RADIATION THERAPY FACILITY BASED ON THE CARBON ION COOLER SYNCHROTRON

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RUPAC2008

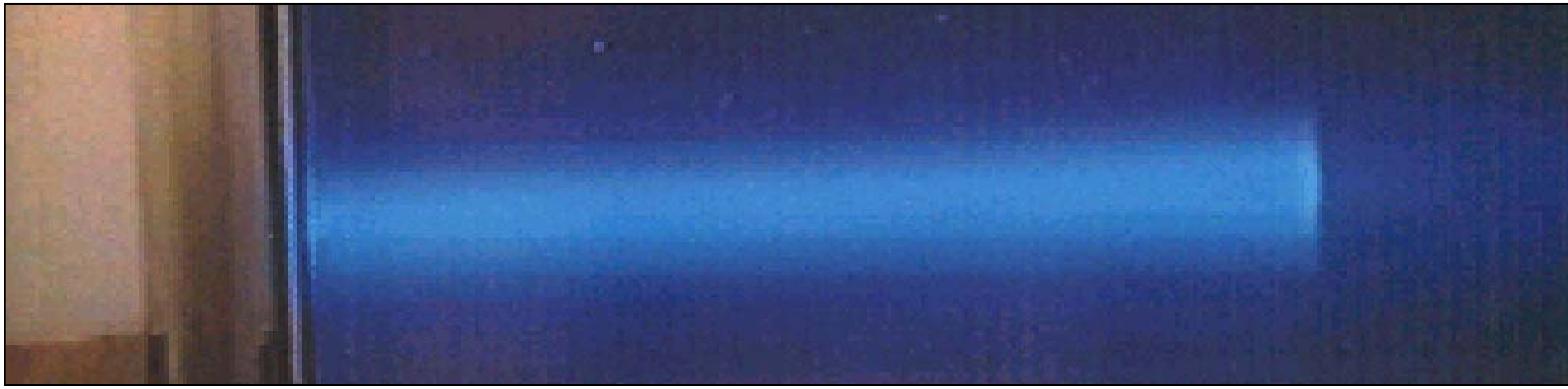
Content

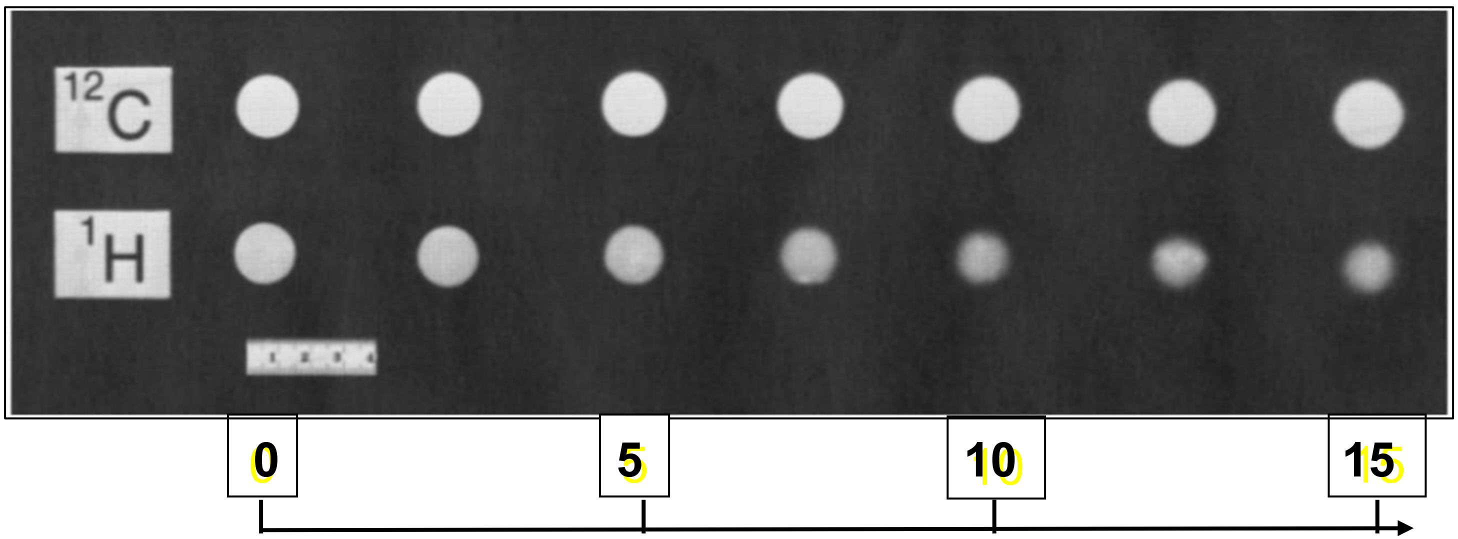
- Key scientific bases of BINP project:
  - Why carbon ion? — High efficiency treatment
  - Why electron cooling? — High Z and easy cooling for accumulation and precise extraction with scanning technology
  - Why booster? — High energy injection C ions 30 MeV/u no space charge problems + proton beam
  - Why electrostatic tandem? — No reasons for increasing energy for fast cycling booster (with cooling at main ring)

Project from physics point of view:

- Ion source principle and experience using C^{-1}
- Tandem
- Booster
- Main ring
- Extraction
- Gantry
- Scanner

Carbon ion beam in the water

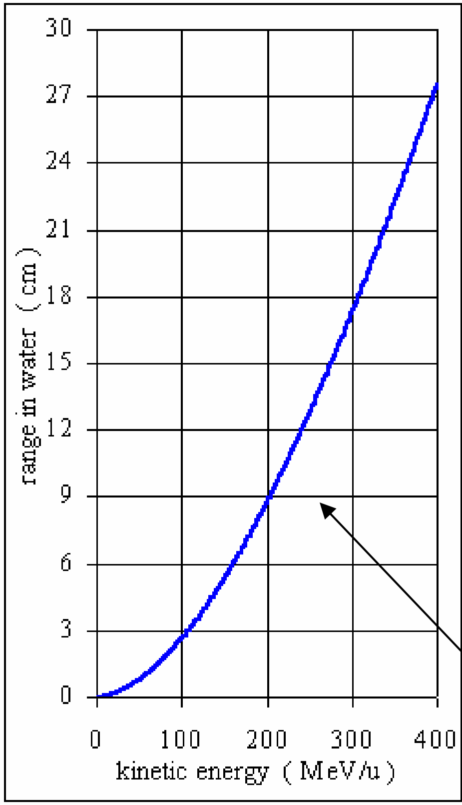


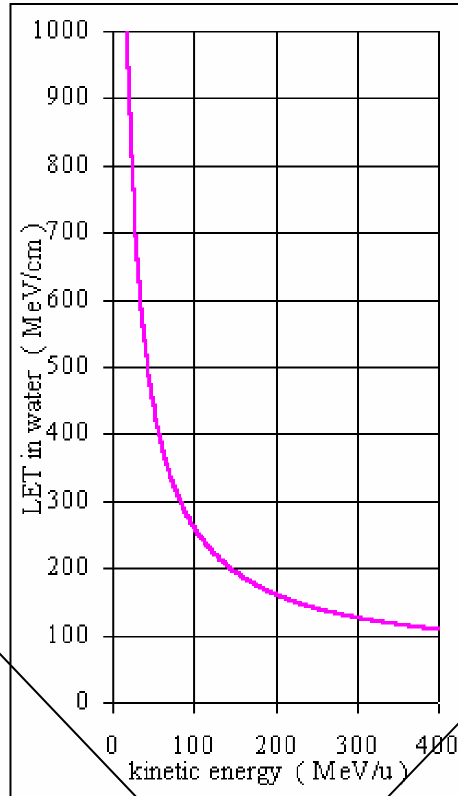


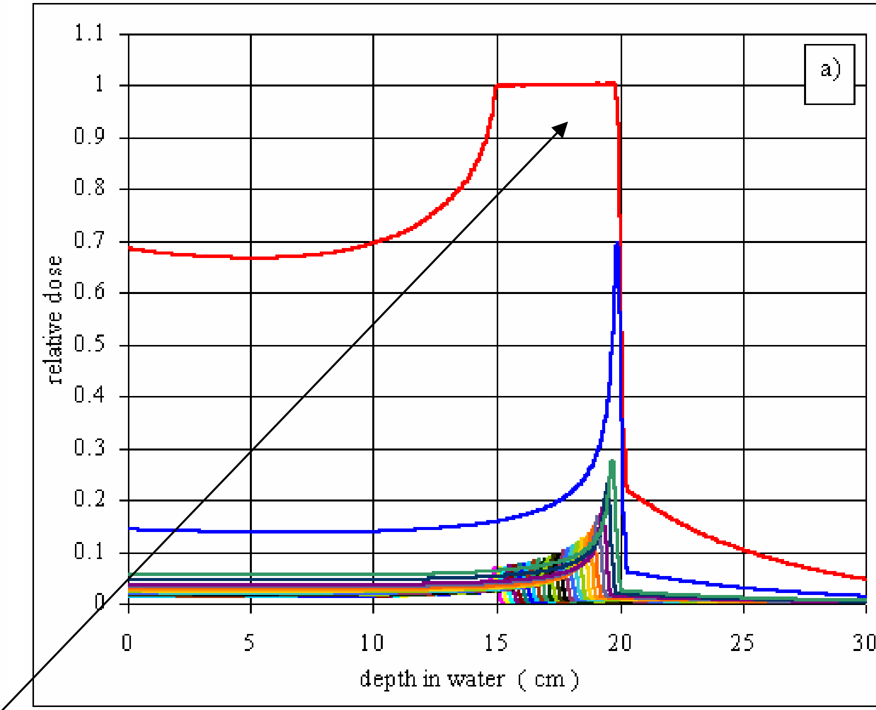
Distance in the water
(cm)

Advantages of carbon ion:
High ionization in track, low scattering, low nuclear reaction rate by nuclear reactions

Disadvantages: large size accelerator



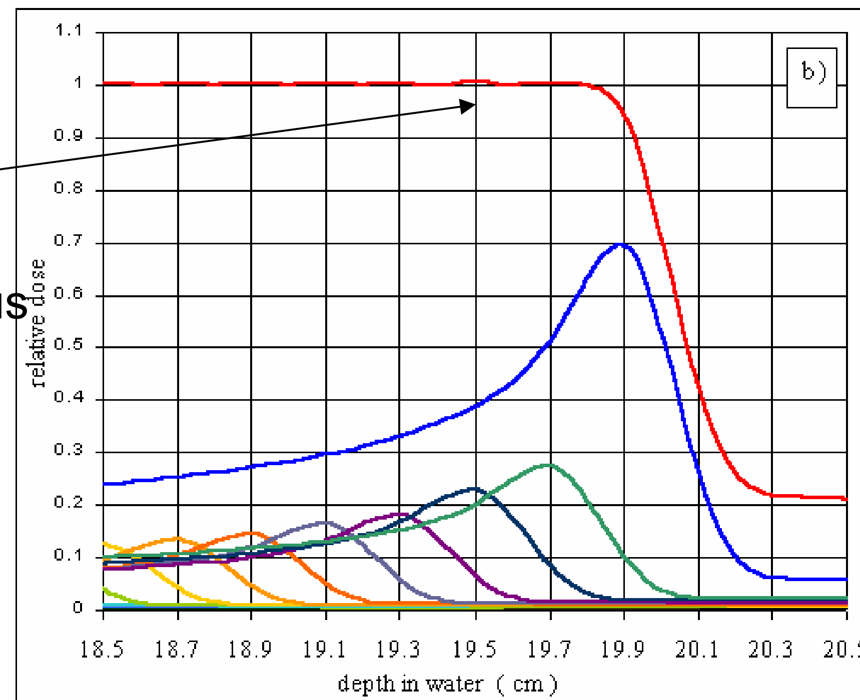




Range in water C 400 MeB/н 27 cm.

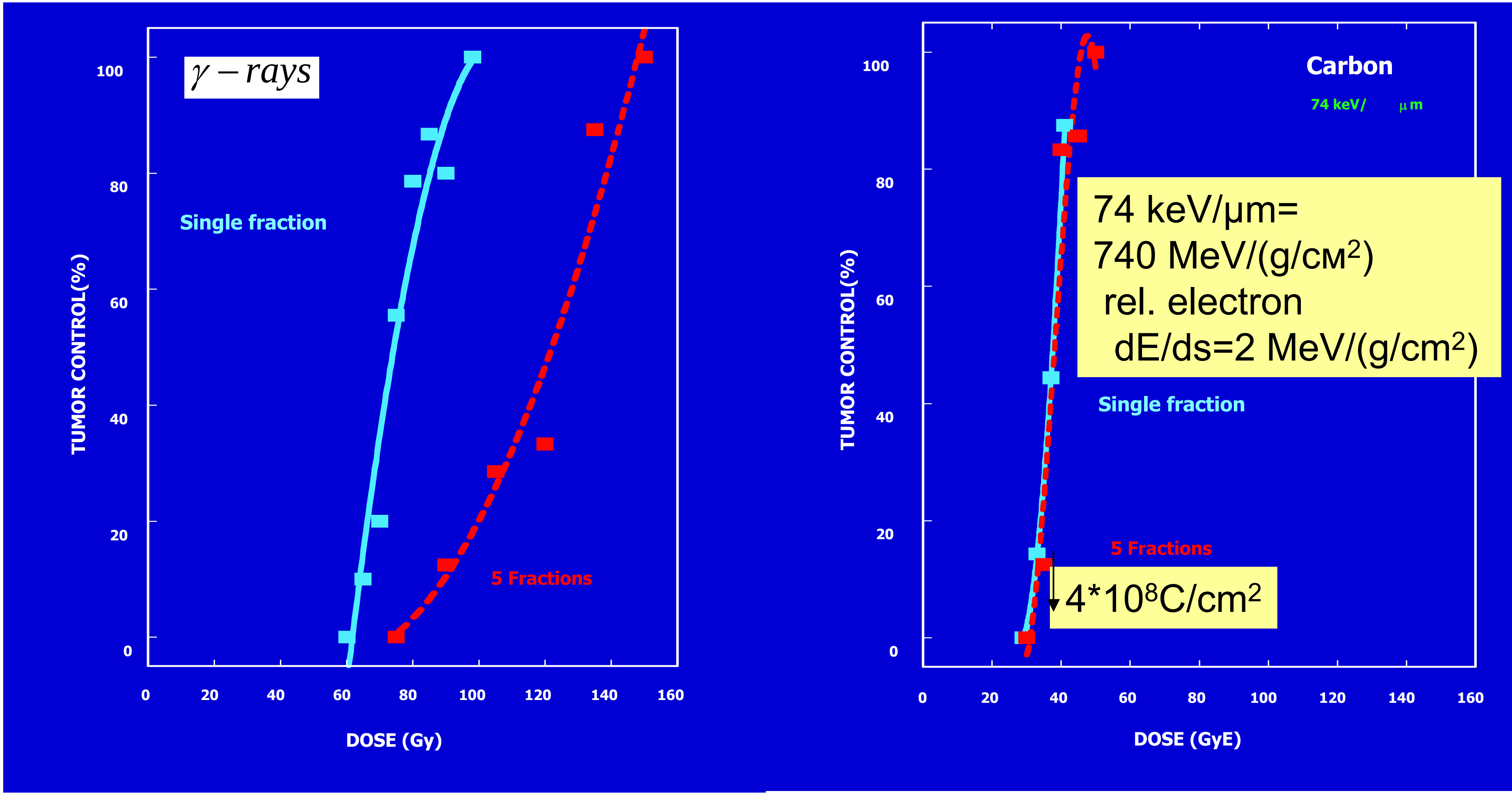
Superposition few energy beams form flat doze zone.

For produce 5 Gy doze in sphere 1 cm radius required 0.021 J energy ions with rest energy 50 MeV/u $N_i=10^8$. Heating of water at radiation zone only 0.001 ^{o}C!



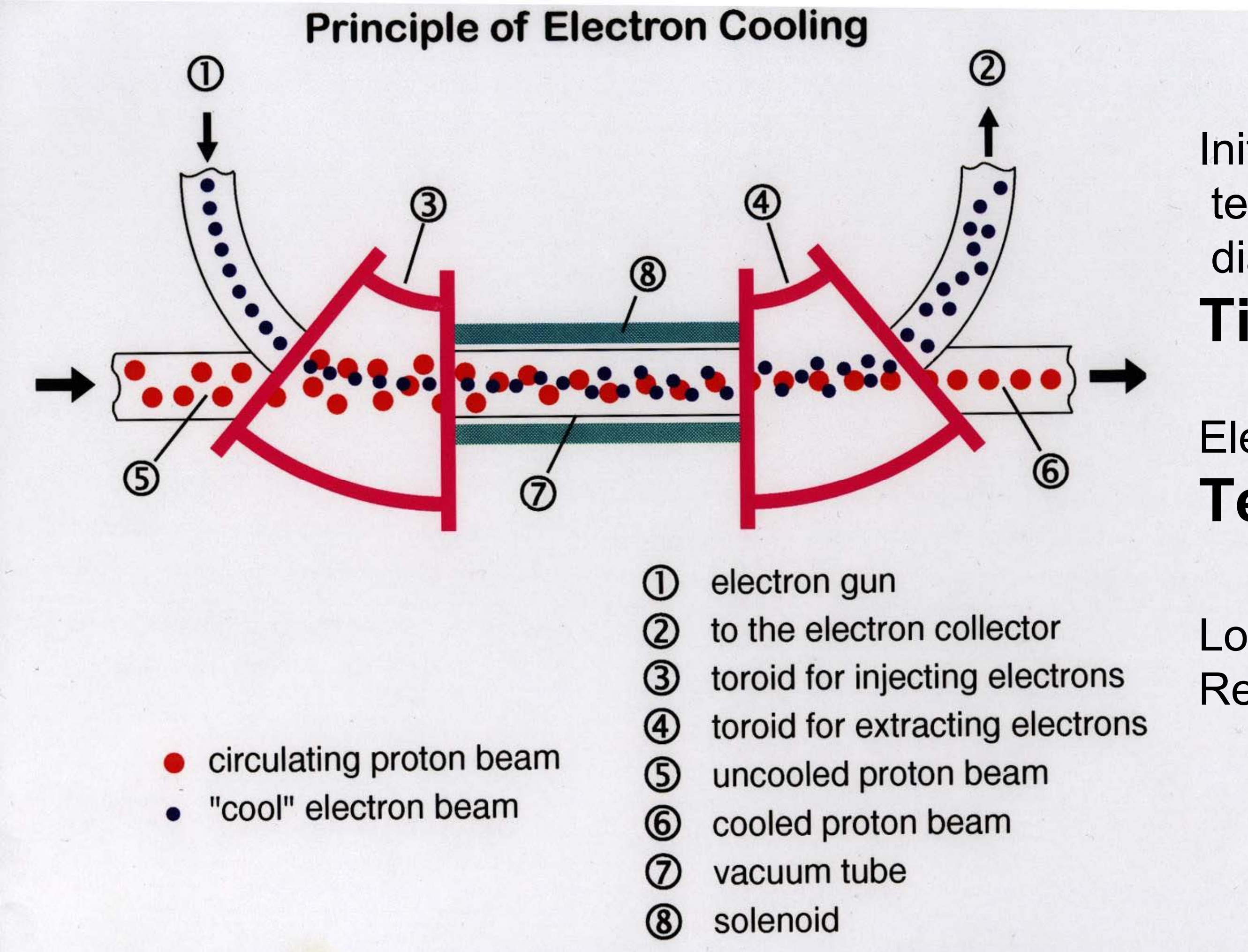
Repair with low ionization and no repair for carbon

it is possible more smoothly killed tumor at few fractions



$$jN = 40Gy/(7.4\times10^{8}eV1.6\times10^{-19}/(g/cm^{2})10^{-3})$$

$$= 4\times10^{8}ion/cm^{2}$$



Initial ion beam (430 MeV/u)
temperature for beam
diameter 1 cm near

Tion= $5*10^6$ K

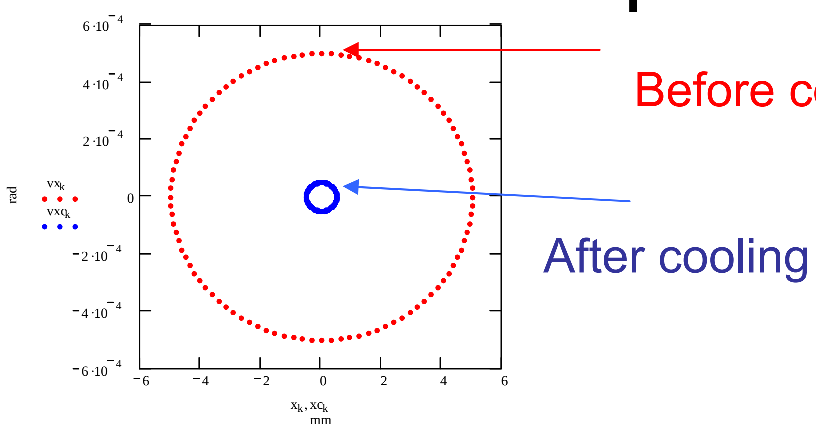
Electron beam temperature

Te=1-50 K

Low intensive ion beam
Really cooled to temperature
near 1-10 K!

What is beam parameters? for irradiation

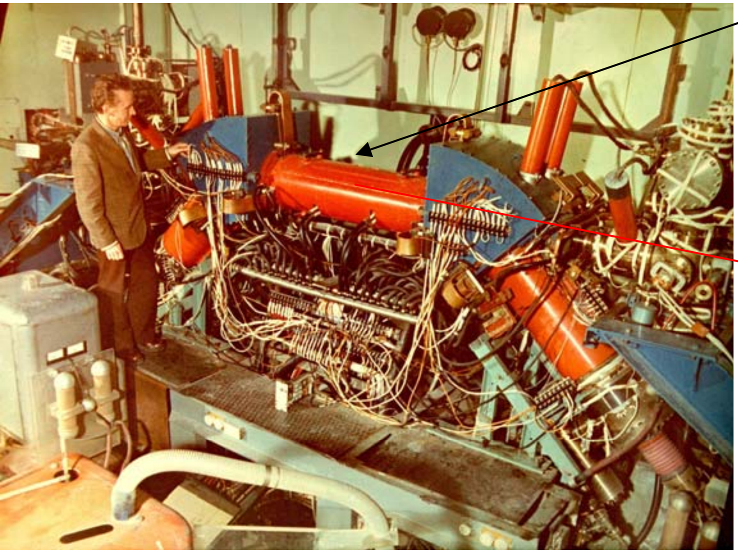
	Without cooling	with cooling
Emittance mm*mrad	1	0.01
Radius of beam mm	5	0.5
Angle spread rad	$5*10^{-4}$	$5*10^{-5}$
Momentum spread	$2*10^{-3}$	10^{-4}



Small transverse beam size:
low aperture magnets,
lower cost,
lower power consumption,
small magnets for gantry, etc.

Photo of the first irradiation of nuclear detector emulsion the p beam after recombination inside BINP electron cooler

First electron cooler INP (Novosibirsk)



H^0

490 *VI. Электронное охлаждение*

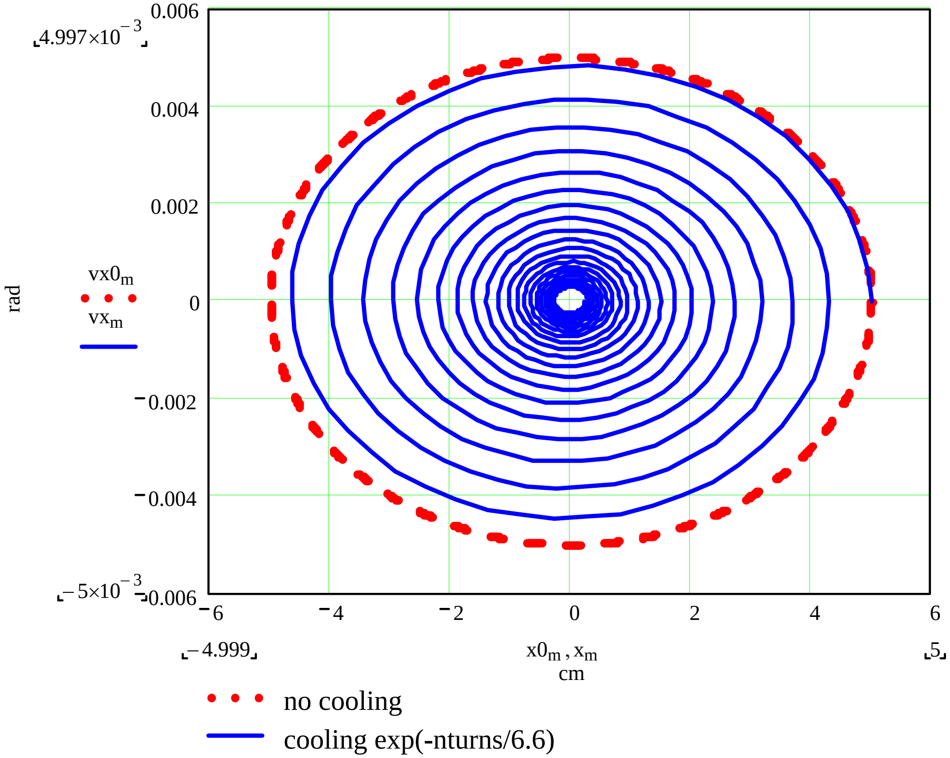
Рис. 4. Фотография ядерной фотоэмульсии, экспонированной пучком быстрых атомов водорода ($v/c = 0{,}35$), возникающих при рекомбинации протонного и электронного пучков на участке охлаждения

Фотоэмульсия расположена на расстоянии 10 м от участка взаимодействия. Метки нанесены через 1 мм. Размер изображения соответствует диаметру протонного пучка 0,5 мм и угловой расходимости $3 \cdot 10^{-5}$ рад

Distance from cooler to detector 10 m, energy of proton beam 65 MeV, radius of the proton beam after pass 10 m 0.5 mm!

$\Delta\theta < 5*10^{-5}$

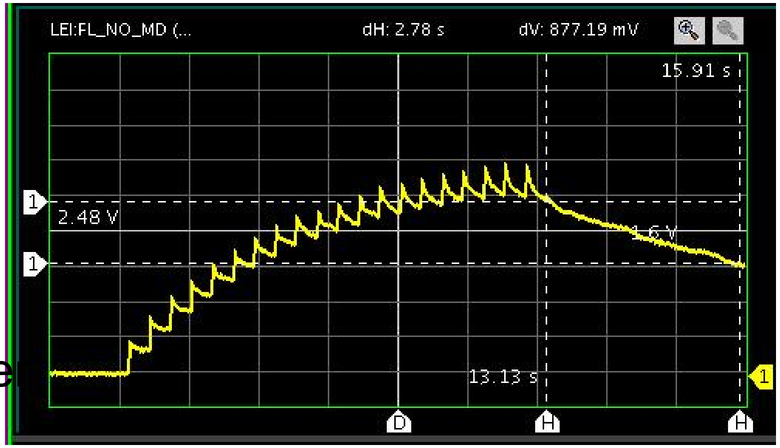
Cooling for accumulation after injection

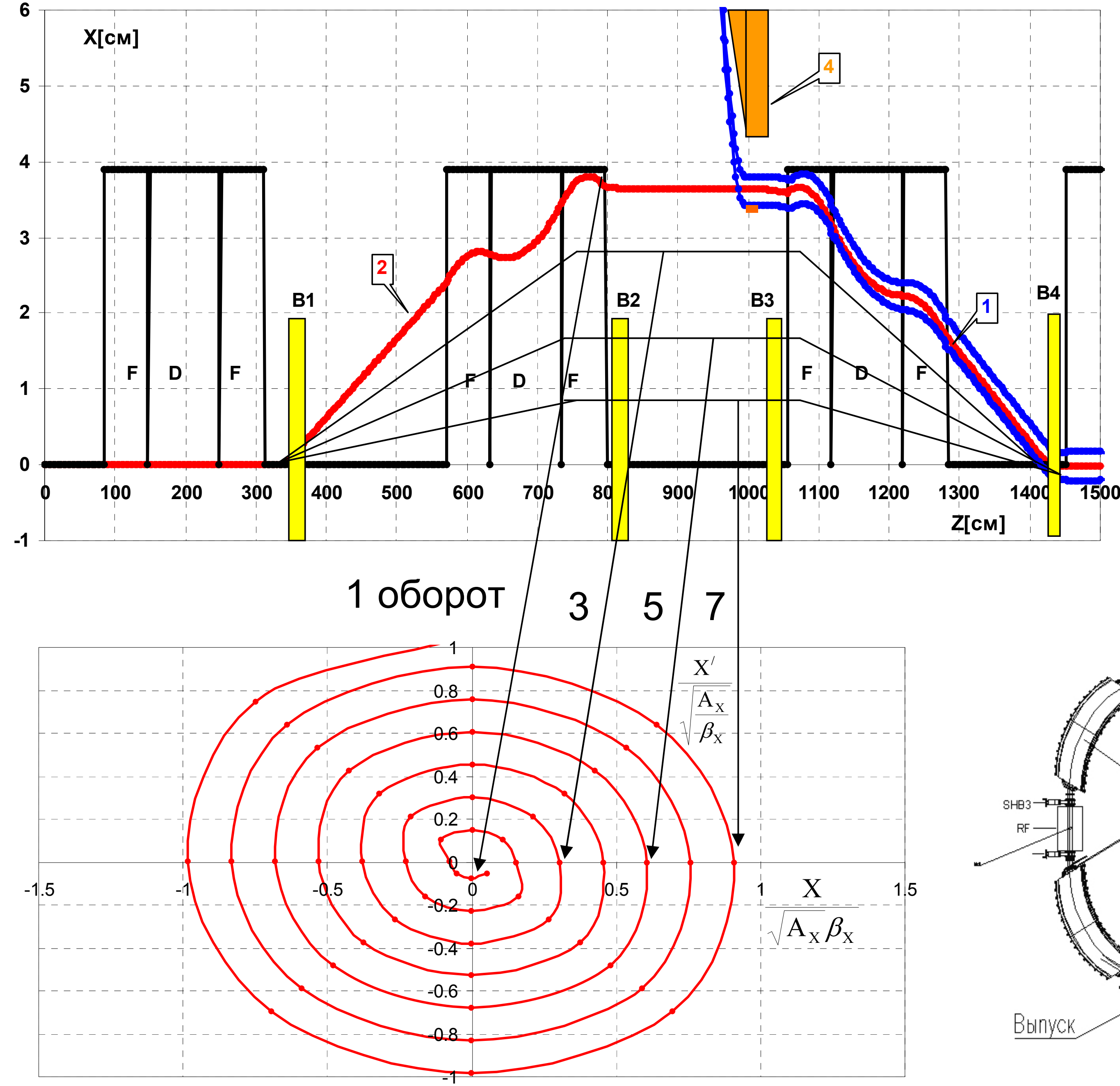


Cooling shrinks ion beam at intensive core with small radius and open phase space for new injection additional injection.

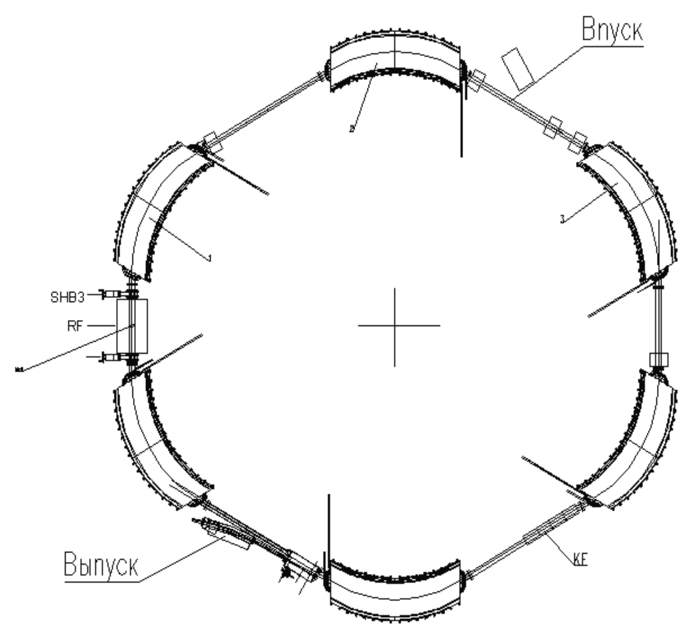
Without cooling it is possible injected only once but with cooling it is possible repeated injections many times step by step increasing intensity after each shoot.

Example accumulation Pb^{+54} ions at LEIR for LHC with using new electron cooler produced at BINP



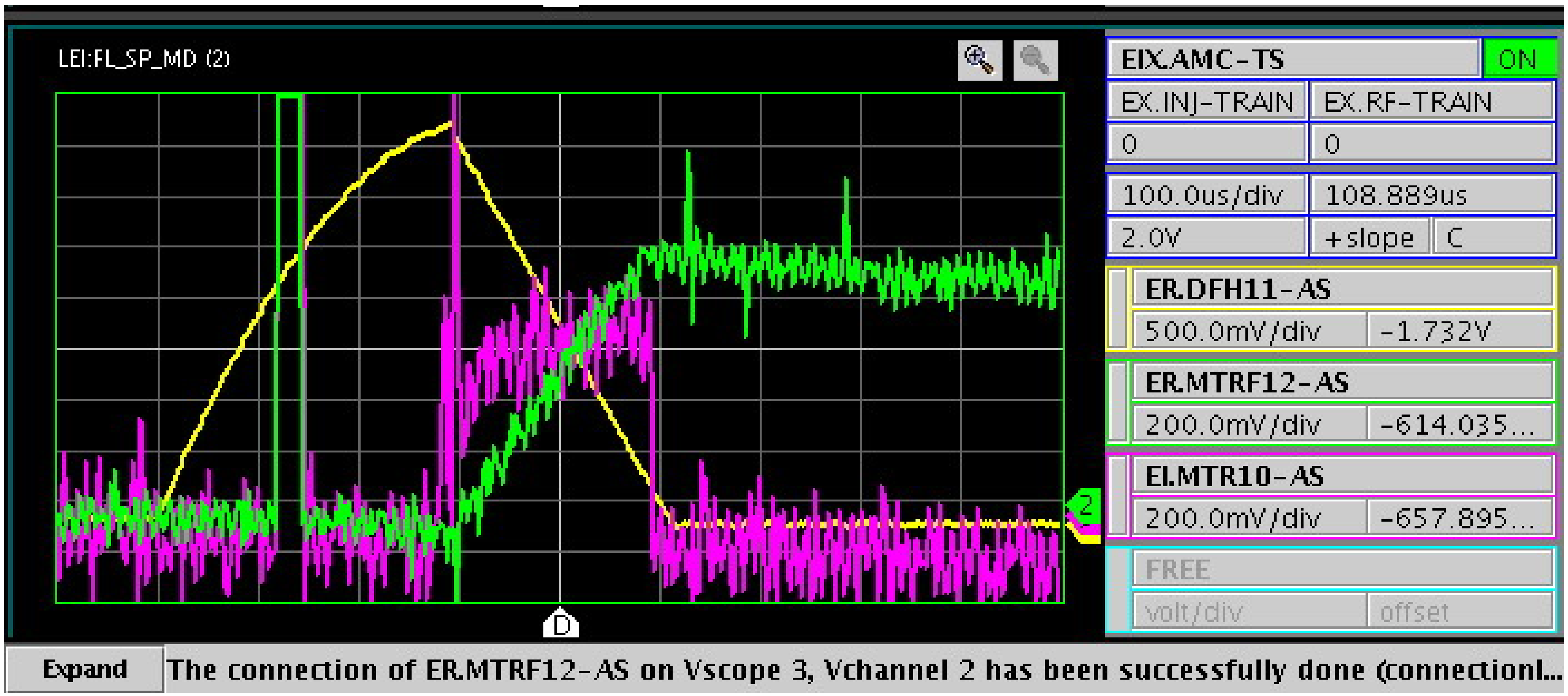


Injection multi turns with filling all available booster aperture.
At start moment bump orbit close to septum and then decay of bump amplitude.

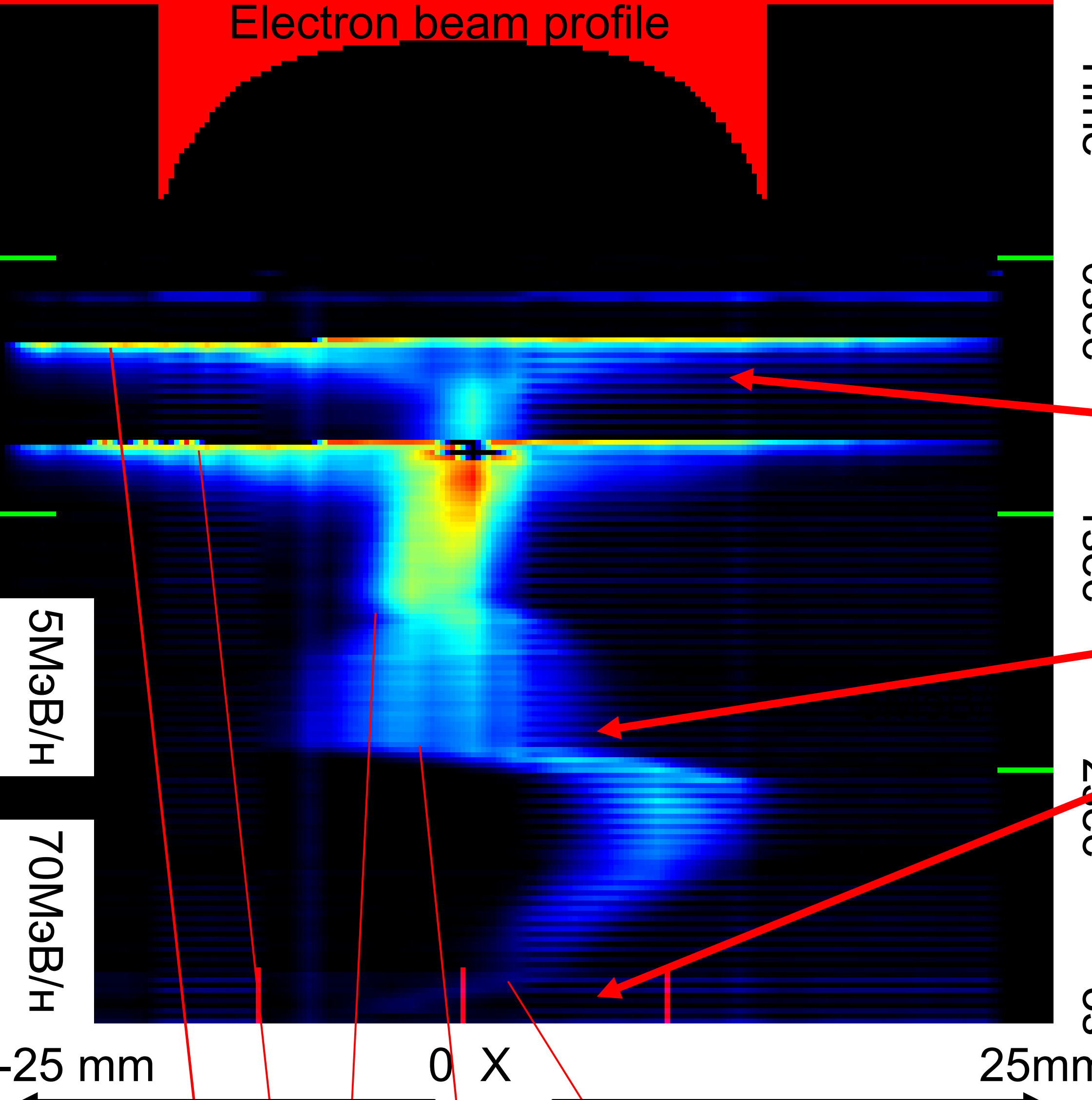


Multi turns injection at LEIR equipped the electron cooler new generation cooler with electrostatic bending and variable electron beam profile

(Pb ions for LHC)



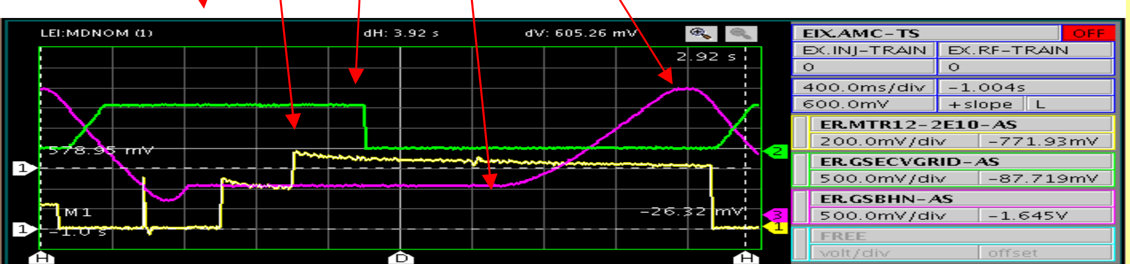
Yellow- bump magnet current, magneto- ion injector, green- ion beam accumulation at LEIR ring 200 $*10^{-6}$ s linear slope increasing storage ion current.

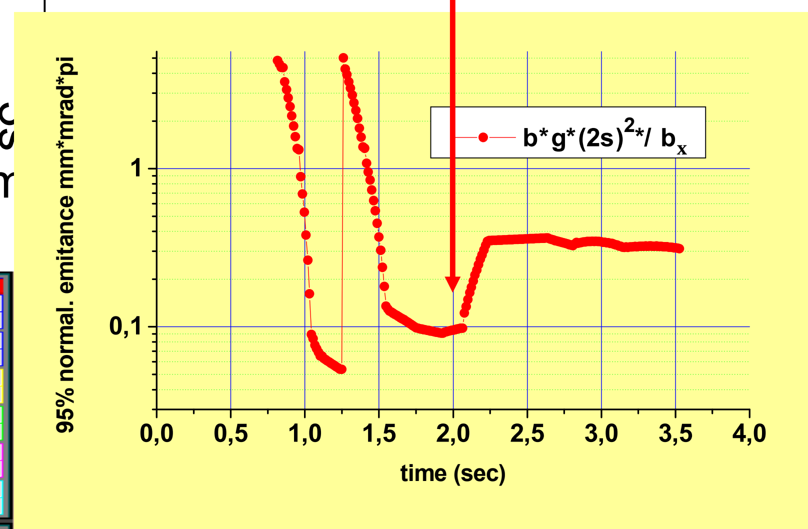


Example of accumulation
two shots injection
and cooling Pb ions beam
LEIR (CERN)
with using BINP cooler

Profile of ion with
injection and
accumulation Pb ions
acceleration
from 5 to 70 MeV/u

switch off cooler





What is optimum for injection energy at main ring (why booster used)?

$$N_{\max} = \frac{2\pi A_i^2 / \beta_\perp \Delta Q}{r_i} \beta^2 \gamma^3$$

Intensity Nmax proportional of the ion energy and Acceptance of the storage ring A_x^2 / β_x

for Ai=0.5 cm beam diameter after injection 1 cm

$\Delta Q = 0.1$, bx=12 m, ri=4.6*10^{-16} cm

For 30 MeV/u we have design number N=2*10^{10} ions with reserve:

reserve:	at aperture Ai=0.5→1 cm	*4
	at tune shift ΔQ=0.1 → 0.25	*2.5
	reserve factors~ 10	

Energy	MeV/u	3	10	30
Number ions		1.8*10^{9}	6*10^{9}	**2*10^{10}**
Cooling time	sec	0.002	0.004	0.015
Cooling current	A	0.02	0.08	0.2

UNILAC—a 120-meter long linear accelerator—
accelerates the ions to 20 percent of the speed of light.
11 MeV/u

In the heavy-ion synchrotron SIS, the ion beam is further accelerated
up to 90 percent of the speed of light in the course of several hundred thousand revolutions.
Energy 2000 MeV/u Diameter of ring ~80 m

b) Linac, Medium Energy Beam Transport

A combination of RFQ and IH-linac structure with a total

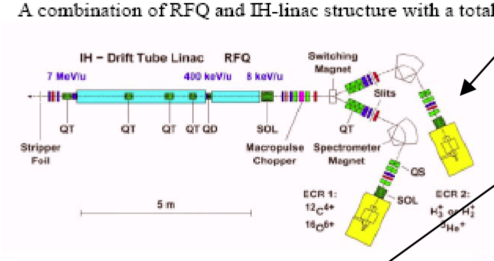


Figure 4: Layout of the injector-linac.

Comparison at the same scale linac 7MeV/u
and booster synchrotron with energy 30 MeV/u

Linac for German project HITAC
With energy 7 MeV/u C,H
Linac phase velocity const for different ion
Means energy per nuclear are constant

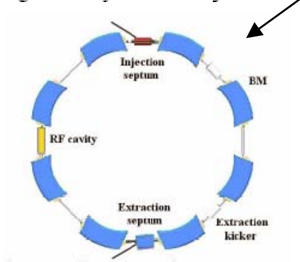
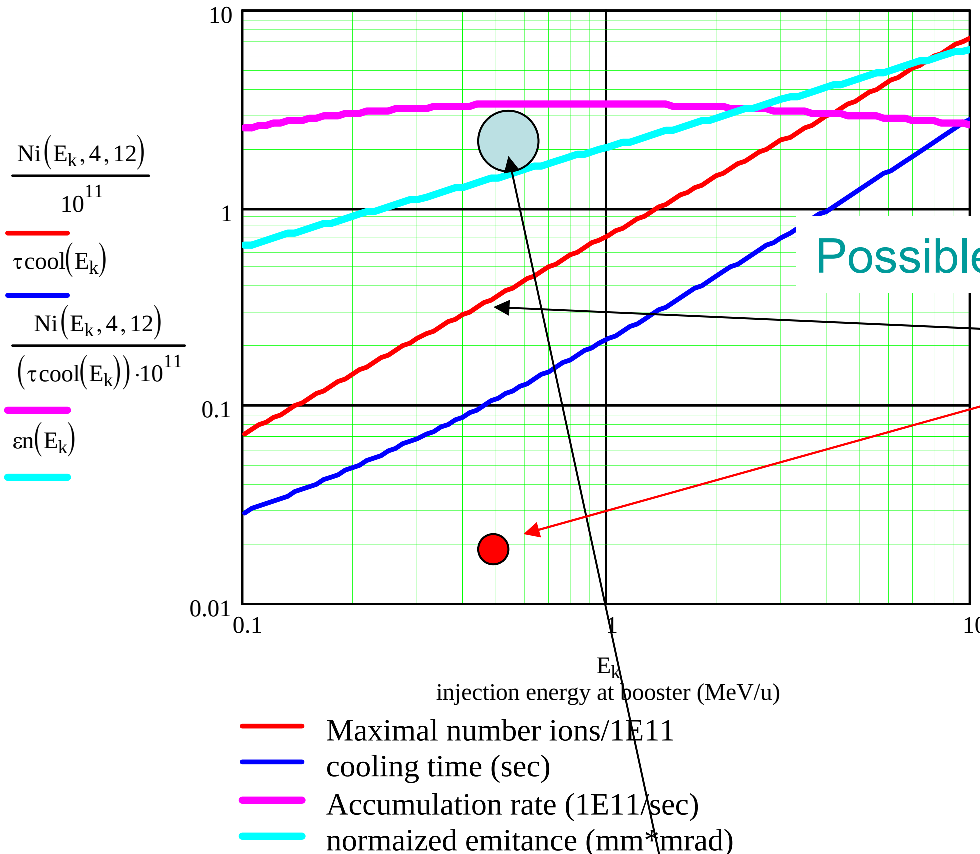


Figure 1: Layout of booster.

30 MeV/u C and 245 MeV p- booster diameter 8.5 m
Compact and universal for different
Ions from p to C practically at the simultaneously
(with few seconds changing parameters of cycle)

What is optimum energy for injection at booster? Accumulation at main ring on 30 MeV/u



Designed number of ion at single cycle of booster

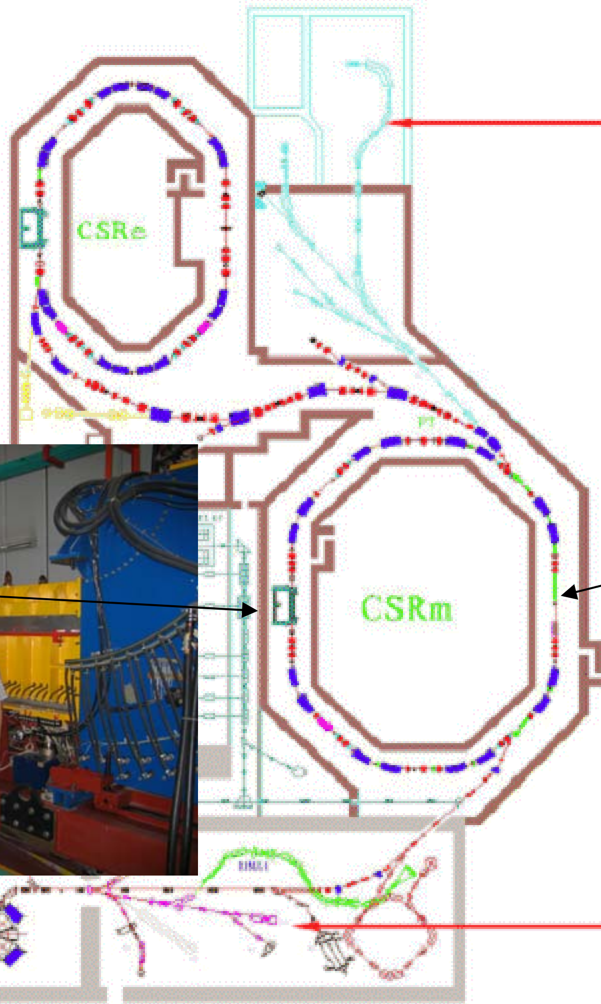
N=$2*10^9$

As the booster is needed for our project and provides the high energy injection at main ring, the tandem accelerator with low energy looks as the optimal solution for injection in the booster.

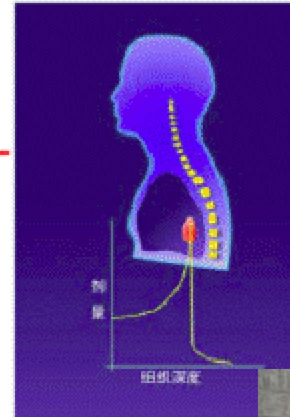
For tandem system of injection with energy 0.417 MeV/u results to maximal number of ions at beam $3*10^{10}$ and we have ions beam normalized emitance 1.3π mm*mrad that cooled at main ring at time less 0.1 sec. Increasing injection energy to 6 MeV/u give profit at maximal number storage ions up to $3*10^{11}$ (single shoot) but cooling times at main ring increased up to 2 sec by increasing emitance of ions beam.

Heavy-ion therapy project @ IMP (2/6)

Institute Modern Physics (Lanzhow)

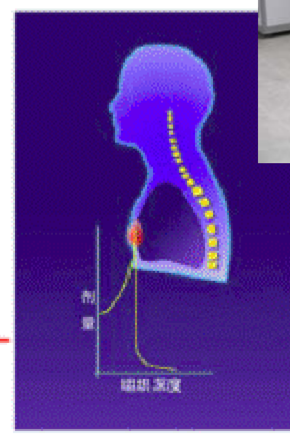


CSRm cooler



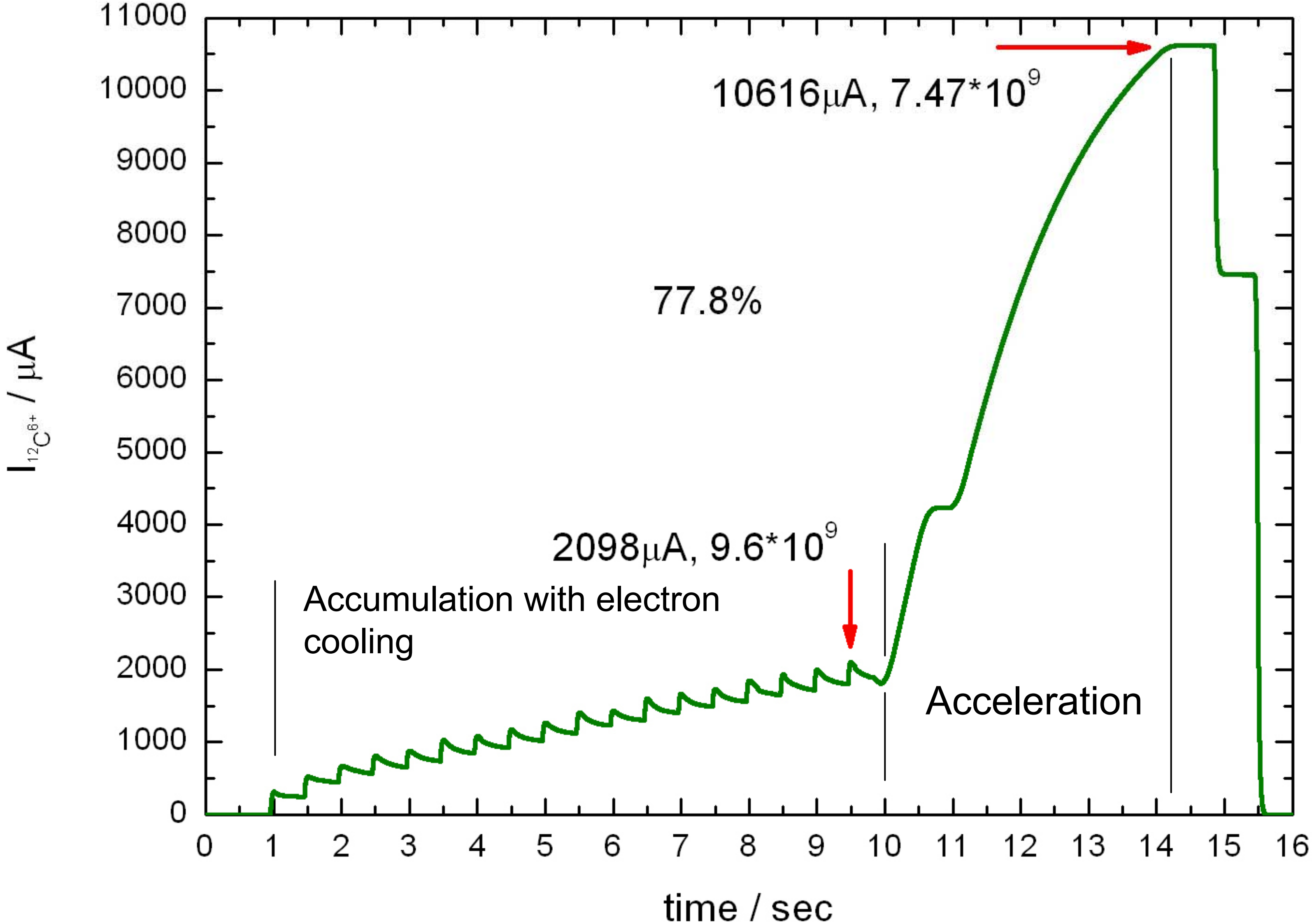
deep-seated tumor therapy

RF cavity



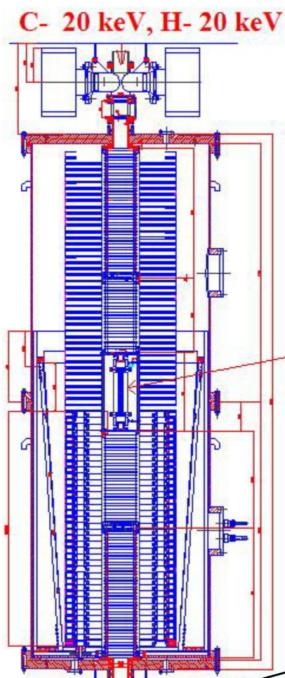
superficially-placed tumor therapy

Photo show elements of CSRm produced BINP: the electron cooler and RF acceleration station

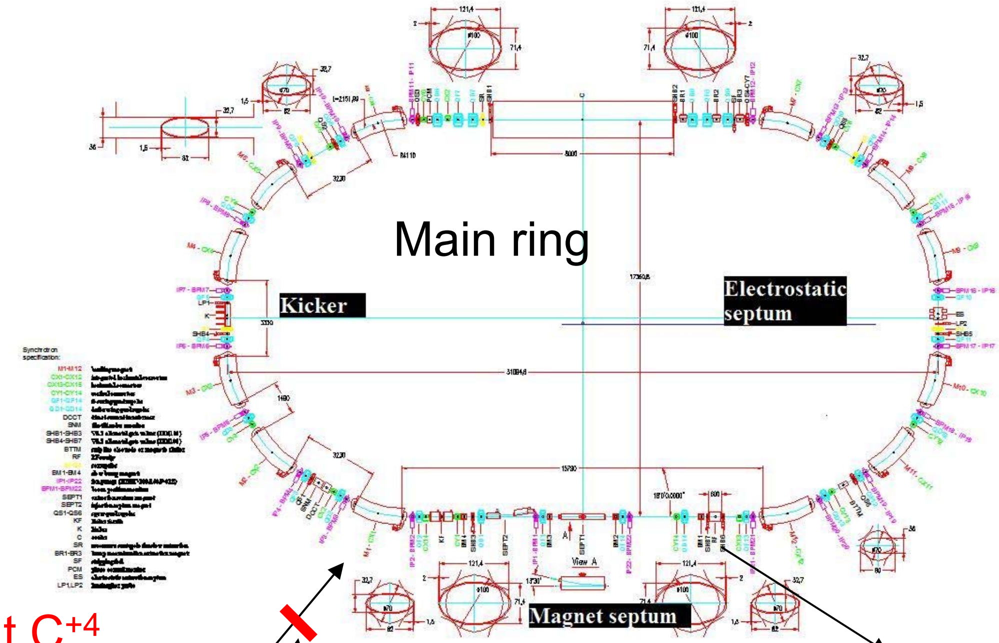


Cycle of accumulation and acceleration Carbon beam
from 7 MeV/u to 1000 MeV/u at CSRm as measured for Carbon beam.

Elements of BINP project of HITS acceleration system



tandem



Main ring

Stripping C^{+3} at C^{+4}

4.82 MeV C^{+4}

2.42 MeV p^{+1} 1ms*10 mkA

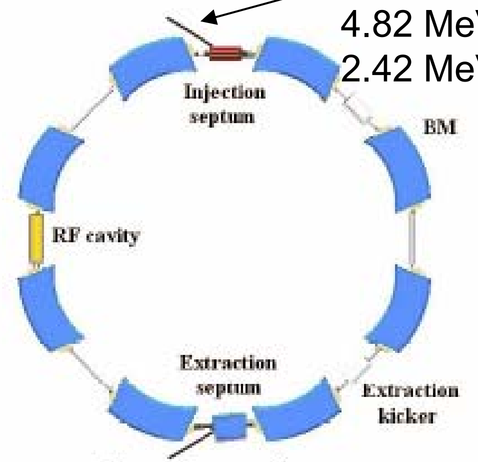


Figure 1: Layout of booster.

Booster

Stripping C^{+4} at C^{+6}

C ions therapy
E=140-430 MeV/u
Ni=2*10^{10}*0.1 Hz
P ionization =1.6 Wt=
16 Gy/s/(100g/tumor)
For scanning irradiation

Proton therapy
E=250 MeV
Np=2*10^{10} *10Hz
P ionization 8 Wt=
80 Gy/s/(100g/tumor)
For passive irradiation

30 MeV/u C^{+4} Ni=2*10^{9}
250 MeV p Np=2*10^{10}
Repetition rate 10 Hz

Table 1: Main parameters of the synchrotron

Ion	$^{12}C^{+6}$
Injection energy, MeV/u	30
Extraction energy, MeV/u	140 – 430
Circumference, m	82.9
Betatron tunes, h/v	2.76 / 2.82
Max $\beta_{x,max}$ / $\beta_{y,max}$, m	35 / 18
Max dispersion function η_{max}, m	4.3
Natural chromaticity x / y	-5 / -4
Cooled emittance, nm·rad	20 – 150
Cooled energy spread, dT_k/T_k	$1\cdot10^{-4}$

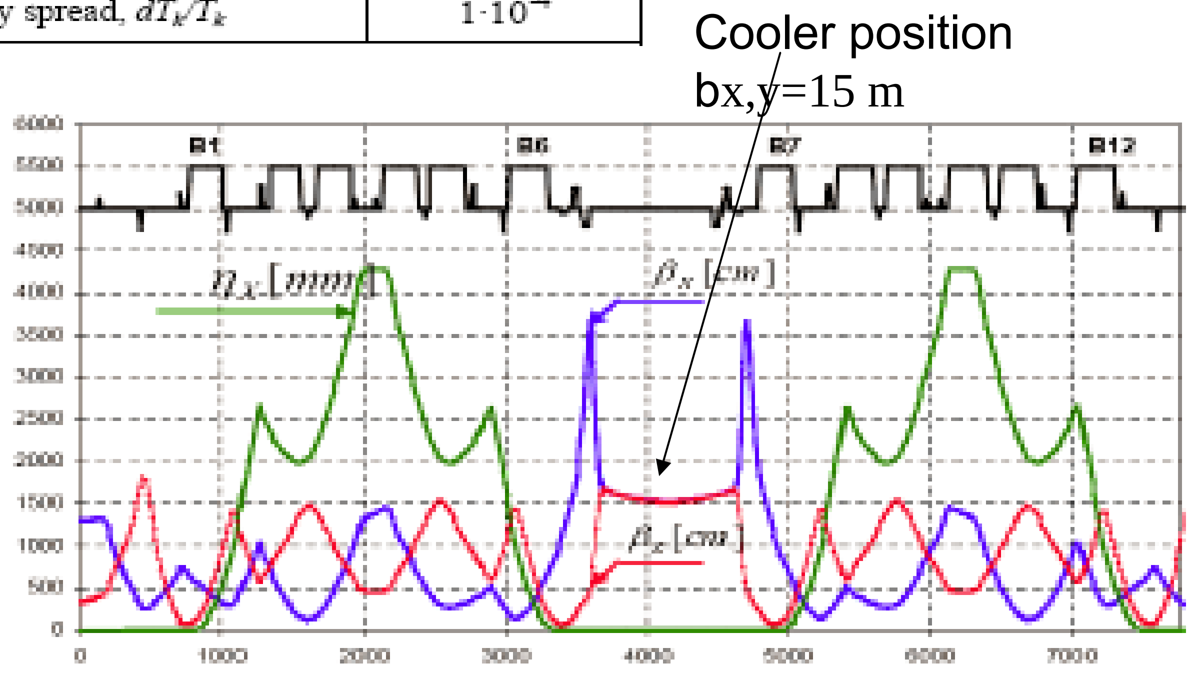
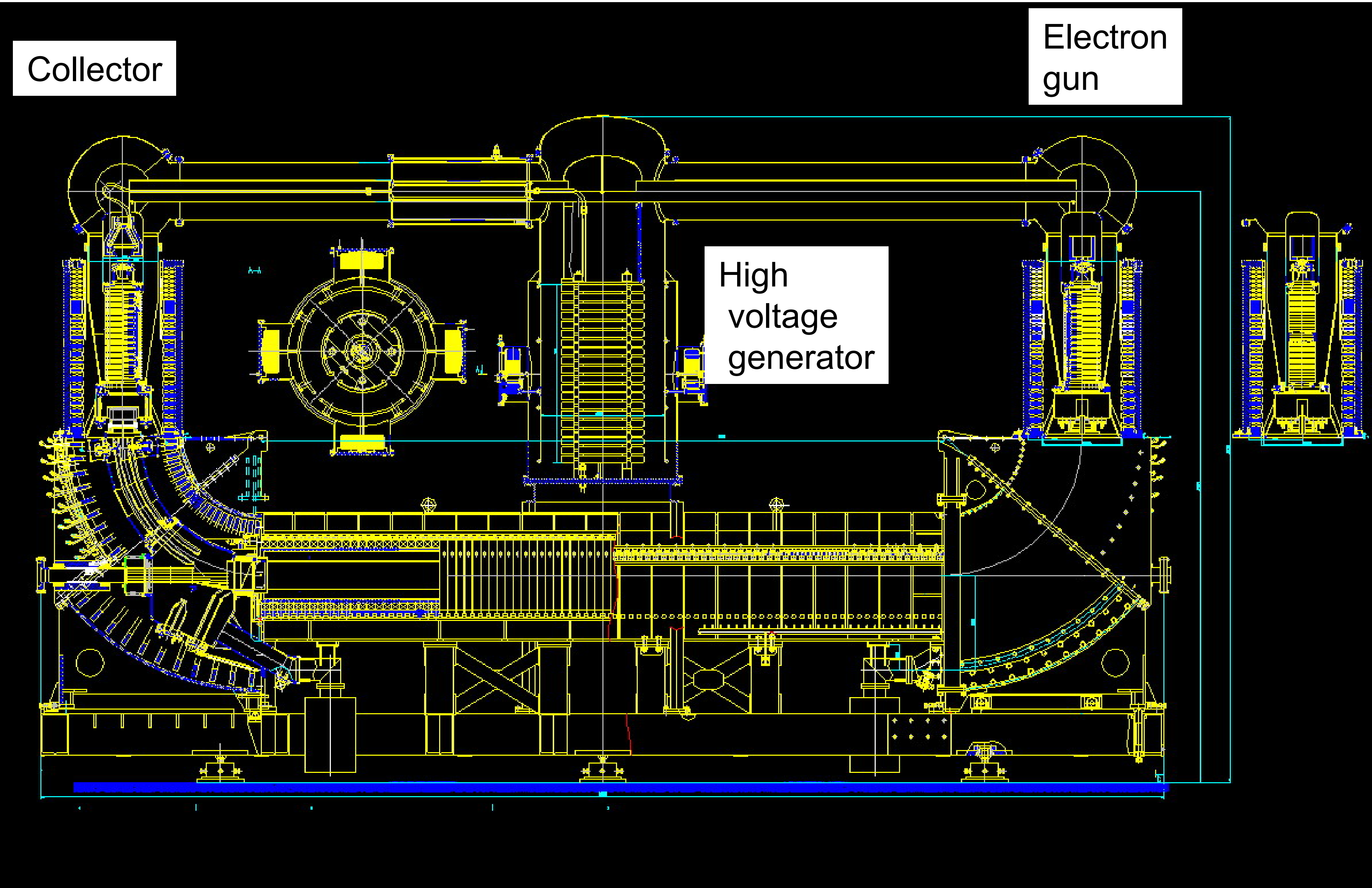
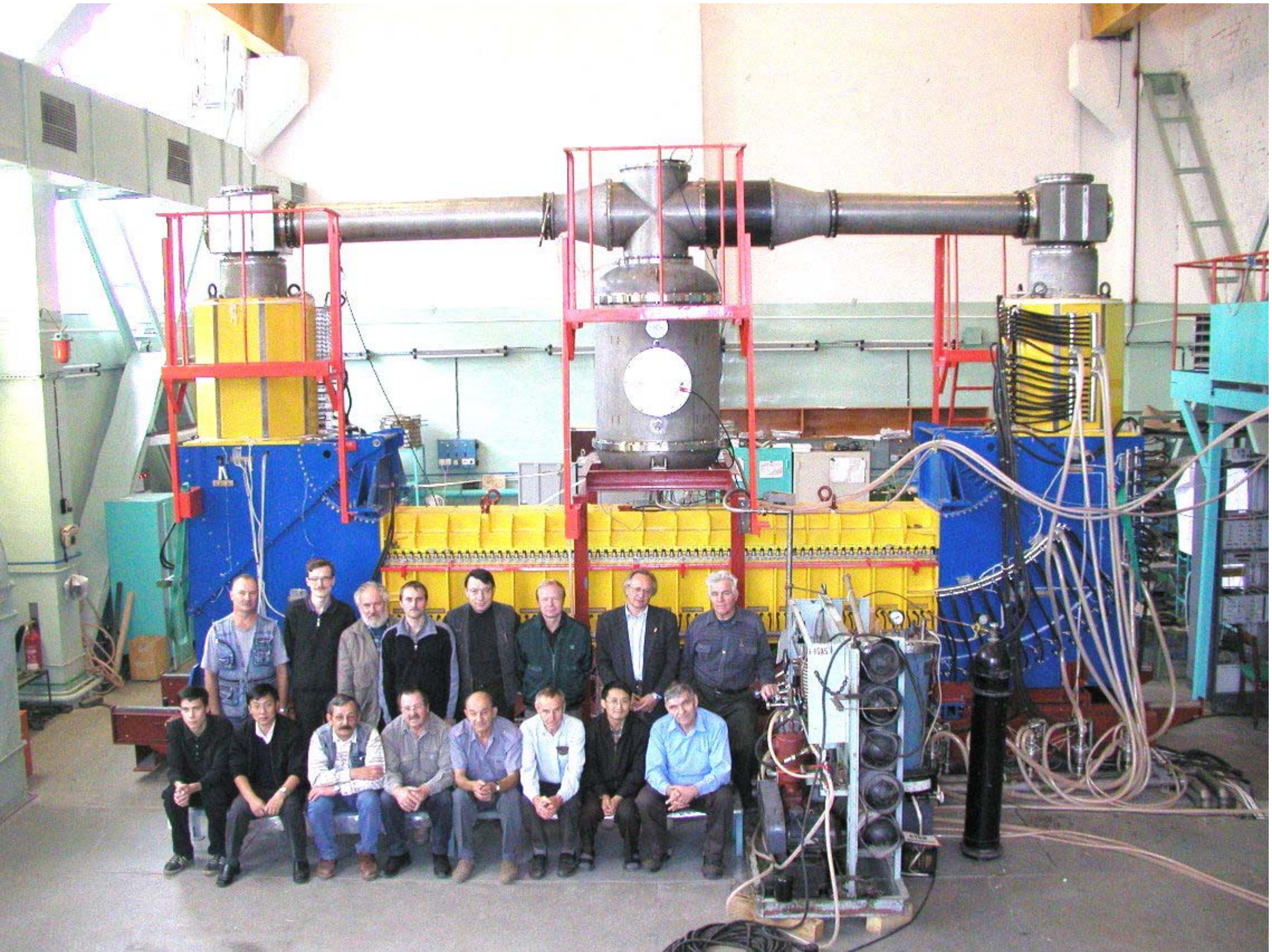


Figure 1: Synchrotron optical functions

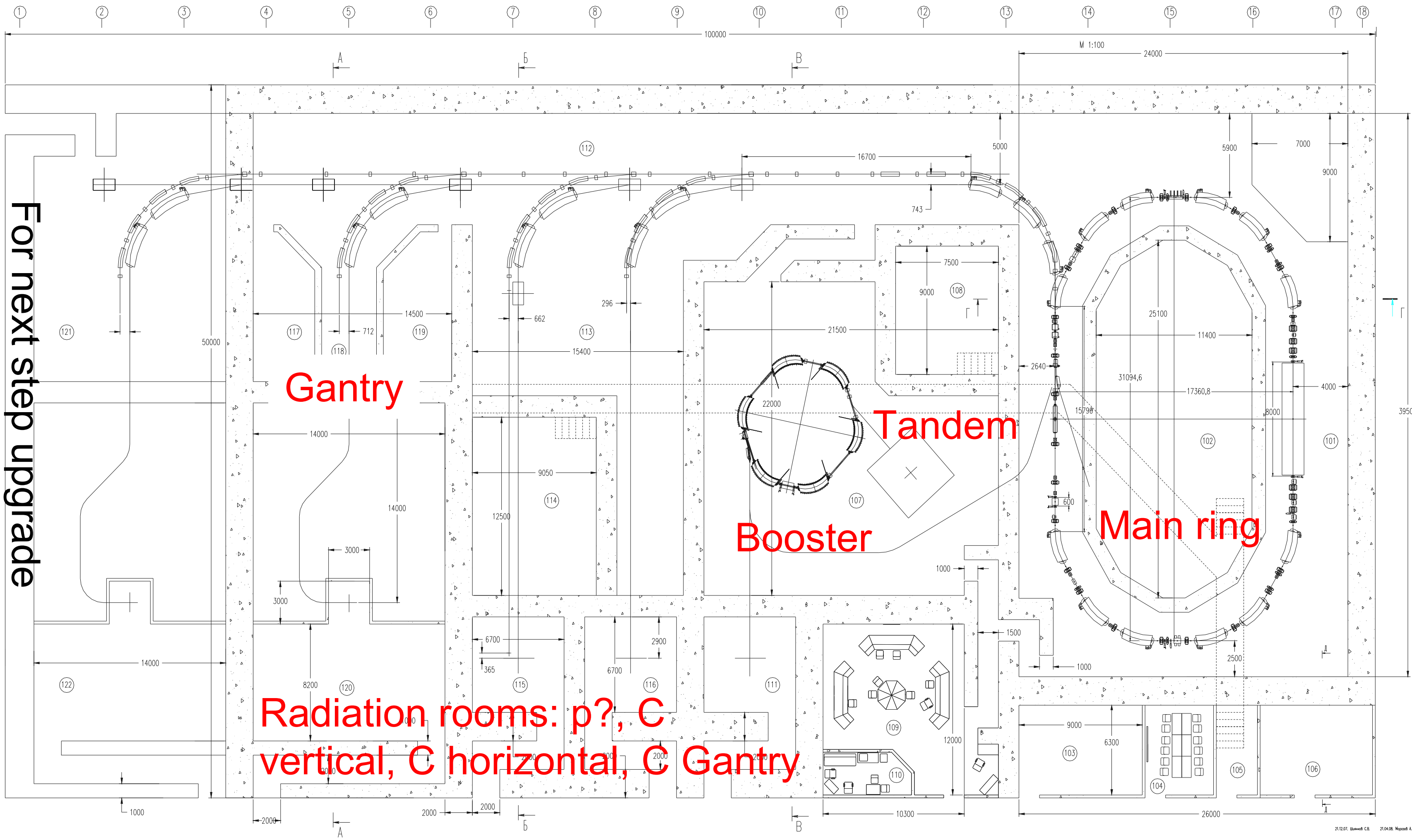
The electron cooler design with the high voltage generator up to 500 kV



Cooler EC300 at BINP just before sending in China

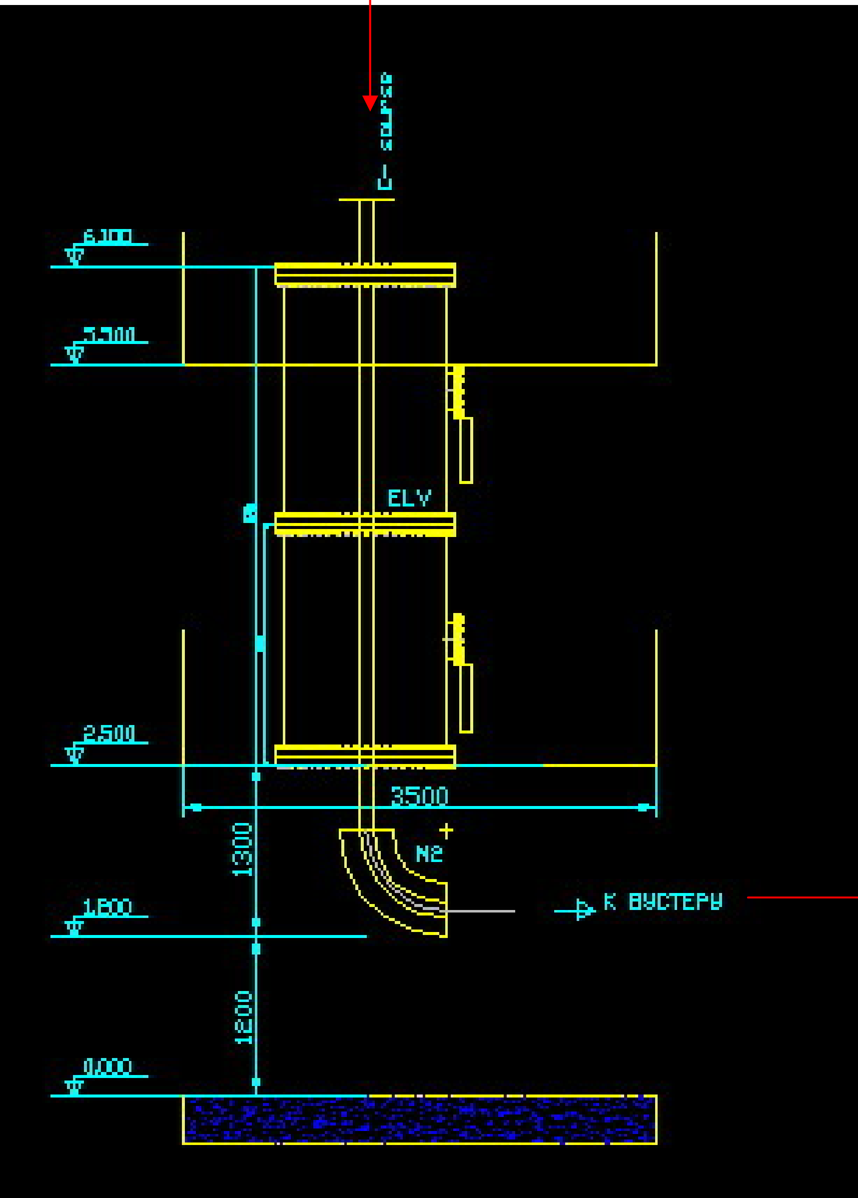


Accelerators complex for the cancer therapy



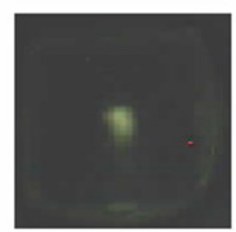
Tandem

Tandem on base
ELV 1.2 MeV
C^{-1} 20 keV 150 μA



C^{+3}
5.02 MeV
50 μA to booster

Acceleration Mass Spectrometer
Used similar C ion source and
Stripping target



15 mm

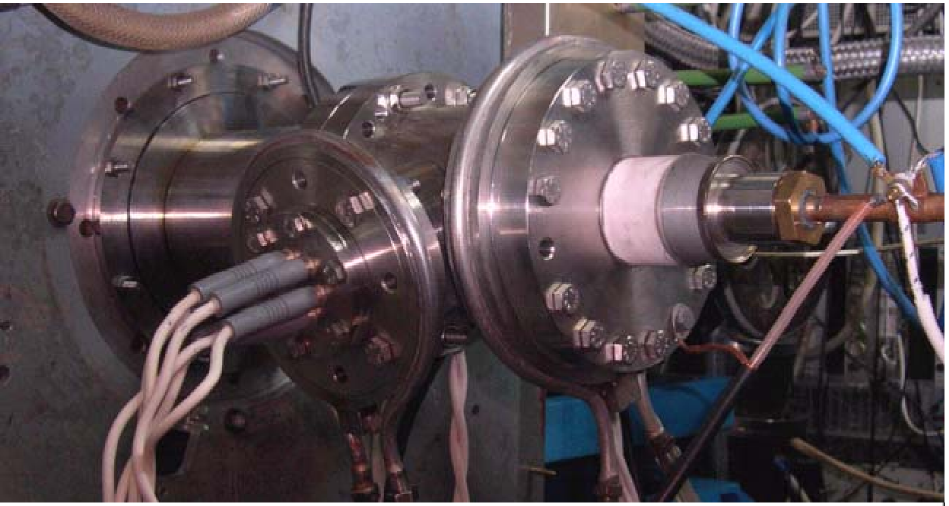
Carbon beam C^{+3} from AMS on energy 1 MeV

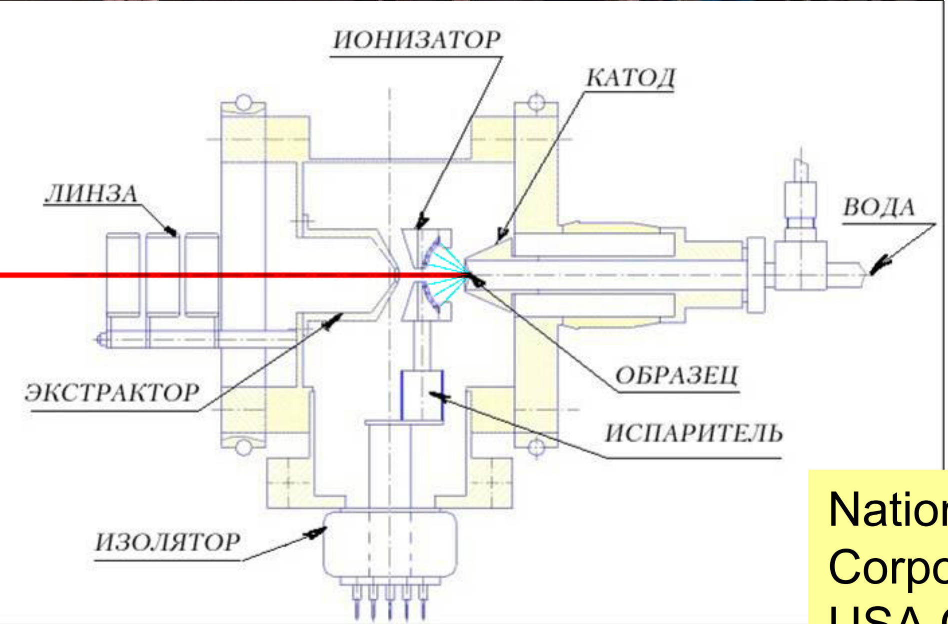
BINP negative ion source C^{-1}

σ=5 мм radius of ion beam
θ=2 mrad angle spread
U0=20 keV energy
Emitance:

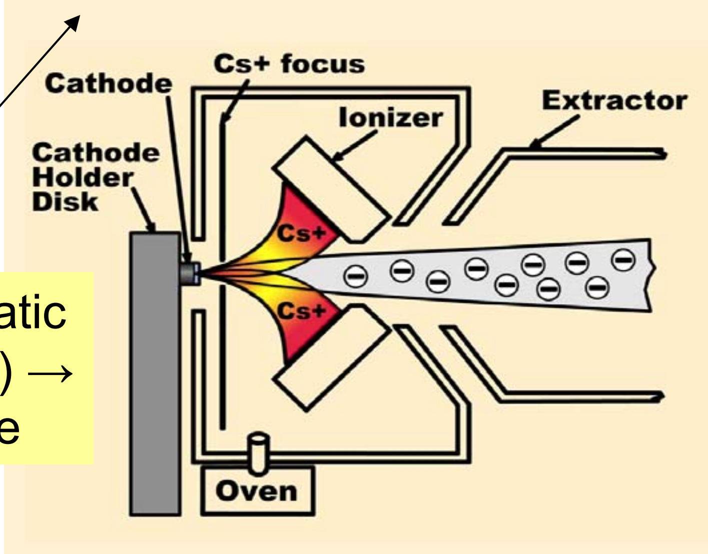
$$\varepsilon = \sigma * \theta * \beta * \gamma * \pi = 5mm * 1mrad * 2 * 10^{-3} * \pi$$

$$0.01 * (mm * mrad)\pi$$





BINP C^{-1} ion source ↑

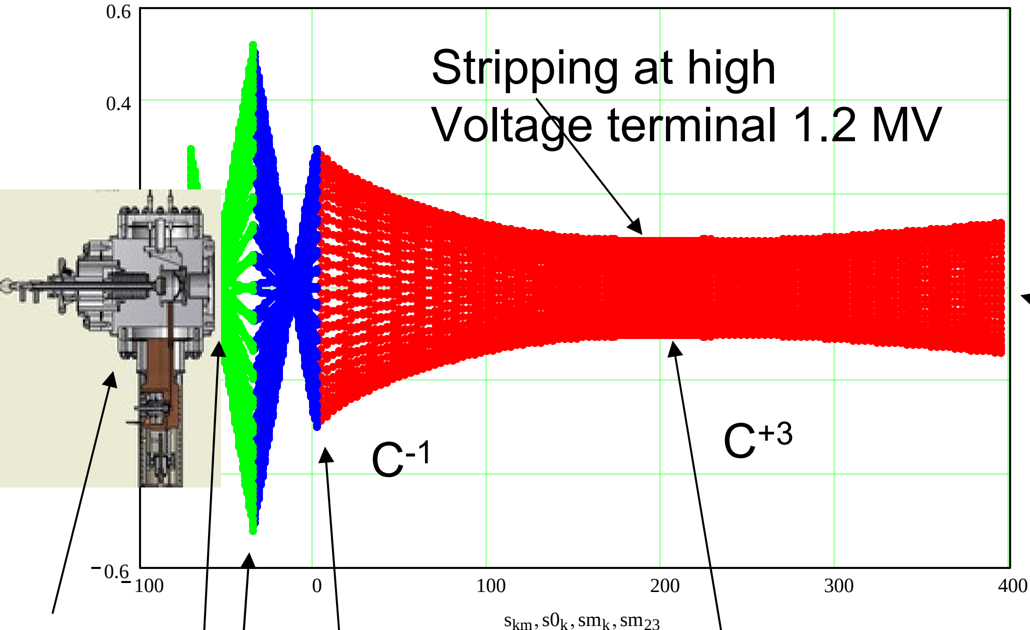


National Electrostatic Corporation (NEC) → USA C^{-1} ion source

Sample from ion source after
DC operation 5 days*8hours
Cs current 100-300 мкА
Sputtered hole 0.7 mm after week operation
Produced 10^{19} negative ions 10mkA*time
For acceleration $2*10^{10}$ ions per cycle with efficiency 0.0001 it can irradiated about $5*10^{4}$ portions per 8 Gy/(100g/tumor) (more then 1 year operation)

So long life time looks too optimistic and we will test pulse mode at nearest future

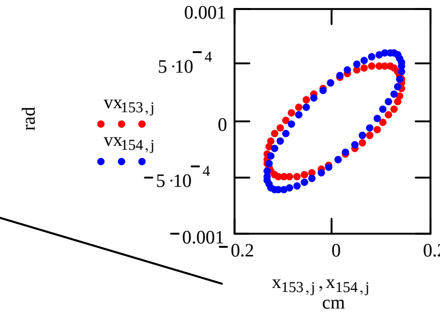
Ion beam at tandem



Ion source

Enter at acceleration tube

Input beam



Outcome ion beam

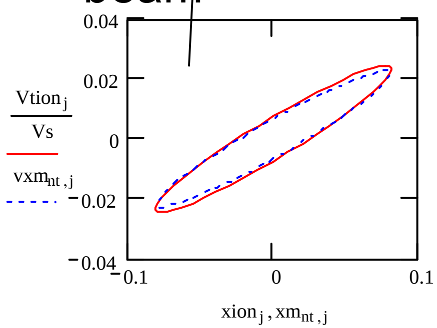
C^{-1} ions with energy 4.82 MэB

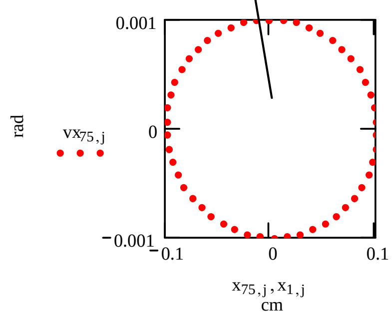
0.4 MэB/н

$$\varepsilon = \sigma_x \times \theta_x \times \beta \times \gamma \times \pi =$$

$$1.5\text{mm} \times 4\text{mrad} \times 0.029 \times 1 \times \pi =$$

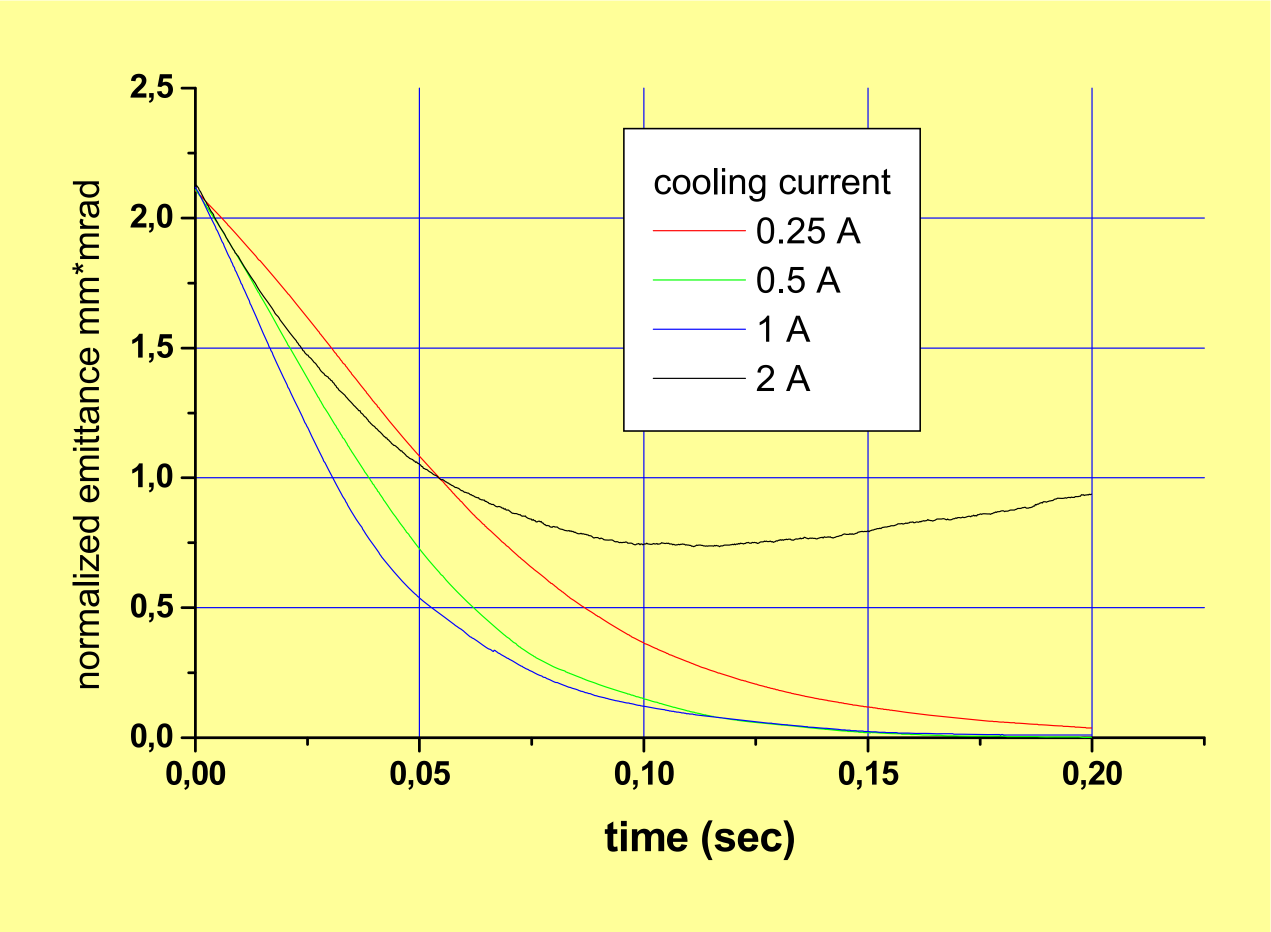
$$0.016 \times \pi mm * mrad$$





Start: low charge ion,
stripping at high energy
when space charge not
so large problem for optic

Cooling at main ring injection energy 30 MeV/u, N=2*10^9
Initial emittance 2 p мм*мрад.



0.5 A electron beam current looks optimal for cooling

Extraction ions for treatment

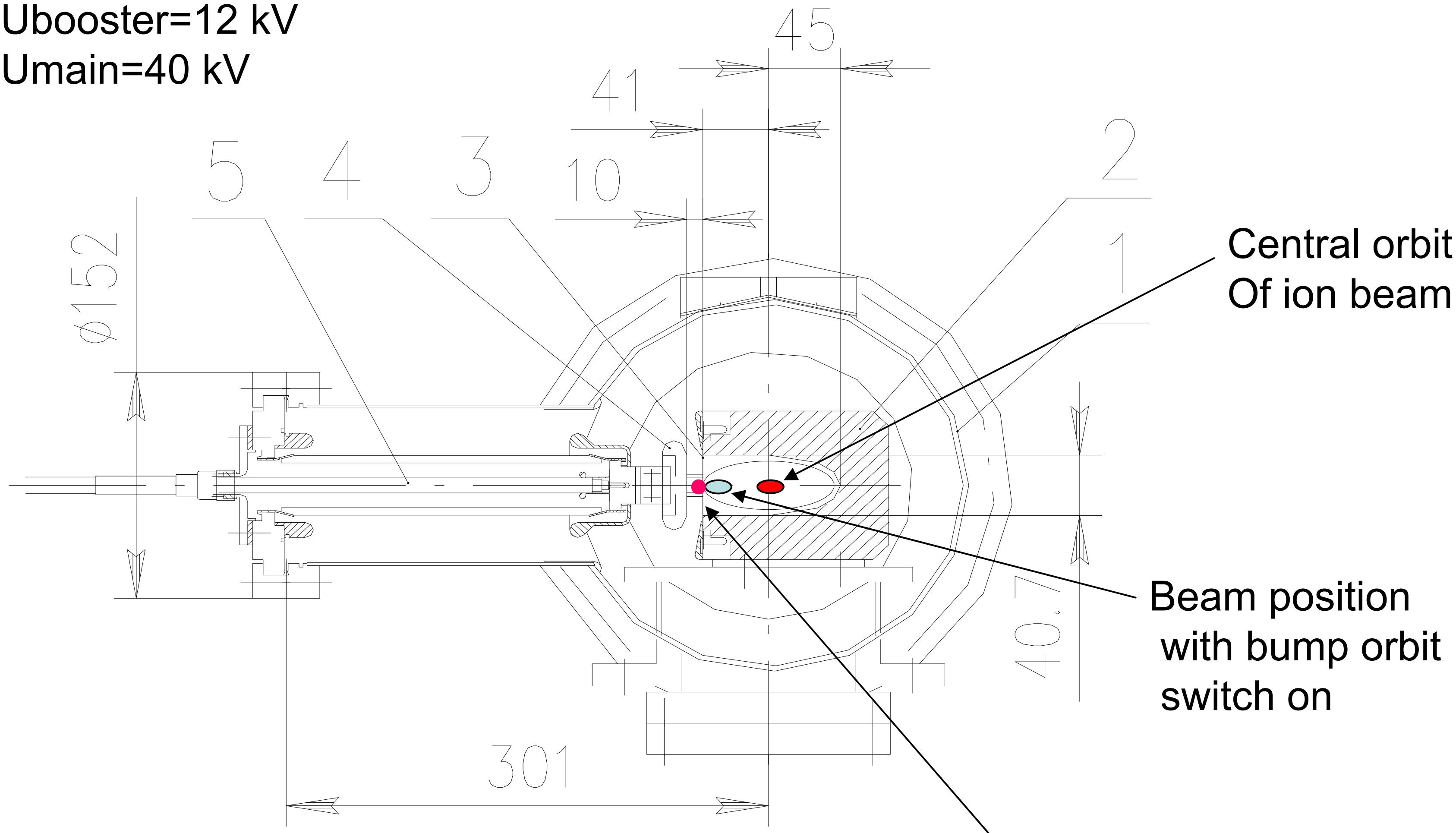
1. Electron ion recombination by electron cooler life time near 400 sec $dN/dt=2*10^{10}/400=0.5*10^{8}$ ions/sec DC beam at time with scanning energy and position. Modulation at time with electron beam current variation and fast dipole magnet gate at transport line. Modulation of energy by simultaneously variation magnet field main ring and energy of electron beam. Time scale fraction of secund.

   synhron

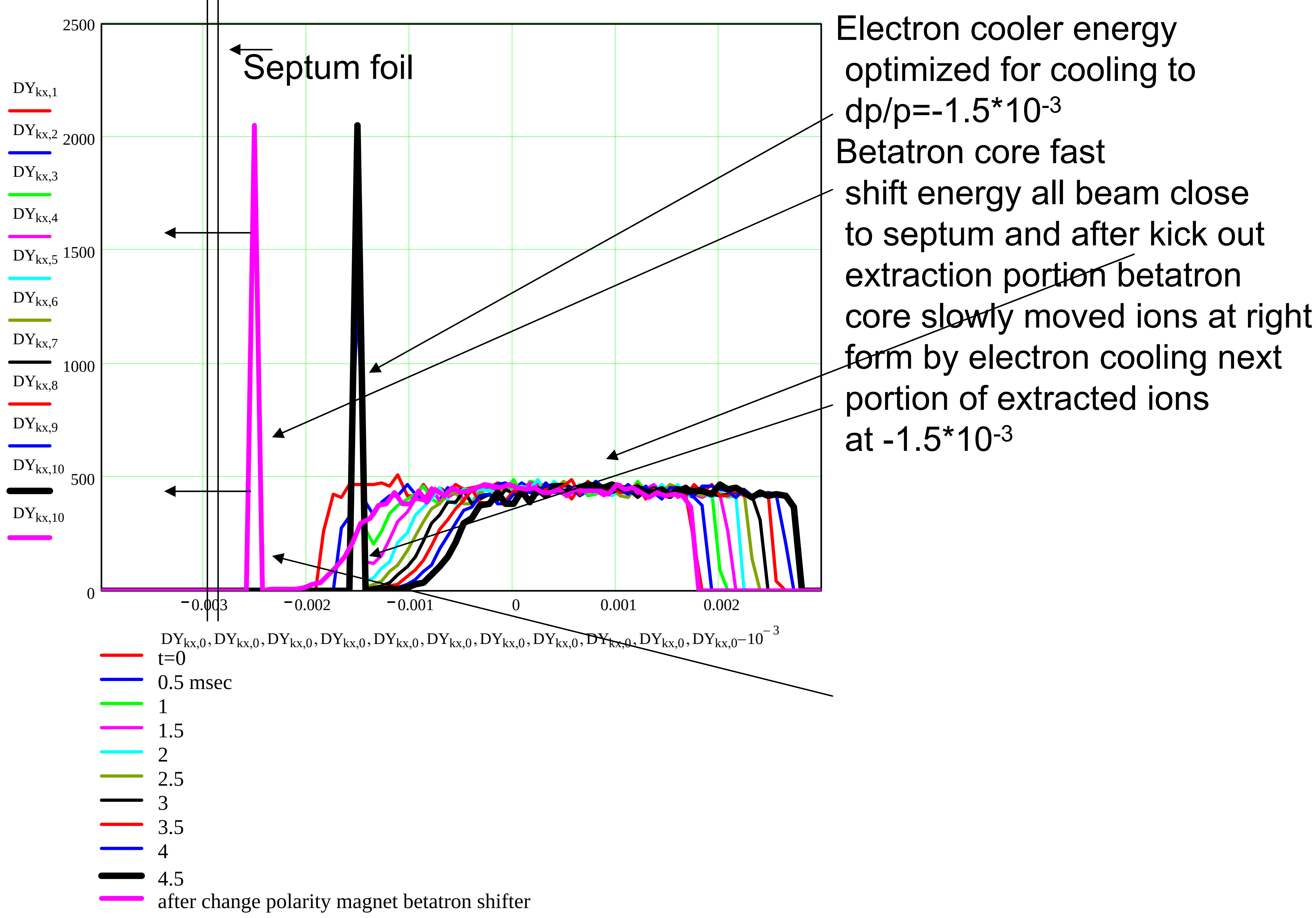
2. Pellet extraction with form small fraction of ion beam 10^{4}-10^{7} ions with time length 0.4 mksec and repetition rate 10-200 Hz

Electrostatic septum
Ubooster=12 kV
Umain=40 kV

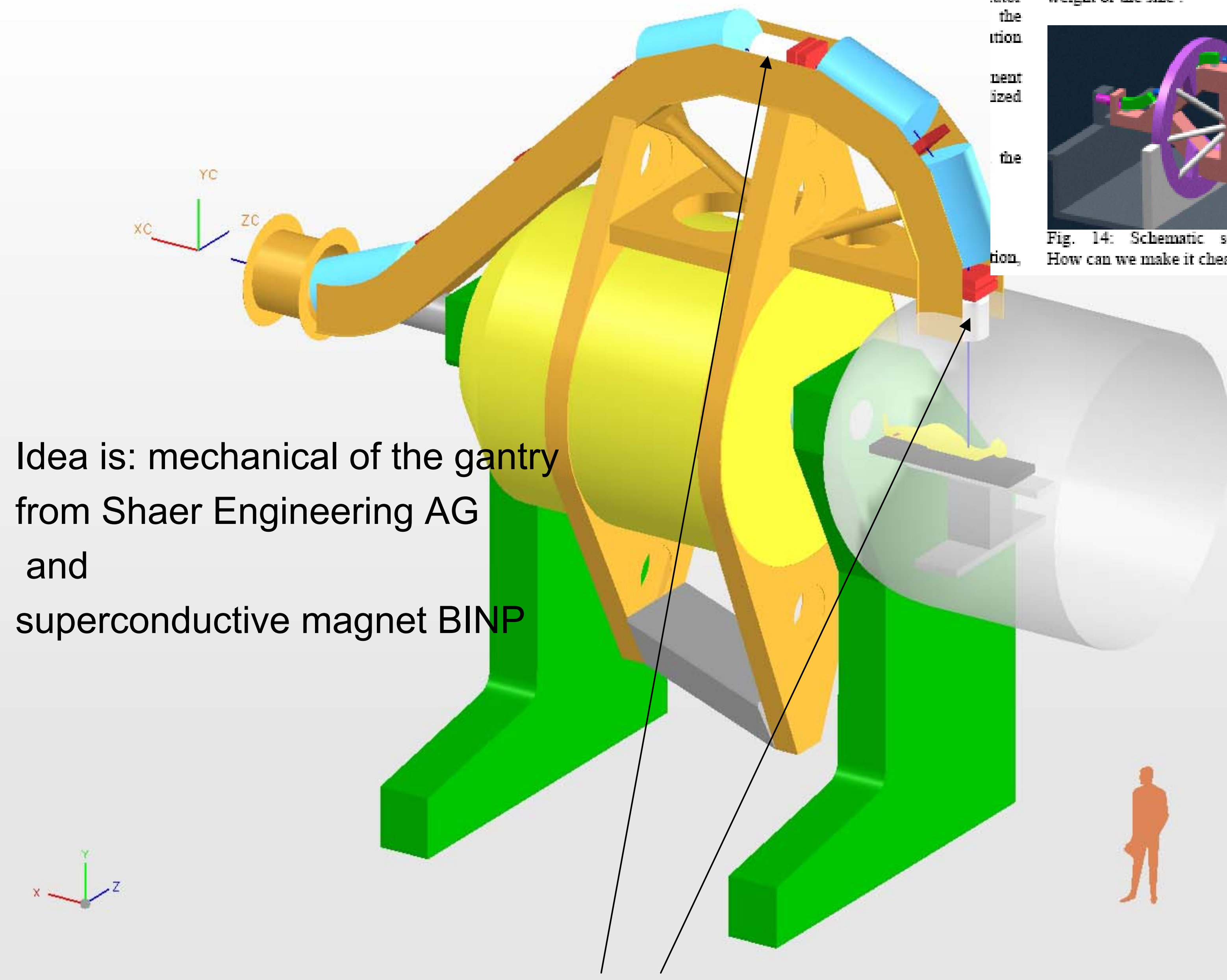
Pellet extraction



1-Vacuum chamber,
2- Frame for foil,
3- Ti foil 0.1 mm,
4- High voltage electrode,
5- High voltage feedthrough.



Electron cooler energy optimized for cooling to dp/p=-1.5*10-3
Betatron core fast shift energy all beam close to septum and after kick out extraction portion betatron core slowly moved ions at right form by electron cooling next portion of extracted ions at -1.5*10-3
Septum foil
2500
2000
1500
1000
500
0
-0.003
-0.002
-0.001
0
0.001
0.002
DYkx,1
DYkx,2
DYkx,3
DYkx,4
DYkx,5
DYkx,6
DYkx,7
DYkx,8
DYkx,9
DYkx,10
DYkx,10
DYkx,0, DYkx,0, DYkx,0, DYkx,0, DYkx,0, DYkx,0, DYkx,0, DYkx,0, DYkx,0, DYkx,0, DYkx,0−10−3
t=0
0.5 msec
1
1.5
2
2.5
3
3.5
4
4.5
after change polarity magnet betatron shifter



Idea is: mechanical of the gantry
from Shaer Engineering AG
and
superconductive magnet BINP

rator the tion ment ized the tion,

weight or the size !

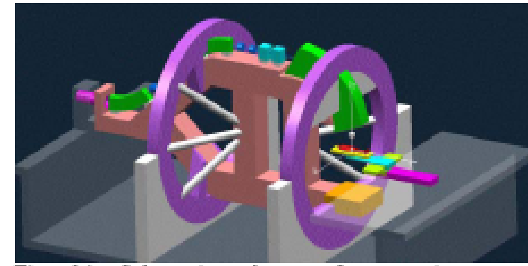
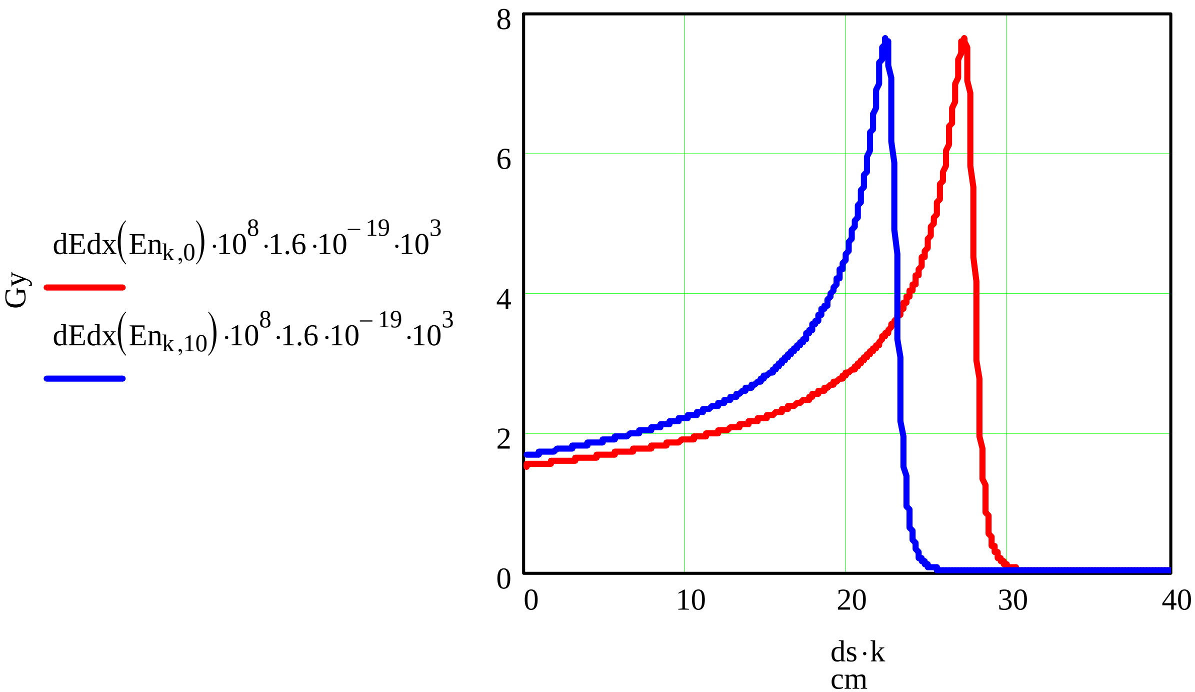


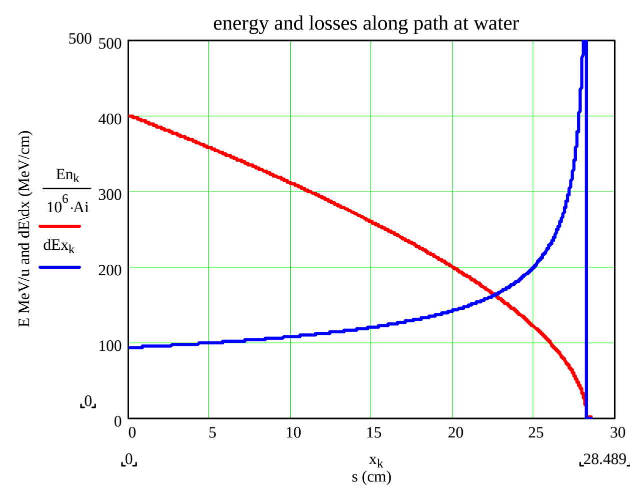
Fig. 14: Schematic scheme of a rotating gantry. How can we make it cheaper ?

Preliminary view of superconductive gantry

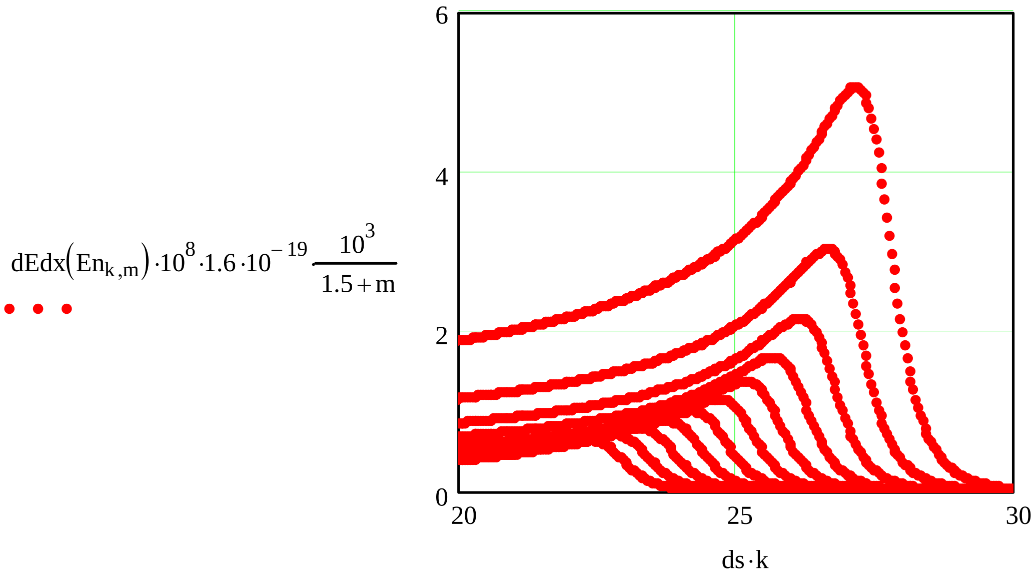
Elements of scanning system



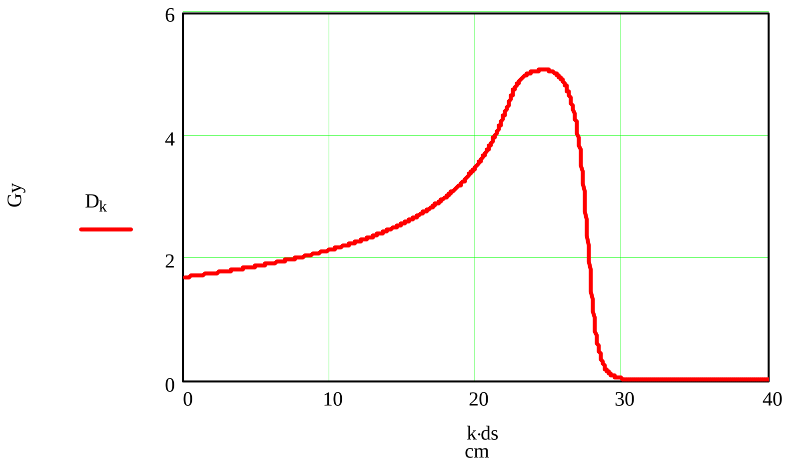
Changing energy from 400
To 360 MeV/u



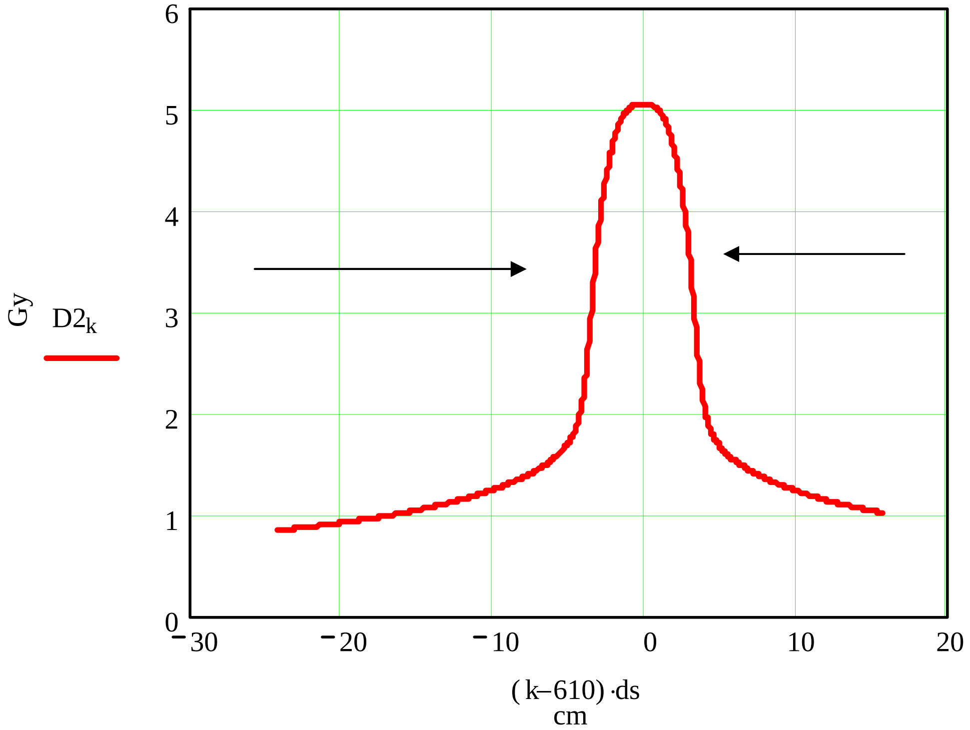
Two beams with 10^8 ions/cm^2
at water with energy 400 MeV/u и 360 MeV/u



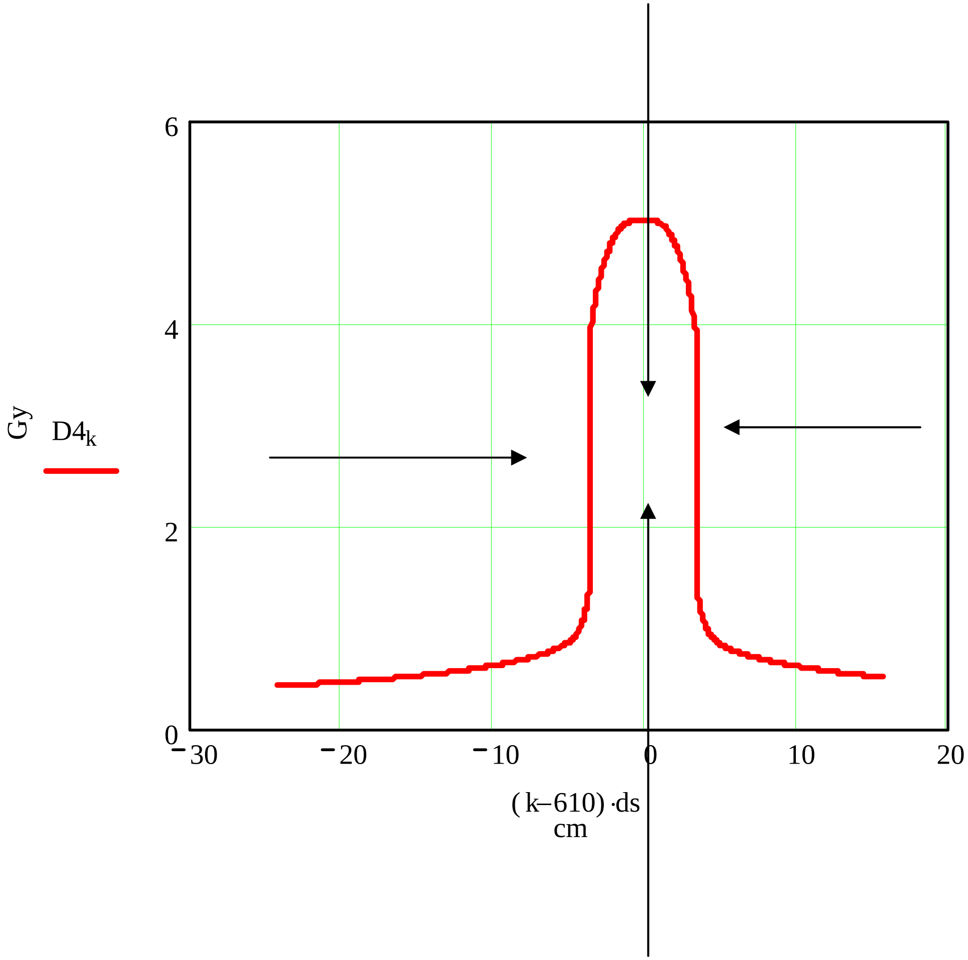
10 beams for form flat top



Ratio doze at tumor to surface doze 2.5



Two side irradiation
ratio=5



4 side irradiation with ion beam radius 3.5 cm
Ratio doze 10

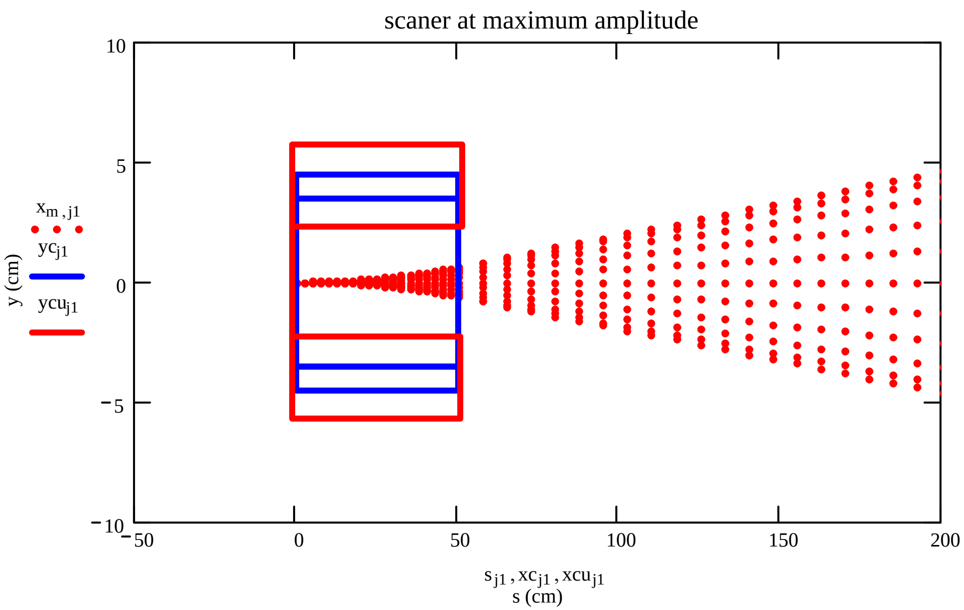
$$Ni := \sum_{l=0}^{10} \frac{2.2 \cdot 10^7 \cdot \pi \cdot r^2}{1.5 + l} \qquad Ni = 2.073 \times 10^9$$

$$Nipmax := \frac{2.2 \cdot 10^7 \cdot \pi \cdot r^2}{1.5} \qquad Nipmax = 5.644 \times 10^8$$

$$Nipmin := \frac{2.2 \cdot 10^7 \cdot \pi \cdot r^2}{1.5 + 10} \qquad Nipmin = 7.362 \times 10^7$$

The visit of BINP team at ITPH for discussion collaboration around TPS at this September give us (BINP) hope to find help at this subject

Final scanner



length 0.5 м
Apperure at magnet ±35 мм
Fast scanning 100 mm

We considering the scanner magnet based on the novel idea of the amorphous iron yoke using. We hope it will provide increasing of the irradiated field.

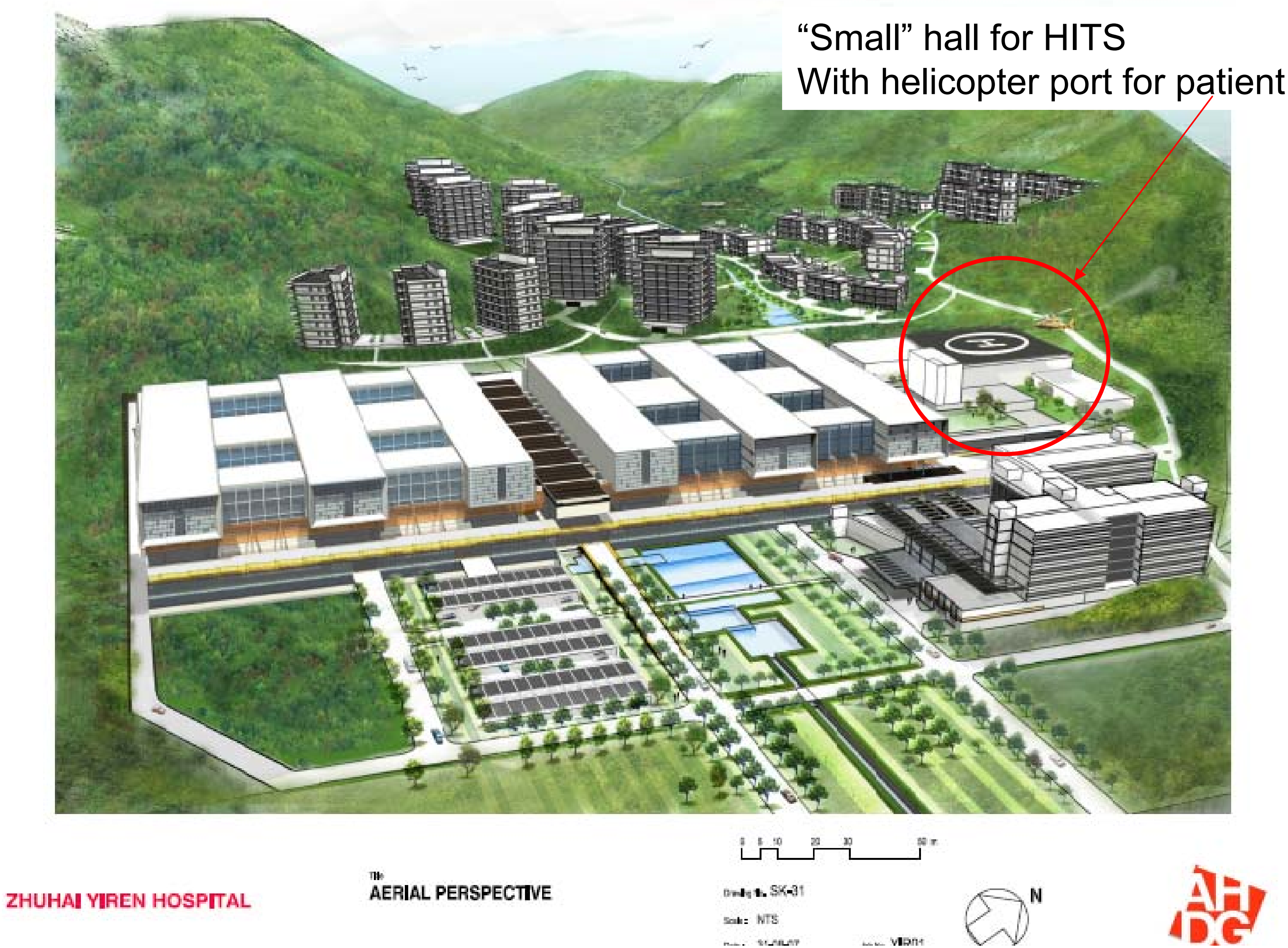
CONCLUSION

1. The carbon ion beam system based on few approved key innovations historically comes from BINP (Novosibirsk): electron cooling, using negative ions for stripping injection, storage rings…
2. Using booster system decreased pre injection electrostatic system energy to 1.2 MV and open proton beam mode operation at parallel with Carbon beam with relatively high energy 250 MeV for proton beam therapy.
3. Electron cooling help made operation of system more easy by low emittance and as results more stable energy and easy extraction. Example of CSRm operation show that electron cooler can operated few months without switch off and any problems.

and PS:-

Discussion with future director of hospital the treatment rooms size
23 Sep. 2008. Beijing

Signing payment agreement
Vice director BINP
E. Levichev and
boss of corporation YIREN
Dr. Sun
24 Sep. 2008



Preliminary view of hospital in Zhuhai