Beam Diagnostics at High Power Proton Beam Lines and Targets at PSI


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Beam Diagnostics at High Power Proton Beam Lines and Targets at PSI

- introduction facility / overview diagnostics
- thermal damage / beam line and target protection
- profile monitors, BPMs
- electronics
- radiation / handling / infrastructure
PSI high power proton accelerator facility

- "user lab" ~400 users/a
- targets M, E for meson production (graphite)
- spallation neutron source SINQ since 1998 (solid stainless steel + Pb target)
- test with liquid Pb-Bi target Megapie ~2006
- ultra cold neutron source UCN ~2007 (solid zircaloy + Pb target)
- operates 4800 h/a ≈ 240 d/a ≈ 8000 mAh/a
- ring cyclotron in operation since 1974 (100 μA design goal --> 2 mA)

Cockcroft-Walton
14 mA, CW
0.87 MeV protons

Inj. 2-cyclotron
72 MeV, 1.9 mA
CW (50 MHz)

(dump)

Ring-cyclotron
590 MeV, 1.9 mA
CW (50 MHz)

8 s pulses to UCN every 800 s
(low current for cancer treatment)

Target M

Target E

Collimators

SINQ
Megapie

581 MeV
1.3 mA

(dump)
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## Overview Diagnostics

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<td>time structure</td>
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thermally radiating sieve
thermal damage

- melting of beam line/cyclotron components by missteered beam
  --> 2...300 days shut down for replacement/repair/remanufacturing
  (no spare parts for many components,
   sometimes lack of documentation/drawings/exact dimensions)
  time $t_{\text{melt}}$ depending on beam diameter/energy

- melting of Megapie target and window by too concentrated beam
  (if beam misses Target E: current density increases by a factor 25)
  --> ~300 days shut down

- fast interlock generation needed (<1 ms)
thermal damage

injection into Ring cyclotron:
- collimator (copper/carbon) /
- coil support
(defect of high-level interlock module, Nov. 2004)
machine protection 1) **collimators/segmented aperture foils**

- with current measurement
- collimators of copper or carbon (with water cooling, if permanent losses)
- foils of nickel/molybdenum (mostly with adjacent foil at +300 V)
  secondary electron yield $\sim 0.05$

(collimators also for beam shaping)

30% of beam lost at collimators and 4 cm thick target by courtesy of G. Heidenreich
also important for tuning:
changes of collimator and ionisation chamber currents
(here between the cyclotrons)
machine protection 2) loss monitoring with ionisation chambers

- placed ~0.1...1 m from beam, fixed position for reproducibility
- useful at beam energies >40 MeV = proton range in steel > 3 mm
- ambient air filled, 300 V, d = 1 cm, 0.002 m
- also circular type around beam tube/cylindrical in shielding
- simple and reliable
- to consider for dose estimates:
  scattering in forward direction,
  shielding by components (!),
  neutrons,
  1 nA signal \( \approx 1.3 \text{ Gy/d} \)
machine protection 2) loss monitoring with ionisation chambers

- chamber signal linear in used range

![Graph showing chamber signal levels and beam intensity relationship.]

@I_{beam, local} = 

1830 μA

1900 μA

1250 μA

70 μA

chamber signal

<0.1 nA

0.1-1 nA

1-10 nA

10-100 nA

100-1000 nA

1000-50000 nA

0.4 μA (average)
machine protection 3) **current monitors/current transmission**

λ/4 resonator excited by axially passing bunches

- **frequency**: 100 MHz (2x bunch)
- **Q cavity**: ~2000
- **3dB bandwidth**: 4 MHz (with filter)
- **output bandwidth**: ~10 kHz
- **dynamic range**: 0.5 μA ... 2.5 mA
- **accuracy**: ~0.5 % calibrated
  - every few days
  - ~5 % long term

(temperature dependent cable damping
 drift of resonator/electronics)

under development:
electronics based on digital receiver
accuracy <1 %, dynamic range 0.05 μA...10 mA
machine protection 3) current monitors/current transmission

- comparison of 2 or 3 beam currents in dedicated CAMAC modules
- taking into account "usual losses" at targets

![Diagram with graph showing current measurements and machine protection system.](image-url)

Current transmission and actual losses are plotted against $I_{\text{MHC4}}$ [$\mu$A].

- Actual losses - usual losses

- Opposite of loss: $\rightarrow$ interlock

- Allowed: $\rightarrow$ interlock

- Losses too high: $\rightarrow$ interlock (allows for some error of current measurements)

- Measurement errors too large: $\rightarrow$ interlock (allowed)

All electronics in central location.
machine protection 4) quasi current transmission via loss monitors

- upper and lower interlock limit of ionisation chamber current proportional to beam current $I_{\text{MHC4}}$
- implemented for chambers behind Target M (losses proportional to beam current)
- applied at beam current $>100 \, \mu\text{A}$

![Graph showing ionisation chamber signal vs. $I_{\text{MHC4}}$ with interlock limits and signal too high or too low conditions.]

$0 \leq 0.0 \leq 0.0$
spallation target protection 1)/2) transmission/shift on collimator

if the beam misses Target E --> no scattering --> too concentrated beam
- and 1) no current loss  --> interlock from current transmission

- and 2) no energy loss  --> beam shifted onto collimator in dispersive transport section
  --> fully passive stopping of bad beam fraction
  --> interlocks from collimator current/chamber current
  generated if ~1‰ of beam misses Target E

side view:

U. Rohrer, 
PSI Annual Report 2004, 
Volume VI, p. 23-26
spallation target protection 3) **harps**

harps for UCN: 4 m and 8 m in front of target
- 16 horizontal wires / 16 vertical wires for measurement
- wire pitch 8 mm
- 40 μm molybdenum wires (clamped)
  (molybdenum not far from thermionic emission
   @ nominal beam parameters & long pulses)
- 16 intermediate diagonal wires at +300 V bias
- retractable
- commissioning 2007

590 MeV, 1.9 mA
8 s pulses to UCN
every 800 s
spallation target protection 4) glowing sieve

video observation of thermal radiation from a tungsten sieve heated by the beam - for Megapie, tested at SINQ ("VIMOS")
spallation target protection 4) glowing sieve

video observation of thermal radiation from a tungsten sieve heated by the beam
- for Megapie, tested at SINQ ("VIMOS")

tungsten sieve 0.3 m in front of target window

collimator

mirror

chalnicon radiation hard camera (no lens!)
spallation target protection 4) glowing sieve

video observation of thermal radiation from a tungsten sieve heated by the beam
- for Megapie, tested at SINQ ("VIMOS")

tungsten sieve 0.3 m in front of target window
- signal from 1000°C
- position \( \pm \sim 1 \) mm
- time resolution \( \sim 40 \) ms

chalnicon radiation hard camera (no lens!)
automatic beam centering: **bpm** and steerer magnets

- frequent beam trips (20...500/day) + fast ramping of beam current (~20 s) + current dependent beam optics
- slow drifts (thermal/ion source/...)

--> automatic centering required (in all beam lines from Injector 2 cyclotron to Target E)

diagram: trajectory for 2000 μA defined by sliders

Actual trajectory for 5 μA

by courtesy of A. Mezger
automatic beam centering: **bpm** and steerer magnets

- single turn coils (broad band)
- preamplifier inside vault (!)
- needs beam current > 5 μA (cable damping up to 20 dB)
- output bandwidth 10 Hz
- centering response ~1 Hz
- accuracy ±1 mm over beam current range

under development:
- faster (~10 kHz) electronics with larger dynamic range (down to ~0.5 μA)
- based on digital receiver/VME
profile monitors

light profile monitors: fluorescence/lens/PMT

wire melting:
@0.87 MeV --> limited duty-cycle
@72 MeV and small beam diameter
--> thermionic emission increases signal
--> interlock from new monitor controller

40 μm Mo wires (1 or 2),
25 μm Mo foils,
33 μm carbon fibres

used for beam setup/development (data to "transport" code)
Electronics

- electronics outside the vaults (2...5 m concrete)
  - no radiation damage/hardness
  - easy access for service
  - 40...150 m long cables

- current measurements with logarithmic amplifiers
  - range 10 pA...10 mA, bandwidth current dependent
  - amplifier ground connected via cable shield to earth at detector (prevents ground loop)
  - cables: good shielding, low microphonics (noise differs by a factor up to 10000!)

- signal evaluation on board and generation of interlock
  - signal hardwired to control system
  - status and last interlock information readable, interlock levels changeable via bus, rules stored in EEPROM
  - sampling at 1...10 kHz
  - some with external/internal trigger and storage and read-out of up to 8 ksamples/channel

- dedicated front ends combined with universal back ends replace dedicated modules

- change from CAMAC to VME
systems recapitulation

- machine protection from missteered beam
  1) collimators/segmented aperture foils ("direct" measurement)
  2) ionisation chambers (loss monitoring)
  3) current transmission
  4) quasi current transmission via loss monitors

- spallation target protection from overly focused beam
  1) current transmission
  2) beam shift onto collimator
  3) harps
  4) glowing sieve

- automatic beam centering
  BPMs

- setup
  wire profiles, light profiles

- in the cyclotrons
  wire probes, phase probes, time structure
radiation hardness

- at hot places:
  - only metals/ceramics
  - metal seals (helicoflex/aluminium edge)
  - mineral insulated cables (few m)
  --> observed damage probably not by radiation
      but of thermal (beam power) or corrosive (cooling water) nature
      (even at wire monitor wires @10^{13} Gy)

- at not too hot, accessible places possible:
  - epoxy parts/lubricated bearings/motors/potentiometers/scintillators/radhard windows
  - viton seals (get hard but seldom leak if not moved)
  - standard cables (get brittle)
closely shielded components

- access to service level ~2 m above beam
  (after removing 4 m of concrete blocks)
- components under an in-vacuum shielding block (steel)
- in a chimney (vacuum chamber with seal at top)
- (inflatable seals at beam level between vacuum chambers)
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handling of closely shielded components

individual adapters to exchange bottle

remote handling facility:
manipulators, movers
(air filters, ...)
components with grips for manipulator

J. Züllig et al.,
PSI Annual Report 2004,
Volume VI, p. 76-77
handling of directly accessible components

e. g.: radial wire probes in cyclotron
- fully removable into housing
- fixed with single screw/guiding rod
- eyes for dedicated crane harness
- dedicated cart
---> removable by a single person

requirements to design:
- fast demountable (few screws, lever mechanisms, guiding rods, ...)
- touchable (no sharp edges, sunk inbus screws, week parts guarded, grips, ...)
- local cranes/lifting gear/fitting carts
- smooth surfaces (for cleaning)
but most important:
- reliable
dose rate in vaults when beam off:
- ~6 h after beam off --> half rate
- "background" up to ~2 mSv/h
  higher at local hot spots
  can change fast
contamination

personal doses:
- legal limit: 20 mSv/a/person
- in 2004 for all accelerators:
  maximum/person: 6.9 mSv
  sum: 74 mSv/196 persons

measures:
- defined areas/access
- dosimetry/supervision by
  radiation surveillance team (~7 members)
- work planning (>50 mSv notifiable)
- temporary shielding
infrastructure for active components

- remote handling facility
- workshop
- mounting room
- storage hall
- exchange bottles
- radiation surveillance
  - personal dosimetry
  - areal & components dosimetry
  - air & waste water monitoring
  (- dosimeter calibration,
   laundry for zone clothes, ....)