First operation for stochastic cooling of p-bars in the CERN AD using optical delay notch filter and plans for 2021 operation

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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 +

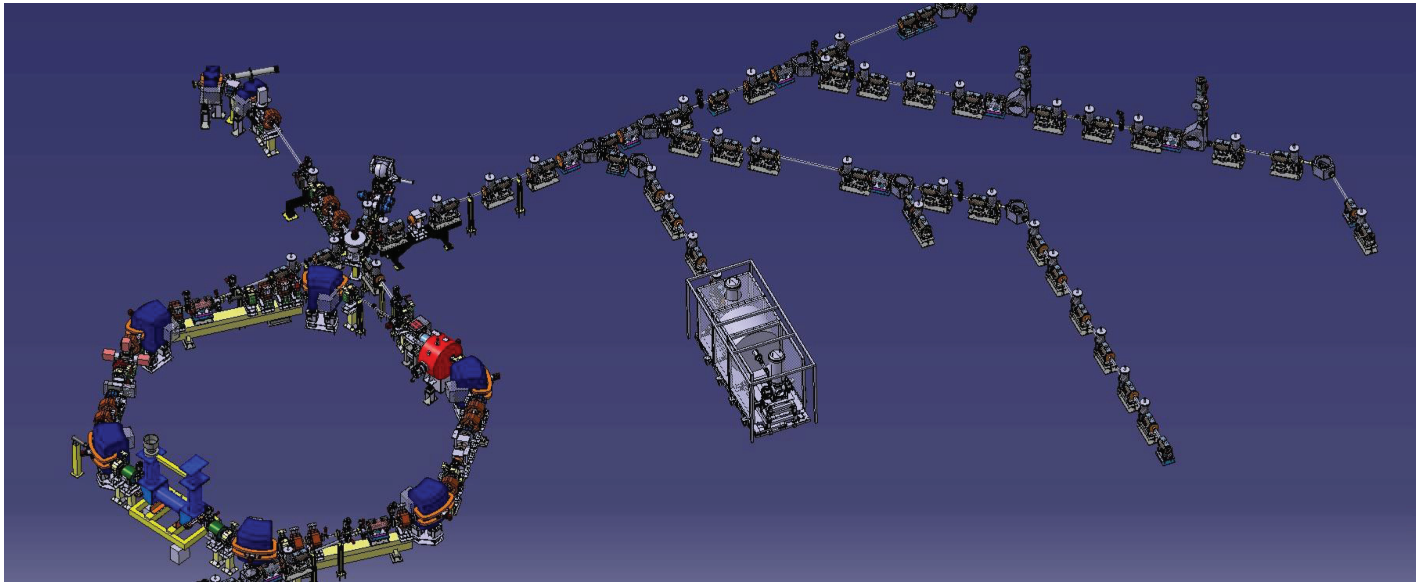
AD Basic Parameters

Circumference	182	m
Production beam	1.5×10^{13}	protons/cycle
Injected beam	5×10^{7}	pbars/cycle
Beam momenta (max-min)	3.57 – 0.1	GeV/c
Momenta for stochastic cooling	3.57 and 2	GeV/c
Transverse emittances	200 - 1	π mmm rad
Momentum spread	6×10^{-2} – 1×10^{-4}	$\delta p/p$
Vacuum pressure	$< 4 \times 10^{-10}$	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

The future of AD with ELENA

- ELENA Commissioning with anti-protons in dedicated periods and machine development sessions between April 2018 and November 2018
- Injection from AD at 100 MeV/c and deceleration to 100 keV in ELENA
- First pbar from ELENA delivered to Gbar experiment in July 2018 at 100 keV
- Second extraction line being installed in current Long shutdown 2019-2020
- Resume operation in 2021 with all Physics users moved from AD to ELENA



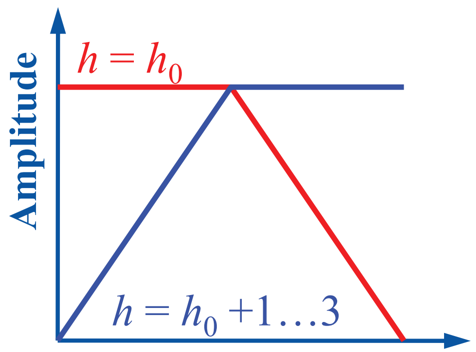
Antiproton production and transfer to AD

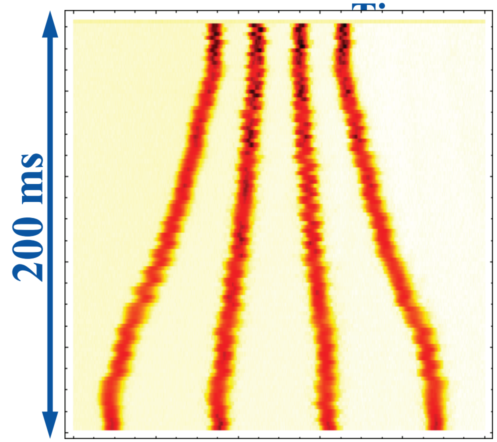
- Primary proton beam beam produced by batch compression in PS
- **At transfer: AD: $f_{rev,AD}$ = 10/3 $f_{rev,PS}$**
- Target located between PS and AD for production of pbars
- Time structure of produced pbars synchronized with 10 MHz RF system to capture the incoming beam on harmonic 6;
- Four bunches proton bunches filling 1/5 of PS (h=20) yield four pbar bunches filling 2/3 of AD on h=6
- For efficient transfer the adjustment of the bunch rotation system is critical and will require careful setting-up at re-start in 2021 to recover past peak performance (95% transmission after first cooling plateau at 3.5 GeV/c)

Incoming beam: Batch Compression in PS for AD Beam

- **AD: $f_{\mathrm{rev,AD}} = 10/3\, f_{\mathrm{rev,PS}}$ → Compress batch to < 30% T_{rev}**

→ Slowly change $h = 8 \to 9 \to 11 \to 13 \to 15 \to 17 \to 20$





→ Compress four bunches to 20 % of the machine circumference

Heiko Damerau

Elements of the stochastic cooling

- Pick-ups, combiners and low noise pre-amplifiers
- Kickers and Power amplifiers
- Signal transmission, processing, control and amplification
  - electronically variable attenuators (solid state), which should be phase–invariant (range 30-60 dB with 1 dB resolution)
  - Variable (electronically or mechanically) delays (amplitude invariant !) from about 10 ps/step to ~1 ns.
  - Gain equalizer (maybe variable) with defined phase.
  - Phase equalizer (maybe variable) with defined gain   don't forget Cauchy, not everything you want is permitted
  - Δ-Σ hybrids with very good isolation, flatness and match
  - Band-limiting filters with well defined out-of-band response and proper phase on the filter slopes
  - Notch filter

Requirements for Pick-Ups

- If static, the aperture is dictated by the largest size of the beam, otherwise we may consider plunging devices
- optimum sensitivity-bandwidth product per unit length, together with a minimum internal noise temperature
- Critical region: transverse sensitivity for beams with already small emittance and a small number of low charge state particles
- Keep the losses low, losses make noise
- Make them EMC leak tight also for signals coming along the beam-pipe
- For cryo operation provide absorbers for the incoming heat radiation from the beam-pipes

Types of Pick-ups

- Strip-line based structures such as the $\lambda/4$ or “loop ” coupler, also “super-electrodes” = 2 $\lambda/4$ loops in series
- Printed structures known as printed loop coupler, patch antenna, slot-line coupler
- Periodic slot type coupler (major slot axis orthogonal to beam direction)
  - TEM-line with periodic slots (Faltin)
  - Wave-guide with periodic slots (Mc Ginnis)
  - Perforated stripline (as used at IMP)
- Traveling wave devices (FORWARD COUPLER !) for low β beams using strip-line sections with external (variable) delays
- Cerenkov and corrugated wall couplers (above 1 Ghz)
- And last not least: The slot rings couplers

Pick-up design aspects for the range $0.4<\beta< 0.9$

- This is the transition region for strip-line like couplers to be used in the backward or forward coupling regime (for $v\approx c$ strip-line work only as backward couplers)
- Interest in using forward coupling since the coupling impedance scales~ to L^2 (L=length) of the structure, while for backward coupler the impedance is ~ L only; Faltin structures can be used down to about β=0.6; caveat :dispersion
- For highly relativistic beams the McGinnis structure is well suited (looks like a Faltin structure, but without inner conductor)
- The problem: Obtaining synchronism with the beam over a large relative bandwidth (several octaves desired) up to about 2 GHz or more
- Avoid dielectric loading to slow down the phase velocity of a (long) strip-line (E/H ratio changing in the wrong way)
- Inductive loading can do the job, but we have to watch for dispersion (perhaps a slotted strip-line with a corrugated ground-plane behind could be used also)

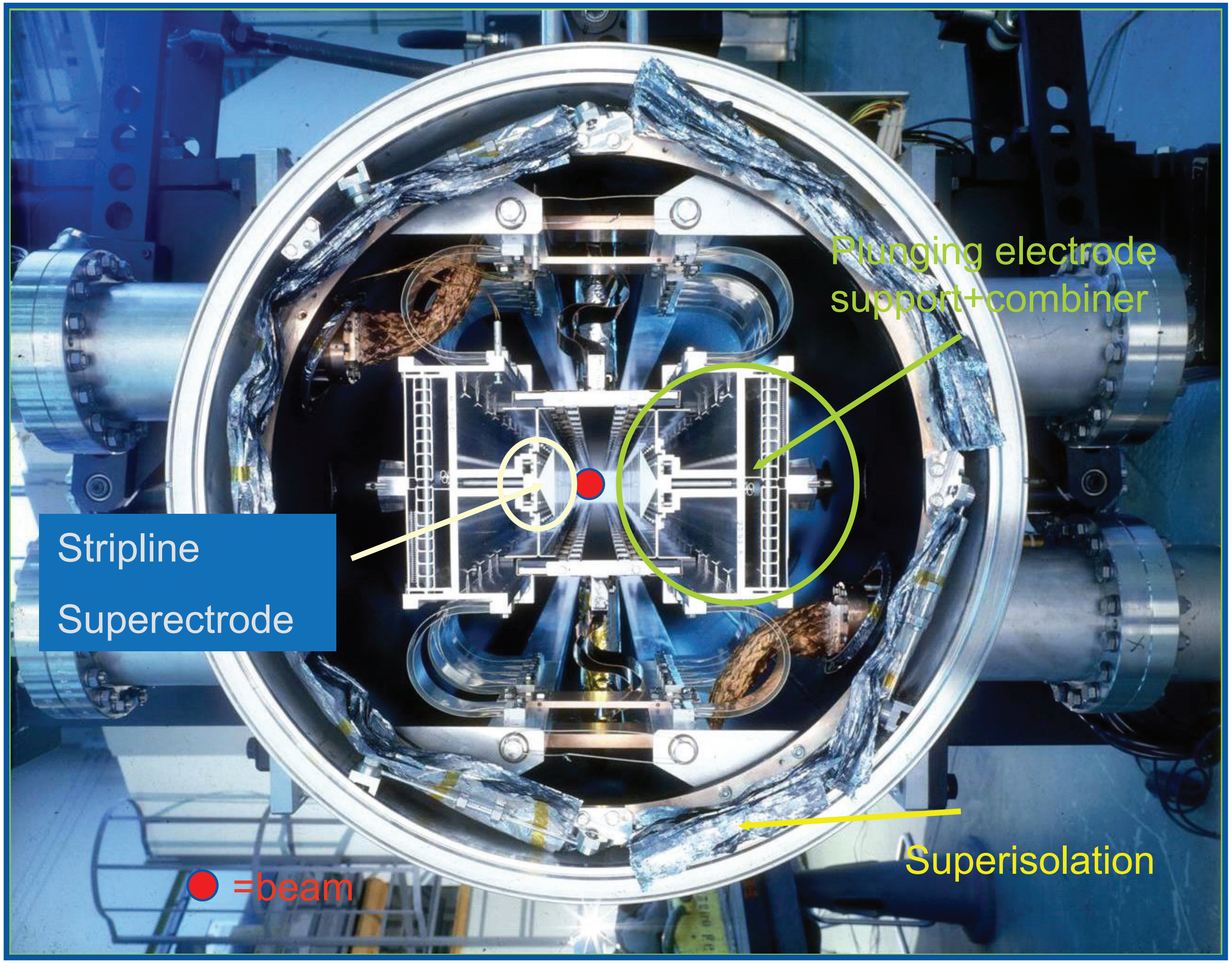
Cryo-cooling and/or plunging PUs?

- Cryo-cooling certainly a way to reduce considerably the thermal noise originating from the pick-up structure. Examples: CERN AC, FNAL
- The effective noise temperature can be lowered down to a few deg K if needed.
- Since only the losses produce thermal noise, a very low loss structure (high Q cavity) can have an effective noise temperature of a few deg K , but staying physically at room temperature, when using an appropriate feedback technique and trading Q value against noise. [c.f. AD beam intensity monitor, F. Pedersen]
- Plunging is a very effective way to increase the transverse sensitivity (AC, AD) and can be used together with cryo-cooling (but its a mechanical challenge)
- Of course the best is, to have plunging cryo pickups for transverse cooling (e.g.CERN AC)

AD Stochastic Cooling choices

- only one band retained from the original equipment in the AAC
  - ~0.85 GHz to ~1.7 GHz
- Stochastic cooling at two momenta
  - 3.5 GeV/c and 2 GeV/c
    - Two notch filters & delays needed for the two longitudinal cooling branches different energies
  - Present pick-up not optimal for both energies
  - Movable structures that close around beam as the beam size shrinks to maintain a high sensitivity

AD plunging cryo-PU (ex CERN-AC)



Low Noise Pre-amplifiers

- The present state of the art for preamplifiers is for
  - un-cooled units i.e.at ambient temperature and 50 Ohm char. Impedance (input and output)
    Noise temperatures well below 70 K for frequencies above 50 MHz to <5 GHz with octave bandwidth and slightly worse with decade bandwidth or more are available
- Cryo-cooled amplifiers (usually GaAs, since the conduction mechanism in Si gets "frozen") are usually better by a factor 2 or more than a comparable ambient operating version
- Caution is needed when installing a cryo-preamp directly in the UHV of a cryo-cooled PU tank (power dissipation, access for maintenance)

Signal combination and noise

- The signal combiner from different PU elements may be, due to its losses, an important source of signal/noise degradation, in particular, if the combiner is at ambient temperature
- Thus, if possible attribute to each PU electrode (or small group of electrodes) output its private, low noise preamp and then go into the combiner, of course more preamps make more (uncorrelated) noise but what counts, is the signal noise ratio
- Using “private” preamps permits easier amplitude and phase adjustment (ampli on/off). They also offer good output/input isolation, but the penalty is complexity
- Watch out for reasonably good out of band response of the combiner network =designing the entire system +- one octave above and below the nominal band
- The region is in particular susceptible to EMI/EMC infiltration..(these days:Cell phone right in cooling frequency band)

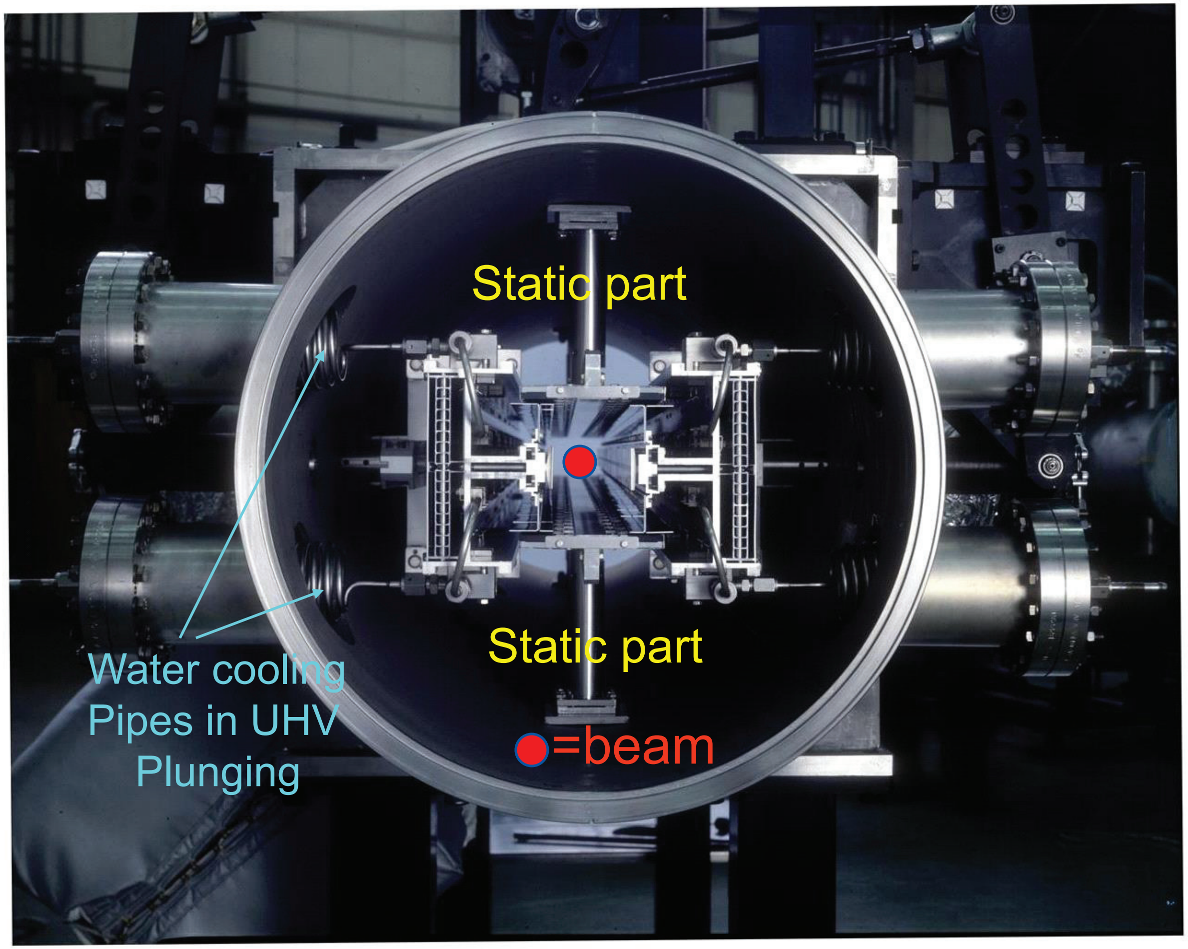
Noise Temperature Calculation

- The pick-up structure, together with its (50Ohm) termination, signal combiner and low noise preamplifiers is a network with inhomogeneous noise temperature distribution. Due to the presence of amplifiers it is non-reciprocal.
- Several techniques how to do the calculation:
  - #1 Assume that all lossy elements except one are at 0 K and work out its fractional noise contribution to the output port. Do that for all elements (superpos.)
  - #2 If the network is reciprocal, assume a unit power fed into the output. Work out the fractional dissipation in each element. This returns the weighting function for each element, which has to be multiplied by its noise temperature and added up.
  - A network of many passive resistors can never have a higher noise temperature than single resistor at the same average temperature

AD choices for kickers

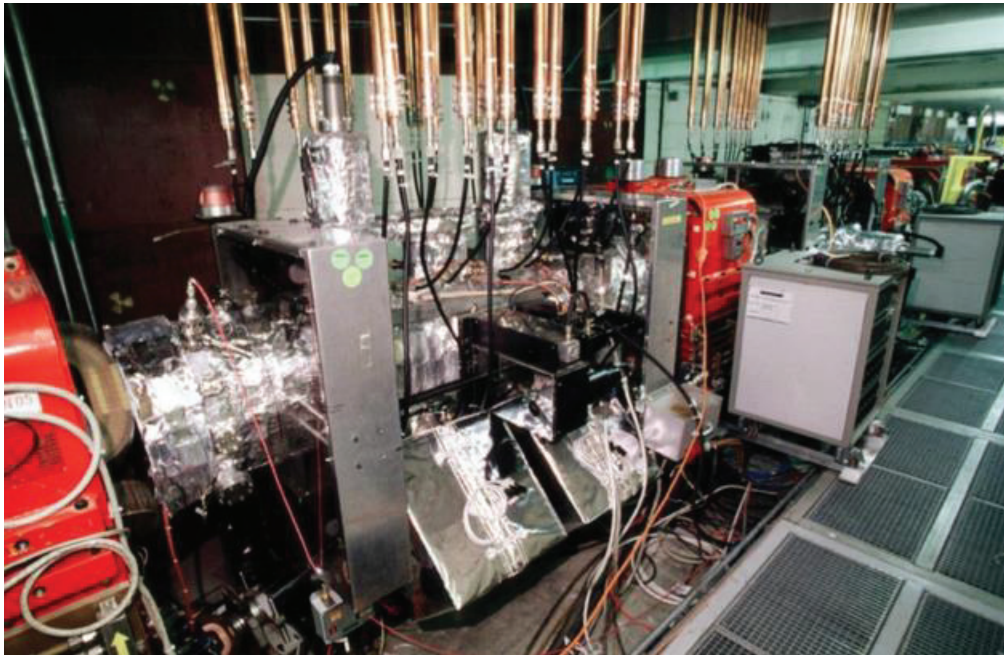
- Kickers are electro-magnetically equivalent to pick-ups, but not from the technological point of view
- They don't need cyro-cooling, but sometimes water-cooling may be mandatory
- Plunging has been foreseen in the AD equipment and can help to reduce the transverse system power requirements, but is perhaps less important than for pick-ups, since most of the power is required when the beam has a large emittance;
- Presently plunging is not used as enough amplifier power is installed (48x100 W) → less strain and risk for the delicate plunging mechanism
- Cooling of loads that are integrated within the kicker tank structure by water
- Correct matching can be verified by time domain reflectometry
- Operation with circulators to protect the power amplifiers from reflected power

CERN AD kicker (ex CERN-AC)



Kicker Tank with RF lines in AD

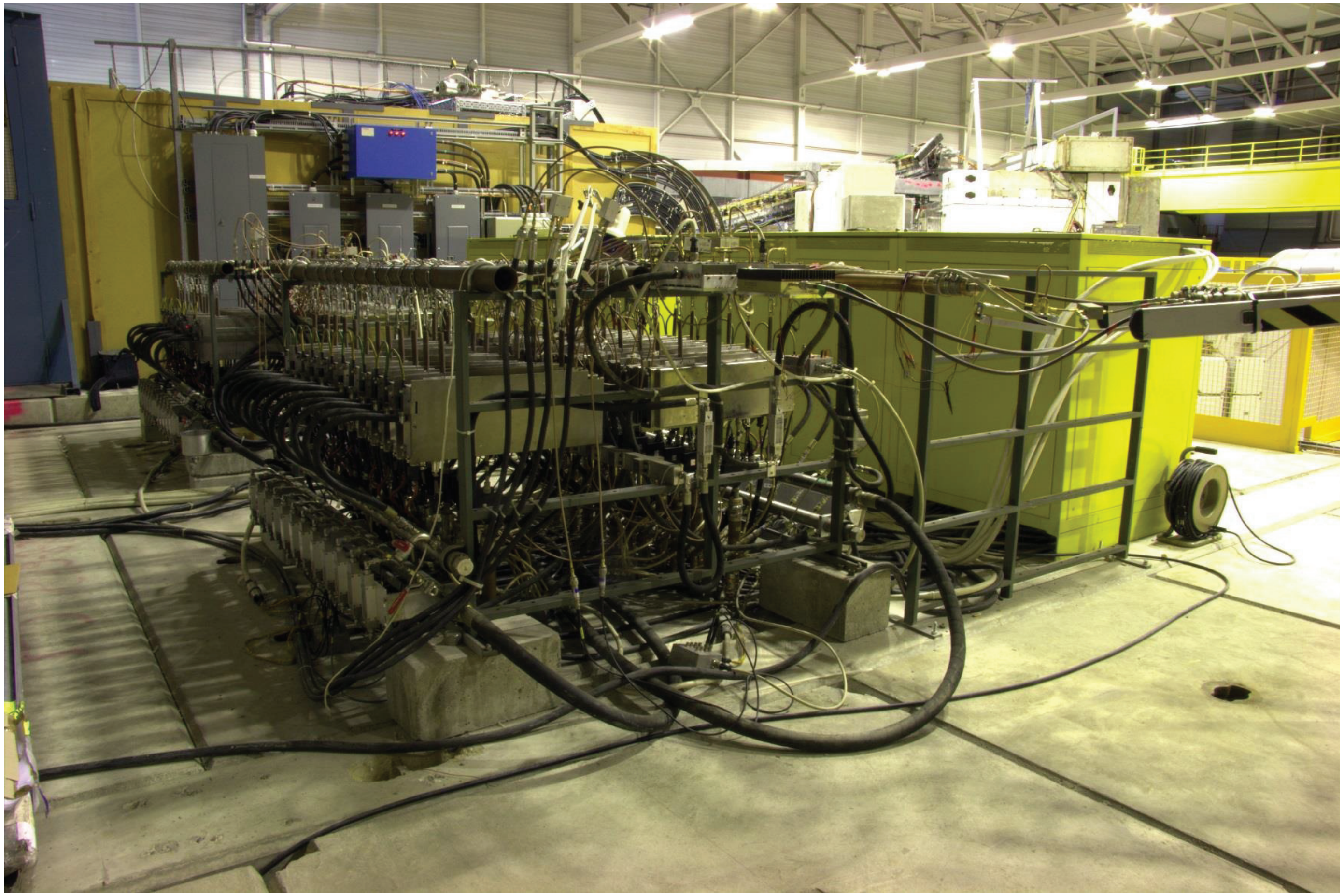
- Dismantling of lines and power amplifiers to give access for maintenance in LS2
- Careful asessement of delay for each of the 48 feeder lines and verification of transmission at start of shutdown
- Re-installation after correction of non-conformities (contact issues observed in connectors)



High Power Amplifiers

- 2 BASIC OPTIONS
  - Solid state class A or maybe AB:
  - units with 100 Watt CW over an octave bandwidth are available up about 4 GHz. (often as water-cooled version in a <10 liter volume housing) This type of amplifier shows good performance wrt nonlinear properties (inter-modulation). No problems with amplitude dependent phase shift
  - TWT (traveling wave tube) [obsolete now] can deliver more than 100 Watt over 2 octaves in the range 1-10 GHz. However many TWTs require internal or external feed-forward (feed-back) loops to compensate for (inherent) amplitude dependent phase shift and to minimize inter-modulation; practically obsolete these days

CERN Stochastic Cooling Amplifiers



48 water-cooled 100 W amplifiers (GaAs, 1980’s)

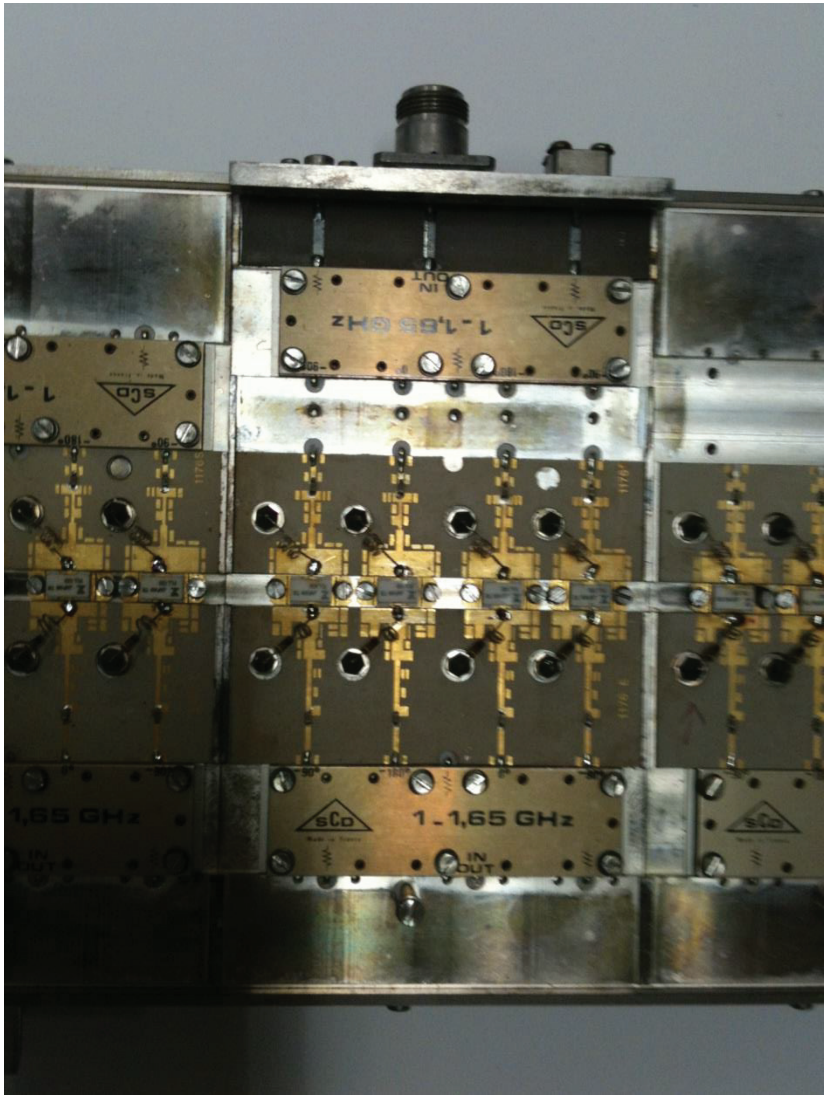
Power Supplies / PLC controls for Stochastic Cooling Amplifiers

New power supplies and renovated controls for power system

Some details (short electric delay !)

CERN AD Stochastic Cooling amplifiers

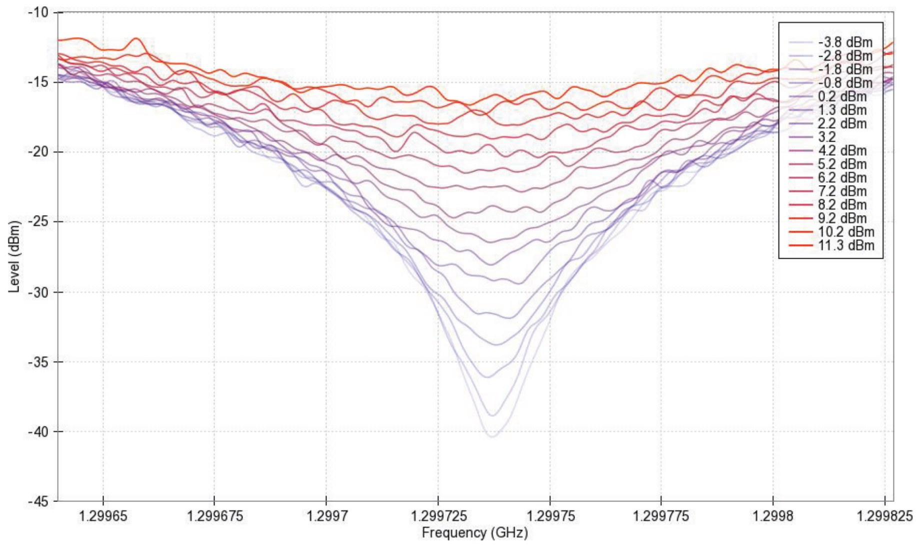
- 48 units in operation
- 100 W in 50 Ohm
- FLL100 replaced by FLL120 MK
  - 16 x FLL120 for power stage
  - 4 x FLL120 driver stage
  - Preamplifier FLL50
- ~ 40 - 41 dB gain
- 10.5 ns delay
- +/- 5 degrees phase
- constant phase shift (permitted)
- 600 MHz to 1800 MHz (3 dB)
- (1 GHz – 1.65 GHz original spec)
- used at 16 V_D (35 A consumption for 100 W)
- Aux Power +/- 5 V, 30 V, 24 V



Maintenance and repair
R. Louwerse + K. Marecaux

Stochastic Cooling Amplifiers

- Possible future replacement by GaN technology
- Not urgent as sufficient spare parts available
- Good operational reliability
- Linearity for new amplifier design needs to be carefully specified
- Filling of notches due to non-linearity of power amplifiers can have impact on the initial cooling rate

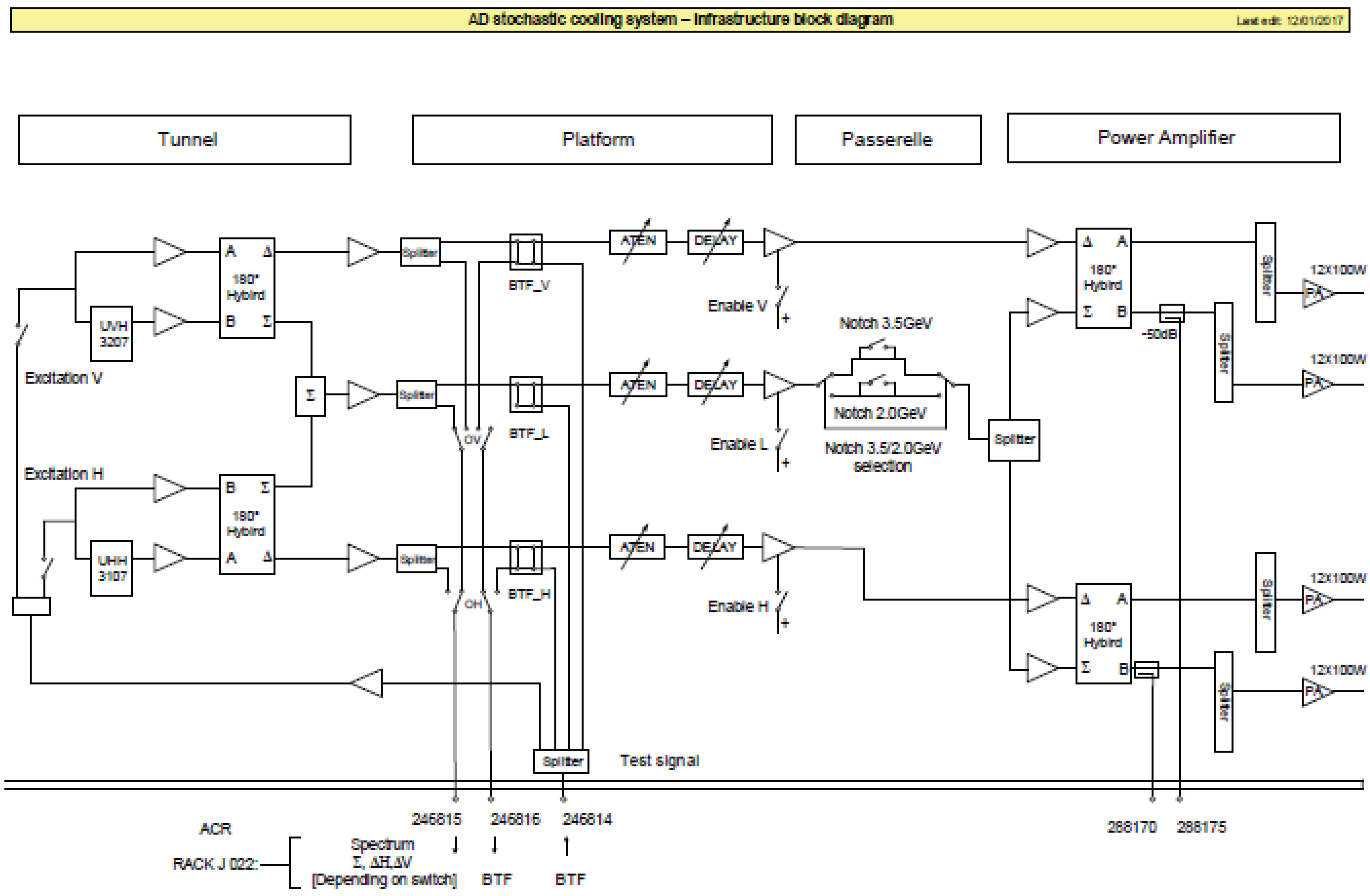


Measurement on CERN amplifier at FZ Juelich (R. Stassen, N. Shurkhno)

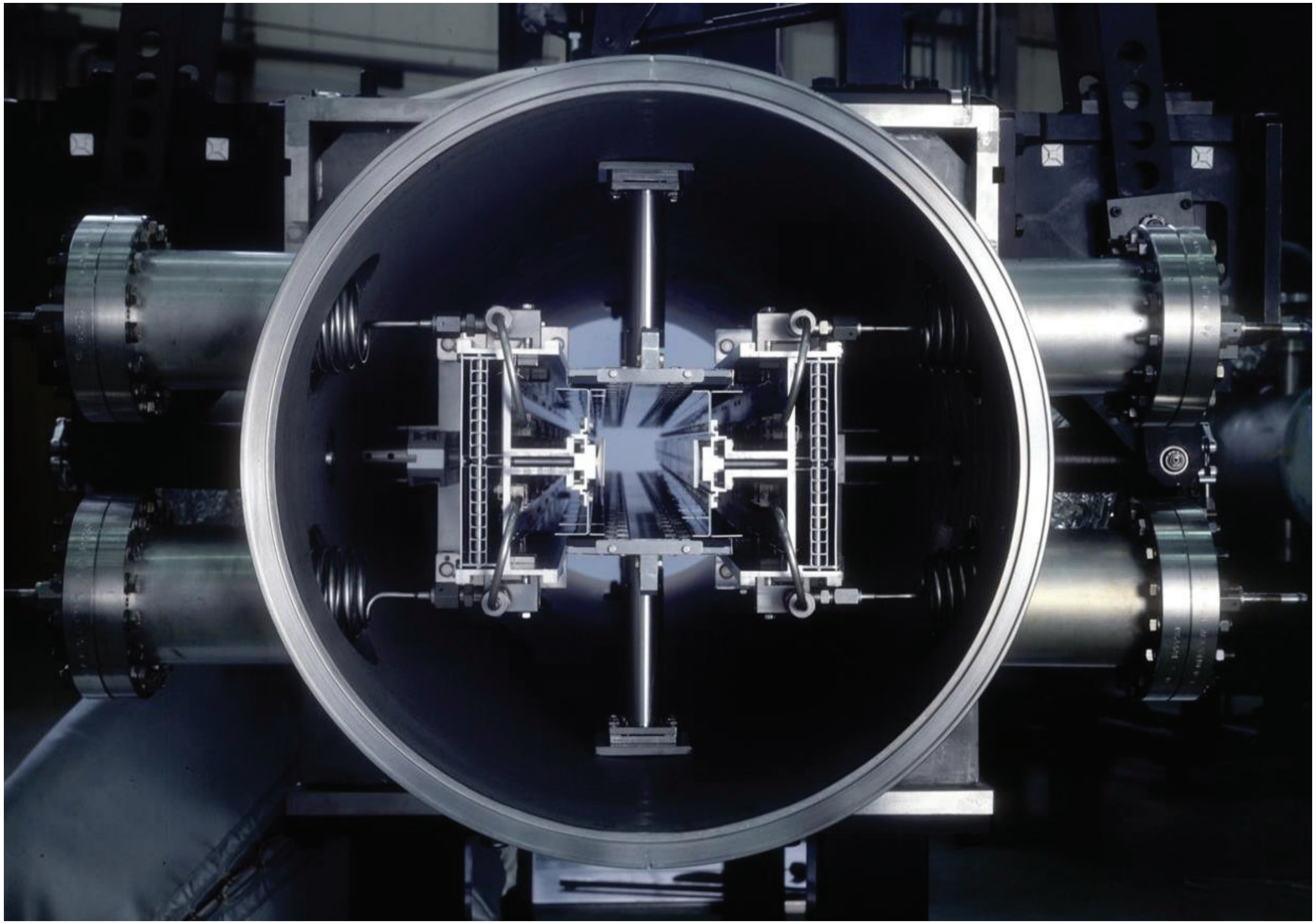
Notch Filters

- There are several basic versions:
- Classical coax delay line type, coaxial hybrid and long line phase dispersion + frequency dependent loss compensation;
- Optical fiber based delay line. Watch out for dynamic range limitation by inter-modulation !Temperature sensitive! Fast fibers with hollow core are very interesting
- Acoustic delay lines (bulk acoustic wave=BAW); no longer under discussion these days
- Digital delay lines; very elegant for long delays but limitations wrt bandwidth, dynamic range(quantization); this type of element has been successfully implemented and operated in LEAR about 30 years ago (with 30 Mhz bandwidth), but now its gaining new interest as the technology becomes ready for GHz bandwidth digital filters, which then also could be used for cooling during the ramp.

Putting it together:
Overview Stochastic Cooling



Kicker Tank

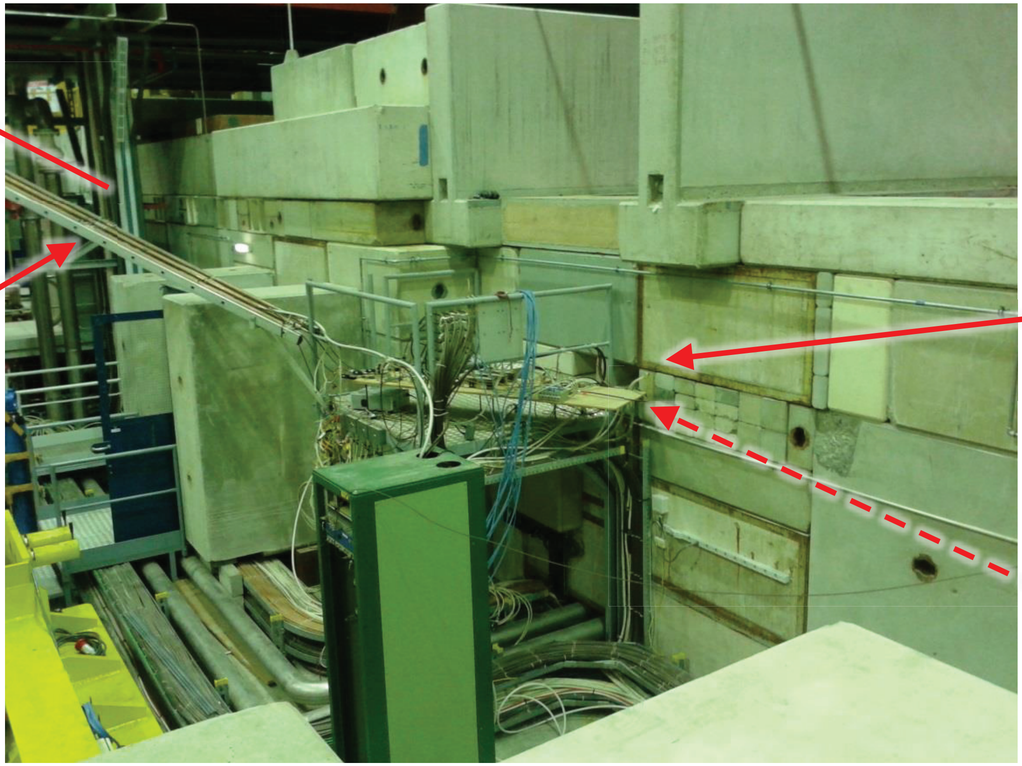


Kicker and Pick-ups

- Tanks with structures for different band recovered from GSI and stored in 867; can be used for spare parts of mechanics or to build new system
- Existing kicker had issue with vacuum in the past (leak in water cooling)
  - leak repaired at the time by injection of resin (delicate, Fritz dixit)
- Situation not comfortable: No spares
- If new construction, review what is needed first
- many ideas if you ask the retired experts: (Fritz, Lars)
  - Team of E. Montesinos has only free capacity after LS2
  - Practically excluded to have something new before LS2; aim for LS3 ?
  - Study now what is the best solution

AD Stochastic Cooling

- Very tight delay budget
- Notch filter with copper cables and delay lines using “air” coaxial lines
- Equalizers to achieve good response and notches over one octave



to power amplifiers

coaxial lines

Platform “Fritz”

from accelerator Tunnel (PUs)

Remote controlled using modern PLC system since LS1 (2015)
Pick-up motor control renovated (stepping motor)

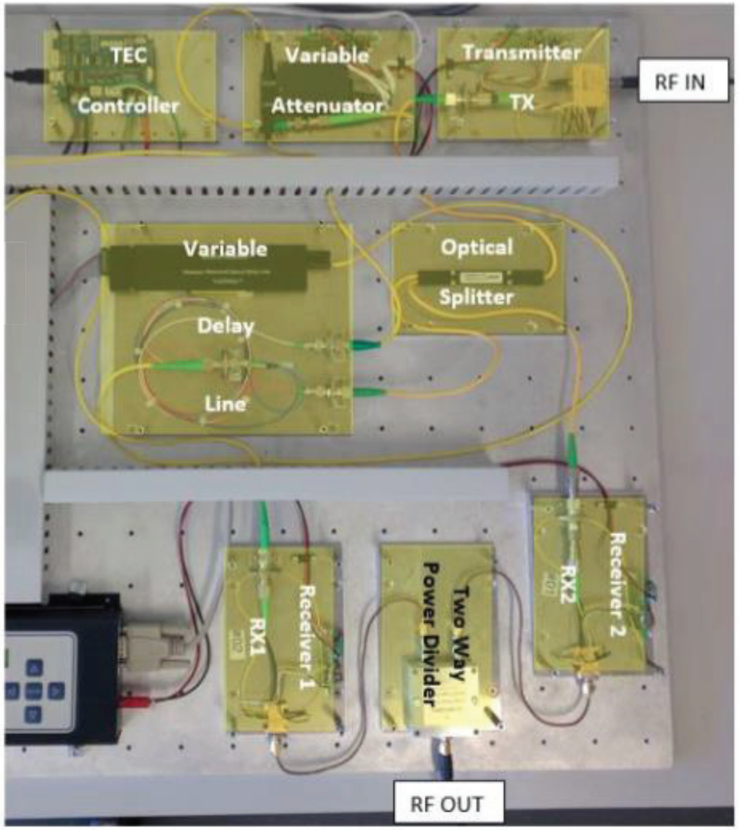
Optical delay line Notch Filter

- Collaboration with Stochastic Cooling Team at GSI (2015 +)
- **Based on optical fiber delay line**
- GSI built notch filter commissioned in lab (Wolfgang Maier, GSI)
- Adaptation of controls to CERN standard PLC system in 2016
- First stability measurements indicate excellent temperature stabilization
- Long term stability of notch filter being improved by change of adjustable delay
- Frist results with beam achieved in 2018 after tedious installation and connection of dedicated RF lines
- If performance confirmed, consider second notch filter for lower energy
  - only temperature stabilization of fiber
  - no active regulation of delay of entire signal path (COSY have active regulation)
- Following commissioning of notch filters → check of delay margin
  - will guide further the layout of the renovation with amplifiers

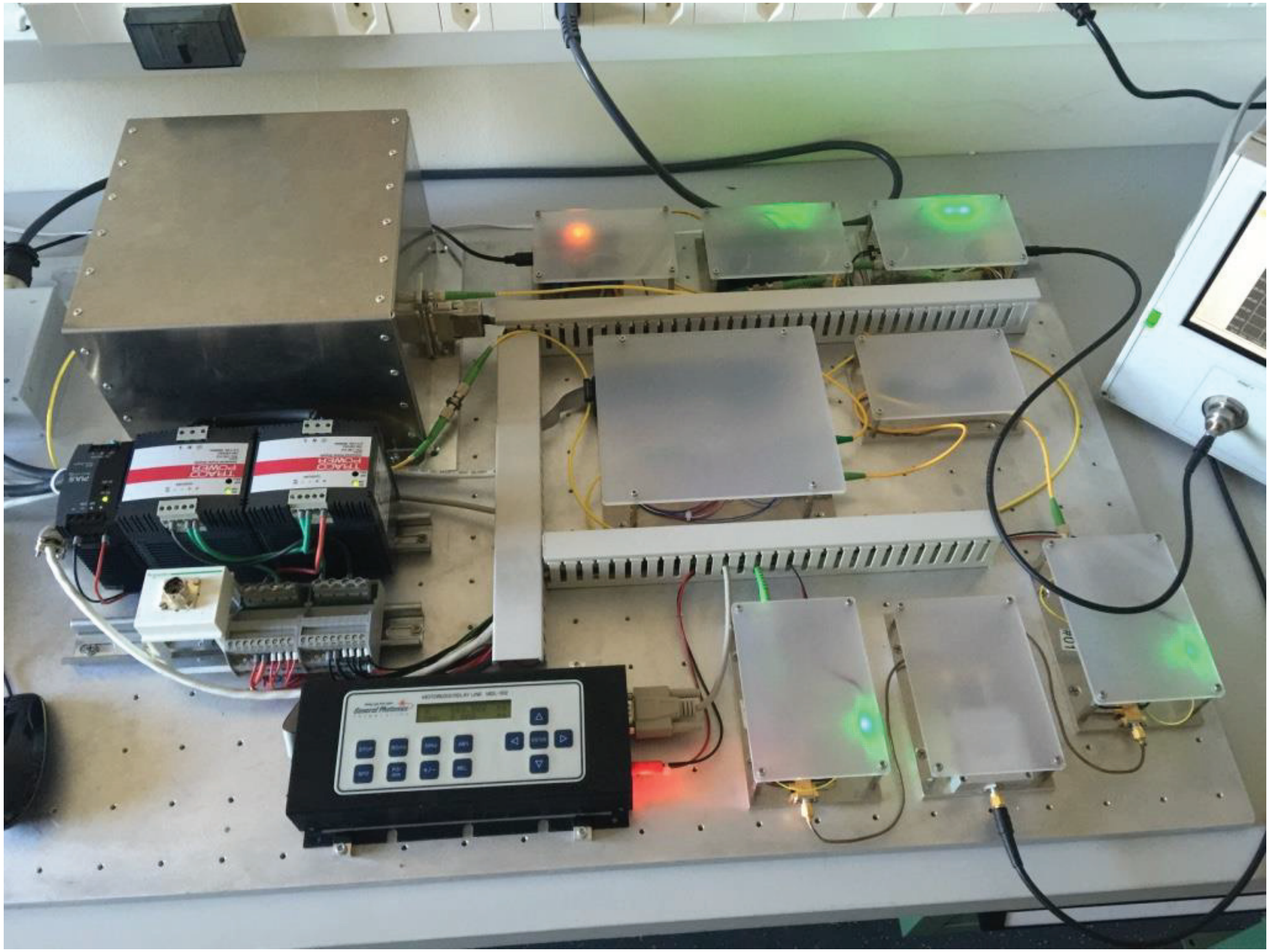
Optical Notch Filter

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

thermally stabilized box with fiber

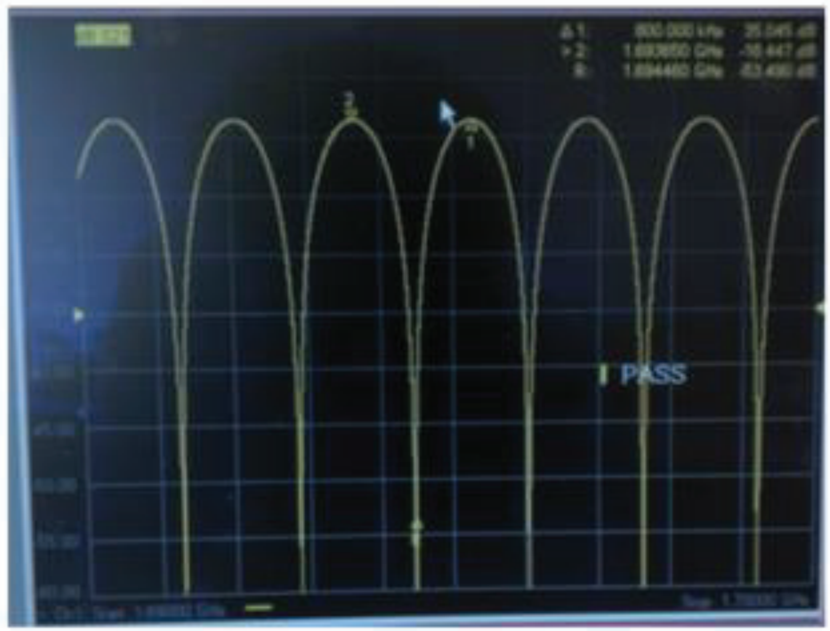


R&D on Optical Notch Filter



Optical Notch Filter

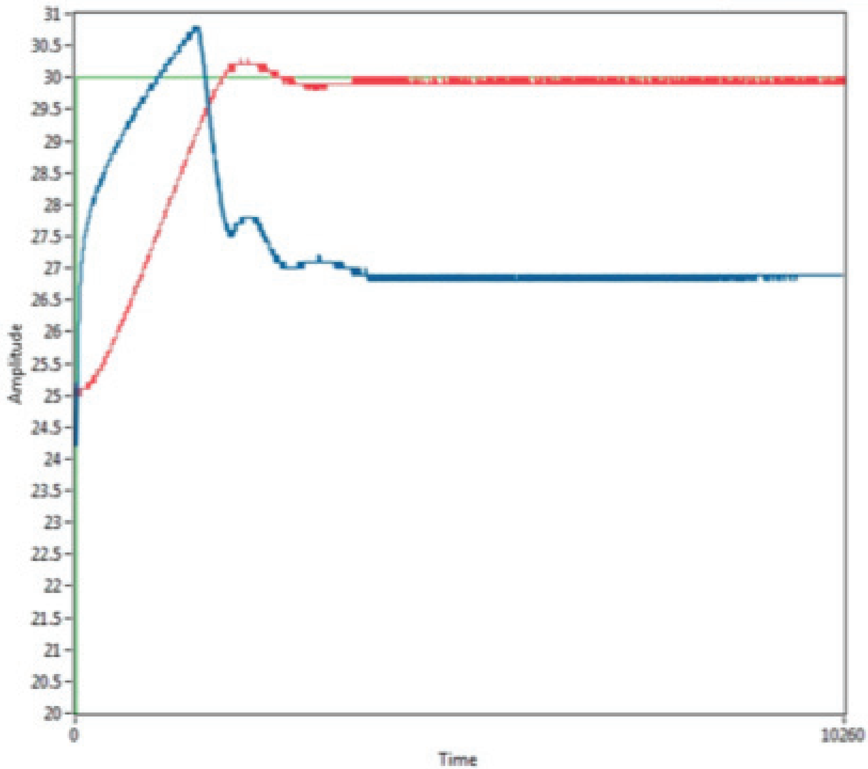
Tuned Notch Filter (3.57 GeV/c)



Tuned notch filter at 1.745 GHz, > 55 dB notch depth;
Specification: 35 dB over operating frequency range
Notch spacing: 1.589478 MHz
24 h stability ok, long term stability to be evaluated
Flatness of notch depths over frequency range to be validated

Control of Notch Filter

- Integration of controls into the CERN infrastructure
- PLC & Software as interface
- Optimization of parameters of PI temperature control
- +/- 0.2 degrees stability achieved (set-point at 30 degrees, i.e. above environment temperature)

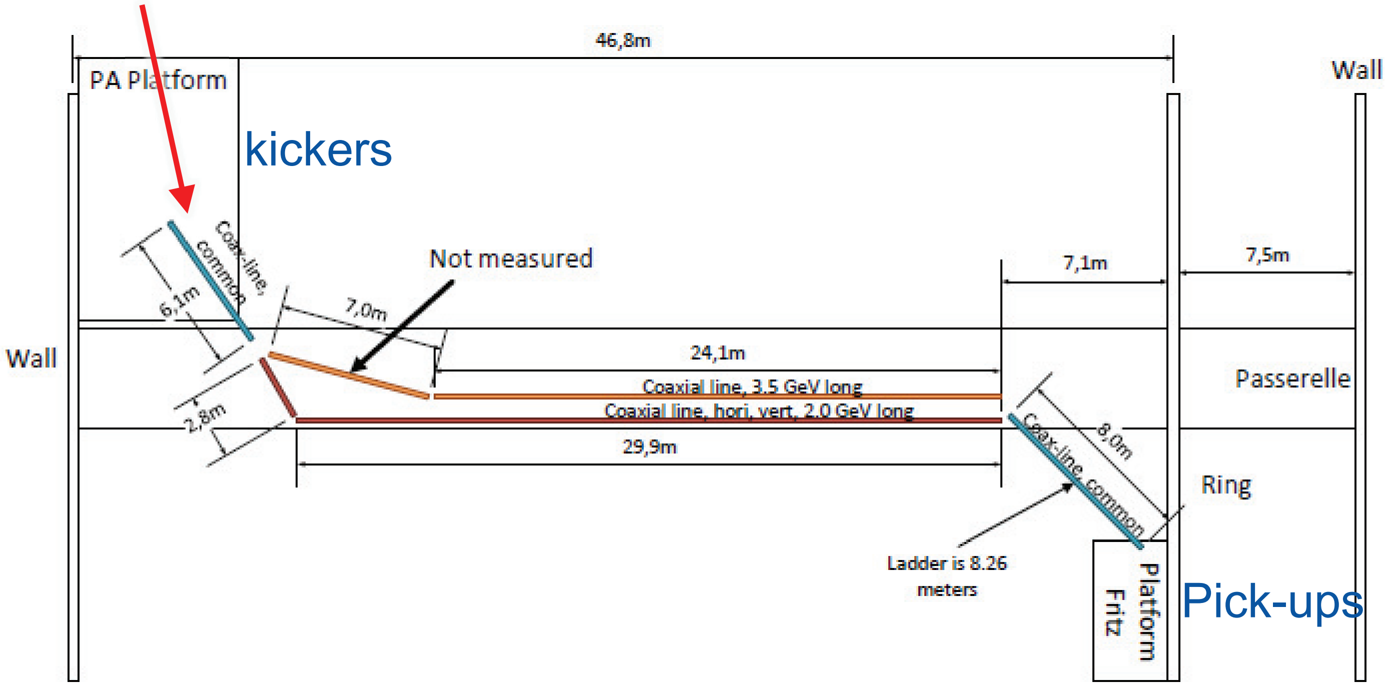


30 degrees C

Max Simonds
Luca Arnaudon
BE/RF/CS

Layout of Transmission Line

Location of optical notch filter
before power amplifiers



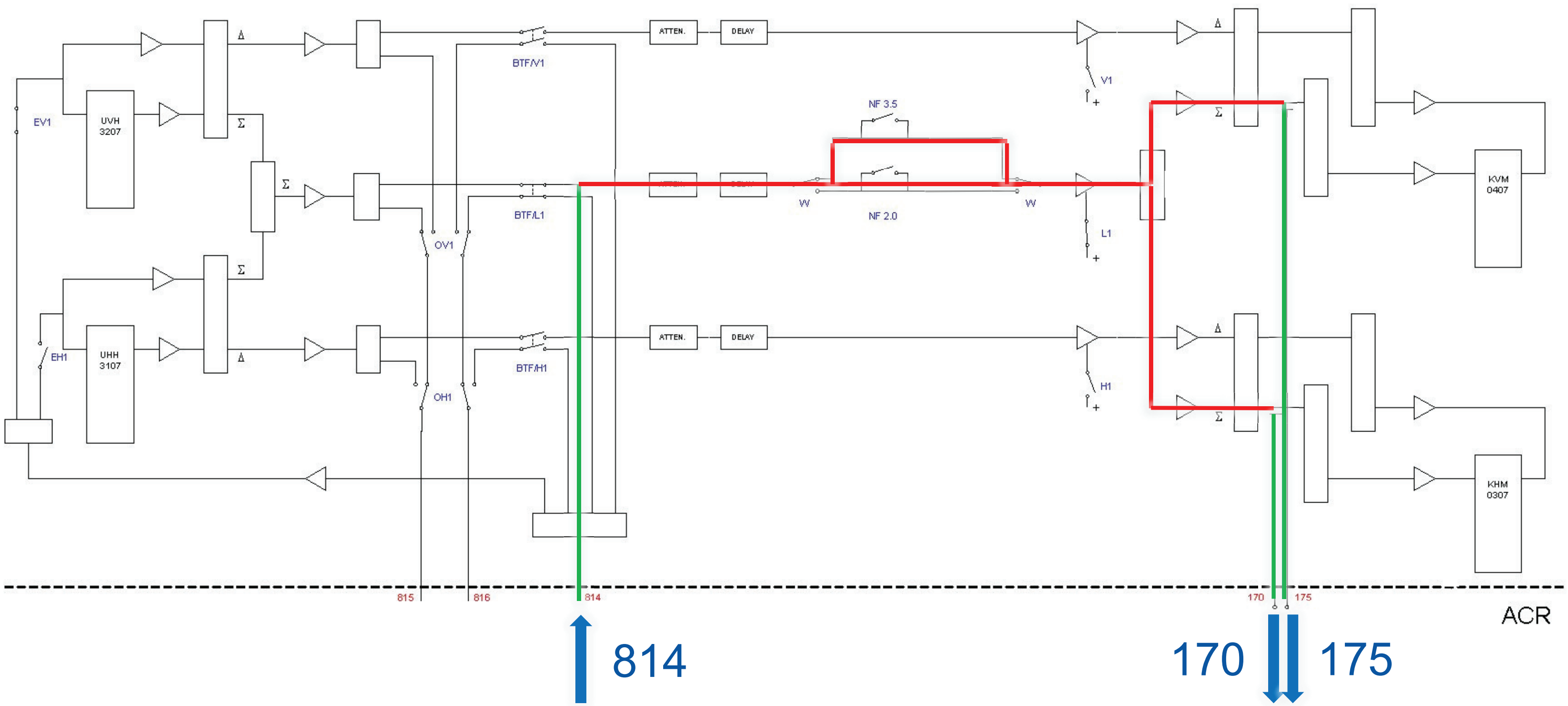
30 m of RF line needed to cross the AD experimental hall

Stochastic Cooling Transmission Lines

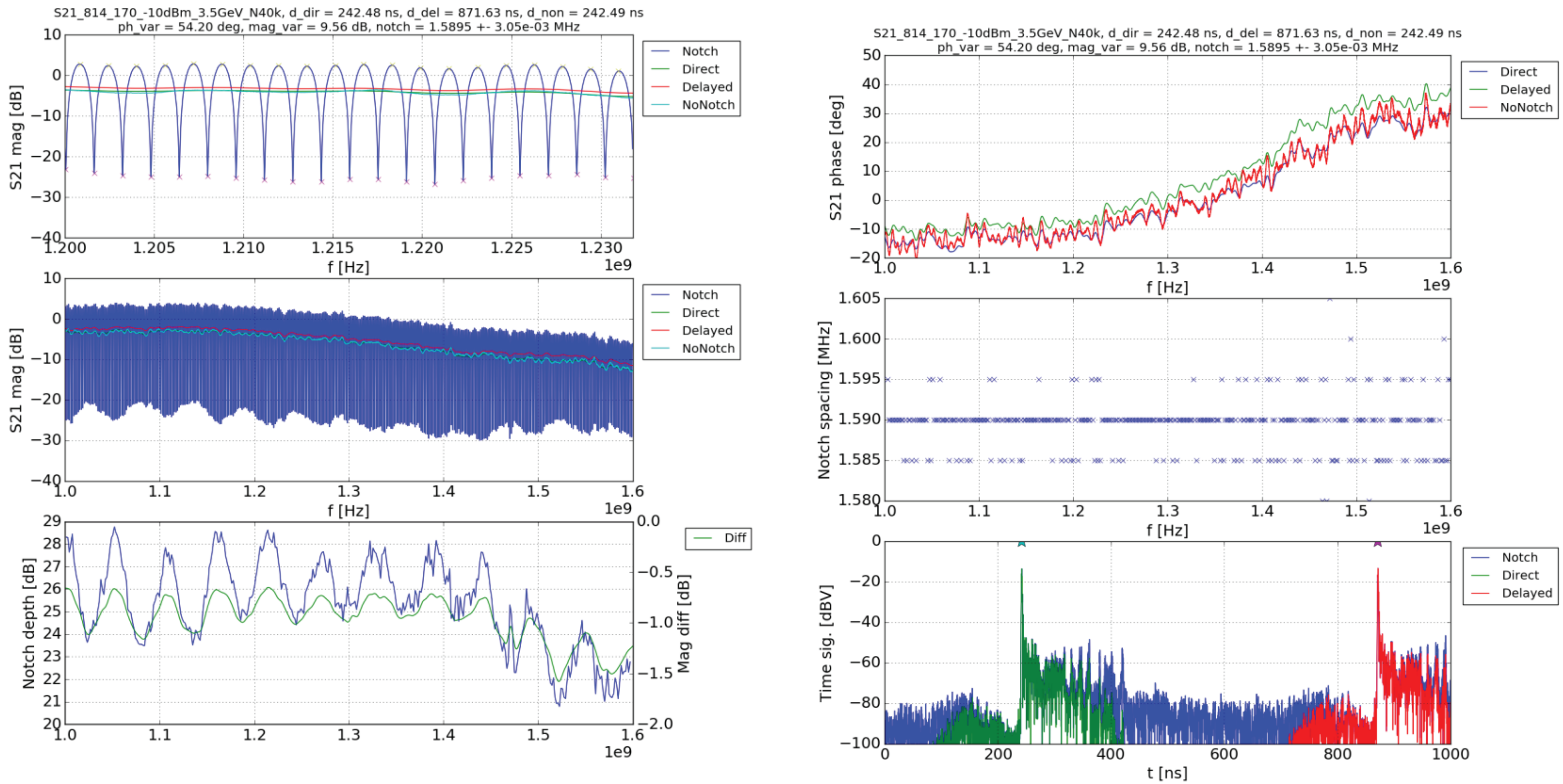
- Separate RF line for operation with the new optical delay line notch filter selected from three spare lines that cross the hall
- Spare lines carefully characterized in delay (spare 1 chosen)
- overall delay saving by suppressing phase equalizers of the old system
- sufficient gain in delay to install the optical set-up

Line	Length [m]	Delay [ns]	Velocity [v/c]
spare 1	29.80	99.51	99.9%
spare 2	29.80	99.52	99.9%
spare 3	~36.84	123.00	~99.9%

Longit. notch filter sig.path response, S21



Filter sig.path response, 3.5 GeV/c, -10 dBm

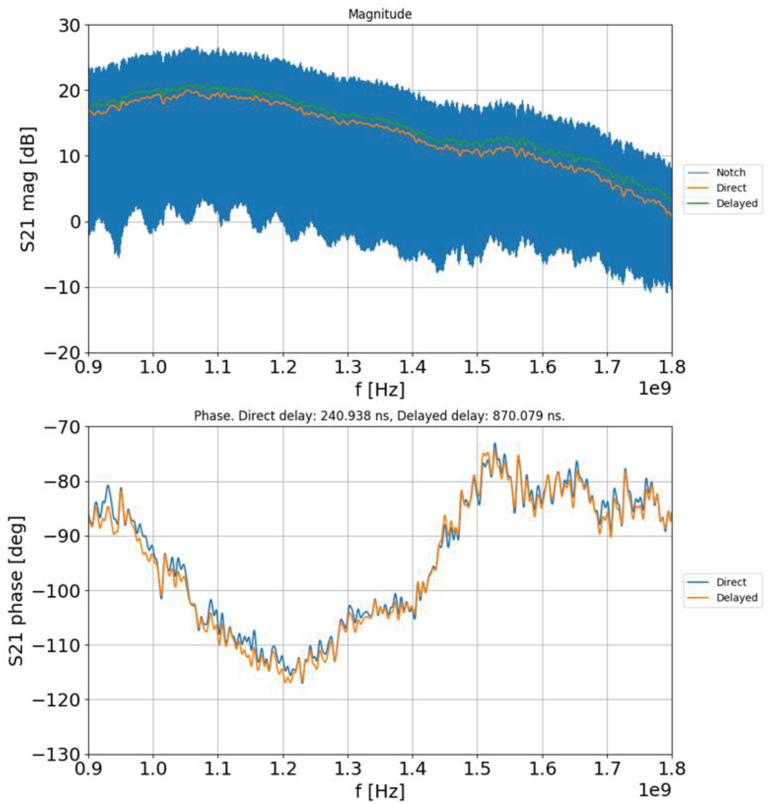


old optical notch filter: ~30 degree variation of phase over cooling band

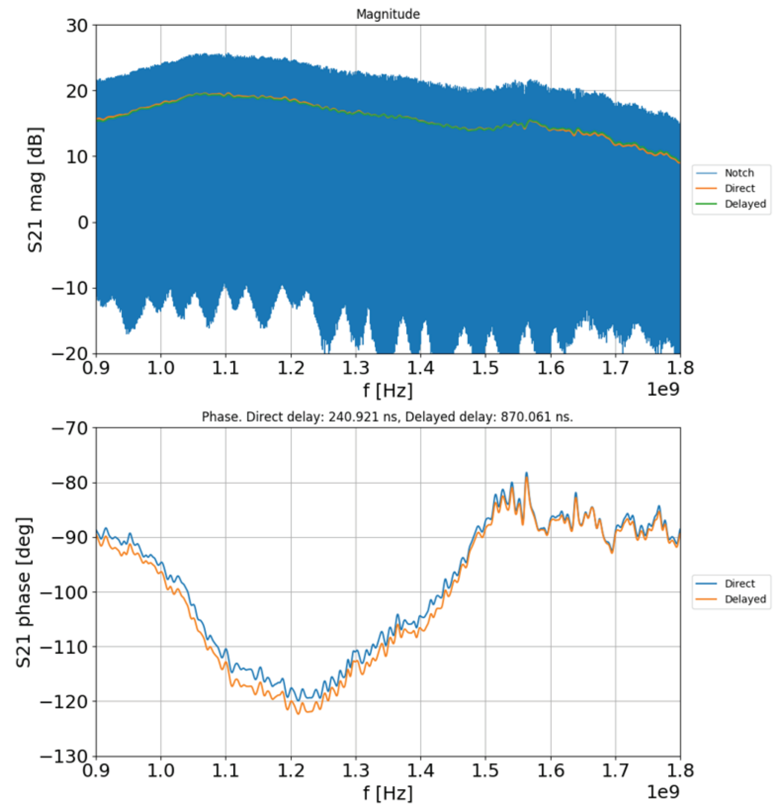
→ Strategy: match the path with optical delay notch filter to have same characteristics

later improvement of the phase flatness is possible by mean of compensation circuits

Adjustment of new path at 3.5 GeV/c



old path with cable notch

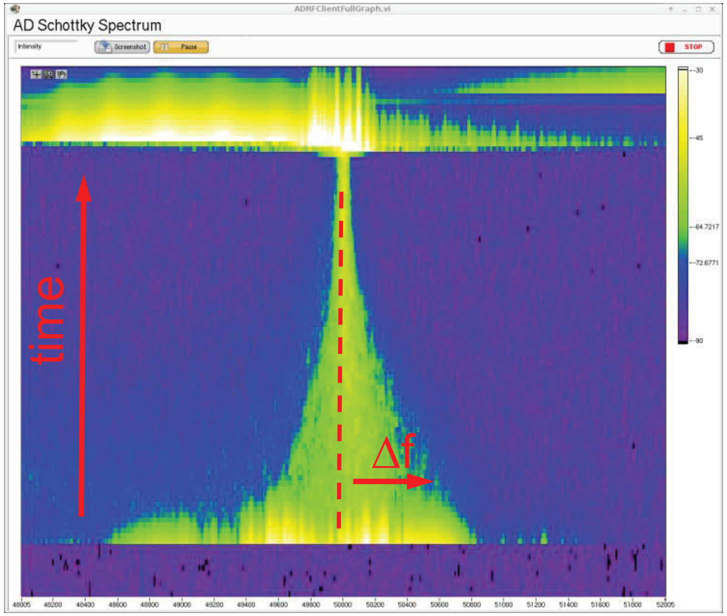


new path with optical delay notch

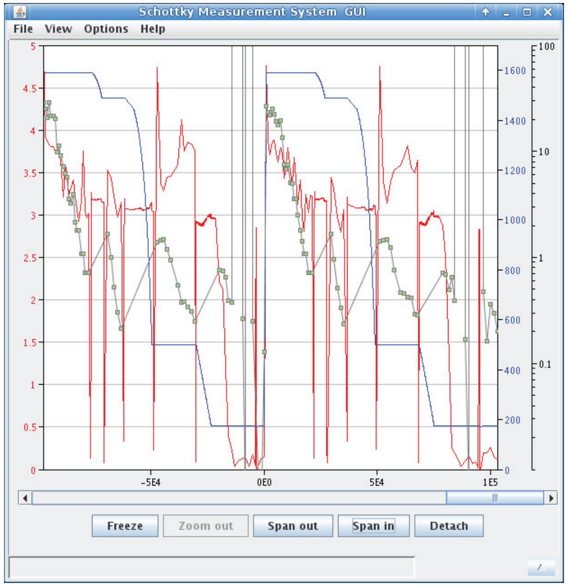
careful adjustment of the new path to match delay and phase shift of the old path key
note the higher gain in the high frequency part of the new branch

Results with optical delay line notch filter

- Adjustment of gain for optimal cooling
- Possibility to switch between optical delay line notch filter and old cable delay plant
- Careful preparation of delay and gain making the two as equal as possible minimised time spent with beam for adjustment
- Stability of adjustable optical delay will be addressed during shutdown (change of component as proposed by GSI colleague)



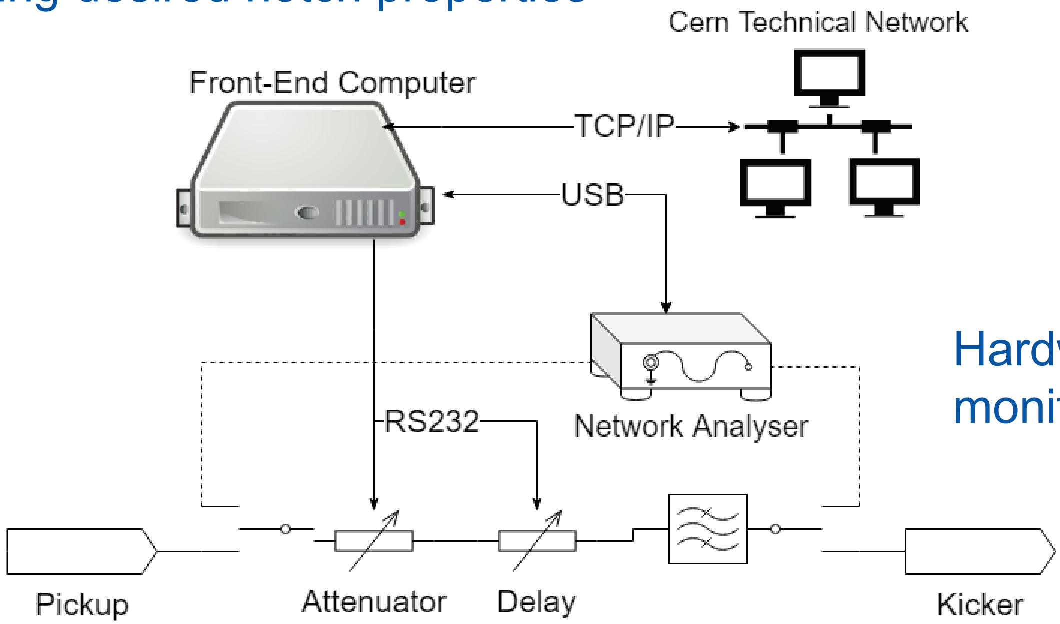
Stochastic Cooling at 3.5 GeV/c with new optical delay line notch



Schottky and intensity measurement

Planned Transfer Function Measurements

- Compact network analyser: Copper Mountain Technologies
- Controlled by software running on Cern front-end computer
- Can be integrated into Cern operator software through internal technical network
- Synchronized with machine cycle to periodically perform transfer function measurements if needed
- Can be integrated in feedforward loop that drives attenuator and delay for maintaining desired notch properties



Hardware transfer function monitoring and control

AD Stochastic Cooling – Performance 3.5 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%)	$5\ \pi$ mm mrad	$3\ \pi$ mm mrad
Ver Emittance (95%)	$5\ \pi$ mm mrad	$4\ \pi$ mm mrad
Momentum width	$+/- 0.5 \times 10^{-3}$	$+/- 0.35 \times 10^{-3}$
Cycle length	60 s	60 s – 100 s

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

F. Casper, EPAC'00, T. Eriksson Cool'13

- ELENA is space charge limited; no upgrade plans for intensity
- Since stochastic cooling takes considerable amount of time: *some interest in faster cooling*

Controls and RF Consolidation in AD

- **C02:** will be replaced by a FINEMET cavity planned for LS2; new controls for finemet system foreseen
- new digital beam control system (LLRF) for restart in 2021
- new Schottky measurement system based on the hardware of the digital LLRF will be used for intensity measurement of the bunched beam and the momentum spread measurement of the un-bunched beam
- **C10:** New controls already in place → no actions foreseen
  - Consolidation of the power system (tunes)
- **TFB (Damper)**: New controls already in place → no actions foreseen
  - used as a exciter
- **Stochastic Cooling pick-up movement control:** New controls in place

Stochastic Cooling in AD - Future

- Pick-up and Kickers
  - no consolidation possible before LS3
  - low probability of failure, possible high impact if kicker vacuum or pick-up movement fails
  - repair procedure for kicker vacuum failure (as was done in the year 2000)
- Notch filter replacement with optical fiber delay lines
  - successful tests with beam in 2018
  - full deployment for 3.5 GeV/c and 2 GeV/c for re-start after LS2
  - dismantling of obsolete equipment in YETS 2021/2022
- Amplifiers
  - de-installation and reinstallation of equipment during LS2 to open AD ring
  - refurbish parts that are not performing or needing replacement during LS2
  - establish a replacement program for amplifiers once electrical delay margin clear after having fully commissioned the optical delay line notch filters