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ABSOLUTE BEAM CURRENT MEASUREMENT FOR SLOW EXTRACTED BEAMS AT CERN's NORTH AREA FACILITY

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Abstract

The North Area facility (NA), built in the 1970s at CERN, hosts several secondary beam lines for a large variety of physics experiments: Neutrino Platform, Dark matter, high-energy physics, R&D, detector validation etc. 400 GeV/c primary proton beams, extracted from the SPS ring, are split along the transfer lines to fire on 4 targets and serve the users with secondary particles such as e-, e+, μ, π, hadrons, kaons... Within a typical slow extraction scheme of 4.8 s, one gets a spill intensity of about $4{\times}10^{13}$ protons heading to the splitters. Available beam intensity monitors are ageing fast and are accurate up to 10 % only, which is incompatible for future high intensity physics programs and new demanding specifications for the beam instrumentation. In the wake of the NA consolidation project, it is proposed to measure the beam intensity with a Cryogenic Current Comparator (CCC). Such devices installed at FAIR (GSI) and in the Antimatter Factory (CERN) have proven to be operational and have a resolution of a few nA. This paper describes the roadmap and challenges to come for the development of the new CCC.

INTRODUCTION

The NA facilities (see Fig. 1), built in the 1970s at CERN, hosts the secondary beam lines and experimental areas of the Super Proton Synchrotron (SPS) complex. Thanks to their versatile beam lines distribution, particle type and energy reach, the demand for beam time by the physics community has been increasing from year to year. A variety of experiments spans from detector R&D and validation, fixed target experiments, Neutrino Platform and Physics Beyond Colliders [1].

During most of the physics run, about $4{\times}10^{13}$ protons at 400 GeV are slowly extracted by a third-integer resonance setting for 4.8 s. The primary beam is split along the transfer line to serve the targets, for an annual integrated intensity of about 10^{19} protons on target (PoT). After 2028 the latter will steadily increase to approximately $5{\times}10^{19}$ PoT with the recently approved SHiP experiment to exploit the future high intensity facility [2]. Low loss and reduced activation of the primary beam lines are of paramount importance to improve the facility's lifetime and ensure a smooth run for the coming 20–25 years.

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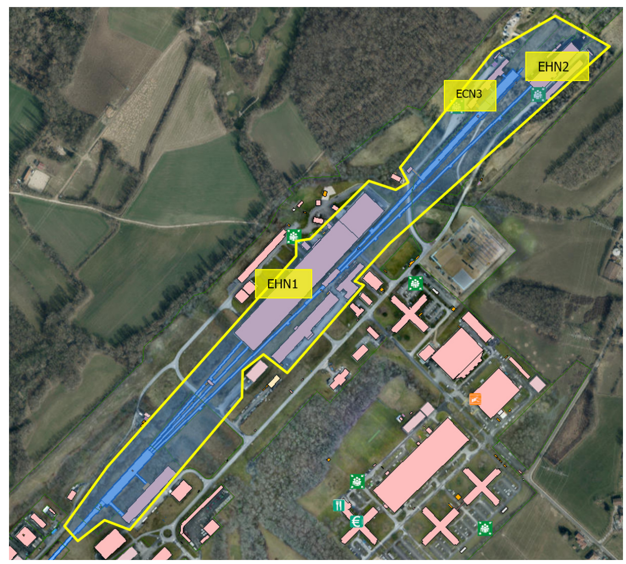

Figure 1: Aerial view of the North Area at CERN, showing the secondary beam lines (blue), two experimental halls (EHN1, EHN2) and the experimental cavern ECN3.

INTENSITY AND TRANSMISSION MEASUREMENTS

Monitoring the transmission efficiency is not trivial due to the lack of significant time structure on the extracted beam because the experiments require a continuous particle flux with a high duty-cycle, i.e. having mainly a DC time structure. Located in the primary beam lines, secondary emission chambers (SEM) are therefore used here as current monitors. Their design is robust and radiation hard. The extracted particles flux hits metal foils and generates secondary electrons which are trapped by polarised foils. In principle the signal is proportional to the spill intensity but slightly distorts the beam and doesn't provide the absolute number of particles. A joint endeavour to calibrate SEMs was difficult and time-consuming [3, 4]. It was shown that the estimated intensities could be wrong by over 20 % due to beam-induced foil damage.

Table 1 summarises the beam parameters for protons in the primary transfer lines. In addition to present operational schemes, it includes new figures compatible with the future SHiP experiment.

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Table 1: Summary of Operational Parameters for Protons

Parameters	Value	Unit	Comment
Pulse intensity	~1-4.2×10^{13}	p/spill	Nominal in NA operation
	~ 7×10^{13}		Ultimate for BDF/SHiP
	~ 2×10^{12}		Low intensity for set-up
Spill length	1 – 10	s	Nominal SPS extraction flat top of 4.8 s
Average beam current	1 – 2	μA	
Extraction rate fluctuations	3×average nominal rate		
Spill structure	DC		Baseline is DC. Possible future scenario with bunched extraction: 200 MHz or 800 MHz
Repetition period	> 7.2	s	
PoT	~ 5×10^{19}	p/year	With SHiP physics run

A demanding high efficiency beam transmission implies deploying an absolute high-resolution monitoring system in the percent range that can be used to determine the flux to BDF/SHiP whilst at the same time offering a way to study and better calibrate the SEMs located throughout the transfer line network.

A NEW CURRENT MONITOR FOR NA

The specifications of the new current monitor listed below shall overcome present and future operational constraints:

- measure the total number of particles during the slow extraction with a resolution of about 1 %, i.e. ~10 nA,
- include a calibration system for absolute measurement,
- provide 1 % accuracy at minimum intensity,
- benchmarking other monitors,
- bandwidth: DC–43 kHz, the SPS revolution frequency
- operate in standalone mode,
- non-invasive for low material budget in the beam line.

To meet these requirements, it is proposed to develop a Cryogenic Current Comparator (CCC). Several laboratories have shown the potential of CCC for an absolute measurement of beam intensity down to the nA level for electrical metrology [5, 6], and they have already been used for beam current measurements in both ring machines and transfer lines [7-10]. In the wake of the FAIR project, active R&D within the CCC collaboration is ongoing to optimize the device, reduce its susceptibility to noise and improve the cryostat design for stand-alone operation mode. One of the first prototypes built for FAIR was tested and installed in the AD ring eventually.

Cryogenic Current Comparator

The CCC is a non-intercepting device measuring the beam intensity via detection of the beam azimuthal magnetic field. It consists of four main parts (see Fig. 2a):

1. The superconducting (SC) meander-shaped magnetic shield suppresses all field components but the azimuthal beam component. The Meissner effect ensures that all magnetic field components must pass through the meander-shaped plates before being detected by the pick-up coil.
2. This weak field created by the beam is concentrated in a high-permeability ferromagnetic ring core.
3. The SC flux transformer couples the core to a highly sensitive magnetic flux sensor, a low-temperature DC Superconducting QUantum Interference Device (DC-SQUID). However, as the excitation flux increases, the output voltage is non-linear, oscillating with a period of one flux quantum $\phi_0 = h/2e = 2.06\times10^{-15}$ T·m^2.
4. To overcome this limitation, the SQUID is operated with a feedback loop circuit, the so-called Flux Locked Loop (FLL) [9]. The FLL extends linearly the dynamic range of the beam current monitor to several orders of magnitude: 5 nA – 20 μA for the CCC in the CERN Antiproton Decelerator (AD).

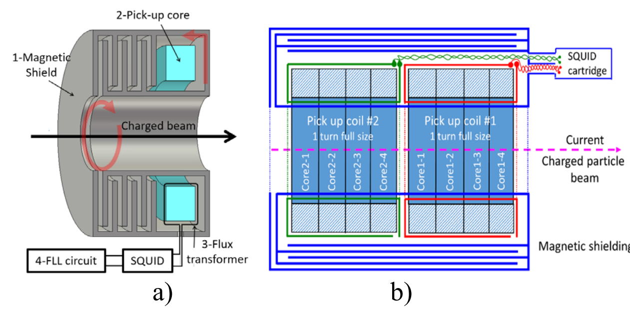

Figure 2: a) Classical design with radial meanders, as deployed in the CERN AD machine; b) dual-core and outer meander axial design.

It was shown that the shielding efficiency mainly depends on the path length of the meanders [11]. An alternative "axial" geometry, developed by IFK Jena is shown in Fig. 2b. It was originally designed to eliminate the low frequency disturbances from magnetization jumps. As the axial meanders have the full length of the detector, a similar number of meanders would provide a larger screening factor than with the classical design: under laboratory conditions, the attenuation of an external axial field of 1 μT was below the detection limit of the acquisition chain, i.e. 5 pA/μT [12].

Unlike the classical geometry, the "axial" design features two identical sets of [pick-up coils / SC transformer / SQUID] as represented in Fig. 2b. However, the signal and ground wiring to the second SQUID is purposely inverted wrt to the first one: thus, their respective analogue signals have opposite signs [13]. Thanks to the combination of a stronger signal coupling due to the cores, and the differential signal processing of both SQUIDs, the RMS current noise density achieved was lower than 2 pA/√Hz. Furthermore, the production process of the SC meander-shaped shielding is much simplified, permitting the use of lead instead of niobium which requires complex and costly electron welding steps. Following these good results, the axial geometry design associated to the double core CCC should be the selected candidate of the CCC for NA.

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CCC Electric Circuit Model

The single core CCC can be schematically split into three cascading blocks (see Fig. 3). The derivation of each block transfer function in the complex frequency domain can be found in, e.g. [9]:

1. A first cold stage circuit comprises lumped elements R, L, C from the ferromagnetic core and the SC coil inductance coupling to the beam current I_{beam}, a low pass filter. Parasitic parts are not considered here for simplicity, but a more complete model is proposed in [14]. Hence the circulating beam I_{beam} generates the flux Φ_i seen by the SQUID. The ratio Φ_i / I_{beam} defines the coupling S_{Ib} between the beam and the transformers.
2. The next part is the SQUID, a SC ring separated by two Josephson junctions. It's an active component that needs polarisation and bias current settings, fixing its working point. Φ_i interacts with the flux sensor, while the feedback flux Φ_f counteracts to minimise the SQUID response $\Phi_{error} = \Phi_i - \Phi_f$.
3. The FLL circuit converts and amplifies Φ_{error} into a voltage V_{out}. The computing of the ratio V_{out} / Φ_i defines the FLL gain G_{FLL} as well as the bandwidth (BW) of the feedback loop which determines its capability to track fast changes, also known as the slew rate (SR).

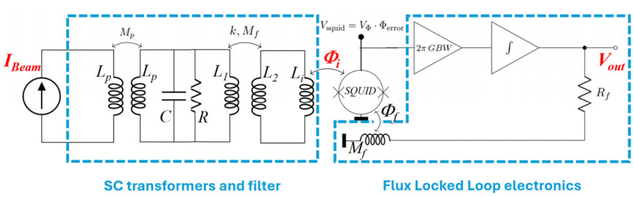

Figure 3: Schematic drawing of the CCC: both SQUID and transformers are SC; the FLL is out of the cryostat.

All in all, the current monitor produces an output voltage proportional to a given beam current. The CCC transfer function, also known as the current sensitivity, is thus derived from the product:

$$V_{out} / I_{beam} = S_{Ib} \times G_{FLL} \quad (1)$$

The AD-CCC, first commissioned with beam in 2015, became fully operational in 2021. The measured DC value of the current sensitivity is 460 mV/µA. The RC filter reduces the signal BW of Φ_i : it is aimed to limit the SR seen by the SQUID to ~1 Mϕ_0/s and dampen high-frequency noise. Combining limited BW with the differential transmission of V_{out} to the digitiser, the classical meander design exhibits an excellent resolution of ~6 nA in a cycling machine environment (see Fig. 4).

An additional SC winding around the core connected to an external current source yields the calibration signal for absolute measurements. The calibration process takes place early in the AD cycle, in the time window between the magnetic ramp-up and before pbar injection. A 3.2 s-long square pulse, of amplitude 10 µA, circulates through the calibration loop. The CCC response $V_{out,\,CAL}$ is digitized by a 16 bit-ADC for computing a final scaling factor.

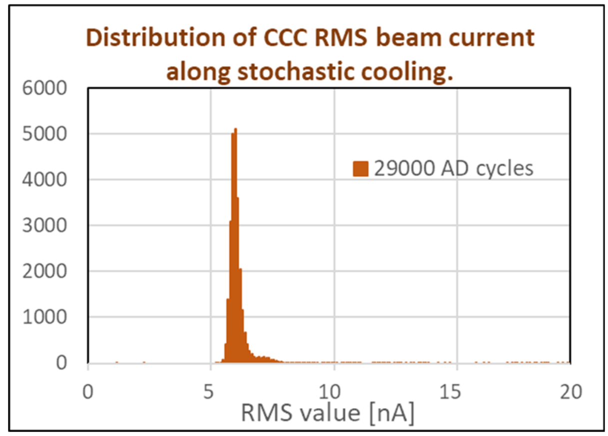

Figure 4: Distribution of RMS beam current deviation, measured with the CCC after 29k AD cycles in 2024.

As an illustration of the system's precision, the standard deviation from a distribution of 30 k calibration pulses is as low as 0.455 per mille. The figures of merit from the AD-CCC have been gathered in Table 2: the latter will serve to benchmark the forthcoming NA beam current monitor. Both SQUID and FLL from Magnicon company installed in the AD system are compatible with the new current monitor's specifications. This will simplify spare part policy and ease maintenance in the future.

Table 2: Characteristics of the AD-CCC

Parameters	Value	Unit	Comment
Dynamic range	0.01-20	µA	12 µA max in AD
Resolution	6	nA	Machine conditions
Current sensitivity	460	mV/µA	DC value
Slew rate	~1	Mϕ_0/s	For Φ_i seen by the SQUID
Scaling factor from calibration	0.6946	nA/ADC bin	Averaged over 30k pulses
Scaling factor standard deviation	0.455	per mille	

Novel CryoFan-Based Cooling Scheme

The detector at CERN's AD facility currently employs liquid helium cooling using a zero boil-off configuration, where a cryocooler-based recondenser enables standalone operation within the existing cryostats. For the proposed cryostat in the NA, a novel semi-dry cooling circuit, utilizing a CryoFan, is being considered [15]. In this design, an additional helium circulation loop connects the separated, mechanically isolated cryocooler interfaces with the detector's support structure. By cooling the support structure through conduction, the lead shield is also cooled, allowing the elimination of the liquid helium bath, along with its vessel and the required ceramic gap for magnetic signals.

R&D is necessary to validate this cooling principle, particularly the weak thermal link to the inner magnetic core, which is critical for achieving operational temperatures below 6 K within a reasonable time frame. A helium pressure above 10 bar allows the CryoFan to circulate the flow in a single-phase condition, minimizing mechanical disturbances transmitted to the detector.

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Vacuum Insulation

Despite the 4.2 K operation in the current CERN CCC a permanent vacuum pumping is established due to possible helium diffusion through the ceramic gap in between the inner helium vessel and the insulation vacuum of the cryostat (helium is not efficiently cryo-pumped by a 4 K surface). Failures of the turbo pump station together with non-operational interlocks have led to air ingress into the insulating vacuum, polluting the 50 layers superinsulation system. An extensive purge and cleaning procedure is required at room temperature to allow re-cooling of the cryostat without thermal bridges to the LHe vessel. The envisaged semi-dry cooling solution for future CCCs would drastically reduce such vacuum failure risks because the design allows for static vacuum operation without active pumping when cold.

CONCLUSION AND OUTLOOK

The steady increase in protons and the future high intensity physics programs at CERN demand an excellent control of the transmission efficiency between the SPS and the primary transfer lines. Indeed, achieving low loss and reduced activation of the facilities implies a beam current monitor featuring a resolution and accuracy in the percent level.

The development of a SQUID-based CCC has reached a degree of maturity which makes them usable for beam diagnostics fields after seventeen years of R&D. It represents a breakthrough in nA level monitoring, capable of coupling signals from a few ~100 kHz signals down to DC.

The Dual Core CCC option is an excellent compromise between current sensitivity, high shielding performance and production cost. Unlike its predecessors immersed in a LHe bath, it is proposed to apply a novel vapor cooling technique to below 6 K to eliminate the liquid-induced acoustic noise and significantly simplify the cryostat design. Lessons have been learnt to prevent, e.g. insulation vacuum issues, with controls interlocks to be implemented to ensure a smooth and standalone operation.

The construction of the new NA current monitor will strongly rely on the CCC collaboration. The baseline shall encompass cryogenics R&D, thermo-mechanical simulations, design, production, tests, and installation. All activities shall include the required manpower. The cryostat's location in the beam line should allow fast access for its maintenance and SEM calibration studies nearby. The project from the agreement signature with the partners to the beam commissioning would be four years, coinciding with the early run of SHiP in ECN3 eventually.

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