Status and prospects of development of the Protvino accelerator complex

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3rd International Conference on Particle Physics and Astrophysics (3rd ICPPA 2017)
Moscow, NRNU MEPHI, October 2-5, 2017

Outlook

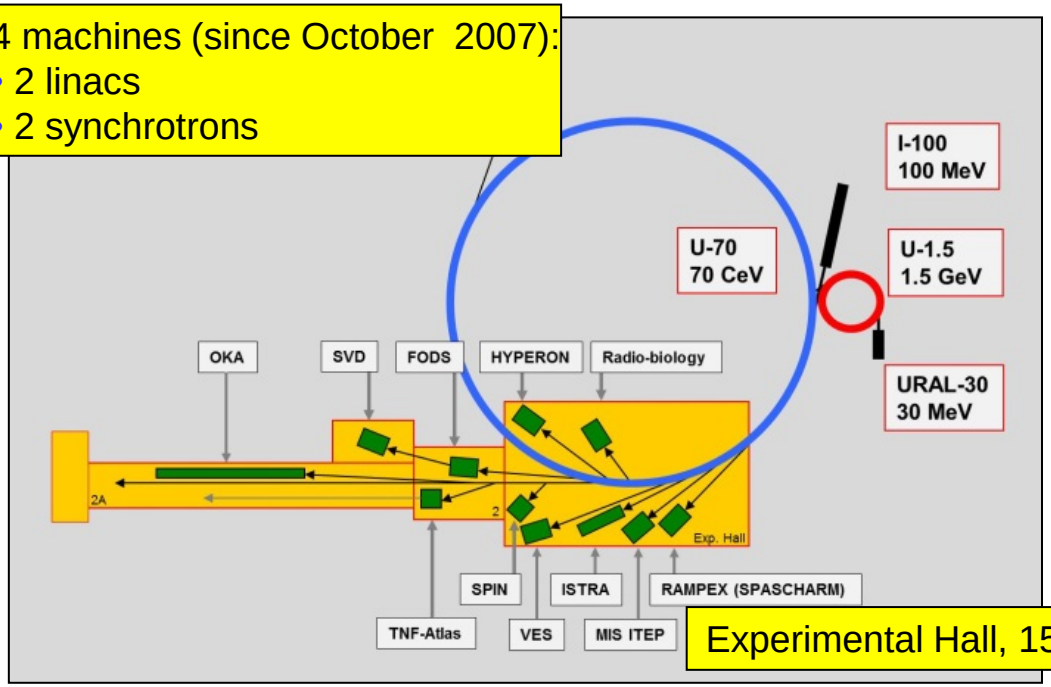
- Generalities
- Runs
- Upgrades
- Acceleration of light ions
- Prospects of development
- Conclusion

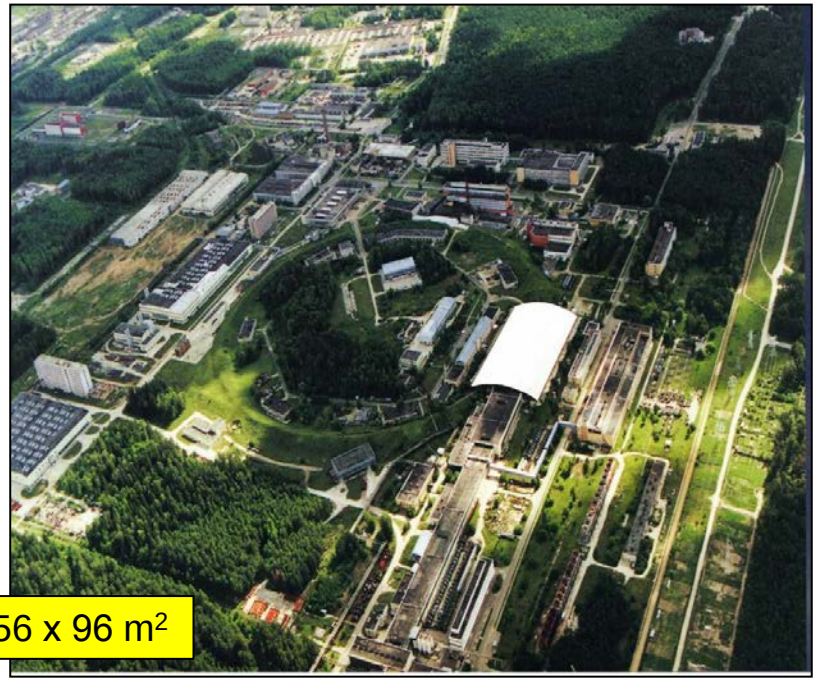
Accelerator Complex U-70 & synchrotron U-70 per se

“Register of unique nuclear physics facilities …”approved by the RF Government order issued on December 30, 2009, No. 2125-p

Layout, AC U-70 vs the U-70 proper

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





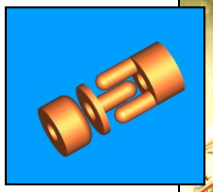
Experimental Hall, 156 x 96 m^2

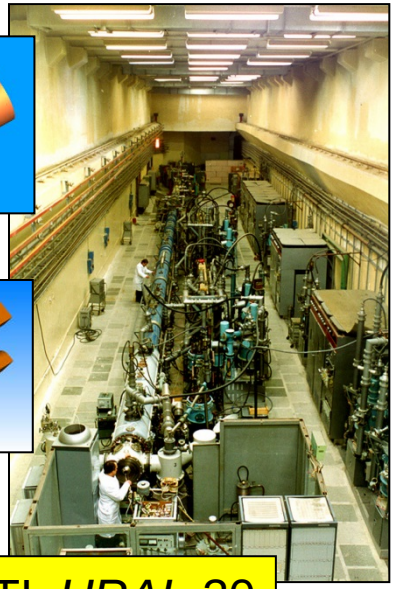
Modes:
- *p* (default, [25] 50-70 GeV) *URAL*-30/*U*-1.5/*U*-70
- light-ion (C, complementary) *I*-100(2 of 3)/*U*-1.5/*U*-70

Light-ion (*C* nuclei):
- (very) high energy 24.1-34.1 GeV/u
- intermediate (though high) energy 453-455 MeV/u

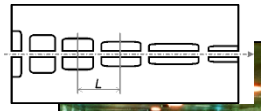
In the SIS-18, SIS-100 name convention:
- LIS-233 [T·m]
- LIS-6.9 [T·m]

Photo album of the machines

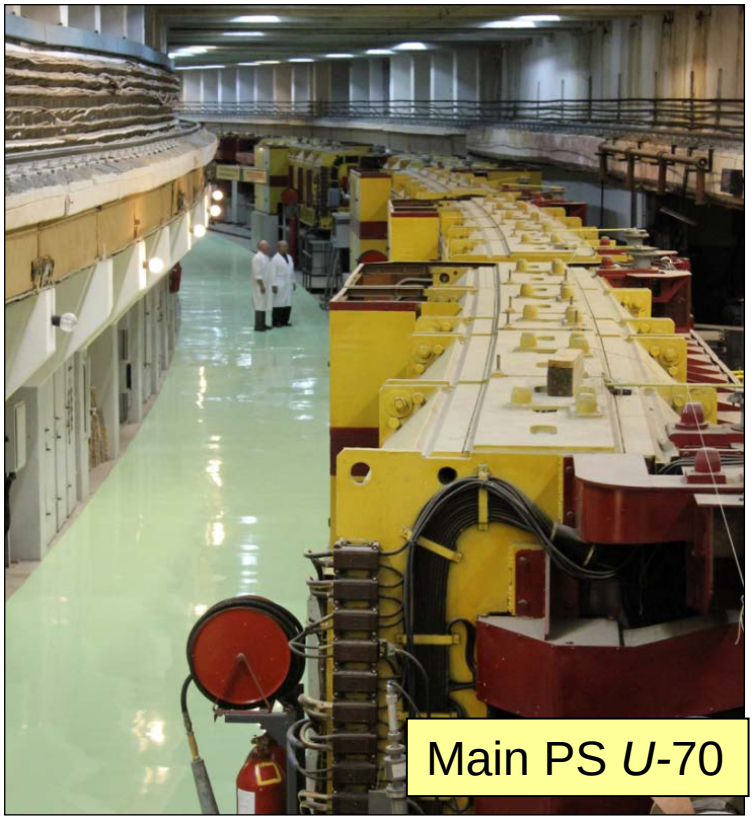




RFQ DTL *URAL*-30

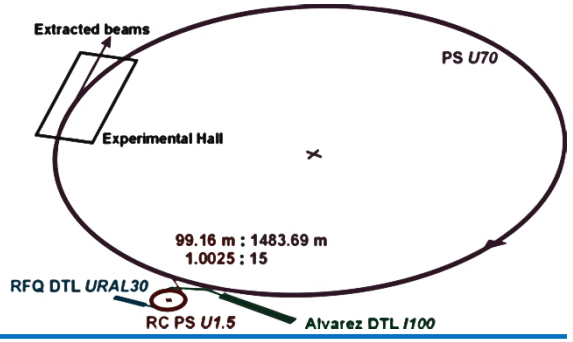


Alvarez DTL *I*-100

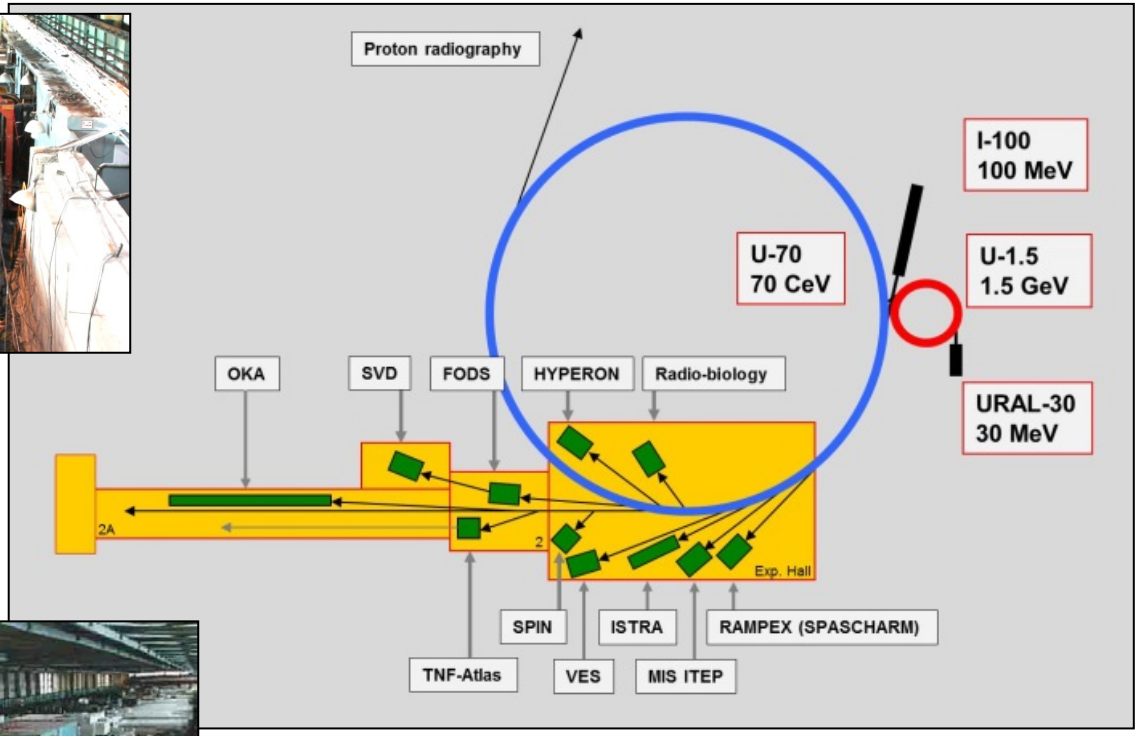


Main PS *U*-70

RC PS *U*-1.5



Fixed-target physics and BTL network



Beams of
p, π, *K*, *e*, ν, *C*

Fields of HEP research:
- *h* spectroscopy
- spin physics
- rare *K*-decays
- *h-A* interactions
- nuclear physics
- [ν physics]

Applied research:
- *p* radiography
- *C* radiobiology
- …

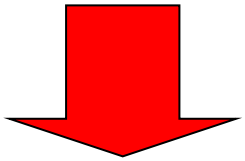
Collaborators:
IHEP, ITEP, JINR,
INR, St.-Pb NPI, BINP,
SINP MSU, NRNU
MEPHI, CERN, …
VNIIEF, MRRC NMRRC
ITEB, IMBP, FMBC…

Up to 9 HEP experiments (= No of setups) per a run,
Up to 7 beam users per a cycle

Goals of activity with accelerators

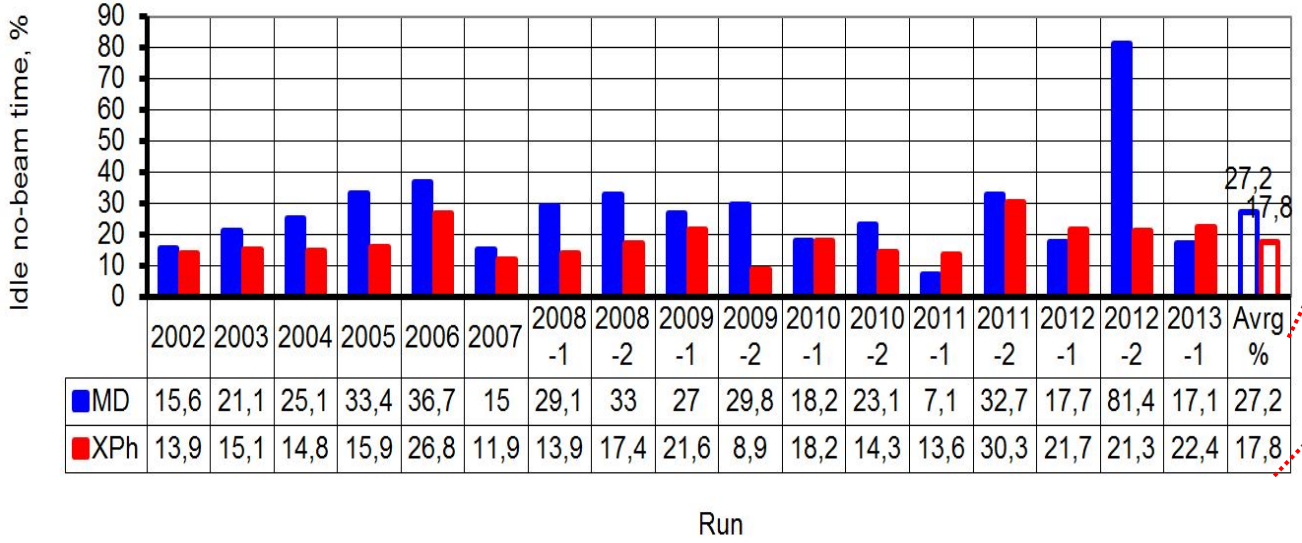
3 [4] goals:

- Regular runs: stable operation and high *p*-beam availability in the 7/24 regime, via proper maintenance
- Improve *p*-beam quality (lower ε, higher *N*, up to $3 \cdot 10^{13}$ ppp), and relevant upgrades
- Implement a complementary light-ion program, $q/A = 0.4–0.5$ (carbon nuclei)
- [Assess other diversification and development options]



U-70 as an universal hadron accelerator complex
- of protons and carbon nuclei
- with high and intermediate energies
- via slow and fast extractions
- for fundamental and applied research in the “fixed target” domain

Statistics



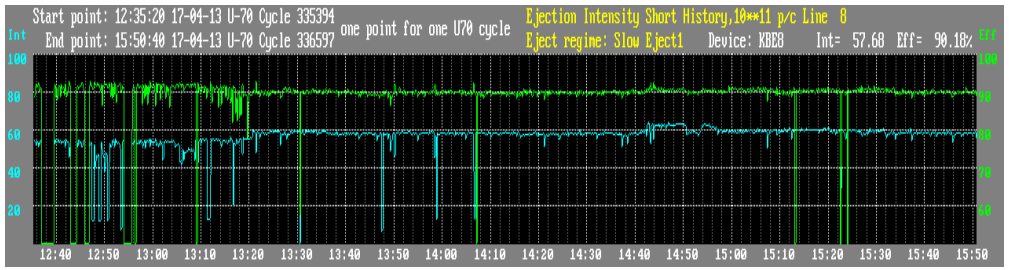
	2002	2003	2004	2005	2006	2007	2008 -1	2008 -2	2009 -1	2009 -2	2010 -1	2010 -2	2011 -1	2011 -2	2012 -1	2012 -2	2013 -1	Avrg %
MD	15,6	21,1	25,1	33,4	36,7	15	29,1	33	27	29,8	18,2	23,1	7,1	32,7	17,7	81,4	17,1	27,2
XPh	13,9	15,1	14,8	15,9	26,8	11,9	13,9	17,4	21,6	8,9	18,2	14,3	13,6	30,3	21,7	21,3	22,4	17,8

Avrg %
27,2
17,8

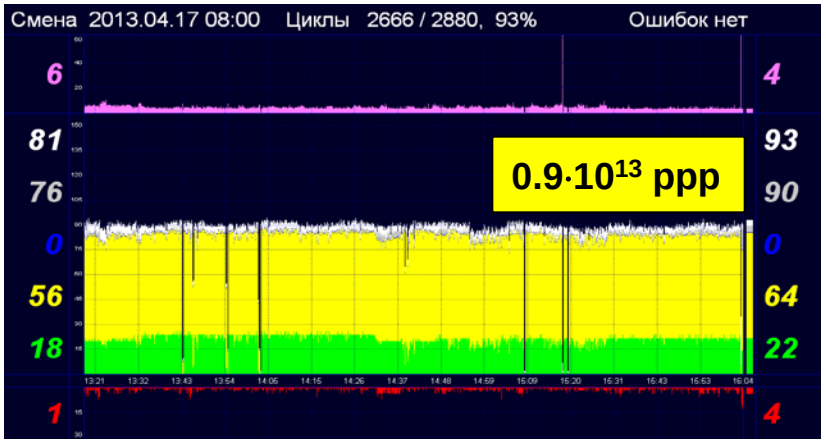
Fractional beam availability for physics = 82.2%

2013 -2	2014 -1	2014 -2	2015-1
n/a	n/a	16.2	on

2 runs (7/24) per year:
- short (XPh 10 days ca) 2 MD(*p*) + ions
- long (XPh 30 days ca) 3 MD(*p*) + ions



Run 2013-1, SSE out/in 90-94% 1-6.5·10^{12} ppp

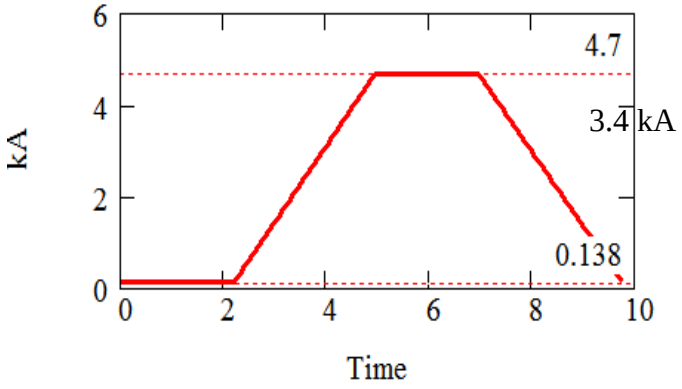


← **3 hr, or 1000 cycles** →

Extraction (fixed target, multi-user)

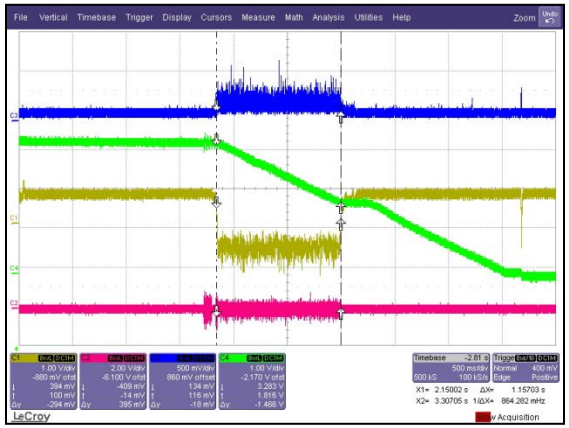
Inventory:

- 1-turn/1-bunch FE
- SRE (Q38 & SSE (new))
- IT (secondary's)
- bent Si-CD SE (new)
- flat-bottom (S)SE (new)
- Mt(4-10)FE (new)

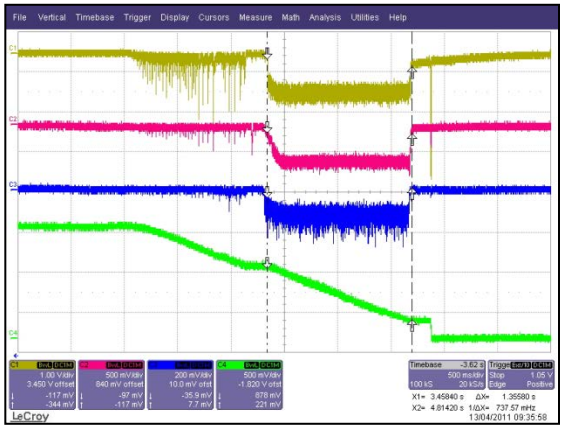


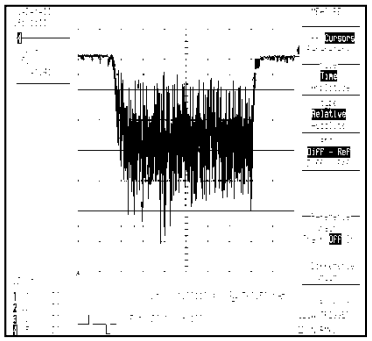
Sequential and parallel flattop sharing

1st ½ of a flattop, SSE

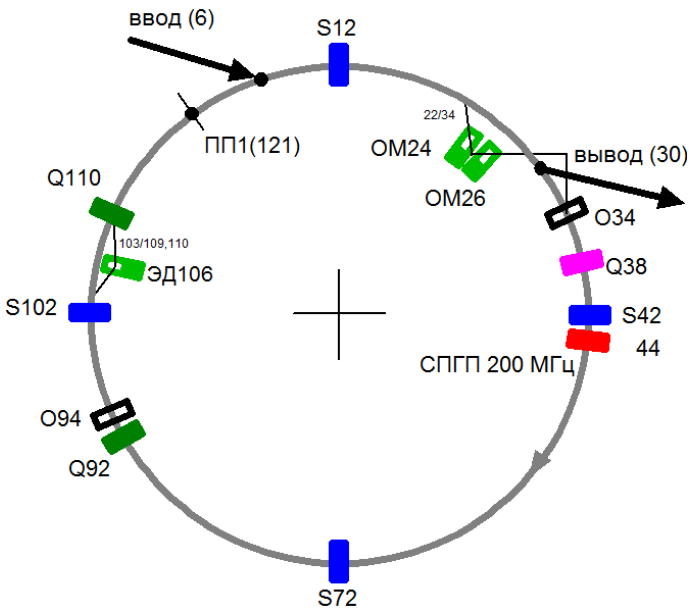


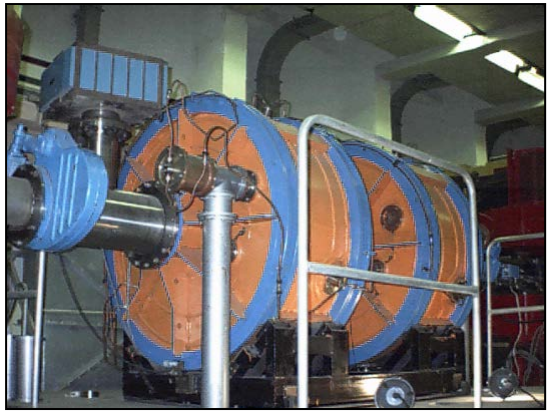
2nd ½ of a flattop, IT & CD





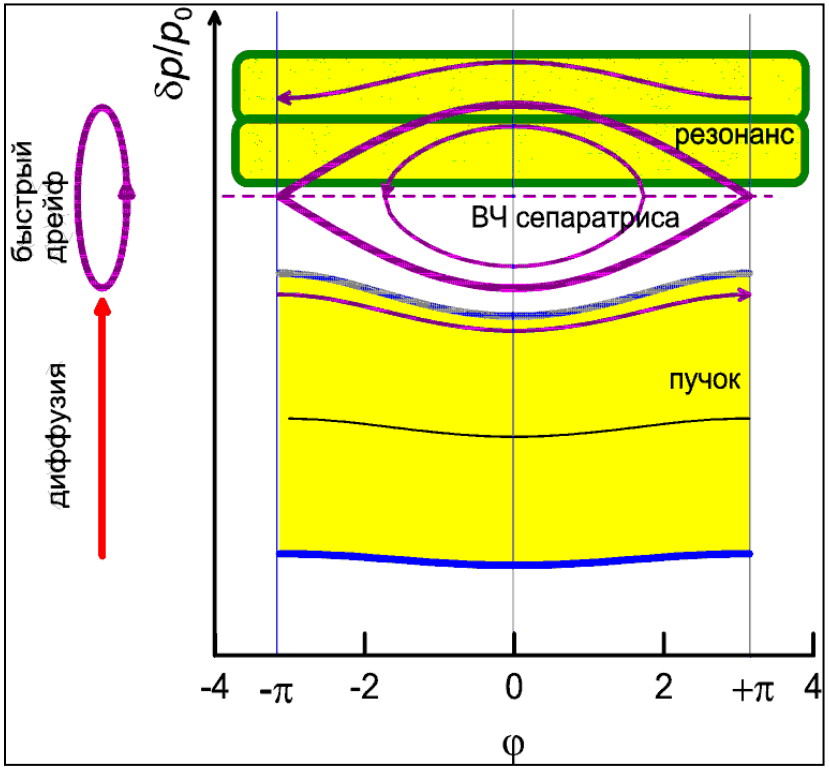
Slow stochastic extraction





200 MHz RF system

3rd integer horizontal resonance $3Q_x = 29$

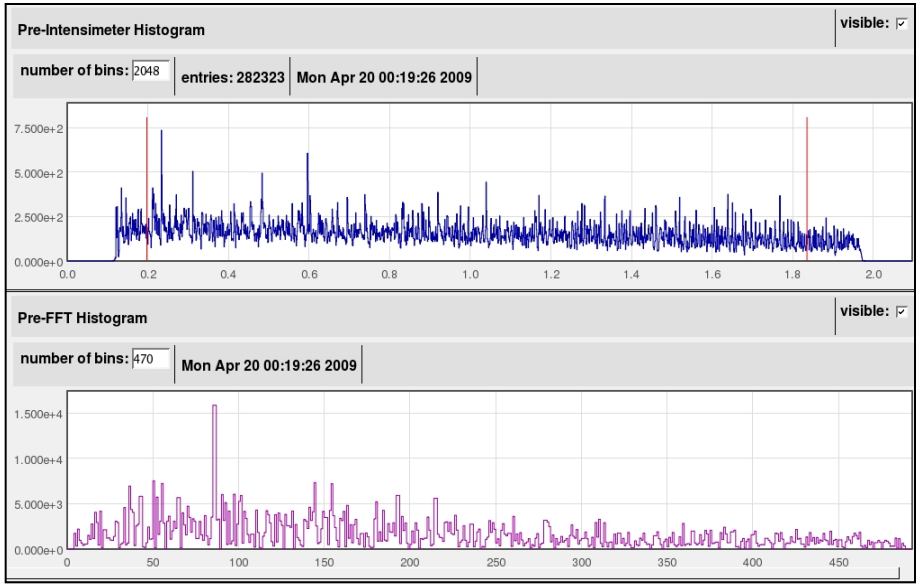


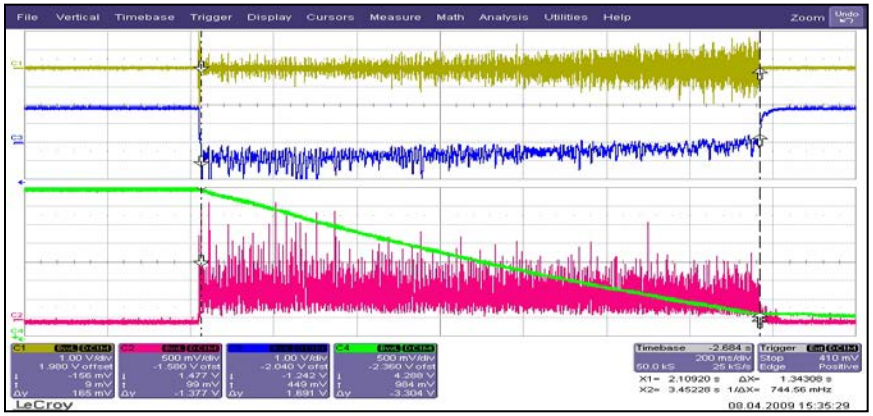
Slow extraction & the OKA experiment

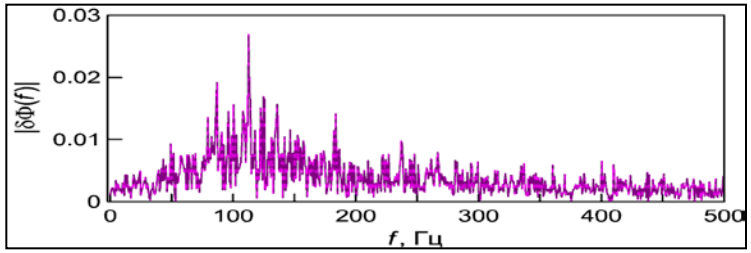
Data: run 2009/1

Technological dara from the *U*70

Data from the OKA facility counters



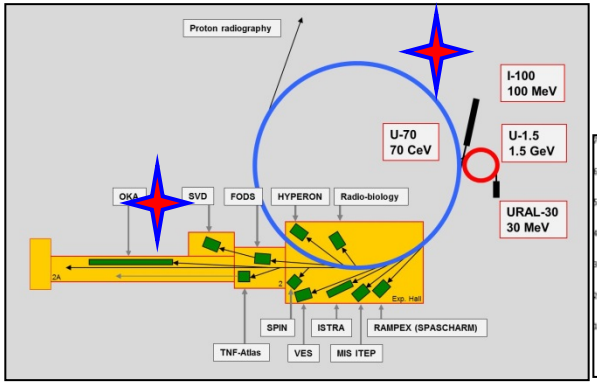




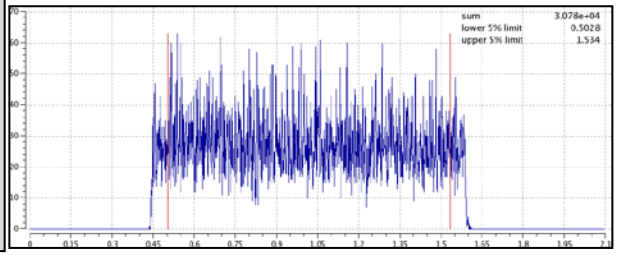
Spill 1.85 s long

$0.95 \cdot 10^{13}$ *p* per a spill

50 GeV

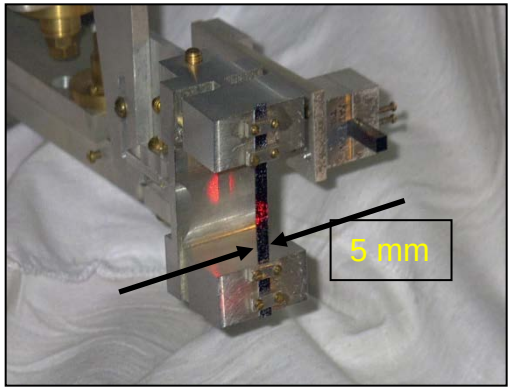


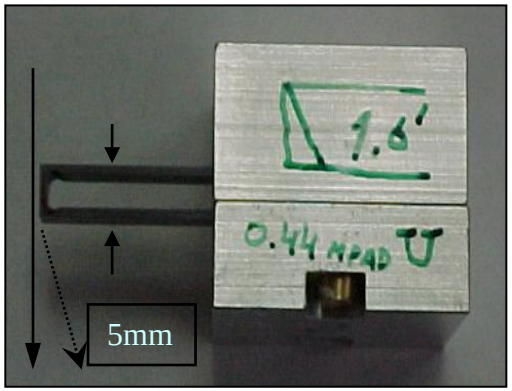
duty factor $\langle\Phi\rangle^2/\langle\Phi^2\rangle$ to 0.94.
No lines of mains harmonics

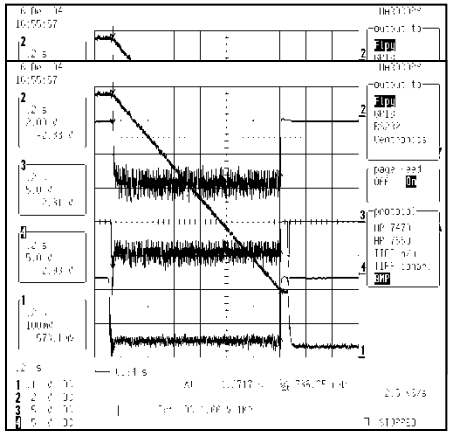


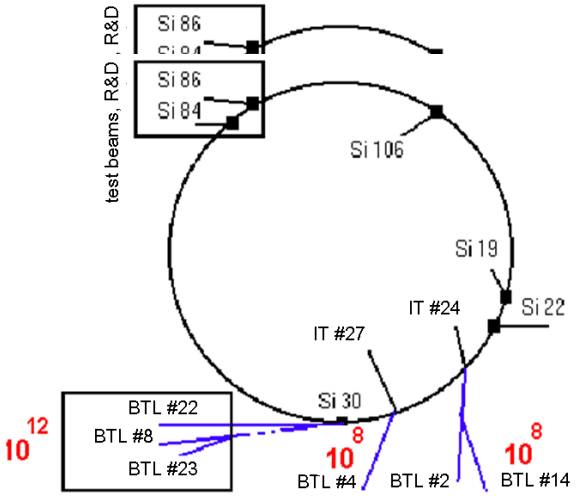
Bent-crystal (Si) deflectors

Run2007: 3 CD(19, 24, 30)
6 experiments





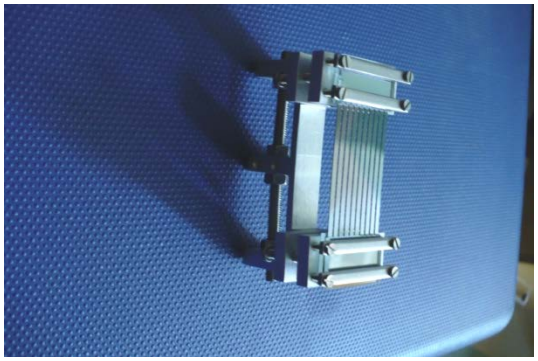




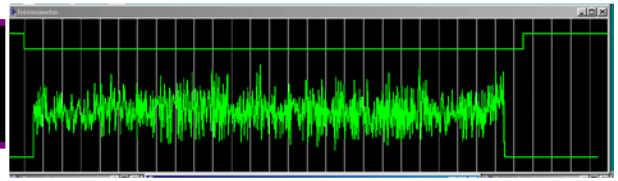
CD19

IT24

IT27

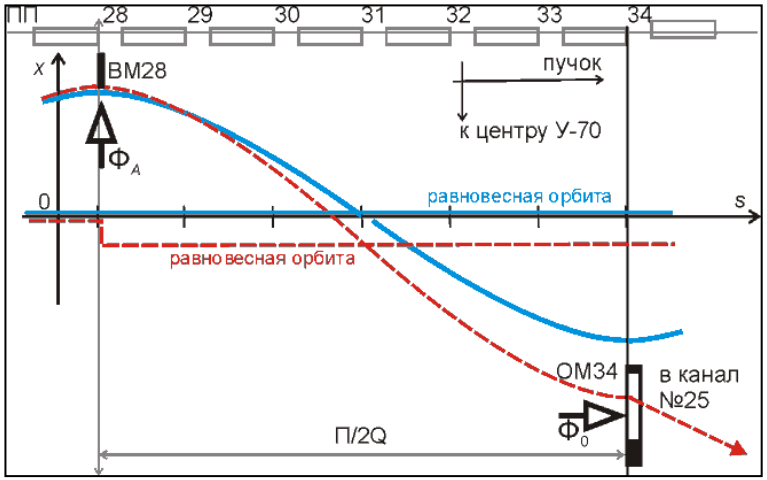


Beam to IHEP-CERN experiment
on radiation sustainability of liquid Ar

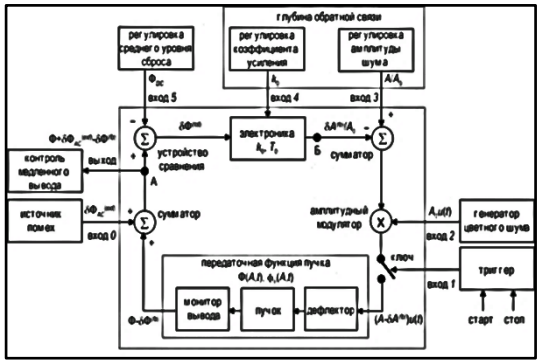


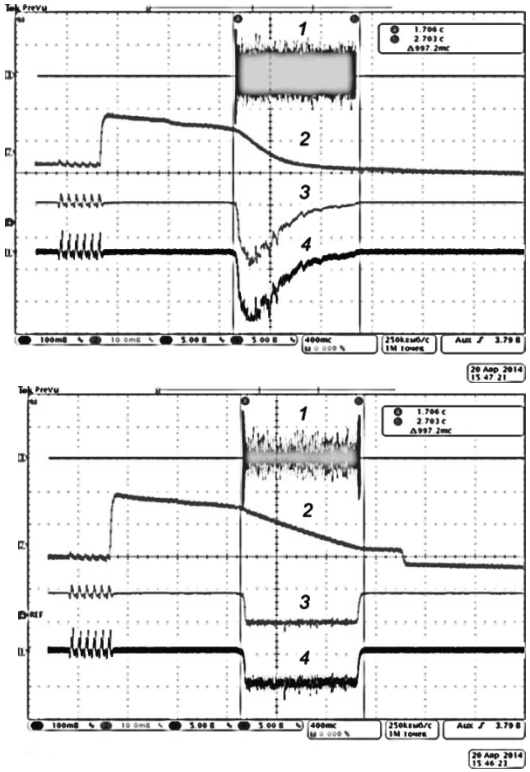
Flat-bottom S(S)E

352 Gs, 1.32 GeV (*p*, test beam) 455 MeV/u (*C*)

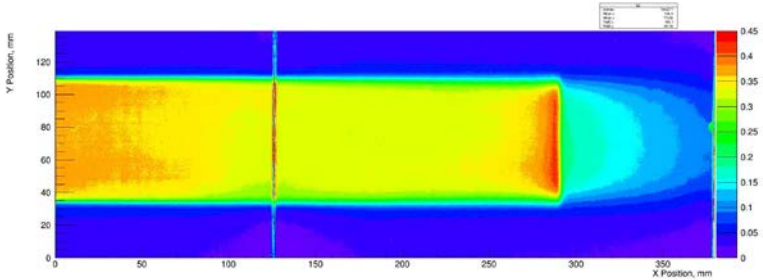


- Square-wave pulses
- Low spill ripple
- Beam spill duration 0.6-1 sec
- Easier beam sweeping and control over dose delivery to target
- Allows for patient's breath synchronization

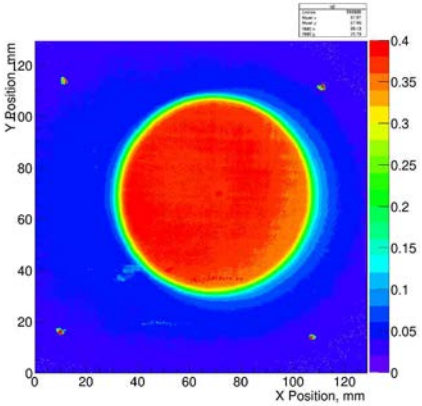




Graphite 32 mm (*p* 1.32 GeV)
Be 4 mm (C 455 MeV/u)



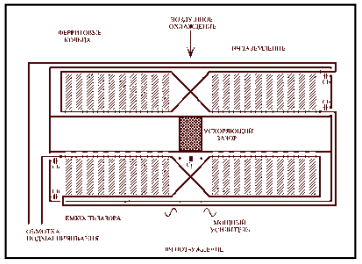
Bragg's peak
30 cm range in a water phantom
Collimator ∅65 cm



> 95% uniformity
at *R* = 3 cm and less

Longitudinal feedbacks

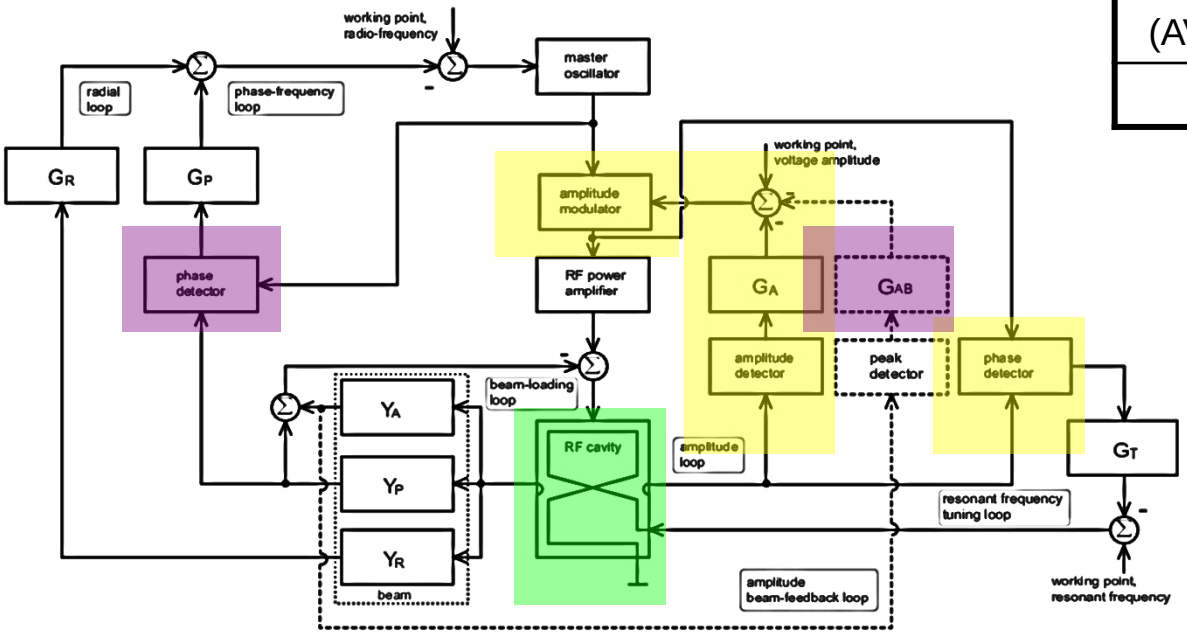
Accelerating system GRAPHITE, 38 ferrite-loaded 1-gap cavities, RF 5.52–6.06 MHz, 10 kV/gap



6 feedback loops:

A (AVC)	T (AFC)	BL	R	P	AB
× 38			× 1		

& dynamic variation of gains in radial (R) and phase (P) loops over acceleration cycle with transition crossing



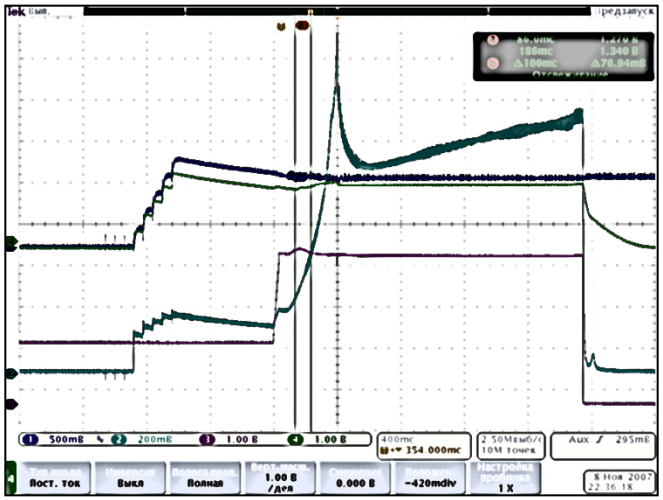
Beam quality, longitudinally

DC CT

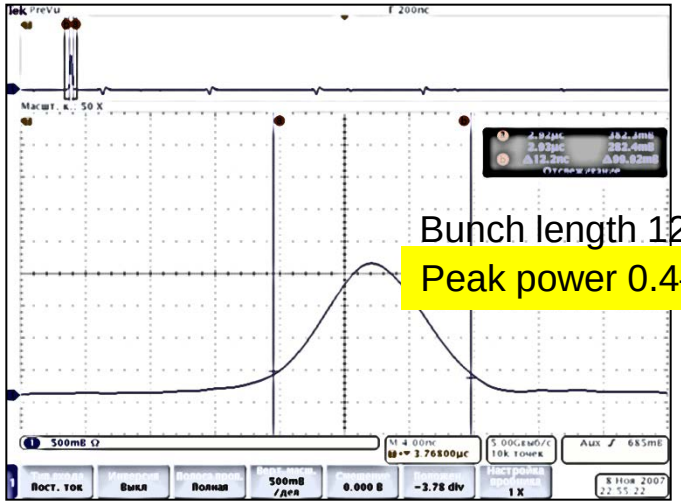
PU

V_{RF}

peak D



without 200 MHz spill cavity below γ_{tr}



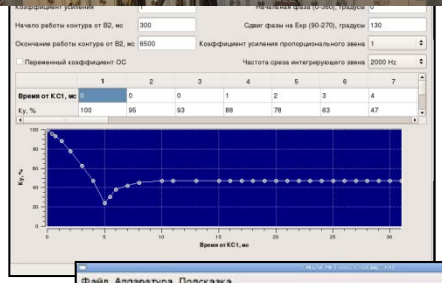
Bunch length 12.2 ns

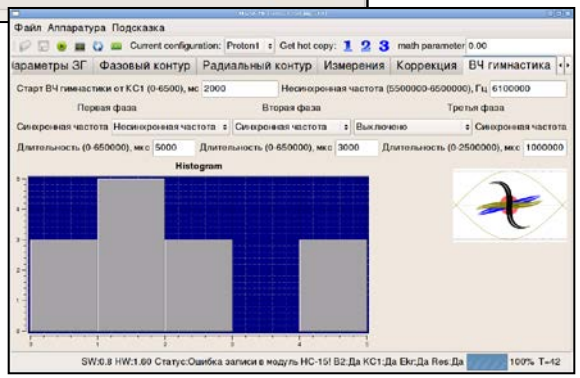
Peak power 0.4–1 TW

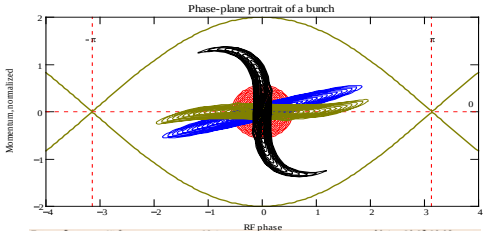
@ 50 GeV

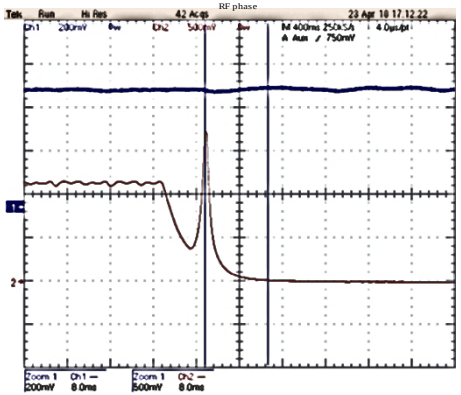
	≤ 2006	> 2007–8
Bunch length (FW@0.9)	36 ns	12–15 ns
Momentum spread $\Delta p/p$	$\pm 1 \cdot 10^{-3}$	$\pm 4–5 \cdot 10^{-4}$

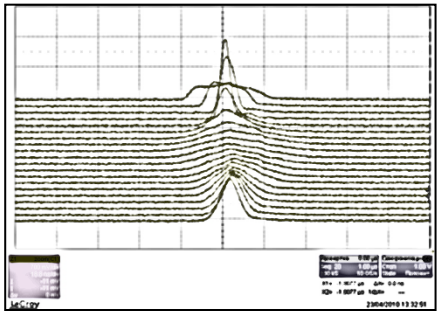
DDS RF master oscillator

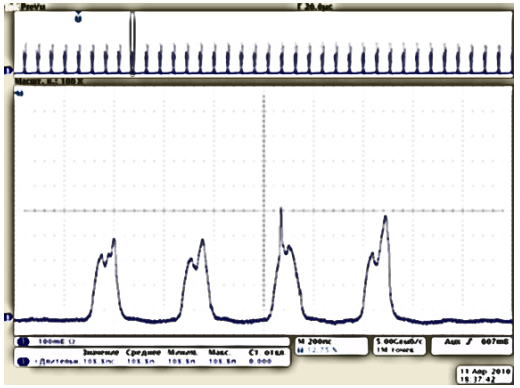


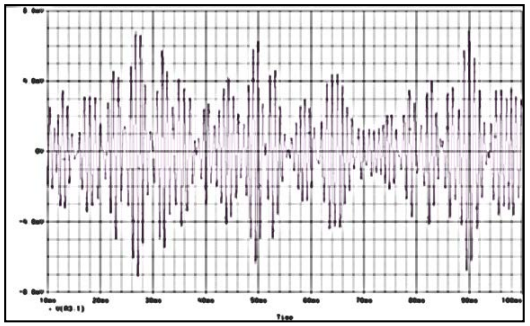


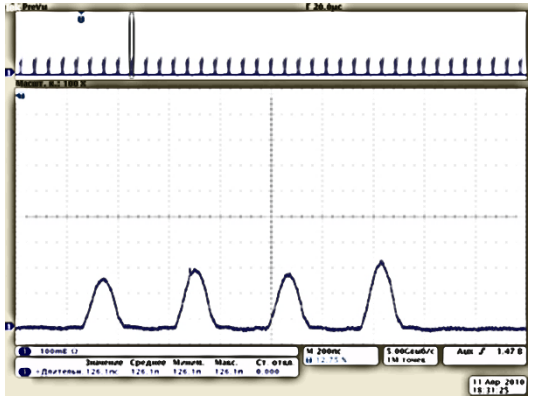






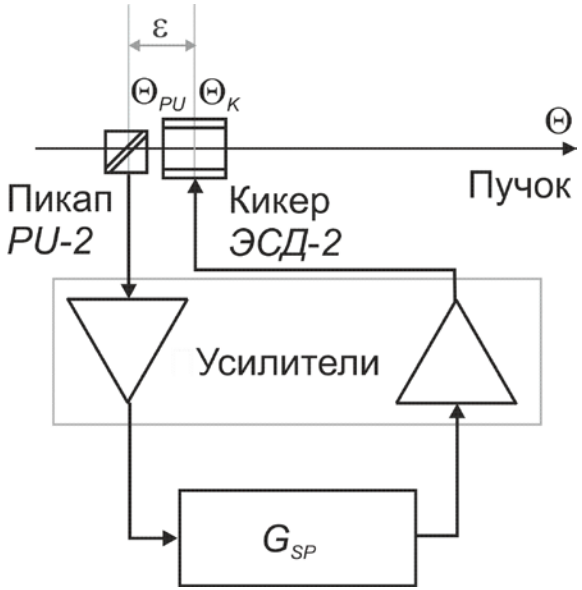


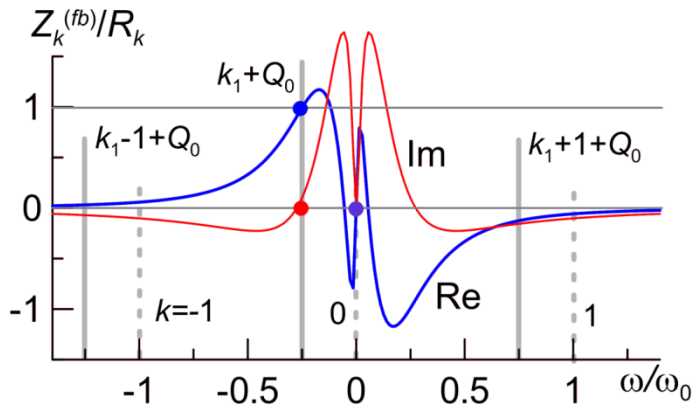


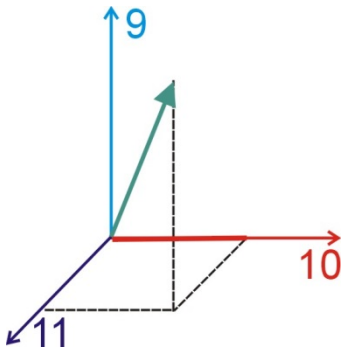


Transverse feedback -1

ESK @ SS2	0 – 0.2 MHz	±35.0 kV	PU @ SS2 (+ @SS116)

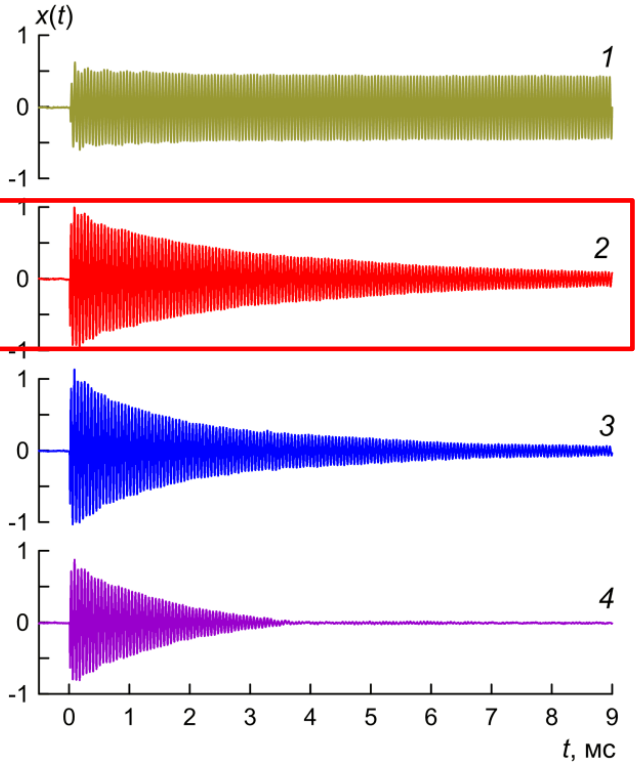






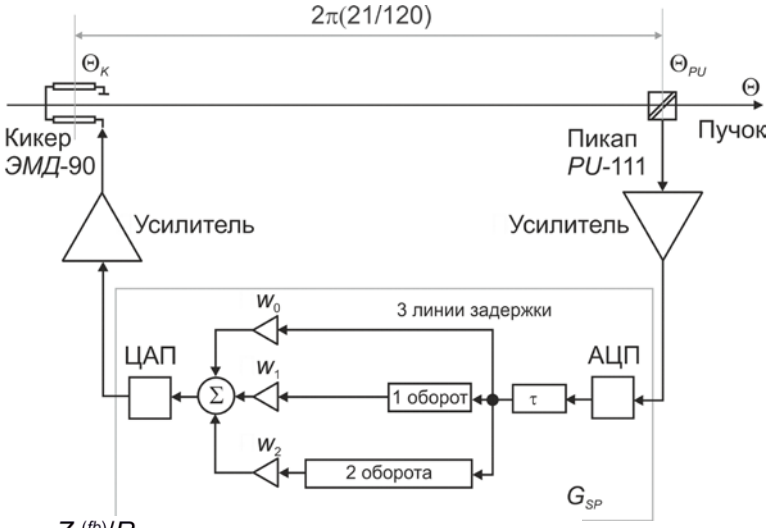
$\mathrm{Im}\,\delta Q = -2.6\cdot10^{-3}$

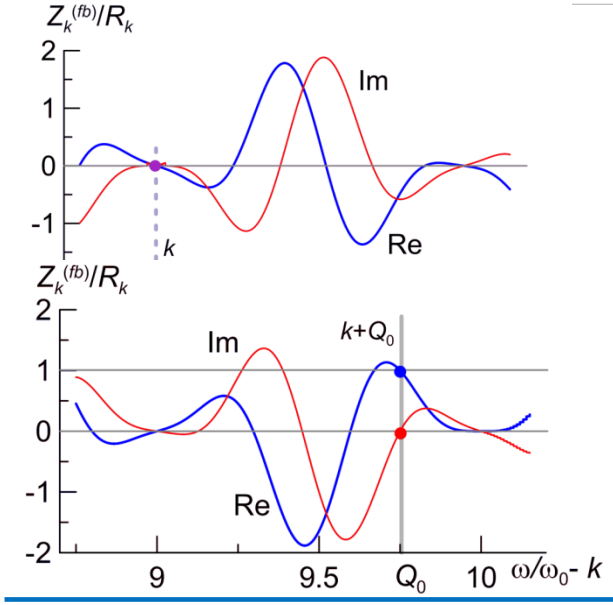
3.4 мс

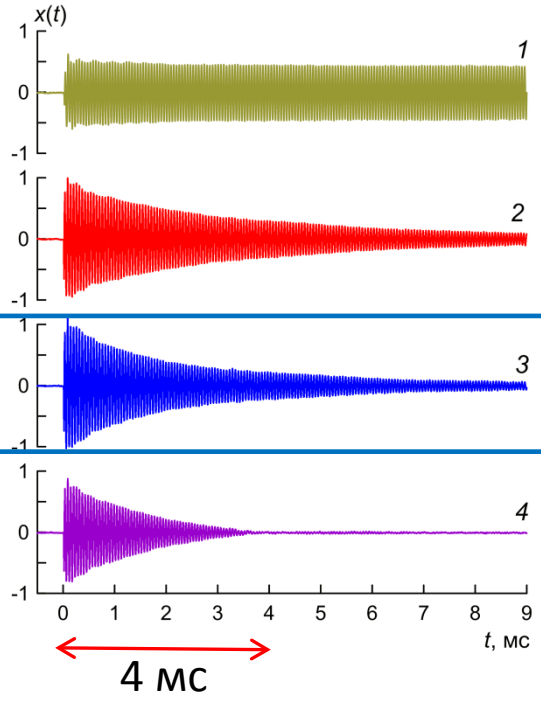


Transverse feedback -2

EMK @ SS90	0.2 – 15 MHz	±10.7 kV	PU @ SS107 + 111

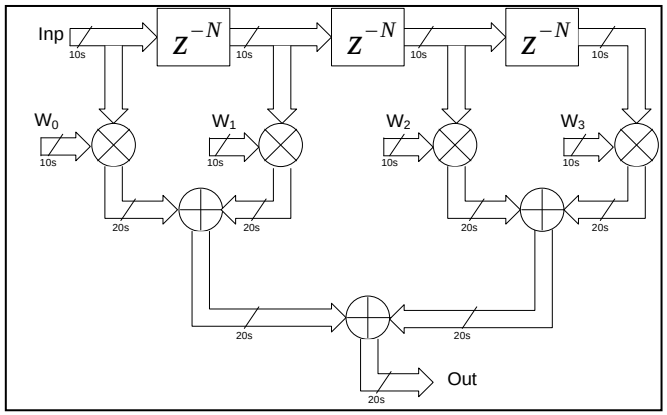






$\mathrm{Im}\,\delta Q = -3.9\cdot10^{-3}$

2.3 мс



FIR-3 & FIR-4 options

Strategy of light ion program

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

Опорные ионы $q = Z$, $q/A = 1/2$		*I*100, 2 р-ра из 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	
	T, MeV		72.71		1 323.8		69 032	50 000
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	23 600
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	34 063

★ Goal attained

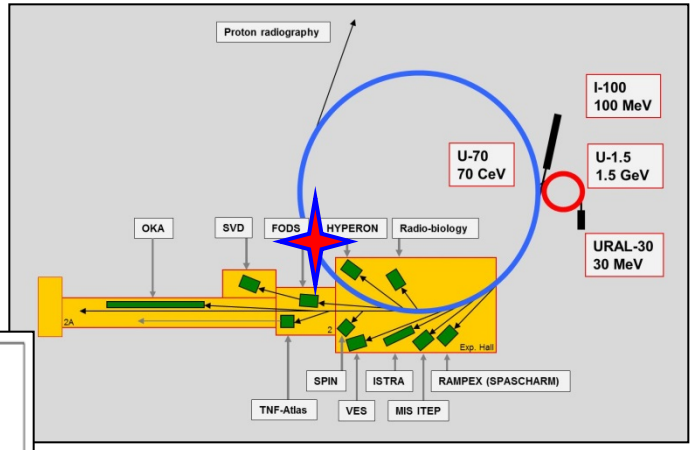
Light ion program milestones

	Deuterons $^{2}H^{1+}$	Carbon $^{12}C^{6+}$
U1.5	16.7–448.6 MeV/u March 30, 2008	16.7–455.4 MeV/u December 08, 2010
U70	23.6 GeV/u April 27, 2010	34.1 GeV/u April 24, 2011
		SE @ 455 MeV/u April 24, 2011
		24.1 GeV/u in BTL#22 & FODS (300 GeV full) April 27, 2012
		Validation tests of top-energy extractions with ion beam April 24, 2013

1st experimental NuPh events

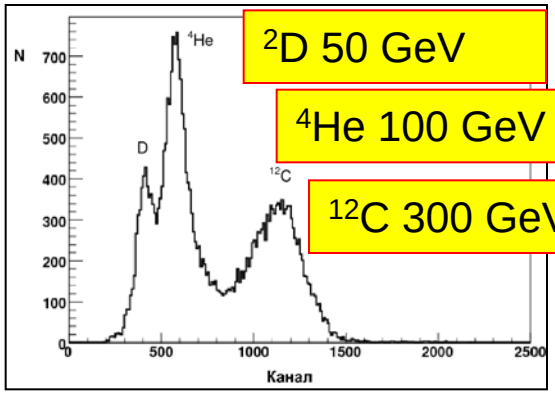
April 27, 2012. 1st ever extracted C beam in 190 m BTL#22 = FRS & FODS (a FOcusing Double-arm Spectrometer) experimental facility

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

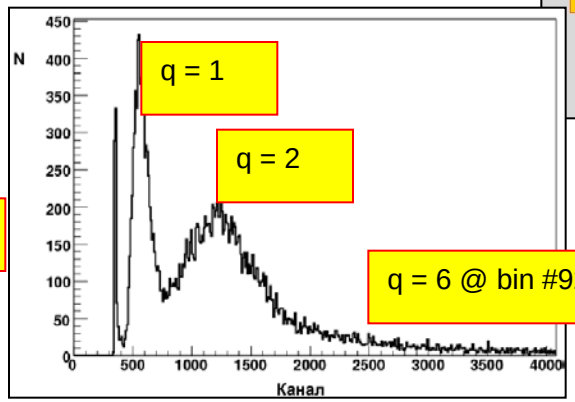


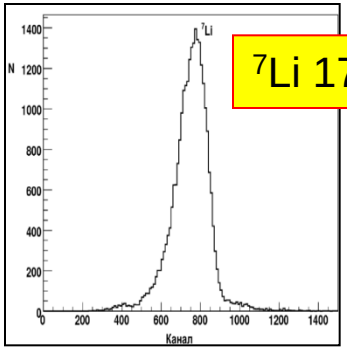
^{2}D 50 GeV

^{4}He 100 GeV

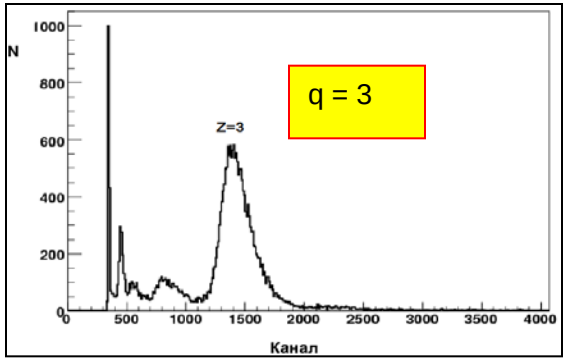
^{12}C 300 GeV

Scintillator counters





^{7}Li 175 GeV

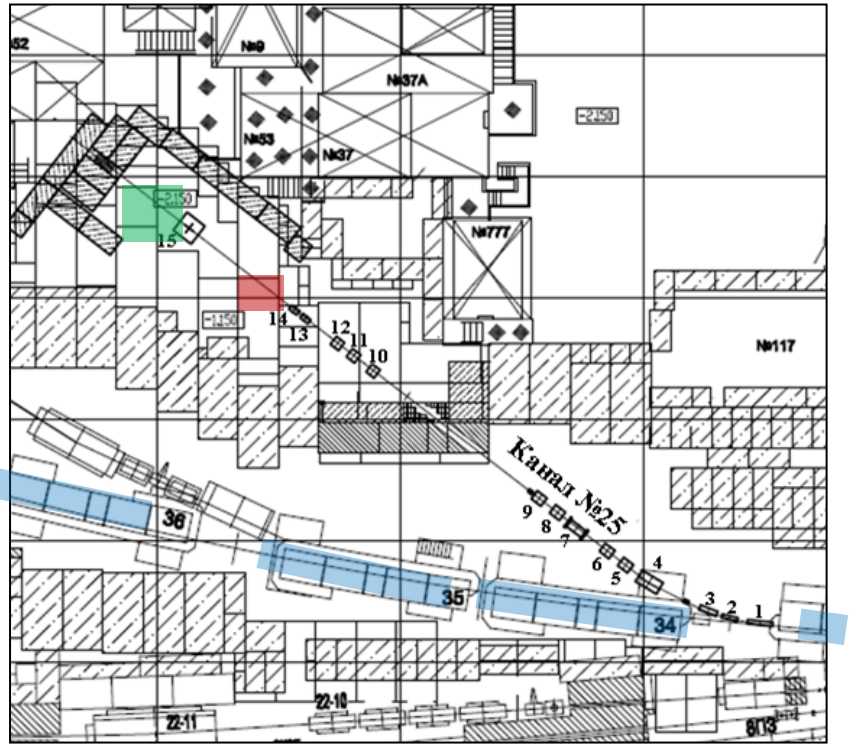


BTL#22 60 GeV/c (p) \pm 1%

a FRS

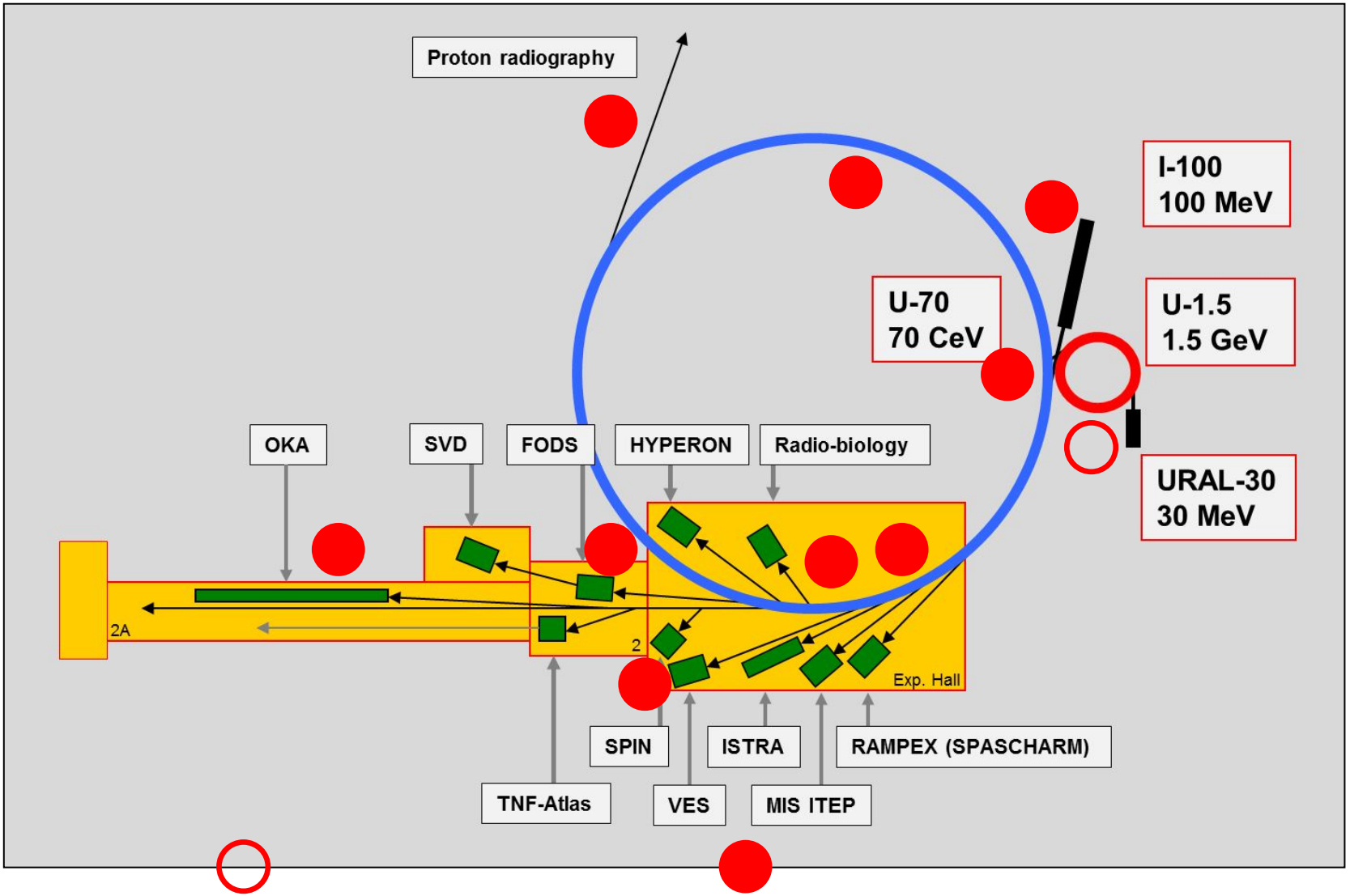
25.7 Gev/c/u q/A=3/7

BTL #25 and radiobiological bench



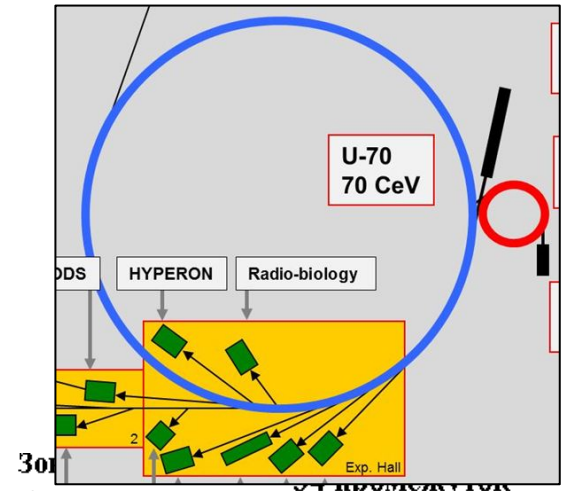
Upgrades of the recent years

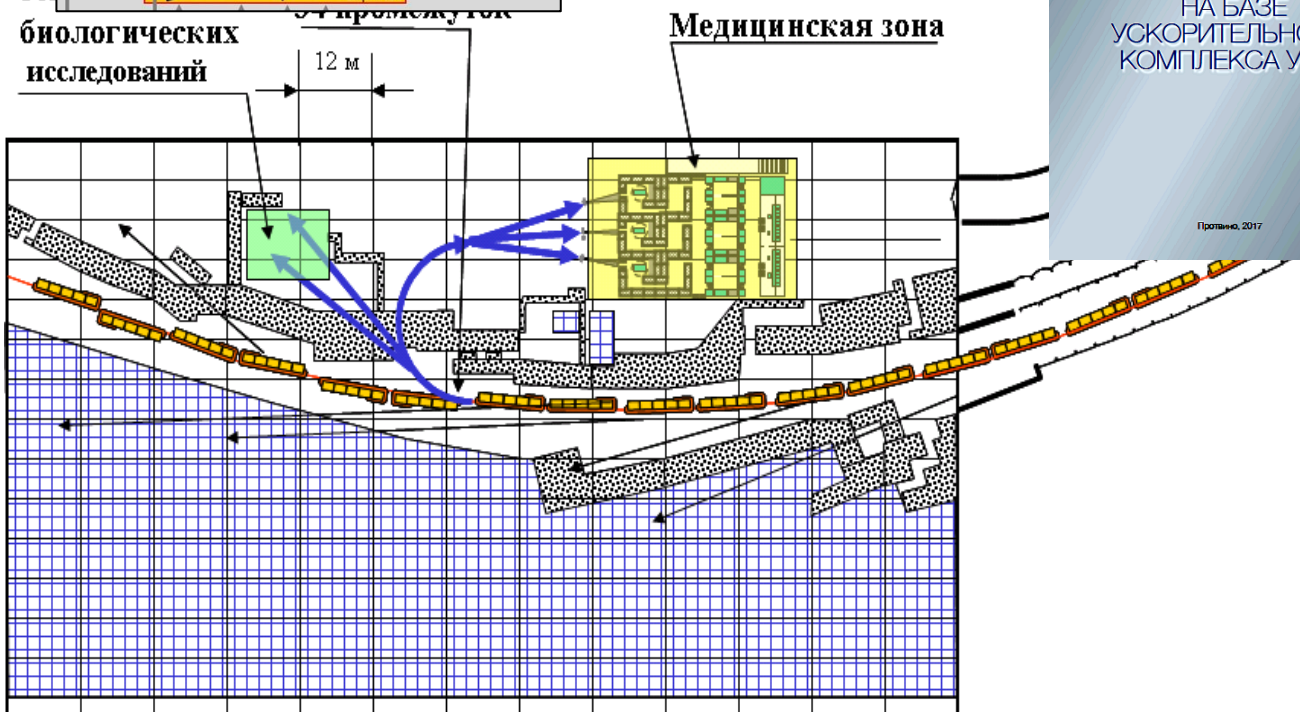
= PoA = points of attraction

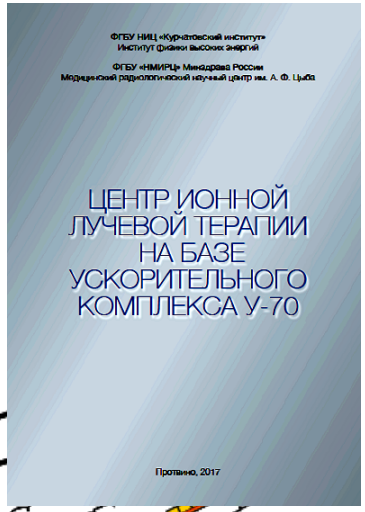


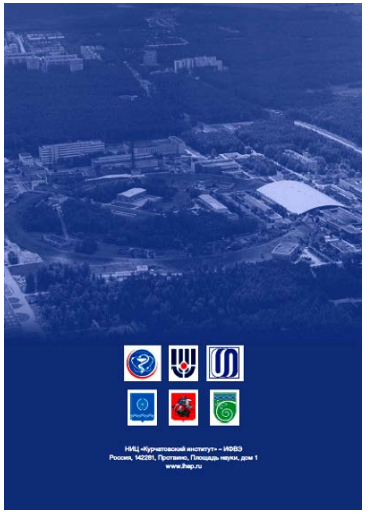
Ion beam therapy center (proposal)

A joint venture by NRC KI – IHEP (Protvino) and NMRRC – MRRC (Obninsk)





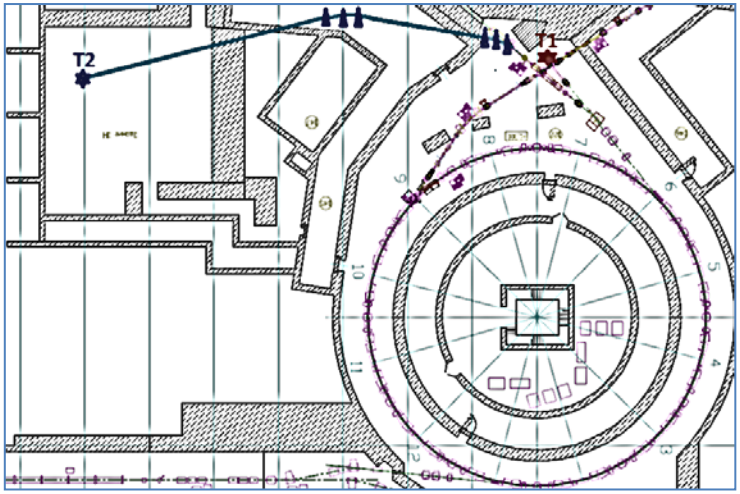




Pulsed *n*-source at U-1.5

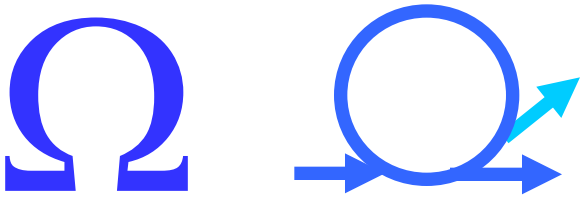
1.32 GeV at peak fractional yield = 30 n/p/GeV
1-1.5·10^{13} p per pulse (6.5 sec)
29 benches (50-80 nsec) in 2 sec

Optional: 0.3-1.32 GeV (p), d, C @ 455 MeV/u max

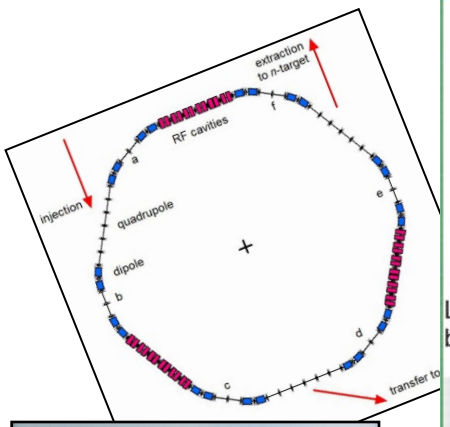


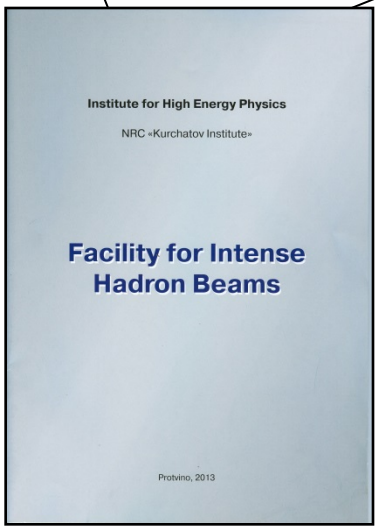
The OMEGA project

445.1 m 0.4-3.5 GeV 25 Hz $7.5 \cdot 10^{13}$ ppp 1 MW

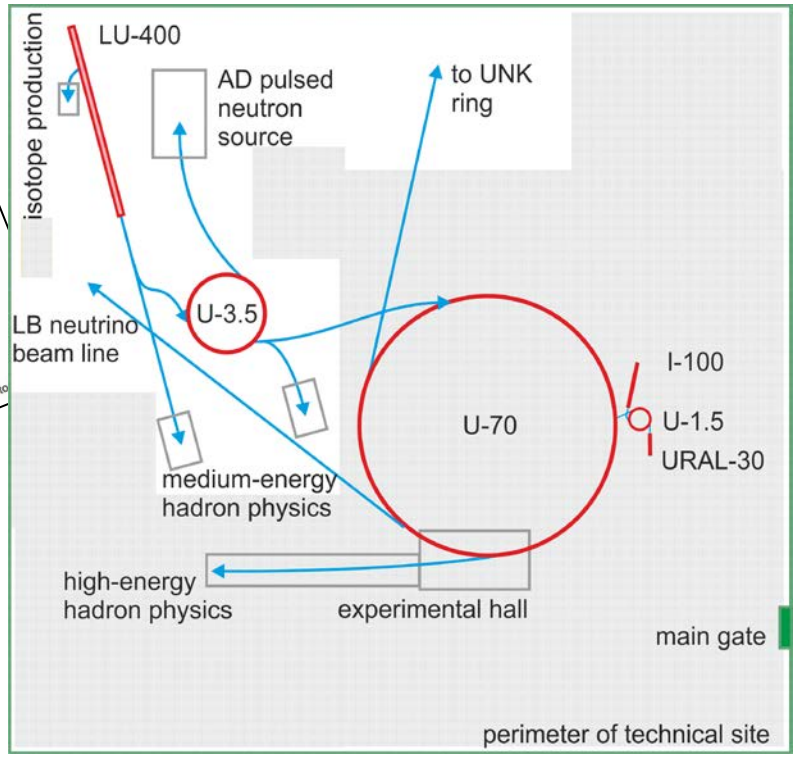


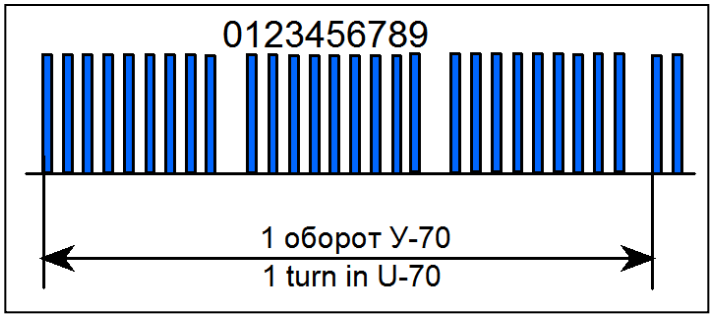
http://www.ihep.ru/ihep/news/IHEP-2-9-10_fin-c.PDF





the extended LoI, 37p, June 2013





Conclusion

Accelerator Complex *U*-70 of NRC “Kurchatov Institute” – IHEP (Protvino):

- comprises 4 machines (*URAL*-30, *I*-100, *U*-1.5, and *U*-70 itself),
- readily ensures running the fixed-target physics program
- is subject to ongoing upgrade program
- has noticeably improved quality of proton beam recently
- ensures a routine acceleration and extraction of light ions to 24-34 GeV per nucleon for high-energy nuclear physics
- now has slow extraction of 455 MeV per nucleon of $^{12}C^{6+}$ beam for radiobiology and future prior-to-therapy studies
- *U*-1.5 and *U*-70 now belong to PS and (L)IS categories
- is open for a few promising options for future development