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Stochastic Beam Cooling in the HESR

- HESR Beam Request -

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BINP – GSI – FAIR 6th workshop

December 1st to 5th, GSI, Darmstadt

Tasks of Stochastic Cooling

HESR in the Modularized Start Version of FAIR (MSV)

- **Antiproton Mode**
  - Beam Accumulation with Moving Barrier Buckets at Injection Energy 3 GeV
  - Internal Target Experiments with Barrier Bucket
    - *High Resolution mode: $\Delta p/p$ (rms) $\sim 10^{-5}$, $N = 10^{10}$*
  - Deceleration to 1 GeV (cooling at 2 GeV, 25 s)

- **Heavy Ion Mode**
  - Injection at 740 MeV/u
  - Internal Target Experiments with Barrier Bucket

Stochastic Cooling (2 – 4) GHz

- **Horizontal and Vertical Cooling**
- **Momentum Cooling**
  - Fast Filter Cooling
  - Time of Flight (TOF) cooling with large cooling acceptance
- Cooling Models
  - Fokker-Planck Equation
  - Particle Tracking Code
    - *Including Synchrotron Motion and Target*

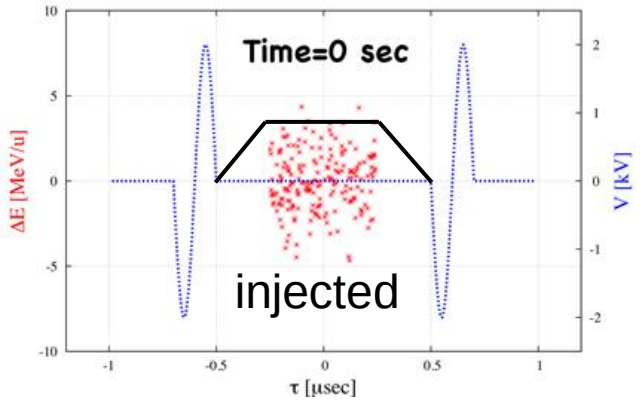
Anti-Proton Beam Accumulation

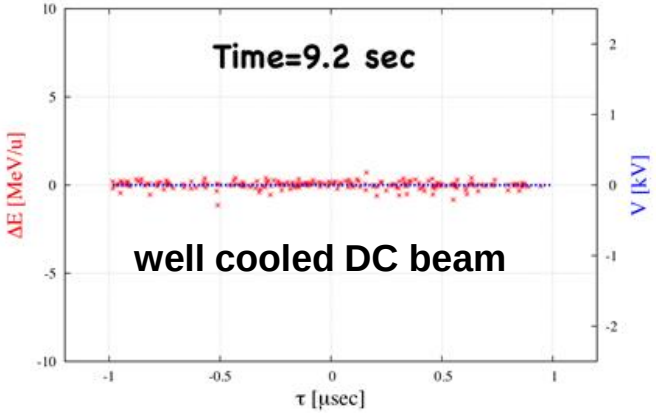
- Main parameters for accumulation

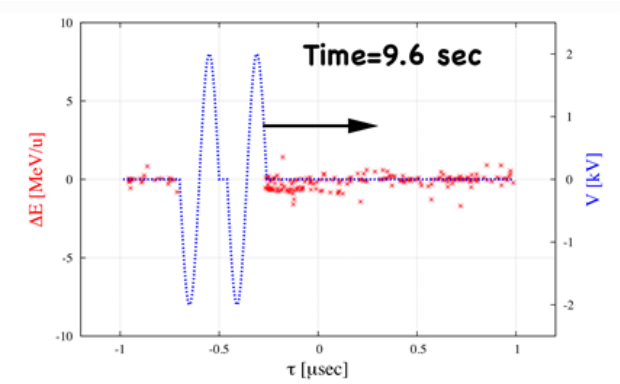
Injected bunch length (tot)	< 500	ns
Bunch momentum spread (rms)	$5 \cdot 10^{-4}$	
Injection kicker magnet (rising&falling time)	250	ns
Flat top time kicker	500	ns
Cycle time	10	s
Barrier peak voltage	2	kV
Barrier voltage frequency	5	MHz
Barrier voltage rising/falling time	0.2	s
Barrier moving time	0.5	s

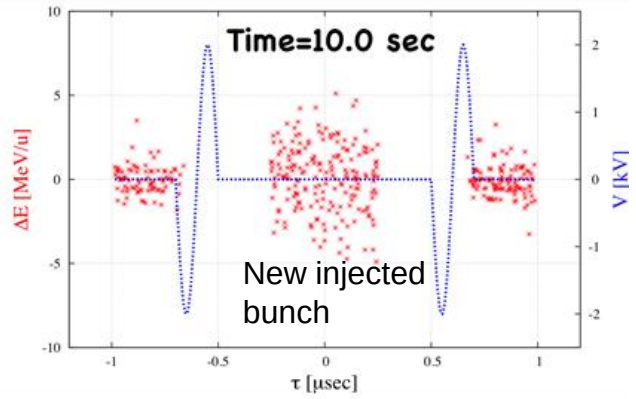
Anti-Proton Beam Accumulation

- Every 10 s one bunch with 10^8 anti-protons injected from CR into a gap created by two barrier pulses
- Repeat 100 times for final 10^{10} anti-protons
- **Stochastic Filter Momentum Cooling is essential!**





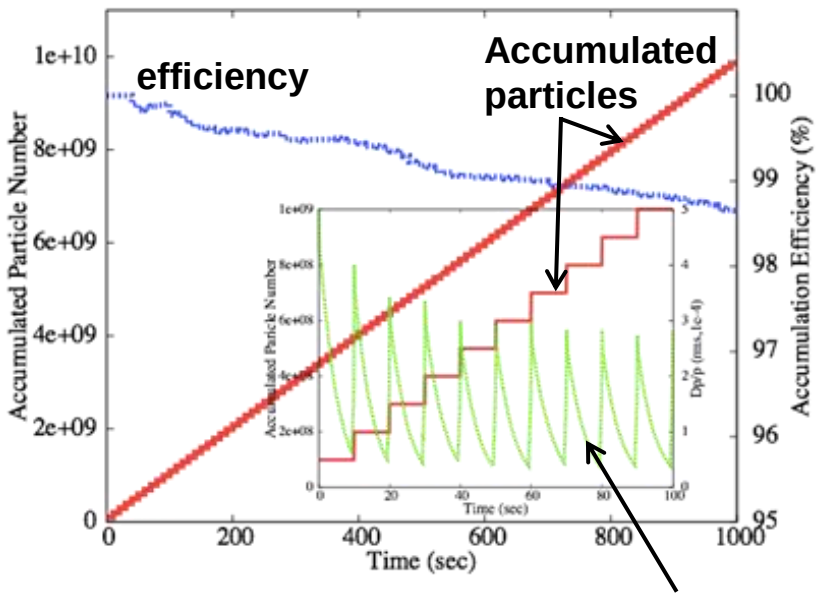


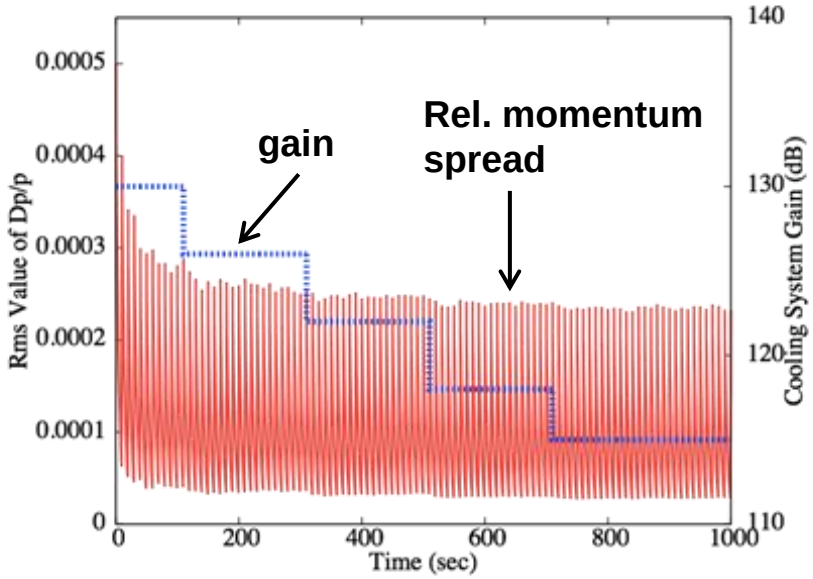


Anti-Proton Beam Accumulation*)

- Electronic gain of SC reduced from 130 dB to 115 dB
- Particle microwave power < 70 W
- Accumulation efficiency 99 %
- Momentum spread (rms) < $2 \cdot 10^{-4}$
- Accumulation time 1000 s: final ≈ 10^{10} anti-protons

*) M. Steck et al., POP Experiments 2010, COOL11





Anti-Proton Acceleration and Internal Target Experiment

- After beam accumulation change lattice to γ_{tr} =14.6
- Adiabatic re-bunching of DC beam (h = 1 cavity)
- Acceleration to 8 GeV without crossing transition energy
- After de-bunching at 8 GeV change transition energy: γ_{tr} = 6.23
- Adiabatic re-bunching and acceleration to 14 GeV
- After de-bunching switch barrier bucket ON adiabatically
- Start cooling and internal target

Beam Quality Requirements of the HESR

- Injection (ions or antiprotons) lattice with $\gamma_{tr} = 6.23$
- Position and angle dispersion zero in straight sections
- Transverse acceptance: 16 mm mrad
- Momentum acceptance: $\pm 2.8 \cdot 10^{-3}$

SC momentum acceptance δ_{SC}	SC method	Kinetic Energy [MeV/u]	$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^2}$	Particle Type
$\pm 1.8 \cdot 10^{-3}$	Filter	3000	0.03	anti-protons

- ***The application of stochastic cooling limits the acceptable momentum spread in the beam bunch delivered by the CR for anti-proton beam accumulation.***

Injected Beam Bunch Requirements Anti-Protons

- The injected anti-proton ***bunch*** should have

Kinetic Energy [MeV/u]	rms rel. Momentum Spread $(\Delta p/p)_{rms}$	Particle Type
3000	**$< 6 \cdot 10^{-4}$**	**anti-protons**

- Transverse emittance $\varepsilon = 6\ \varepsilon_{rms} < 16$ mm mrad
- Bunch length < 500 ns

$$\varepsilon = \frac{phase\ space\ area}{\pi}$$

Heavy Ion Beam Operation

- Injection of a $^{238}U^{92+}$ beam from CR into HESR
  - Beam preparation at 740 MeV/u
  - Mean energy loss compensation with Barrier Bucket (BB) cavity
  - Stochastic cooling with internal hydrogen target

- Injection of a $^{238}U^{92+}$ beam from CR into HESR
  - Capture and acceleration to 4.5 GeV/u
  - Beam preparation at 4.5 GeV/u
  - Stochastic cooling with internal hydrogen target and BB operation

Target thickness: $N_T = 4 \cdot 10^{15}$ cm^{-2}

Ion Beam Injection from CR to HESR

Ion beam preparation in the CR*):

- **Bunch Rotation** in the CR of injected beam delivered from SIS 100.
  Leads to a relative momentum spread
  $\delta \approx 1.5 \times 10^{-4}$ (rms)
- **Adiabatic re-bunching** (350 ms) of the ion beam to provide time gap of 200 ns for extraction kicker:
  - **relative momentum spread of bunch $\delta = 3.3 \times 10^{-4}$ (rms)**
  - **bunch length $\sigma_\tau = 110$ ns (rms)**
- **Kicker Extraction of beam bunch to HESR**

Main CR parameters:

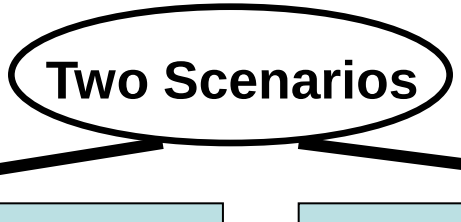
Ion	$^{238}U^{92+}$	
Kinetic energy	740	MeV/u
β	0.83	
γ	1.794	
Number of bunches	1	
Number of ions	10^8	
Frequency slip factor η	0.186	
Revolution frequency	1.124	MHz
Ring length	221.45	m

Transverse emittance**):
$\varepsilon_{x,y} = 0.125$ mm mrad (rms)

*) T. Katayama, "Stochastic Cooling of Heavy Ion Beam in Collector Ring, Draft of SPARC proposal", March 2012

**) C. Dimopoulou's note on "HESR FOR IONS WITH THE 2 MeV ECOOLER", 26.10.2011

Injection at 740 MeV/u



Injection Into Moving Barriers:

- Injection into barriers
- Move barriers to reduce momentum spread
- Cool beam into stable bucket area
- Start experiment with internal target, TOF cooling is ON

Injection Into Standing Bucket

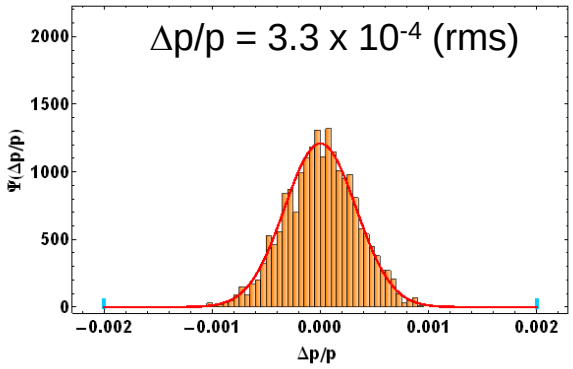
- Capture beam with cavity at fundamental frequency (h = 1)
- Adiabatically reduce voltage
- Switch OFF h = 1 cavity and switch on BB cavity
- De-bunching in BB cavity, beam becomes quasi DC
- Start **TOF cooling** and insert target

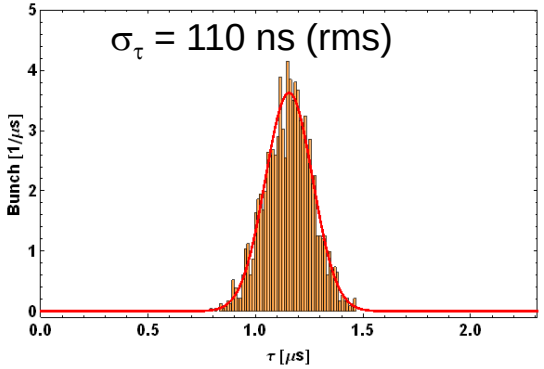
Detailed presentation on SPARC2012 Vienna, November 26th-28th, 2012, Vienna

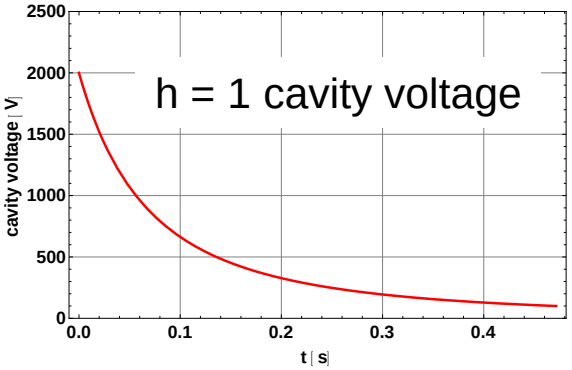
Adiabatic Compression of Momentum Spread

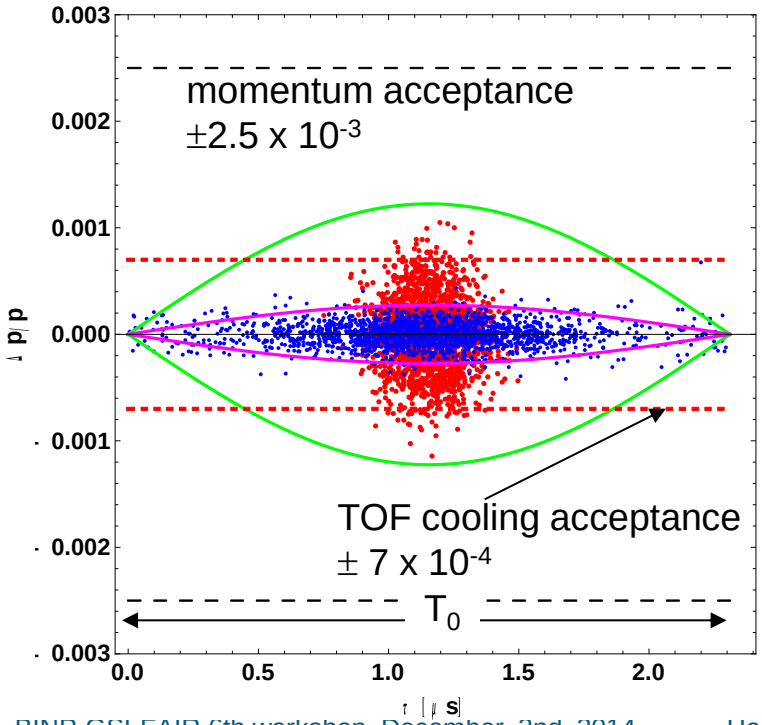
with h = 1 cavity

Injected bunch:









Synchrotron Motion in Phase Space (τ, Δp/p):

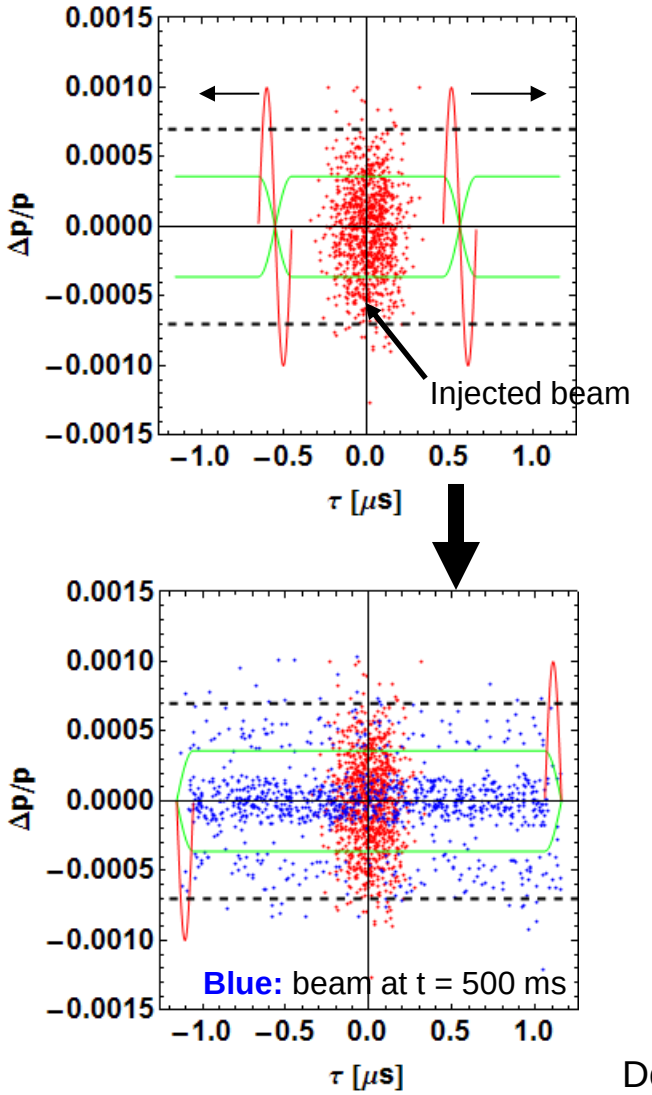
Initial:
phase space: red dots
separatrix: green

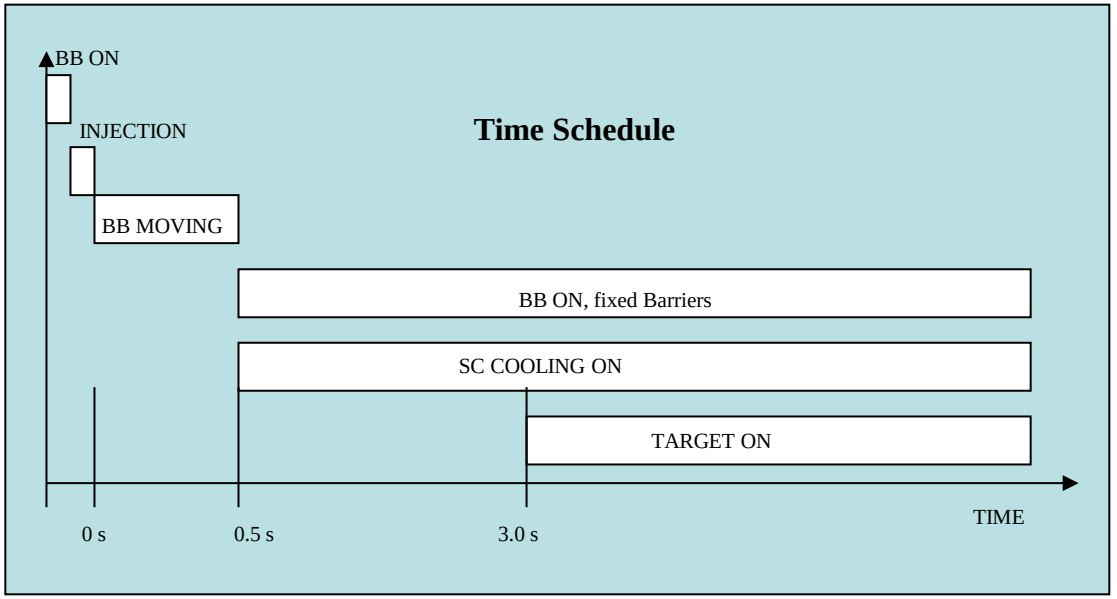
Final after 470 ms:
phase space: blue dots
separatrix: magenta

Final:

- Momentum spread $\delta_{rms} \approx 1.2 \times 10^{-4}$
- Beam distributed almost along the entire ring.
- Beam fits into BB separatrix
- Beam fits into TOF cooling acceptance

Injection into Moving Barrier at 740 MeV/u

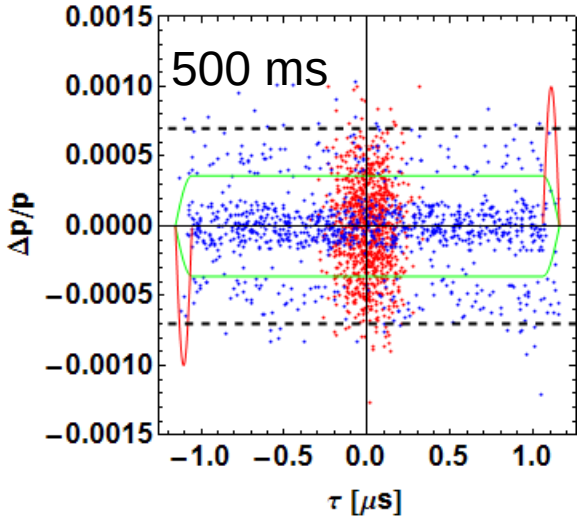


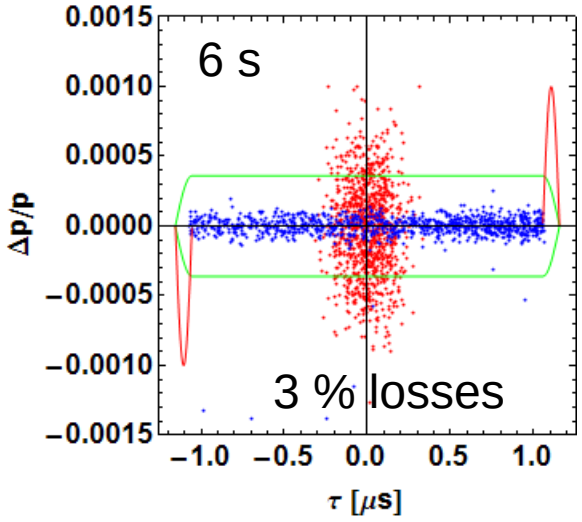


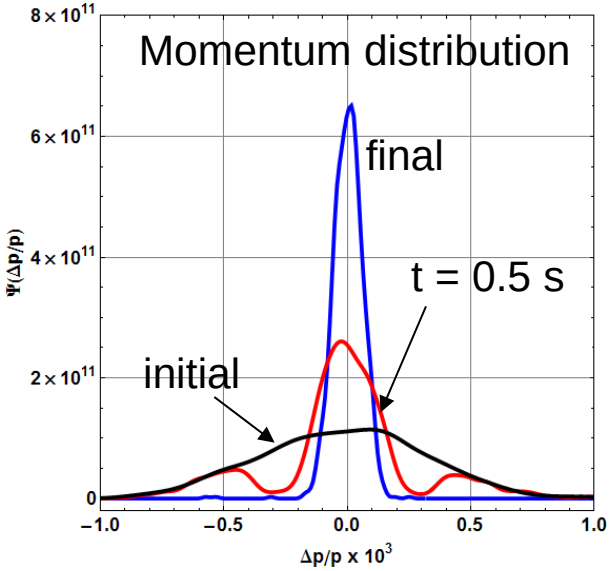
- Two HESR cavities each 2 kV peak create two barriers 1.1 μs apart
- Injection of N = 10^8 Uranium ions into BB
- Barrier moved within 500 ms to adiabatically reduce the momentum spread of particles inside the separatrix (green).

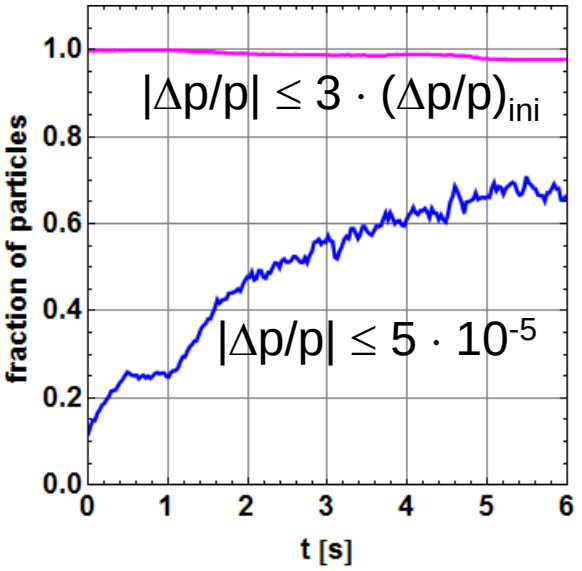
Dotted line: momentum acceptance of TOF cooling system: $\pm 7 \cdot 10^{-4}$

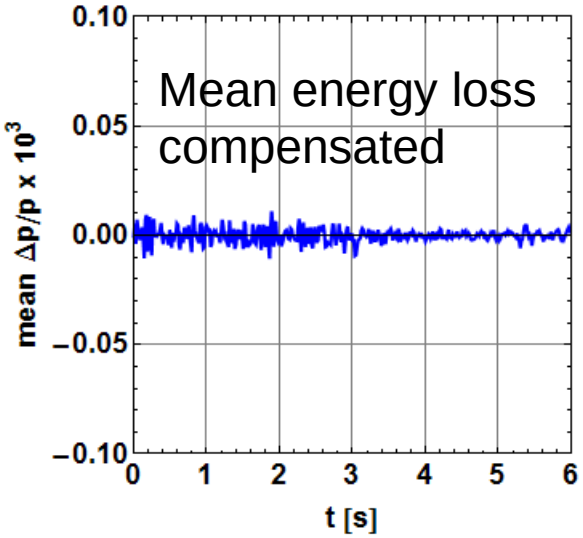
Internal Target and TOF Cooling at 740 MeV/u

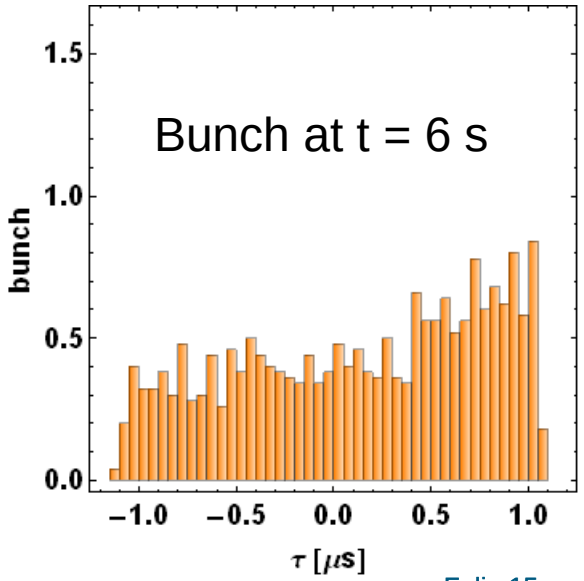












Injected Beam Bunch Requirements Ions

- The injected ion ***bunch*** should have

Kinetic Energy [MeV/u]	rms rel. Momentum Spread $(\Delta p/p)_{rms}$	Particle Type
740	$< 2 \cdot 10^{-4}$	ions

- Transverse emittance $\varepsilon = 6\ \varepsilon_{rms} < 16$ mm mrad
- Bunch length $\approx$ 100 ns

TOF cooling acceptance: $7 \cdot 10^{-4}$

Summary

- The injected ion or anti-proton ***bunch*** from the CR should have

Kinetic Energy [MeV/u]	rms rel. Momentum Spread $(\Delta p/p)_{rms}$	Particle Type
3000	$< 6 \cdot 10^{-4}$	anti-protons
740	$< 2 \cdot 10^{-4}$	Ions

- Transverse emittance $\varepsilon = 6\ \varepsilon_{rms} < 16$ mm mrad
- Bunch length < 500 ns

$$\varepsilon = \frac{phase\ space\ area}{\pi}$$