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Prospects of light ion program in IHEP (part 1)

Status of ion acceleration in IHEP (part 2)

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- Look over the light ion program
- Status (current scope and outcomes of activity):
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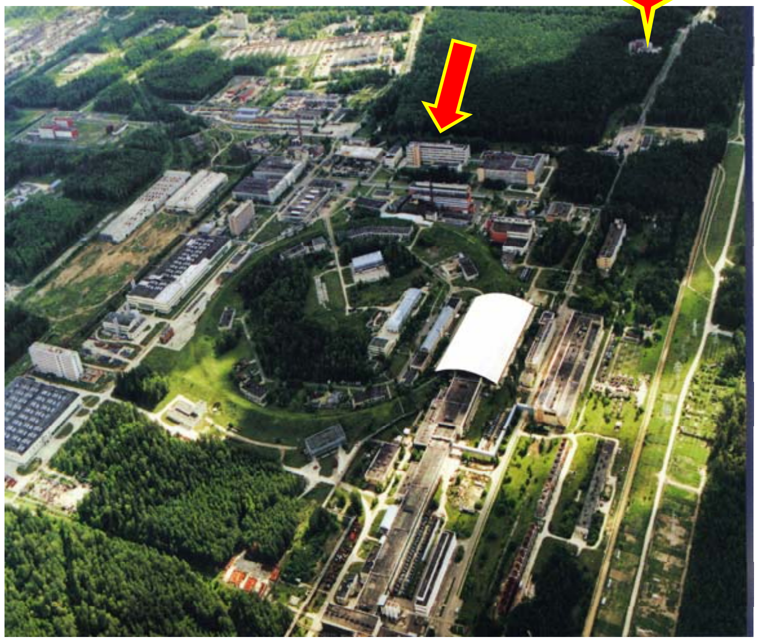
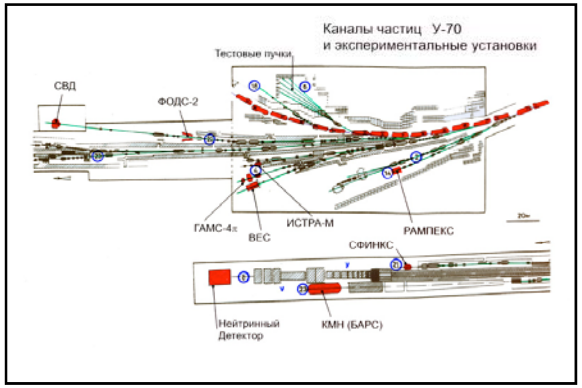
  - Alvarez DTL *I*100
  - BTL *I*100 - *U*1.5
  - Injection into *U*1.5
  - *U*1.5 machine proper
  - *U*70 en route to light ions
- Conclusion

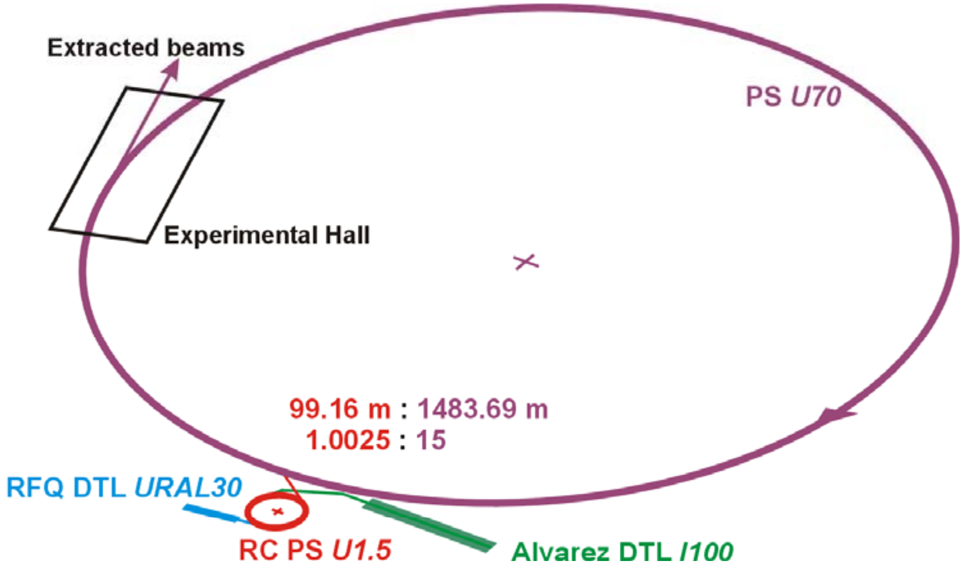
Layout of accelerator complex *U*70





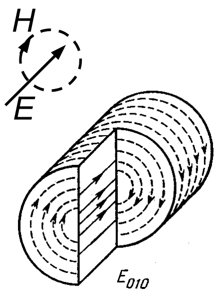
experimental area

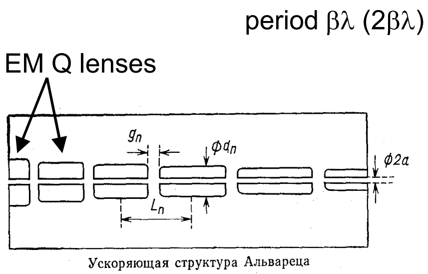
	*U*1.5	*U*70
$B\rho$, T·m	0.8 -- 6.9	6.9 -- 233.4
f_{RF}, MHz	0.75 -- 2.79	5.52 -- 6.06
P, Torr	$2{\cdot}10^{-7}$	$5{\cdot}10^{-7}$

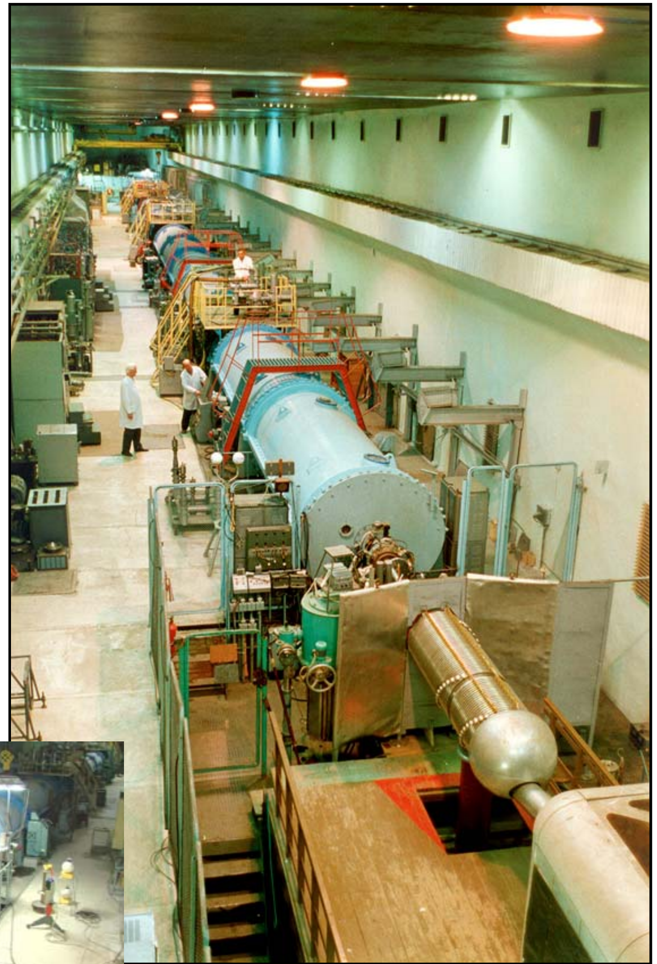


Alvarez DTL /100

• Type	Alvarez DTL
• Energy, *p*	0.7–100 MeV
• Pulsed current	100 mA
• Radio frequency	148.5 MHz
• Pulse length	12–40 μs
• Repetition rate	0.2–1 Hz
• No of tanks	3
tank #1	93+2·½ DT, 29.9 m
tank #2	41+2·½ DT, 27.6 m
tank #3	26+2·½ DT, 21.9 m



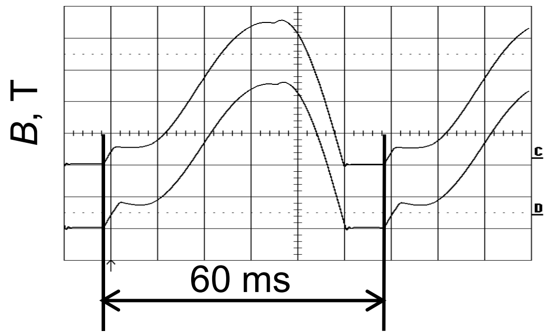


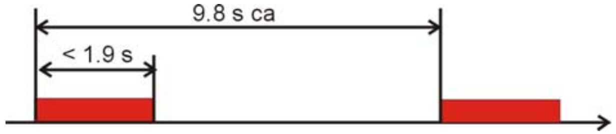


Rapid cycled PS *U*1.5

- Energy, *p* — 30 MeV – 1.32 GeV
- Orbit circumference — 99.16 m
- Curvature radius — 5.73 m
- Top $B\rho$ — 6.9 T·m
- Radio frequency — 0.75 – 2.79 MHz
- RF harmonic number — 1
- Intensity — 2 – $9{\cdot}10^{11}$ p p b
- Repetition rate — 16.6 Hz
- Up to 32 60 ms long pulses @ 0.1 Hz
- PPM & IPM modes
- Beam availability — > 95 %

8 ferrite-loaded RF cavities
0.6 — 60 kV total





24 dipoles, 24 QF, 12 QD

M-FDF-M, 3.75° edge f.

12 periods

WP (3.85H, 3.80V)

Main ring PS *U*70

• Energy, *p*	1.32 – 50/60/70 GeV
• Orbit circumference	1483.699 m
• Curvature radius	194.125 m
• Top $B\rho$	233 T·m (i.e. ¾ of SIS300)
• Intensity	< $1.4 \cdot 10^{13}$ p p p
• Repetition rate	0.1 Hz ca
• 1 run per year, duration	1500 hr
• Beam availability	> 85%

120 dipoles (CF)

FODO

60 periods

12 super periods

WP (9.9H, 9.8V)

$$\frac{2\pi\rho}{\Pi} = \frac{2\pi \cdot 194.125\,\mathrm{m}}{1483.699\,\mathrm{m}} \cong 82\%$$

- 40 ferrite loaded cavities (5.52 – 6.06 MHz), max 10 kV/gap
- RF harmonic number 30
- Auxiliary 200 MHz RF system (of 2 cavities), 450 kV total

Generalities

Goal:
- To extend functionality of *U*70 for applied and fundamental research
- To provide extracted beams of *p* and light ions (*d*, *C*) on a fixed target
- To, thus, convert *U*70 to an universal hadron accelerator (& storage) ring
- To provide (a.s.a.p.) carbon-**beam-therapy** compliant **beams**

Boundary conditions:
- To comply with overall layout limitations of the existing machines
- To be non-invasive, never preclude the existing *p*-program
- To be cost-effective, the utmost use of existing capital equipment
- To implement proven technologies

Consequences:
- In a non-SC synchrotron, feasible vacuum $P > 1\text{-}5\cdot10^{-8}$ Torr
- Unsuitable optics and no place to assemble collimators to localize beam losses from an intermediate charge-state ion beam
- No place for stripping-foil target assembly for charge-exchange (non-Liouvillean) injection into *U*70
- No place for any cooling inserts in *U*70 whatsoever
- Prescribed variation range of rigidity $B\rho$ in lattice, and frequency f_{RF} in RF systems
- Technical limitations in *I*100 at the 4π-mode imposing $1/3 < q/A < 1/2$

Reference ions

Fully stripped (bare) ions, $q = Z$
Charge-to-mass ratio $q/A = 1/2$

Reference ions:
- ${}_{1}H^{1+}$ protons, p
- ${}_{2}H^{1+}$ deuterons, d
- ${}_{12}C^{6+}$ carbon

Why light ions? To be on the safe side w.r.t.:
- Coulomb betatron tune shift, $N_B \propto (B\rho)^2/\beta A$
- MCS on residual gas, $d\varepsilon/dt \propto P/(B\rho)^2\beta$
- Ionization losses on residual gas, $d\ln p/dt \propto -Pq/B\rho\beta^2$
- IBS, $\tau \propto (B\rho)^2/N_B\beta q^2$
- *e*-capture (recombination) on residual gas, $\sigma \propto \beta^3 q^2/T^{17/4}$

Prospects of going to heavier ions will be assessed later with more experimental data at hands

Kinematics

		*I*100		*U*1.5		*U*70	
		IN	OUT	IN	OUT	IN	OUT
p, *pilot* beam	β		0.3724		0.9000		0.9999
	*B*ρ, T·m		*1.2558*		6.8659		233.38
	T, MeV		72.71		★ 1 323.8		69 032
d	β		0.1862		0.7392		0.9996
	*B*ρ, T·m		*1.1856*		6.8659		233.38
	T, MeV/u		16.691		★ 454.56		34 057
C	β		0.1862		0.7414		0.9996
	*B*ρ, T·m		*1.1776*		6.8659		233.38
	T, MeV/u		★ 16.678		456.53		34 063

★ Milestones are accomplished

Updates to ring machines

	*U*1.5	*U*70
min f_{RF}, MHz	0.75 → 0.56	5.52 → 4.48-4.49 (inherent min = 2.60)
min *B*, T	0.14 → 0.21-0.22	the same
law $f_{RF}(B)$	vary	vary
γ_{tr}-crossing (*t*)	none	vary

Beam intensities

Ions	N_{B0}	qN_{B0}	weight
proton *p*	$2\text{-}9{\cdot}10^{11}$	$2\text{-}9{\cdot}10^{11}$	1
deuteron *d*	$1{\cdot}10^{11}$	$1{\cdot}10^{11}$	10
carbon ${}_{12}C^{6+}$	$3{\cdot}10^{9}$	$2{\cdot}10^{10}$	50

In-out sensitivity of beam diagnostics

+
Vacuum system (MCS, ionization losses)
WP, resonances and dynamic aperture
…

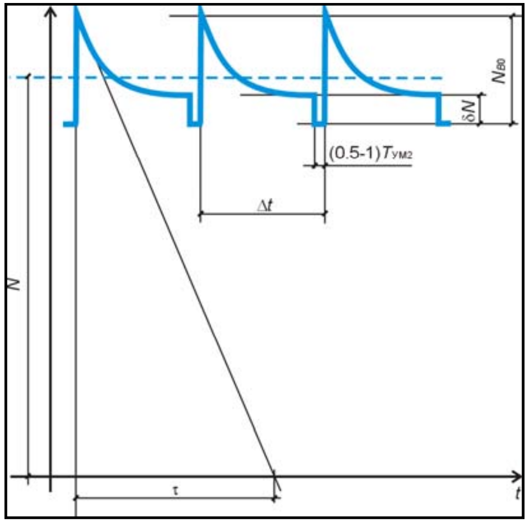
Scenarios

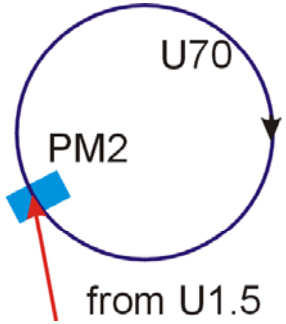
There are **two options** with light ions:

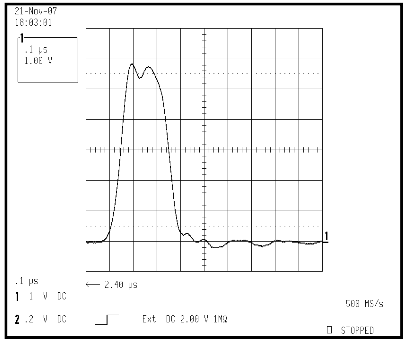
- 1. Storage ring (beam stretcher) 0.45-0.46 GeV/u with a full-energy injection and a CW (e.g. stochastic) beam extraction
    - Bunched beam
    - Azimuthally uniform beam
- 2. Accelerator to 34 GeV/u
    - Low beam current, high rep rate
    - High beam current, low rep rate

Storage ring, 0.45-0.46 GeV/u

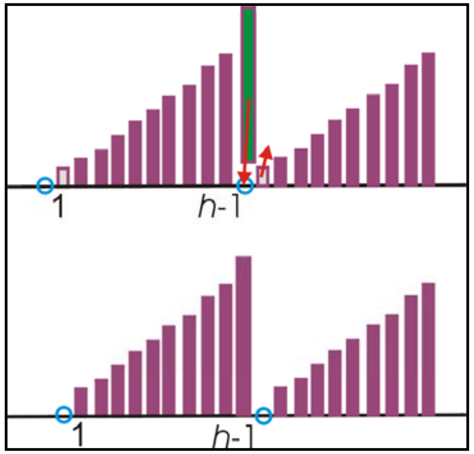
Accumulation in a longitudinal phase plane
Imperfect (horizontal) injection scheme



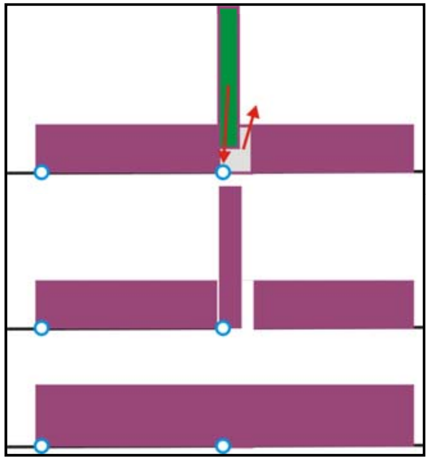




Δt = 1-2 s
T_{PM2} = 300 ns
T_0 = 6.7 μs
τ = a few tens of s
h = 30



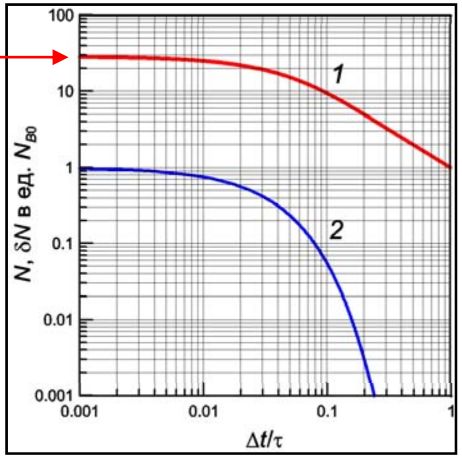
Bunched beam,
bunch-to-bucket transfer



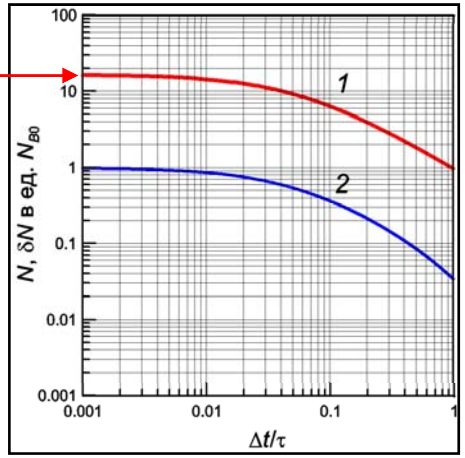
Un bunched beam

Storage ring (2)

h -1=29



T_0/T_{PM2}=16.7



Advantages of storing bunches:

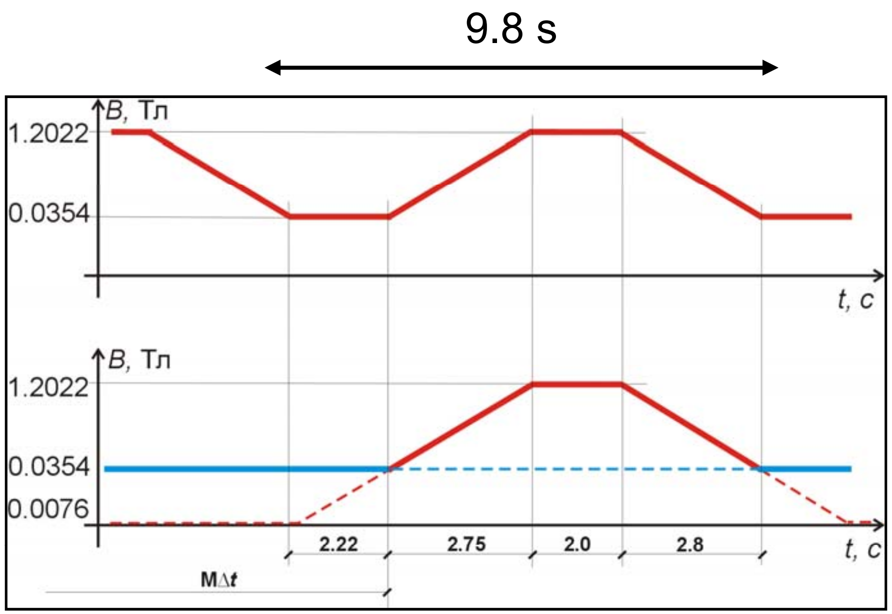
- more effective beam accumulation
- finite full-filling time = $(h\text{-}1)\Delta t$, otherwise – exponential law $N(t)$
- easier beam diagnostics
- built-in compensation of ionization losses inside RF buckets

BUT: difference in beam life-times might turn crucial

Accelerator, 34 GeV/u

Conventional cycle,
M = 1-3

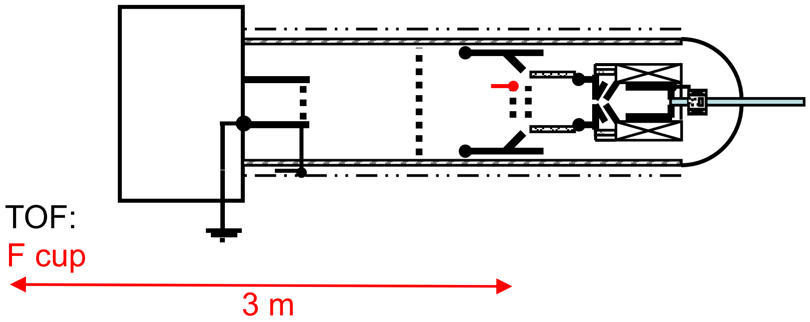
Extended cycle,
max M = 29

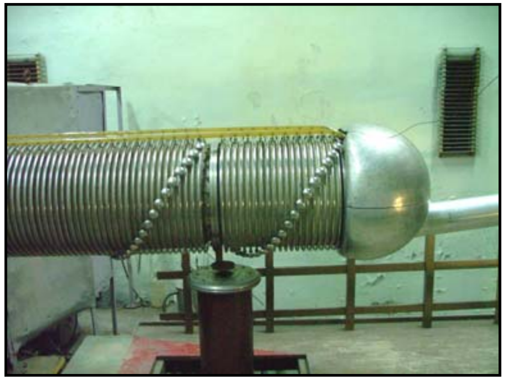


Cycle rep period:
$T_{U70} = M \cdot \Delta t + 7.6$ s

Status: ion gas source

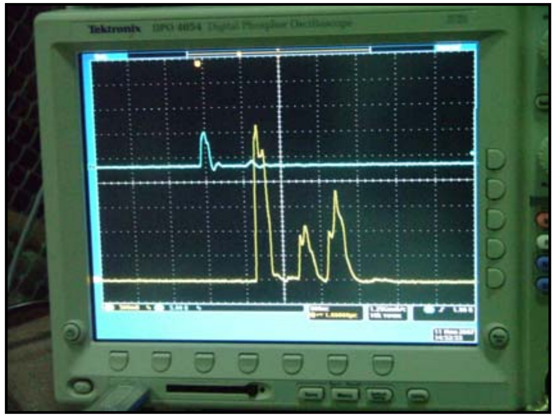
p, *d* ion gun (duoplasmatron)
+ fast chopper





HV platform
to +750 kV

control over *q*/*A* content

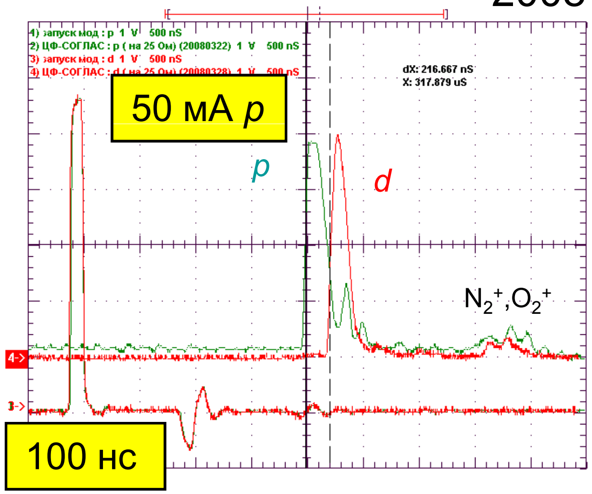


p

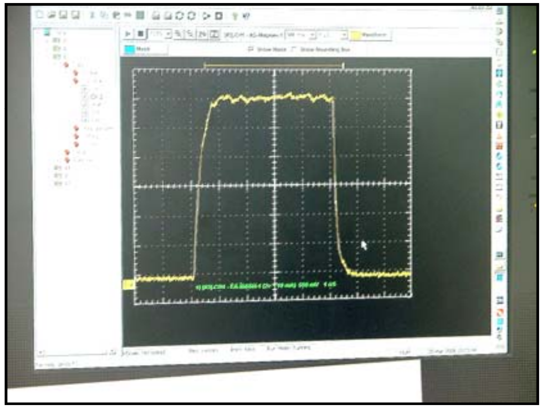
N^+, O^+

N_2^+,O_2^+

2008

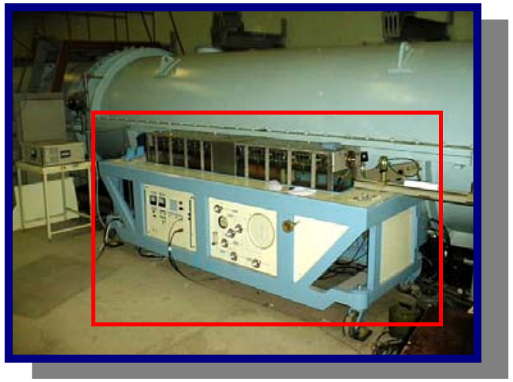


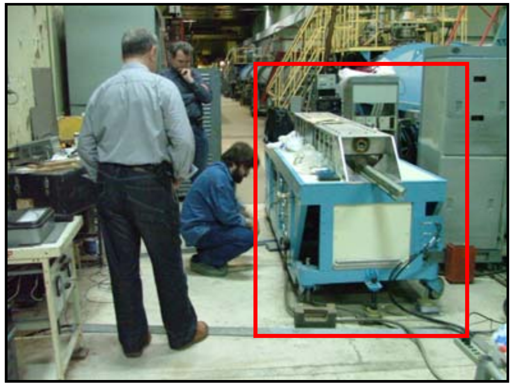
2008



15 мА *d* 5 μs 16.7 MeV/u

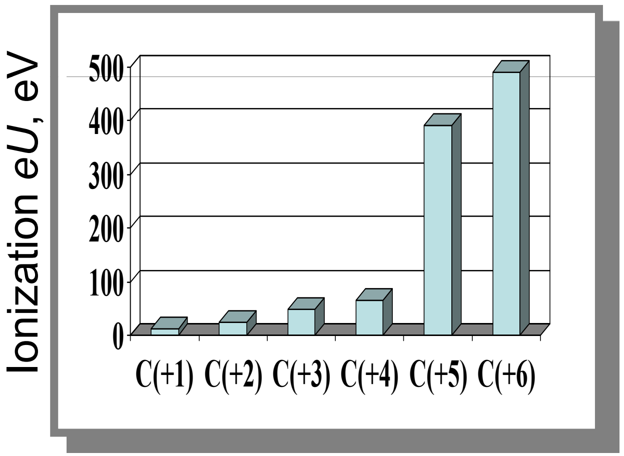
Status: laser SS C ion source

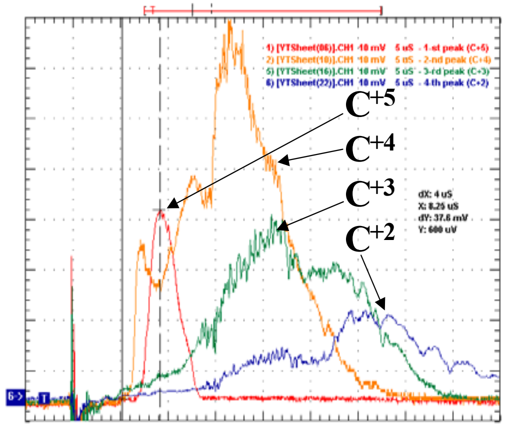


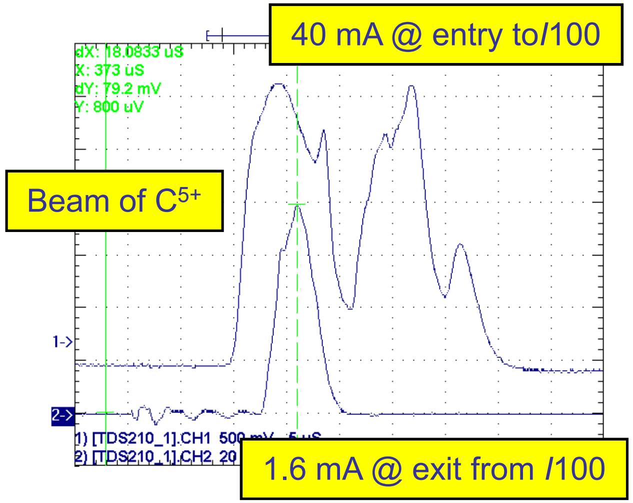


IHEP laser (CO_2, 2.7 J, 10 μm, 0.25 Hz)

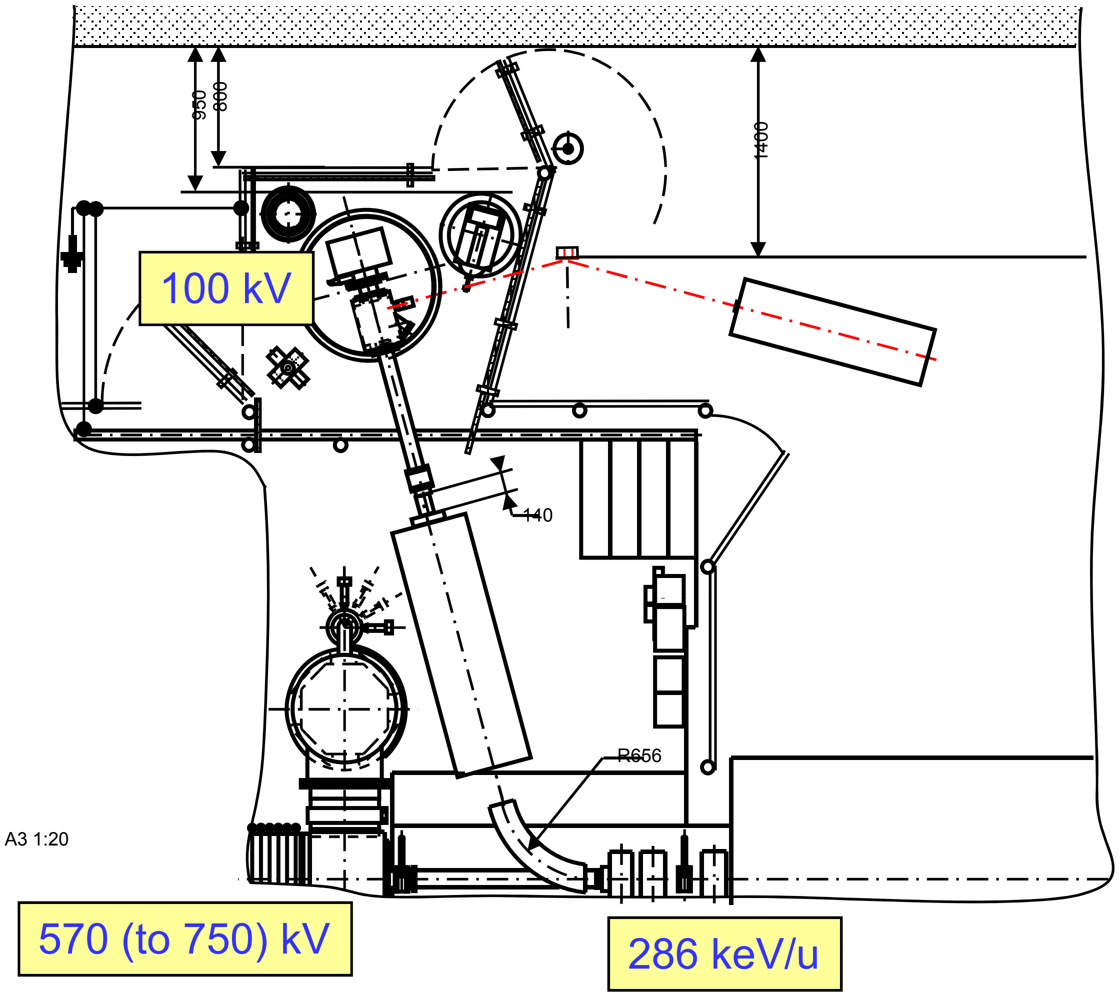
IGP of RAS laser (…, 10 Hz)







RFQ fore-injector of C



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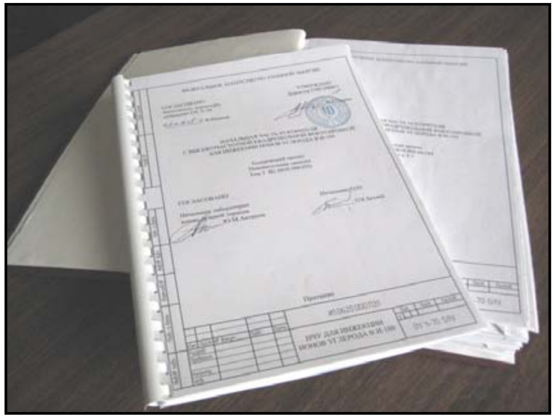

ФЕДЕРАЛЬНОЕ АГЕНТСТВО ПО АТОМНОЙ ЭНЕРГИИ

СОГЛАСОВАНО
Заместитель директора,
начальник ОУ У-70
С.В.Иванов

УТВЕРЖДАЮ
Директор ГНЦ ИФВЭ

НАЧАЛЬНАЯ ЧАСТЬ УСКОРИТЕЛЯ
С ВЫСОКОЧАСТОТНОЙ КВАДРУПОЛЬНОЙ ФОКУСИРОВКОЙ
ДЛЯ ИНЖЕКЦИИ ИОНОВ УГЛЕРОДА В И-100

Технический проект
Пояснительная записка
Том 1 И1.0620.000.П31

СОГЛАСОВАНО

Начальник лаборатории
ионно-лучевой терапии
Ю.М.Антипов

Начальник ОЛУ
О.К.Беляев

Протвино

И1.0620.000.П31

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НЧУ ДЛЯ ИНЖЕКЦИИ ИОНОВ УГЛЕРОДА В И-100

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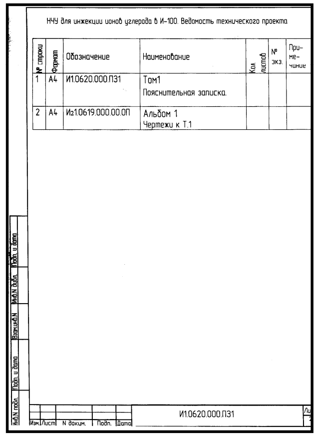

НЧУ для инжекции ионов углерода в И-100. Ведомость технического проекта

№ строки	Формат	Обозначение	Наименование	Кол. листов	№ экз.	Примечание
1	А4	И1.0620.000.П31	Том1 Пояснительная записка.			
2	А4	И21.0619.000.00.0П	Альбом 1 Чертежи к Т.1			

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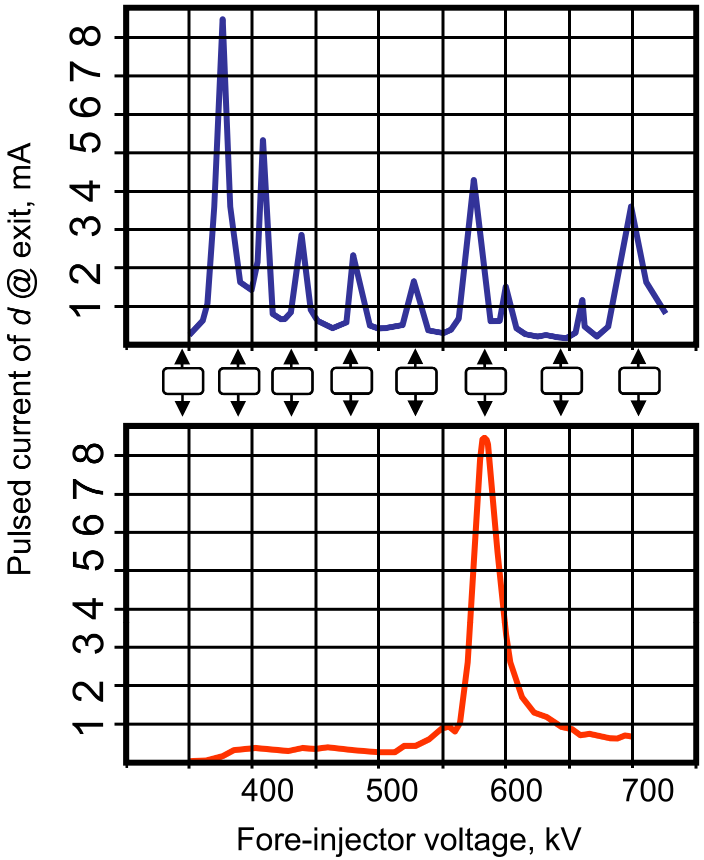
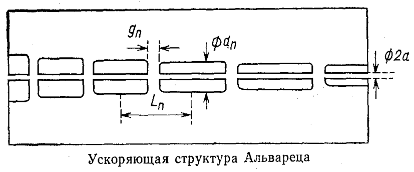
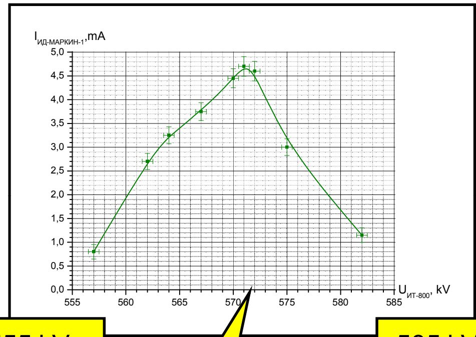
Status: /100



period = βλ (2βλ, …)





555 kV

585 kV

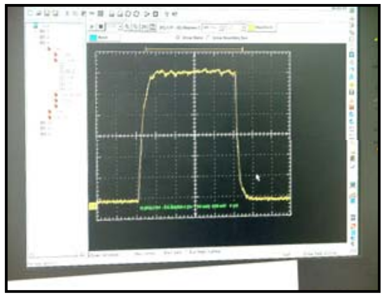
570 kV

2π-mode, *p* (*h* = 1)
4π-mode, *d*, C (*h* = 2)

$\beta_h = \beta_1/h$
$G_h = G_1/(h \cdot q/A)$
$(Vg)_h = (Vg)_1/(h^2 \cdot q/A)$
$(Vg)_h = V_h \cdot g_h$

$1/3 < q/A < 1/2$

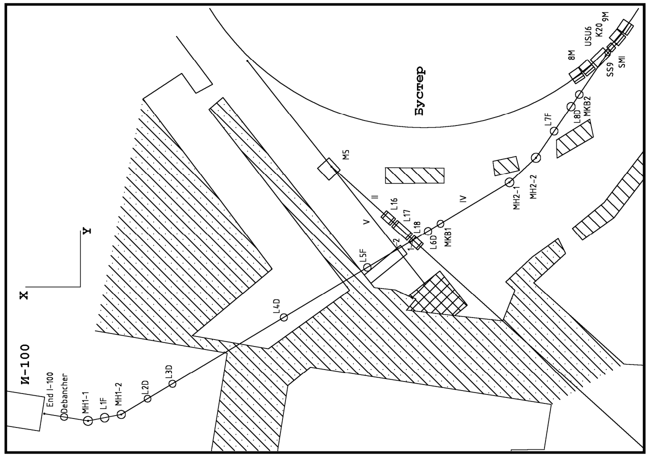
1st MD run of 2008

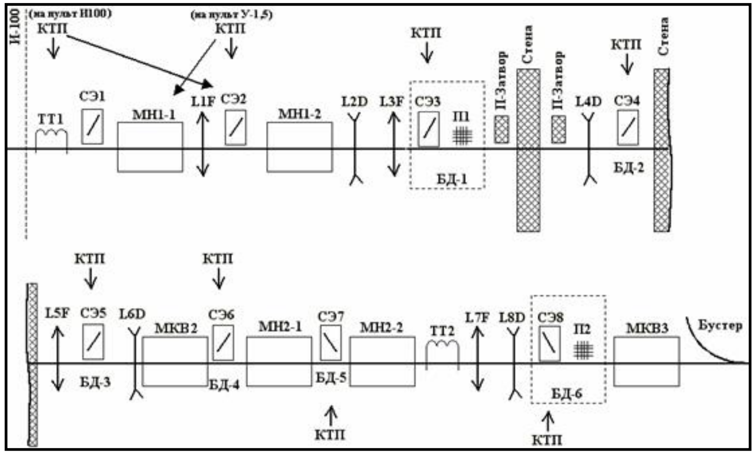


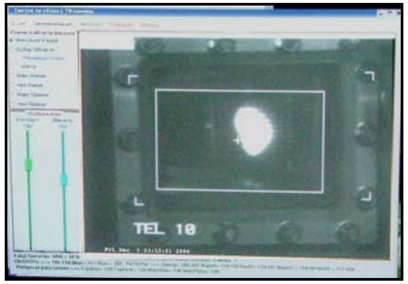
15 мА *d* 5 μs 1 6.7 MeV/u

Status: BTL *I*100-*U*1.5

44 m long
4 bends
8 quads
2 V-correctors
beam diagnostics





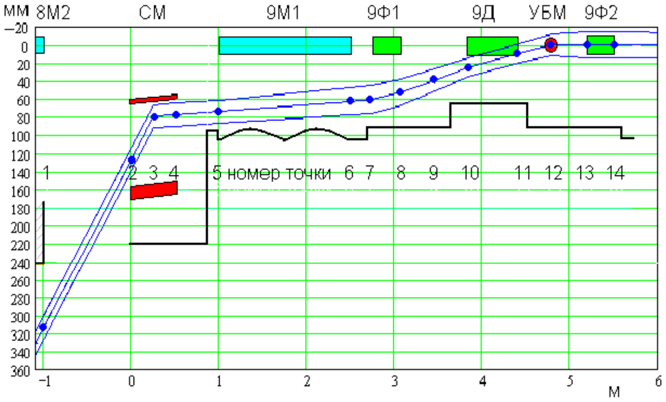


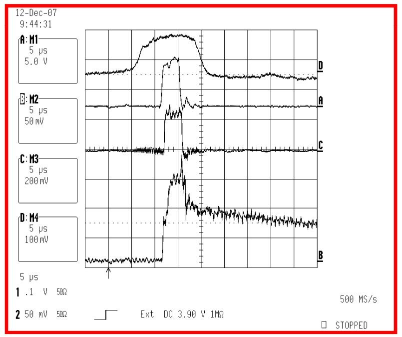
Commissioned with 72.7 MeV *p* (17.11.06) and 16.7 MeV/u *d* (01.12.06)

Status: 9th SS of *U*1.5 & others

Reassemble 9th SS of *U*1.5 and update other equipment:

- A wider dipole
- New vacuum chamber
- Away 1 RF cavity (now, a spare unit)
- 177 mrad septum magnet with its PSU
- 23 mrad kicker magnet with its PSU
- The other ancillary equipment
- New RF master oscillator
- Extra capacitive loads to 8 RF cavities
- Improved (though, partially) beam diagnostics, …

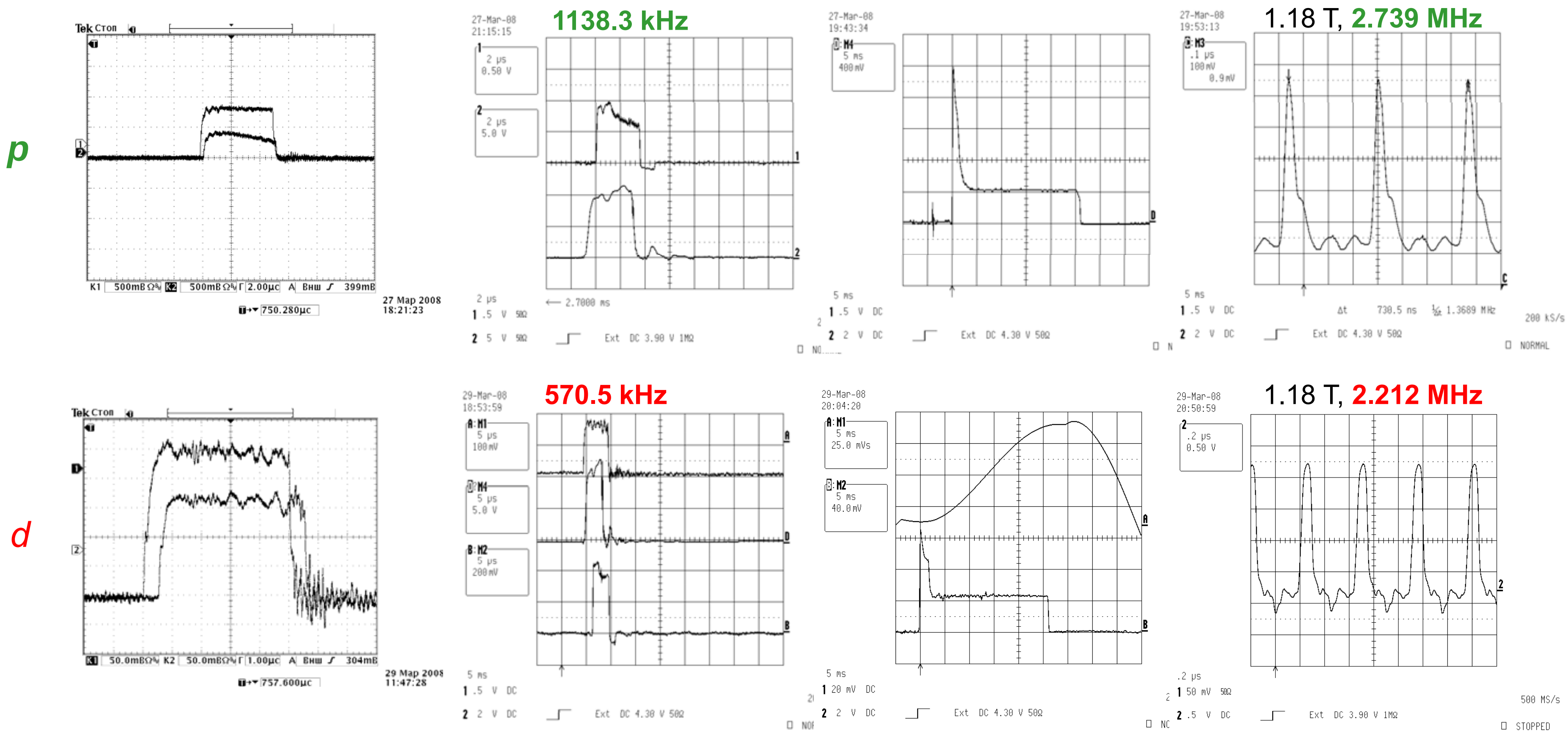




10-12.12.07; *p;* 72.7-1320 MeV; $3{\cdot}10^{10}$ ppb; 35% through *U*1.5

Status: *U*1.5 in a whole

29-30.03.08; *d*; 16.7- 455 MeV/u; 3·10^{10} ppb; 34% through *U*1.5



Status: *I*100 to *U*1.5 in a whole

1st MD run of 2008

	Exit from *I*100	Exit from BTL	1st turn	Circulation	Start of acceleration	Extraction
p, 72.7 – 1320 MeV	48 mA	20 mA	15 mA	$8.2{\cdot}10^{10}$	$6.7{\cdot}10^{10}$	$1.5{\cdot}10^{10}$
TOTAL:	$3.0{\cdot}10^{8}\ p_{U1.5}/\mathrm{mA}_{I100}$, IN-OUT$_{U1.5}$ = 18%					
d, 16.7 – 455 MeV/u	15 mA	9.6 mA	8 mA	$8.8{\cdot}10^{10}$	$8.1{\cdot}10^{10}$	$3.0{\cdot}10^{10}$
TOTAL:	$2.0{\cdot}10^{9}\ d_{U1.5}/\mathrm{mA}_{I100}$, IN-OUT$_{U1.5}$ = 34%					

OUTCOME:

- Quality *p* from *I*100 yet to be improved
- Good quality of *d* beam
- Further improvement of fast injection kicker magnet PM3 is required
- 2-turn injection scheme for *d*, C should be assessed
- Beam capture efficiency and excessive momentum spread (a debuncher cavity)

Status: *U*70 en route to ions

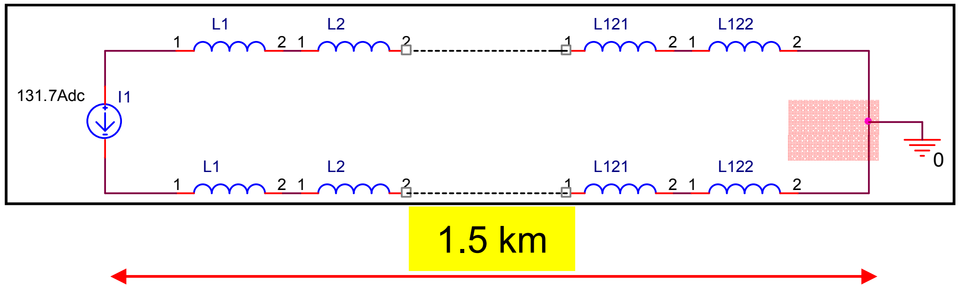
1st MD of 2008: beam test with a stand-alone DC power supply unit for the *U*70 ring magnet

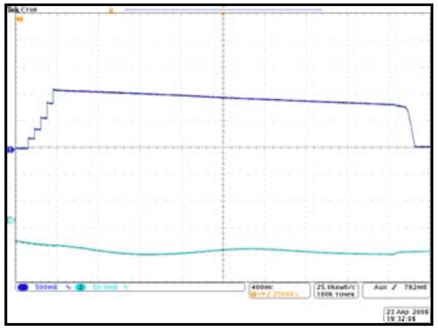
Goal:
- cheap MD runs (1.32 GeV *p*, 0.45 GeV/u *d*, C);
- storage/stretcher ring of light ions 450 MeV/u;
- medical applications of C beams

Preliminary job: long-line impedance measurements, two competitive DC PSUs

2 PSU: building #10, 131.7 A and (*building #175, 129.8 A*)

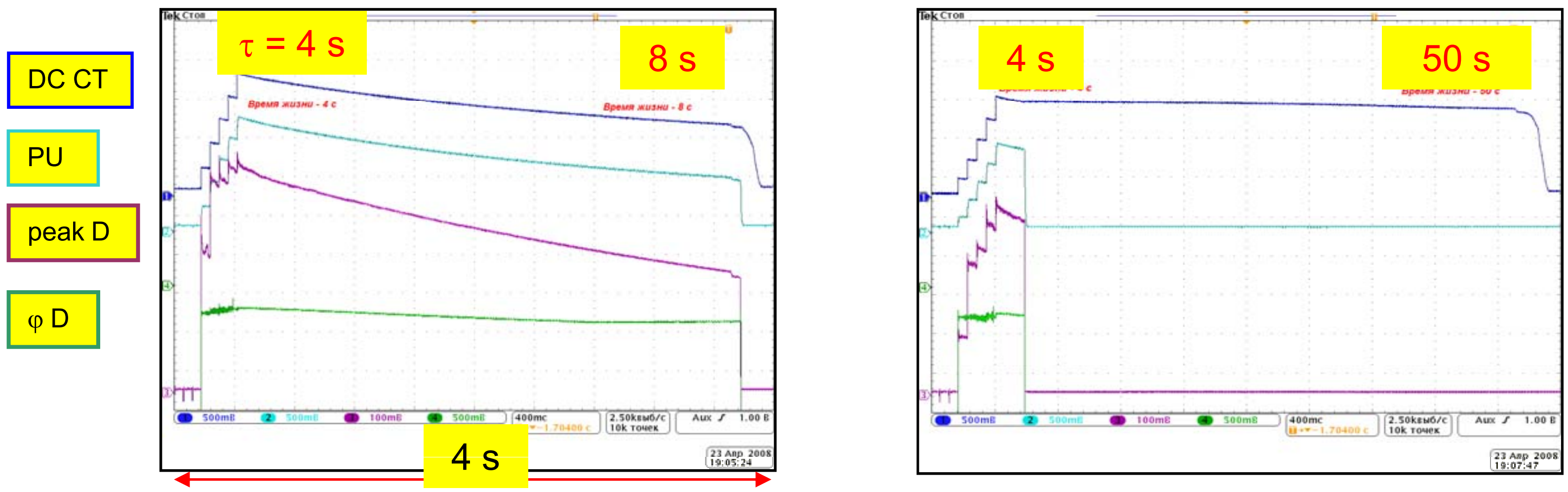
Experimental studies: 07.03 and 23.04.08

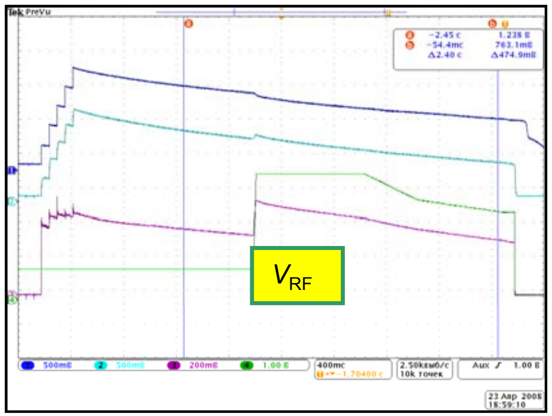




354 ± 0.05 Gauss

Status: *U*70 en route to ions (2)





- Significant difference in τ of bunched versus unbunched beams
- Vacuum conditions are better than expected
- Dynamical reasons of shortening τ:
  - Coulomb betatron tune shift, effect of local beam charge density, $30/5 \times 2 \times 1.5 = 18$
  - Synchro-betatron resonances, $mQ_x + nQ_y + (pQ_s) = k$
  - Dynamic aperture (distortions of the CO, WP, etc) …

  PROBLEMS: residual D field due to G and S correction circuits

Conclusion

- IHEP-Protvino runs a set of diverse proton accelerators comprising 2 synchrotrons and 3 *p*-linacs, 2 of the latter being now integrated into injector chain of the accelerator complex
- Accelerator side of light-ion program here well advances: by 1st half of 2008, 455 MeV/u deuterons were made available from *U*1.5
- High time to have a closer look at the would-be dedicated experimental-physics program

Welcome to IHEP-Protvino,
and have the effective 3rd WS on the LINC physics!