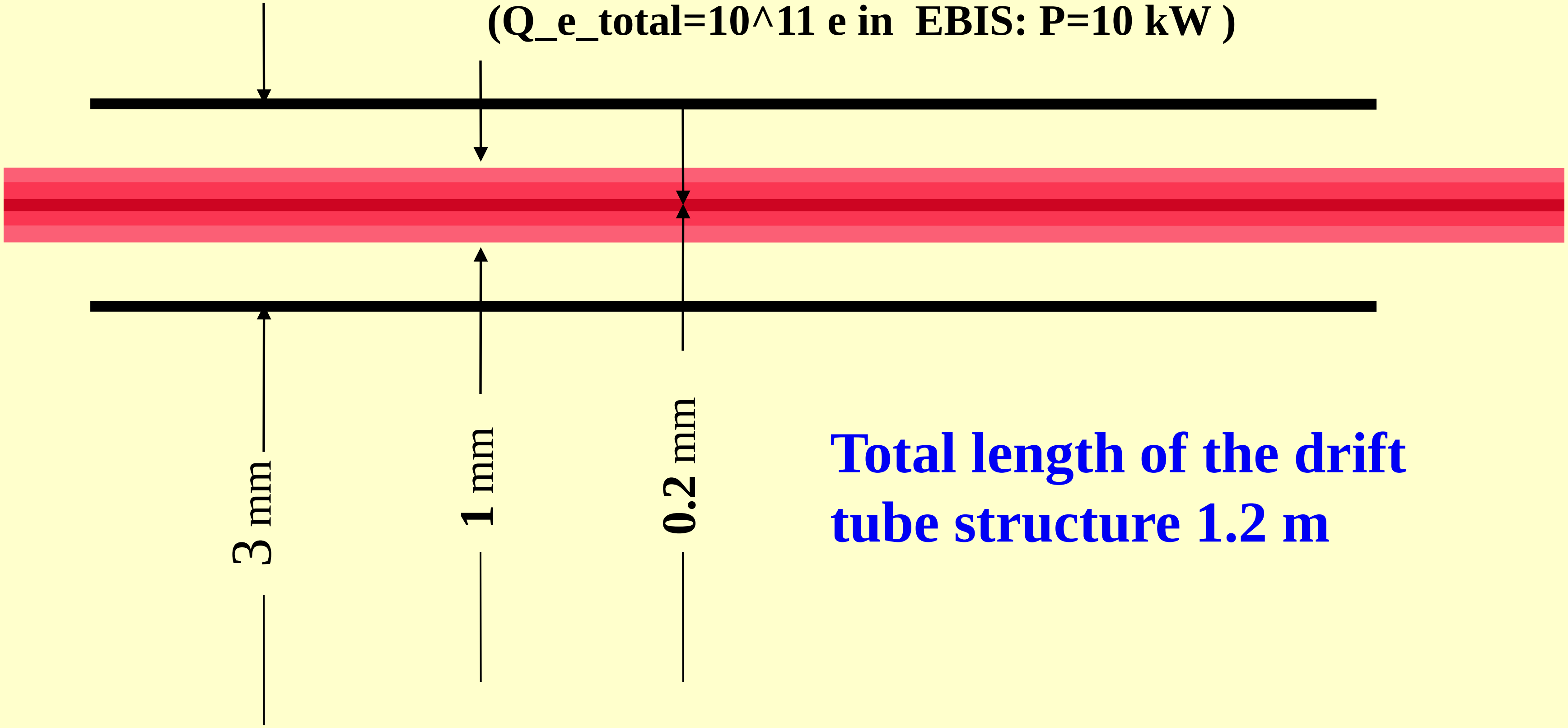
EBIS in the electron reflex mode of operation

Experimental conditions in ionization region (110 cm length): Drift tube temperature 4.2 K , Vacuum P < $\mathbf{10^{-12}}$ torr, B_max= 3.3 T; IrCr cathode 1-2 mm diameter; e-gun Pierce type, I_emiss.~8-12 mA.

e-string: J= 100 - 270 [A/cm^2], (5x10^{11} e/cm^3) . Number of reflections 100 - 300.

Q_e_total=10^11 e, Consumption power P=50 W!

(Q_e_total=10^11 e in EBIS: P=10 kW)



Total length of the drift tube structure 1.2 m

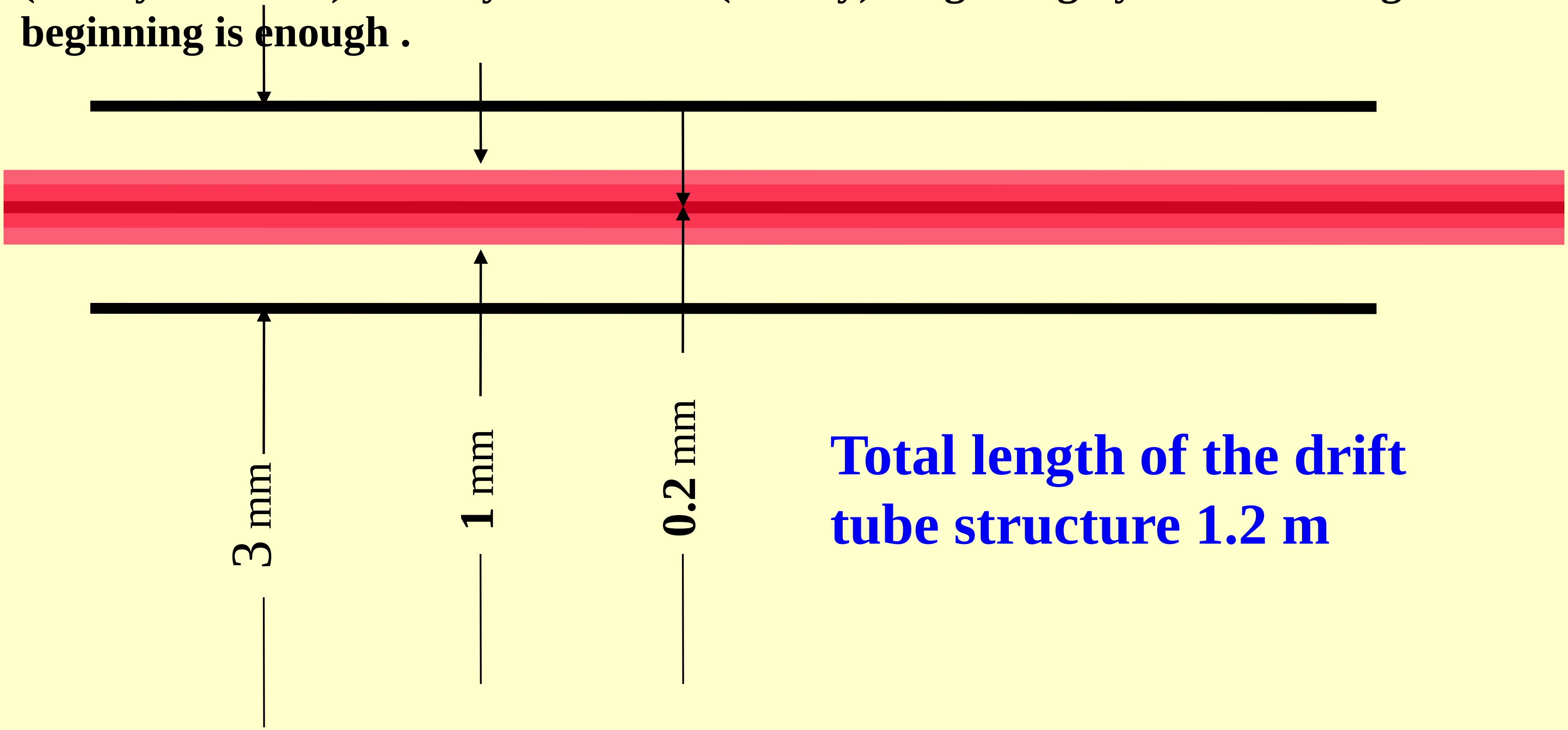
3 temperature terminals : room (anodes), 78 K 3+3 drift tube sections

(injection of neutrals: gases, Ferrocene, Au (evaporation from tungsten wire)),

Ionization region 110 cm , 26 separated druft tubes – 4.2 K.

Cryopumping only ! Works excellent. Turbopumps are not used during operation

(60 days or more). 5-6 days of anodes (mainly) outgassing by e-beam/string after beginning is enough .

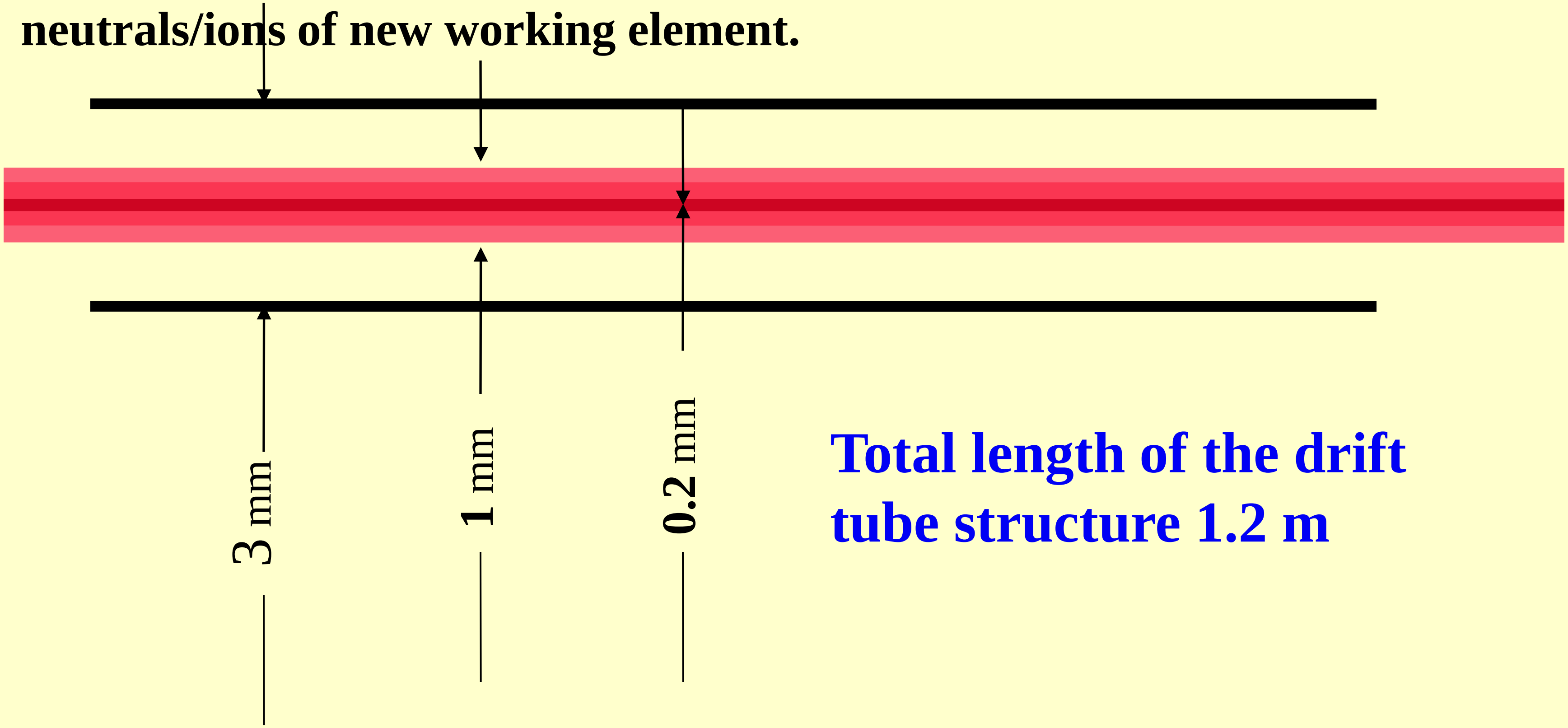


Total length of the drift tube structure 1.2 m

1) NO any “MEMORY” effect was observed in 4.2 K drift tube sections!

2) Xe remnants were observed: localization 78 K drift tubes in injection region. Xe and more heavy gases (Rn) are partially frosen at 78 K,

and then could decopule drift tube wall under bombardment by other neutrals/ions of new working element.



Total length of the drift tube structure 1.2 m

WHY REFLEX MODE?

TO REDUCE CONSUMPTION POWER,

SAVING ALL OTHER

EBIS ADVANTAGES

Q^- (e-ch./m)	EBIS	ESIS
10^{11}	10 KW	50 W (Krion-2)
10^{12}	200 KW	200 W (expected Krion-6T)
~~10^{13}~~	~~5000 KW~~	2 KW (expected Krion –Tubular)

EBIS

$$Q^- = Q^+ = 10^{13} I_e L / E_e^{1/2},$$

Q in elementary charges,

I_e in A, L in m, E_e in V.

For example: $Q = 10^{11}$ el.ch. = 15 nC.

I=1 A, L=1 m, E_e=10000 V,

P = 10 kW.

Electron string is formed in nonlinear process via strong instability of trapped electrons and exists as a dynamic equilibrium of injecting and loosing electrons.

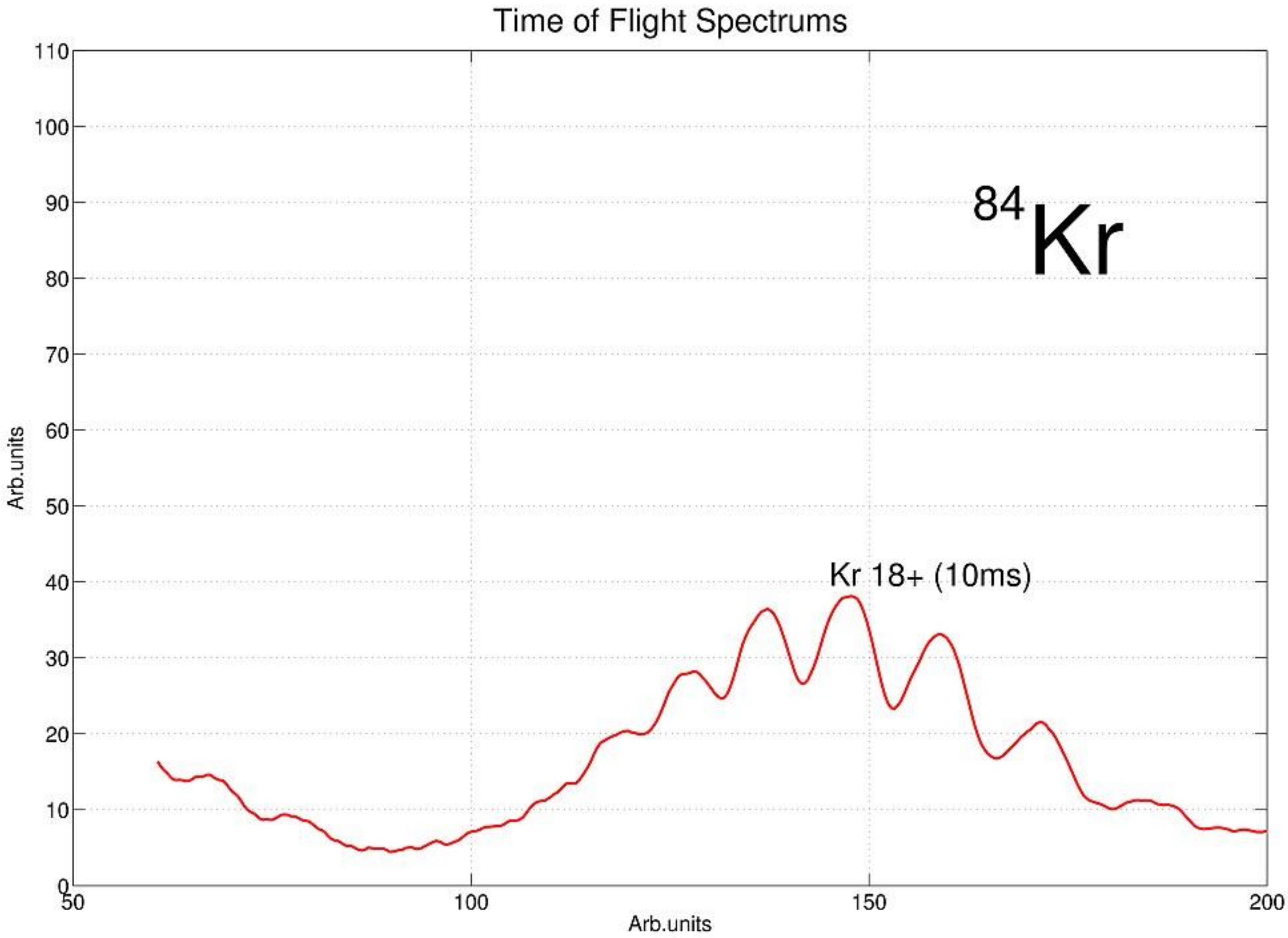
Nonlinear development and partial saturation (self-suppression) of various intabilities:

- **Two beam instability (with l=1,2... in linear perturbation theory);**
- **Initial stage of Virtual cathode formation with loss of low energy tail.**
- **Not squeezed state; no low energy electrons.**

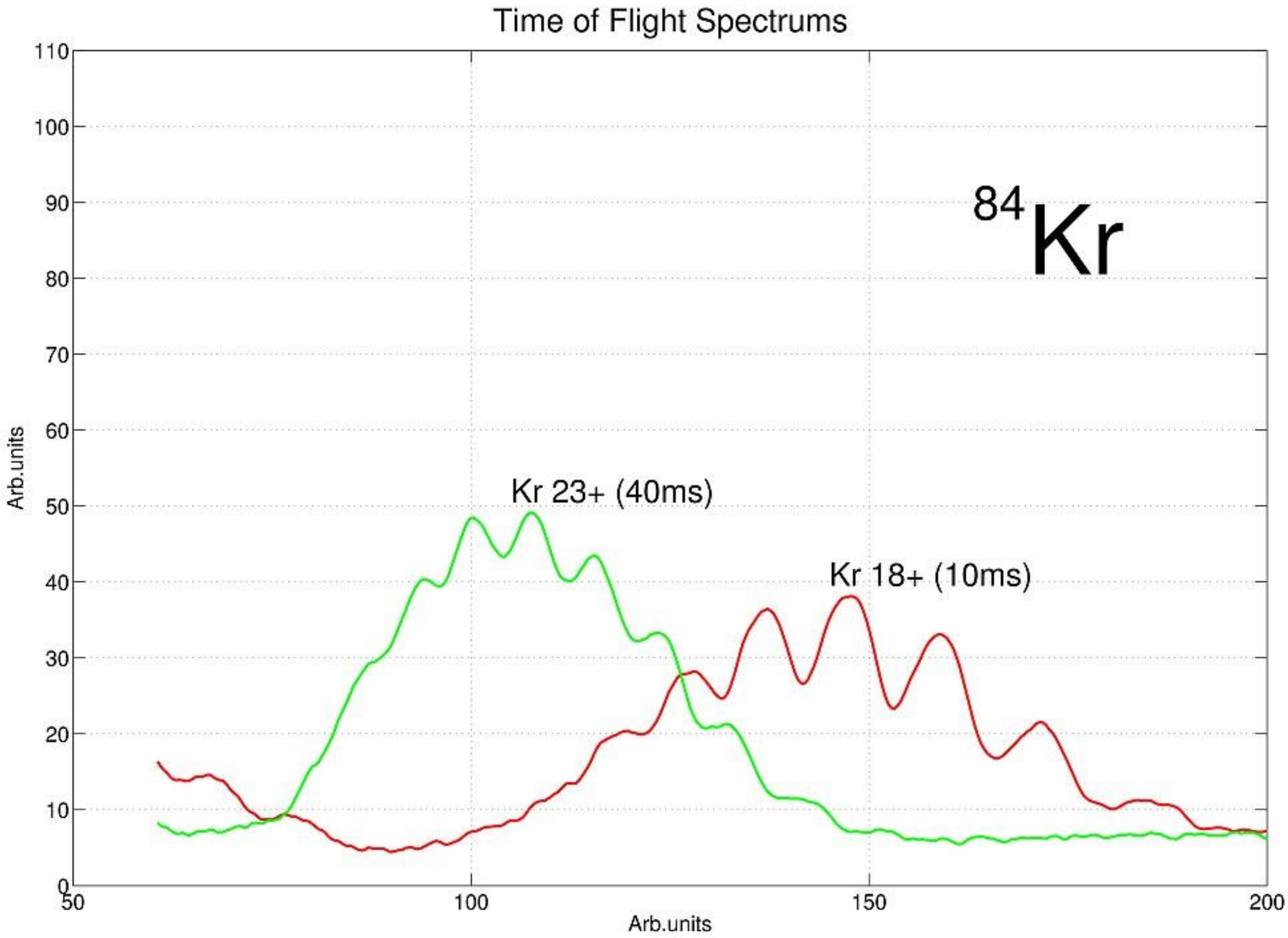
work is in progress

JINR

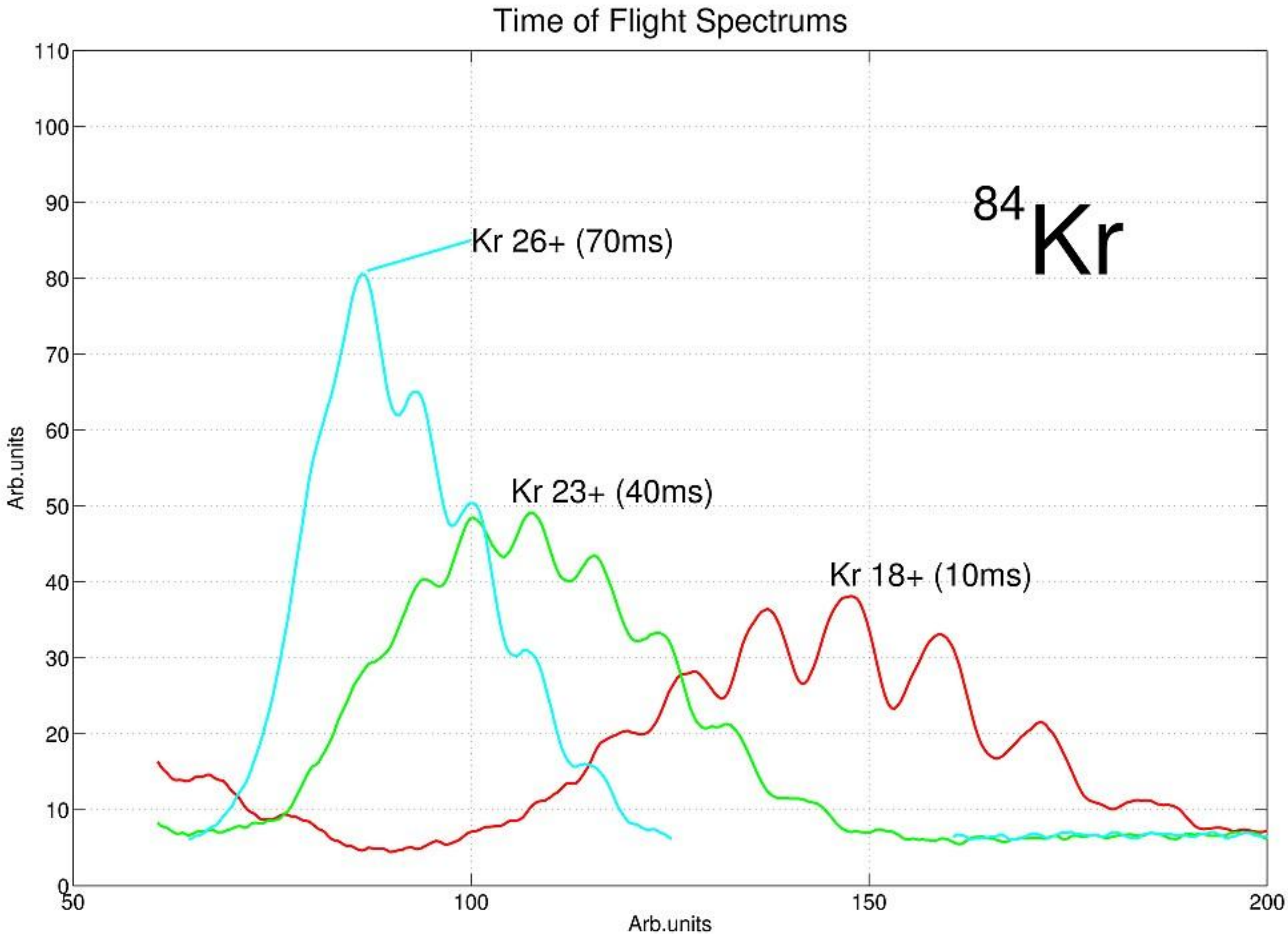
Tue Oct 27 12:32:12 MSK 2009
ch1: dT=1.03us dV=25.6mV
ch1
^{84}Kr18+
1
AVG
CH1 5mV~
MTB 250ns 16040ns ext+

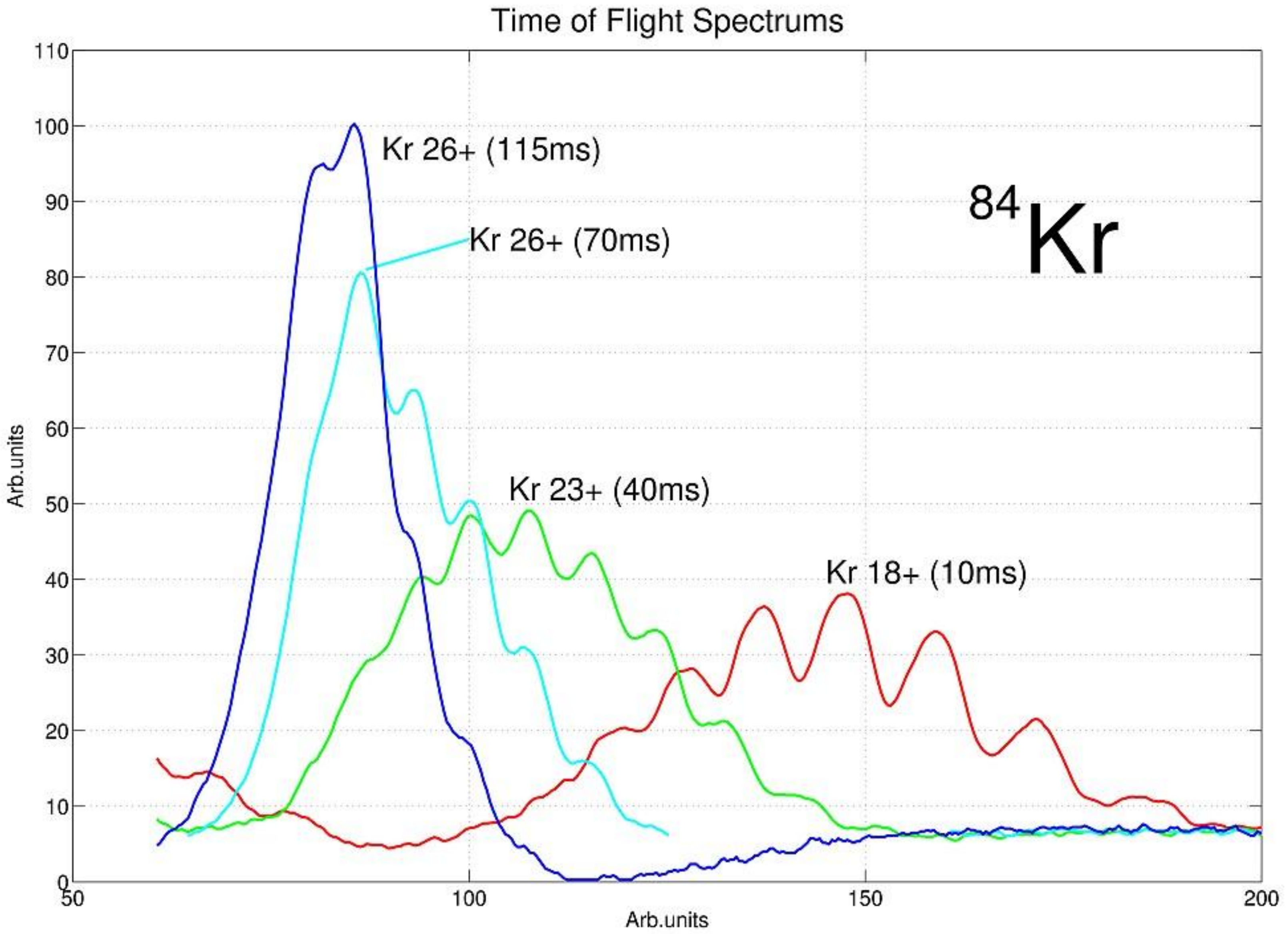


Time of Flight Spectrums
^{84}Kr
Kr 18+ (10ms)
Arb.units
Arb.units
110
100
90
80
70
60
50
40
30
20
10
0
50
100
150
200

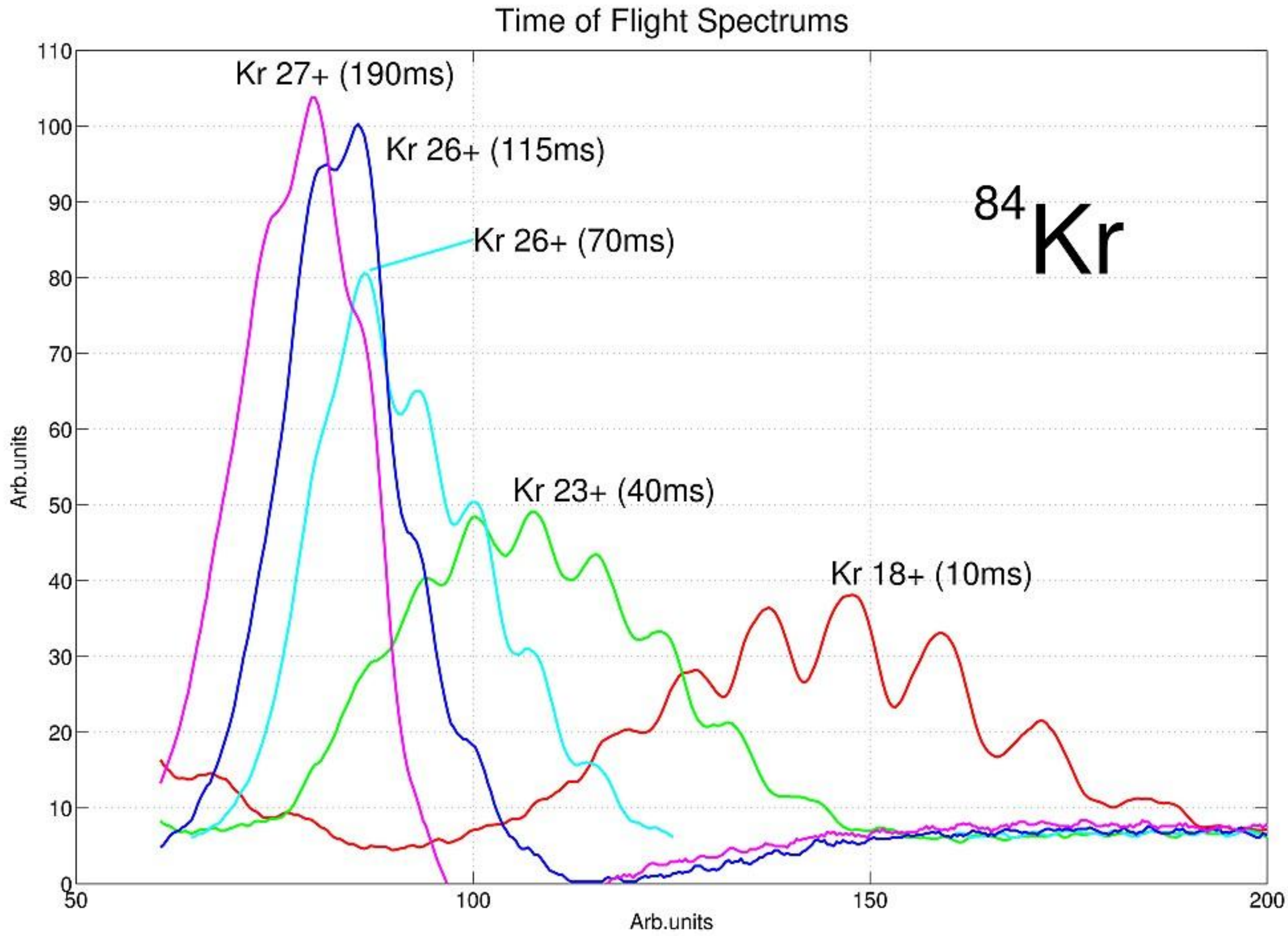


Time of Flight Spectrums
^{84}Kr
Kr 23+ (40ms)
Kr 18+ (10ms)
Arb.units
Arb.units
0
10
20
30
40
50
60
70
80
90
100
110
50
100
150
200


Time of Flight Spectrums
84Kr
Kr 26+ (70ms)
Kr 23+ (40ms)
Kr 18+ (10ms)
Arb.units
Arb.units
0
10
20
30
40
50
60
70
80
90
100
110
50
100
150
200

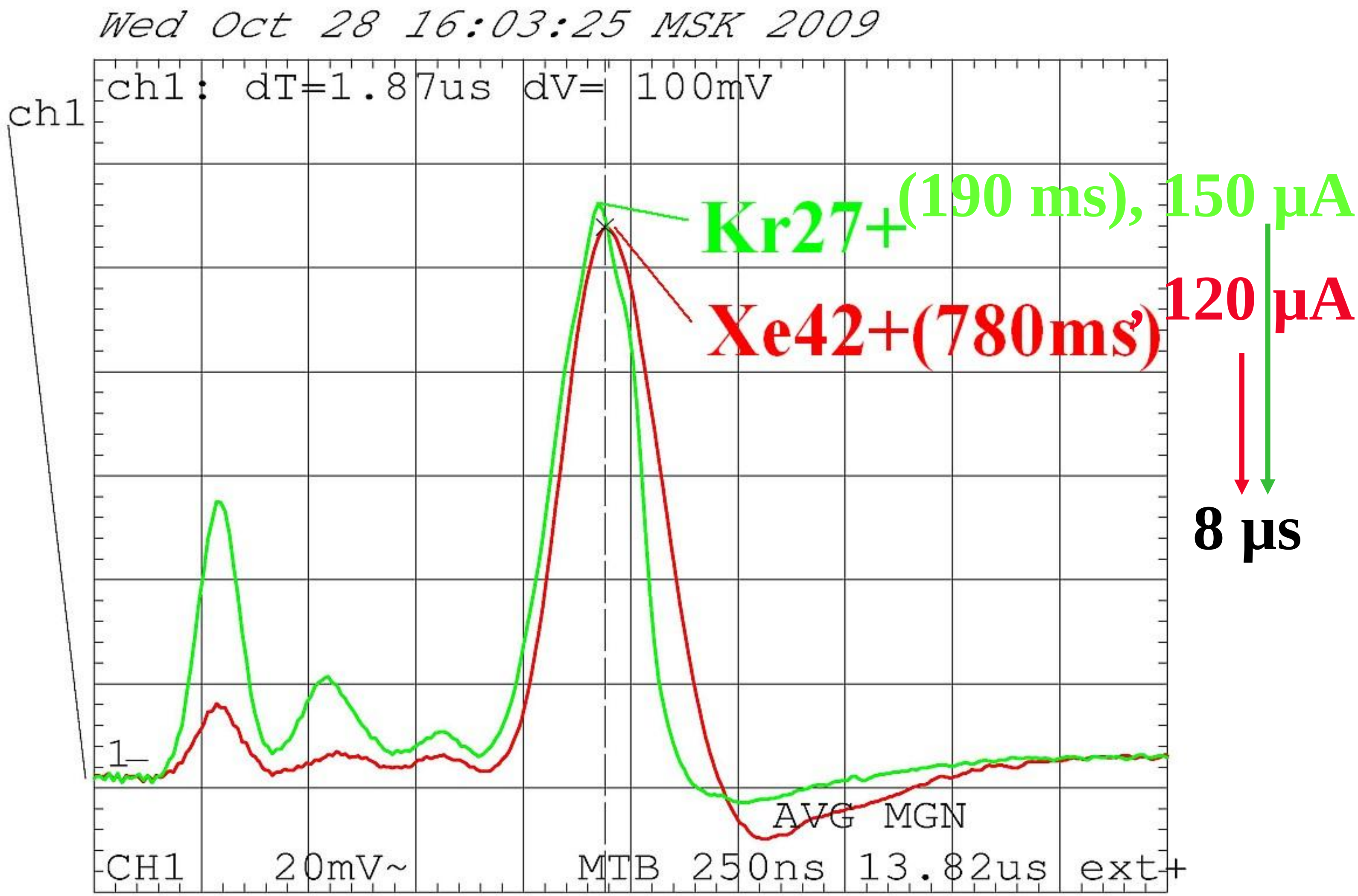


Time of Flight Spectrums
Kr 26+ (115ms)
Kr 26+ (70ms)
Kr 23+ (40ms)
Kr 18+ (10ms)
^{84}Kr
Arb.units
Arb.units
0
10
20
30
40
50
60
70
80
90
100
110
50
100
150
200


Time of Flight Spectrums
Kr 27+ (190ms)
Kr 26+ (115ms)
Kr 26+ (70ms)
Kr 23+ (40ms)
Kr 18+ (10ms)
^{84}Kr
Arb.units
Arb.units
0
10
20
30
40
50
60
70
80
90
100
110
50
100
150
200

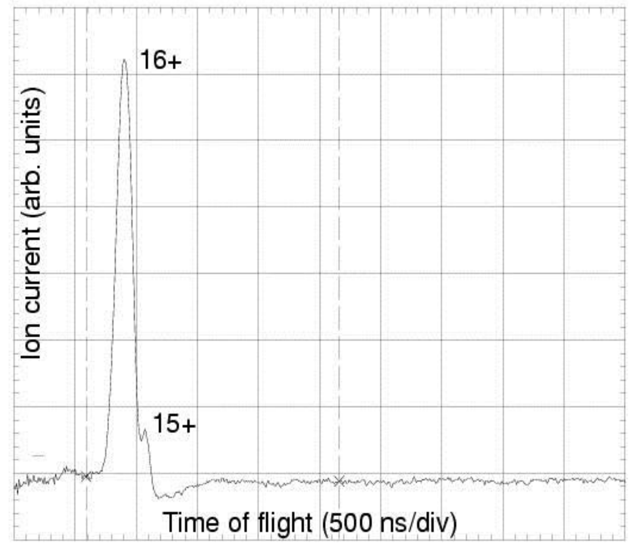
124Xe42+ procuded with Krion-2 ESIS

E=4.5KeV(E_{inj})+1.1KeV(V_{str})

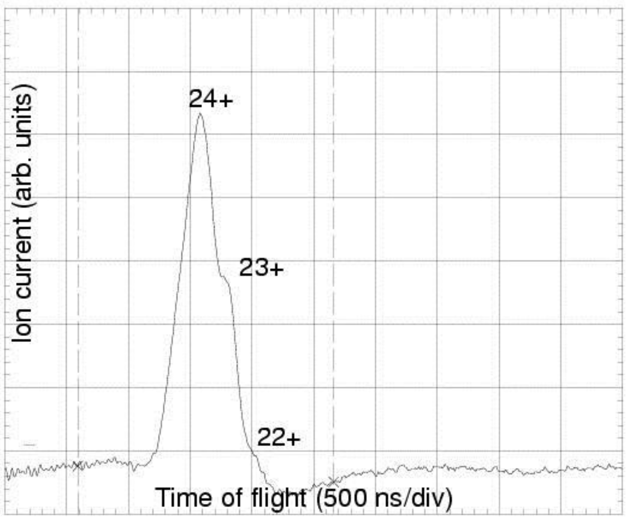


Charge state distribution of Ar ions after 500 ms confinement in an electron string space.

I_{Ar16+} = 200 μA in 8 μs



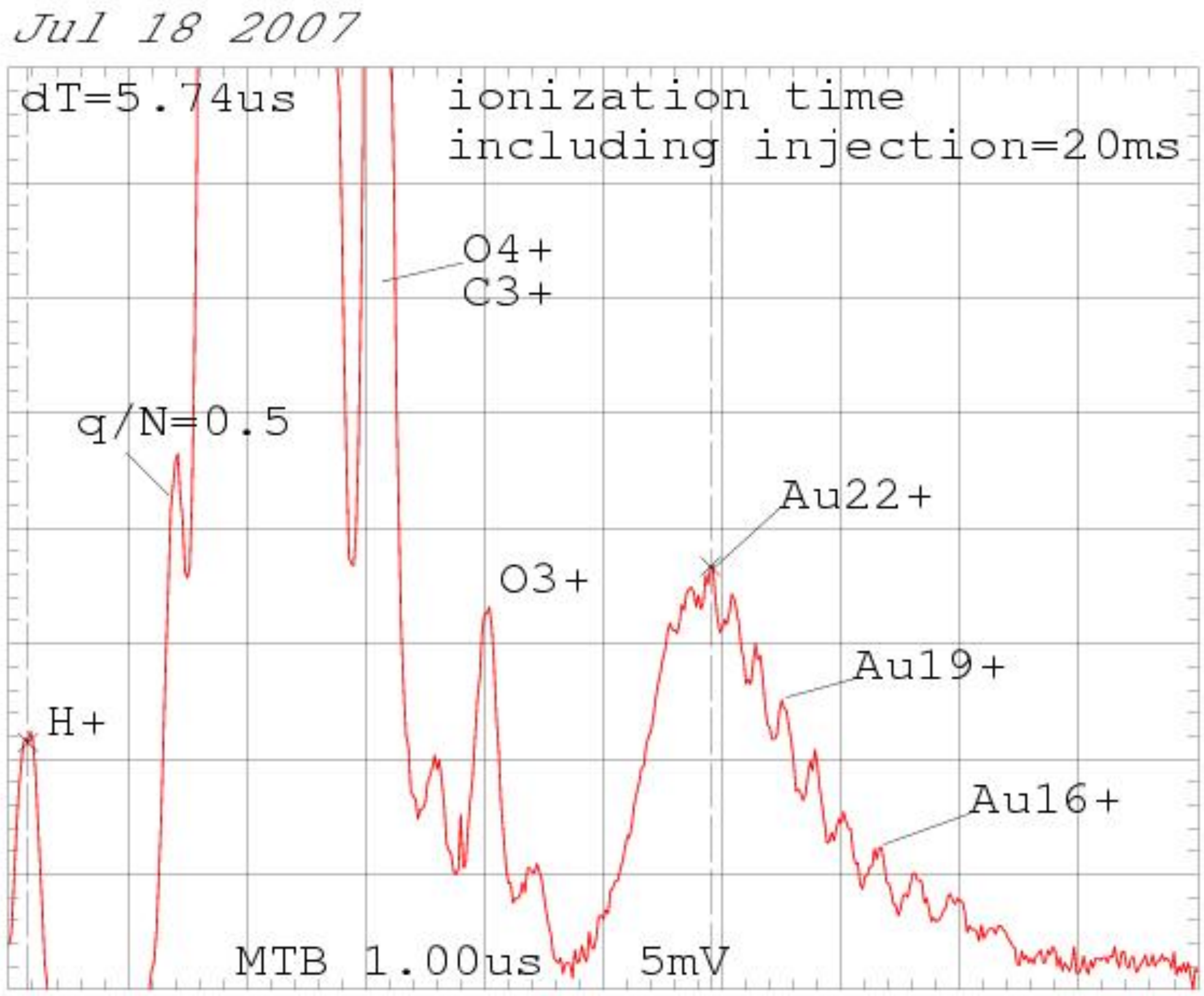
I(Fe24+) = 150 μA in 8 μs

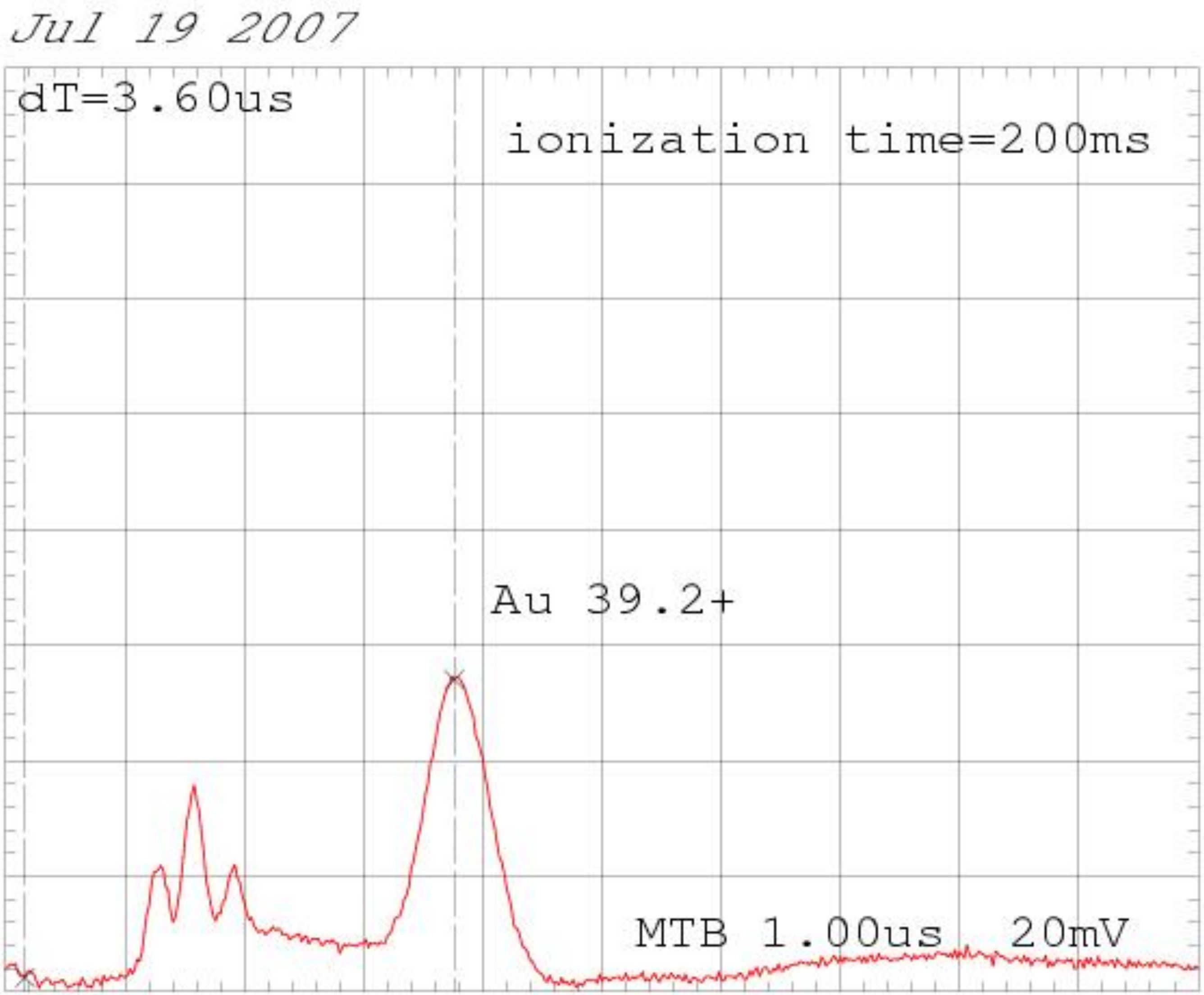


Charge state distribution of Fe ions after 1100 ms confinement in space of an electron string.

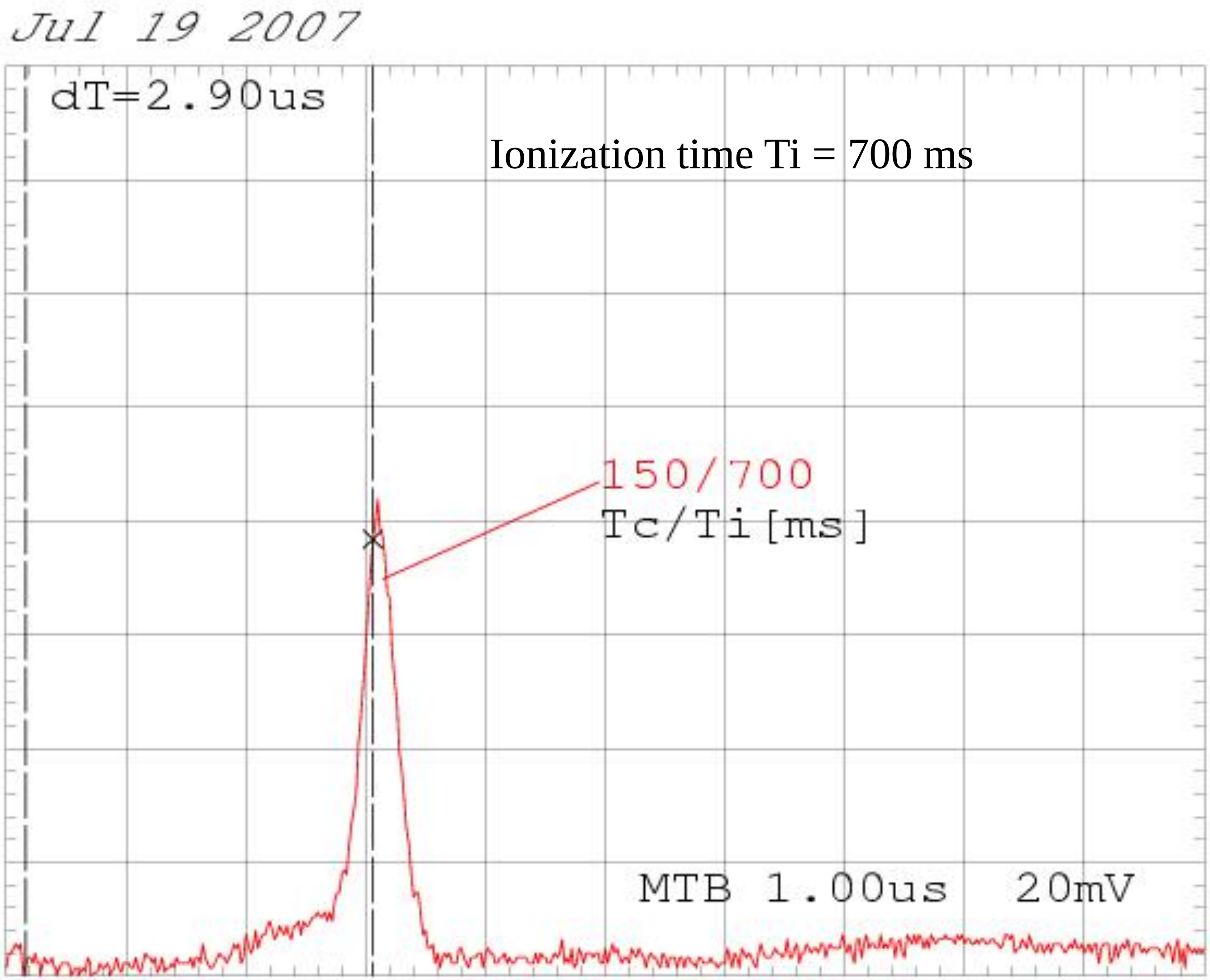
Ion-ion cooling

TOF spectra just after Au injection

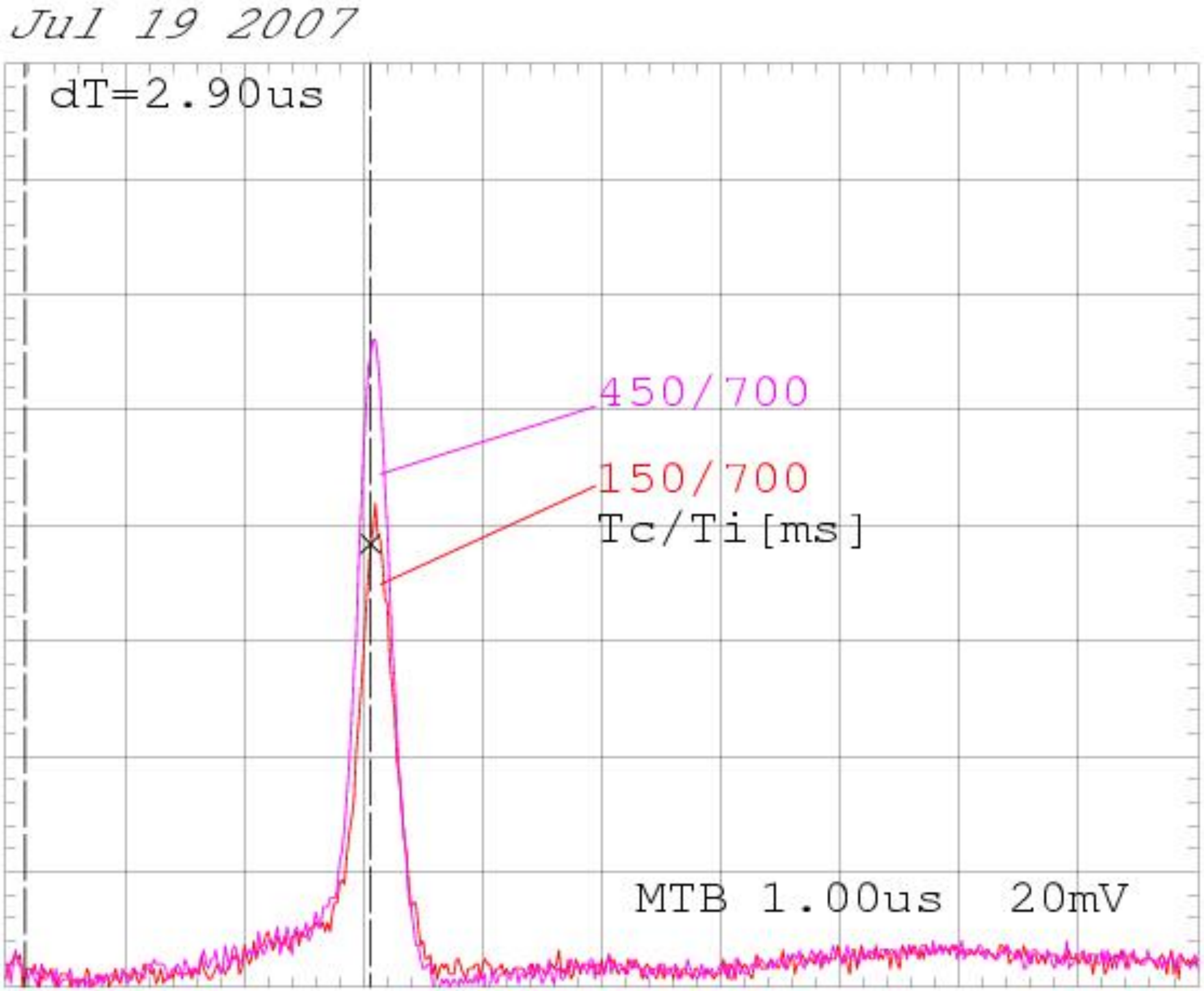



Jul 19 2007
dT=3.60us
ionization time=200ms
Au 39.2+
MTB 1.00us 20mV

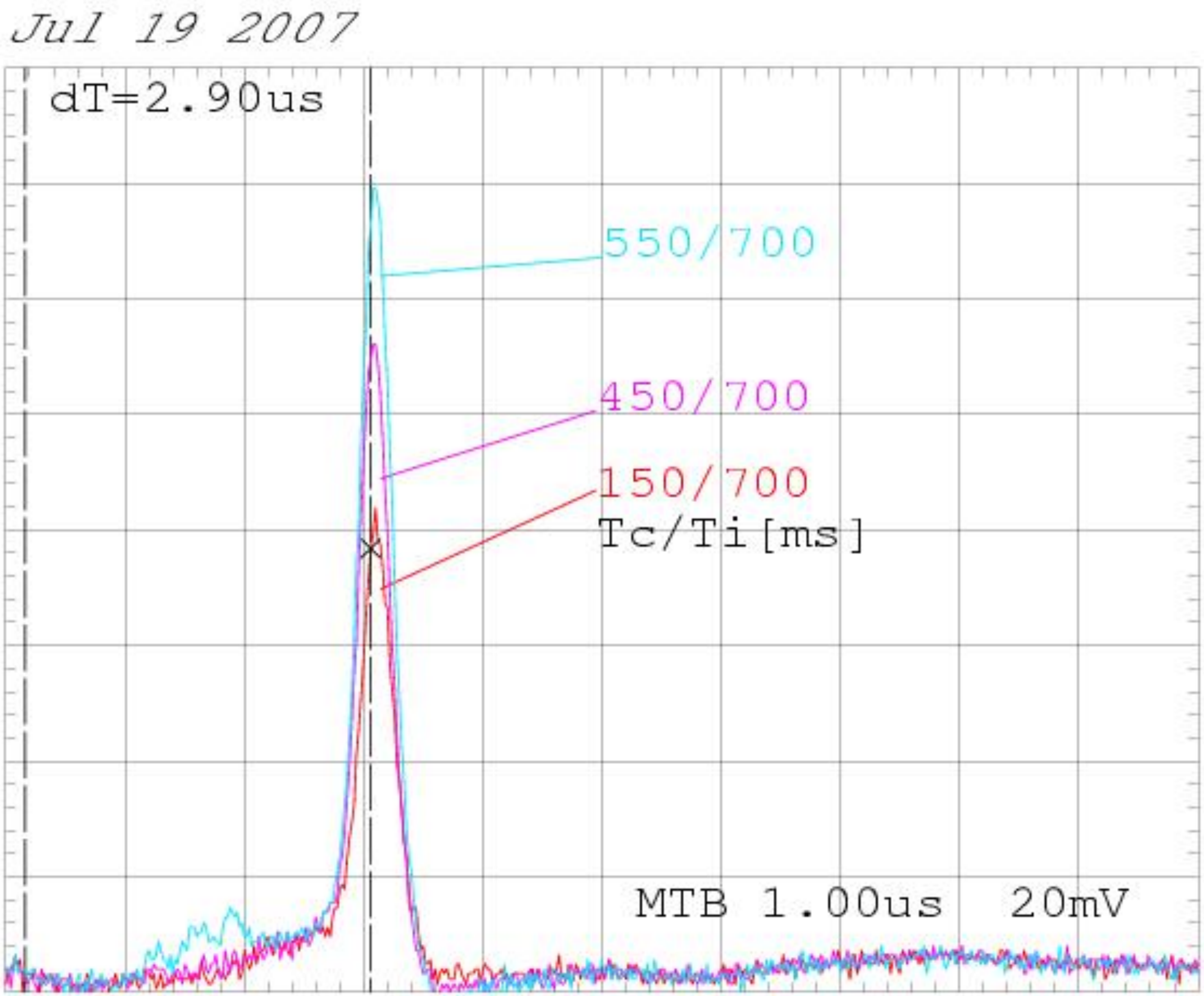
Au TOF spectra, mean q Au = 50.2+



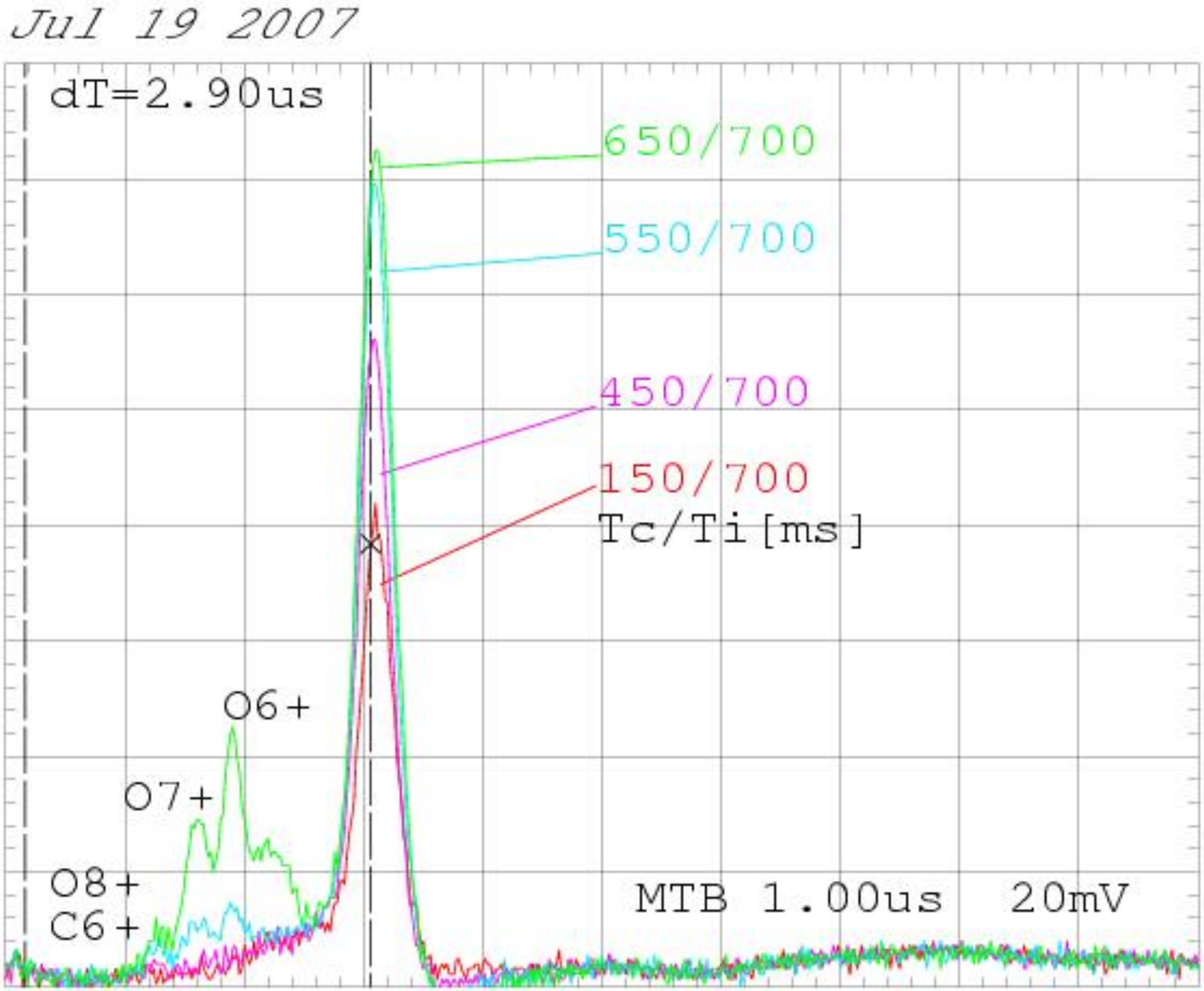
Au TOF spectra, mean q Au = 50.2+



Au TOF spectra, mean q Au = 50.2+



Au TOF spectra, mean q Au = 50.2+

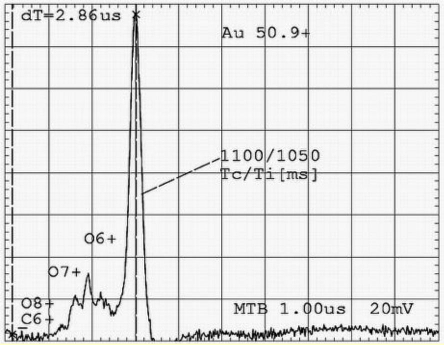


GAS PULSE INJECTION FOR PRODUCTION OF HIGHLY CHARGED IONS

Ion-ion cooling of highly charged ions in ESIS

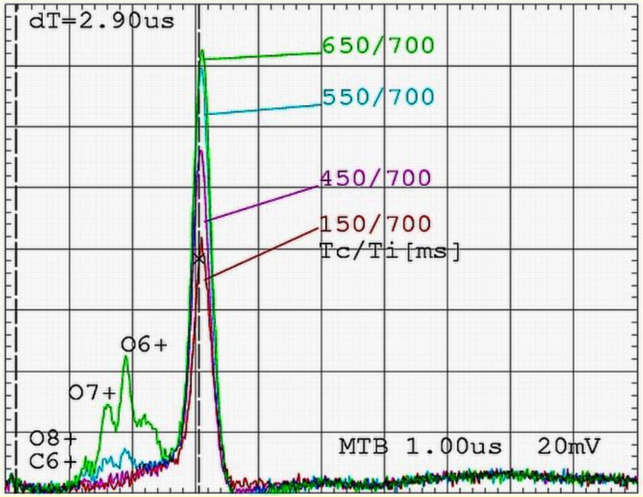
The Ion-ion cooling with use of C and O coolant ions produced at gas pulse injection permits to increase the Au^{51+}ion yield by factor 2.

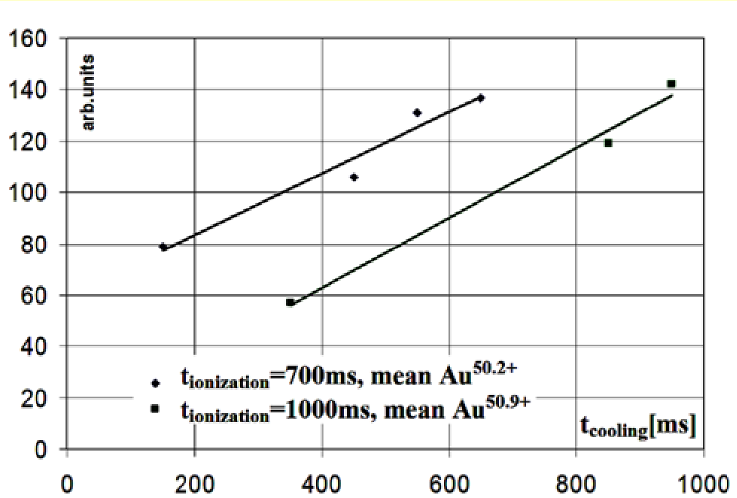
The intensity of Au^{51+} ions at ion-ion cooling was 10^8 per pulse.



Ion charge state spectrum after 1,1 s of confinement.

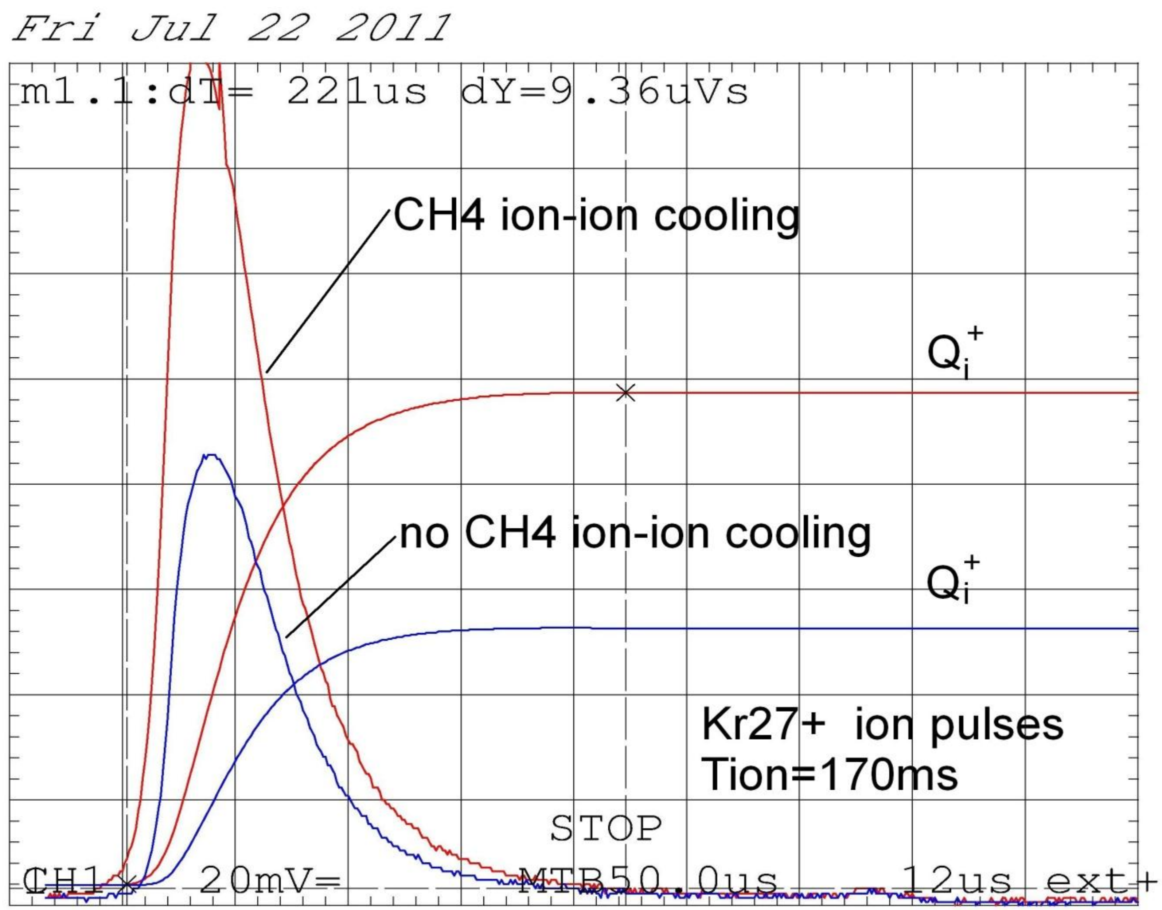
Au ion yield & ion spectra (q_{Au} = 50.2) for various injection time of coolant (CO) gas. T_i =700 ms -ionization time, red – cooling gas injection time T_c = 150 ms, magenta - T_c = 450 ms, blue - T_c = 550 ms, green - T_c = 650 ms.





Au ion yield versus cooling time.

Total Kr27+ ion pulse without ion-ion cooling - (blue) and with use of (CH_4) ion-ion cooling - red.



Preliminary results on ion-ion cooling

- Ion-ion cooling effectively works: it allows to reduce ion losses considerably, approaching to the natural limit of trap capacity.

Further plans.

- Towards Au69+ intense beams
  (with new 6T Krion-6T source):
  cooling by the **ions** (Ar8+ ?) to avoid charge exchange with neutrals of coolant gas,
  produced at separate drift tube space of ESIS.

Experimental set-up for pulse injection of methane into Krion-2 ESIS (schematic drawing).

1) Gas injection section (78 K)

2) Drift tube sections at 4.2 K

6) Methane freezing-evaporation cell.

7) The cell rod, covered with aluminized Mylar or graphite.

10) Copper wire, connected to 4.2 K terminal.

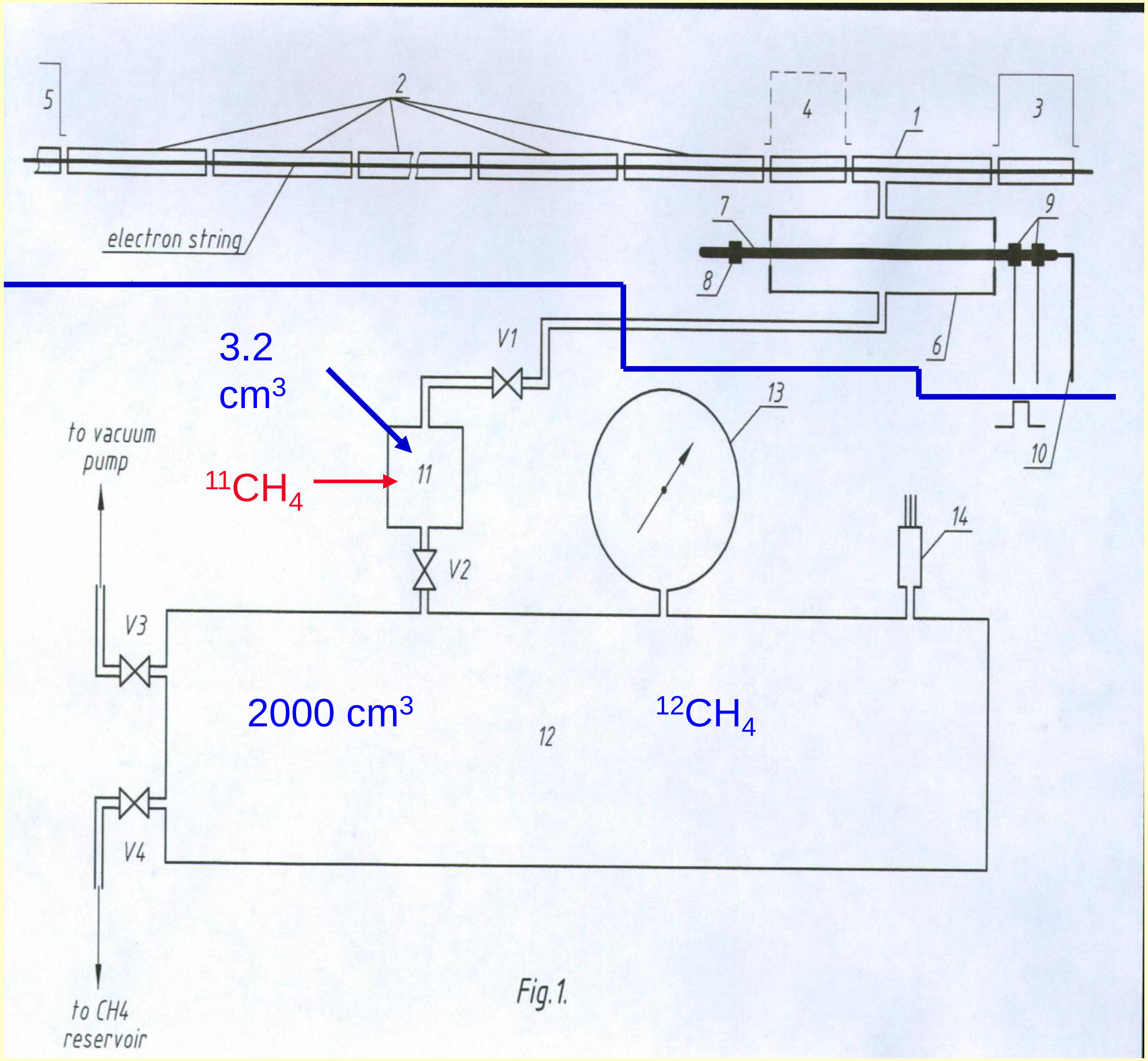
11), 12), 13), 14) Elements of the system for isolation of 10^{14} molecules of methane.

P1 = 338 Tor

P2 = 0.54 Tor

P3= $8.7 \cdot 10^{-4}$ Tor

i.e. app. 10^{14} in $3.2\ cm^3$



Cryogenic cell for pulse injection of gases (schematic view)

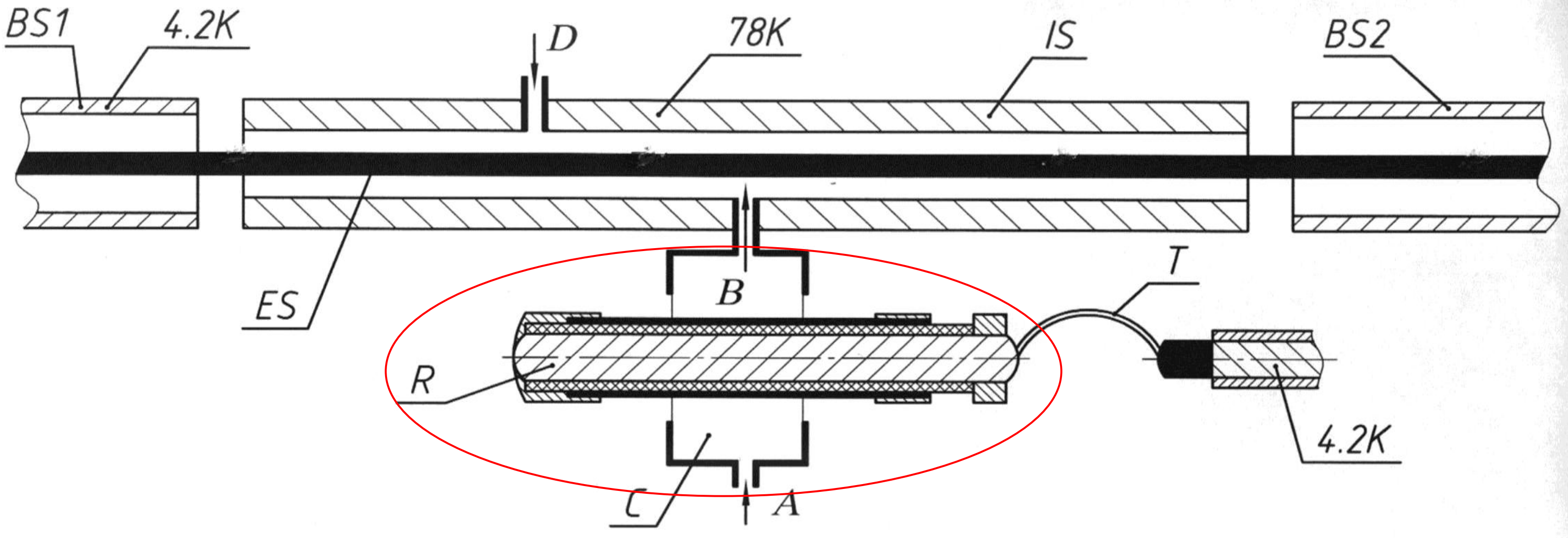
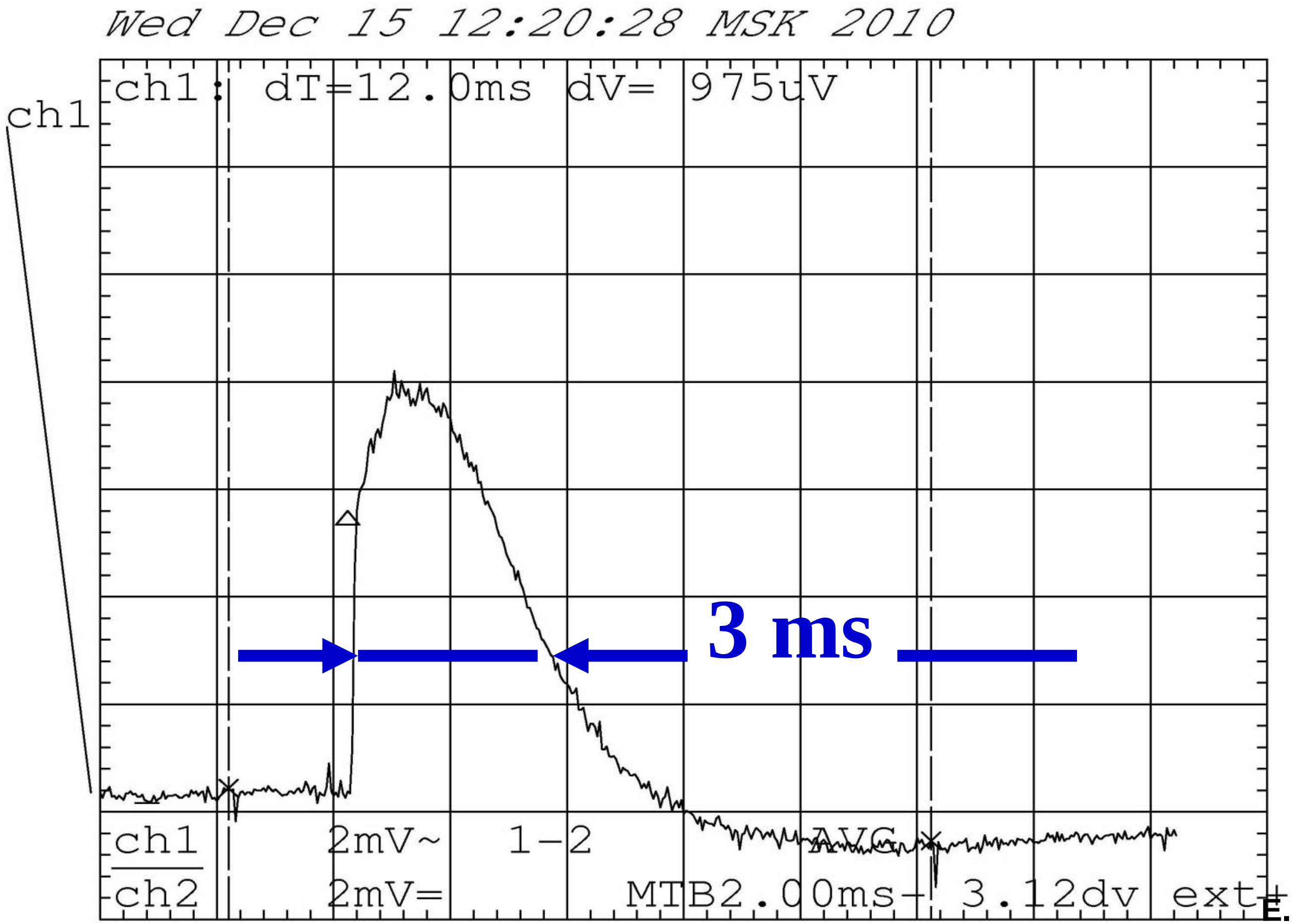


Fig.1

Pulse injection of Argon into the electron string.



E.D. Donets
12.09.2011

Expected parameters of new stand Krion-6T ESIS

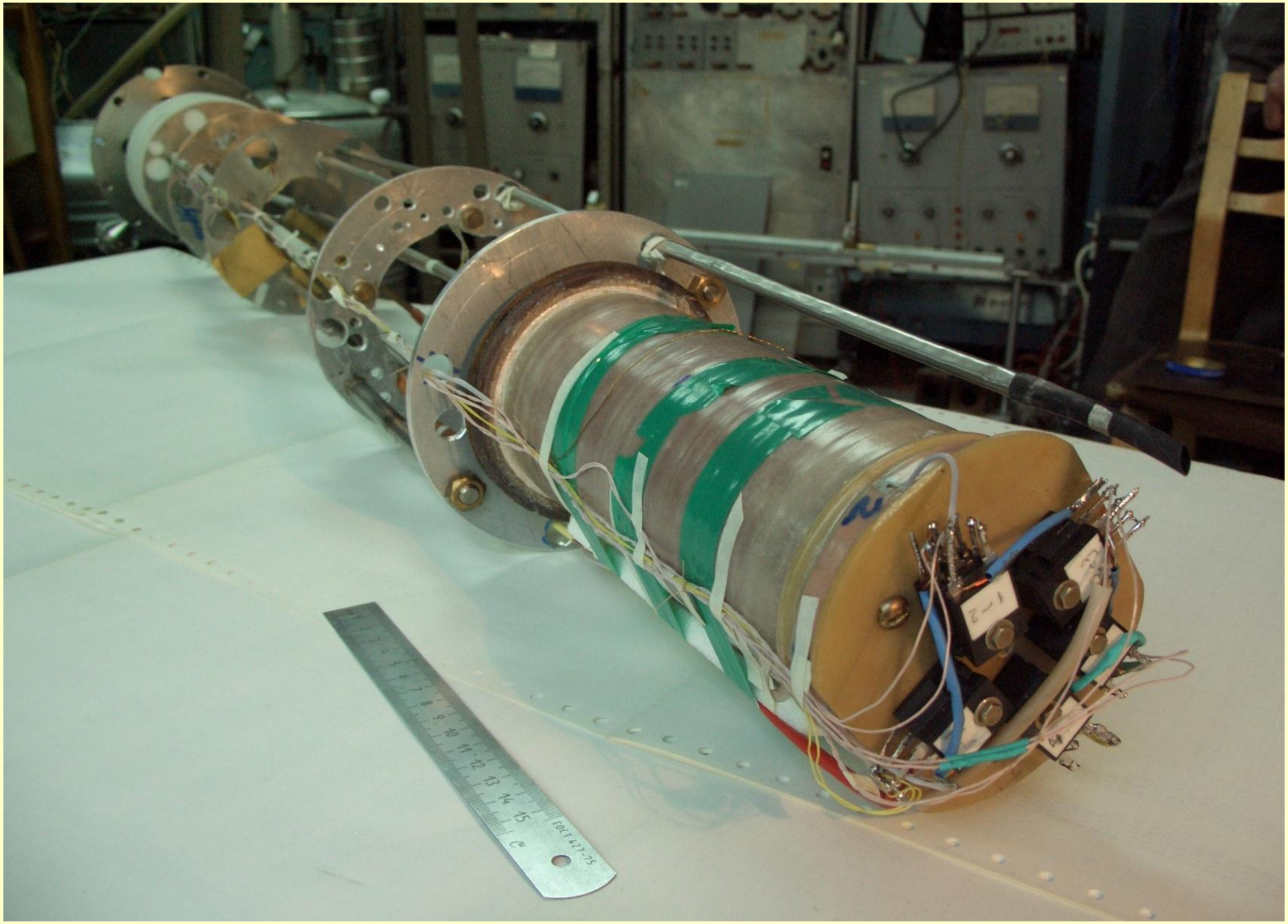
1) Magnetic field in ESIS: up to B= 6.0 T,

2) Electron injection energy: $E_e \leq 25$ keV.

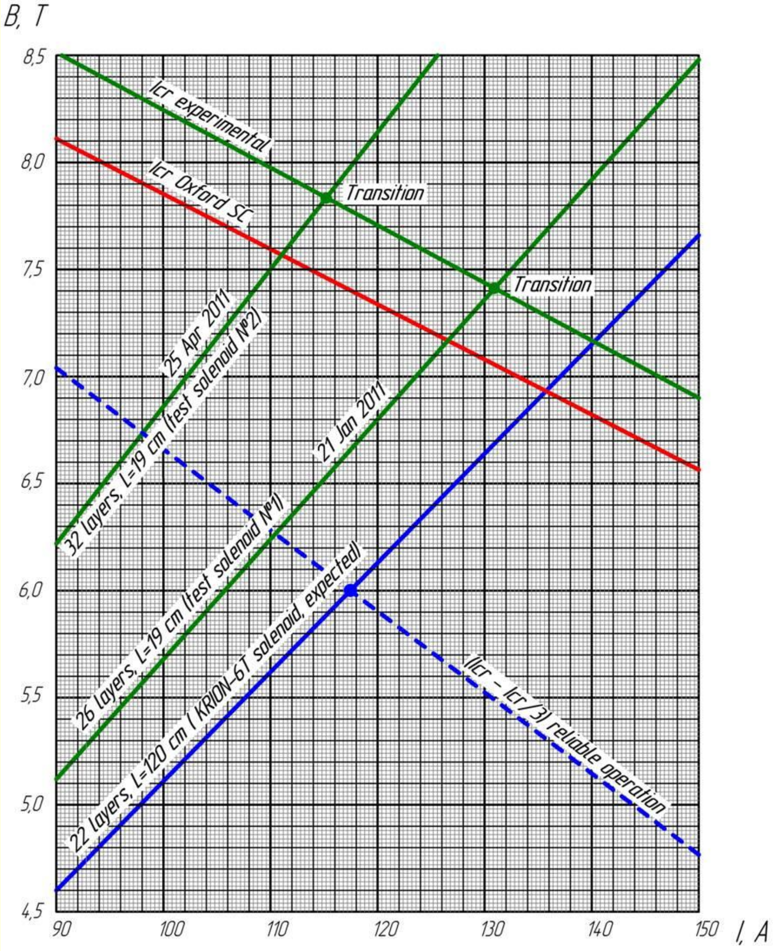
Working element/charge state	**Au^{31+}**
Expected ion yield *N_i* *(number of Au31+ ions in pulse)*	**$2÷4 \times 10^9$**
Repetition rate	**50 ÷ 60 Hz**
Extraction time form the ESIS	**$8 ÷ 30 \times 10^{-6}$ s**
RMS emittance	**<u>0.6 π mm mrad</u> (for 8×10^{-6} s extraction time); <u>0.15 π mm mrad</u> (for 30×10^{-6} s extraction time).**
Peak current in pulse	**up to 10 mA**

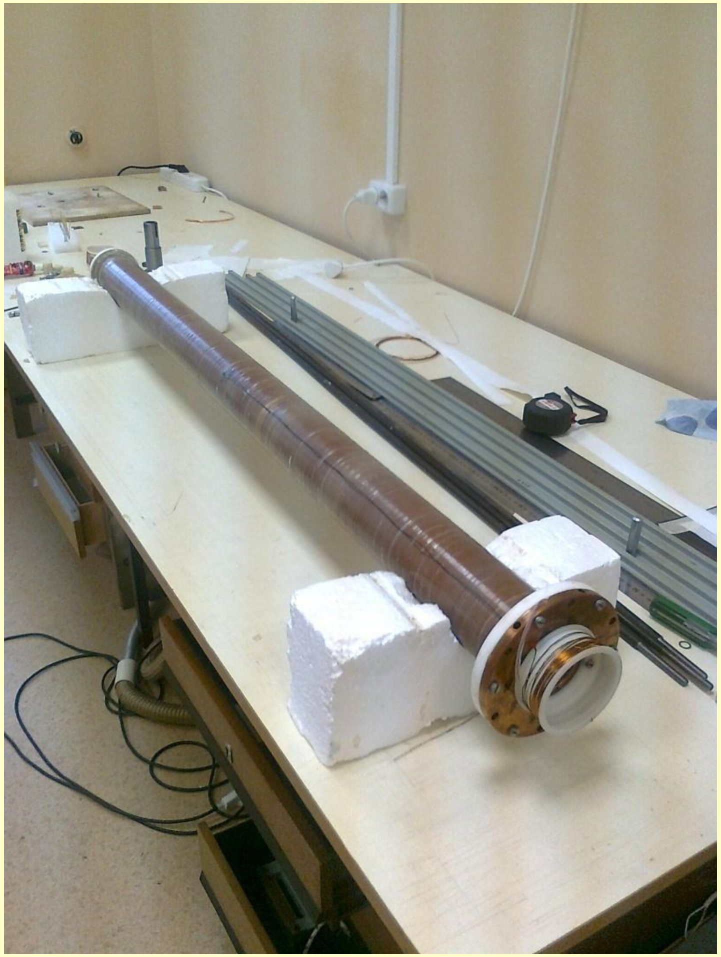

VAT
VARIAN

Superconducting test coil (L=19 cm, 32 layers of SC wire) : preparation for testing in a liquid helium.

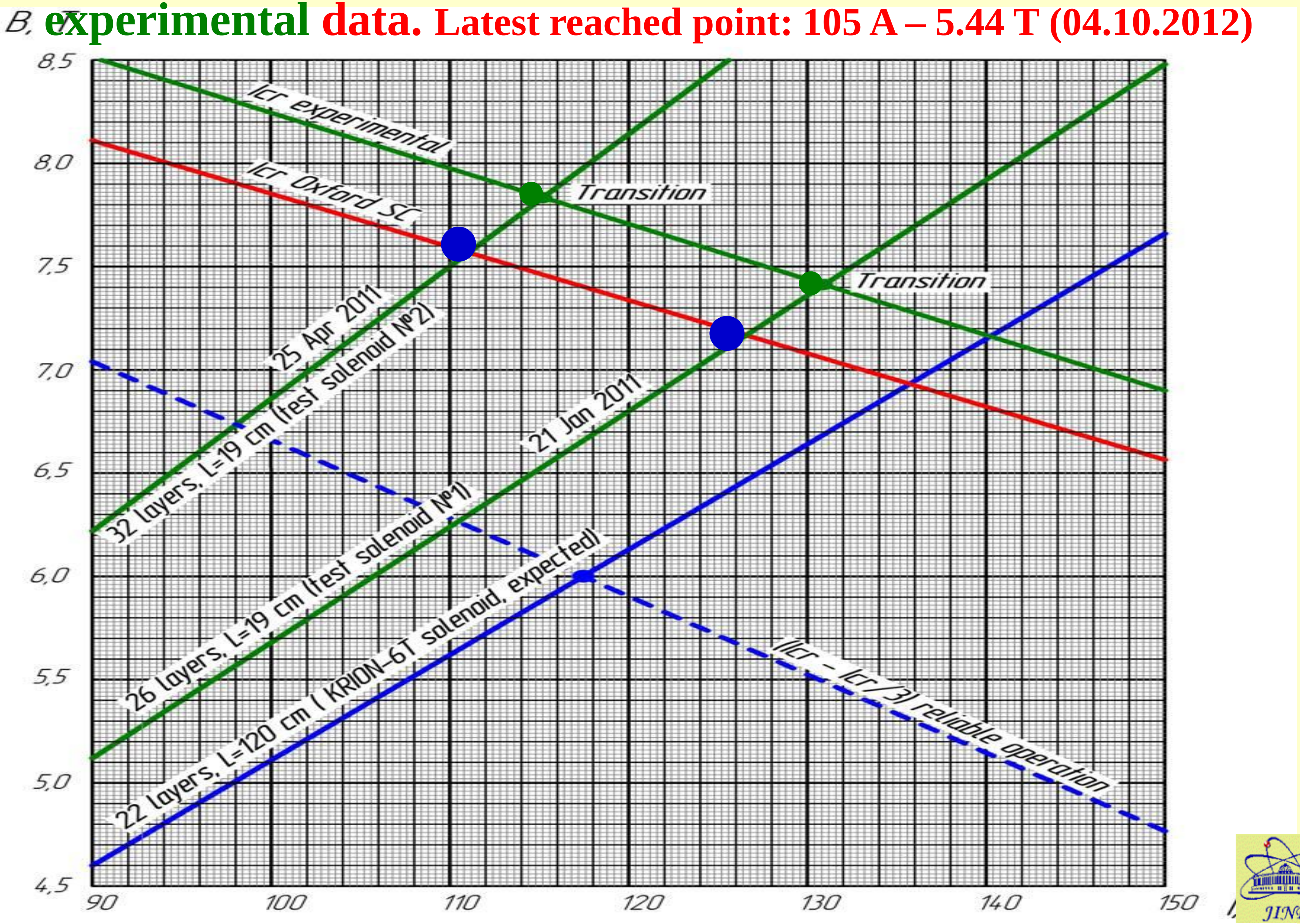


SC solenoid: 1.2 m length, 22 layers; technology was elaborated and manufacturing has been done in ESIS group (VBLHEP,JINR)

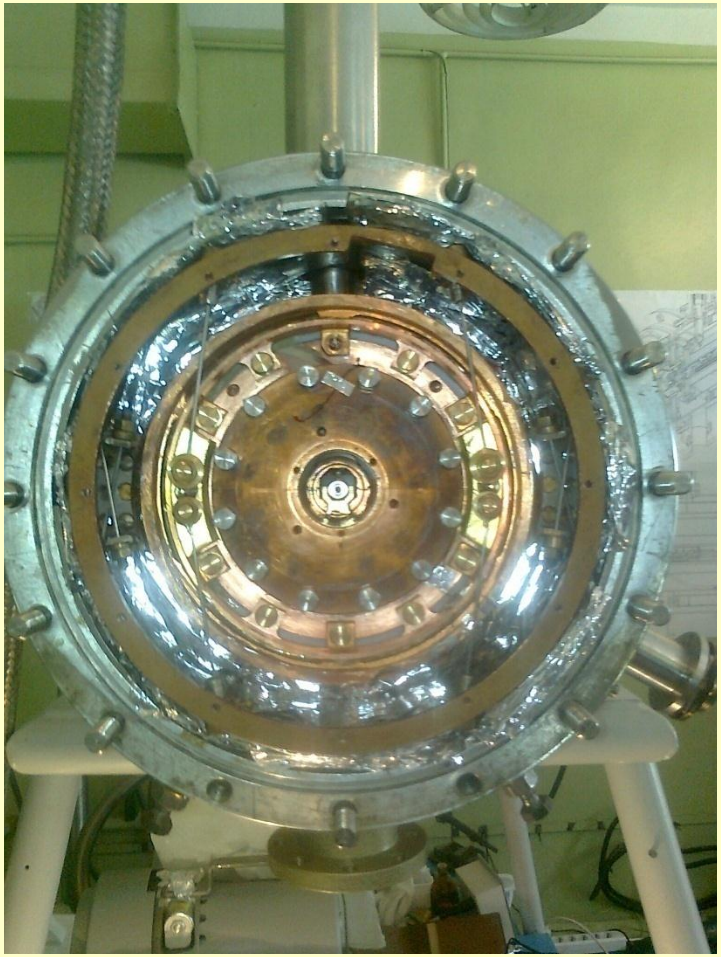




Magnetic field versus electron current: expected and experimental data. Latest reached point: 105 A – 5.44 T (04.10.2012)



SC solenoid inside of Krion-6T ESIS (left); test assembling of the quench protection system (right).



Nearest future plans:

1) First e-string tests are planned in October 2012.

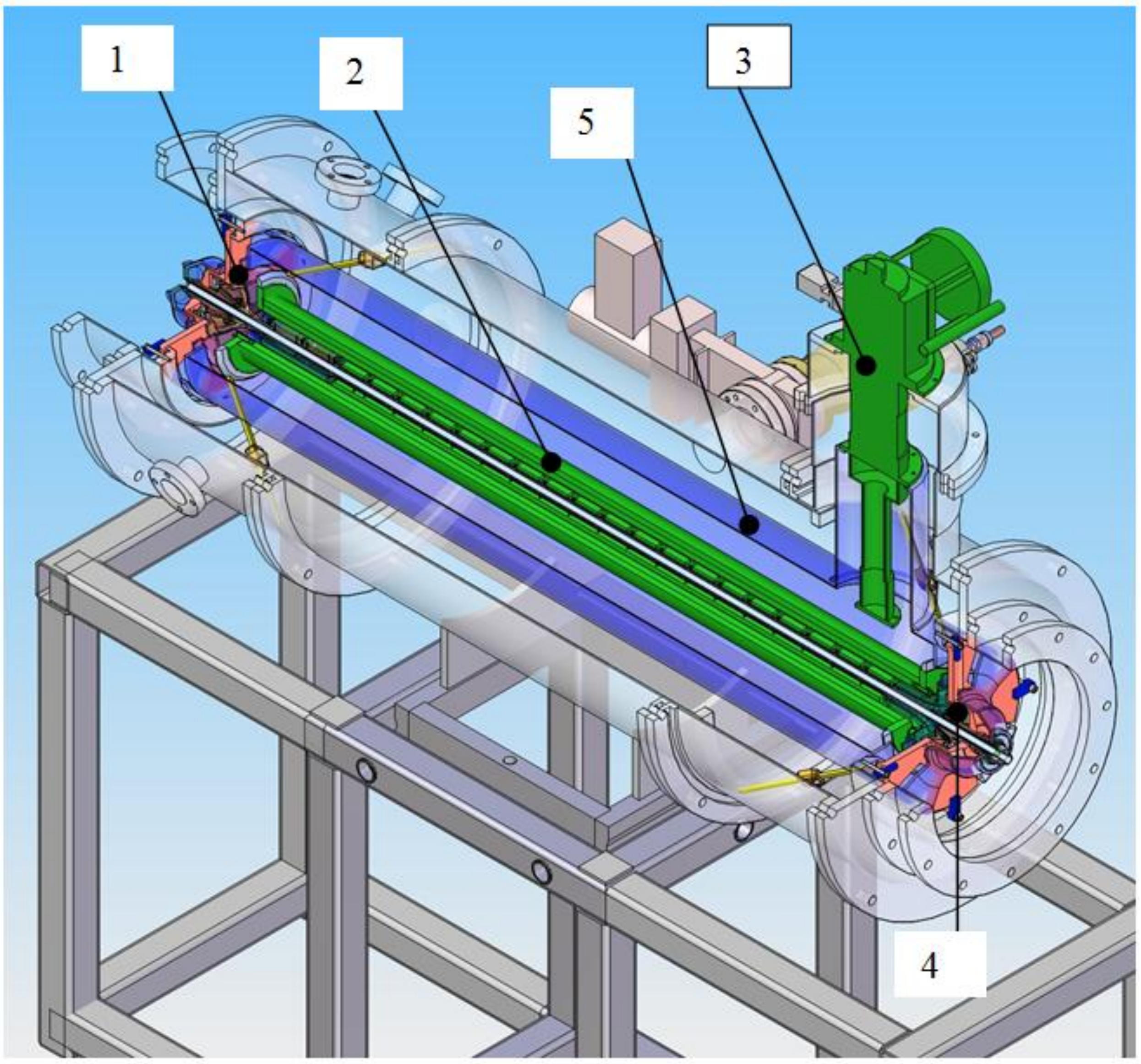
2) Then, basic studies on e-string and heavy ion production in new range of relevant parameters (electron energy up to 25 KeV, confining magnetic field up to 6 T, et cetera)…

3) … towards Au65+ ÷Au69+ beams production for their possible acceleration on existing LU-20/Nuclotron facility (LU-20 accepts ions with charge state to mass ratio > 1/3) in 2013?

JINR

Thank you for your attention!

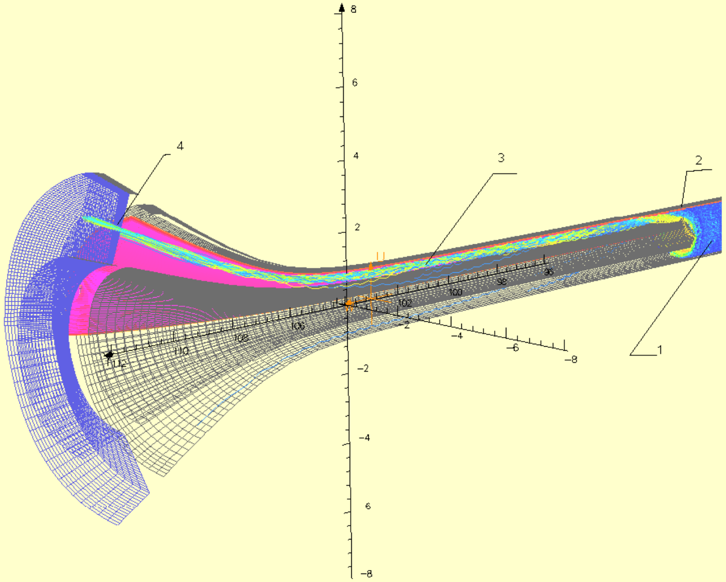
TUBULAR ELECTRON STRING ION SOURCE



1-electron gun, 2- superconducting solenoid, 3-cryo-cooler, 4- reflector electrode, 5- thermal shielding at temperature of 40 K.

ION OPTICAL SYSTEM

- The method of the off–axis TESIS ion extraction was proposed to get TESIS beam emittance comparable with ESIS one.



OPERA 3D simulation of the ion optic system and the ion off-axis extraction channel.

- The extracted ion beam has an ellipsoidal shape ($\Delta r_{i,}$ Δy_i are radial and azimuthal directions)

$$\Delta r_i = 2 \text{ mm}, \Delta y_i = 8 \text{ mm}.$$

- Normolized radial $\varepsilon_{r\text{-}n}$ and azimuthal $\varepsilon_{\varphi\text{-}n}$ emittances of the extracted ion beam:

$$\varepsilon_{r\text{-}n} \cong \beta_i \cdot \Delta r_i^2 / 4\rho_i \cong 0{,}05\pi \cdot \text{mm} \cdot \text{mrad},$$

$$\varepsilon_{\varphi\text{-}n} \cong \beta_i \cdot \Delta r_i \cdot \Delta y_i / 4\rho_i \cong 0{,}15\pi \cdot \text{mm} \cdot \text{mrad}.$$

- The radial and azimuthal emittances of the ion beam accelerated to energy of eU_{ac} =25·Z keV

$$\varepsilon_r \cong 5\ \pi \cdot \text{mm} \cdot \text{mrad and } \varepsilon_\varphi \cong 20\ \pi \cdot \text{mm} \cdot \text{mrad}.$$