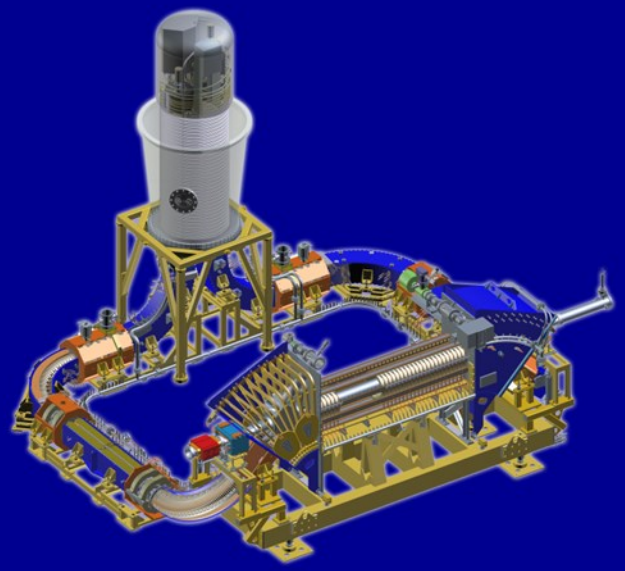
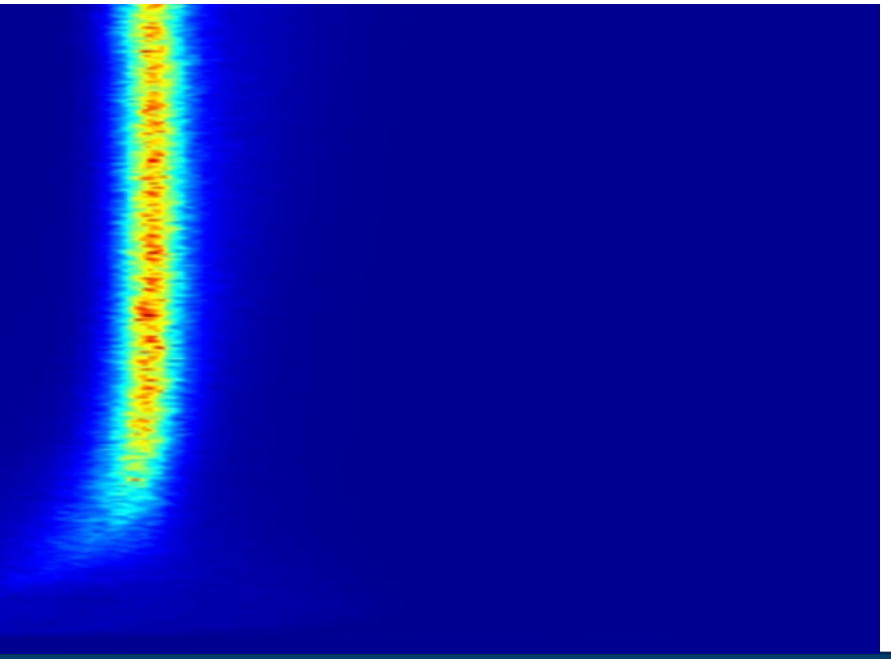




RECENT DEVELOPMENTS AND EXPERIMENTAL RESULTS FROM ELECTRON COOLING OF 2.4 GeV/c PROTONS AT COSY

P. Niedermayer, A. Halama, V. Kamerdzhiev, N. Shurkhno, R. Stassen (FZJ, Jülich),
V. Reva (BINP SB RAS, Novosibirsk), T. Katayama (Nihon University, Narashino, Chiba)

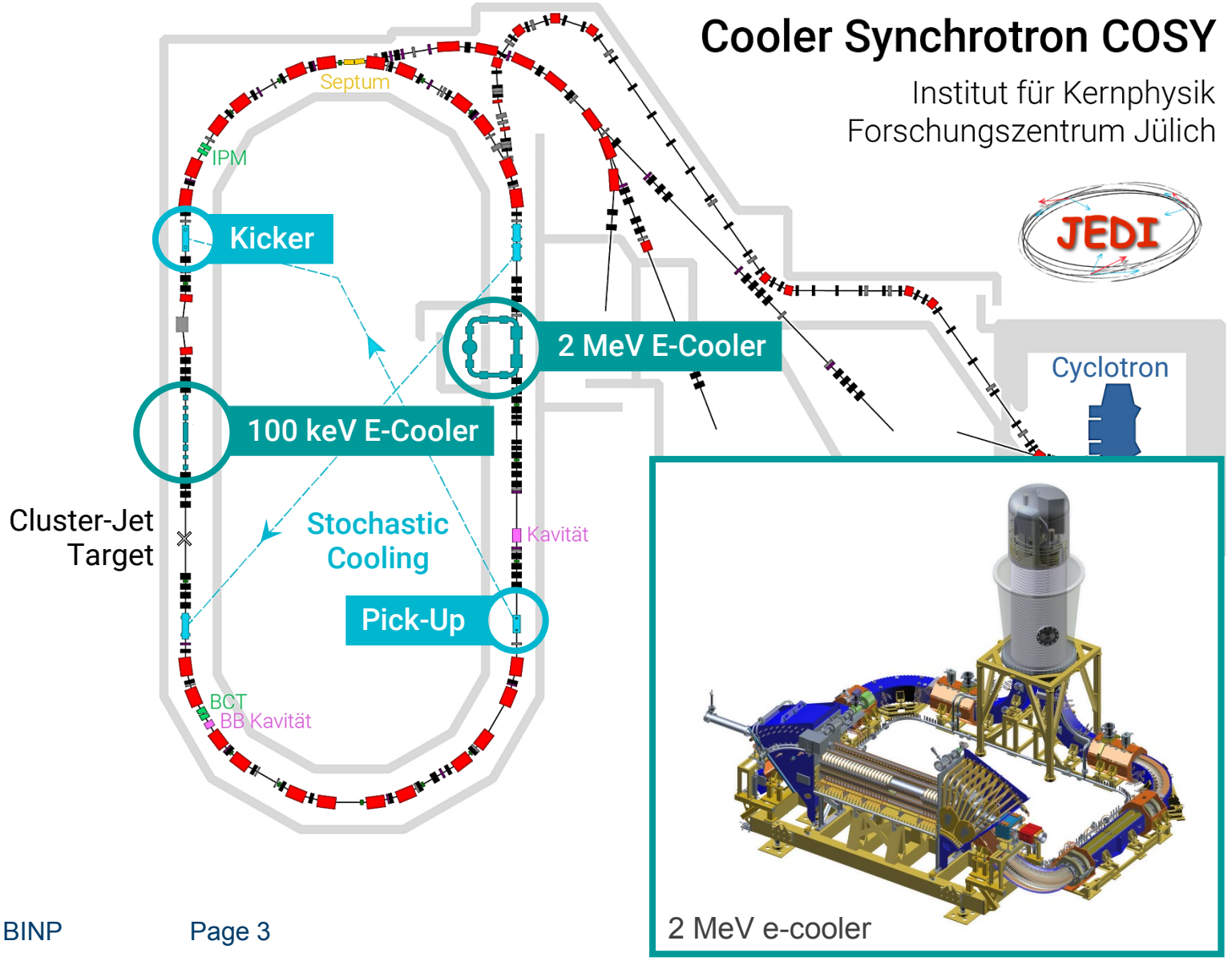
COOL 2019 I BUDKER INP, NOVOSIBIRSK I SEPTEMBER 23–27, 2019

CONTENTS

COOLER SYNCHROTRON COSY

With electron and stochastic cooling

- Circumference: 184 m
- Polarized/unpolarized H^+ and D^+
- Energy: 45 MeV – 2700 MeV
- Beam cooling
  - Stochastic cooling
  - 100 keV electron cooling
  - **2 MeV electron cooling**
    - Build at BINP
    - Operated since 2013



COSY EXPERIENCE OF ELECTRON COOLING

Summary of achievements with 2 MeV electron cooler

Energy	Current	Cooling time (e^{-1})		Conditions (initial)		
$E_{kin,e}$ / keV	I_e / A	$\tau_{\parallel}$ / s	$\tau_{\perp}$ / s	$N_{protons}$	$\Delta p/p$	ϵ_x ; ϵ_y / mm·mrad
109	0.5		50..60			
192	0.5	≈ 20	≈ 100			
316	0.3	≈ 20	50..60			
908	0.8	< 40	≈ 90			
908	**0.6**	**20(1)**	**130(4)**	$3 \cdot 10^8$	$76(3) \cdot 10^{-5}$	0.282(2) ; 0.798(2)
908	**0.6**	**7.7(3)**	**88(2)**	$3 \cdot 10^8$	$61(2) \cdot 10^{-5}$	0.089(2) ; 0.122(1)
1257	0.5	≈ 100				
1500	0.1	—	—			

The values indicated do not represent the best possible cooling but show achievements considering initial conditions and available optimisation time

The Cooler Synchrotron COSY

EPICS INTEGRATION OF THE COOLER CONTROLS SYSTEM

Experiments with combined electron and stochastic cooling

Electron velocity Profile

EPICS INTEGRATION OF THE 2 MEV COOLER

Implementation status

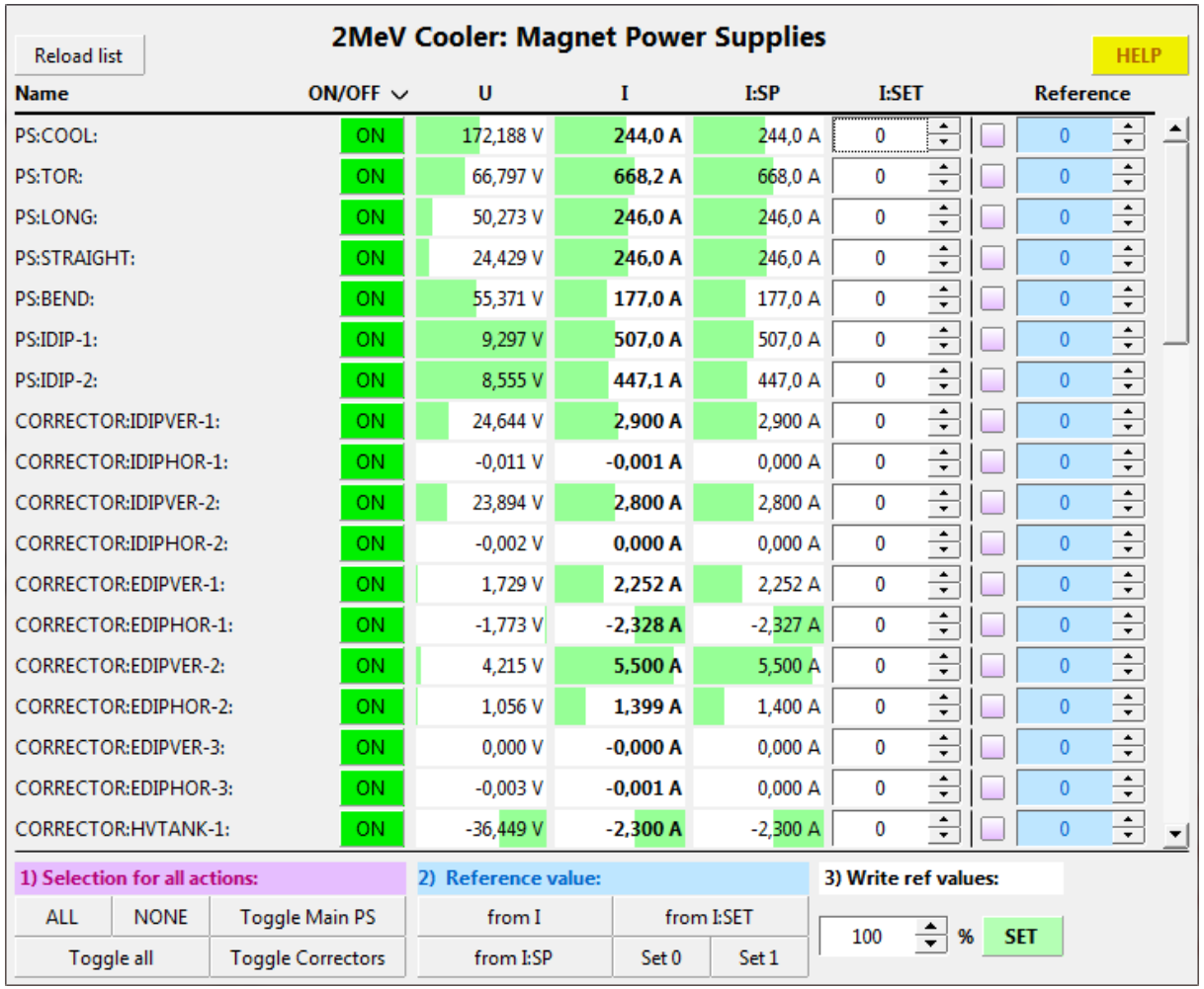
- Standalone cooler control system
- Integration into COSY control system EPICS
  (Experimental Physics and Industrial Control System)
- All systems covered by readout
- Central archiving
  - All data continuously stored in one place
  - Easy data analysis and correlation
- Cooler BPM data used for orbit correction
- Control of magnetic system and electron gun

Parameter Statistics	
Readout	**1029**
Analogue parameters	610
Set-point (DAC)	71
Measured (ADC)	539
Binary status	381
Other	38
Control	**123**
Analogue (DAC)	63
Binary status	60

EPICS INTEGRATION

Related systems

- 2 MeV e-cooler
- Schottky spectrum measurement
- Ionization profile monitor (IPM)
- 100 keV e-cooler (readout only)
- Stochastic cooling (ongoing)



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EPICS INTEGRATION

Related systems

- 2 MeV e-cooler
- Schottky spectrum measurement
- Ionization profile monitor (IPM)
- 100 keV e-cooler (readout only)
- Stochastic cooling (ongoing)

2MeV Cooler: Electron physics

Rest mass:	0,511 MeV/c^2
Rest energy:	0,511 MeV
Kinetic energy:	**0,908 MeV**
Total energy:	1,419 MeV
Relativistic mass:	1,419 MeV/c^2
Momentum of e:	1,324 MeV/c
Momentum of p:	2,431 GeV/c
Lorentz factor:	2,777
Beta factor:	0,933
Speed:	279679 km/s
Current:	**0,630 A**
Charge density:	2253,209 pC/m
Density:	1,406E10 1/m
Electrons in cooler:	8,987E10
e in cooling section:	3,783E10

EPICS INTEGRATION

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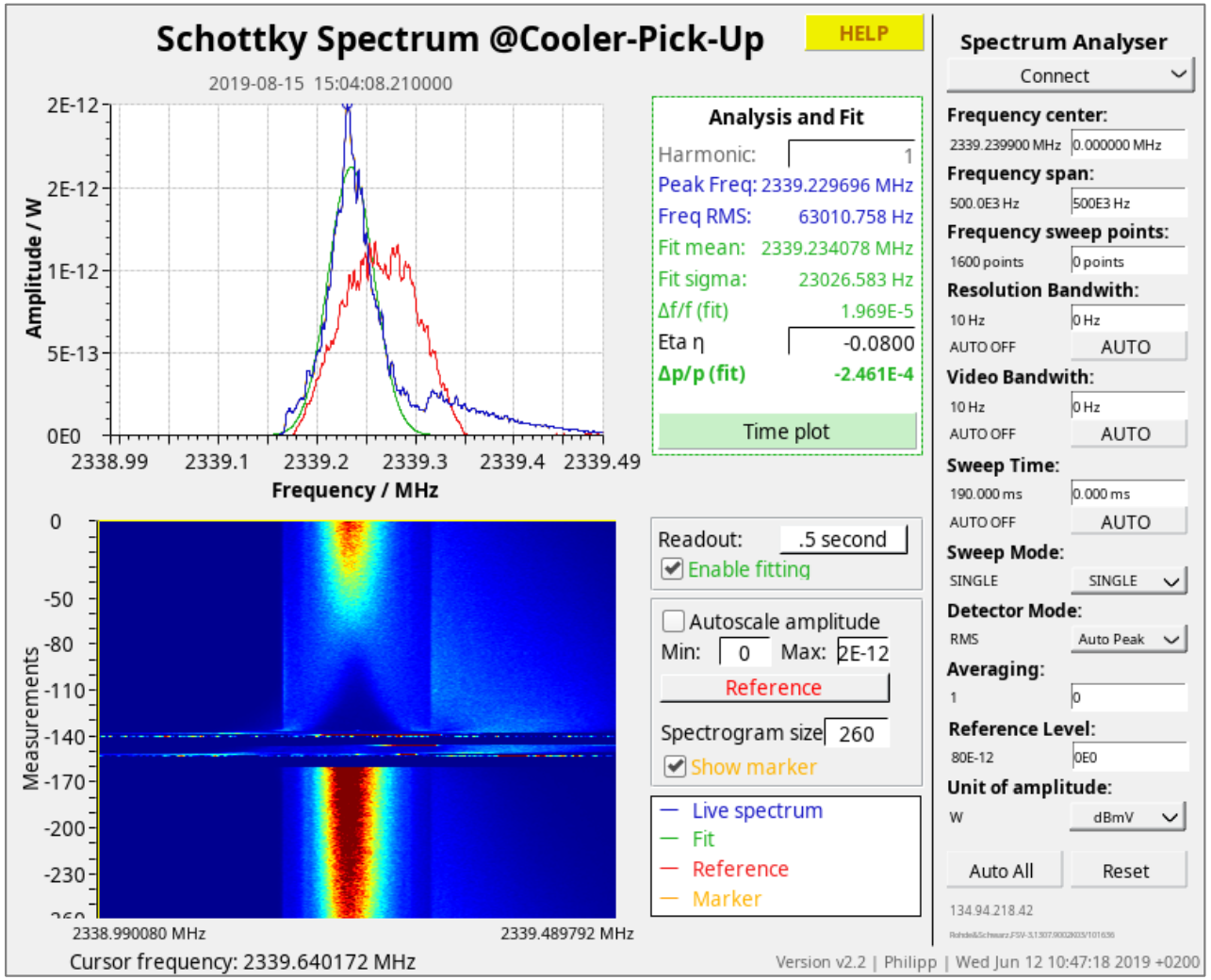


EPICS INTEGRATION

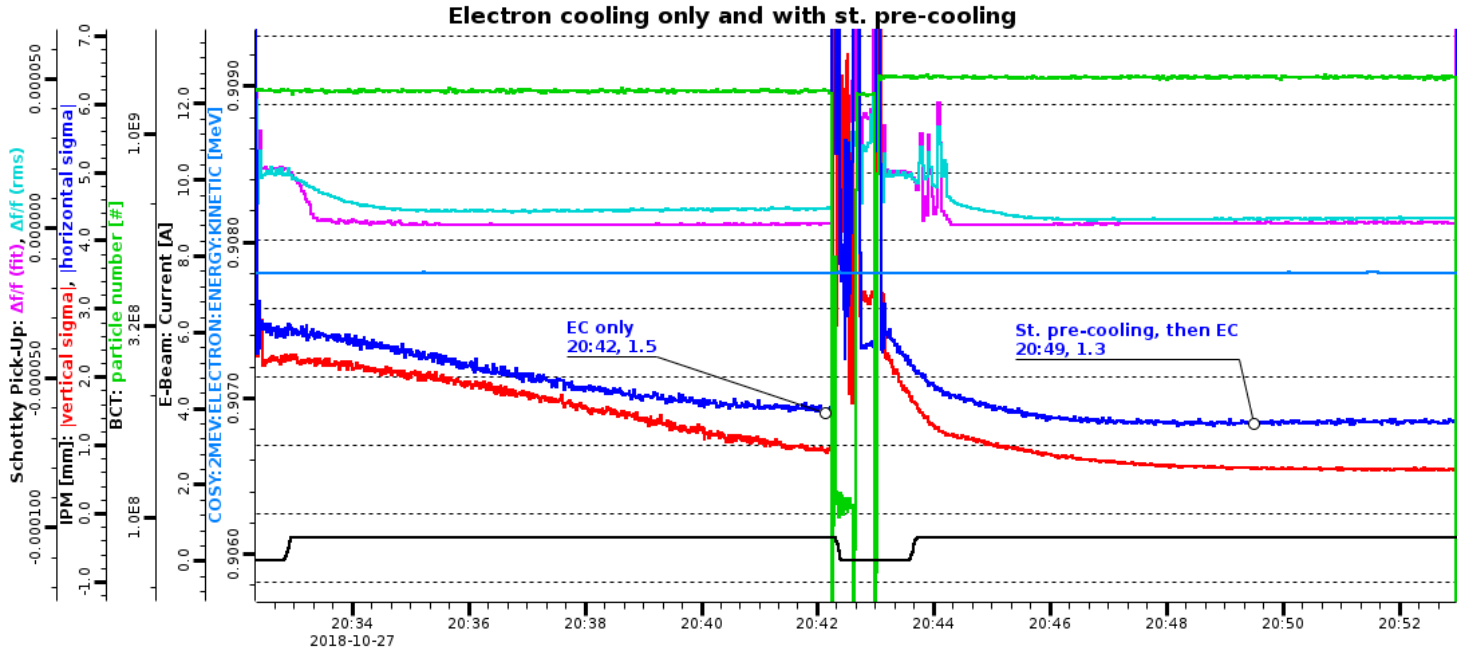
Related systems

- 2 MeV e-cooler
- Schottky spectrum measurement
- Ionization profile monitor (IPM)
- 100 keV e-cooler (readout only)
- Stochastic cooling (ongoing)

➔ All data saved in one place

➔ Established EPICS toolset

➔ On-the-fly correlation and plotting



NEW RAMP EDITOR

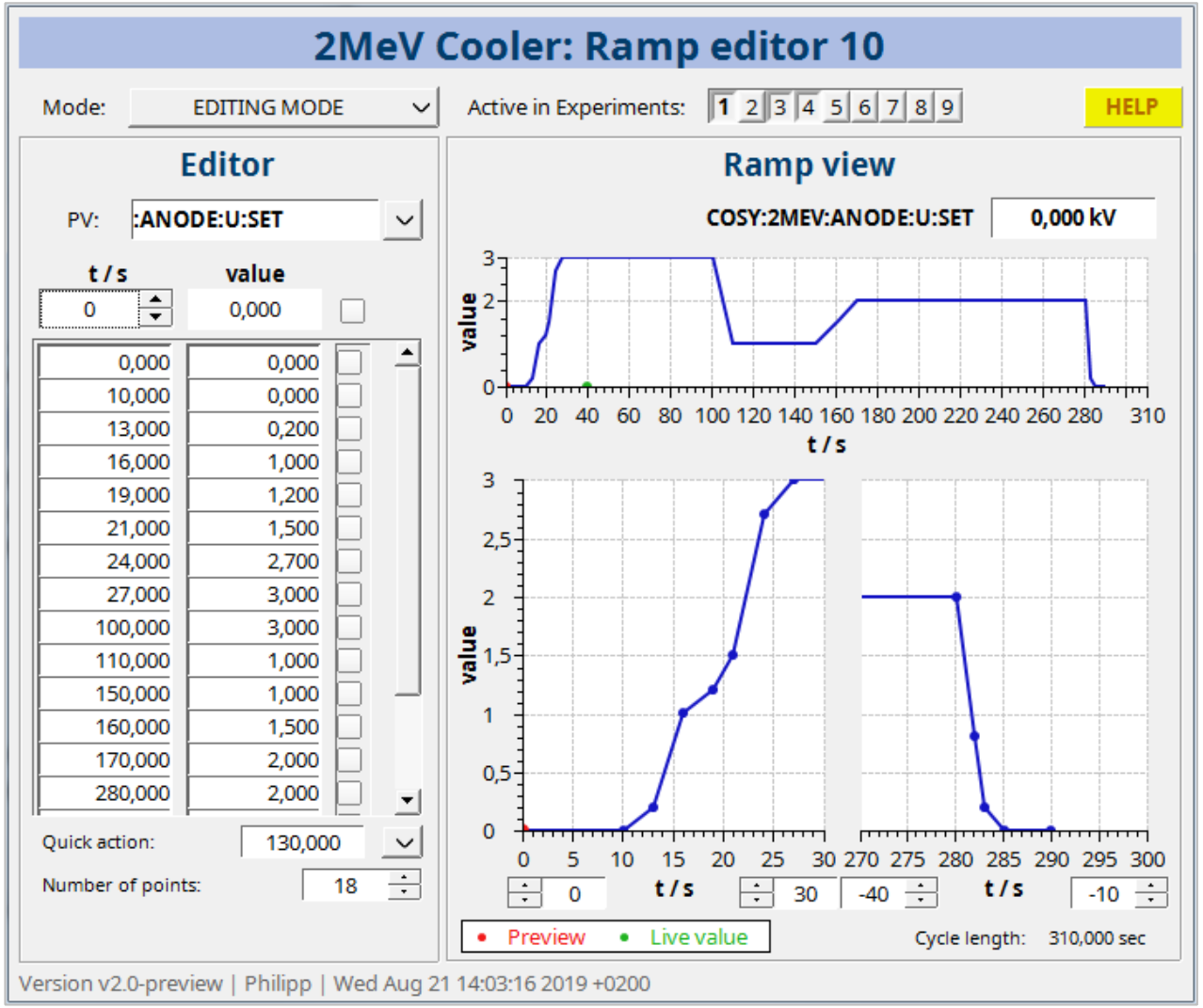
For e-cooler and any EPICS based system

- Automated control of parameters
- Based on COSY timing and experiments
- Definition of arbitrary waveforms
- For any parameter (cooler and beyond)

➔ Ramp up with minimal beam loss

➔ Reproducible cooling properties

➔ Systematic parameter scans



The Cooler Synchrotron COSY

EPICS integration of the cooler control system

EXPERIMENTS WITH COMBINED ELECTRON AND STOCHASTIC COOLING

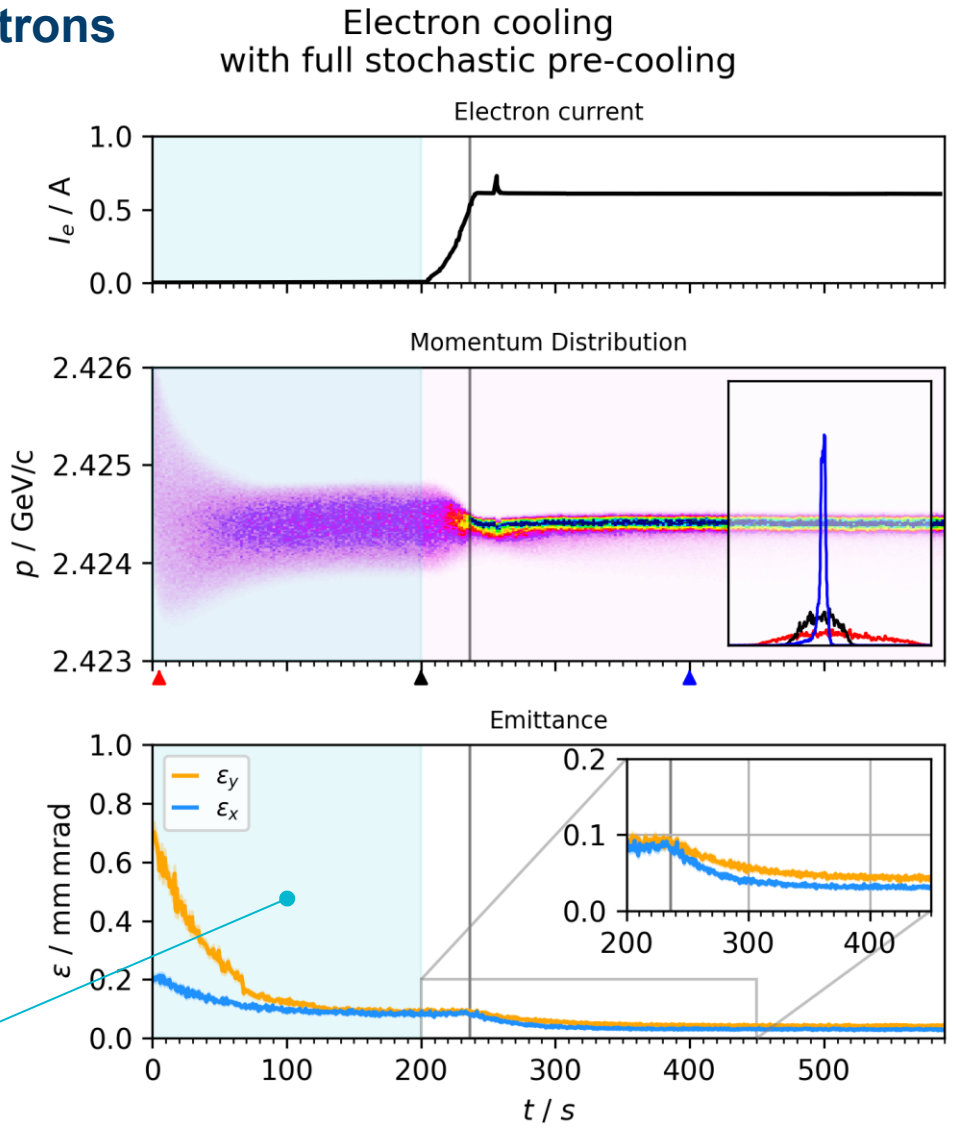
Electron velocity Profile

COMBINED ELECTRON AND STOCHASTIC COOLING

Proton beam at 2.425 GeV/c | 908 keV electrons

- Fast stochastic cooling at high emittance
- Fast e-cooling at low emittance
  - $\tau \approx 18$ s, $\Delta p/p = 3 \cdot 10^{-5}$

➔ Combine advantages of both systems



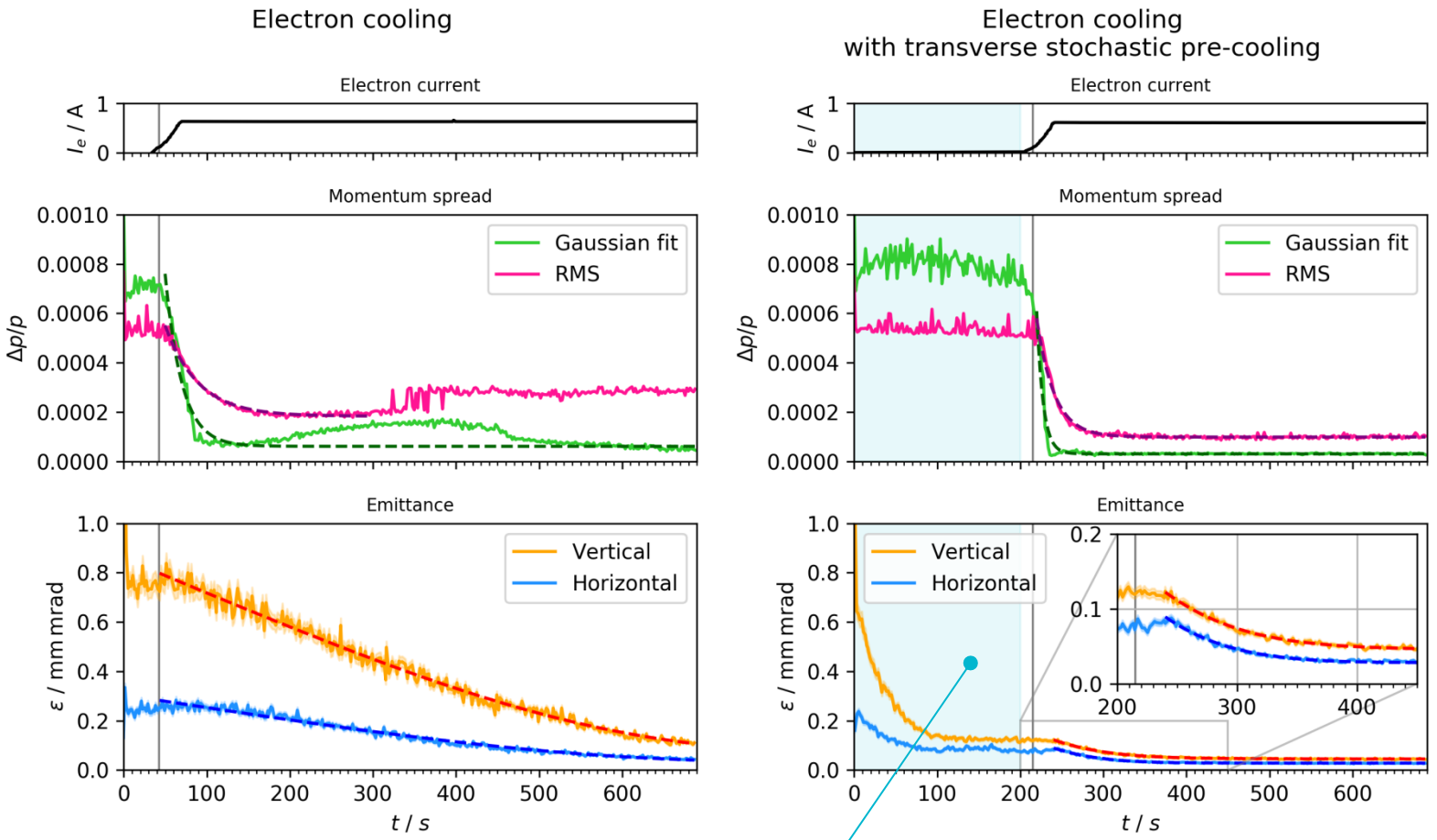
3D stochastic pre-cooling

COMBINED ELECTRON AND STOCHASTIC COOLING

Proton beam at 2.425 GeV/c | 908 keV electrons

Stochastic pre-cooling:

- Faster emittance e-cooling
  $T_{cool,x} \approx 125\ \mathrm{s} \rightarrow 70\ \mathrm{s}$
- Faster momentum e-cooling
  $\tau \approx 20\ \mathrm{s} \rightarrow 8\ \mathrm{s}$
- Lower momentum spread
  $\Delta p/p \approx 6 \cdot 10^{-5} \rightarrow 3 \cdot 10^{-5}$
- Further emittance cooling:
  factor 3 compared to SC



Stochastic emittance pre-cooling

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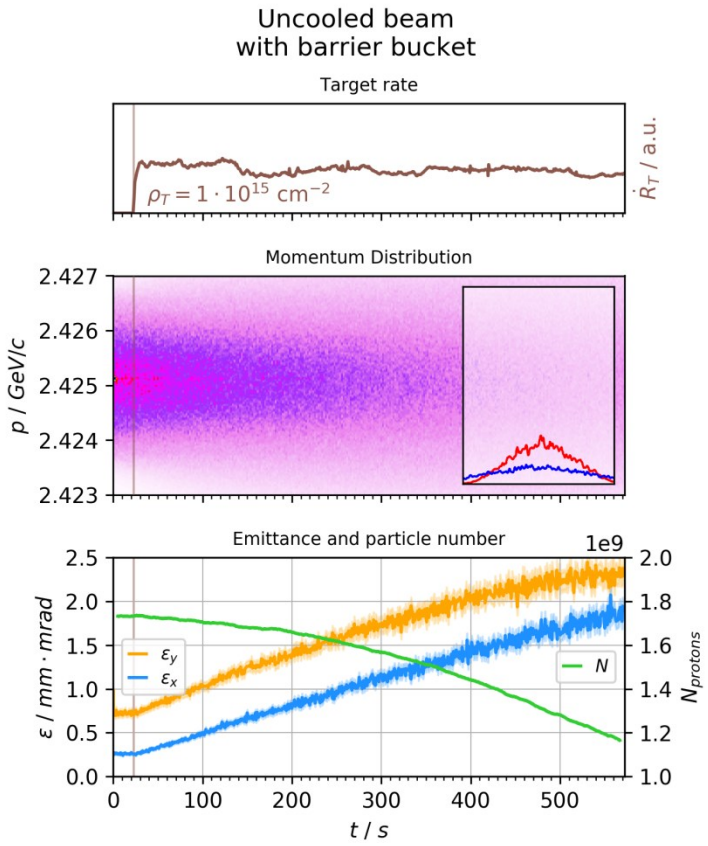
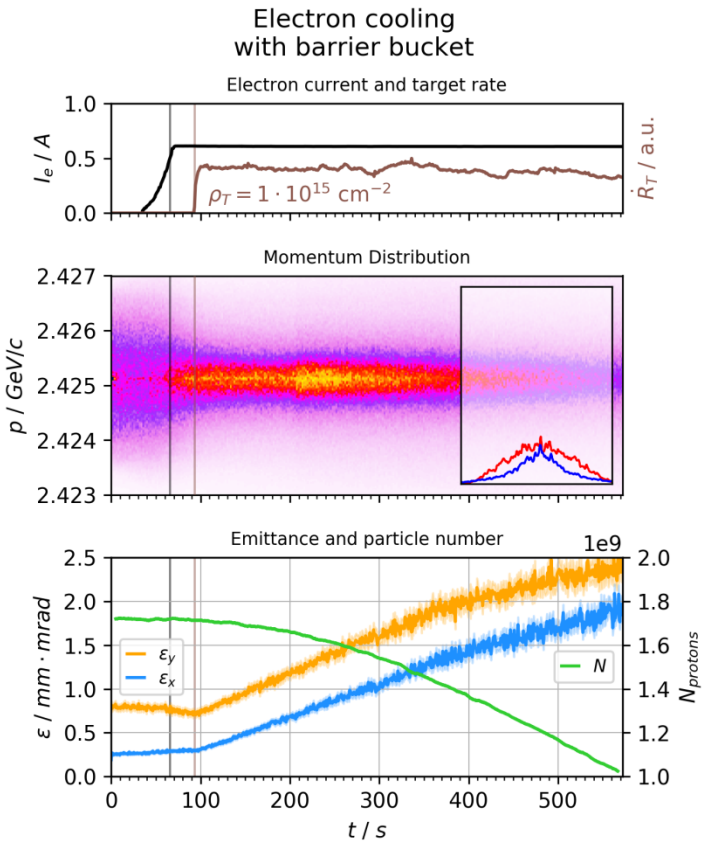
ELECTRON COOLING & PANDA CLUSTER-JET TARGET

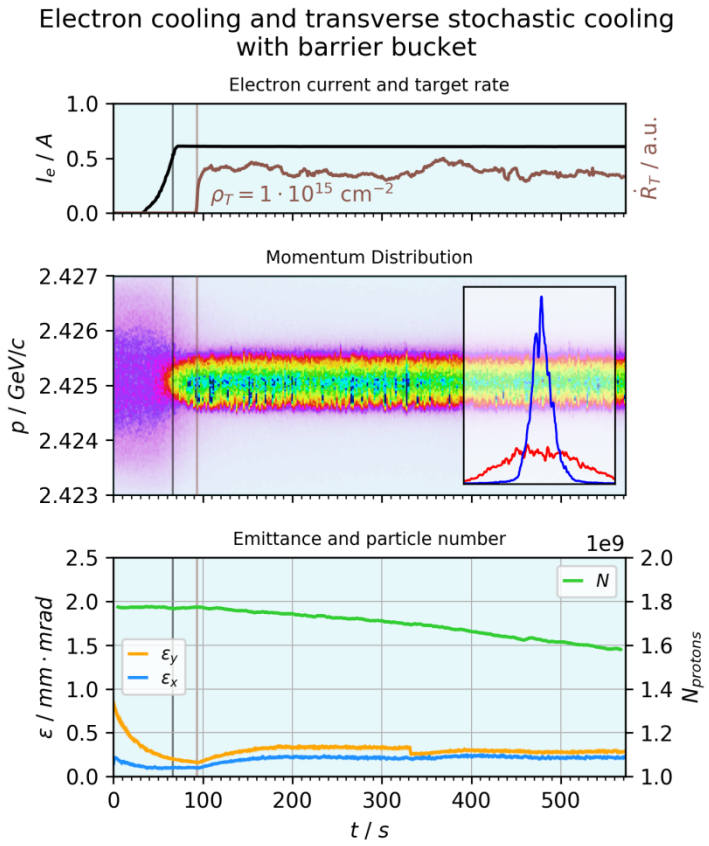
Proton beam at 2.425 GeV/c | 908 keV electrons | Target density of 10^{15} cm^{-2} | Barrier Bucket



$\Delta p/p = 11.1 \cdot 10^{-4}$



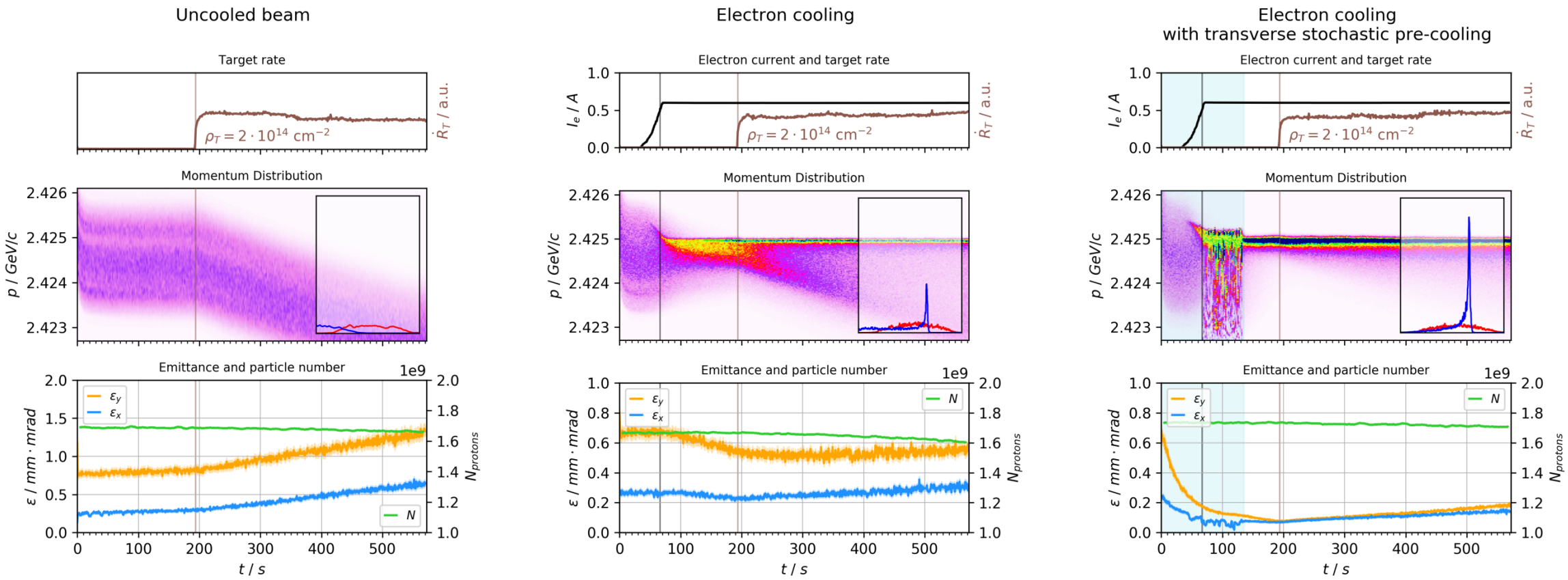
$\Delta p/p = 5.3 \cdot 10^{-4}$



$\Delta p/p = 2.1 \cdot 10^{-4}$

ELECTRON COOLING & PANDA CLUSTER-JET TARGET

Proton beam at 2.425 GeV/c | 908 keV electrons | Target density of $2 \cdot 10^{14}$ cm^{-2}

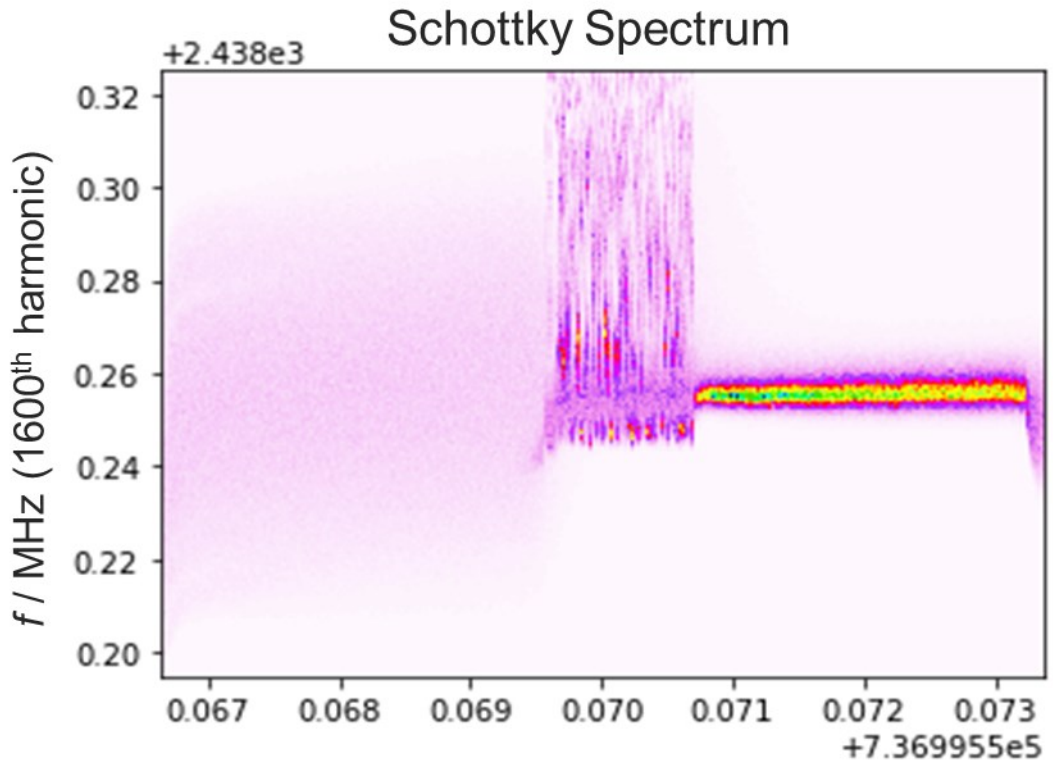


$$\Delta p/p = 2.9 \cdot 10^{-5}$$

ARTEFACT IN SCHOTTKY SPECTRUM

Simultaneous operation of stochastic and electron cooling

- Simultaneous *transverse* stochastic and electron cooling
- Artefact visible in *longitudinal* Schottky spectrum
  - Measured with stochastic cooling pick-up
  - Not visible in IPM
- Dependence on pick-up, cooling loop, electron beam energy?
  → To be addressed in next beam time



The Cooler Synchrotron COSY

EPICS integration of the cooler control system

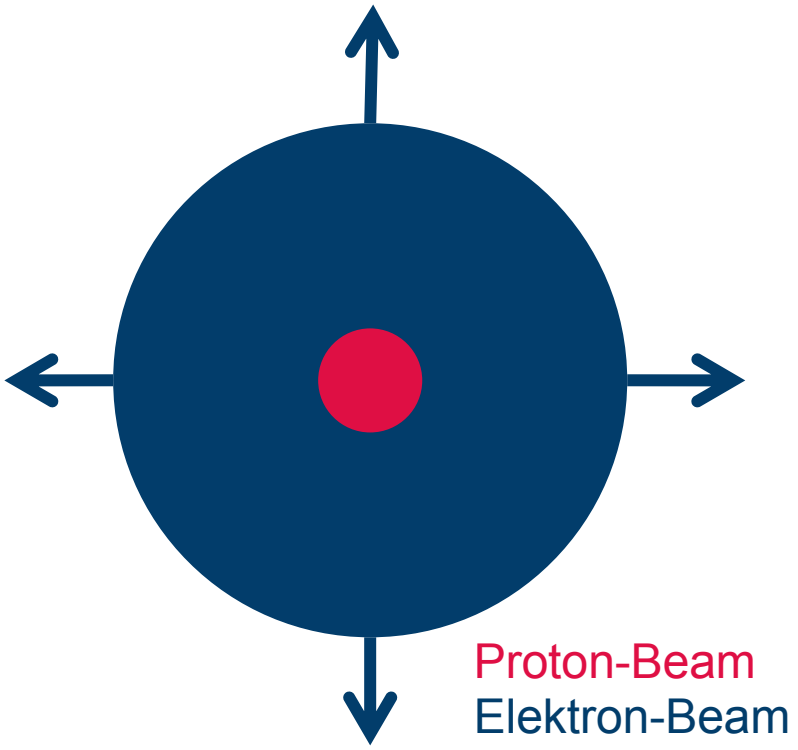
Experiments with combined electron and stochastic cooling

ELECTRON VELOCITY PROFILE

ELECTRON VELOCITY PROFILE

Method: electron velocity distribution probing with the proton beam

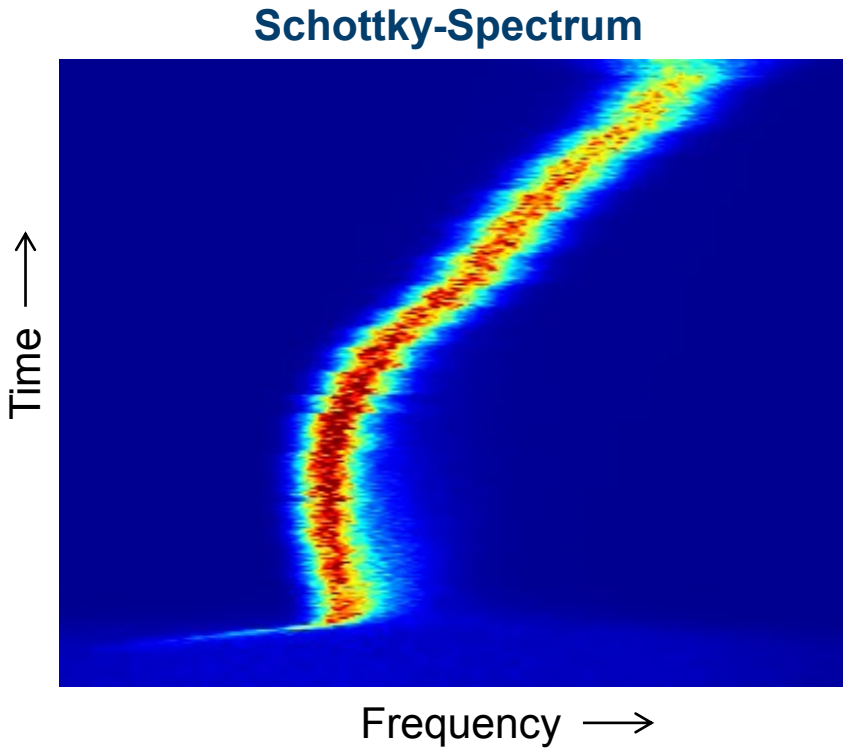
- Electron gun optimized to cooling rate
- Cooled proton beam (pencil beam)
- Electron orbit shifts



ELECTRON VELOCITY PROFILE

Method: electron velocity distribution probing with the proton beam

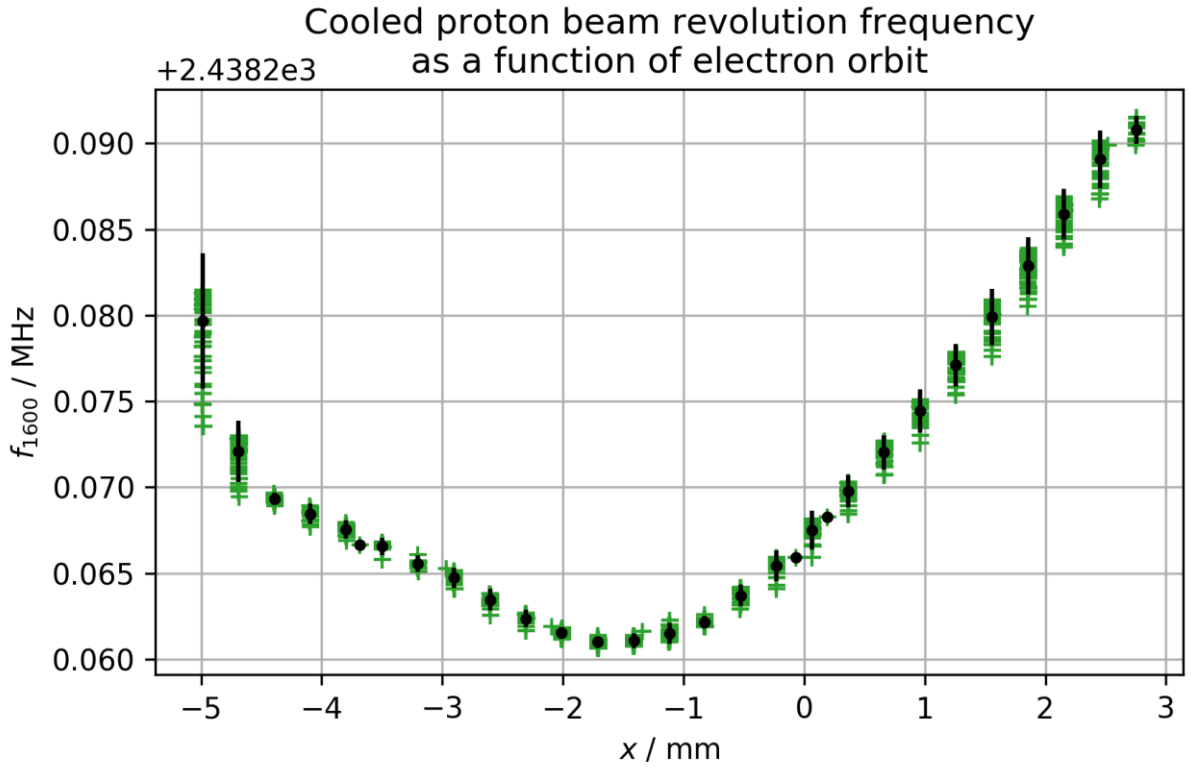
- Electron gun optimized to cooling rate
- Cooled proton beam (pencil beam)
- Electron orbit shifts
- Schottky measurement
  → Frequency as function of beam position



ELECTRON VELOCITY PROFILE

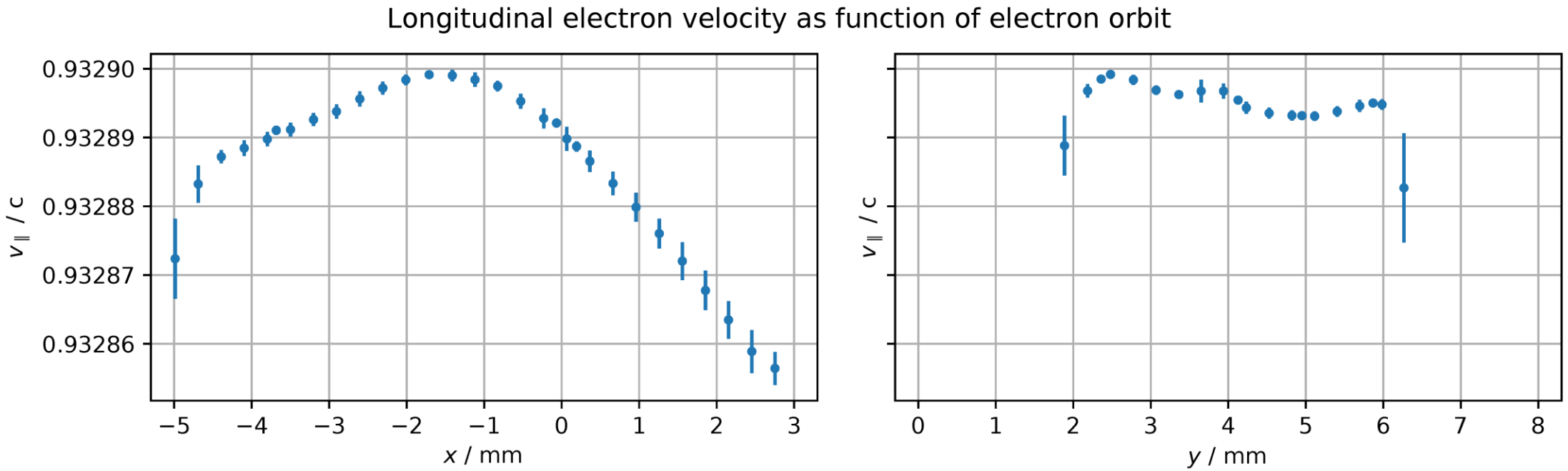
Method: electron velocity distribution probing with the proton beam

- Electron gun optimized to cooling rate
- Cooled proton beam (pencil beam)
- Electron orbit shifts
- Schottky measurement
  → Frequency as function of beam position
- Determination of $v_p = v_{e,\parallel}$
  → Velocity profile



ELECTRON VELOCITY PROFILE

Measurement results



$U_{grid} = 0.75\ \mathrm{kV}$
$U_{anode} = 3.8\ \mathrm{kV}$
$I_e = 0.63\ \mathrm{A}$

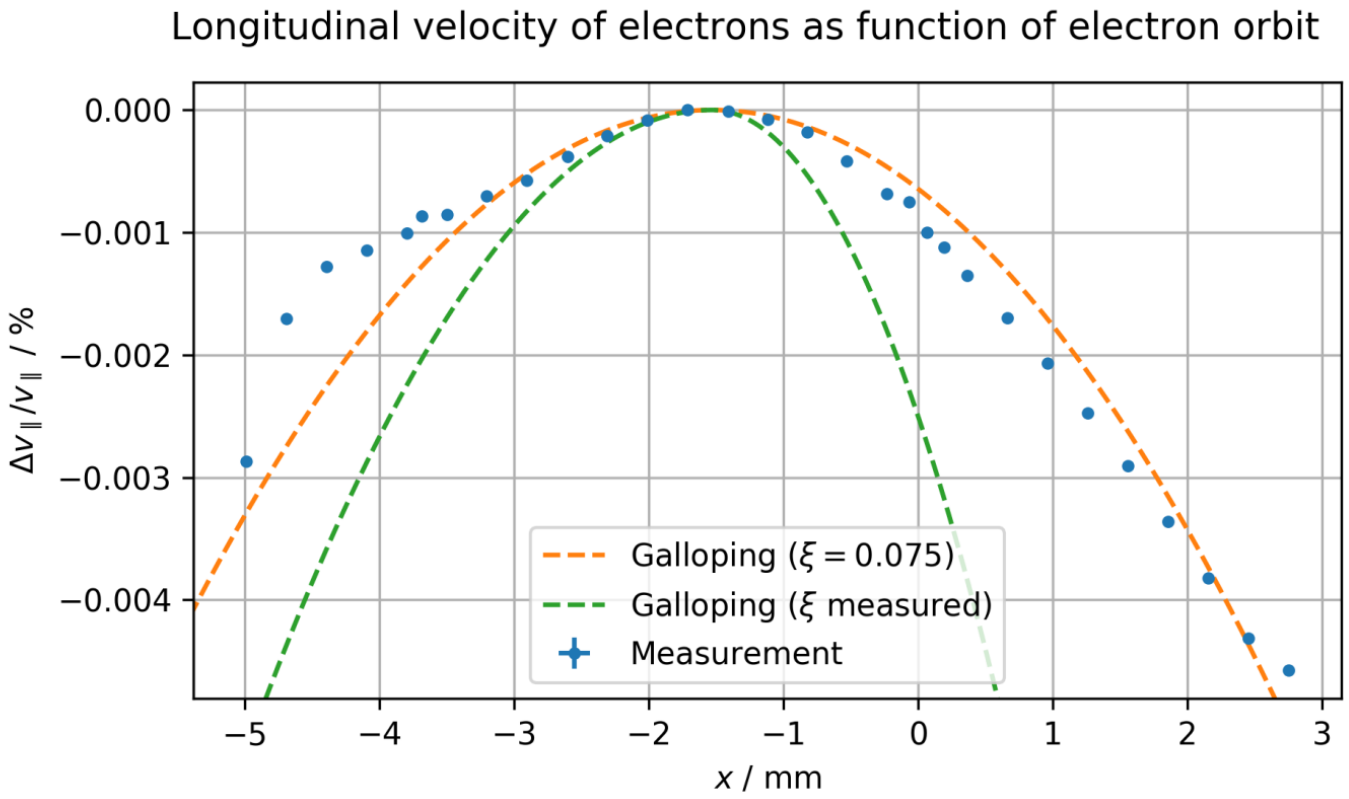
- Reduced longitudinal velocity indicates transverse motion
  → **Larmor oscillation** limits transverse cooling
- Worst for large proton beams or huge beam offset

ELECTRON VELOCITY PROFILE

Comparison to galloping/scalloping effects

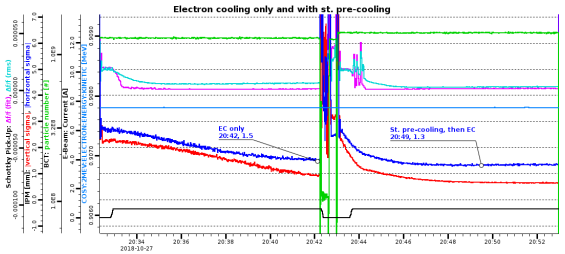
- Can partially be explained by galloping/scalloping
- Not yet considered:
  - Higher order (asymmetric) Larmor oscillations due to bends
  - Space charge effects
  - Influence of gun settings (beam density profile)

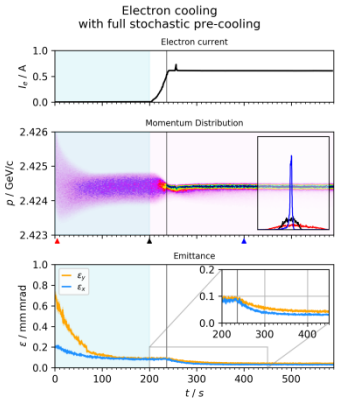
➔ To be addressed in next beam time

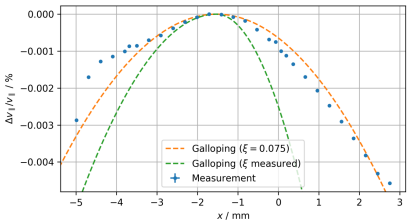


SUMMARY

- EPICS integration of the cooler and related beam control systems
  - → Central archiving for easy data analysis and correlation
  - → System integration and automated control with ramp editor
- Electron cooling with stochastic emittance pre-cooling
  - → Significantly faster cooling and lower equilibrium momentum uncertainty
  - → Advantages of both systems combined
- Electron velocity profile measured
  - → Limits cooling performance especially for large-diameter proton beams
  - → Can partially be explained by galloping/scalloping







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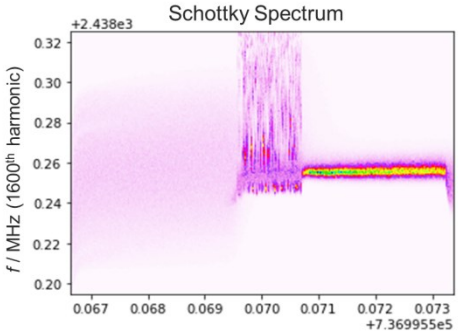
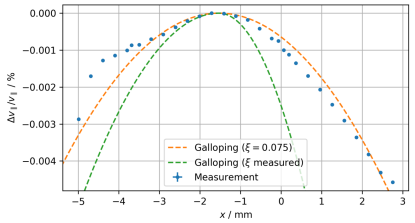
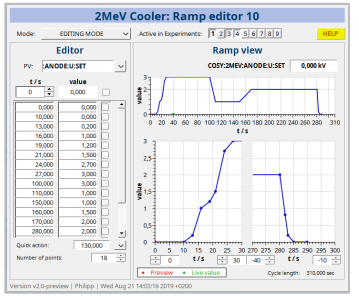
OUTLOOK

Plans for the next beam time

- Schottky spectrum artefact for combined SC and EC
  - → Identify cause
- Study of transverse cooling process
  - → Detailed study of electron velocity profile
  - → Electron temperature (recombination study), beam spectra
  - → Solenoid field straightness
  - → Larmor compensation on model basis
- EPICS based control of electron cooler
  - → Further automation
  - → Usage of data across systems







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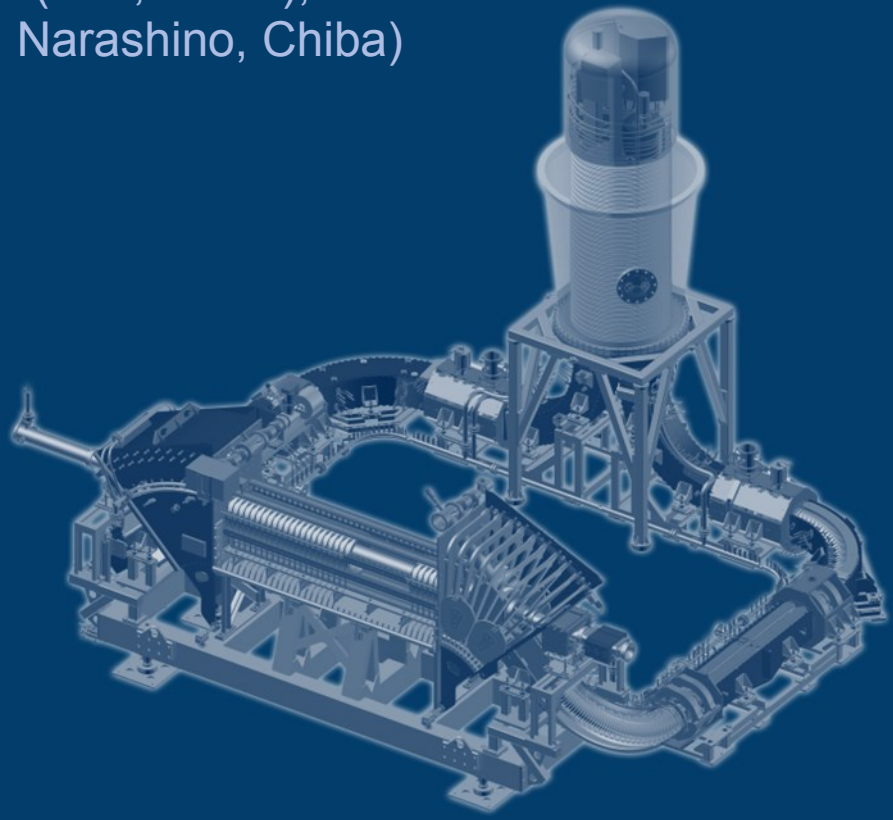
THANK YOU!



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