Slow Extractions from the U-70

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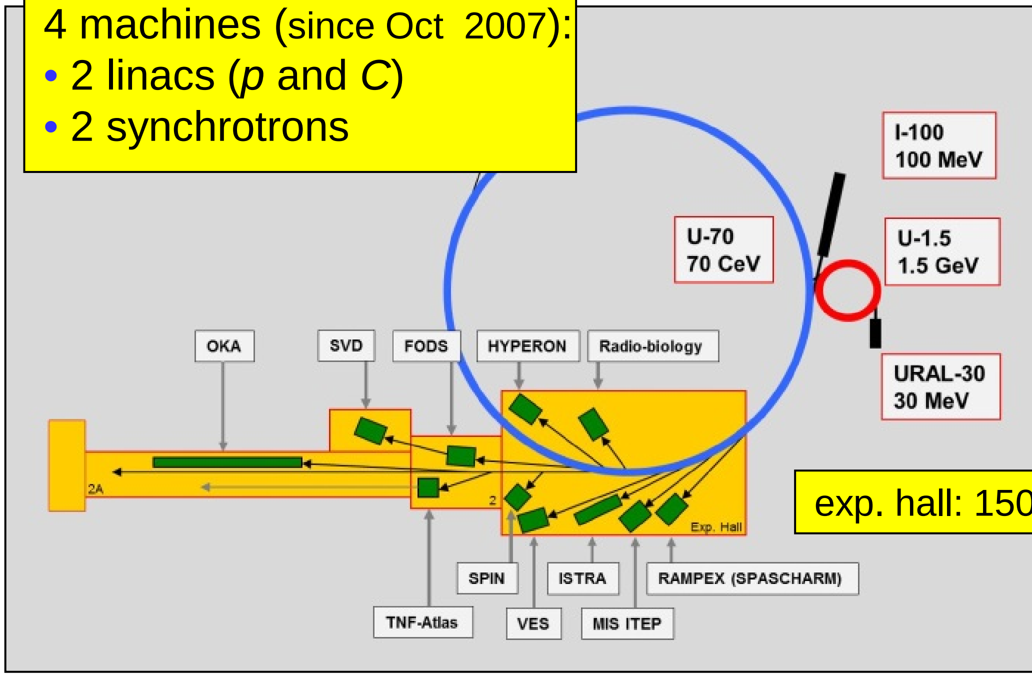
The Slow Extraction Workshop
[the EuCARD-2 XRING and HIC for FAIR workshop]
Darmstadt, Germany, June 1-3, 2016

Outlook

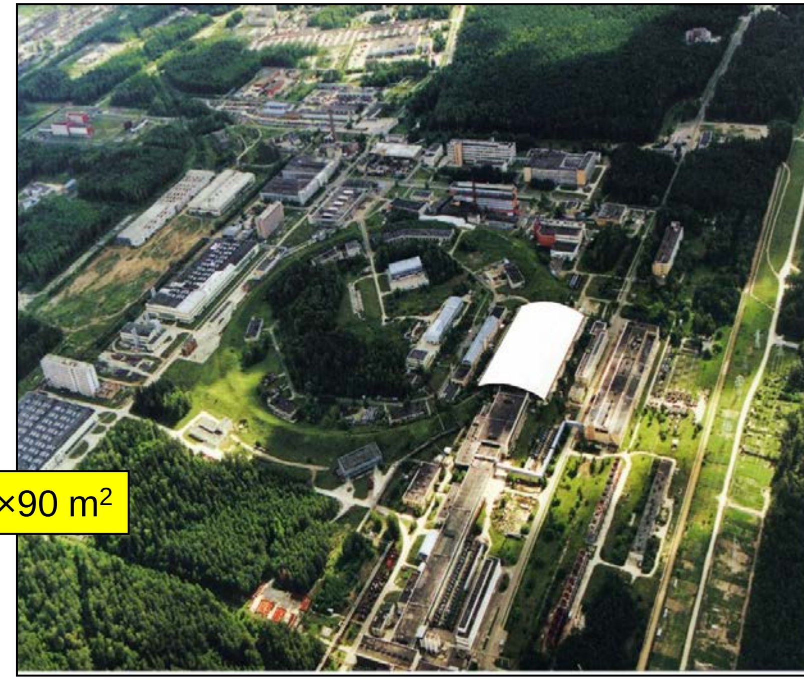
- Generalities (U70, layout, extractions, …)
- Translation (*V*) versus Diffusion (*D*) for a SE
- Stochastic SE at flattop (via a $3Q_x = n$)
  - Bidirectional extraction exercise
  - Coherent stability of a waiting stack during SSE
- SSE at flat bottom (via a thin degrader IT)
- Beam FB and square-wave stochastic spills
- Conclusion
- List of references

Layout

4 machines (since Oct 2007):
- 2 linacs (*p* and *C*)
- 2 synchrotrons



exp. hall: 150×90 m^2

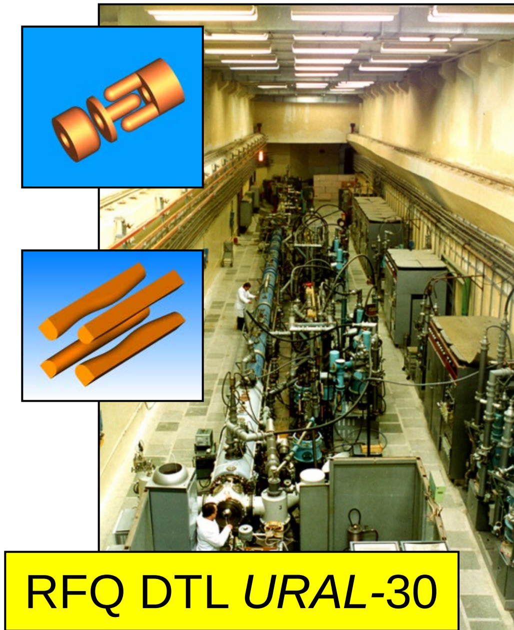


Modes:
- proton (default, [25], 50-70 GeV) URAL-30/U-1.5/U-70
- light-ion (*C*, complementary) I-100(2 of 3)/U-1.5/U-70

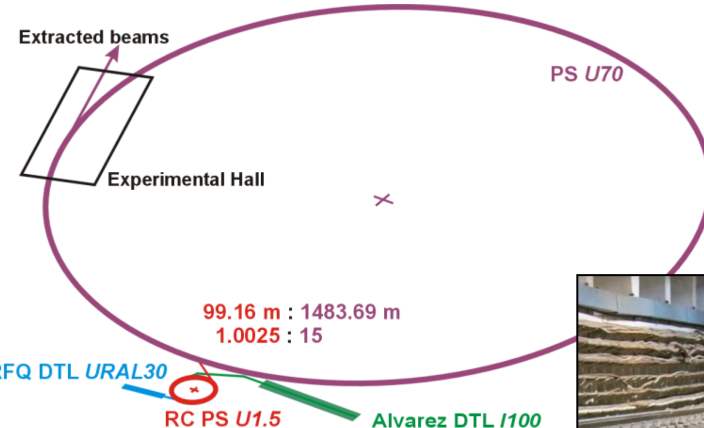
Top magnetic rigidity:
- U-70 233 T·m
- U-1.5 6.9 T·m

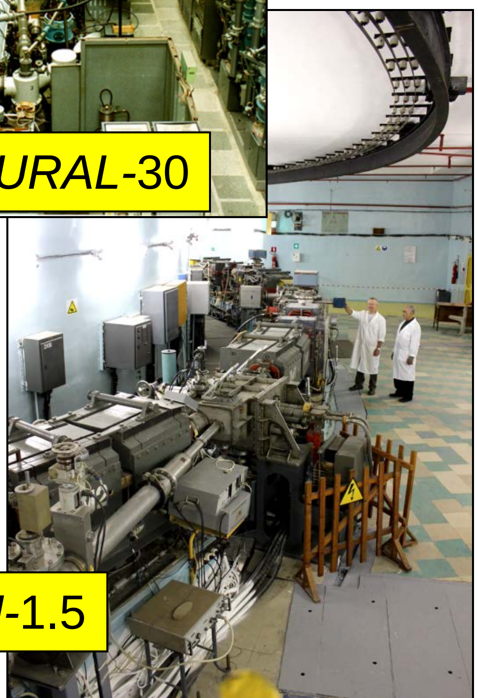
Carbon nuclei:
- (*very*) high energy 24.1-34.1 GeV/u
- intermediate (*though high*) energy 453-456 MeV/u

Photo album of machines

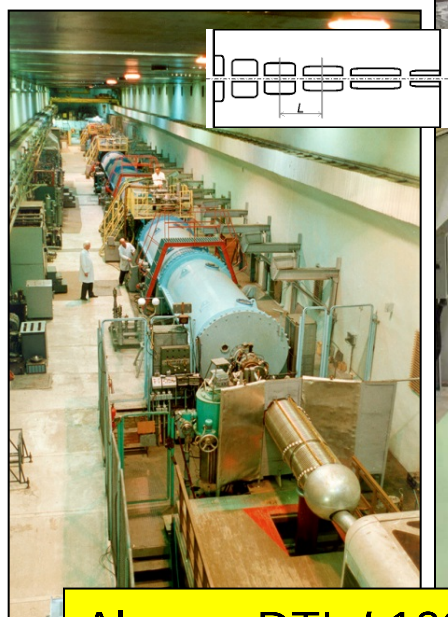


RFQ DTL *URAL*-30

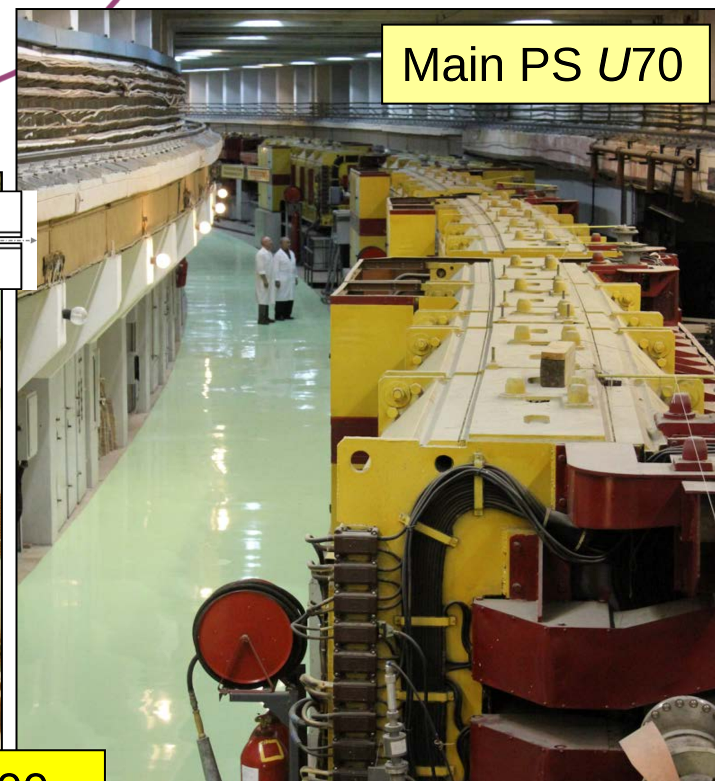




RC PS *U*-1.5



Alvarez DTL *I*-100



Main PS *U*70

Full inventory of extractions

Extractions @ U-70:

- *1-turn/1-bunch FE*
- *multi-turn (4-10) FE* (new)

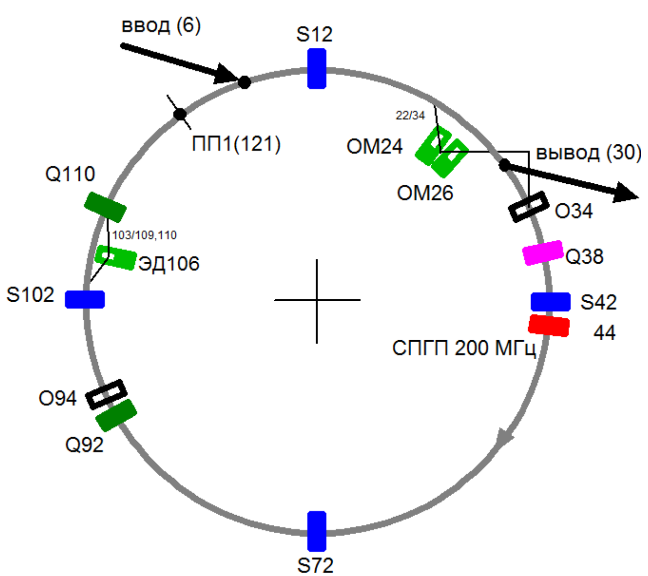
- IT, secondary particles
- bent-Si CD (new)

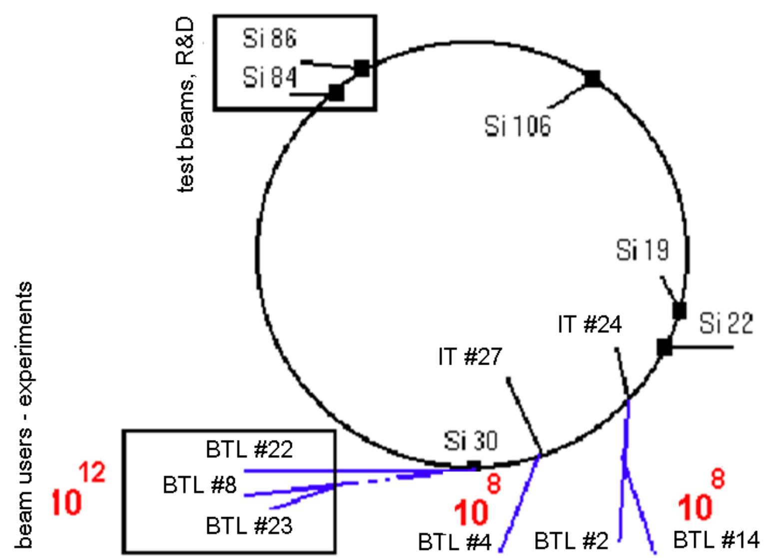
- RSE (*Q*38 & S_LSE (new))
- S_TSE at flat bottom (new)

U-70 = a test pad for the SE physics:

Kick-off mechanisms via
- nuclear interactions
- Si crystal channeling
- ionization losses
- 3rd order integer resonance

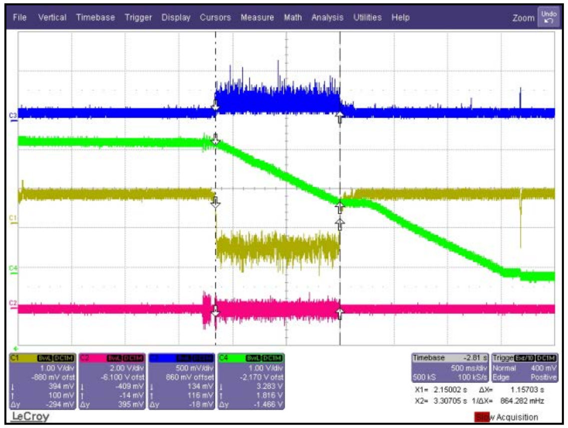
Feeding fluxes
- translational (variable WP, CO-bumps)
- diffusive (over momentum, over radial betatron oscillations)



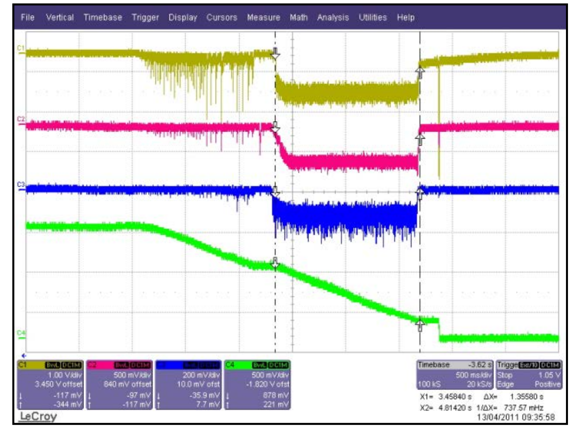


Foresight: all SEs when in use

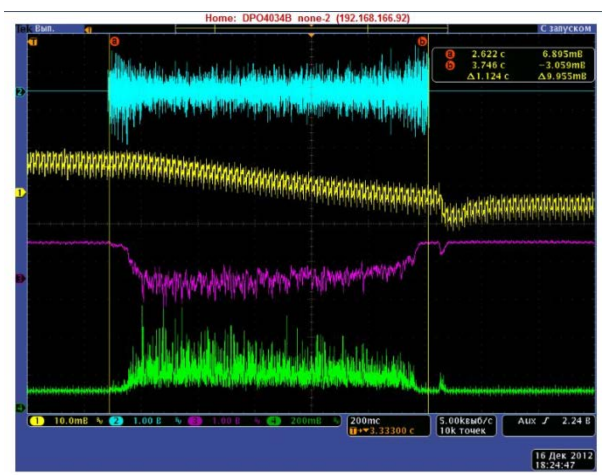
Routine operation: sequential and parallel beam sharing at flattop



SSE, *p*, 50 GeV, (1-7) $\cdot 10^{12}$ ppp 1.25 s spill

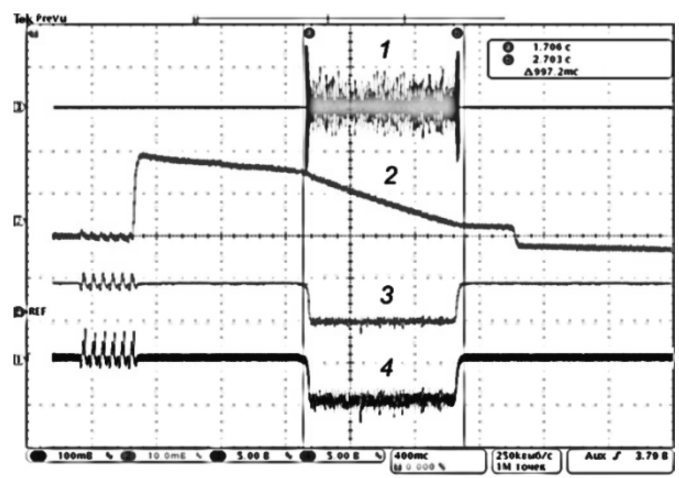


SE CD+IT, *p*, 50 GeV, $3\cdot 10^{12}$ ppp 1.35 s spill



Dynamic range 3 orders of magnitude

SSE, *C*, 24.1 GeV/u, $1.7\cdot 10^{9}$ ipp 1 s spill

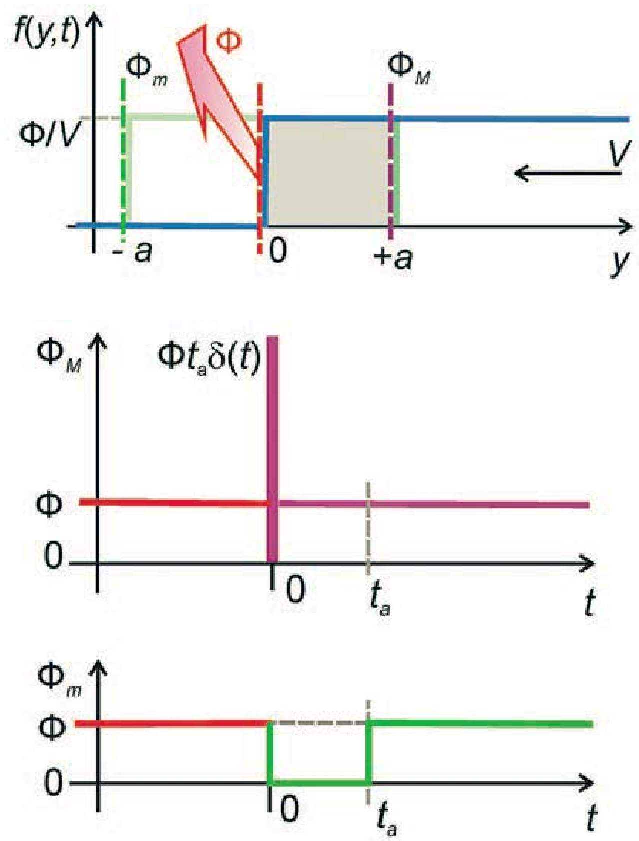


SSE, *C*, 456 MeV/u, $2\cdot 10^{9}$ ipp 0.6-1 s spill

Translation (V) versus Diffusion (D)

$$A, \qquad t_A, \qquad \Phi = \frac{N}{t_A}, \qquad \frac{a}{A}, \qquad \tau$$

$$t_a = \frac{a}{V} = \left(\frac{A}{V}\right)\frac{a}{A} = t_A\frac{a}{A}$$



Notations:

A – waiting beam stack width

$\pm a$ – magnitude of fast jumps due to optics (the worst case) , in commeasurable to A units

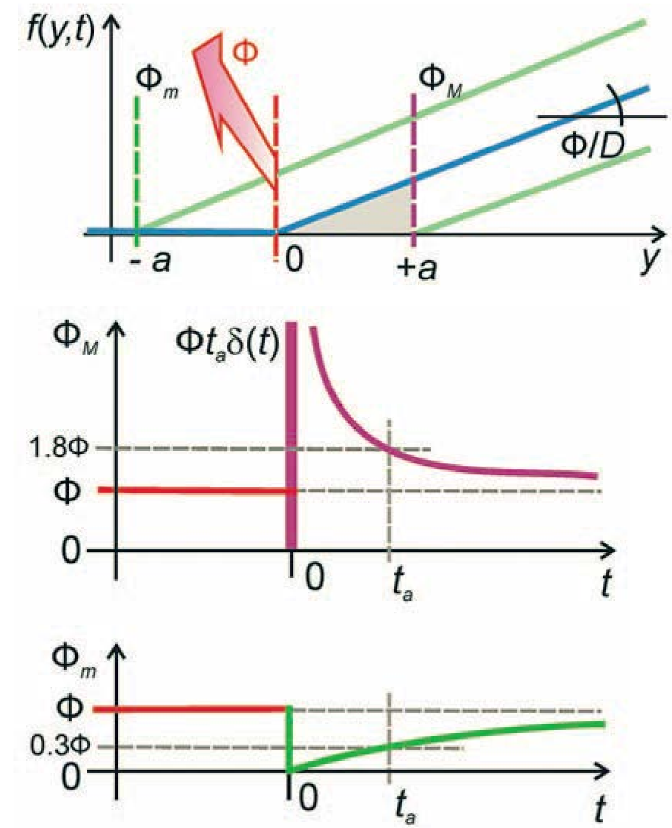
t_A – spill duration

t_a – relaxation time to heal $\pm a$ - scale perturbation

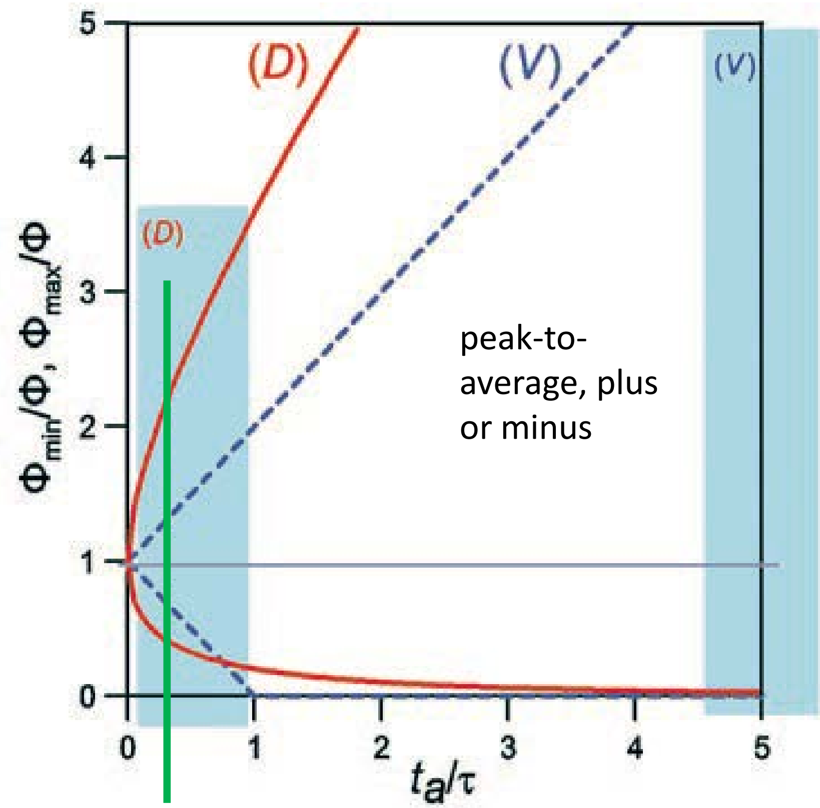
Φ – extracted flux

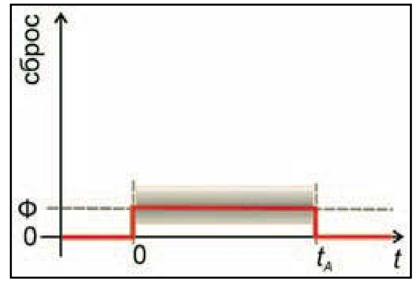
τ - time constant of subsequent averaging during acquisition (next page)

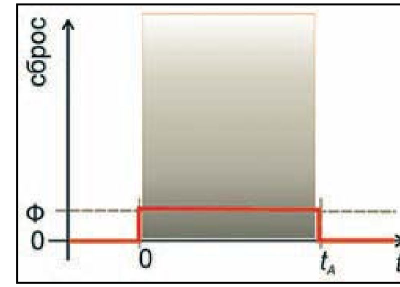
$$t_a = \frac{a^2}{2D} = \left(\frac{A^2}{2D}\right)\frac{a^2}{A^2} = t_A\frac{a^2}{A^2}$$

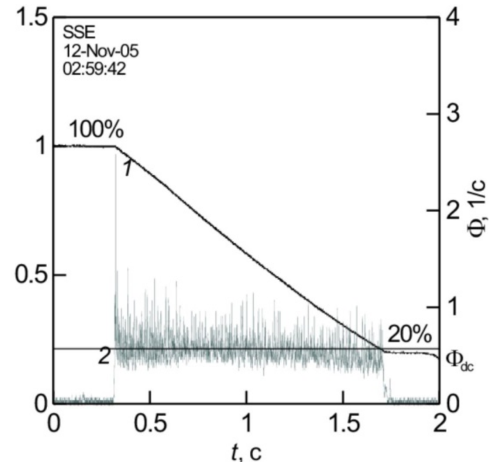


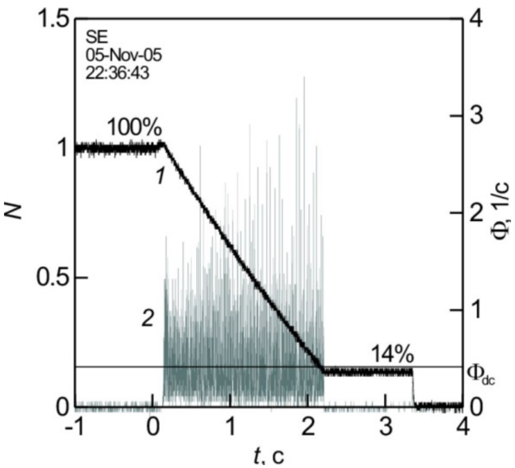
Immunity to ripples of MO

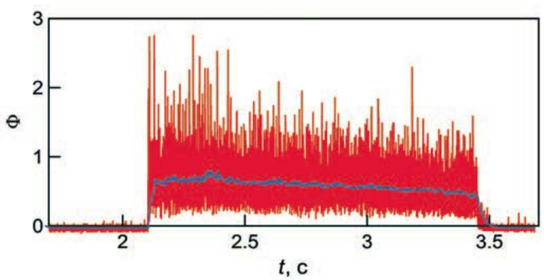


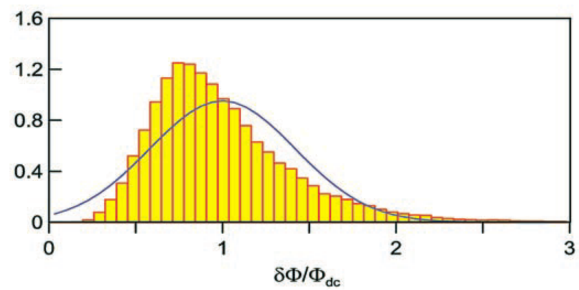


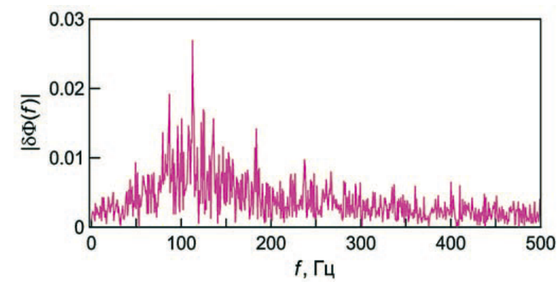






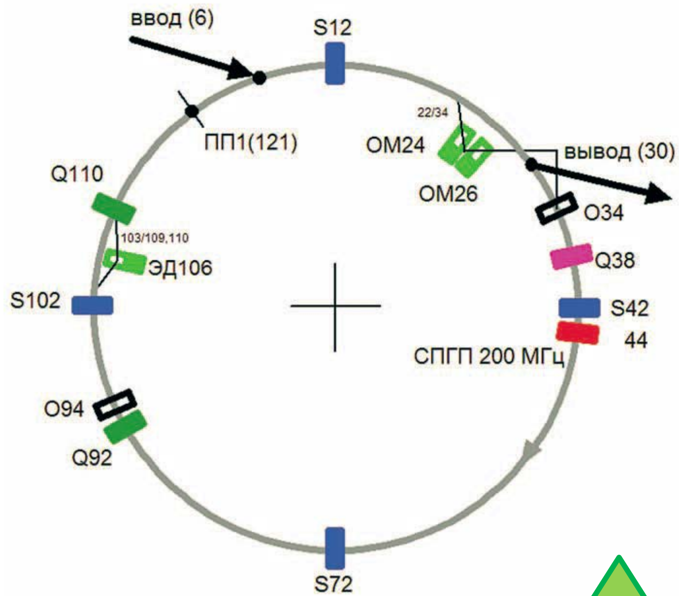


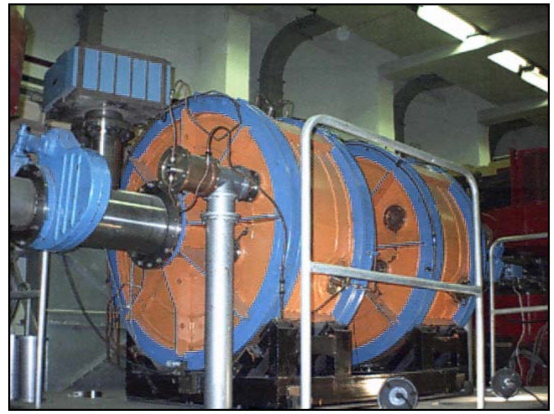




Local (for the U-70) rule-of-thumb: proportion **½ : 1 : 2**

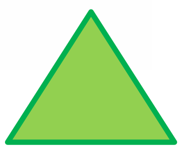
SSE at flattop (1)

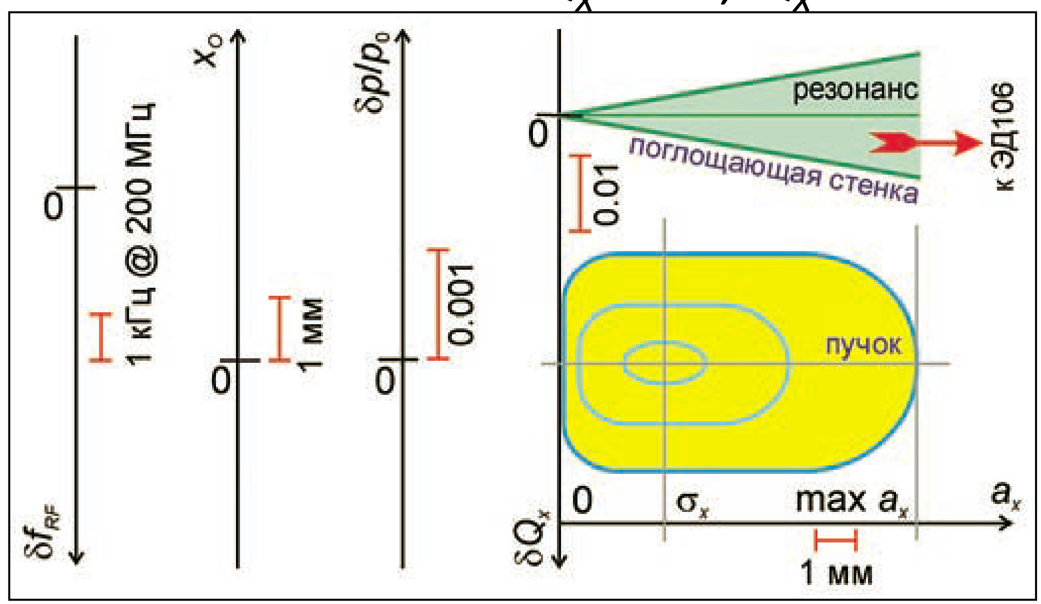


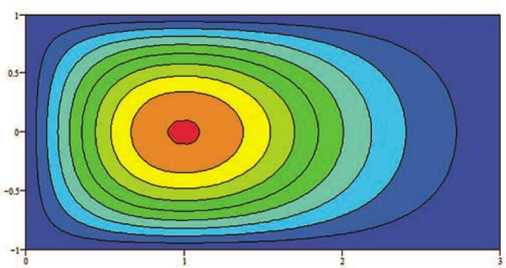


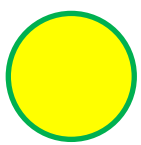
h = 30×33 = 990
f = 200 MHz
V = 450 kV/turn

$3Q_x = 29$, $Q_x = 9.7$ ca



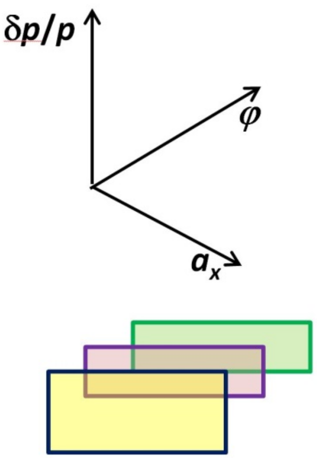




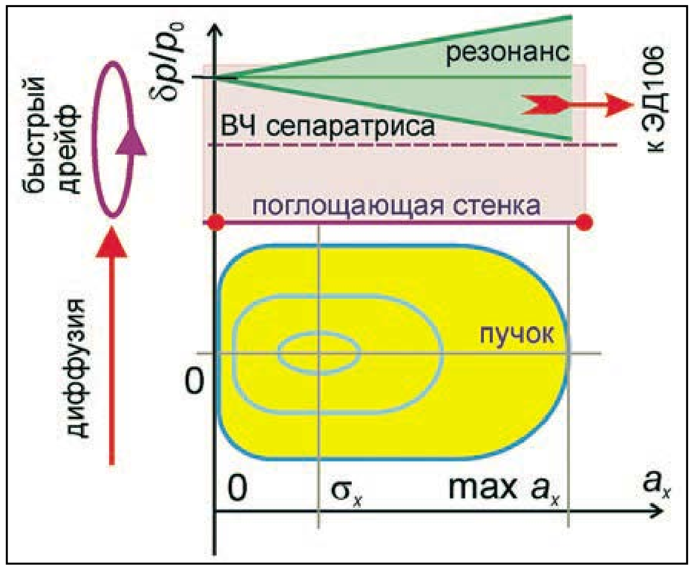


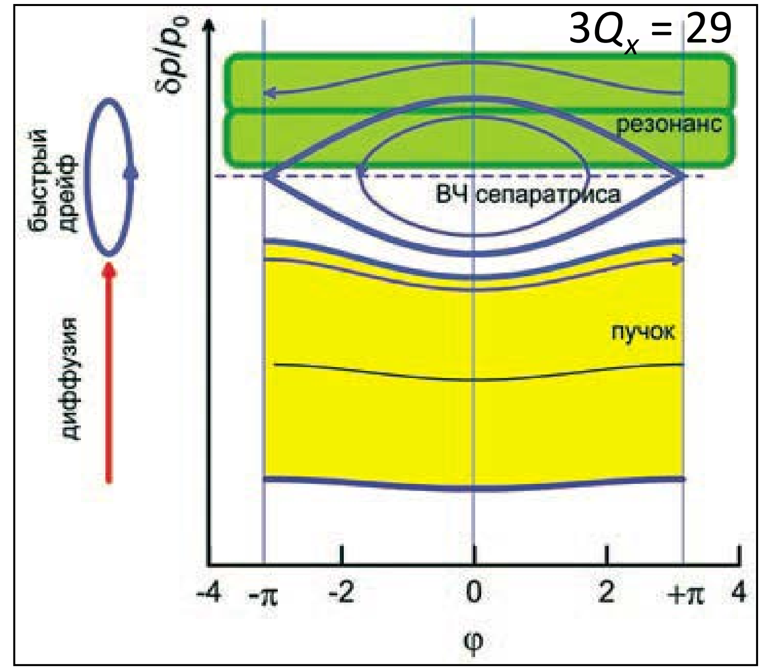
a Steinbach diagram, rotated

SSE at flattop (2)



$3Q_x = 29$





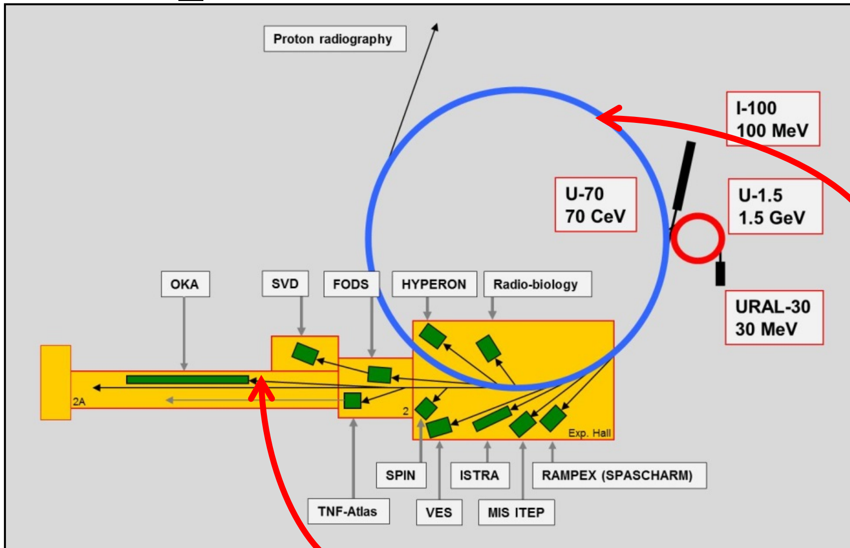
FEATURES:

- A "chimney" zone + a beam trap inside empty RF buckets
- Re-feeding depleted by SE 200 MHz "bunches"
- Inversion of beam halation
- Surplus stochastic acceleration of extracted fraction
- No sweeping (drift) over extracted momenta during a spill

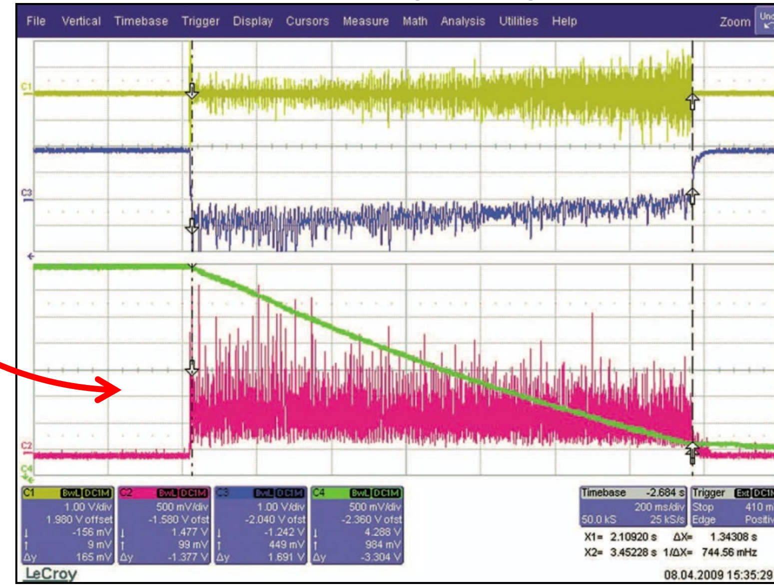
- Adjustable trajectory of WP to resonance in the (Q_x, Q_y)-plane
- Absorbing wall (sink) = const(a_x)
- Phase mixing and randomizing
- "Ribbon" waiting beam less prone to coherent instabilities
- Close to applicability margin from shorter extraction t

Flattop SSE in operation (1)

Run 2009_1

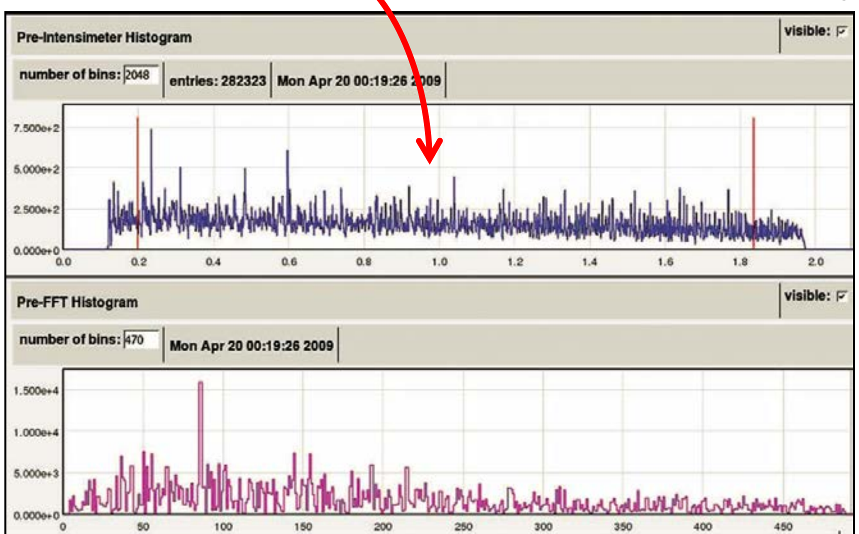


Technological signals from U-70



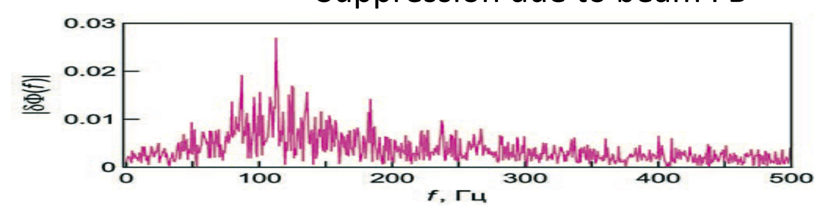
50 GeV p; 1.85 sec; $9.5 \cdot 10^{12}$ ppp

Head counters of OKA facility



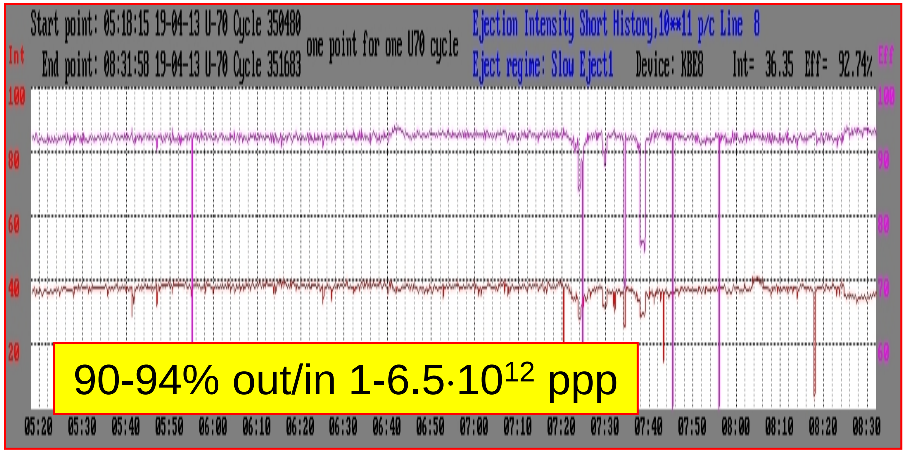
Mixing due to 200 MHz RF and $3Q_x$=29 + a carrier noise leakage

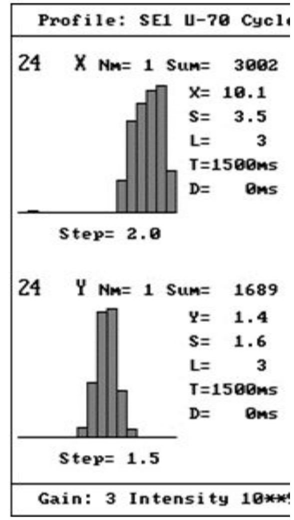
Suppression due to beam FB

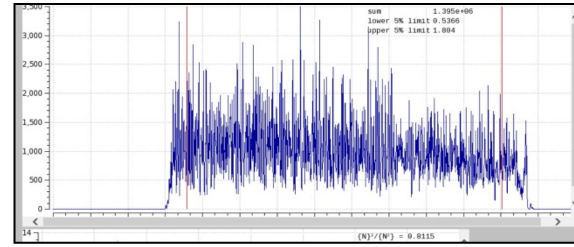


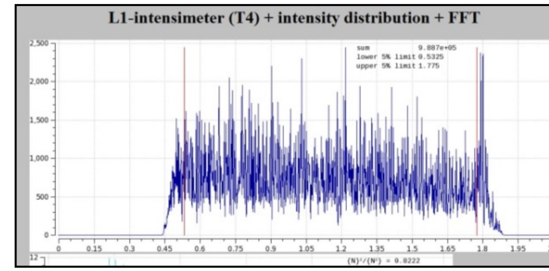
Flattop SSE in operation (2)

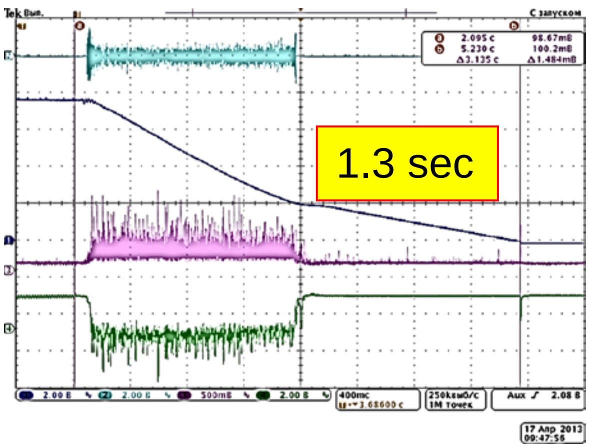
Run 2013-1, protons

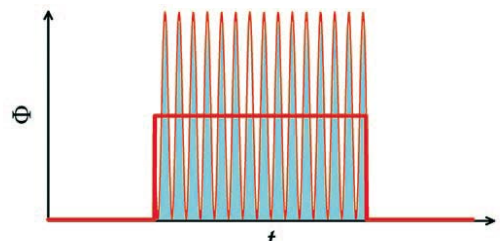






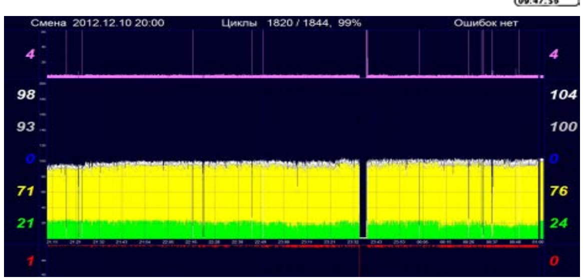






duty factor $\langle\Phi\rangle^2/\langle\Phi^2\rangle$ до 0.82
dispersion $\sigma^2 = 0.22$
no cut-offs and lines of the mains harmonics

duty factor $\langle\Phi\rangle^2/\langle\Phi^2\rangle = 2/3$
dispersion $\sigma^2 = 0.5$



4% loss

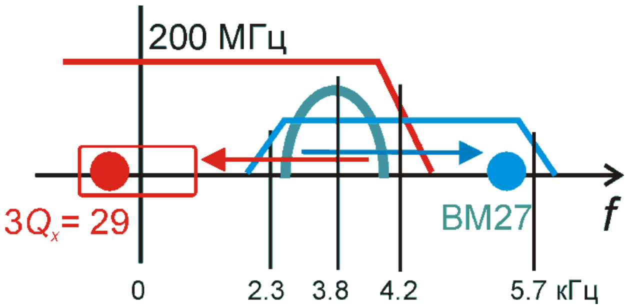
$1.05 \cdot 10^{13}$ ppp total

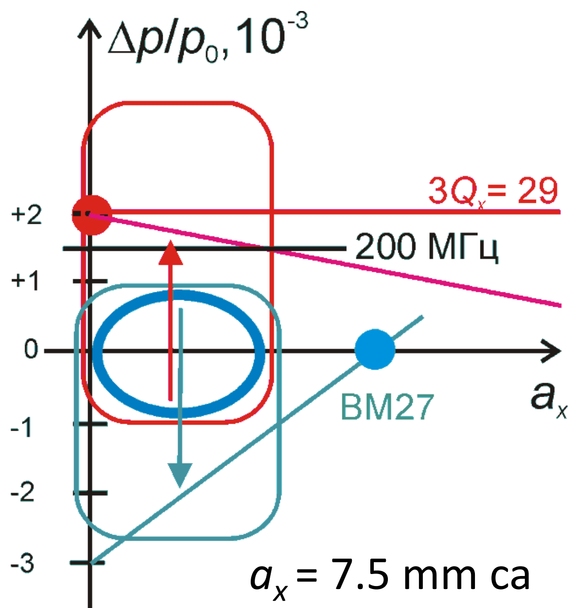
$7\text{-}7.6 \cdot 10^{12}$ ppp via the SSE

Flattop SE @ U-70:
- effective
- intensive
- slow
- low-ripple

Bidirectional SSE exercise

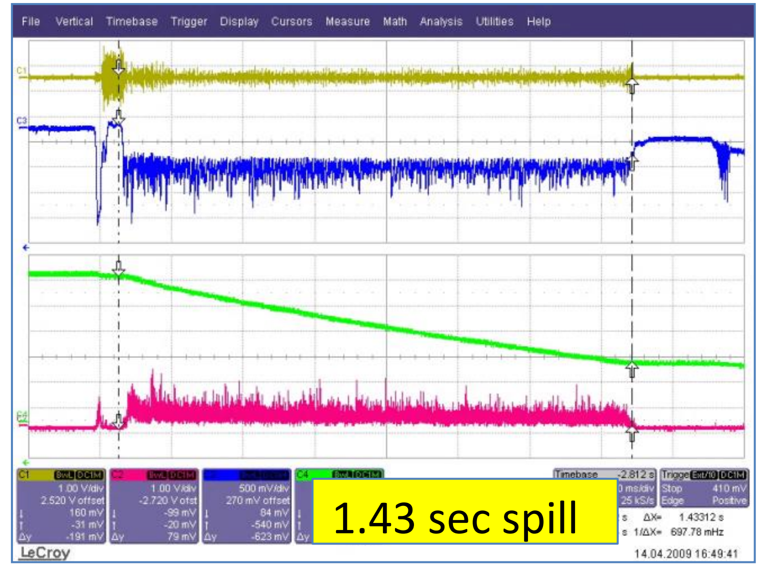
Run2009_1: noise for RSE @ $3Q_x = 29$ and IT-27 in parallel



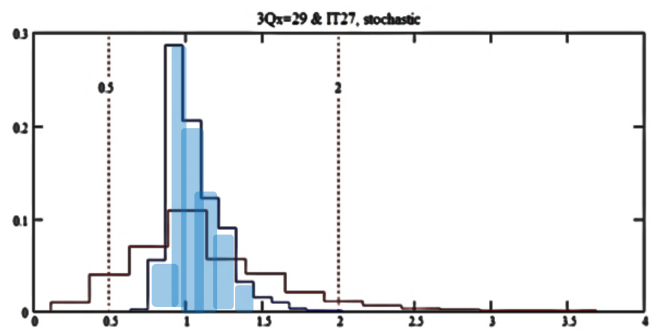


a_x = 7.5 mm ca

x_{27} = -35/-37 mm



about 10:1 beam splitting



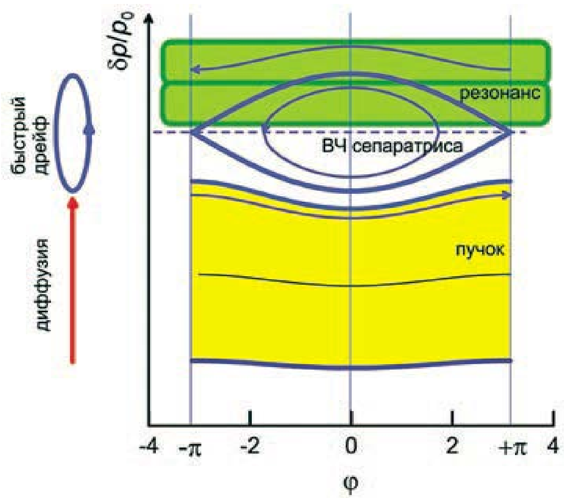
Duty factor $\langle\Phi\rangle^2/\langle\Phi^2\rangle$ =

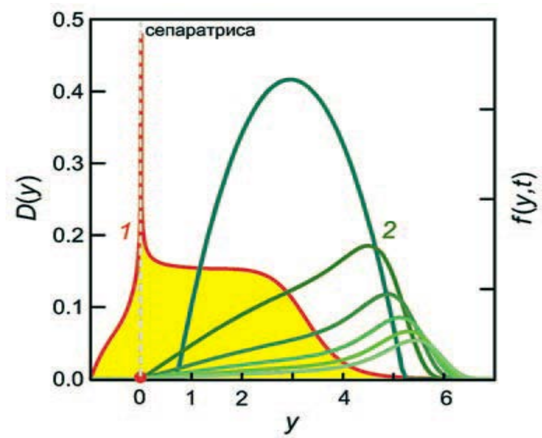
- **0.97 (IT27, 1 kHz (-3 dB) FB)**
- **0.78 ($3Q_x$=29, <50 Hz ca FB)**

Effect of open-loop beam FB bandwidth

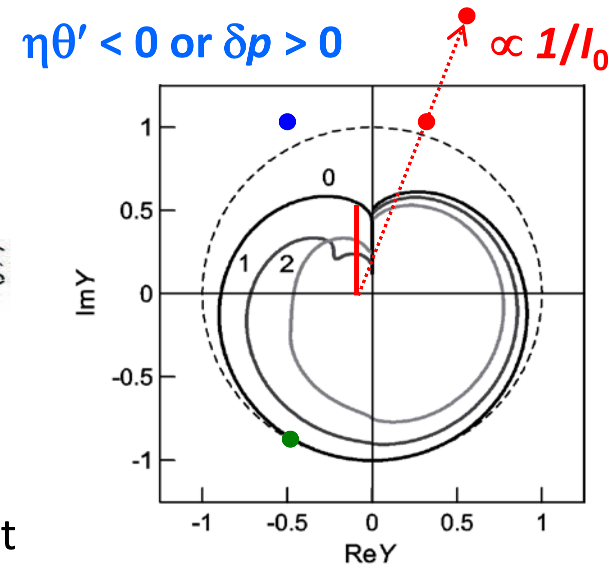
SSE and coherent instabilities

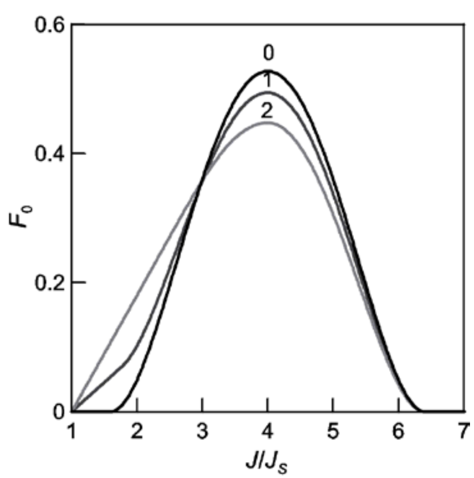
Asymmetries' in $F_0(J)$ and $Y^{(C)}$. Consequences of sign toggling in k, η, θ' in threshold maps.

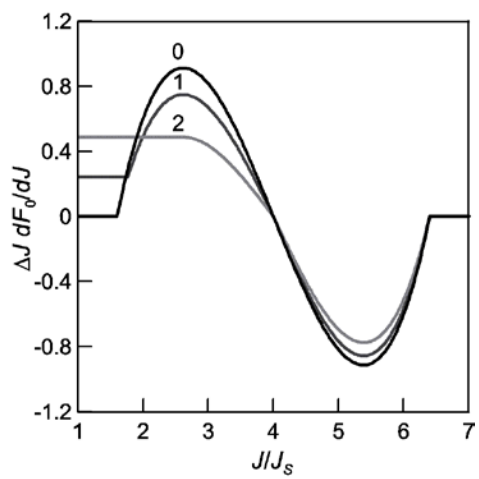




+ a “loss-of-memory” effect







$$\left|\frac{Z_k(k\omega_0)}{k}\right| \le \frac{|R|}{\Lambda} \cong \frac{1}{\Lambda}\frac{\beta^2|\eta|\gamma E_0}{eI_0}\left(\frac{\Delta J}{\eta\omega_0}\right)^2$$

E_K = 60 GeV, $N = 1\cdot 10^{13}$ ppp

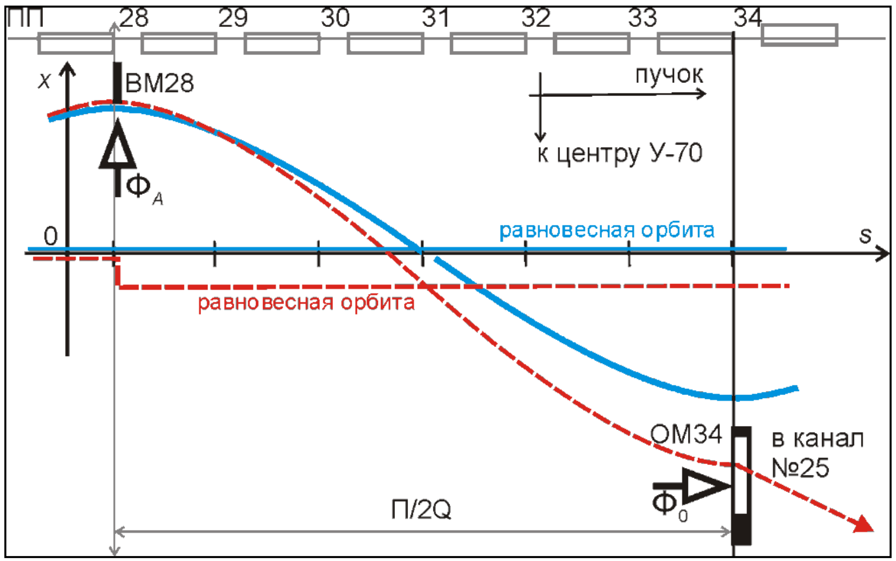
$|Z_k/k|$ < 3 kOhm

SSE = a better coherent stability of waiting beam stack

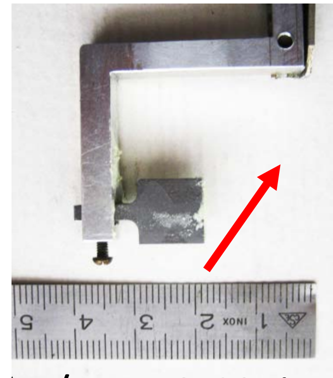
Flat-bottom SSE

Piccioni-Wright, $^{12}C^{6+}$, 455 MeV/u

“window of possibilities” for Carbon



$$\Phi_A = \Phi_0$$



$\Delta p/p_0$ = -0.69%

Be 4 mm h = 10 mm

ESD2 @ SS2

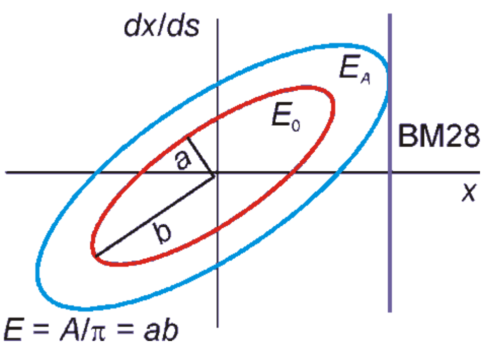
L = 1 m

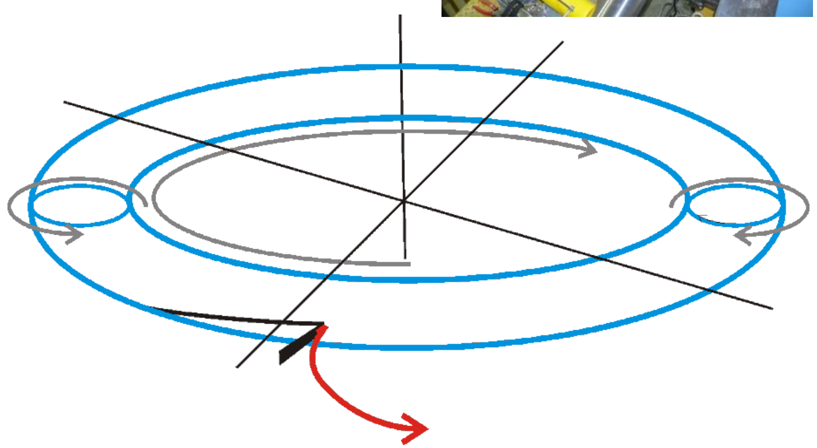
d = 0.1 m

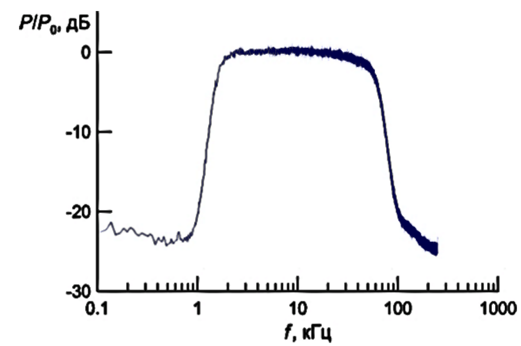
V = 3 kV

EL = 30 кВ

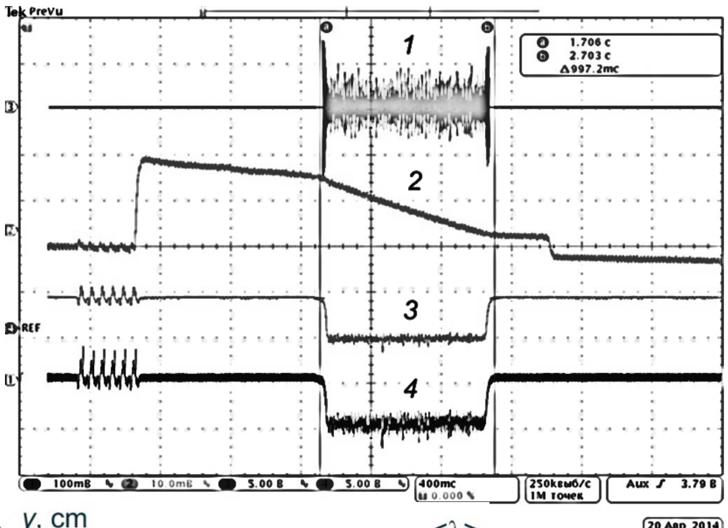
T > 0.1-0.2 sec



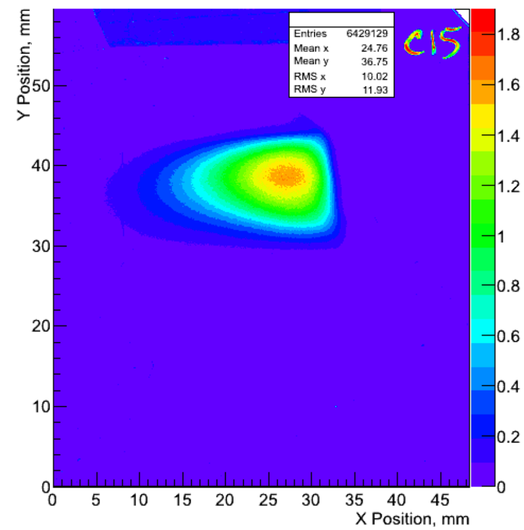




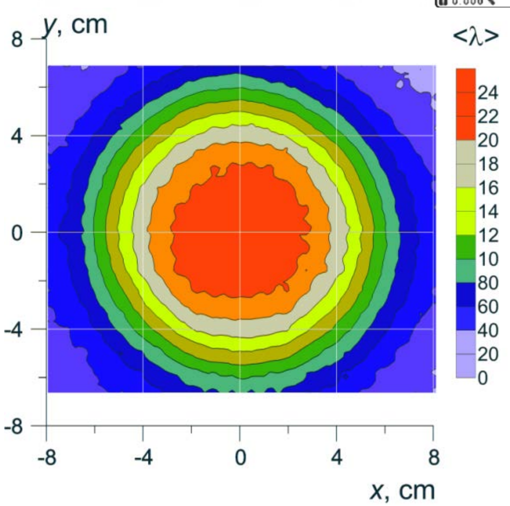
Flat-bottom SSE in operation



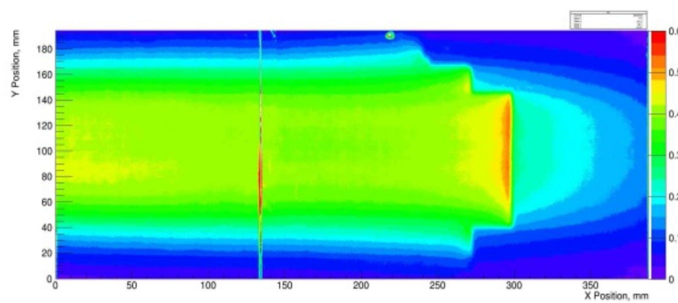
456 MeV/u *C*
0.6-1 sec
$1.5\cdot\cdot 10^{9}$ ipp (8 sec)
45-55% out/in



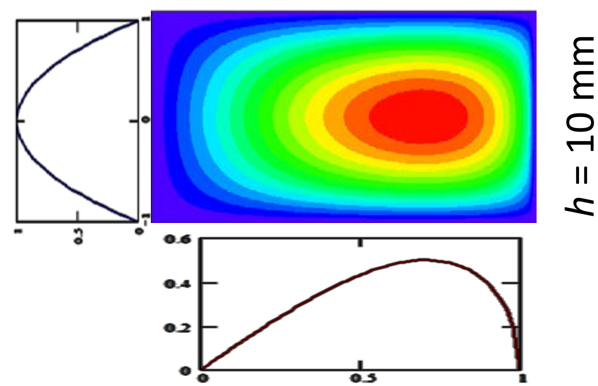
Flat bottom S_TSE is well in demand and serves applied fixed-target research



>95% flatness @ $R \leq 3$ cm



Bragg's law of dose deposition
30 cm range in a water phantom

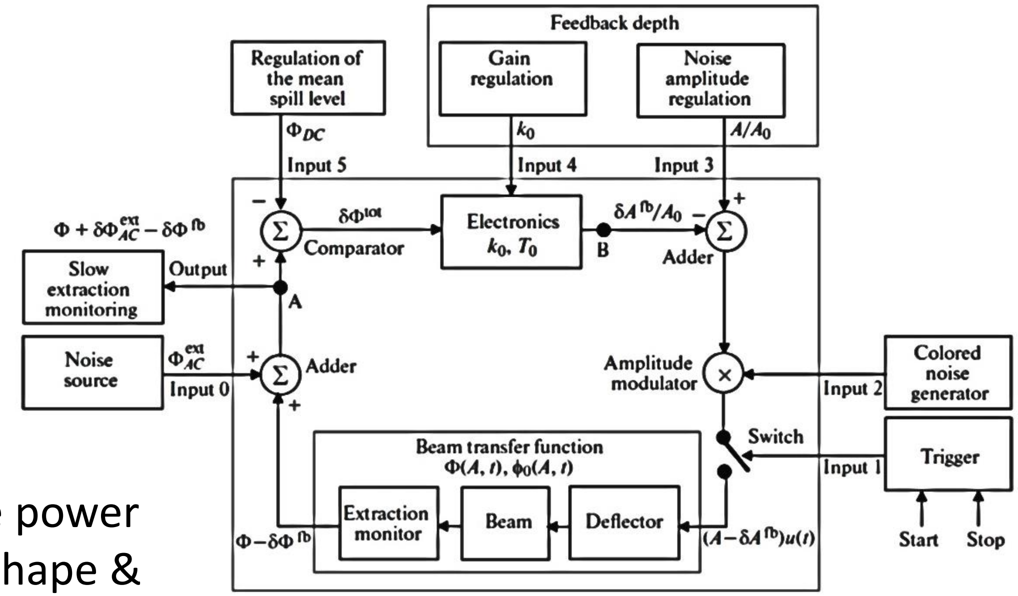


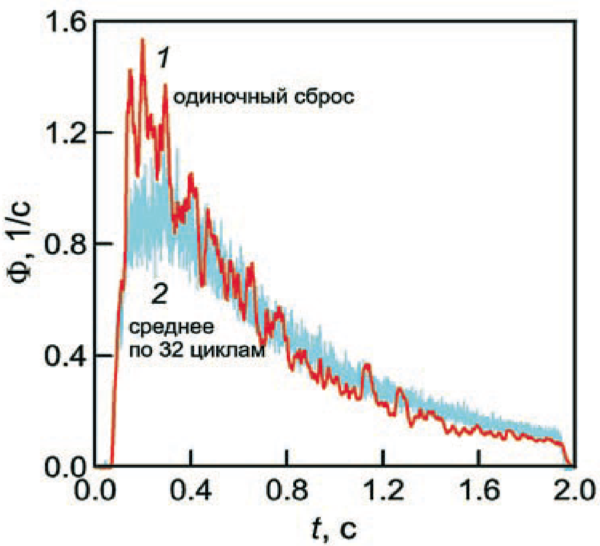
By-product of amplitude selection:
½ compression in momentum spread for a bunched beam

Beam feedback to flatten spills

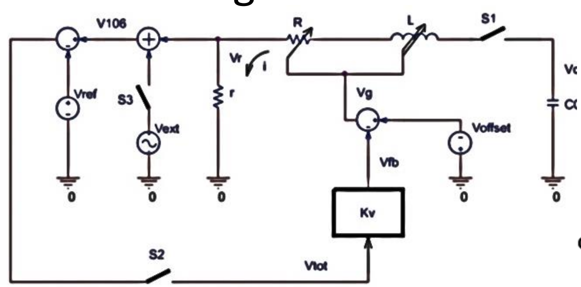
Object under control:

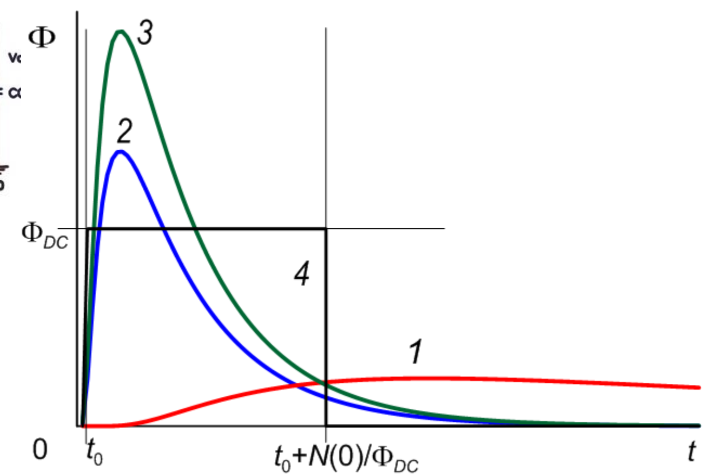
- non-linear,
- non- t-invariant,
- depleted,
- without a “reverse gear”





Fixed noise power spectrum shape & variable magnitude

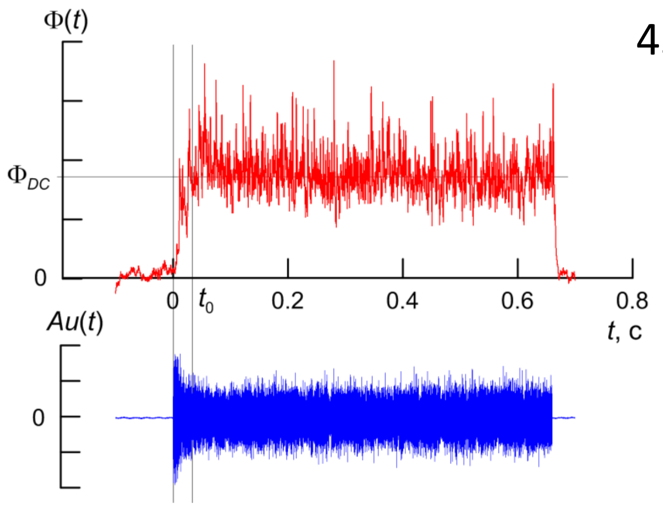


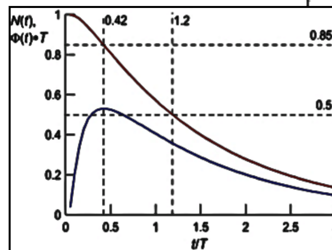


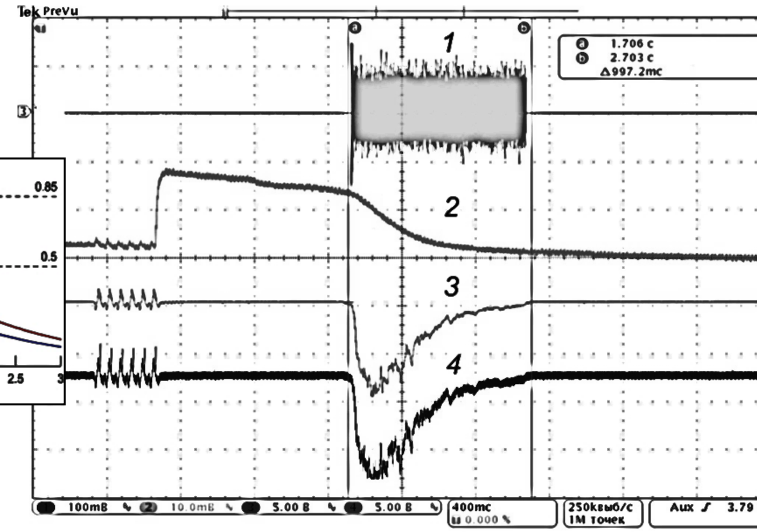
$$\delta N^{(tot)}(t) = \frac{\delta N^{(ext)}(t)}{1 + K_0 \Phi_0 \left(\frac{A^2}{A_0^2} t\right)}$$

Square-wave stochastic spills

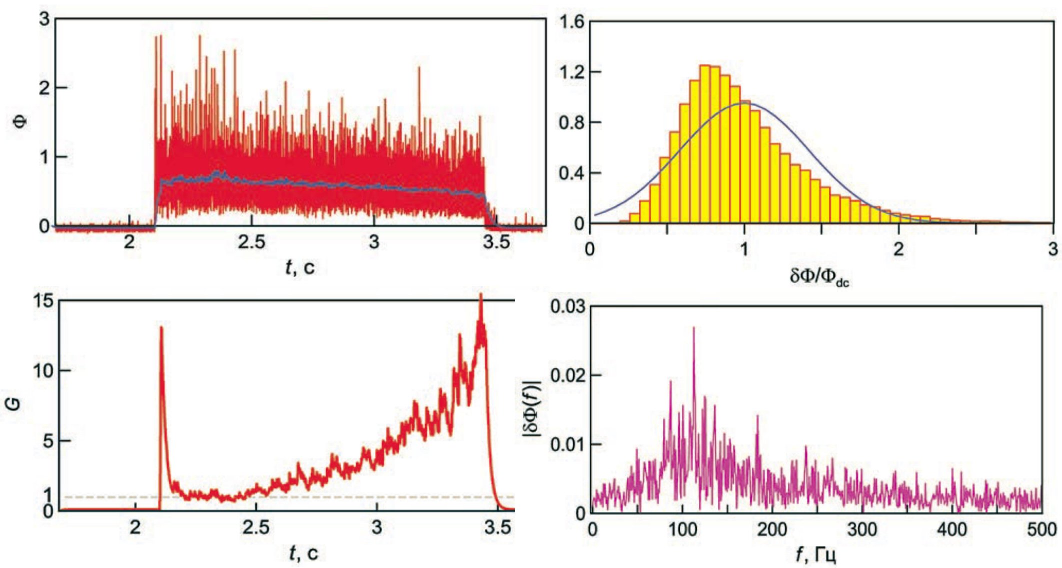
455 MeV/u, *C*

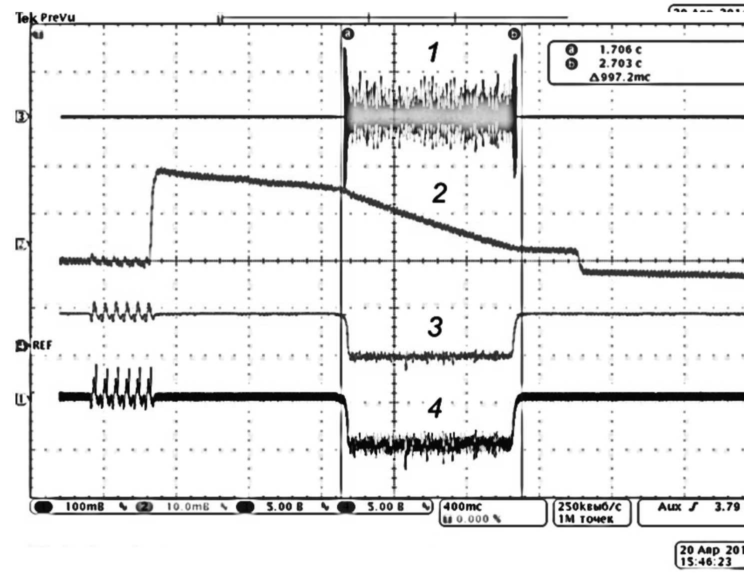






50 GeV, *p*





Conclusion

In the U-70, two stochastic SEs are now routinely employed leaving no place for translational feeding de-facto. **Our experience tells that:**

- To minimize spill ripples is to: (1) lower ripple amplitude *a* in optics + (2) apply to shorter relaxation times $\propto a^2$ for a diffusive feeding (compared to $\propto a^1$ for a translational one)
- There is pear-to-peak asymmetry of ripples w.r.t. to average + suppressed tendency to blackout cut-offs during stochastic extraction
- Reducing coherent ripples in SE spills with a beam feedback circuit in a resonant ($3Q_x = n$) scheme is noticeably LPF-limited due to a virtual (non-dissipative, nonlinear) bandwidth of coherent response of an extracted fraction propagated along $3Q_x = n$ phase-plane trajectories
- In the stochastic SE, some leakage of carrier (transport) noise ripples into a spill is inevitable. Beam user *t*-resolution over a spill must smear this leakage out (say, by observer inherent time constant > 10 noise autocorrelation times). Otherwise, stochastic feeding procedure would turn inappropriate and rather degrade higher-frequency content of spills

Next page is a list of the author's papers for further details in written on the subject matter, if required

References

#	Title	Journal and web-address
1	Experimental Investigation of Stochastic Slow Extraction from the U-70 Synchrotron	Instruments and Experimental Technique, Vol. 49, No. 2, 2006, pp. 157–173. http://link.springer.com/article/10.1134%2FS0020441206020023
2	A Feedback Circuit for the Stochastic Extraction of Protons from the U70 Synchrotron: Development and Beam Tests	Instruments and Experimental Technique, Vol. 49, No. 6, 2006, pp. 752–764. http://link.springer.com/article/10.1134%2FS0020441206060029http://link.springer.com/article/10.1134%2FS0020441206060029
3	Stochastic Slow Extraction from the U-70	News and Problems of Fundamental Physics (in Russian). Vol. 2(6), 2009, p. 5- 25. # ISSN: 1999-2858 http://exwww.ihep.su/ihep/journal/IHEP-2-2009.pdf
4	Longitudinal Instability of a Continuous Beam in a Proton Synchrotron	Atomic Energy, Vol. 104, No. 1, 2008. http://link.springer.com/article/10.1007%2Fs10512-008-0007-9#page-2
5	Transverse Noise Blow-up of the Beam in the U-70 Synchrotron	Instruments and Experimental Technique, Vol. 56, No. 3, 2013, pp. 249–255. http://link.springer.com/article/10.1134%2FS0020441213020140#/page-1
6	Attaining Square-Wave Stochastic Slow Extraction Spills from the U-70 Synchrotron	Instruments and Experimental Techniques, 2015, Vol. 58, No. 4, pp. 456–464. http://link.springer.com/article/10.1134%2FS0020441215040053