Beam Diagnostics for Cyclotrons

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on this lecture

How to spend only 45 minutes on beam diagnostics for cyclotrons?

option a) take few examples of diagnostics inside a cyclotron (e.g. radial probe, phase probes)
discuss it in depth

option b) give an overview of diagnostics inside a cyclotron
discuss operation in different types of cyclotrons/for different applications

option c) give an overview on diagnostics in general (methods, monitors, tasks)
with some weight on cyctrotron & its injection lines

here I follow mostly option c), but

→ nearly nothing about details / technical issues / the „art of construction“ / electronics

→ just to tell what is around in the field
(and still this are only examples, many other realizations exist)

→ references to literature are given as a starting point

→ more slides/information than digestable immediately

→ don‘t try to read everything now

→ it is not really a lecture, but I hope you can profit from it

Beam Diagnostics for Cyclotrons

A) introduction: environment / tasks / beam parameters

B) effects used for transversal profile measurement: basic physics/techniques

C) diagnostics along the beam path: practical examples mostly from PSI‘s Injector 2

- 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

D) transversal information (in cyclotron): radial probes (for high/low current)

E) longitudinal information (in cyclotron): phase probes, bunch shape, ...

F) beam losses & beam halo: protection / insight

the field in general

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

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
- since then improvement mainly in detail
    - better sensors
    - better electronics (analogue & digital)
    - (better drives)

→ improved diagnostics

(but also improved machines around it)

the field in general

A wealth of literature on beam diagnostics

Proceedings Cyclotron Conferences 1959-...,

Beam Diagnostics Conferences BIW 1989-2012, DIPAC 1993-2011, IBIC 2012-...,

Accelerator Conferences PAC, EPAC, APAC, IPAC, LINAC, HB

→ JACoW http://www.jacow.org/ (not all from the beginning)

(Brandenburg et al. DIPAC03, Dölling DIPAC2005, ...)

http://accelconf.web.cern.ch/AccelConf/d03/papers/CT10.pdf http://accelconf.web.cern.ch/accelconf/d05/TALKS/ITTA02_TALK.PDF

Journals: Rev. Sci. Instrum., Phys. Rev. ST-AB, Nucl. Instr. Meth. A, JINST, ...

including overviews

JUAS (e. g. Forck 2011) http://www-bd.gsi.de/conf/juas/juas_script.pdf

CAS (e. g. Wittenburg/Braun/Bravin et al. 2008, 2010) http://cas.web.cern.ch/cas/France-2008/Lectures/Dourdan-lectures.htm

http://cas.web.cern.ch/cas/Bilbao-2011/Lectures/BilbaoLectures.htm

CARE-Conf-08-033-HHH http://adweb.desy.de/mdi/CARE/Bad_Kreuznach/Reports/ABI-Workshop_Proceedings_all.pdf

Wittenburg HB2006, Raich DIPAC2005, Plum BIW04 p. 23, . . .

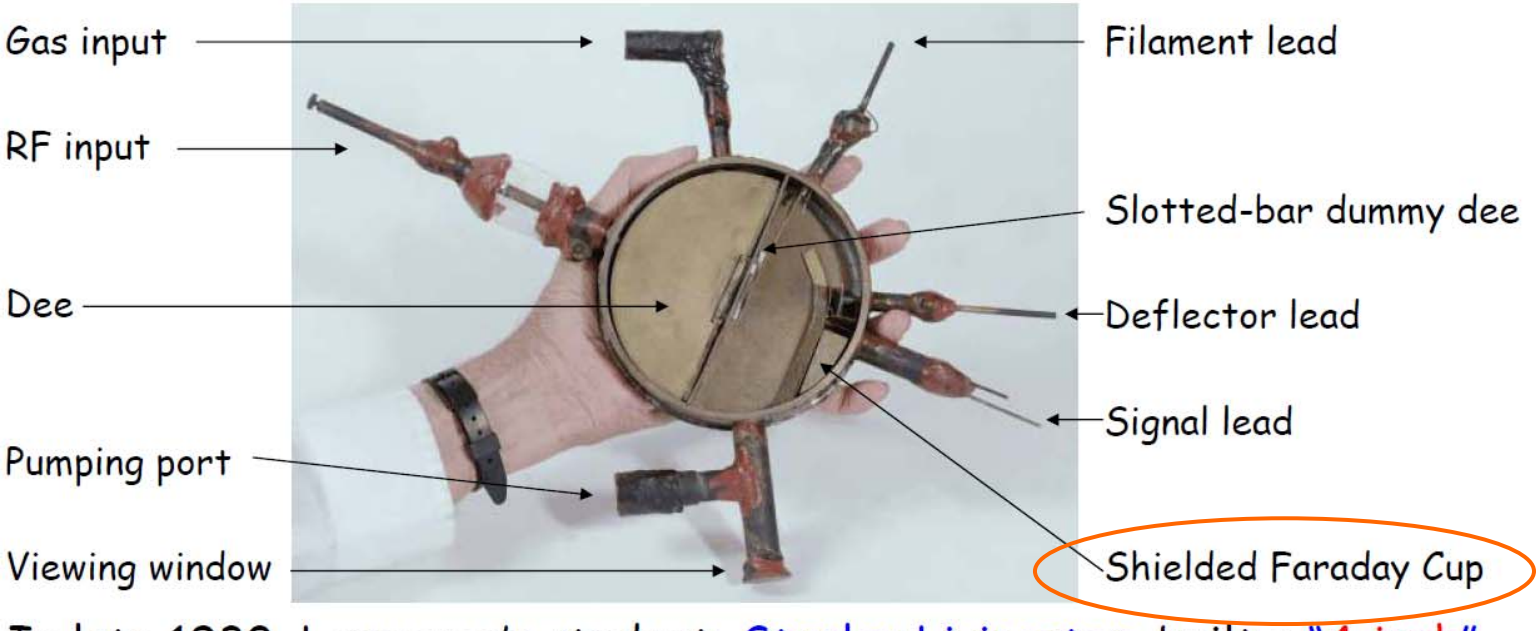
http://accelconf.web.cern.ch/AccelConf/abdwhb06/PAPERS/TUAZ01.PDF http://accelconf.web.cern.ch/AccelConf/d05/TALKS/ITMM01_TALK.PDF

and overviews for cyclotrons

Mackenzie CYC78, Clark CYC66, Olivo CYC75, ... Dölling CYC10

p. 2312 http://accelconf.web.cern.ch/accelconf/c66/papers/a-002.pdf p. 331 http://accelconf.web.cern.ch/accelconf/Cyclotrons2010/talks/wem2cio04_talk.pdf

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.

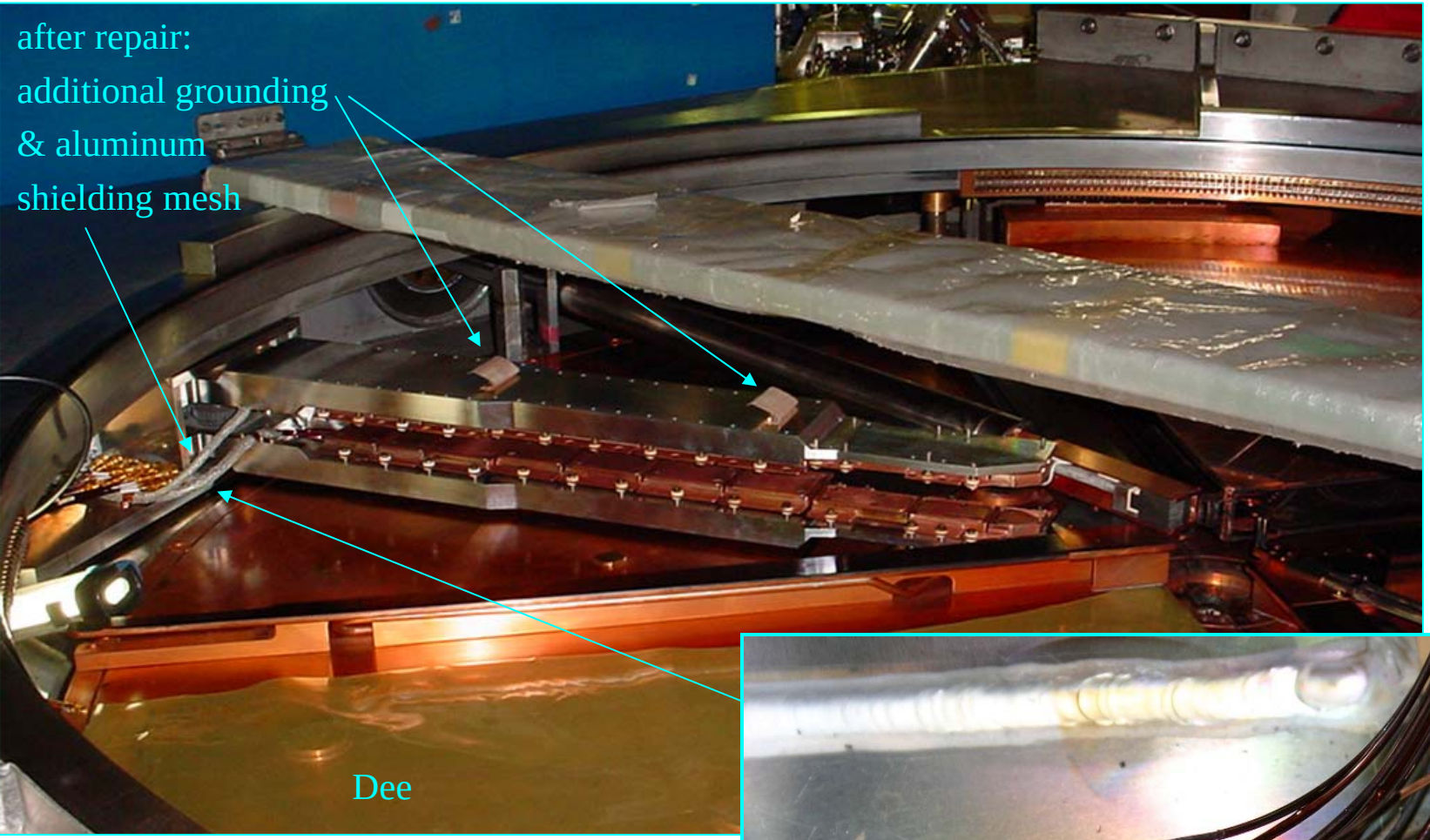
from M.K. Craddock, Lecture "Introduction to Particle Accelerators", see also CYC10 p. 1, http://accelconf.web.cern.ch/accelconf/Cyclotrons2010/talks/mom1cio02_talk.pdf

boundary conditions from different cyclotrons

property of cyclotron	*impact on boundary conditions for diagnostics in cyclotron via*	*affected requirement to diagnostics*
high/low beam current	thermal/radiation load, activation (direct/indirect, shielding difficult)	machine protection activation control reliability/maintainability
high/low beam energy	penetration depth, cross sections	
protons/H^-/heavier ions	residual gas pressure	
external/internal source	available space, magnetic field	
separate sectors/compact	RF nearby	
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

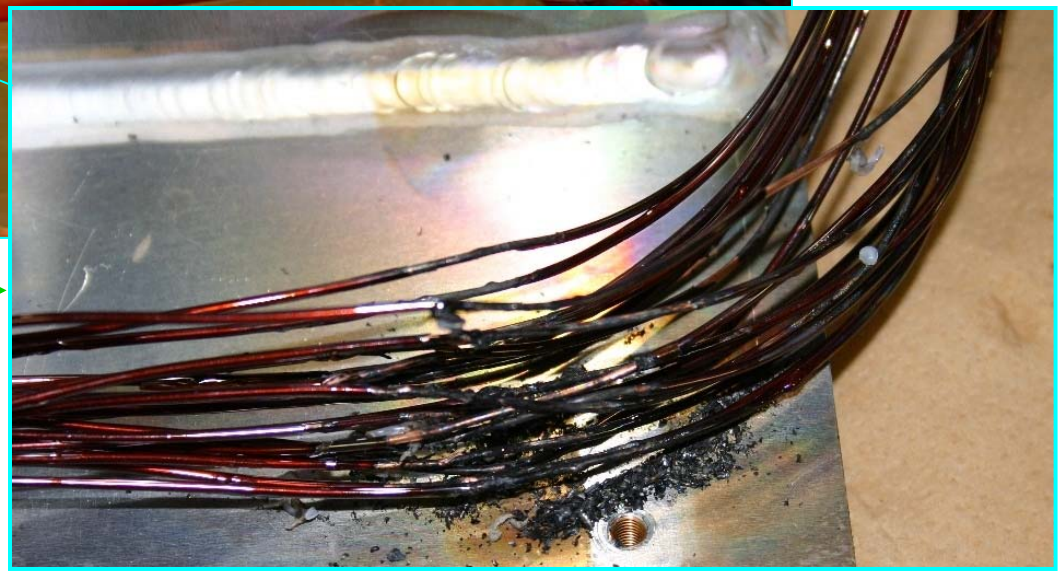
a difficult environment



JAEA
930 AVF
cyclotron

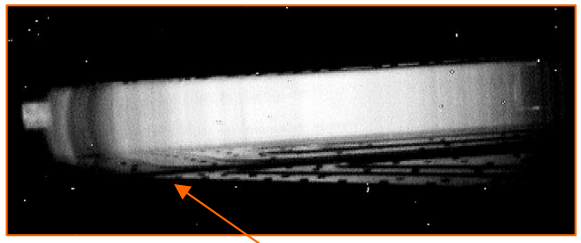
phase probe signal cables damaged by RF after introduction of Flat-Top system of few kV, 80-100 MHz

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



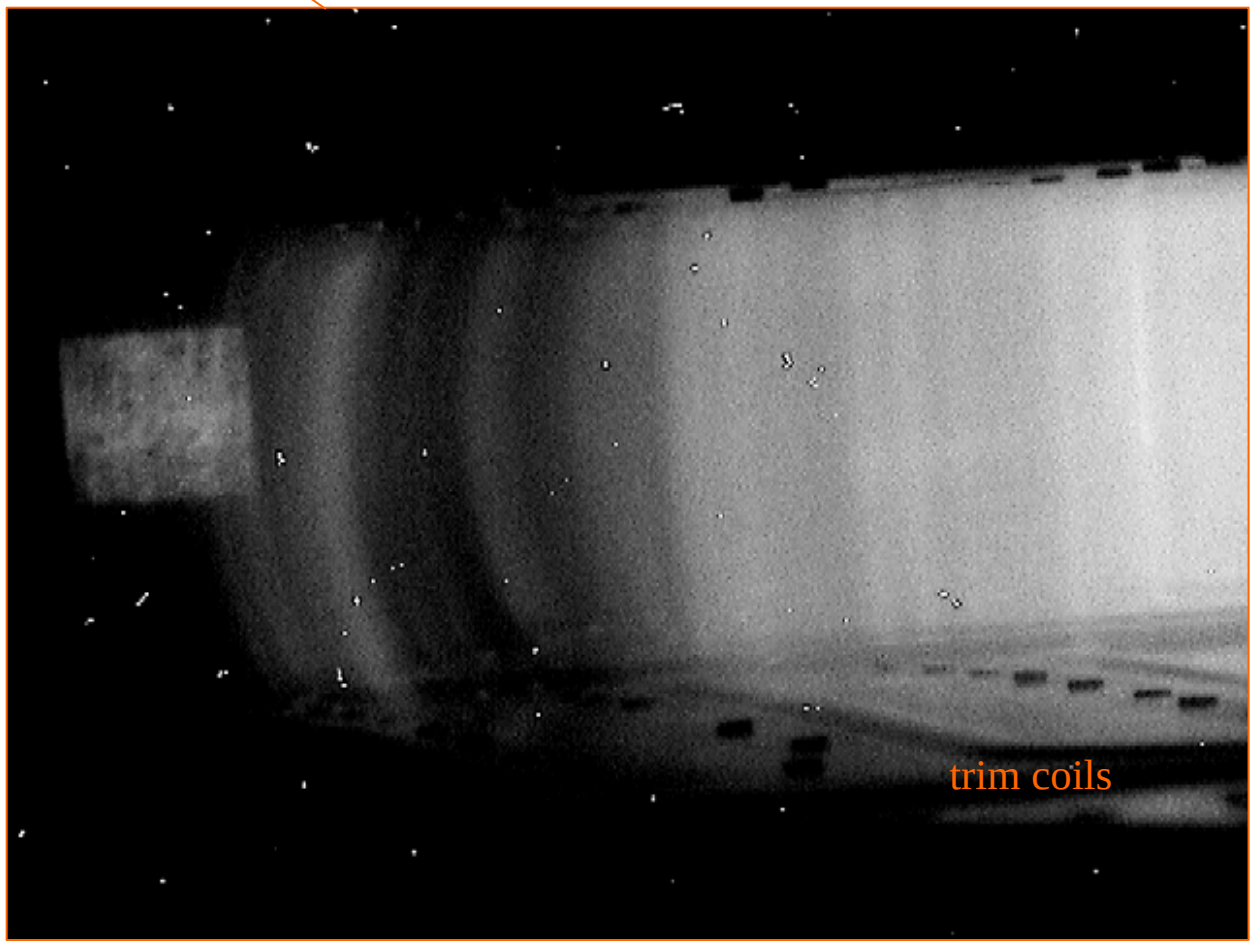
all pictures from S. Kurashima, JAEA

a difficult environment



radial view into PSI Ring cyclotron

- RF on (~3 MW), magnet on (~1.7 T)
- beam off
- ~10^{-6} mbar



thin plasma
in sector magnet
at lower machine radii
(always present?)

impact on

- electrostatic septa
- probe measurements?

pictures from R. Kan, PSI, see also D. Goetz et al., CYC10, p. 341, http://accelconf.web.cern.ch/accelconf/Cyclotrons2010/talks/wem2cco03_talk.pdf

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	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		- wire monitor, harp
- 2D		- screen
- transverse emittance - 1D	- „2 slit“ / „3 profile“	
- 2D	- 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

7 min

B) effects used for transversal profile measurement

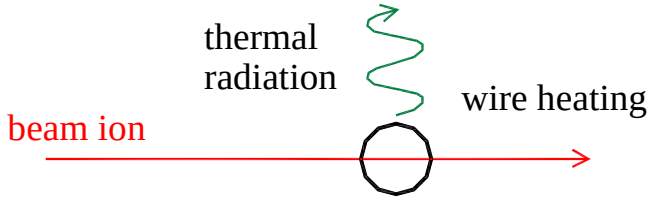
(depending on geometry also for full beam or beam halo,
also part of emittance measurement)

(effects / methods usable for beam measurements in general)

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

Dölling, CYC10 p. 344, http://accelconf.web.cern.ch/accelconf/Cyclotrons2010/papers/wem2cio04.pdf, see also Koziol, CAS2000 p. 154, http://cdsweb.cern.ch/record/425460/files/CERN-2005-004.pdf

temperature measurement



$P_{in} = U_{beam} * I_{beam}$

P_{in} = wire mass * stopping power * beam current density

[V A] [kg] [V m²/kg] [A/m²]

„direct“: of stopper block

or of cooling water in&outlet (+ flow measurement)

- can be calibrated by ohmic heating
- thermoelements are radiation hard
- small influence of (low energy) stray particles

indirect: of wire (or foil)

- vibration resonance shift (very sensitive)
  Arutunian, BIW08, http://www.als.lbl.gov/biw08/papers-final/MOSTFA01.PDF
- resistance
- light emission (non-linear)
- thermionic emission current (non-linear)

wire melting/evaporation? → energy balance

Liaw, Cameron, PAC2001, http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/WPAH120.PDF
Sapinski, et al., DIPAC09, http://accelconf.web.cern.ch/AccelConf/d09/papers/tupd40.pdf,
HB10, http://accelconf.web.cern.ch/AccelConf/HB2010/papers/mopd61.pdf, BIW12, to be published

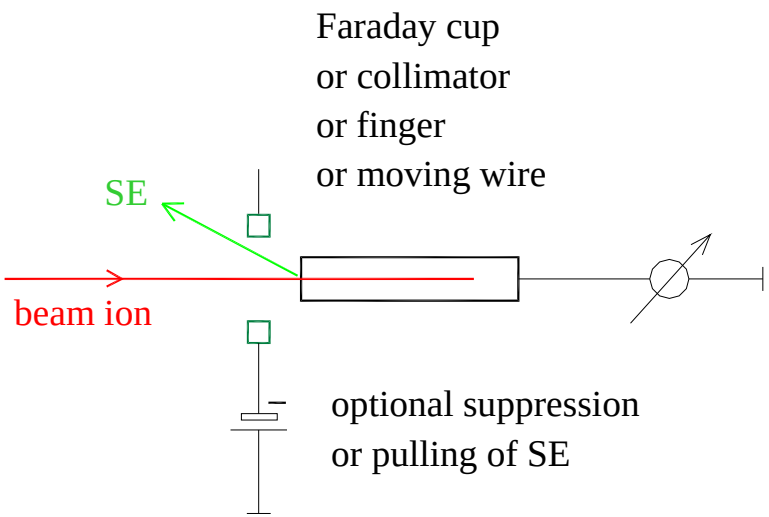
Example: carbon fibre, diameter 33 um

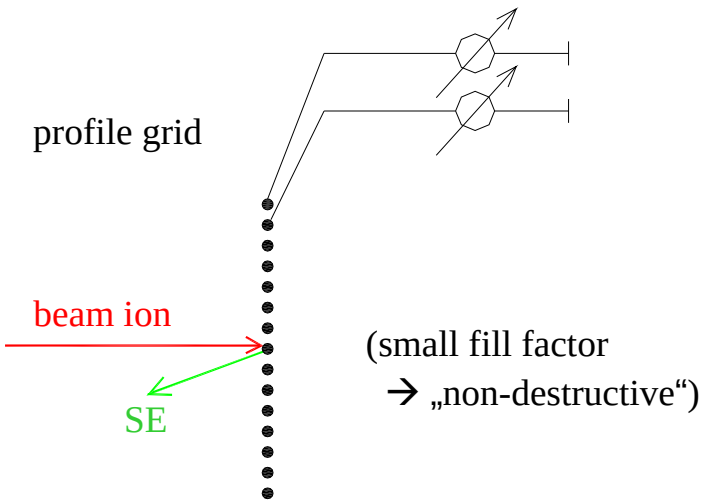
- 2000 K reached at DC current density

2.3 uA/mm2	for	1 MeV protons
13		10
82		100

- approx. 40x higher current density for flying wire
  (5 m/s, 10 mm beam diameter)

direct measurement of current of stopped beam fraction





- stopping material thick enough? → for protons projected range http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html
  → for ions e. g. http://www.srim.org, http://geant4.cern.ch

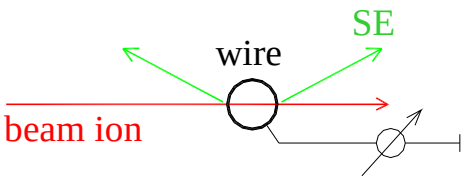
- signal altered by secondary electron emission at surface, SE energy mostly around 2 eV, yield >1 at low beam energies
  for absolute measurements: suppression with electrode at ~100 V (electrode not to be hit by beam!)
  or with permanent magnets → Faraday cup
  for most applications: better to let SE escape or to pull them away

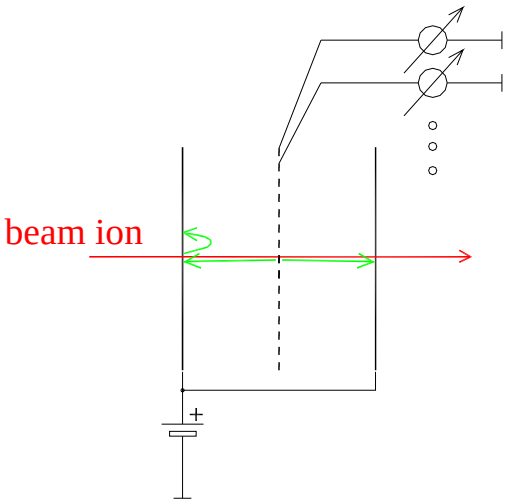
- signal altered by stray particles (residual gas ions, external SE)

- with magnetic fields & beam space charge → path of SE or stray particles difficult to predict (ExB-drift, ...)

- if directly water cooled: at very small currents measurement can be disturbed by water conduction

secondary emission current, direct measurement





wires or strips
or full foil
(fill factor, thickness
→ destructive or „not“)

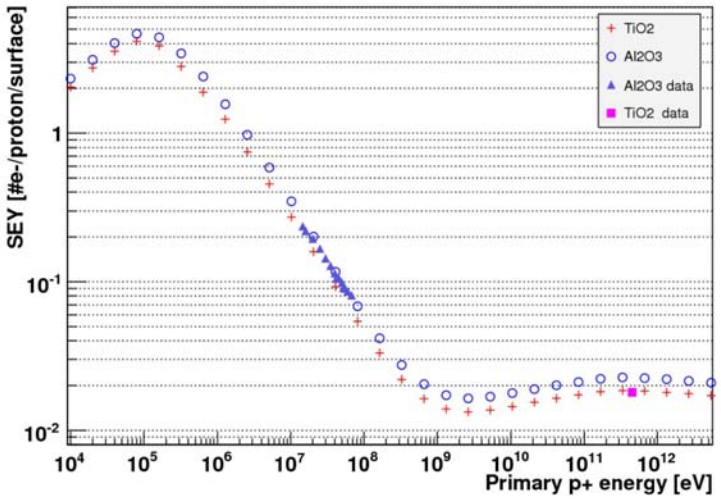
- at higher energies: ions not stopped,
  signal only from SE

- optional pulling of SE by external electrodes or adjacent foils
  (foils also block stray particles, filtering of high voltage needed)

- SE-yield depends on surface material
  & structure & contamination,
  ion species & energy

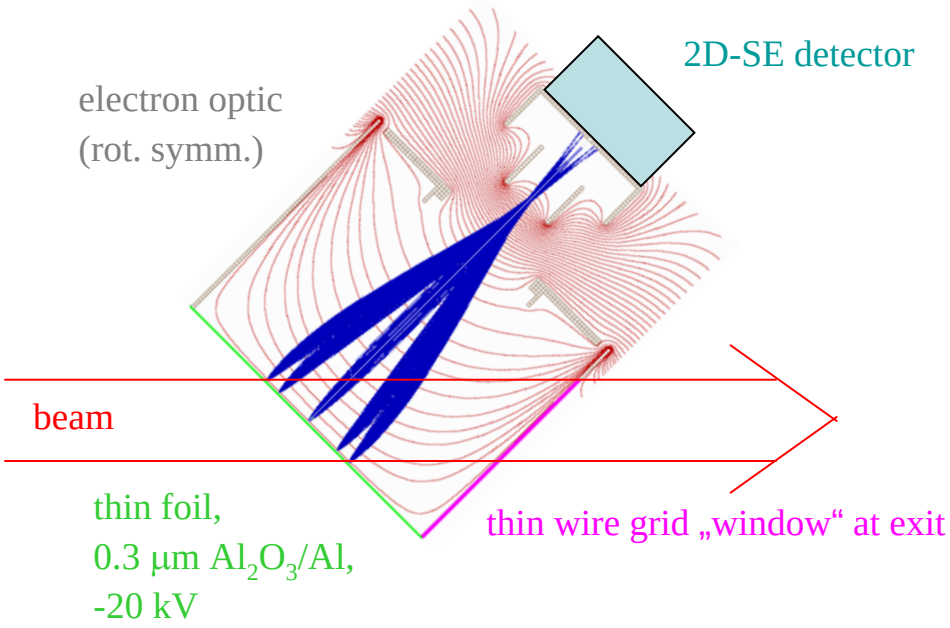
- SE-yield depends on irradiation history,
  Titanium is good Ferioli, Jung, DIPAC97, pp. 168-170

- signal is very fast (<ps)
  and linear (large dynamic range)



Kramer et al., DIPAC2007, http://accelconf.web.cern.ch/AccelConf/d07/papers/wepc03.pdf

secondary emission current, 2D-measurement



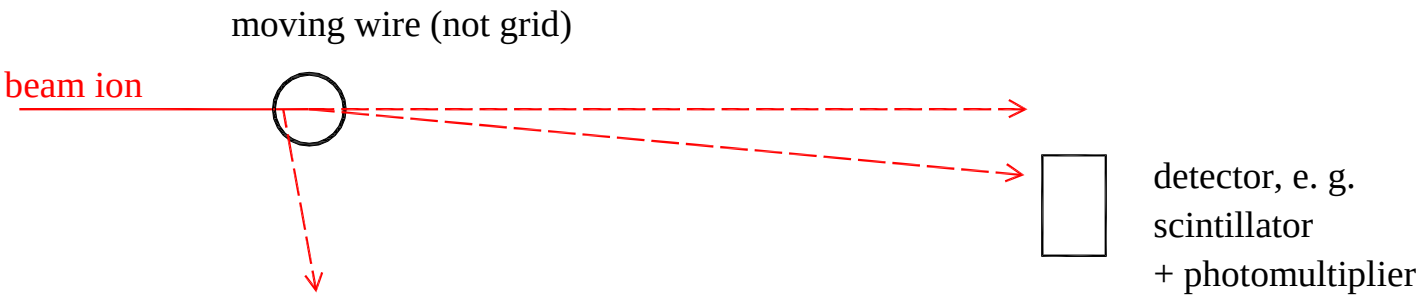
according to Badano et al., DIPAC03/07
http://accelconf.web.cern.ch/AccelConf/d03/papers/CT09.pdf
http://accelconf.web.cern.ch/AccelConf/d07/papers/wepc20.pdf

- ~non-destructive
- fast
- sensitive
- fragile foil? → careful venting of beam line

other variants:
Kruglov et al., Nuclear Instruments and Methods in Physics Research A 441 (2000) 595-604
Shapira et al., Nuclear Instruments and Methods in Physics Research A 454 (2000) 409-420

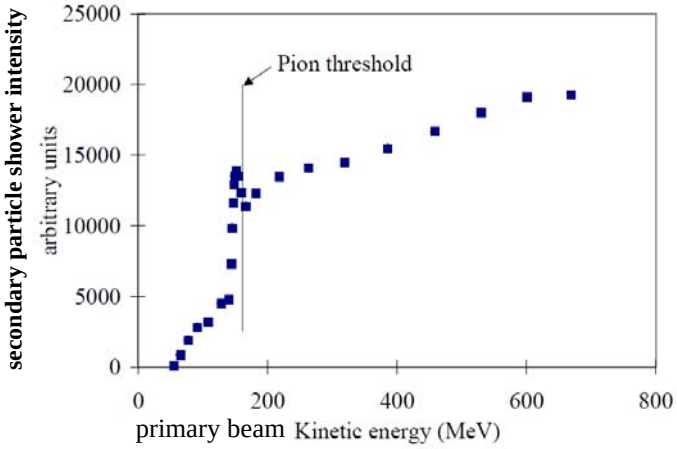
very fast:
http://accelconf.web.cern.ch/accelconf/HB2010/talks/weo2a02_talk.pdf

detection of scattered or secondary particles

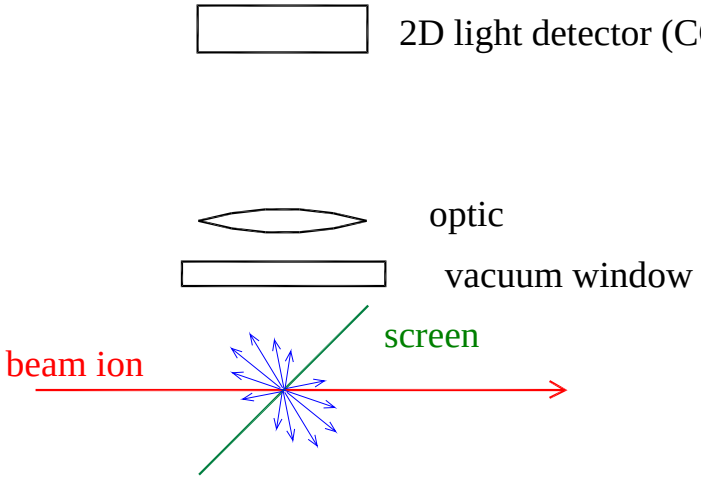


- scattering at high and low energies
  (at not too low energies ~according to Rutherford formula)
- creation of secondaries at higher energies
- very large dynamic range (if background radiation low, coincidence technique)

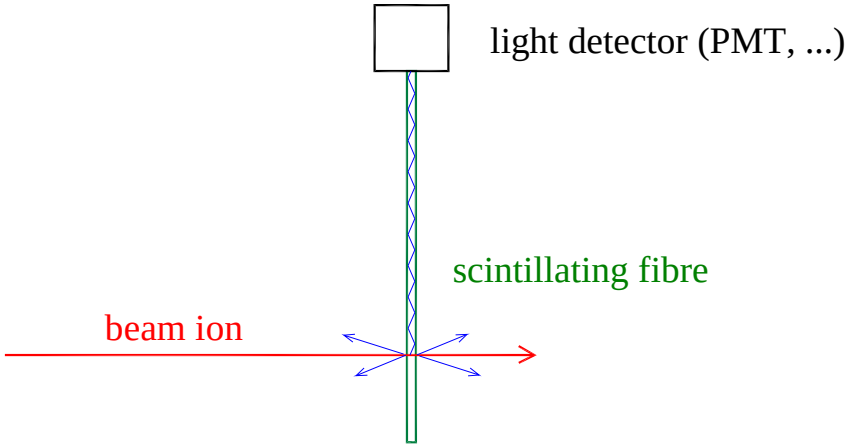
Raich, DIPAC05,
http://accelconf.web.cern.ch/AccelConf/d05/TALKS/ITMM01_TALK.PDF



scintillating screens & fibres



instead of moving wire or grid



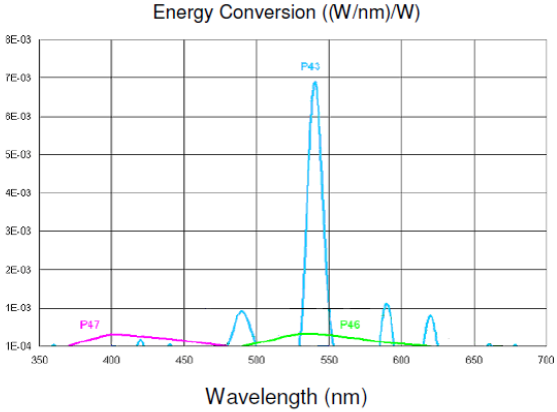
- light emission spectrum (to be compatible with light detector)

- decay time ns .... >s

- doped bulk anorganic material (ceramic, glass, crystal → rugged)
  doped plastics
  thin coating on metal (phospor powders → fragile)
  thin layer in plastic (intensifying screens, Kodak Lanex = P43)

- image broadening by light scattering → thin screen

- saturation, thermal damage, radiation hardness
  → for limited beam current



http://www.proxitronic.de/datasheets/20091001_ebv.pdf

Type	Composition	Light Emission				Decay Time	
		Range		Maximum	Color	Decay of Light Intensity	
		from	to	typically at		from 90 % to 10 % in	from 10 % to 1 % in
P 43	Gd_2O_2S:Tb	360 nm	680 nm	545 nm	green	1 ms	1,6 ms
P 46	$Y_3Al_5O_{12}$:Ce	490 nm	620 nm	530 nm	yellow green	300 ns	90 µs
P 47	Y_2SiO_5:Ce,Tb	370 nm	480 nm	400 nm	blue white	100 ns	2,9 µs

http://cas.web.cern.ch/cas/France-2008/Lectures/Bravin.pdf
Jung et al., DIPAC03, http://accelconf.web.cern.ch/AccelConf/d03/papers/IT03.pdf
Gütlich et al., DIPAC09, http://accelconf.web.cern.ch/AccelConf/d09/papers/tupb04.pdf
DIPAC11, http://accelconf.web.cern.ch/AccelConf/DIPAC2011/papers/mopd57.pdf
http://accelconf.web.cern.ch/AccelConf/DIPAC2011/papers/mopd53.pdf
Re et al. PAC2005, http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/RPAT002.PDF

effects on foils & films

paper/Kapton foil coloration

- colouring by beam heating
- readout with scanner
- not linear

radiographic film

- like photographic film
- development needed

track-etch foil

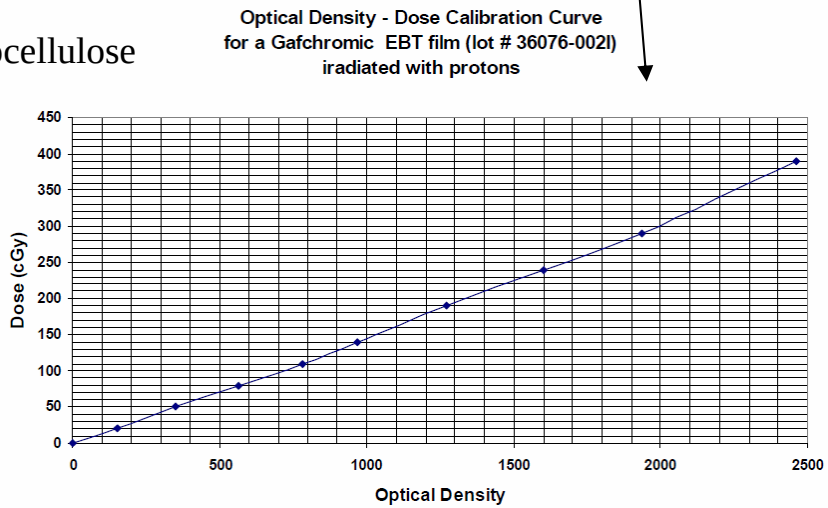
- tracks in nitrocellulose
- etched
- counted

radiochromic film

- optical density increases with dose
- dose range 0.001 ... 100 Gy
- easy to use (no light sensitivity, no development)
- readout with flatbed scanner
- can be calibrated

http://www.gafchromic.com/

Mumot et al., PTCOG46, http://ptcog.web.psi.ch/PTCOG46/May%2022,%202007,%20morning/(22)-(5.22)(9.00)M.Mumot(Dose%20distribution%20measurements).pdf

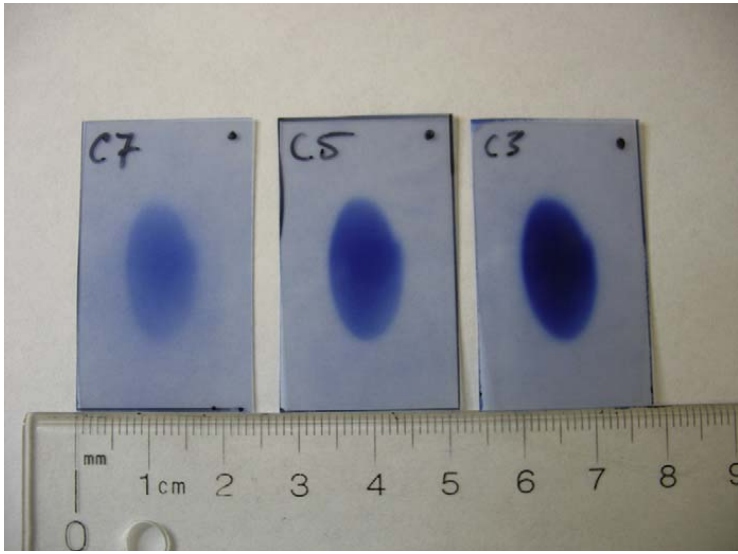


Bues, PTCOG45, http://online1.ispcorp.com/_layouts/Gafchromic/content/presentech/pdf/14MBues.pdf

foil activation

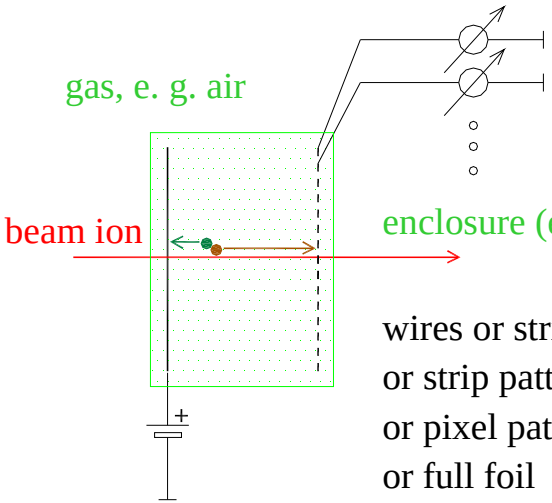
- activation of metal or polyethylene foil (if ion energy above a few MeV)
- contact radiography to
  a) imaging plate (semistable excitation)
     read-out with laser scanner
     (deexcitation observed with PMT)
     few µSv/h detectable, 50 µm resolution
     → very large dynamic range
  b) radiochromic film
     → large dynamic range
- linear

Clarke et al., NIM A 585 (2008) 117–120
Tamburella, Giles, NIM B 266 (2008) 4678-81



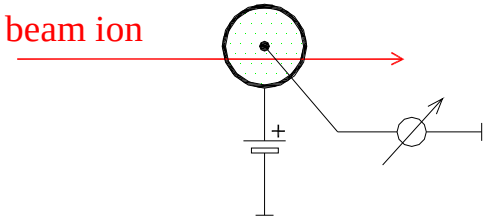
Avila-Rodriguez et al., Applied Radiation and Isotopes 67 (2009) 2025–2028

ionisation chamber



wires or strips (100% fill factor anyway)
or strip pattern on substrate
or pixel pattern Amerio et al., Med. Phys. 31 (2004) 414-21
or full foil
(if very thin → „less-destructive“)

instead of moving wire



- signal enhanced by ion pair generation η = stopping power * gas density * gas length / energy per ion pair

	[eV m²/kg]	[kg/m³]	[m]	[eV]
example: 10 MeV protons in 1 cm air	1400	4e6	1.2	0.01	34.23

stopping power: http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

- saturation effects only at higher beam current densities, (but signal still increasing)

- charge collection time $t_{coll} = (gap)^2 * (\text{high voltage})^{-1} * k^{-1}$

  example: gap 10 mm, high voltage 300 V

  mobility of air $k_{air} \sim 1.7 \cdot 10^{-4}\ m^2\ s^{-1}\ V^{-1}$ → $t_{coll} = 2$ ms

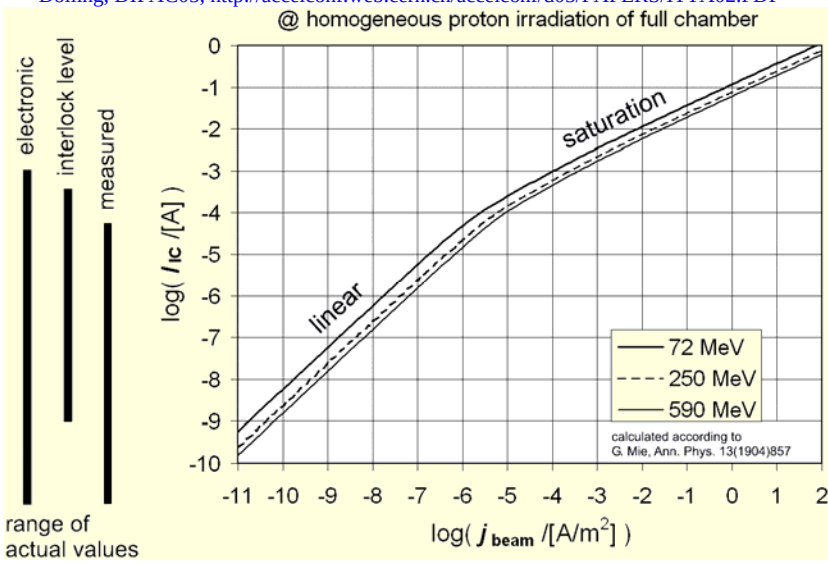
- faster if only electrons used for signal

  („Frisch-grid chamber“, nitrogen filled, $t_{coll} \sim \mu s$)

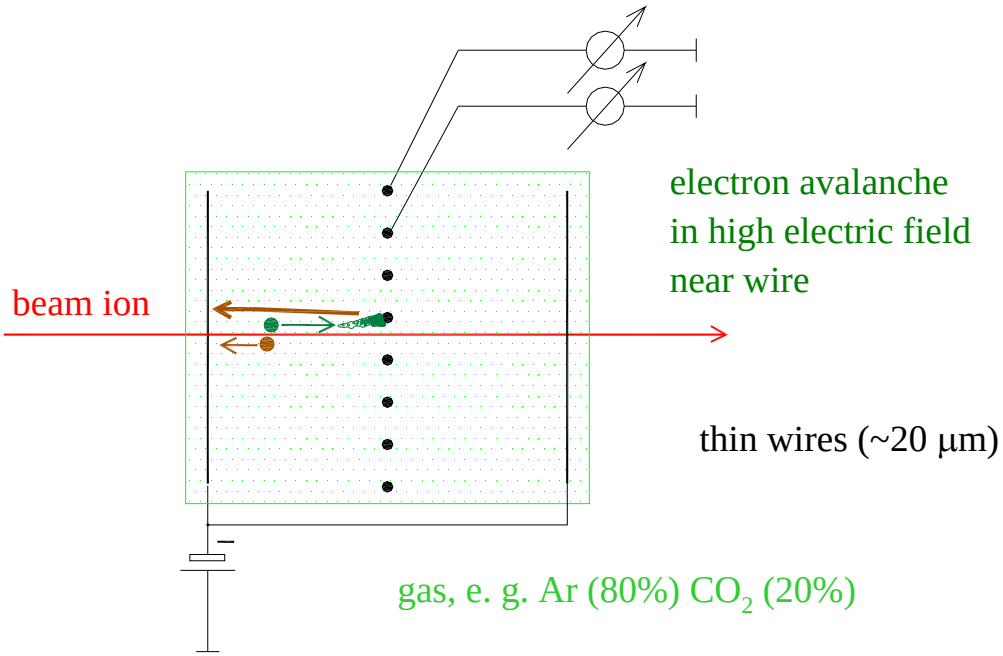
- low energy limit: penetration of window

  example: 50 µm Ti → protons of 2.8 MeV

Dölling, DIPAC05, http://accelconf.web.cern.ch/accelconf/d05/PAPERS/ITTA02.PDF

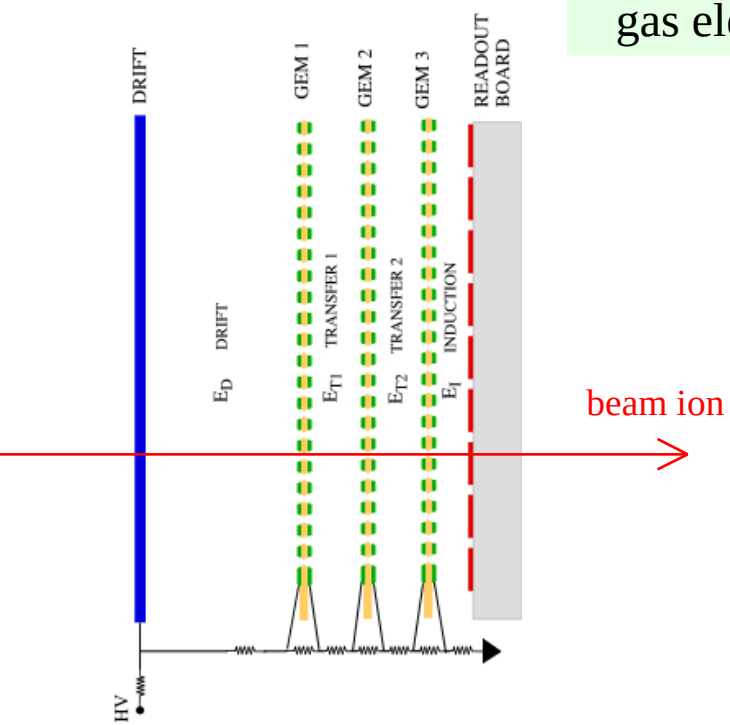


proportional chamber

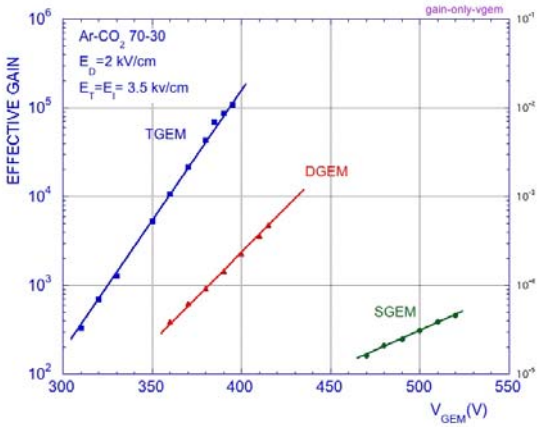


- signal additionally enhanced by electron avalanche amplification by ~10^4
- amplification dependent on beam current density → non-linear
- gas flow needed

gas electron multiplier (GEM)

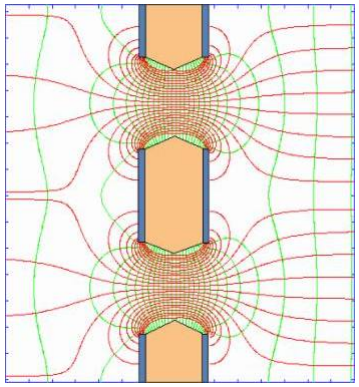


- signal additionally enhanced by electron avalanche by 10^2 – 10^5 depending of number of GEMs



front: ionisation chamber
gas, e. g. Ar (70%) CO_2 (30%)
middle: 1-3 GEM foils
rear: strip pattern 1D or 2x 1D or pixels

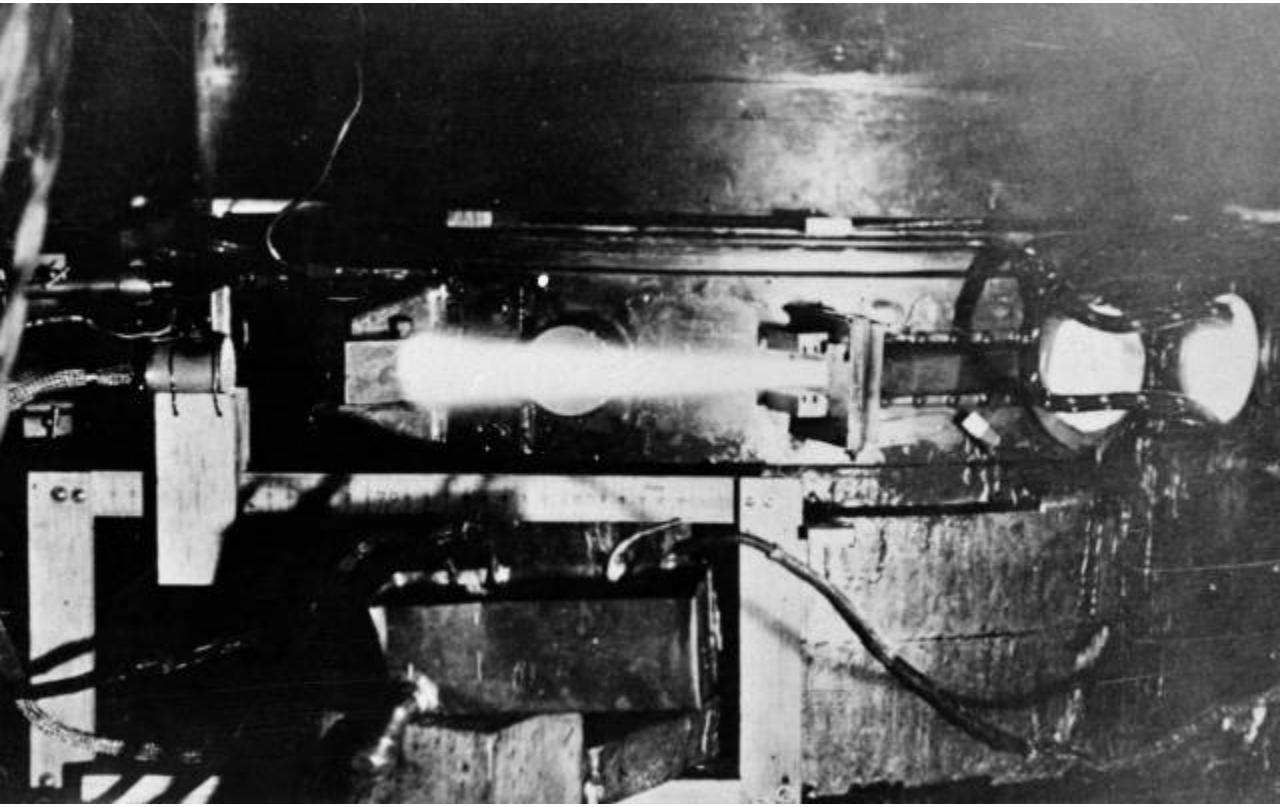
- less discharges with more GEMs
- amplification not dependent on beam current density
  → linear (at not too high current densities)
- radiation hard
- gas flow needed



electron avalanche
in high electric field
in holes

pictures from Gas Detectors Development Group, CERN, http://gdd.web.cern.ch/GDD/

beam induced fluorescence (BIF)



The first external cyclotron beam, obtained on March 26, 1936. The glow arises from the ionization of the air by the 5.8 MeV deuterons.
http://imglib.lbl.gov/LBNL_Res_Revs/RR_online/81F/81fchp2.html

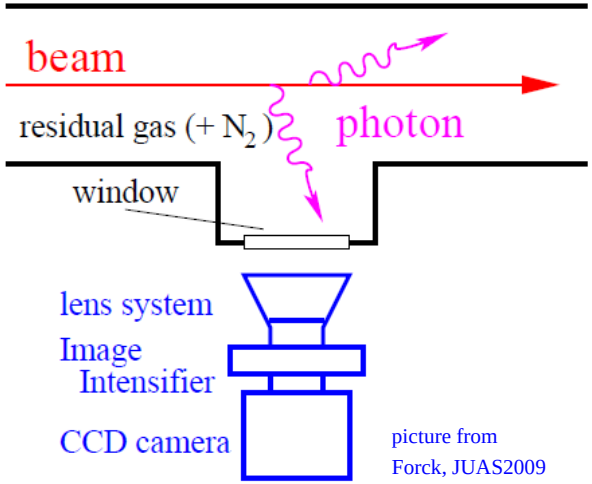
in air: deuterons stopped after half a meter

↓ scaled by 10^{-9} in pressure (10^{-6} mbar)

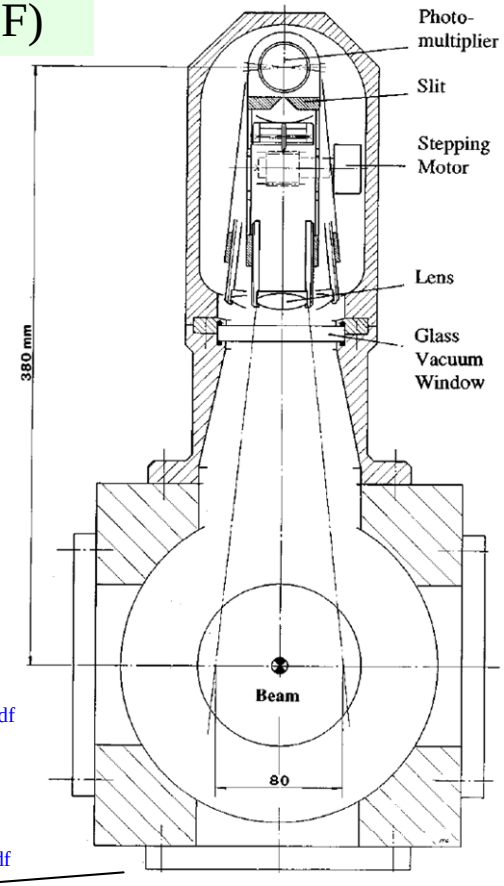
in residual gas: distance earth – moon (i. e. non-destructive)

very faint glow

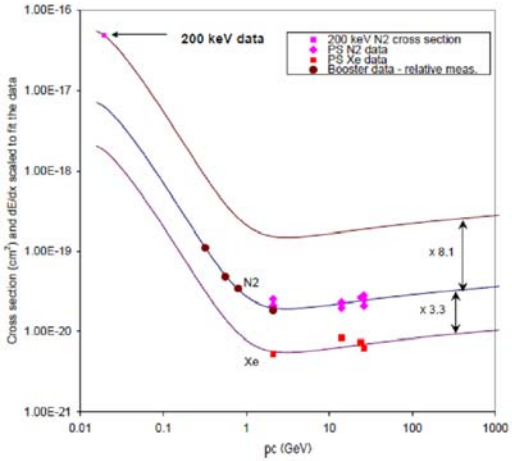
beam induced fluorescence (BIF)



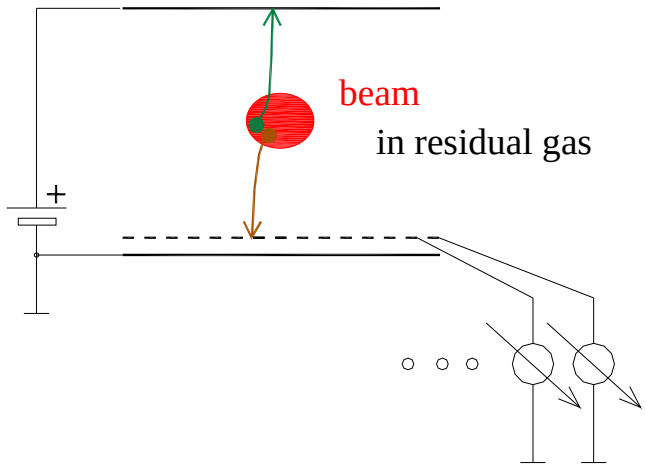
picture from Forck, JUAS2009



- detectors — Becker, DIPAC11, http://accelconf.web.cern.ch/AccelConf/DIPAC2011/papers/weod01.pdf
  - ICCD or EMCCD — Becker et al., BIW08, http://www-bd.gsi.de/uploads/paper/TUPTPF054.pdf; Jung, DIPAC99, http://accelconf.web.cern.ch/AccelConf/d99/papers/CT12.pdf
  - multichannel PMT — Plum et al., LHC Emittance Workshop (2000), see below; Dietrich et al., EPAC08, http://accelconf.web.cern.ch/AccelConf/e08/papers/tupc022.pdf
  - scanning PMT — Rezzonico et al., Rev. Sci. Instrum. 67(1996)1246-8; Joho et al., PAC1985 http://accelconf.web.cern.ch/AccelConf/p85/PDF/PAC1985_2666.PDF
  - TV camera — Chamberlin et al. PAC1981 http://accelconf.web.cern.ch/AccelConf/p81/PDF/PAC1981_2347.PDF
- cross sections energy dependent (Bethe-Bloch) → easier at low energy
  Plum et al., Nuclear Instruments and Methods in Physics Research A 492 (2002) 74–90
  Plum et al., LHC Emittance Workshop (2000),
  http://emittanceworkshop.web.cern.ch/EmittanceWorkshop/Slides%20M.Plum/GSPM.pdf (link not valid)
- spectral components — Becker et al., DIPAC09, http://accelconf.web.cern.ch/AccelConf/d09/papers/tupb02.pdf
  BIW10, http://accelconf.web.cern.ch/AccelConf/BIW2010/papers/tupsm020.pdf
  Ausset et al. EPAC02, http://accelconf.web.cern.ch/AccelConf/e02/PAPERS/THPRI066.pdf
- distortion & limited dynamic range by
  background radiation, delayed deexcitation (in helium gas) & reflections



residual gas ions (with external fields)



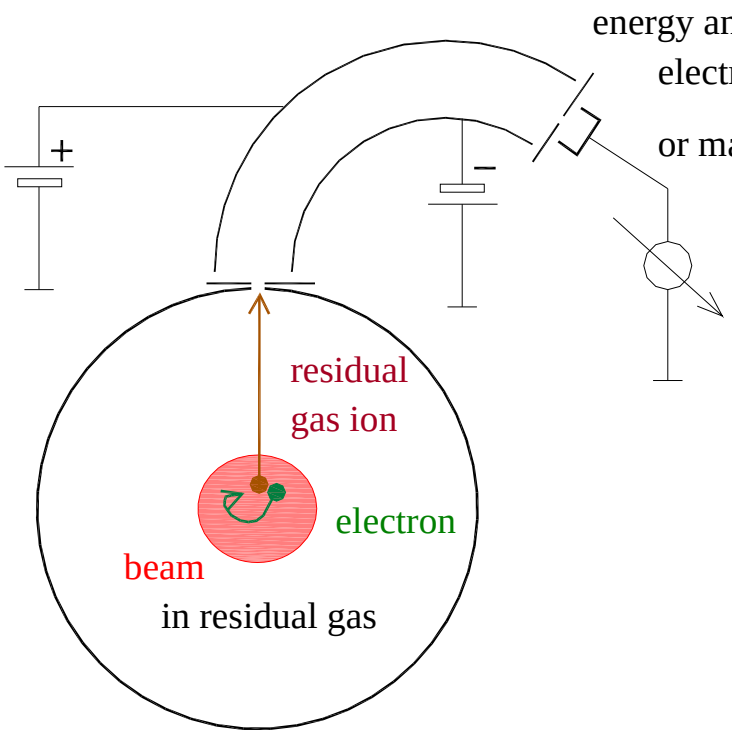
1D-detector for residual gas ions
(strip pattern & current measurement
or MCP + CCD or ...)

- profile broadened by beam space charge (improved by vertical magnetic field & detecting electrons)
- non-destructive but eventual beam space charge neutralisation disturbed by external electric field
- sensitive

Kamerdzhiev, DIPAC09, http://accelconf.web.cern.ch/AccelConf/d09/papers/tupb12.pdf

DeLuca, PAC69, http://accelconf.web.cern.ch/AccelConf/p69/PDF/PAC1969_0813.PDF

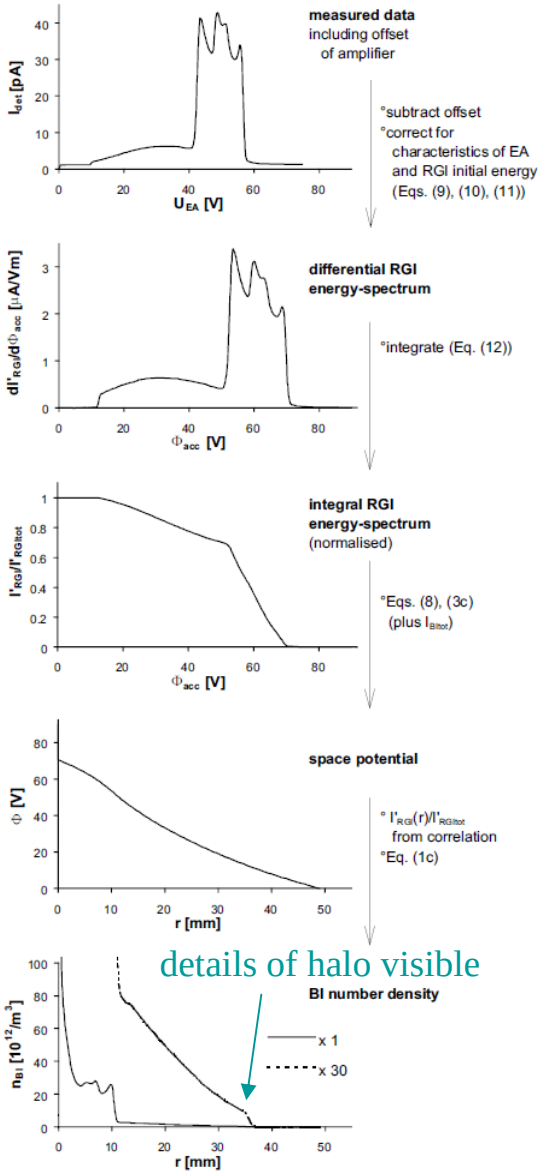
residual gas ions (with beam space charge field)



energy analyser

electrostatic Dölling et al., DIPAC99, LINAC96, ICIS97: Rev. Sci. Instrum.69 (1998) 1094-9

or magnetic Arauzo et al., NIMA 461 (2001) 111–114

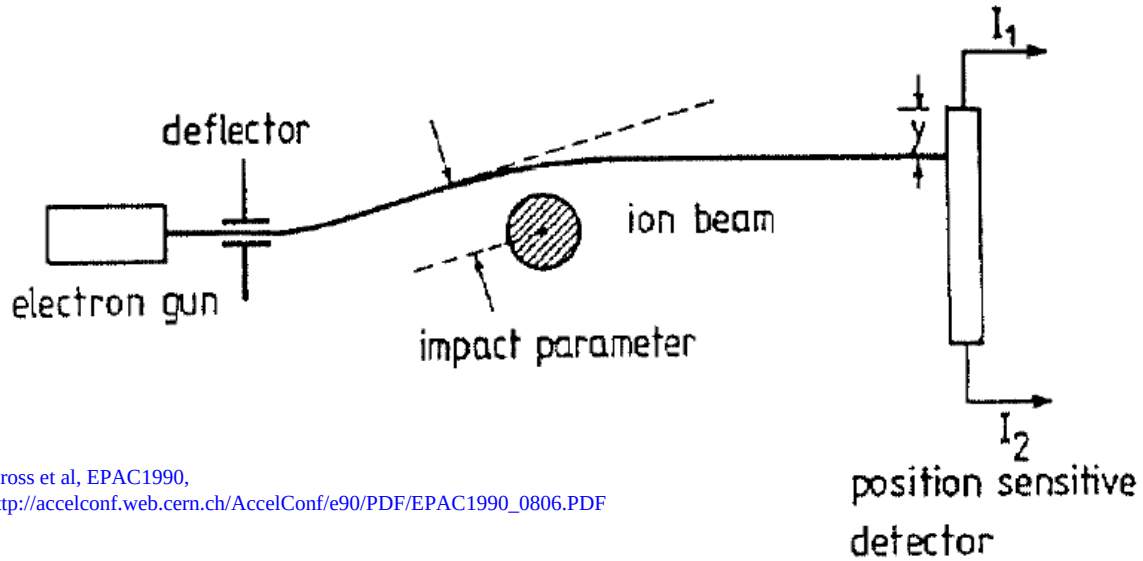


details of halo visible

- beam ion distribution creates residual gas ions & accelerating potential
- a positive beam potential depth of at least a few V is required
- analytical solution for charge density distribution of round non-neutralized beams
- non-destructive
- distortion of signal by charging of surfaces & stray magnetic fields

Dölling, DIPAC99,
http://accelconf.web.cern.ch/AccelConf/d99/papers/CT02.pdf

electron beam probe



Gross et al, EPAC1990,
http://accelconf.web.cern.ch/AccelConf/e90/PDF/EPAC1990_0806.PDF

„re-invented“ several times:

Garscadden et al., J. Electron. Contr. 9 (1960) 473

Harp et al., Rev. Sci. Instrum. 36 (1965) 960

Shiloh et al., Rev. Sci. Instrum., 54 (1983) 46

Shestak et al., Triumf Design Note TRI-DN-87-36 (1987)

Prabir et al., Rev. Sci. Instrum. 76 (2005) 023301

and many others

- beam space charge potential deflects transversal electron beam
- deflection depending on impact parameter is measured
- analytical solution for charge density distribution of round beams (Abel inversion) Stallings, J. Appl. Phys. **42** (1971) 2831
- a positive beam potential depth of at least a few V is required
- non-destructive
- charging of surfaces and stray magnetic fields can be problematic
  - → higher electron energy (→ less sensitivity) e. g. 75 keV Aleksandrov et al., DIPAC09, http://accelconf.web.cern.ch/AccelConf/d09/papers/tuoa03.pdf
  - → ions Bosser et al., CERN/PS 2000-071, http://cdsweb.cern.ch/record/478698/files/ps-2000-071.ps.gz

18 min

C) diagnostics along the beam path

most examples from PSI's high power proton facility

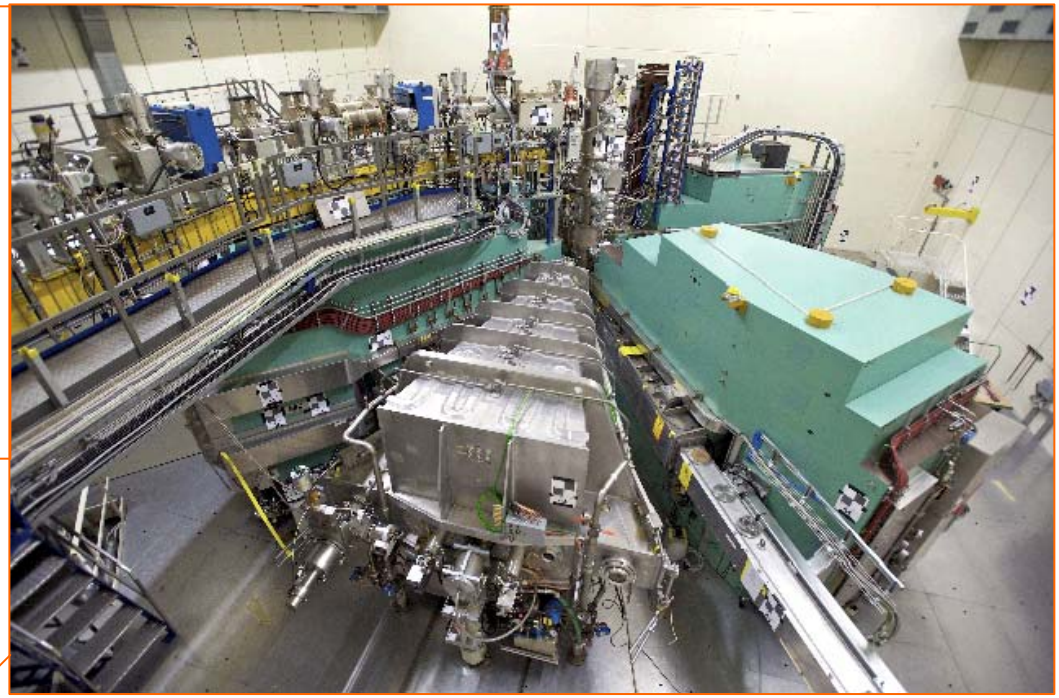
+ external examples

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

Injector 2 cyclotron

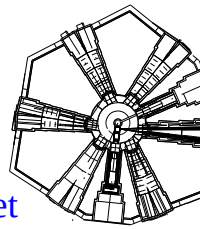
- high beam current
- separated sectors
- normal conducting

→ some space for diagnostics



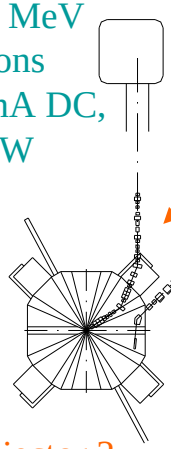
spallation neutron source SINQ since 1998

(liquid Pb-Bi target during 2006)

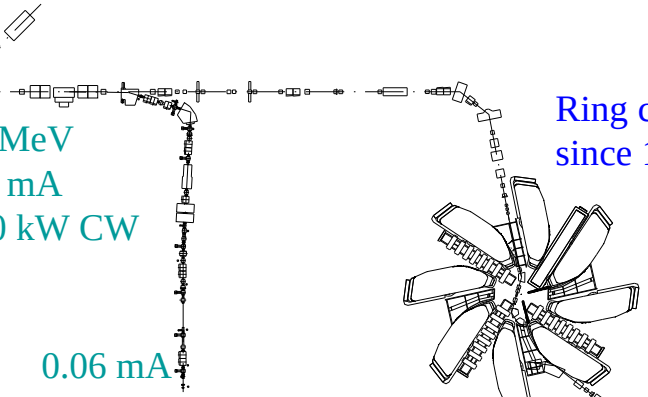


581 MeV
1.5 mA
0.9 MW

0.87 MeV
protons
10 mA DC,
10 kW



radial probe



72 MeV
2.2 mA
160 kW CW

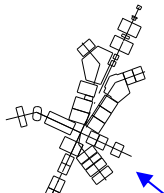
Injector 2 cyclotron

0.06 mA

isotope production

Ring cyclotron since 1974

590 MeV
2.2 mA
1.3 MW
CW (50MHz)



meson production targets

~4 s pulses to UCN every 400 s from 2011

ion source & injection line:

matching the beam core to the cyclotron acceptance

beam position, profile, current

60 keV LEBT, 2 solenoids
~fully space-charge compensated
27 mA extracted
H_2^+, H_3^+ stopped at collimators

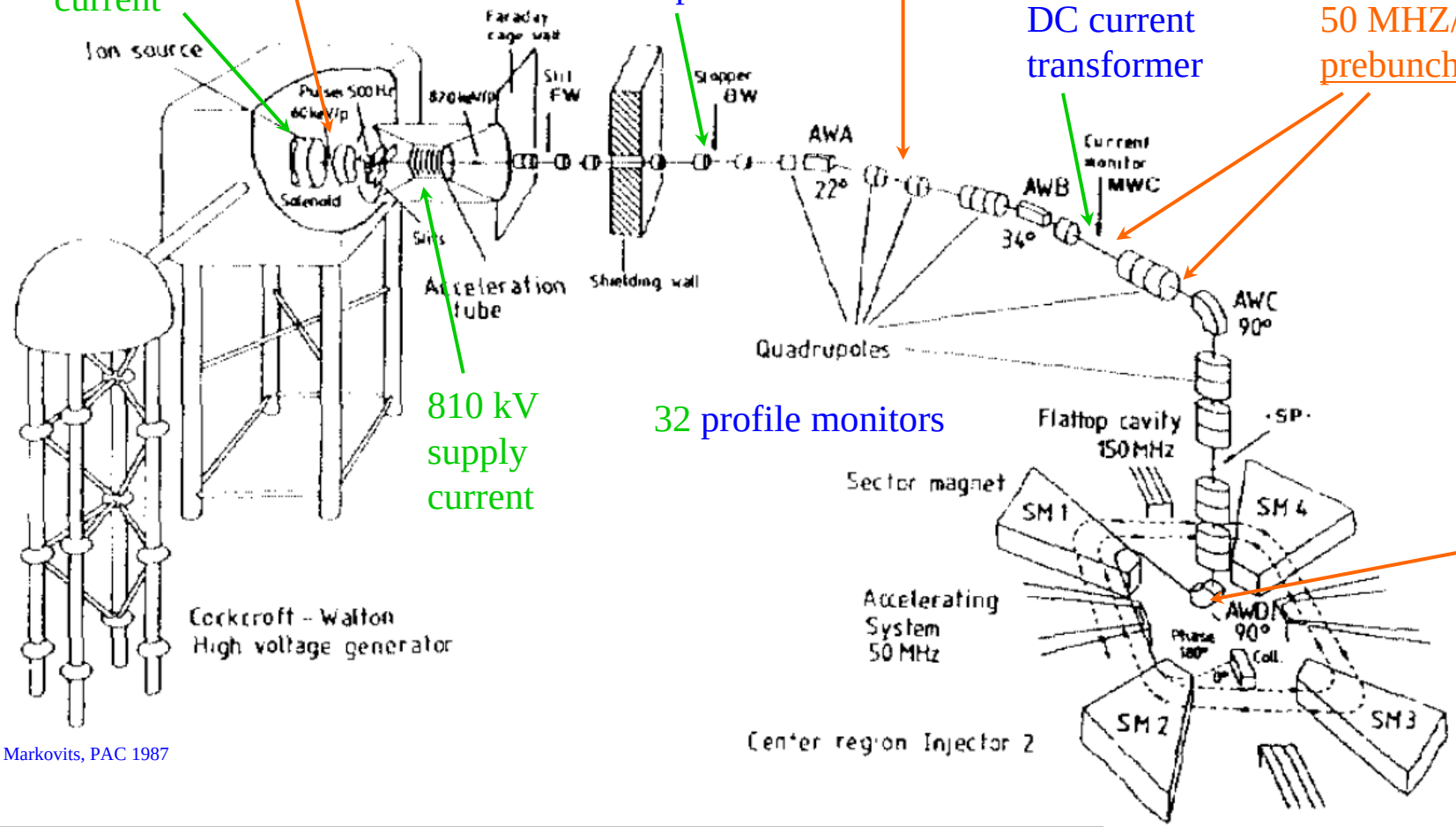
870 keV transport, magnetic quadrupoles
~50%(?) space-charge compensated
~10.6 mA protons at entrance
~1.6 mA cut at ~30 (fixed) collimators → beam shaping

60 kV supply current

Faraday cup

DC current transformer

50 MHZ/150 MHz prebunchers



810 kV supply current

32 profile monitors

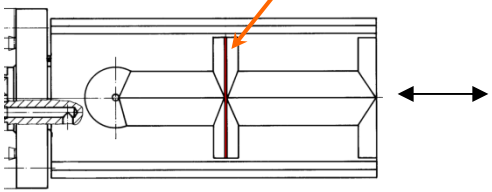
~9 mA protons at exit

Markovits, PAC 1987

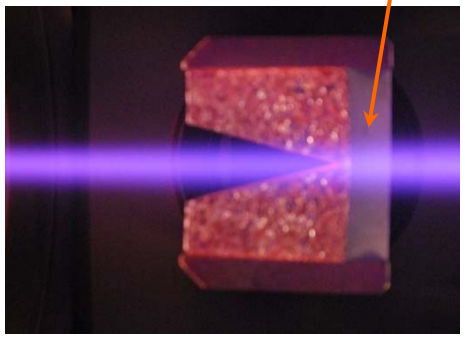
profile monitors

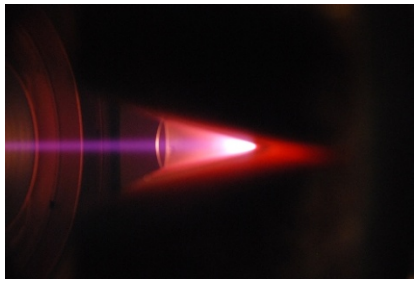
calorimetric slit scanner
(at 60 keV, destructive)

Olivo, CYC87 p. 519



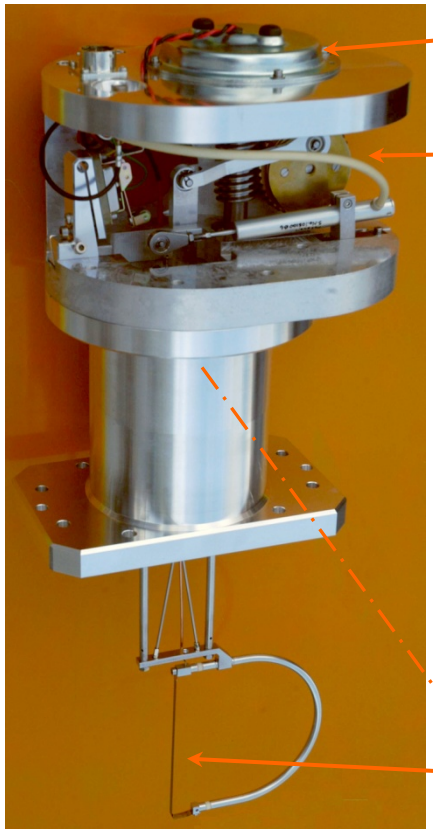
- internal cooled copper block behind vertical slit
- measurement of water in-/outlet temperatures





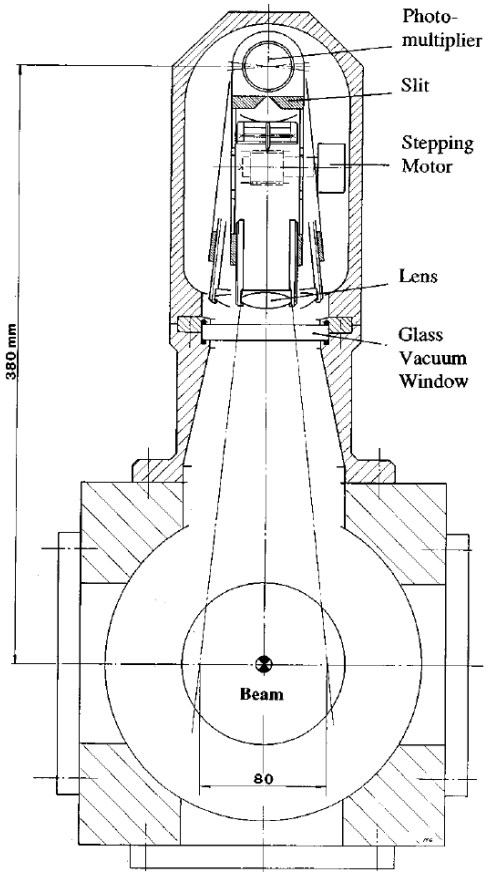
wire scanner
(870 keV 11 mA
up to 20% DC)

Rezzonico, CYC87 p. 457



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

PMT and lens scanned

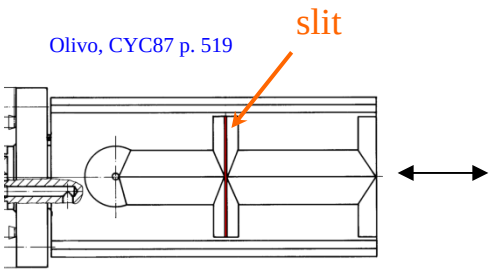


profile monitors

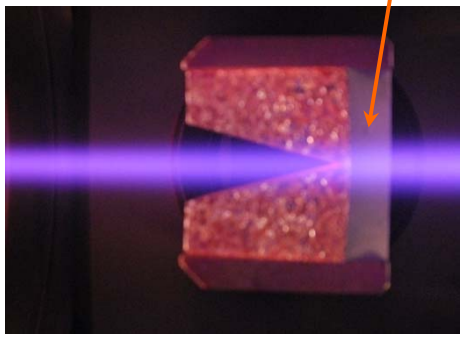
for high beam power

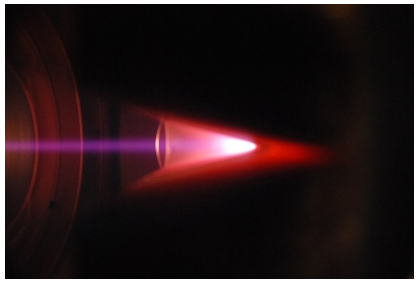
calorimetric slit scanner
(at 60 keV, destructive)

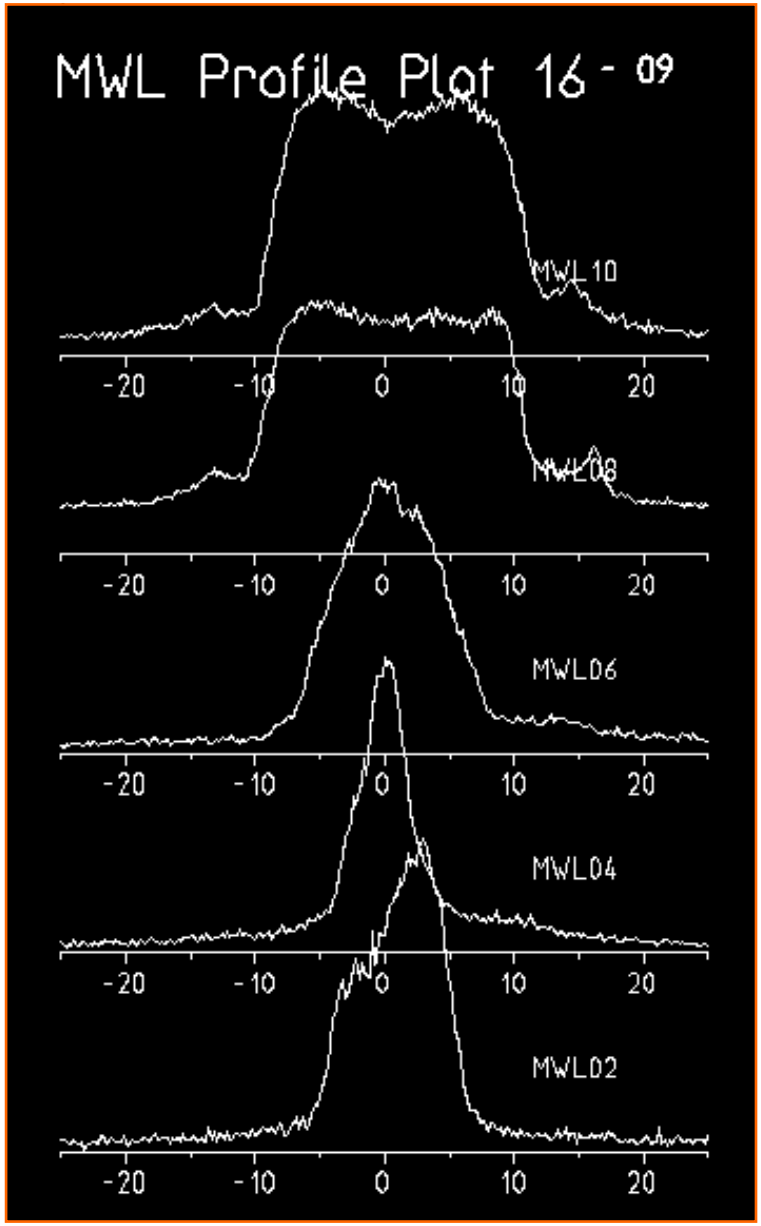
Olivo, CYC87 p. 519



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

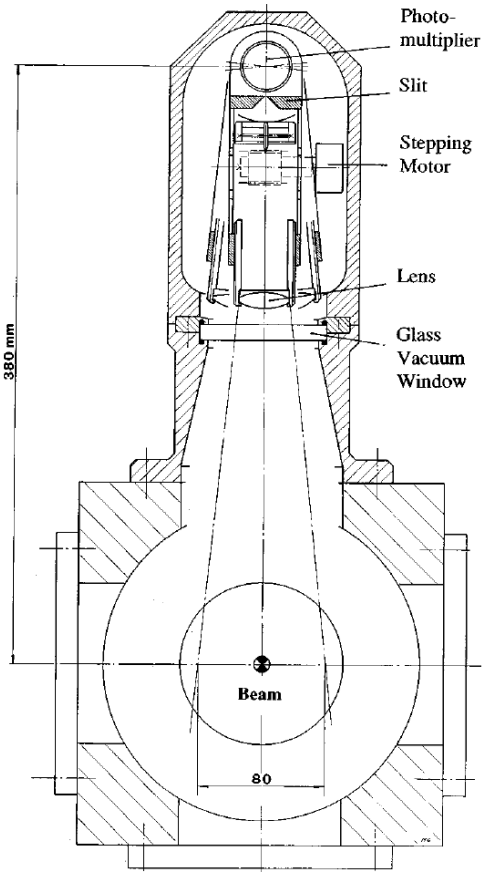






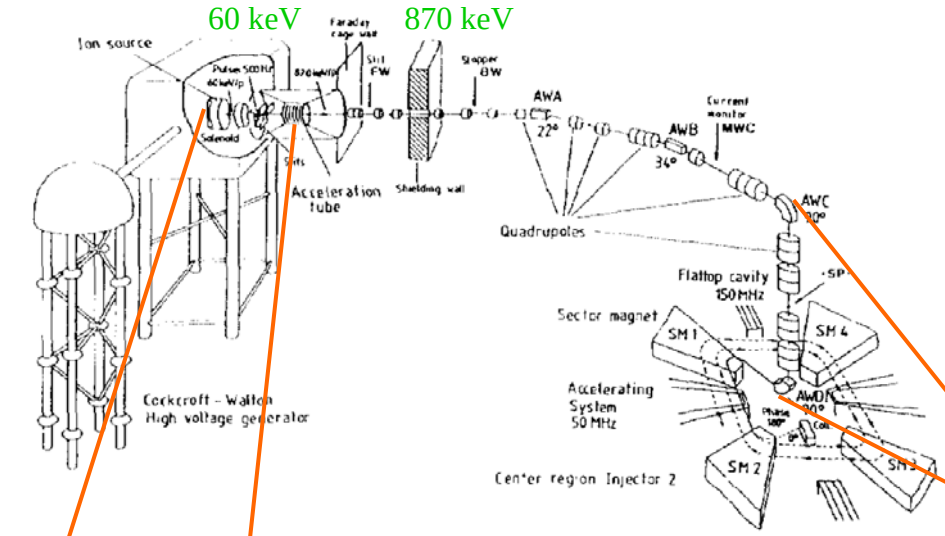
beam induced fluorescence monitor
(870 keV full beam non-destructive)

PMT and lens scanned



emittance from many profiles + Transport fit

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



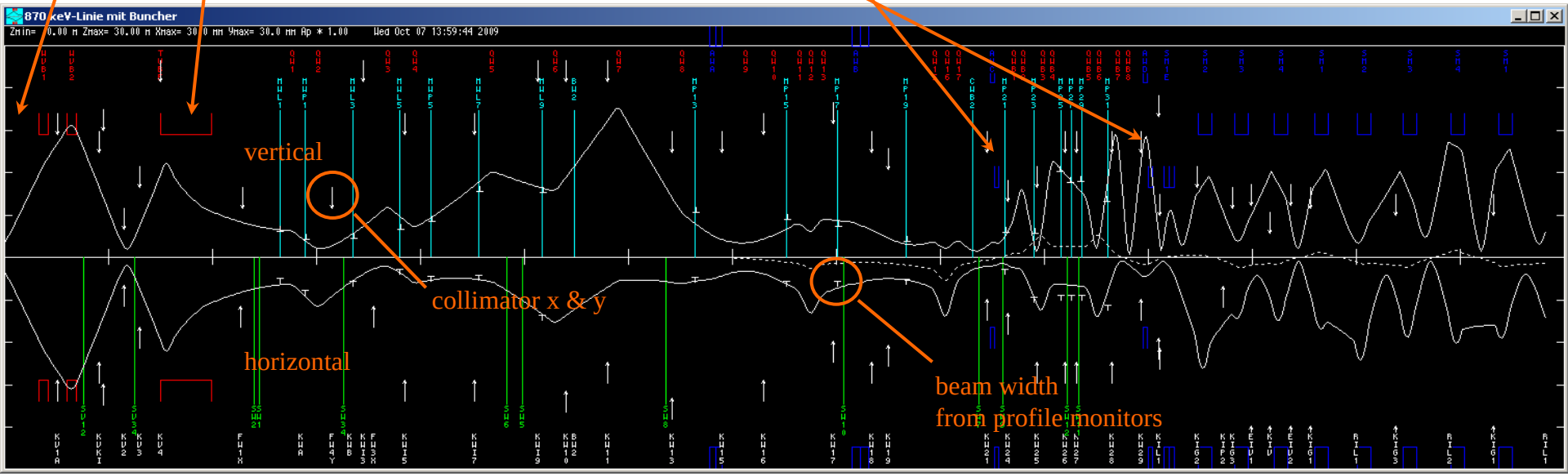
for high beam power (in principle)

profiles measured at 13% DC

space charge neutralisation ~0.5 for good fit

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

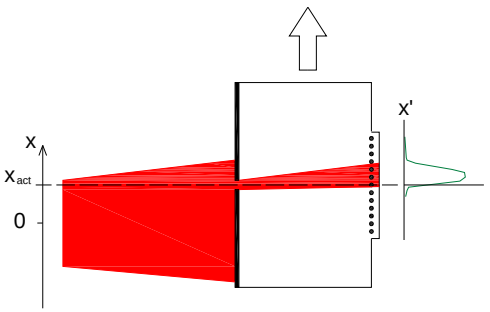
PSI Graphic Transport by U. Rohrer includes linear space charge
download from http://people.web.psi.ch/rohrer_u/index.html

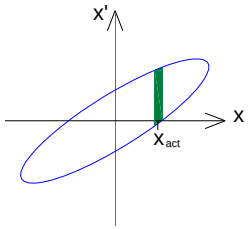


direct emittance measurement

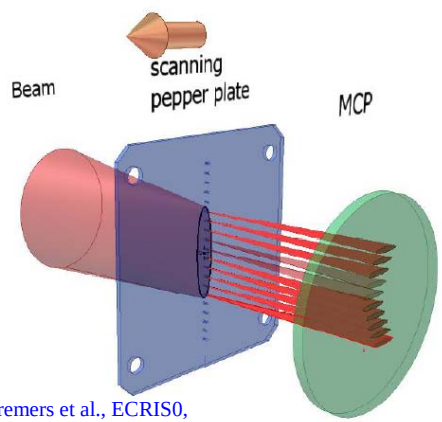
- destructive, limited in beam power & energy

moving slit + grid





moving line of holes + screen



more information than slit + grid

Kremers et al., ECRIS0,
http://accelconf.web.cern.ch/accelconf/ecris08/papers/thco-a02.pdf

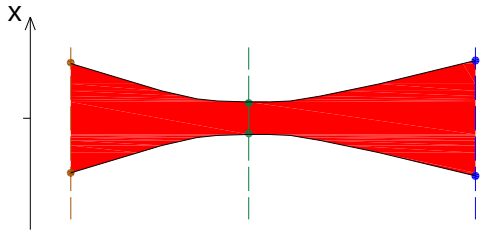
+ many other configurations (pepperpot, Allison-scanner, ...

http://adweb.desy.de/mdi/CARE/Bad_Kreuznach/Reports/ABI-Workshop_Proceedings_all.pdf

profile based emittance measurement

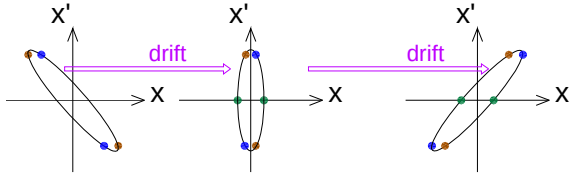
- input only 3 beam widths → less information

3-profile method

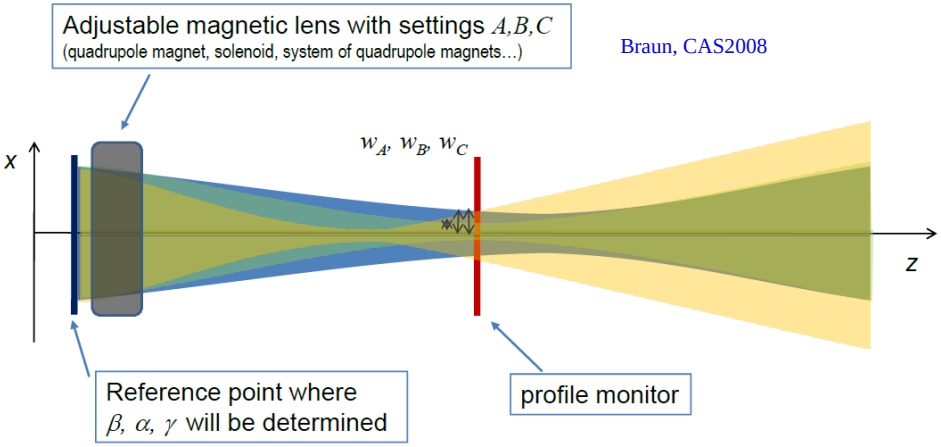


for high beam power

or high energy



Q-pole variation method

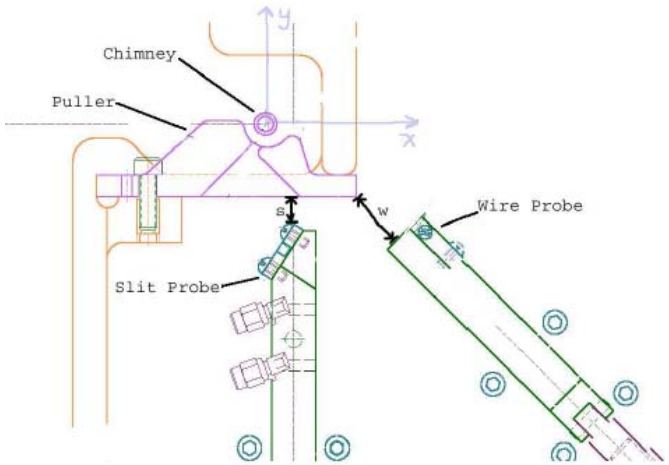


Braun, CAS2008

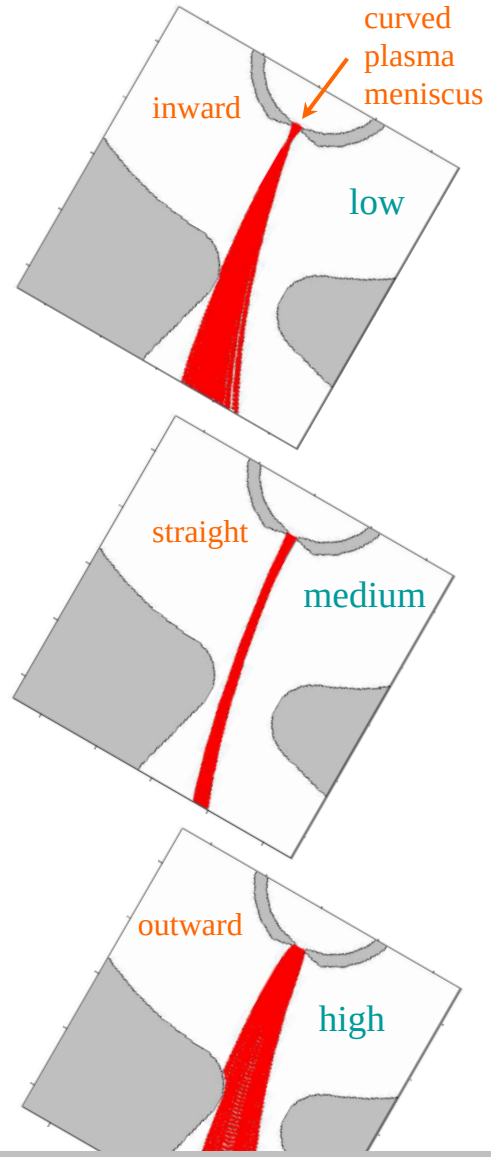
needs „beam gymnastics“ → difficult for high power beams

emittance of internal ion source [MSU]

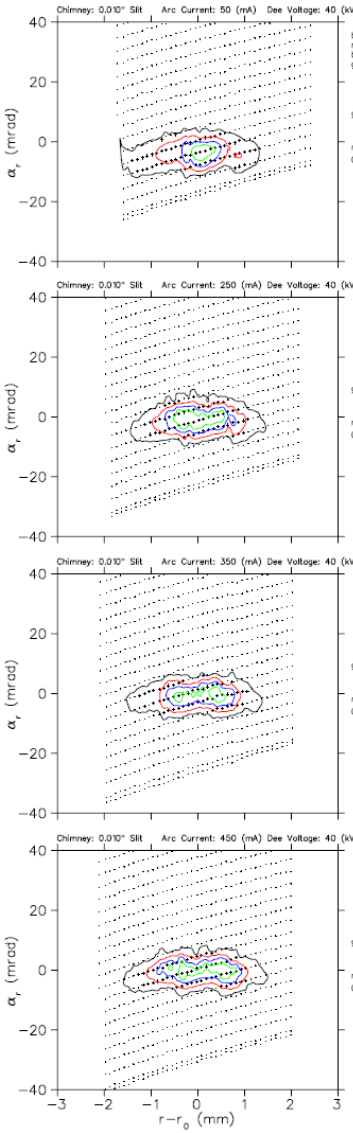
test stand simulates cyclotron center
with internal source
including magnetic field
and fixed puller voltage/geometry:



numerical simulation
for different plasma pressures:



Measurement of radial emittance



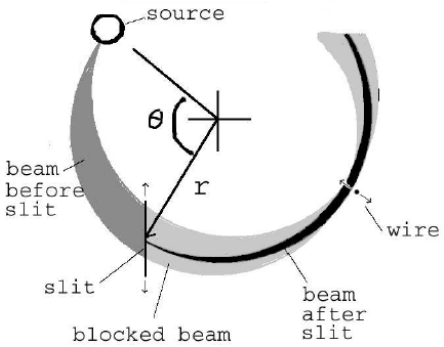
arc 50 mA
beam **52** μA

arc 250 mA
beam **165** μA

arc 350 mA
beam **195** μA

arc 450 mA
beam **227** μA

slit – wire emittance measurement
for radial emittance:



(similar for axial emittance)

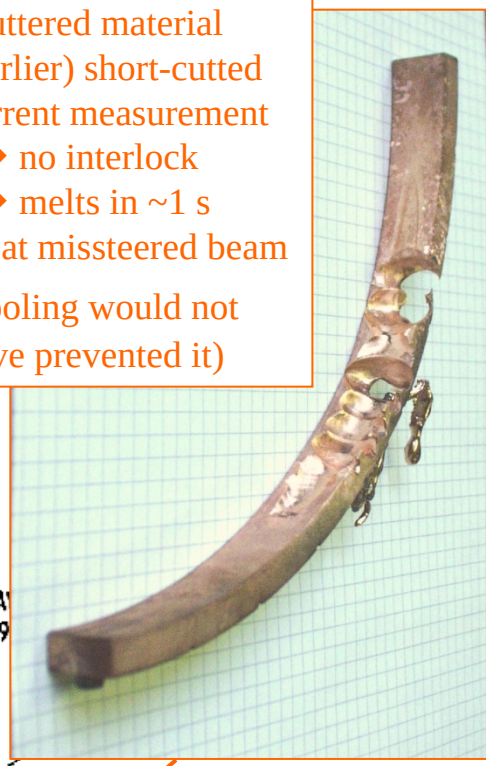
all figures from E. R. Forringer, Dissertation 2004, MSU
http://www.nscl.msu.edu/ourlab/publications/download/Forringer2004_199.pdf

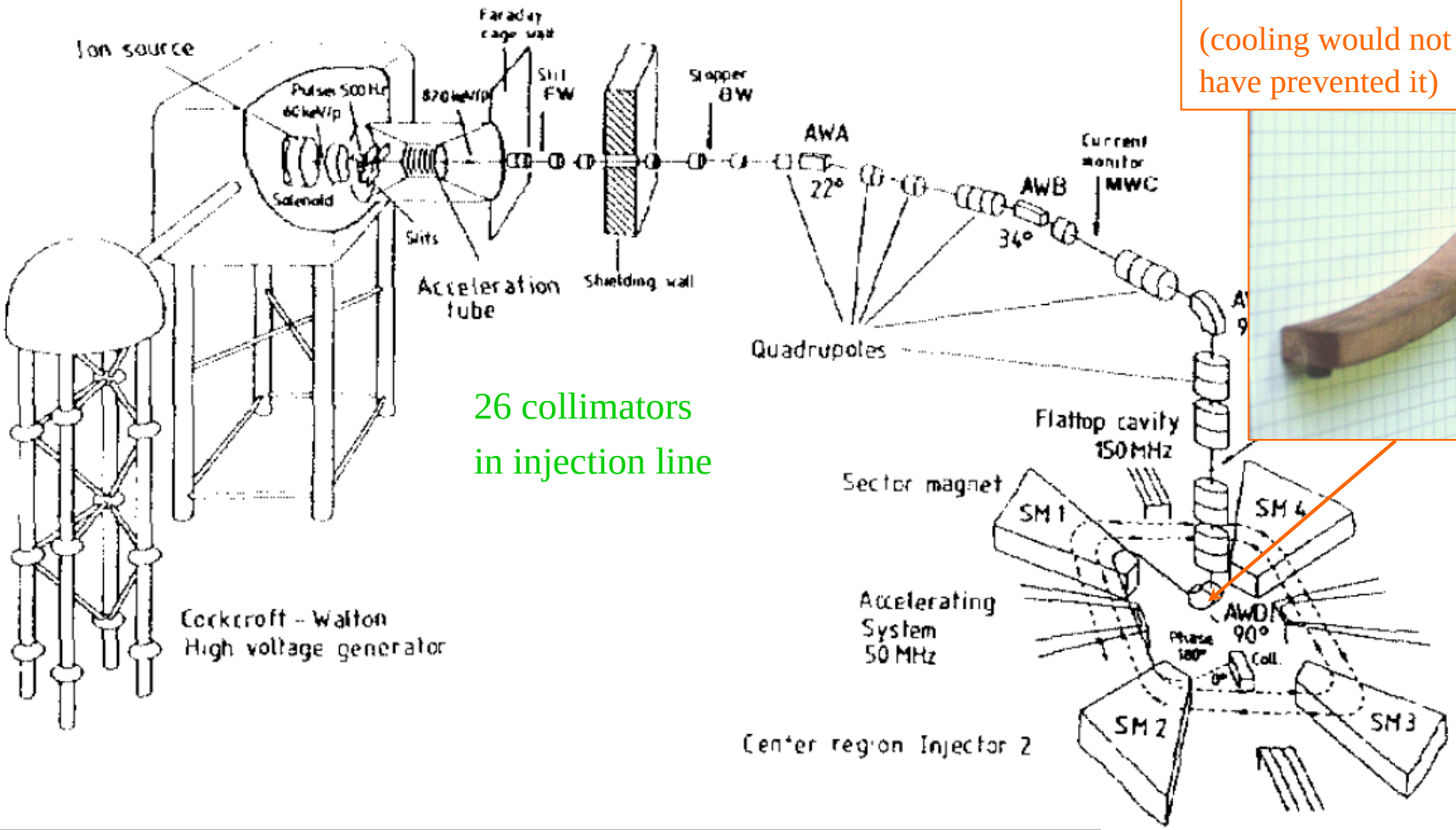
collimators with current readout

- 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)





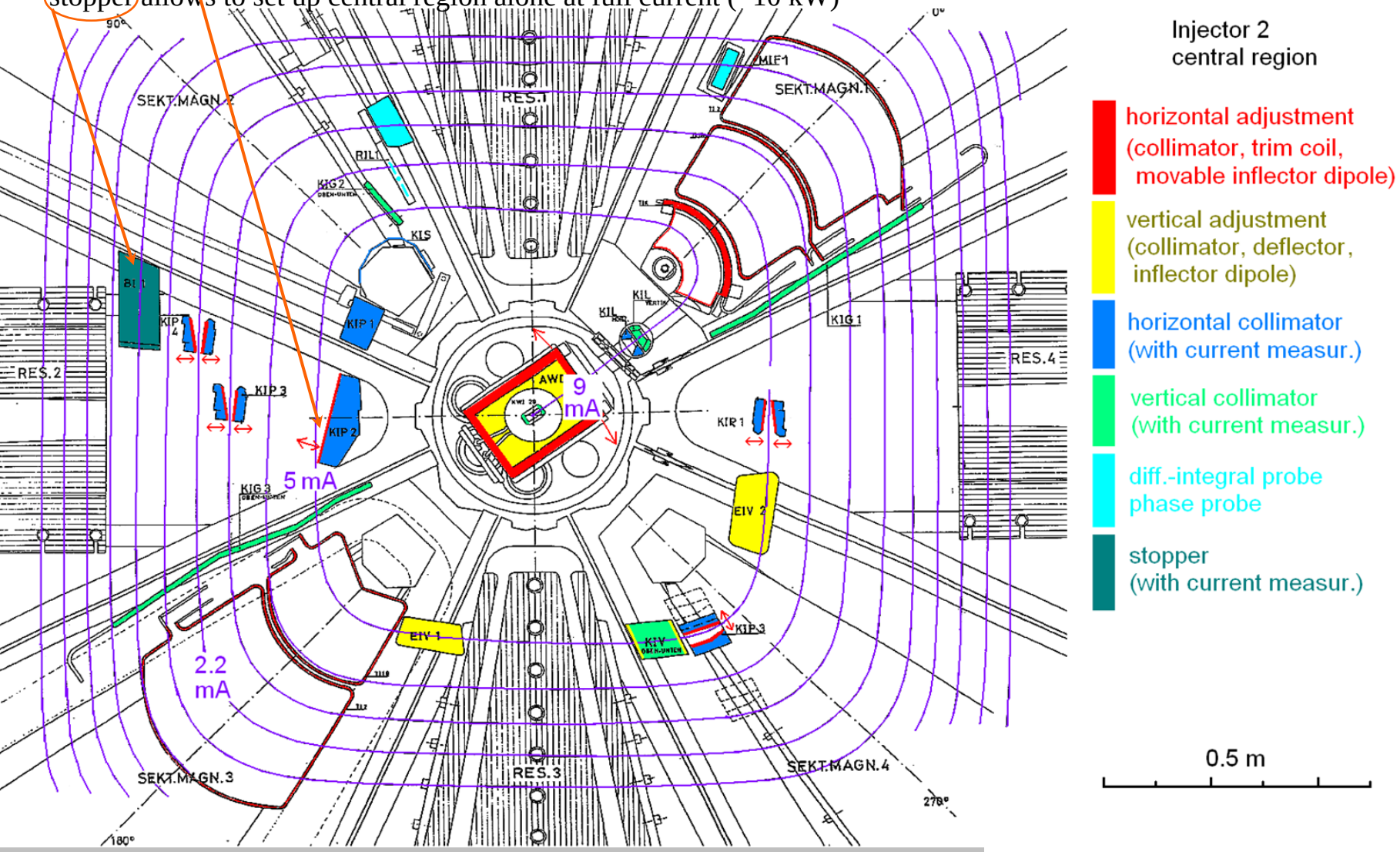
26 collimators
in injection line

injection, central region

beam shaping & betatron oscillation alignment

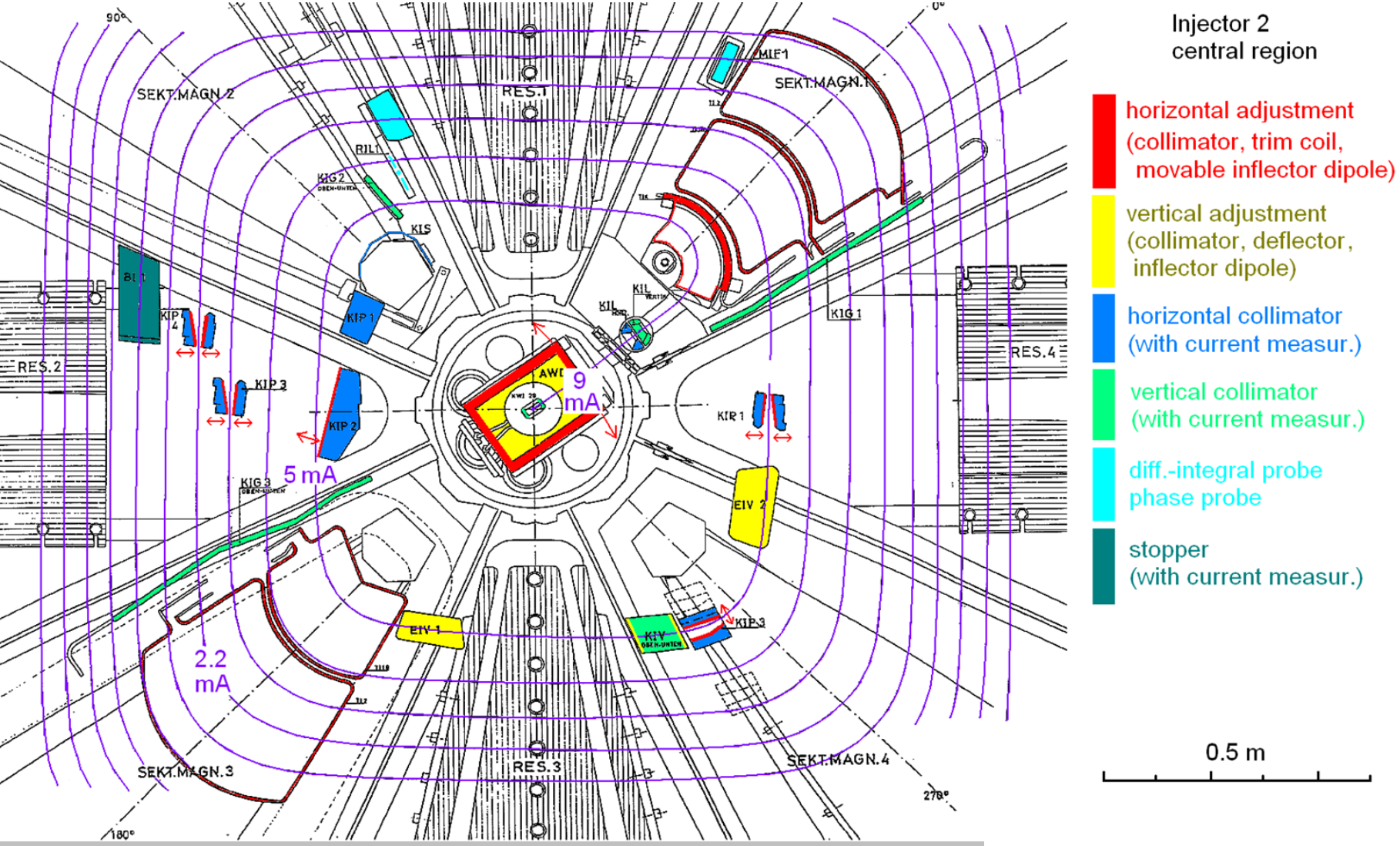
current set & beam shaping

- by cutting into beam with movable cooled collimators with current measurement (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

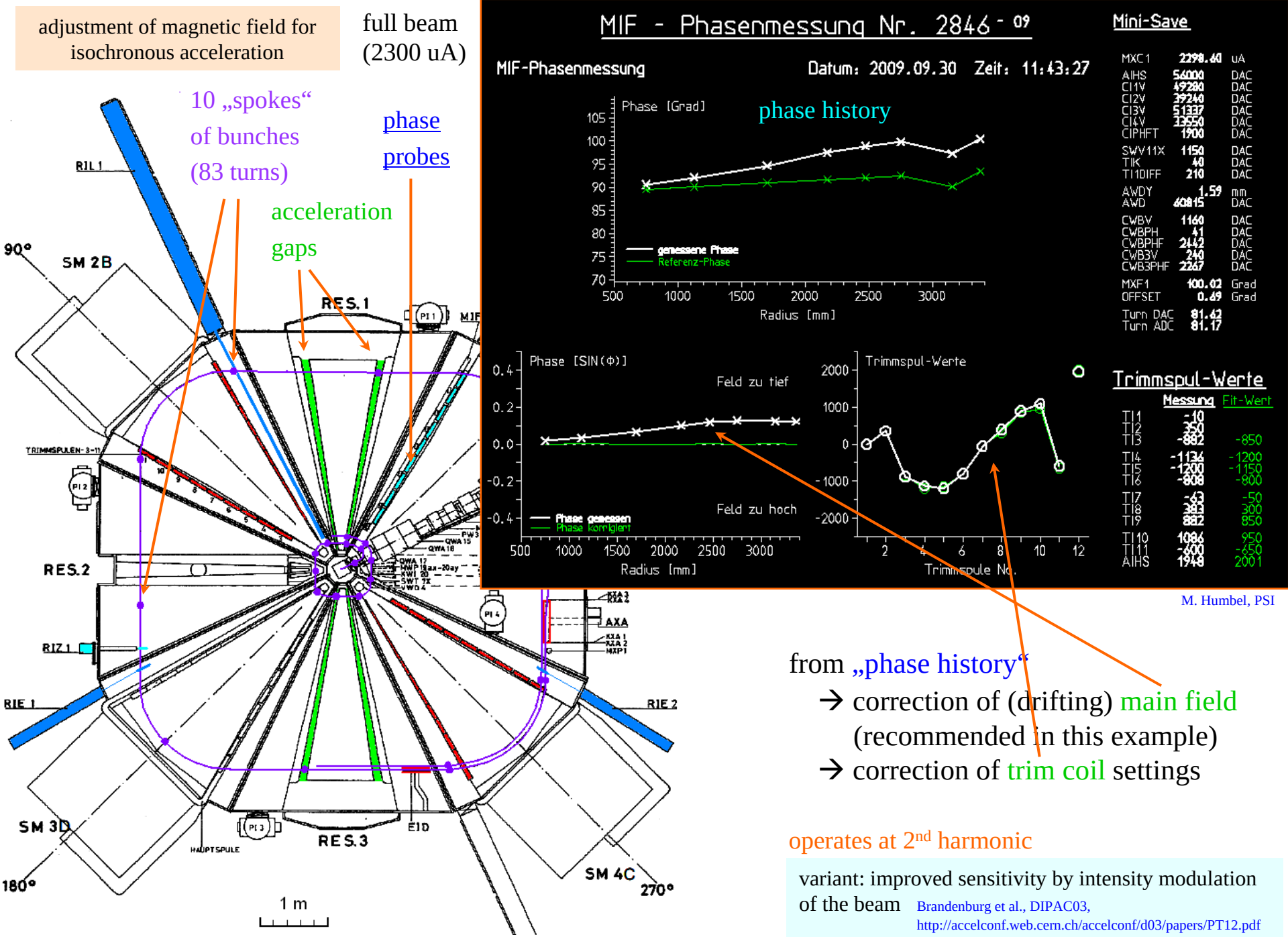


acceleration:

adjustment of magnetic field and RF fields

adjustment of magnetic field for isochronous acceleration

full beam (2300 uA)



M. Humbel, PSI

from „phase history“

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

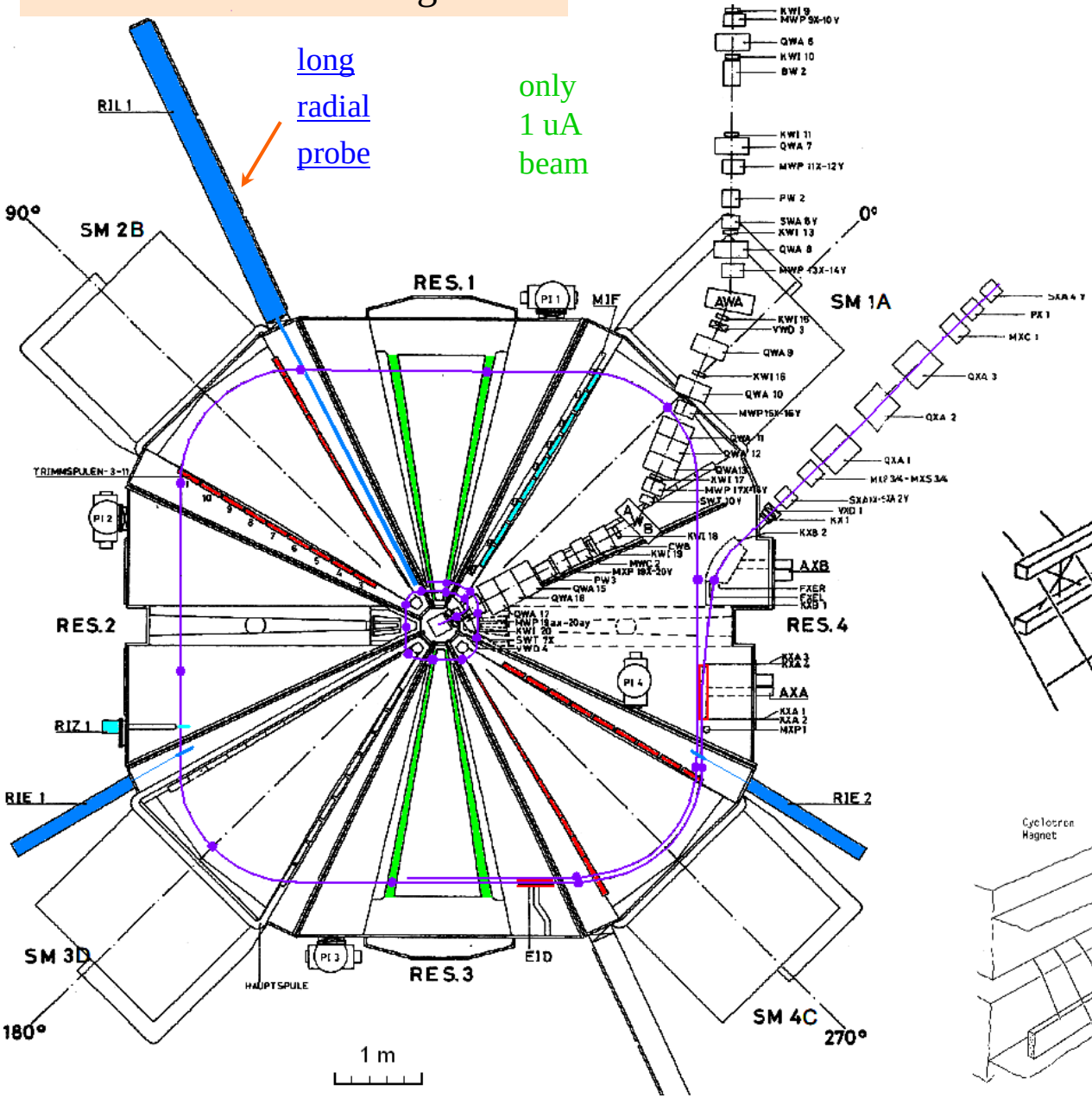
→ correction of trim coil settings

operates at 2nd harmonic

variant: improved sensitivity by intensity modulation of the beam Brandenburg et al., DIPAC03, http://accelconf.web.cern.ch/accelconf/d03/papers/PT12.pdf

beam centering & betatron oscillation alignment

finding the beam and „pulling“ it to greater radii

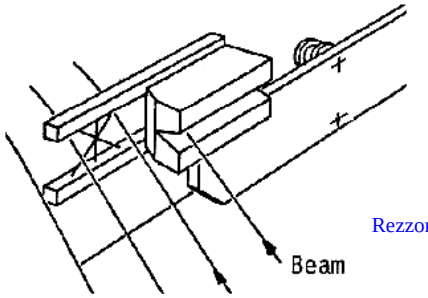


horizontal adjustment (trim coils, electrostatic septum, septum magnet)

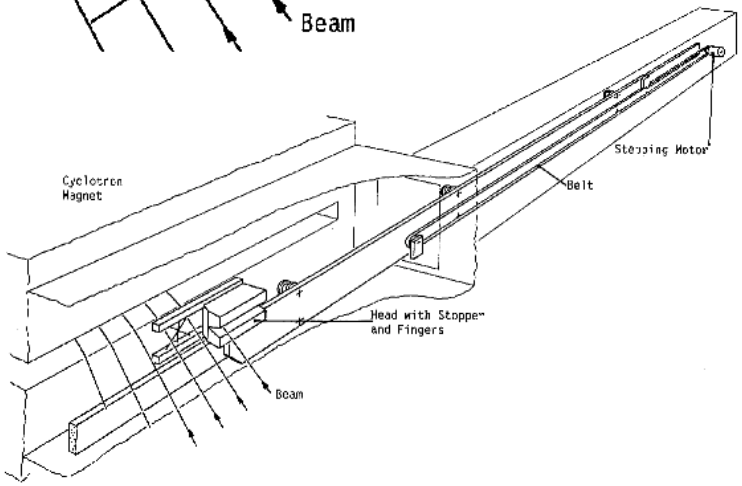
accelerating gaps

phase probes, time structure probe

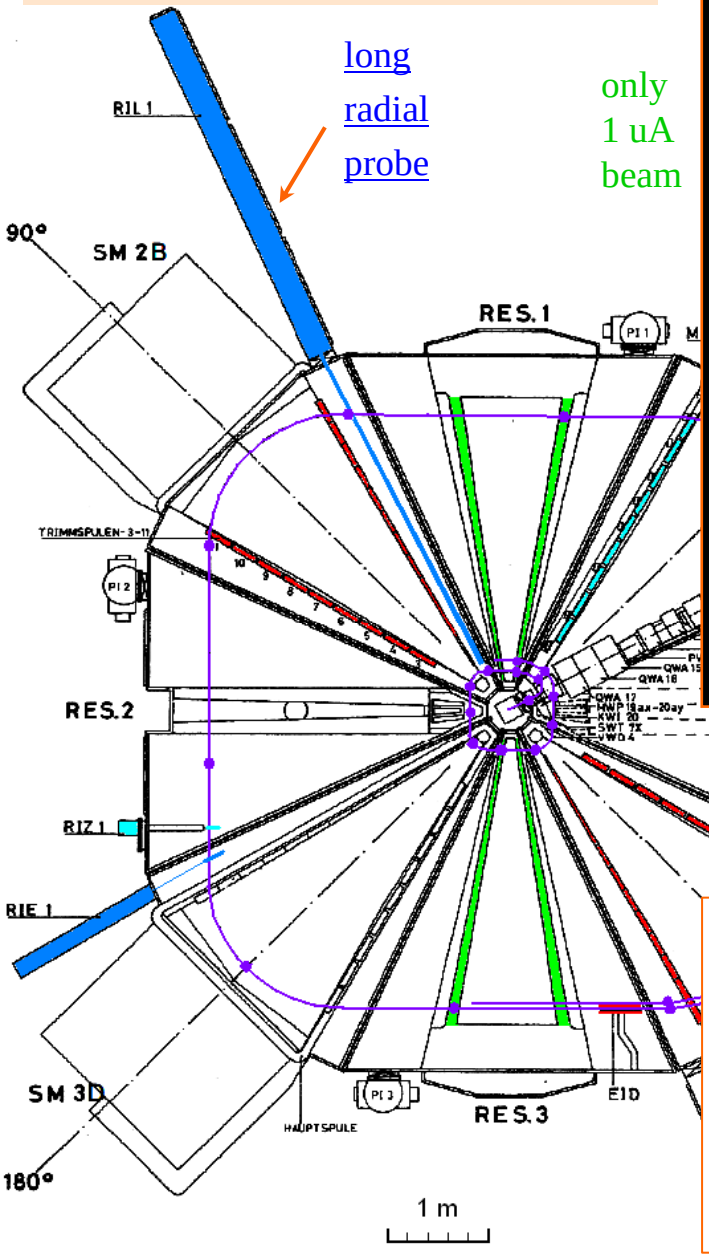
radial probes

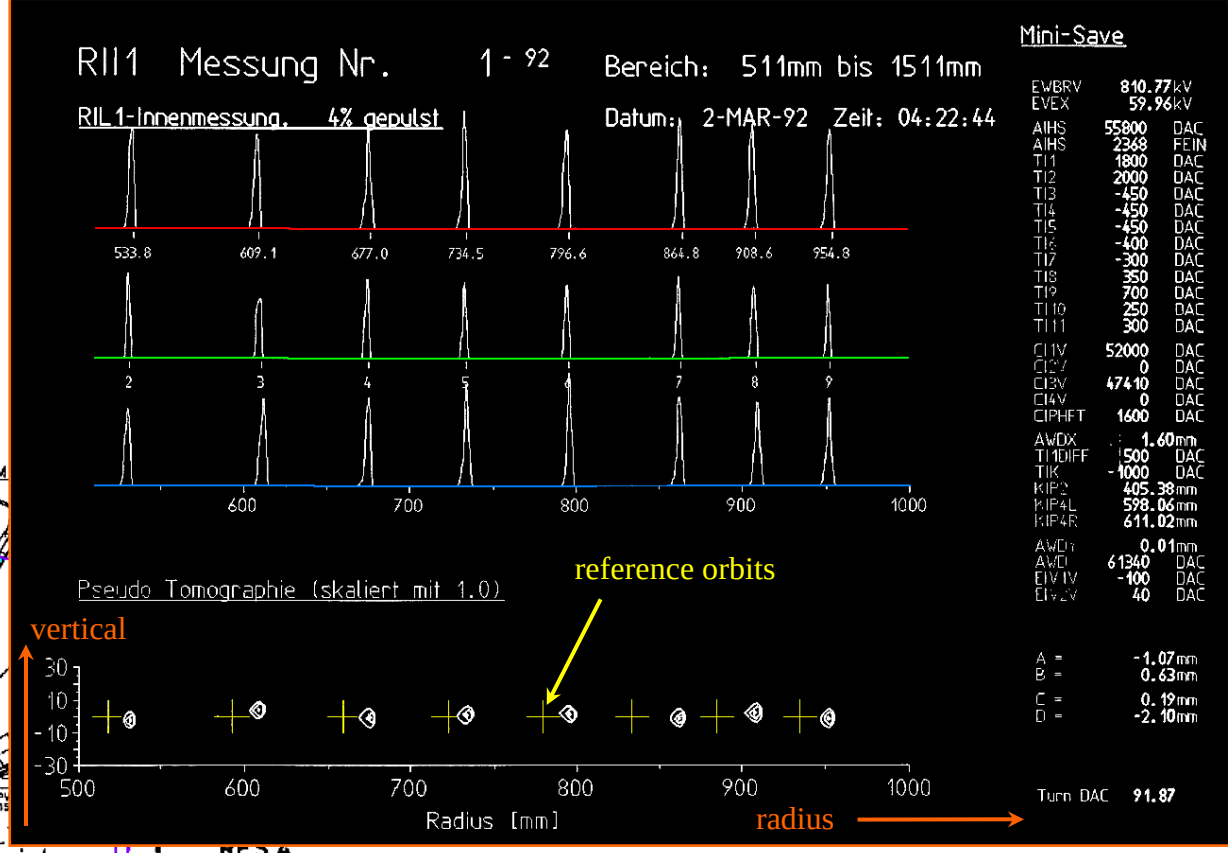


Rezzonico, CYC86, p. 457



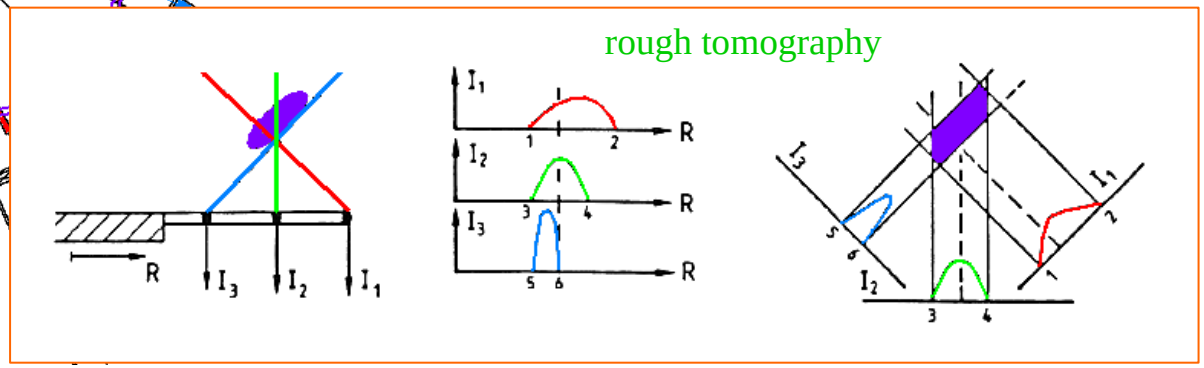
beam centering & betatron oscillation alignment



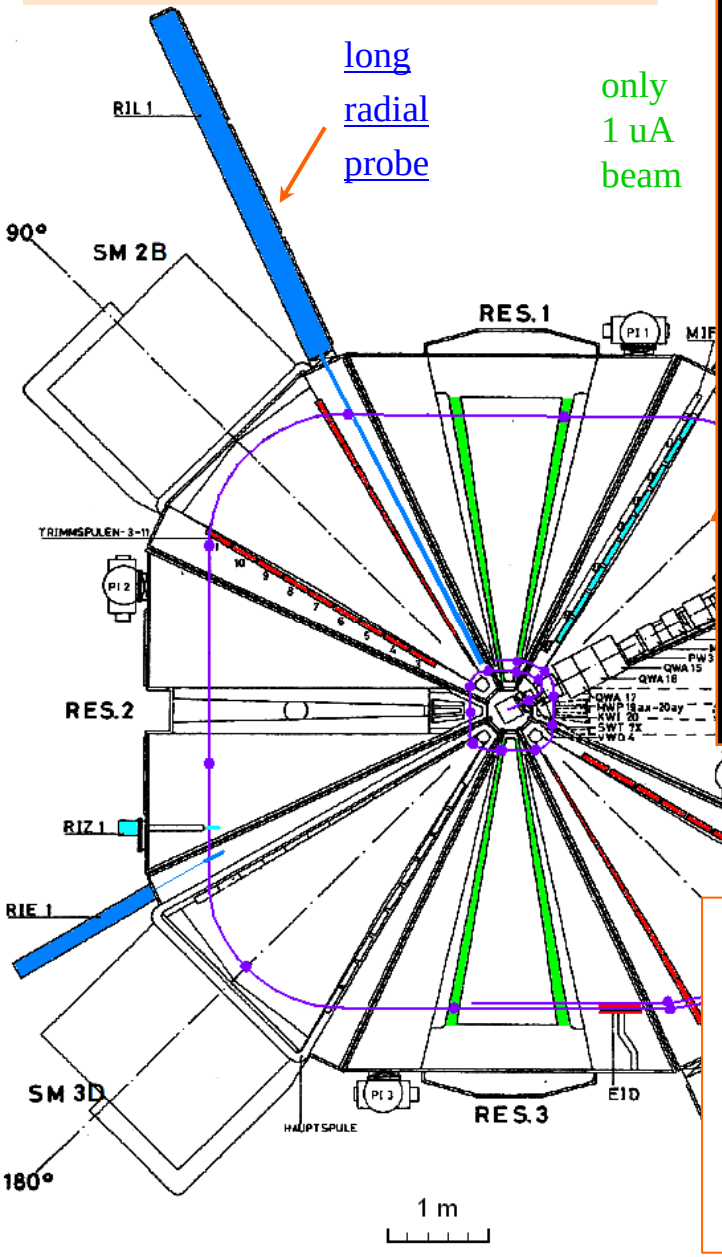


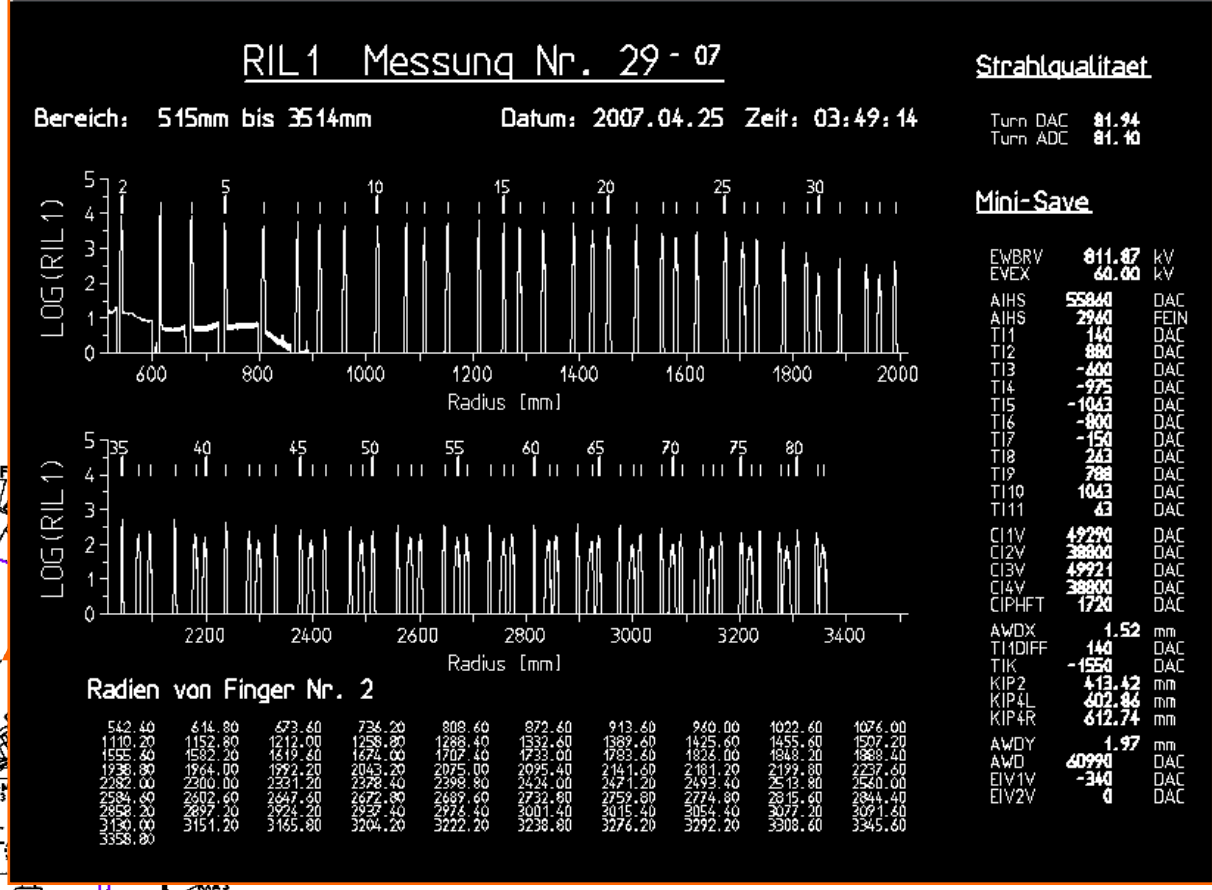
M. Humbel, PSI

intentionally introduced radial betatron oscillations



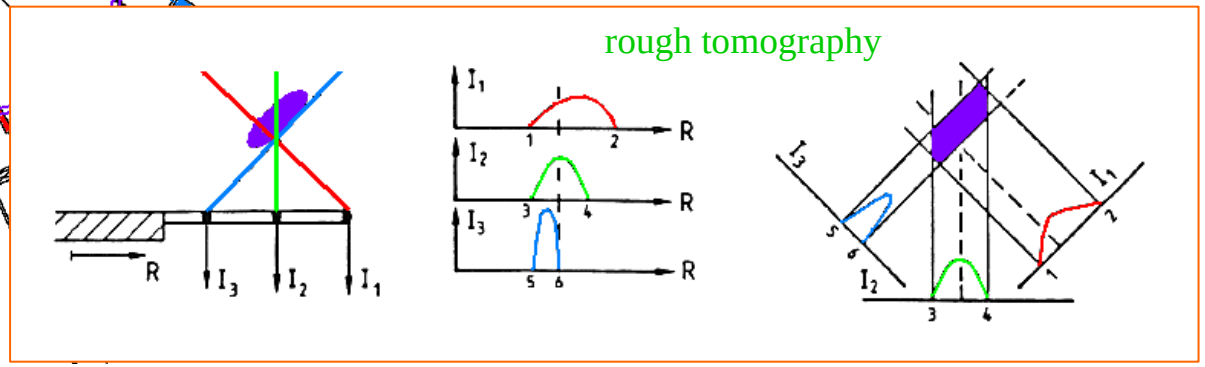
beam centering & betatron oscillation alignment



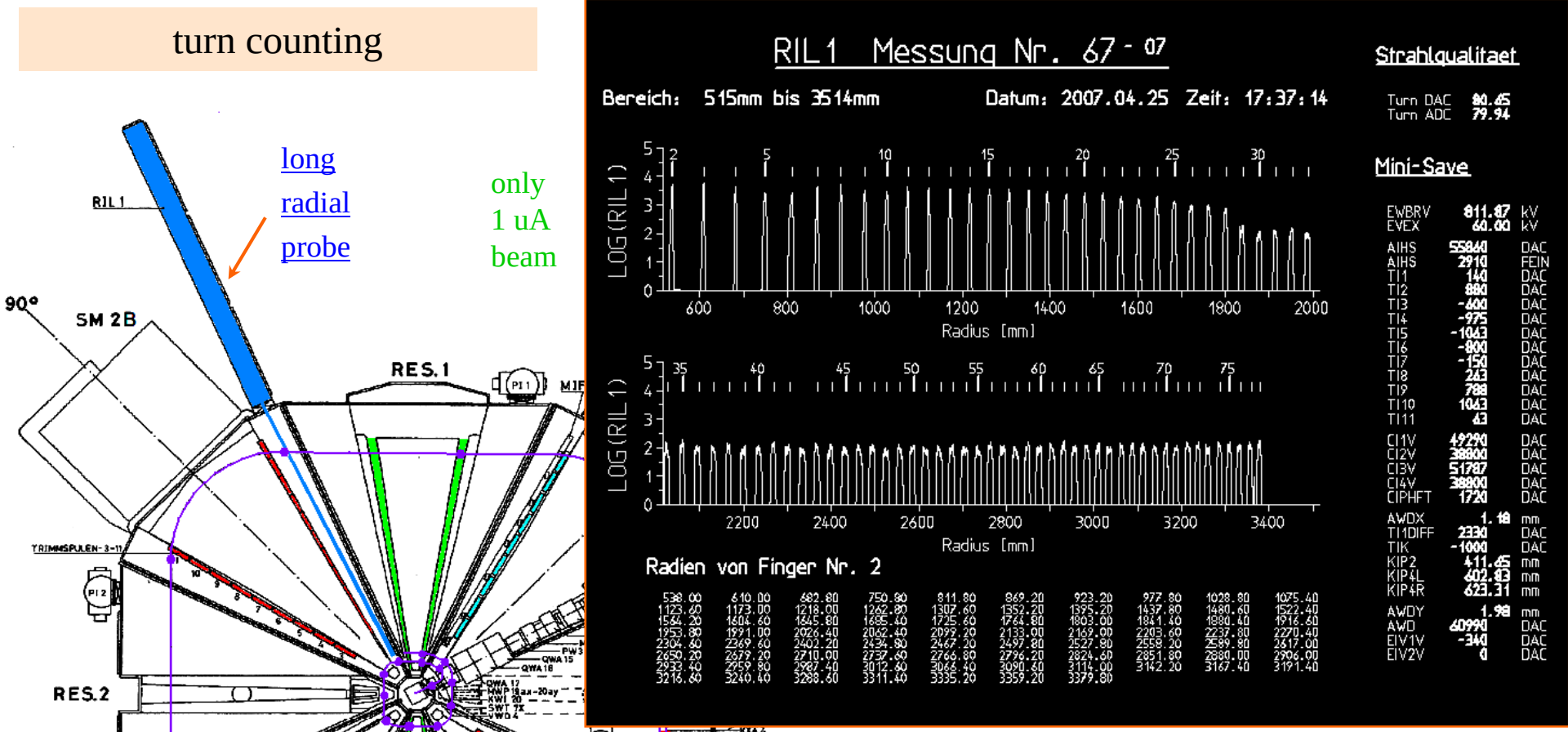


intentionally introduced radial betatron oscillations
(only vertical wire displayed)

rough tomography



turn counting



M. Humbel, PSI

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

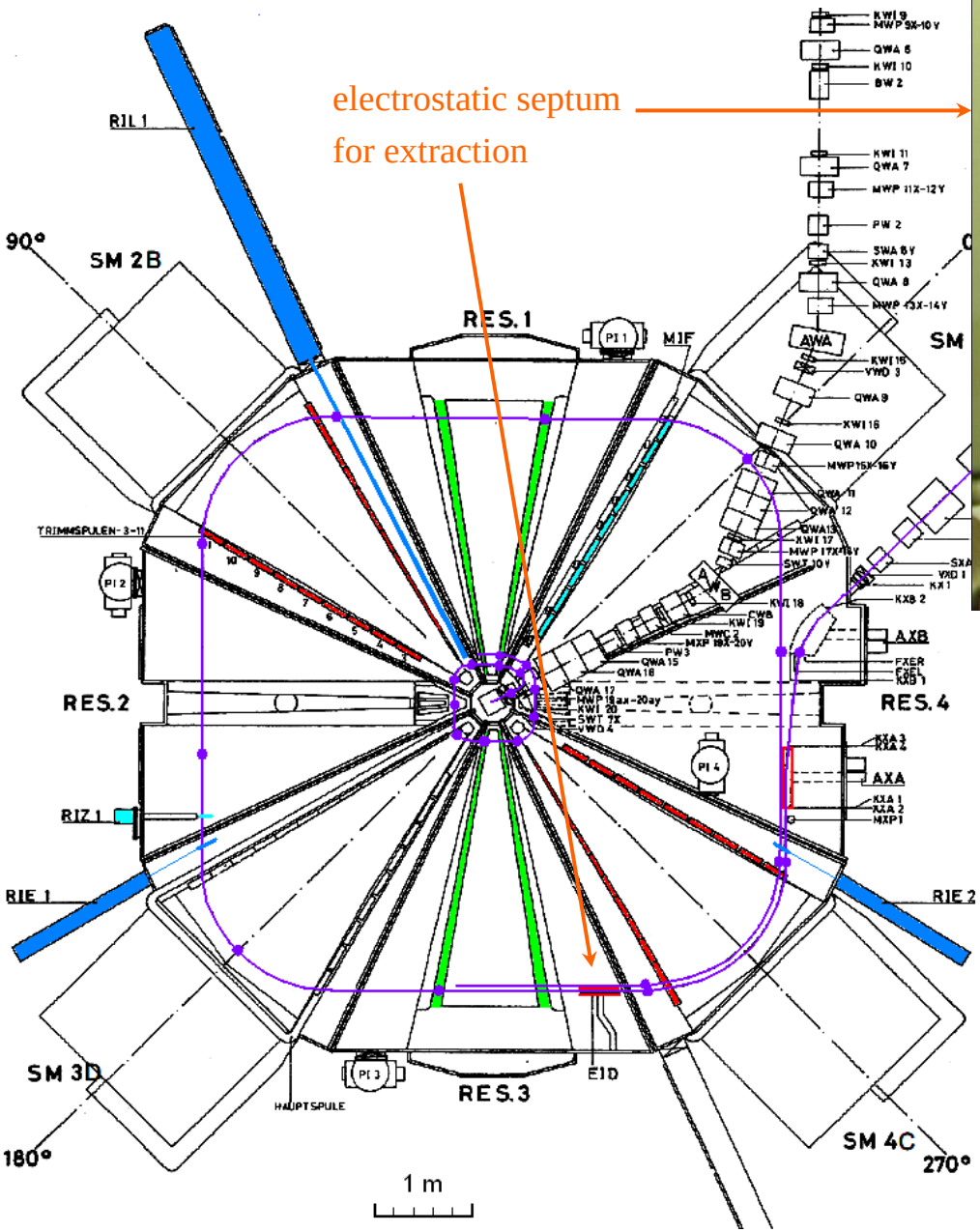
alternative (also for not separated turns):
- measurement of modulated beam
  (maybe from ion source noise)
  with phase probes before and after the cyclotron
- cross correlation → time of flight

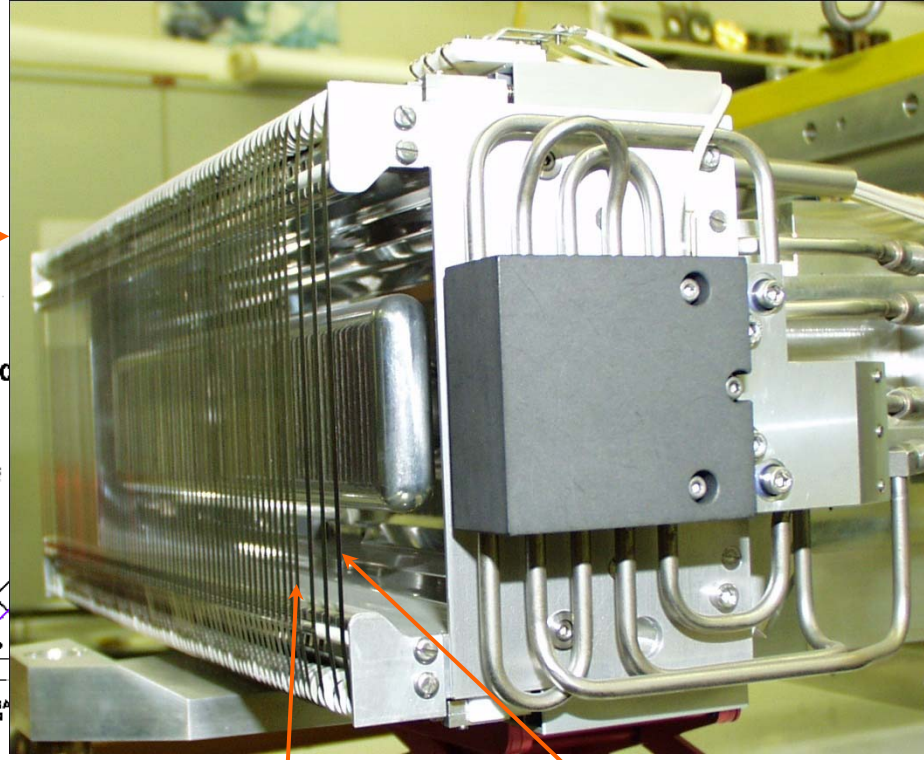
Craddock et al., CYC75, p. 240
Loyer et al., PAC1985, http://accelconf.web.cern.ch/accelconf/p85/PDF/PAC1985_1938.PDF

extraction:

turn separation & efficiency

turn separation





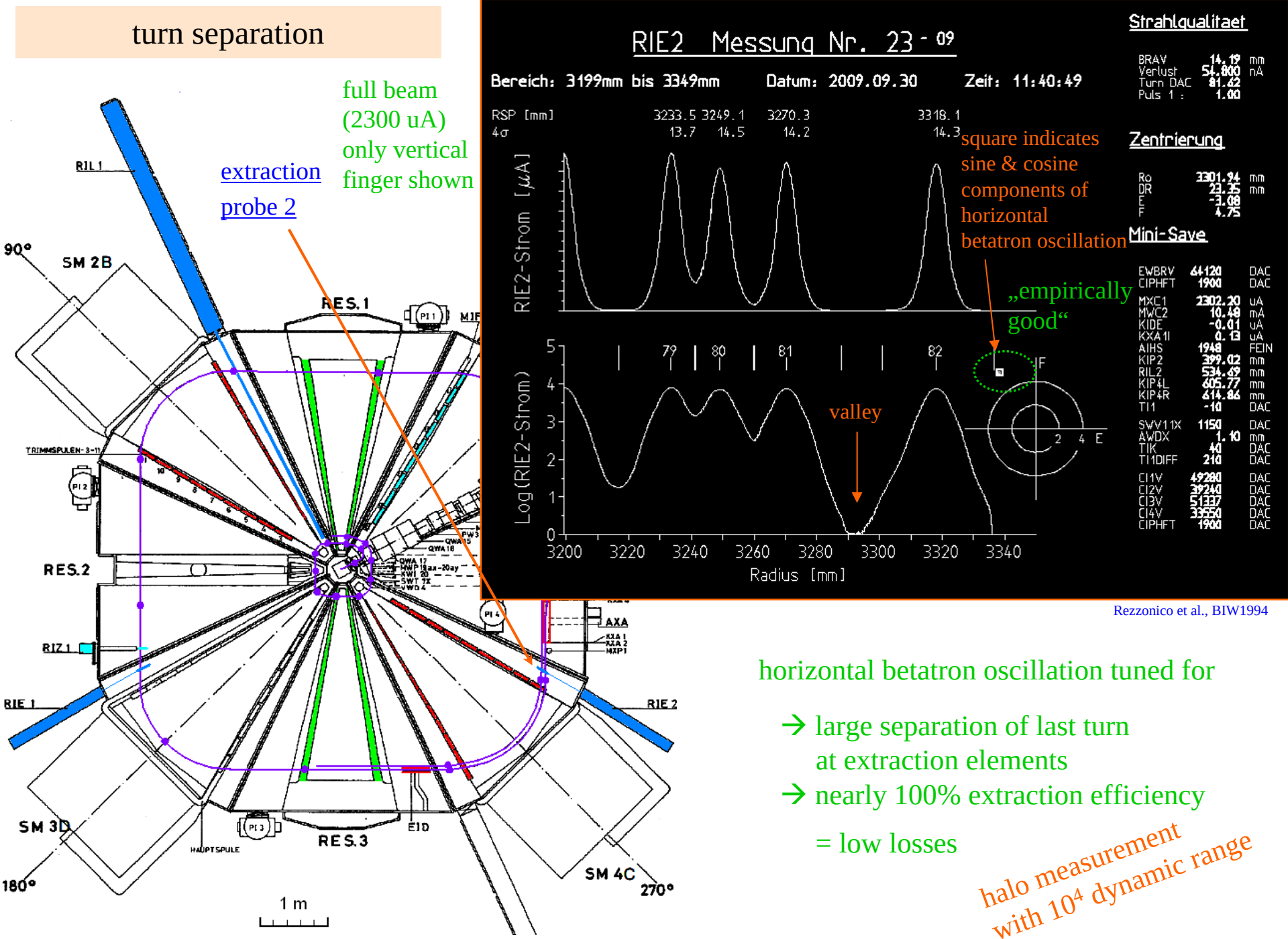
D. Götz, PSI

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



Rezzonico et al., BIW1994

horizontal betatron oscillation tuned for

→ large separation of last turn at extraction elements

→ nearly 100% extraction efficiency

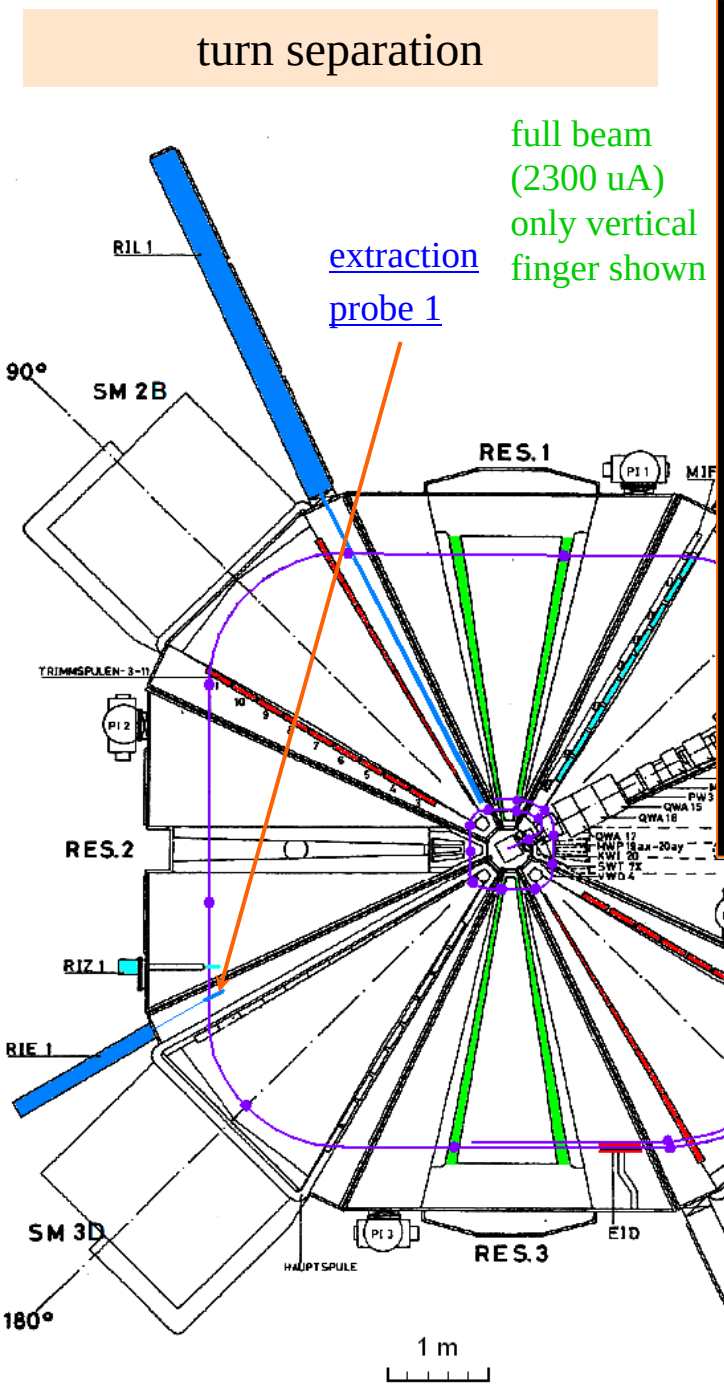
= low losses

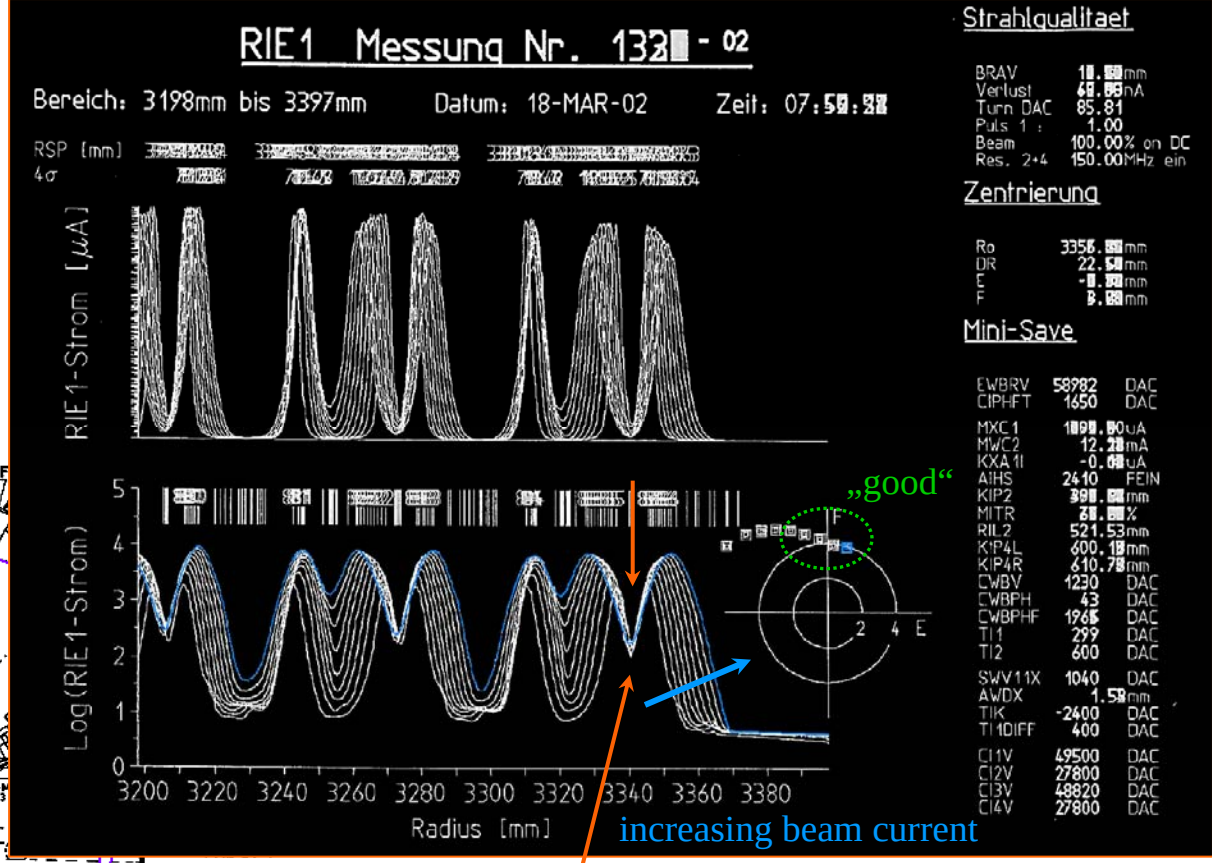
halo measurement with 10^4 dynamic range

turn separation

full beam (2300 uA) only vertical finger shown

extraction probe 1





M. Humbel, PSI

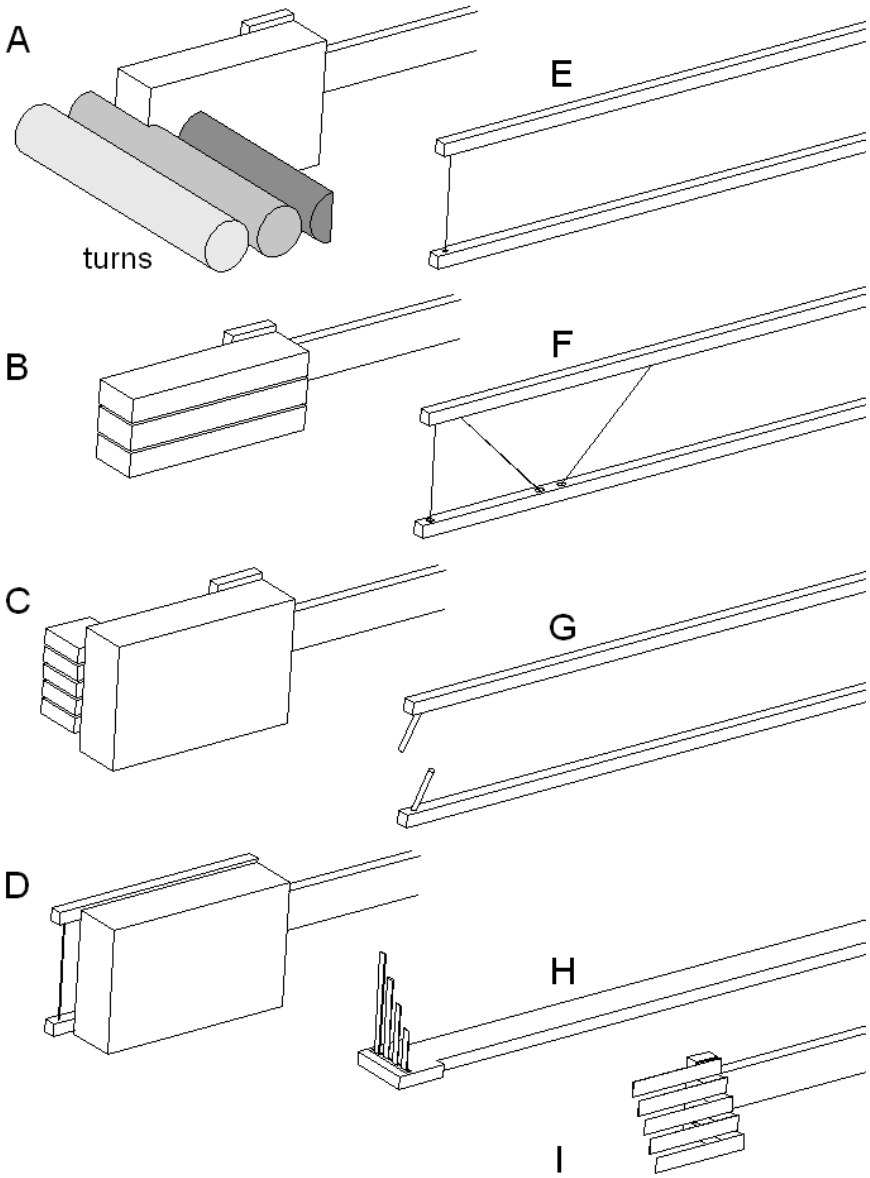
developing valley for extraction elements unchanged by beam current variation (accomplished by cutting the beam single-sided with a collimator in the machine center)

→ good extraction efficiency at all currents

29 min

D) transversal information (in cyclotron): radial probes at high / low current

radial probes: types and uses

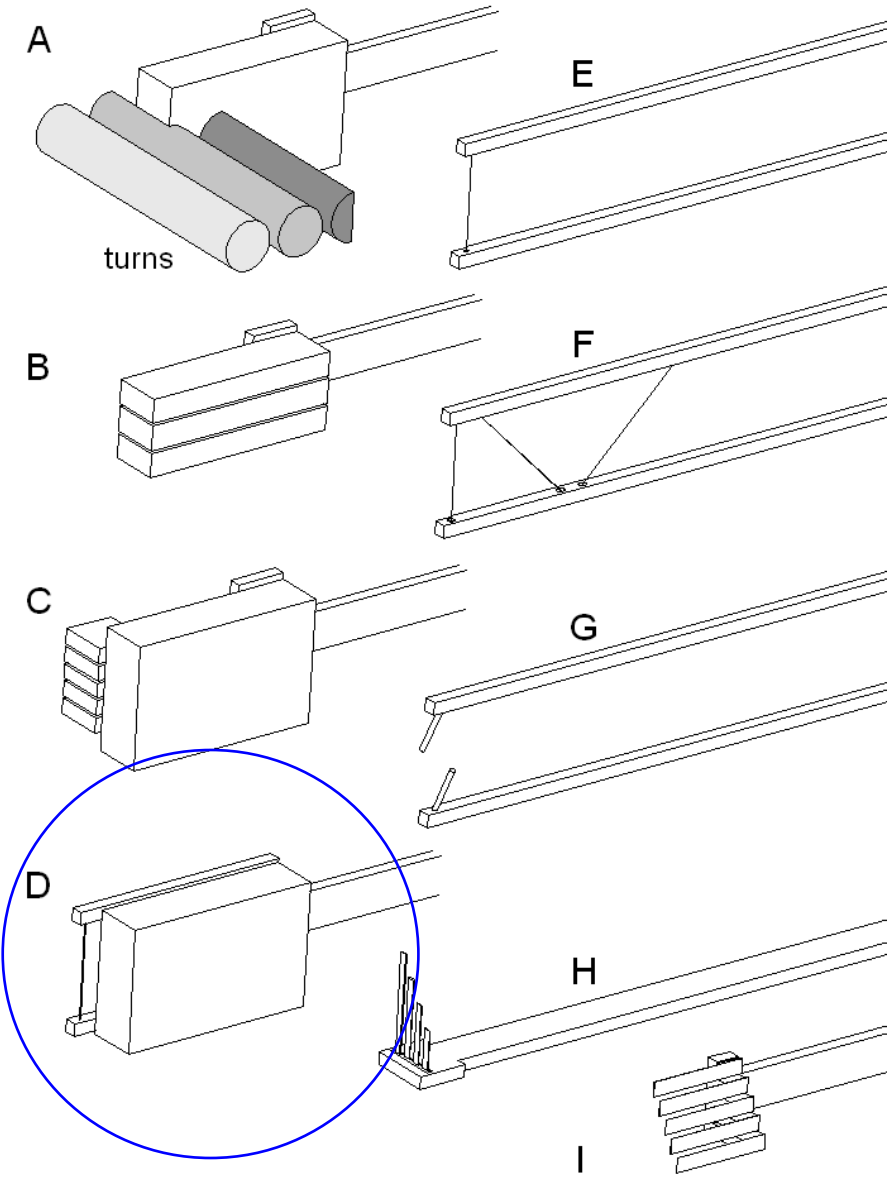


schematic

- radial: integral (thick) or differential

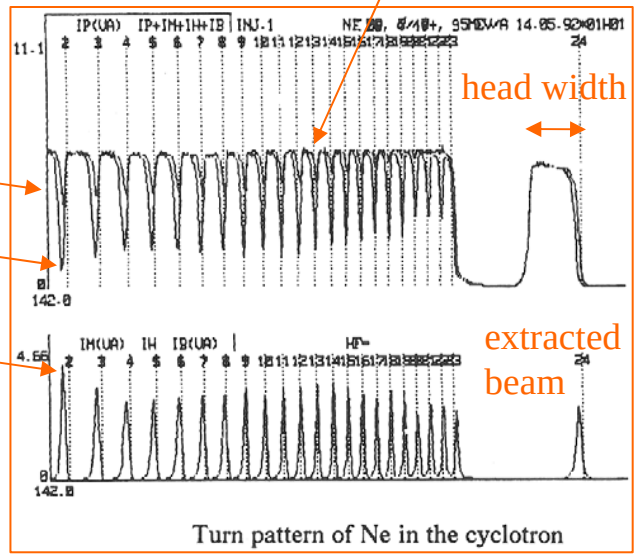
- axial: segmentation / tomography

radial probes: types and uses



integral + differential probe
at separated turns

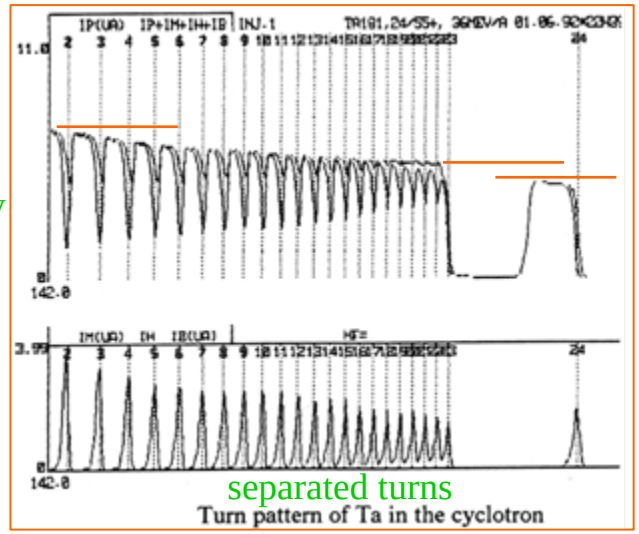
probe efficiency <1
visible only when turn is cut



radius

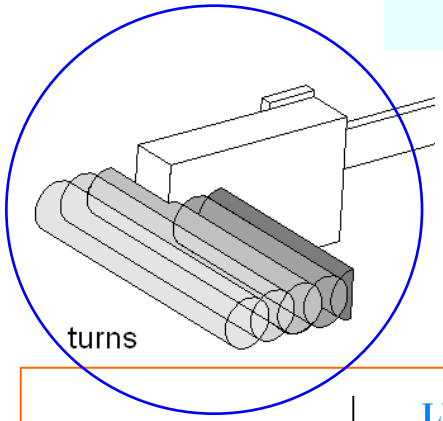
losses
extraction efficiency

turn structure



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

radial probes: types and uses



integral probe at not separated turns

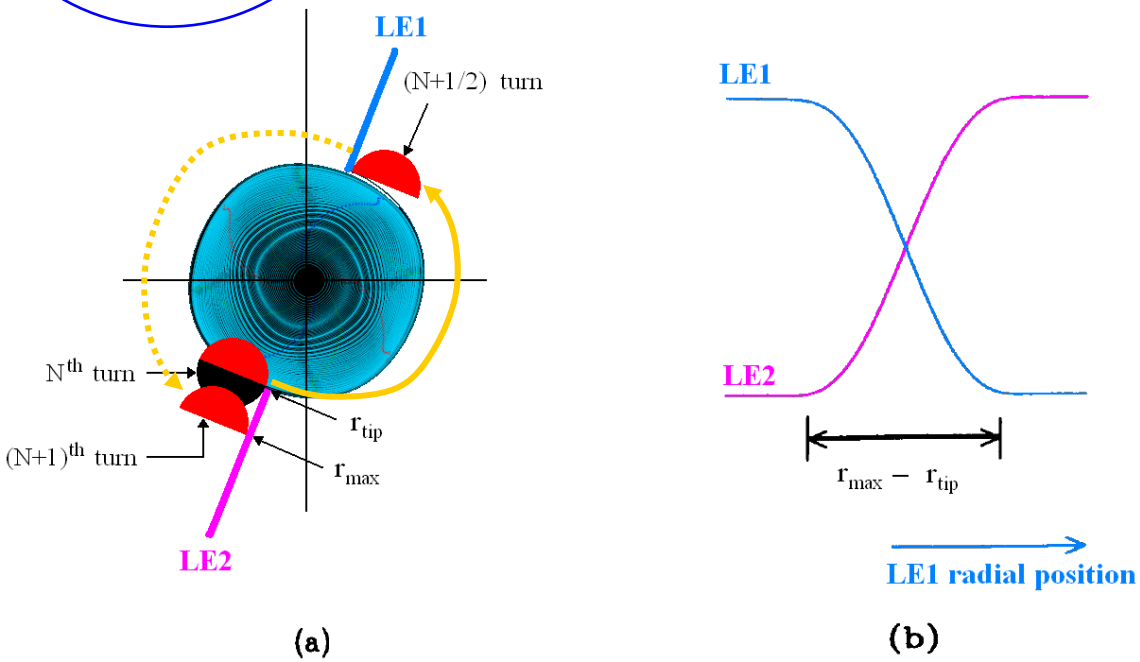
shadow method

→ ~ 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.

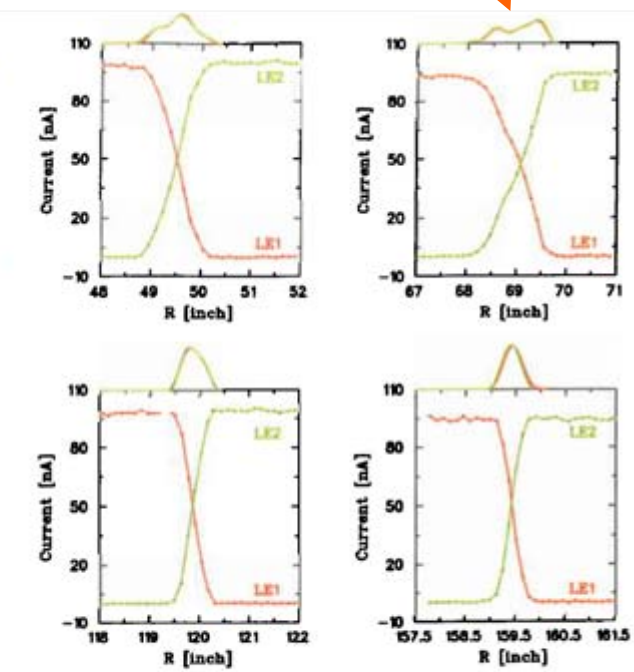
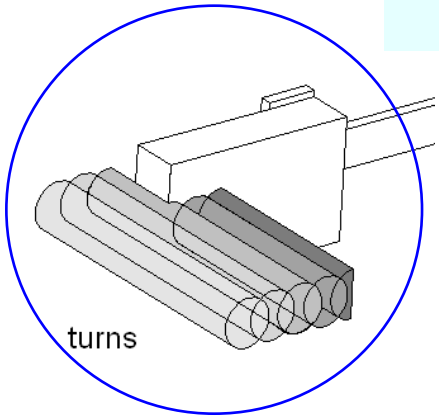


Figure 11: *Measured beam currents on LE1 and LE2 vs the radial position of LE1, with LE2 parked at defferent radii. Shown on the top are the beam distributions along the radius. The data at ~ 69 inch clearly shows that beam hitting LE2 is coming from 2 turns.*

from Rao et al., TRI-DN-04-8,
http://legacyweb.triumf.ca/publications/pub/dn/2004/TRI-DN-04-08.pdf

see also Schreuder, NIM 95 (1971) p. 237

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

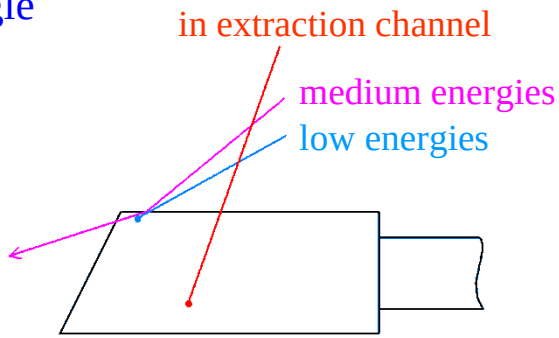
radial betatron oscillations visible

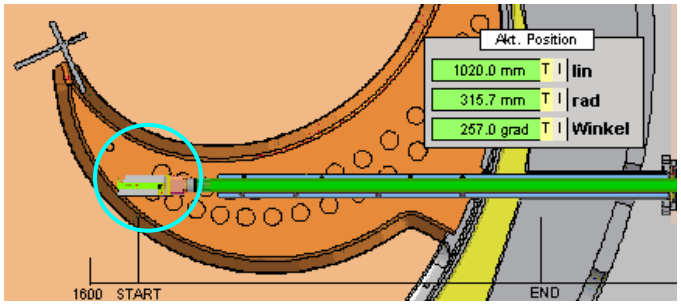
→ information on radial beam centering

at low & high energies: full beam stopped

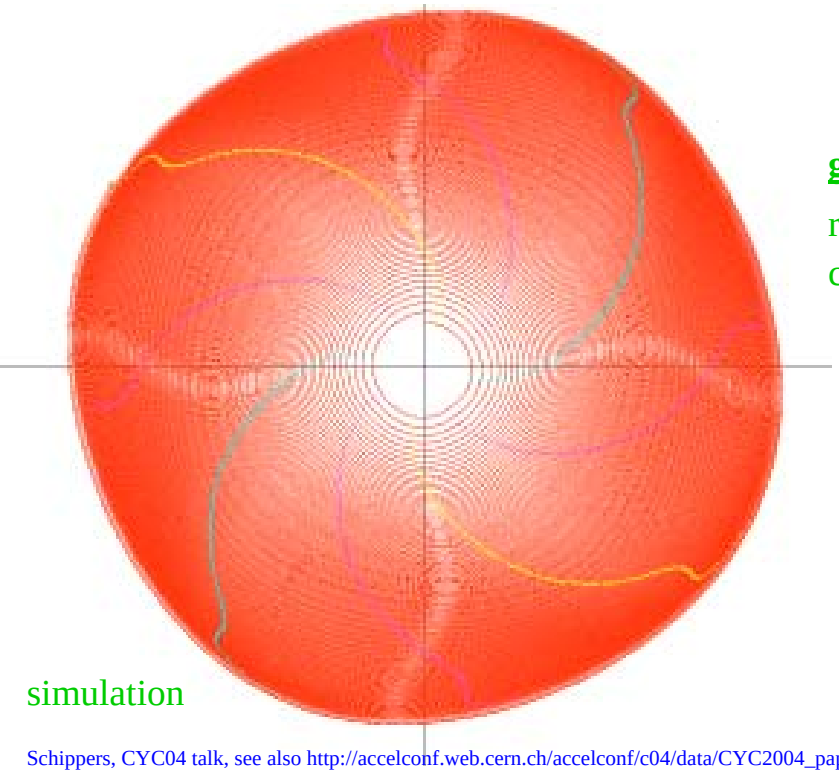
→ behaves as integral probe

→ extraction efficiency





PSIs medical cyclotron (Varian, 250 MeV, compact), Geisler et al., CYC07 talk, see also http://accelconf.web.cern.ch/accelconf/c07/PAPERS/9.PDF

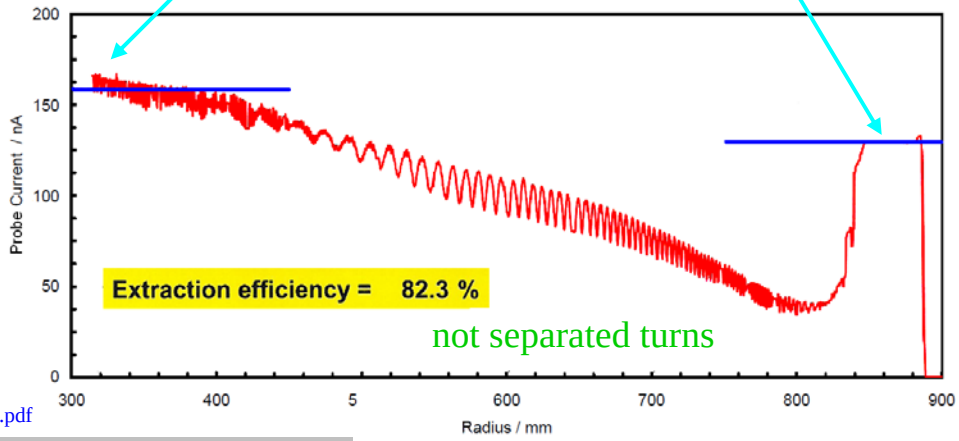


simulation

good

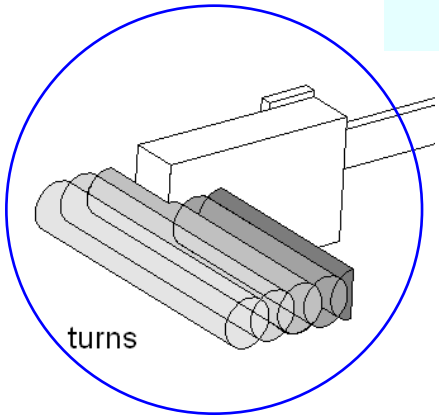
radial

centering



Schippers, CYC04 talk, see also http://accelconf.web.cern.ch/accelconf/c04/data/CYC2004_papers/21A3.pdf

radial probes: types and uses / signal



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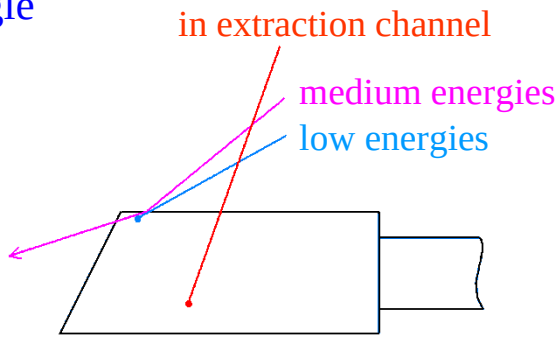

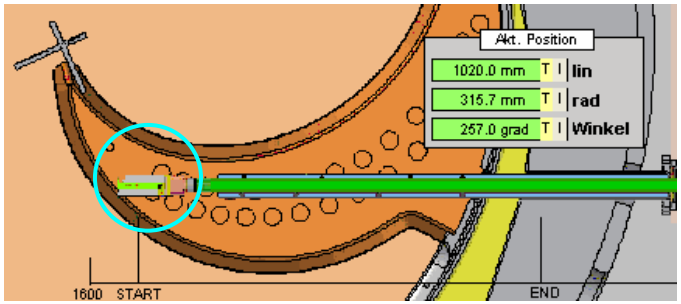

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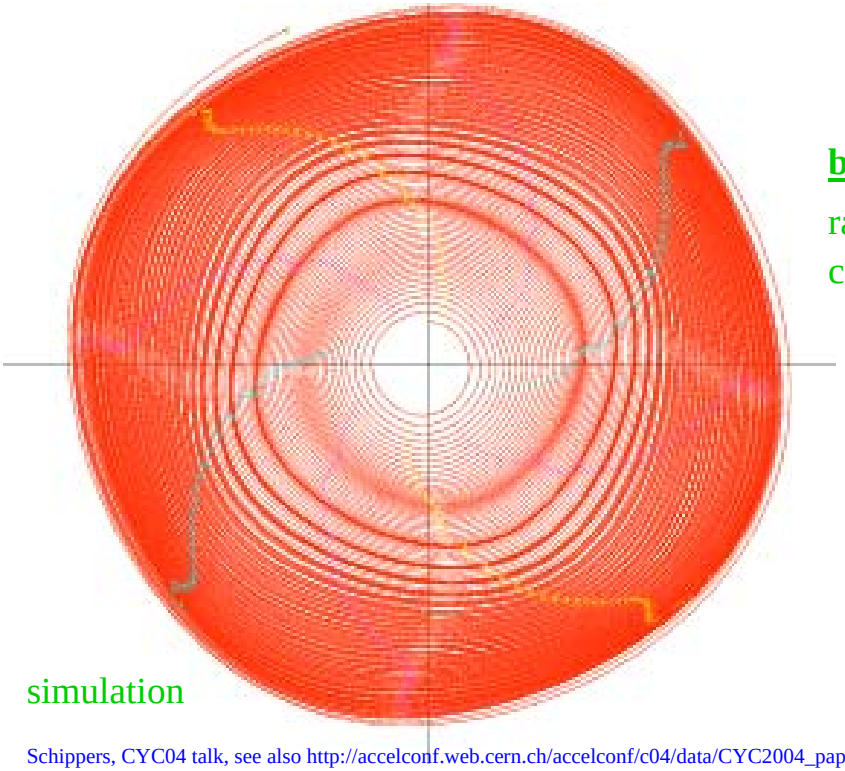
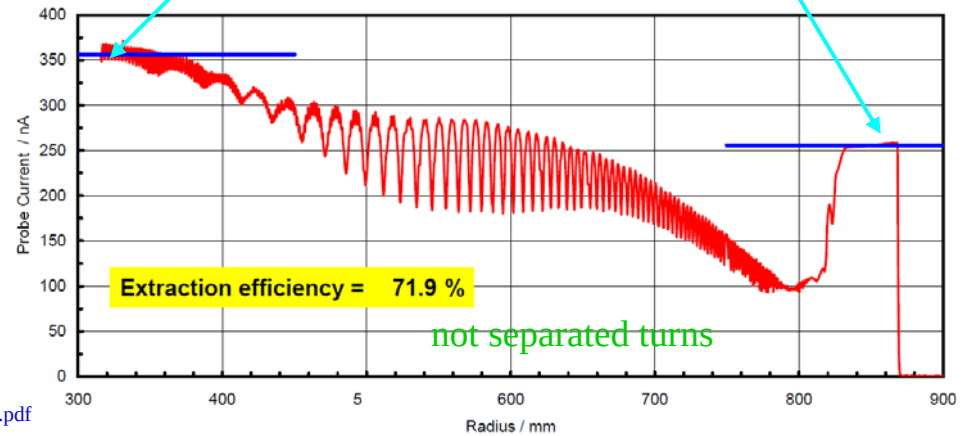


simulation

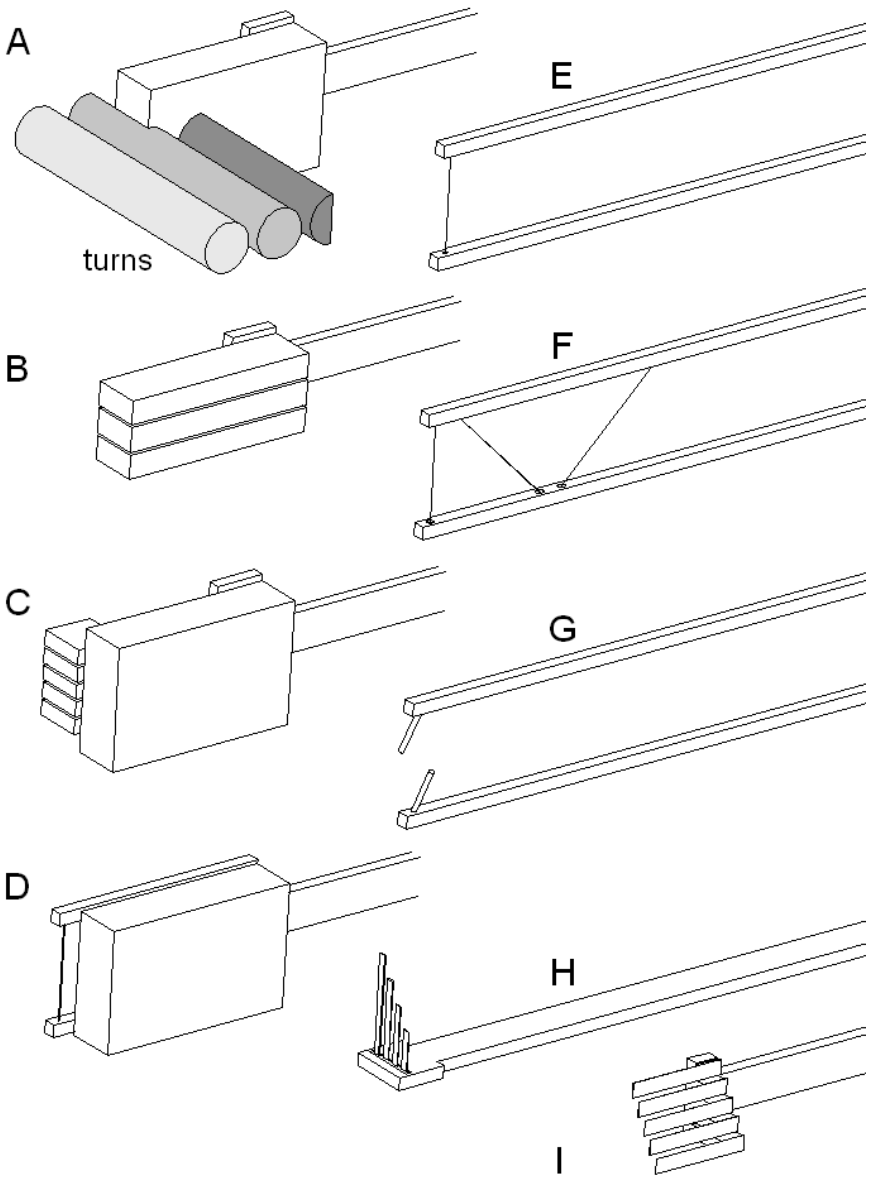
bad

radial centering



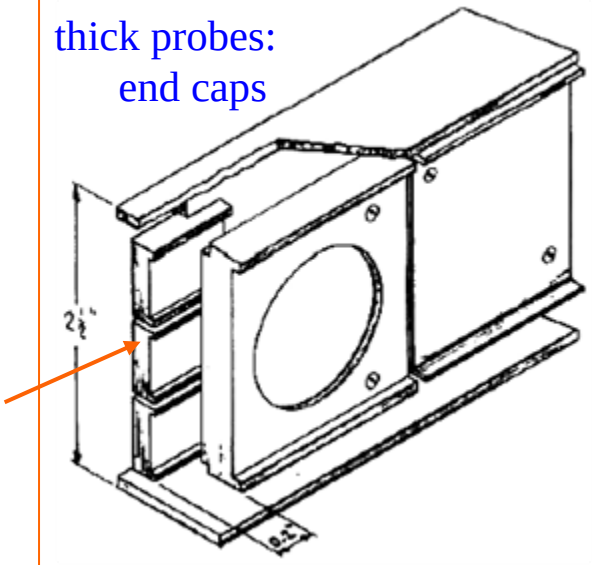
Schippers, CYC04 talk, see also http://accelconf.web.cern.ch/accelconf/c04/data/CYC2004_papers/21A3.pdf

radial probes: signal



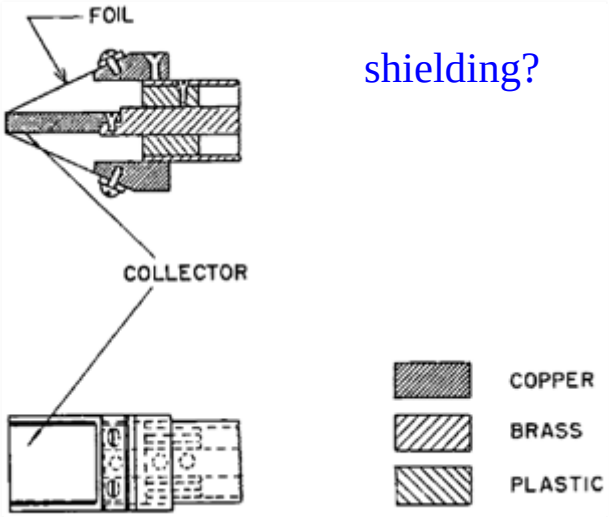
secondary electron capture
(also: bias
or pulling electrode)

thick probes:
end caps



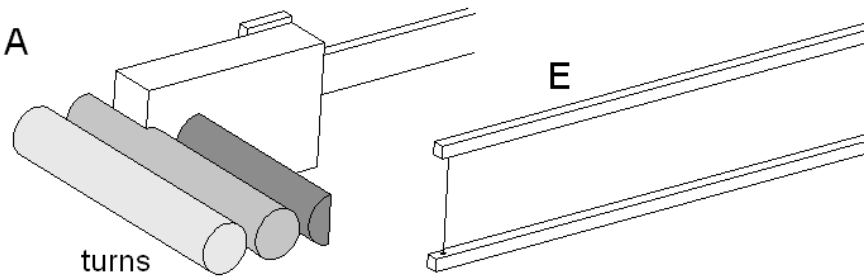
TRIUMF, Craddock et al., CYC75 p. 240

shielding?



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

radial probes: high current



thermal limits at
high current

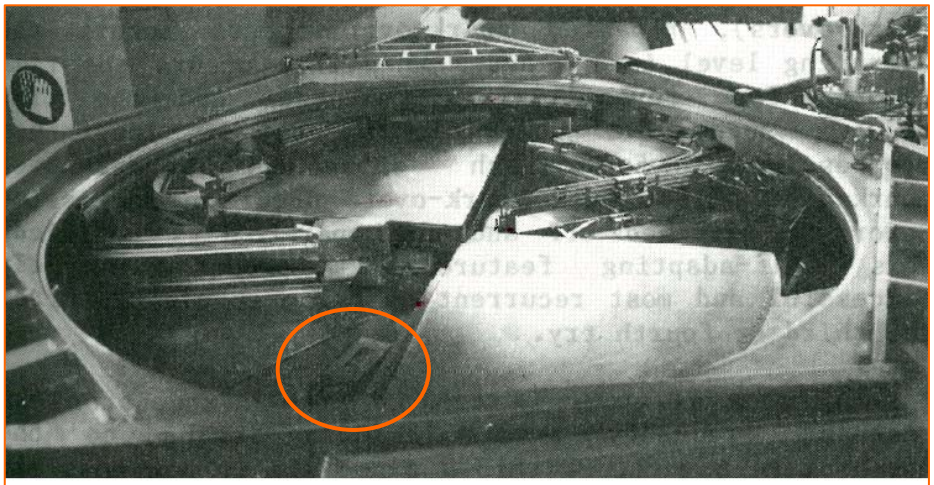
size limitation
→ power limitation
~15 kW protons

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

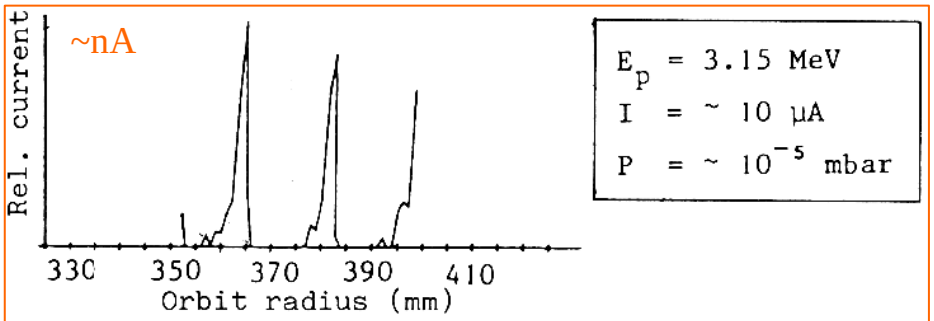
thin carbon fibres have highest performance
but give small electrical signal

alternatives?

residual gas ion monitor

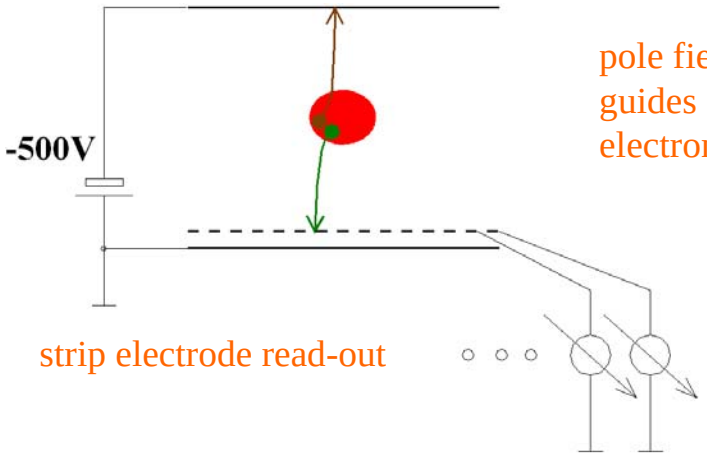


The layout inside the vacuum chamber of SPC1. Components that can be seen are the first slit system, electrostatic- and first magnetic channel, ion source (slightly withdrawn) and, to the left of the dee in the foreground, the ionisation beam profile monitor.



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



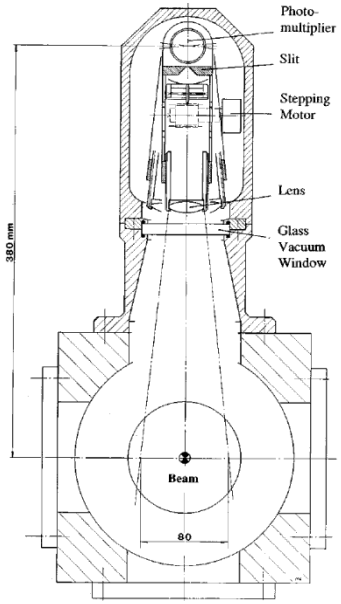
signal level OK at 10^{-6} mbar
(amplification by e.g. MCP not needed)

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

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

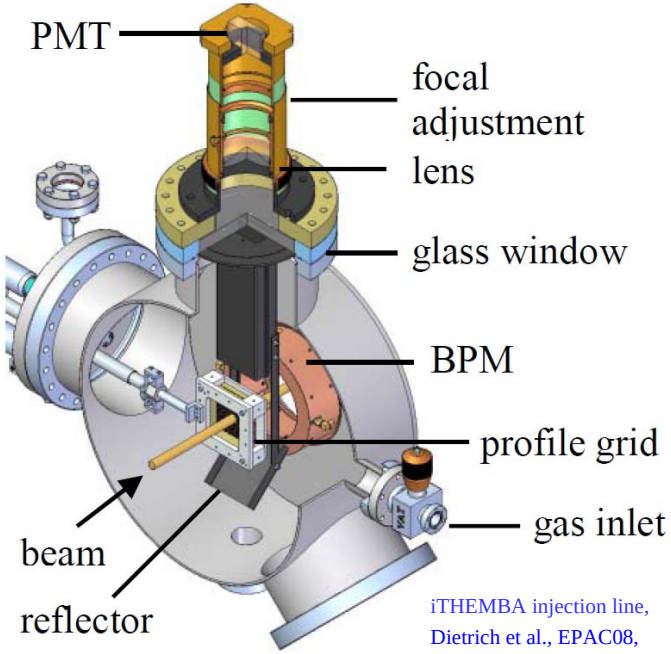
beam induced fluorescence

single PMT



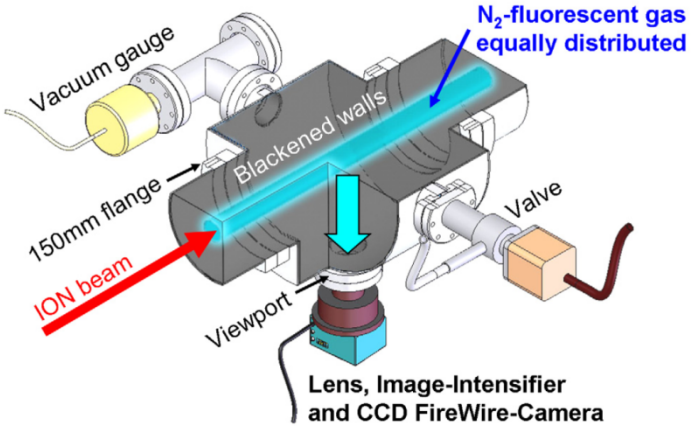
PSI, Rezzonico, CYC87 p. 457

32 channel PMT



iTHEMBA injection line,
Dietrich et al., EPAC08,
http://accelconf.web.cern.ch/accelconf/e08/papers/tupc022.pdf

MCP + CCD



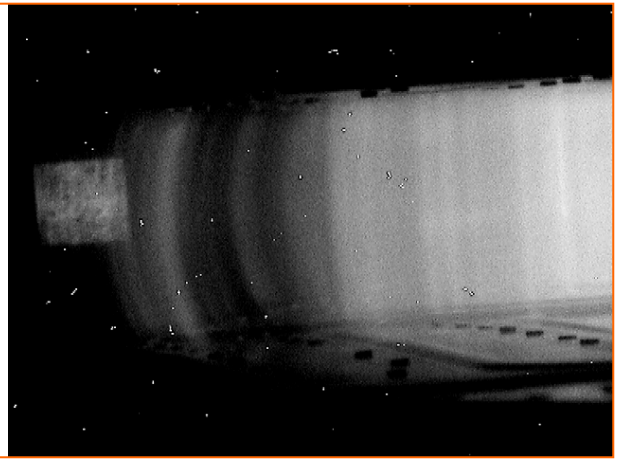
GSI, Forck, IPAC10,
http://accelconf.web.cern.ch/accelconf/IPAC10/html/author.htm

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

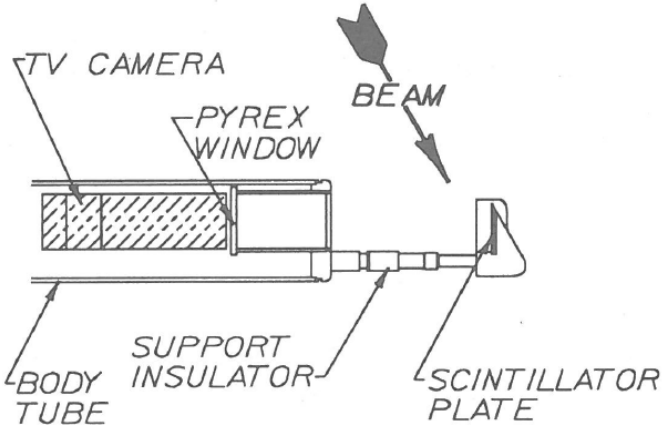


Figure 1. Sketch showing the head of the TV probe. The angle the beam makes with the scintillating plate changes between 35 and 65 degrees.

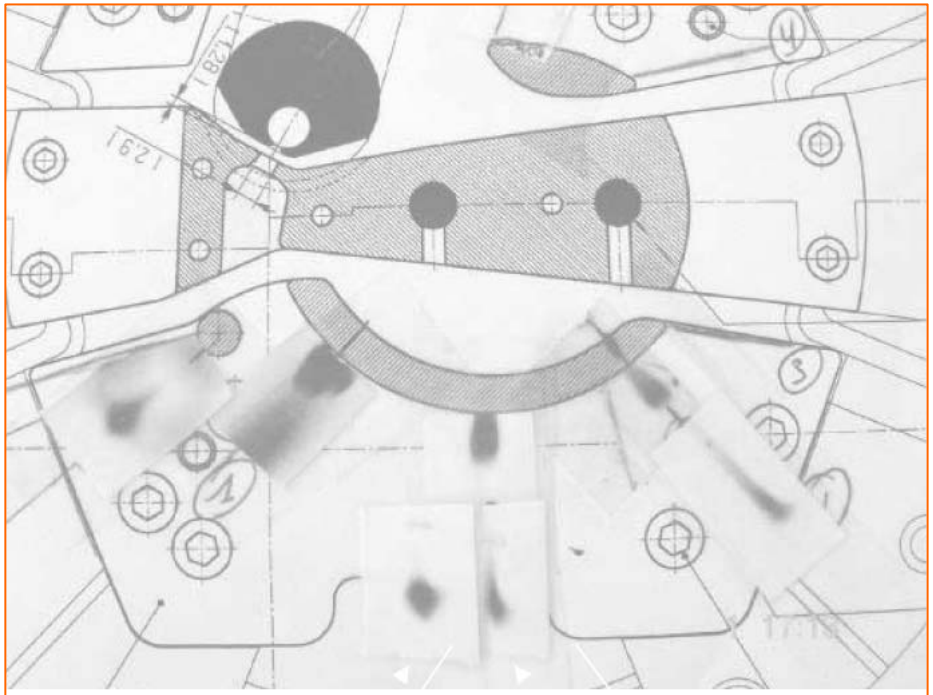
MSU, Marti et al., CYC92 p. 435

also (since long):

with external observation

foil based methods

thin paper burn



IBA, Kleeven, CYC01, http://accelconf.web.cern.ch/accelconf/c01/cyc2001/paper/L-1.pdf

Figure 12: Beam spots in the central region

also (for commissioning):

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

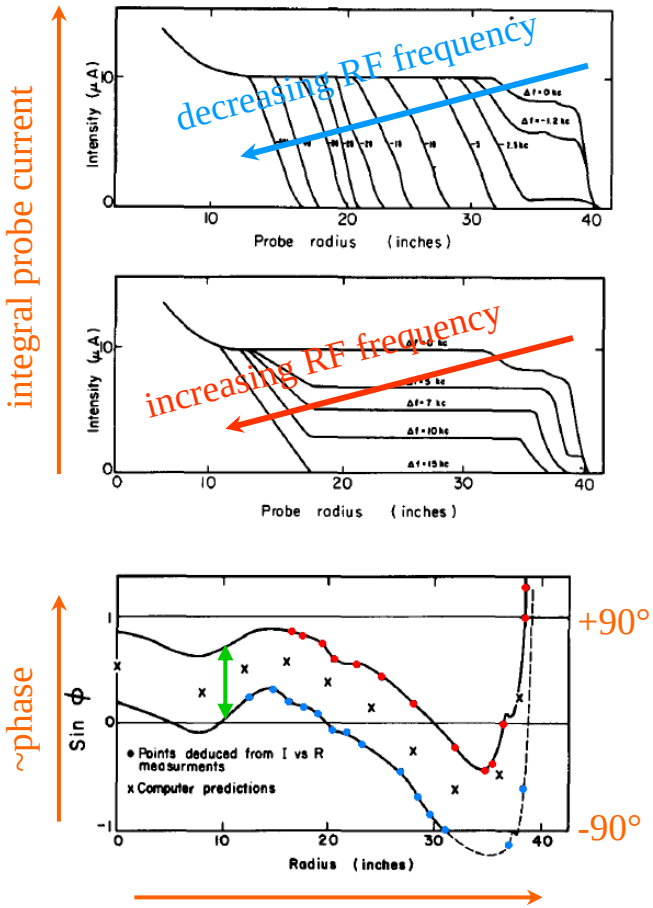
36 min

E) longitudinal information (in cyclotron)

Garren & Smith detuning

phase probes

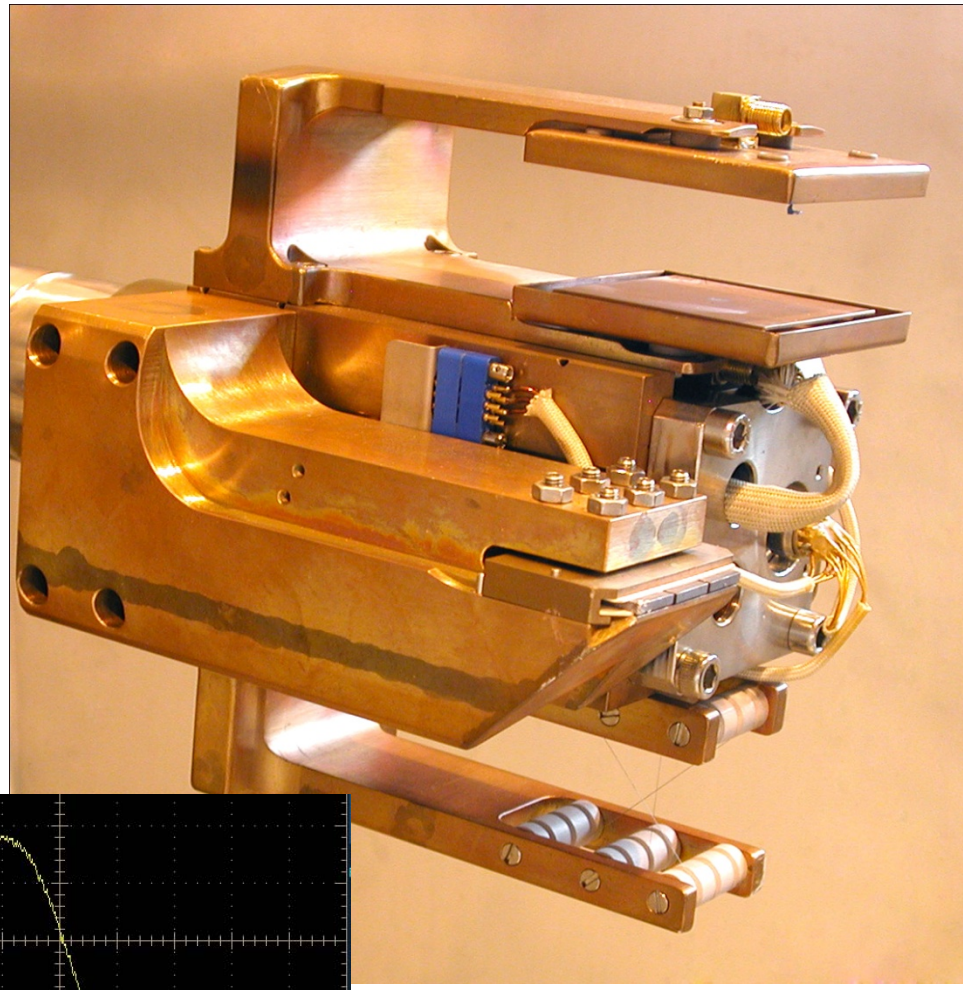
(usually resonance curve shown
at fixed radius, main field varied)



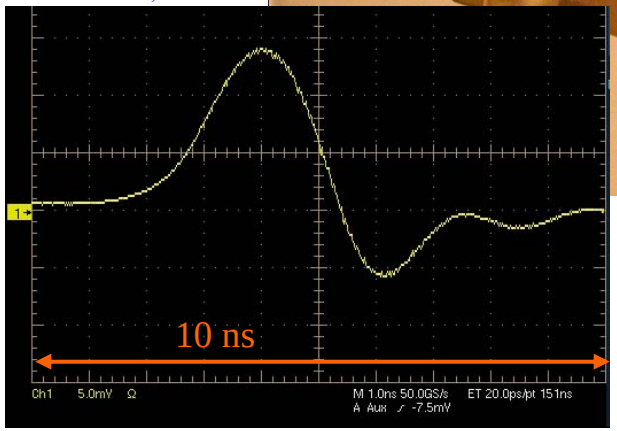
Garren & Smith,
CYC63, http://accelconf.web.cern.ch/accelconf/c63/papers/cyc63a03.pdf

can deliver
local phase width
around center phase

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



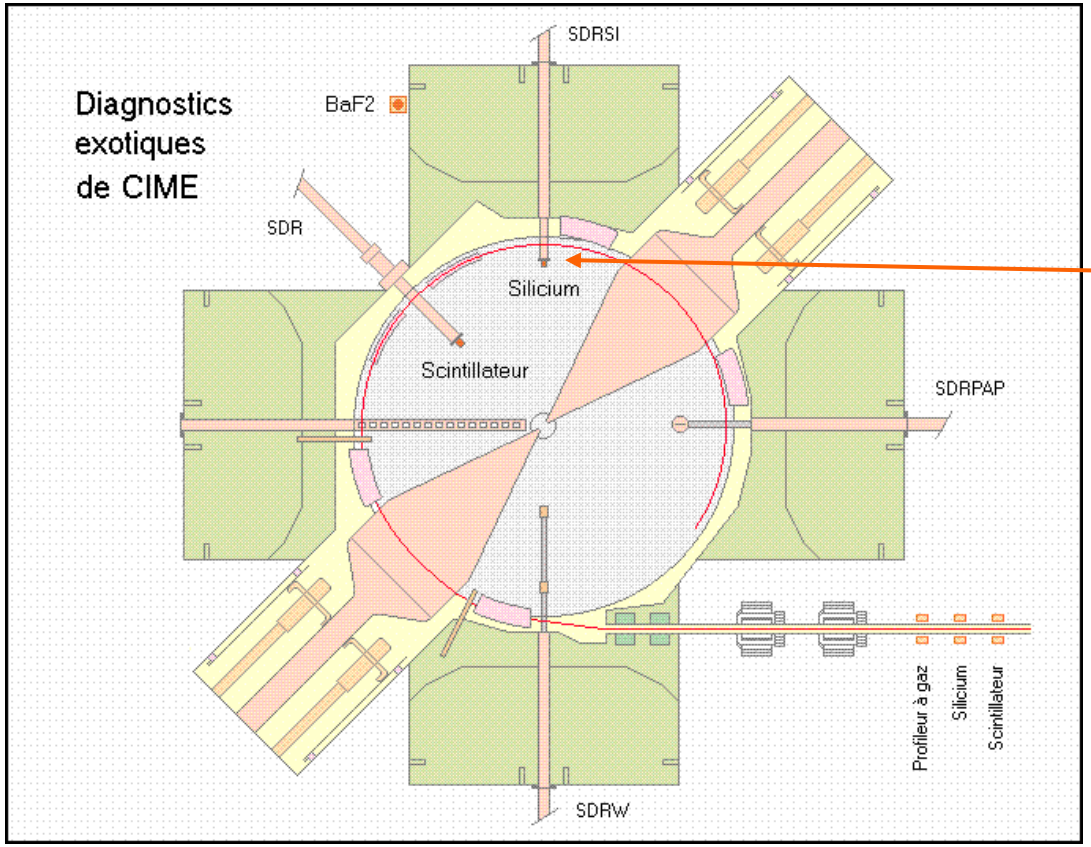
both pictures
D. Fourie, iTHEMBA



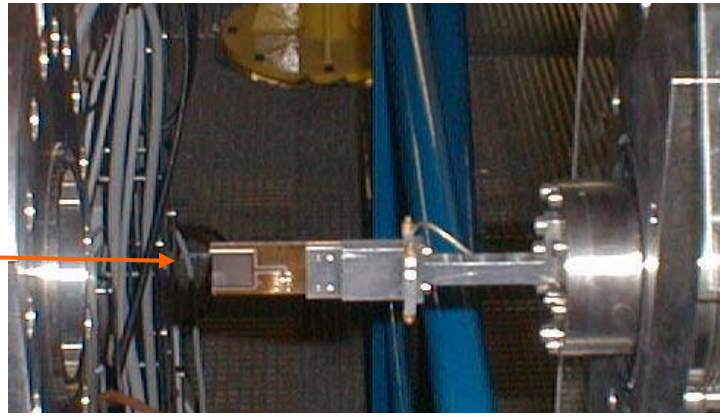
can deliver
- center phase (very accurate)
- time structure
(not for very short bunches)

bunch shape & energy measurement

silicon detector placed directly in very low current beam



silicon detector
on radial probe (shield removed)



probe head with shield & preamplifier

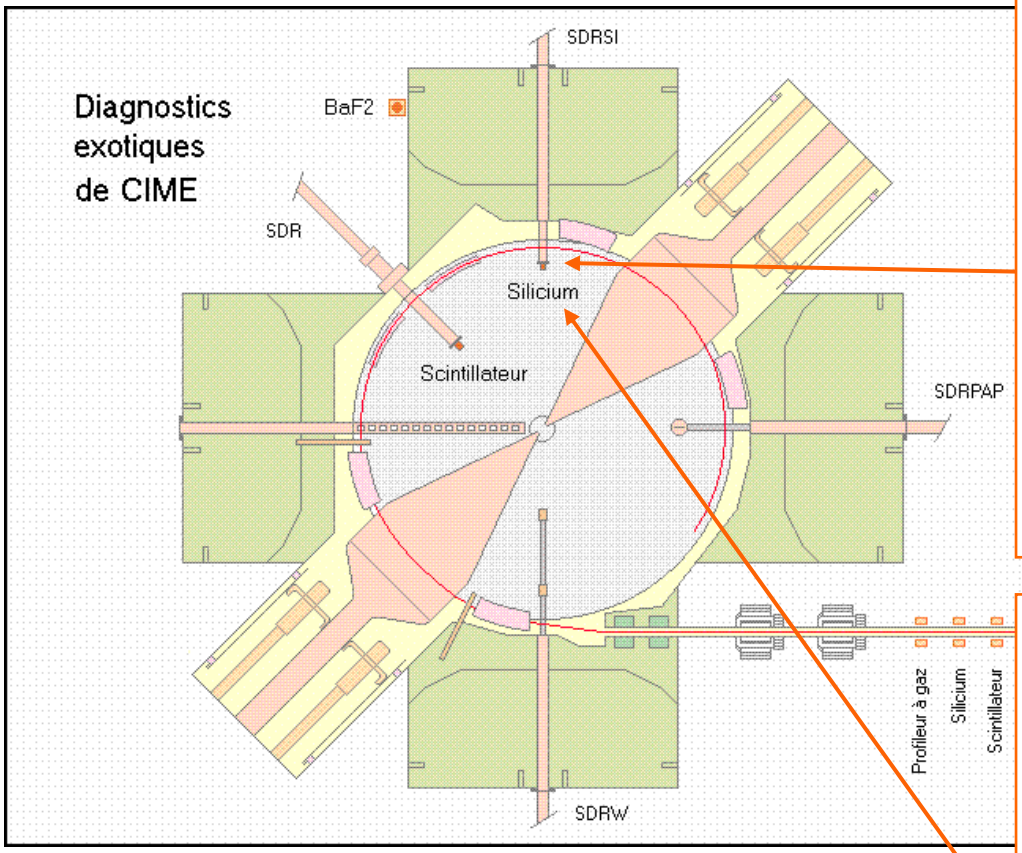
all pictures F. Chautard, GANIL

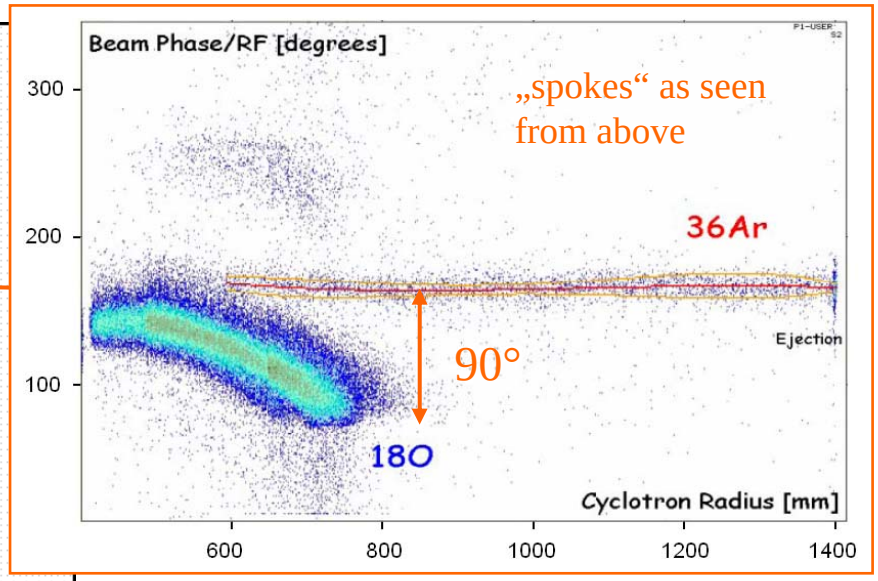
can deliver
- time structure (moderate resolution)
- beam particle energy spectrum (thick detector)
- beam particle stopping power (thin detector)

bunch shape & energy measurement

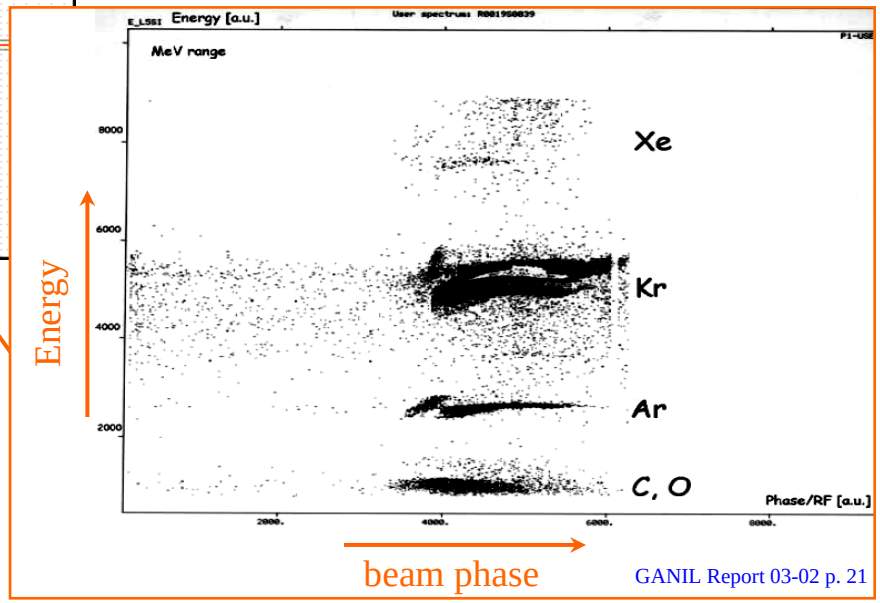
cyclotron separates different particles by q/m

time-structure shows separation (radius varied)





Chautard et al., CYC01, http://accelconf.web.cern.ch/accelconf/c01/cyc2001/paper/P4-17.pdf



GANIL Report 03-02 p. 21

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

probe at fixed radius

bunch shape detector (high beam current)

based on scattered protons:

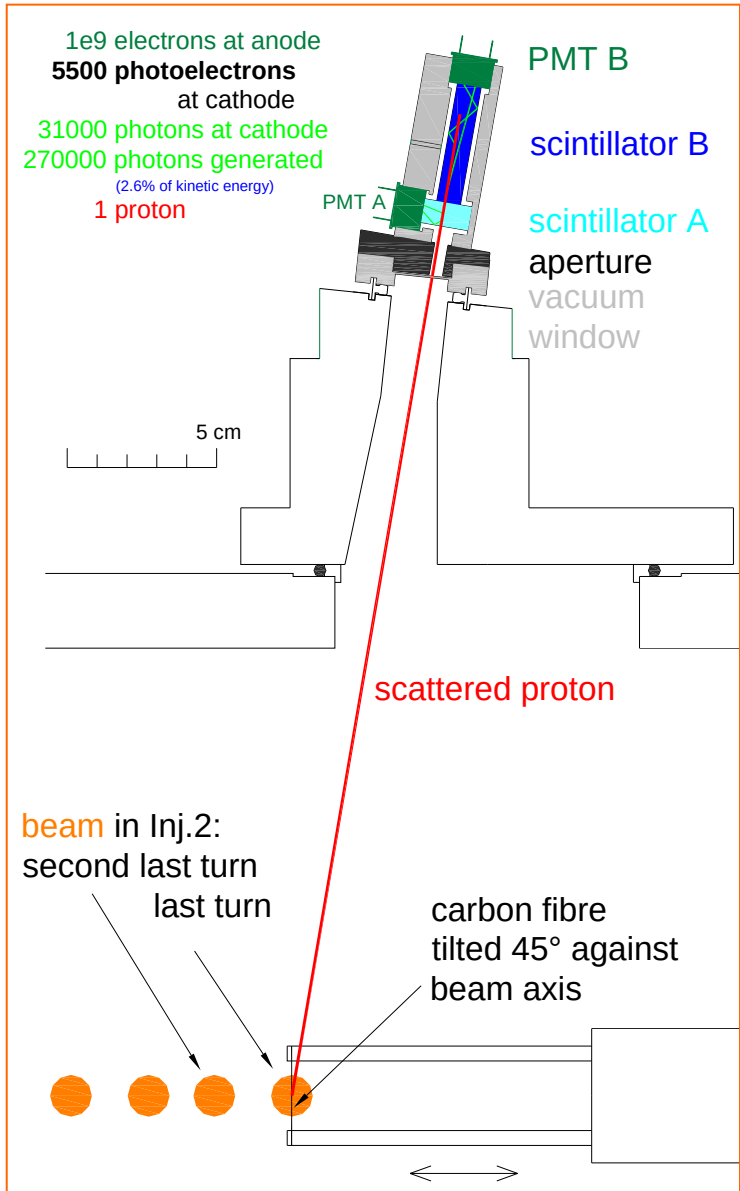
- measure longitudinal and radial density distributions of the beam bunches (averaging over many bunches)
- arrival time of scattered protons compared to RF reference (discriminator & Time-to-Ampl. Converter & Multi-Channel-Analyzer)
- resolution incl. electronics ~31 ps fwhm (determined from correlation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

Dölling, HB10, http://accelconf.web.cern.ch/accelconf/HB2010/papers/mopd62.pdf

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	

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



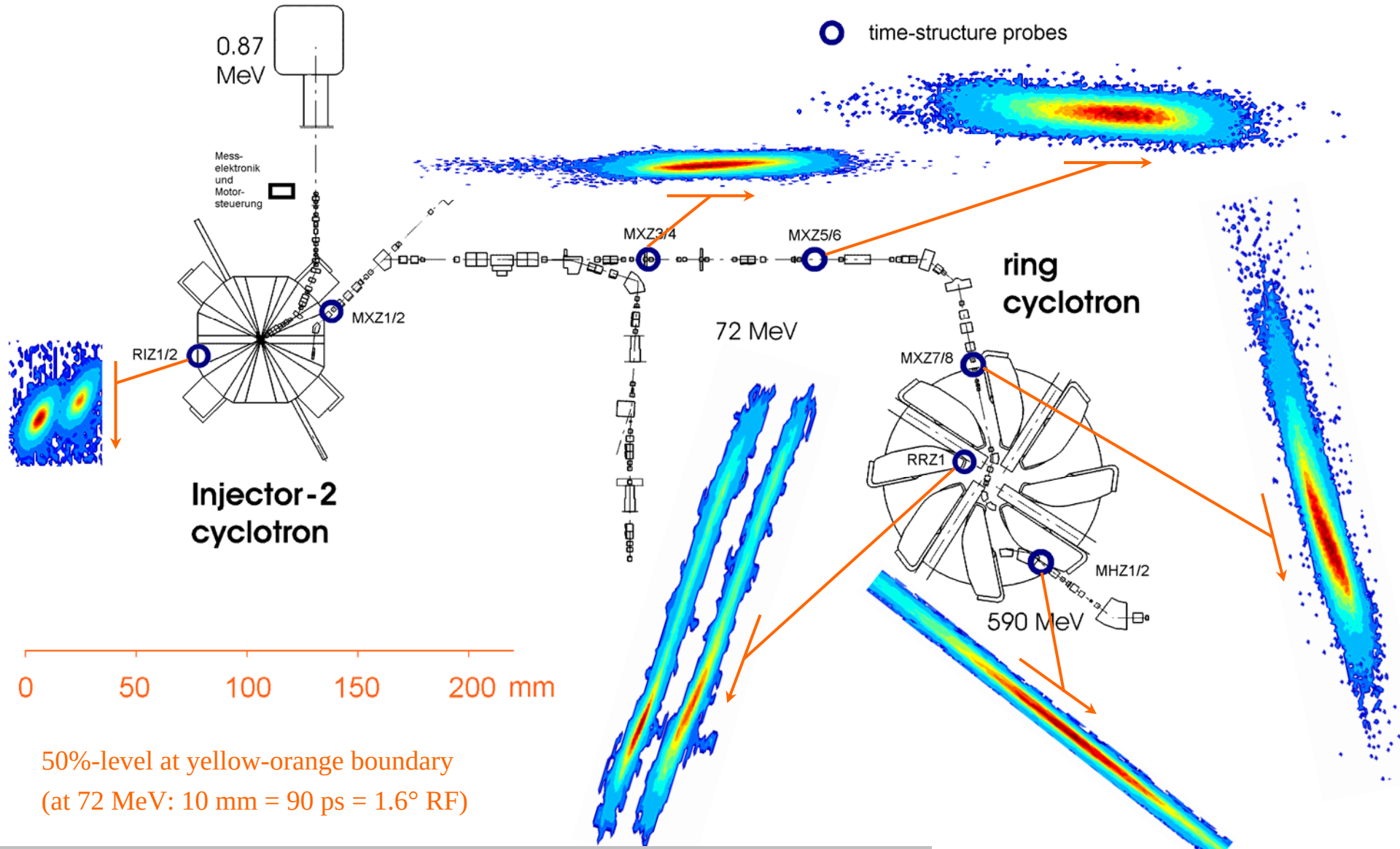
Dölling, DIPAC01, http://accelconf.web.cern.ch/accelconf/d01/papers/PS05.pdf

(much faster with RF-deflection of secondary electrons from biased wire)

Feschenko et al., LINAC86, p. 323
Feschenko et al. PAC01, http://accelconf.web.cern.ch/AccelConf/e90/PDF/EPAC1990_0750.PDF
Bylinsky et al., EPAC94, http://accelconf.web.cern.ch/AccelConf/e94/PDF/EPAC1994_1702.PDF
Feschenko et al., PAC07, http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/THOAAB01.PDF
Aleksandrov et al., BIW12, MOPE041

bunch shape detector (high beam current)

2.3 mA proton beam, moving bunches as seen from above
→ detailed input to beam dynamic simulations



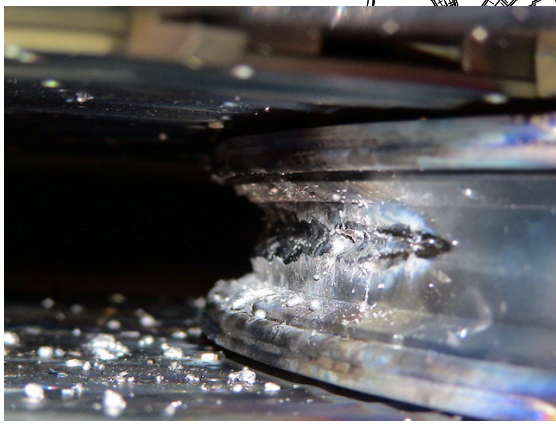
50%-level at yellow-orange boundary
(at 72 MeV: 10 mm = 90 ps = 1.6° RF)

40 min

F) beam losses & beam halo

beam losses: „protection aspect“

- activation
- melting of cyclotron components by missteered (high power) beam
  → fast interlock generation needed (~1 ms)



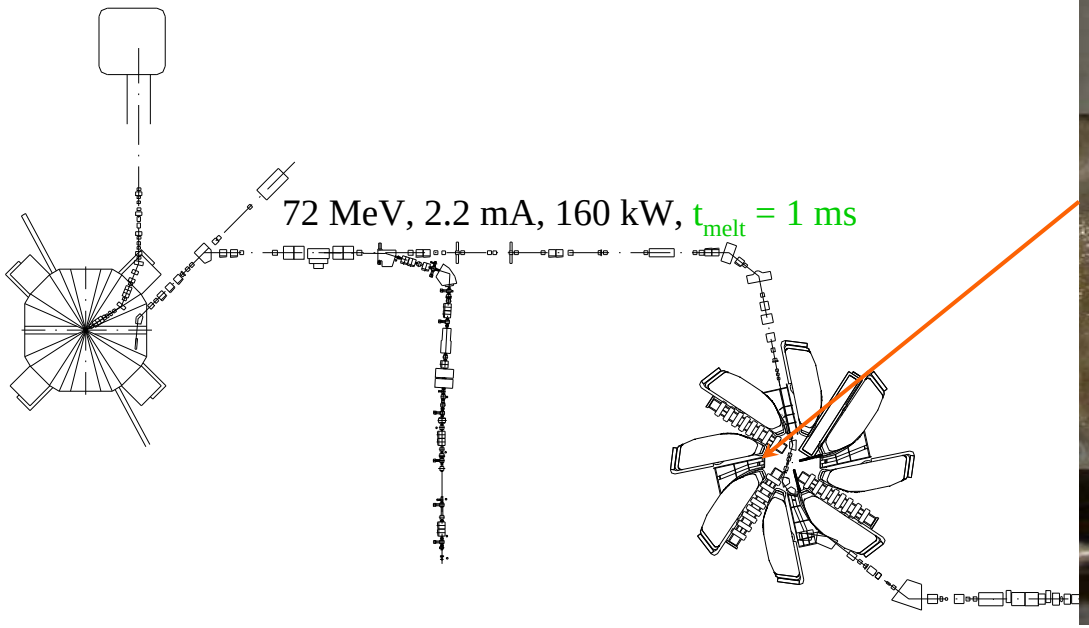
collimators

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

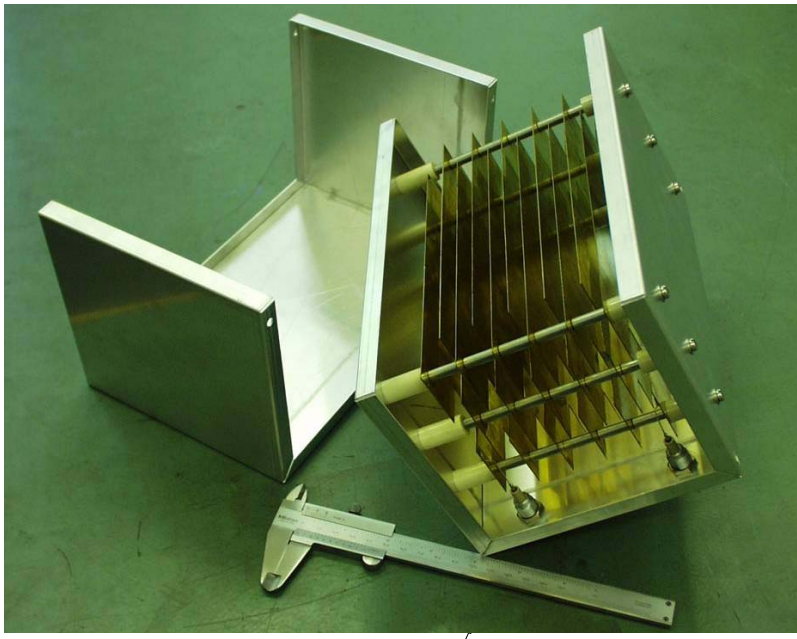
590 MeV, 2.2 mA, 1.3 MW, t_{melt} = 10 ms

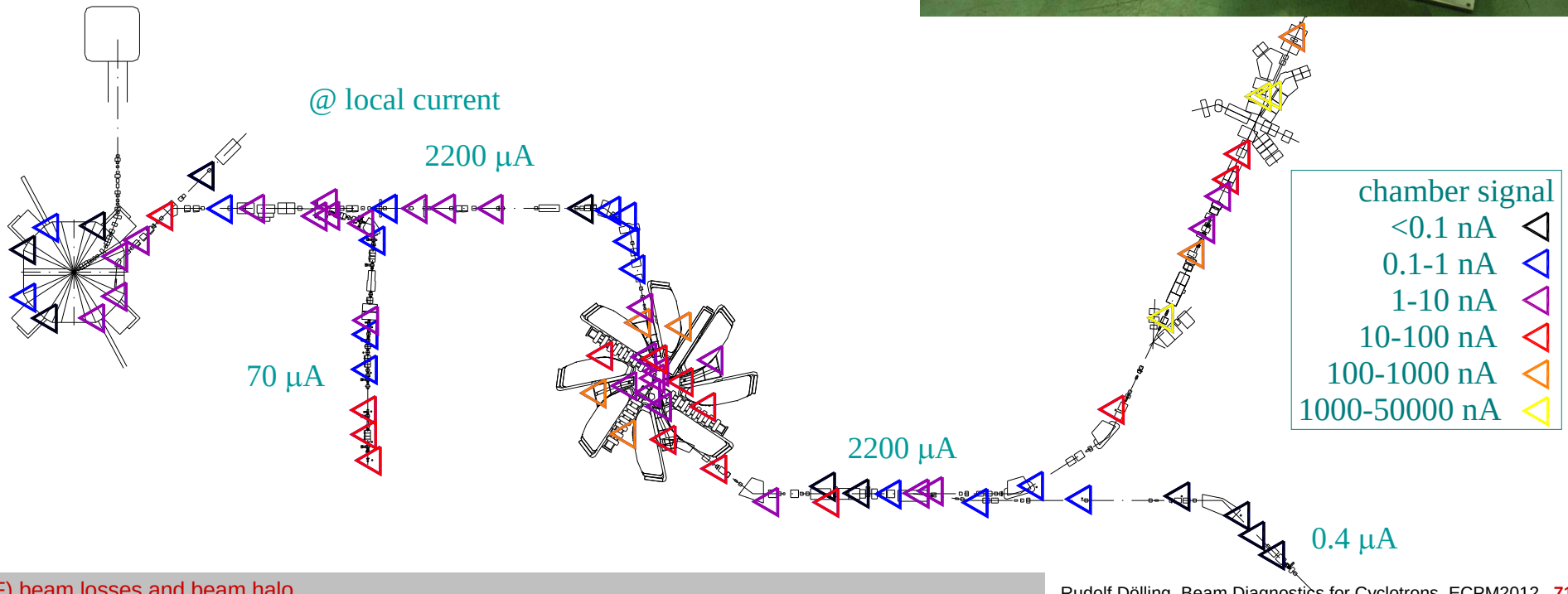
beam losses: „protection aspect“

ionization chambers

- most simple variant: ambient air filled, 300 V
- 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





beam losses: „protection aspect“

- radiation induced attenuation of optical fibers (range few kGy, position resolution ~1 m)
  Wulf, Körfer, DIPAC09, http://accelconf.web.cern.ch/AccelConf/d09/papers/weoa01.pdf

(Roughly) Estimated Sensitivities

- **Ionization chamber:** **70 µC/Gy**
  1 liter argon
  S ≈ active mass · charge per ionization energy ≈ $V \cdot \rho \cdot e/E_{ion}$ ≈ 1 l · 1.8 g/l · e / 26 eV
- **Long ionization chamber:** **20 µC/Gy**
  1 meter length, 1 cm radius, argon
  S ≈ active mass · charge per ionization energy ≈ $\pi r^2 \cdot L \cdot \rho \cdot e/E_{ion}$ ≈ 314 cm³ · 1.8 g/l · e / 26 eV
- **PIN diode:** **6 µC/Gy**
  1 cm² surface, 100 µm depletion depth
  S ≈ active mass · charge per excitation energy ≈ $A \cdot d \cdot \rho \cdot e/E_{ion}$ ≈ 10 mm³ · 2.3 g/cm³ · e / 3.6 eV
- **Secondary emission monitor:** **500 pC/Gy**
  100 cm² surface, 0.01 average secondary emission yield (SEY)
  S ≈ surface · SEY · electron charge · density of primaries per dose ≈ A · SEY · e · (ρ/(dE/dx))
  ≈ 100 cm² · 0.01 · e · 1/(2 MeV·cm²/g)
- **Aluminum cathode electron multiplier:** **5 µC/Gy**
  10 cm² surface, 0.01 average secondary emission yield (SEY), tube gain 10^5
  S ≈ surface · SEY · electron charge · density of primaries per dose · gain ≈ A · SEY · e · (ρ/(dE/dx)) · G
  ≈ 10 cm² · 0.01 · e · 1/(2 MeV·cm²/g) · 10^5
- **PMT with organic scintillator:** **200 C/Gy**
  1 liter scintillator, 60% collection efficiency, 30% photocathode efficiency, tube gain 10^5
  S ≈ active mass · photon yield per energy · collection efficiency · photocathode efficiency · gain · electron charge
  ≈ V · ρ · Y · C · P · G · e = 1 l · 1 g/cm³ · 1/(100 eV) · 0.6 · 0.3 · 10^5 · e
- **Bare PMT (Čerenkov light):** **4 mC/Gy**
  10 cm² surface, 1 mm thick, 30% photocathode efficiency, tube gain 10^5
  S ≈ active volume · density of primaries per dose · photon yield per length · photocath. efficiency · gain · electron charge
  ≈ A · d · ρ · (ρ/(dE/dx)) · Y · P · G · e ≈ 1 cm³ · 1/(2 MeV·cm²/g) · 260/cm · 0.3 · 10^5 · e
- **PMT with Čerenkov fiber:** **2 µC/Gy**
  1 meter length, 100 µm radius, 2% collection efficiency, 30% photocathode eff., tube gain 10^5
  S ≈ active volume · density of primaries per dose · photon yield per length · coll. eff. · photoc. eff. · gain · electron charge
  ≈ πr^2 · L · ρ · (ρ/(dE/dx)) · Y · C · P · G · e ≈ 31 mm³ · 1/(2 MeV·cm²/g) · 260/cm · 0.02 · 0.3 · 10^5 · e

Flexible gain → linearity and calibration problematic!

Radiation damage problematic!

ERL Instrumentation Workshop, Cornell University, 2-3 June 2008 — Lars Fröhlich, DESY

http://tesla.desy.de/~lfroehli/download/ERL_instrumentation_ws_2008_BLMs.pdf see also Wittenburg, CAS2008, http://cas.web.cern.ch/cas/France-2008/Lectures/Wittenburg-BLM.pdf

linear in used range, very radiation hard

linear even at very high dose rate, very radiation hard

very sensitive

only for relativistic particles (β>0.68)

beam losses & beam halo: „knowledge aspect“

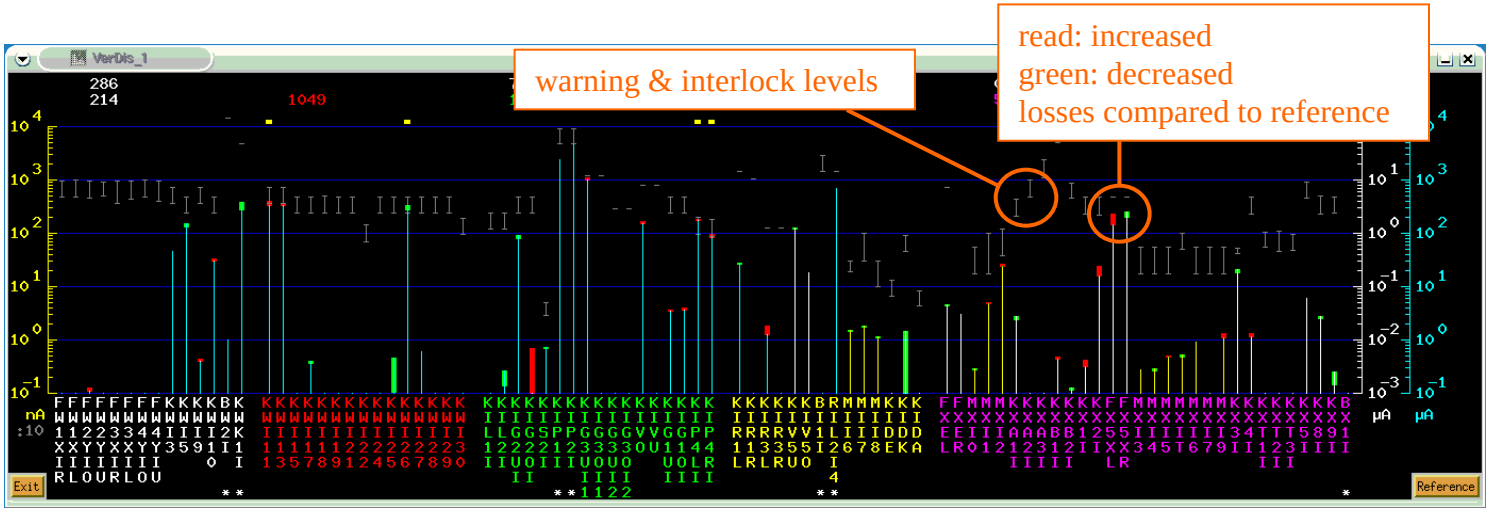
„empirical tuning“ has its limits:

- 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 needed for progress („a real understanding of losses“)



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

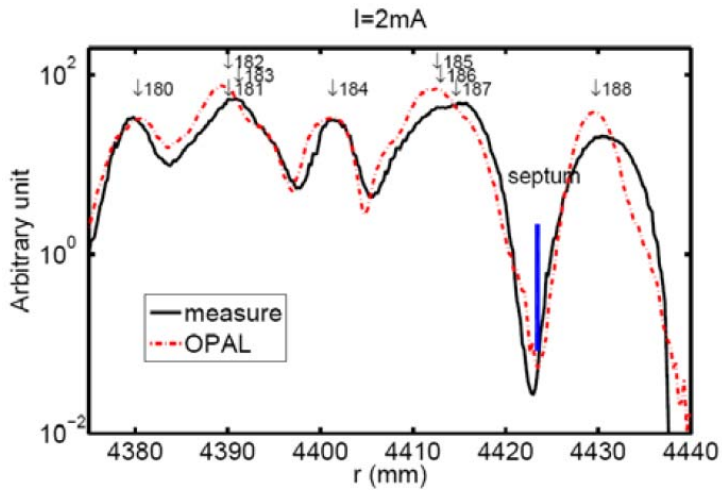
A. Mezger, PSI

beam losses & beam halo: „knowledge aspect“

detailed numerical simulations

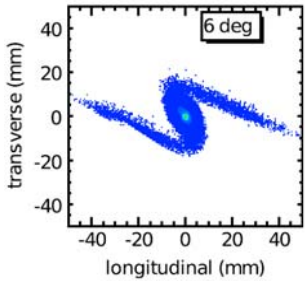
- including beam halo, scattering at collimators, 3D-poisson solver, space charge neutralisation
- lead to a better understanding of the losses: *where* (at low energies) *to cut and how to match the halo*
- a very high dynamic range is needed: every 10 nA of beam losses are important
- fitting capabilities needed in order to find the best fit to a large set of detailed profile & loss data (detailed information on quality/error has to be provided with each measurement)
- very encouraging work is in progress:

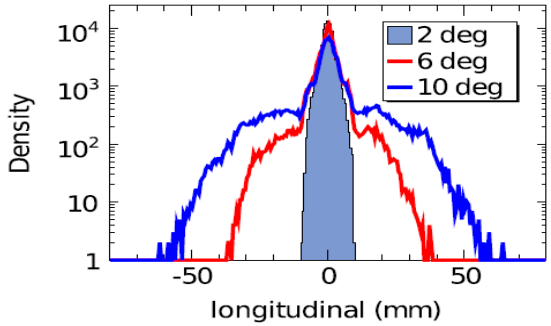
simulation of turn-pattern at exit of Ring cyclotron



Bi et al., CYC10, http://accelconf.web.cern.ch/accelconf/Cyclotrons2010/papers/mopcp045.pdf

simulation of 3 mA in Ring cyclotron including neighboring turns





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

beam losses & beam halo: „knowledge aspect“

input from beam diagnostics to *detailed* simulations of beam losses

- losses are measured with large dynamic range
  - at collimators (limited by stray particles)
  - with loss monitors

but spatial resolution is usually modest

- transverse and longitudinal profiles (1D, 2D)
- emittance (2D, 4D)

accuracy and dynamic range have limits

↓

actually it is not really clear what the requirements to precision/resolution/dynamic range of measurements are in this context

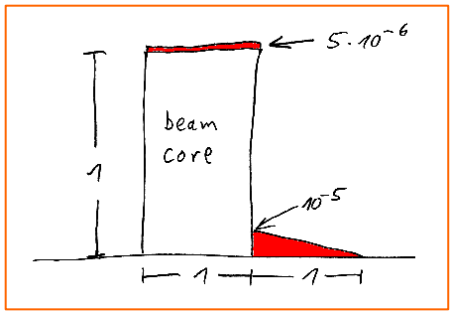
(requirements need to be evaluated by simulations)

beam losses & beam halo: „knowledge aspect“

are „future losses“ visible in in a projected 1D profile?

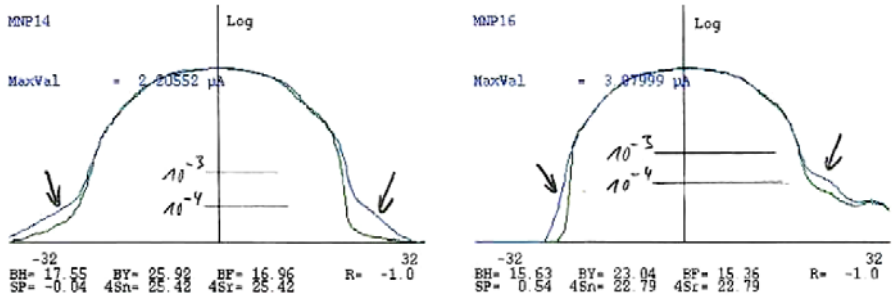
- at a high current beam (2 mA) a relevant loss (~10 nA) is a beam fraction of 5e-6

- in a projected 1D profile (e.g. from a wire scanner) a dynamic range of ~1e6 is needed to see the 10 nA compared to the 2 mA (of cause the loss particles are only visible if located in the halo and not in the beam core)



- <u>in beam lines</u> (low background & stray particles) this is feasible for wire scanners using detection of scattered particles and maybe even with direct wire current measurement

- example of purposely caused losses with known origin, which change the beam profile:



Detection of beam ions, scattered ~20 m upstream by a 33 um carbon fibre placed in the beam, with two vertical wire scanners in front of the Ring cyclotron. The beam losses in Ring cyclotron are increased by the order of 100 nA.
(This is qualitative because the logarithmic current amplifiers are too slow compared to wire speed at currents below a 3e-4 level.)

(we need to improve this by a factor of 10 to 100)

<u>in the cyclotrons</u> this is much more difficult (high background & stray particles)

→ separate measurement of beam core and halo

44 min

Thanks for listening!

beam current and its noise

at high currents:

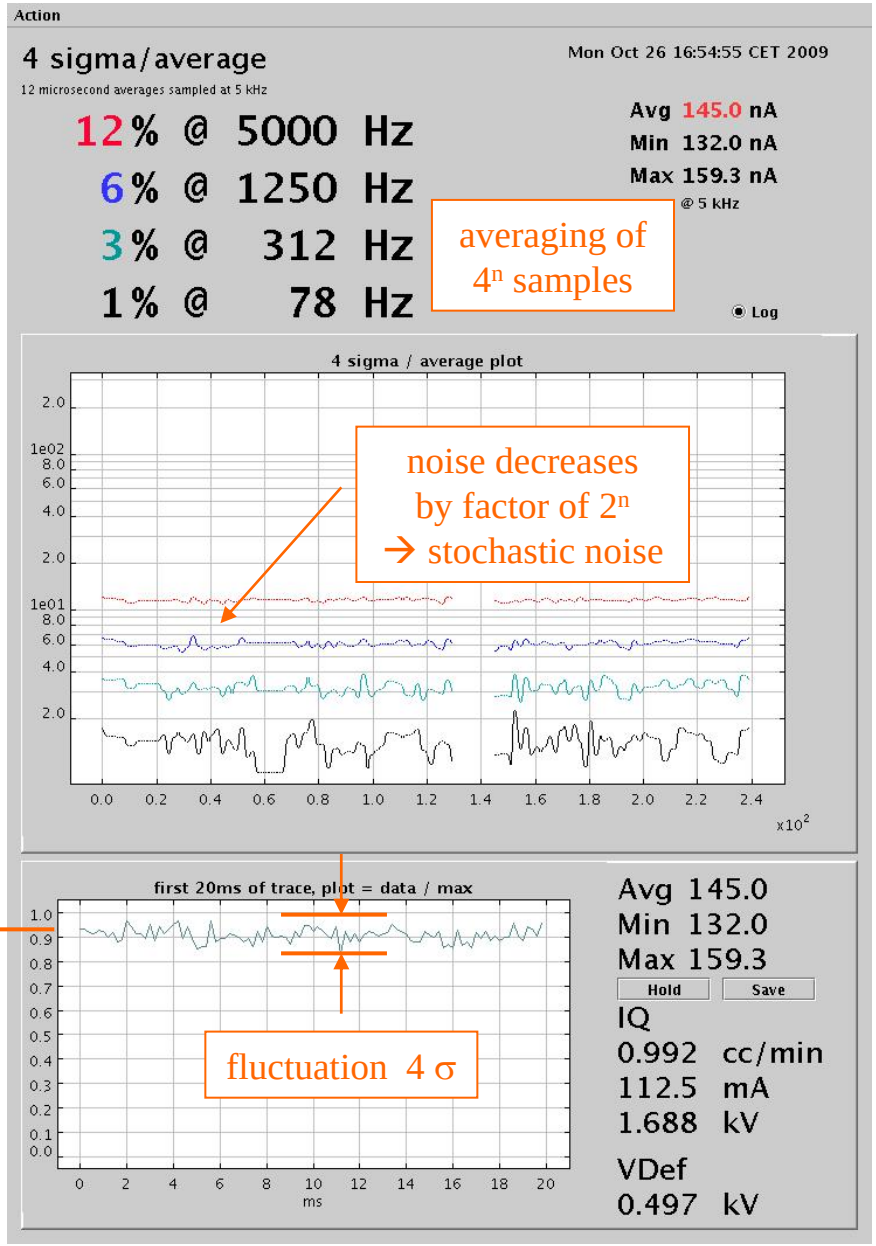
- DC/AC current transformers
  Denard, CAS2008, http://cas.web.cern.ch/cas/France-2008/Lectures/Denard.pdf
  Webber, Proc. AccApp'07 p. 145-151
- resonant cavity Reimann, Rüede, NIM 129 (1975) 53-58

at low currents:

- Cryogenic Current Comparator
  Vodel et al., DIPAC2007, http://accelconf.web.cern.ch/AccelConf/d07/papers/wepb30.pdf
- thin SEMs or ionisation chambers (scattering!)

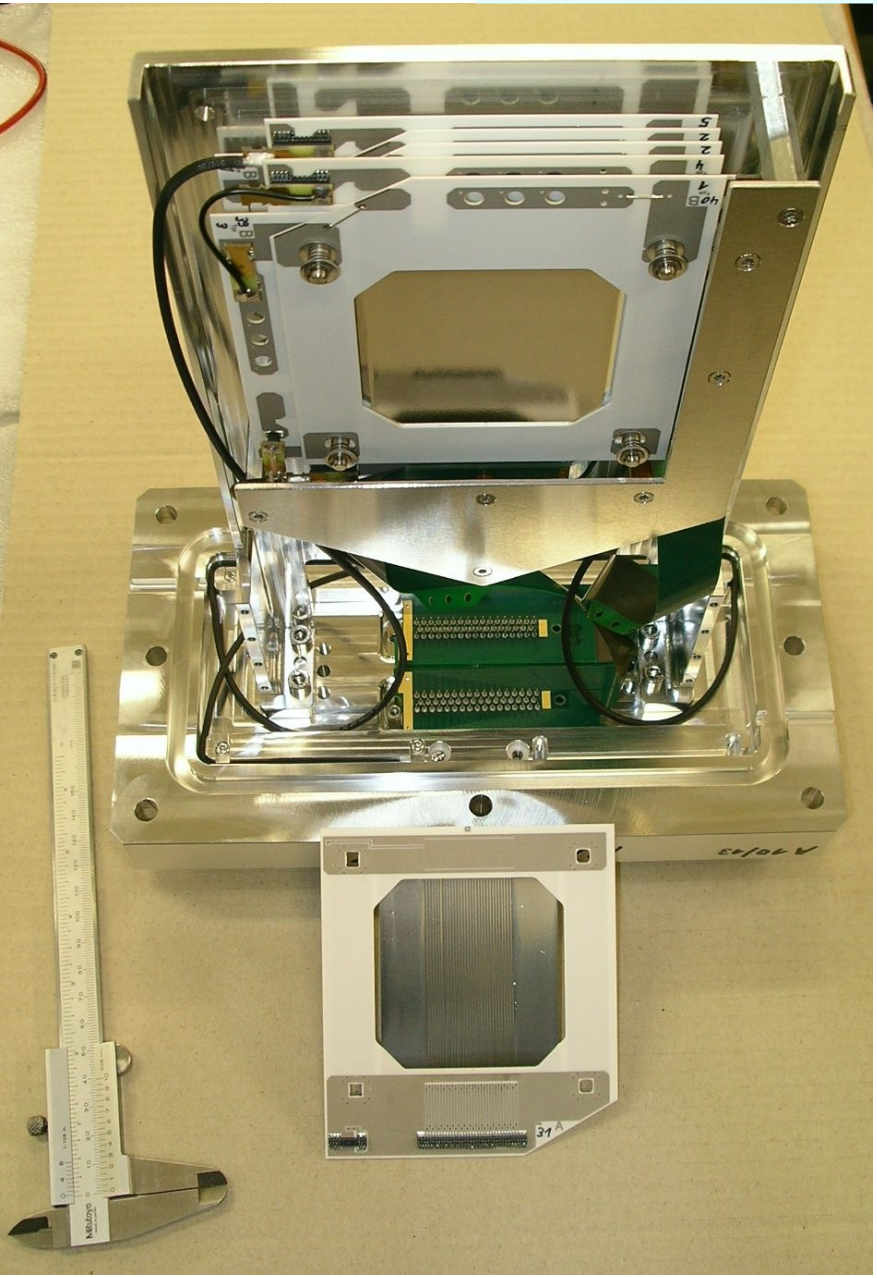
example:
ionisation chamber behind PSIs medical cyclotron
Dölling et al., Proc. AccApp'07 p. 152-159

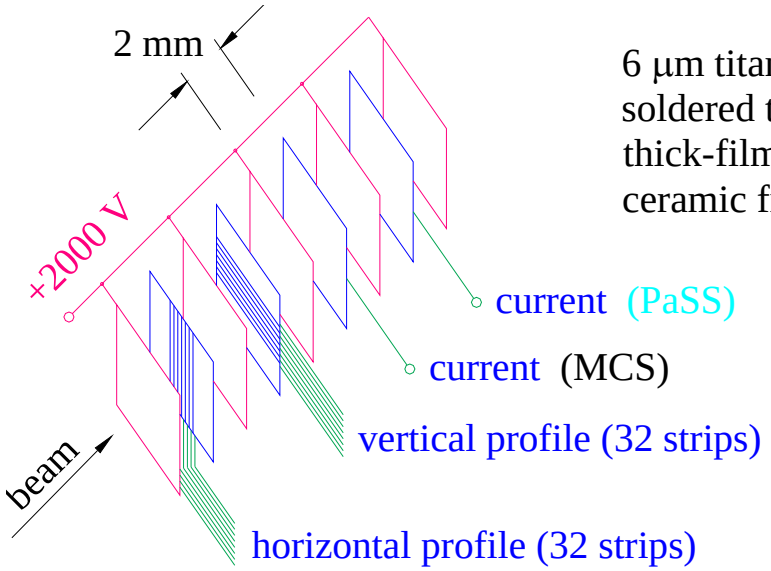
measures current fluctuations from the internal ion source
Schippers et al., CYC07, http://accelconf.web.cern.ch/AccelConf/c07/PAPERS/300.PDF



average beam current

beam current and its noise





6 µm titanium foils soldered to thick-film coated ceramic frames

thin SEM or ionisation chamber behind PSIs medical cyclotron

used for proton beam 250 MeV

IC: in a N_2 filled box
with thin Ti-windows
signal amplified by 43
thermal limit: 1 µA beam

SEM: in vacuum
signal „amplified“ by 0.053
microphonics

Dölling et al., Proc. AccApp'07 p. 152-159