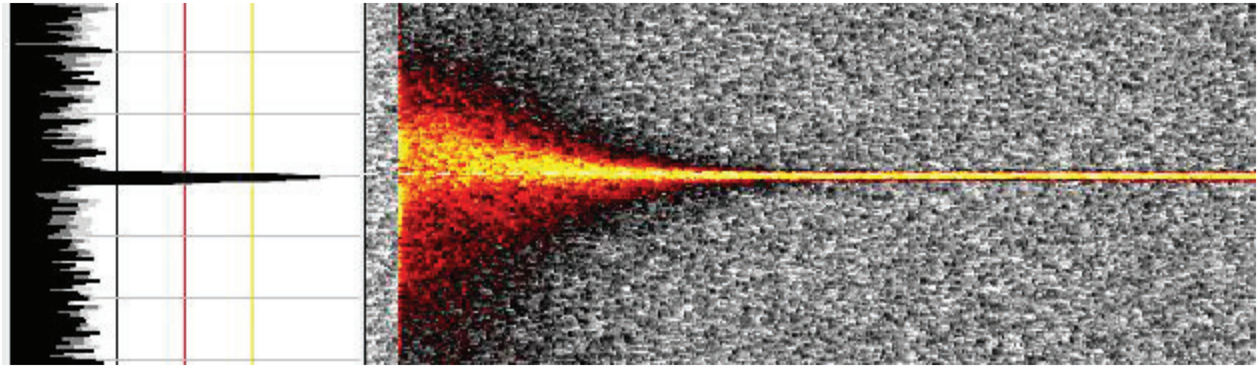
Recommissioning of the CERN AD Stochastic Cooling System in 2021 after Long Shutdown 2



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Acknowledgements: GSI, CERN BE-OP, SY-RF, TE-VSC, TE-MSC, EN-MME, EN-CV

Long shutdown 2 (LS2): 2019-mid 2021

- LHC and all injectors were stopped in December 2018 to permit implementation of the hardware modifications of the LHC Injector Upgrade Project (LIU)
  - start-up of AD with beam re-scheduled due to COVID-19 sanitary crisis to mid 2021 → AD without beam for more than two years, 2020 shutdown work impacted due to COVID-19
- Considerable modifications in the AD complex of accelerators
  - New antiproton target, new RF system in AD (power system and LLRF), new PLC controls, new software for all RF
  - Migration of all users from AD to ELENA in LS2
  - AD magnet consolidation and new LNE00 extraction from ELENA → partial dismantling of stochastic cooling system

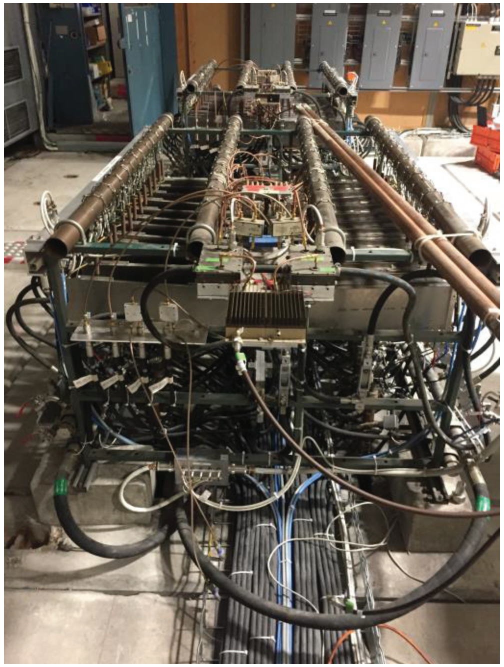
AD Basic Parameters

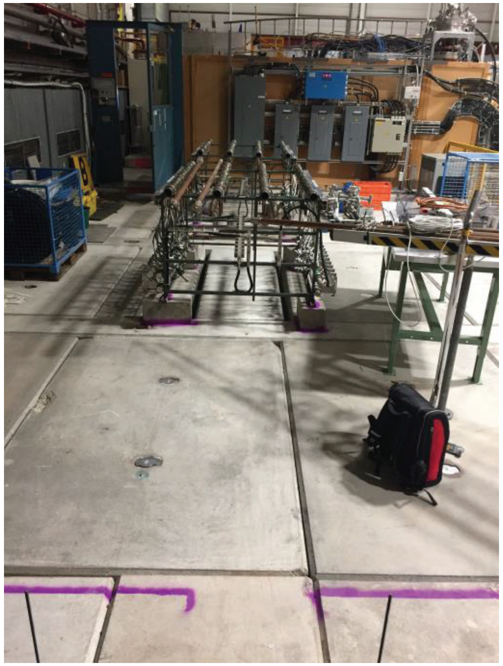
Circumference	182	m
Production beam	$1.5x10^{13}$	protons/cycle
Injected beam (~record)	$5x10^{7}$	pbars/cycle
Beam momenta (max-min)	3.57 – 0.1	GeV/c
Plateaus for stochastic cooling	3.57 and 2	GeV/c
Transverse emittances	200 - 1	π mmm rad
Momentum spread	$6x10^{-2}$ – $1x10^{-4}$	δp/p
Vacuum pressure	< $4x10^{-10}$	Torr
Cycle length	~100	s
Deceleration Efficiency	~85	%

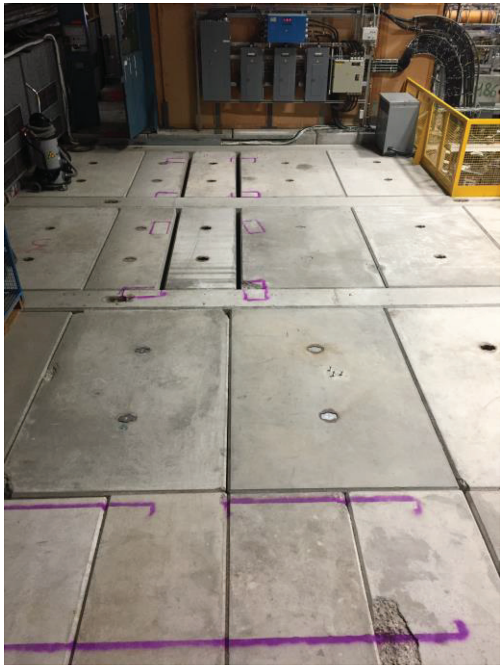
Production Beam very challenging for PS (26 GeV/c p^{+}) → batch compression
Bunch rotation with 10 MHz pulsed cavity system in AD after injection

Dismantling of Power System

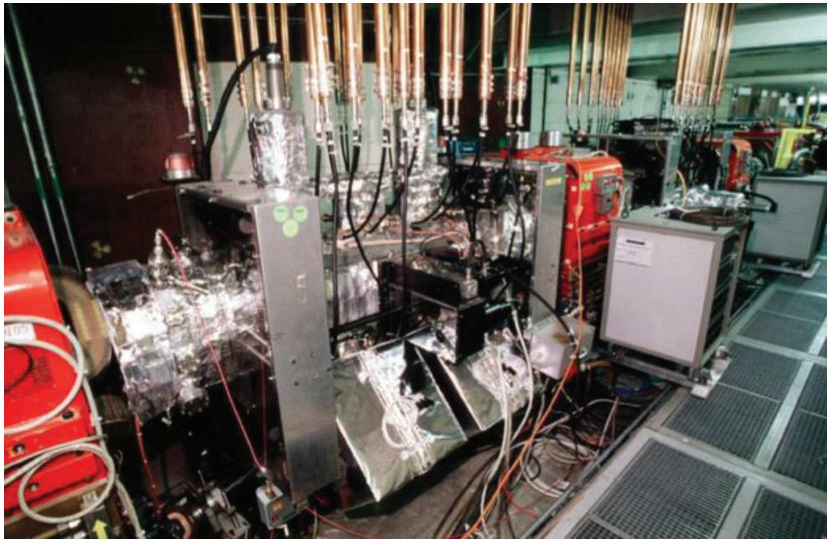
- All 48 power amplifiers removed including all associated RF cabling and fan-out, DC powering and water cooling

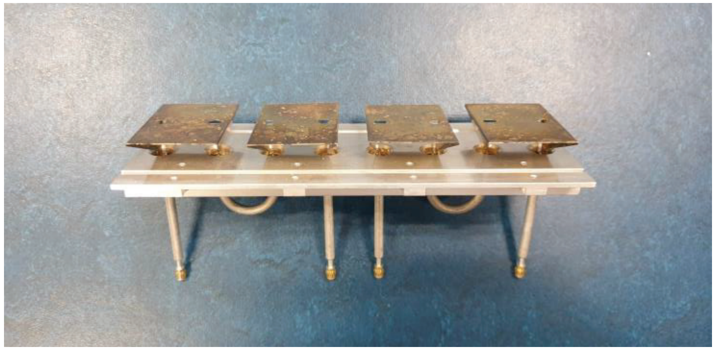






Removal RF lines to kickers



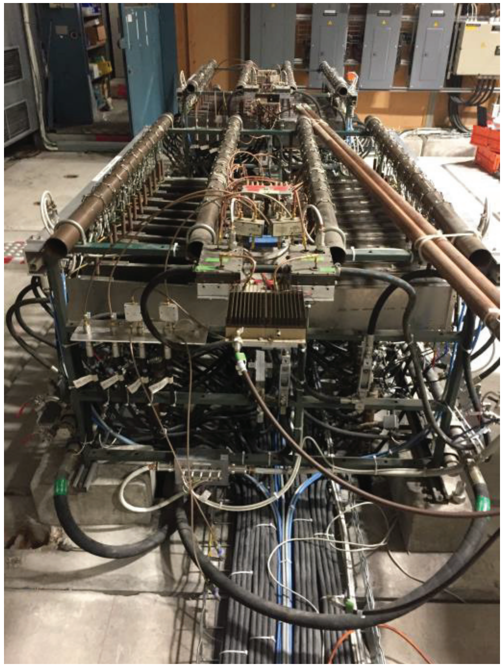


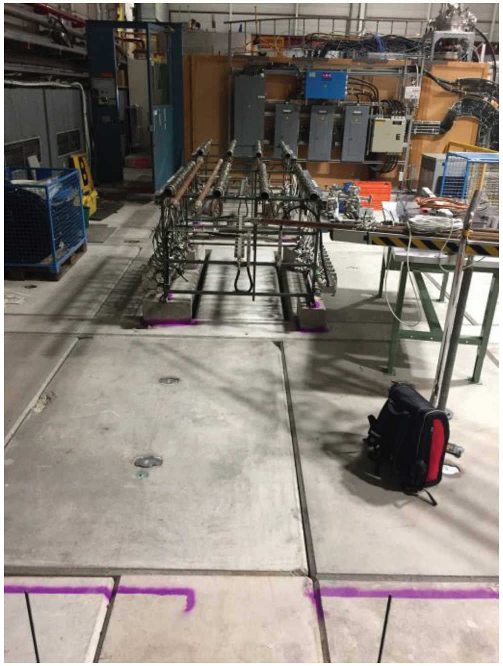
λ/4 “super-electrodes” as used in pick-up and kicker loads inside vacuum tank

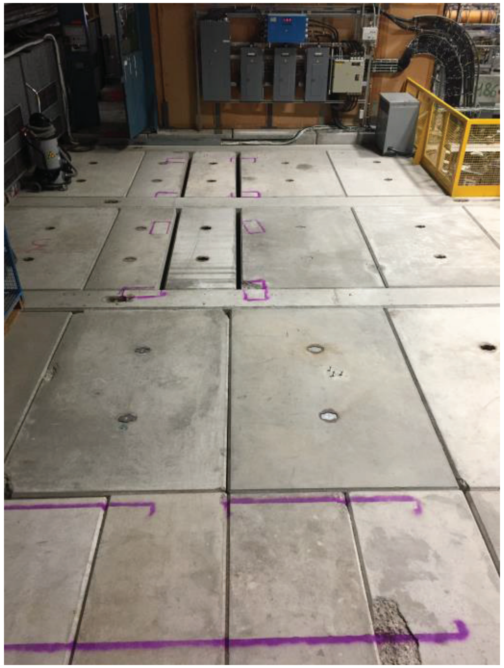
- Two kicker tanks (H, V)
- Longitudinal signal split equally to drive common mode on the transverse kickers

Dismantling of Power System

- All 48 power amplifiers removed including all associated RF cabling and fan-out, DC powering and water cooling







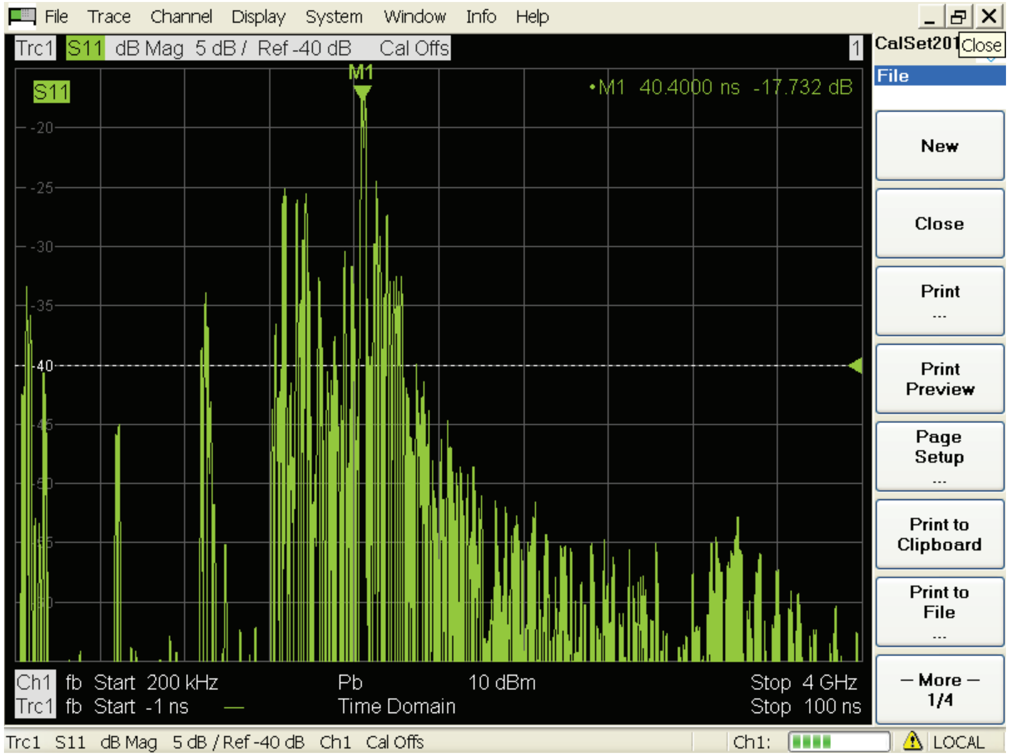
Reflectometry before dismantling

- Reflectometry was used to have reference measurements for the length of the lines and to check for bad contacts before dismantling

example of time domain reflectometry (with NWA, “synthetic pulse”) on line connecting amplifiers to kickers

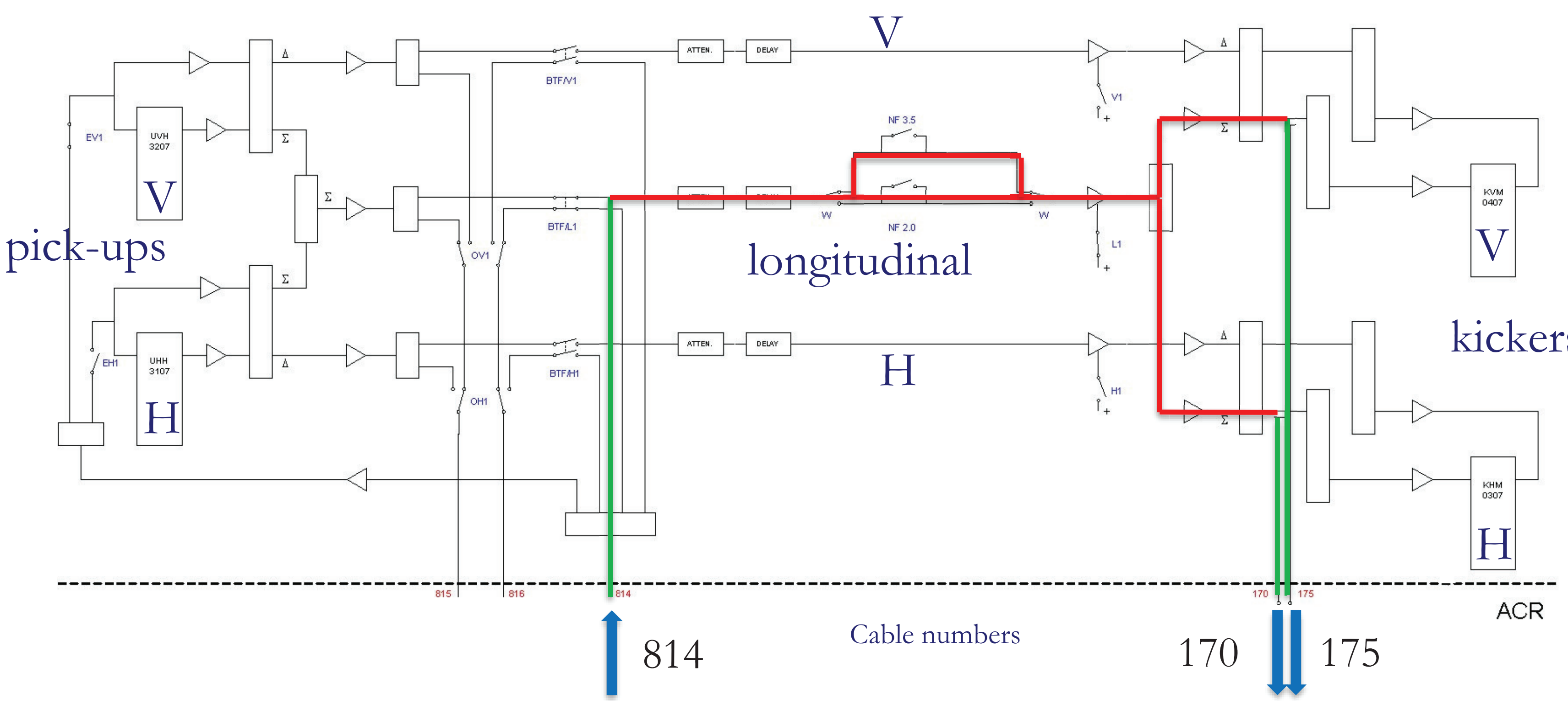
matching inside the tank can also be checked (-17.7 dB)

small reflections at visible



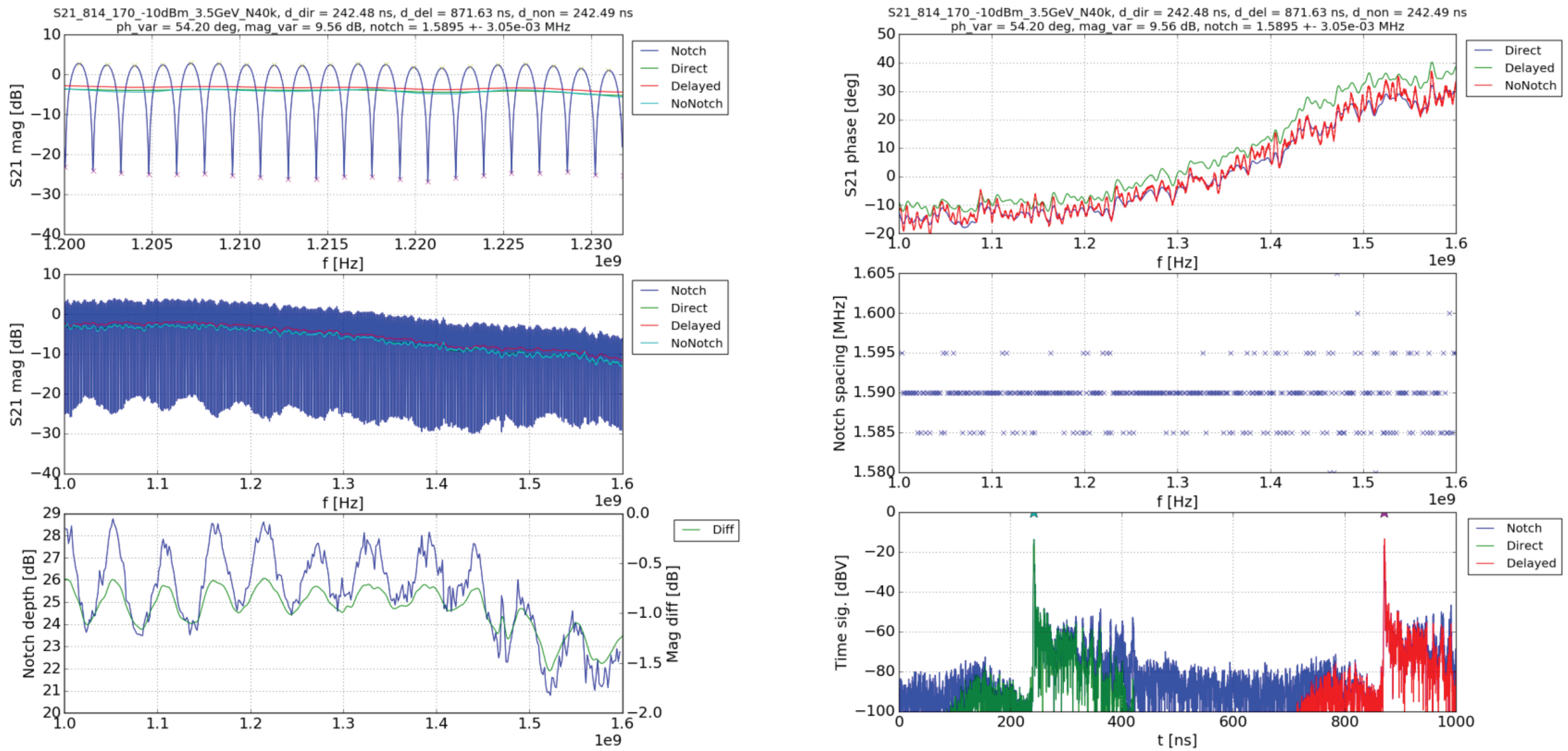
Reference Measurements (1)

- Reference measurements for signal path lengths of notch filter
  - 3.57 GeV/c new optical delay line notch filter
  - 2.0 GeV/c notch filter using existing legacy cabling plant



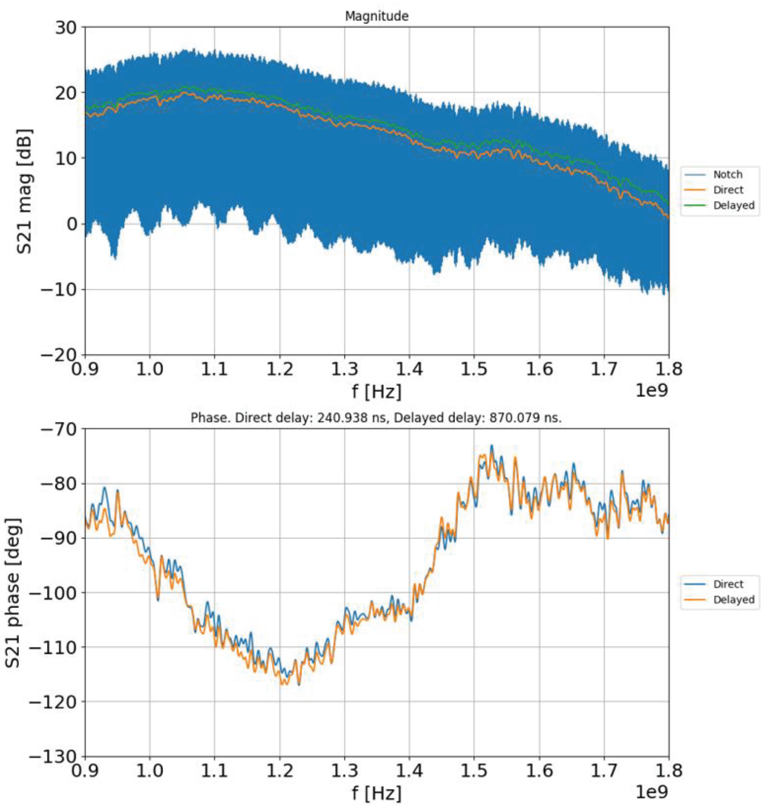
Reference Measurements (2)

- 3.57 GeV/c legacy notch filter with copper cables

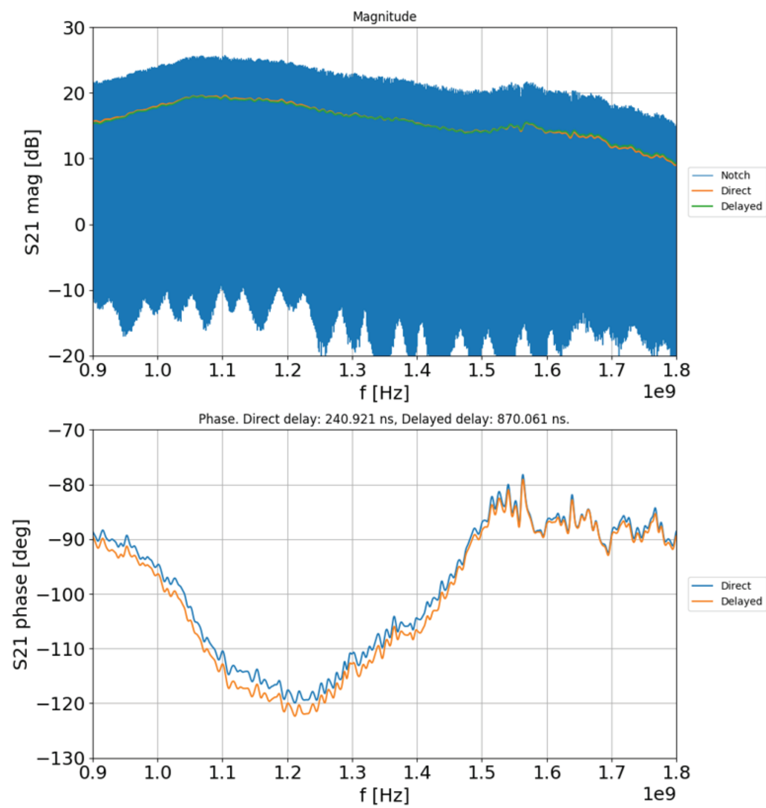


Reference Measurements (3)

- Comparison of 3.57 GeV/c new optical path notch filter and legacy notch filter with copper cables



old notch filter



new notch filter (fibers)

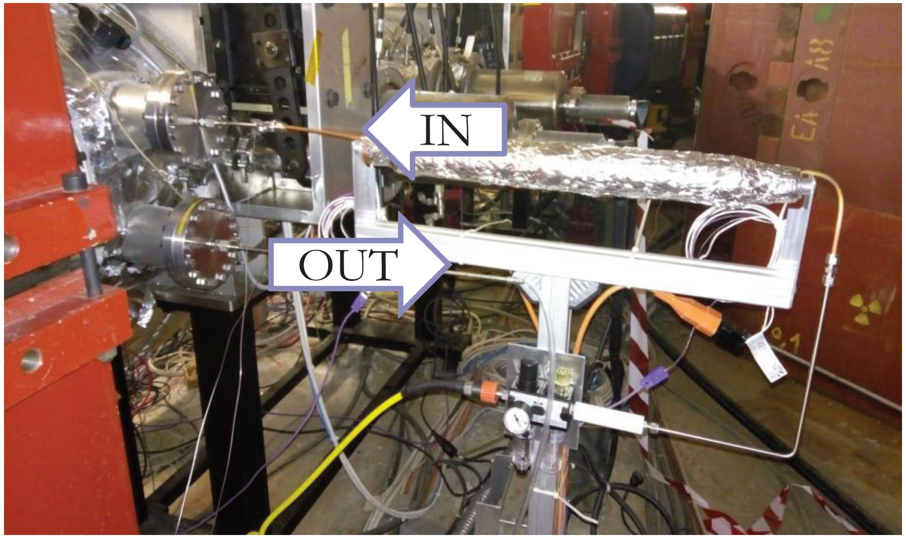
Fiber notch filter: 1st test with beam 2018 → operationally used all the time in 2021

Vacuum Issue at start-up 2021 (1)

- Due to venting of the machine for the magnet exchanges bake-out before start-up was required
- Delicate, as equipment dates from the CERN AC (anti-proton collector machine) that did not require a baked vacuum
- Baking of kicker tanks not regularly needed (vacuum not opened), delicate because of the water cooling pipes inside the vacuum (for the cooling of the RF loads)
- A leak was detected after bake-out in spring 2021 between water cooling pipes and beam vacuum on the horizontal kicker tank
- A similar leak was fixed during the initial commissioning period of AD in 2000 by araldite treatment

Vacuum Issue at start-up 2021 (2)

- Run of 2021 saved by using year 2000 procedure for repairing the vacuum leak
  - injection of resin, curing with heated compressed hot air
  - the resine is a special araldite type of mixture with high viscosity
  - water cooling volume completely filled with resin during the procedure, while tank is kept heated and under vacuum



Issues at recommissioning

- Despite care taken with reference measurements the scale of the dismantling and changes fine adjustment of delays and relative delays required more time than expected
  - essentially most difficult start-up since initial commissioning
    - storing beam at 3.57 GeV/c for ~1.5 hours possible by increased cooling (magnet cooling limitation)
    - in year 2000 it was possible to keep machine at 3.57 GeV/c without boosting cooling
    - initially low intensity
- Beam transfer function measurements require additional amplification of signals (additional losses due to cables used for this type of measurement (potential improvement possible)
- Combination of electrically non-centered transverse signal from pick-ups and residual longitudinal kick when transversely exciting can lead to confusion when measuring BTFs
  - new machines: foresee a means to center your signals

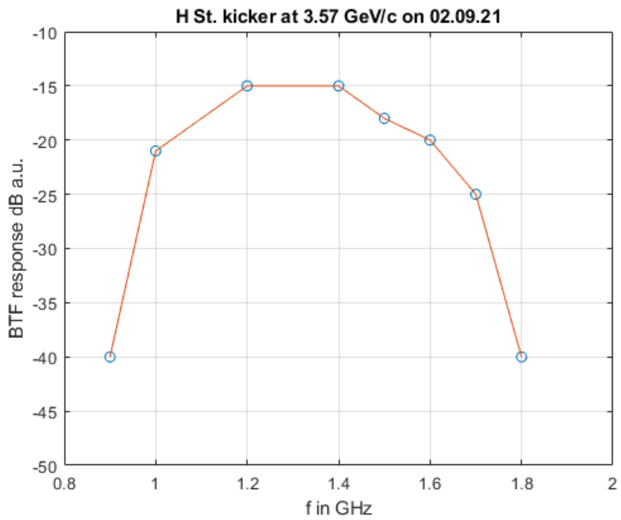
Commissioning with beam

- Delay adjustments are critical to the level of 30 ps at 1.6 GHz
  - 1 GHz → 50 ps equivalent to 18 degrees
  - response within entire frequency range matters
- Observation of Schottky spectra essential
  - injected beam: Δp/p: +/- 3% filling momentum aperture
  - Bunch rotation (h=6, 10 MHz) → Δp/p: +/- 0.75%
  - stochastic cooling at 3.57GeV/c and 2 GeV/c
- Schottky spectra available from the longitudinal magnetic pick-up
  - analogue down conversion from $2xf_{rev}$ to a common IF of 50 kHz for different energies, followed by digitization

Beam transfer functions (BTFs)

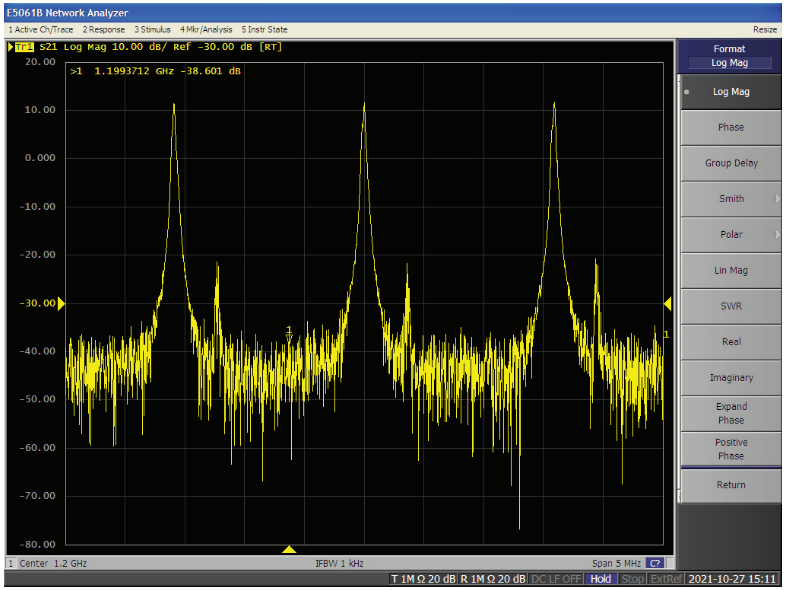
- used beam transfer function to adjust overall delay
- order of commission at a given energy important
  - longitudinal cooling before transverse cooling
  - if beam degrades it can repeatedly longitudinally cooled to be reused in the same fill for more BTFs
- magnitude response of BTF can be used to estimate overall bandwidth of system

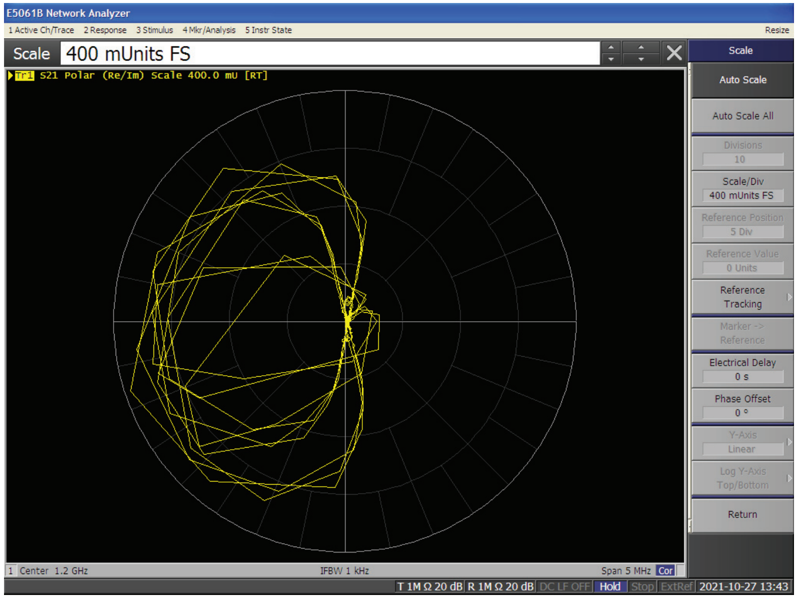
example: Magnitude response at
3.57 GeV/c, horizontal plane, open loop



BTFs

- Examples of BTFs 3.5 GeV/c, longitudinal plane, 1200 MHz

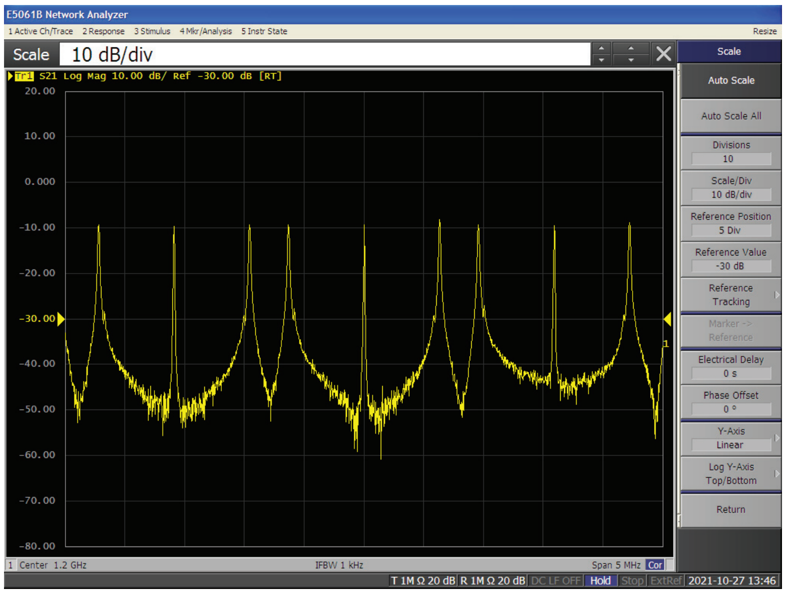


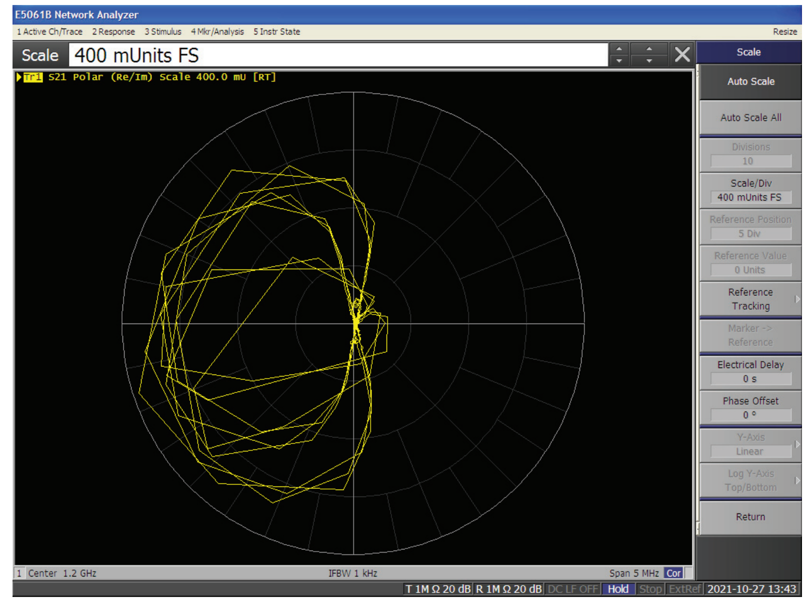


span: 5 MHz
Longitudinal BTF measured with notch filter open (short branch only)
→ align open loop BTF circles in polar coordinates towards -1 by adjusting loop delay

BTFs

- Examples of BTFs 3.5 GeV/c, horizontal plane, 1200 MHz

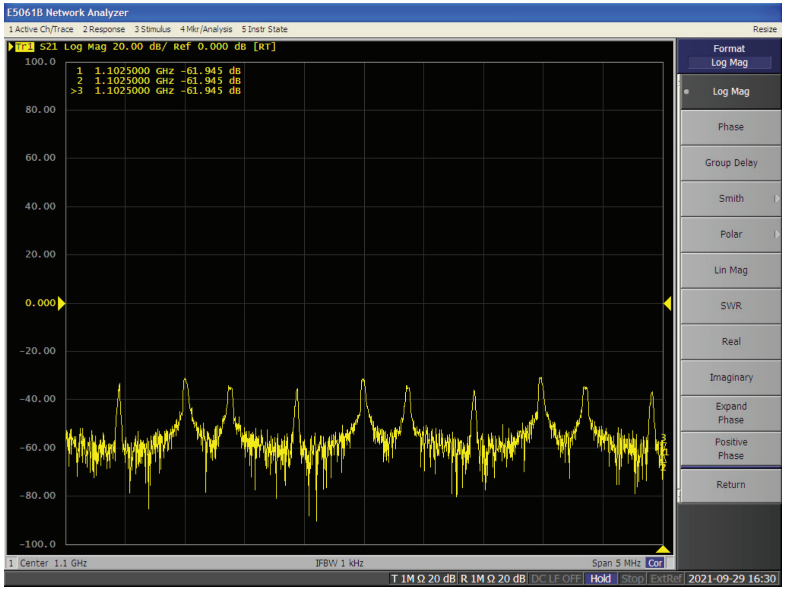


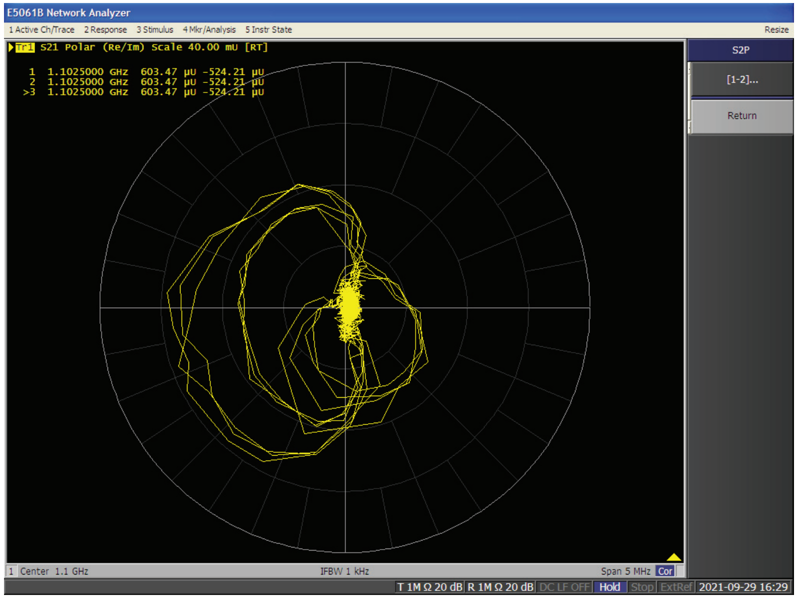


span: 5 MHz
transverse signals contain longitudinal signal
→ improvement of symmetry needed (pick-up electronics, kicker powering, beam position), phase of longitudinal unwanted signal oriented also to -1 in polar plane; loop delay rotates circles; non-optimal phase advance rotates 1-q and q group circles in opposite direction

BTFs

- Examples of BTFs 2 GeV/c, vertical plane, 1100 MHz

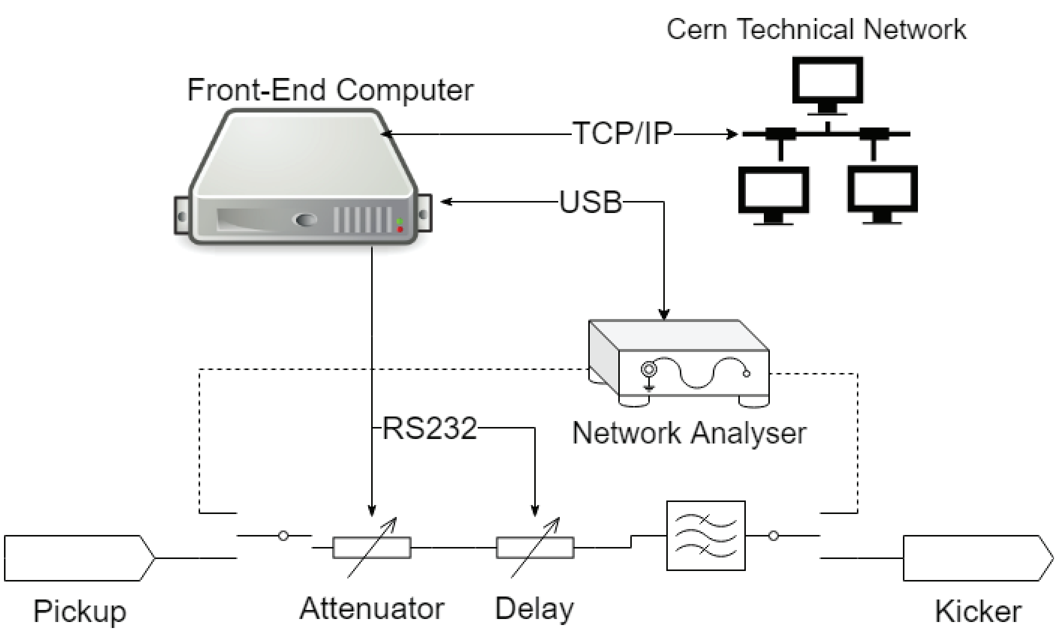


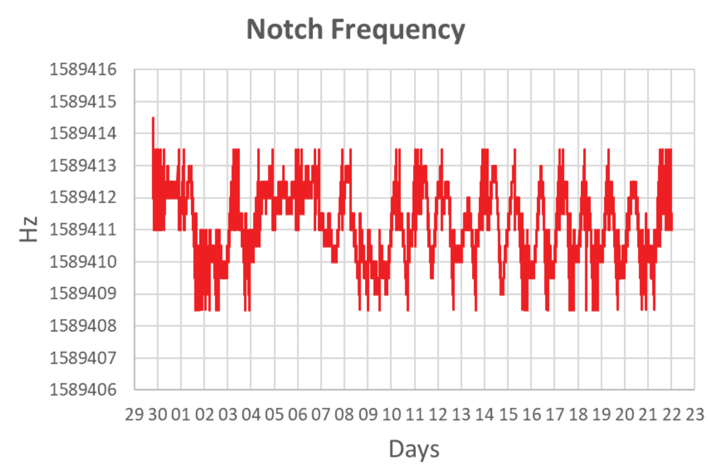


span: 5 MHz
transverse signals contain longitudinal signal
→ improvement of symmetry needed (pick-up electronics, kicker powering, beam position); transverse cooling is heating longitudinally

Monitoring of optical delay notch

- Notch filter with optical delay line is monitored in operation using a compact Network Analyser
  - In between cycles the notch at the 1000th revolution harmonic is checked → delay correction applied if notch frequency deviates; nota bene: long fiber is in a temperature stabilized box kept well above ambient temperature (i.e. by heating)

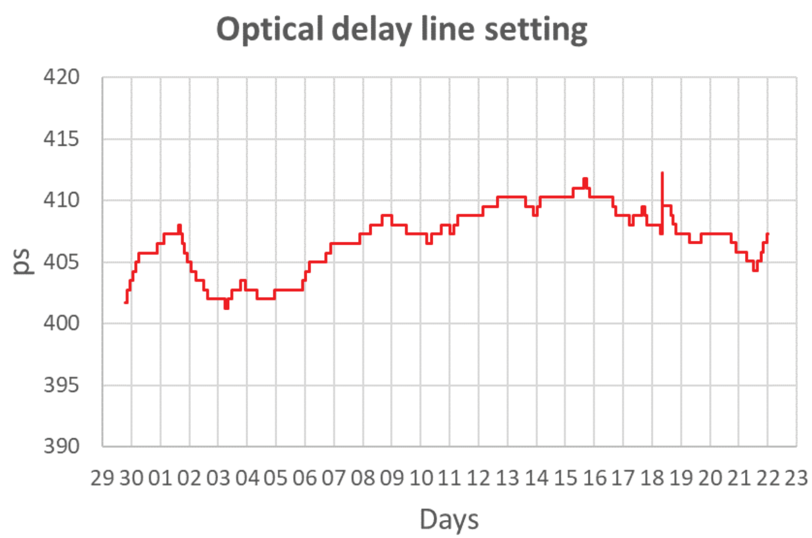




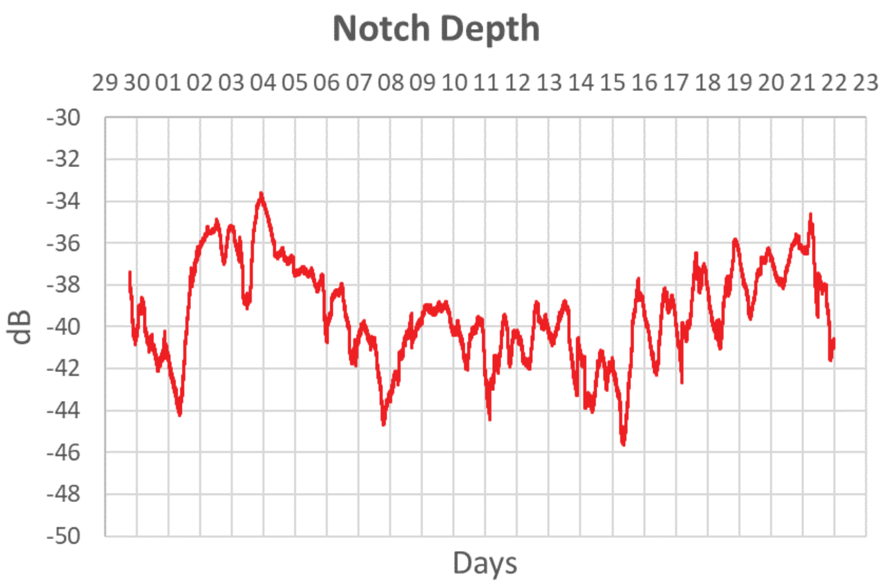
September → October 2021

Monitoring of optical delay notch

- Correction applied to keep notch (1000th harmonic) frequency at the canonical value of 1.589411 GHz
  - notch depth maintained at >30 dB



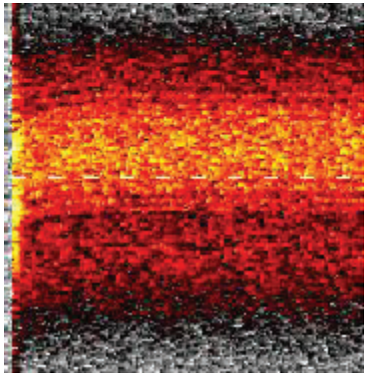
September → October 2021



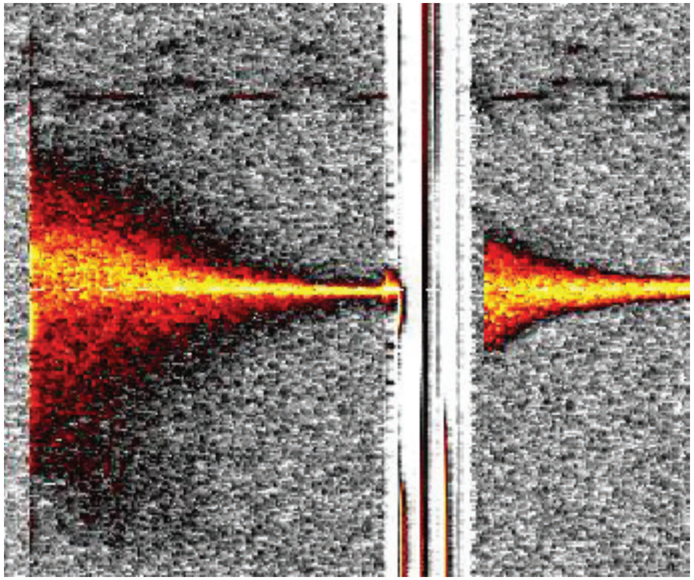
September → October 2021

Performance with beam

- Performance with beam longitudinal cooling



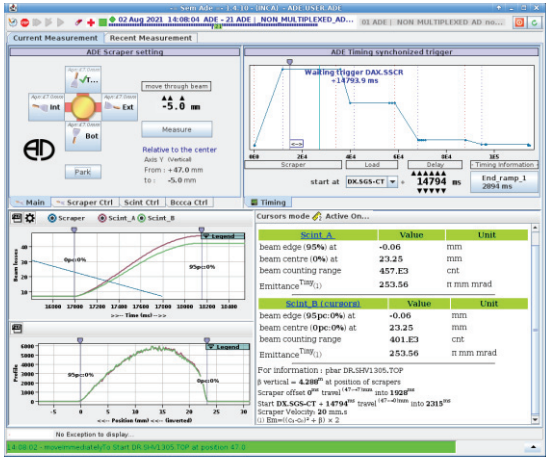
no cooling, only bunch rotation
Δp/p: +/- 0.75%



3.5 GeV/c   2.0 GeV/c

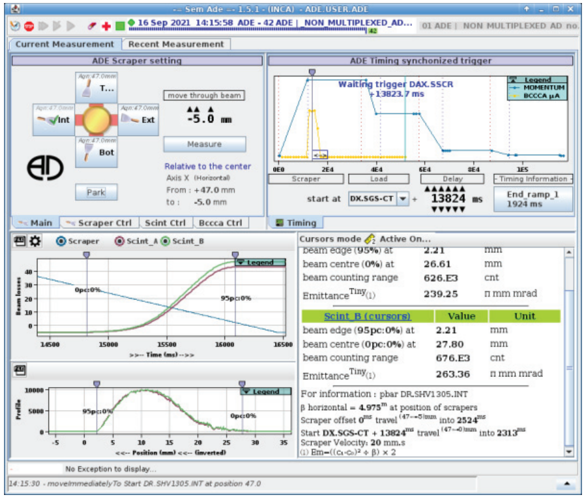
Performance with beam 3.5 GeV/c

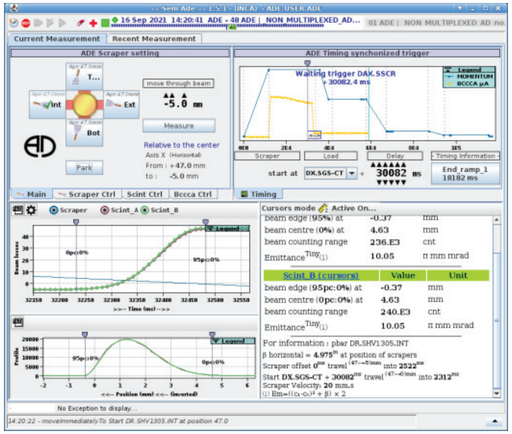
- Performance with beam transverse cooling at 3.5 GeV/c:
  - Horizontal: 230 → 10 π mm mrad
  - Vertical: 230 → 12 π mm mrad



horizontal

vertical





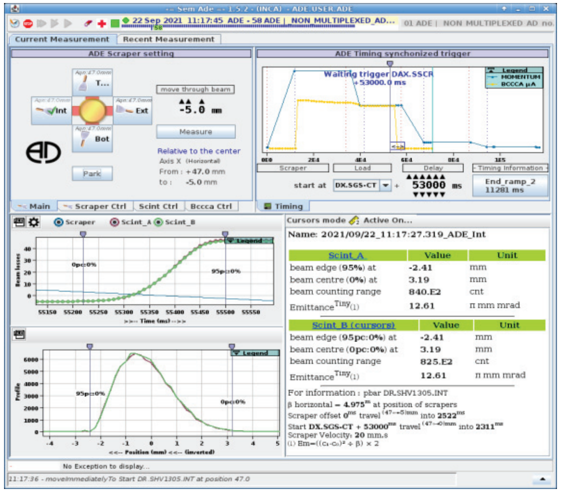
Due to new software relative figures only can be trusted

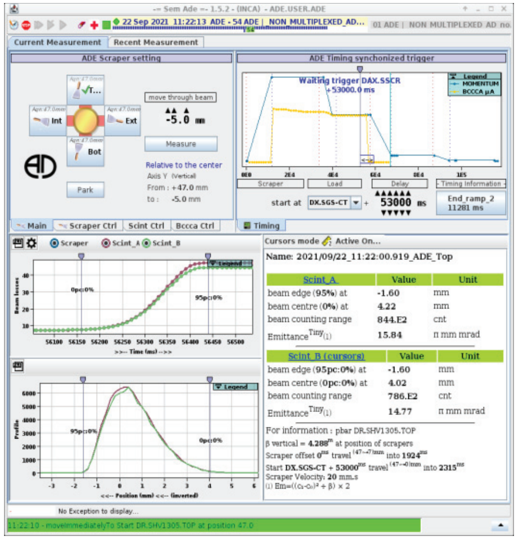
Performance with beam 2.0 GeV/c

- Performance with beam transverse cooling at 2.0 GeV/c:
  - ☐ Horizontal: 18.5 → 12.6 π mm mrad
  - ☐ Vertical: 28.9 → 15.8 π mm mrad

vertical

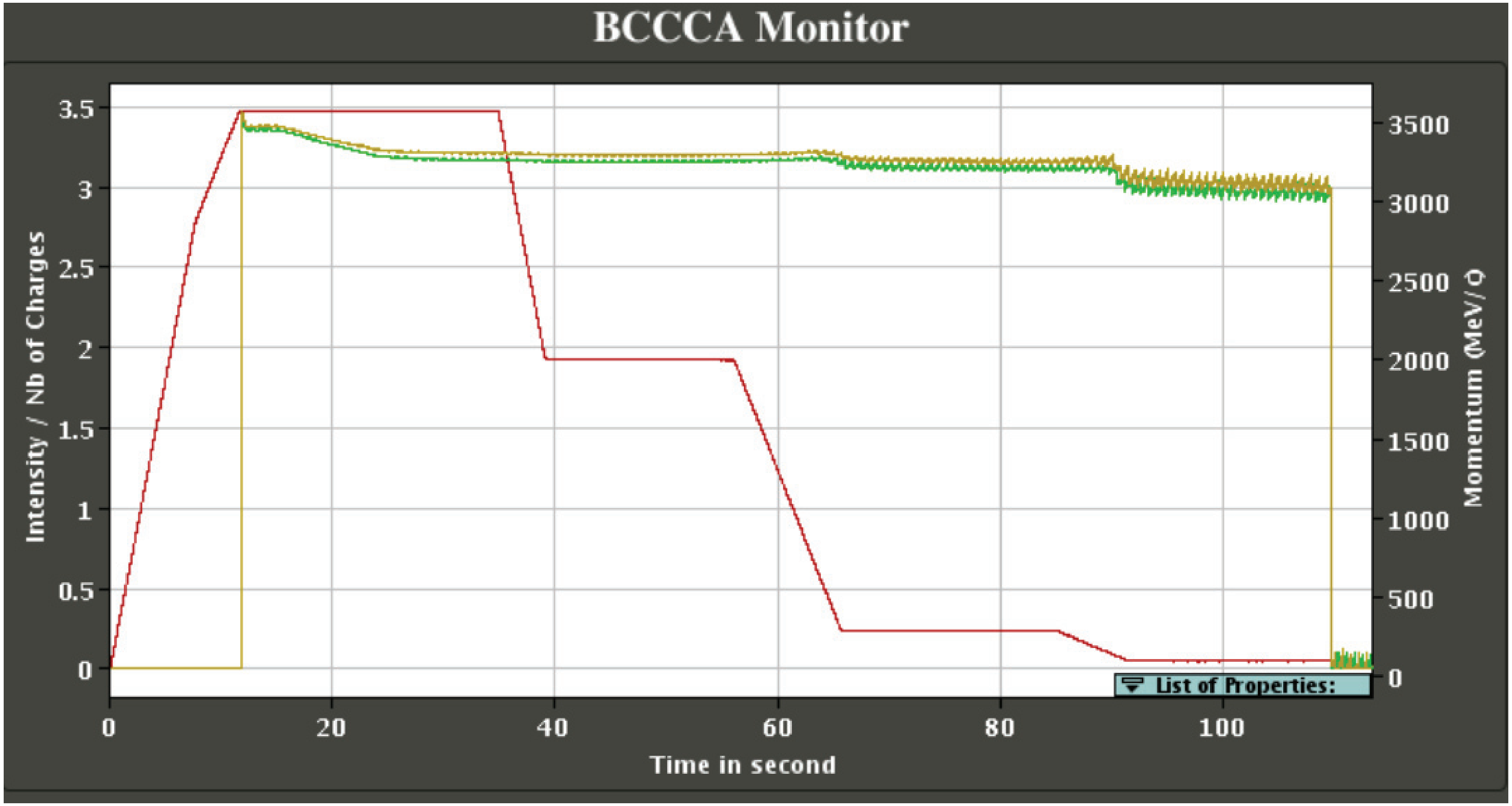
horizontal





Performance with beam

- Performance with beam intensity
  - superconducting beam current transformer



Future plans

- Define a consolidation program for kickers and power amplifiers
- Implement optical delay notch filter 2 GeV/c
- Automate transfer function measurements to enable regular checks and where required cycle-to-cycle adjustments
  - non-invasive observables
    - beam loss
    - Schottky spectra
    - Potential of IPM monitor for transverse emittance measurements to be explored

Summary

- Repair of leak in horizontal kicker tank water cooling after bake-out successful
- Complete recommissioning of power RF system of stochastic cooling after CERN long shutdown 2
- Hardware transfer functions and Beam transfer functions extensively used to set-up the system
- New PLC system and control room level software
- Automatic notch filter frequency stabilization by cycle-to cycle hardware transfer function measurement

Spare Slides

Brief History of Stochastic Cooling at CERN

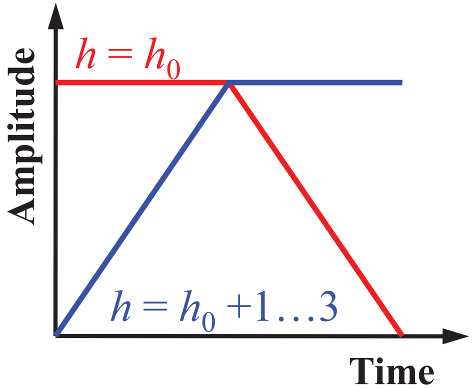
- 1968 Idea of Stochastic Cooling by Simon van der Meer
- 1972 First observation of Schottky noise at ISR
- 1972 Theory of Transverse Stochastic Cooling
- 1975 First experimental observation in ISR
- 1975 pbar accumulation schemes for ISR and SPS
- 1978 Refinement of Theory and detailed experimental verification at ICE
- 1982 accumulation of several 10^{11} pbar in AA
- 1986 Construction of AC
- 1996 End of operation of AAC (AA+AC)
- 1998 AD, "Anti-Proton Decelerator" converted from AC

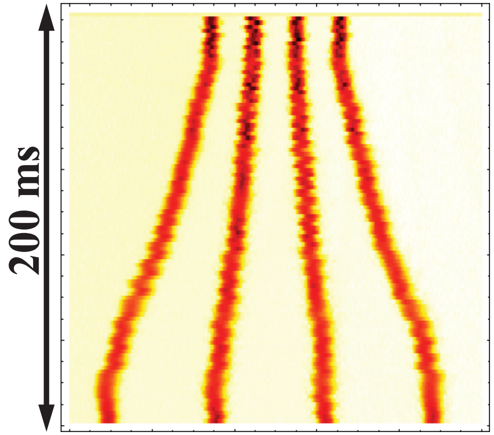
- 2016 ELENA commissioning → post-deceleration from 100 MeV/c to 100 keV
- 2018 Start of long shutdown #2 "LS2" at the end of the 2018 run
- 2021 Re-start, ELENA supplies anti-protons to users

- Today stochastic cooling is used at CERN only in AD
  - single band (~0.85 GHz – ~1.7 GHz)
  - All three planes: H, V, and filter-cooling for longitudinal cooling
  - pick-ups and kickers with combined signals for all long. plane, movable plates for pick-up used
  - 48, 100 W amplifiers (GaAs from 1980's)
  - Beam to users (2000: 1550 h → > 5000 hours / year today, 90% availability, AD uptime 95%)
  - Consolidation program under way: expect operation of AD/ELENA → 2030 +

Incoming beam: Batch Compression in PS for AD

- AD: $f_{\text{rev, AD}} = 10/3\ f_{\text{rev, PS}} \rightarrow$ Compress batch to < 30% T_{rev}
- Slowly change $h = 8 \rightarrow 9 \rightarrow 11 \rightarrow 13 \rightarrow 15 \rightarrow 17 \rightarrow 20$





→ Compress **four bunches to 20 %** of the machine circumference

AD Stochastic Cooling – Performance 3.57 GeV/c

Circumference	Design	Achieved
Intensity at 3.5 GeV/c	5×10^{7}	5×10^{7}
Cooling Time	20 s	20 s
Hor Emittance (95%)	5 π mm mrad	3 π mm mrad
Ver Emittance (95%)	5 π mm mrad	4 π mm mrad
Momentum width	$+/- 0.5 \times 10^{-3}$	$+/- 0.35 \times 10^{-3}$
Cycle length	60 s	60 s – 100 s

Performance as reported in F. Casper, EPAC'00, T. Eriksson Cool'13

AD Stochastic Cooling – Performance 2 GeV/c

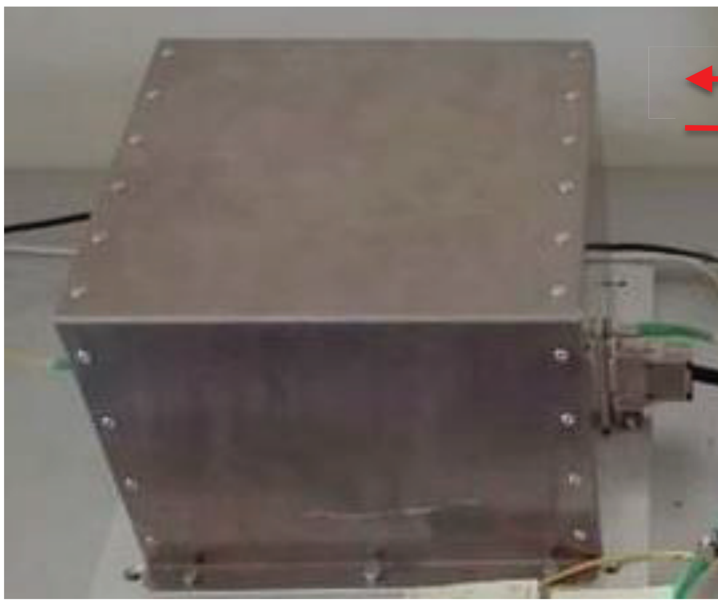
Circumference	Design	Achieved
Intensity at 3.5 GeV/c	5×10^{7}	(5×10^{7})
Cooling Time	15 s	15 s
Hor Emittance (95%)	5 π mm mrad	2.9 π mm mrad
Ver Emittance (95%)	5 π mm mrad	3.3 π mm mrad
Momentum width	+/- 0.15×10^{-3}	+/- 0.08×10^{-3}
Cycle length	60 s	60 s - 100 s

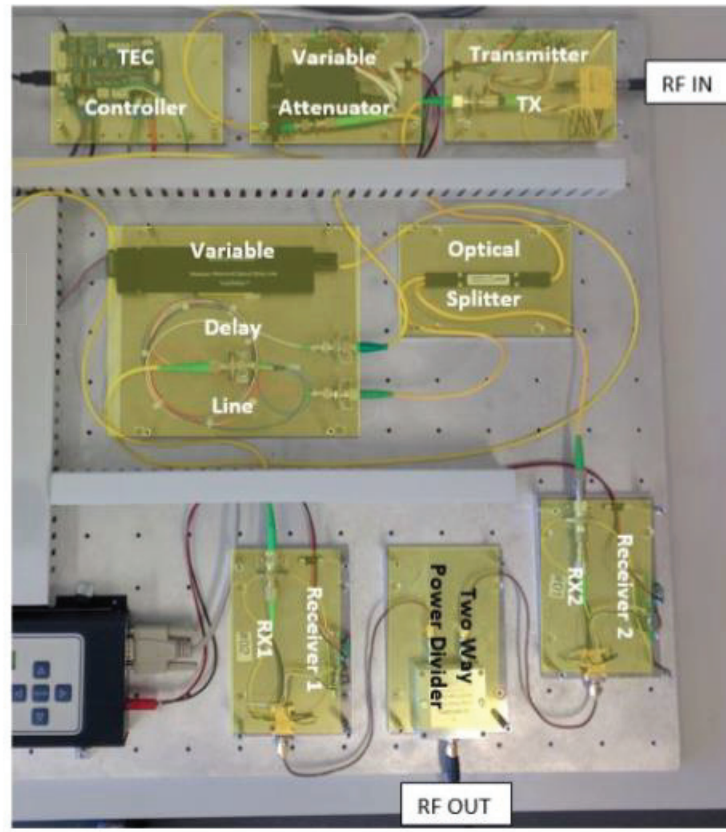
Performance as reported in F. Casper, EPAC'00, T. Eriksson Cool'13

Optical delay notch filter

Built at GSI at the request of CERN and
assembled in lab at CERN (Wolfgang Maier, GSI)

thermally stabilized box with fiber





Optical delay notch filter