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

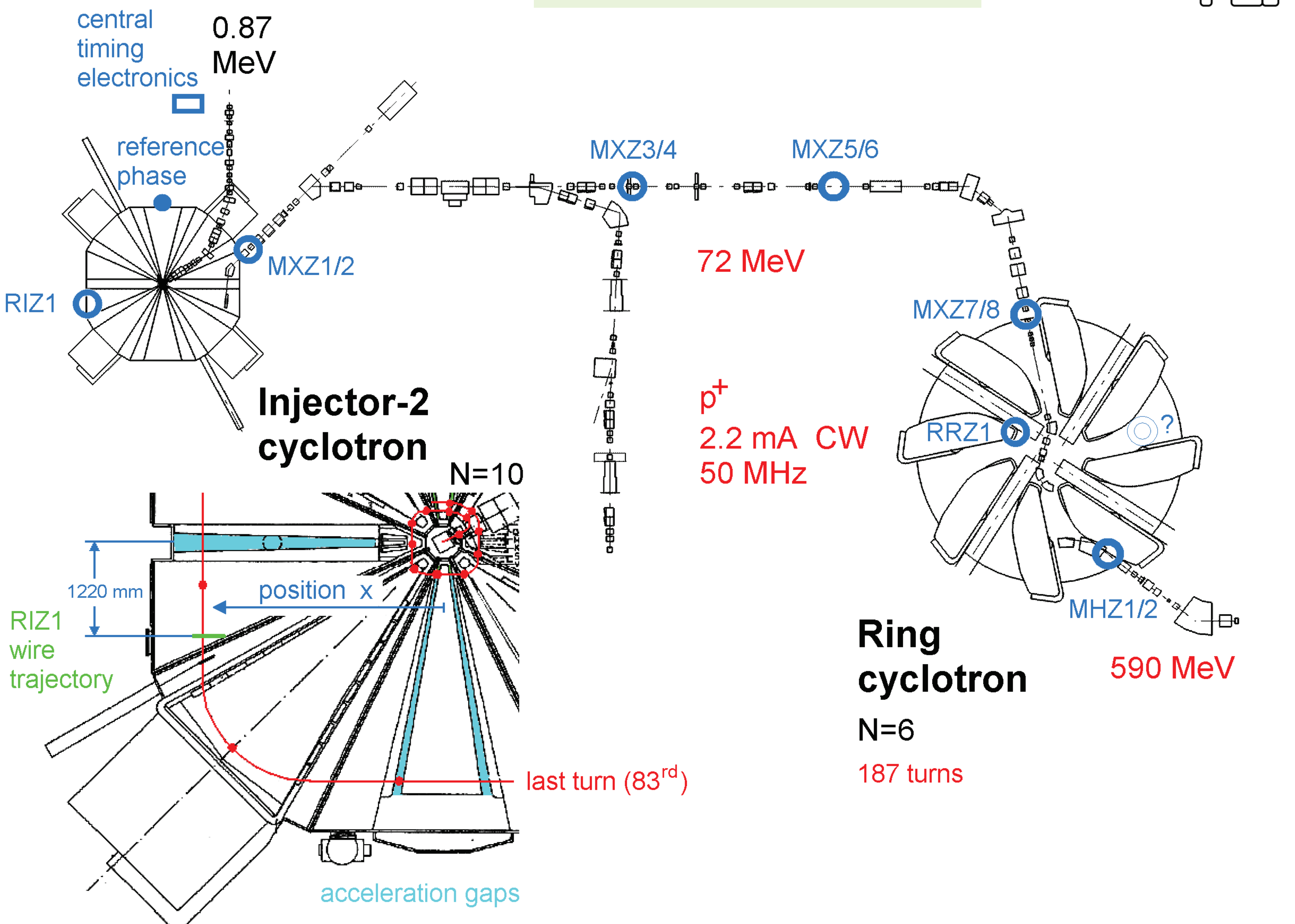
results

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

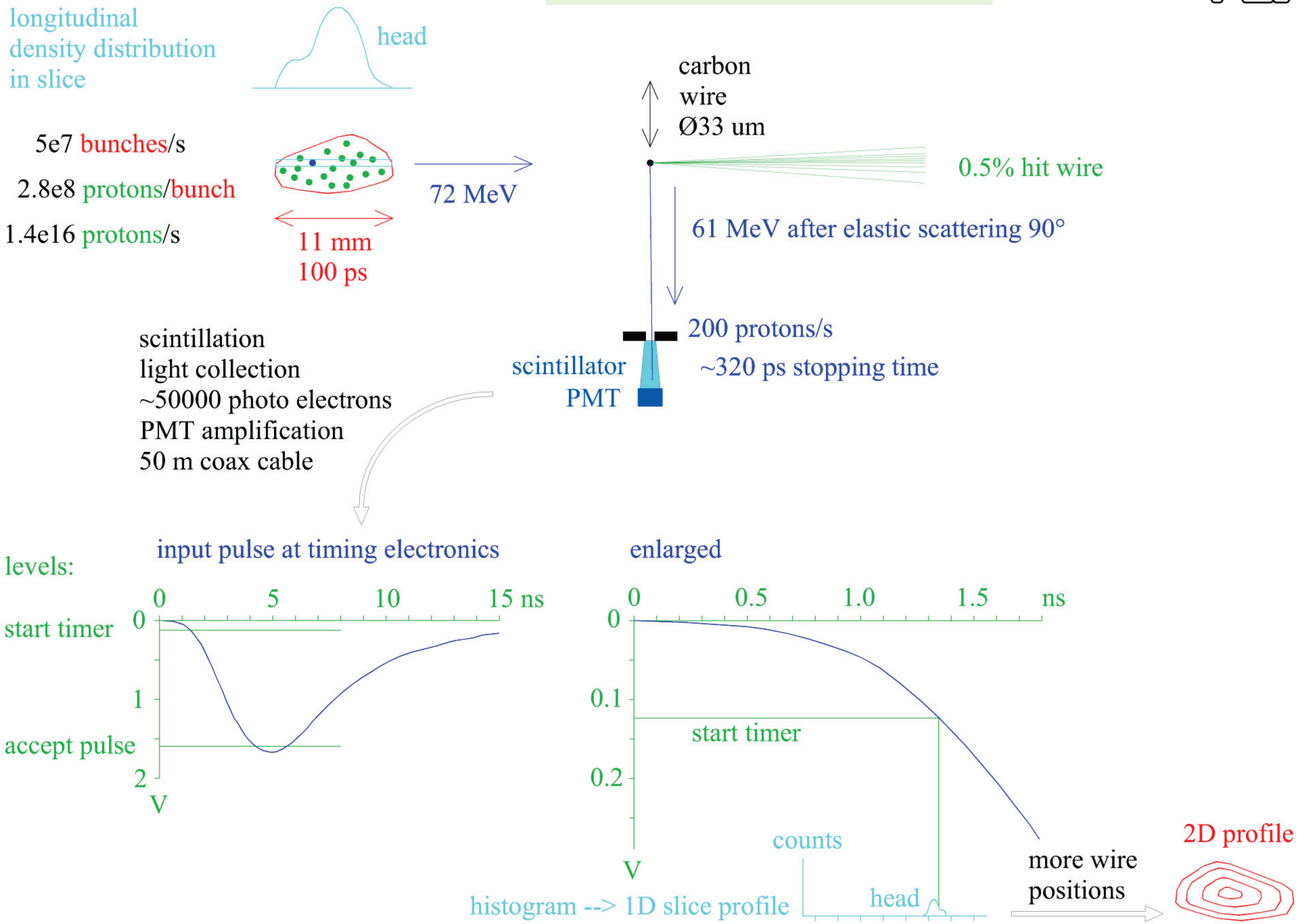
eventual next steps

relation to beam dynamics simulations and machine development

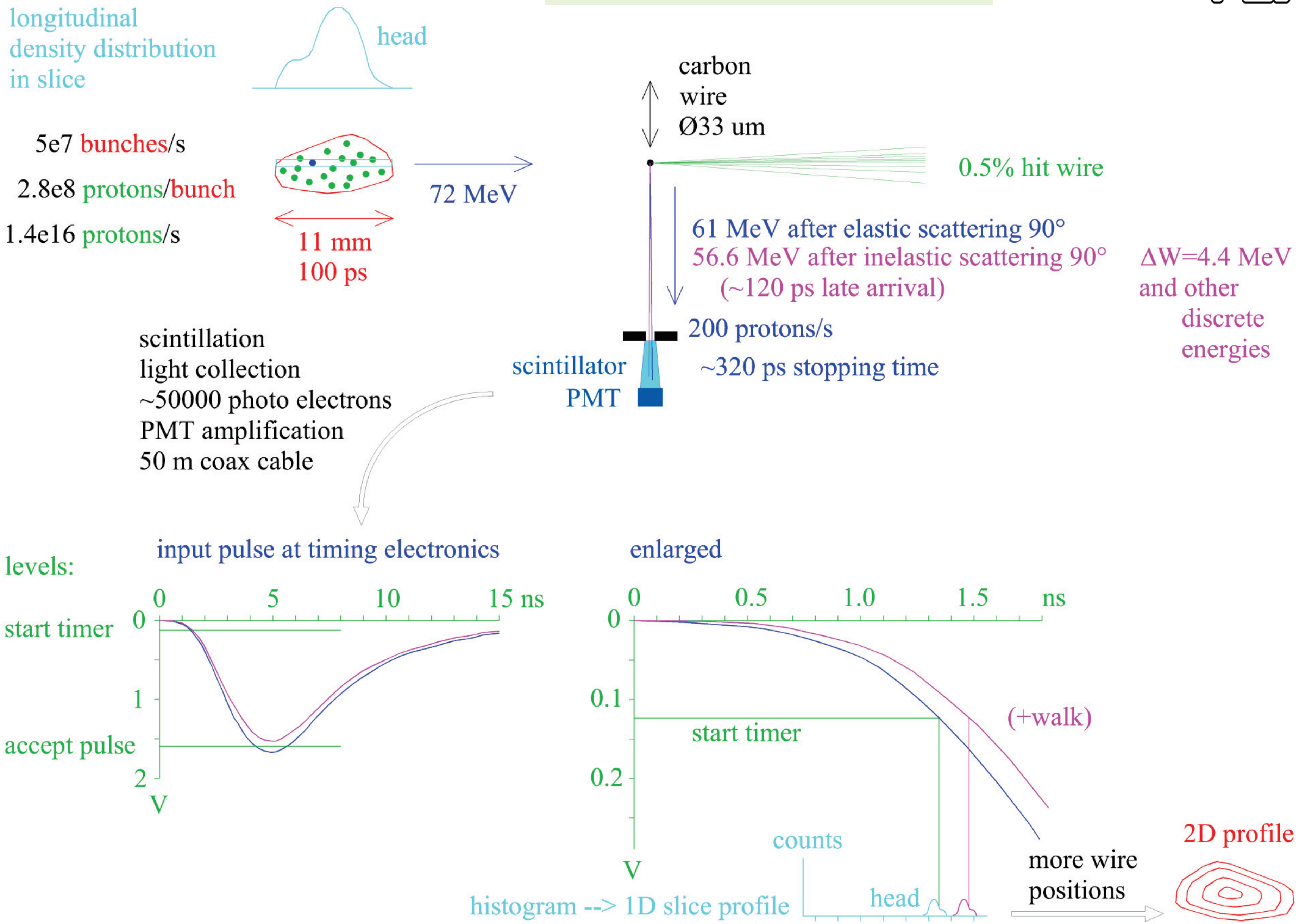
measurement locations



measurement principle



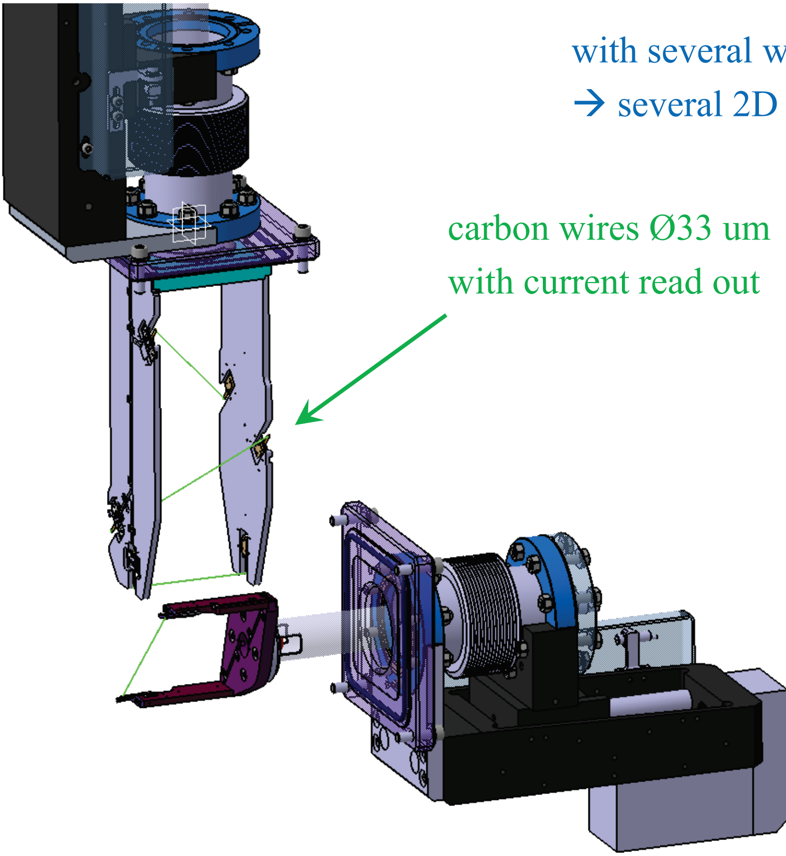
measurement principle



at beam lines

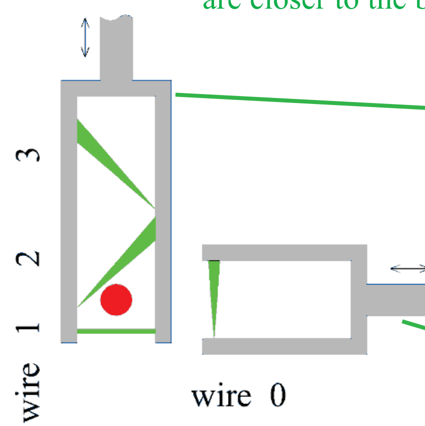
with several wire orientations

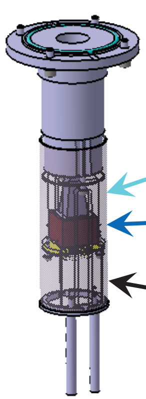
→ several 2D projections of 3D density distribution



carbon wires Ø33 um
with current read out

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



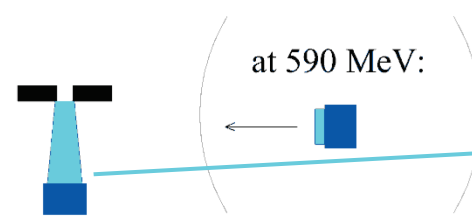


scintillator

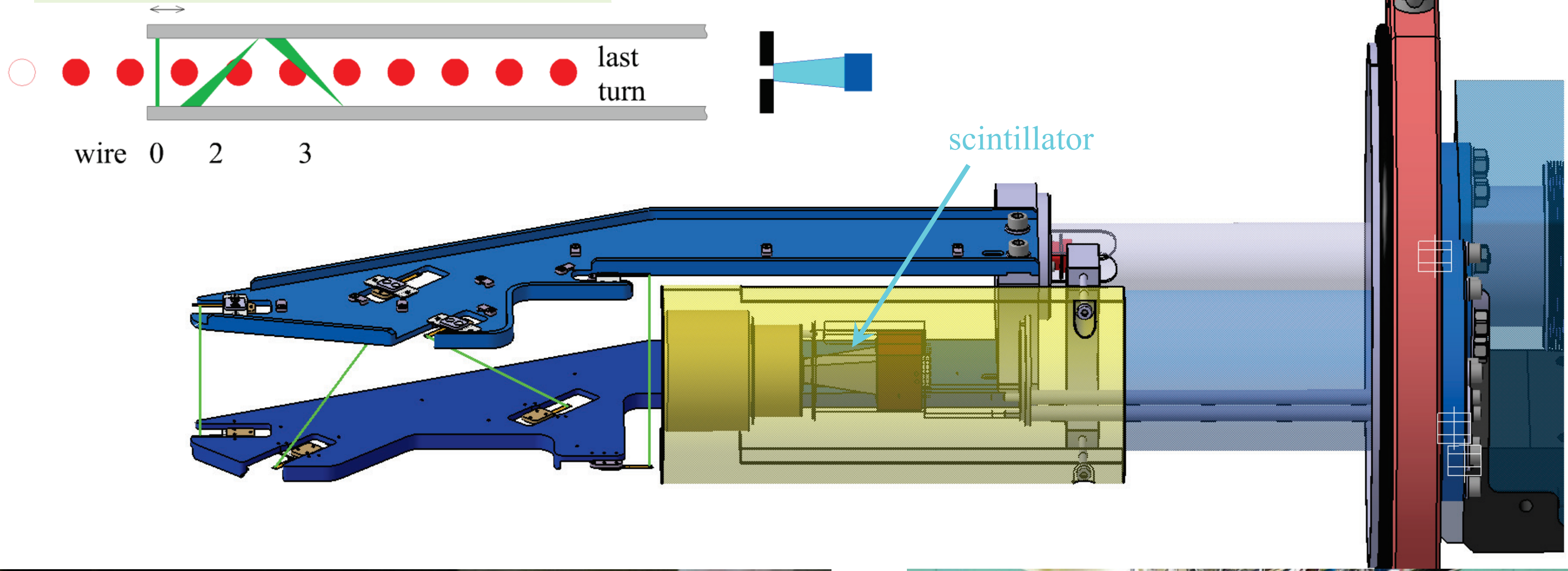
PMT

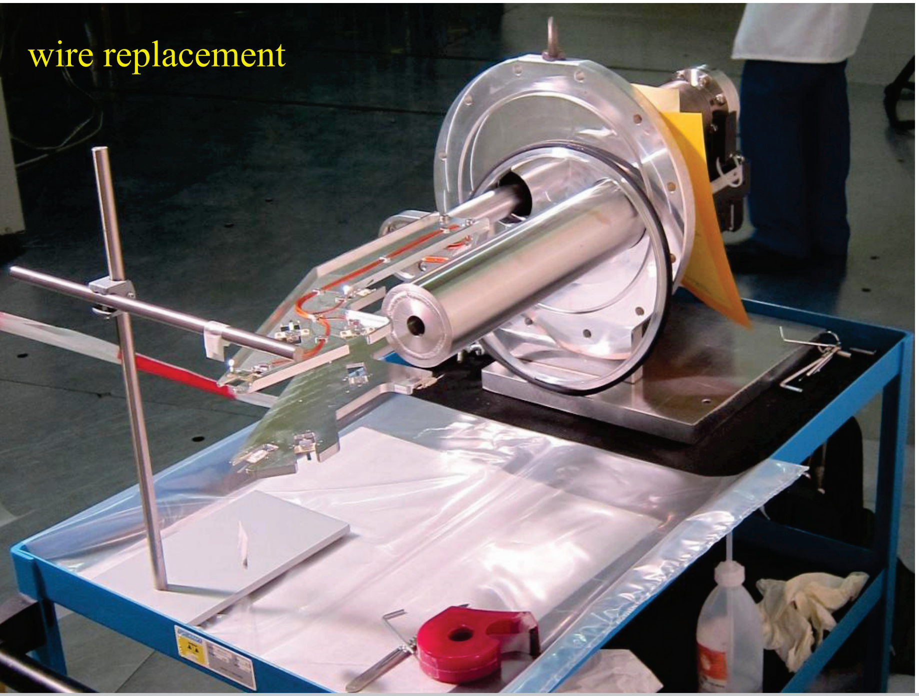
Mumetal shield

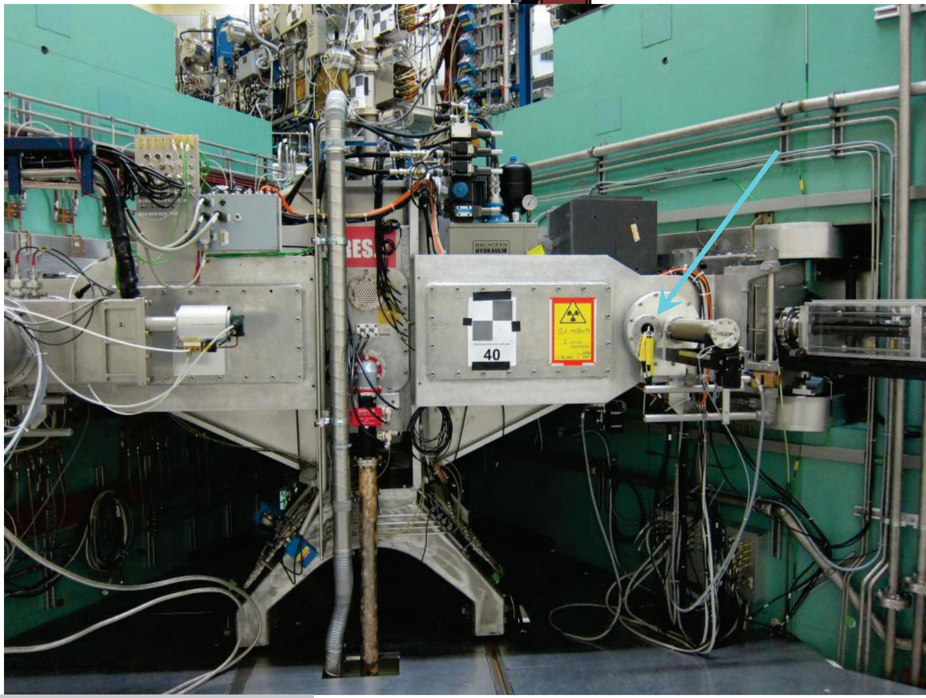
at 590 MeV:



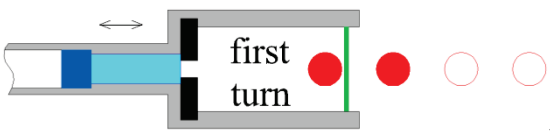
detector setup at Injector 2

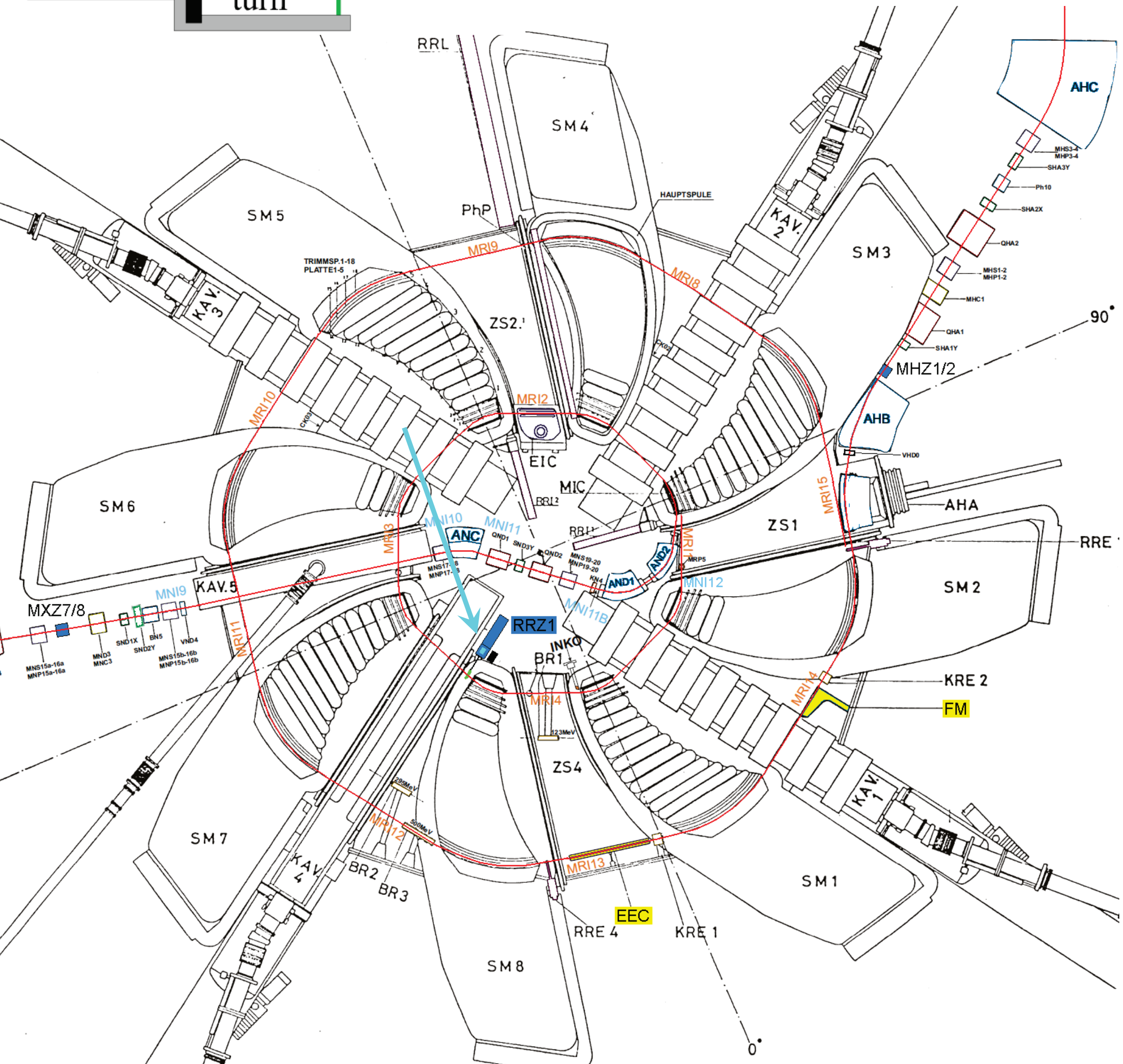


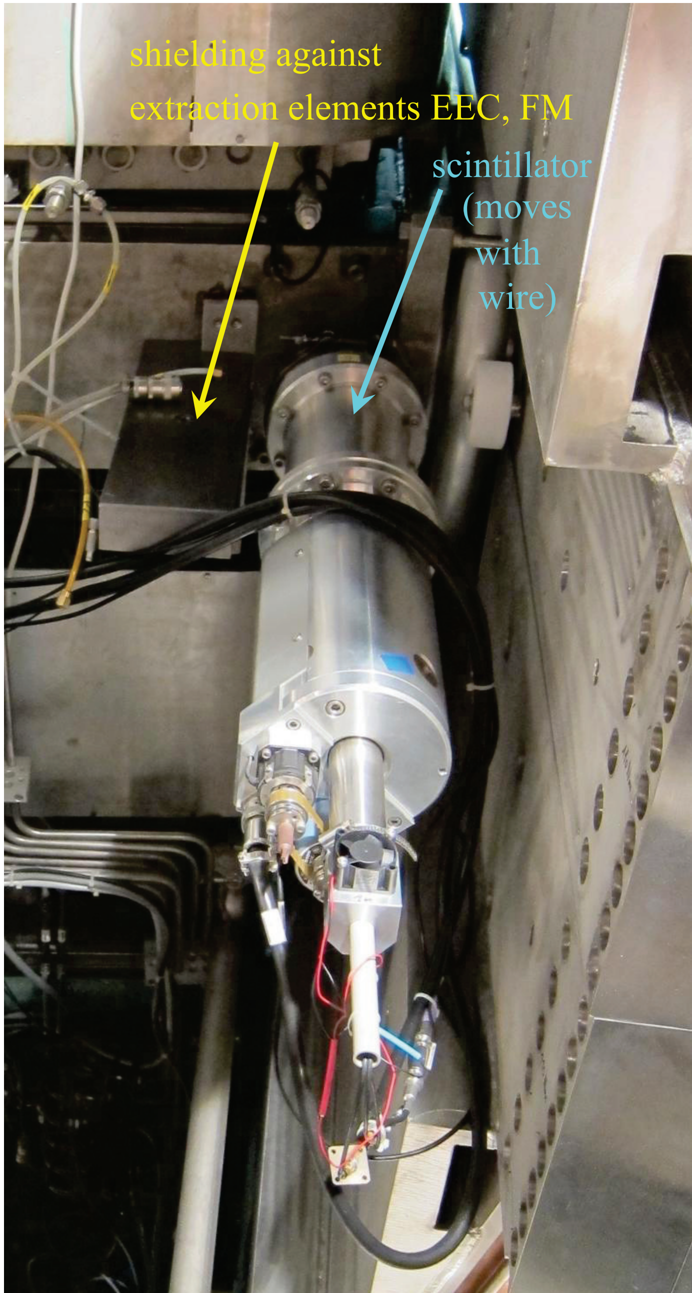




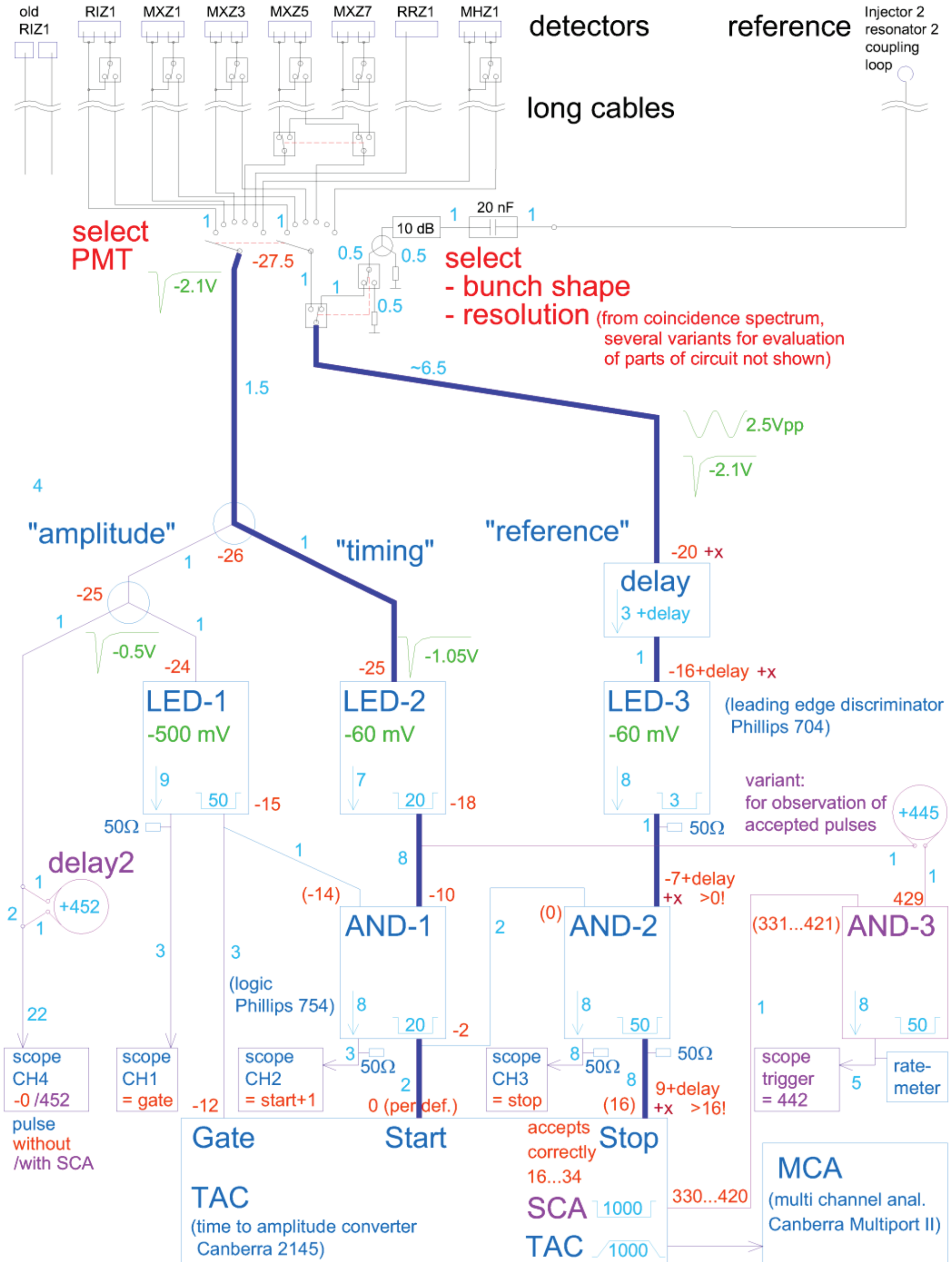
detector setup at Ring cyclotron





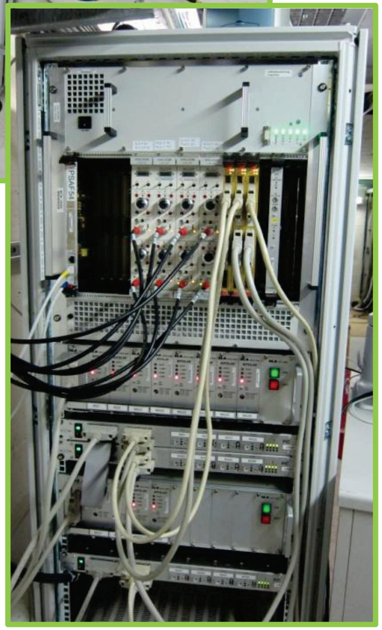


electronics



- timing modules (NIM)
- relays

- high voltage
- wire current readout (logarithmic ampl.)
- motor drivers

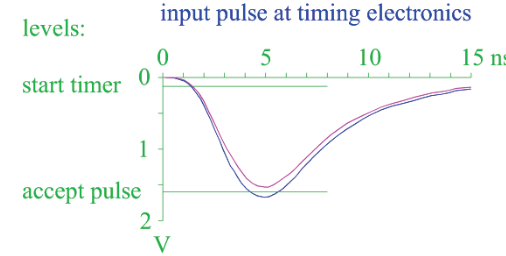


setting the PMT voltage

@fixed beam energy (at beam lines)

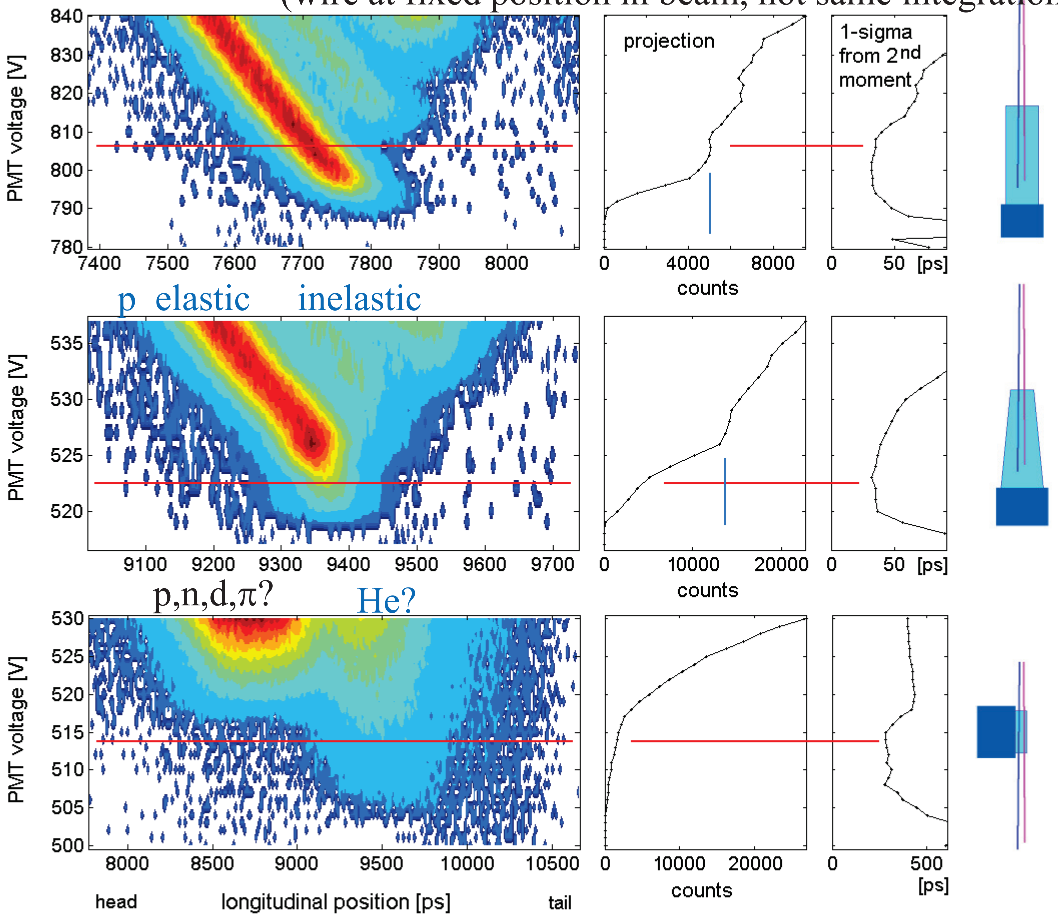
discrimination in order to only accept a single species:

- instead of adjusting the discriminator level, the PMT voltage → gain → 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)



p elastic

(wire at fixed position in beam, not same integration time)



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
→ long measurement duration

setting the PMT voltage

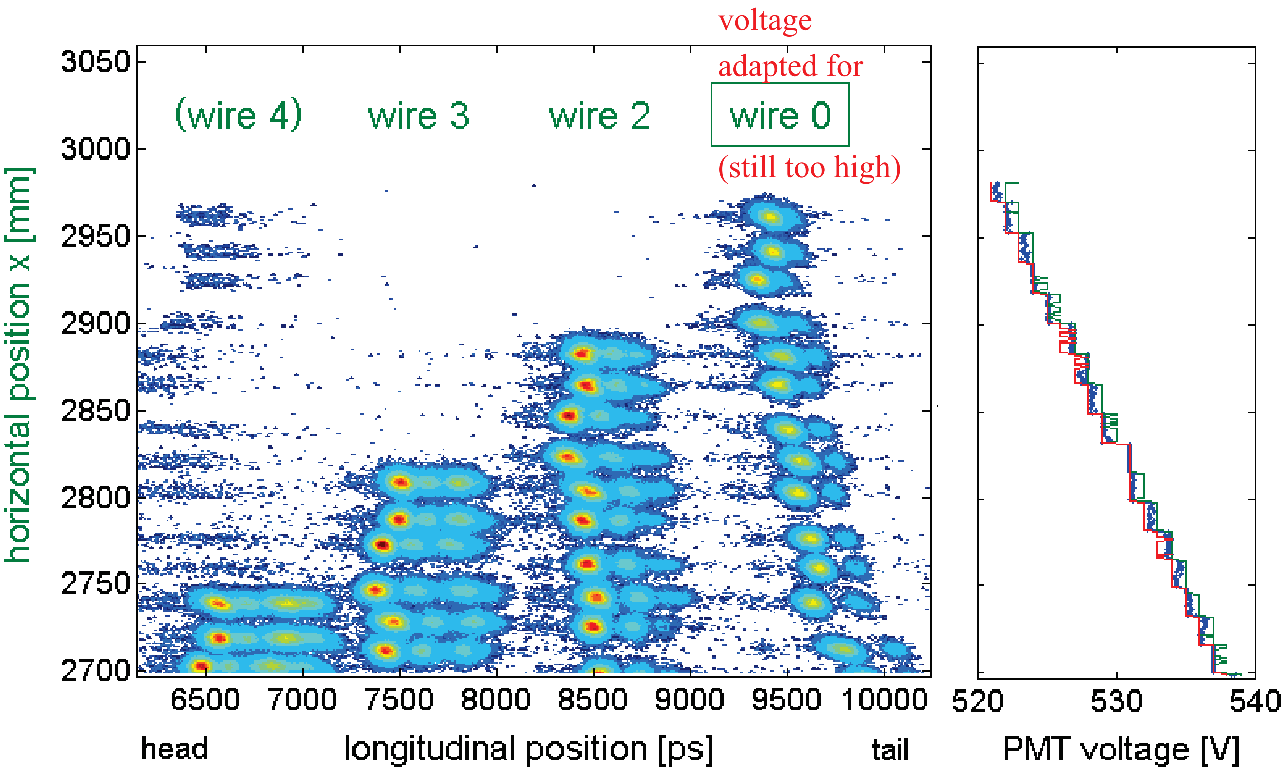
@varied beam energy (Injector 2)

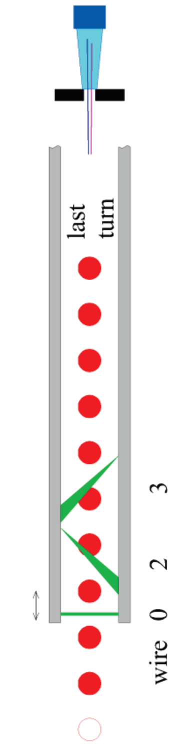
Bunch center energy changes from turn to turn → PMT voltage to be varied with probe position.

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.)





57 - 72 MeV
(new detector)

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

@varied beam energy (Injector 2)

PAUL SCHERRER INSTITUT PSI

effects →	consequences →	evtl. corrections
- distance wire – detector changes	→ shifts TOF of elastically scattered proton	→ geometric correction
	→ shifts solid angle to detector aperture	→ geometric correction
- systematic variation of beam energy with radius (in bunch and from turn to turn)	→ shifts TOF of elastically scattered proton	→ geometric correction* *
	→ shifts PMT pulse height (walk)	→ PMT voltage adapted at meas.
	→ shifts scattering cross section	→ empiric correction* *
- time resolution of measurement	→ elongates	→ crude correction

* 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:

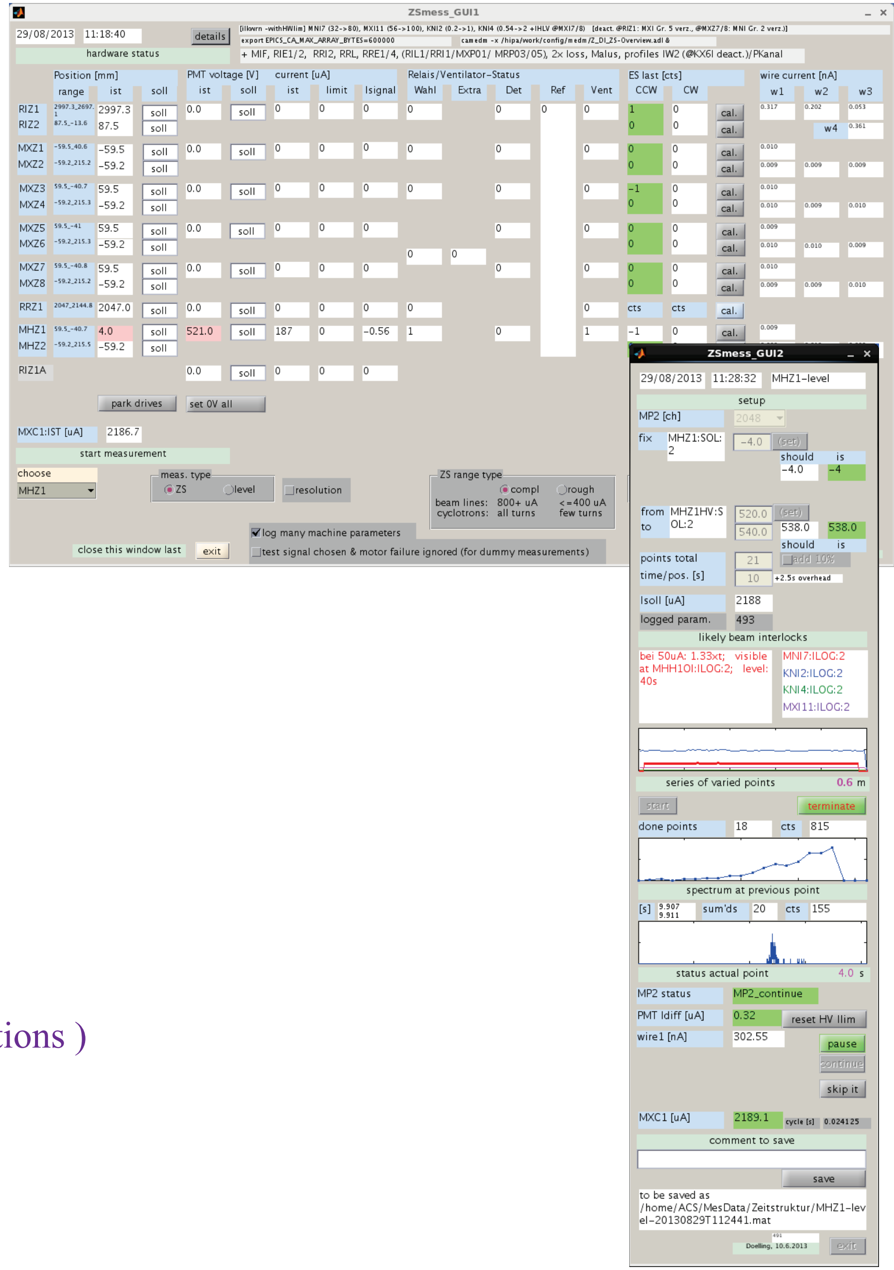
- beam energy spread at each radius → spreads TOF → *
- detector aperture allows range of scattering angles → spreads energy and cross section → *
- quantum efficiency/gain changes over PMT surface → affects PMT pulse height (walk)
- light collection efficiency dependent on impact position → affects 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 software



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

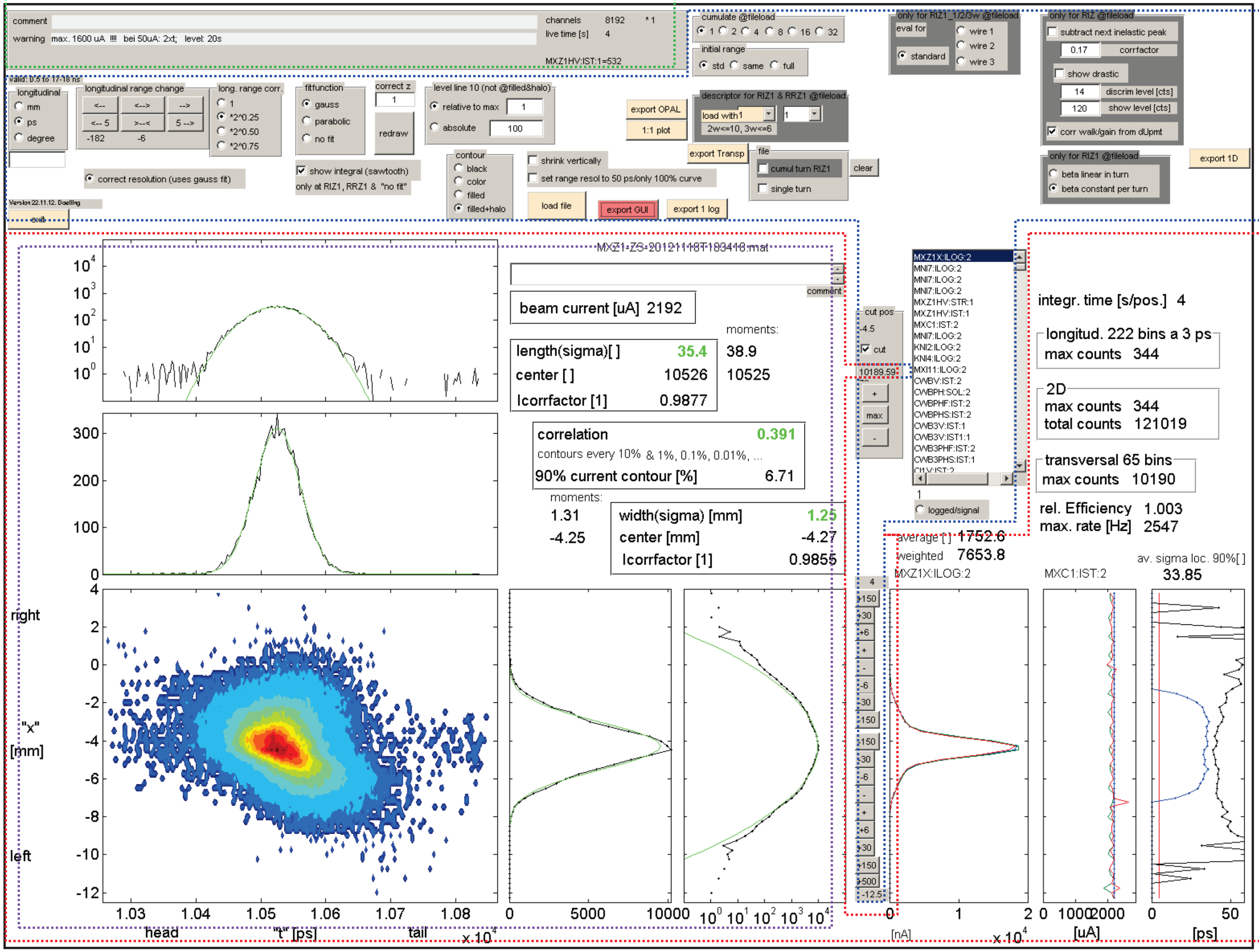
functionality

- sets relays
- proposes useful voltage and position ranges for all locations & measurement modes
- steers drives, starts/stops/reads MCA (waits if beam is missing)
- monitores 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

evaluation software

- 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

measurement settings



evaluation & display settings

results

input for simulation

technique

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

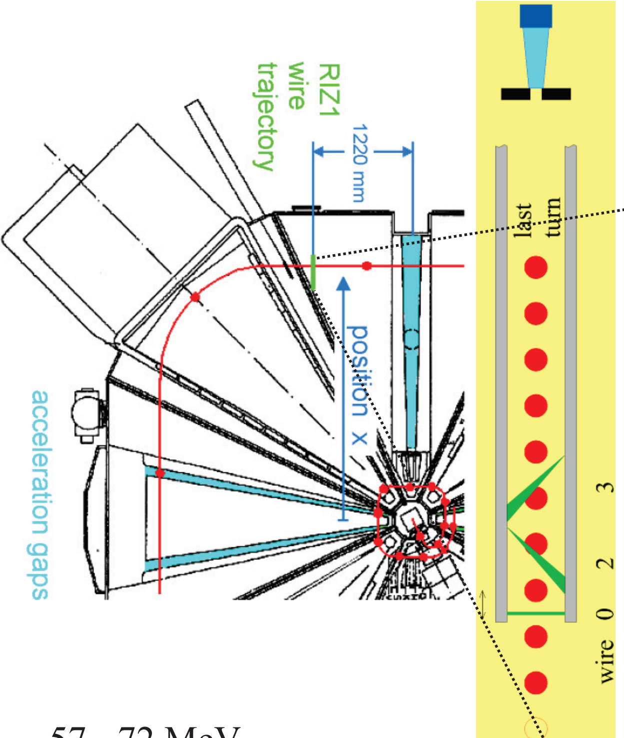
results

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

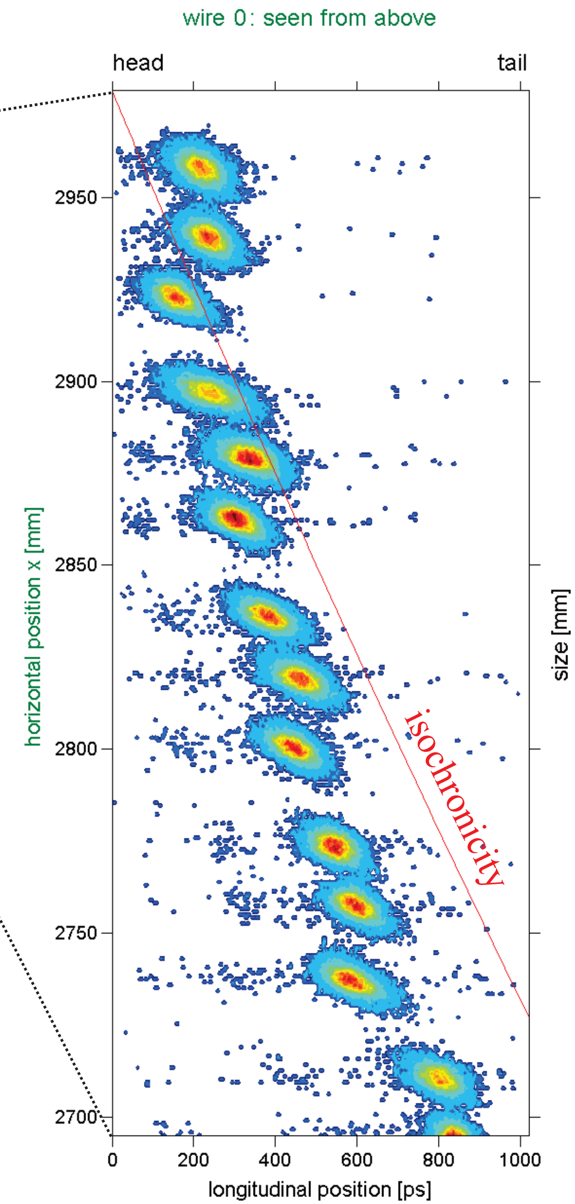
eventual next steps

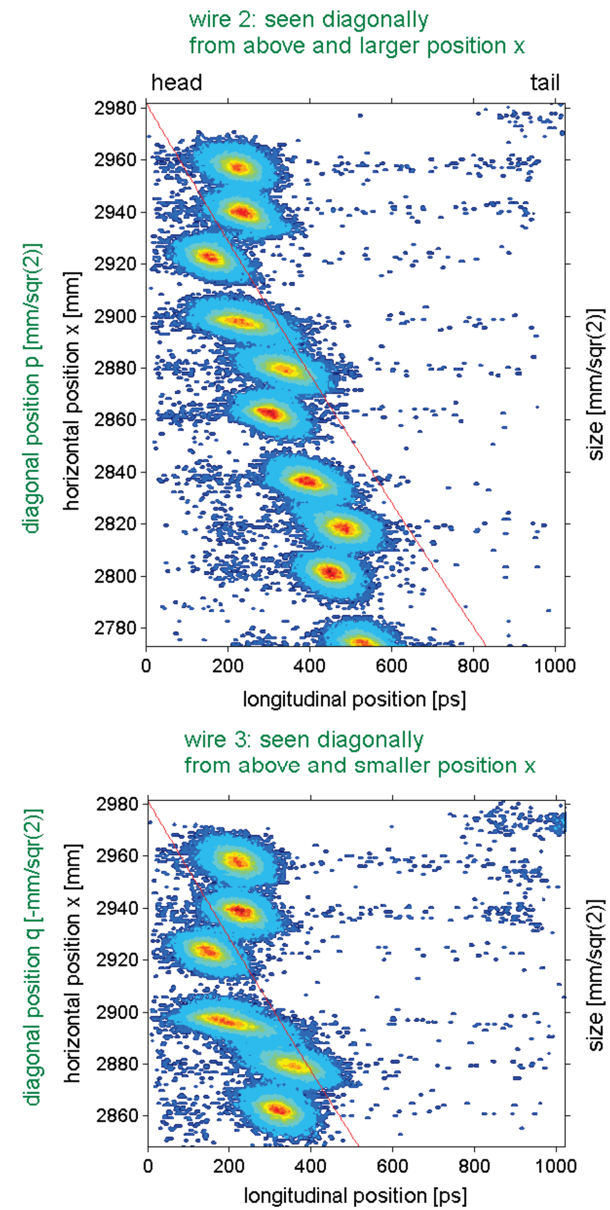
relation to beam dynamics simulations and machine development

beam at Injector 2 last turns



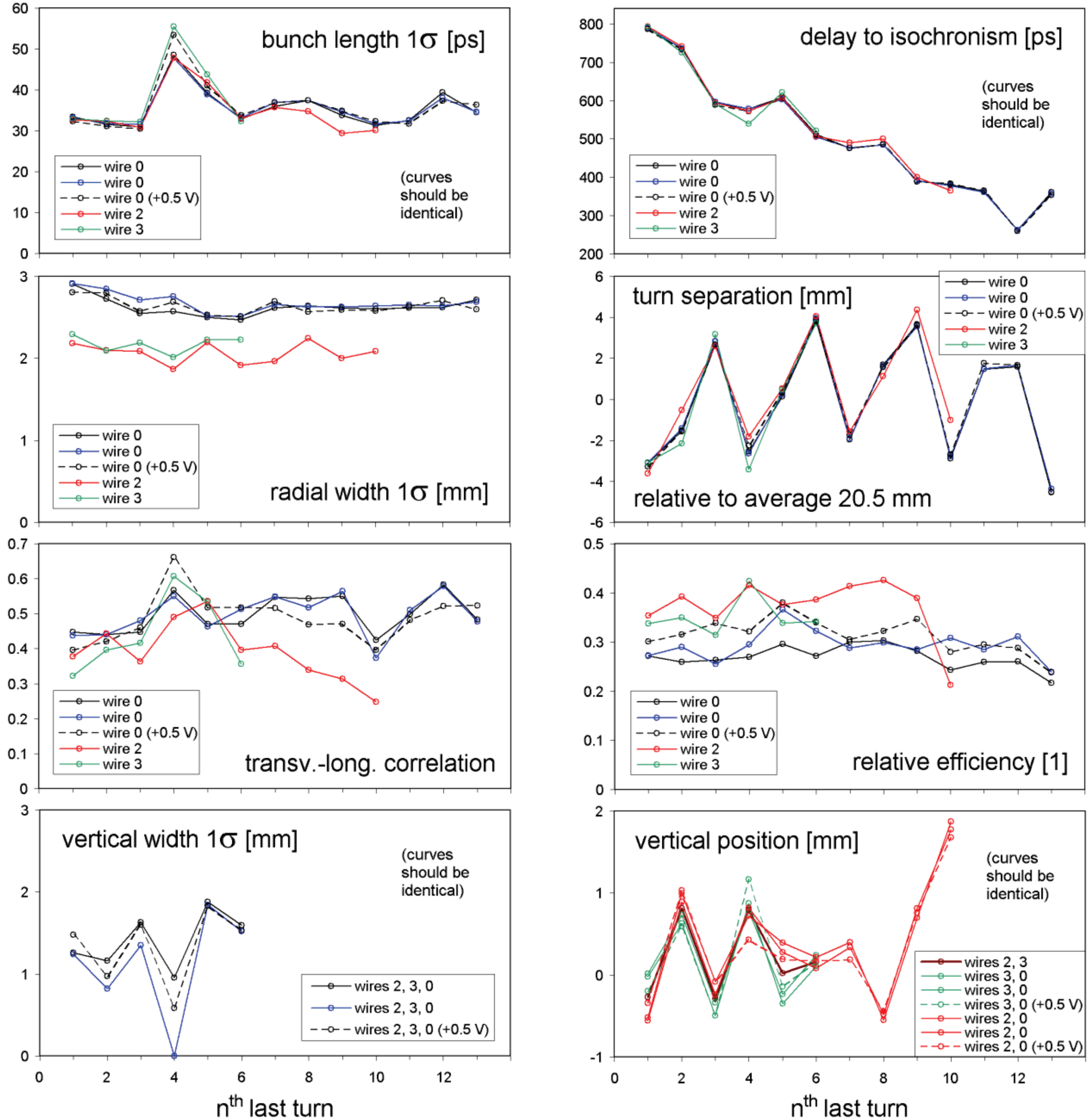
57 - 72 MeV
production beam 2200 uA





- Three separate scans with correspondingly adapted PMT voltage ramps.
- A relative phase slip of ~9° builds up over the last 11 turns.

beam at Injector 2 last turns



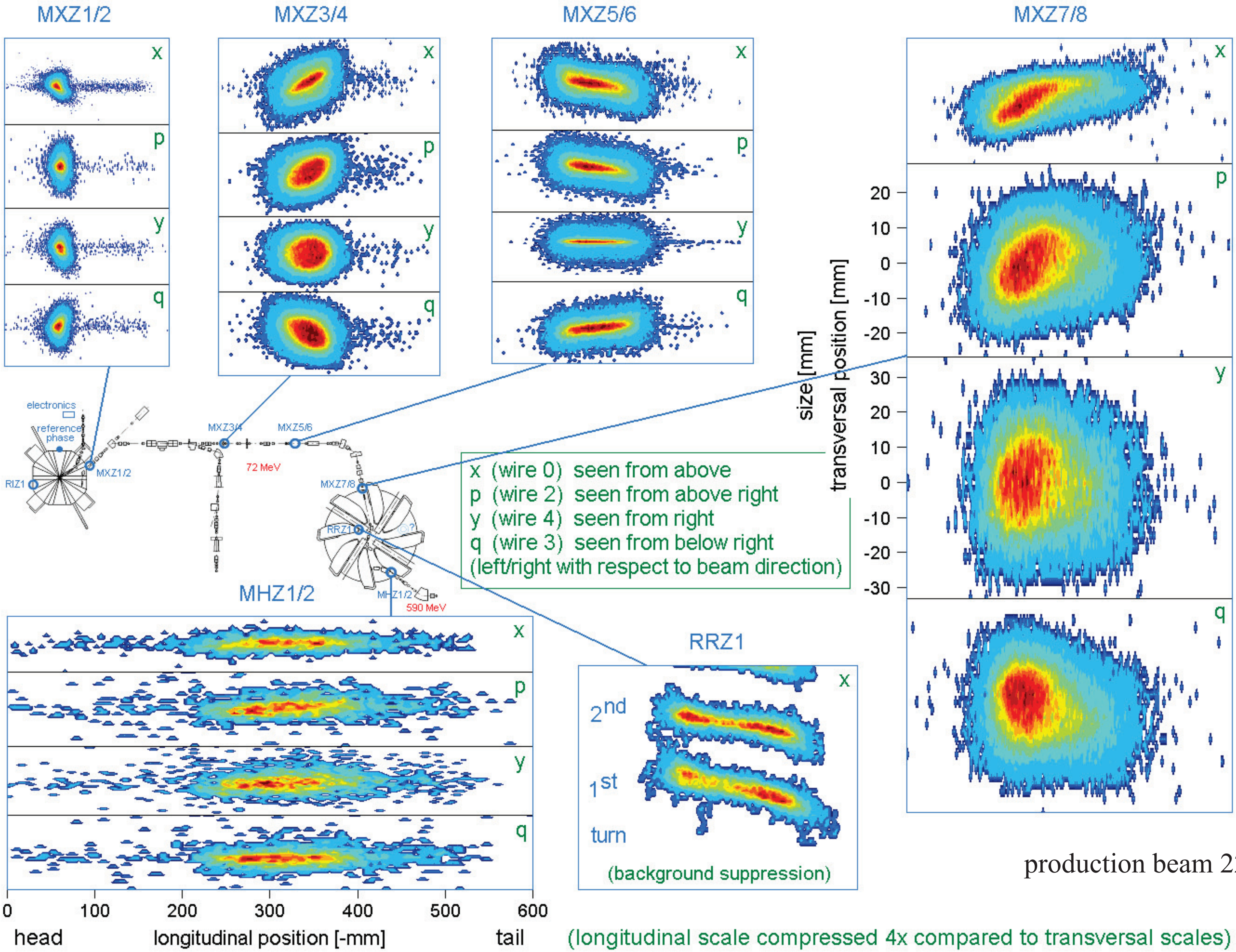
condensed to bunch parameters of many turns at 2200 uA

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

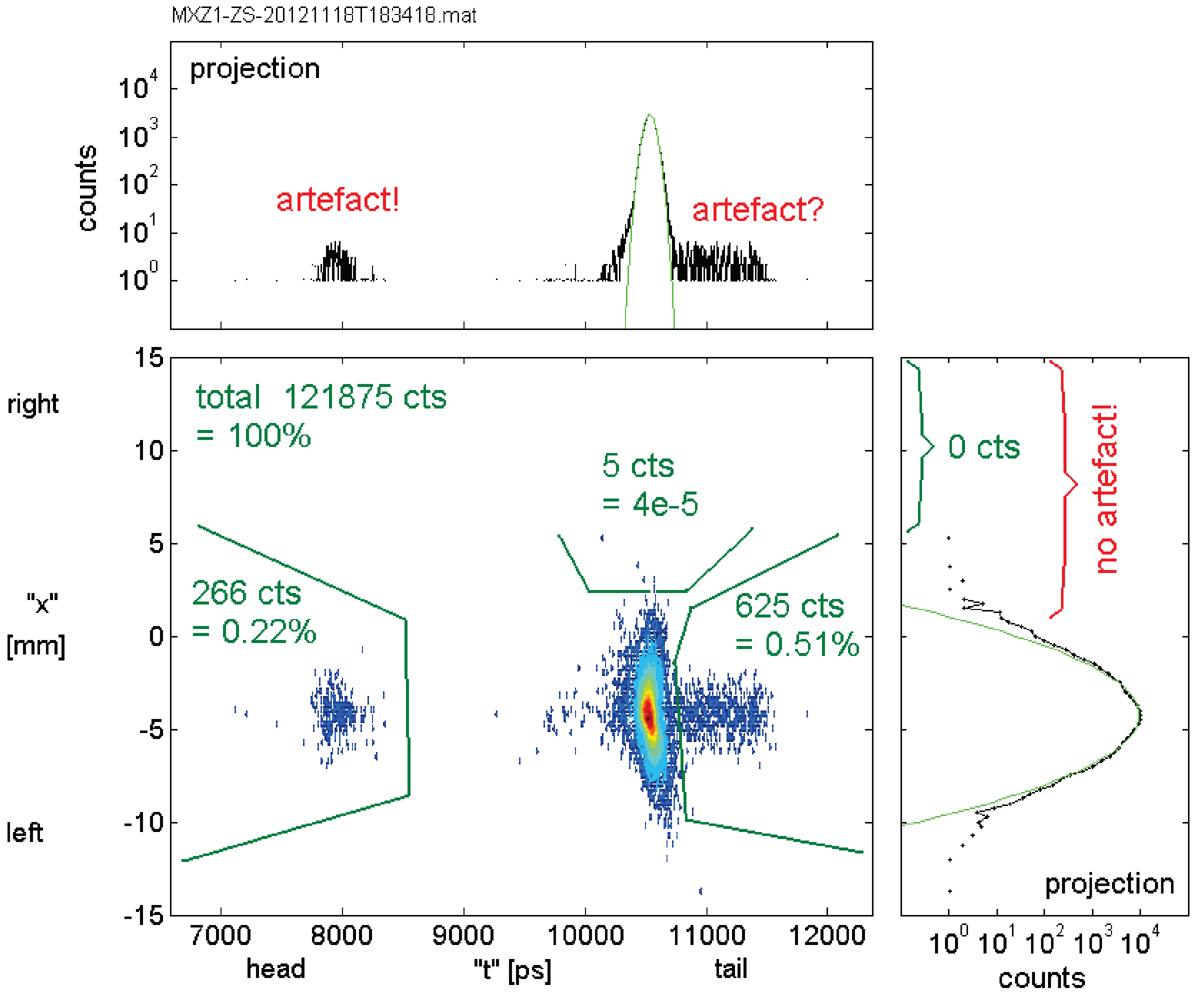


production beam 2200 uA

(longitudinal scale compressed 4x compared to transversal scales)

results

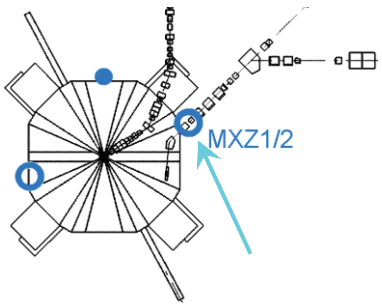
performance: artefacts?



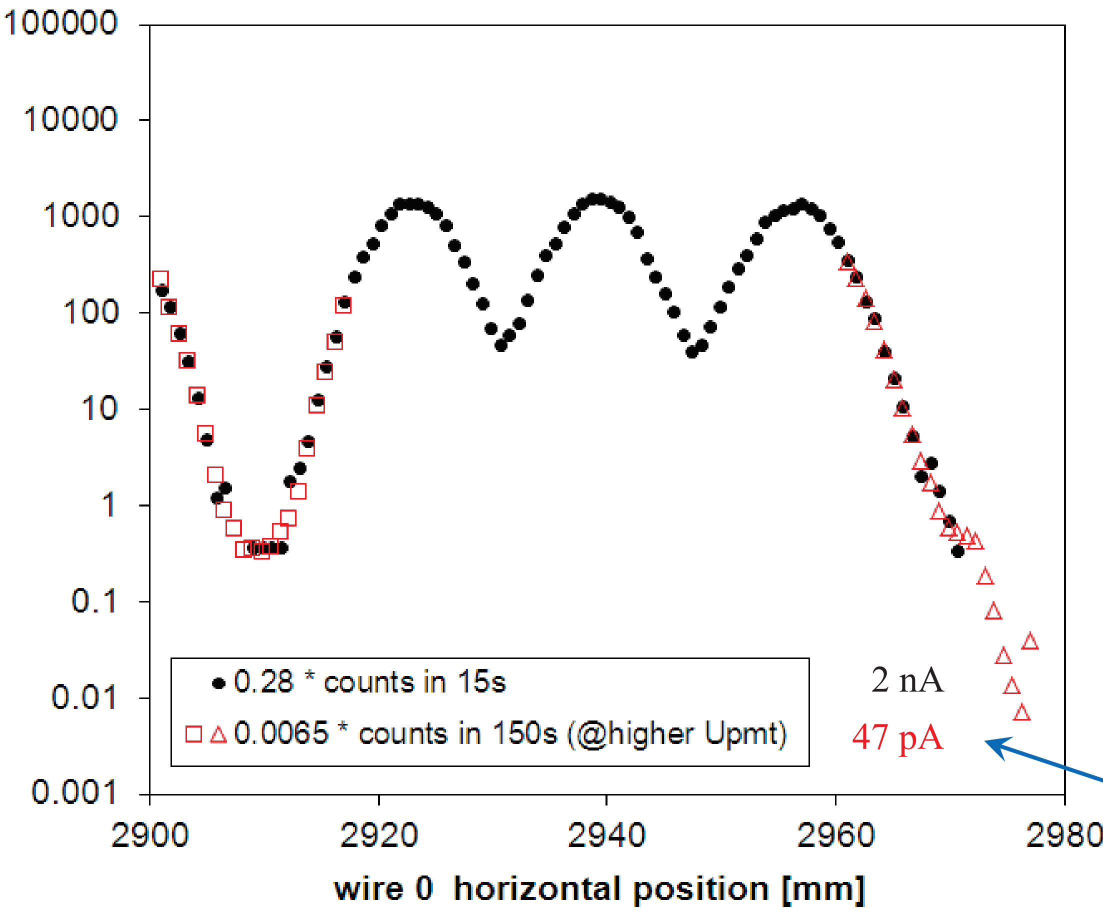
possible sources of artificial counts:
- background radiation
  (especially difficult when correlated
  i.e. created by loss generated by the wire)
- coupling of stray RF fields to measurement cable (correlated)
- reflections in timing circuit

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"



performance: dynamic range



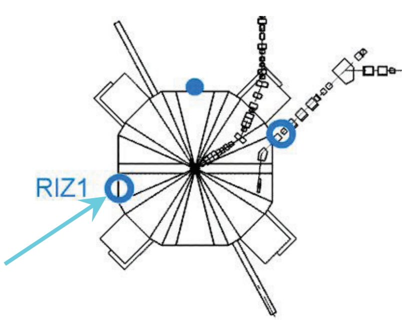
The dynamic range can be extended by longer integration times at wire positions where the signal is low.

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 uA
last turns in Injector 2
"quiet environment"

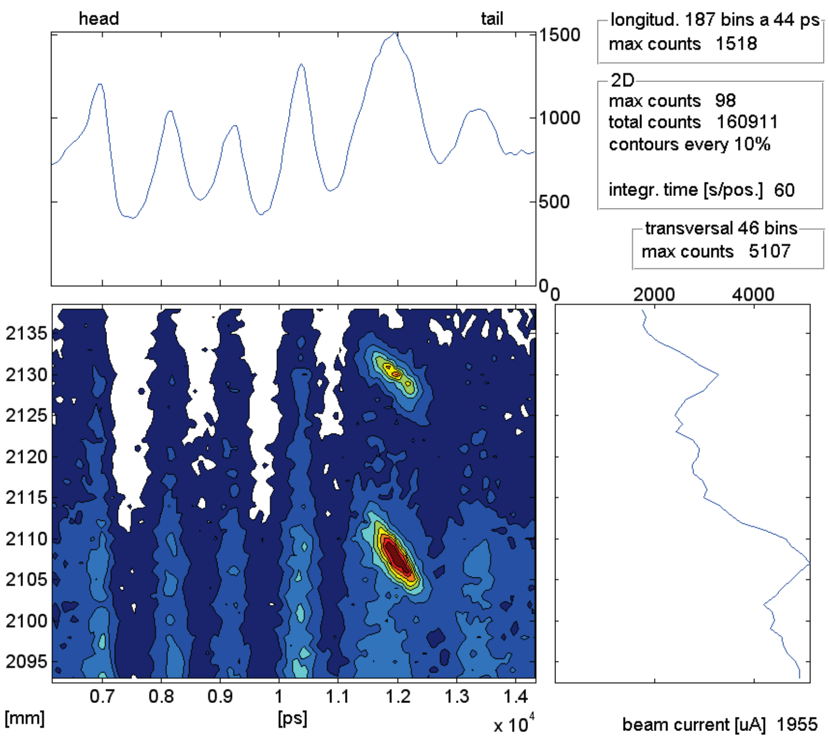


performance: dynamic range

PAUL SCHERRER INSTITUT

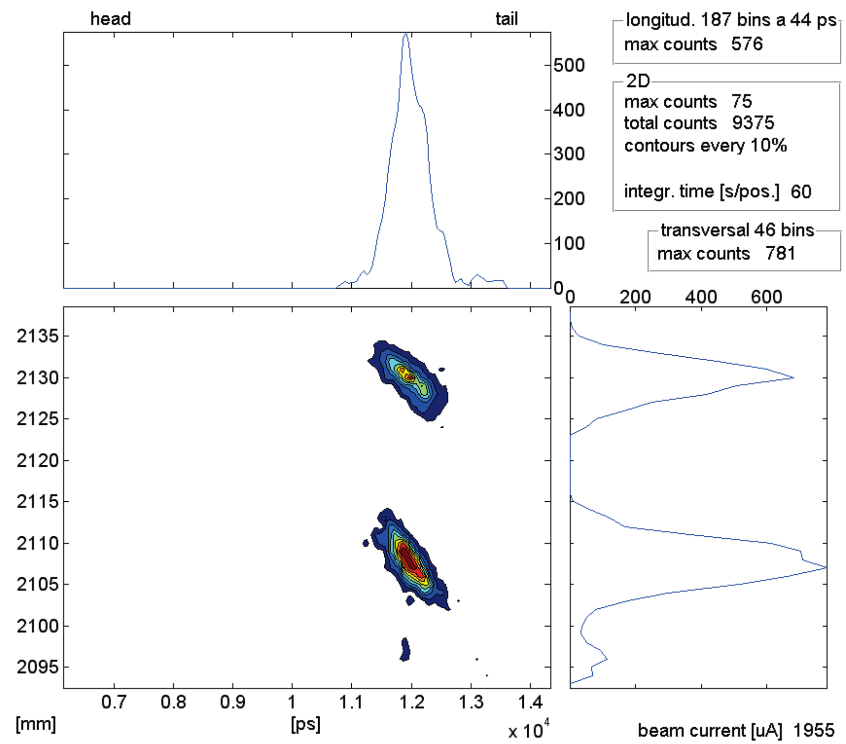
an example of a low dynamic range:

raw data



Dölling, HB2010

filtered



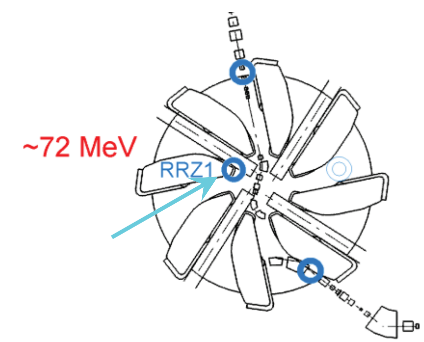
production beam 2200 uA

in Ring cyclotron

at high beam loss

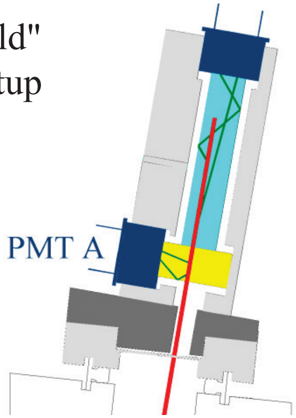
not a "quiet environment“

(and a degraded scintillator)

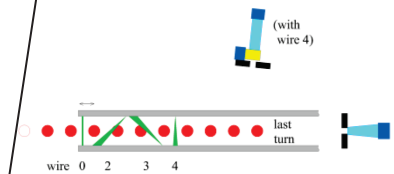


performance: time resolution

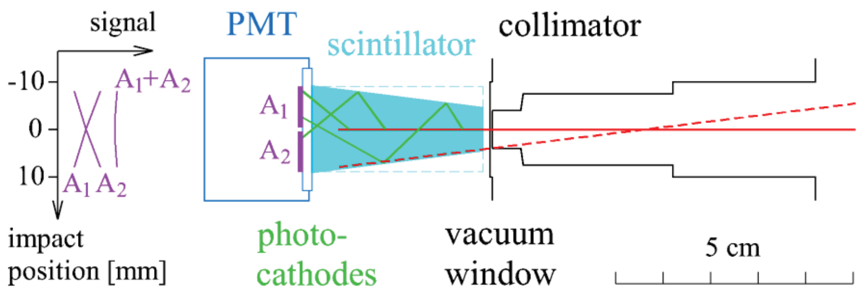
"old" setup

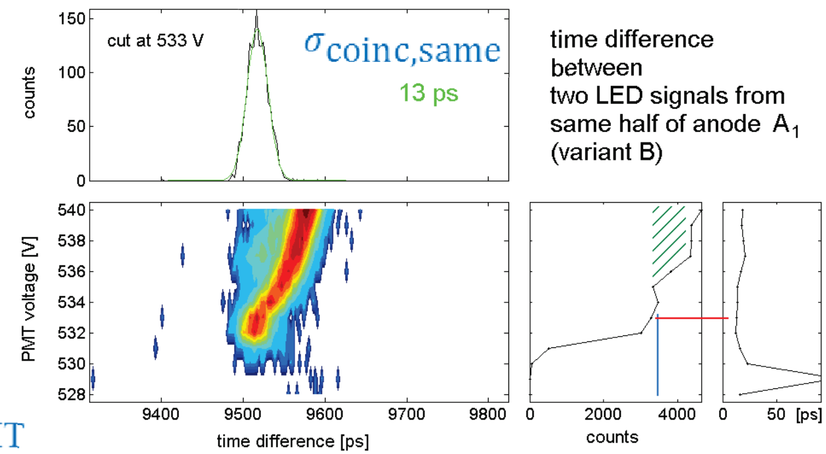


Time resolution from coincidence spectrum $\sigma_{coinc} = 26$ ps
and quadratic addition of the contributions of both sensors, weighted by the number of photoelectrons created at each detectors photocathode
→ $\sigma_{det\ B} = 13$ ps
(17 ps with degraded scintillators)



"new" setup

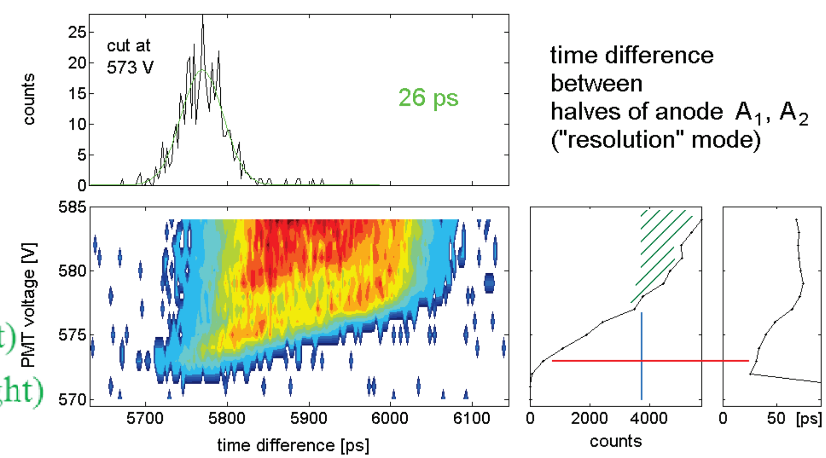




time difference between two LED signals from same half of anode A_1 (variant B)

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

→ 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.)



time difference between halves of anode A_1, A_2 ("resolution" mode)

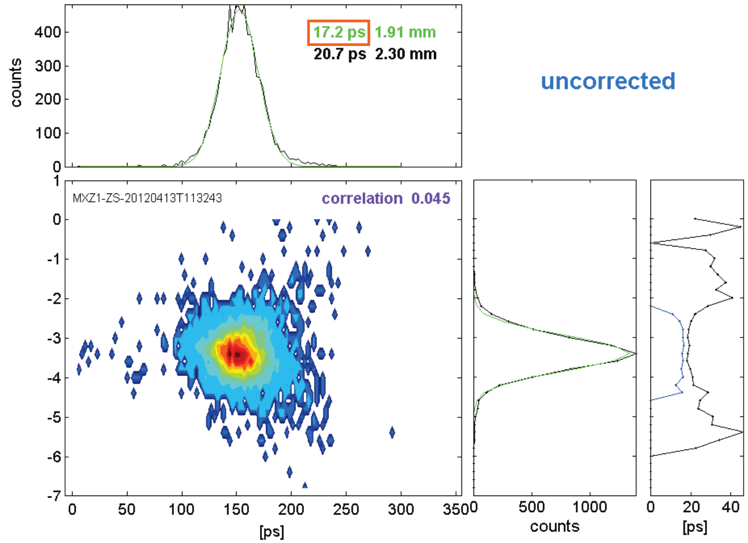
→ Time resolution of the subsequent parts of the system:

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

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

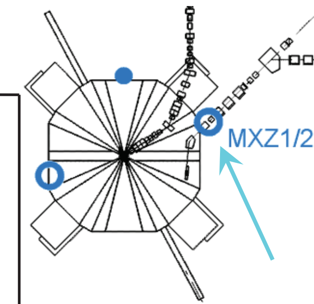
→ lower limit for full system

performance: time resolution



uncorrected

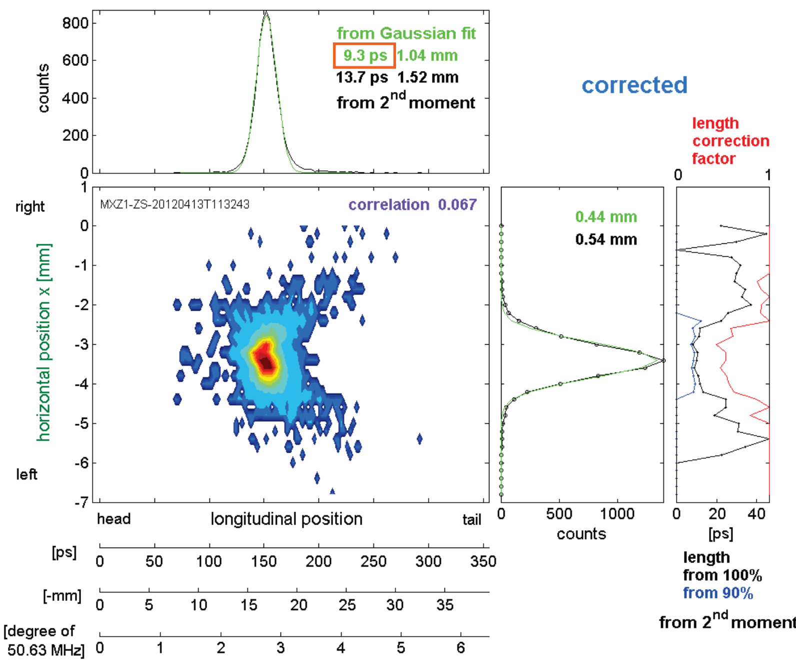
shortest measured bunch length = 17.2 ps is an upper limit of the time resolution of the full system 6.5 ps $\leq \sigma_{full} \leq$ 17.2 ps



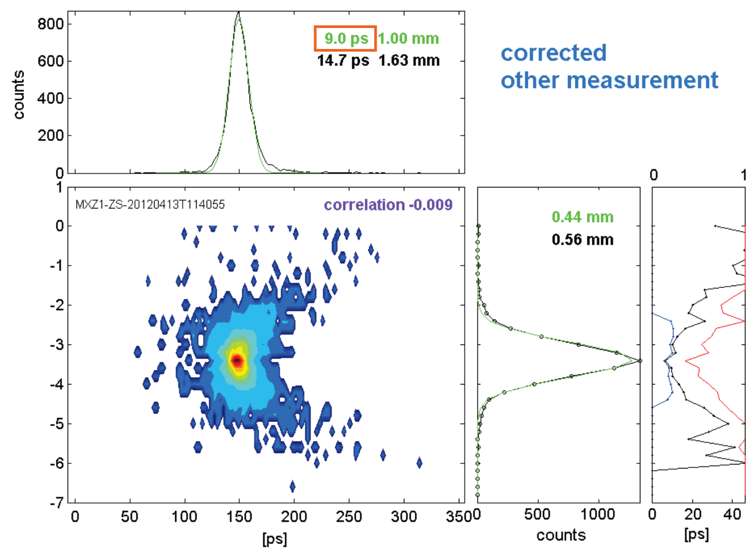
correction of resolution (assumed to be 13.5 ps) by quadratic subtraction:

this comes to its limits!

This is at 72 MeV !



corrected



corrected other measurement

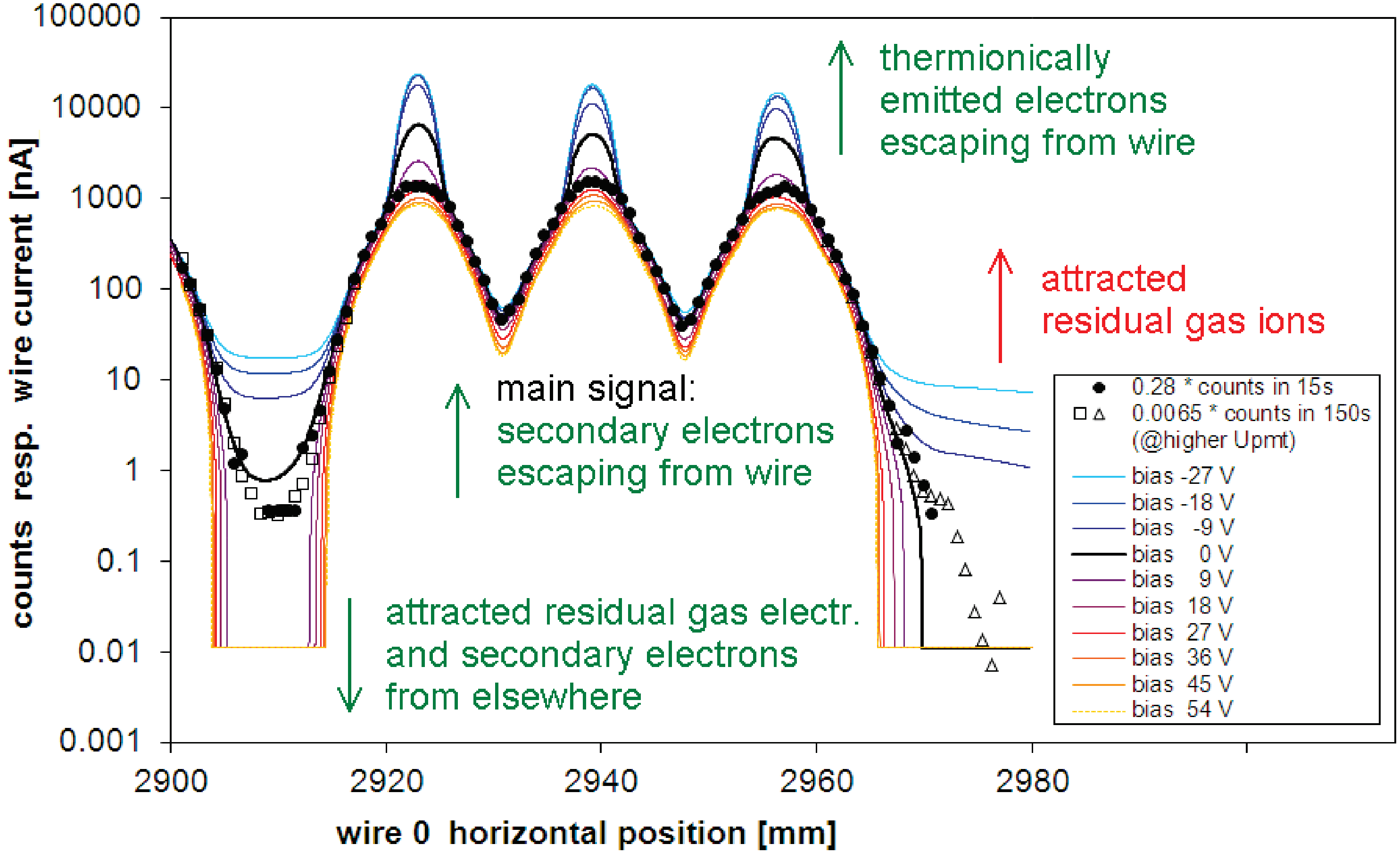
At 590 MeV it is worse but still good enough.

beam 50 uA after Injector 2

Dölling, HB2012

results

reference for wire probes/monitors with current reading



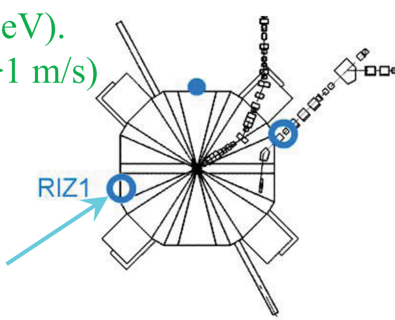
wire current is measured

production beam
2200 uA
last turns in Injector 2
carbon wire Ø33 um
"quiet environment"

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).



technique

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

results

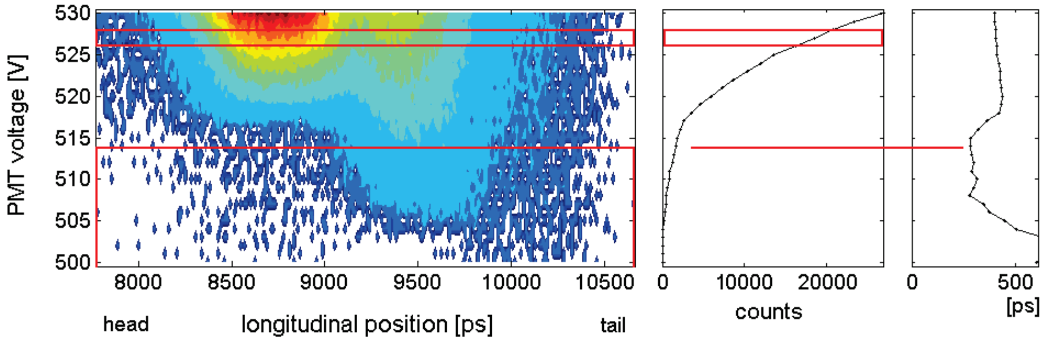
- on beam parameters
- on the methods performance/problems
- on wire probe performance

eventual next steps

relation to beam dynamics simulations and machine development

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

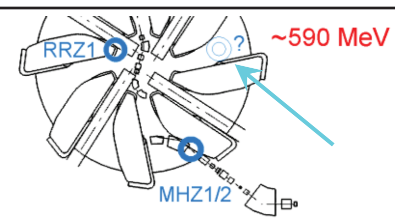
second detector
after ~0.5 m
further path

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



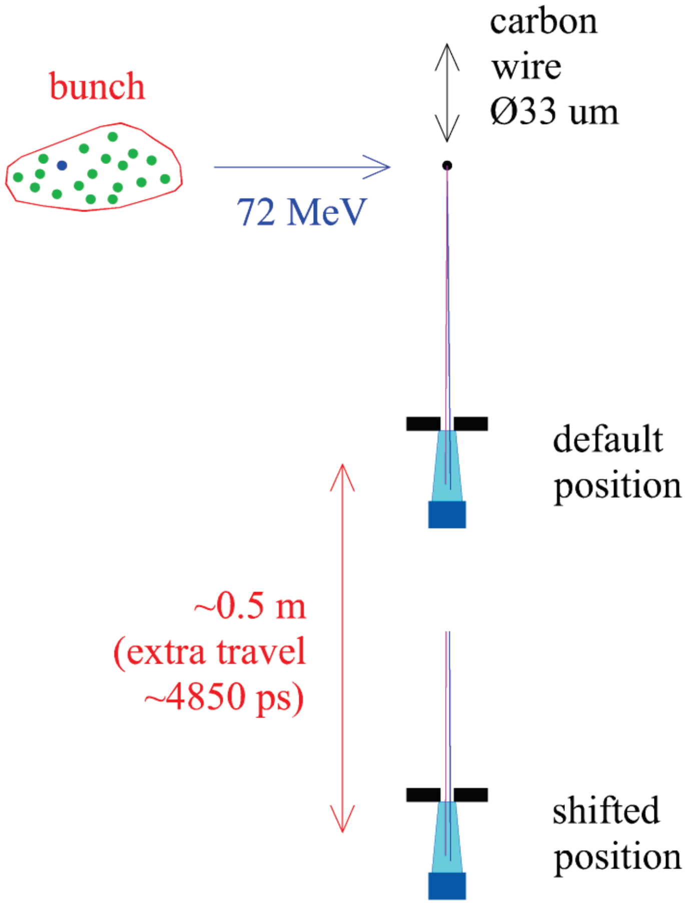
beam energy measurement at 72 MeV

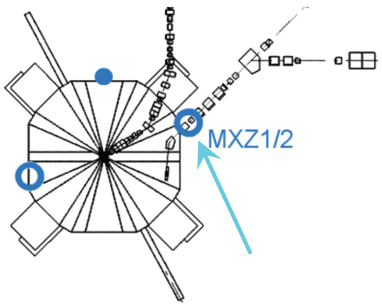
PAUL SCHERRER INSTITUT PSI

The energy of the beam after the Injector cyclotron can be determined to ~1e-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.





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

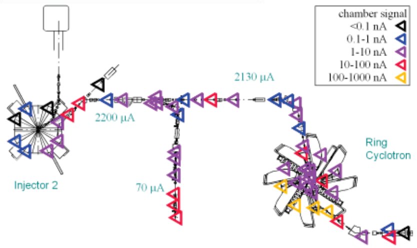
my personal view on the future development of our machine

PAUL SCHERRER INSTITUT

standard operation | machine development

machine

space charge, tails, scattering
10 nA loss → sign. activation
loss details matter



operators

empirical tuning
("turning all knobs")
matching core&halo
→ 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 $I_{max} \sim n_{turn}^{-3}$)

Transport-code

extensive
detailed simulations
matching core&halo

detailed models:
tails, profiles
("cutting early")

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

Yang, Bi, Wei, Zhang, Adelmann, ...

not used

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)
→ step up efforts with detailed simulations
(a breakthrough is needed and will be worth the effort)

trouble shooting / reproduce last good setting
beam centering
machine protection

beam diagnostics

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

optimum
effective
sensitivity
[nA]

error margins
to be specified
individually

relation to beam dynamics simulations and machine development

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

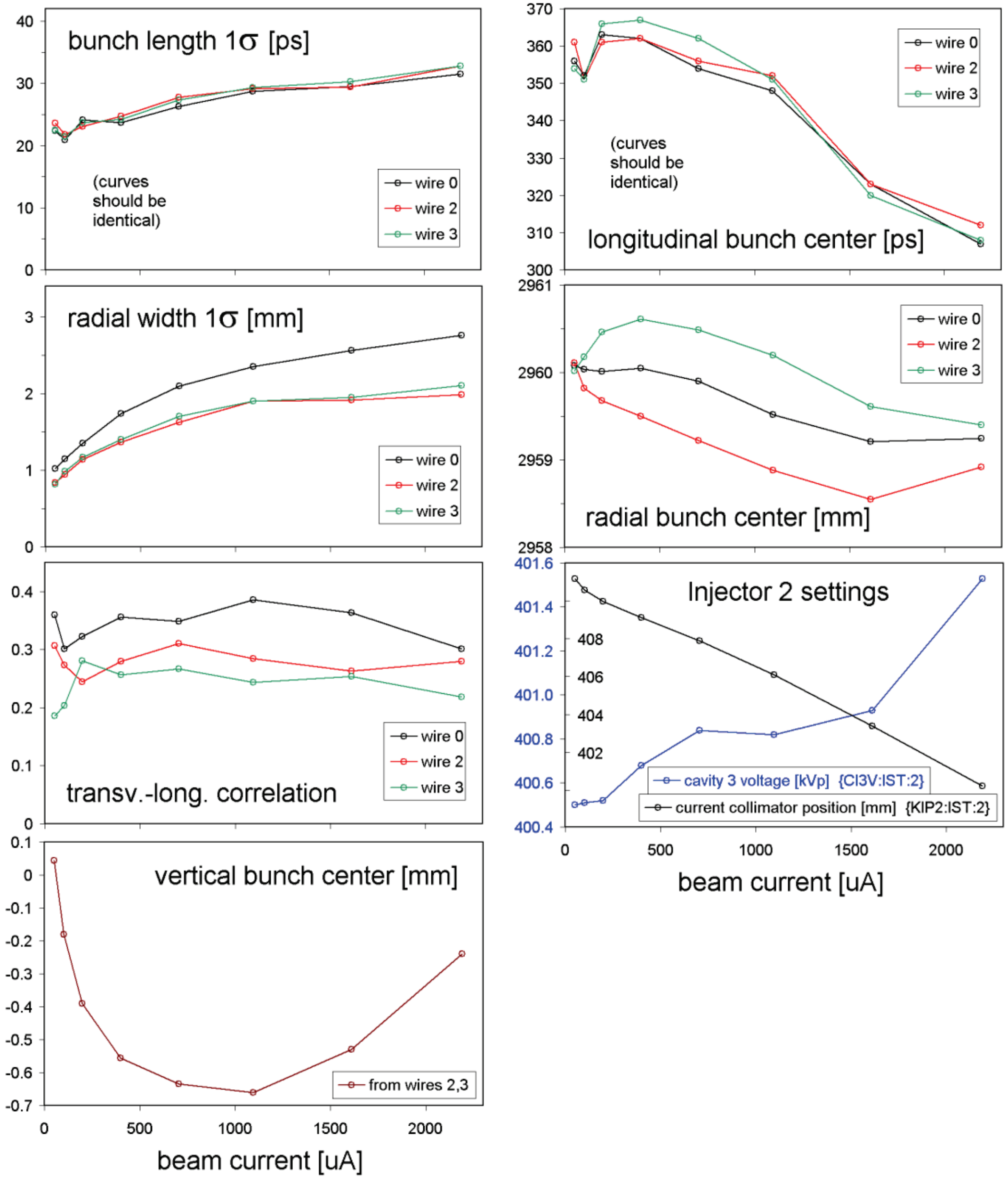
eventual next steps

relation to beam dynamics simulations and machine development

Thanks for listening!

back-up slide: beam at Injector 2 last turns

PAUL SCHERRER INSTITUT PSI



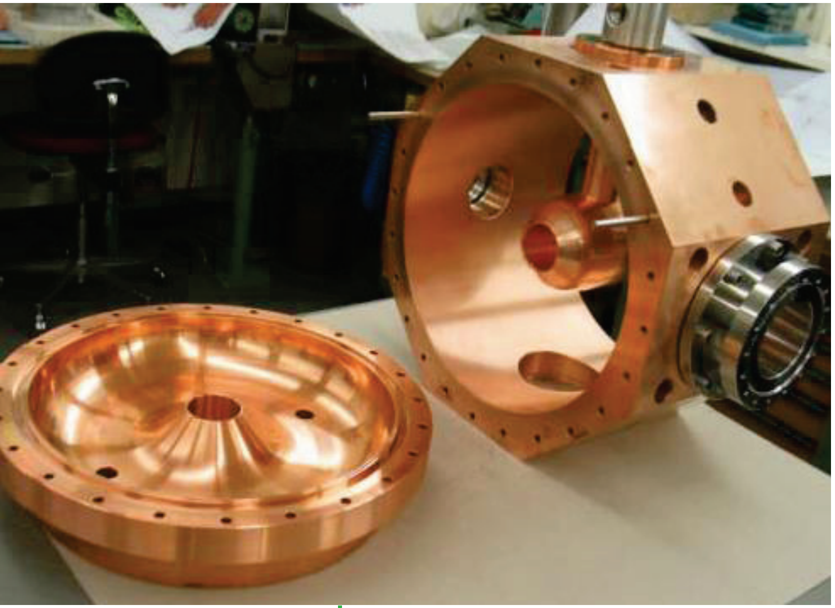
condensed to bunch parameters
of last turn at varied current

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

back-up slide: "super-buncher"



Schmelzbach et al., EPAC06

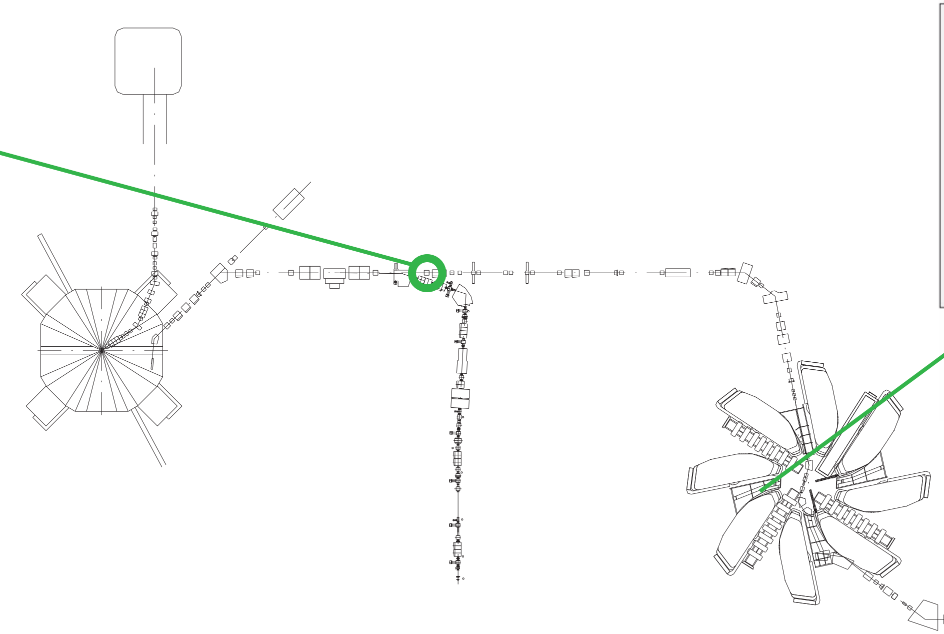
idea: restoring short beam at entrance of Ring cyclotron
→ roll-up there (?)

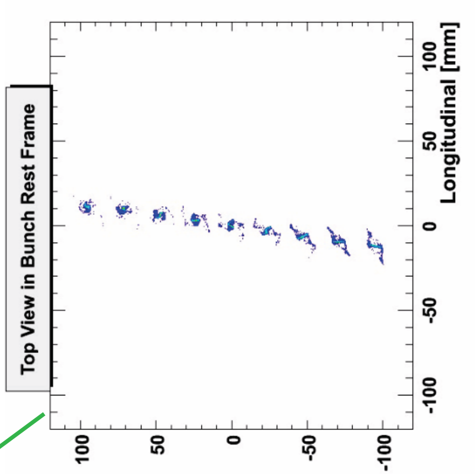
(layout based on 1D bunching simulation)

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

M. Humbel et al., this conference

probable explanation:
difficult to match beam and halo





J. Yang et al., HB2008

back-up slide: simulations

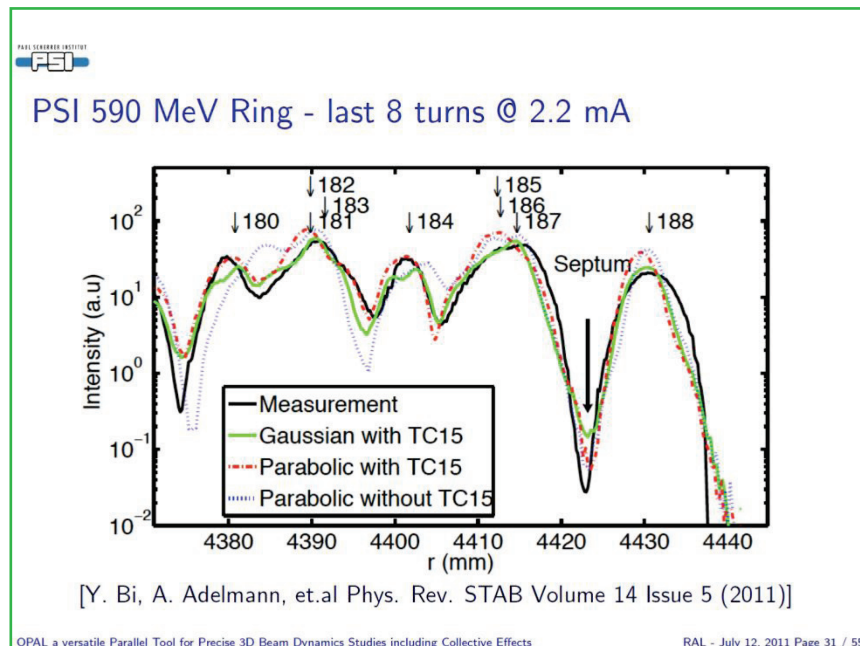
possible strategy: understanding beam losses in detail

→ where (at low energies) to cut and how to match the halo („collimation system“)
→ controlled beam tails, „matching of beam & halo“
→ lower losses

this needs
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