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Light Ions in Accelerator Complex U70 of IHEP

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XXI International Baldin Seminar on High Energy Physics Problems
"Relativistic Nuclear Physics and Quantum Chromodynamics",

XXI Baldin ISHEPP-2012

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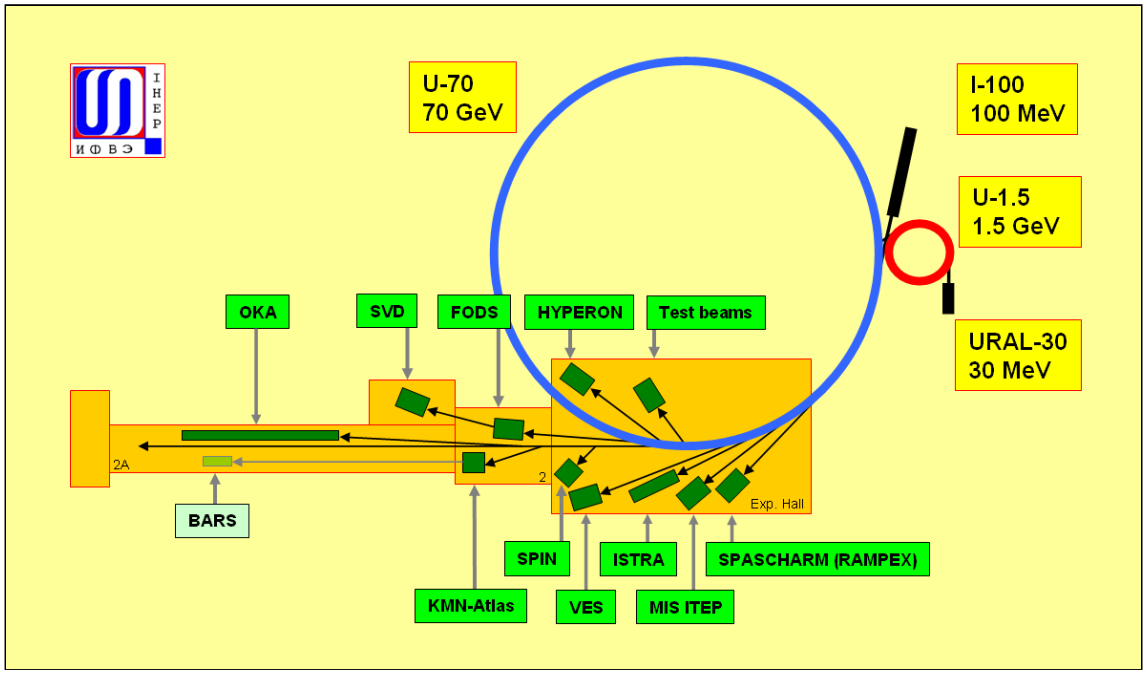
Outlook

- Generalities
- Run by run progress since 2008
- Conclusion

Layout



4 machines (since Oct 2007):
- 2 linacs
- 2 synchrotrons

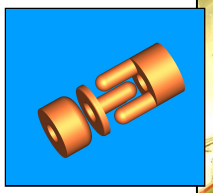
Modes:
- proton (default) *URAL*30-*U*1.5-*U*70
- light-ion (*d*, C) *I*100(2 of 3)-*U*1.5-*U*70

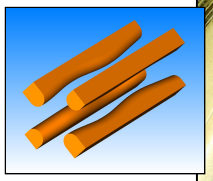
to note: OKA (#21), FODS (#22), stretcher (#25)

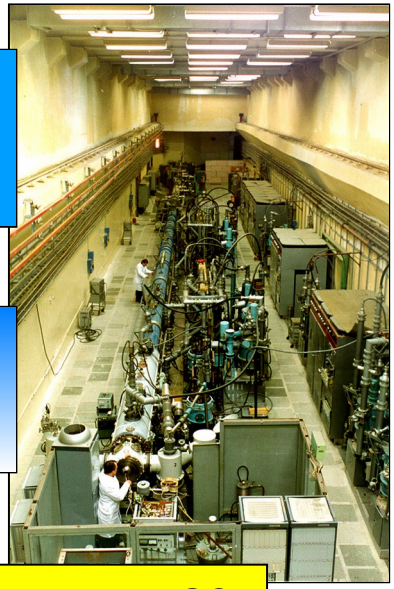
Light-ion:
- high energy 24.1-34.1 GeV/u
- intermediate energy 453-455 MeV/u

"AC U-70" in wide sense:
- 4 accelerators,
- BTL network, and
- all experimental facilities

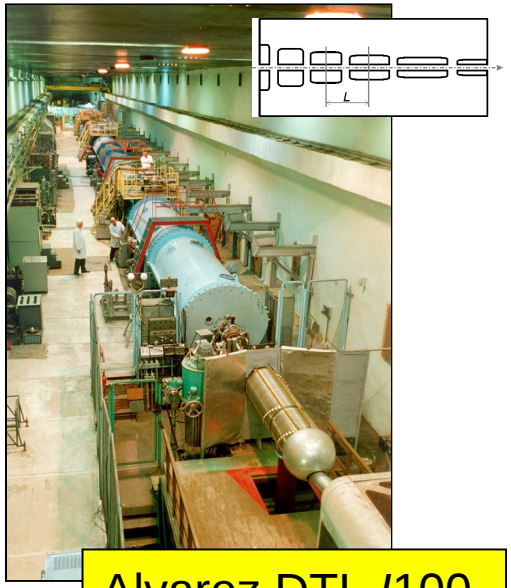
Photo album of machines





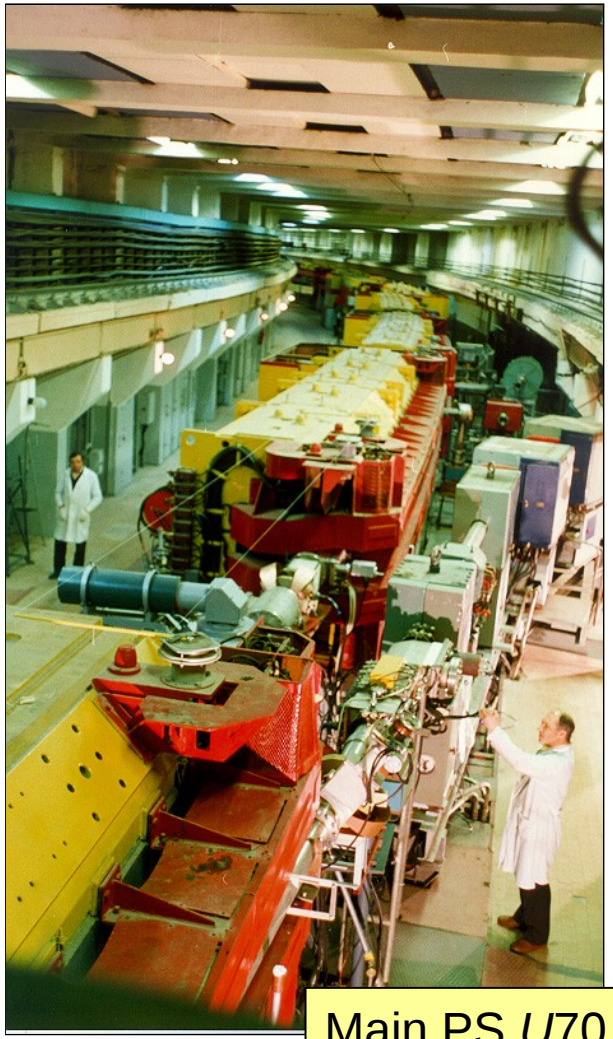


RFQ DTL *URAL*30



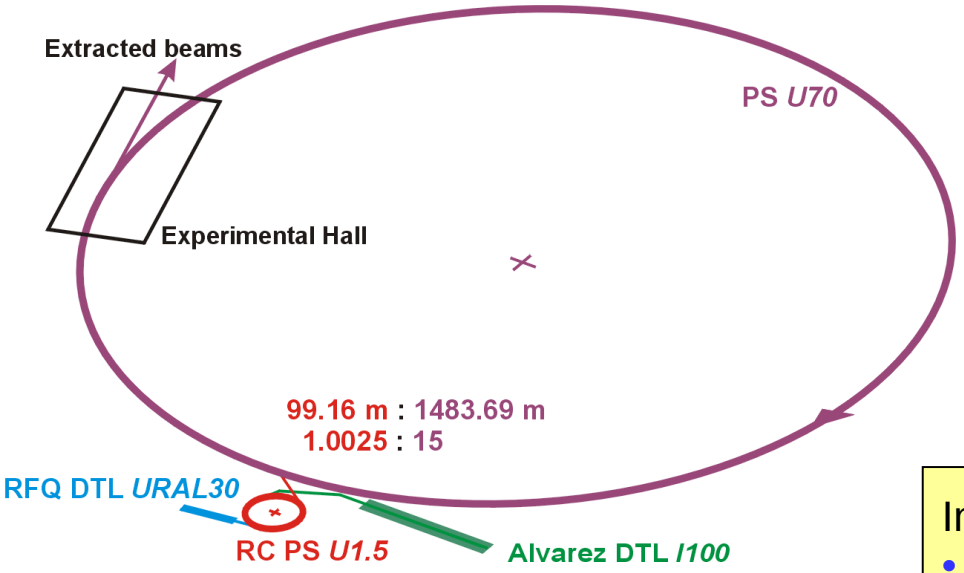
Alvarez DTL *I*100

RC PS *U*1.5



Main PS *U*70

General



	*U*1.5	*U*70
*B*ρ, T·m	0.8 -- 6.9	6.9 -- 233.4
f_{RF}, MHz	0.75 -- 2.79	5.52 -- 6.06
P, Torr	$2 \cdot 10^{-7}$	$5 \cdot 10^{-7}$
N, qpp	$2\text{-}5 \cdot 10^{11}$	$2\text{-}10 \cdot 10^{12}$

In a SIS18, SIS100 name convention:
- LIS-233 [T·m]
- LIS-6.9 [T·m]

*I*100: Alvarez DTL, 0.7—100 (72.7) MeV *p*; 16.7 MeV/u *d*, *C* (@ 4π)

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

Boundary conditions:
- To comply with overall layout limitations of the existing machines (densely packed)
- 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 $P > 1\text{-}5 \cdot 10^{-8}$ 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
- $^{12}C^{6+}$ ($^{12}C^{5+}$) 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, $\sigma \propto \beta^3 q^2/T^{17/4}$
- *e*-stripping on residual gas loss channel closed

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

Strategy

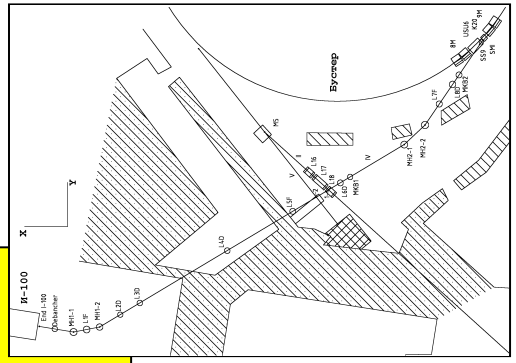
Incremental:

- ion species — *p – d - C*
- along cascade — [*I*100 - BTL] - *U*1.5 - BTL - *U*70 flat bottom circulation (DC PSU, RMG) - *U*70 fixed-field variable-RF acceleration - *U*70 transition crossing – *U*70 ramping to flattop field
- intensity [qpp] — 1 – 1/10 – 1/50 *&* low-*N pilot p*-beams prior to *d*, *C*-beams

Reference ions *q* = *Z*, *q*/*A* = 1/2		*I*100, 2 cav of 3		*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	49 0
	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	23 6
	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	24.1--34 1
	T, MeV/u		16.678		456.53		34 063	

Prehistory @ *I*100 & *U*1.5

Alvarez DTL, 2 tanks of 3, 4π -mode, *d*, *C* to 16.7 MeV/u
- BTL I100/U1.5



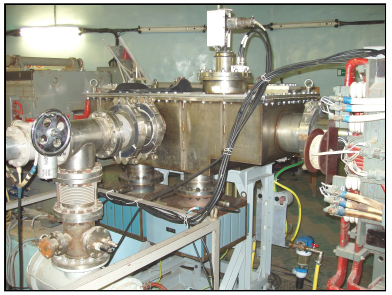
44 m long
4 bends
8 quads
2 V-correctors
beam diagnostics

Reassemble SS#9 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, …

run 2006

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

run 2007

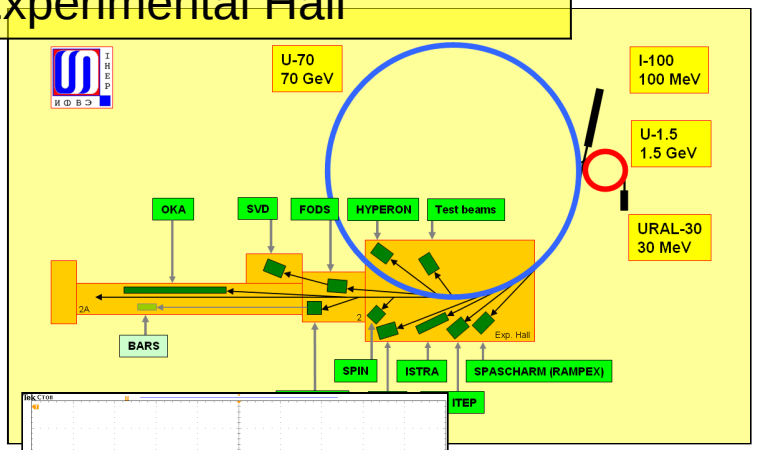


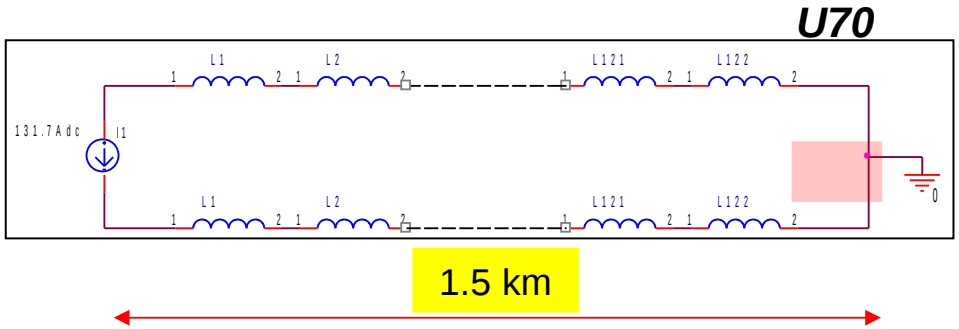
29-30.03.08; ***d***; 16.7- 455 MeV/u; $3 \cdot 10^{10}$ *d*pb; 34% through *U*1.5, **1st time** in record of service

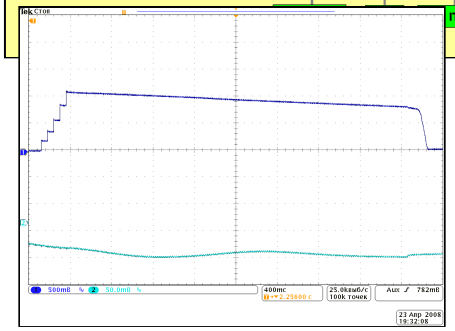
Prehistory @ *U*70

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) 130 A 20kW;
- storage/stretcher ring for light ions 450-5 MeV/u;
- applied & medical applications of intermediate-energy C beams
- an ‘ad hoc’ 350 m long BTL form *U*1.5 to the Experimental Hall



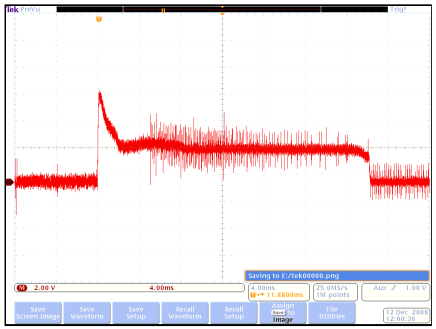


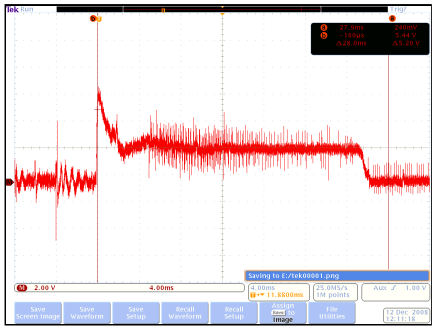


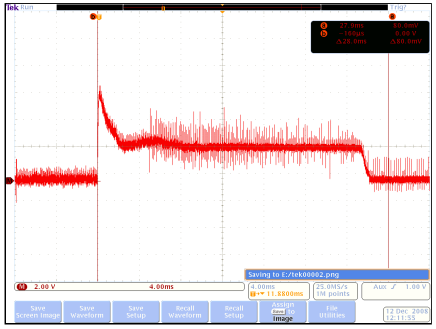
354 ± 0.05 Gauss

Run 2008-2

***U*1.5**





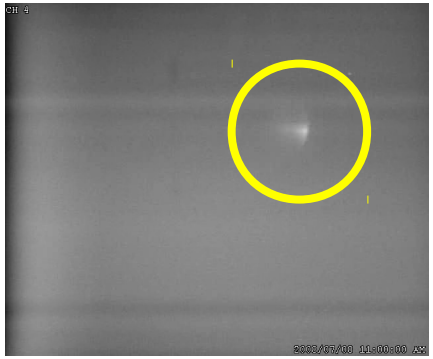


10–12.12.08; *d*; 16.7– 455 MeV/u, 2nd time in record of service

U70 Preparatory activity:

1. Standalone DC PSU (131.1 A) of ring magnet
2. Coasting *p* @1.32 GeV (354 Gauss)
3. Injection of *p* under RF off
4. Imitation of low-*N* *d*-bunch, $3 \cdot 10^{10}$ ppb
5. Settling issued DC CT…

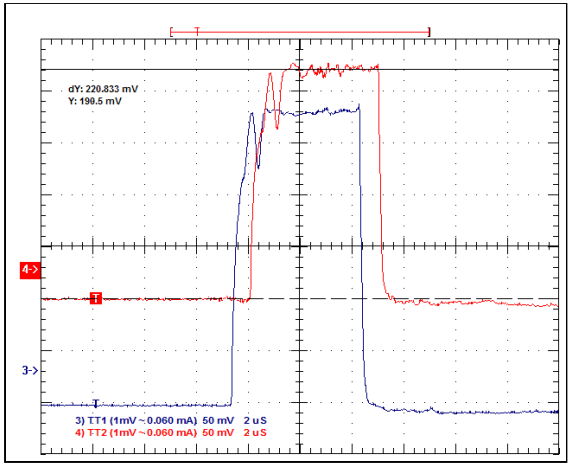
d in U70 after 4 bending magnets of 120, sc screen in SS#10

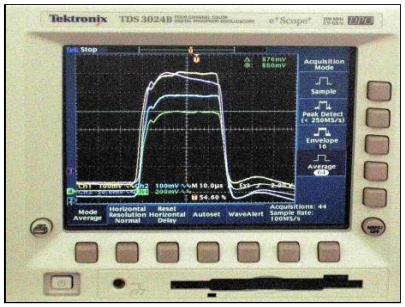


1st ever light-ion (*d*) beam in the *U*70

Run 2009-1 (1)

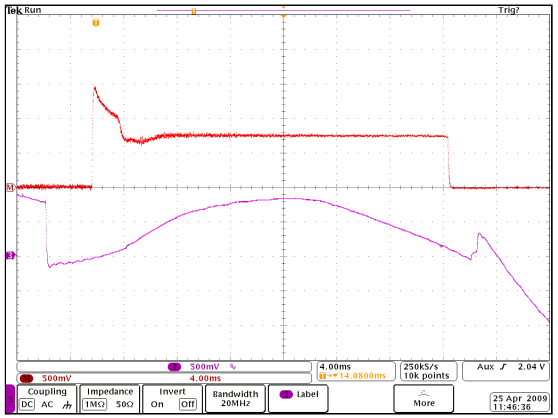
***I*100**: *d*, 16.7 MeV/u (16–17 mA; 40 μs) → (15 mA; 5 μs)



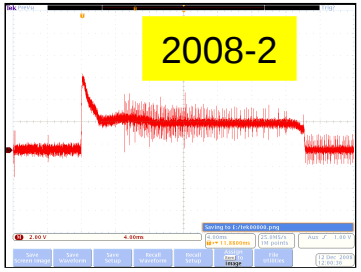


Reserves in matcjng BTL *I*100/*U*1.5 (beam envelopes)

***U*1.5**: *d*, 16.7 – 448.6 MeV/u 50% in-out



Impoved beam diagnostics, compare with

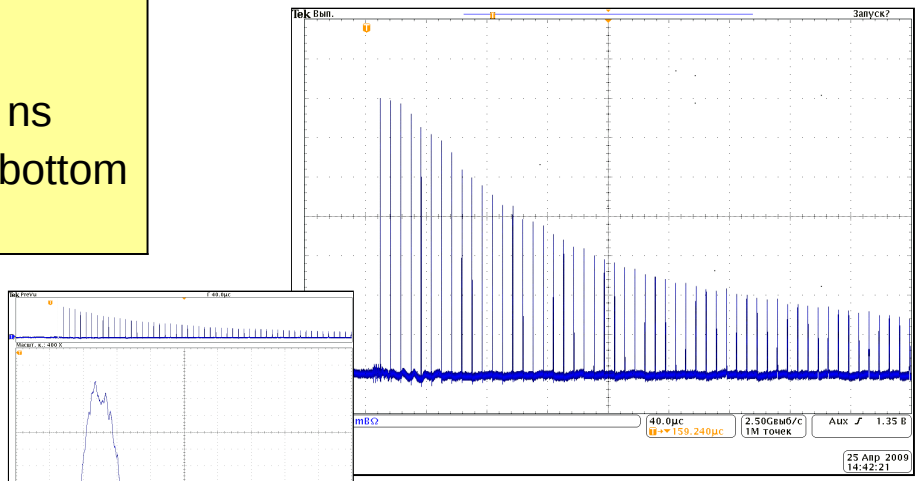


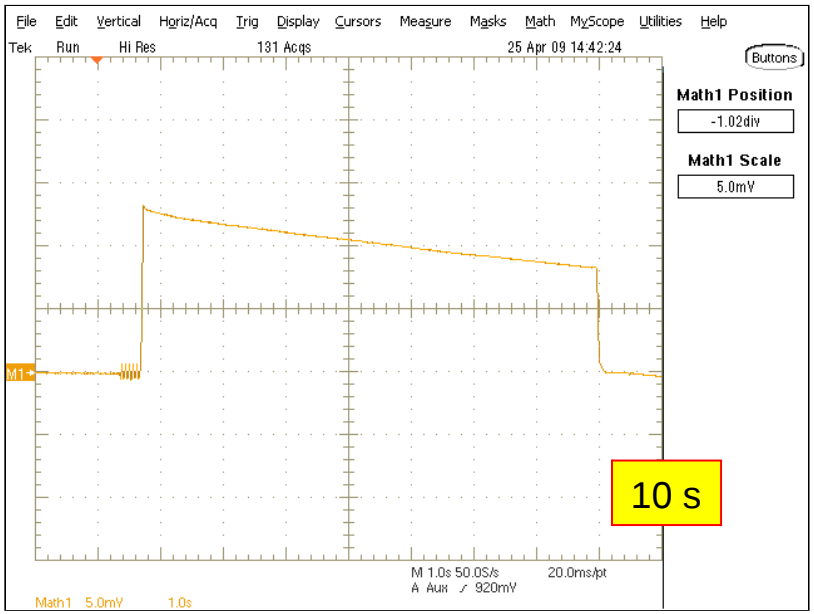
Run 2009-1 (2)

April 25, 2009

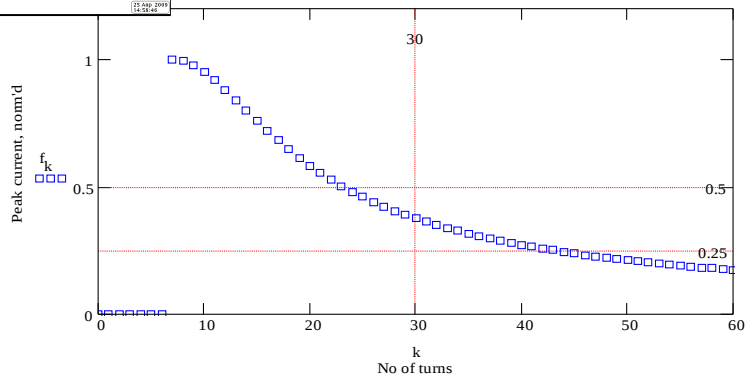
U70: *d*, 448.6 MeV/u coasting
128.38 A DC stand-alone PSU
B = 350.93 ± 0.01 Gauss
$4.5 \cdot 10^{10}$ *d*pp
$\Delta p/p_0 = \pm 3.6 \cdot 10^{-3}$, Δt_{b0} = 100 ns
7.5 s long circulation @ flat-bottom
life time 30–40 s

Rotation period (*d*) 6.72 vs (*p*) 5.44 μs





10 s

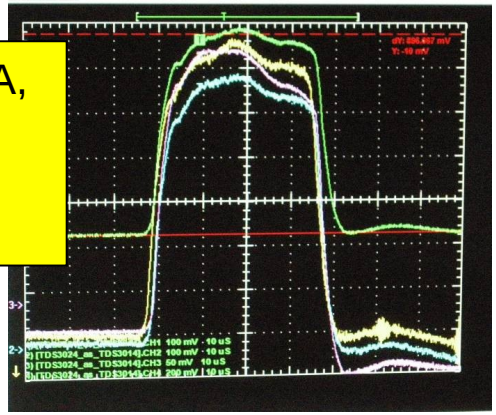


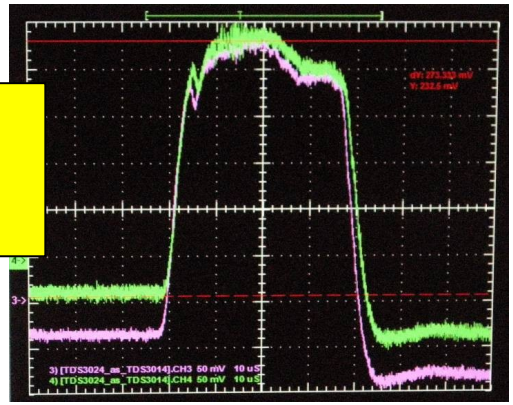
Run 2009-2 (1)

***I*100**: *d*, 16.7 MeV/u
Smooth operation
Idle time = 0 ca

***U*1.5**: *d*, 16.7 – 448.6 MeV/u
Problems with RF capture
Low intensity < 10^{10} *d*pb (by the way, it is C-beam would-be intensity)
Frequent failures with transfer synchronization

d – 19 мА,
40 μs,
No
chopper





BTL *I*100-*U*1.5, in-out 90%

Run 2009-2 (2)

U70: 8 of 40 RF cavities set back to factory defaults

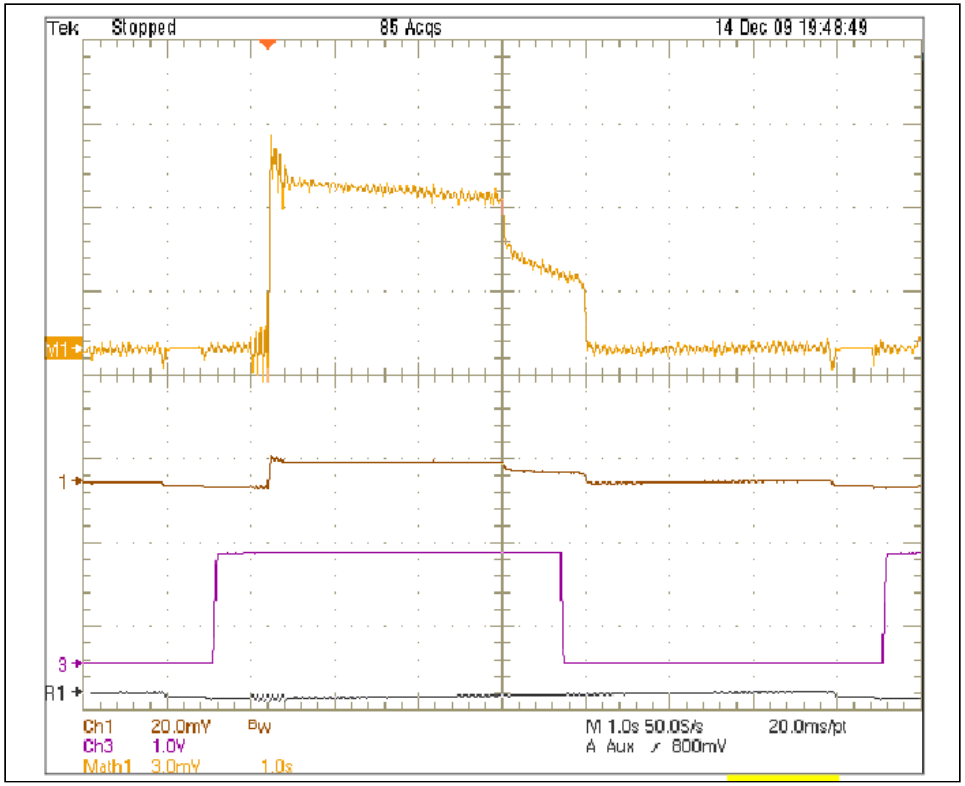
New digital MO

DC stand-alone PSU

Long lasting circulation of azimuthally uniform and **bunched** *d* beams

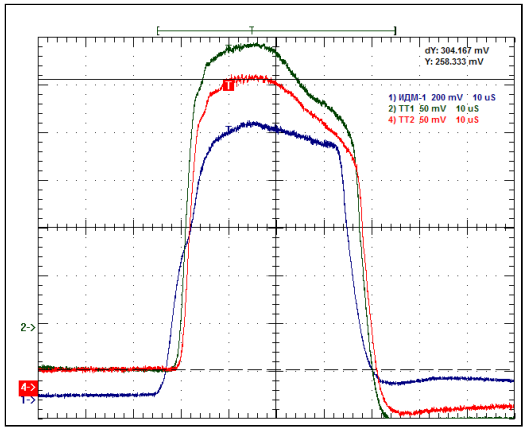
PHASOTRON FIXED-FIELD ACCELERATION OF DEUTERONS

RF +10 kHz (smoothly) whence +3.8 MeV per nucleon followed by beam loss at chamber outer wall



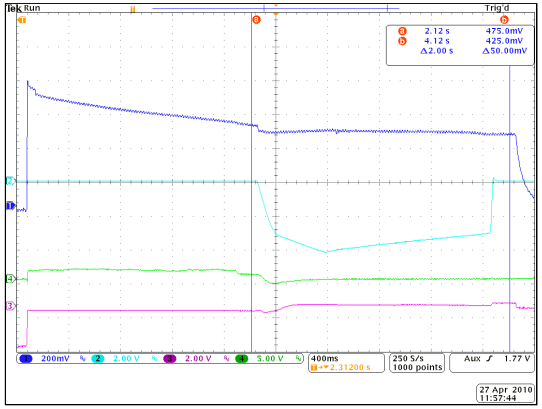
Run 2010-1

***I*100-*U*1.5-*U*70**: Huge scope of preliminary work -- DDS MO, technological feedbacks (gain ×20 & SNR), beam diagnostics (DCCT), transfer synch, pilot low-intensity *p*-bunch *with* $N = 10^{10}$, RF system in *U*1.5 etc



***I*100**: 21 mA *d* pulsed 40 μs 91% in-out in BTL

***U*1.5**: from $1.4 \cdot 10^{11}$ to $8.6 \cdot 10^{10}$ *d*pb in-out

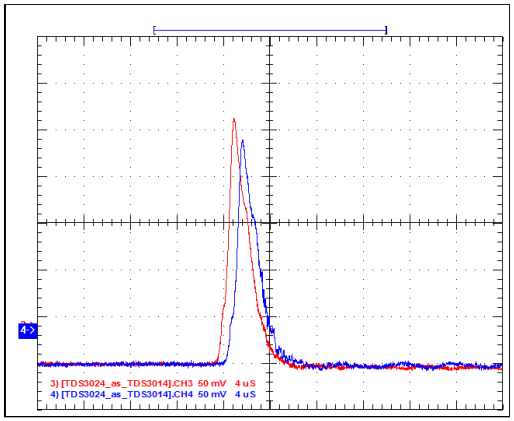


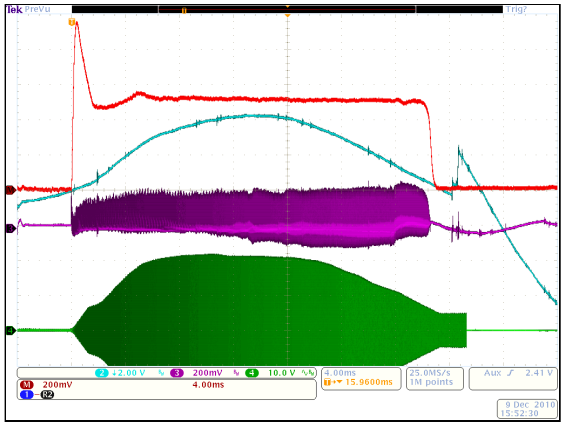
U70: from $4 \cdot 10^{10}$ to $2.5 \cdot 10^{10}$ *d*pb in-out transition crossing

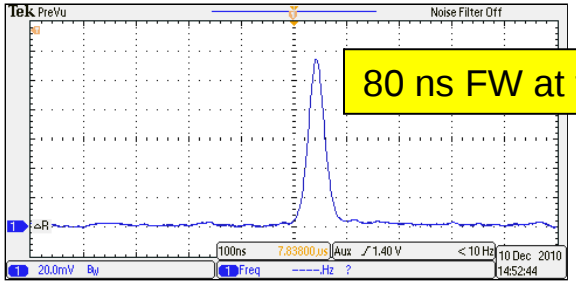
April 27, 2010 Deuterons were accelerated 23.6 GeV/u in the *U*70 (flattop 8441 Gs)

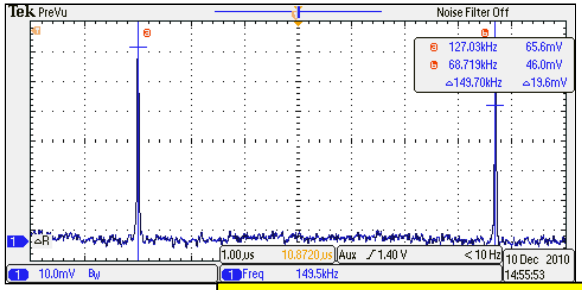
Run 2010-2

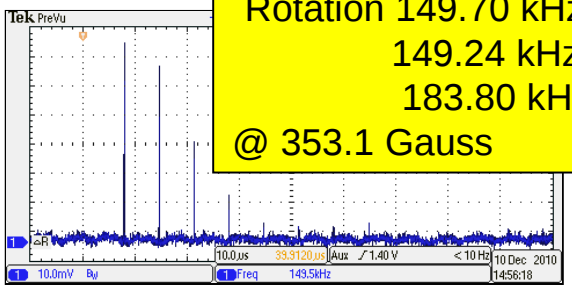
December 8, 2010. Carbon ions were accelerated to 455.4 MeV/u in the *U*1.5 and committed 1st turns around the *U*70 at flat-bottom











***I*100**: max 21 mA $^{12}C^{6+}$
Pulsed 5 μs
91% in-out in BTL

***U*1.5**: from $5.3 \cdot 10^9$ to $3.5 \cdot 10^9$ *C*pb, to 65% in-out

Rotation 149.70 kHz (*C*)
149.24 kHz (*d*)
183.80 kHz (*p*)
@ 353.1 Gauss

U70: 1st turns of *C* around

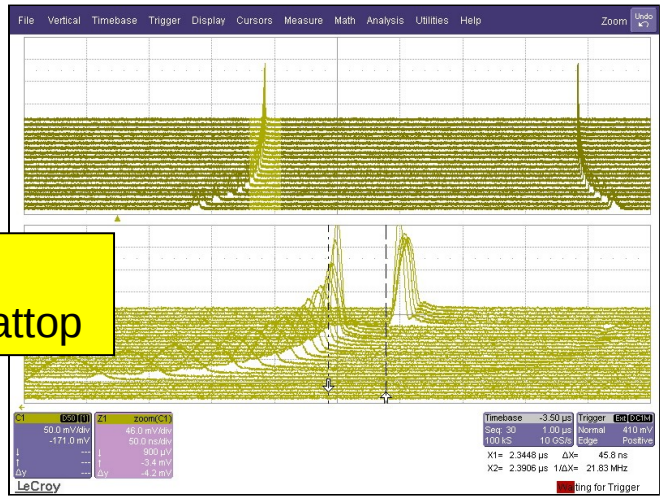
Run 2011-1 (A)

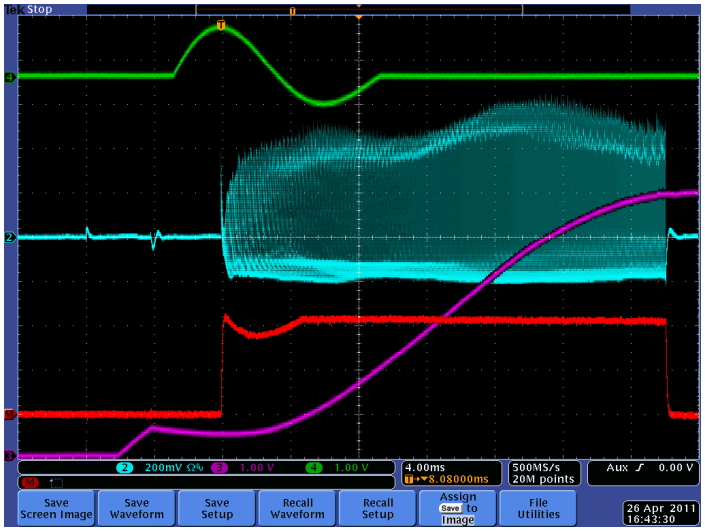
April 24, 2011. Carbon ions were accelerated to top available 34.1 GeV/u in the *U*70, $5 \cdot 10^9$ ipb

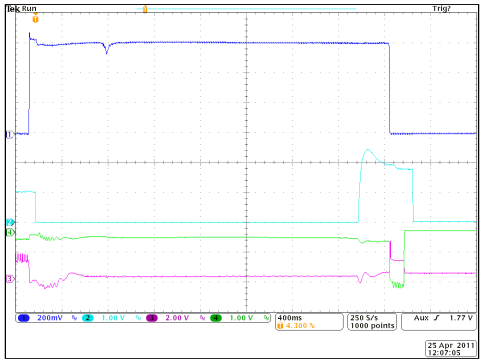
***I*100**: 12-14 max 17 mA $^{12}C^{6+}$
Remote rotation of Graphite Block in LSS ion sourse
800-1000x8 s

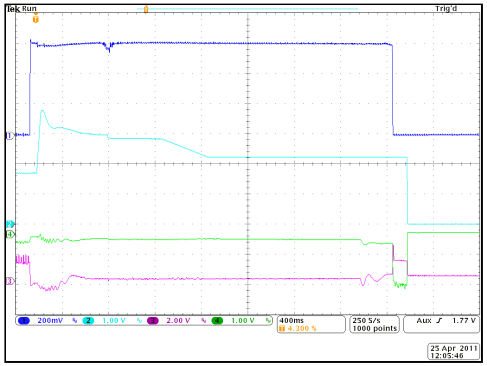
***U*1.5**: smooth & effective operation

U70: transitiom crossing and acceleration to 1.2 T flattop



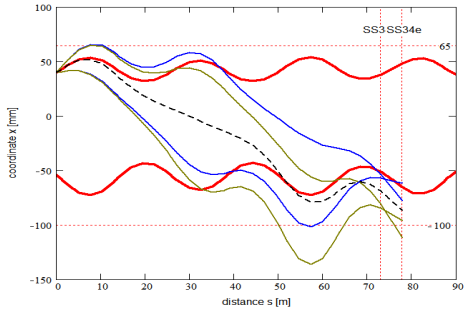


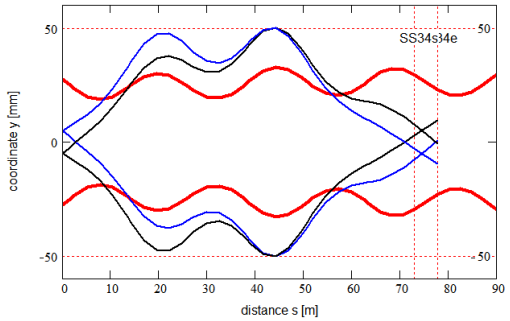


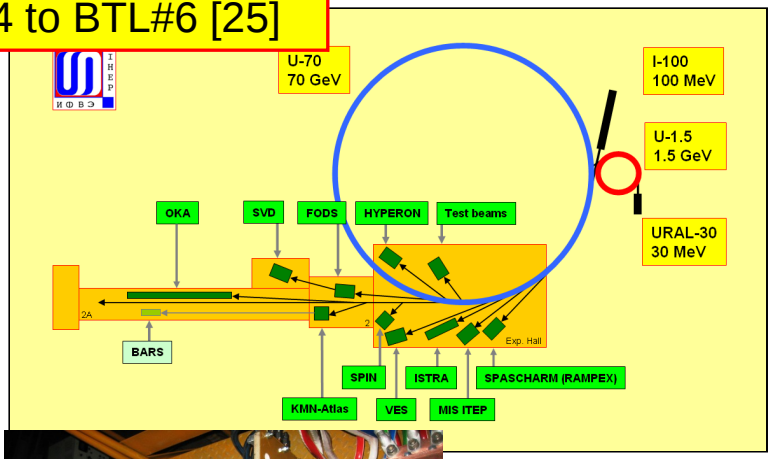


Run 2011-1 (B)

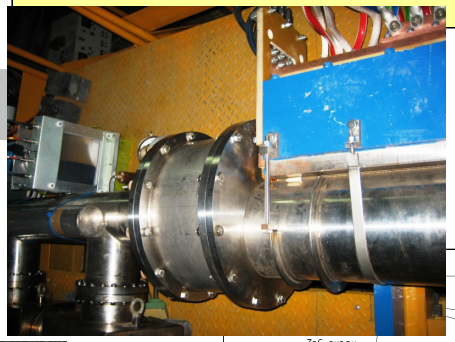
April 24, 2011. First SE of C @ 453 MeV/u from SS#34 to BTL#6 [25]



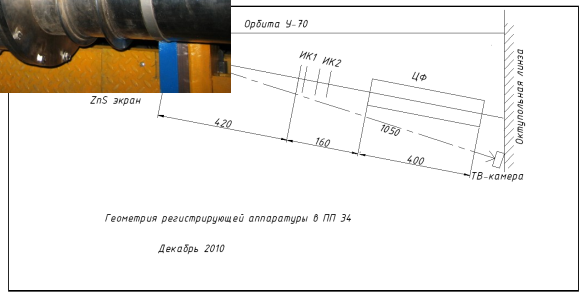




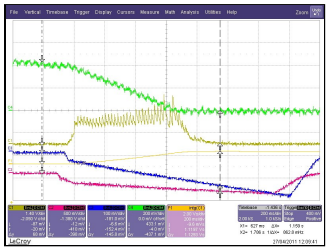
O#34

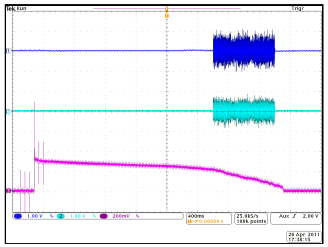


Beam diagnostics

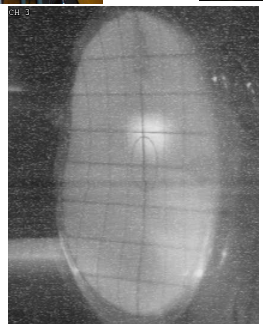


IT#28

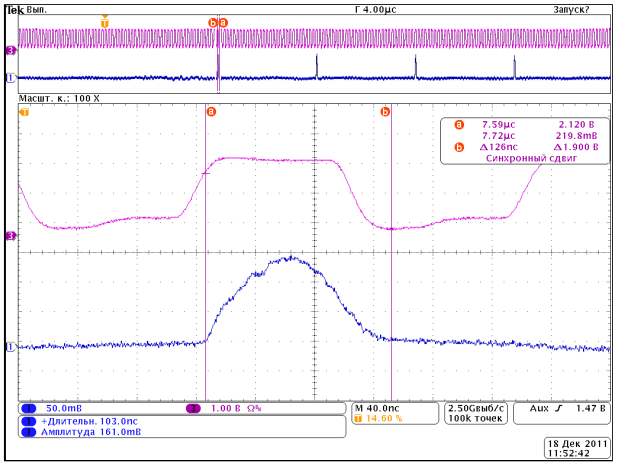


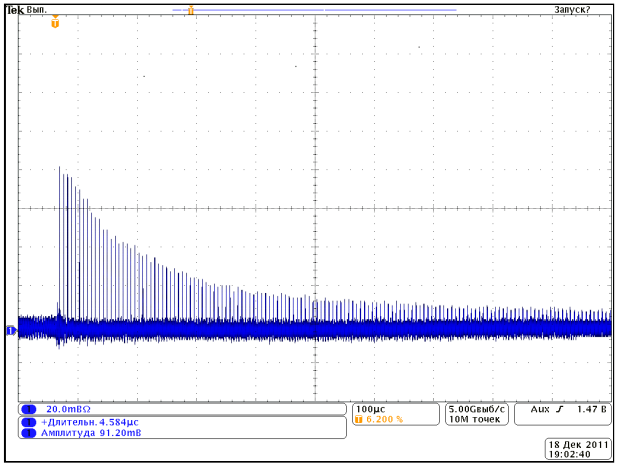


SM#34

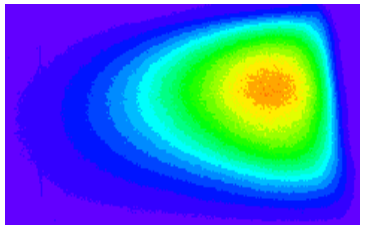


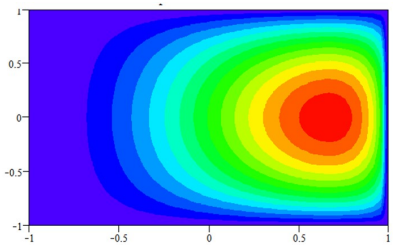
Run 2011-2



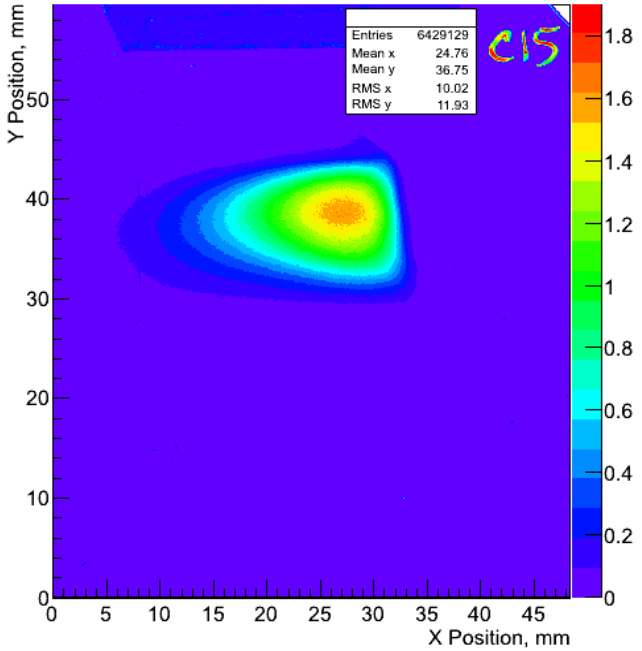


±60 ns. ±1.9·10^{-3}, parano[ic bumch





EBT2 foil, 3 cycles



Run 2012-1 (A)

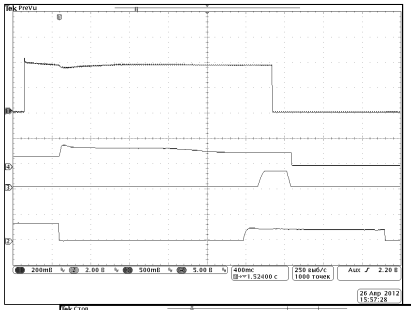
April 24, 2012. C 24.1 GeV/u (flattop 0.859 T) $5 \cdot 10^9$ ipp (8 s).

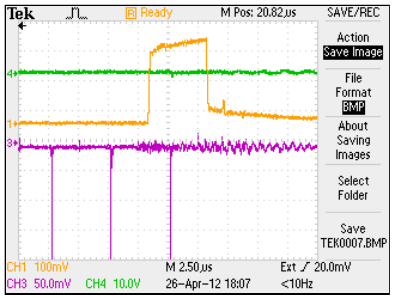
1st ever tests all HE extractions with the C beam

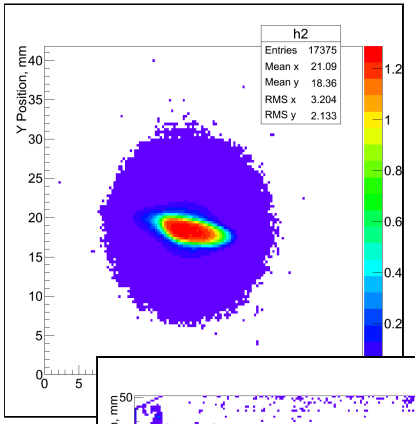
FE

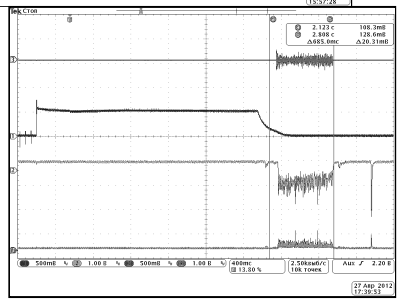
SE

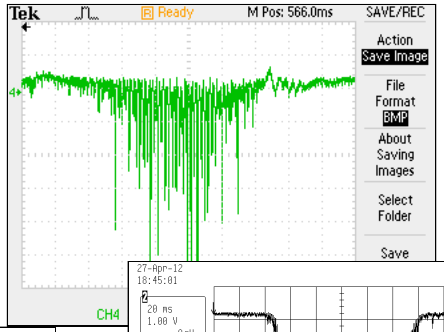
CD#22

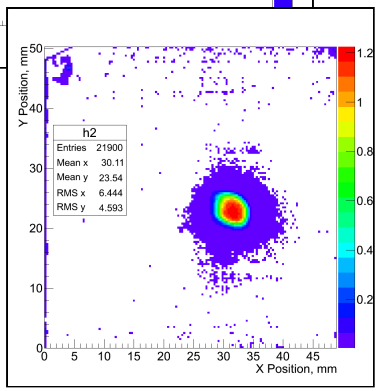


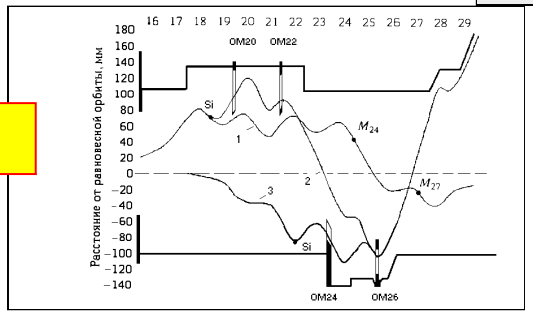


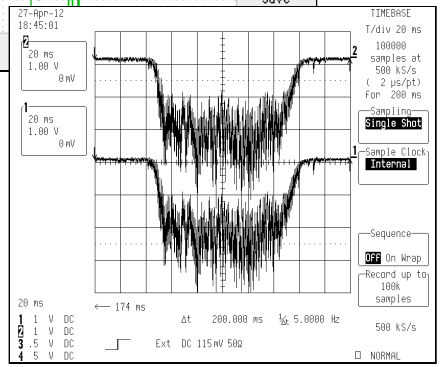








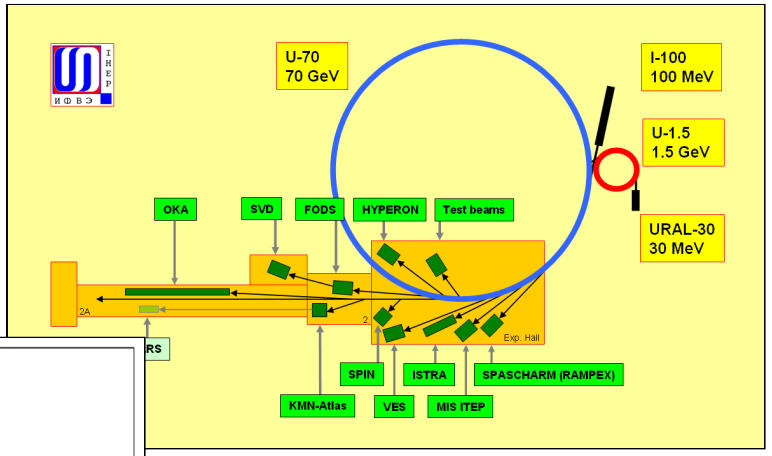




Run 2012-1 (B)

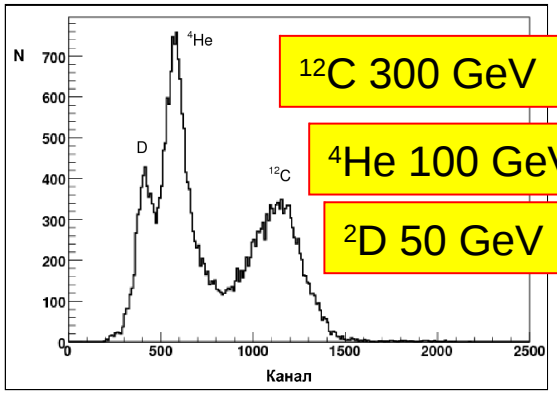
April 27, 2012. 1st ever extracted C beam in 190 m BTL#22 = **FRS** & FODS (a FOcussing 2-arm Spectrometer) experimental facility

24.1 GeV/u or 300 GeV full E



BTL#22 50 GeV/c (p),
25 Gev/c/u q/A=1/2

Hadron calorimeter

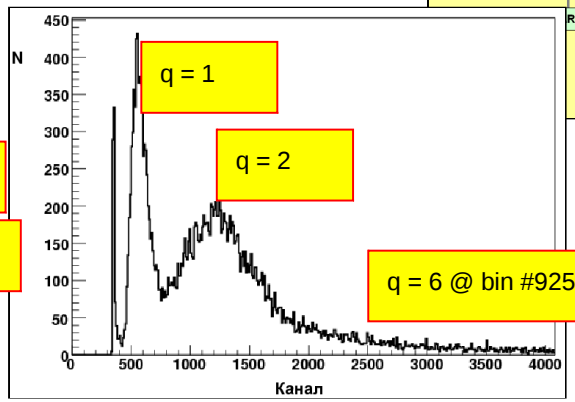


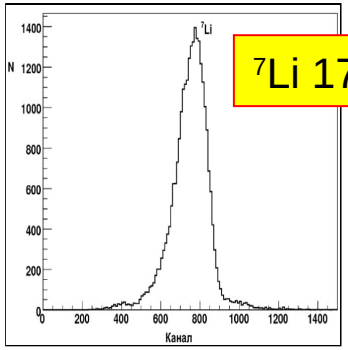
^{12}C 300 GeV

^{4}He 100 GeV

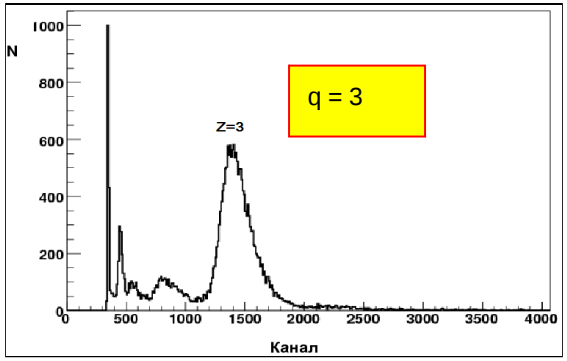
^{2}D 50 GeV

Scintillator counters





^{7}Li 175 GeV



BTL#22 60 GeV/c (p) \pm 1%

a FRS

25.7 Gev/c/u q/A=3/7

Conclusion

Accelerator complex *U*70 of IHEP-Protvino:

- important (POP) milestones of light-ion program are accomplished
- *U*70 is on a way towards routine acceleration abd extraction of light-ions (C) to 24-34 GeV per nucleon for high-energy nuclear physics
- now has slow extraction of 450-5 MeV per nucleon of $^{12}C^{6+}$ beam at U70 flat-bottom (a beam stretcher mode)
- both *U*1.5 and *U*70 are now not only proton but (light-) ion synchrotrons as well
- plans for runs 2012-2 and further foresee operation witn HE and IE C ions, assembly of BTL#25, purchasing a new DC PSU, tests of C beam decceleration, etc
- light-ion program of IHEP-Protvino proceeds at a good (affordable) pace