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HESR Stochastic Cooling System, Design, Construction and Test Experiment at COSY

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Outline

- History of slot-ring structures
- Proof of structures at COSY and Nuclotron
- First experiments with HESR cooling tanks at COSY
- Next steps

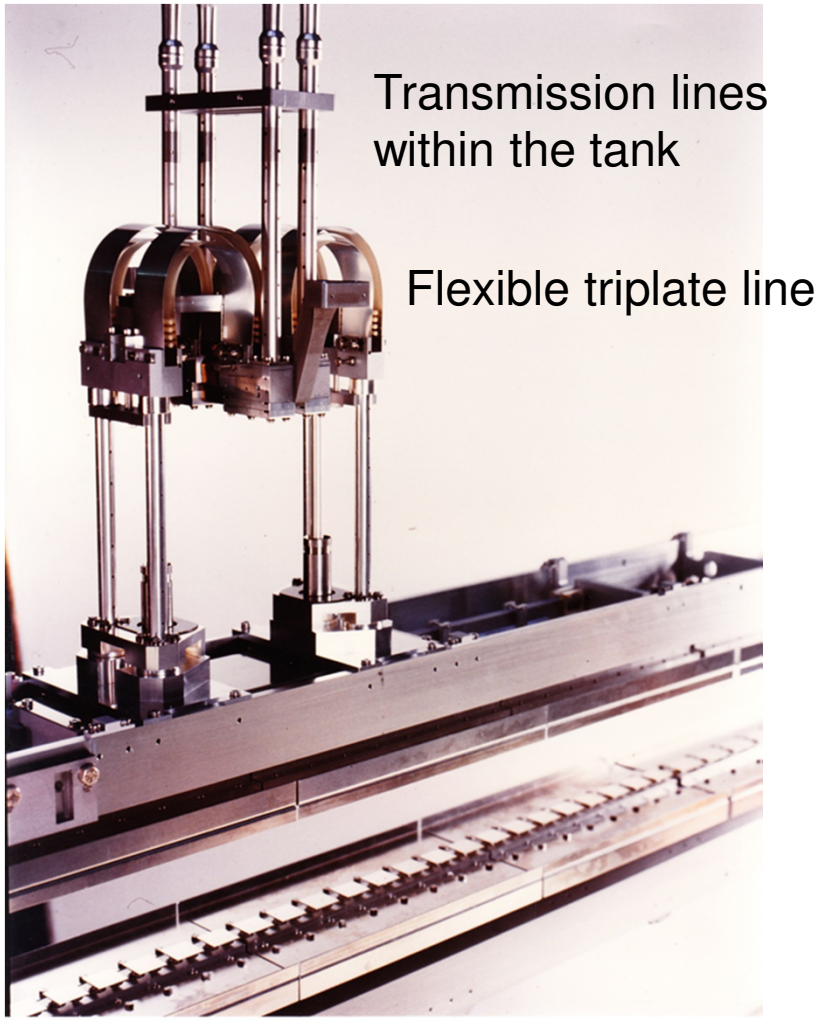
History of slot-ring couplers

COSY SC was based on AA-design from CERN using a plunging system:

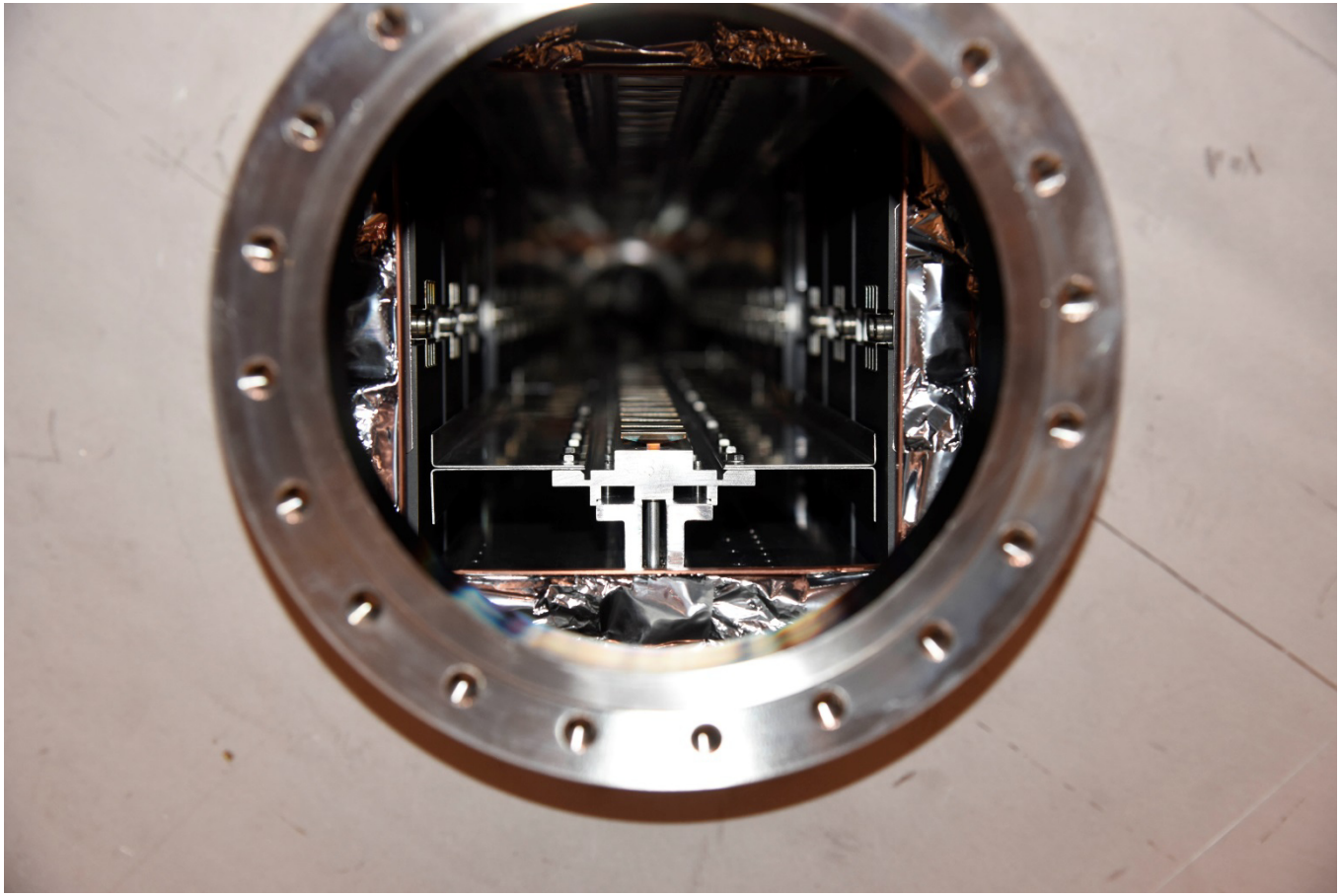
- Aperture change: 140 mm – 20 mm
- Min cycle-length: 4 sec
- Skewing and asymmetric movement possible

But the used stepper-motor driven plunging caused the most downtime of the SC

Complicate and expensive

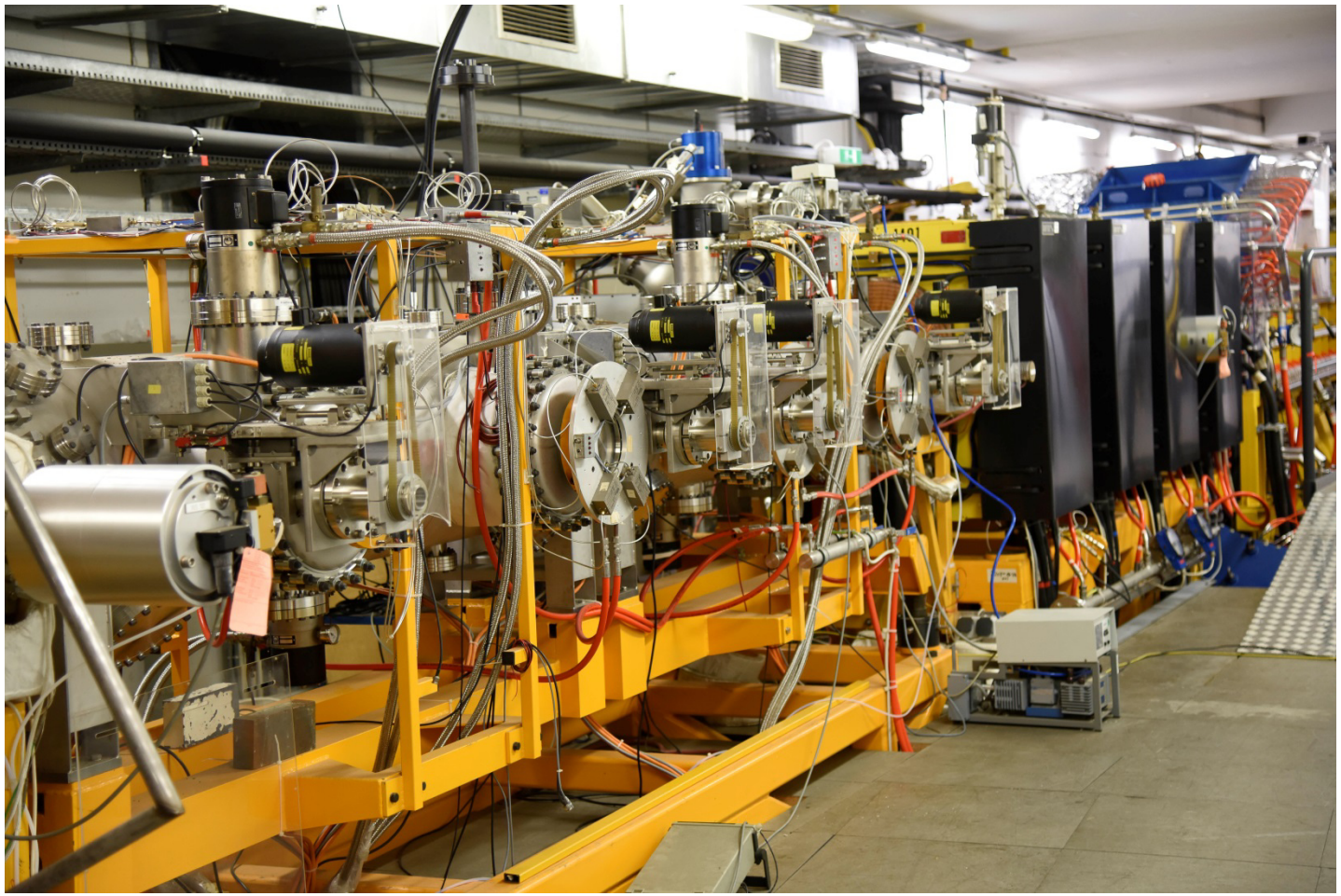


Movable Electrode Bars for Vertical Cooling Plane

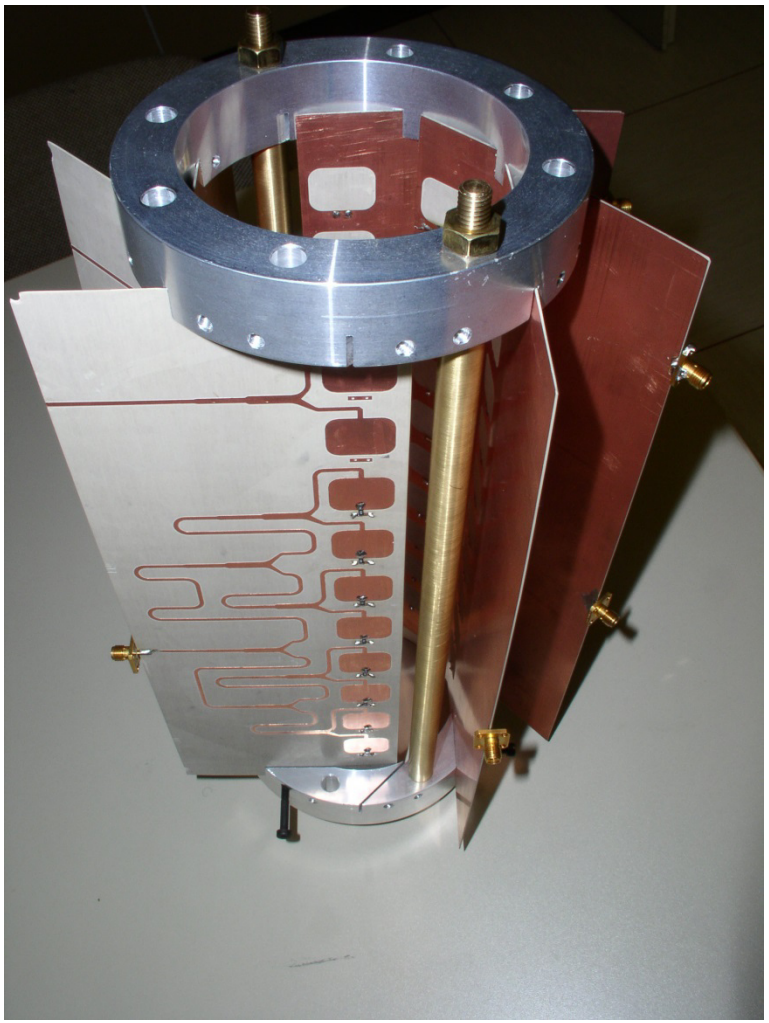


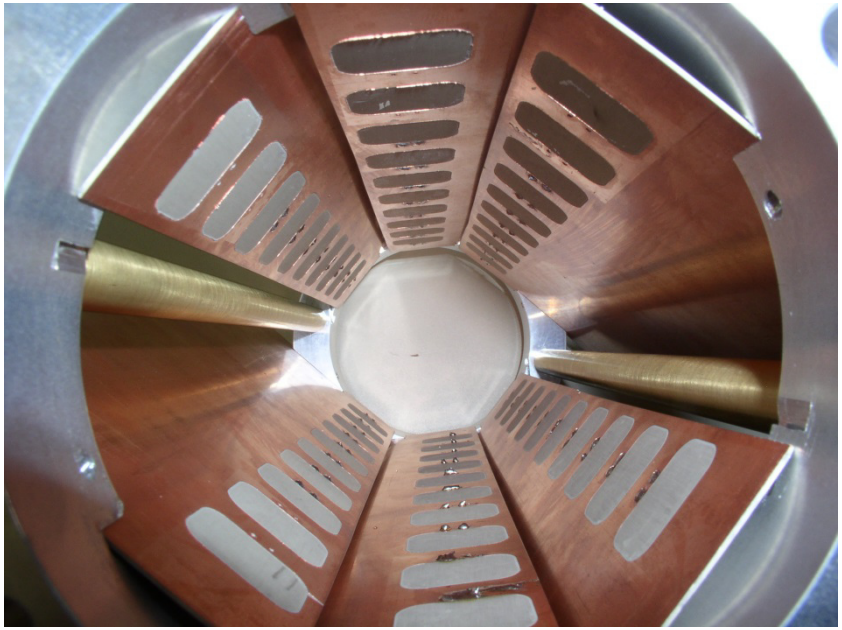
One Vertical Pickup Tank

Horizontal Pickup Tanks



Octagonal structures



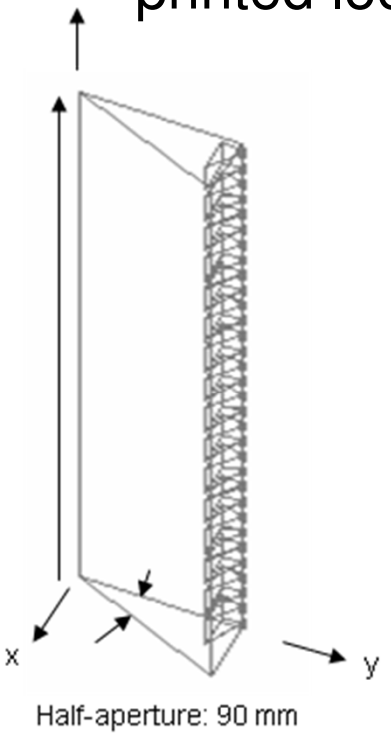


Aperture of HESR much smaller (90mm) than COSY aperture (140mm)

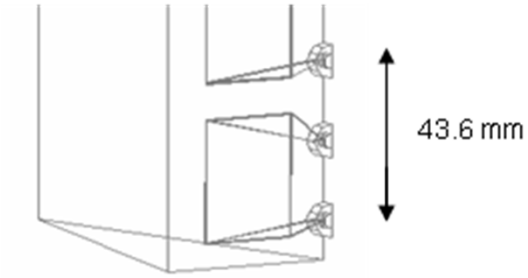
-> looking for a structure without plunging

Slot-ring couplers

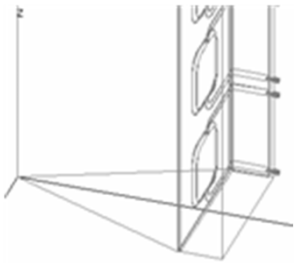
- At the same time Lars simulated slot-couplers, so why not making beam surrounding slot-couplers with octagonal arrangement of electrodes
- Besides round slot-ring we analyzed also AC-type loops, printed loops and modified CR-type structures



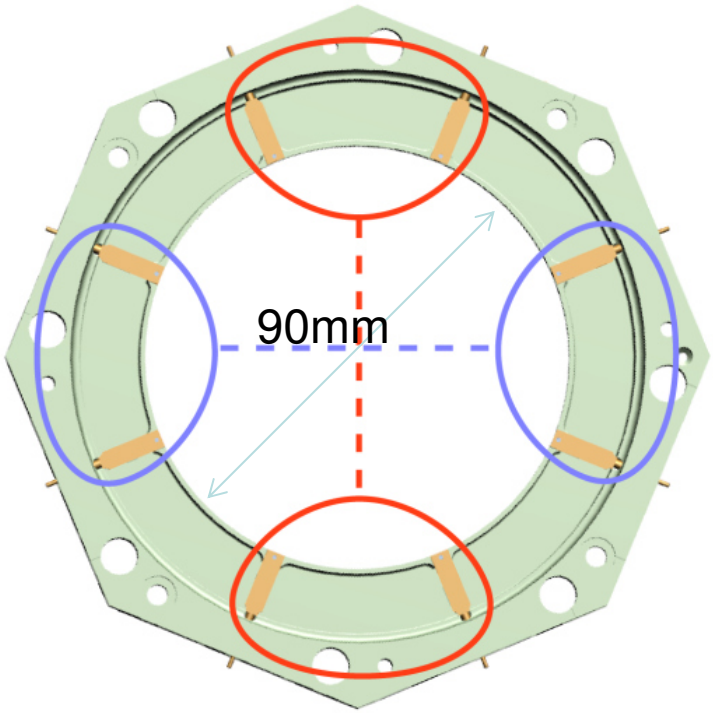
AC-type loops in octagonal structure

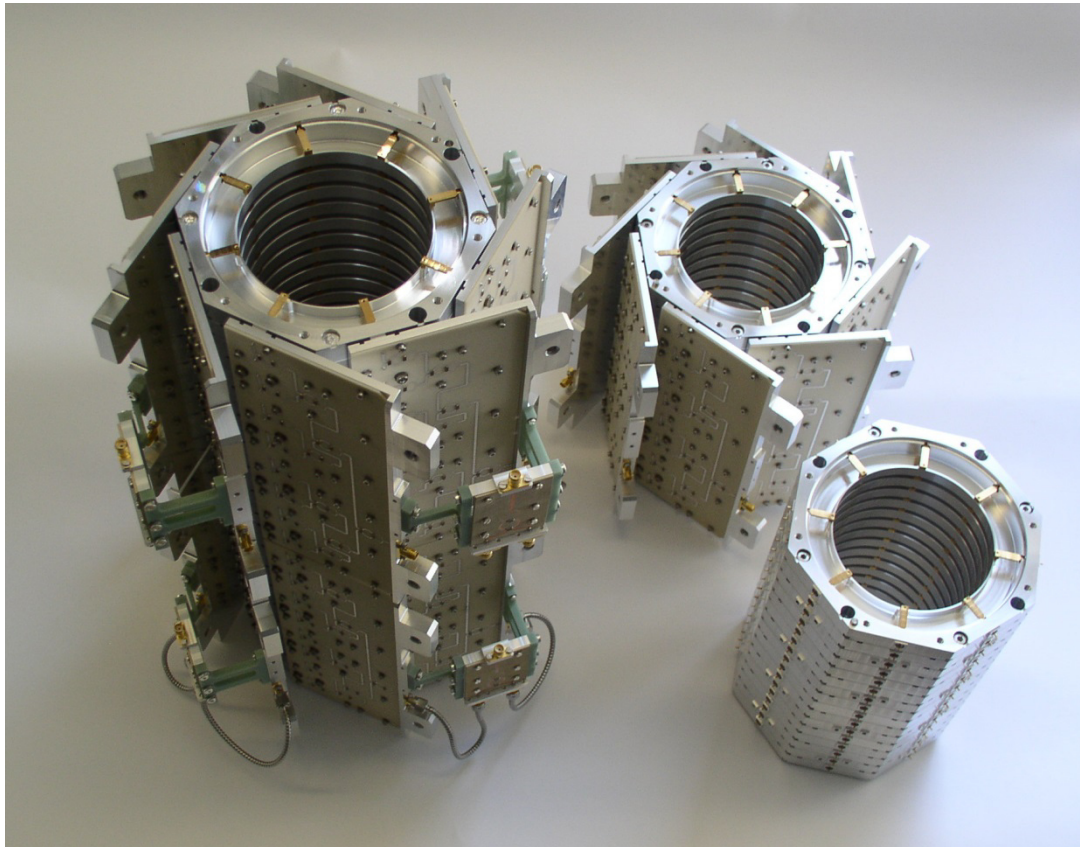


printed loops in octagonal structure



Slot ring couplers



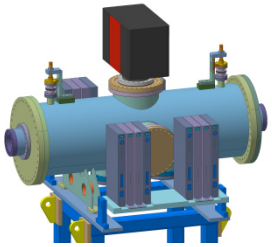


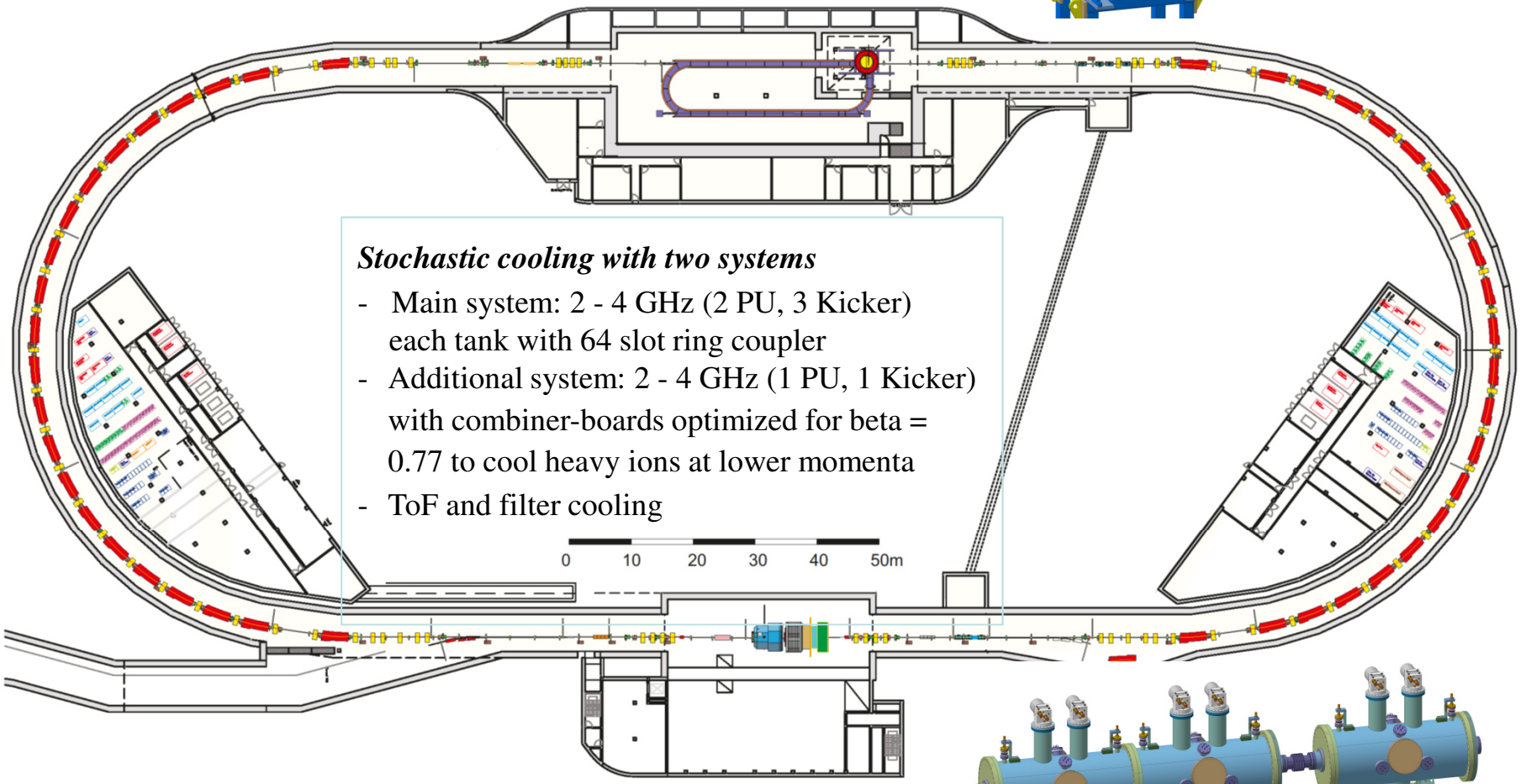
- Self-supporting structure
- No plunging
- All three cooling planes with same structures
- No aperture reduction
- 8x50 Ω electrodes for broadband operation

Stochastic cooling at HESR

Each kicker of the main system can be used for horizontal, vertical or longitudinal cooling

Kicker
3x + 1x



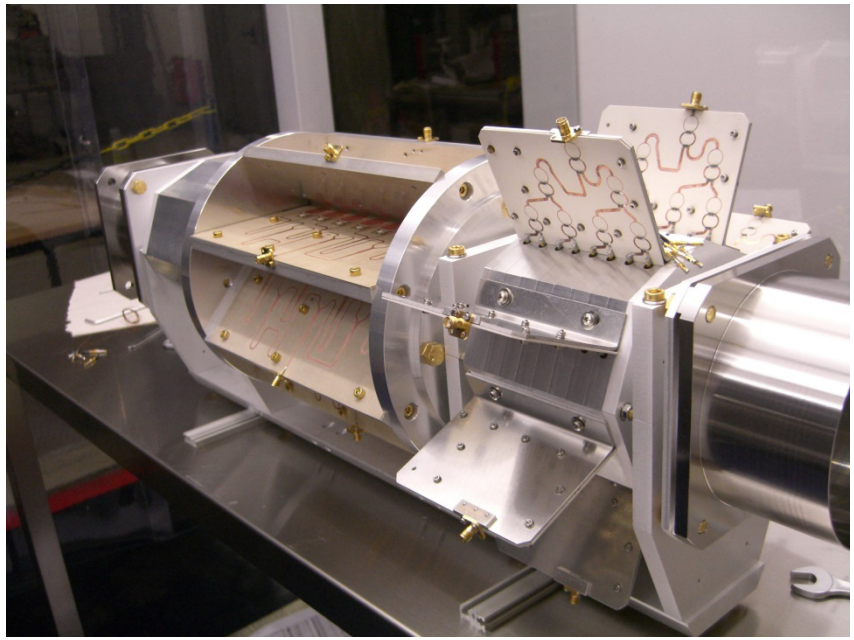


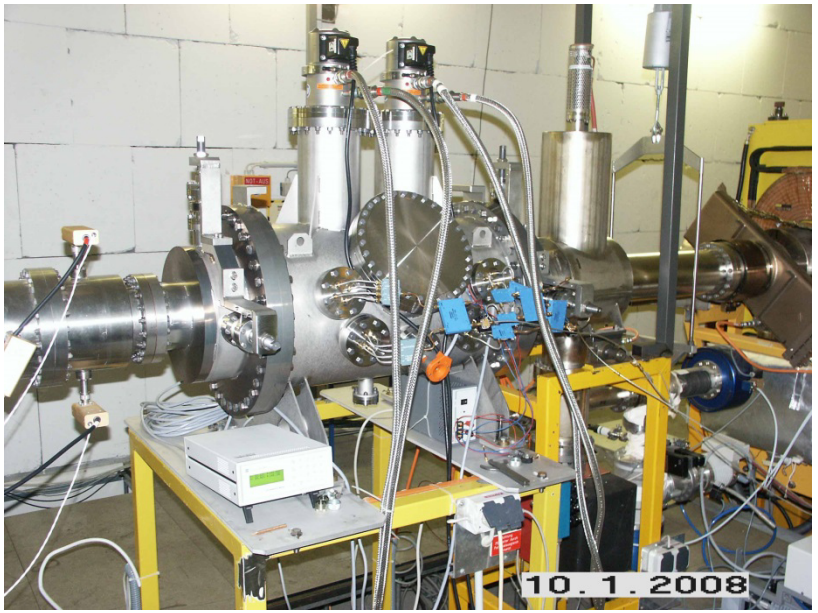
Stochastic cooling with two systems

- Main system: 2 - 4 GHz (2 PU, 3 Kicker) each tank with 64 slot ring coupler
- Additional system: 2 - 4 GHz (1 PU, 1 Kicker) with combiner-boards optimized for beta = 0.77 to cool heavy ions at lower momenta
- ToF and filter cooling

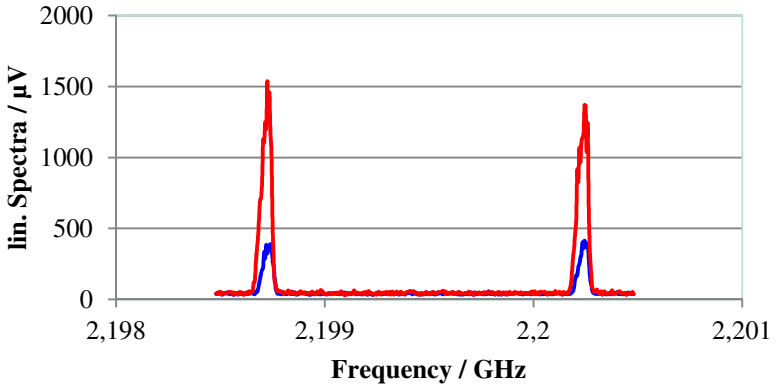
Pickup
2x + 1x

Test tank with lambda/4 printed loop structures and slot ring structures

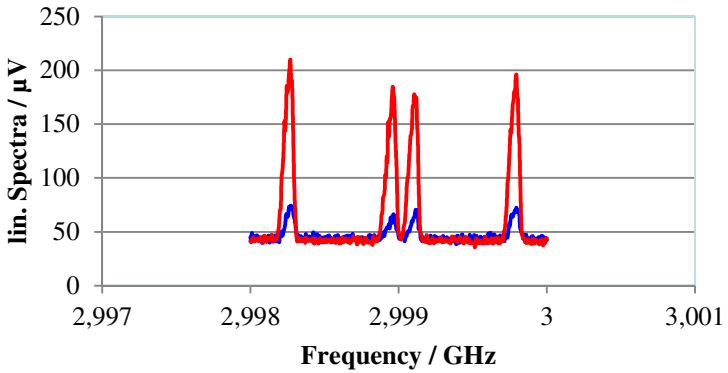




longitudinal: red slot-coupler, blue lambda/4



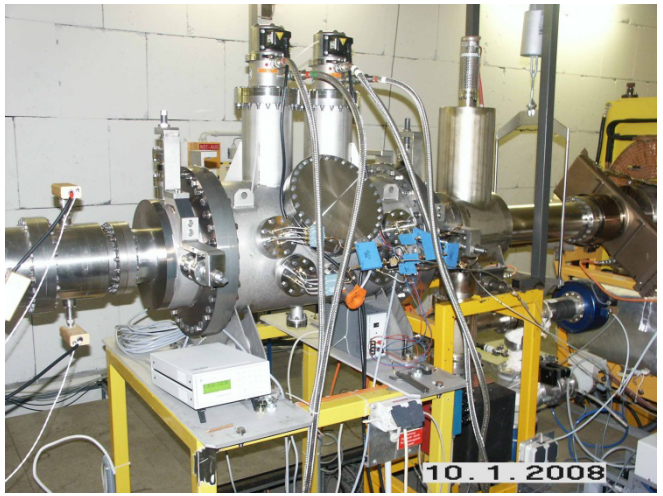
vertical sidebands: red slot-coupler, blue lambda/4



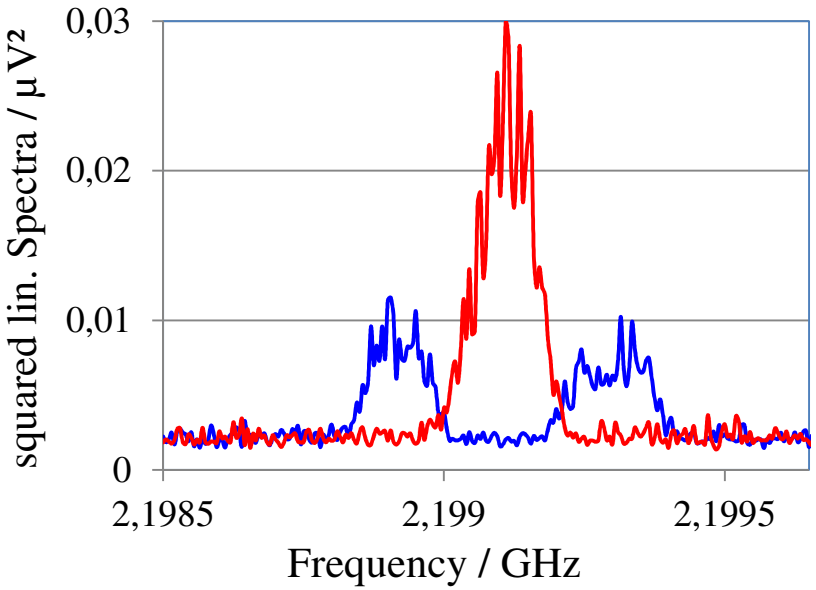
Pickup tests at COSY

16 rings in test-tank cooled down to 30K:

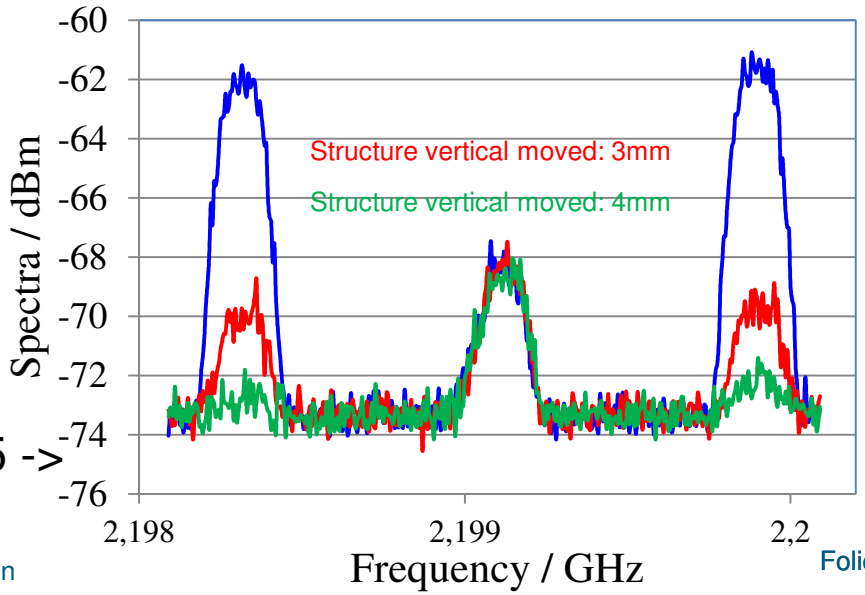
Beta-functions at TP1: Horizontal 5.2 m
Vertical 14 m



Slot coupler: red vertical, blue horizontal



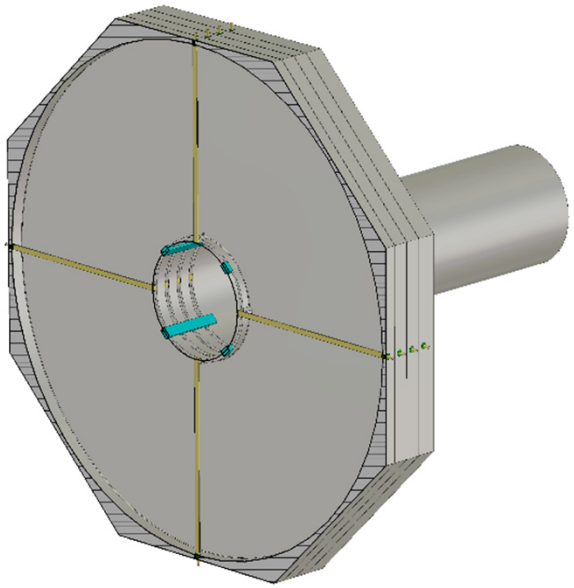
longitudinal parts in vertical transvers signal



Betatron sidebands measured with the same structure (vertical tune close to 3.5 -> bandoverlap)

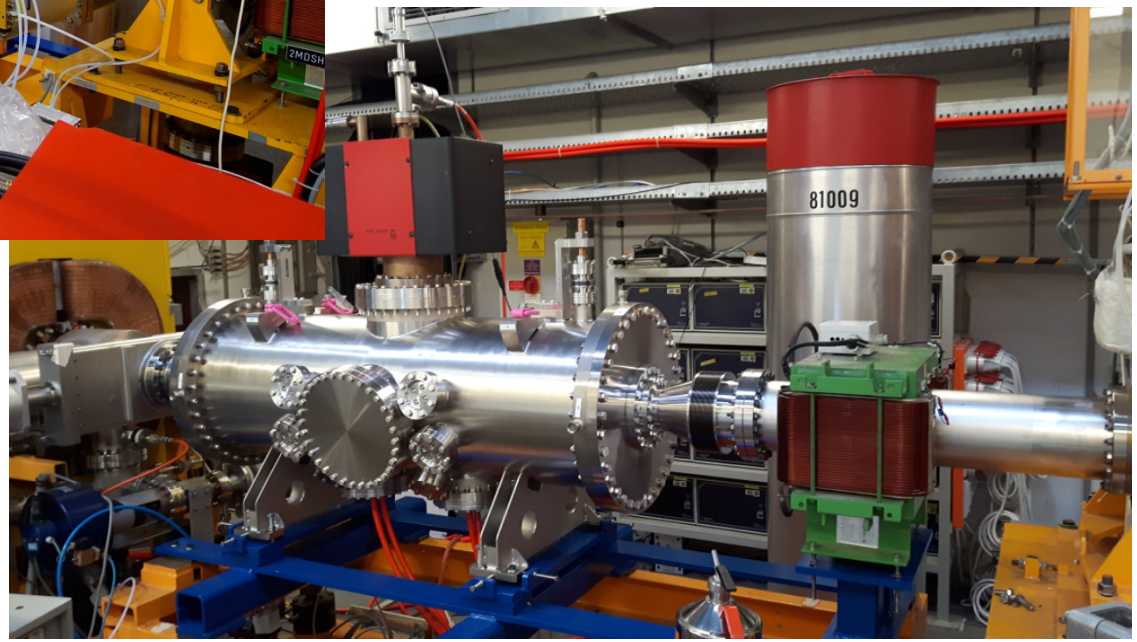
Structures for EDM (electric dipole moment) experiment based on slot-ring couplers

Bernd Breitkreutz developed slot-ring couplers for the EDM project (see Poster).

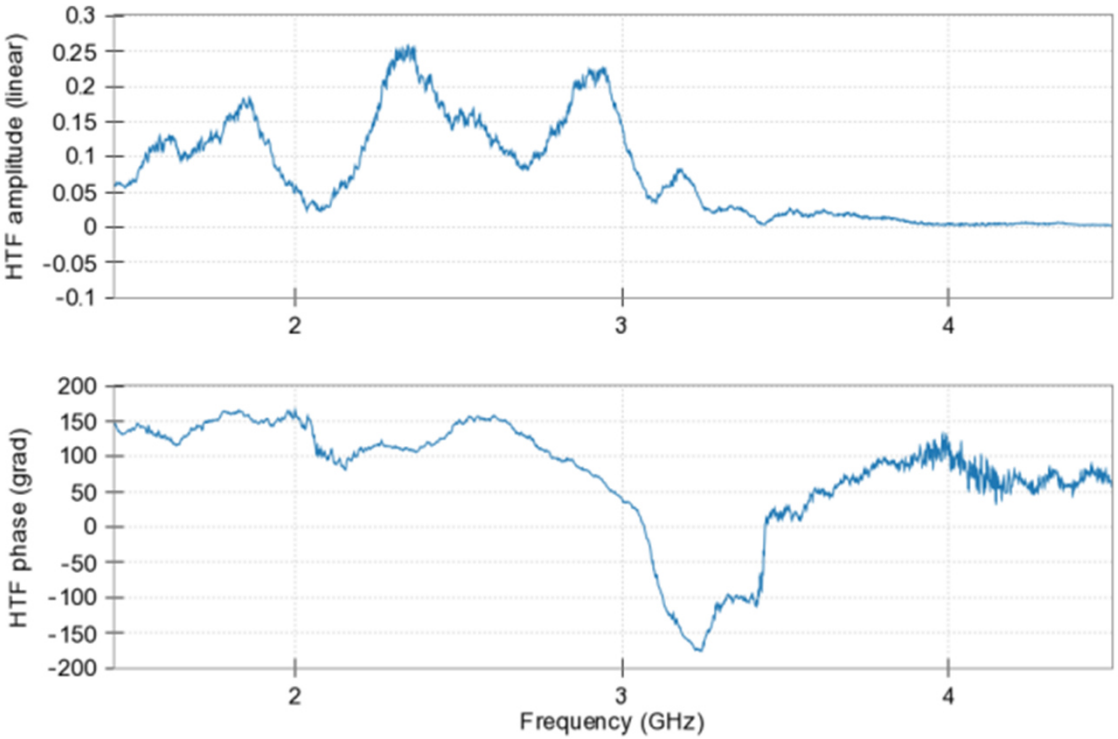


- β = 0.46
- Frequency range 350 – 700 MHz

Installation of one HESR PU and one HESR Kicker at COSY



BTF new system

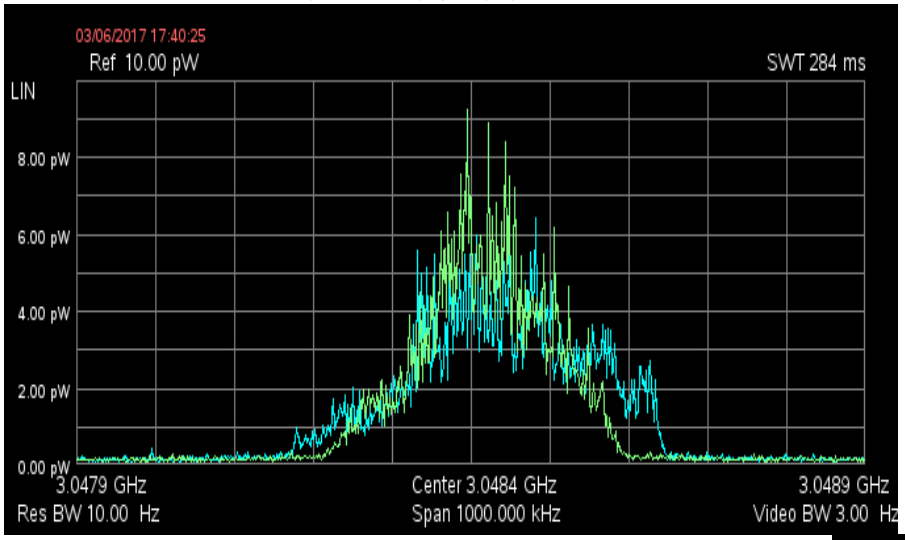


- Large amplitude change
- Amplitude more or less zero above 3 GHz
- Large phase change around 3 GHz

Each component of whole system was measured, but no reason for strange behavior found

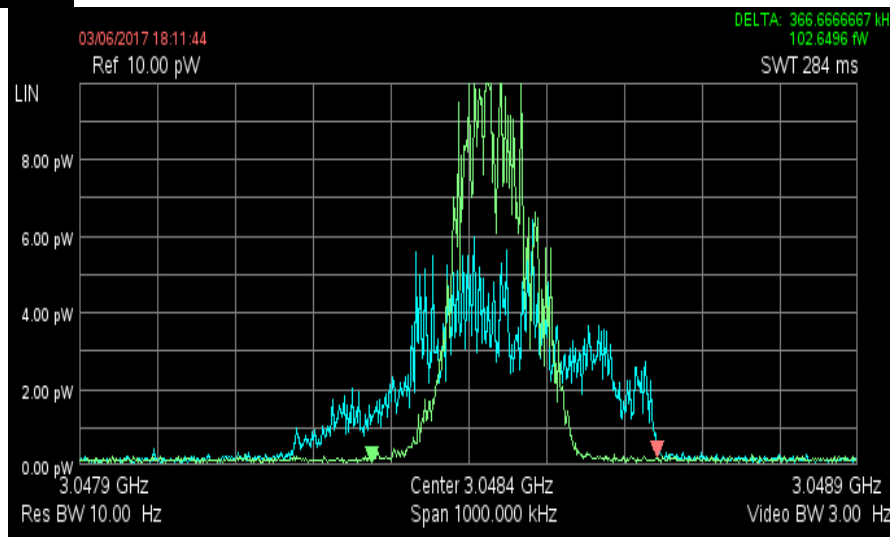
But small longitudinal cooling was visible

ToF method



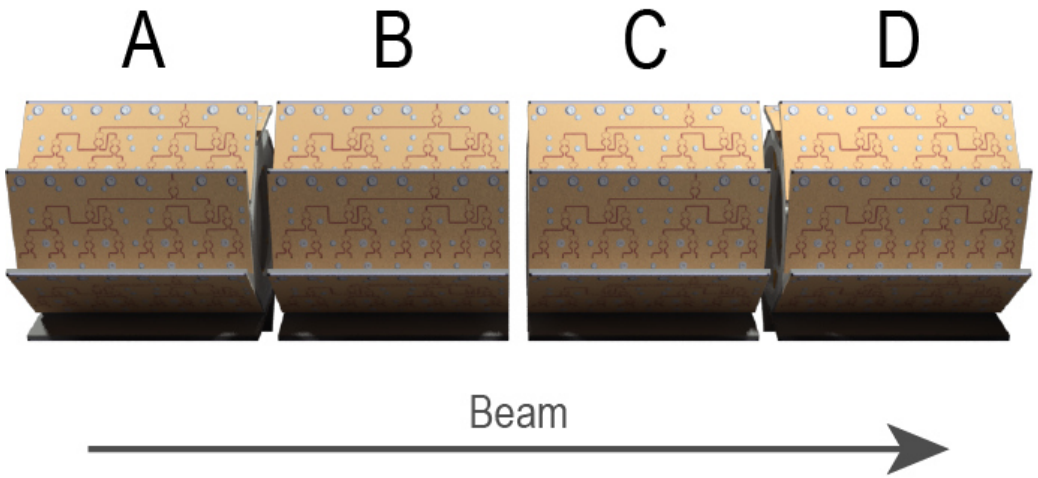
Beam was initial heated for a better visualization of cooling effect

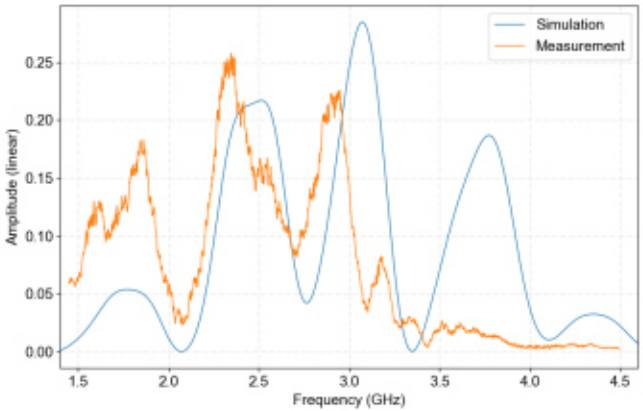
Notch-filter cooling



longitudinal cooling with both methods visible, but with long cooling times. The cooling works like a system with reduced bandwidth.

Reason found in wrong orientation of kicker

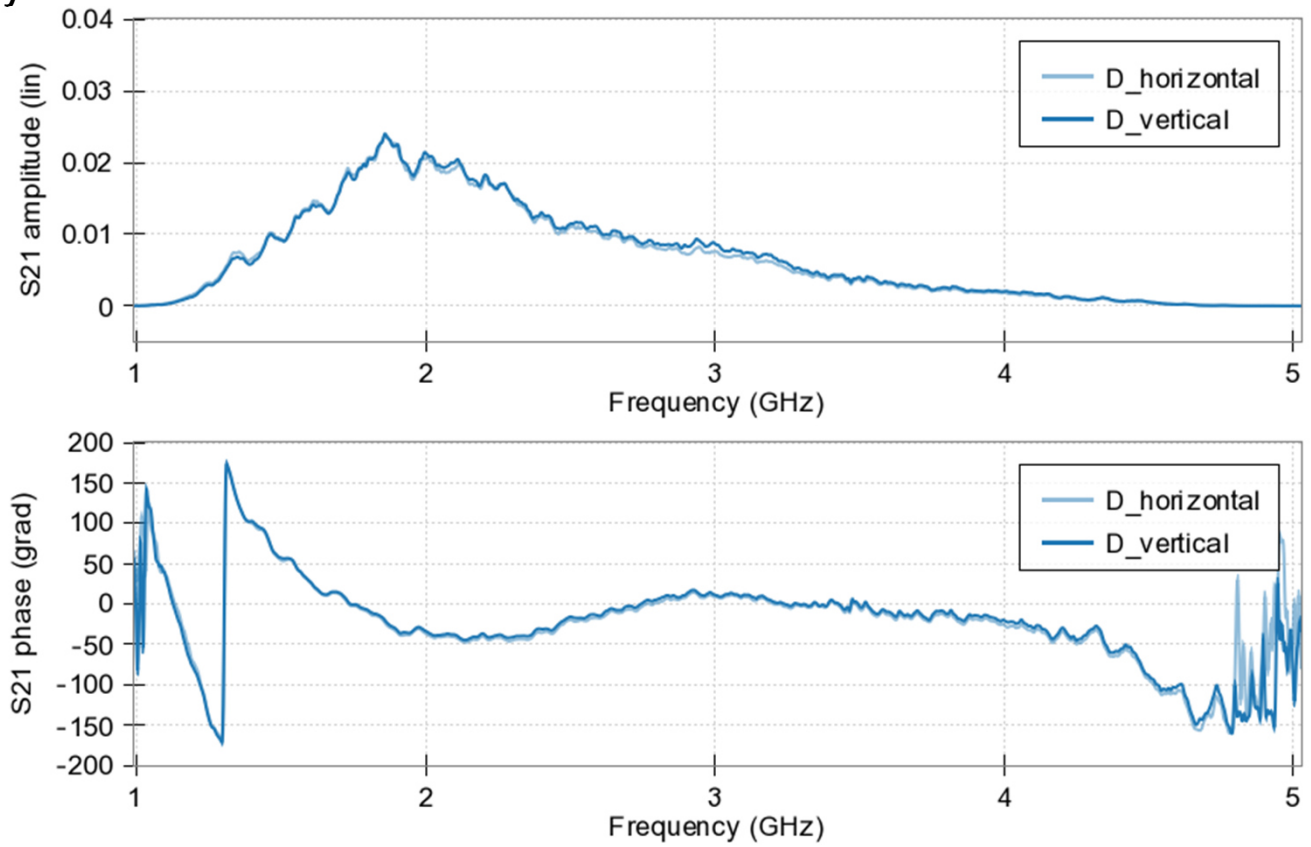




- Combiner-boards distribute the signals to each ring with optimized delay
- Distribution different for PU and Kicker
- Simulations of wrong orientated combiner-boards show similar behavior

Additional measurements

The kicker was successfully rotated in the April shutdown 2017 and additional open loop measurements were done within a few hours end of May

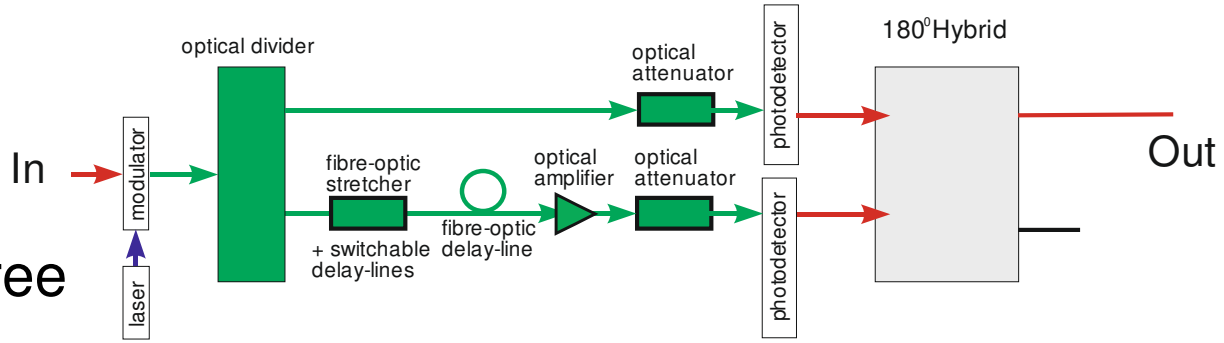


now the system acts as expected with very good phase response

Optical notch-filter

Advantage:

- compact design
- quasi dispersion-free
- Low rel. bandwidth



Disadvantage:

- high temperature dependence
- reduced dynamic range

Changes during last beam-time:

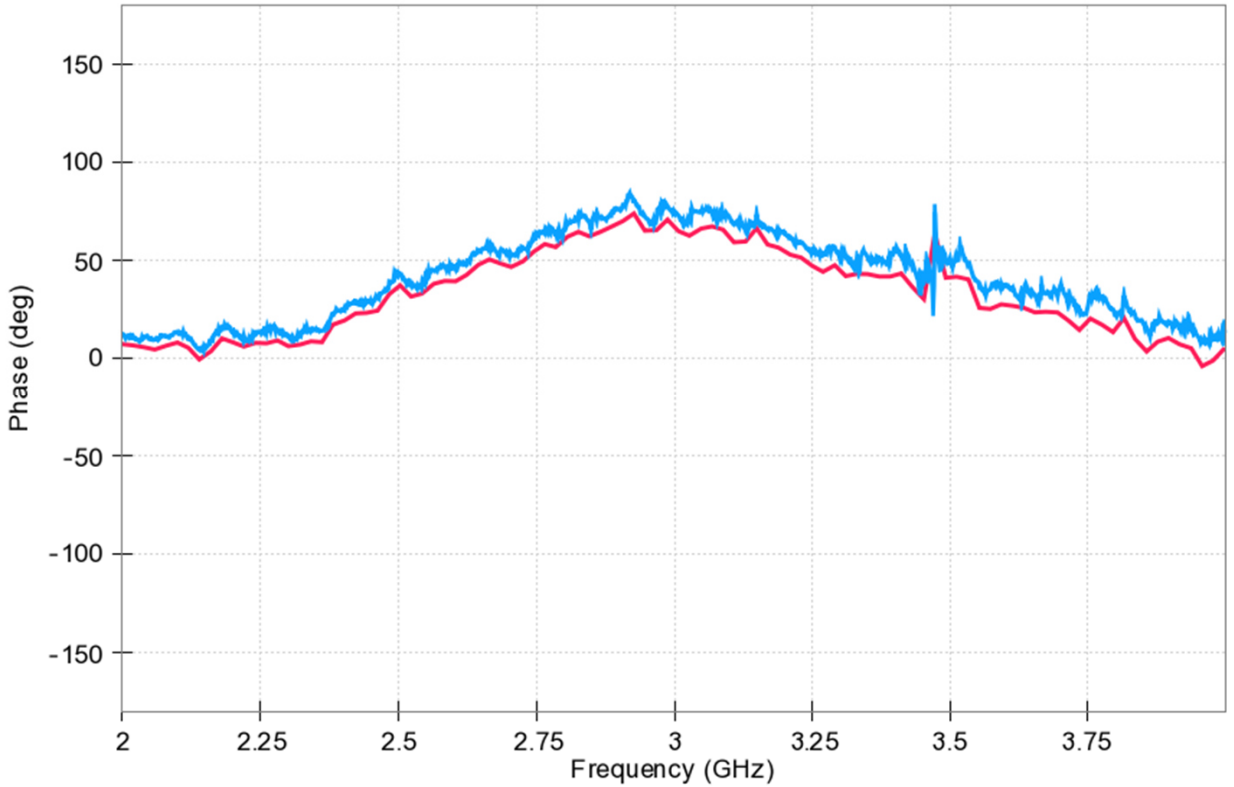
additional delay-lines in long path

optical amplifier in long path

- HESR:
  $\eta \sim 0.06$; $\Delta p/p \sim 2E\text{-}5$
  => $\Delta f/f \sim 1E\text{-}6$
  Higher slope of notches required
  Fibre: 30 ps/km/°C; $\Delta t < 2ps$
  => Temp-control < 0.16°C or
- => phase control circuit with pilot signal

Fast BTF measurement to adjust system delay

- Two methods were used to obtain the system delay within a short measurement time: single widespan sweep with point on each harmonic and multiple sweeps of harmonics (talk Nikolay Shurkhno)

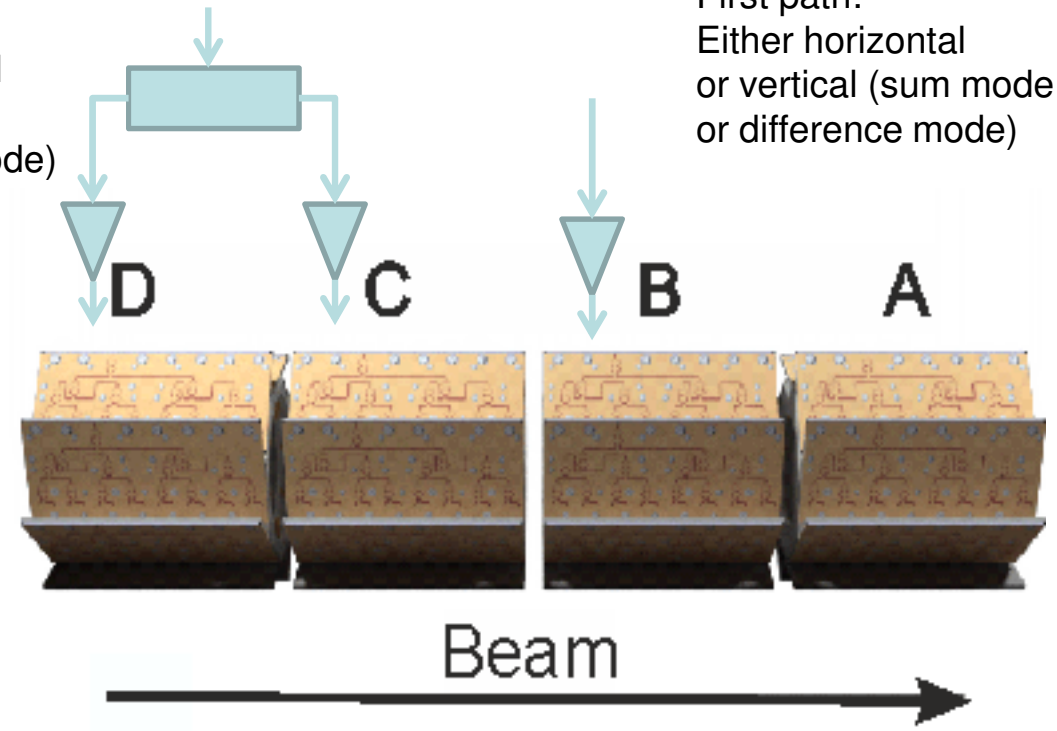


Cooling results

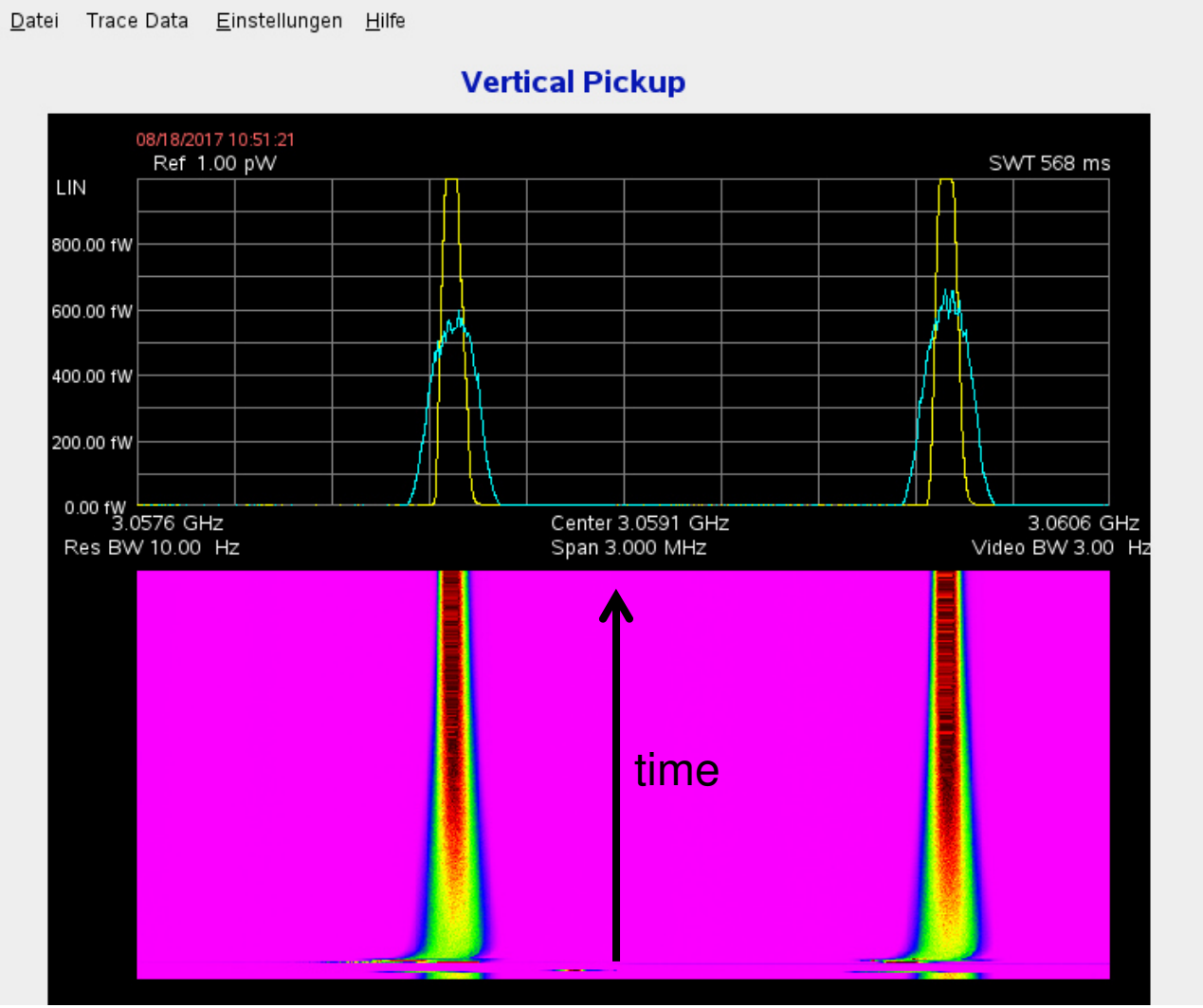
- Momentum: 2.425 GeV/c, η ≈ 0.07
- Protons, particle numbers varied: 2E8 – 7E9
- Cycle-length for all results: 5 min

Second path:
Using two groups combined with special switchable delay lines (vertical difference mode)

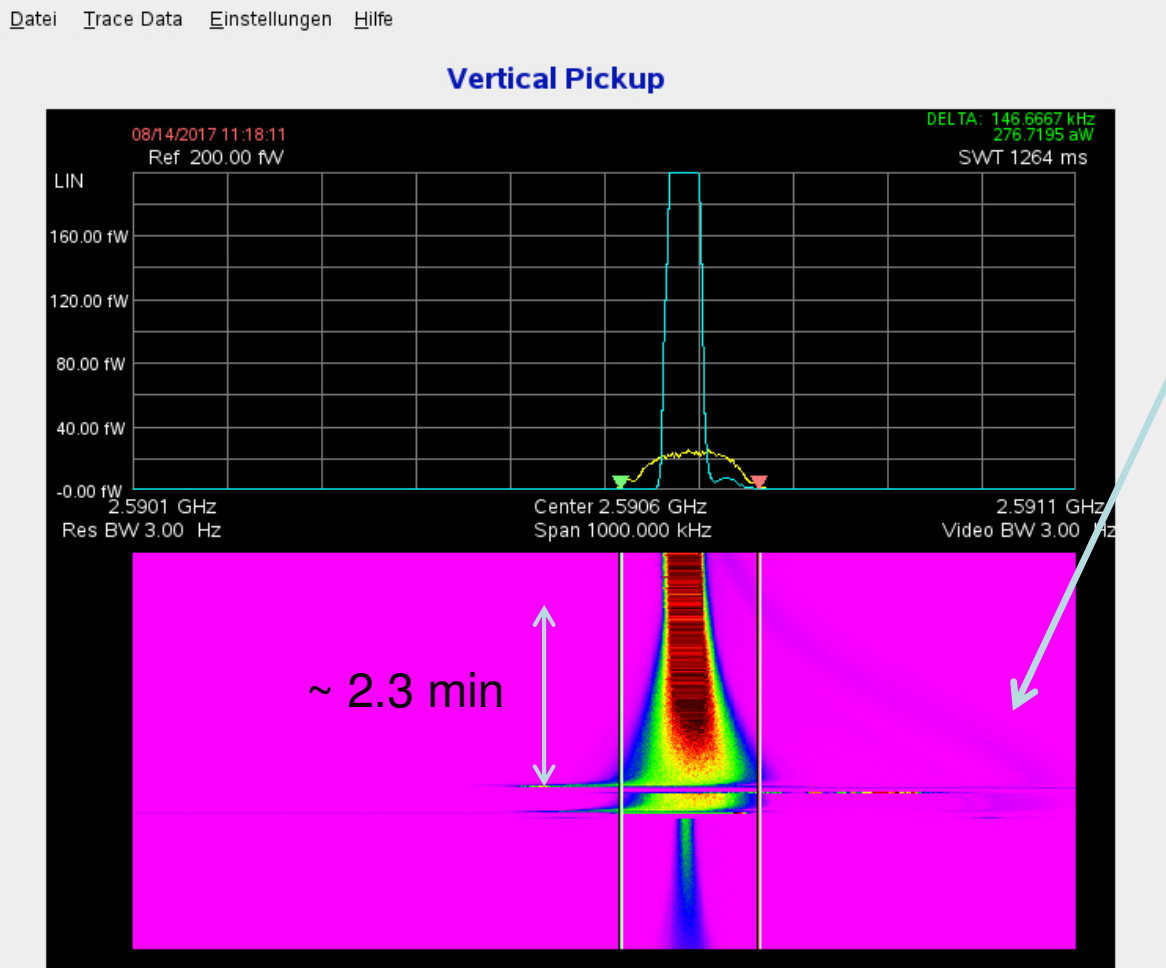
First path:
Either horizontal or vertical (sum mode or difference mode)



Longitudinal cooling 7E9 particles

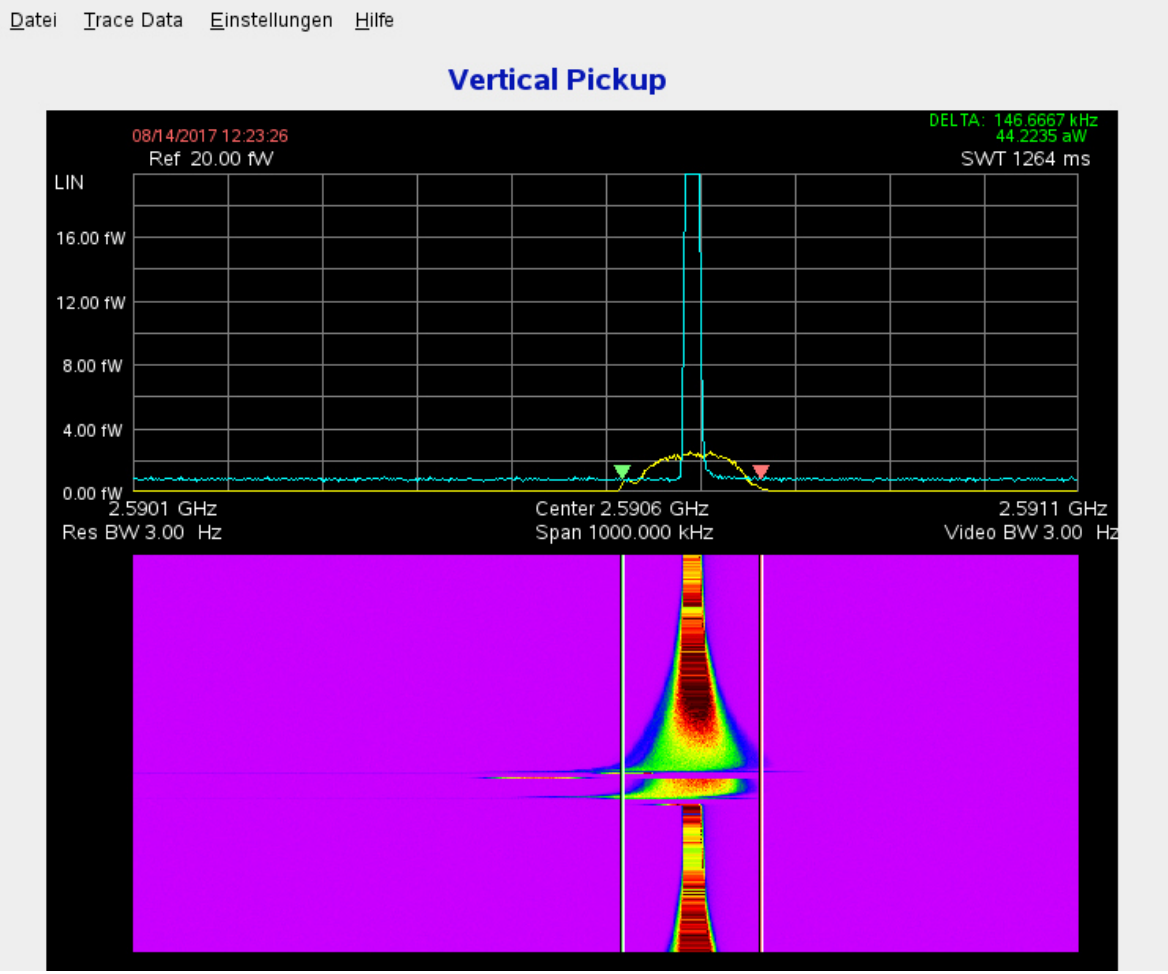


Longitudinal cooling 7E9 particles



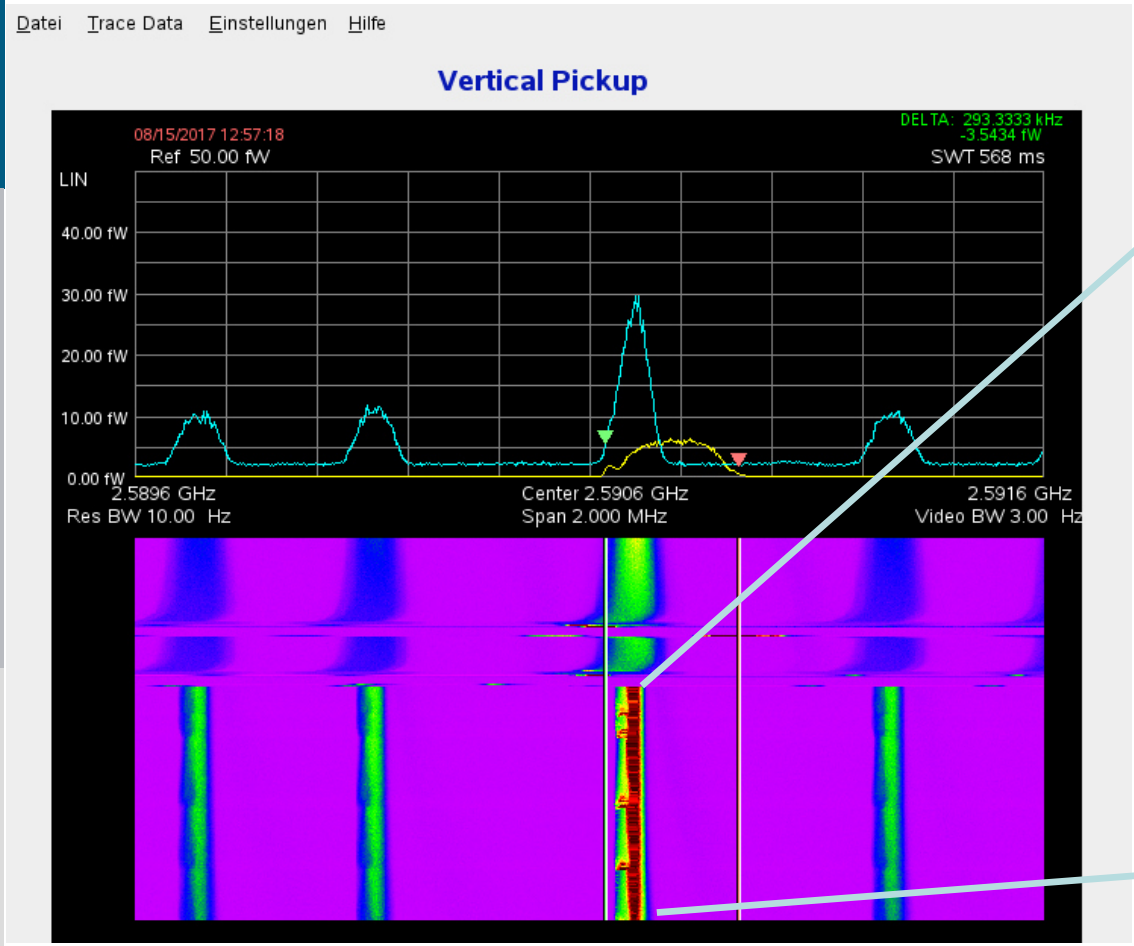
Even particles shifted to lower energies during re-bunching were captured by the filter cooling

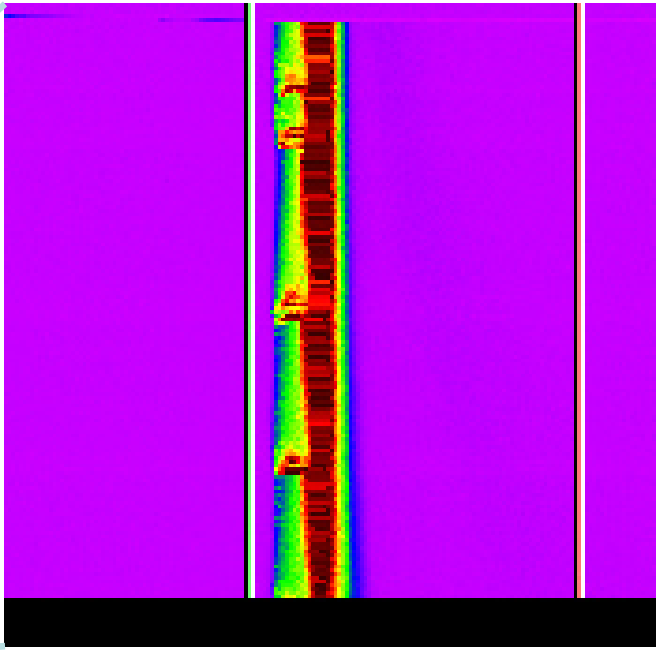
Longitudinal cooling 2E8 particles



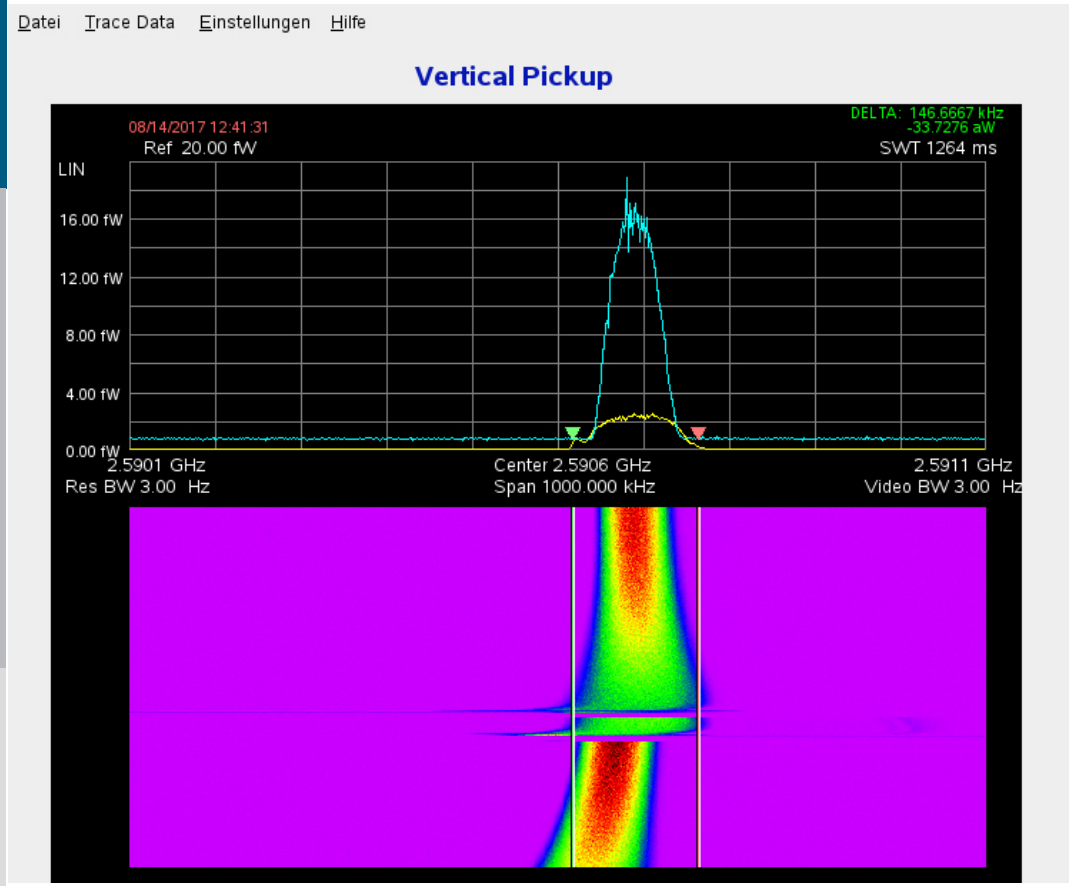
Slightly faster cooling and smaller equilibrium
Constant gain!

Instabilities visible, but no beam loss



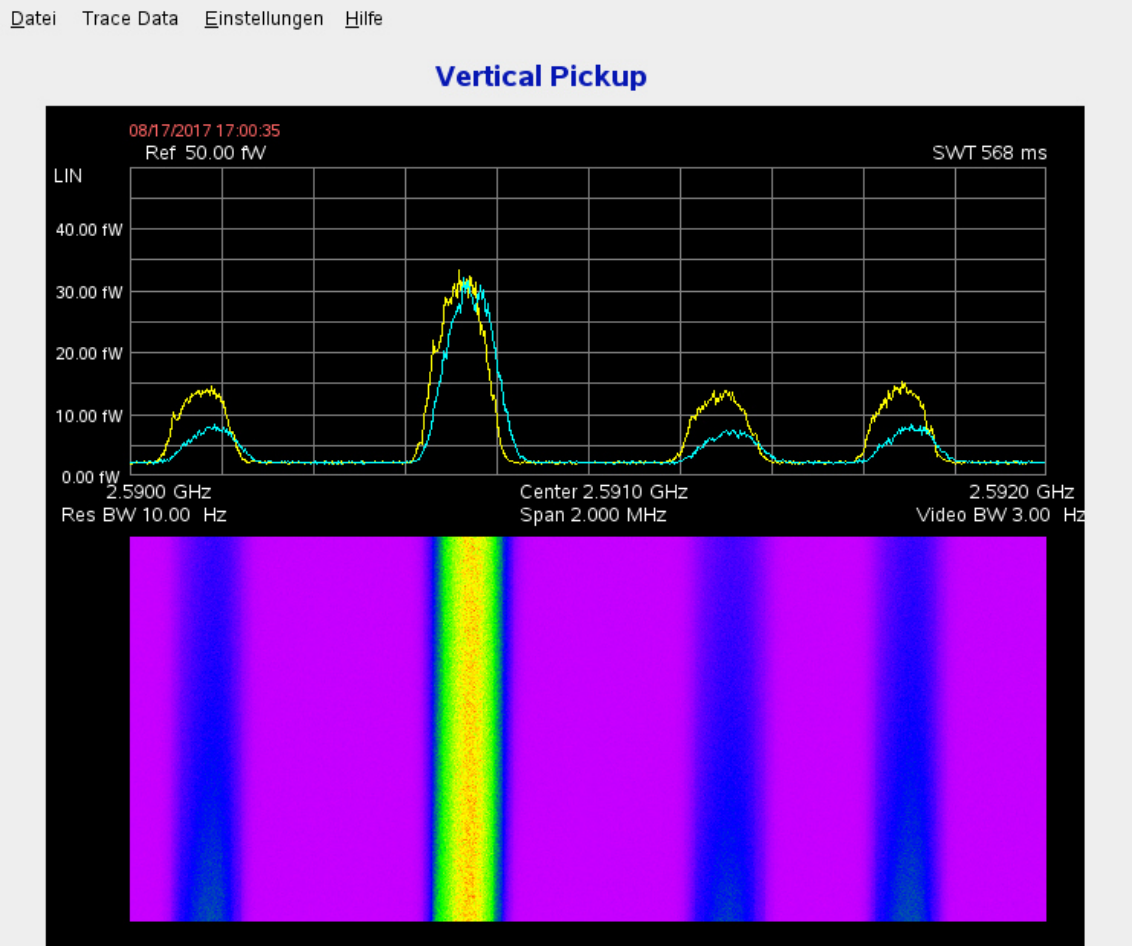


ToF cooling (2E8 particles)



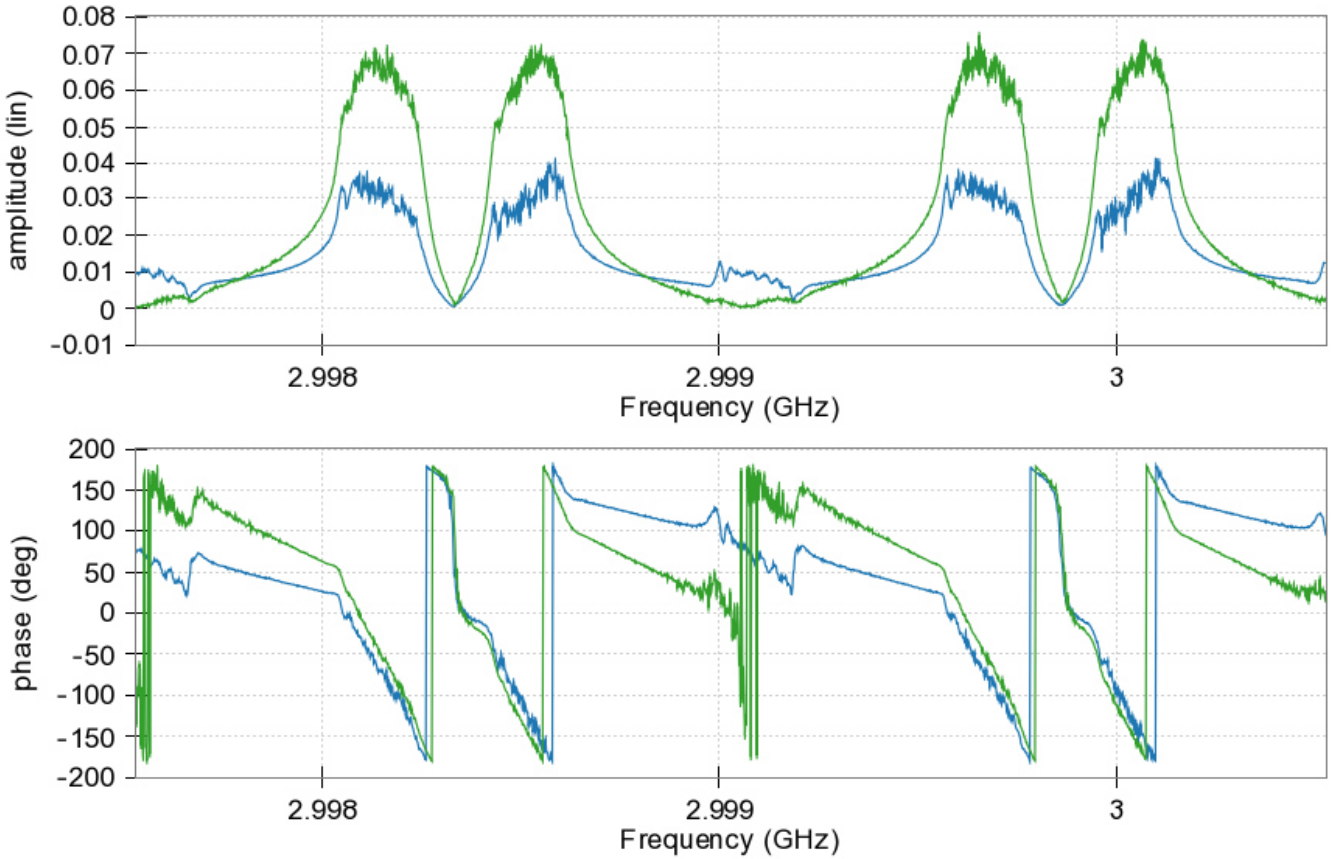
The 180° phase shift between ToF and filter cooling was realized by removing a delay of 150 ps instead of an additional 180° phase shifter

First vertical cooling using the same transmission line as for longitudinal cooling

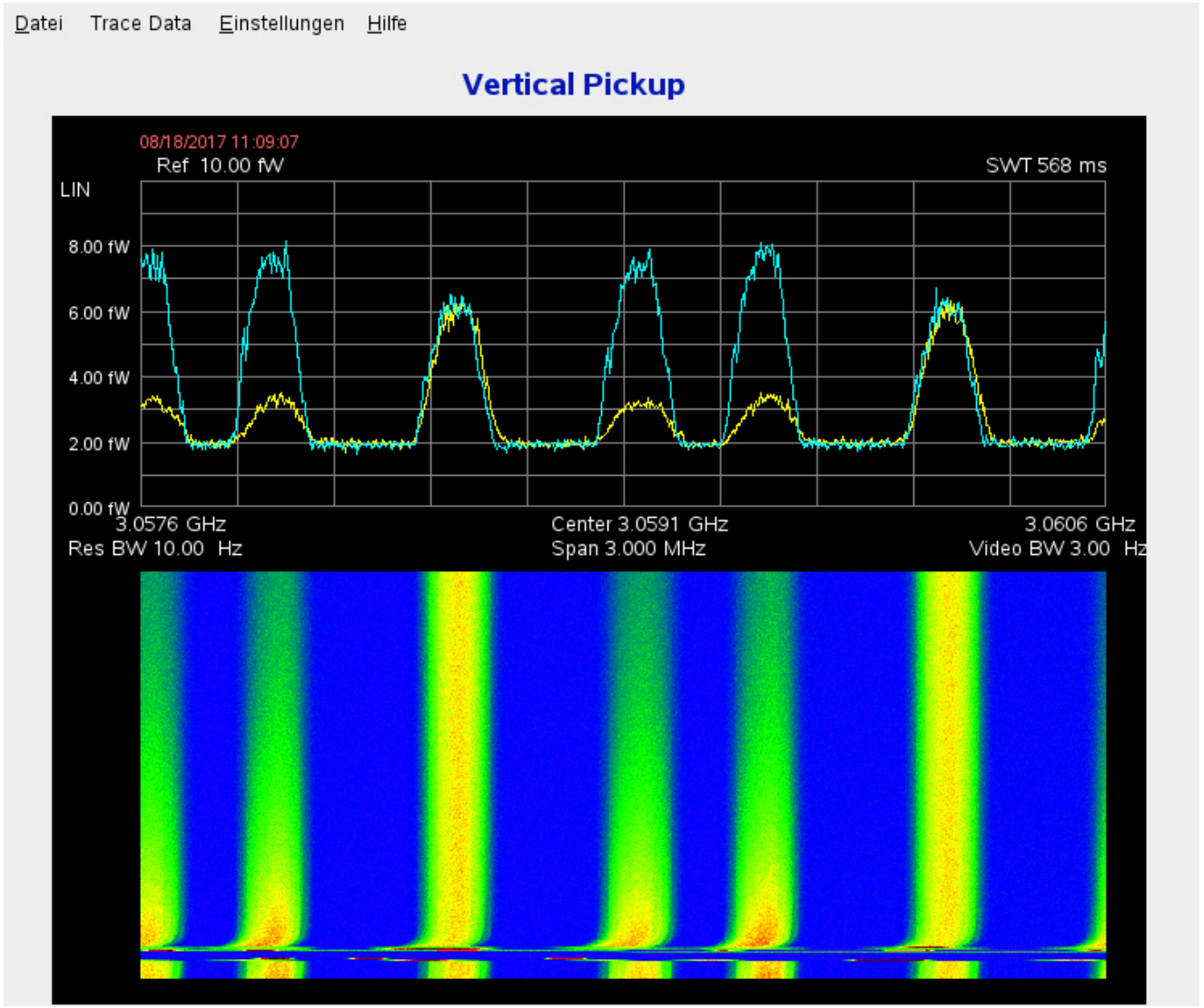


7E9 particles, system-delay and beam-position not yet optimized resulting in a small momentum shift

Vertical BTF with and without notch-filter



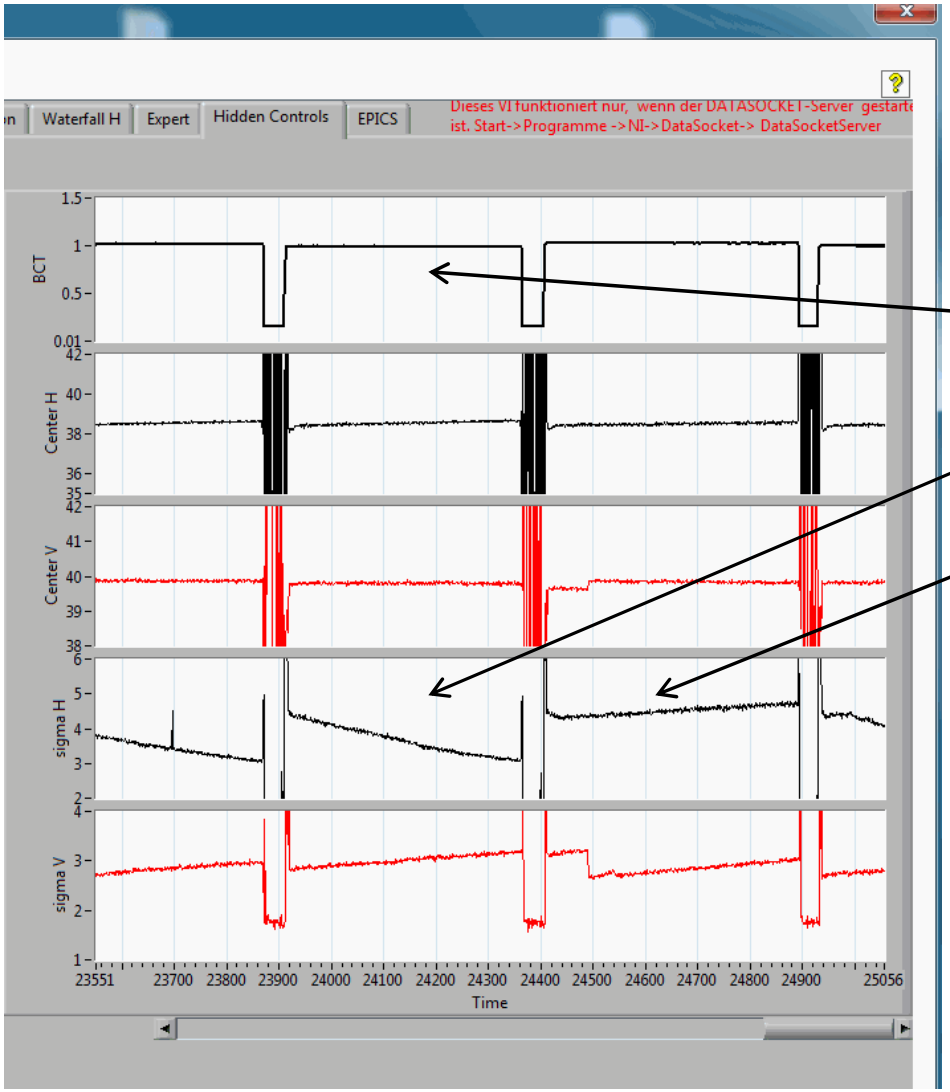
Transverse (vertical) cooling 7E9 particles



Cooling after optimization of system delay

Even after beam centering, longitudinal part visible (limited isolation in hybrid), but does not influence transvers cooling

Beam profile measurements with IPM



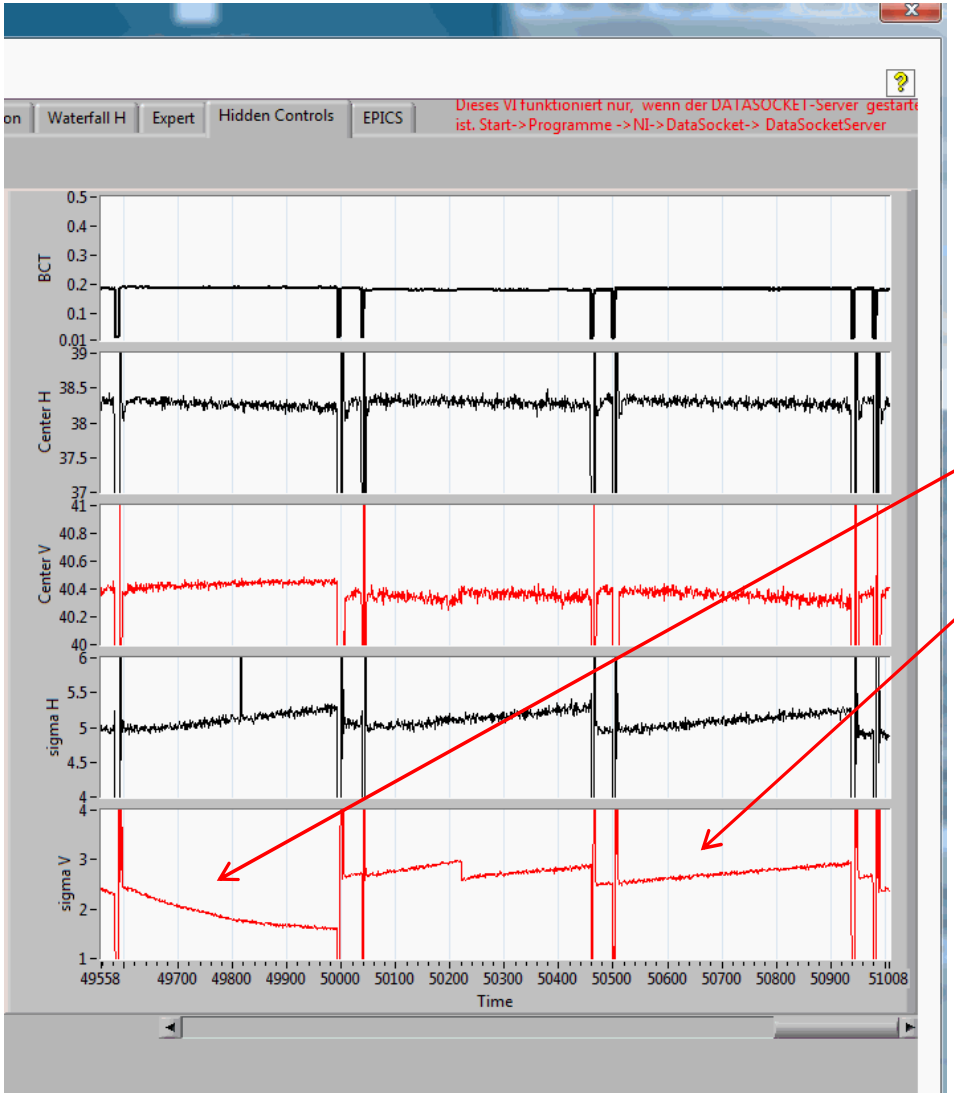
Cycle length: 5min

BCT: no particle loss

Horizontal cooling on

Horizontal cooling off

Beam profile measurements with IPM



Cycle length: 5min
Switched to vertical plane,
No other changes

BCT: no particle loss

vertical cooling on

vertical cooling off

Second path with hollow fiber line

After successful demonstration of vertical cooling, we installed a new transmission line using a hollow fiber line (very attractive for HESR).

NKT Photonics
the power of light

Crystal Fibre • *aero*LASE • Koheras • SuperK

HC-1550-02

Hollow Core Photonic Bandgap Fiber

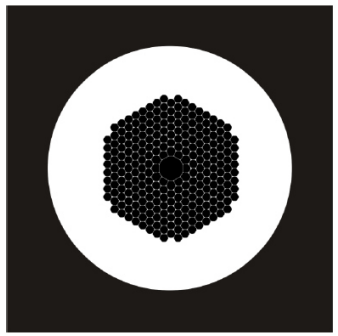
Hollow Core · Spectral Filtering

- < 5% of optical power located in silica
- Gaussian-like fundamental mode
- Can be filled with gas
- Negligible bend loss
- Fresnel reflection of core mode to air $<10^{-4}$
- Mode effective index close to unity
- Numerical Aperture ~ 0.2
- Pure silica for good temperature stability

Hollow core Photonic Bandgap Fibers guide light in a hollow core, surrounded by a microstructured cladding of air holes and silica.

Since only a small fraction of the light propagates in silica, the

Schematic fiber cross section

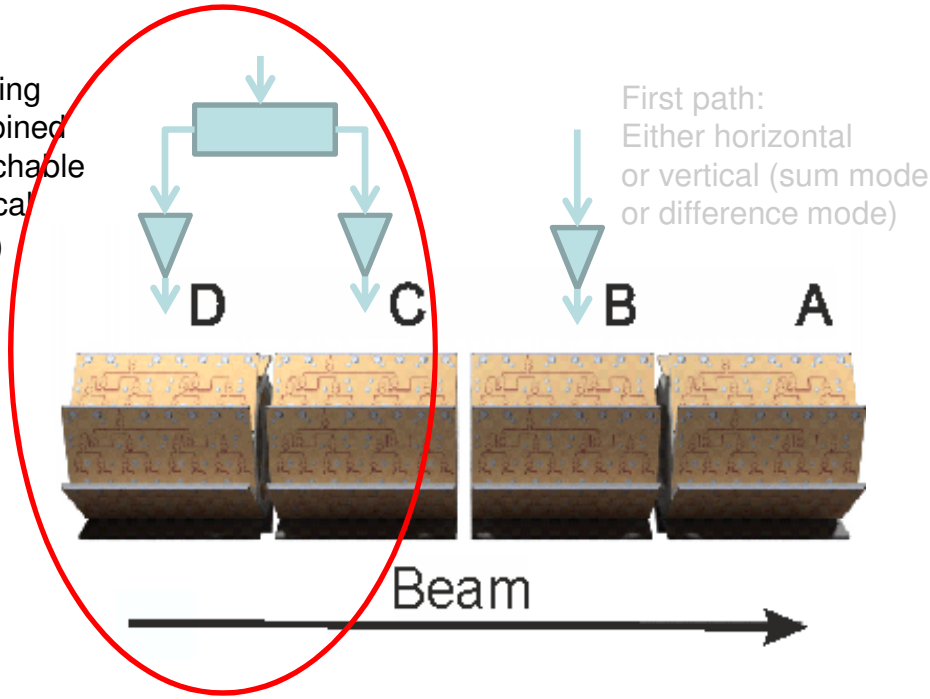


High speed: ~99%c
Attenuation: 10dB with FC/APC connectors and 50m length (fiber itself: <0.03 dB/m)
Sensitive against movements

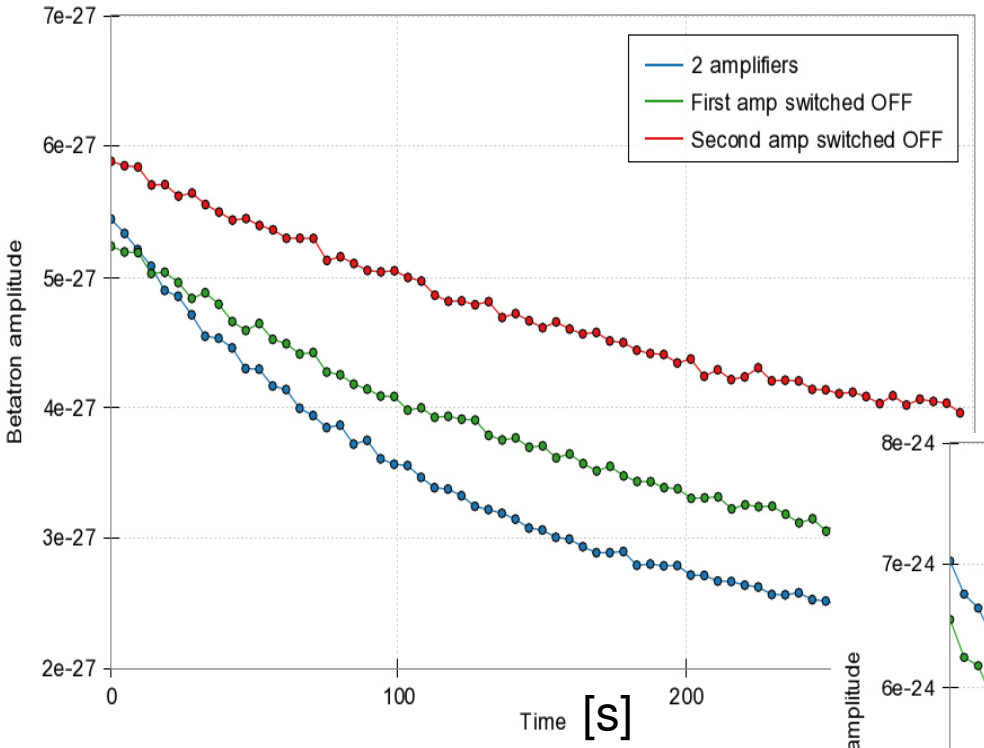
temperature gradient?

Second path for vertical cooling

Second path: Using two groups combined with special switchable delay lines (vertical difference mode)

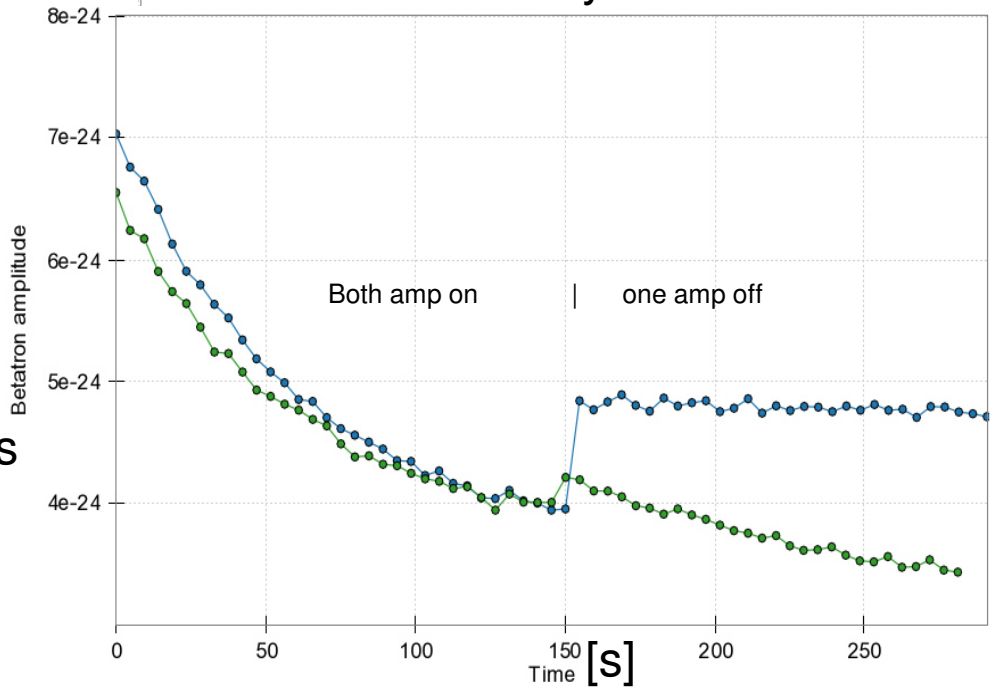


Cooling with different groups

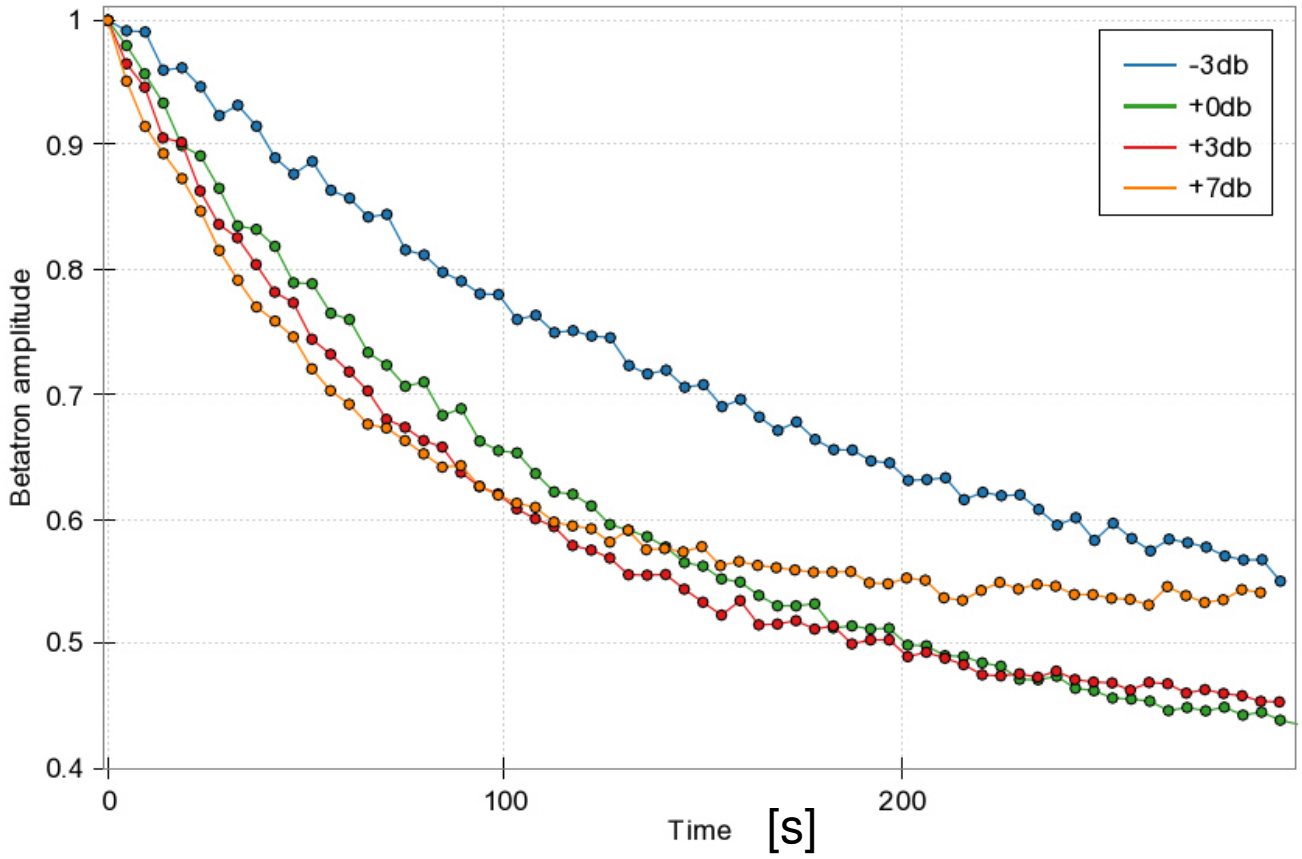


Spectra were measured at 3 GHz within the loop, each point represents the maximum of upper sideband!

Signal-suppressions are different not only due to gain but also due to different delay

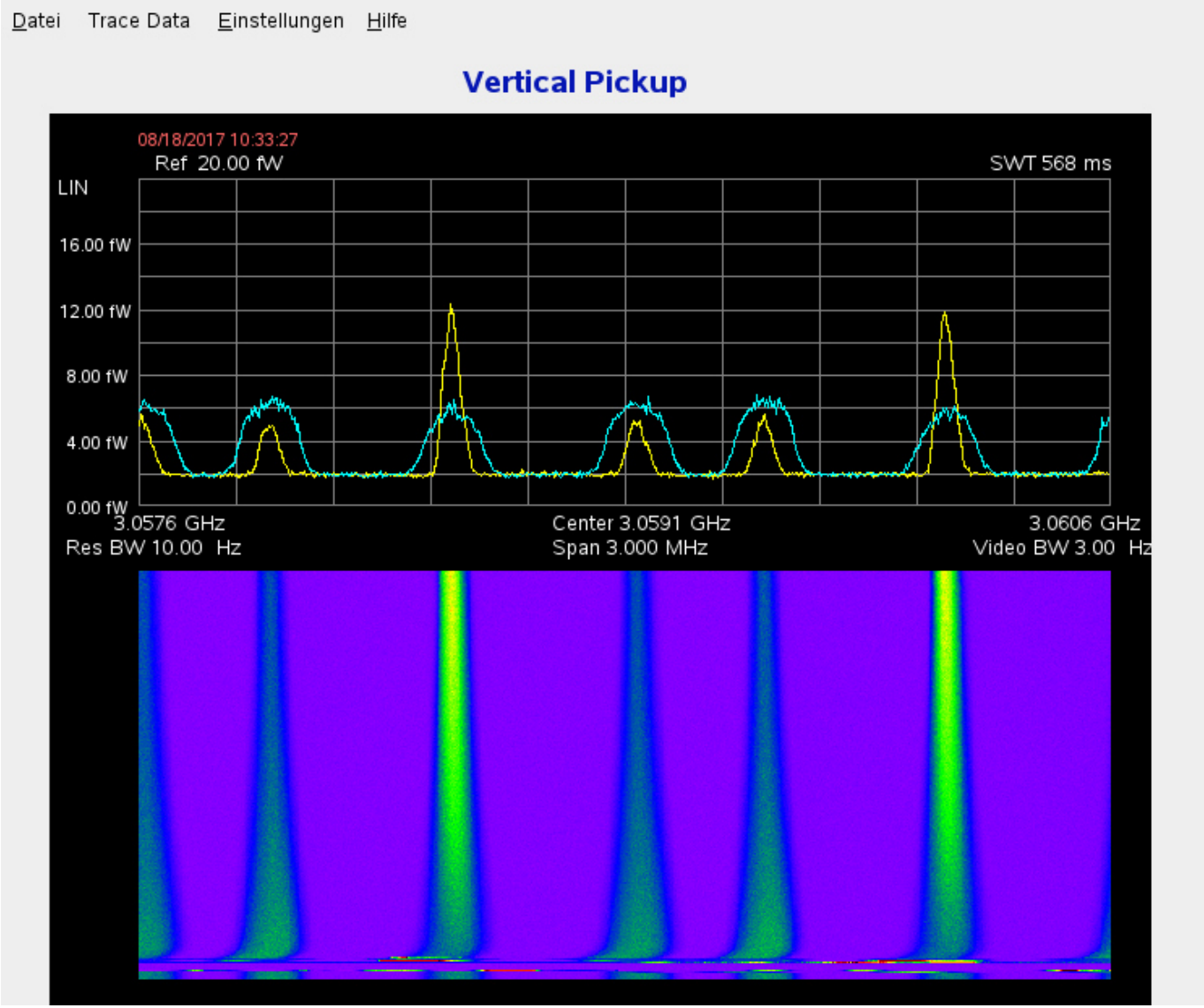


Vertical cooling with different gains

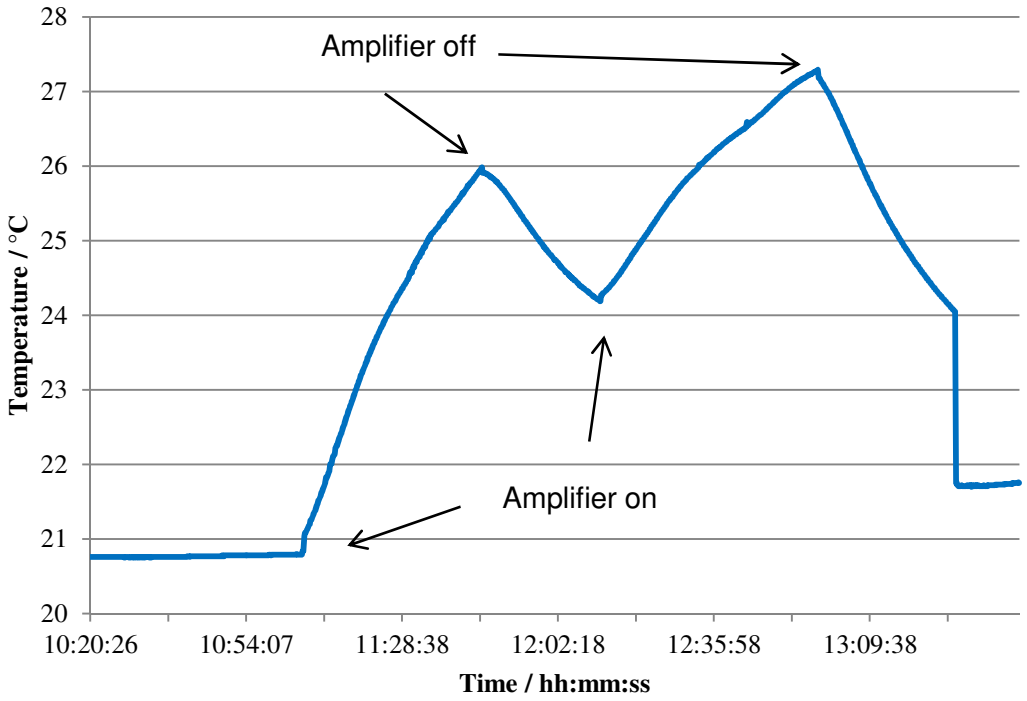


Higher gain increase initial cooling speed but equilibrium will be higher
-> gain control during cooling

2d cooling (long. + vertical) of 5E9 particles



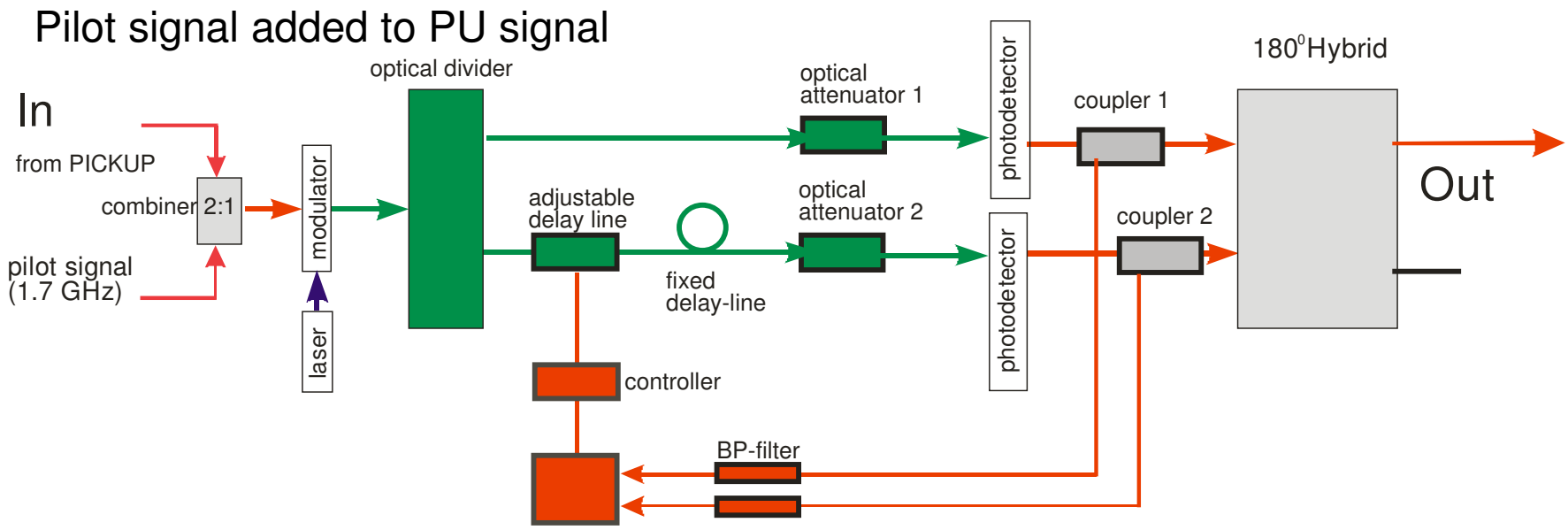
Temperature at combiner-boards

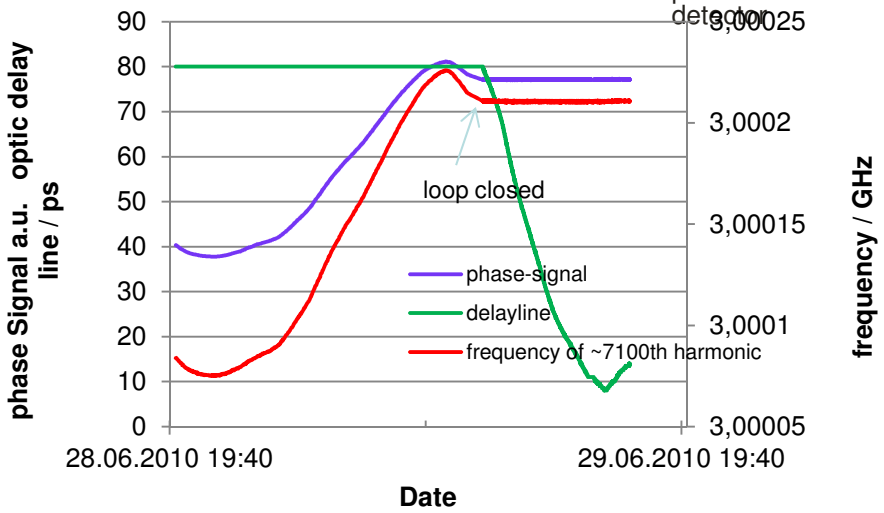


Max. noise power (GaN amplifier in saturation): increase of temperature only 7.5°C within 40 min, but without reaching equilibrium

No significant temperature increase found during cooling experiments (three amplifier during longit. + vertical cooling temperature increase: 1-2°C)

Next steps: Notch-filter frequency control and system delay control (1)

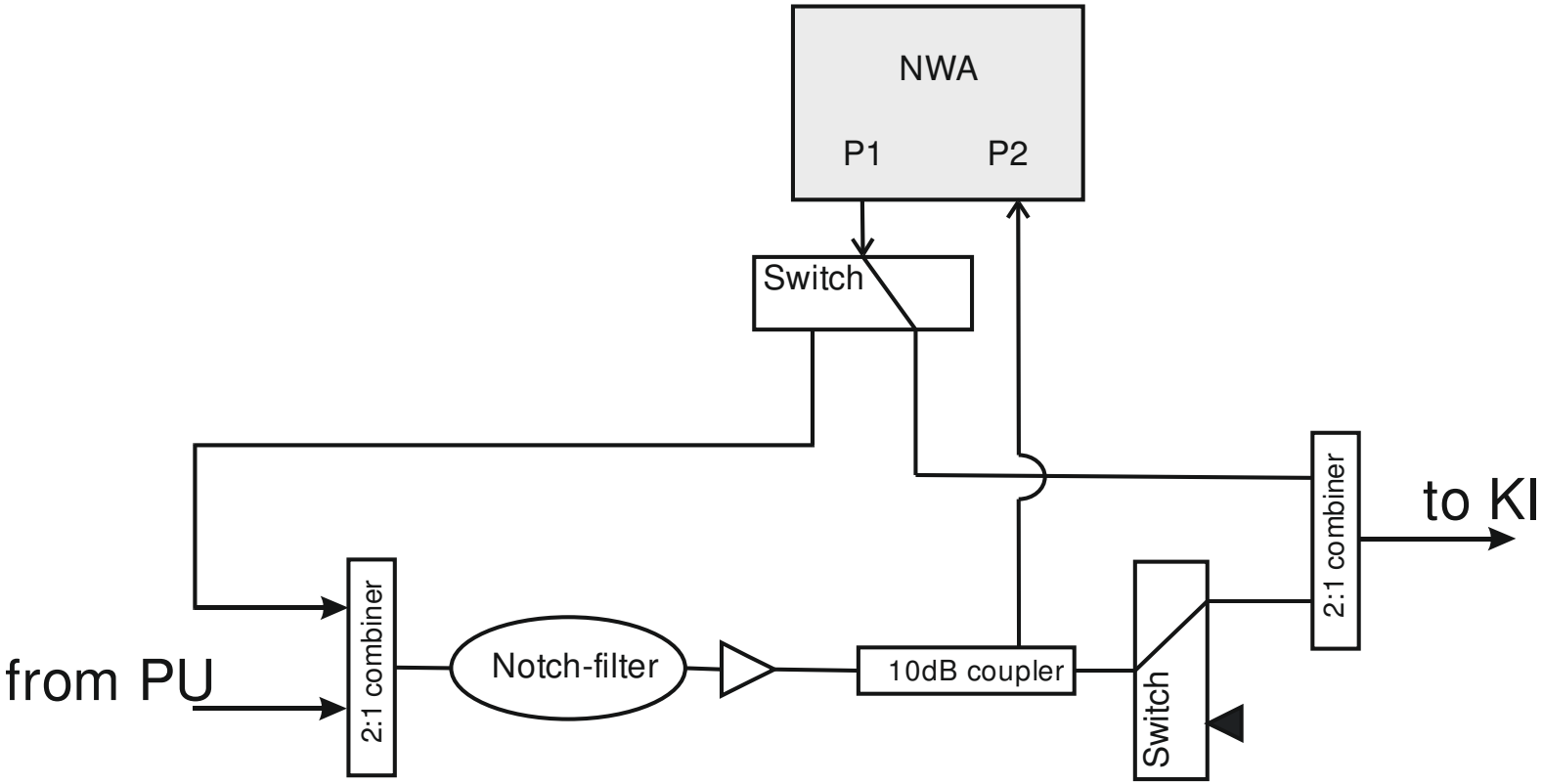




Good results during tests in the lab, but still not tested with beam

Next steps (2): Nikolay's new measurement setup (talk by Nikolay)

BTF during cooling: first quick measurement done already during last beam time



summary

- Very fast setup of notch frequency and system delay with new programs
- Longitudinal filter and ToF cooling demonstrated
- First transverse cooling with slot-ring couplers in both planes
- GaN amplifiers work without problems (not switched off during acceleration)
- Cooling of combiner-boards at kicker sufficient
- First use of hollow fiber transmission line (50m)

Thank you for your attention