Bunch-Shape Measurements at PSI’s High Power Cyclotrons and Proton Beam Lines

Rudolf Dölling, Paul Scherrer Institut, CH-5232 Villigen-PSI

**technique**
- measurement locations, measurement principle
- setup of detectors and timing&other electronics
- measurement and evaluation procedure, corrections, software

**results**
- on beam parameters
- on the methods performance/problems
- on wire probe performance

**eventual next steps**

**relation to beam dynamics simulations and machine development**
R. Dölling, Bunch-Shape Measurements, CYCLOTRONS’13

**measurement principle**

- longitudinal density distribution in slice
- 5e7 bunches/s
- 2.8e8 protons/bunch
- 1.4e16 protons/s
- 11 mm, 100 ps

**Technique**

- carbon wire Ø33 μm
- 0.5% hit wire
- 61 MeV after elastic scattering 90°
- 200 protons/s
- ~320 ps stopping time

- scintillation
- light collection ~50000 photo electrons
- PMT amplification
- 50 m coax cable

**Levels:**

- input pulse at timing electronics
- start timer
- accept pulse

**Enlarged:**

- start timer
- counts
- more wire positions

**Histogram --> 1D slice profile**

2D profile
R. Dölling, Bunch-Shape Measurements, CYCLOTRONS'13

**measurement principle**

- Longitudinal density distribution in slice
- 5e7 bunches/s
- 2.8e8 protons/bunch
- 1.4e16 protons/s

**Technique**

- Carbon wire Ø33 um
- 0.5% hit wire
- 61 MeV after elastic scattering 90°
- 56.6 MeV after inelastic scattering 90° (~120 ps late arrival)
- ΔW = 4.4 MeV and other discrete energies

**Scintillation light collection**
- ~50000 photo electrons
- PMT amplification
- 50 m coax cable

**Levels:**
- Input pulse at timing electronics
  - Start timer
  - Accept pulse

**Enlarged**
- Start timer
- More wire positions
- 2D profile

**Histogram --> 1D slice profile**

**Timing Electronics**
- 0 ns
- 5 ns
- 10 ns
- 15 ns
- 0 V
- 1 V
- 2 V
detector setup at beam lines

with several wire orientations
\[ \rightarrow \text{several 2D projections of 3D density distribution} \]

carbon wires Ø33 um with current read out

(schematic, seen in beam direction, the broader printed wire ends are closer to the beholder)

scintillator

PMT

Mumetal shield

at 590 MeV:
detector setup at Injector 2

wire replacement

wire 0 2 3

last turn

scintillator
shielding against extraction elements EEC, FM
scintillator (moves with wire)
select 
- bunch shape 
- resolution (from coincidence spectrum, several variants for evaluation of parts of circuit not shown)

- timing modules (NIM)
- relays
- high voltage
- wire current readout (logarithmic ampl.)
- motor drivers
setting the PMT voltage

- instead of adjusting the discriminator level, the PMT voltage $\rightarrow$ gain $\rightarrow$ pulse height is varied
- precision is needed (1V steps or better)
- stability is needed (to prevent walk)
- in some locations to be checked weakly (degradation of scintillator due to radiation)

@fixed beam energy (at beam lines)

72 MeV (small aperture)
"clean" separation
all elastically scattered usable

72 MeV (large aperture)
only 40% of
all elastically scattered usable

590 MeV (not stopped)
no discrete energies
only a few slower particles usable $\rightarrow$ long measurement duration
Bunch center energy changes from turn to turn → PMT voltage to be varied with probe position. Some error introduced by assumptions on how local beam energy increases with radius:
- increase per turn, linear with bunch center radius (betatron oscillations introduce error)
- same energy all over a bunch (not linear with actual radius, effect of space charge induced vortex motion?)
→ beam dynamic simulations needed for information
(Pulse-height resolution not good enough to measure energy differences in bunch.)

setting the PMT voltage

@varied beam energy (Injector 2)

contour levels every 10% and at 1% and 0.1% (10%-level at border between cyan and light blue) → halo over-emphasized
### Effects and Consequences

<table>
<thead>
<tr>
<th>Effects</th>
<th>Consequences</th>
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</thead>
<tbody>
<tr>
<td>- distance wire – detector changes</td>
<td>- shifts TOF of elastically scattered proton</td>
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<tr>
<td></td>
<td>- shifts solid angle to detector aperture</td>
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<tr>
<td>- systematic variation of beam energy with radius (in bunch and from turn to turn)</td>
<td>- shifts TOF of elastically scattered proton</td>
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<td>- shifts PMT pulse height (walk)</td>
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<td>- shifts scattering cross section</td>
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<td>- time resolution of measurement</td>
<td>- elongates</td>
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<td><strong>evtl. corrections</strong></td>
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* with assumptions on energy variation

* can be accounted for by including scattering and transport to detector in beam dynamics simulation (predict histogram)

More issues, all elongating, hardly to correct for:

- beam energy spread at each radius
  - spreads TOF
  - affects scattering cross section

- detector aperture allows range of scattering angles
  - spreads energy and cross section

- quantum efficiency/gain changes over PMT surface
  - affects PMT pulse height (walk)

- light collection efficiency dependent on impact position
  - affects PMT pulse height (walk)
  - affects TOF of light & PMT transfer time

And

- PMT base line distortion (by EMV or background radiation) systematically/statistically
  - affects discrimination

→ significantly more complicated than e.g. wire monitor evaluation
measurement modes (can be chosen for every wire)
- 2D projection of bunch shape (standard):
  slice time-structure measured at a serious of wire positions
  ~6 minutes/full projection
  ~30 min in Ring cyclotron (smaller aperture, not stopped)
- check of PMT voltage:
  slice time-structure measured for several PMT voltages
  (at fixed wire position)
- check of time resolution:
  as above but coincidence signal instead of reference signal

functionality
- sets relays
- proposes useful voltage and position ranges
  for all locations & measurement modes
- steers drives, starts/stops/reads MCA (waits if beam is missing)
- monitors PMT base current for over-current condition
- logs ~500 machine parameters (settings, losses)
  plus wire current, plus PMT voltage & base current
  at each wire position (min/max/av)  (→ test case for simulations)
- (some machine interlock levels has still to be increased by
  hand to allow for increased losses from wire)
- gives progress information
- still not a „standard“ application
- starts with useful time and position ranges for all locations & measurement modes
- performs corrections (configurable)
- shows 1 logged machine parameter (out of ~500)
- writes data to files
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relation to beam dynamics simulations and machine development
57 - 72 MeV
production beam 2200 uA

- Three separate scans with correspondingly adapted PMT voltage ramps.
- A relative phase slip of ~9° builds up over the last 11 turns.
condensed to bunch parameters of many turns at 2200 uA

extracted from the three scans (plus two repetitive scans, one with increased PMT voltage) individually

derived from a combination of two scans

(lines only to guide the eyes)
beam after at Injector 2

MXZ1/2  MXZ3/4  MXZ5/6  MXZ7/8

MXZ1/2

MXZ3/4

MXZ5/6

MXZ7/8

production beam 2200 uA
possible sources of artificial counts:
- background radiation
  (especially difficult when correlated
  i.e. created by loss generated by the wire)
- coupling of stray RF fields to
  measurement cable (correlated)
- reflections in timing circuit

even in a "quiet environment" it is difficult
to judge what is an artefact
- transversal tails are presumably real
- longitudinal tails may eventually be
  artefacts

production beam 2200 uA
behind Injector 2
"quiet environment"
The dynamic range can be extended by longer integration times at wire positions where the signal is low.

For transversal profiles, even the PMT voltage can be increased, in order to make use of the inelastically scattered protons. (An overlap is needed to find the suitable scaling factor.)

→ 5 orders of magnitude reached

Sensitivity
≡ beam passing through the wire which corresponds to 1 count

production beam 2200 μA
last turns in Injector 2
"quiet environment"
an example of a low dynamic range:

raw data

filtered

production beam 2200 uA in Ring cyclotron at high beam loss not a "quiet environment" (and a degraded scintillator)
Time resolution from coincidence spectrum $\sigma_{\text{coinc}} = 26$ ps and quadratic addition of the contributions of both sensors, weighted by the number of photoelectrons created at each detectors photocathode

$\Rightarrow \sigma_{\text{det B}} = 13$ ps

(17 ps with degraded scintillators)

Idea: replace separate PMTs bei separate cathodes/anodes of same PMT

$\Rightarrow$ Does not work because of dependency of signal amplitude at each anode on impact position of proton: „detectors“ are not independent but inversely correlated. (Sum signal is nearly independent of position. Time resolution of full system depends also on this detailed dependency.)

$\Rightarrow$ Time resolution of the subsequent parts of the system:

$\sigma_{\text{sub50}} = 13$ ps/$\sqrt{2} = 9.2$ ps (measured at 50\% signal height)

$\sigma_{\text{sub100}} = 9.2$ ps/$\sqrt{2} = 6.5$ ps (estimated for 100\% signal height)

$\Rightarrow$ lower limit for full system
Results: time resolution

shortest measured bunch length = 17.2 ps is an upper limit of the
time resolution of the full system $6.5 \text{ ps} \leq \sigma_{\text{full}} \leq 17.2 \text{ ps}$

correction of resolution (assumed to be 13.5 ps) by quadratic subtraction:
this comes to its limits!

beam 50 uA after Injector 2
Thermionic emission dominates current signal of slowly moved wire probe in narrow beam (@72 MeV). Can be suppressed by positive wire bias. (Simulations: will be <1% of regular signal if wire speed >1 m/s)

Stray particles limit dynamic range of wire probe (depends on environment). When thermionic emission is not developed, 0 V bias gives the best result (in this environment). Bunch shape measurement is clearly superior (but slow).
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relation to beam dynamics simulations and machine development
improvements at 590 MeV

longer drift needed for full separation?

no discrete energies

ΔE discriminator acceptance window → better rate

(LED acceptance level only a few slower particles usable)

coincidence measurement

second detector after ~0.5 m further path

has also to be passed for acceptance

→ better immunity against background radiation
→ better dynamic range

eventually an additional probe at the last turns of the Ring cyclotron

eventual next steps
The energy of the beam after the Injector cyclotron can be determined to \( \sim 1 \times 10^{-3} \) by making the distance detector-wire variable (by setting the detector on a motorized feedthrough) and taking the time spectra at two different distances.

Eventually it is possible to unfold some details of the beam energy distribution.
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relation to beam dynamics simulations and machine development
my personal view on the future development of our machine

standard operation

machine
space charge, tails, scattering
10 nA loss \(\rightarrow\) sign. activation
loss details matter

operators
empirical tuning
("turning all knobs")
matching core\&halo
\(\Rightarrow\) optimum for
given setup (?)
machine "model"
by experience

beam dynamics
estimations and
"simple" simulations
matching beam core
"simple" models:
beam core, no tails,
few moments
(Joho's \(I_{\text{max}} \approx n_{\text{turn}}^3\))

Transport-code

intensive
detailed simulations
matching core\&halo
detailed models:
tails, profiles
("cutting early")

OPAL-code
3D space charge
scattering at
collimators
B, E field maps

Y, Bi, W, Z, A, ...

few moments
detailed information
still not used

"understanding" losses
predictive capability on effect
of proposed hardware changes

probably the only practical way for improvement
(production machine, complexity, activation)
\(\Rightarrow\) step up efforts with detailed simulations
(a breakthrough is needed and will be worth the effort)

beam diagnostics

loss monitors 0.005
BPMs
wire probes
wire scanners 10
bunch shape monitors 0.05
later: emittance scanner 4D
collimator currents 10
phase probes 0D
1D
2D
0D

optimum
effective
sensitivity
[nA]

relation to beam dynamics simulations and machine development
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**relation to beam dynamics simulations and machine development**

Thanks for listening!
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back-up slide: beam at Injector 2 last turns

condensed to bunch parameters of last turn at varied current

extracted from the three scans (plus two repetitive scans, one with increased PMT voltage) individually

(parameters logged during measurement)

derived from a combination of two scans
idea: restoring short beam at entrance of Ring cyclotron
→ roll-up there (?)

(layout based on 1D bunching simulation)

preliminary tests: full voltage / envisaged operation
not possible yet due to increased losses

probable explanation:
difficult to match beam and halo

Schmelzbach et al., EPAC06

J. Yang et al., HB2008

M. Humbel et al., this conference
possible strategy: understanding beam losses in detail
- where (at low energies) to cut and how to match the halo ("collimation system")
- controlled beam tails, "matching of beam & halo"
- lower losses

detailed simulations

detailed input from diagnostics ← bunch-shape measurement, halo measurement

what precision of measurement & simulation is needed? (maybe less than anticipated at first glance)

encouraging steps done (OPAL code includes space charge, fields, scattering, optimisation, not neutralisation)

still much to do (put many details to input file: collimators, trim coils, measured profiles, ...
space-charge neutralisation at 0.87 MeV?)

and still far from full description or prediction

will it work?

it is essential for further development of the machine