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Acceleration of Deuterons up to 23.6 GeV per nucleon through I100, U1.5, and U70 of IHEP

(oral WECHA02)

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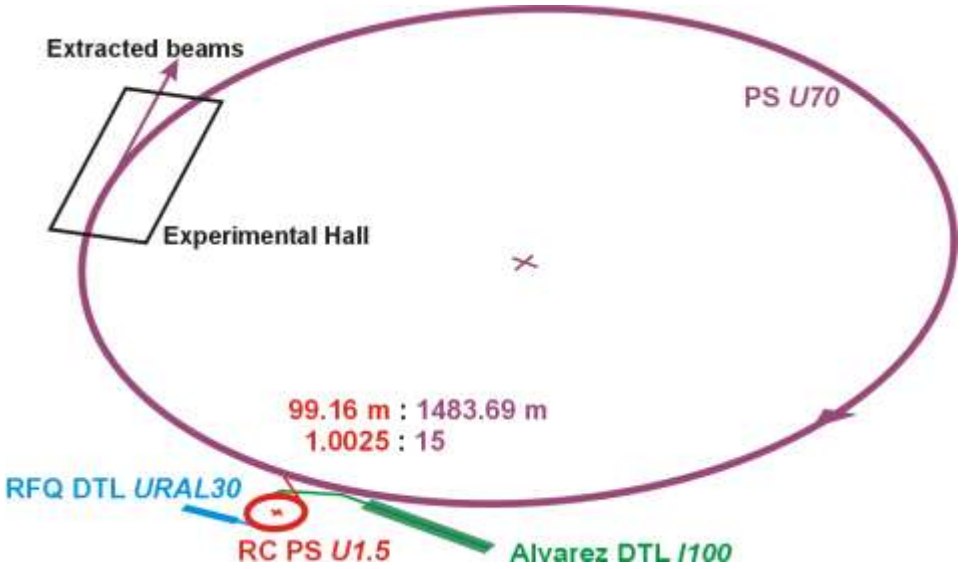
Outlook

- Generalities
- Prehiistory (prior to RuPAC-2008)
- Run 2008-2
- Run 2009-1
- Run 2009-2
- Run 2010-1
- Conclusion

General



	*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	$2 \cdot 10^{-7}$	$5 \cdot 10^{-7}$

*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
- 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 $q/A = 1/2$

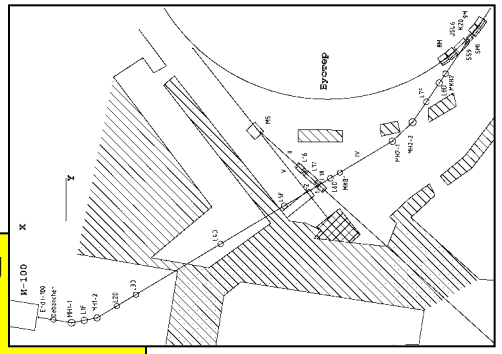
Reference ions:
- $_1H^{1+}$ protons, *p*
- $_2H^{1+}$ deuterons, *d*
- $_{12}C^{6+}$ carbon

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

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 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

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

Prehistory @ *U*70

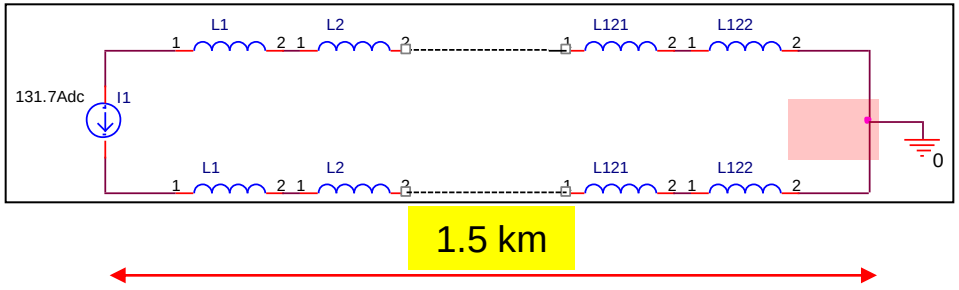
1st MD of 2008: beam test with a stand-alone DC power supply unit for the *U*70 ring magnet

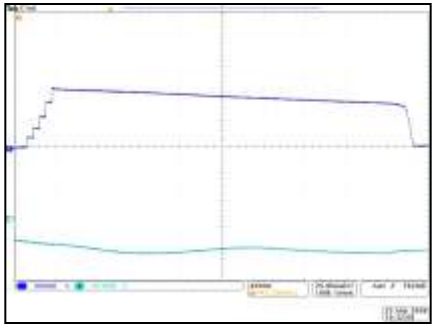
Goal:
- cheap MD runs (1.32 GeV *p*, 0.45 GeV/u *d*, C);
- storage/stretcher ring of light ions 450 MeV/u;
- medical applications of C beams

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

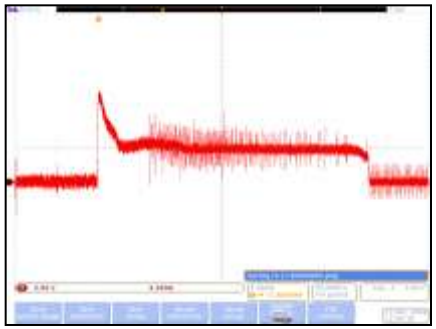


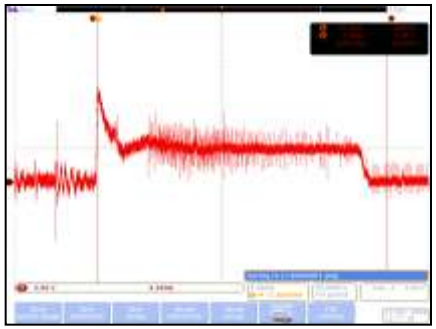


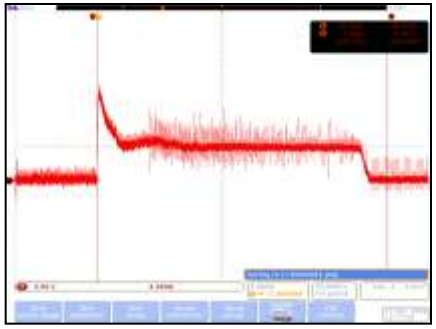
354 ± 0.05 Gauss

Run 2008-2

***U*1.5**







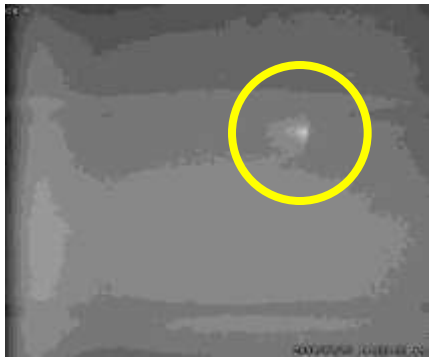
10–12.12.08; *d*; 16.7– 455 MeV/u, 2nd time in record of service

U70

Preparatory activity:

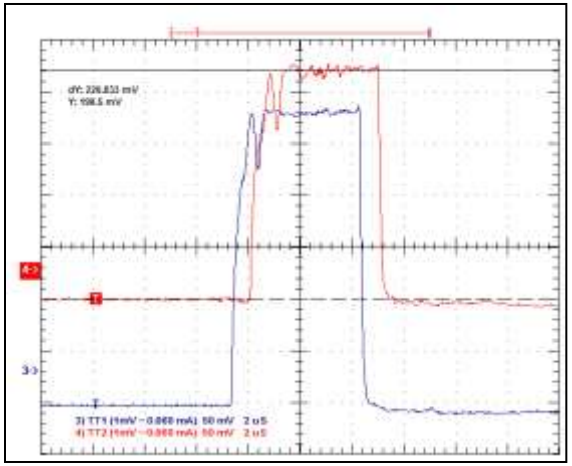
1. Standalone DC PSU (131.1 A) of ring magnet
2. Coasting *p* @1.32 GeV (354 Gauss)
3. Injection of *p* under RT off
4. Imitation of low-*N* *d*-bunch, $3 \cdot 10^{10}$ ppb
5. Settling issued DC CT…

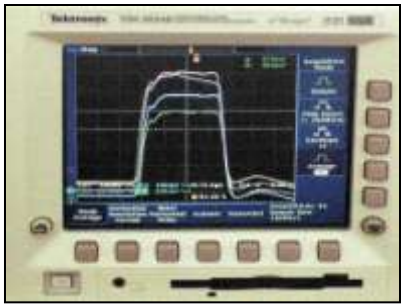
d in U70 after 4 bending magnets, sc screen in SS10



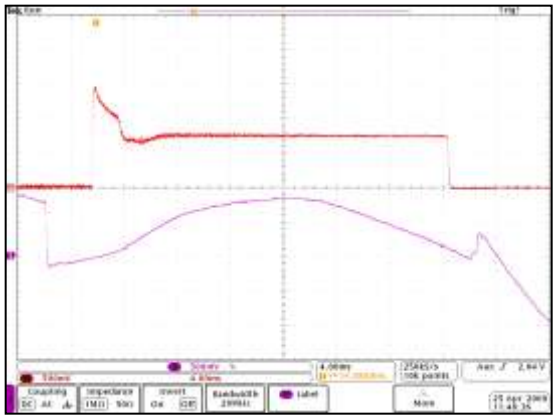
Run 2009-1 (1)

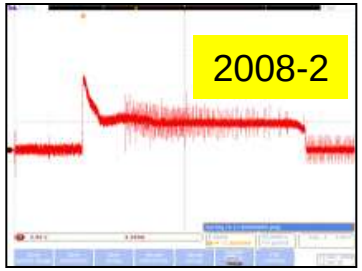
***I*100**: *d*, 16.7 MeV/u (16–17 mA; 40 μs) → (15 mA; 5 μs)





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





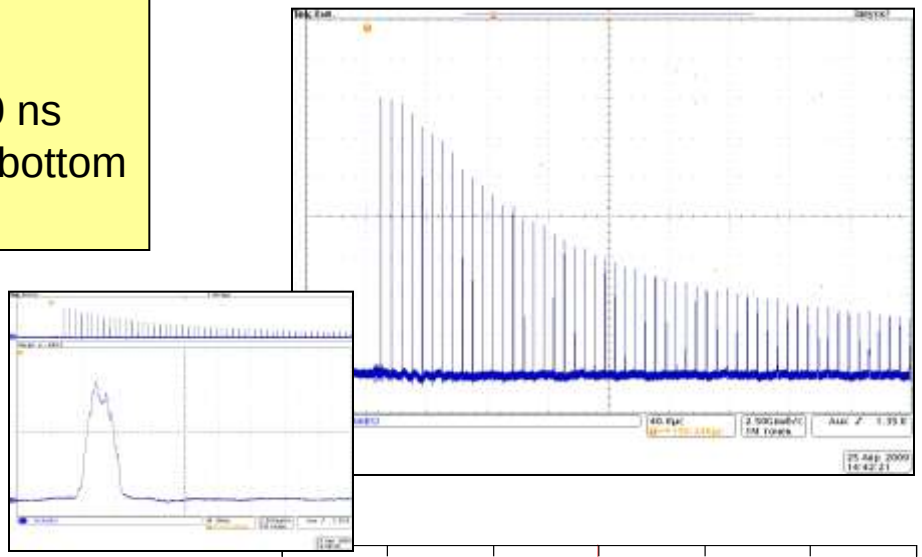
Reserves in matcjng BTL *I*100/*U*1.5 (beam envelopes)

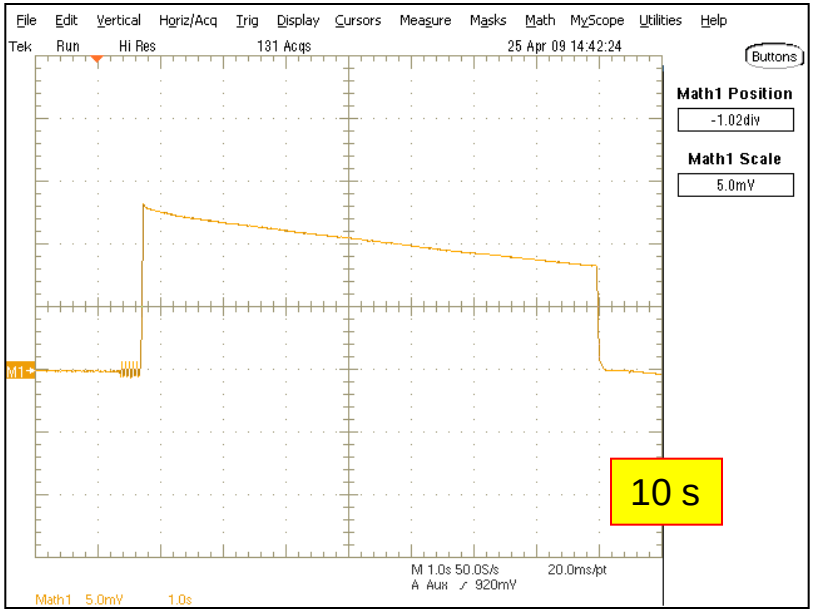
Run 2009-1 (2)

April 25, 2009

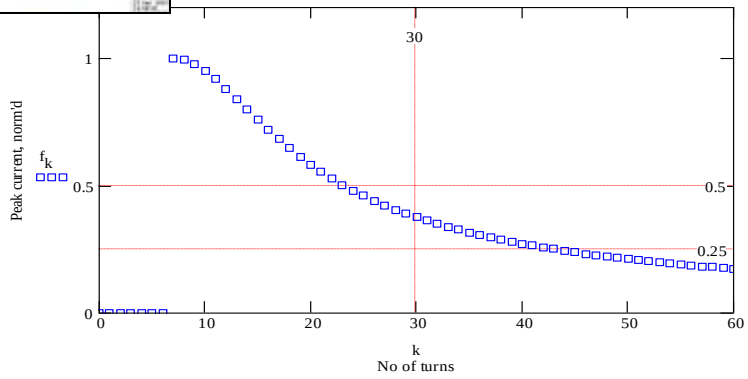
U70: *d*, 448.6 MeV/u coasting
128.38 A DC stand-alone PSU
B = 350.93 ± 0.01 Gauss
$4.5 \cdot 10^{10}$ *d* p p
$\Delta p/p_0 = \pm 3.6 \cdot 10^{-3}$, Δt_{b0} = 100 ns
7.5 s long circulation @ flat-bottom
life time 30–40 s

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





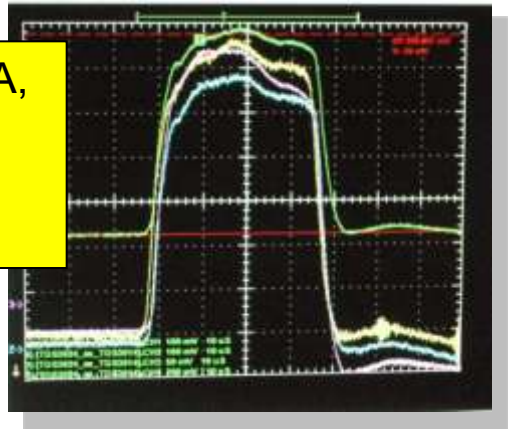
10 s

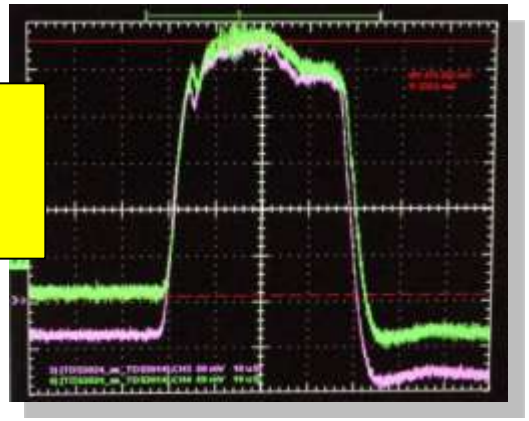


Run 2009-2 (1)

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

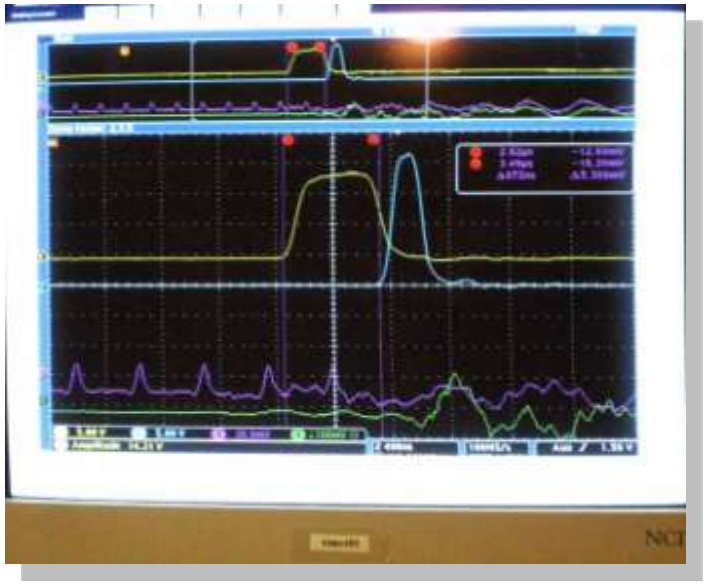
d – 19 мА,
40 μs,
No
chopper





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

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



Run 2009-2 (2)

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

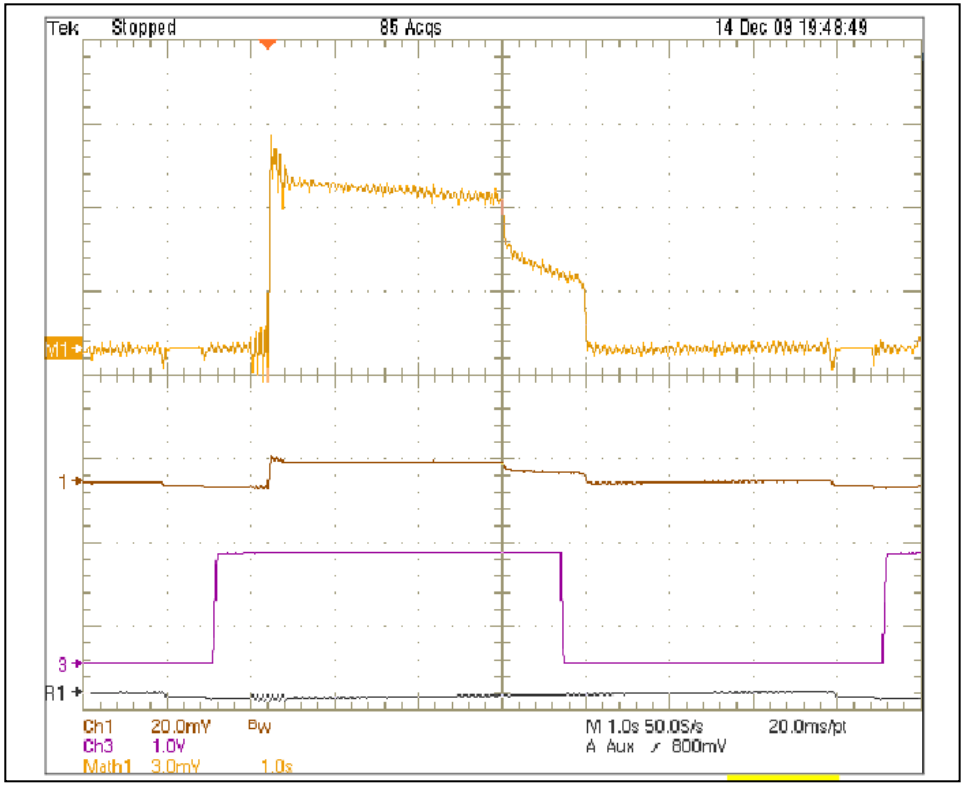
New digital MO

DC stand-alone PSU

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

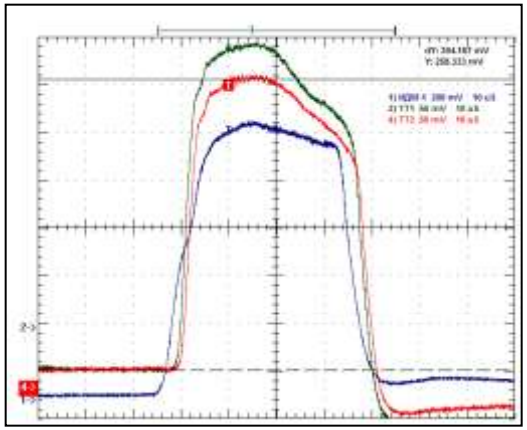
PHASOTRON FIXED-FIELD ACCELERATION OF DEUTERONS

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

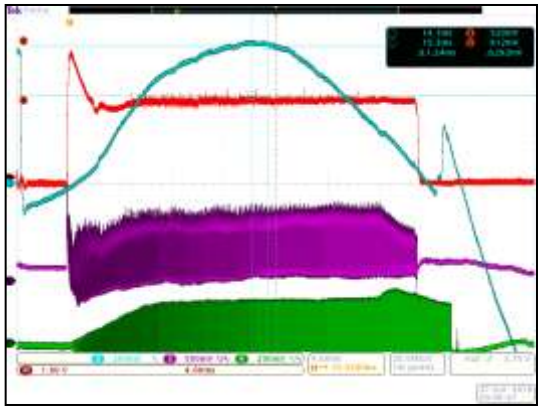


Run 2010-1

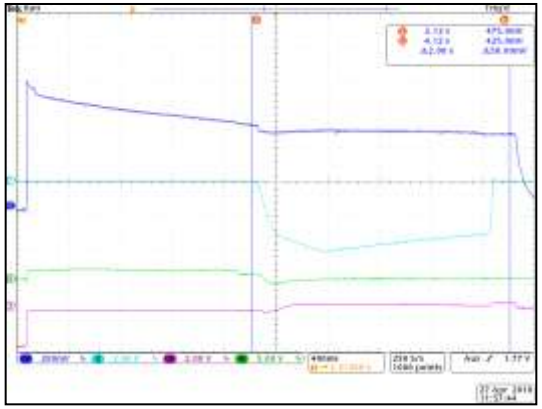
***I*100-*U*1.5-*U*70**: Huge scope of preliminary work -- DDS MO, technological feedbacks (gain ×20 & SNR), beam diagnostics (DCCT), transfer synch, pilot low-intensity *p*-bunch *with* $N = 10^{10}$, RF system in *U*1.5 etc



***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

Conclusion

Accelerator complex *U*70 of IHEP-Protvino:

- important (POP) milestone of light-ion program in *U*70 is accomplished
- *U*70 is on a way towards routine acceleration of light-ions to 34 GeV per nucleon
- both *U*1.5 and *U*70 are now not only proton but (light-) ion synchrotrons as well
- plans for runs 2010-2 and 2011-1 foresee operation witn C ions and tests of a slow extraction system on a flat-bottom DC *B*-field of *U*70 (beam stretcher mode)
- light-ion program of IHEP-Protvino proceeds at a good pace