Longitudinal stacking and electron cooling of ion beams in the ESR as a proof of principle for FAIR

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Overview

- Motivation: Stacking of Rare Isotopes in the NESR @FAIR

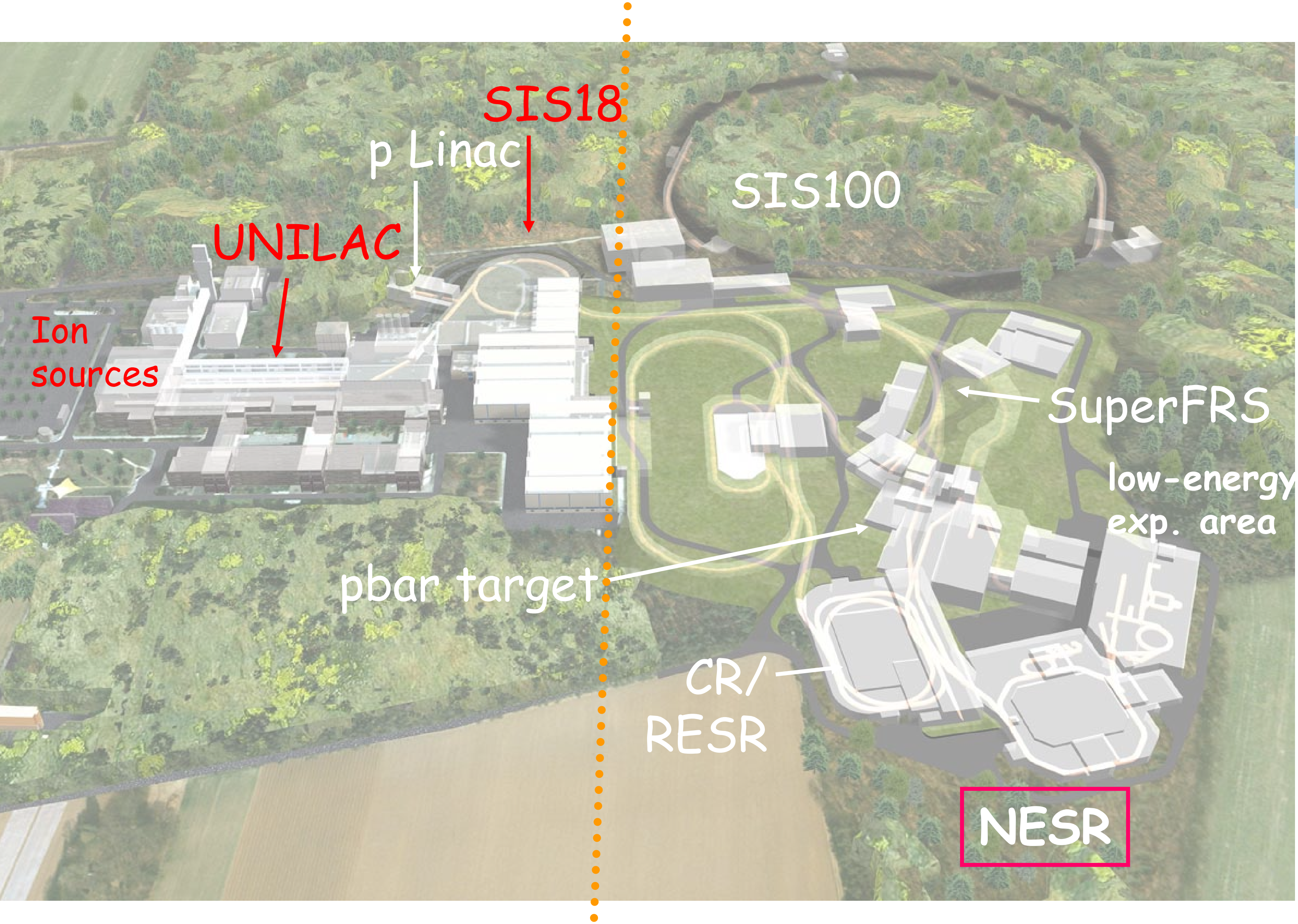
- Cooling-stacking experiments in the ESR:

  - Long. accumulation with Barrier Buckets

  - Long. accumulation with the sinusoidal RF at h=1

- Conclusions & Outlook

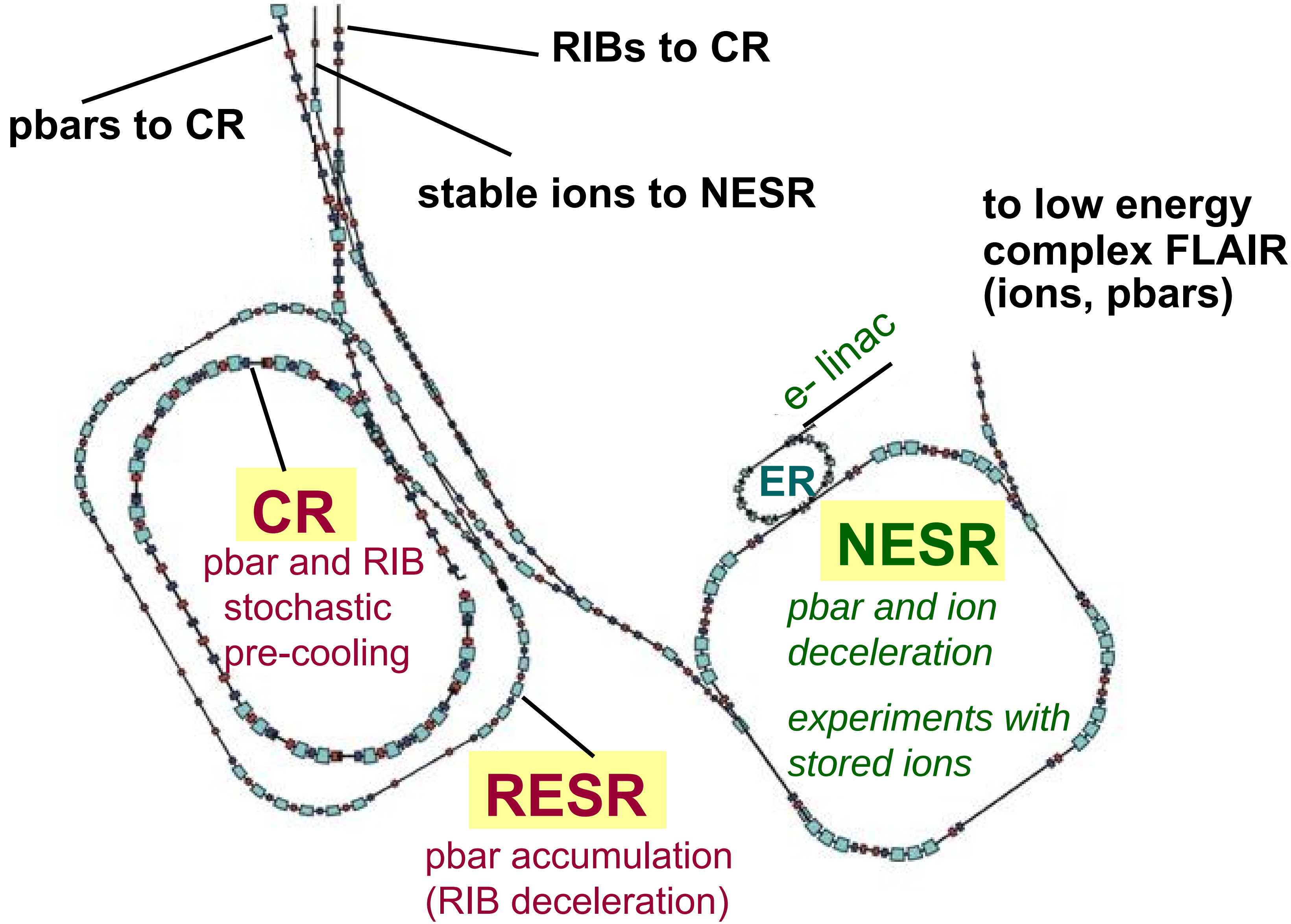
FAIR Facility for RIBs and pbars



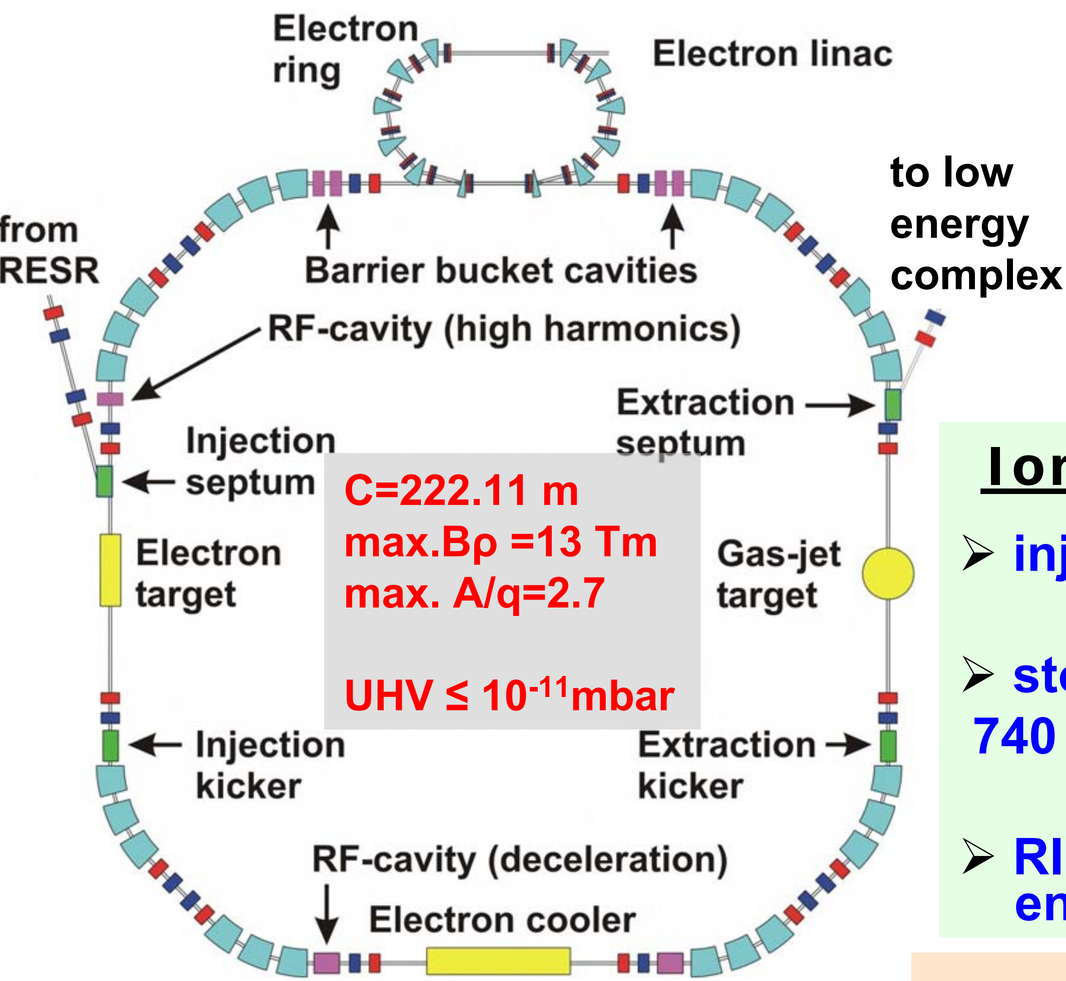
RIBs

pbars

The FAIR 13 Tm storage rings



NESR Operation with ions



C=222.11 m
max.Bρ =13 Tm
max. A/q=2.7

UHV ≤ 10^{-11}mbar

momentum acceptance (ε_H=0): ±2.1 %
transverse accep. H/V (Δp/p= ±1.5%):
160 / 50 mm mrad

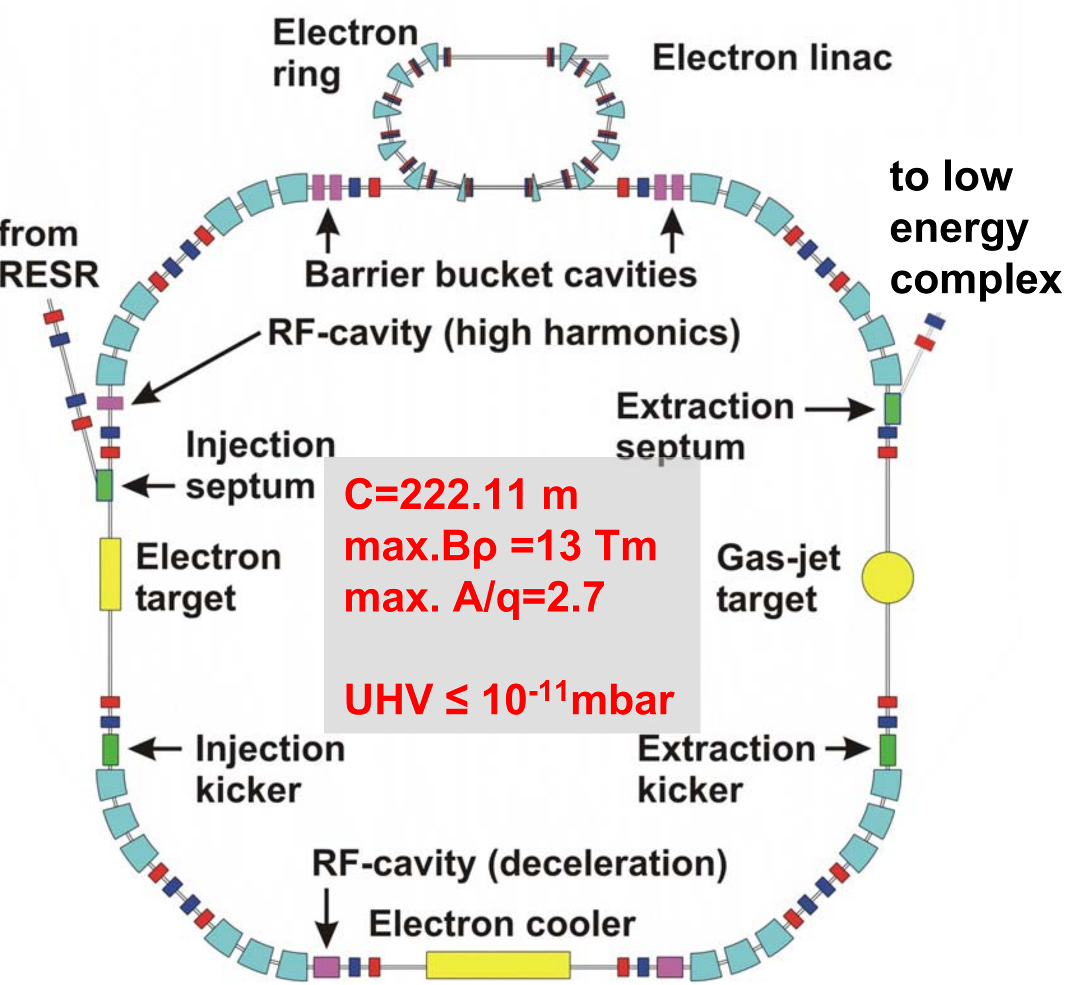
Ions (Stable & Rare Isotopes)

- injection at 100 - 740 MeV/u
- storage and e-cooling in the range 740 → 4 MeV/u (max. decel. rate 1 T/s)
- RIB accumulation at injection energy assisted by electron cooling

Experiments

- experiments with internal target
- electron target (2nd electron cooler)
- laser interactions (cooling, spectroscopy)
- collider mode with electrons/pbar

NESR Operation with antiprotons



momentum acceptance (ε_H=0): ±2.1 %
transverse accep. H/V (Δp/p= ±1.5%):
160 / 50 mm mrad

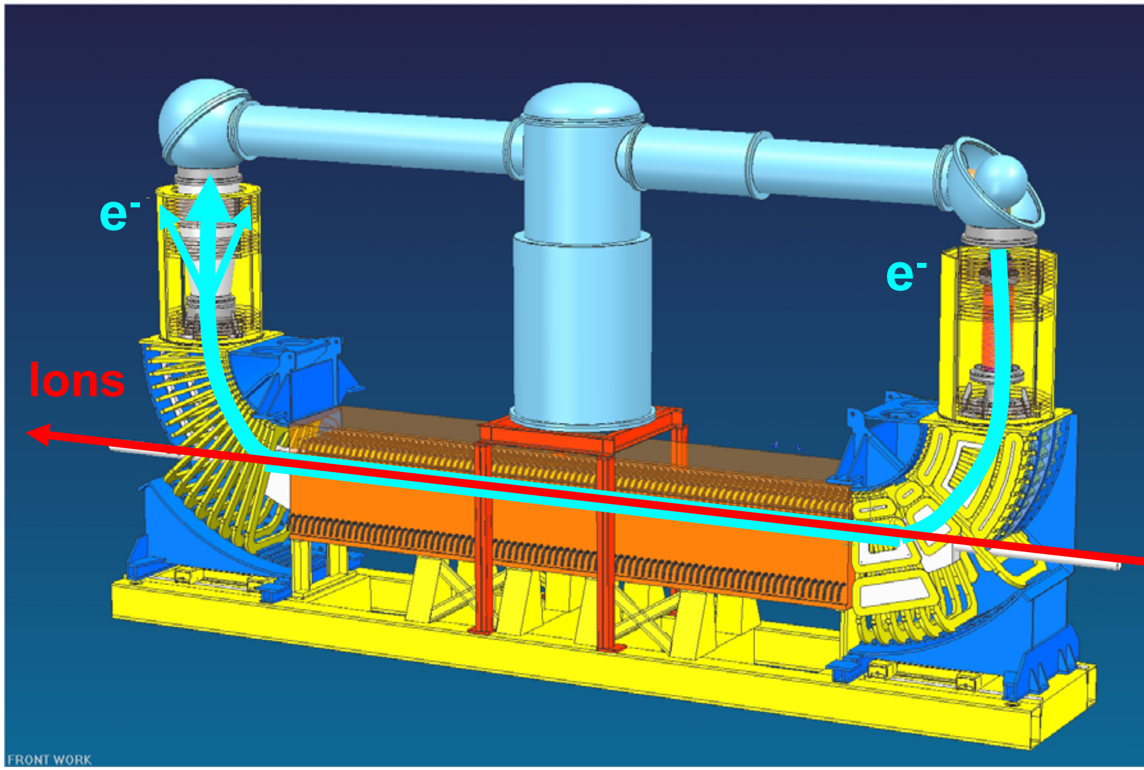
Antiprotons

deceleration 3000 → 800 → 30 MeV

electron cooling at 800 MeV

The NESR Electron Cooler

design by BINP, Novosibirsk

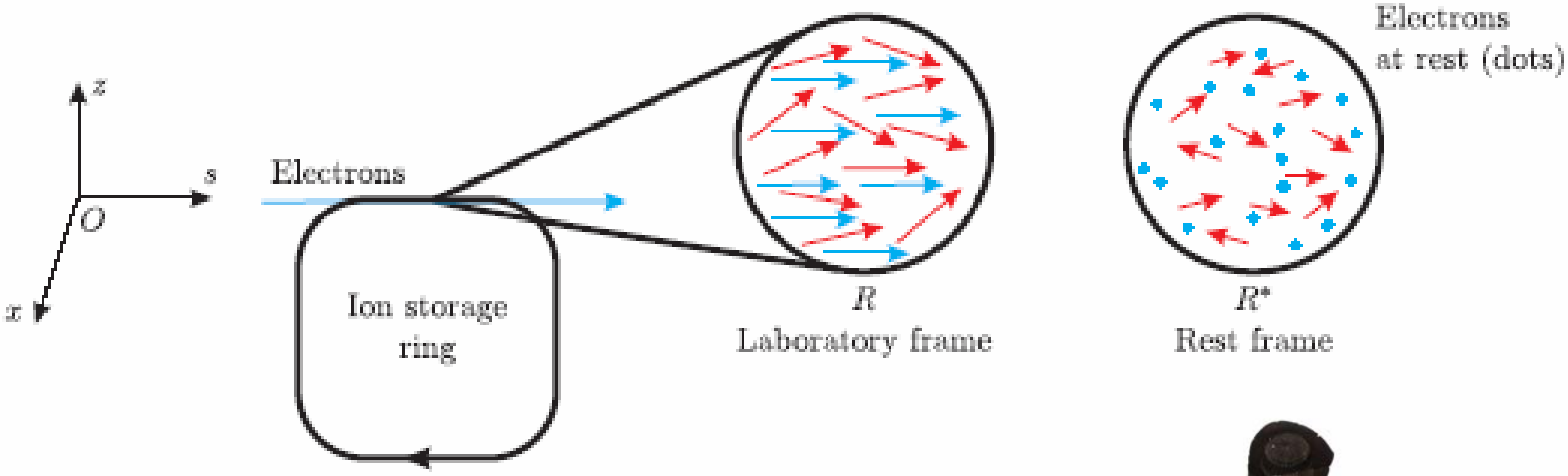


Cooler Parameters

energy	2 - 450 keV
max. current	2 A
cathode radius	1 cm
beam radius	0.5-1.4 cm
hollow cathode option	
magnetic field	
gun	up to 0.4 T
cool. sect.	up to 0.2 T
straightness	$\leq 5\times10^{-5}$
adiabatic expansion option	
cool. section length	5 m
max. power in collector	15 kW
vacuum	$\leq 10^{-11}$ mbar

Issues:
- high voltage up to 500 kV
- fast ramping, up to 250 kV/s
- magnetic field quality

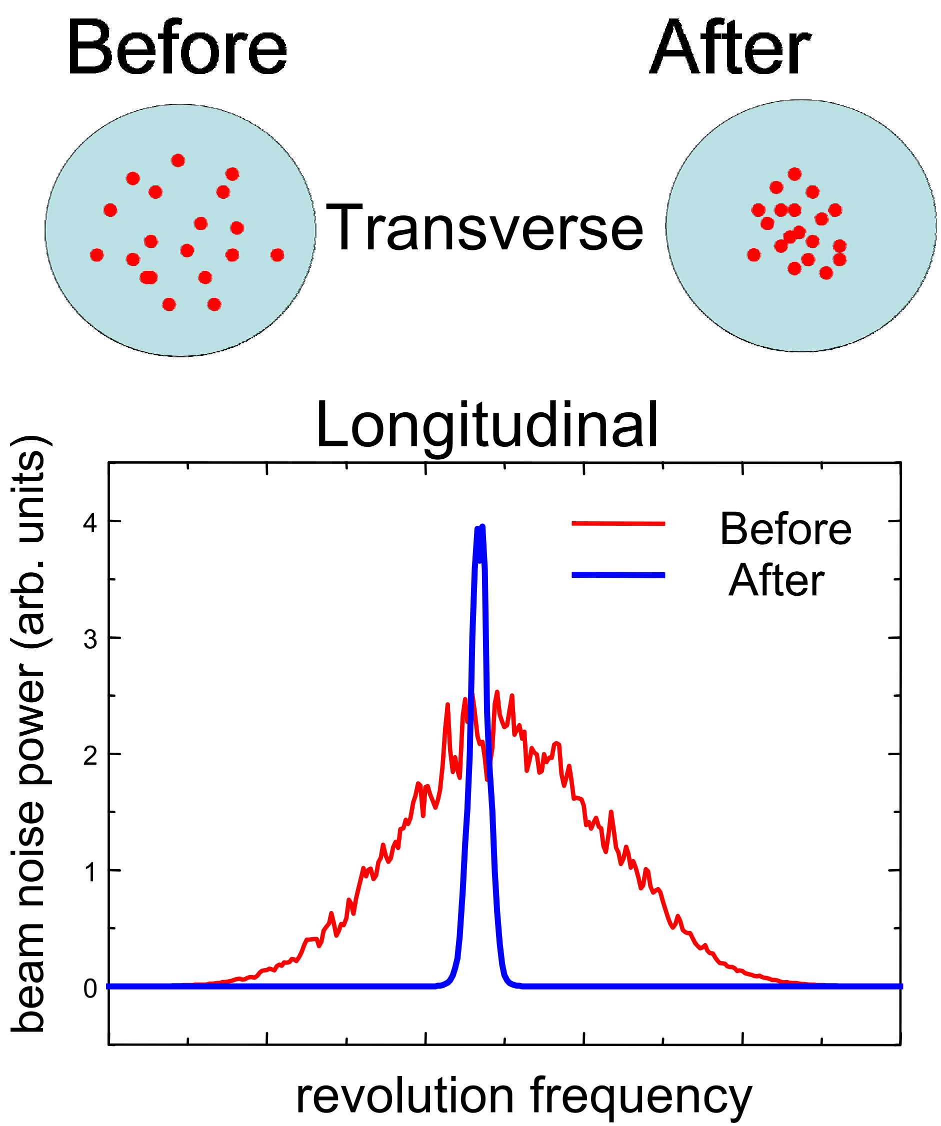
Principle of electron cooling



Cooling rate

$$\frac{1}{\tau_{cool}} \propto \frac{q^2}{A} \cdot \frac{n_e L_c}{\beta^3 \gamma^5 \theta_{rel}^3}$$

Storage ring with beam cooling



Electron cooling

- Increase phase space density
- Accumulation of ions
- Compensate diffusion (phase space growth) during deceleration
- Counteract heating effects i.e. in targets

Accumulation of RIBs at injection energy

Why ?

Increase the intensity of RIBs for internal experiments;
in particular to reach high luminosity in the e-ion collider mode.

How ?

Longitudinal beam compression at injection energy
(i.e. at 100-740 MeV/u) supported by electron cooling

i) using Barrier Bucket pulses
i) by multiple injections on the unstable fixed point
of the sinusoidal RF bucket at h=1

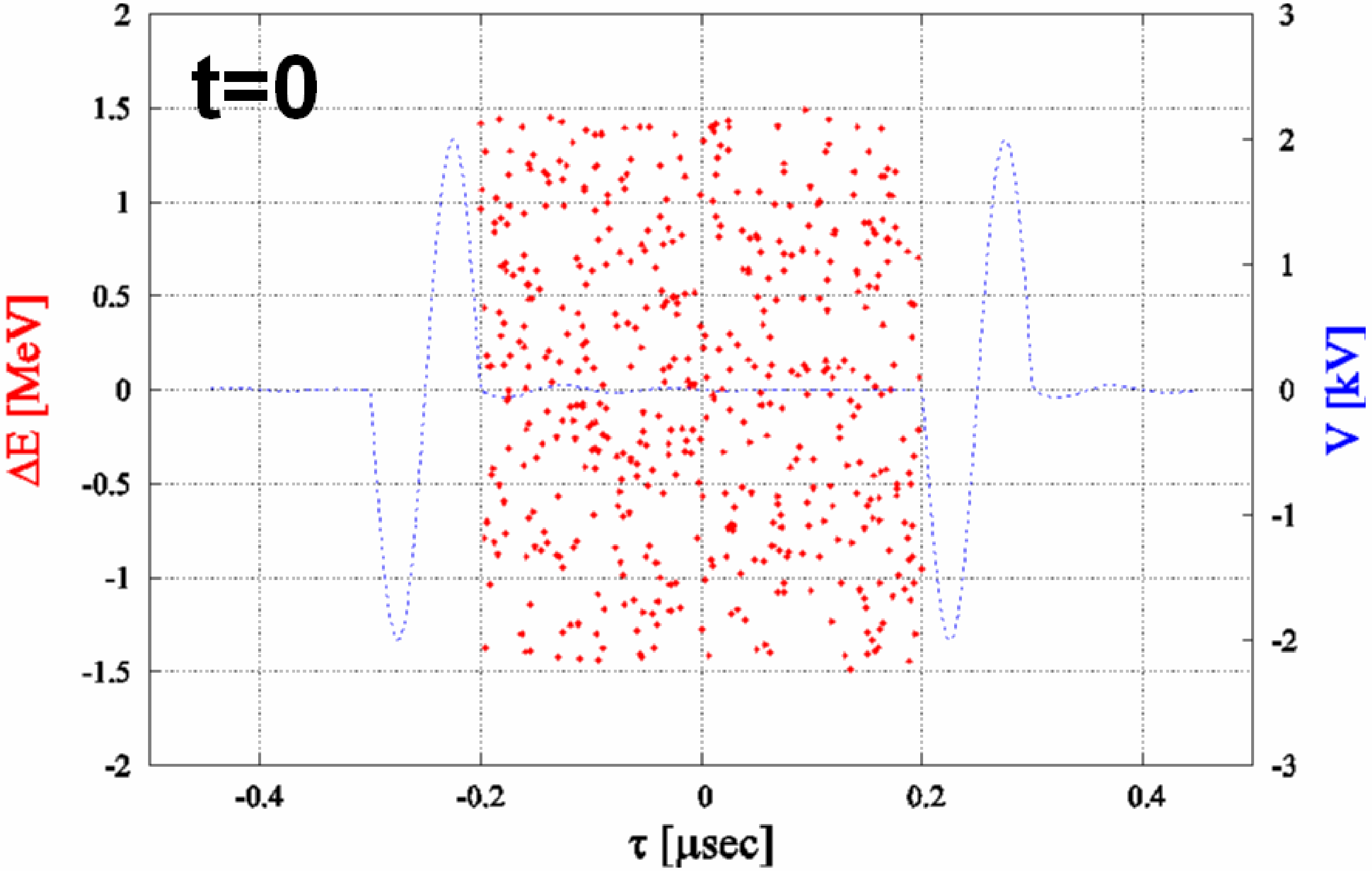
Goal

Stacking cycle time (between 2 successive injections) < 2 sec:
•limitations by RIB lifetimes
•profit from SIS100 cycle time of 1.5 sec

Accumulation of RIBs at injection energy

Longitudinal stacking with Barrier Buckets (Simulations by T. Katayama)

$^{132}Sn^{50+}$ at E_k = 740 MeV/u (0.9 μs revolution period)



Continuous electron cooling maintains the stacked beam and merges it with the freshly injected beam !

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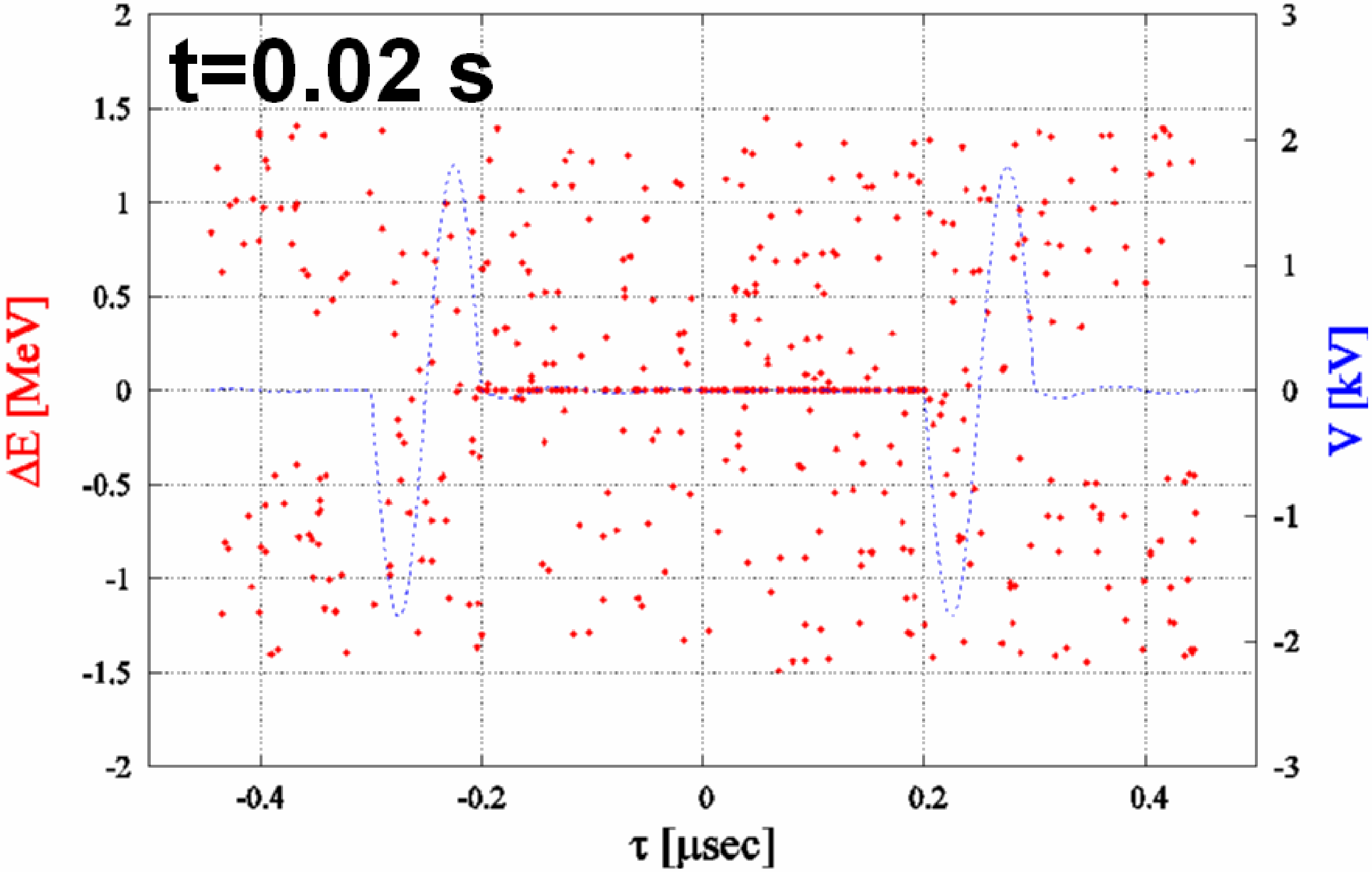

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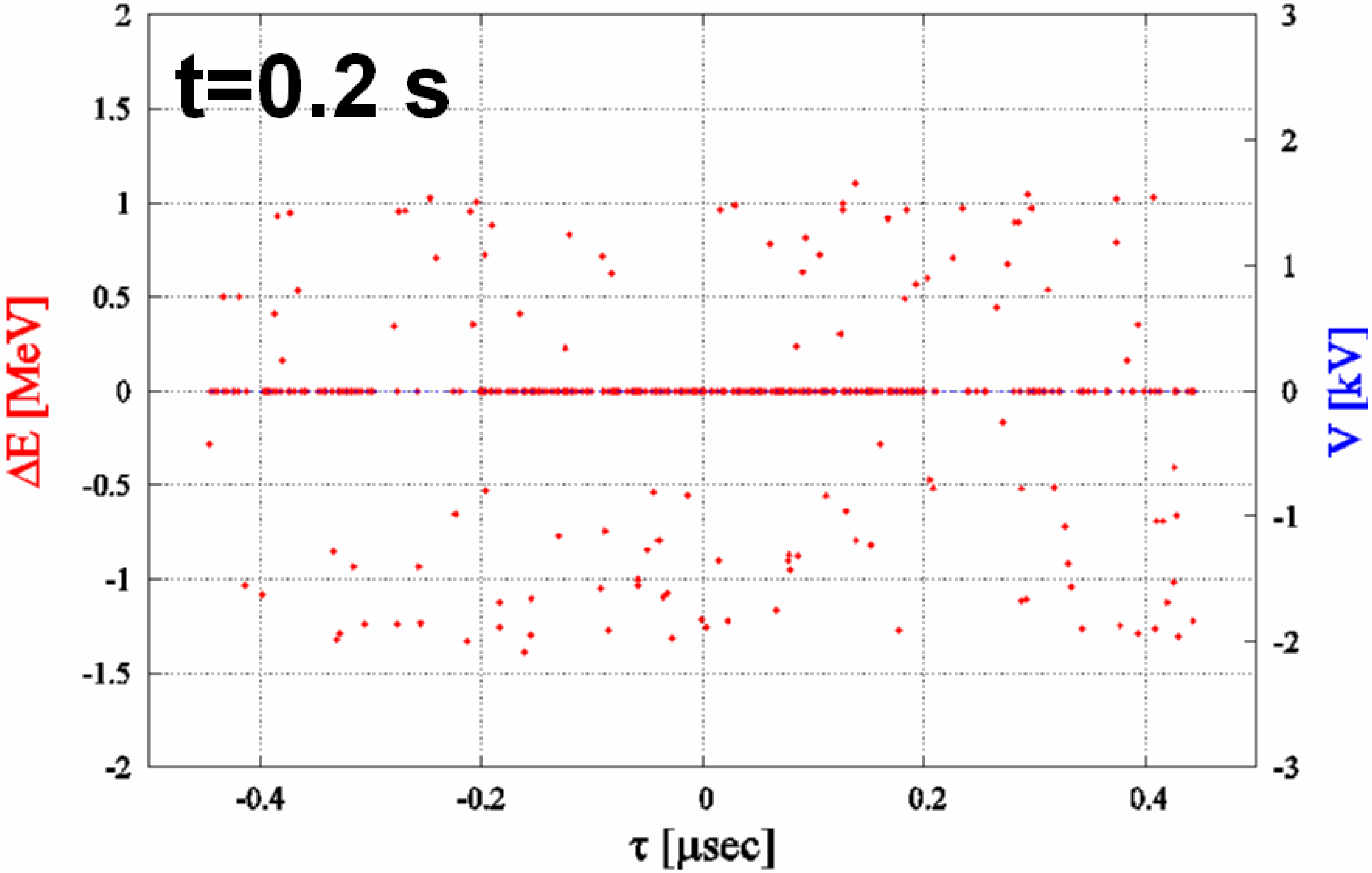

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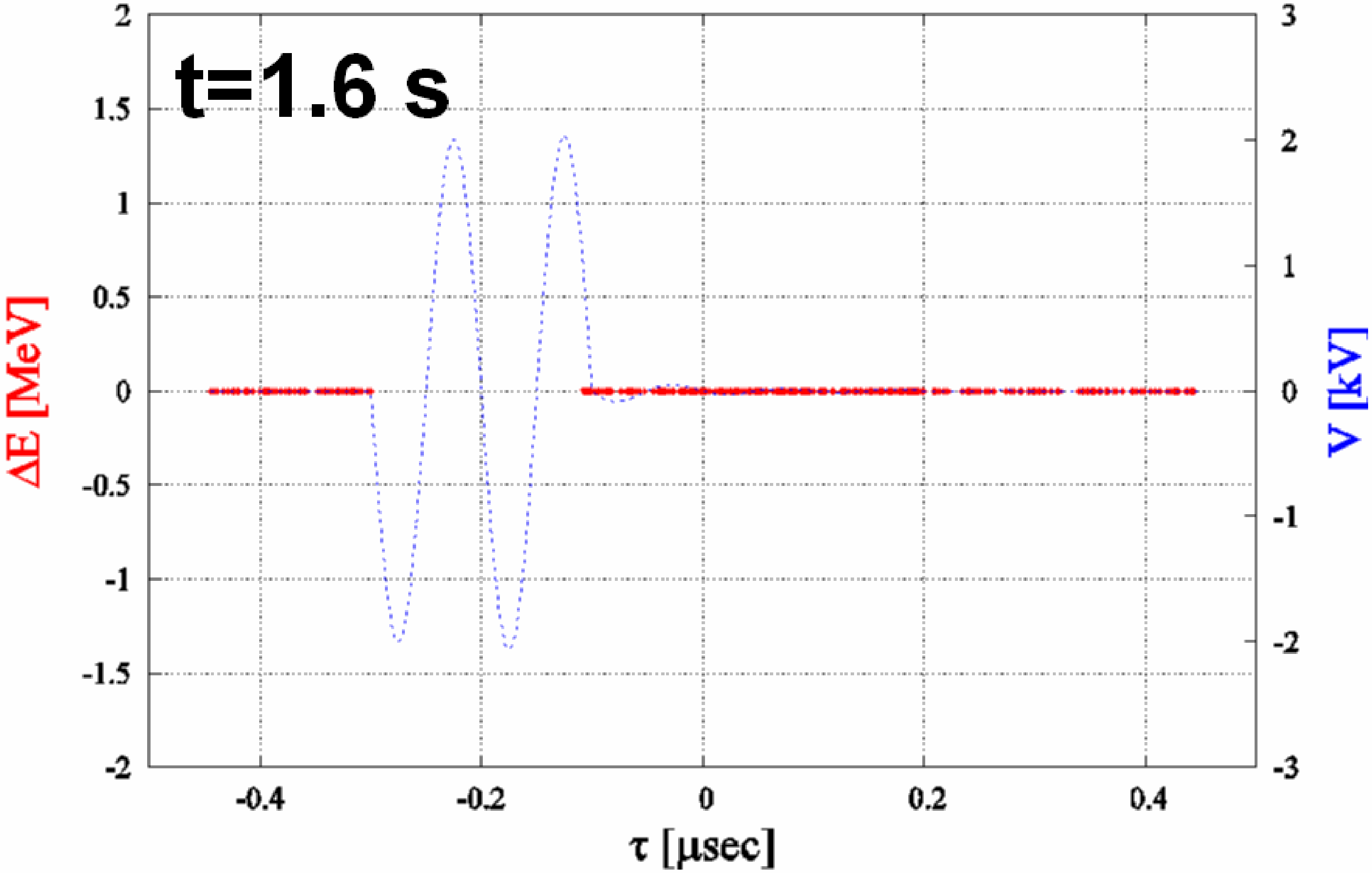

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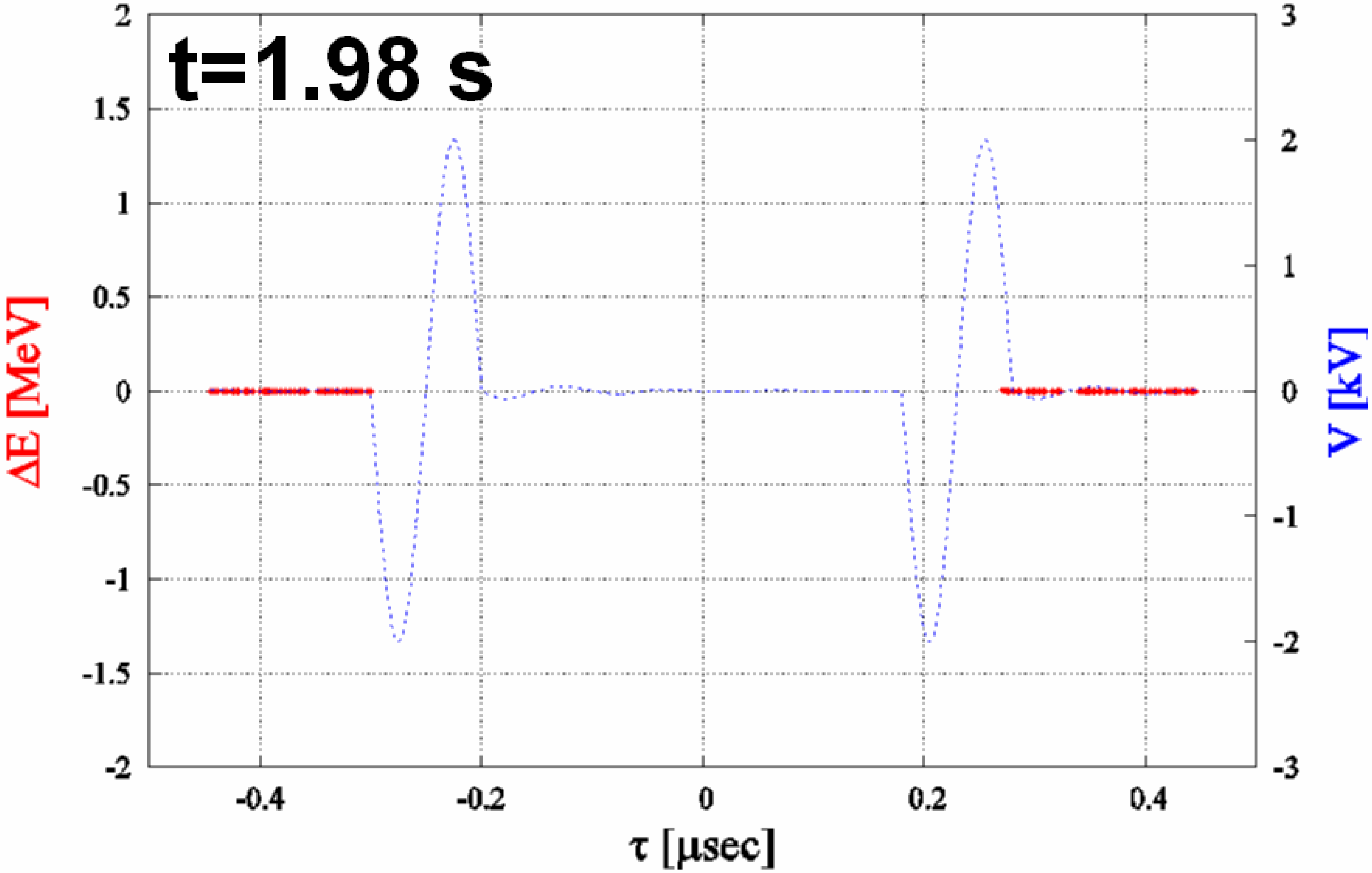

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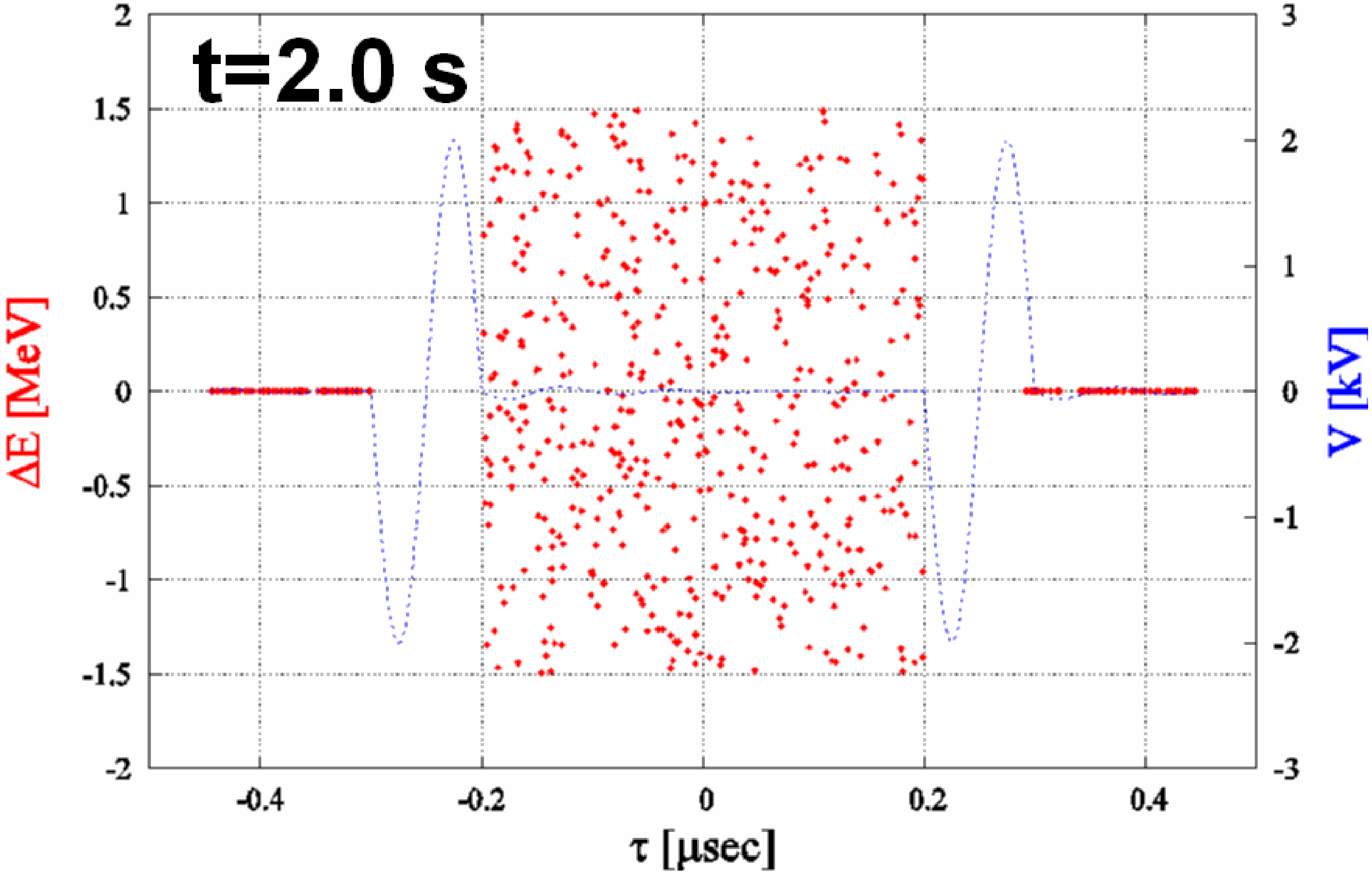
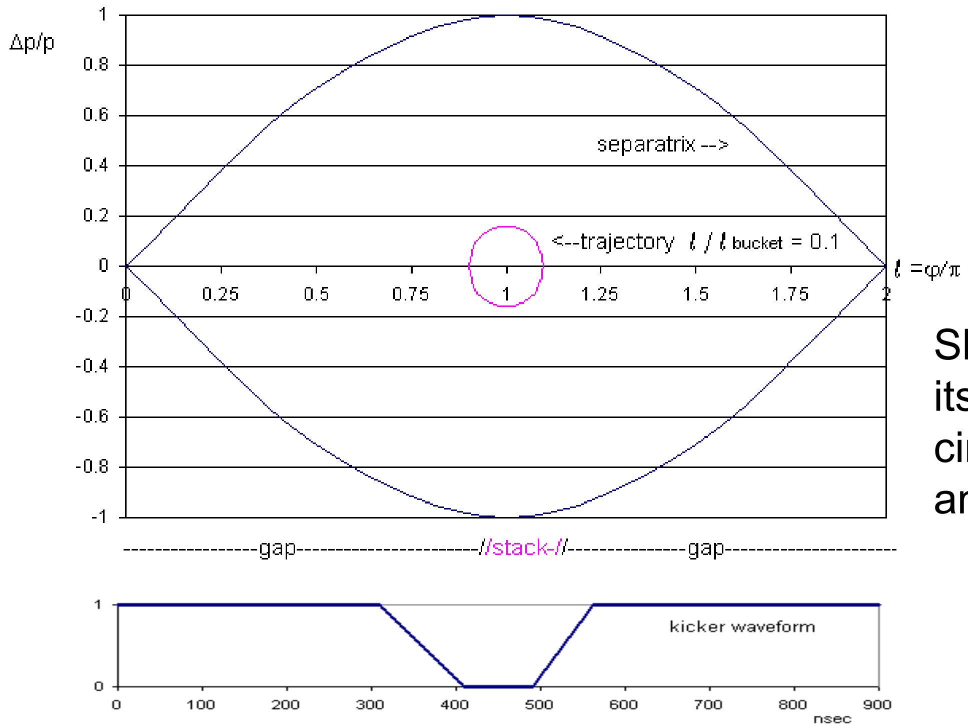


Continuous electron cooling maintains the stacked beam and merges it with the freshly injected beam !

Accumulation of RIBs at injection energy

Stacking by multiple injections on the unstable fixed point of the RF bucket at h=1 (D. Möhl)

ECOOL always ON.



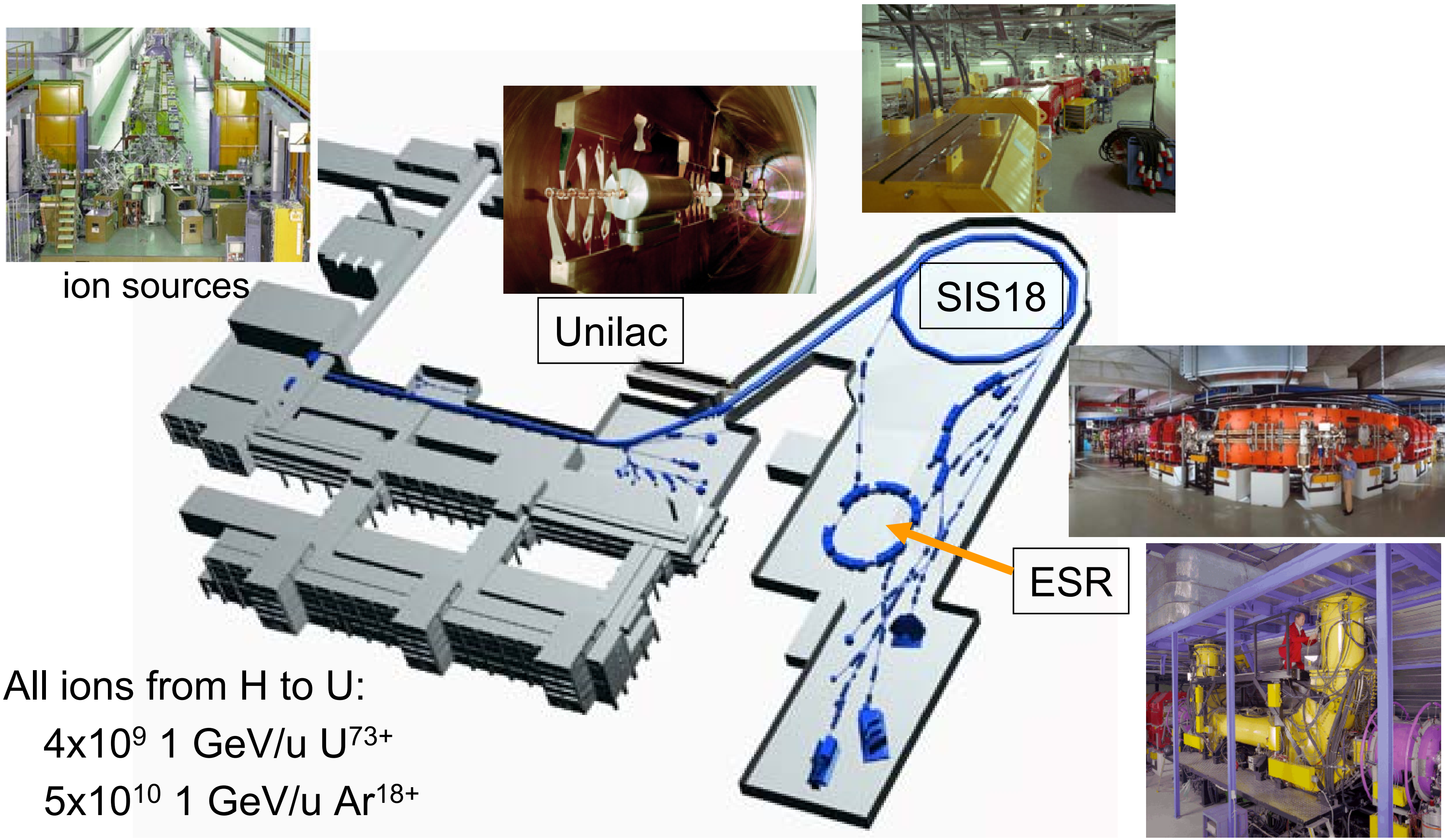
Sketch of the stationary h=1 bucket, its inner trajectory covering 10% of the circumference containing the stack, and kicker waveform to inject the new batch.

Procedure:

1. Increase RF voltage adiabatically to bunch the stack over a small part of the ring.
2. Inject new batch on the free part of the circumference i.e. on the unstable fixed point.
3. Decrease RF (non-adiabatically so as not to dilute the new bunch) to debunch and merge new batch and stack.

Proof of principle by experiments in the ESR

The existing GSI accelerator complex



All ions from H to U:

4×10^9 1 GeV/u U^{73+}

5×10^{10} 1 GeV/u Ar^{18+}

Proof of principle by experiments in the ESR

$^{40}Ar^{18+}$ at Ec=65.3 MeV/u (β=0.356, γ=1.07, T_{rev} ≈1 μs)

SIS (C=216m)
h=2
f_{rev}~0.5 MHz

1 of the 2 bunches
~300 ns (FWHM)

ESR (C=108 m)
h=1
f_{rev}~1 MHz
Barrier Buckets or sine pulse
±170 V max.

f_{rf}= 1 MHz

Synchronised SIS & ESR RF

Successive injections of bunches from SIS (~10^7 ions, ~300 ns long) to accumulate up to a few times 10^8 ions in ESR.

For injected beam: e-cooling time to equilibrium ~ 13 s at I_e=0.1 A
(// from Schottky pickup; hor. from rest gas monitor)

Tested both schemes under same conditions !

Stacked beam in ESR

In the cooling section: 2 main competing processes

Cooling rate

$$\frac{1}{\tau_{cool}} \propto \frac{q^2}{A} \cdot \frac{n_e L_c}{\beta^3 \gamma^5 \theta_{rel}^3}$$

Equilibrium

$$\frac{1}{\tau_{cool}} = \frac{1}{\tau_{IBS}}$$

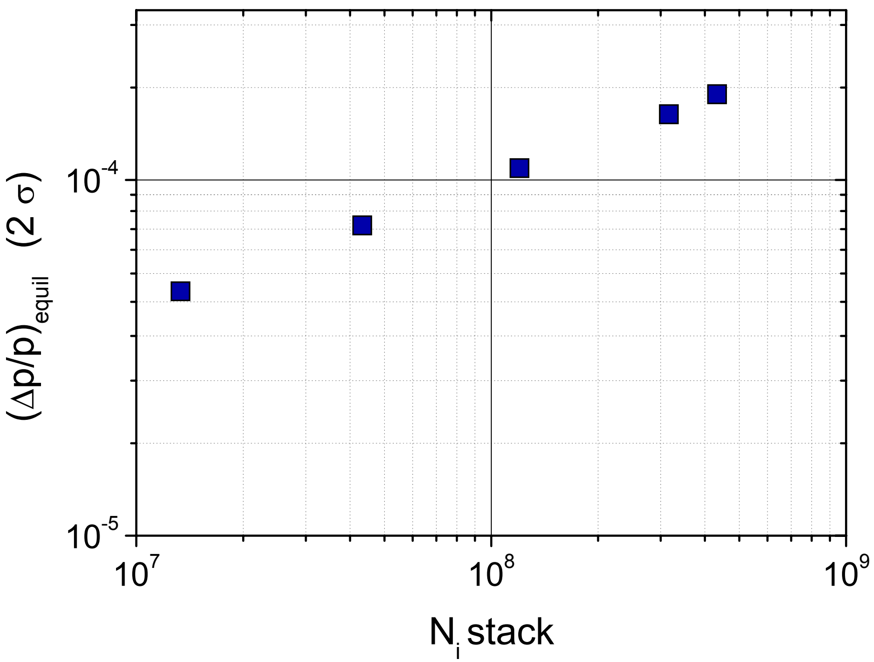
IBS heating rate

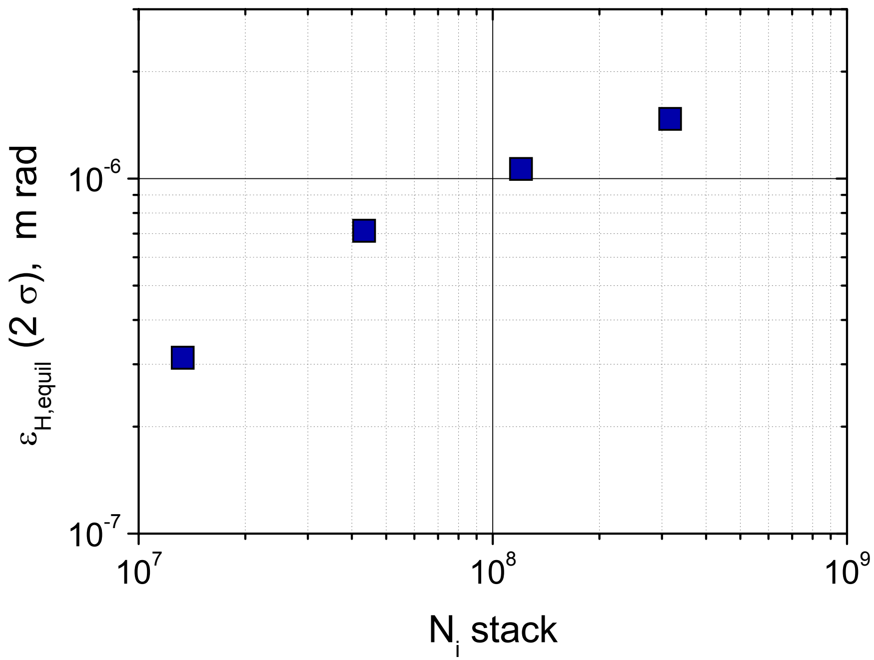
$$\frac{1}{\tau_{IBS}} \propto \frac{q^4}{A^2} \cdot \frac{N_i}{\beta^3 \gamma^4 \varepsilon_H \varepsilon_V (\Delta p/p)}$$

Stacked beam in ESR

Stacked coasting beam at equilibrium between cooling & IBS:

$N_i = 10^8$ ($I_{ESR} = 0.3$ mA), Ie=0.1 A → $(\Delta p/p)_{equil} = 1\ 10^{-4}$, $\varepsilon_{h,equil} \approx 1$ mm mrad





Scaling laws: $(\Delta p/p)$**equil** ~ $(N_i/B)^{0.36}$ $Ie^{-0.3}$

$(\varepsilon_{h,v})$**equil** ~ $(N_i/B)^{0.41}$ $Ie^{-0.3}$

Bunching factor: $B = T_{bunch(stack)}/T_{rev}$

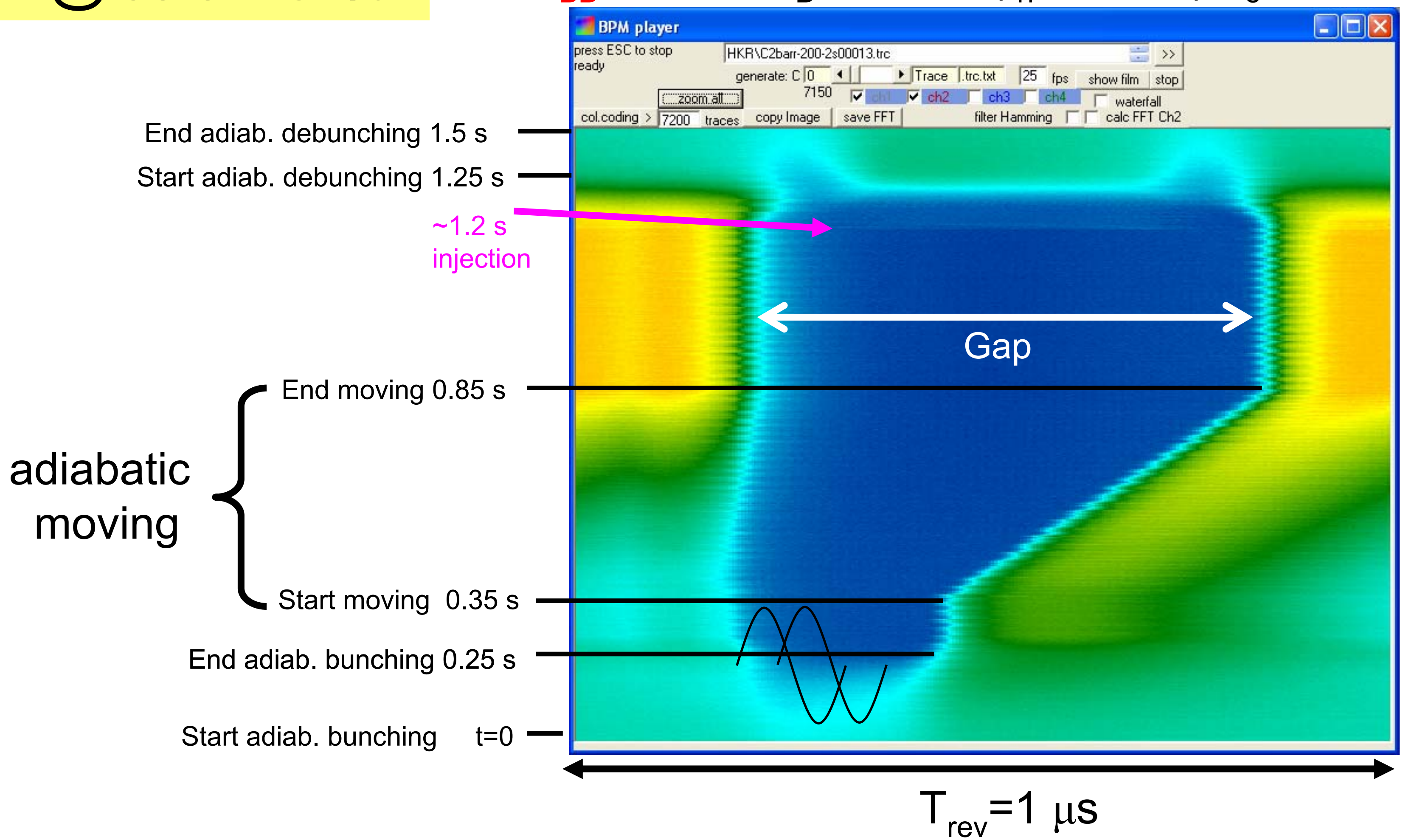
Stacking with Barrier Buckets

Beam signal in the ESR PU

(1 frame/ 200 revolutions for a total time of 1.46 s)

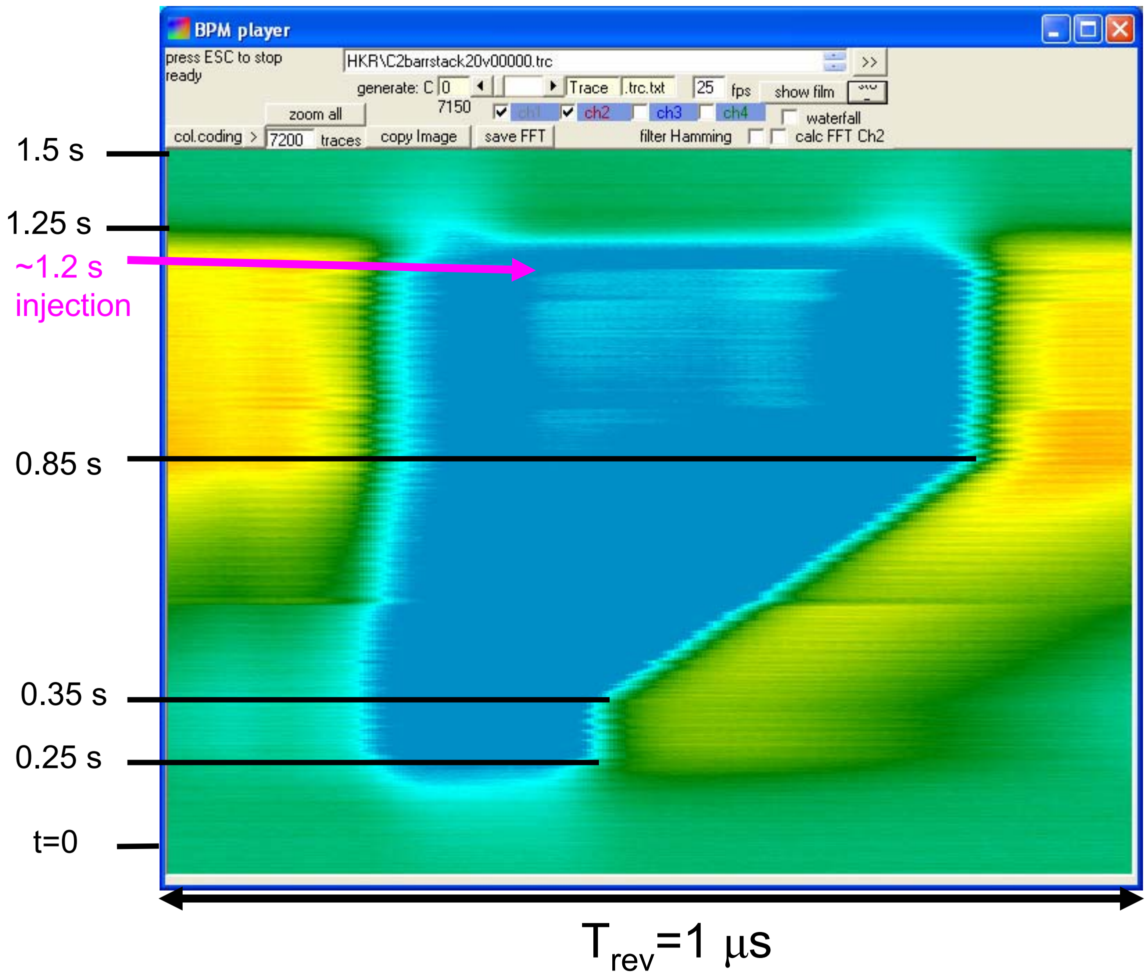
$^{40}Ar^{18+}$ @ 65.3 MeV/u

V_{BB}=120 V, T_B=200 ns (f_{rf}=5 MHz), I_e=0.1 A



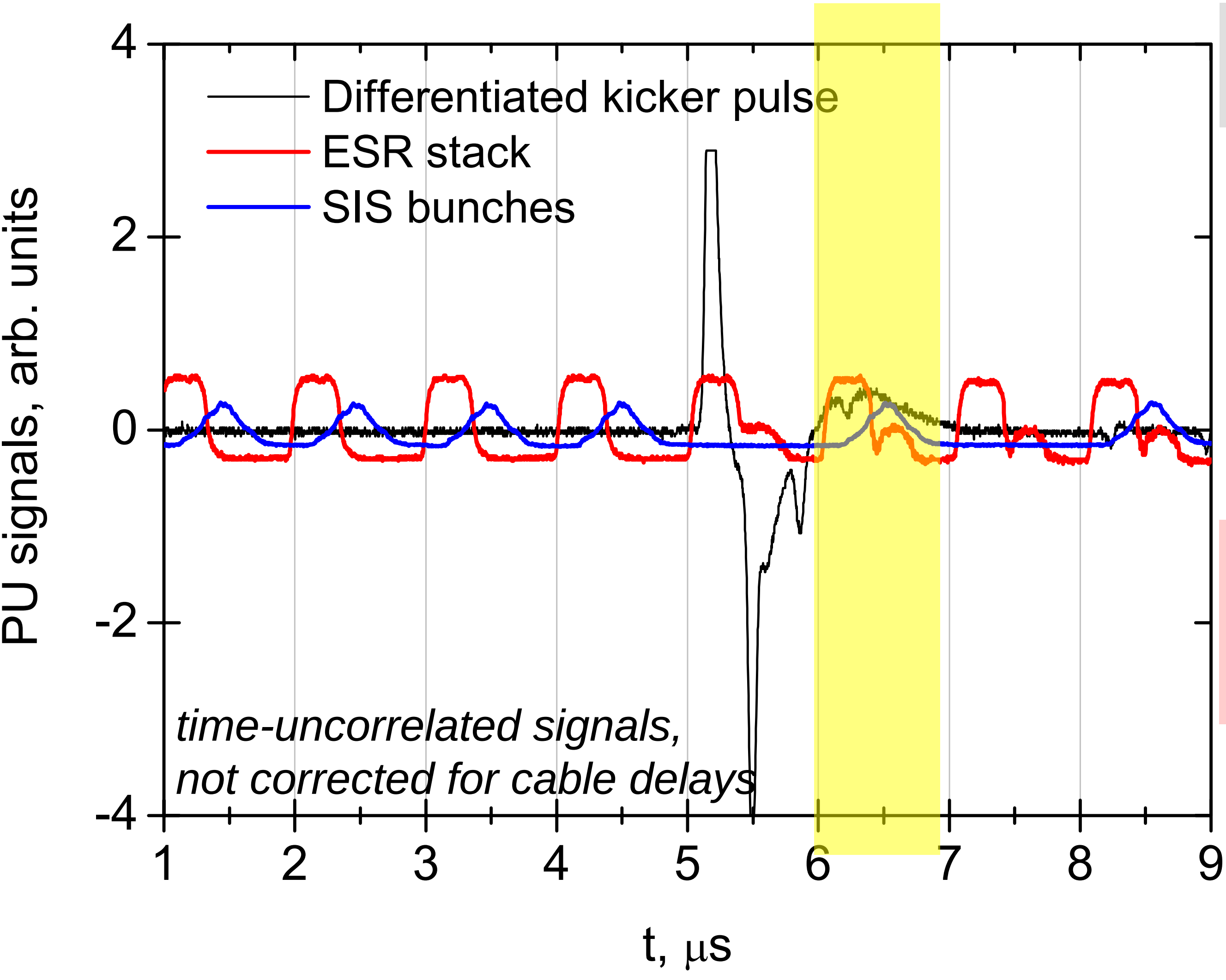
Stacking with Barrier Buckets

V_{BB}=20 V, T_B=200 ns (f_{rf}=5 MHz), I_e=0.1 A



Stacking with Barrier Buckets:Timing

V_{BB}=120 V, T_B=200 ns (f_{rf}=5 MHz), I_e=0.1 A, stacking cycle=9 s



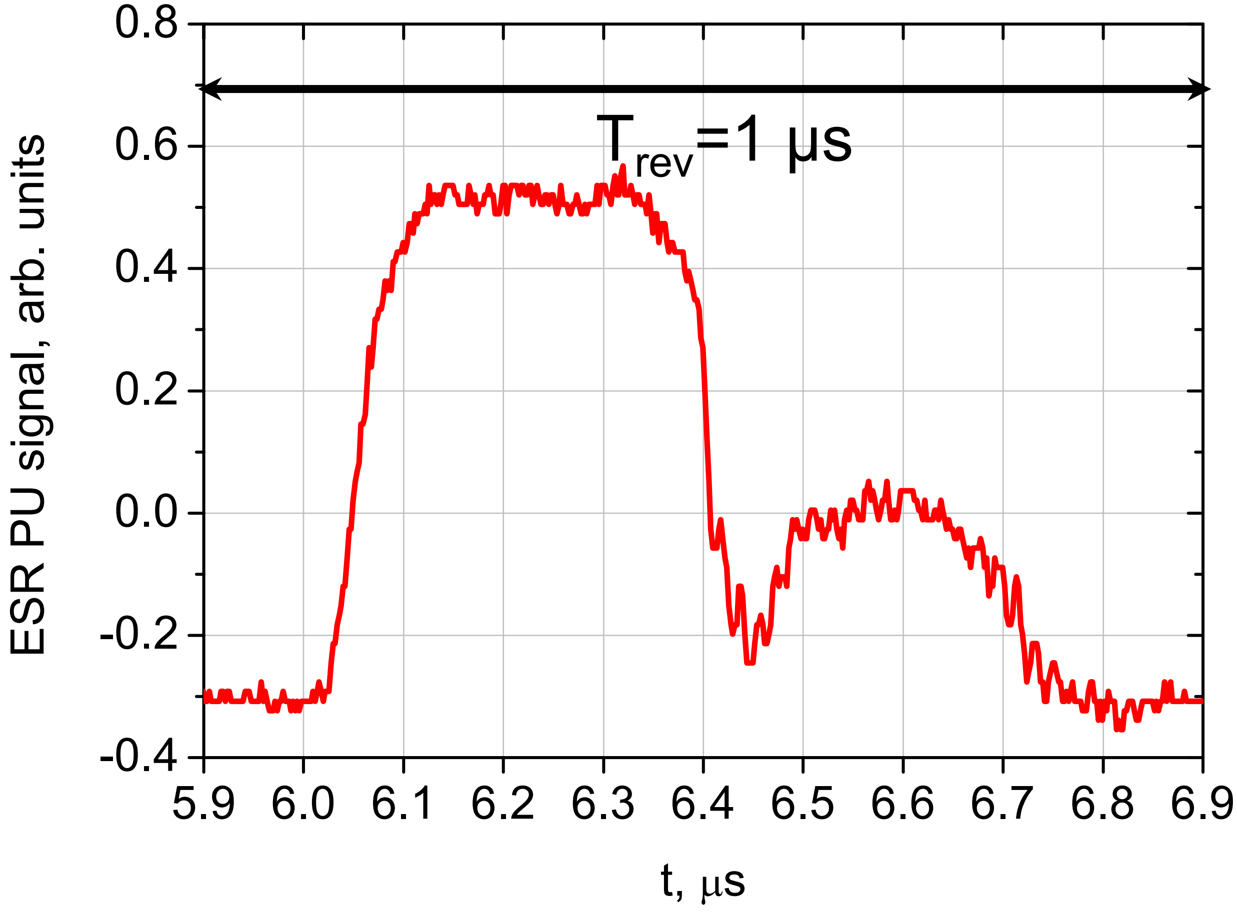
Injection kicker pulse: total ~500 ns

SIS bunch length: 300-350 ns(FWHM)

ESR stack length: T_{stack}= 400 ns (75% of uniform distribution)

Stacking with Barrier Buckets:Timing

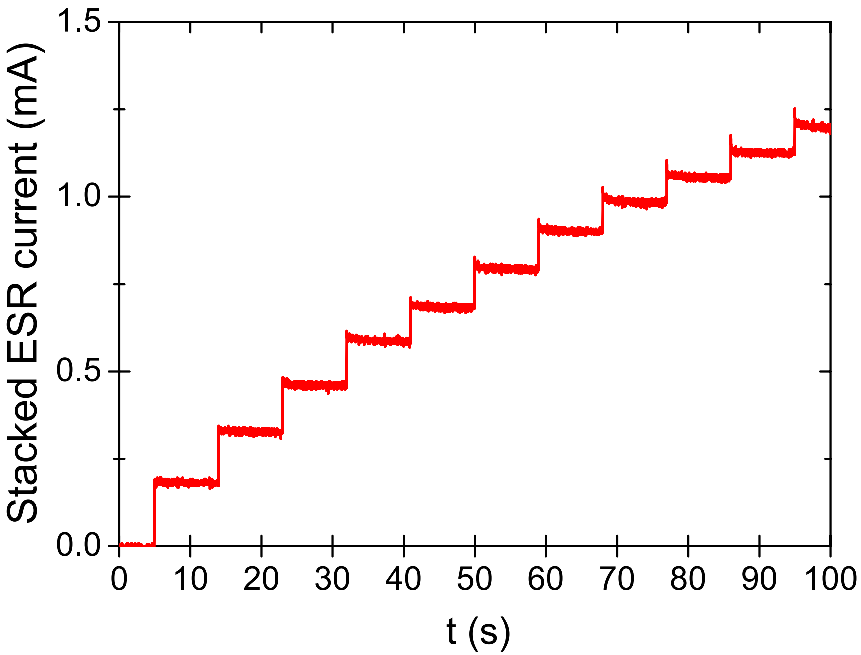
ESR Stack with freshly injected bunch in the Barrier Bucket gap

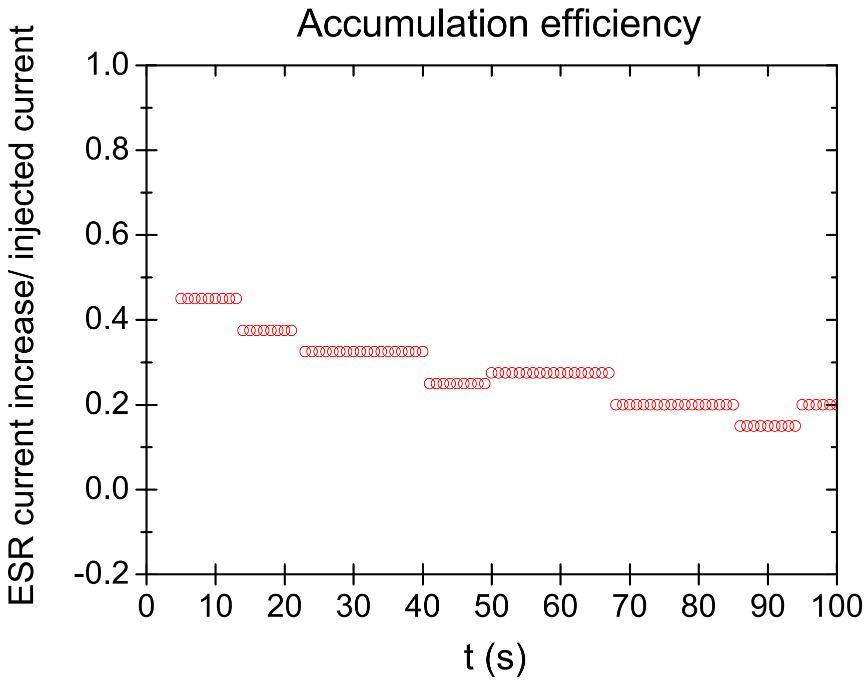


Stacking with Barrier Buckets

Beam accumulation measured by the ESR current transformer

V_{BB}=120 V, T_B=200 ns (f_{rf}=5 MHz), I_e=0.1 A, stacking cycle=9 s





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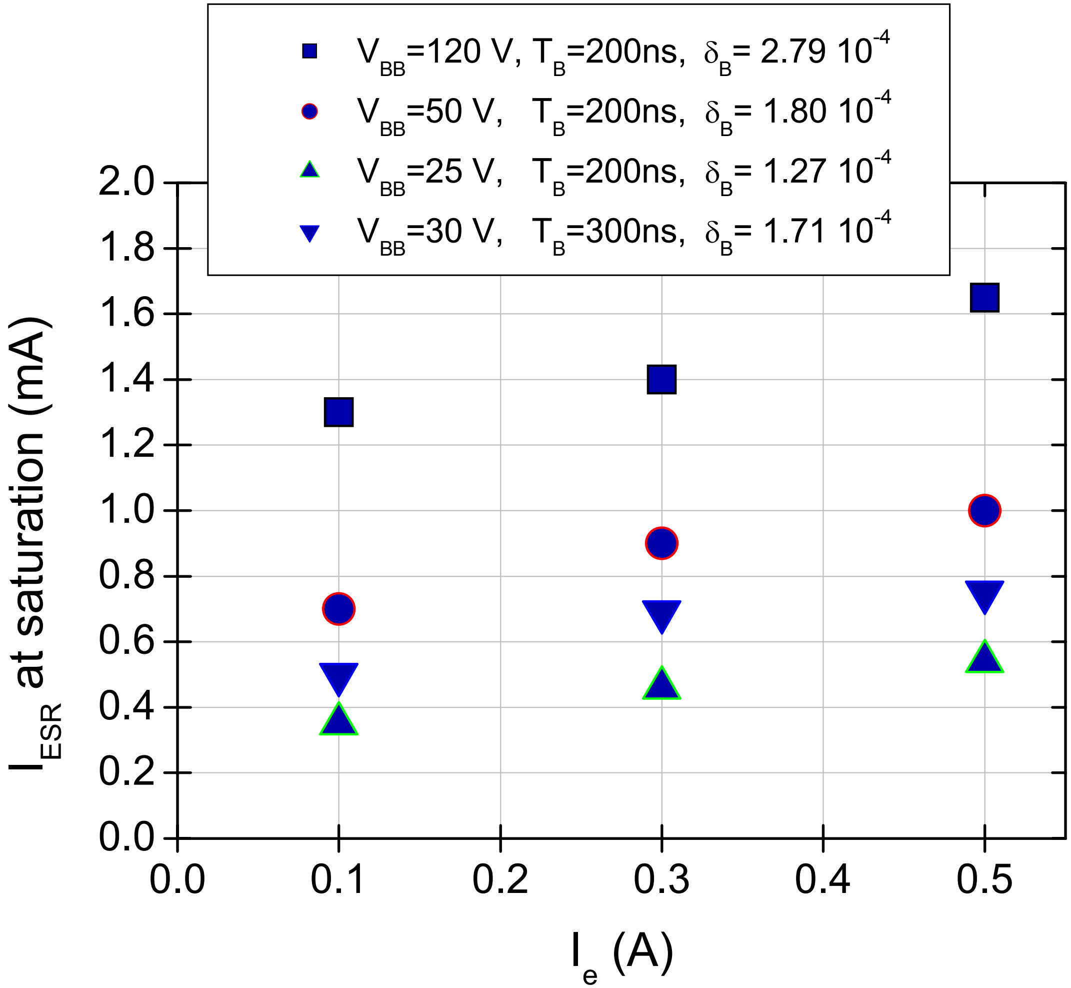


RF bucket height: $\pm\delta_B$

$$\delta_B = \sqrt{\frac{2\ Qe\ V_{rf}}{\pi\beta^2\ \eta\ h\ E_{0,tot}}} \propto \sqrt{V_{rf}\ \mathrm{T_B}}$$

$h = T_{rev}/T_B \approx 5$

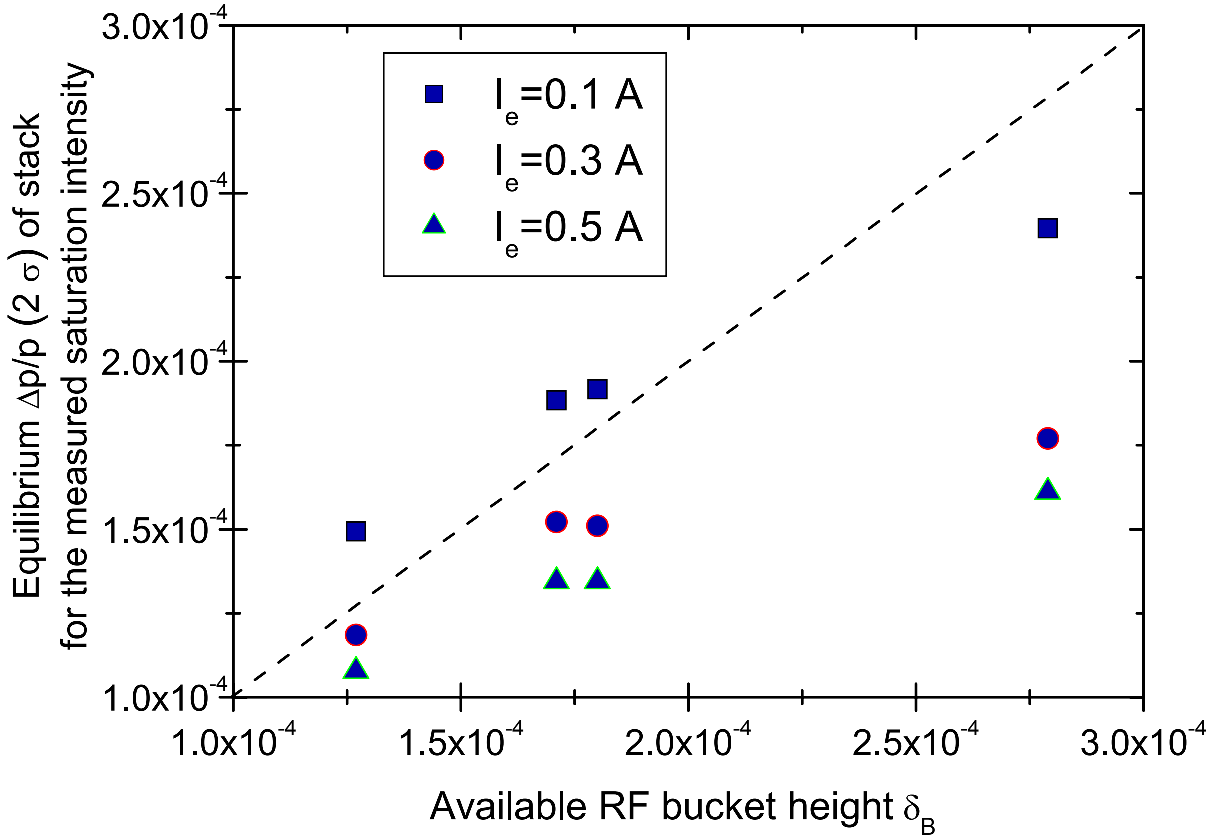
What is the $\Delta p/p$ of the stack at saturation intensity?

→ Results of BB stacking-cooling simulations by T. Katayama

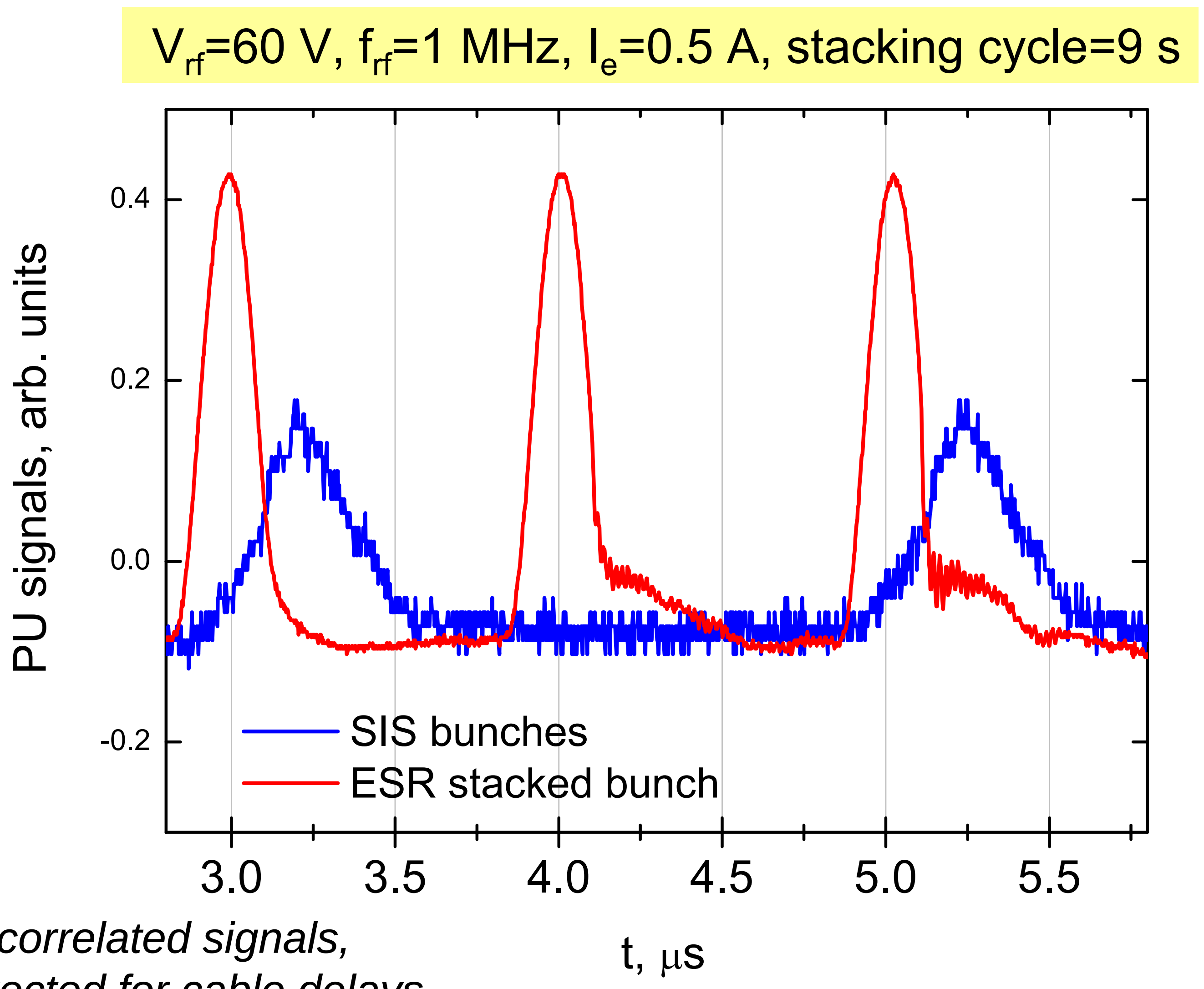
Stacking with Barrier Buckets

→Estimation assuming equilibrium between cooling and IBS in saturated stack:

$$\Delta p/p \sim (I_{ESR,sat} / B)^{0.36} \quad I_e^{-0.3}, \qquad B = T_{stack}/T_{rev} = 0.4$$



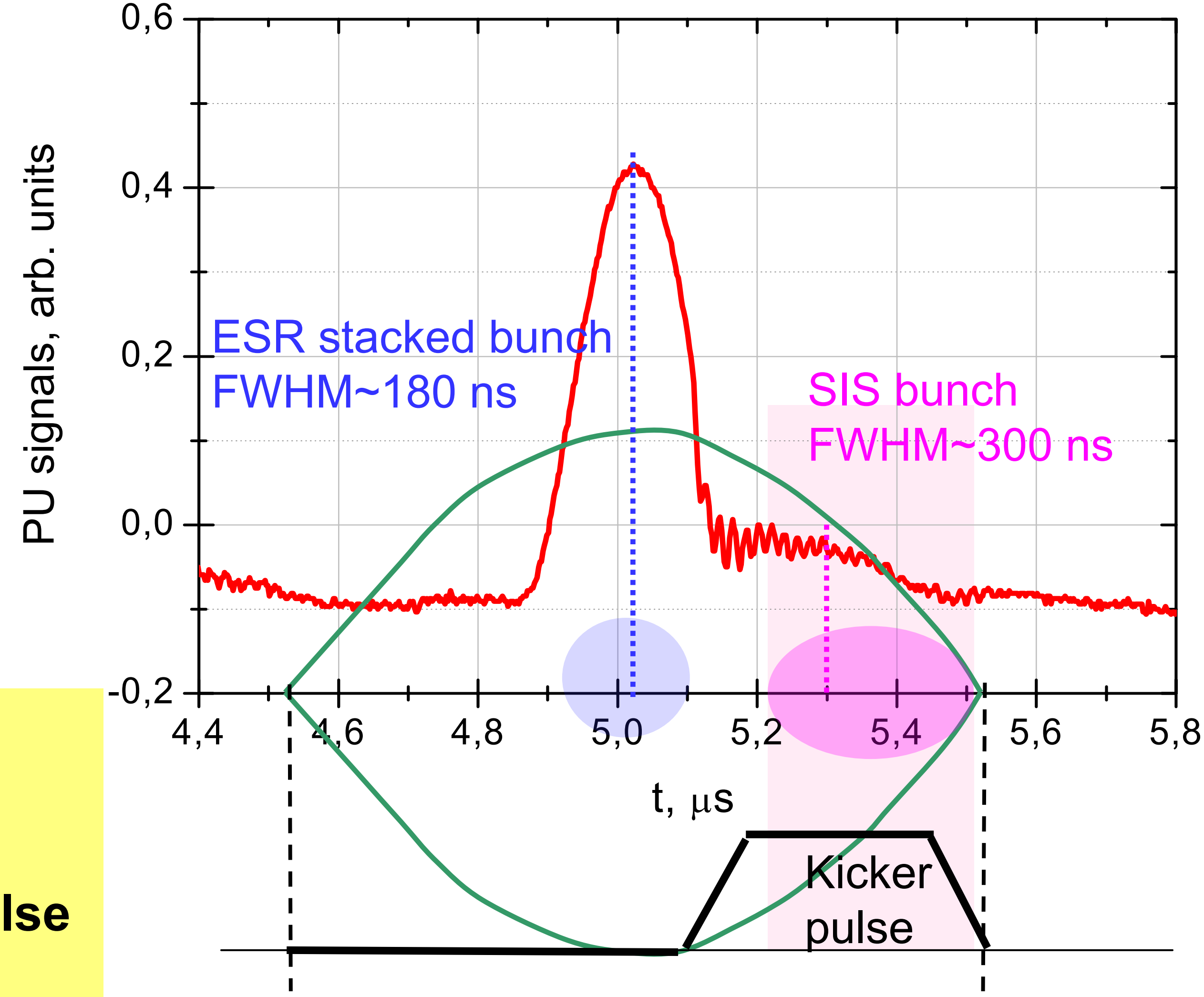
Stacking with sinusoidal RF at h=1



time-uncorrelated signals,
not corrected for cable delays

Stacking with sinusoidal RF at h=1

V_{rf}=60 V, f_{rf}=1 MHz, I_e=0.5 A, stacking cycle=9 s



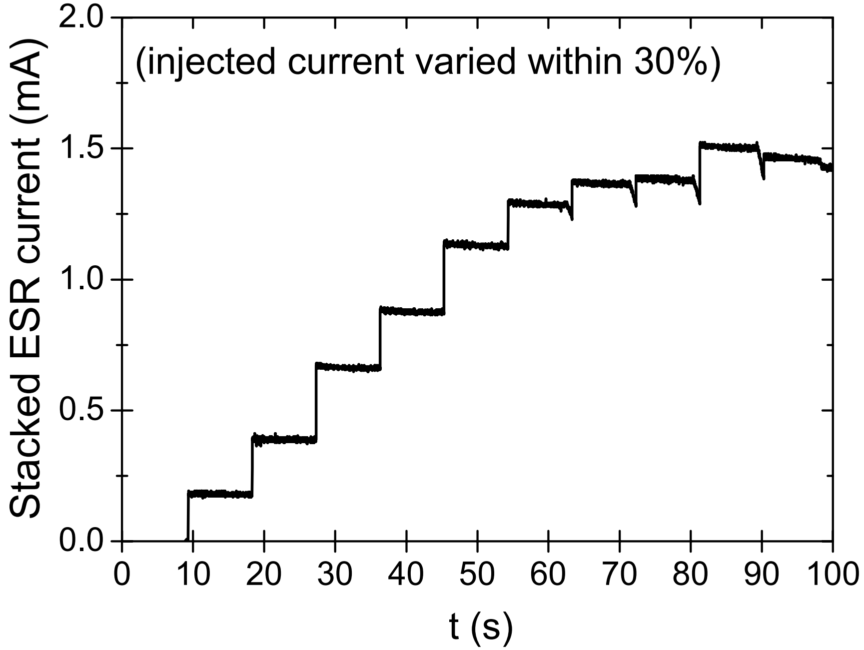
Qualitative information:
relative phase
of stacked bunch,
new bunch & kicker pulse
w.r.t. separatrix

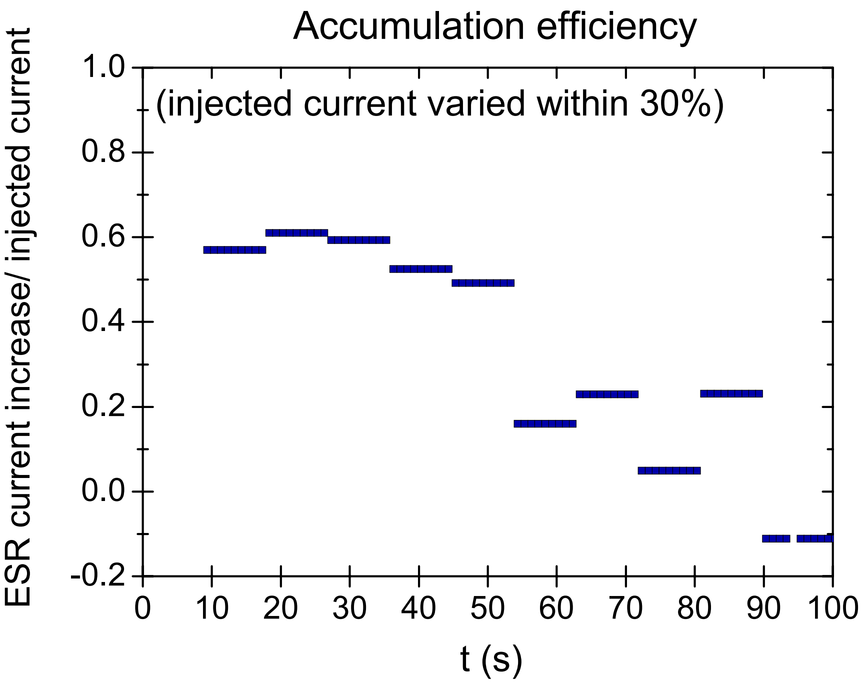
Stacking with sinusoidal RF at h=1

Beam accumulation measured with the ESR current transformer

V_{RF}=120 V, f_{rf}=1 MHz, I_e=0.1 A

stacking cycle=9 s





Problems:

- Imperfect synchronisation RF-kicker, variable kicker pulse length
- Adiabatic bunching (~0.25 s) fast w.r.t. e-cooling

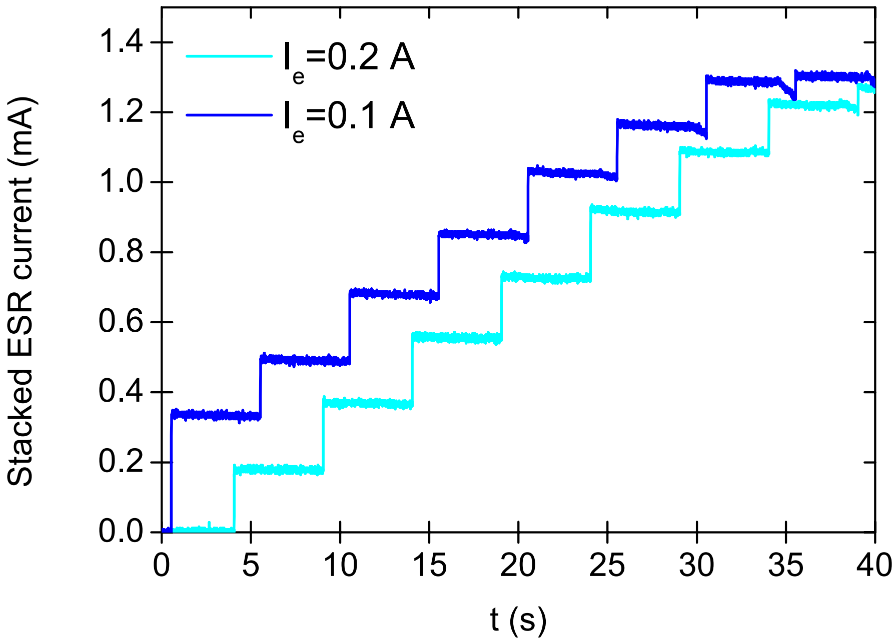
→ Stack losses after every injection

Stacking with sinusoidal RF at h=1

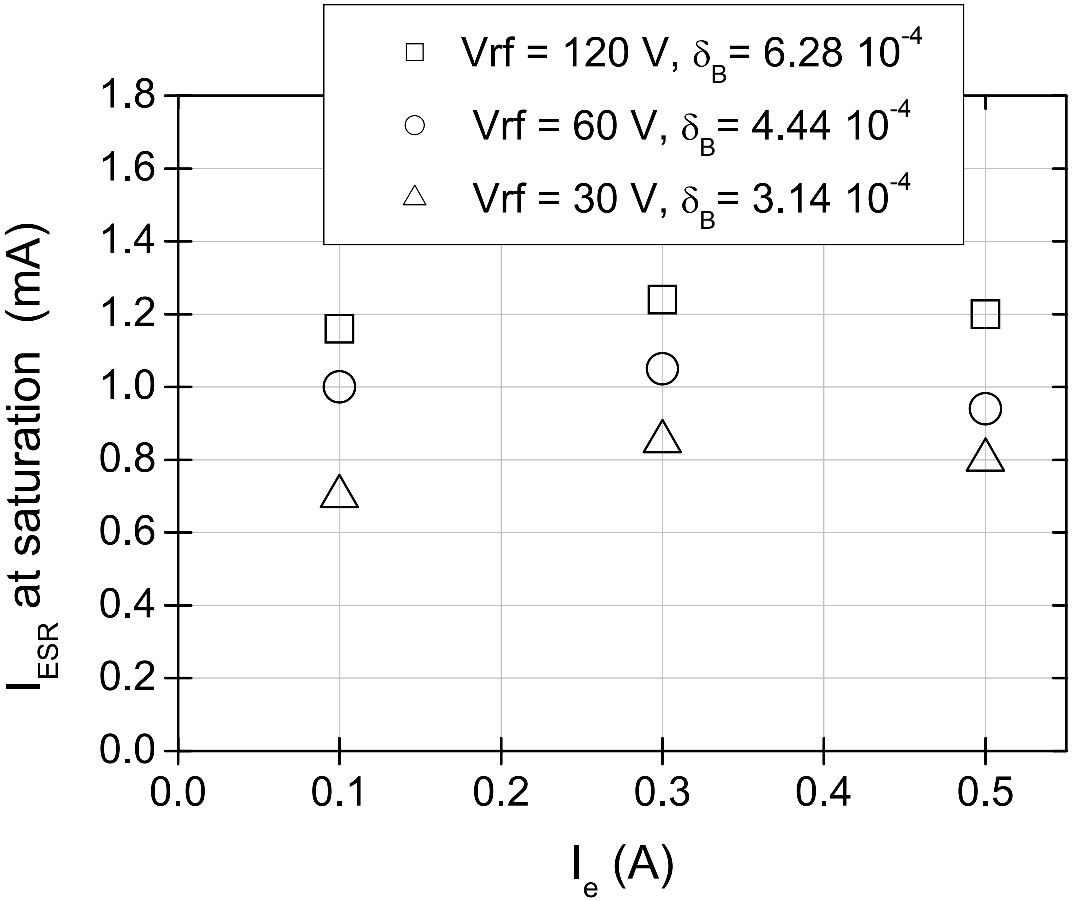
Beam accumulation measured with the ESR current transformer

V_{RF}=120 V, f_{rf}=1 MHz, I_e=0.1 A

stacking cycle=5 s



Stacking with sinusoidal RF at h=1



RF bucket height: $\pm\delta_B$

$$\delta_B = \sqrt{\frac{2\ Qe\ V_{rf}}{\pi\beta^2\ \eta\, h\, E_{0,tot}}}$$

h=1

The $\Delta p/p$ of the stack at saturation intensity is given from the RF bucket formula if we measure with the pickup the corresponding bunch length!

$$\frac{\sigma_t}{T_{rev}} = \frac{\sigma_s}{C} = \sqrt{\frac{\beta^2\ \eta\ E_{0,tot}}{2\pi\ \ Qe\, h\, V_{rf}}}\ \frac{\Delta p}{p}$$

Stacking with sinusoidal RF at h=1

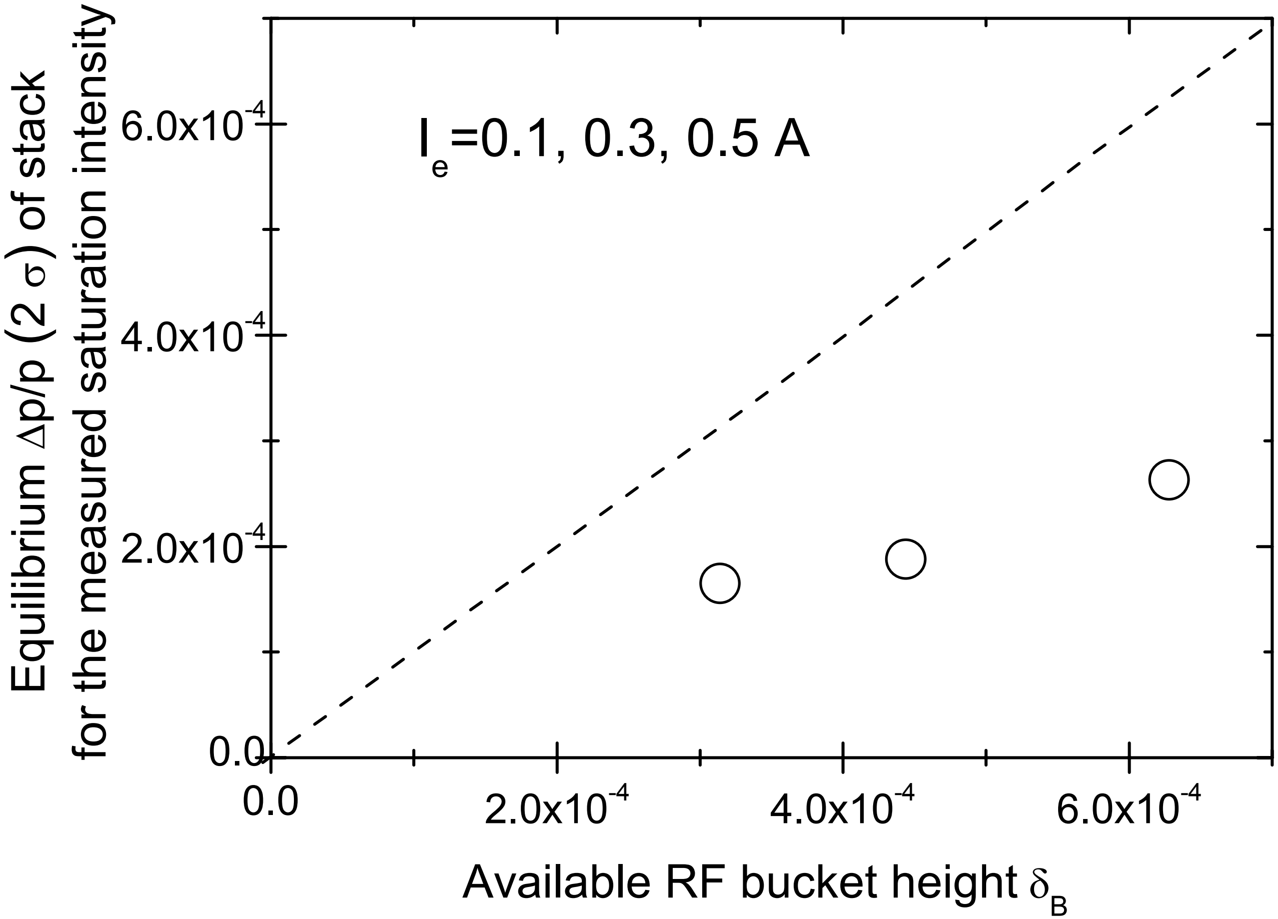
Stacked bunch length at saturation measured with the pickup, for different RF voltages and electron currents.

Vrf (V)	I_{ESR} at saturation (mA)	bunch length of stack (FWHM)	$\Delta p/p$ of stack (FWHM)	Bucket height +/- δ_B	$B=T_{stack}/T_{rev}$
120	1.2-1.4	160 ns	$3.10\ 10^{-4}$	$6.28\ 10^{-4}$	0.157
60	0.9-1.0	175 ns	$2.40\ 10^{-4}$	$4.44\ 10^{-4}$	0.172
30	0.7	200 ns	$1.94\ 10^{-4}$	$3.14\ 10^{-4}$	0.197

- **At saturation, the stacked bunch occupied ~20% of the ring and filled 50-60% of the momentum acceptance of the RF bucket at h=1, for all applied voltages.**

- **Within the pickup resolution (~10 ns): bunch length independent of I_e.**

Stacking with sinusoidal RF at h=1



Conclusions

- **Both long. stacking methods with cooling successfully tested in the ESR → proof of principle for RIBs in NESR**
- Procedure and results essentially understood.
- Accumulated intensity limited by (i) the available RF voltage i.e. bucket area and (ii) by the electron cooling strength.
- Accumulation speed limited mainly by electron cooling strength.
- Long kicker pulse w.r.t. revolution period restricted flexibility in stack/bunch/BB length manipulations.

Conclusions (continued)

- Not optimal h=1 stacking,dedicated experiment planned

("cleaner" RF & kicker conditions, long kicker pulse for high injection efficiency, longer bunching & stacking cycles to allow better cooling, synchronisation RF-cooler during bunching)

- For the same Vrf, stacking at h=1 offers $\sqrt{\frac{Trev}{T_B}}$ larger confinement strength than stacking with BB.

- Easier to deduce stack parameters for stacking at h=1, dedicated simulations necessary for stacking with BB.

Outlook for the NESR

- **The exp. results in the ESR confirm the requirements for the NESR systems:**

- Faster cooling foreseen (higher & variable electron beam density)
  → stacking cycles below 2 s (RIBs lifetime, SIS100 cycle)

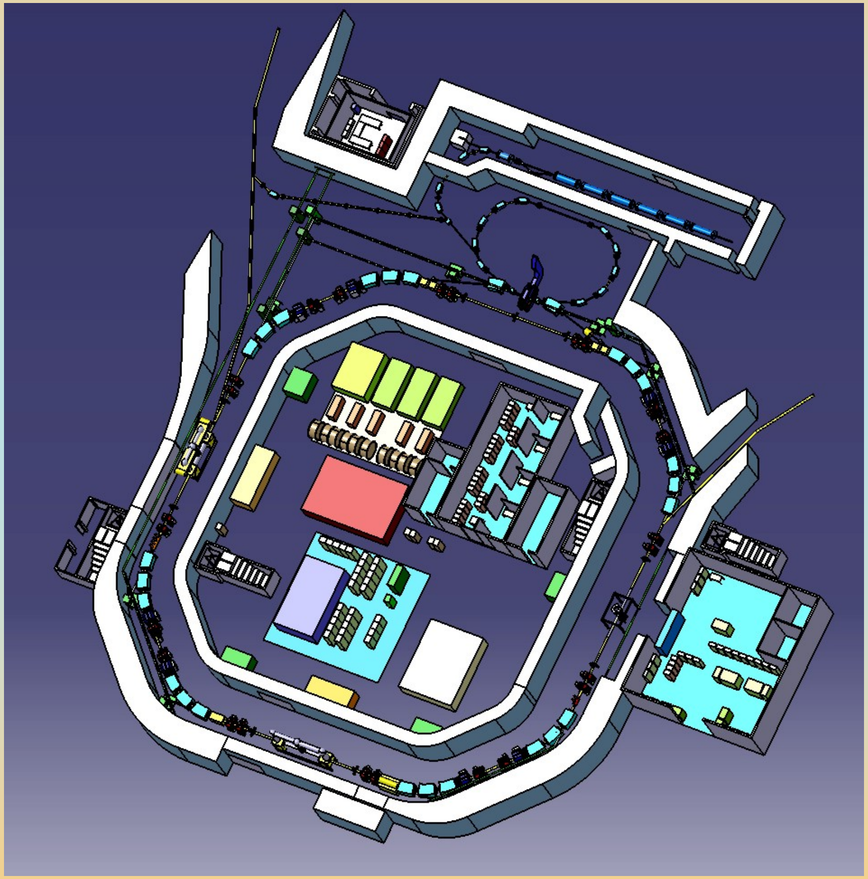
- Barrier Bucket RF system with max. voltage of +/-2 kV at 5 MHz

- Short adjustable (~100 ns) injection kicker flat top and rise/fall times essential for stacking

- Appropriate & sufficient beam diagnostics

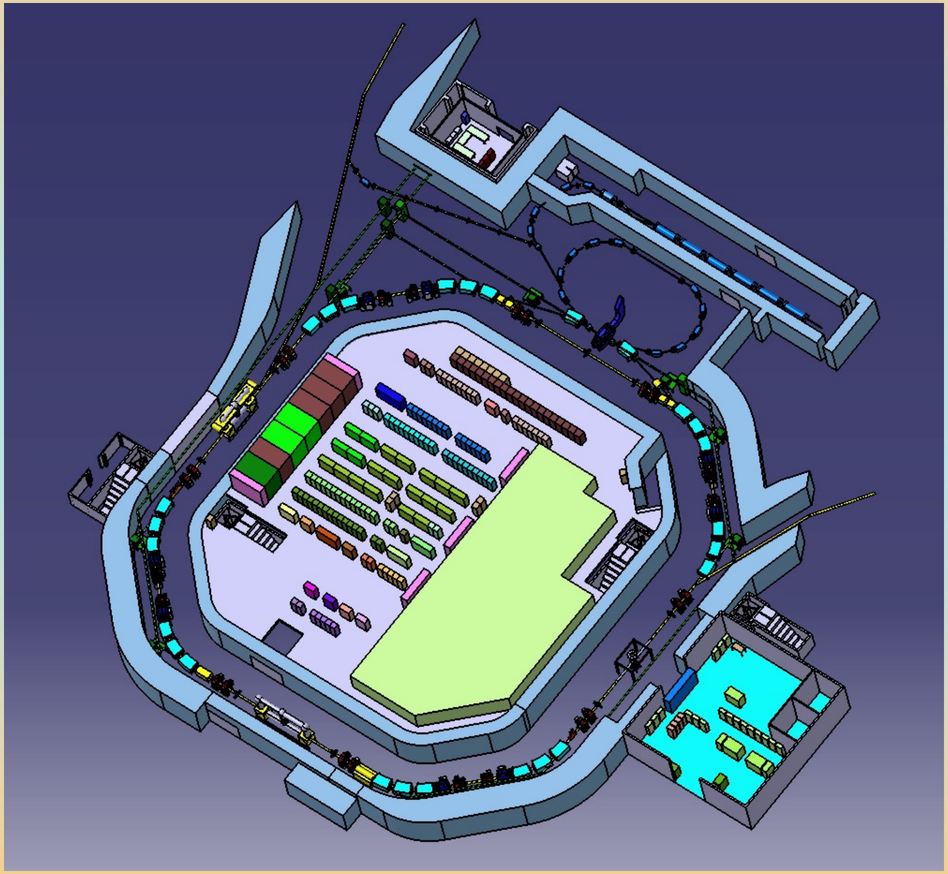
NESR Civil Construction Planning

Lower (ring) level



rf, diagnostics, vacuum, controls

Upper level



power converters, common systems

Integration of technical components and experiments underway

References

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•*FAIR Baseline Technical Report, http://www.gsi.de/fair/reports/.*

• *C. Dimopoulou et al.,Proccedings of COOL07*
• *T. Katayama et al., Proccedings of COOL07,*
(to be published on JACoW : http://accelconf.web.cern.ch)

•*M. Steck et al., Proceedings of EPAC 06, published on JACoW*

•*V.V. Parkhomchuk et al.,GSI-Acc-Report-2005-04-001*