Beam Diagnostics for Cyclotrons

CYCLOTRONS'10 , Lanzhou, September 6 – 10, 2010

Rudolf Dölling, Paul Scherrer Institut, Villigen-PSI, Switzerland

introduction: environment / tasks / effects used for measurement

diagnostics along the beam path

- ion source & injection line: matching the beam to cyclotron acceptance
- injection, central region: beam shaping & current set, betatron oscillation alignment
- acceleration: adjustment of magnetic field and RF fields
- extraction: turn separation & efficiency

transversal information: radial probes, high / low current

longitudinal information

beam losses & beam halo at high current

PAUL SCHERRER INSTITUT

beam diagnostics is a very large field

- used at different machines: linear & circular accelerators for electrons, protons, hadrons
- many physical effects are used to sense the beam
- a large variety of technical realisations in many labs → a wealth of literature

Proceedings Cyclotron Conferences since 1959, BIW since 1989, DIPAC since 1993, PAC, EPAC, APAC, IPAC, LINAC → JACoW
JUAS (e. g. Forck 2009), CAS (e. g. Wittenburg/Braun/Bravin et al. 2008)

beam diagnostics *for cyclotrons* is a subset

- not all techniques usable due to special boundary conditions
- specific tasks in cyclotrons
- different types of cyclotrons have different needs

→ adapted diagnostics

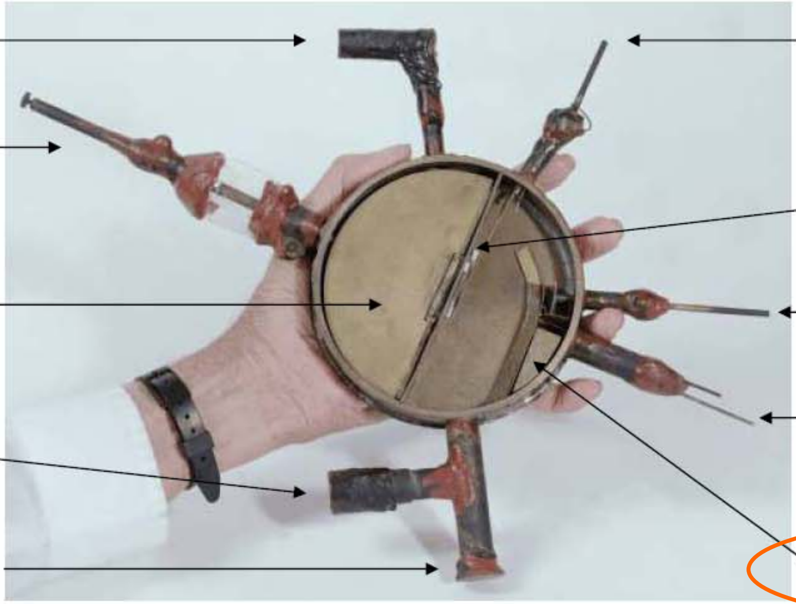
and well-established

- nearly all principle diagnostic techniques used today were already present in the 1970s
  (compact review by Mackenzie CYC78 p. 2312, also Clark CYC66 p. 15, Olivo CYC75 p. 331)
- since then improvement mainly in detail
  - better sensors
  - better electronics (analogue & digital)
  - (better drives)

→ improved diagnostics

(but also an improved machines around it)

the field in general



In late 1930, Lawrence's student, Stanley Livingston, built a "4-inch" version in brass. Clear evidence of magnetic field resonance was found in November, and in January 1931 they measured 80-keV protons.

Ions were produced from the residual gas by a heated filament at the centre. Note the liberally applied red sealing wax for vacuum tightness - and Glenn Seaborg's left hand.

from M.K. Craddock, Lecture "Introduction to Particle Accelerators", http://trshare.triumf.ca/~craddock/PH555/Intro-1.pdf

boundary conditions from different cyclotrons

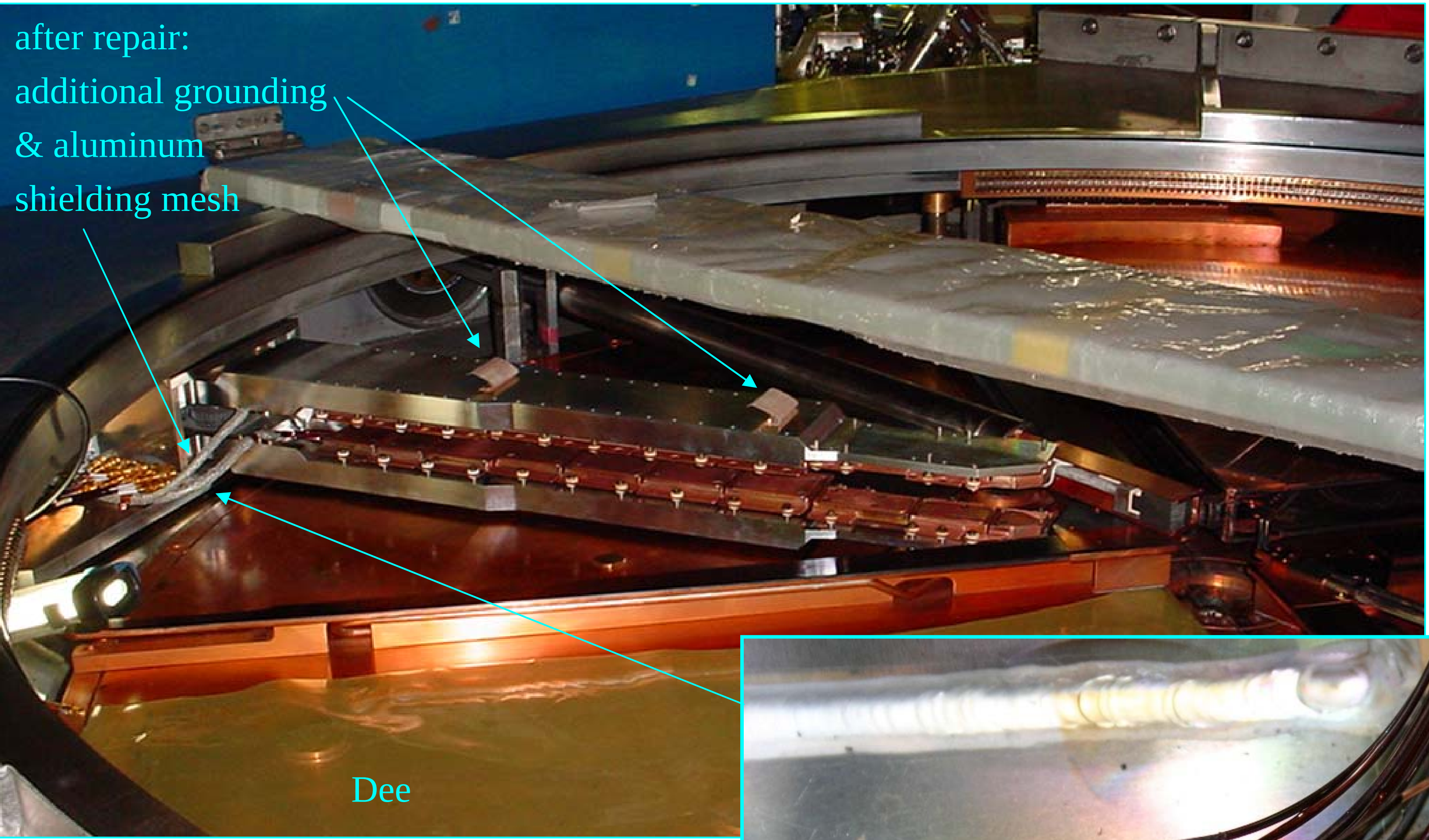
PAUL SCHERRER INSTITUT

property of cyclotron	*impact on boundary conditions for diagnostics in cyclotron via*	*affected requirement to diagnostics*
high/low beam current high/low beam energy protons/H$^-$/heavier ions external/internal source separate sectors/compact	thermal/radiation load, activation (direct/indirect; shielding difficult) penetration depth, cross sections gas pressure available space, magnetic field RF nearby	machine protection activation control reliability/maintainability
normal/superconducting		
standalone/coupled machine		
turnstructure: separated/not	→	different techniques
single-/multispecies	→	frequentness of setups (particle identification)
downtime critical/not	→	reliability/maintainability
unique/series model	→	amount of diagnostics

this is different in cyclotrons

a difficult environment

JAEA
930 AVF
cyclotron

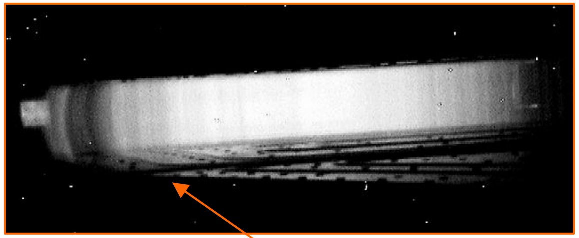


phase probe signal cables damaged by RF after introduction of Flat-Top system of few kV, 80-100 MHz

(now still noise is picked up and hence phase measured with Flat-Top off)

all pictures from S. Kurashima, JAEA

a difficult environment

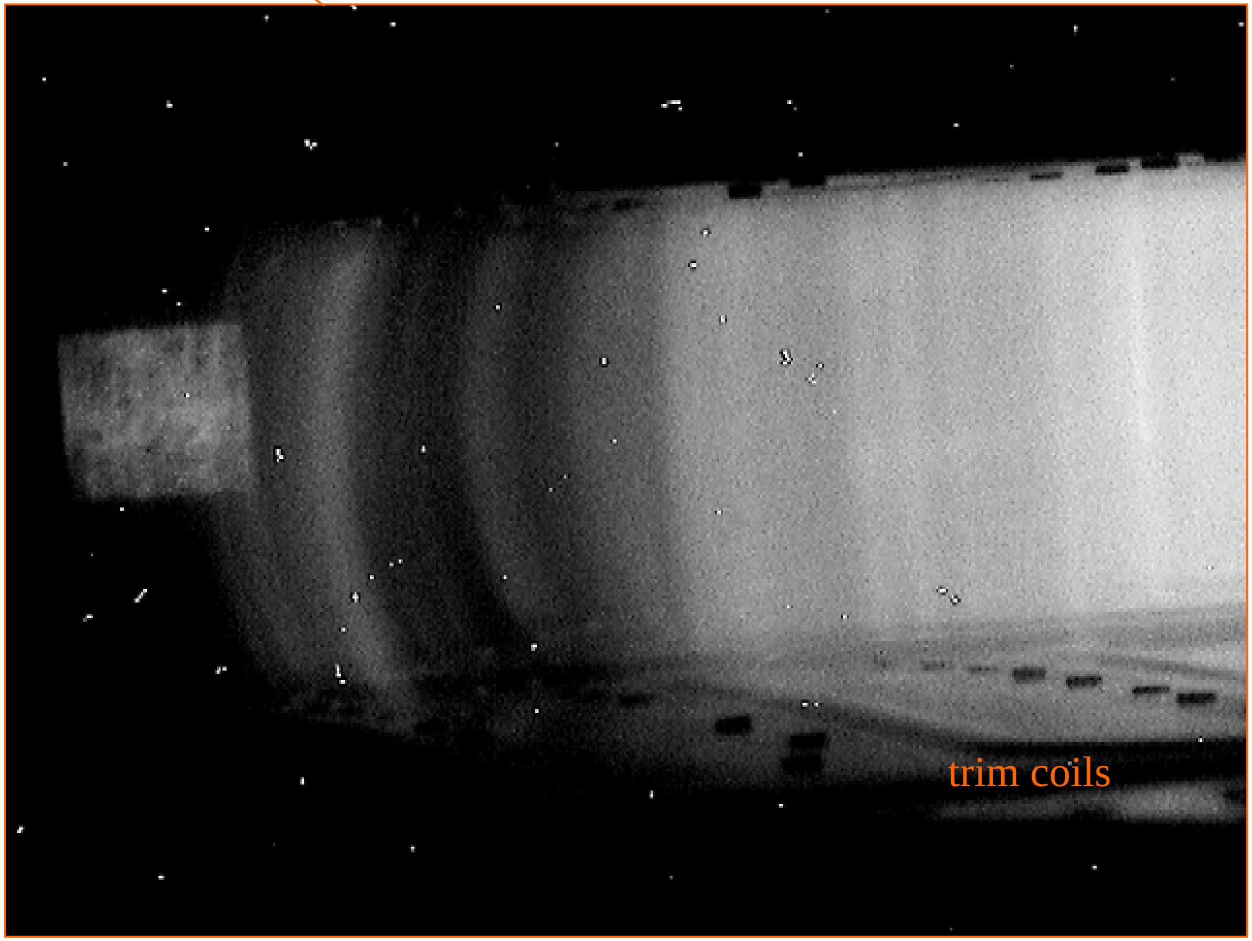


radial view into PSI Ring cyclotron

RF on (~3 MW), magnet on (~1.7 T)

beam off

~10^{-6} mbar



pictures from R. Kan, PSI, see also D. Goetz et al., this conference

thin plasma

in sector magnet

at lower machine radii

(always present?)

impact on

electrostatic septa

probe measurements?

tasks of beam measurements

- for machine **safety** (prevent the beam from melting something) ms
  e. g. collimator with current measurement
- for machine **stabilisation** s
  e. g. closed loop beam current stabilisation by adjustment of ion source arc current
- for machine **setup & tuning** 1 day ... 1 week
  e. g. phase measurement for adjustment of main coil current
- at **beam development** (finding new settings, with or without changed hardware)

- for **error search** 1 month

- only at **commissioning** once
  e. g. finding trim-rod settings for centered beam

for all tasks beam measurements should deliver the ε of information

which is still needed in spite of

- good design due to theoretical understanding & simulations & field mapping & experience
- suitable operation due to -"-
- good stability of machine components and environment
- reliable machine components

(these fields have improved much over the years, but the demands also increase)

beam parameters to be determined

beam properties	*familiar monitors* in beam lines	*familiar monitors* both
- current of full beam	- current transformer	- stopper, Faraday-cup
- transverse position of full beam	- BPM	
- phase of bunch center		- phase probe
- transverse profile - projection - 2D		- wire monitor, harp - screen
- transverse emittance - 1D - 2D	- „2 slit“ / „3 profile“ - pepperpot / „4-slit“	
- longitudinal profile		- time structure meas.
- longitudinal emittance		
- beam ion energy distribution		
- beam losses		- loss monitors

specific in cyclotrons	in cyclotron
- turn separation	- radial probes
- betatron oscillations - amplitudes	(diff., int., viewer, ...)
- frequencies	„
- centering	„
- precession	„
- turn number	„ / phase probes
- isochronism, phase history	- phase probes

beam parameters to be determined

PAUL SCHERRER INSTITUT PSI

beam properties	*familiar monitors* in beam lines	both
- current of full beam	- current transformer	- stopper, Faraday-cup
- transverse position of full beam	- BPM	
- phase of bunch center		- phase probe
- transverse profile - projection - 2D		- wire monitor, harp - screen
- transverse emittance - 1D - 2D	- „2 slit“ / „3 profile“ - pepperpot / „4-slit“	
- longitudinal profile		- time structure meas.
- longitudinal emittance		
- beam ion energy distribution		
- beam losses		- loss monitors

important for high current machines

to see the beam halo which causes losses of ~10^{-4}

(as input for beam dynamic simulations)

specific in cyclotrons	in cyclotron
- turn separation	- radial probes
- betatron oscillations - amplitudes	(diff., int., viewer, ...)
- frequencies	„
- centering	„
- precession	„
- turn number	„ / phase probes
- isochronism, phase history	- phase probes

dynamic range up to10^5 needed (for projected profile)

effects / methods usable for measurements

PAUL SCHERRER INSTITUT

information 1D: 1D-profile 2D: 2D-profile Dz: long. prof. Pos.: position E: energy C: full current	*configuration*	*usable effect/device*	*usable* A) for machine safety B) permanently C) for tuning D) at setup E) for error search F) only at commiss.	*destructive*	*able to work inside cycl.*	*alrdy. used inside cycl.*	*usabl. at good vacui*	*beam current range* (assumed DC beam at 70 MeV, 10 mm diameter, to be determined more precisely)	*common names*
		beam self fields							
Pos, Dz, C	pickups	comparison of capacitively or inductively coupled RF currents	A B C D E	no	x	**x**	x	nA … A	pickup, BPM, phase probe
C, (Dz)	transformer	DC or AC current transformer, wall current monitors	A B C D E	no	?		x	nA … A	DCCT, ACCT, wall curr. m.
1D, C, (Dz)	"wire"	electron (or ion) beam probe	B C D E	no			x	mA … >A	electron beam probe
1D, C	residual gas	residual gas ions (with beam space charge field)	?	no			(x)	mA … >A	[21]
		direct beam current							
1D (/+Dz), C	in full beam	probe finger: current of stopped beam fraction (/+50Ω-readout)	D E	yes	x	**x**	x	nA … uA	radial probe/Faraday cup
<1D	beam edge	collimator: -"-	A B C D	"no"	x	**x**	x	pA … mA	collimator
1D, C	wire	wire: -"-	C D E	~no	x	**x**	x	-	wire scanner
		heating of introduced solid matter							
1D, C	in full beam	probe finger: direct (or cooling water) temperature measurement	D E	yes	x	x	x	nA … uA	calorimeter probe
<1D	beam edge	collimator: -"-	B C D	"no"	x	x	x	nA … mA	
1D, C	wire	vibration resonance shift	C D E	~no	?		x	pA … uA	vibrating wire scanner
1D	wire	wire: resistance	C D E	~no	x		x	uA … mA	
E, C	in full beam	probe finger: 2 thermocouples + degrader	C D E	yes	x		x	nA … mA	[22]
2D, C	in full beam	metal/carbon foil: thermal light emission/thermionic emission	A B F	~yes	x	x	x	uA	[23, 6]
1D	wire	wire: -"-	C D E	~no	x	x	x	uA … mA	
		changes to introduced solid matter							
2D	in full beam	paper/Kapton/Mylar darkening, metal foil burn	F	yes	x	**x**		nA … uA	foil burn
2D, C	in full beam	radiochromic film	F	yes	x	**x**		<pA … nA	
2D, C	in full beam	foil activation analysis, autoradiograph	F	yes	x	**x**	x	pA … uA	autoradiograph
		secondary particles from introduced solid matter							
1D, C	wire	wire: secondary emission current, direct measurement	C D E	~no	x	**x**	x	pA … mA	wire scanner
<1D, C	beam edge	foil: -"-	A B C D E	"no"	x	**x**	x	pA … uA	SEM foil, aperture foil
2D, C	in full beam	foil: secondary emission current + pulling + 2D-electron detector	A B C D E	~no	x		x	pA … uA	
1D, Dz, C	wire	wire + detection of scattered or secondary particles	C D E	~no	x	**x**	x	nA … mA	time structure m./wire scanner
Dz, C	in full beam	foil + detection of scattered or secondary particles	C D E	~no	x	**x**	x	nA … mA	time structure measurement
2D, C	in full beam	scintillating screens + 2D-light detector	C D E	yes	x	**x**	x	pA … uA	scintillator screen/viewer probe
1D, Dz, C	"wire"	scintillating fibres + (external) PMT	C D E	~no	x		x	<pA … nA	
Dz, C	in full beam	scintillator + (external) PMT	C D E	yes	x	x	x	<pA	time structure measurement
<=2D,Dz,E,C	in full beam	silicon/diamond bulk/strip/pixel detector	C D E	yes	x	x	x	<pA/<nA	silicon strip detector
		secondary particles from introduced dense gases							
1D, C	"wire"	coaxial ionisation chamber	C D E	~yes	x		x	<pA … uA	
1D, C	in full beam	ionisation chamber + strip-electrode readout (in beam/not)	(B) C D E	yes/~yes	x		x	<pA … uA	strip ionisation chamber
2D, C	in full beam	ionisation chamber + pixel-electrode readout (in beam)	C D E	yes	x		x	<pA … uA	pixel ionisation chamber
1D	in full beam	proportional chamber	C D E	~yes			x	<<pA … nA	wire chamber
1D, 2D, C	in full beam	GEM	C D E	yes	x?		x	<<pA … nA	GEM
		secondary particles from residual or thin gas							
2D, C	gas curtain	beam induced fluorescence + (external) light detector	A B C D E	~no				nA … >A	gas curtain
1D, C	residual gas	beam induced fluorescence + (external) light detector	A B C D E	no	x	x	(x)	mA … >A	BIF monitor
1D (2D), C	residual gas	res. gas ions/electrons with external fields + strip(/+energy) det.	A B C D E	~no	x	x		uA … A	residual gas profile monitor

see also Koziol, CAS2000 p. 154, http://cdsweb.cern.ch/record/425460/files/CERN-2005-004.pdf, Dölling, ECPM09, http://www.kvi.nl/~agorcalc/ECPM2009/EducationalSession/4_Doelling.pdf

4 min

diagnostics along the beam path

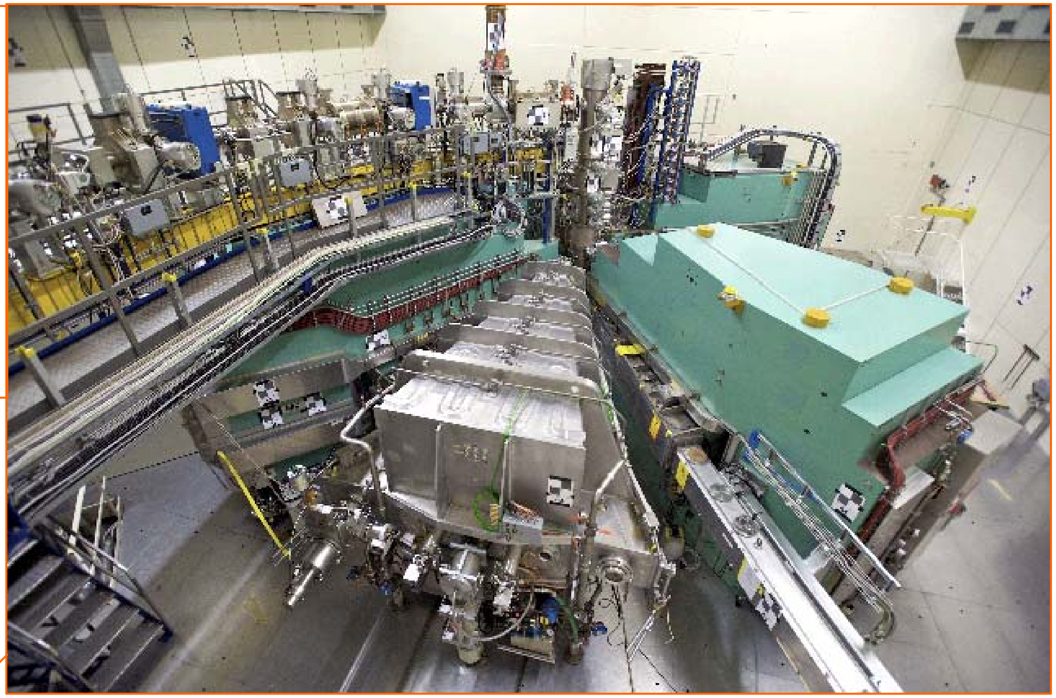
most examples from PSI's high power proton facility

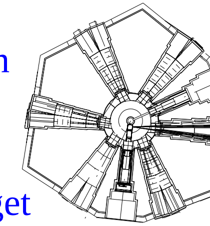
+ external examples

which operates ~4800 h/a for ~400 users/a

Injector 2 cyclotron

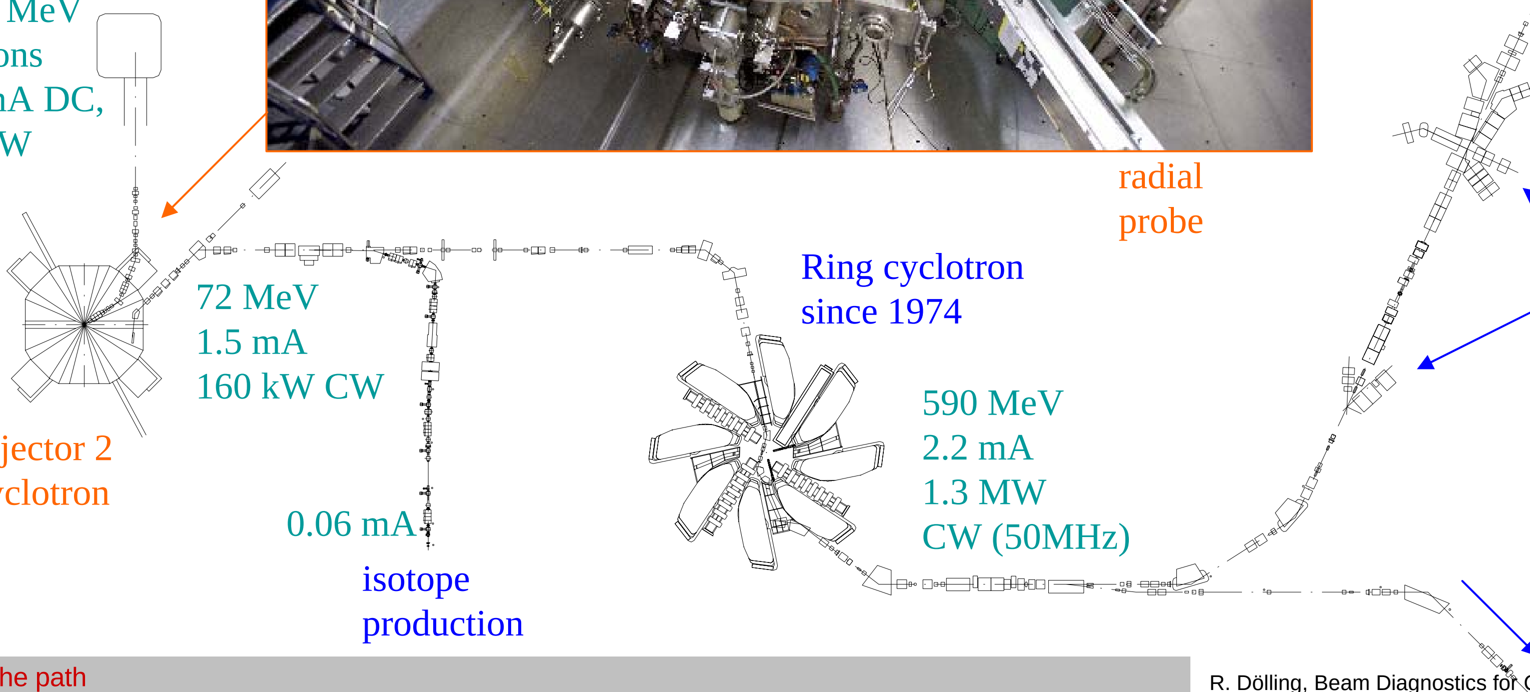
- high beam current
- separated sectors
- normal conducting
  → some space for diagnostics





spallation neutron source SINQ since 1998

(liquid Pb-Bi target during 2006)

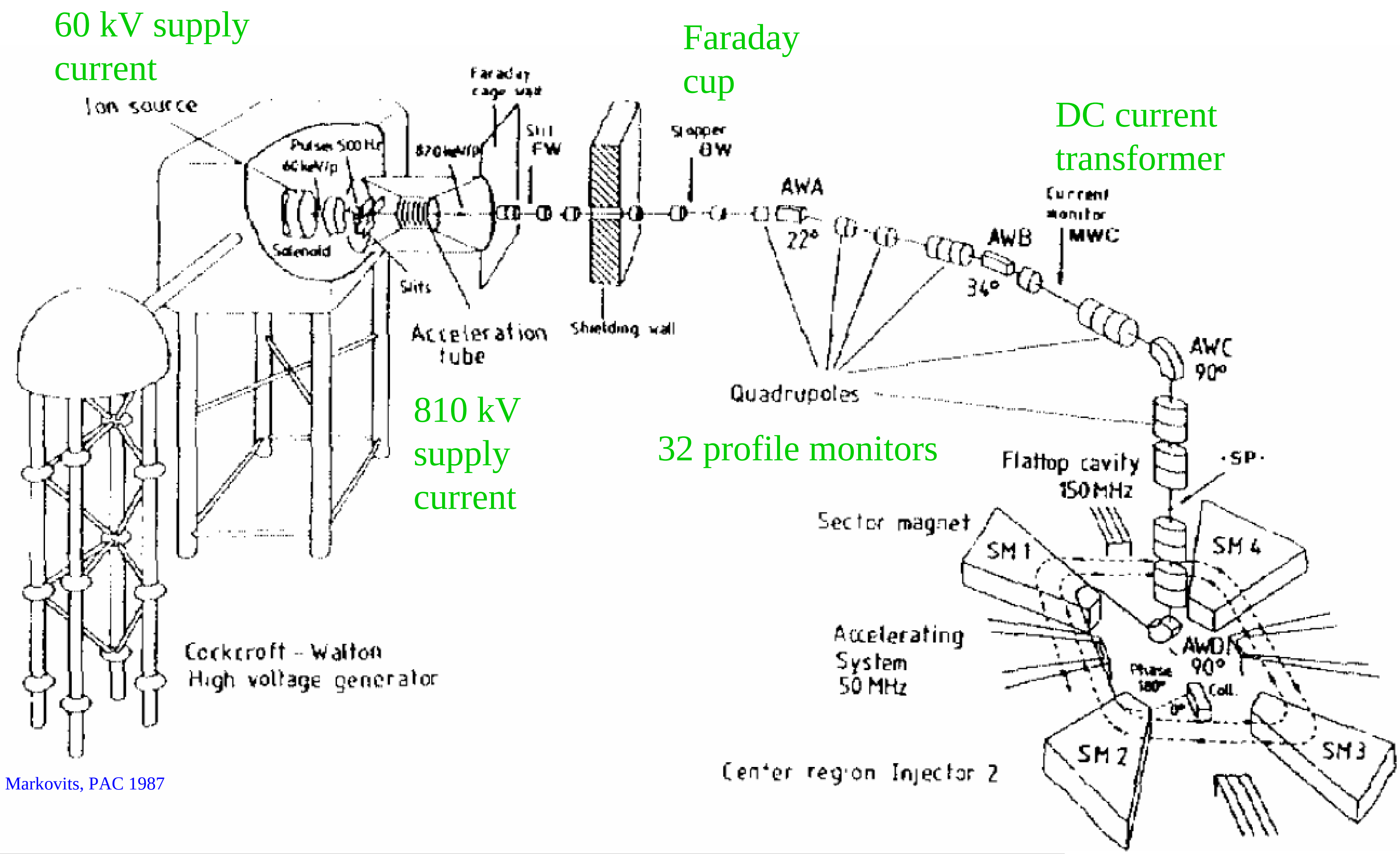


ion source & injection line:

matching the beam core to the cyclotron acceptance

beam position, profile, current

- beam positions, widths, current → normal operation, beam alignment (or online centering)
- beam profiles → beam development or troubleshooting



Markovits, PAC 1987

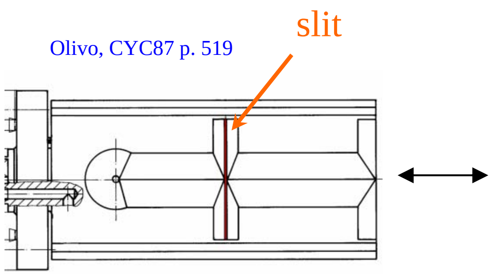
along the path: injection line (matching the beam core to the cyclotron acceptance)

profile monitors

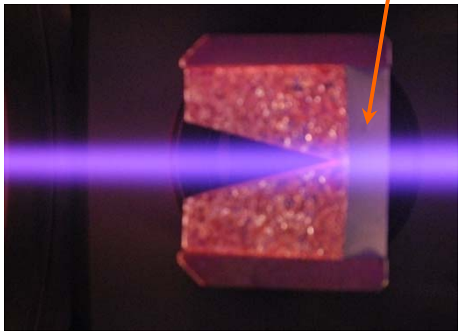
calorimetric slit scanner

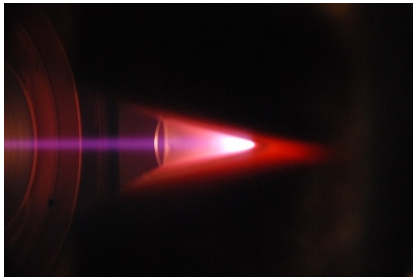
(at 60 keV, destructive)

Olivo, CYC87 p. 519



- internal cooled copper block behind vertical slit
- measurement of water in-/outlet temperatures

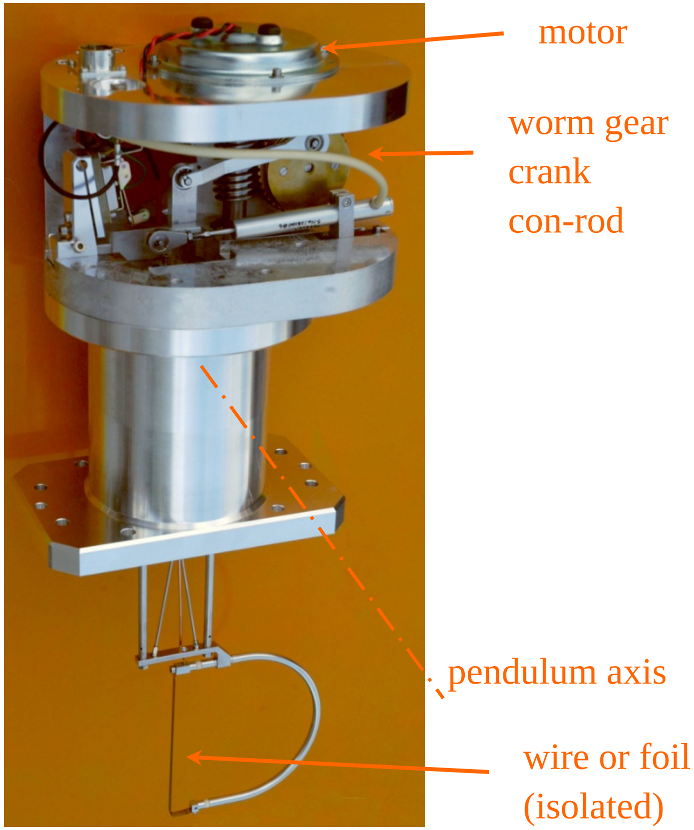




wire scanner

(870 keV 11 mA
up to 20% DC)

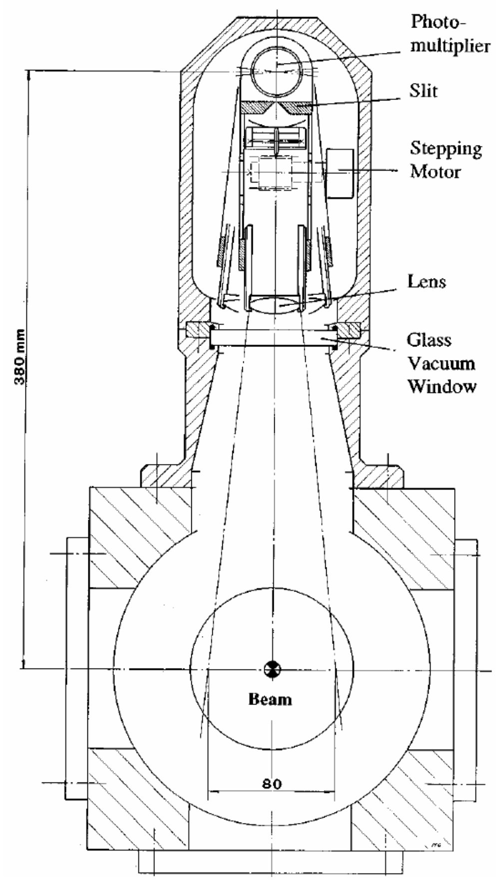
Rezzonico, CYC87 p. 457



beam induced fluorescence monitor

(870 keV full beam
non-destructive)

PMT and lens scanned

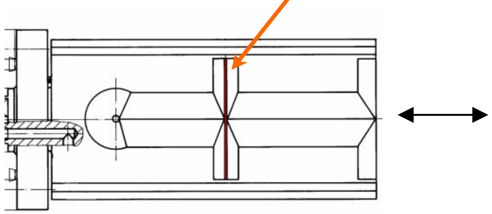


along the path: injection line (matching the beam core to the cyclotron acceptance)

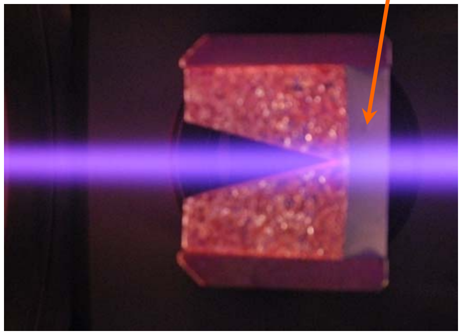
profile monitors

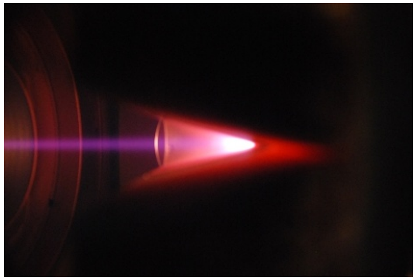
calorimetric slit scanner
(at 60 keV, destructive)

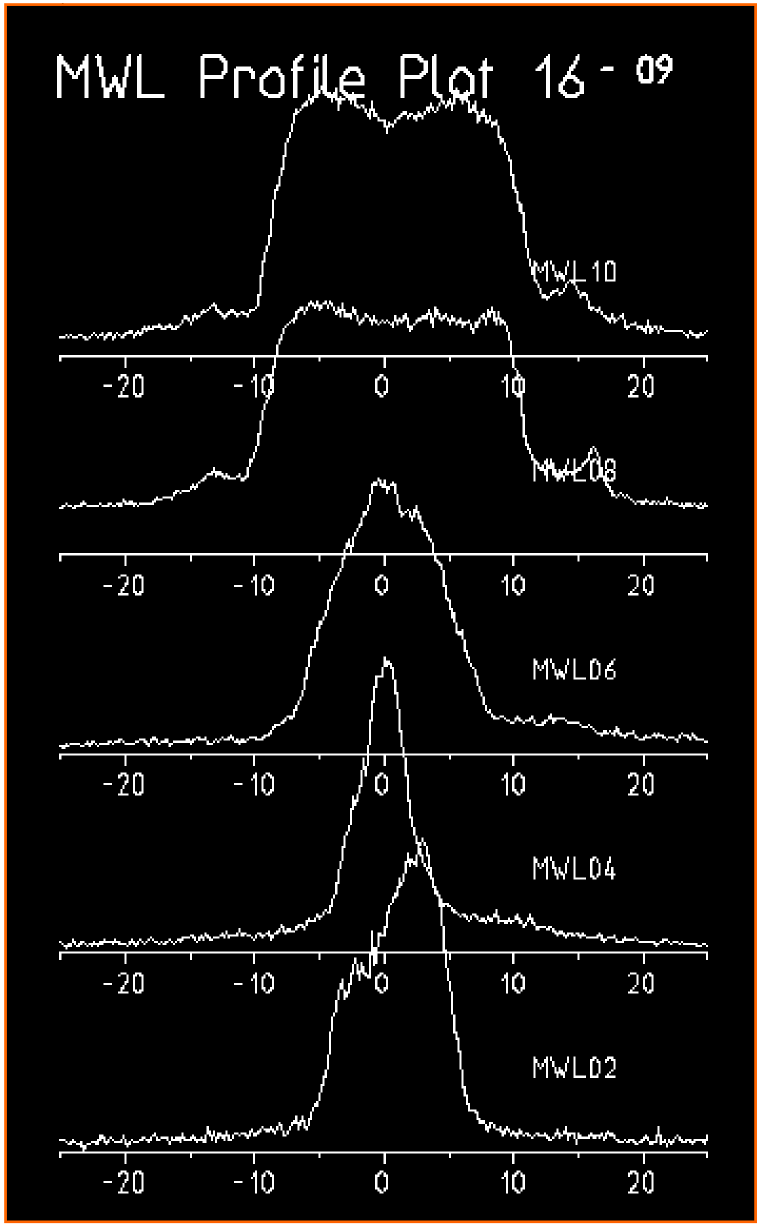
Olivo, CYC87 p. 519



- internal cooled copper block behind vertical slit
- measurement of water in-/outlet temperatures

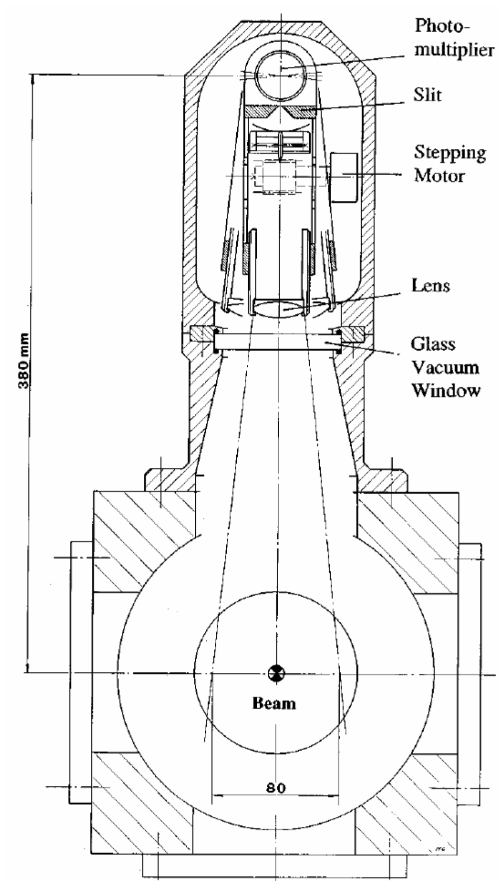






beam induced fluorescence monitor
(870 keV full beam
non-destructive)

PMT and lens scanned

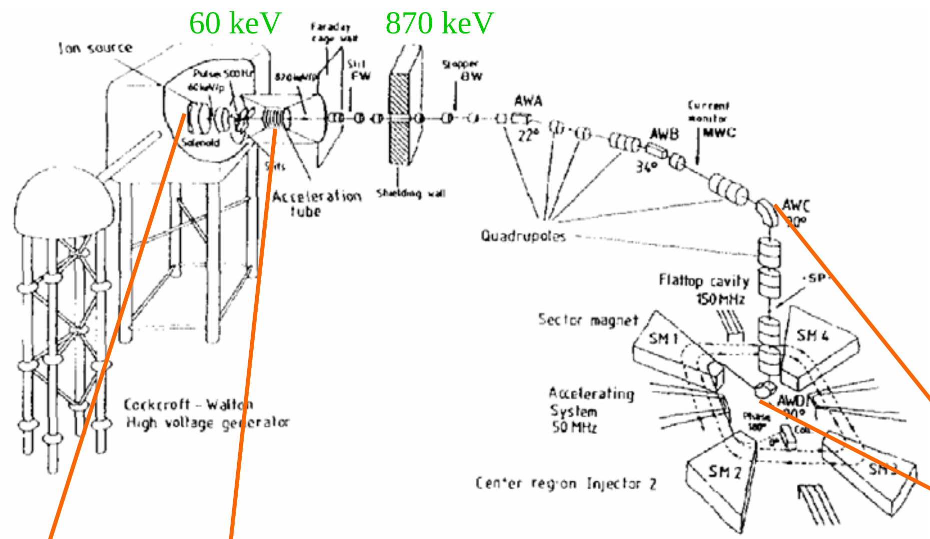


along the path: injection line (matching the beam core to the cyclotron acceptance)

emittance from many profiles + Transport fit

PAUL SCHERRER INSTITUT PSI

- input: magnet currents & beam width from profile monitors
- enveloppe fit (over-determined) by „simple“ Transport calculation (matrices) including linear space charge → emittance



for high beam power (in principle)

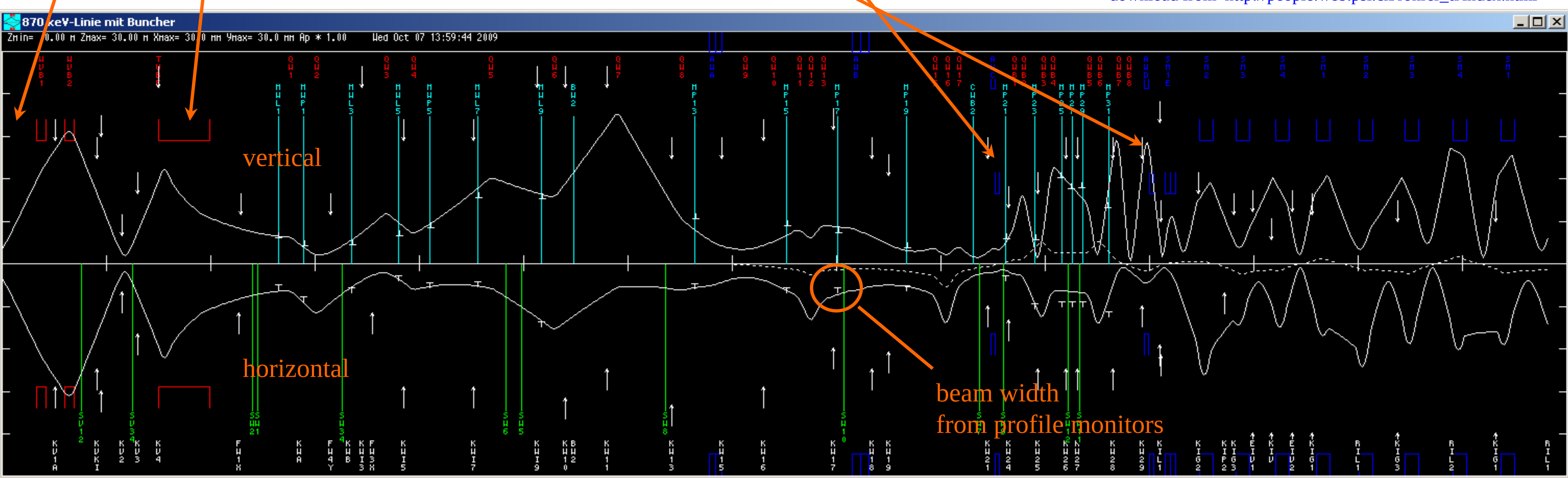
profiles measured at 13% DC

space charge neutralisation ~0.5 for good fit

→ $\varepsilon = 6\,\pi$ mm mrad @870 keV

PSI Graphic Transport by U. Rohrer includes linear space charge

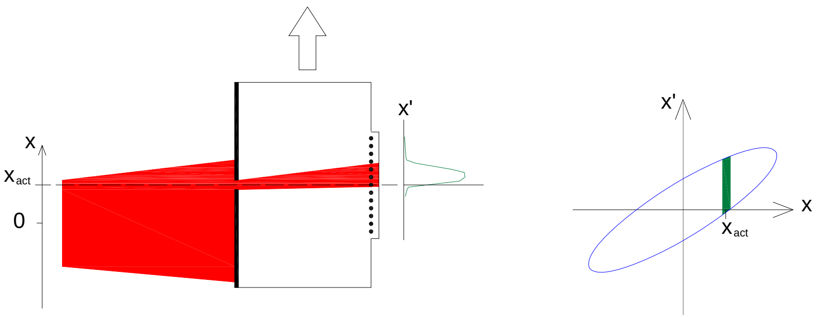
download from http://people.web.psi.ch/rohrer_u/index.html



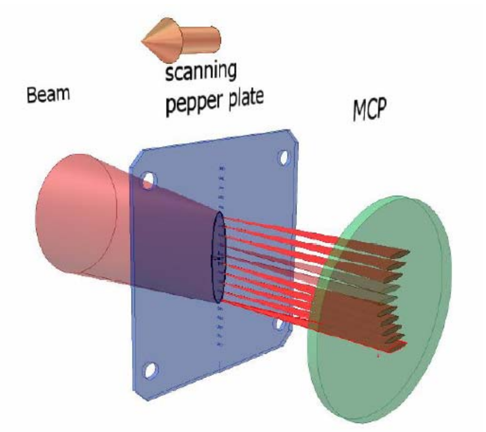
direct emittance measurement

- destructive, limited in beam power & energy

moving slit + grid



moving line of holes + screen



more information than slit + grid

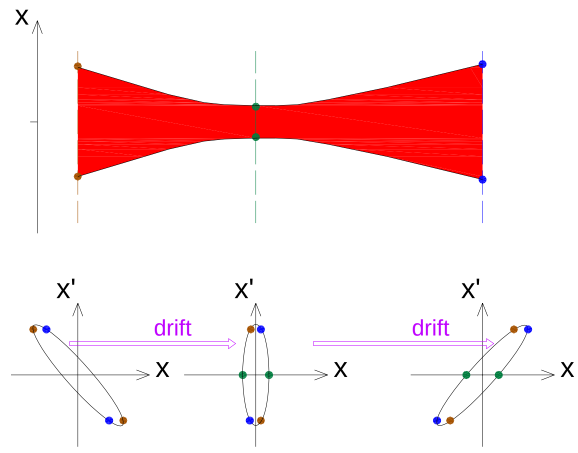
Kremers et al., ECRIS08 p. 204

+ many other configurations (pepperpot, Allison-scanner, ...

profile based emittance measurement

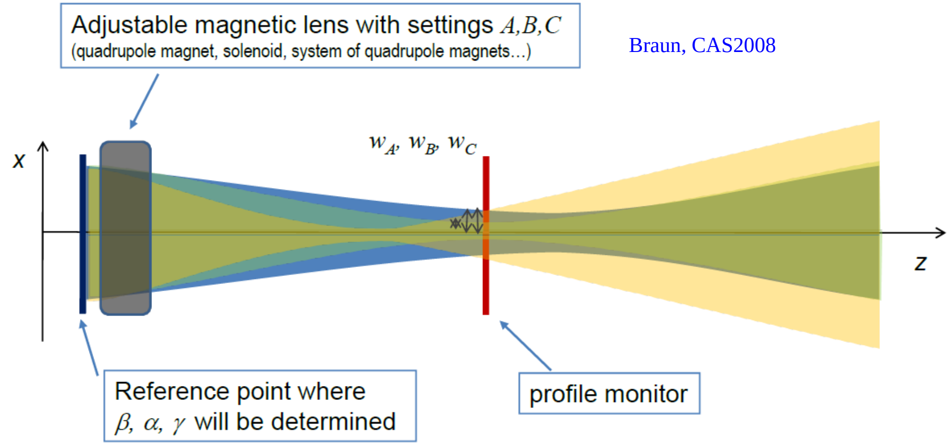
- input only 3 beam widths → less information

3-profile method



for high beam power

Q-pole variation method

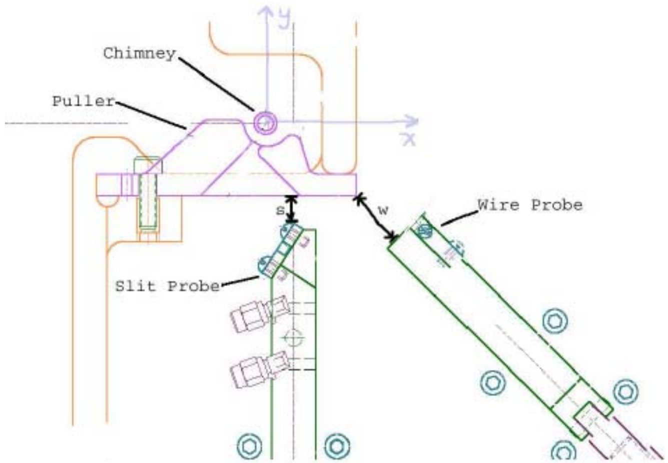


Braun, CAS2008

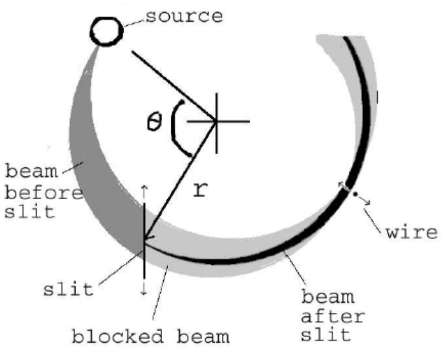
needs „beam gymnastics“ → difficult for high power beams

emittance of internal ion source [MSU]

test stand simulates cyclotron center
with internal source
including magnetic field
and fixed puller voltage/geometry:

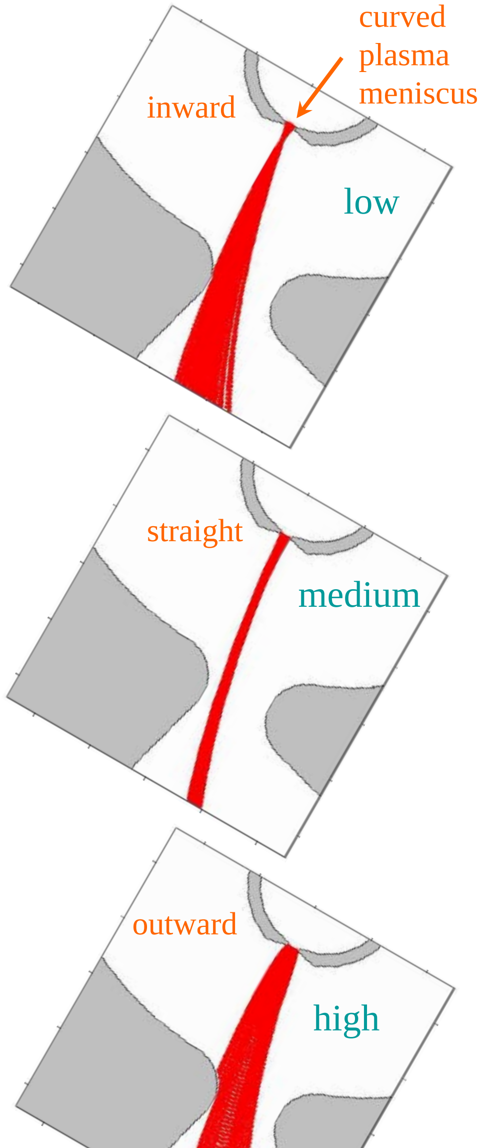


slit – wire emittance measurement
for radial emittance:

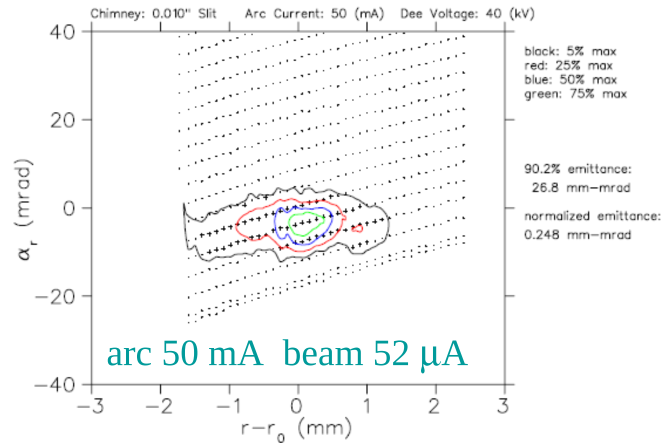


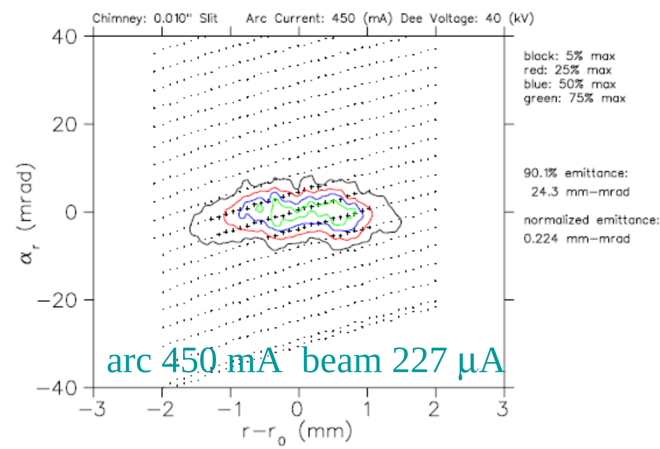
(similar for axial emittance)

numerical simulation
for different plasma pressures:



Measurement of radial emittance





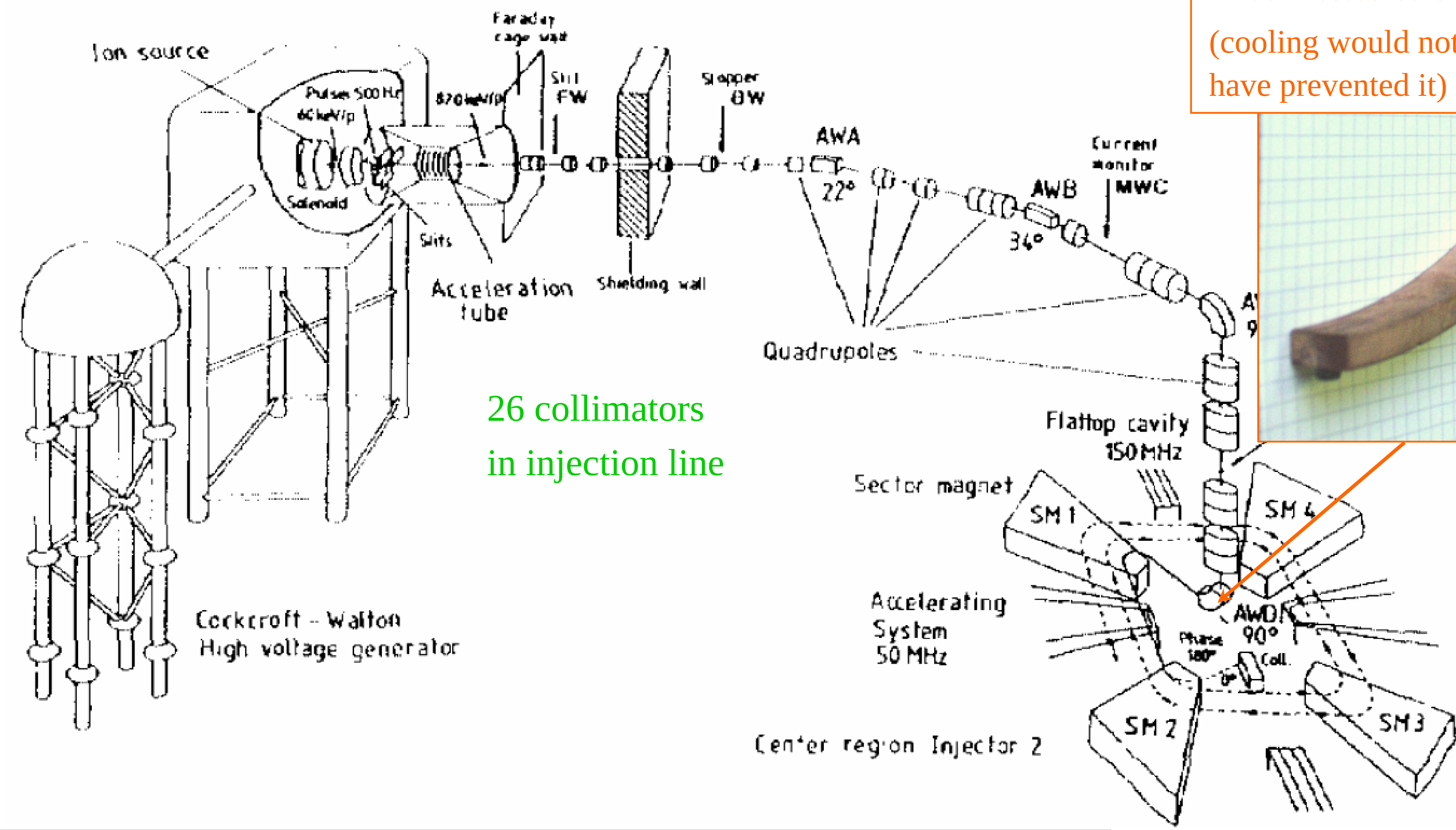
all figures from E. R. Forringer, Dissertation 2004, MSU
http://www.nscl.msu.edu/ourlab/publications/download/Forringer2004_199.pdf

collimators with current readout

- help to „guide“ the beam through the machine
- protect the machine by interlock generation
- shape the beam (this may need cooling)

sputtered material
(earlier) short-cutted
current measurement
→ no interlock
→ melts in ~1 s
at missteered beam

(cooling would not
have prevented it)



26 collimators
in injection line

PAUL SCHERRER INSTITUT

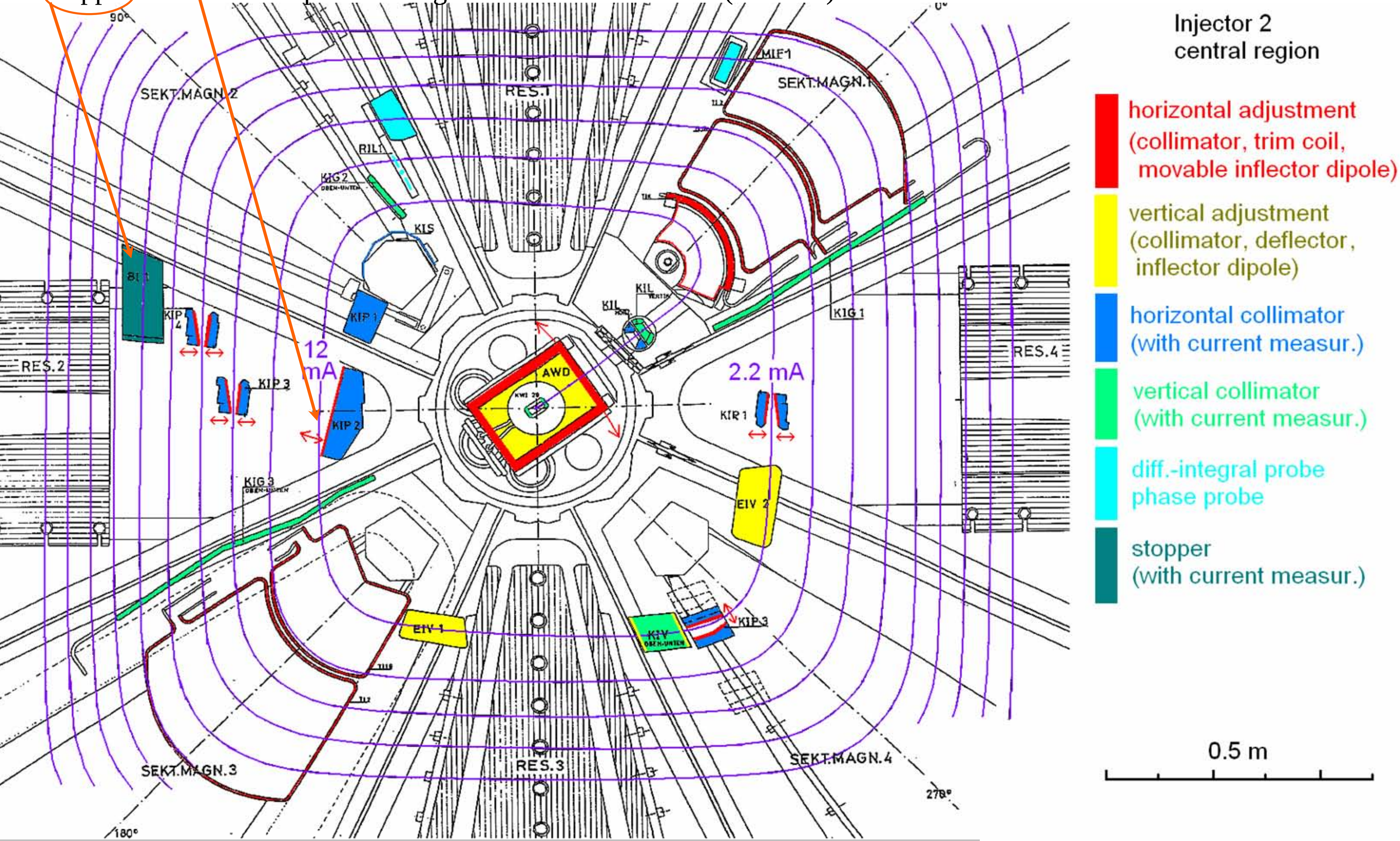
7 min

injection, central region

beam shaping & betatron oscillation alignment

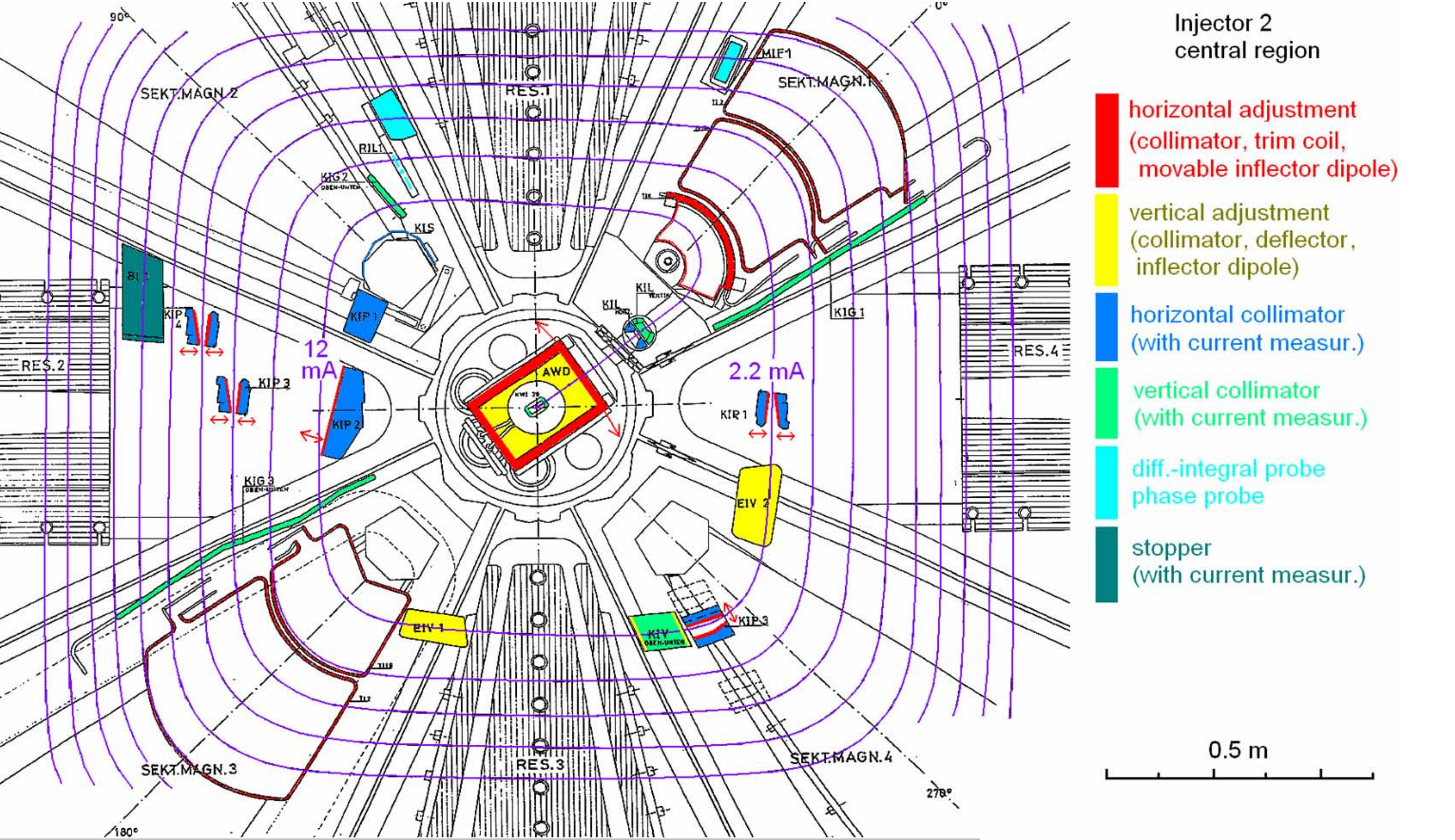
current set & beam shaping

- by cutting into beam with movable cooled collimators (no activation below a few MeV)
  (current set combined with phase selection, dominates „injection efficiency, ~13 kW)
- again: collimators help to „guide“ the beam and to protect the machine
- stopper allows to set up central region alone at full current (~10 kW)



beam centering & betatron oscillation alignment

- beam „positions“ at full current: known only from collimator currents, at low current: from radial probe
- vertical centering with vertical adjustments
- horizontal betatron oscillations around the centered path adjusted with horizontal adjustments

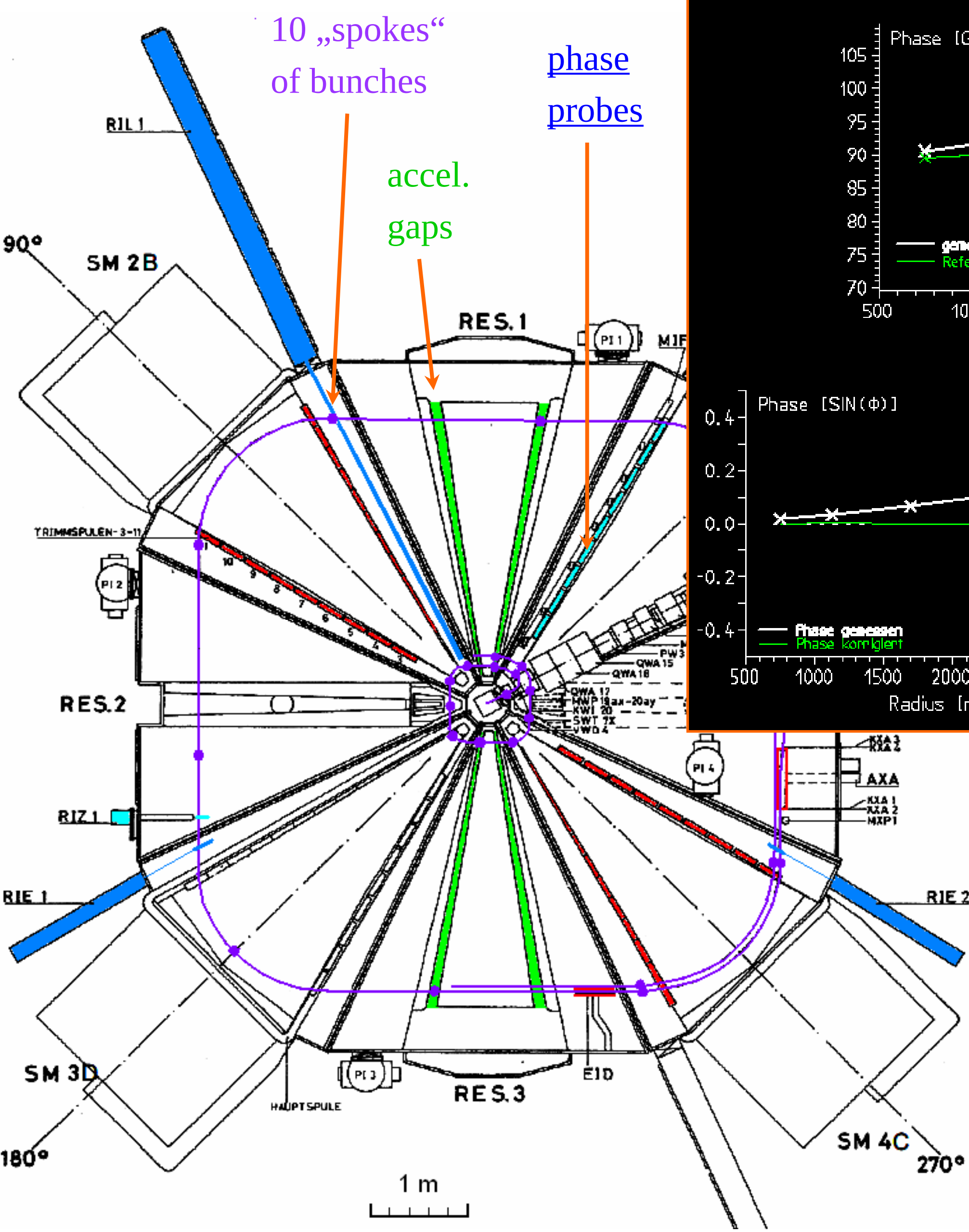


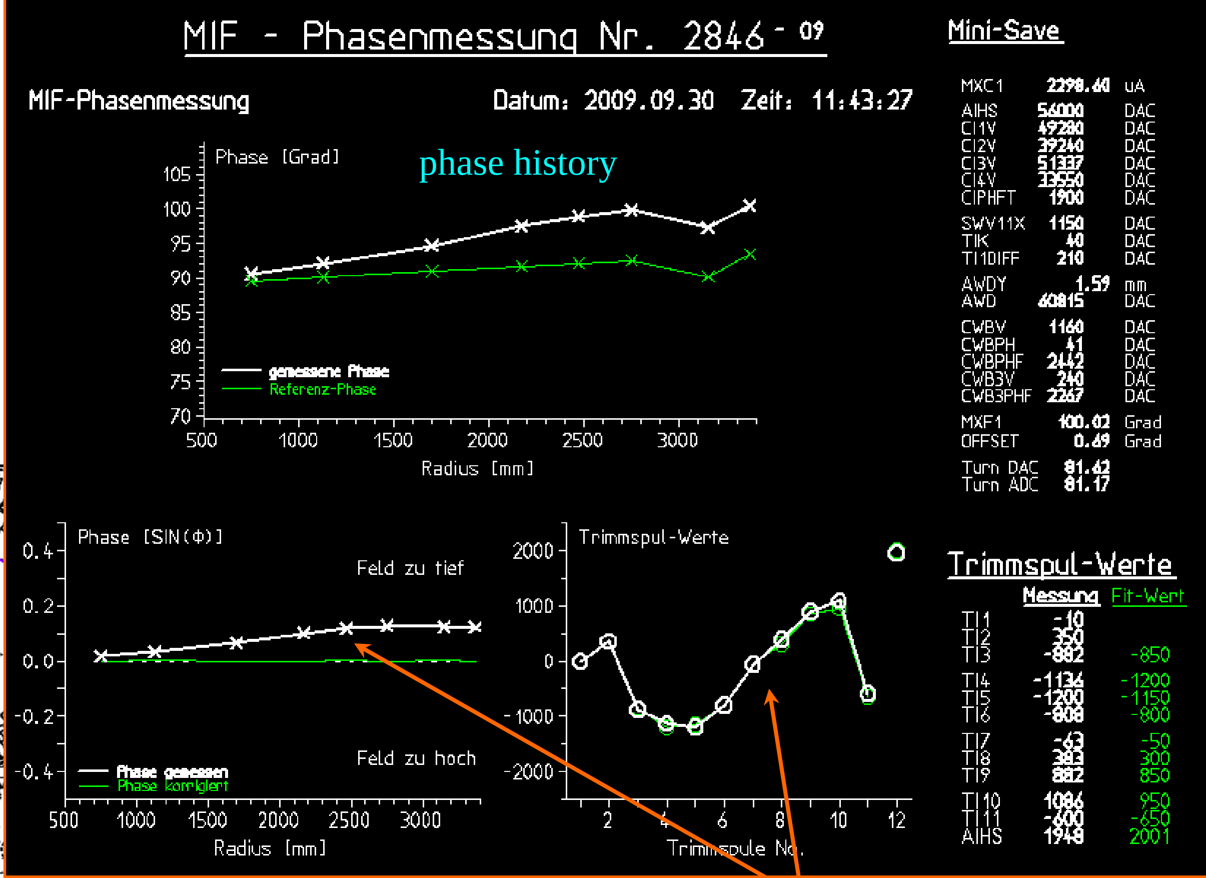
acceleration:

adjustment of magnetic field and RF fields

isochronism

full beam (2300 uA)





M. Humbel, PSI

from „phase history“

→ correction of (drifting) main field (recommended in this example)

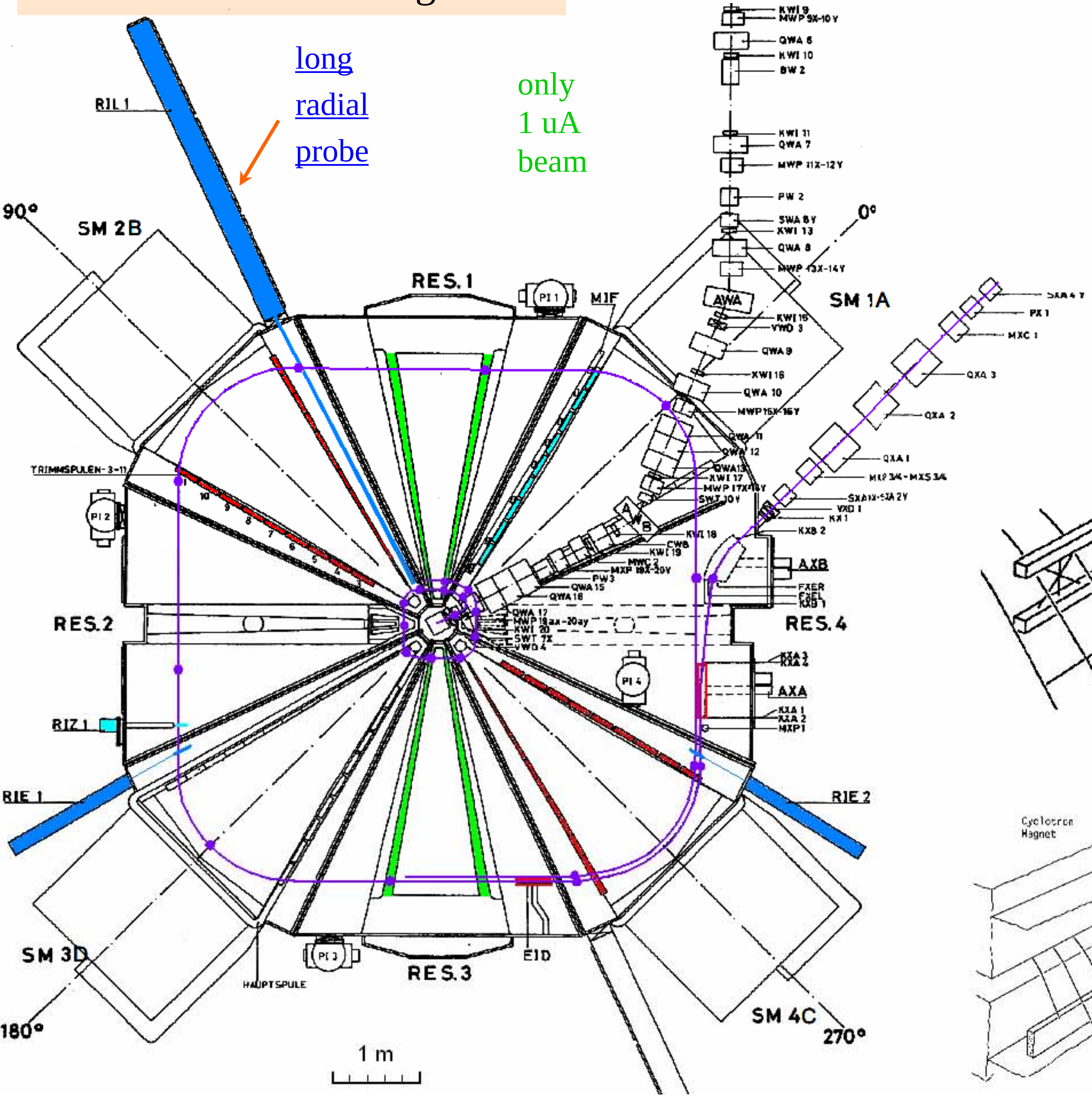
→ correction of trim coil settings

operates at 2^{nd} harmonic

variant: improved sensitivity by intensity modulation of the beam Brandenburg et al., DIPAC03

check of beam centering & betatron oscillation alignment

finding the beam and „pulling“ it to greater radii

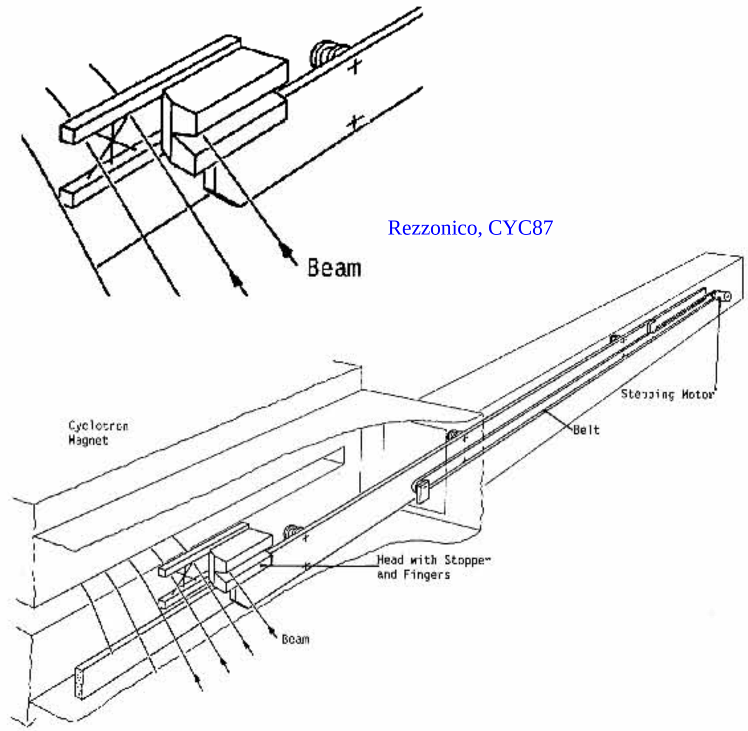


horizontal adjustment (trim coils, electrostatic septum, septum magnet)

accelerating gaps

phase probes, time structure probe

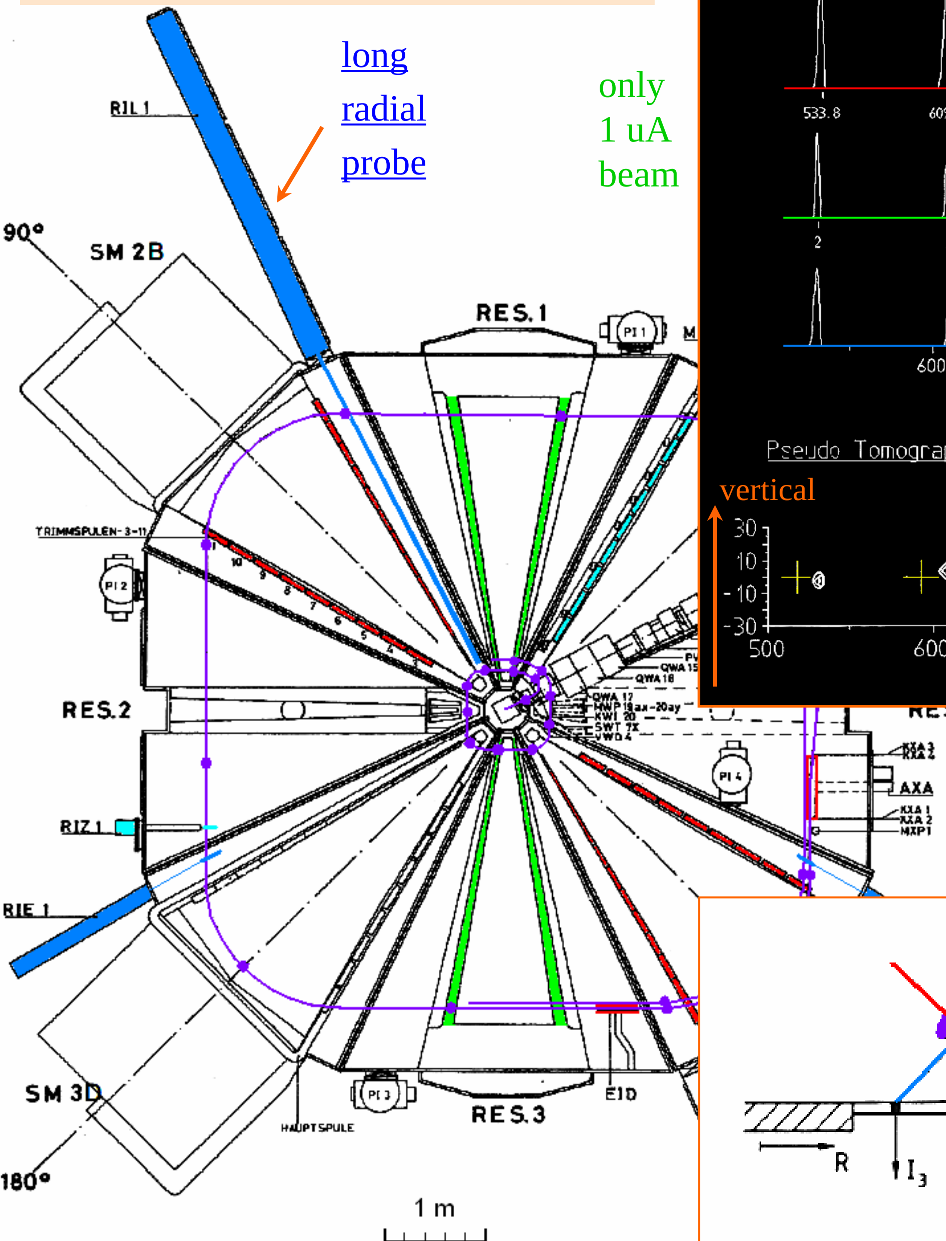
radial probes

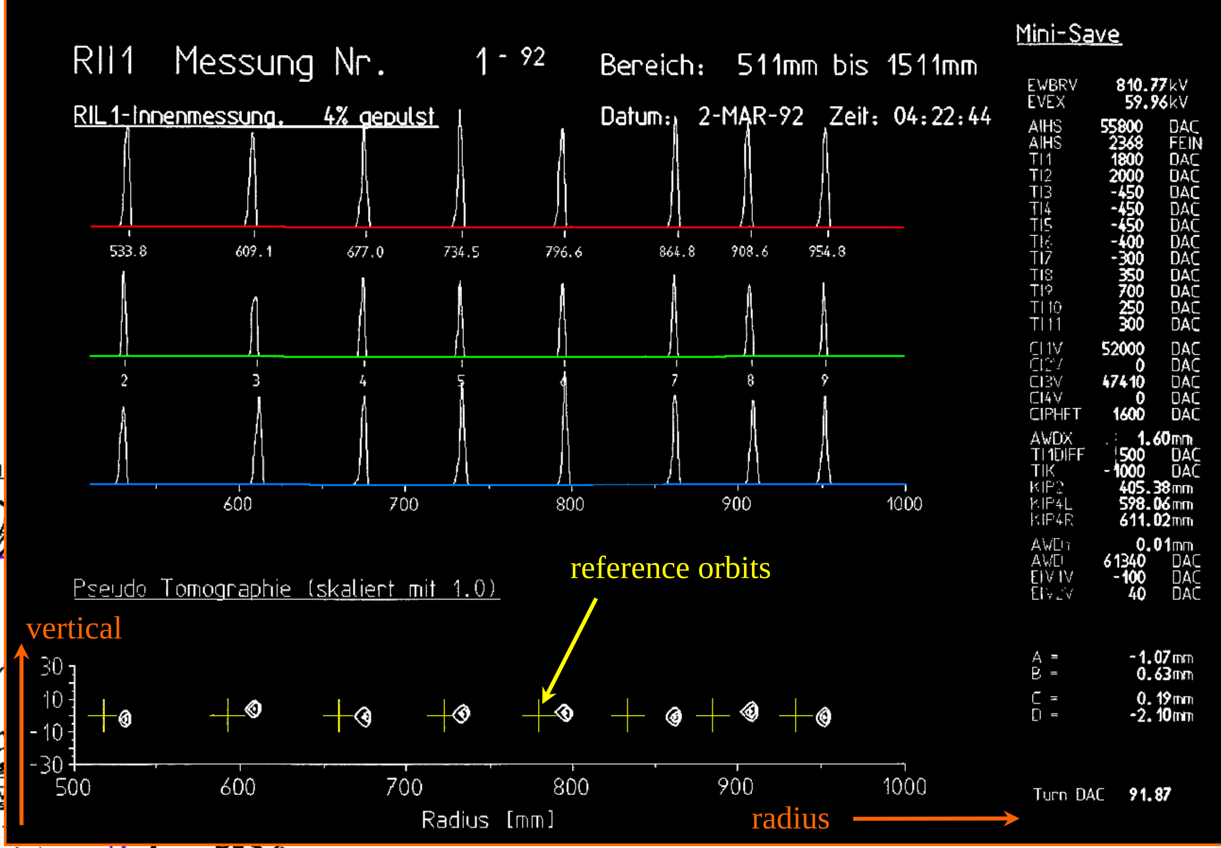


Rezzonico, CYC87

along the path: acceleration (adjustment of magnetic field and RF fields)

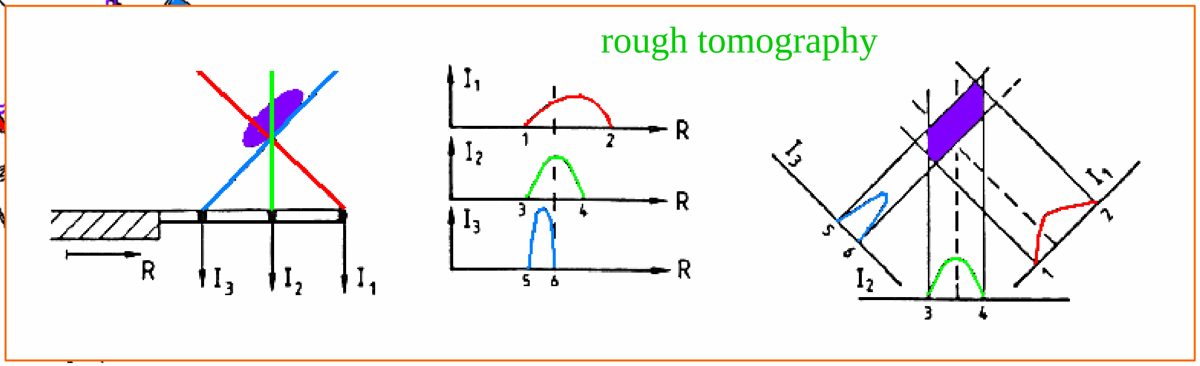
beam centering & betatron oscillation alignment





M. Humbel, PSI

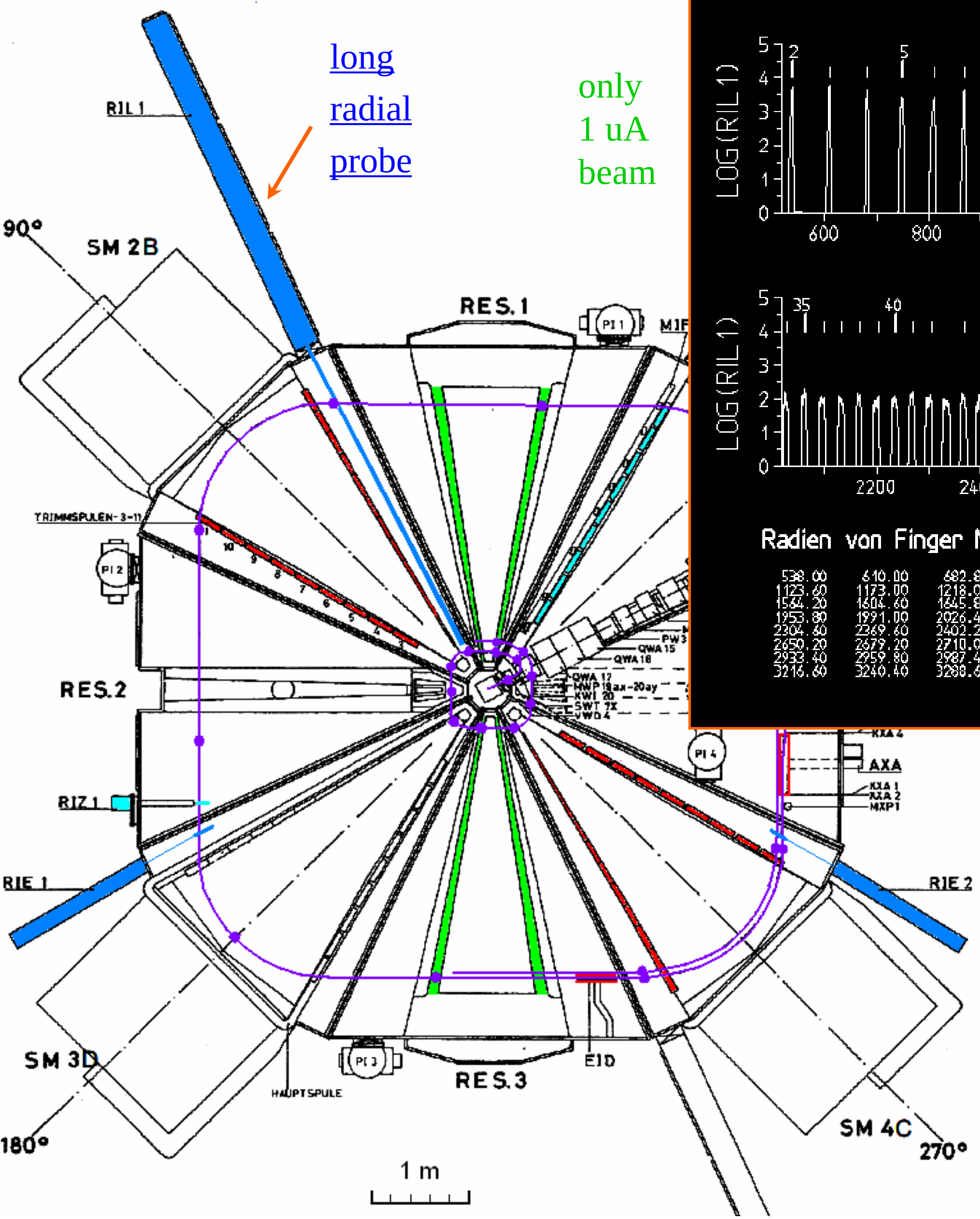
intentionally introduced radial betatron oscillations

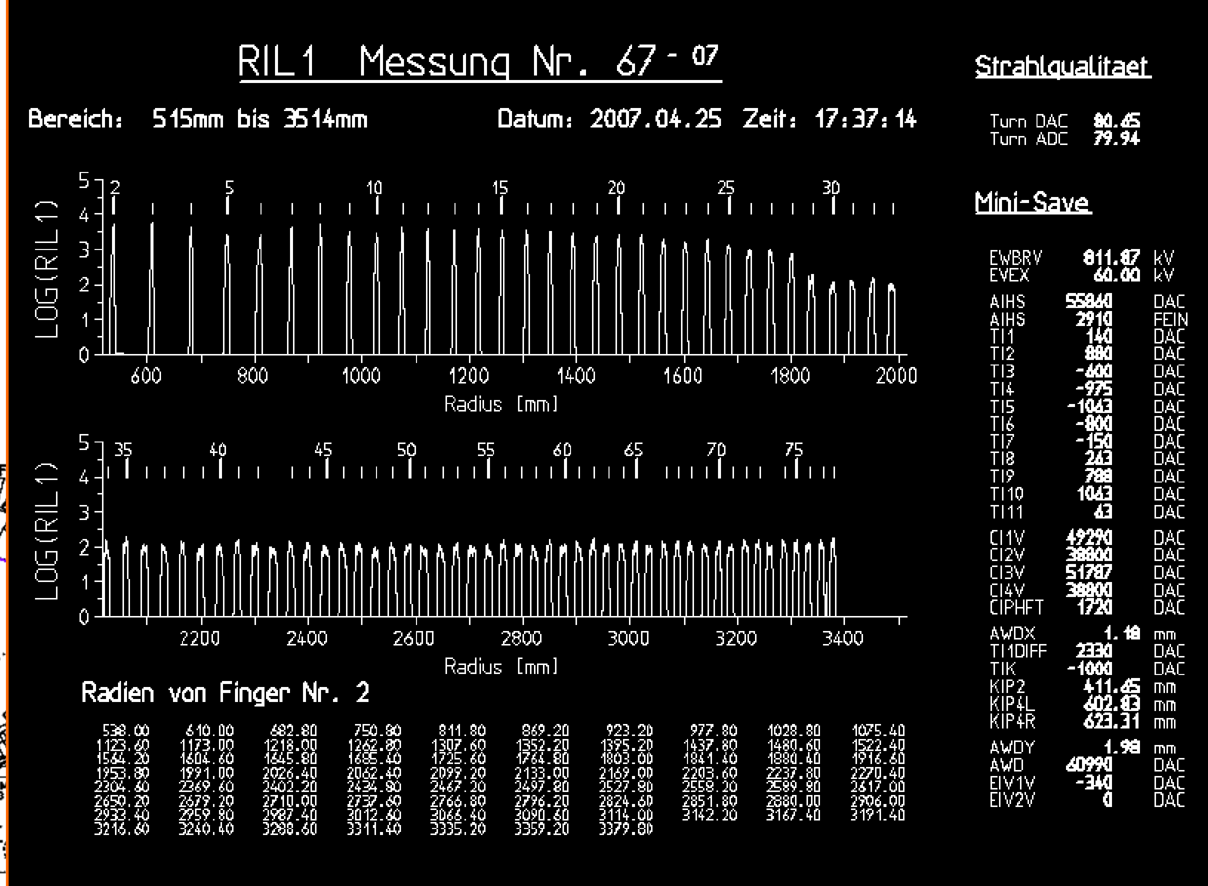


turn counting

long radial probe

only 1 uA beam





M. Humbel, PSI

radial betatron oscillations eliminated temporarily for turn counting (only vertical wire displayed)

alternative for not separated turns:
- measurement of modulated beam (maybe from ion source noise) with phase probes before and after the cyclotron
- cross correlation → time of flight

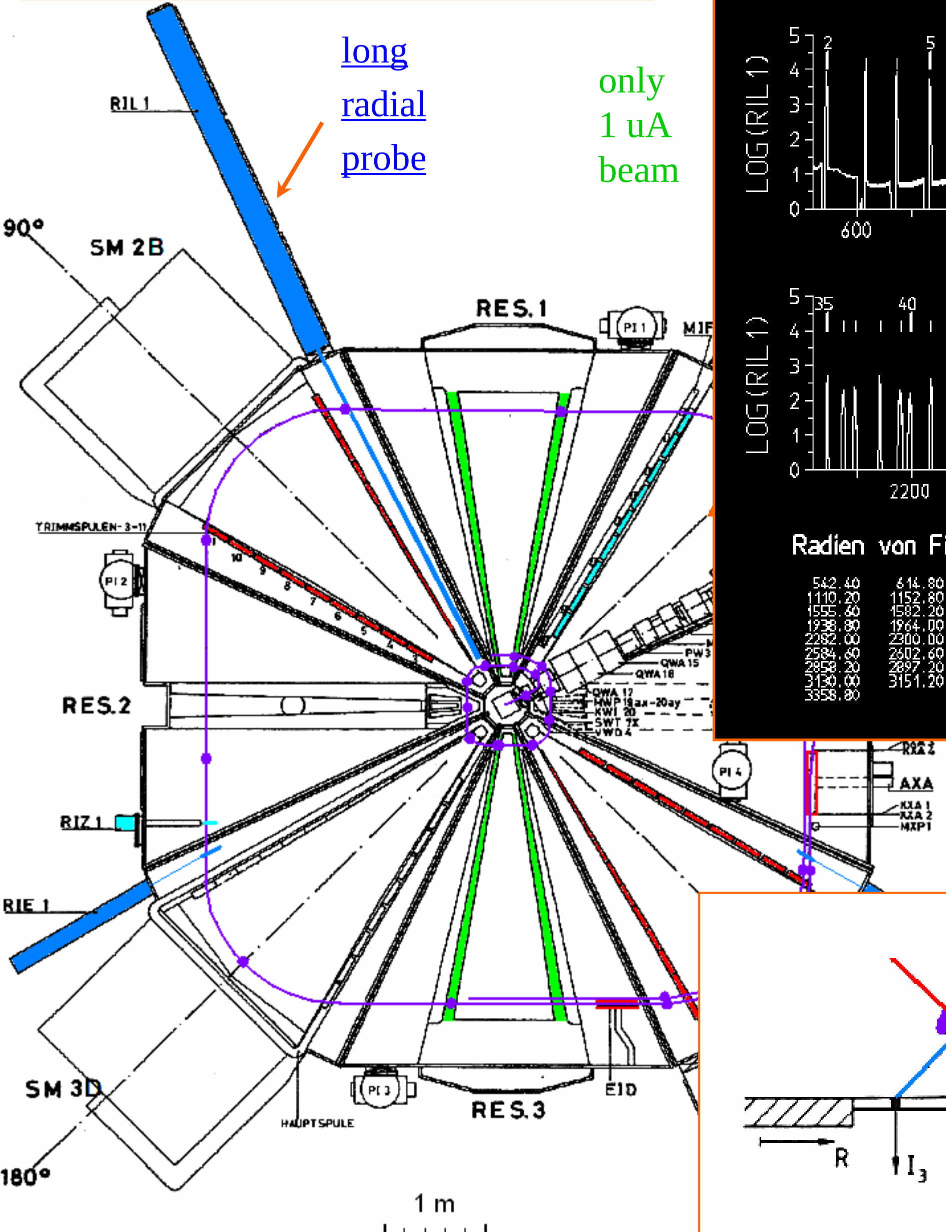
Craddock et al., CYC75, Loyer et al., PAC1985

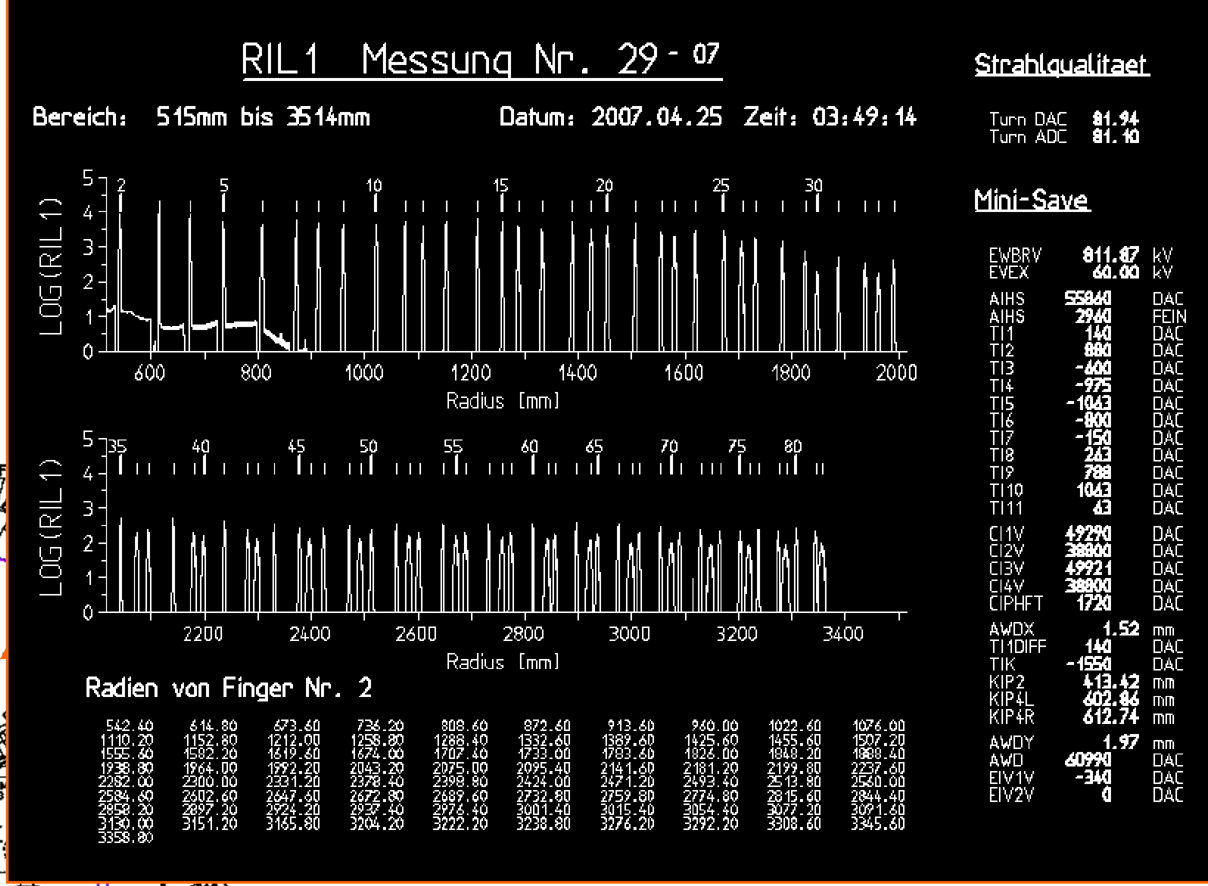
along the path: acceleration (adjustment of magnetic field and RF fields)

beam centering & betatron oscillation alignment

long radial probe

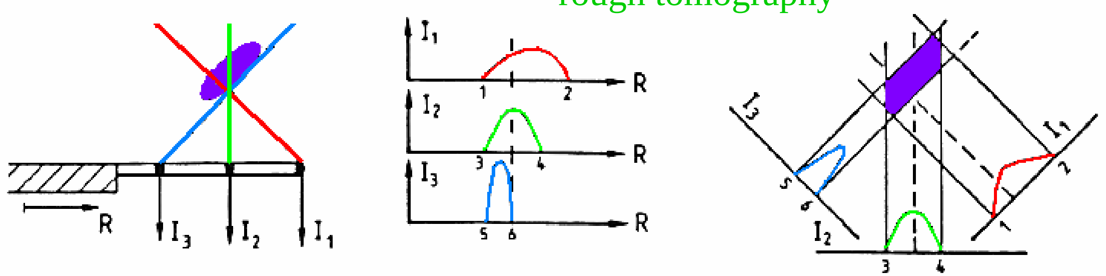
only 1 uA beam





intentionally introduced radial betatron oscillations
(only vertical wire displayed)

rough tomography

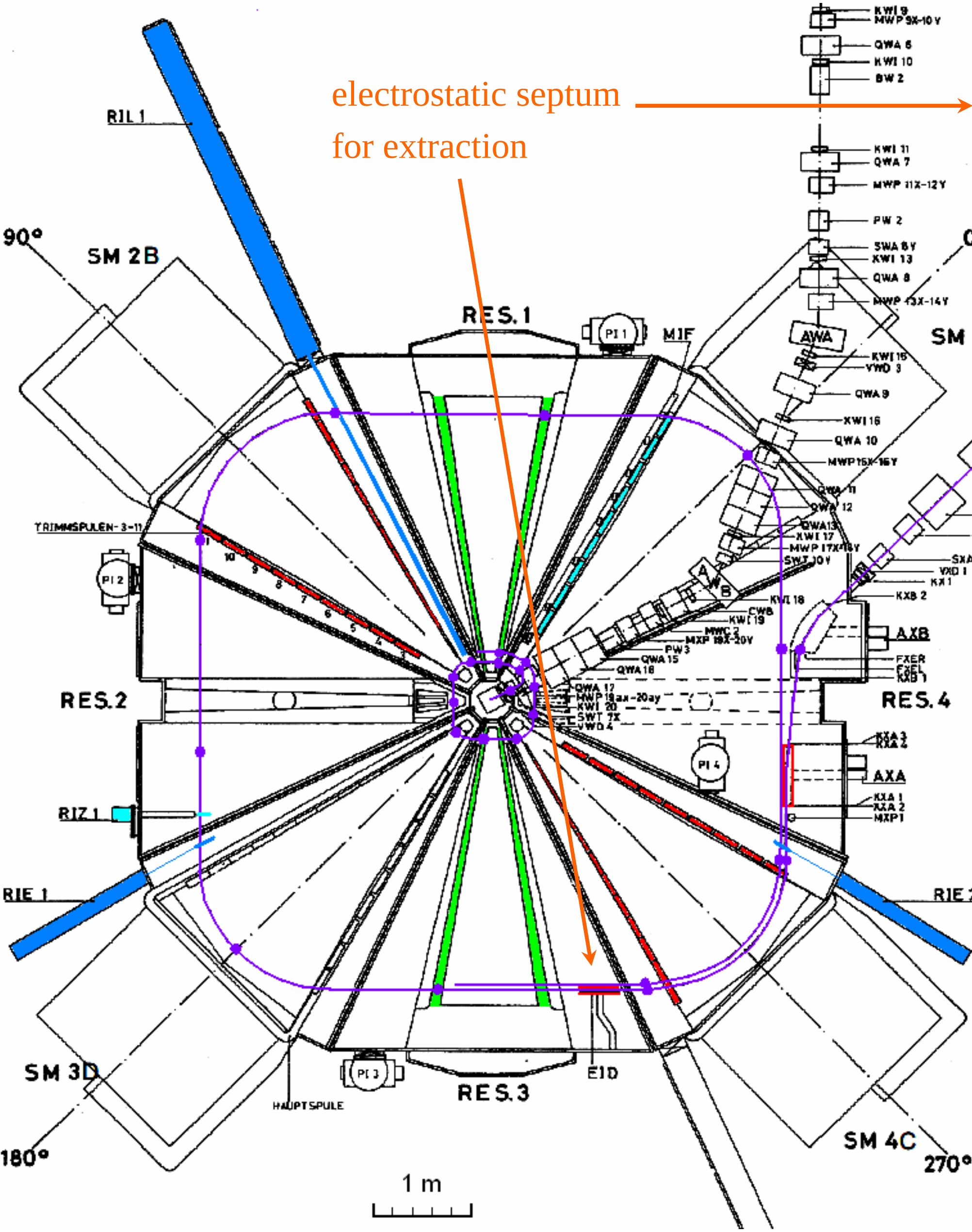


along the path: acceleration (adjustment of magnetic field and RF fields)

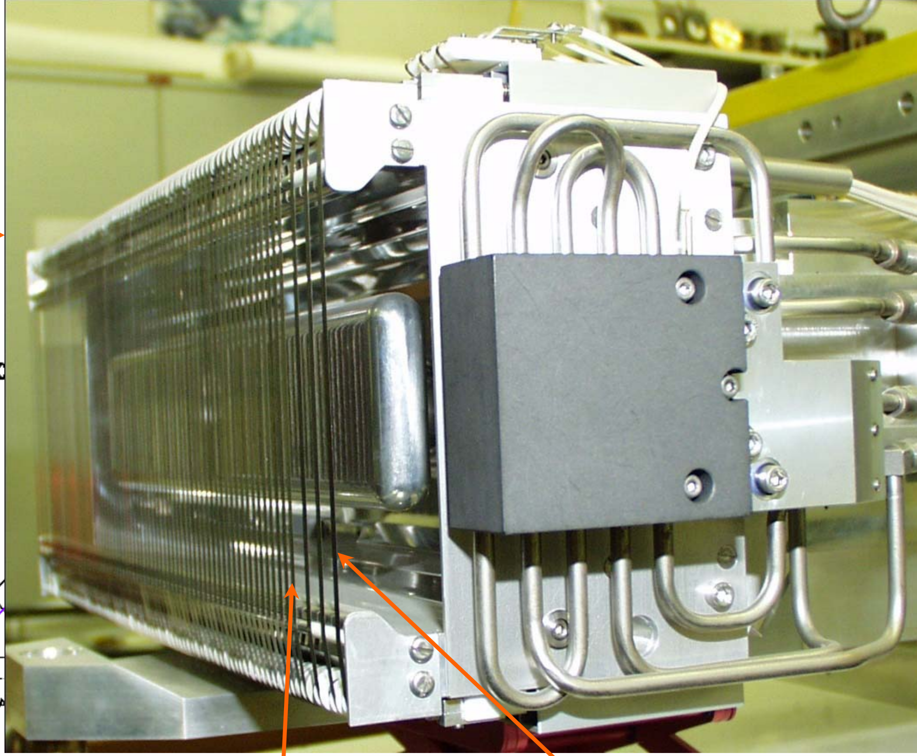
extraction:

turn separation & efficiency

turn separation



electrostatic septum
for extraction



D. Götz, PSI

3 strips with current
measurement

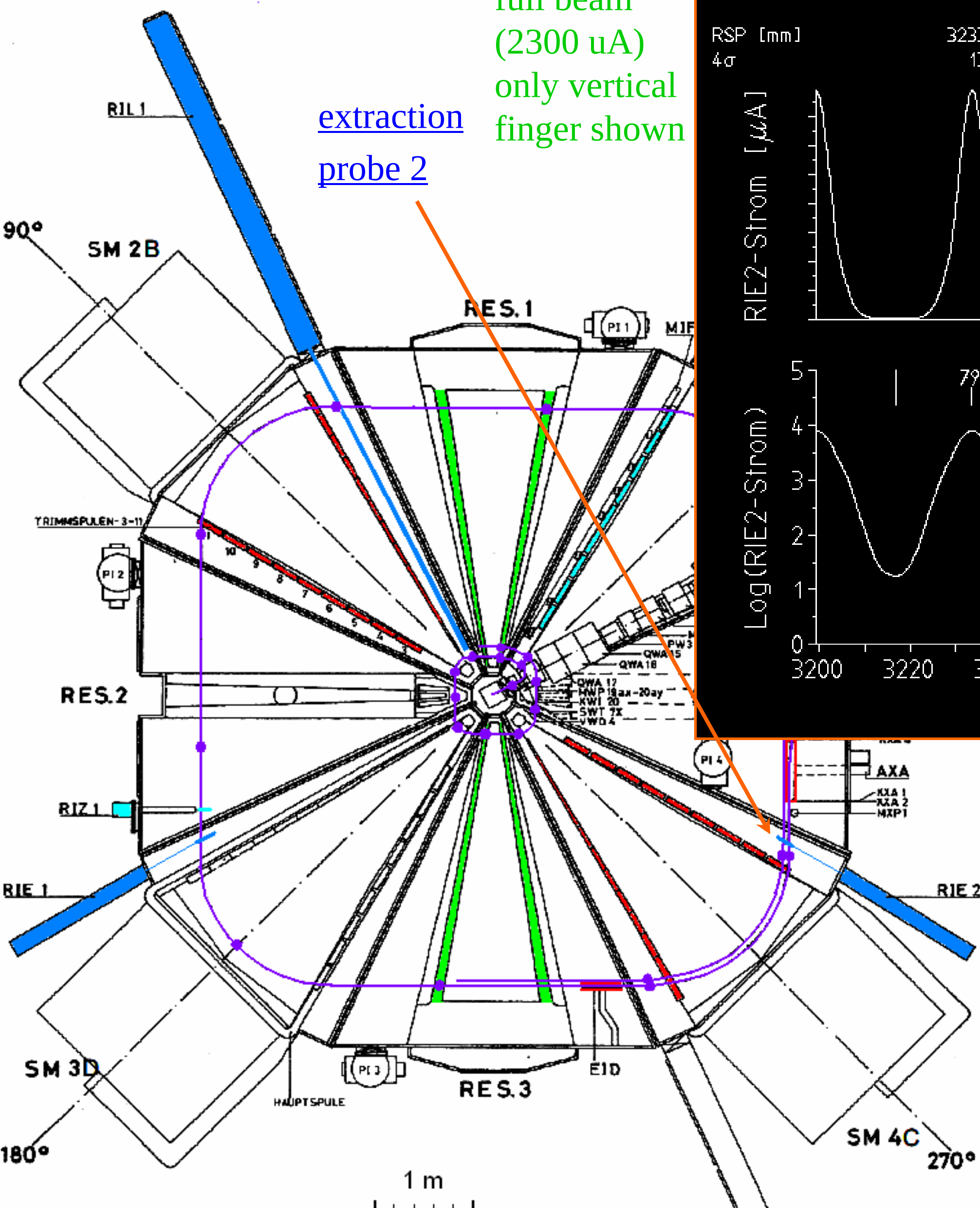
septum foils
between the last 2 turns

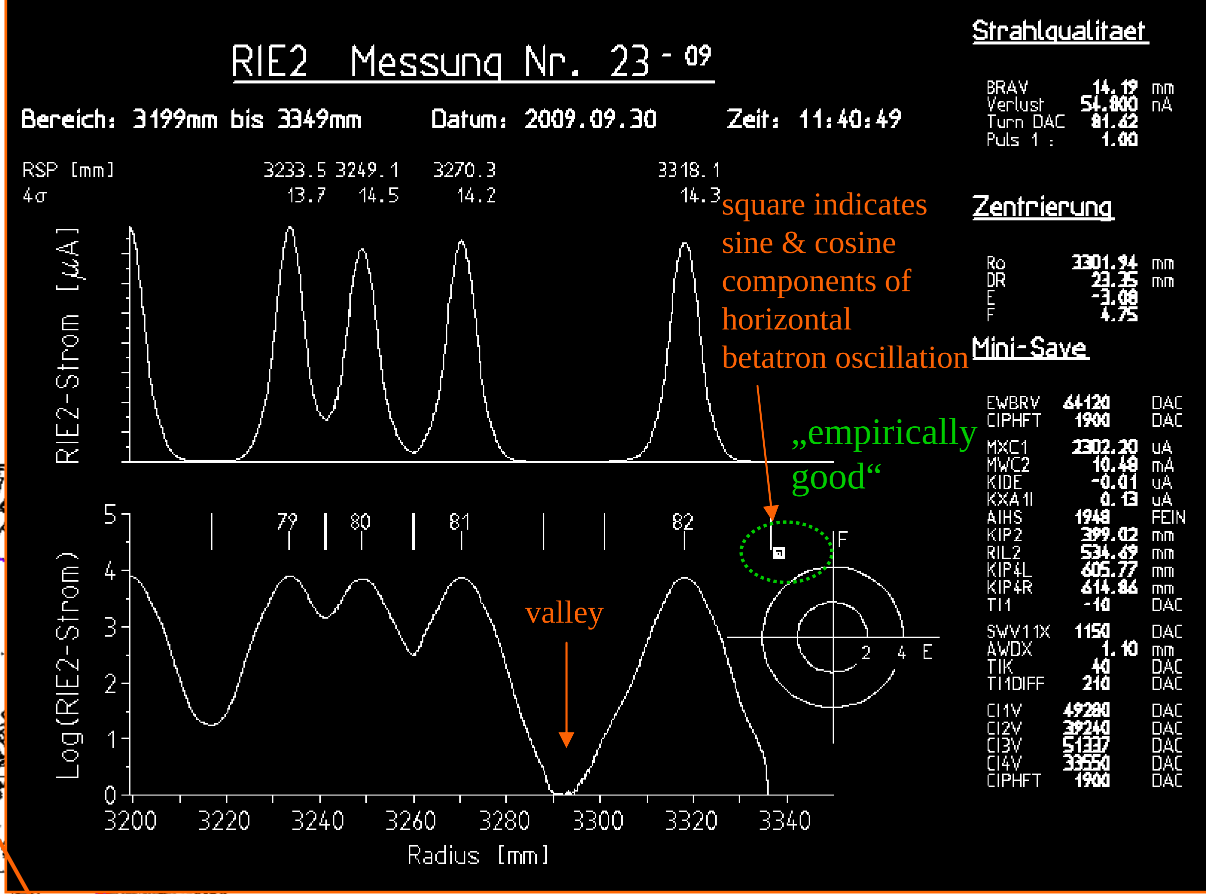
as few as possible beam should hit the foils
in order to prevent beam loss !

turn separation

extraction probe 2

full beam (2300 uA) only vertical finger shown





square indicates sine & cosine components of horizontal betatron oscillation

„empirically good“

valley

Rezzonico et al., BIW1994

horizontal betatron oscillation tuned for

→ large separation of last turn at extraction elements

→ nearly 100% extraction efficiency

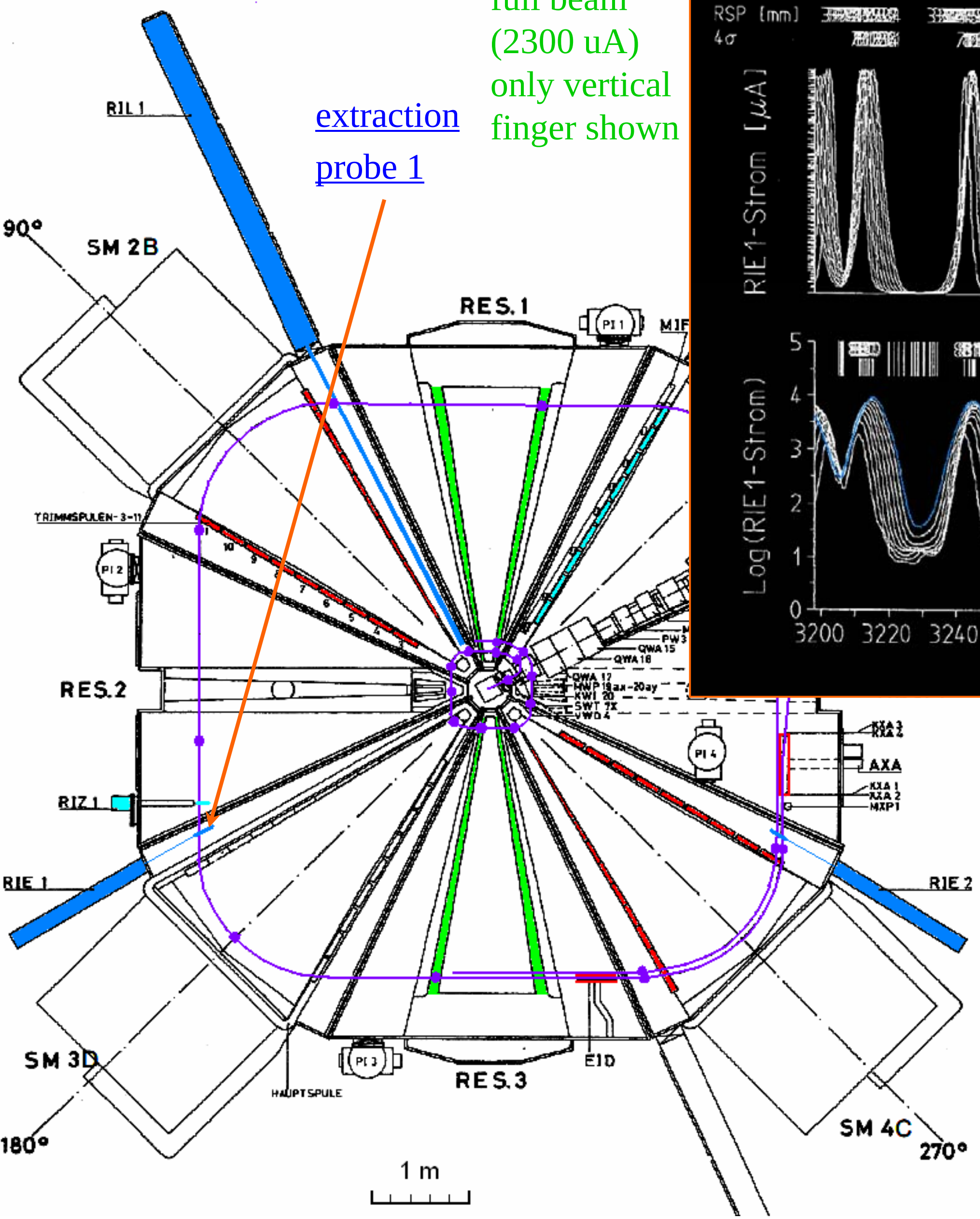
= low losses

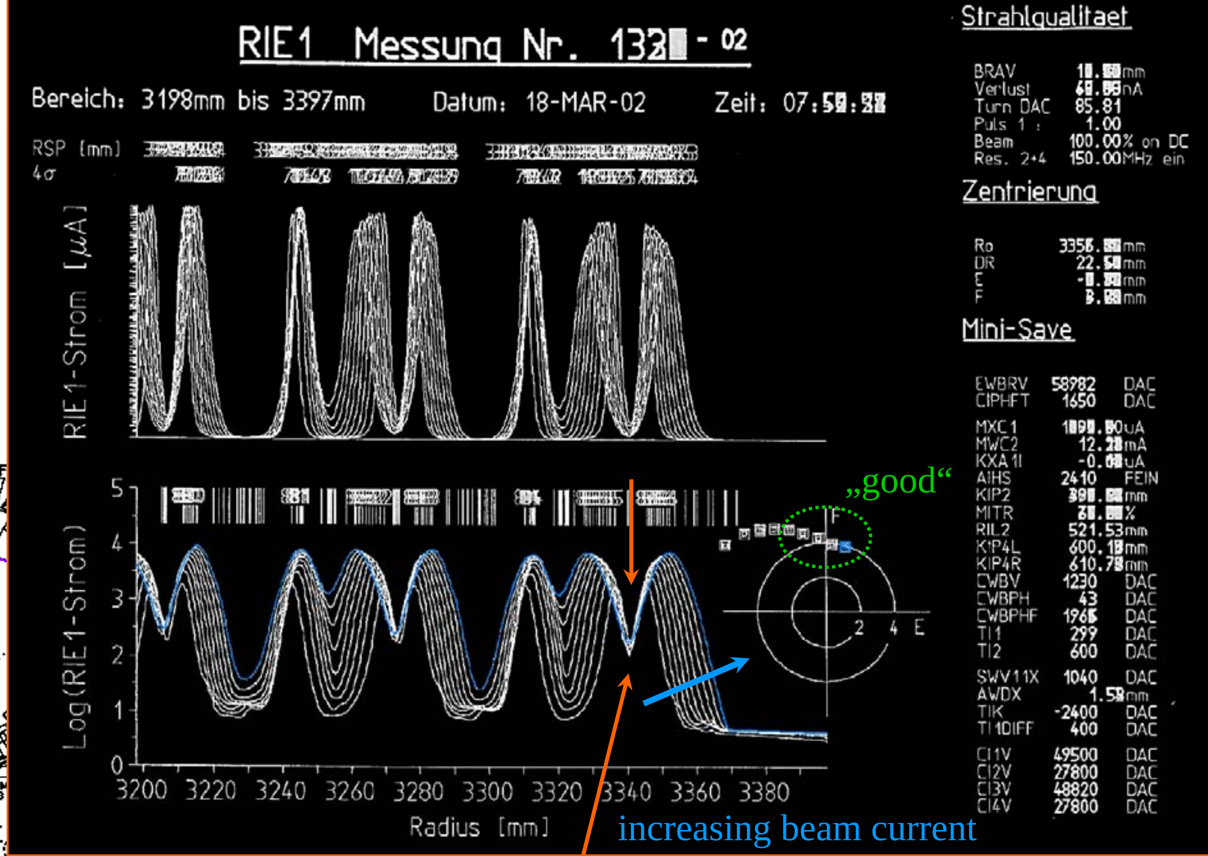
halo measurement with 10^4 dynamic range

turn separation

extraction probe 1

full beam
(2300 uA)
only vertical
finger shown





„good“

increasing beam current

M. Humbel, PSI

developing valley for extraction elements unchanged by beam current variation (accomplished by cutting the beam single-sided with a collimator in the machine center)

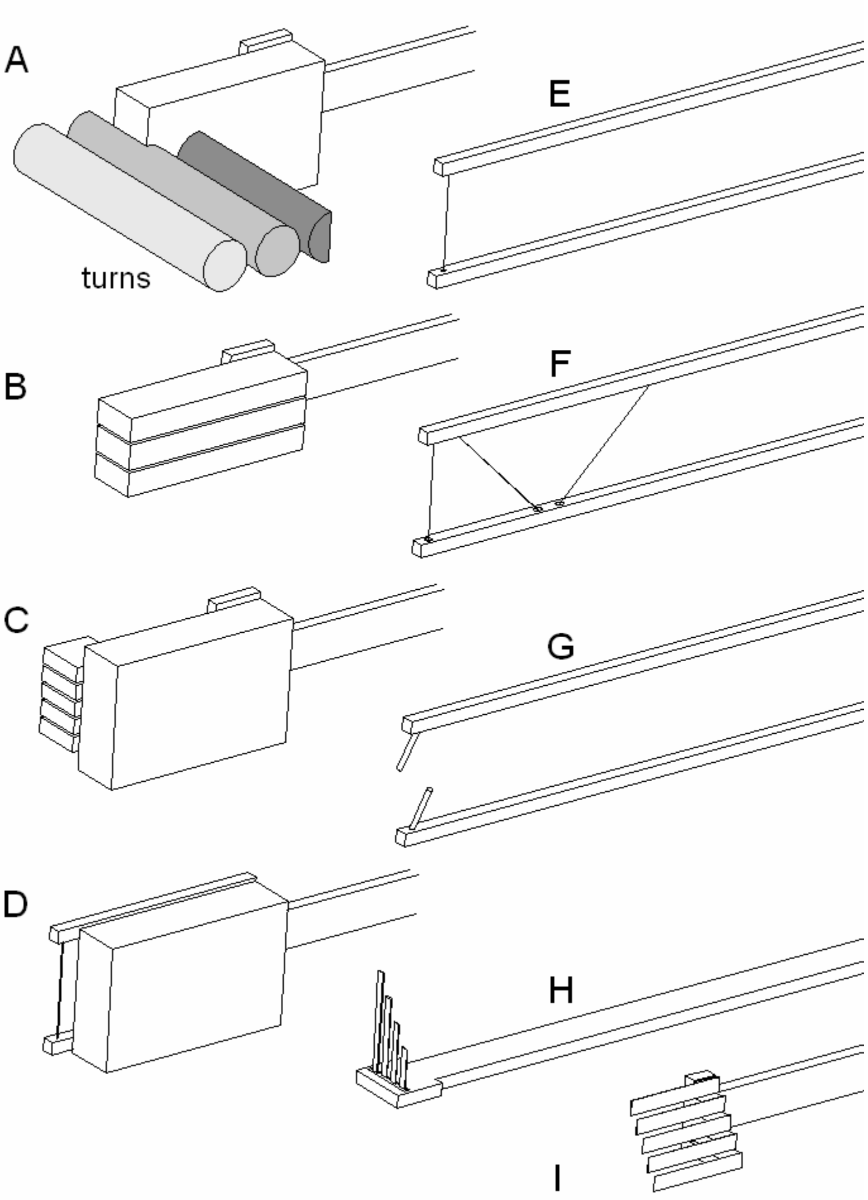
→ good extraction efficiency at all currents

PAUL SCHERRER INSTITUT

12 min

transversal information

radial probes: types and uses

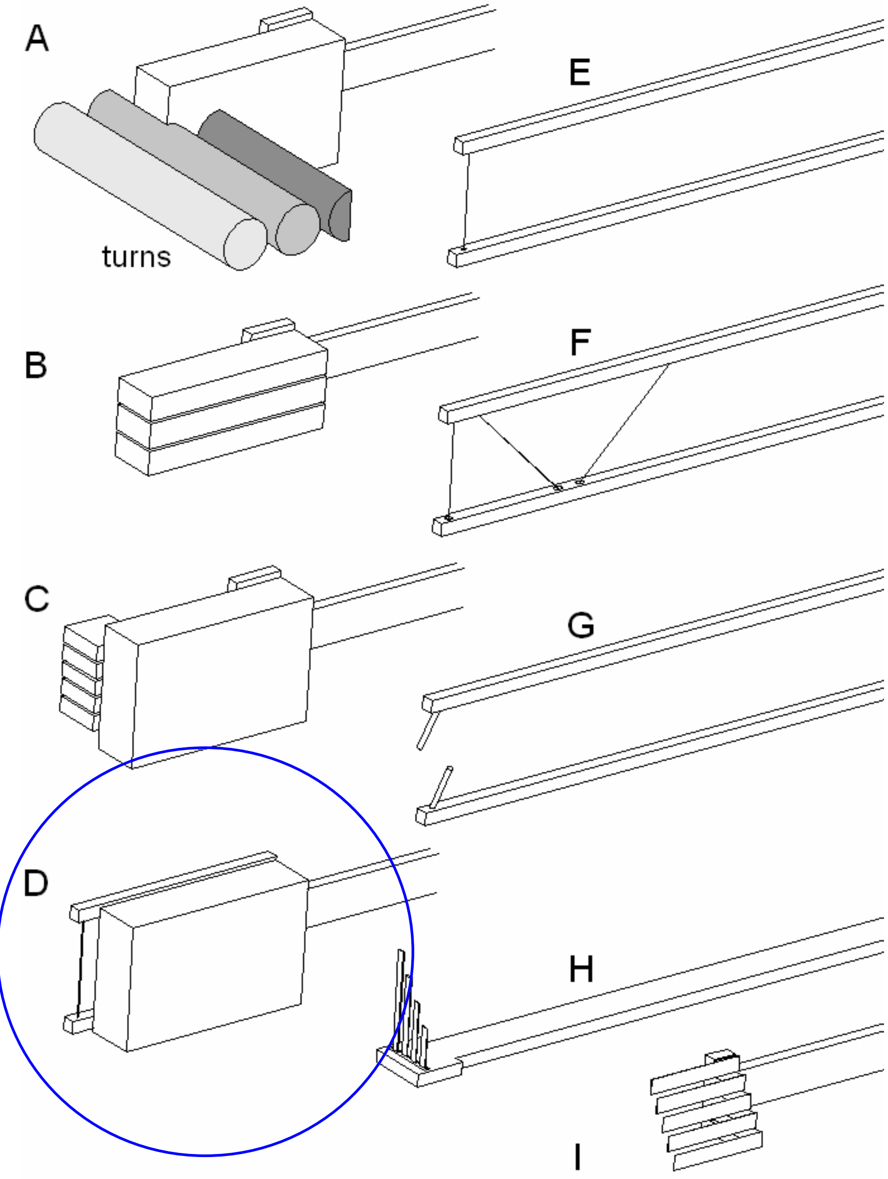


schematic

- radial: integral (thick) or differential
- axial: segmentation / tomography

radial probes: types and uses

PAUL SCHERRER INSTITUT PSI



integral + differential probe at separated turns

probe efficiency <1
visible only when turn is cut

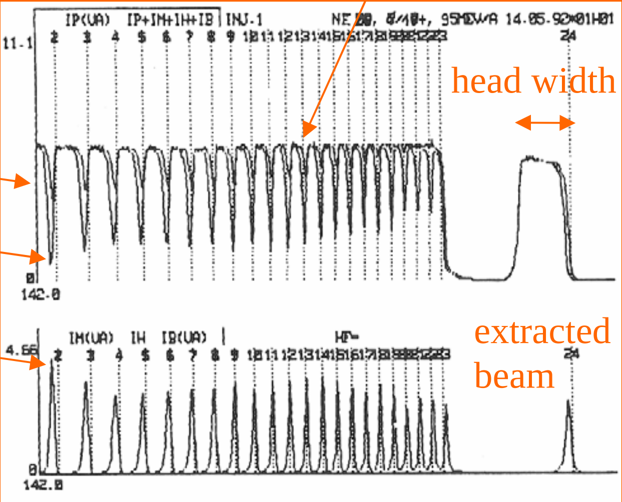
sum

integral

differential

head width

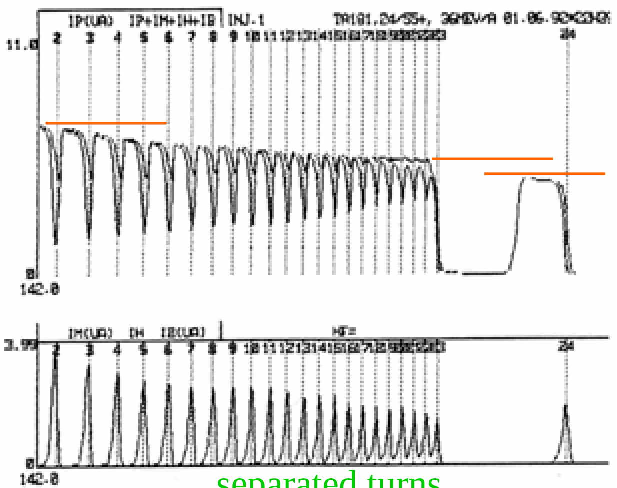
extracted beam



Turn pattern of Ne in the cyclotron

losses
extraction efficiency

turn structure

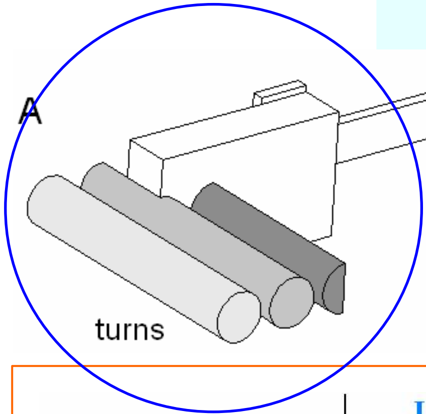


separated turns

Turn pattern of Ta in the cyclotron

GANIL NCO1 injector, Ricaud et al., CYC92 p. 446

radial probes: types and uses



integral probe at not separated turns

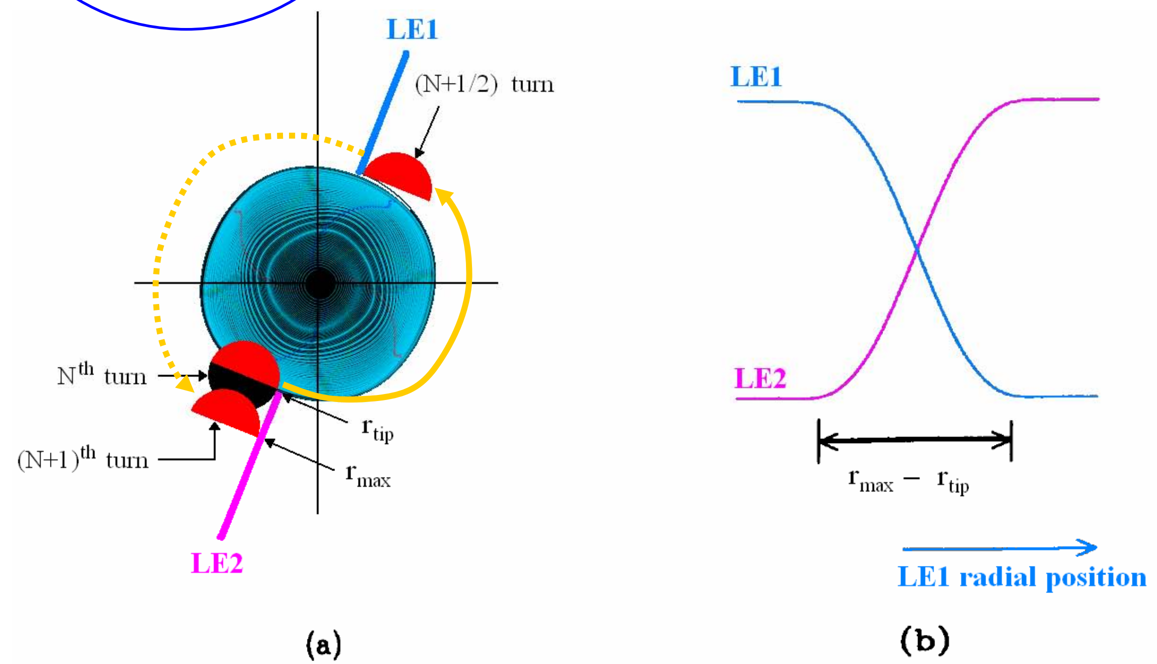
[shadow method](#)

→ ~ turn profile

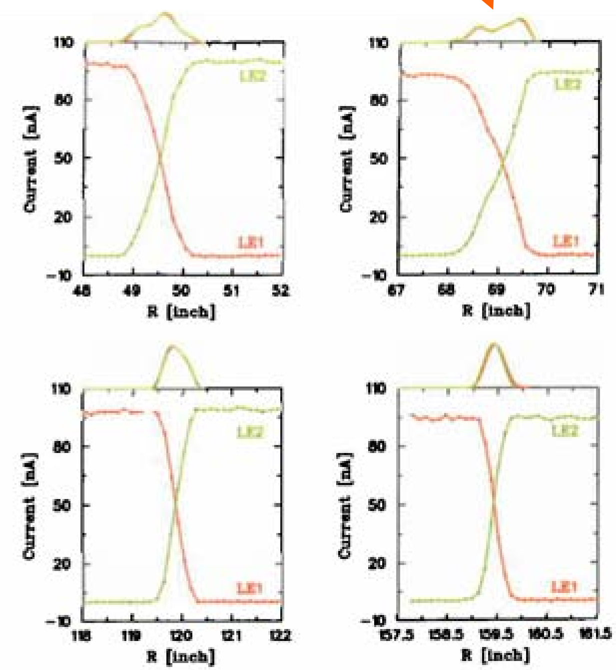
→ ampl. incoherent betatron oscill. (from shadow width)

[50% method](#)

→ centering (centered if probe radii identical at crossover)



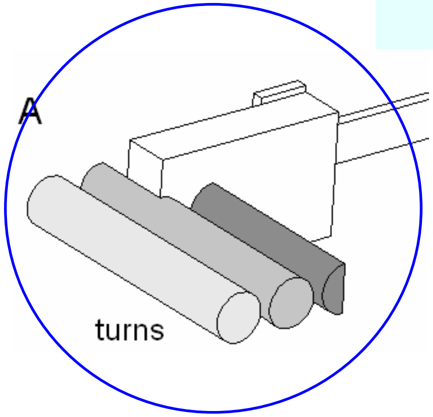
Schematic diagram showing the principle of LE1-LE2 shadow measurement. ν_r is assumed to be $\simeq 1.0$. (a) a fraction of a beam spot hits on N^{th} turn, the missing portion hits on $(N+1)^{th}$ turn; (b) expected variations of beam current on LE1 and LE2 as LE1 moves across the beam paths.



TRIUMF, Rao et al., TRI-DN-04-8

Figure 11: *Measured beam currents on LE1 and LE2 vs the radial position of LE1, with LE2 parked at defferent radii. Shown on the top are the beam distributions along the radius. The data at ~ 69 inch clearly shows that beam hitting LE2 is coming from 2 turns.*

radial probes: types and uses



integral probes: efficiency depends on impact angle

here: in mid-range efficiency <<1

→ behaviour similar to differential probe

probe measures turn density

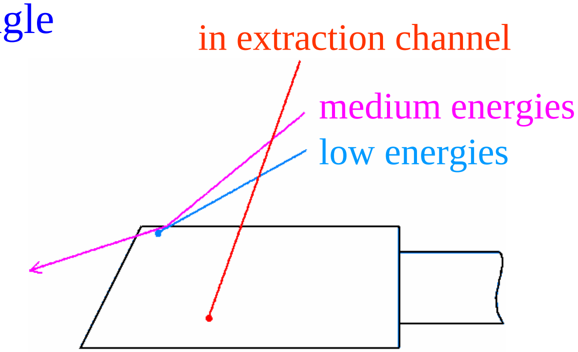
radial betatron oscillations visible

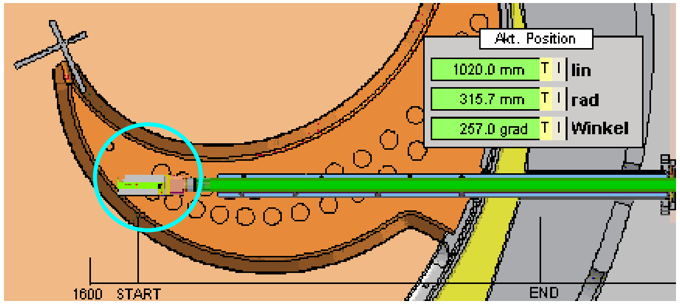
→ information on radial beam centering

at low & high energies: full beam stopped

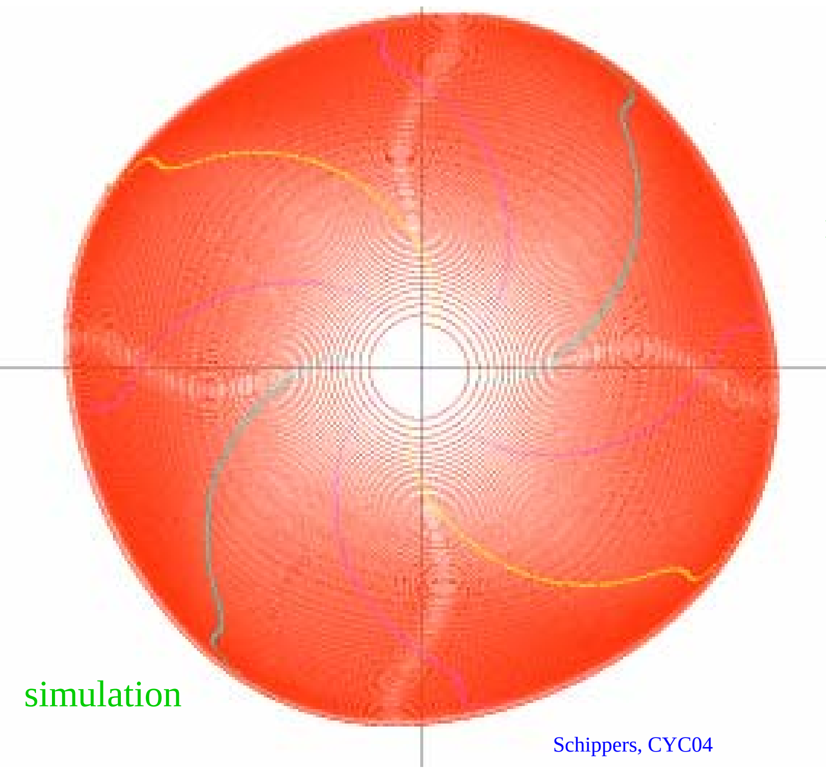
→ behaves as integral probe

→ extraction efficiency





PSIs medical cyclotron (Varian, 250 MeV, compact), Geisler et al., CYC07

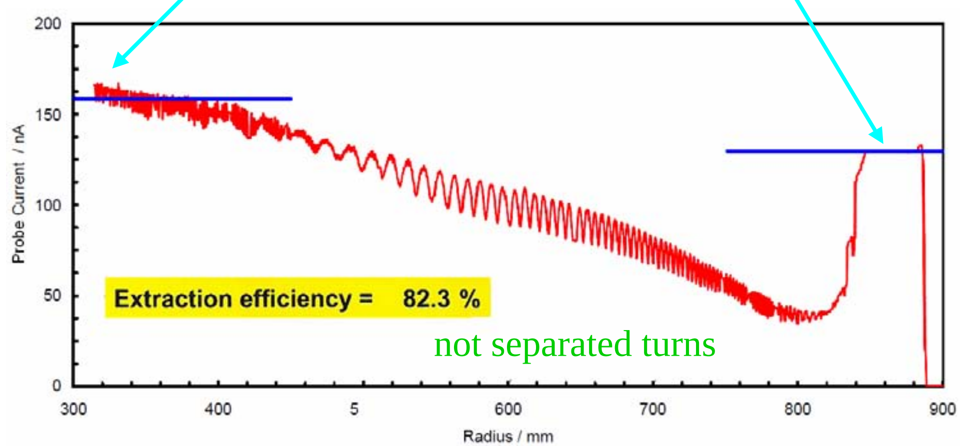


good

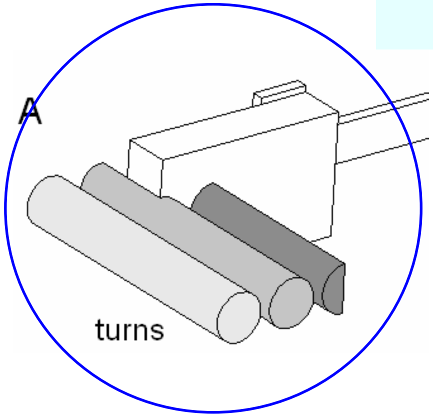
radial

centering

Schippers, CYC04



radial probes: types and uses / signal



integral probes: efficiency depends on impact angle

here: in mid-range efficiency <<1

→ behaviour similar to differential probe

probe measures turn density

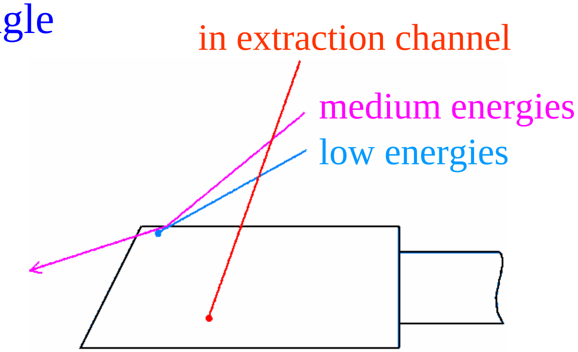
radial betatron oscillations visible

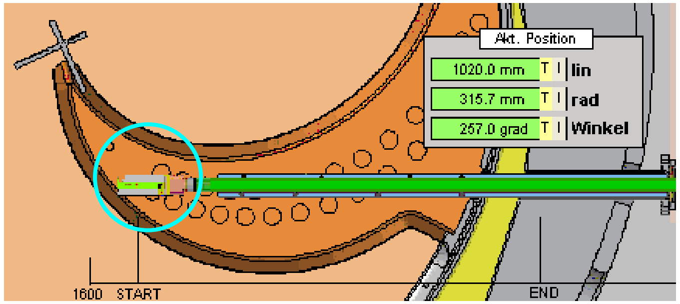
→ information on radial beam centering

at low & high energies: full beam stopped

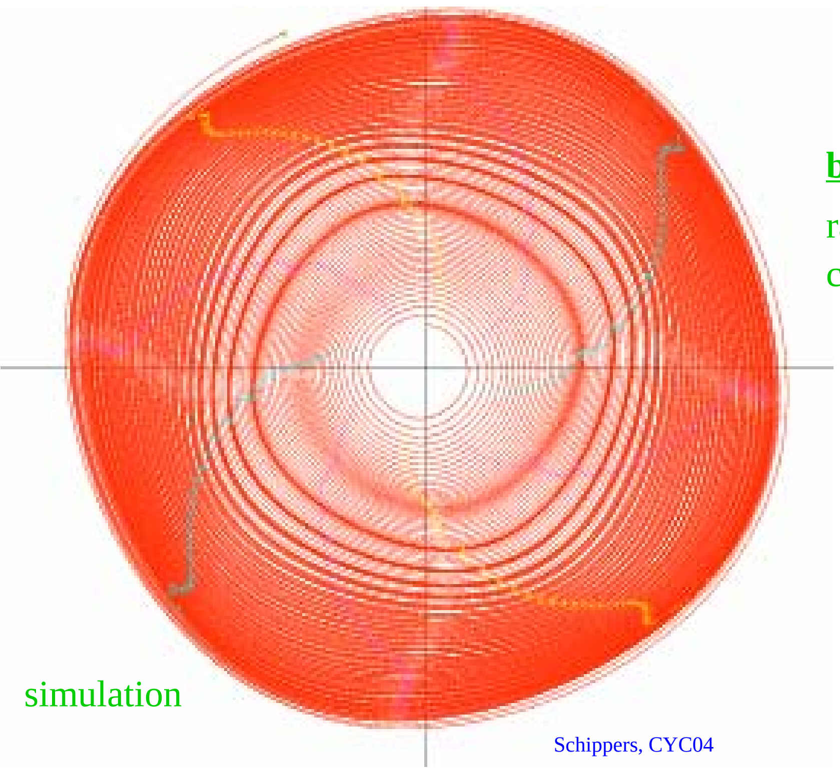
→ behaves as integral probe

→ extraction efficiency





PSIs medical cyclotron (Varian, 250 MeV, compact), Geisler et al., CYC07

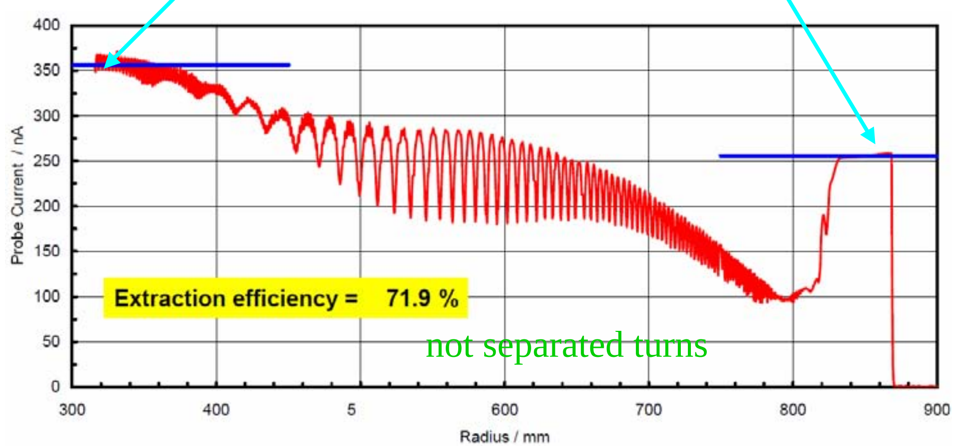


simulation

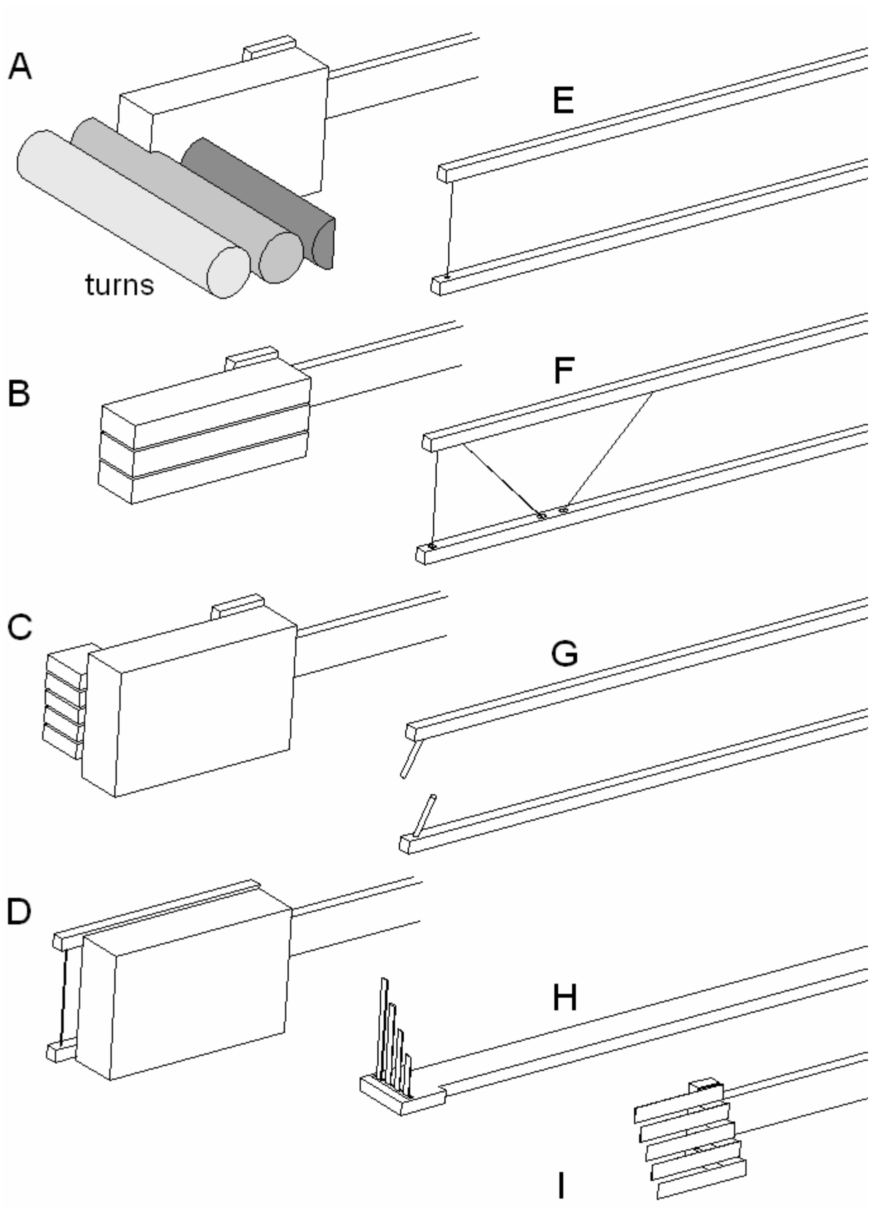
Schippers, CYC04

bad

radial centering

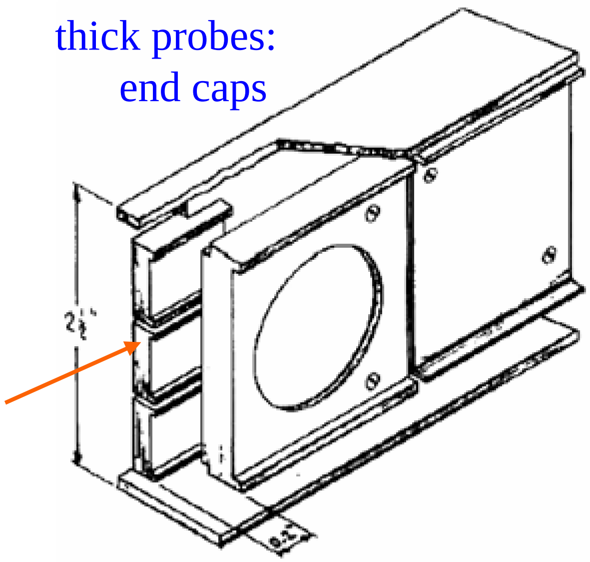


radial probes: signal

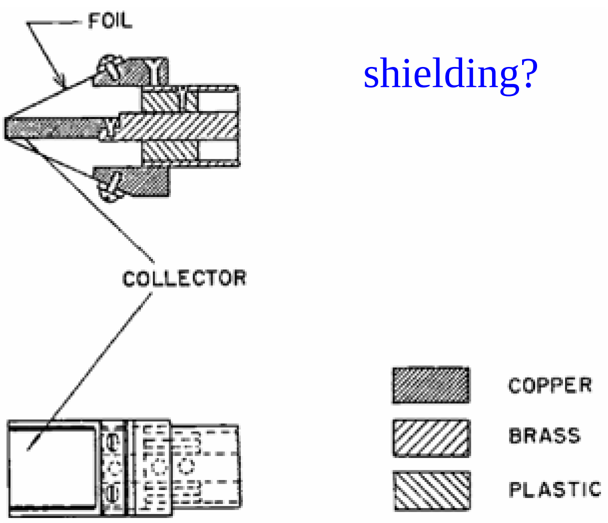


secondary electron capture
(also: bias or pulling electrode)

thick probes:
end caps



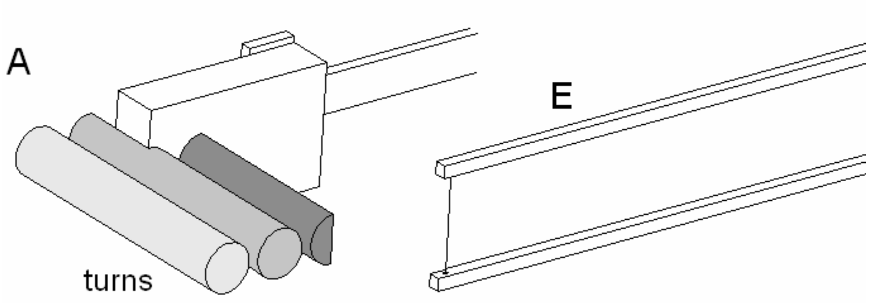
TRIUMF, Craddock et al., CYC75 p. 240



shielding?

UCLA 50 MeV, Clark et al., CYC62 p. 1

radial probes: high current



thermal limits at
high current

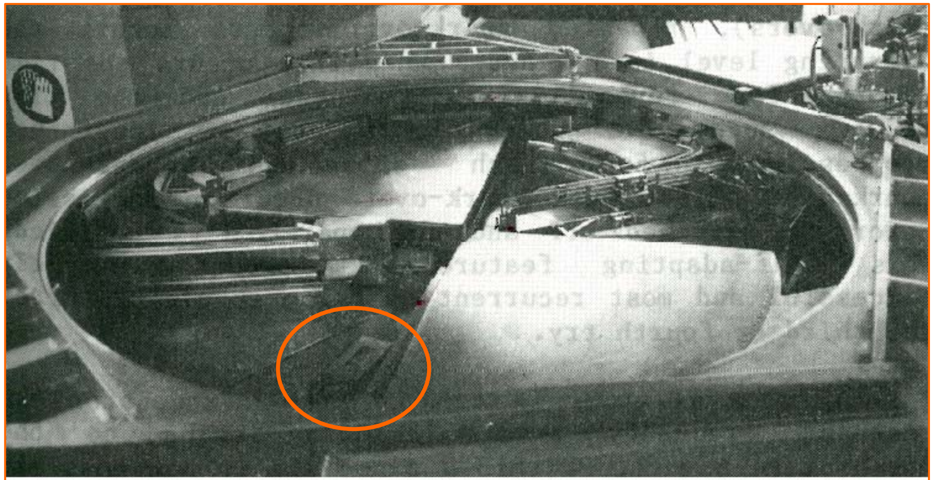
size limitation
→ power limitation
~15 kW protons

power input maximal
if beam particle just stopped
→ difficult at low energies (few MeV)
and heavier beam particles

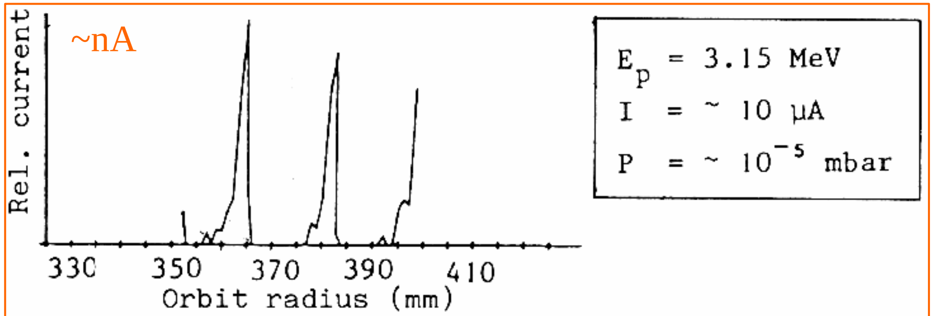
thin carbon fibres have highest performance
but give small electrical signal

alternatives?

UCLA 50 MeV, Clark et al., CYC62 p. 1

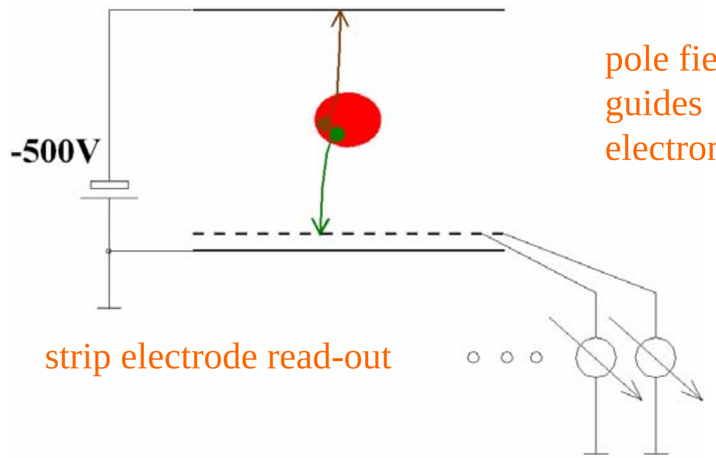


The layout inside the vacuum chamber of SPC1. Components that can be seen are the first slit system, electrostatic- and first magnetic channel, ion source (slightly withdrawn) and, to the left of the dee in the foreground, the ionisation beam profile monitor.



Beam profile of an internal beam (orbits 12 and 13) as recorded on the ionisation beam profile monitor installed in the pole-gap of SPC1.

iTHEMBA Injector SPC1, du Toit et al., CYC86 p. 109



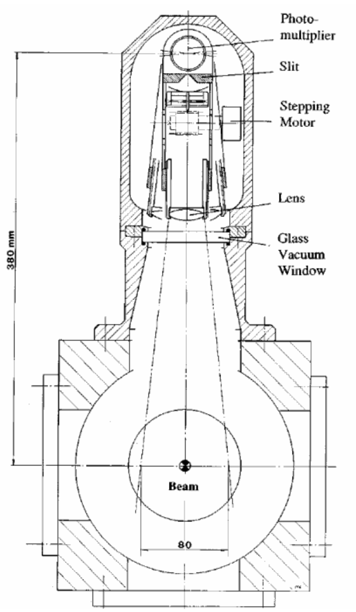
signal level OK at 10^{-6} mbar
(amplification by e.g. MCP not needed)

dynamic range?
- probably determined by stray particles
- probably <1000

(later abandoned due to isolation problems from sputtering in machine center

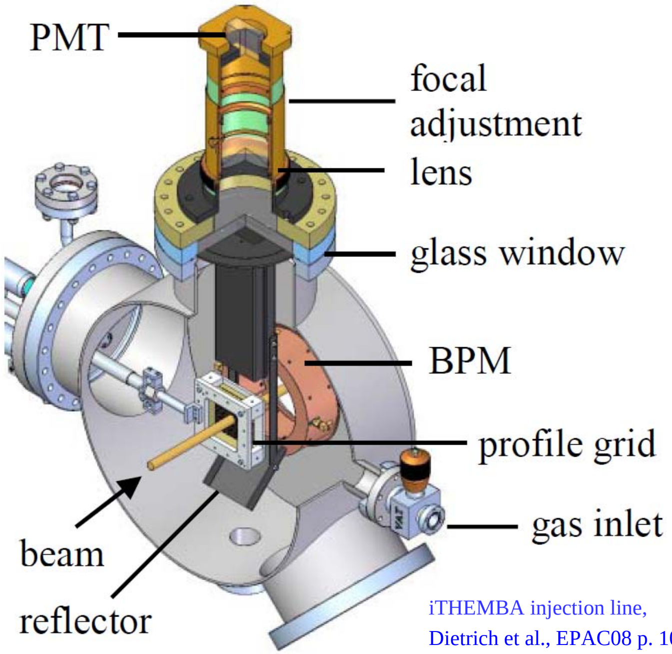
beam induced fluorescence

single PMT



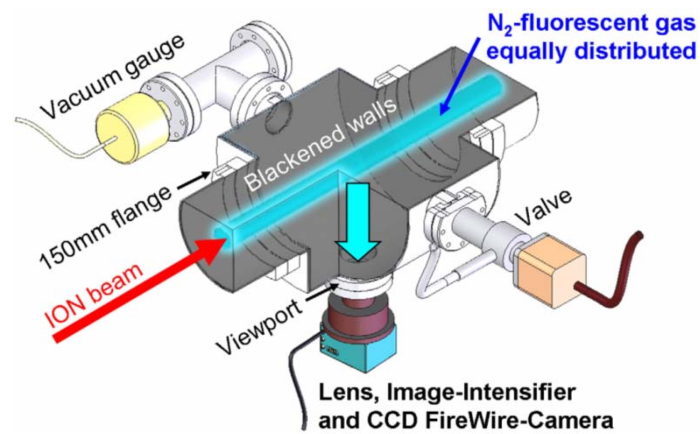
PSI, Rezzonico, CYC87 p. 457

32 channel PMT



iTHEMBA injection line,
Dietrich et al., EPAC08 p. 1095

MCP + CCD



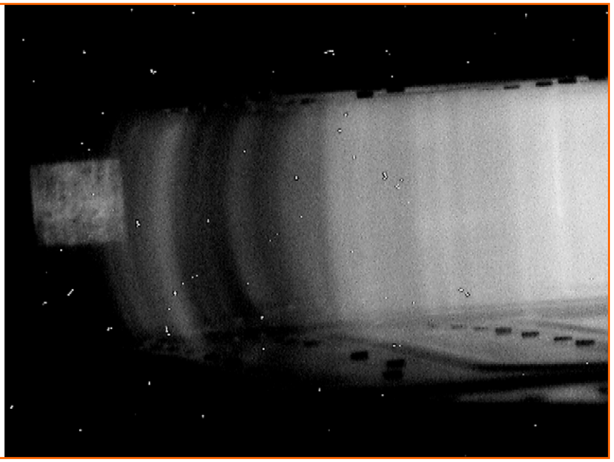
GSI, Forck, IPAC10 p. 1261

all used in beam lines

- (less signal than RGI)
- dynamic range?
  determined by stray light
  at best ~500

in the cyclotron?

- disturbing light
- radiation hard & sensitive camera?
  or relay optic
- PMT/MCP magnetic shielding?



screens

viewer probe

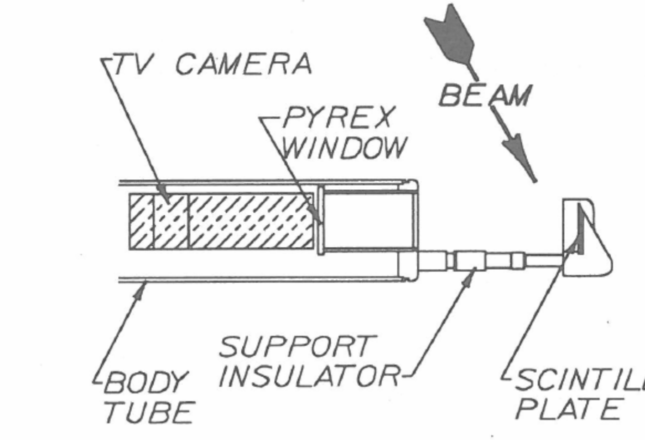


Figure 1. Sketch showing the head of the TV probe. The angle the beam makes with the scintillating plate changes between 35 and 65 degrees.

MSU, Marti et al., CYC92 p. 435

also (since long):

with external observation

foil based methods

PAUL SCHERRER INSTITUT PSI

thin paper burn

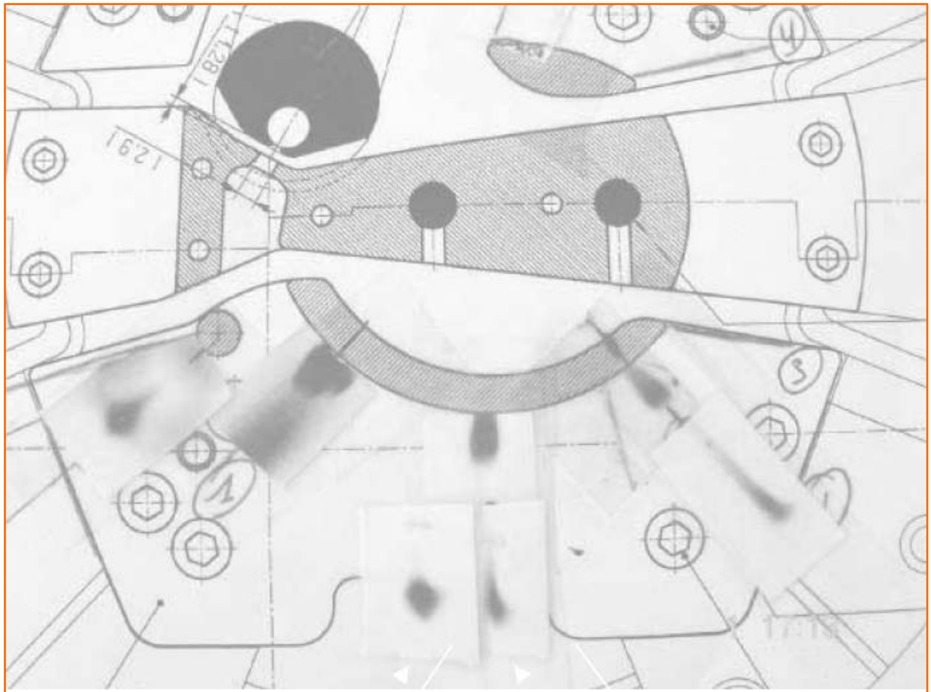


Figure 12: Beam spots in the central region

IBA, Kleeven, CYC01 p. 69

also (for commissioning):

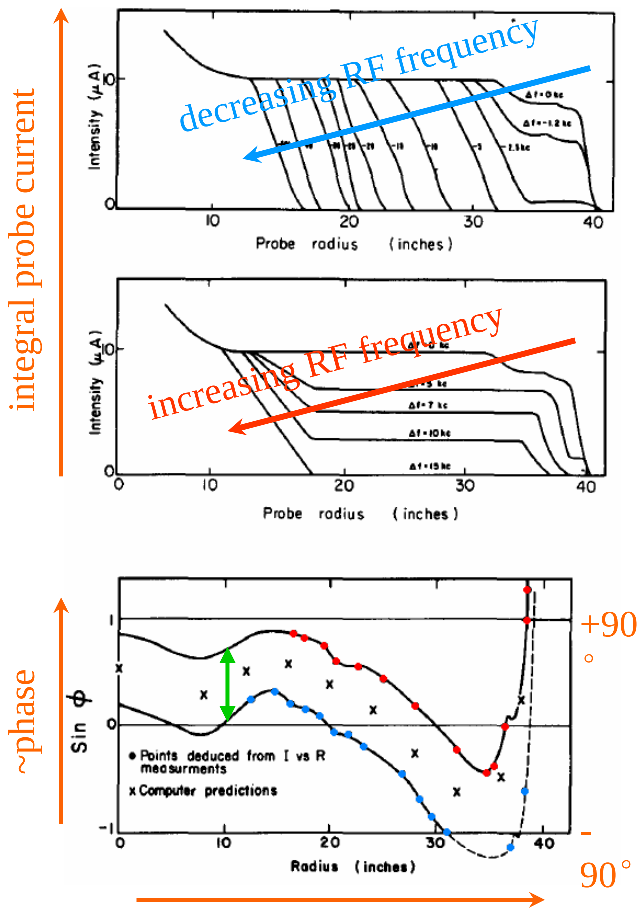
- Kapton, Mylar,
- stainless steel
- track-etch foil
- radiochromic film
- radiographic film
- foil activation
- radiography

18 min

longitudinal information

Garren & Smith detuning

(usually resonance curve shown
at fixed radius, main field varied)



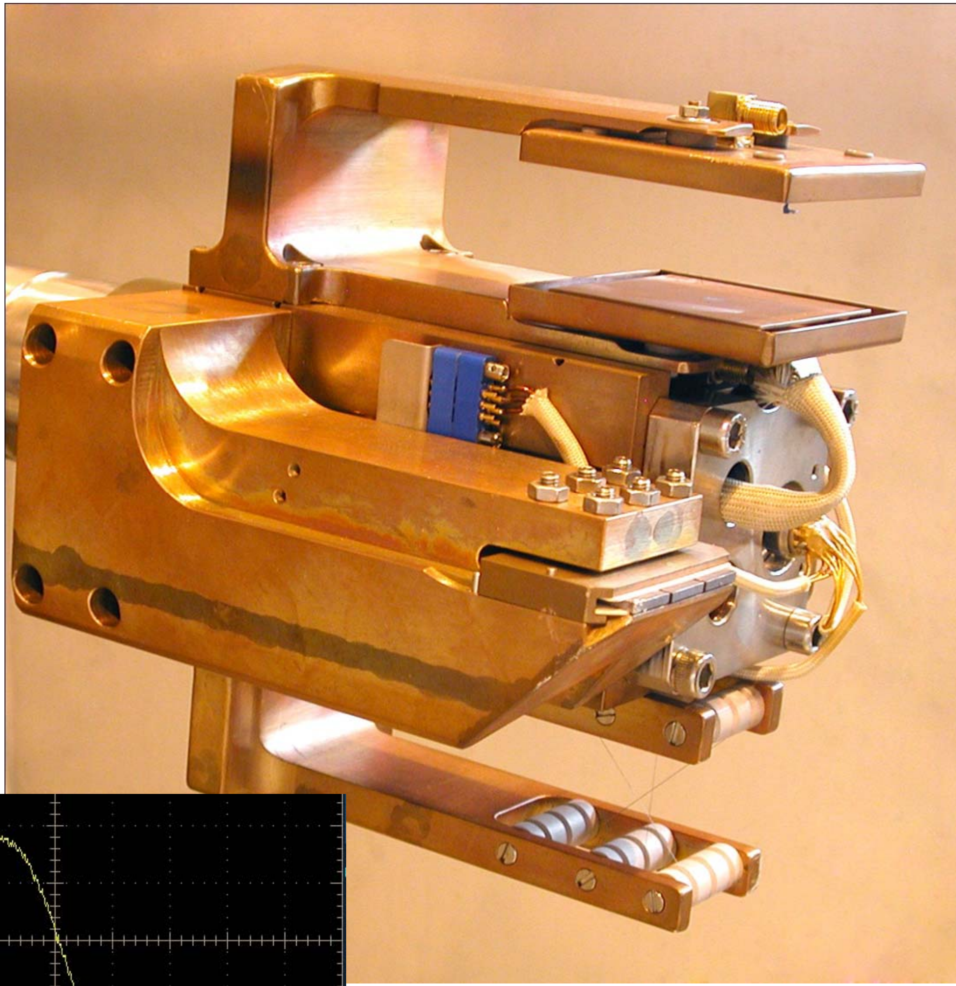
integral probe head radius

Garren & Smith, CYC63 p. 18

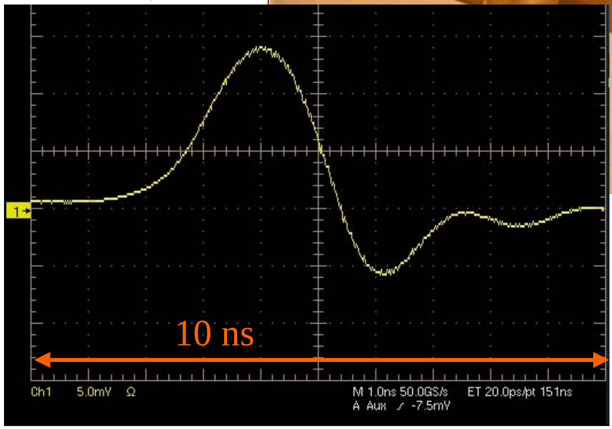
can deliver
local phase width
around center phase

phase probes

here: at multi-head radial probe (usually: fixed pickups)

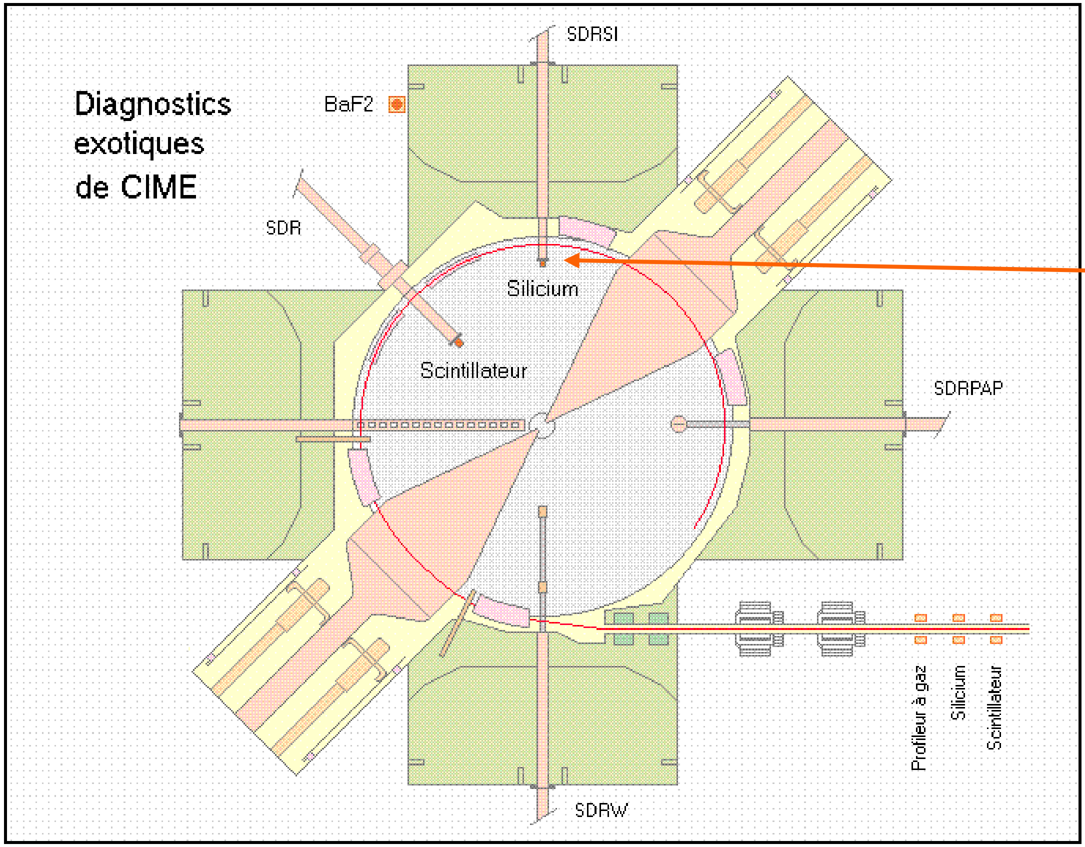


D. Fourie, iTHEMBA

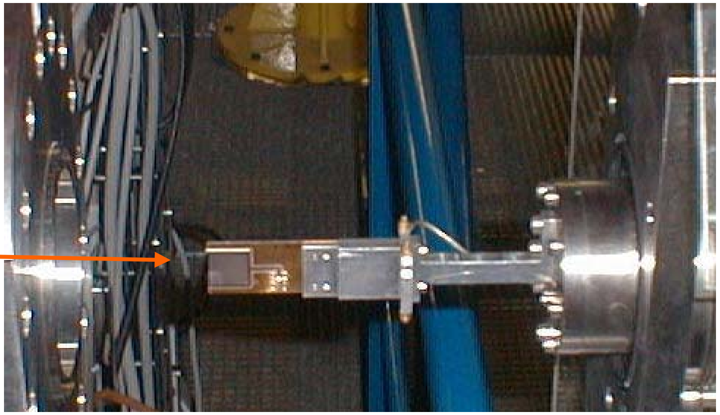


can deliver
- center phase (very accurate)
- time structure
(not for very short bunches)

silicon detector placed directly in very low current beam



silicon detector
on radial probe (shield removed)



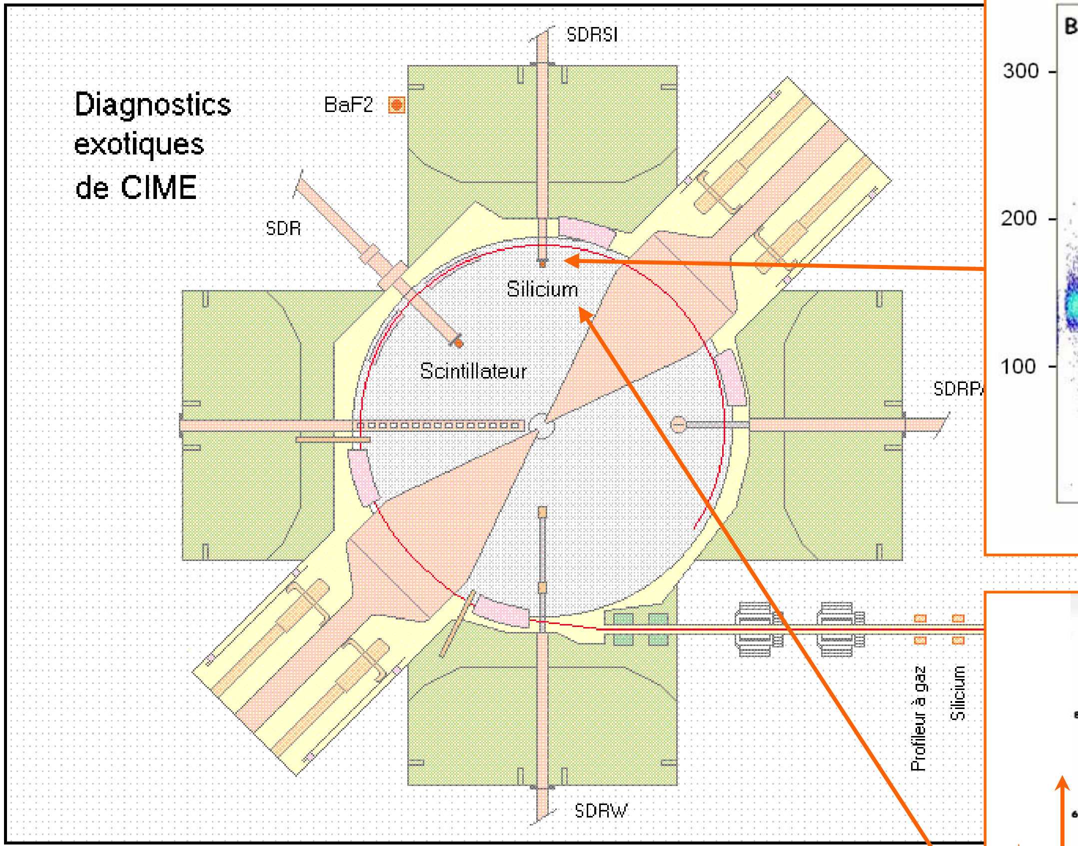
probe head with shield & preamplifier

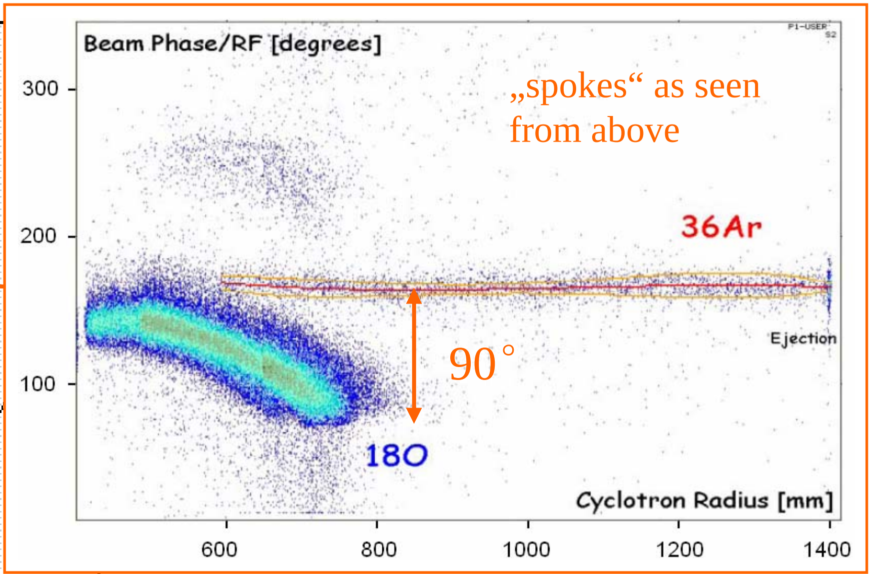
all pictures F. Chautard, GANIL

can deliver
- time structure (moderate resolution)
- beam particle energy spectrum (thick detector)
- beam particle stopping power (thin detector)

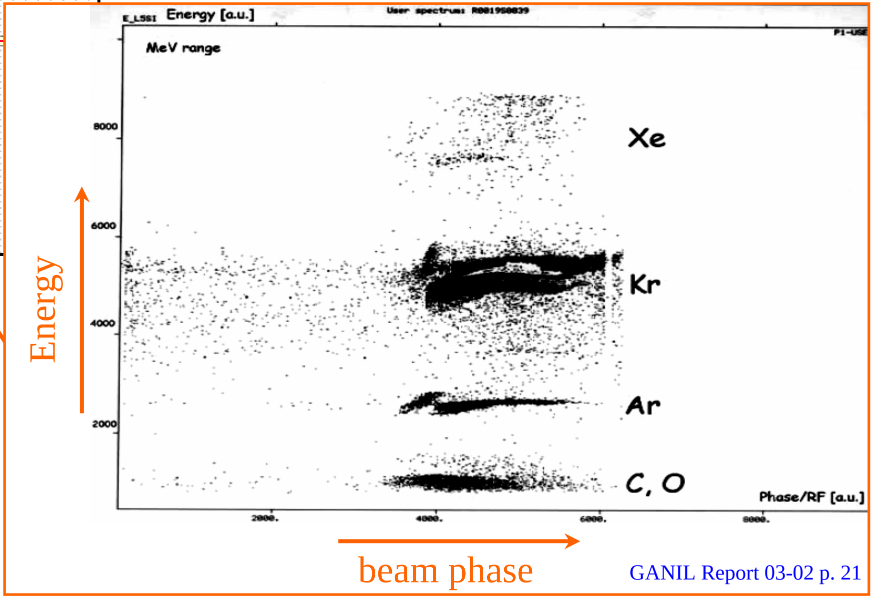
cyclotron separates different particles by q/m

time-structure shows separation (radius varied)





Chautard, CYC01 p. 370



GANIL Report 03-02 p. 21

particle species identified by energy
(although time-structure overlaps)

probe at fixed radius

time-structure probes at high current

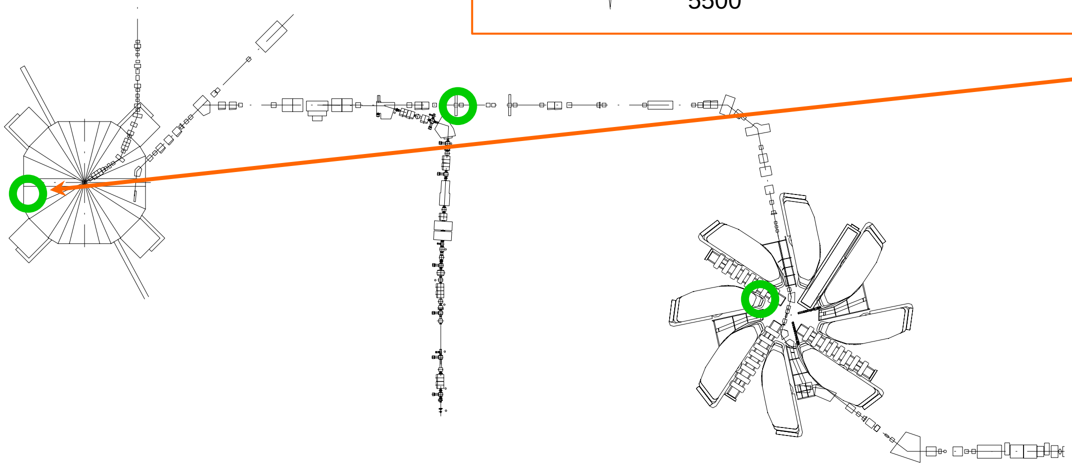
PAUL SCHERRER INSTITUT PSI

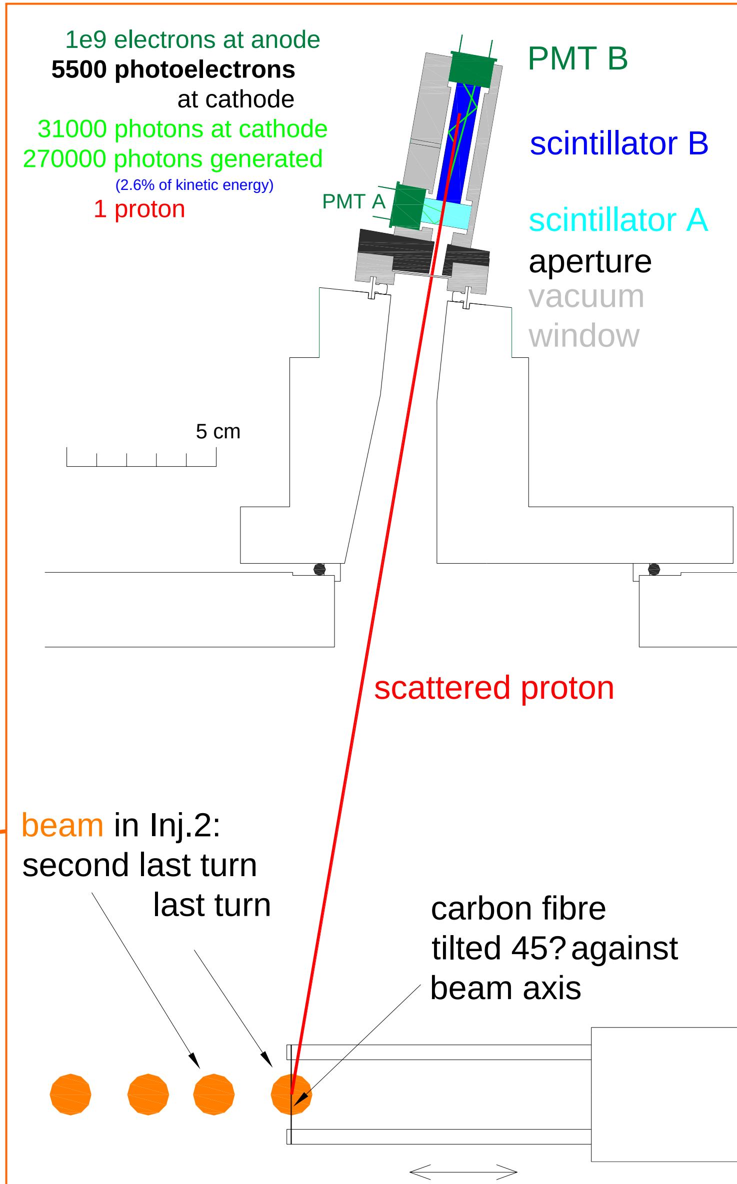
- measure longitudinal and radial density distributions of the beam bunches (averaging over many bunches)
- arrival time of scattered protons compared to RF reference (discriminator & Time-to-Ampl. Converter & Multi-Channel-Analyzer)
- resolution incl. electronics ~31 ps fwhm (determined from correlation between detectors A, B)
- data used for layout of buncher between cyclotrons

simple estimate of time resolution of detector B

PMT transit time spread (TTS)	**250** ps	(R7400)
scintillator response	**1360** ps	(NE111)
path in scintillator	**400** ps	

$$dt = 1.2 \sqrt{\frac{250^2 + 1360^2 + 400^2}{5500}} = 23 \text{ ps fwhm}$$





Dölling, DIPAC01 p. 111

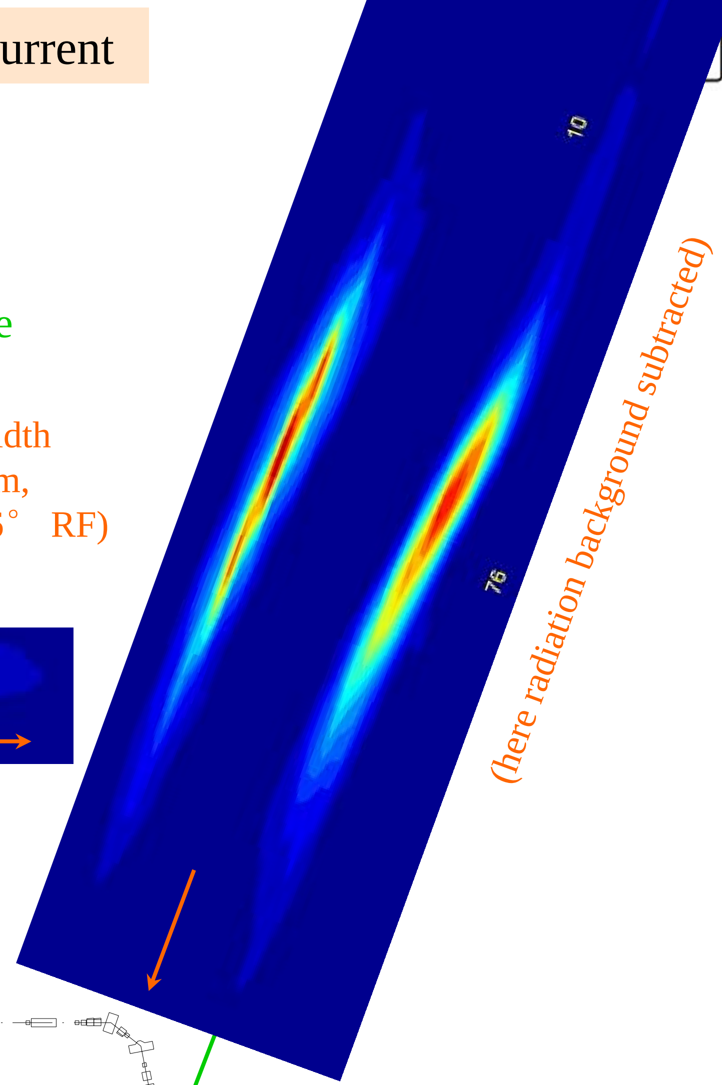
time-structure probes at high current

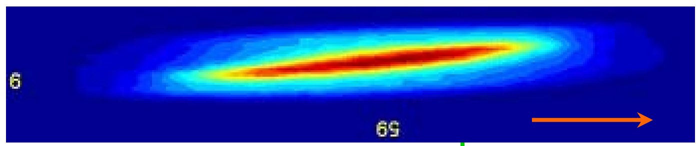
with several wire orientations
→ several 2D projections
of 3D density distribution
→ detailed input to
beam dynamic simulations

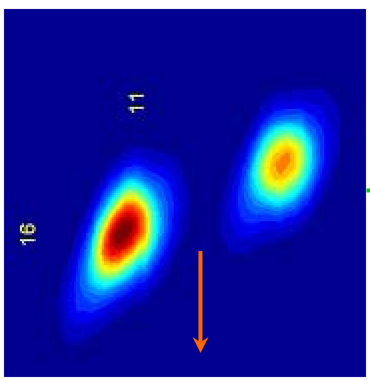
moving bunches
as seen from above

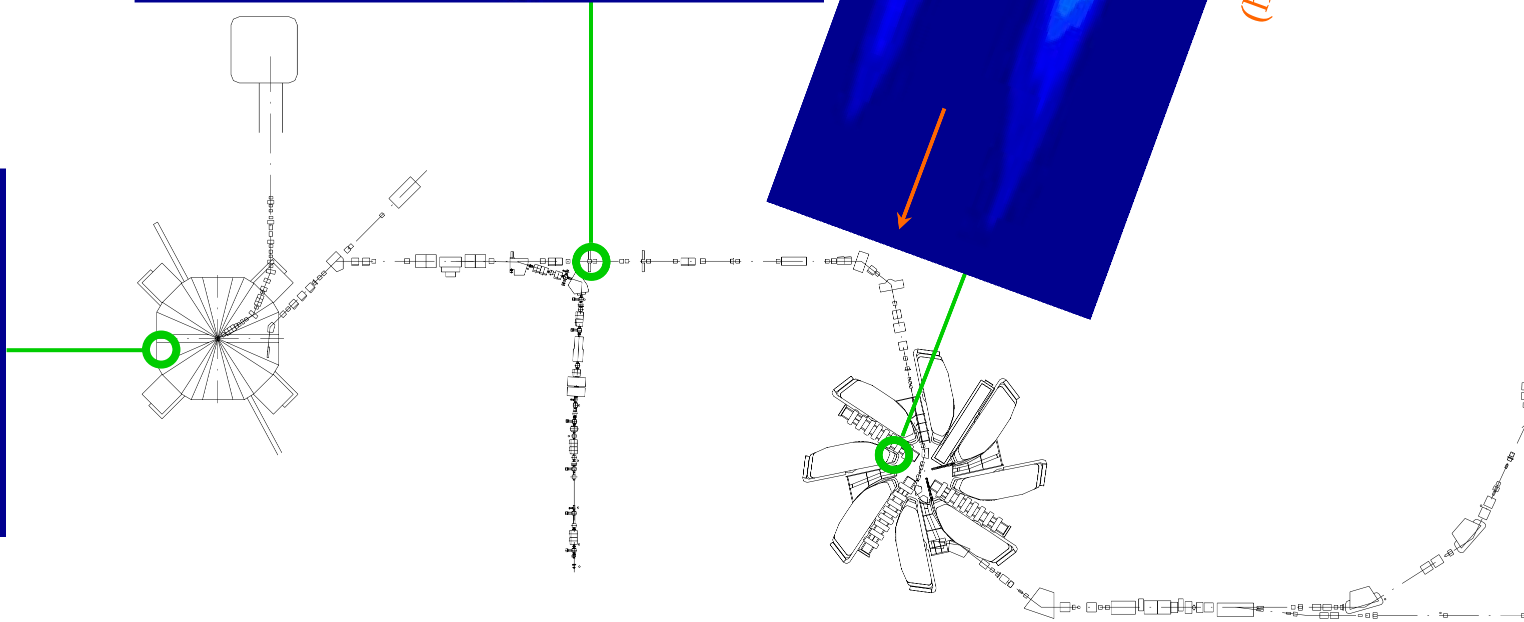
(at 72 MeV, 2.3 mA)
numbers give full width
of parabolic fit in mm,
10 mm = 90 ps = 1.6° RF)

(here radiation background subtracted)







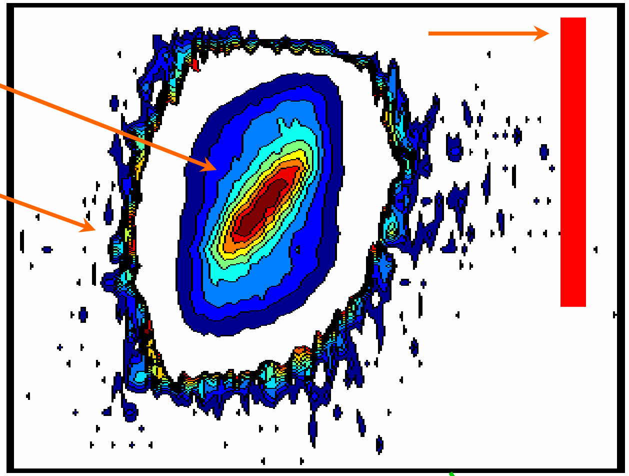


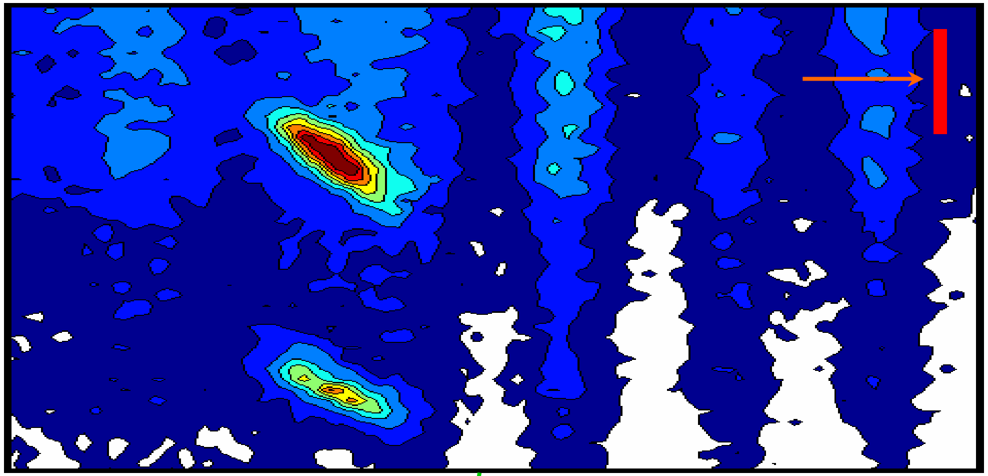
Dölling, PSI Ann. Rep. 2004 vol. VI p. 15

time-structure probes at high current

each 10%

each 10%/125



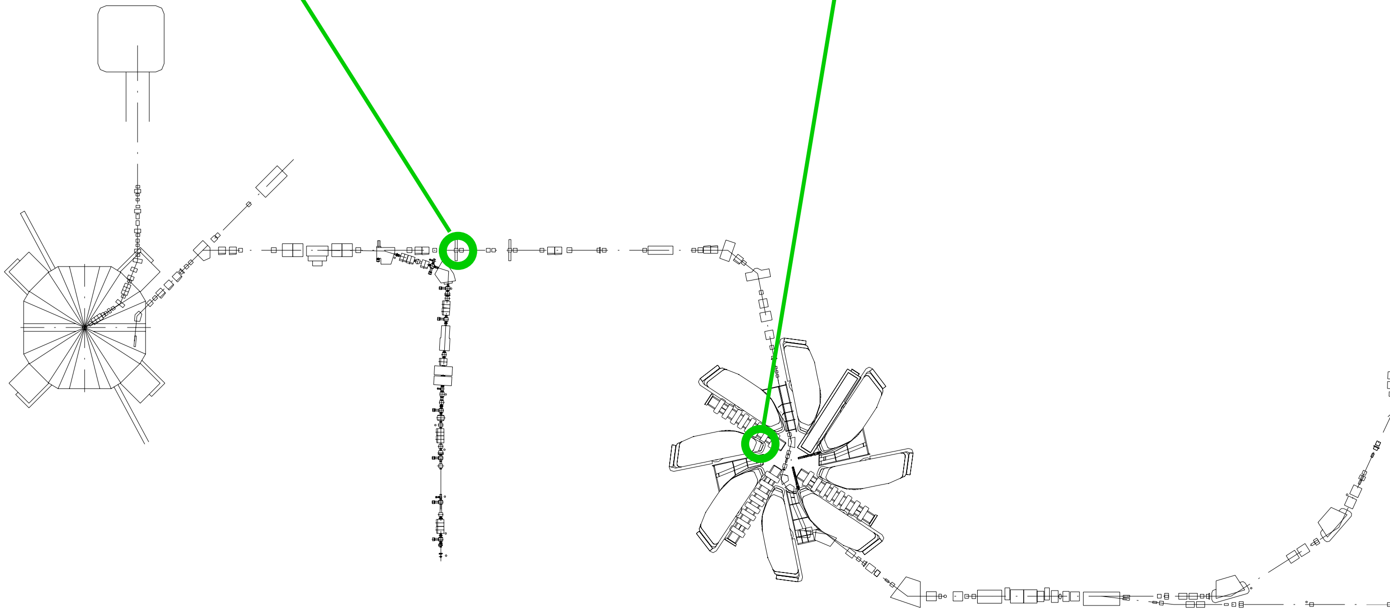


good resolution and dynamic range in low radiation environment

(nearly no backgound)

rectangles indicate 10 mm x 10 mm

worse with high radiation background



23 min

beam losses & beam halo

at high current

losses: „protection aspect“

- melting of cyclotron components by missteered
- fast interlock generation needed (~1 ms)
- prevent activation

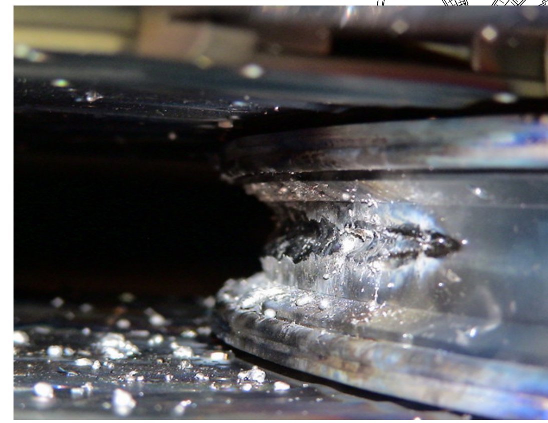
collimators

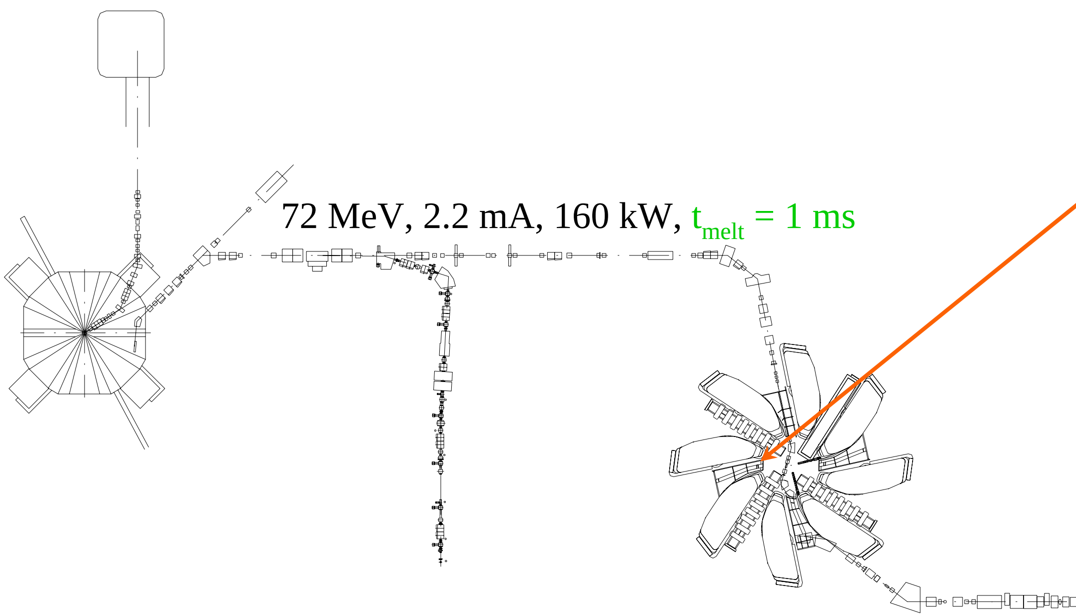
with current readout

injection into Ring cyclotron:

collimator and coil support destroyed

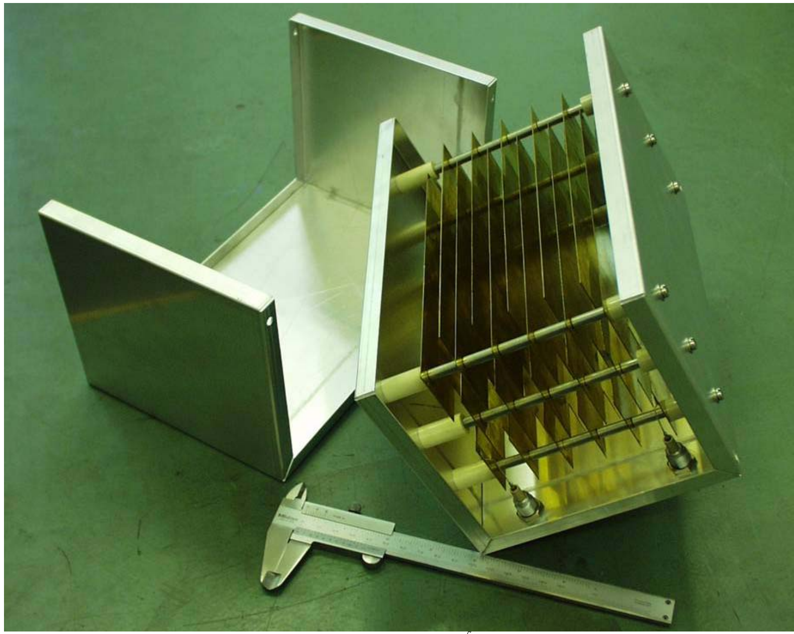
(defect of high level interlock module)





72 MeV, 2.2 mA, 160 kW, t_{melt} = 1 ms

590 MeV, 2.2 mA, 1.3 MW, t_{melt} = 10 ms



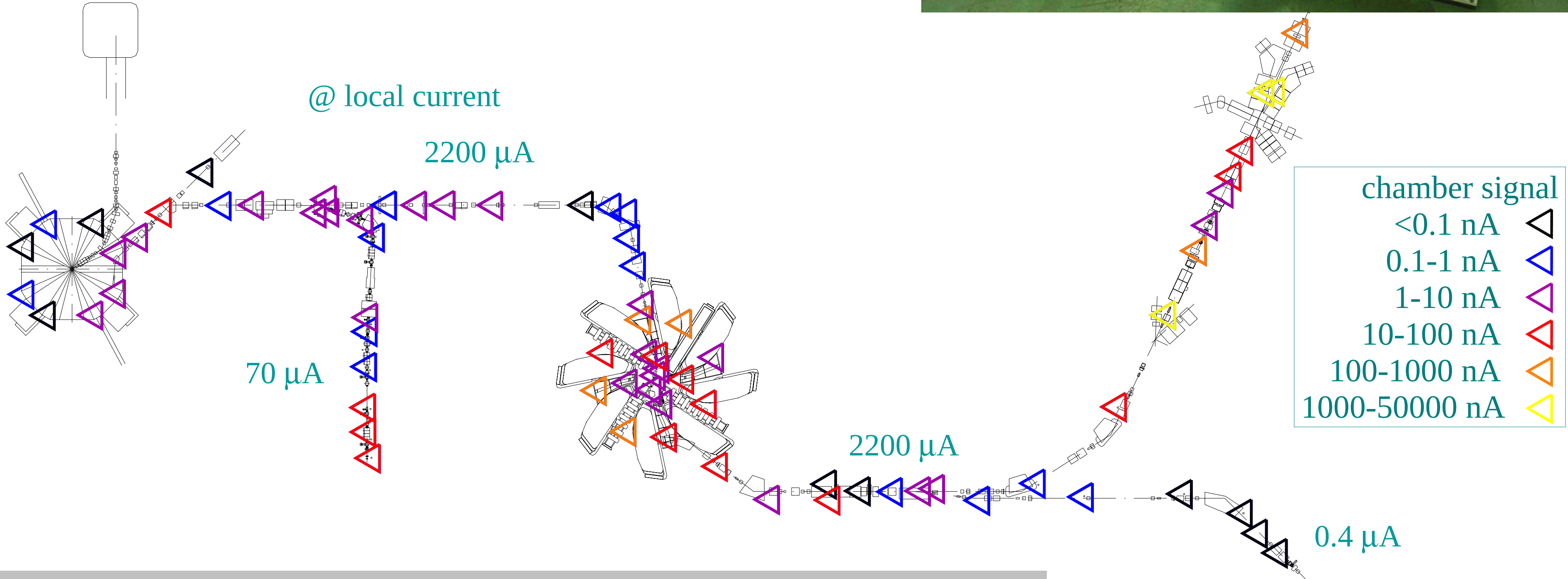
loss monitors

- ionization chamber (ambient air filled, 300 V)

many other methods available

e.g. Wittenburg CAS2008, L. Fröhlich, ERL Instrumentation Workshop, Cornell Univ., 2008

- useful at beam energies >40 MeV → proton range in steel > 3 mm
- placed ~0.1...1 m from beam, fixed position for reproducibility
- approximate calibration by steering low current beam into wall



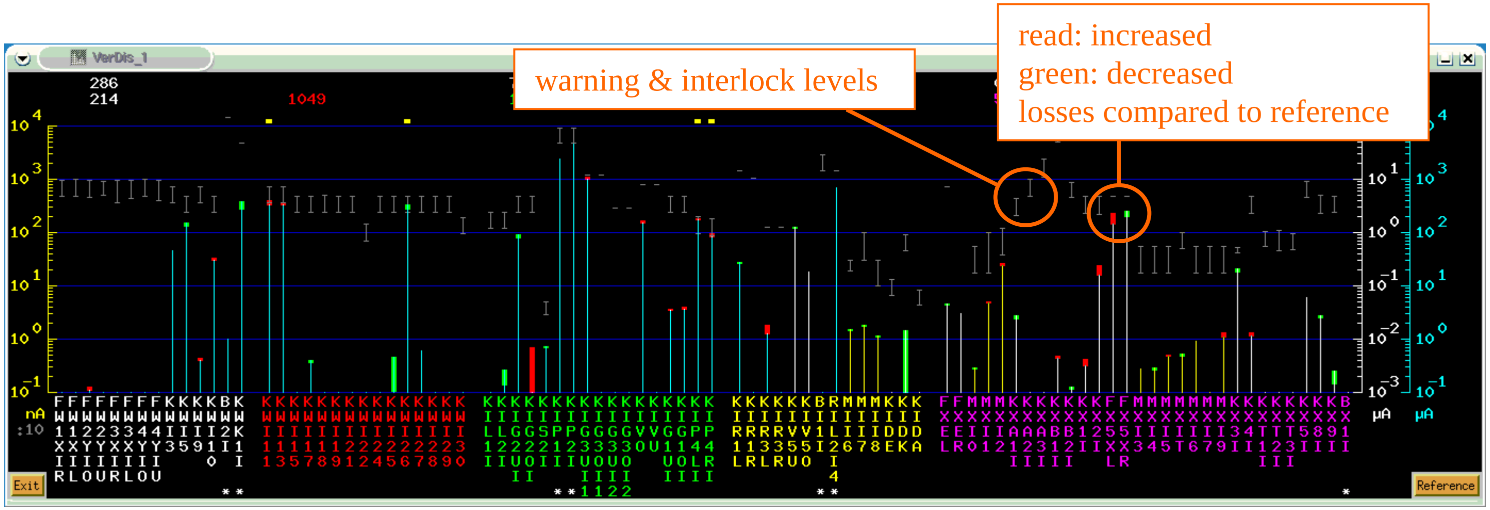
- losses lead to activation, this limits the beam current (personal dose at maintenance)
- to prevent losses, the beam halo must be cut or matched through all the machine (some controlled loss in shielded locations allowed)
- it is difficult to measure and simulate the beam halo (new halo by scattering at collimators, ...)
- hence empirical tuning is used („turn all available knobs“) based on collimator/loss monitor readings
- „knowledge aspect“ diagnostics only needed at trouble („what is different than yesterday?“)

→

- delivers optimum for *given* machine configuration
- cannot suggest *changes* of machine configuration for improvement
- difficult to find hidden causes in case of persistantly bad beam quality

→

detailed beam dynamic simulations & halo diagnostics needed for progress

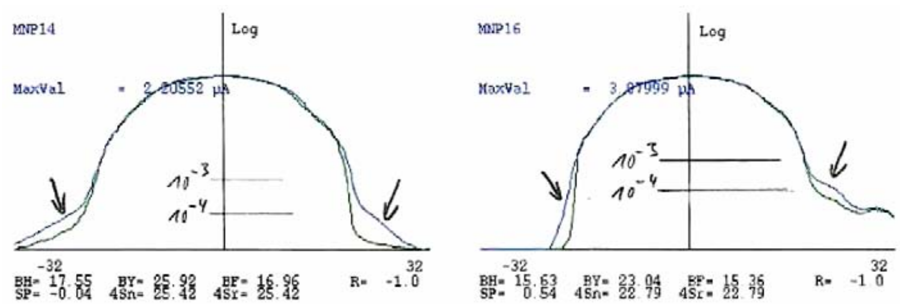


depiction of changes of collimator currents and lossmonitor readings used for „empirical“ tuning

A. Mezger, PSI

- a dynamic range of up to 10^5 is required
  (in a projected profile) to see „the future losses“

losses caused purposely with known origin and amplitude
provide a cross-check for simulations:



detection of beam ions
scattered ~20 m upstream
by a 33 mm carbon fibre placed in the beam
with two vertical wire scanners in front of the
Ring-cyclotron
(losses in Ring cyclotron increased ~40%)

- in beam lines this seems feasible (low background & stray particles)
  for wire scanners
  (at least at locations where they survive the beam power)
  (space-charge neutralisation?)

- in the cyclotrons this is much more difficult (high background & stray particles)

→ separate measurement of beam core and halo
e.g. by moving a finger-detector at a radial probe axially as far as heating allows it
(e.g. a fully shielded small ionization chamber or diamond detector)

- this will provide a detailed input for beam dynamic simulations

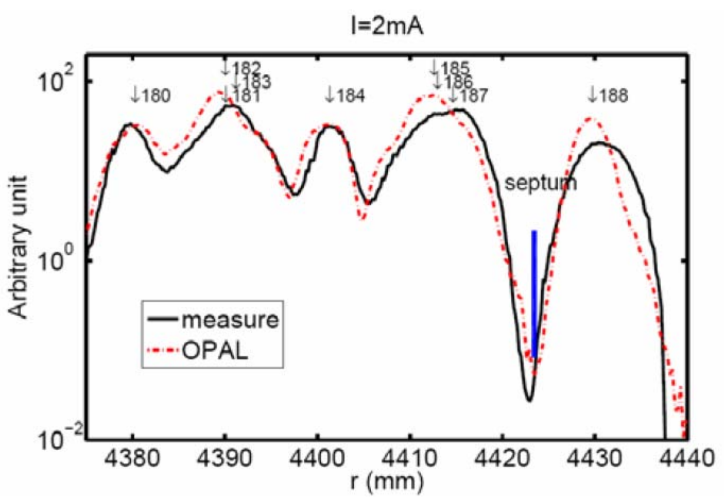
halo simulation

- *detailed* numerical simulations
  (including beam halo, scattering at collimators, 3D-poisson solver, space charge neutralisation)
  lead to a better understanding of the losses: *where* (at low energies) *to cut and how to match the halo*

- fitting capabilities must be included in order to find the best fit
  to a large set of detailed profile & loss data

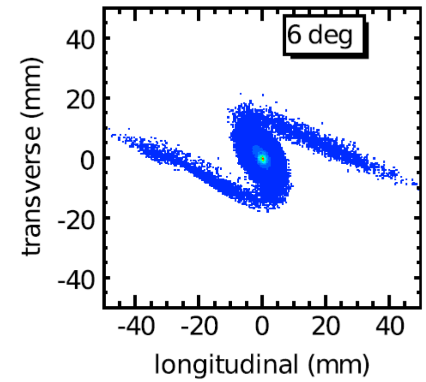
- very encouraging work in progress:

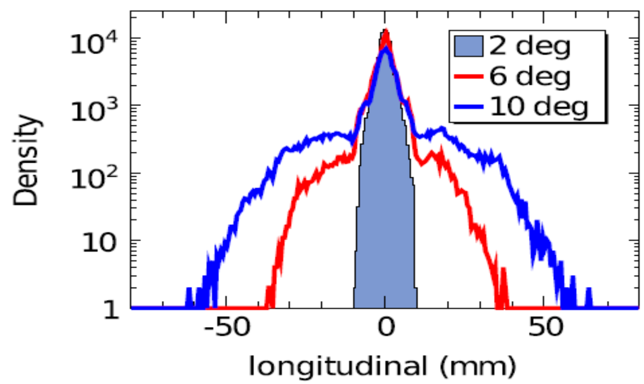
simulation of turn-pattern at exit of Ring cyclotron



Bi et al., this conference

simulation of 3 mA in Ring cyclotron
including neighboring turns





Yang et al., Phys. Rev. ST Accel. Beams 13, 064201 (2010)

Thanks for listening!

Thanks for contributed information & slides!