IHEP (U-70) slow extraction overview

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2nd Slow Extraction Workshop
CERN, Genève, November 9-11, 2017

Outlook

***Program Committee recommendations for machine overviews**:*

- ~~*details spared for technical talks*~~ no U-70 dedicated technical talk, hence a few technical details are here;
- *emphasis on operation (where possible);*
- *quantify attainable ~~loss levels and~~ spill quality;*
- *list operational problems and issues;*
- *list any specific loss reduction techniques applied;*
- *list any spill quality improvements applied;*
- *mention stability/reproducibility (do machines have a super-cycle, hysteresis effects?);*
- ~~*are activation levels and remote handling issues?*~~
- ~~*key instrumentation for intensity calibration, efficiency, losses, spill quality.*~~

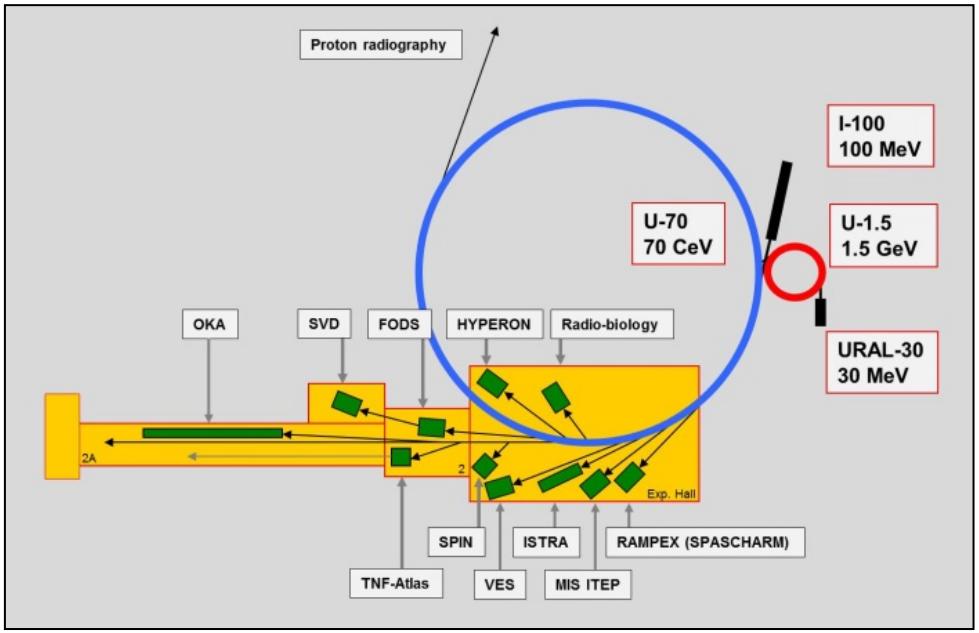
Other talk topics to be touched (mentioned in other report recommendations)

- *Separatrix folding*
- *RF KO vs quad driven extraction: losses vs spill quality* Better compare Translation vs Diffusion, a separate talk today
- *Stochastic noise injection*
- *Feedback and feedforward spill control*
- *Reproducibility of spill quality - machine stability studies*
- *Mains 50 Hz noise: ~~active filtering and~~ other compensation techniques. State of the art*

Where

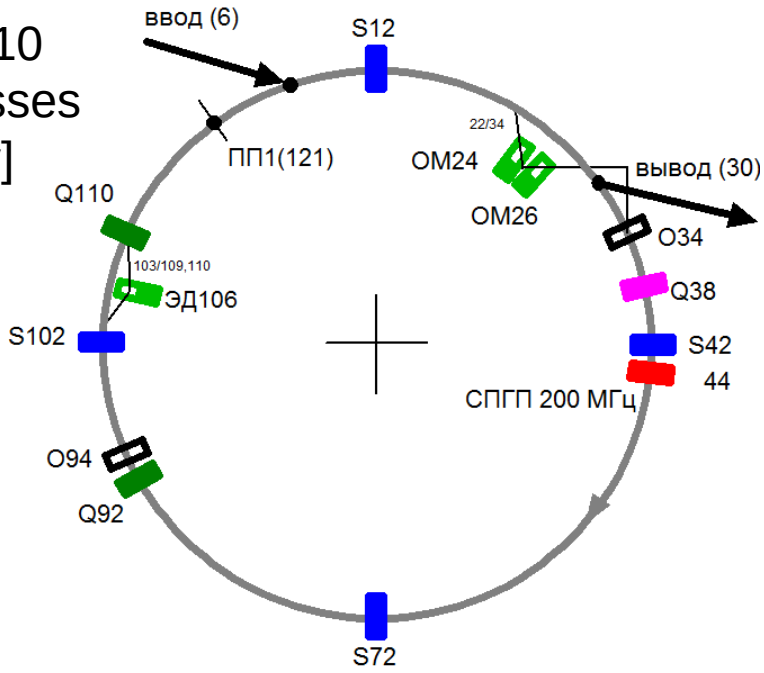
Proton (light-ion) synchrotron U-70

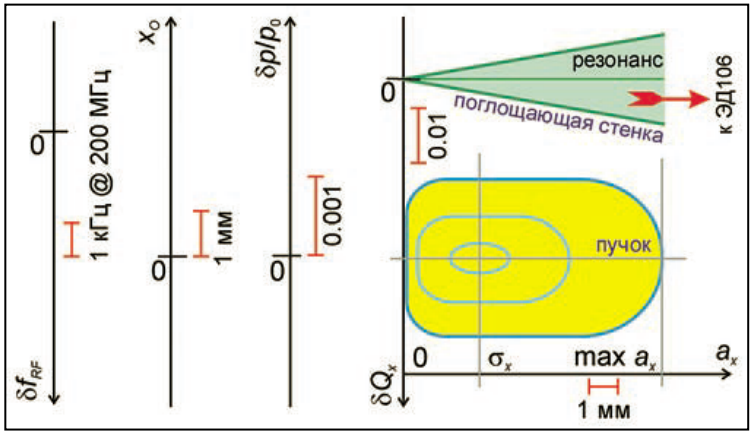
• Energy	1.32 – 50/60/70 GeV
• Orbit length	1483.699 m
• Bending radius ρ	194.125 m
• Magnetic rigidity $B\rho$	233 T·m (max)
• Intensity	< $1.4 \cdot 10^{13}$ ppp
• Ramping cycle	0.1 Hz ca
• 1-2 runs/ year, duration	1000-1500 hr
• Beam availability for physics, 24/7	> 85%



Hardware

*Q*92 and *Q*110 to reduce losses [Yu. Fedotov]





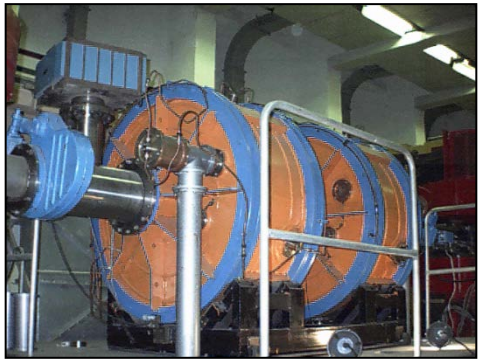
a Steinbach diagram, rotated

3rd order horizontal resonance $3Q_x = 29$

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

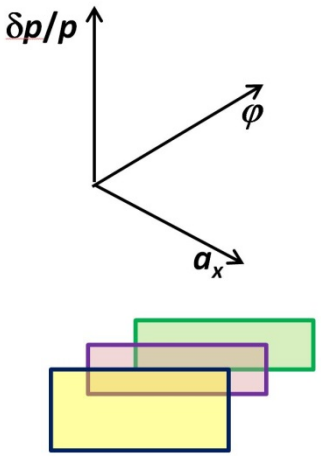
2 feeding alternatives:

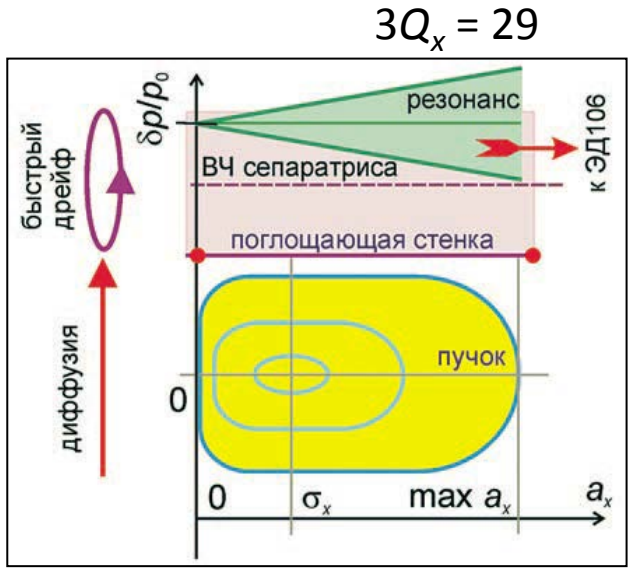
- *Q*38, translation (drift)
- RF200 MHz, diffusion

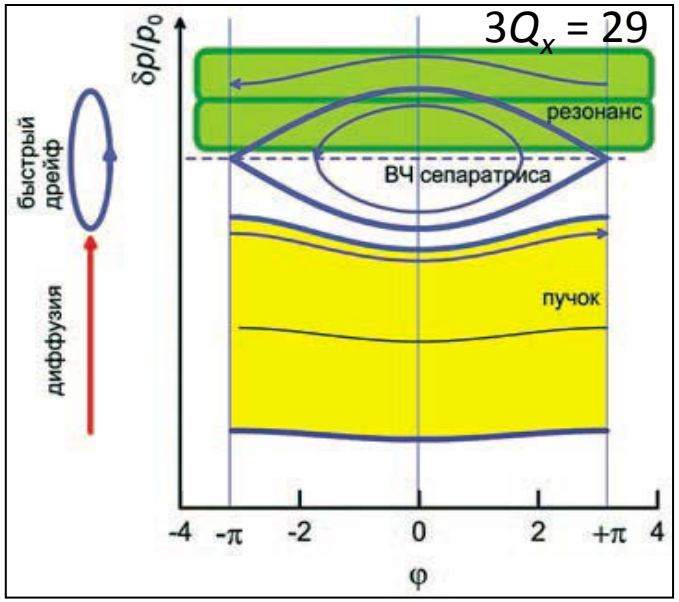


Aux RF system 200 MHz
2 cavities 450 kV/turn total
Operational RF
5.52 – 6.06 MHz, *p*
$h_1 = 30$
$h_2 = 33 \times 30 = 990$

Two-step feeding the $3Q_x = 29$







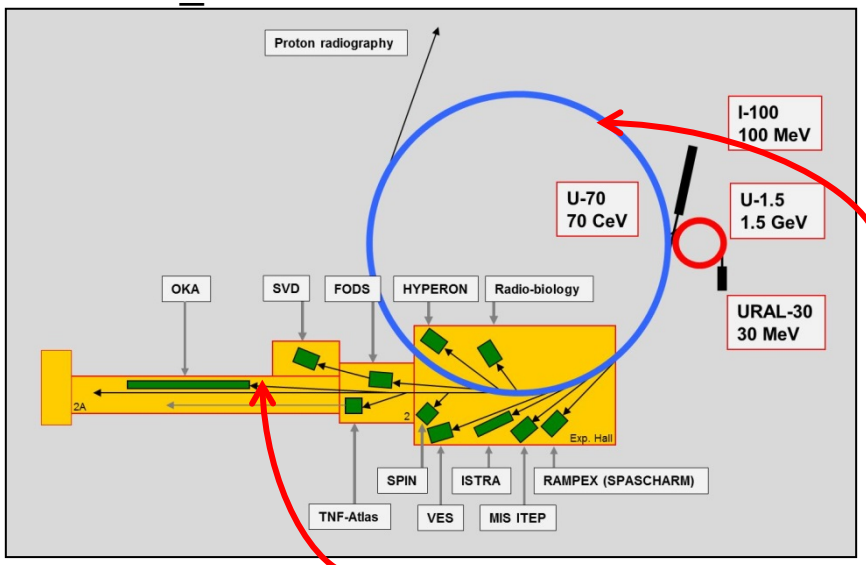
FEATURES:

- A “chimney” zone (recall separatrix folding technique) + a beam trap inside empty RF buckets
- Separatrixes are transparent w.r.t. diffusion
- Re-feeding depleted by SE 200 MHz “bunches”
- Surplus stochastic acceleration of extracted fraction
- No sweeping (drift) over extracted momenta during a spill

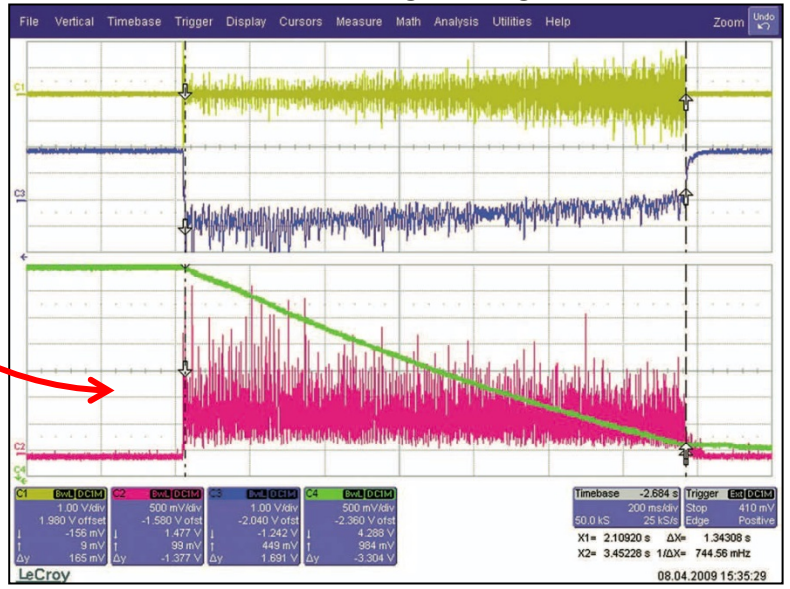
- Adjustable trajectory of WP to resonance in the (Q_x, Q_y)-plane
- Absorbing wall (sink) = const (a_x)
- Phase mixing and randomizing
- “Ribbon” waiting beam less prone to coherent instabilities
- Close to applicability margin from shorter extraction t

Operation (1)

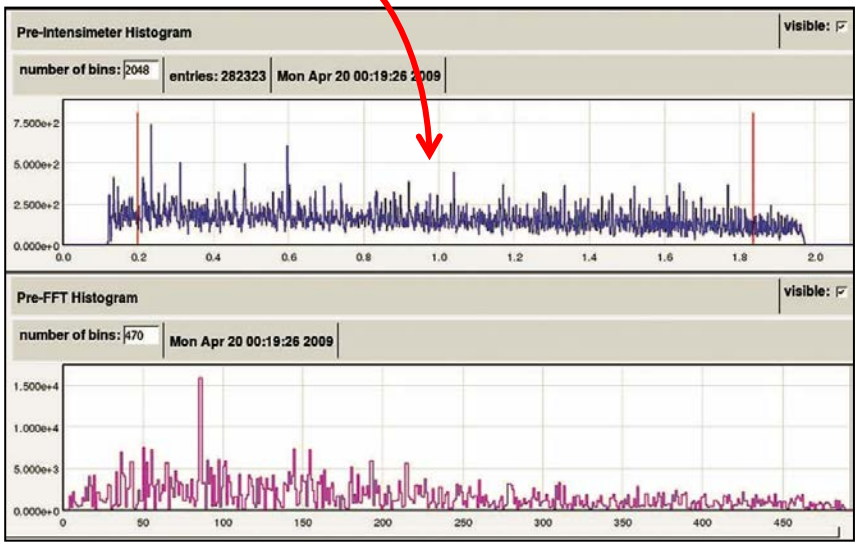
Run 2009_1



Technological signals from U-70



Head counters of OKA facility

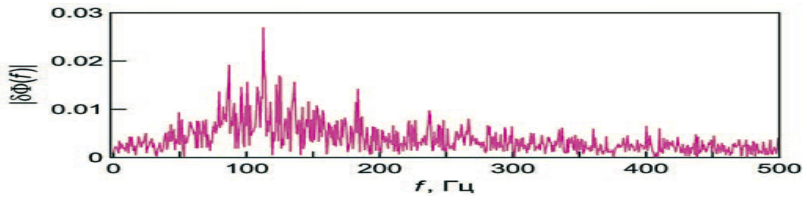


50 GeV *p;* 1.85 sec; $9.5 \cdot 10^{12}$ ppp

No lines of 50 Hz and their multiples

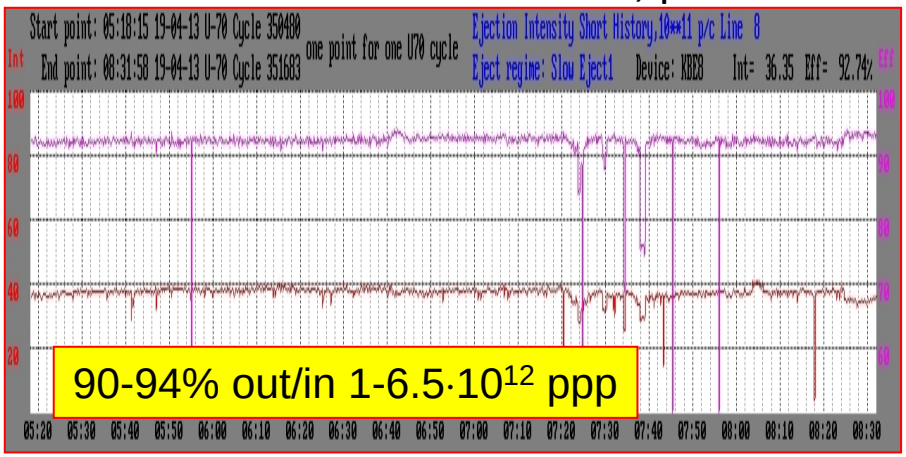
Mixing due to 200 MHz RF and $3Q_x$=29 + a carrier noise leakage

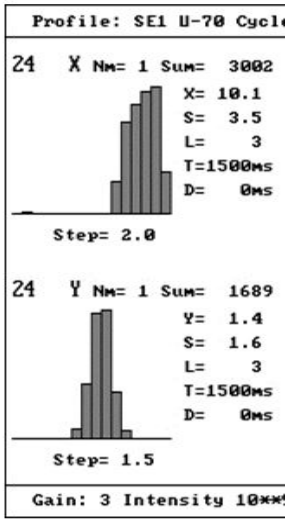
Suppression due to beam FB

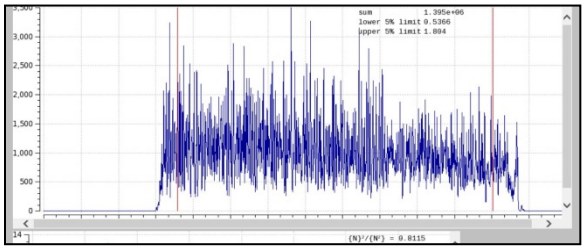


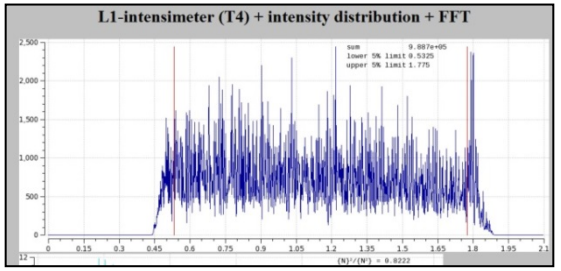
Operation (2)

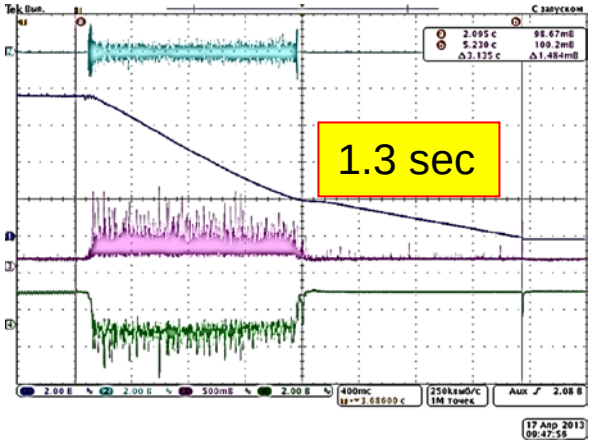
Run 2013-1, protons

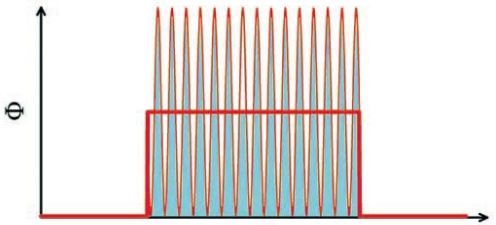






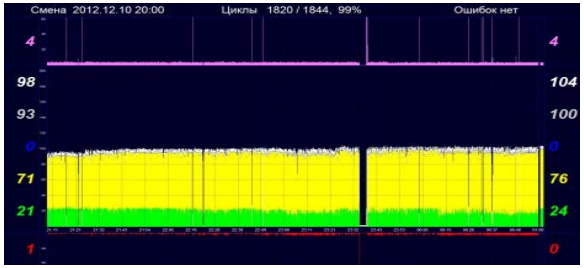






duty factor $\langle\Phi\rangle^2/\langle\Phi^2\rangle$ = 2/3
dispersion σ^2 = 0.5

duty factor $\langle\Phi\rangle^2/\langle\Phi^2\rangle$ to 0.82
dispersion σ^2 = 0.22
no cut-offs and lines of the mains harmonics
½ : 1 : 2 rule-of-thumb for U-70



4% loss

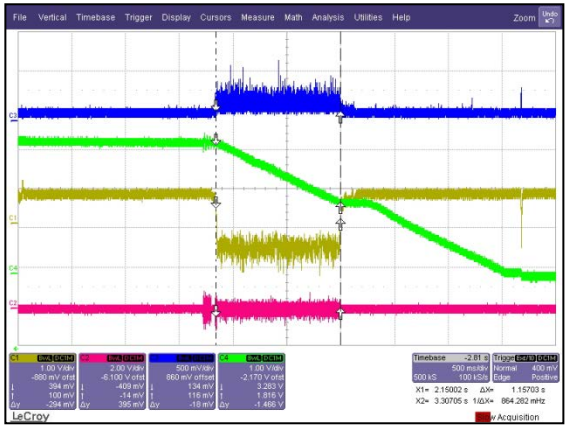
1.05·10^13 ppp total

7-7.6·10^12 ppp via the SSE

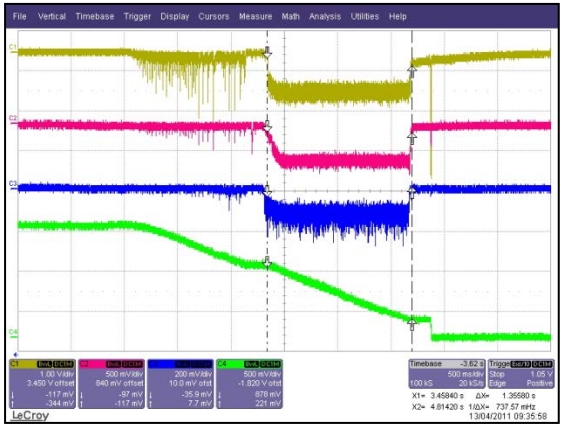
Flattop SE @ U-70:
- effective
- intensive
- slow
- low-ripple

Operation (3)

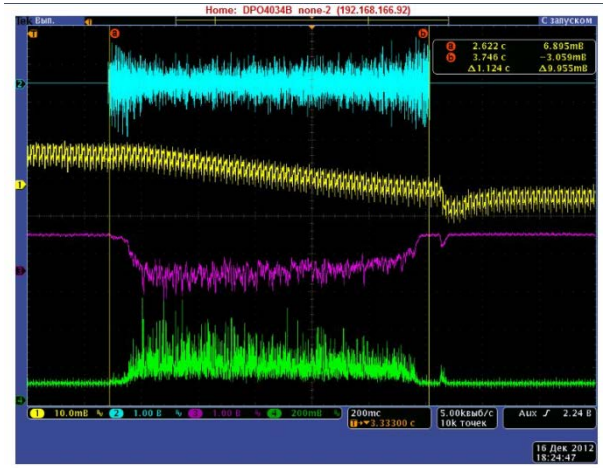
Routine operation: sequential and parallel beam sharing at flattop



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

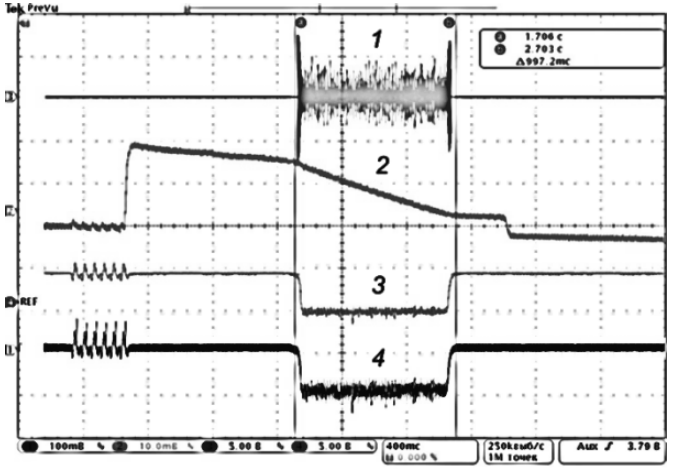


SE CD+IT, *p*, 50 GeV, 3·10^{12} ppp 1.35 s spill



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

Dynamic range 3 orders of magnitude



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

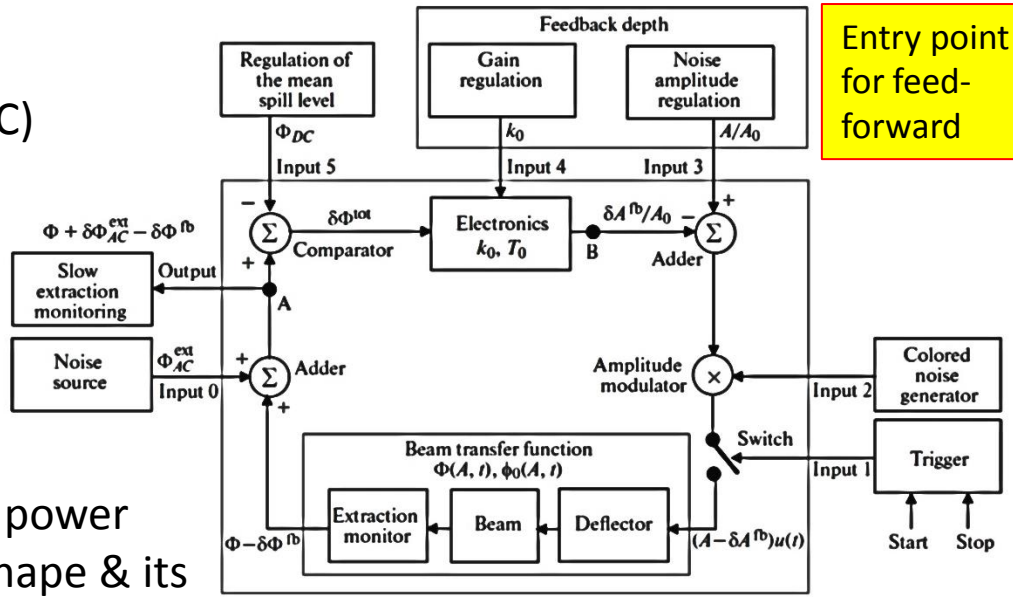
Beam feedback [with a feed-forward entry]

to

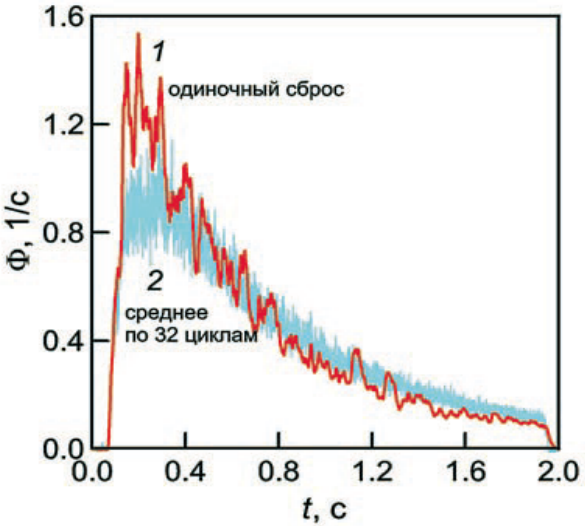
- flatten spills (DC)
- reduce ripple (low-pass AC)

Object under control:

- non-linear,
- non- *t*-invariant (depleted, hysteresis)
- without a “reverse gear”



Entry point for feed-forward

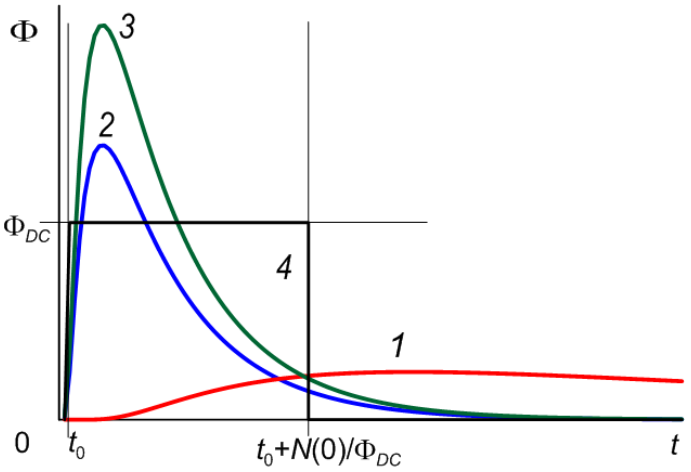


Fixed noise power spectrum shape & its variable magnitude

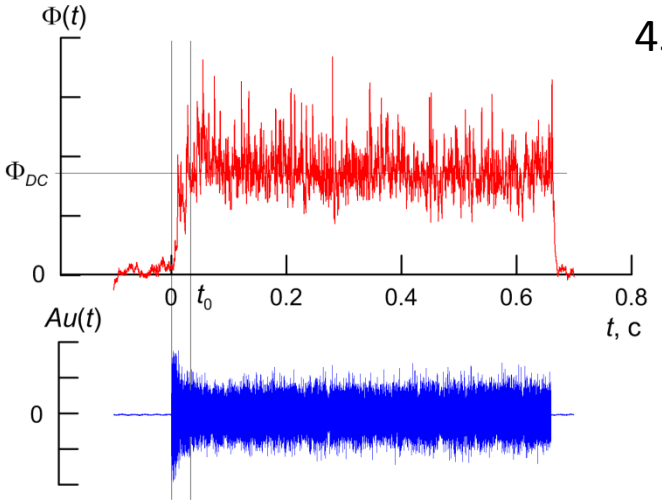
a ‘hysteresis” effect

$$\Phi(t) = G(t)\ \Phi_0\left(\int_0^t G(t)dt\right)$$

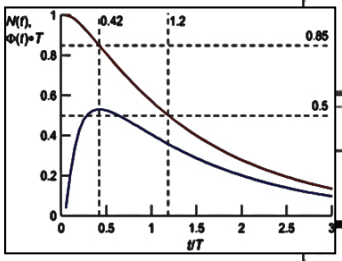
$$\delta N^{(tot)}(t) = \frac{\delta N^{(ext)}(t)}{1 + K_0\Phi_0\left(\frac{A^2}{A_0^2}t\right)}$$

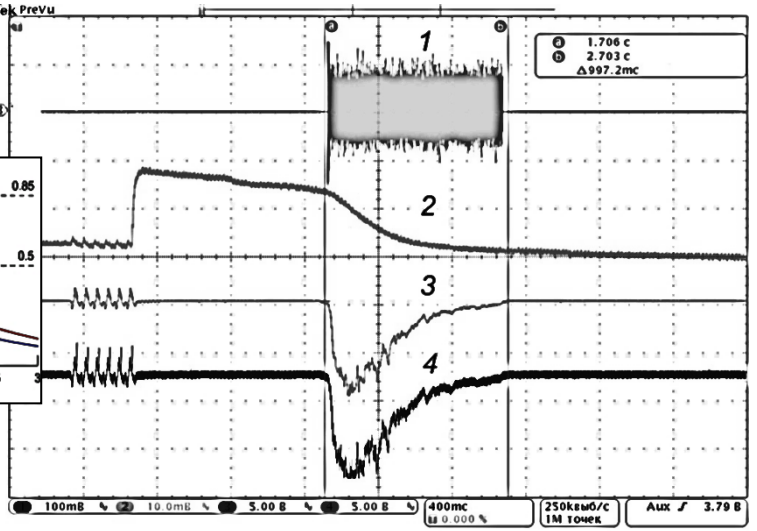


Square-wave spills

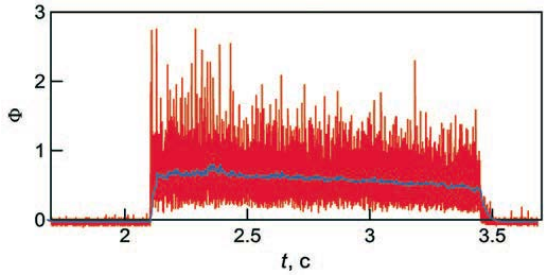


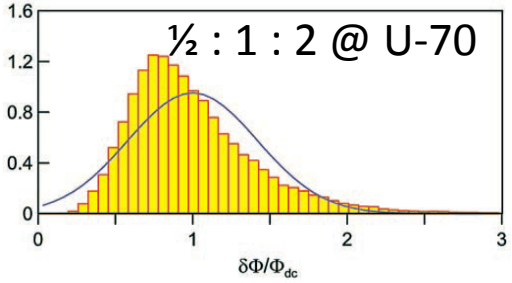
455 MeV/u, *C*

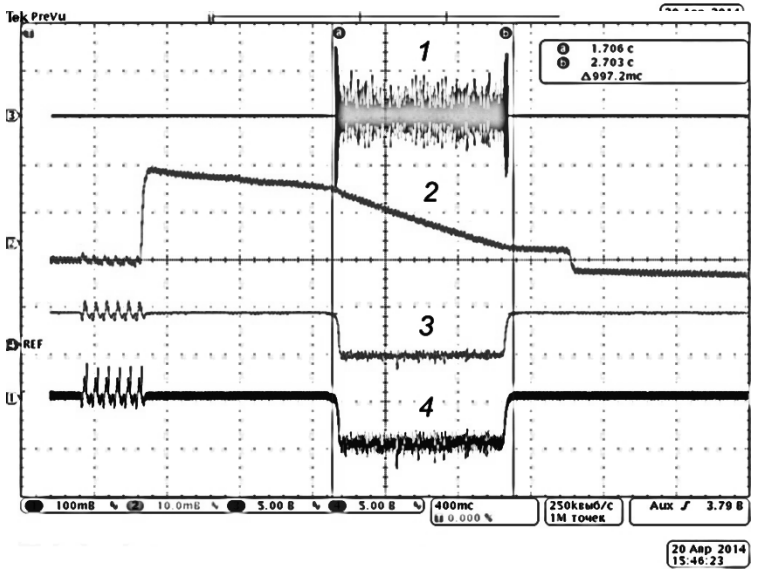




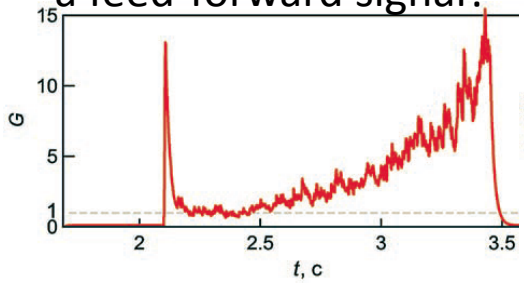
50 GeV, *p*



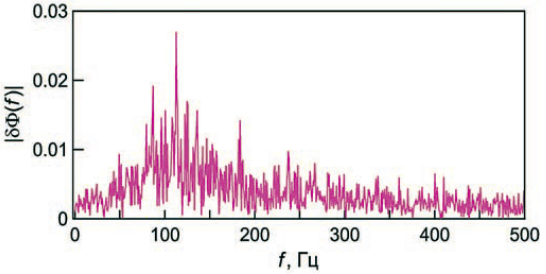




a feed-forward signal?



“bandwidth” of resonance



Conclusion

Almost a replica from that at the 1st SE WS (Darmstadt, 2016)

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 $\propto a^2$ inherent to 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 (few tens of Hz) due to a virtual (non-dissipative, nonlinear) bandwidth of coherent response of an extracted fraction propagated along $3Q_x = n$ phase-plane trajectories
- Feed-forward spill control is redundant. Feedback option is sufficient and easier
- 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 time). Otherwise, stochastic feeding procedure would turn inappropriate and rather degrade higher-frequency content of spills