EXPERIENCE WITH HIGH-POWER OPERATION OF THE PSI PROTON ACCELERATOR FACILITY

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Abstract

The PSI proton accelerator delivers a maximun current of 2 mA (routinely 1.9 mA) at 590 MeV. Ongoing developments aim at an upgrade of the beam current to 3 mA. This will result in an increase of the beam power from 1.2 to 1.8 MW on the meson production targets and from 0.8 to 1.2 MW on the neutron spallation source SINQ. Our approach to the safe operation of a facility a these power levels is presented. This includes considerations on the design of the cyclotrons, the beam lines and the tools to handle highly radioactive components. The protection of the facility via device controls, beam diagnostics and loss monitoring is discussed. The specific requirements for operation with a sensitive liquid metal target like MEGAPIE will also be addressed.

INTRODUCTION

A high power proton beam of 590 MeV is produced at PSI by using two consecutive cyclotrons, and delivered to two meson production targets and a neutron spallation source. The production beam current has increased over the years to 1.9 mA. After the passage of the graphite targets M and E, the remaining ~1.3 mA of beam is transported to the spallation neutron source "SINQ", which uses as target solid lead rods with a steel cladding. Proper scattering of the beam at Target E is crucial for the safe operation of the spallation source.

Beam is delivered for ~5000 hours per year. The evolution of the performance of the accelerator complex is illustrated in Fig. 1. High power operation became possible after the rebuilding of the target E station in 1990 and the commissioning of a high intensity injector cyclotron. Since the facility is in permanent development and some systems are operated at the limit of the technology (HF) or are inherently critical in the particular environment (electrostatic elements) occasional failures are not unexpected. Other problems (e.g. site power, cooling) are not specific to the high-power operation. Altogether, an availability of 85-90% is achieved.

The operation of an accelerator facility at this power is characterized by high radiation levels and the complication arising from the handling of activated components, that make maintenance a challenging task. While this issue can be addressed by an adequate design and dedicated tools and procedures, damages arising from the thermal load due to a miss-steered beam may have dramatic consequences.

Melting of beam line/cyclotron components can occur

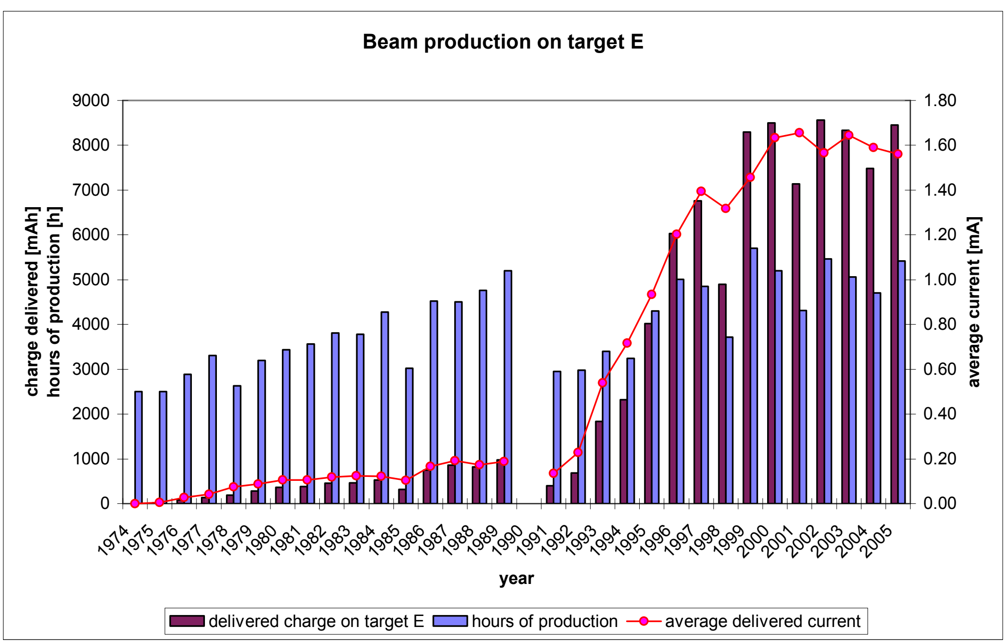


Figure 1: Performance of the PSI proton accelerator since the first operation in 1974

in 10 ms at 590 MeV or 1 ms at 72 MeV (depending on the beam diameter). Such an event could cause 2 to 300 days of shutdown for replacement, repair or remanufacturing of components, since many built-in parts are not easily accessible or deeply buried under densely packed shielding. Furthermore, there are no spare parts for many components.

Two new developments are of special interest in considering the safe operation of our facility. The test of the liquid Pb-Bi target MEGAPIE is scheduled for 2006 and the facility for ultra cold neutron production UCN is in construction.

Melting of the MEGAPIE target and window by an overly concentrated beam could cause a long shutdown. This can occur if the beam misses Target E, while it will then not be scattered, resulting in an increase of current density at the target and window by a factor ~25, which will melt after ~170 ms.

In the last twenty years we identified four incidents leading to thermal damages at our facility. Two were due to human errors during operation, of which one was in fact the consequence of a risky operation with an incomplete subsystem, and the second one resulted from a misunderstanding during a test of the interlock system. One incident was due to an underestimate of the beam tail at the location where a new component with a reduced aperture was installed in the beam line without a suitable halo detector, and the last one was due to the failure of a high-level interlock module.

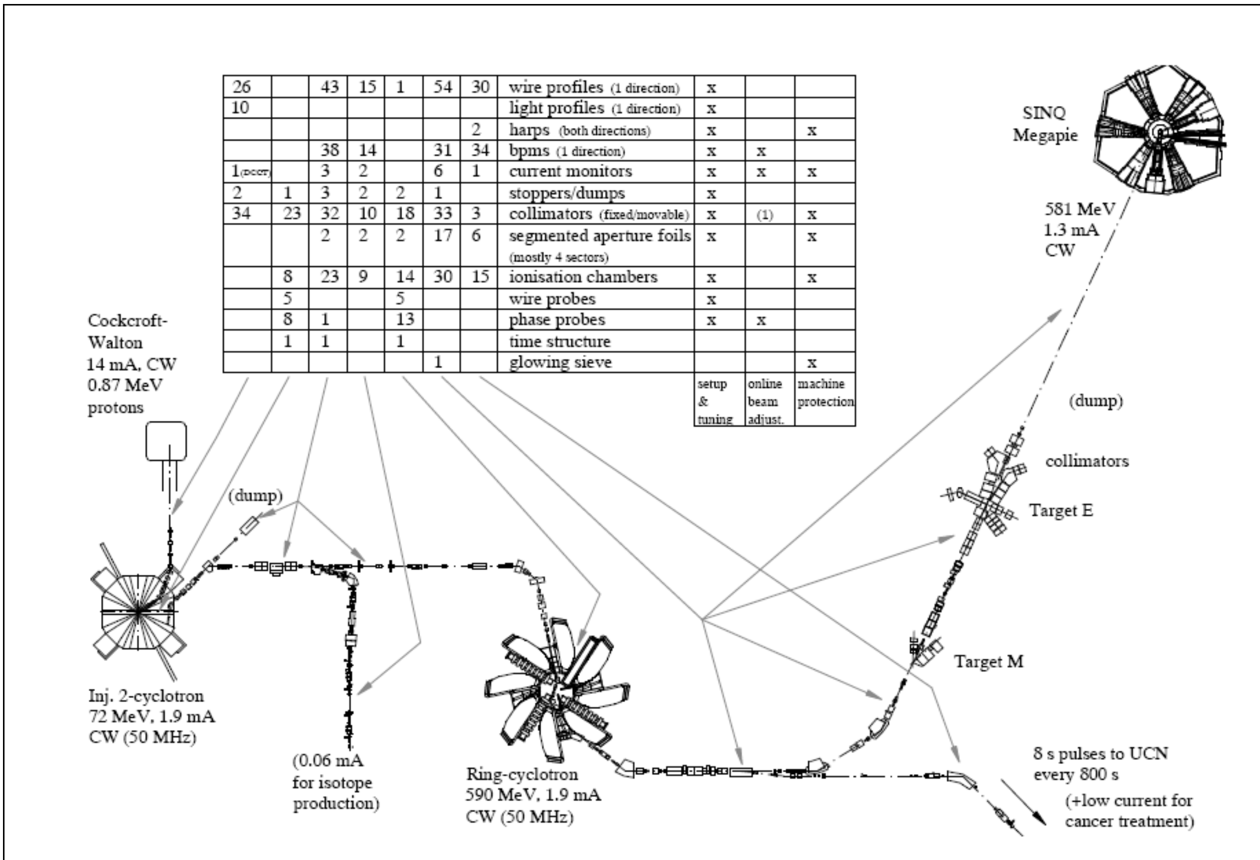
The consequences of these incidents were fortunately limited to a few days of beam interruption. While this record doesn't look dramatic, in one case the potential of a beam interruption lasting several weeks was present. Nevertheless, we consider that a good balance between invested effort and protection level has been achieved at our facility. Improvements or refinement of the concept are indeed implemented during the continuous renewal of aging components.

In the following we discuss devices and procedures having proven their ability to efficiently insure the safe operation of a high power proton facility. New systems recently installed for the protection of the MEGAPIE test are also presented.

MACHINE PROTECTION

A large variety of diagnostics are used, with strong emphasis on the detection of the beam losses. Fast (< 1 ms) redundant systems are needed for the generation of interlocks. Therefore, the detector signals are evaluated in the readout electronics and interlock signals are hard-wired to the control system.

The diagnostics used for protection, setup and operation are listed in Figure 2. Most of the systems were introduced decades ago and have since been improved



26		43	15	1	54	30	wire profiles (1 direction)	x		
10							light profiles (1 direction)	x		
						2	harps (both directions)	x		x
		38	14		31	34	bpms (1 direction)	x	x	
1 (DCCT)		3	2		6	1	current monitors	x	x	x
2	1	3	2	2	1		stoppers/dumps	x		
34	23	32	10	18	33	3	collimators (fixed/movable)	x	(1)	x
		2	2	2	17	6	segmented aperture foils (mostly 4 sectors)	x		x
	8	23	9	14	30	15	ionisation chambers	x		x
	5			5			wire probes	x		
	8	1		13			phase probes	x	x	
	1	1		1			time structure			
					1		glowing sieve			x
								setup & tuning	online beam adjust.	machine protection

Figure 2: Overview of the facility and the diagnostics used

several times.

Collimators and aperture foils

Thick collimators of copper or carbon and thin (mostly 4-segment) nickel or molybdenum aperture foils with current measurements are used for the protection of subsequent components. Additional foils at a bias of +300V are placed adjacent to one or both sides of the foils to remove the secondary electrons (yield ~0.04). The collimators (and sometimes even the vacuum chambers) are cooled if losses occur permanently. The collimators are also used for beam shaping and the signal changes (together with those of the loss monitors) provide useful information for beam setup and tuning.

Loss Monitors

Simple ionisation chambers, formed by two interleaved stacks of metal sheets for high voltage and signal, filled with ambient air (Fig. 3) are placed next to the beam.

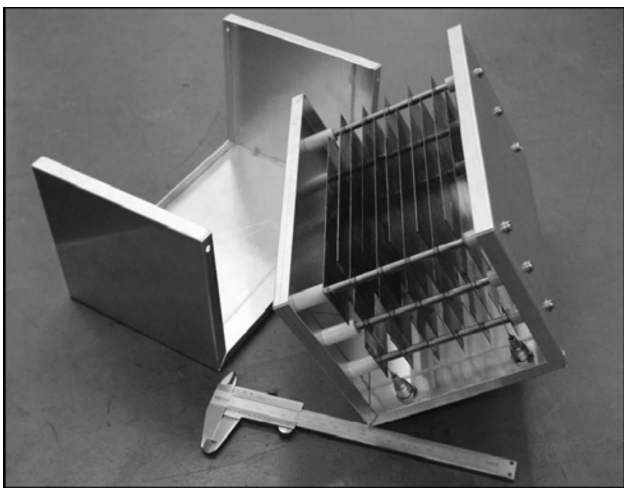


Figure3: Ionisation chamber (bias +300V, volume 2 liter, separation of sheets 1 cm, 1 nA signal corresponds to a dose rate of ~1.3 Gy/d). Ring-shaped chambers for placement around the beam tube and cylindrical chambers for introduction into concrete shielding are also used.

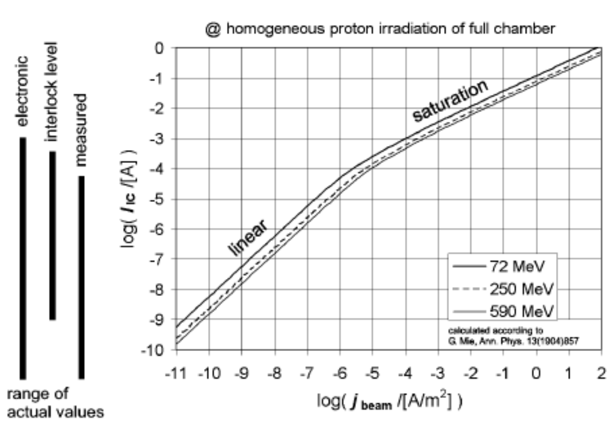


Figure 4: The response of the ionisation chamber is linear in the used regime [1].

Current Monitors and Transmission

Capacitively loaded quarter-wave coaxial resonators working at the double bunch frequency are used as current monitors [2]. The long-term stability of the current reading is limited due to temperature effects in the resonator (±1%), the long cables (±2%) and the electronics (±1%). Hence, calibration to the beam dump current is regularly performed. During this process, the loss monitors are observed in order to ensure that the losses are "correctly low". The transmission is determined by comparing the currents of two or more current monitors [3, 4]. The currents are filtered with a current dependent time constant (110 ms to 10 ms for 0 to 1.5 mA) to reduce noise. An interlock is generated if the actual losses deviate significantly from the "usual losses". Figure 5 shows transmission measurements as ratio of current detected downstream and upstream of Target E.

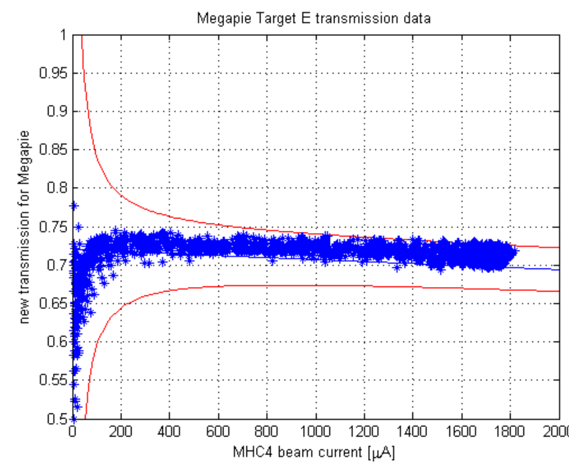


Figure 5: Observed transmission through Target E as a function of the beam intensity and range of permitted limits.

In addition, another type of transmission measurement is done around Target E: The signals of the downstream loss monitors are roughly proportional to the beam current and can be used instead of the second current monitor. Hence interlocks are generated if the losses are too low [4]. This system is applied at beam currents above 0.1 mA and has a response time of ~1 ms.

SPALLATION TARGET PROTECTION

Dispersive Shift onto a Collimator

In the case that the beam misses Target E, the transmission measurements will respond. Another redundant technique was implemented for the same situation: The beam fraction missing the target undergoes no energy degradation. Hence, it follows a different path in a dispersive transport section where it is intercepted by a collimator. The current readings from the collimator and a nearby loss monitor cause an interlock, even if only 0.1% of the beam misses the target [5].

Since our general philosophy prohibits the use of the Run Permit System of the accelerator as a primary protection system for other parts of the facility, and since the MEGAPIE test is seen as a potential risk, its safety system rely first on independent signals, i.e. a separate Target E transmission measurements, a current signal from the collimator mentioned above and a video system to be discussed in the next paragraph. It acts directly on the beam prior injection, and if needed on the ion source.

Glowing Sieve

A critical density distribution at the target could also arise from a wrong setting of the beam line. This is prohibited by hardware windows set on the magnet currents. Finally, the control of the beam current density in front of the spallation source target is provided by video observation of the thermal radiation from a tungsten sieve placed in the beam tube and heated by the beam.

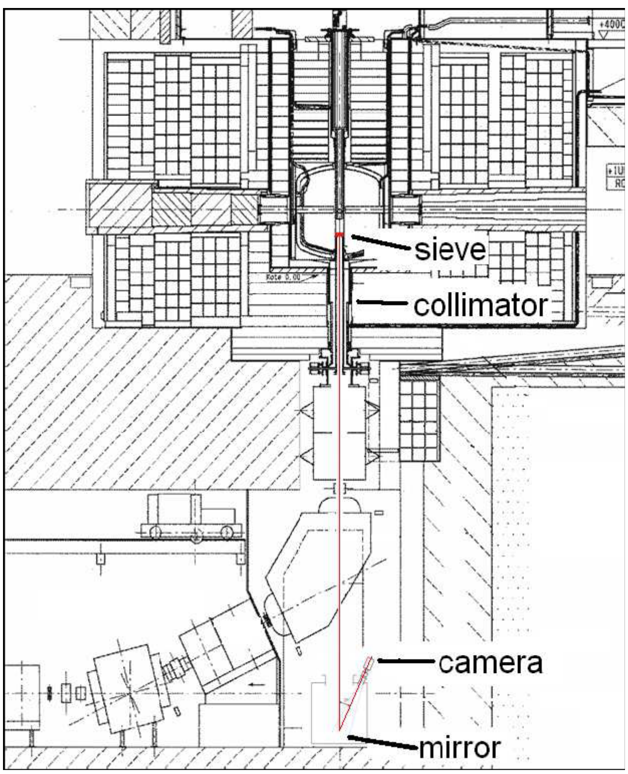


Figure 6: Glowing sieve under the spallation target.

This device has been developed and tested recently [6]. The light from the sieve passes several meters through the beam pipe and is projected by a parabolic mirror, as the only optical element, onto the sensor of a chalnicon radiation hard camera (Fig. 6).

For temperatures above 1000 °C, which are reached already at nominal beam current and size, a signal is detected above the background level which increases rapidly with beam current density (Fig. 7).

The system compare frames recorded at a frequency of 50 Hz. Using the total signal, it is sensitive and fast (~40 ms) enough to protect the MEGAPIE target from an overly concentrated beam. In addition, the position resolution of ~±1 mm is sufficient to detect the beam shift associated with a beam fraction missing the Target E.

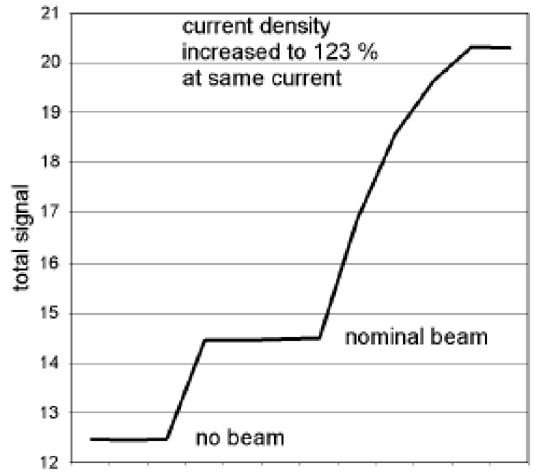


Figure 7: Response to beam current density. The temporal dependency (horizontal axis) stems from the beam adjustment and not from the detector system.

MACHINE OPERATION

Control of the Beam Position

The frequent sparking (at best ~20 times , at worse 500 times per day when the machine was exposed to air) of the electrostatic septa used for injection and extraction in the cyclotrons, causes beam trips. The beam is switched off and the current then ramped up in ~20 s. The beam optic is current dependent due to space charge effects and due to the way the beam current is regulated by cutting into the beam with a moving collimator. An automatic beam centering is therefore required and is provided by Beam Position Monitors and steerers.

The BPMs use single turn coils to couple inductively to the bunched beam (Fig. 9). A preamplifier is located ~1 m from the BPM in the vault. At present, the device works with beam currents above ~5 µA. With an output bandwidth of ~10 Hz, a centering response of ~1 Hz is reached. The position accuracy is ~±1 mm over the full current range. New electronics based on digital receivers are under development with a larger dynamic range down to 0.5 µA and larger bandwidth of ~10 kHz.

RADIATION AND HANDLING

An imperative requirement in operating a high power facility is to keep it maintenable and repairable. This impose basic choices at the design stage: For cyclotron equipped with extraction septa a high energy gain is needed to achieve a good turn separation. With a turn separation of 7 σ the losses can be held as low as .02 to .03 %. The main beam losses we tolerate are roughly (at 1900 mA): at 72 MeV: 0.5 mA at extraction of Injector 2, 5 mA at the following beam cleaning, 0.5 mA at injection into the ring cyclotron, and at 590 MeV: 0.5 mA at extraction of the ring cyclotron, 0.3 mA (average) at the following splitter, 28 mA at Target M and 560 mA at Target E. At locations with very high radiation levels during operation, only metal and ceramic parts are used, e.g. helicoflex or aluminium edge seals, mineral insulated cables, etc. In accessible places with lower radiation levels, other materials are also in use: epoxy parts, lubricated bearings, motors, potentiometers, scintillators, radiation hard glass windows, viton seals (which get hard but seldom leak if not moved), standard cables (which get brittle).

In the areas accessible for service, the background radiation can be of the order of mSv/h with higher local hot spots. The background decays to half in approximately 6 hours. Diagnostics, as well as other components, are designed to be fast demountable (few screws, lever mechanisms, guiding rods), easy to handle (no sharp edges, countersunk hexagon socket screws, weak parts guarded, grips, etc.) with a minimum of personnel (local cranes, lifting gear, special trolleys) and easy to clean (smooth surfaces). Nevertheless, reliability is the most important property.

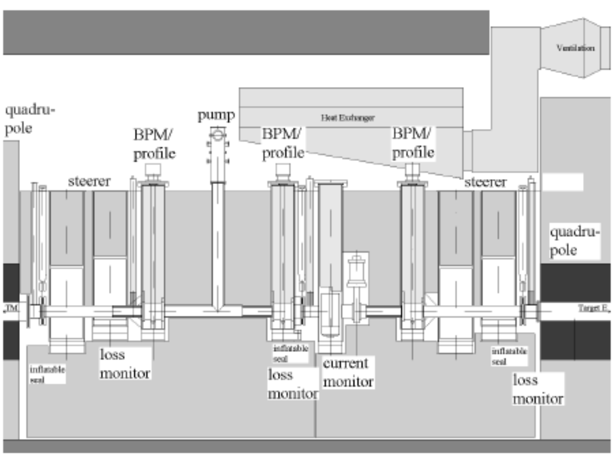


Figure 8: Closely shielded components.

In the target regions, the concept of closely shielded components has been applied [7]. After removing 4 m of concrete shielding, access is given to a service level ~2 m above the beam. The diagnostic components are placed under in-vacuum shielding blocks in chimneys (vacuum chambers with seals at the top). The chimneys are densely surrounded by shielding blocks. Drives, feedthroughs, pumps, etc. are located on top and can be easily serviced (Fig. 8).

The components can be extracted vertically into a shielded transport box, after connecting to it with individual adapters (Fig. 9), and transported to a remote handling facility. Even the vacuum chambers, which are connected to each other by inflatable metal seals, can be removed, but this could take some weeks.

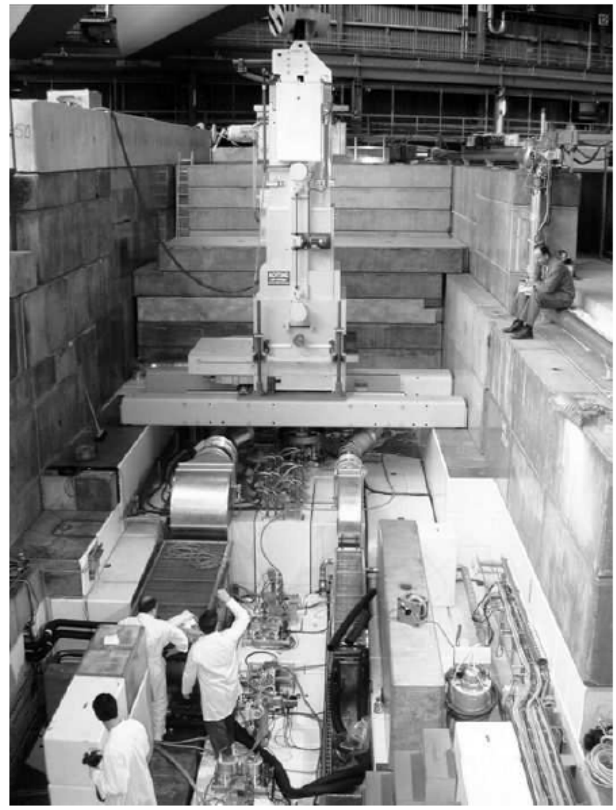


Figure 9: Shielded transport box [8].

REFERENCES

[1] R. Dölling, "Profile, Current and Halo Monitors of the PROSCAN Beam Lines", BIW04, AIP Conf. Proc. 732, pp. 244-252

[2] R. Reimann M. Rüede, "Strommonitor für die Messung eines gepulsten Ionenstrahls", NIM 129 (1975) pp. 53-58

[3] L. Rezzonico, "Transmissionsmessgeräte für Protonenstrahlen", PSI-Internal Note, April 1, 1996, and P.-A. Duperrex, "Transmissionskontrolle und neues Target E", PSI-Internal Note, October 5, 1996, and U. Müller, "Verbesserungsvorschläge für die bestehenden Strommonitore", PSI-TM 84-05-02, 2002

[4] U. Rohrer, "The multilevel protection system for the vacuum chambers of the high-intensity 590 MeV proton beam lines", PSI Annual Report 2003, Vol. VI, pp. 45-48

[5] U. Rohrer, "First beam tests with the new slit collimator in the proton beam line to SINQ", PSI Annual Report 2004, Vol. VI, pp. 23-26

[6] K. Thomsen, "VIMOS, a novel visual device for near-target beam diagnostics", Proc. ICANS-XVII, Santa Fe, 2005, to be published

[7] H. Frei et al., SIN Annual Report 1981, pp. 46-47, and SIN Annual Report 1984, pp. 11-17

[8] J. Züllig, A. Strinning, A. Geissler, "A new transport flask for PSI beam line components and the UCN collimator", PSI Ann. Rep. 2004, Vol. VI, pp. 76-77