Beam Diagnostics for Cyclotrons

Educational Session, ECPM XXXVII, Groningen, 28-31 Oct. 2009

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A) basic physics: effects used for transversal profile measurement

B) diagnostics along the beam path

- ion source & injection line: matching the beam to cyclotron acceptance
  emittance, profile, current
- injection, central region: beam shaping & current set, betatron oscillation alignment
  current, rough profile, collimator currents
- acceleration: adjustment of magnetic field and RF fields
  current, rough profile, bunch phase
- extraction: efficiency, beam parameters, stability
  current, profile, longitudinal profile, emittance

C) machine protection & control of activation
  loss monitors, collimator currents

categorisation of beam measurements

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beam properties

- current of full beam
- transverse position of full beam
- phase of bunch center
- transverse profile - projection
  - 2D
- transverse emittance - 1D
  - 2D
- longitudinal profile
- longitudinal emittance
- beam ion energy distribution

usage

- for machine safety
- permanently
- for tuning
- at setup
- for error search
- only at commissioning

familiar monitors

- current transformer (DCCT, ACCT), Faraday-cup
- beam position monitor (BPM capacitive or inductive coupling)
- phase probe (capacitive coupling)
- wire monitor, wire grid („harp“)
  screen
- emittance measurement device (slit-slit/slit-grid/Allison/3 profile/Q-pole variation)
  pepperpot

monitor properties

- resolution
- temporal resolution / rate
- destructive vs. non-destructive (loss of beam up time, machine activation)
- low current limit (sensitivity, noise)
- high current limit (thermal damage, outgassing/sputtering)
- life time (radiation damage/hardness)
- reliability, cost, ...

special „cyclotron environment“ for monitors, drives, cooling

- high magnetic field / stray field (particularly compact cyclotrons)
- little space (particularly compact cyclotrons)

  → compact monitors, no radiation shielding, nearby activated components, RF nearby

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how to spend only 45 minutes on the vast field of diagnostics of cyclotrons & their injection lines? (disclaimer)

• focus on measurement principles / monitors relevant for tuning & performance
nearly nothing about details / technical issues / the „art of construction“ / electronics

• examples are only examples:
most examples based on PSI machines, but
many different machines with different diagnostic needs
many other variants of diagnostics in operation worldwide for a long time
choice of references is subjective

• useful methods are usually not new: nearly everything is described in the 1960‘s to 1980‘s and hidden somewhere in Proc. Int. Conf. on Cyclotrons and their Applications (ICCA)
Clark, ICIC1966, http://accelconf.web.cern.ch/AccelConf/c66/papers/a-002.pdf, Olivo, ICCA1975, p. 331-340

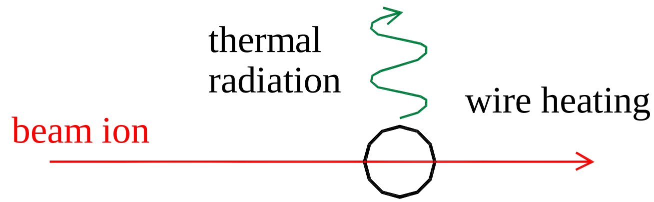
• more information on beam diagnostics (mostly not from cyclotrons):

JACoW, http://accelconf.web.cern.ch/accelconf/ (includes Proc. ICCA since 2001)
Forck, JUAS 2009, http://www-bd.gsi.de/conf/juas/juas_script.pdf
Wittenburg/Braun/Bravin et al. CAS 2008, http://cas.web.cern.ch/cas/France-2008/Lectures/Dourdan-lectures.htm
Wittenburg, HB2006, http://accelconf.web.cern.ch/AccelConf/abdwhb06/PAPERS/TUAZ01.PDF
Raich, DIPAC2005, http://accelconf.web.cern.ch/AccelConf/d05/TALKS/ITMM01_TALK.PDF
Brandenburg et al., DIPAC03, http://accelconf.web.cern.ch/AccelConf/d03/papers/CT10.pdf
Dölling, DIPAC2005, http://accelconf.web.cern.ch/accelconf/d05/TALKS/ITTA02_TALK.PDF
• • •

effects used for transversal profile measurement

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

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



P_{in} = wire mass * stopping power * beam current density
[V A] [kg] [V m^2/kg] [A/m^2]

„direct" temperature measurement 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 temperature measurement 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

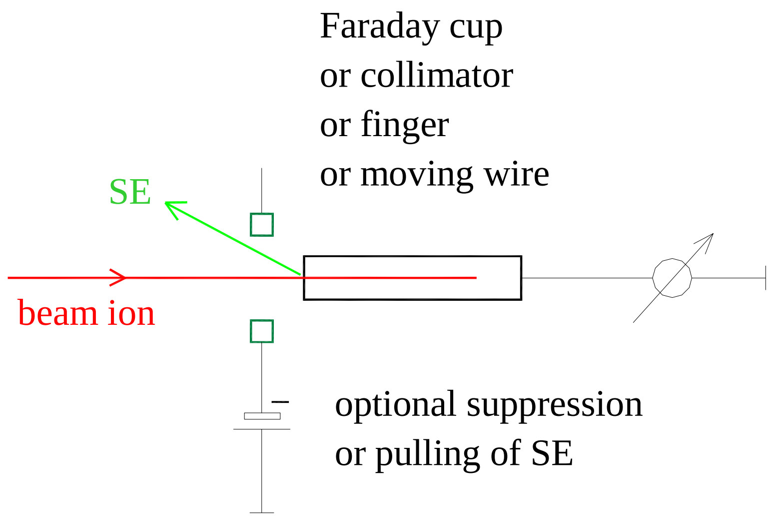
Liaw, Cameron, PAC2001, http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/WPAH120.PDF
Sapinski, Kroyer, BIW08, http://www.als.lbl.gov/biw08/papers-final/TUPTPF066.pdf

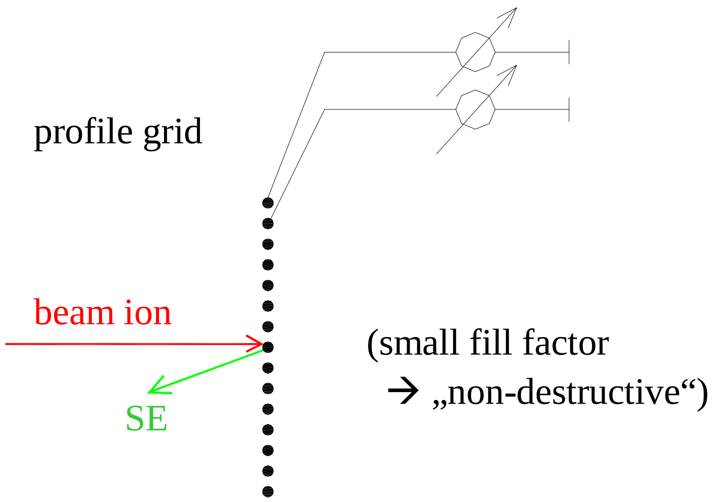
Example: carbon fibre, diameter 33 um

- 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

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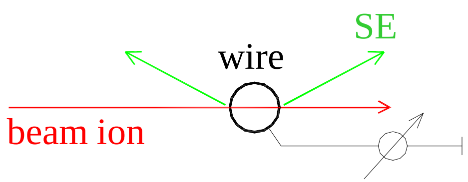
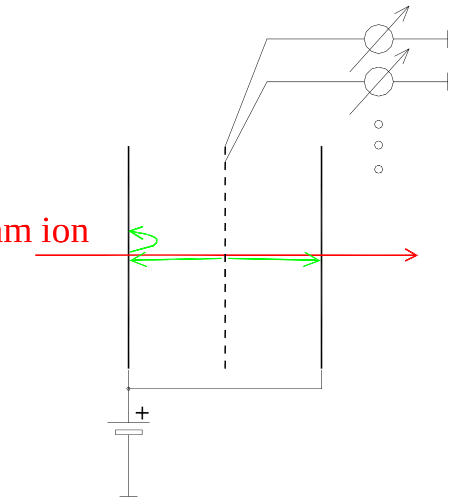




wires or strips
or full foil
(fill factor, thickness
→ destructive or „not“)

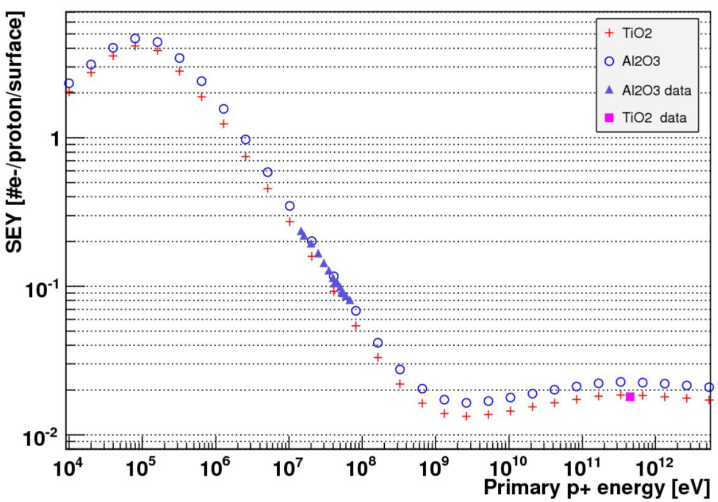
- at higher energies: ions not stopped,
  signal only from SE

- 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

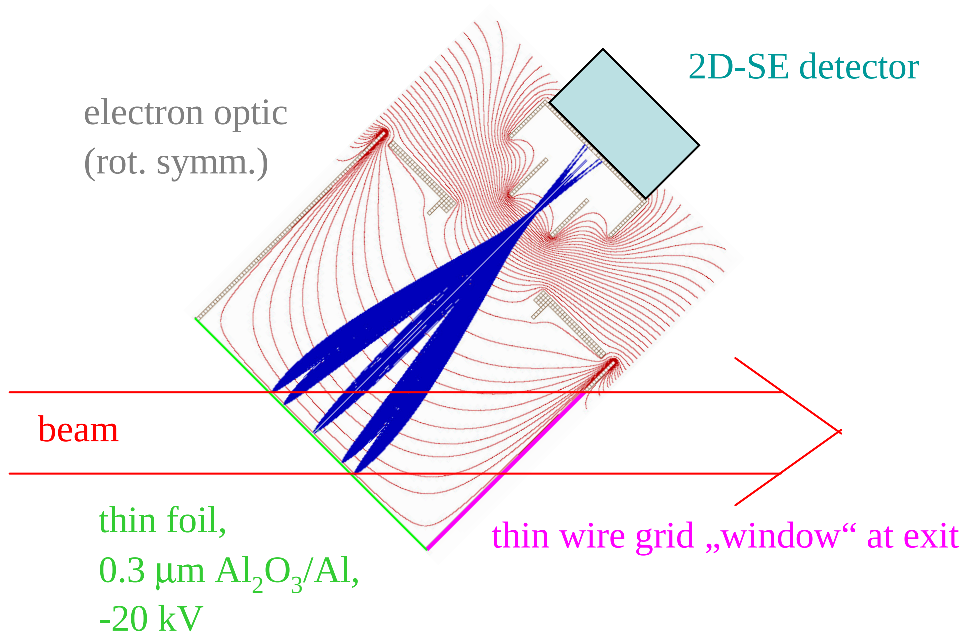
- SE-yield depends on irradiation history,
  Titanium is good Ferioli, Jung, DIPAC97, pp. 168-170

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



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

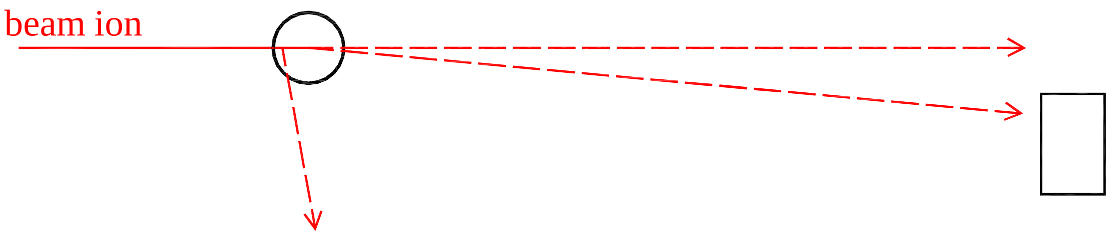
secondary emission current, 2D-measurement



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

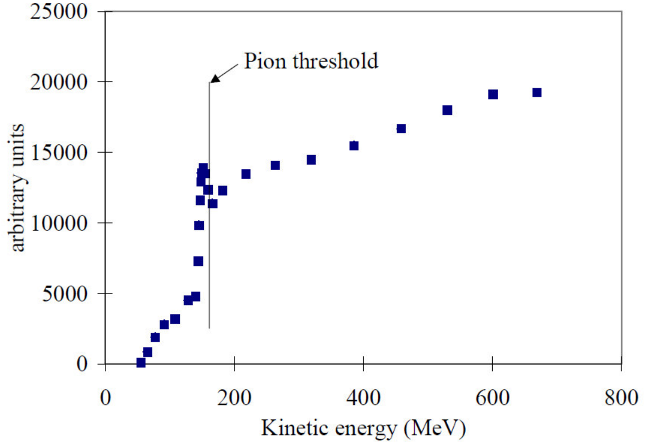


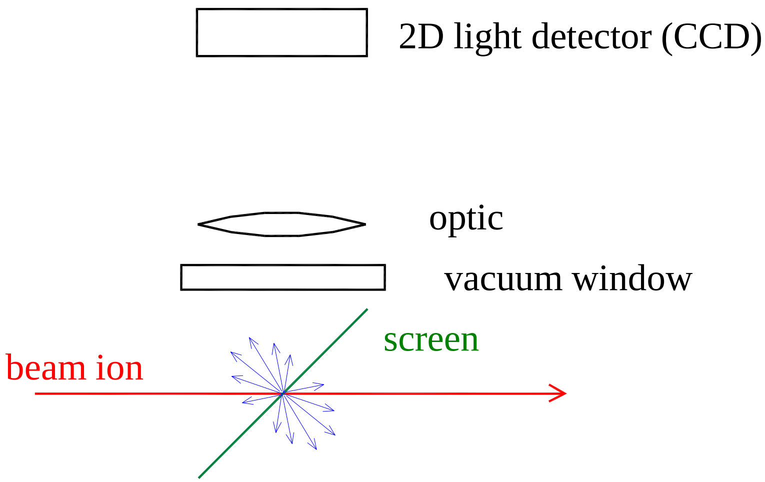
- scattering at high and low energies
  (at not too low energies ~according to Rutherford formula)

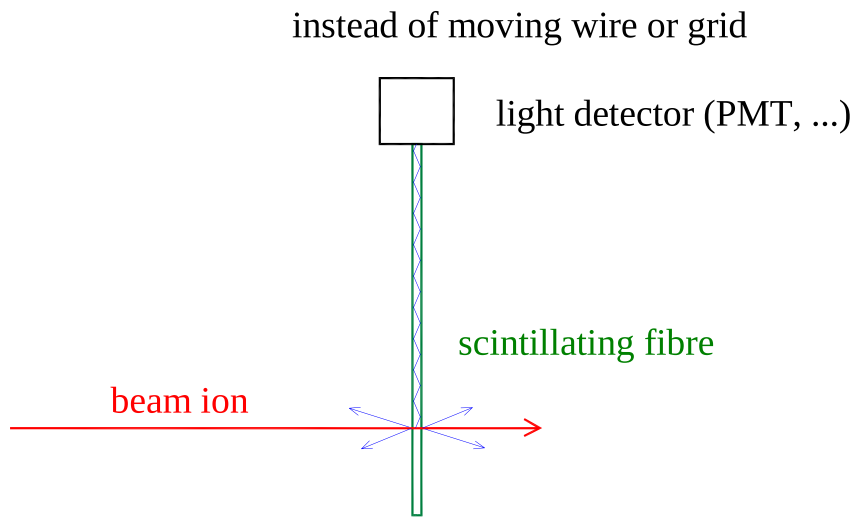
- creation of secondaries at higher energies

- very large dynamic range (if background radiation low)

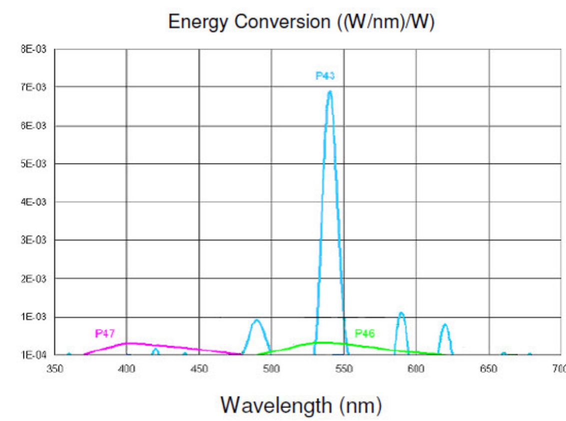
Raich, DIPAC05,
http://accelconf.web.cern.ch/AccelConf/d05/TALKS/ITMM01_TALK.PDF







- 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
Re et al. PAC2005, http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/RPAT002.PDF

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

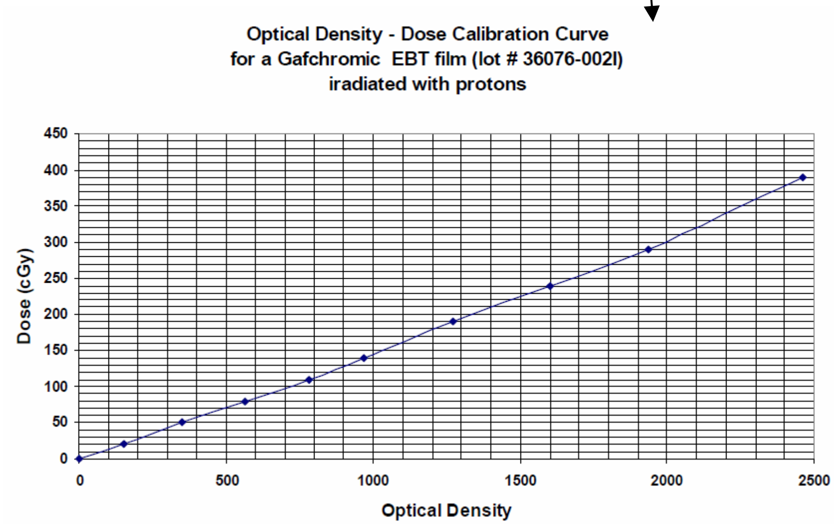
http://www.gafchromic.com/

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

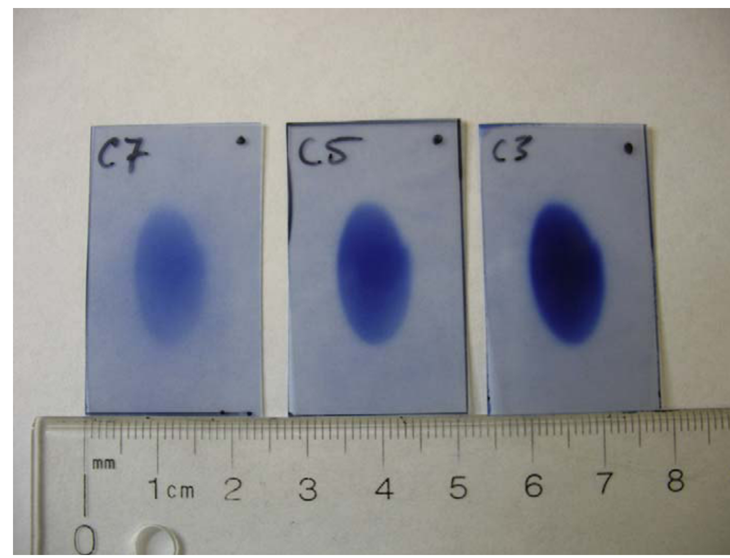
foil activation

- 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



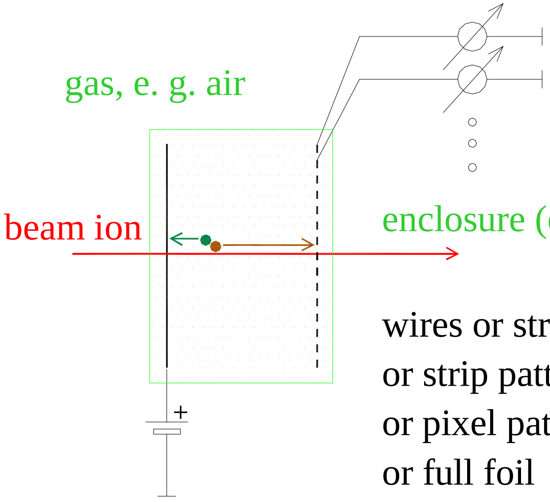
Bues, PTCOG45, http://online1.ispcorp.com/_layouts/Gafchromic/content/presentech/pdf/14MBues.pdf



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

ionisation chamber

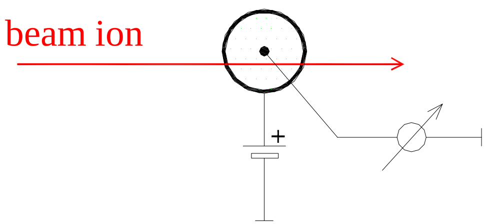
gas, e. g. air



enclosure (excludes stray particles)

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

	stopping power	gas density	gas length	energy per ion pair
	[eV m^2/kg]	[kg/m^3]	[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 * (high voltage)$^{-1}$ * k^{-1}

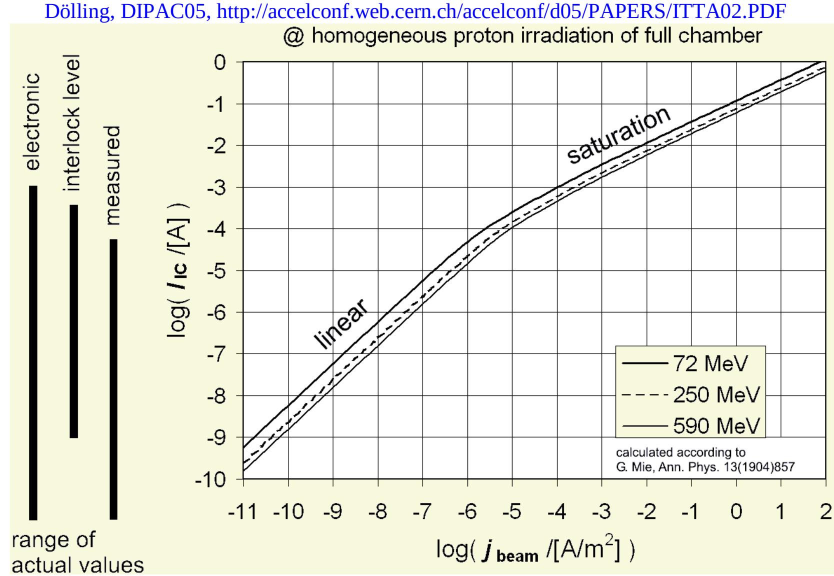
  example: gap 10 mm, high voltage 300 V

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

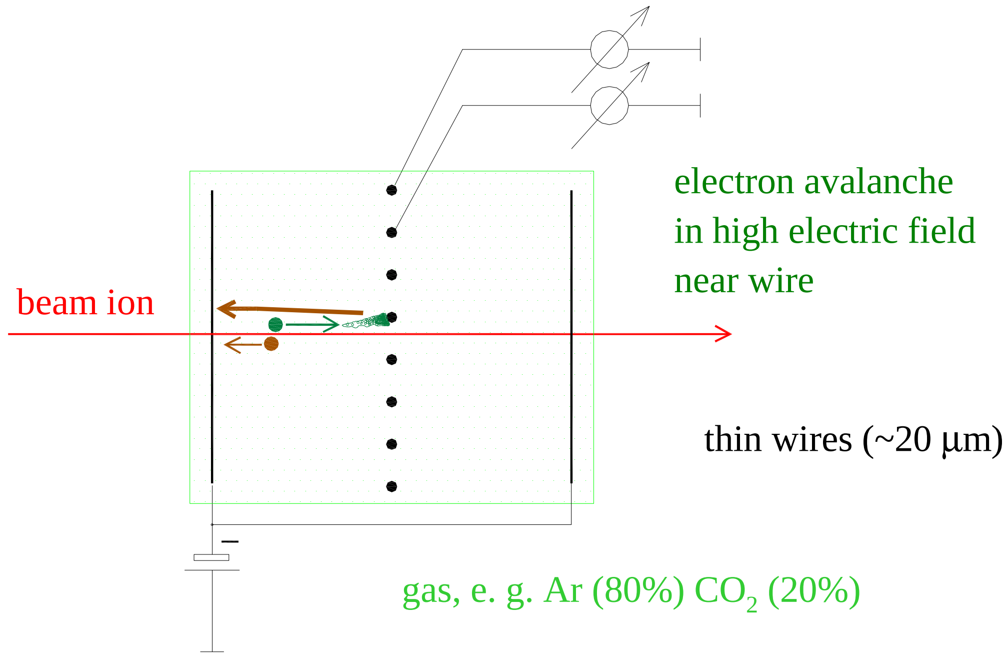
- faster if only electrons used for signal
  („Frisch-grid chamber", nitrogen filled, t_{coll} ~µs)

- 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

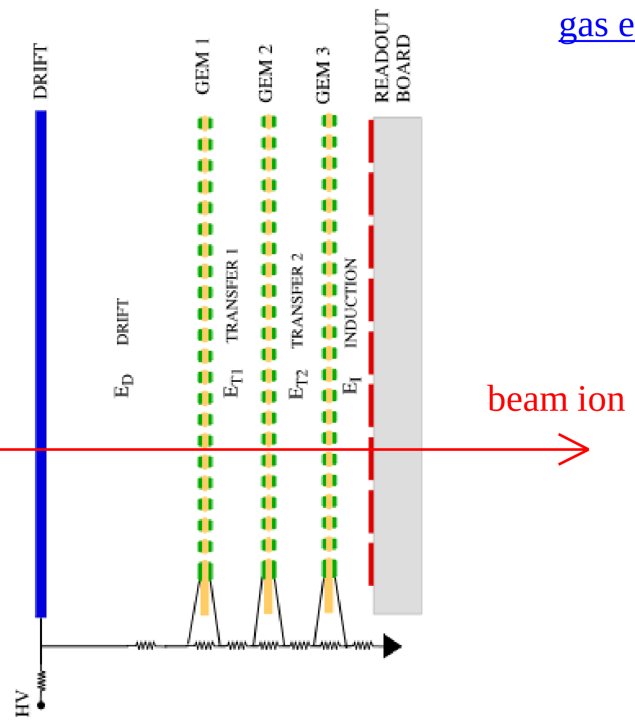


proportional chamber



- 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)

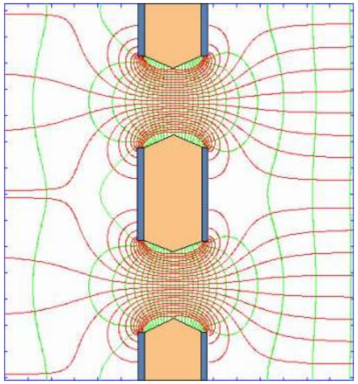


front: ionisation chamber

gas, e. g. Ar (70%) CO_2 (30%)

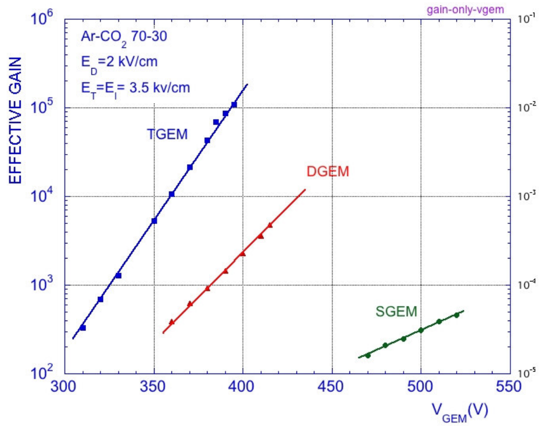
middle: 1-3 GEM foils

rear: strip pattern 1D or 2x 1D or pixels



electron avalanche
in high electric field
in holes

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

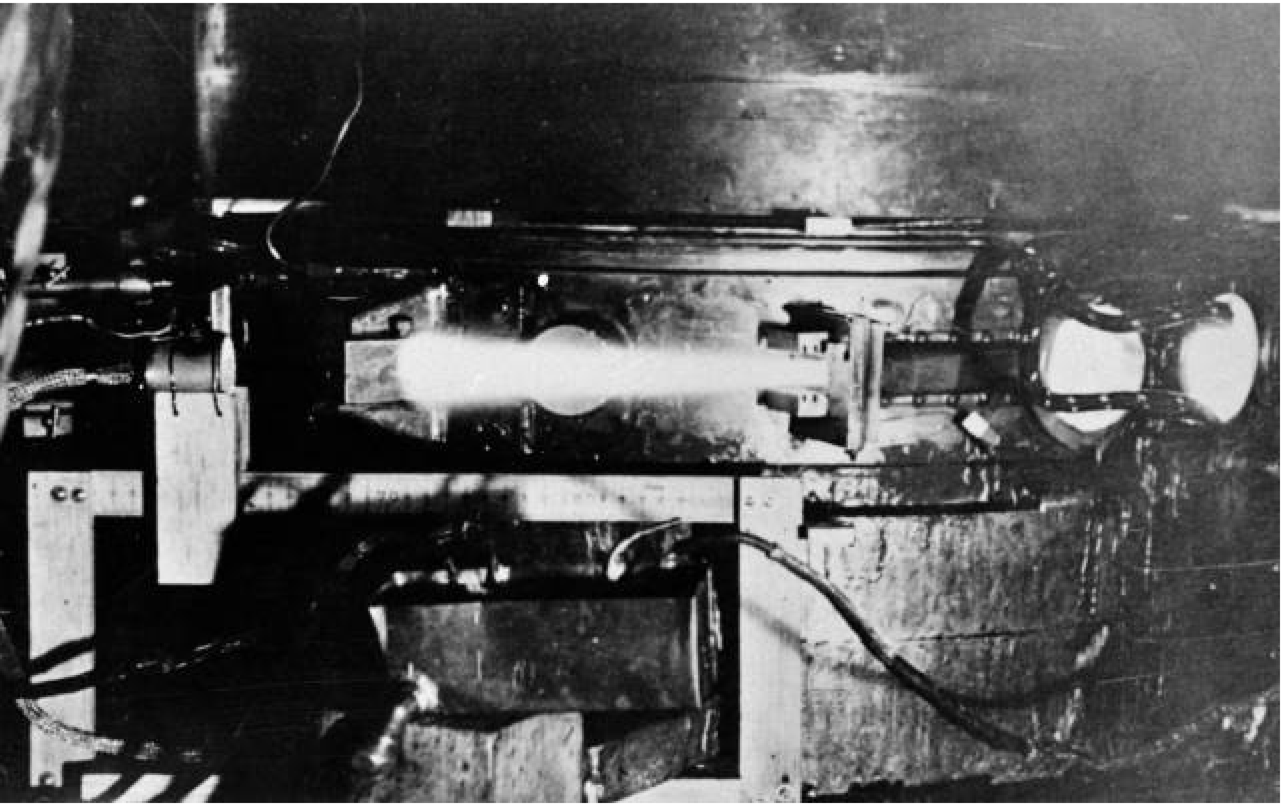


- less discharges with more GEMs
- amplification not dependent on beam current density

  → linear (at not too high current densities)
- radiation hard
- gas flow needed

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

beam induced fluorescence



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

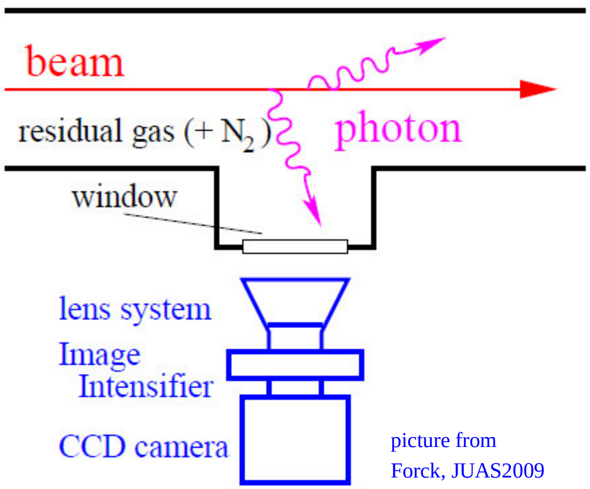
in air: deuterons stopped after half a meter

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

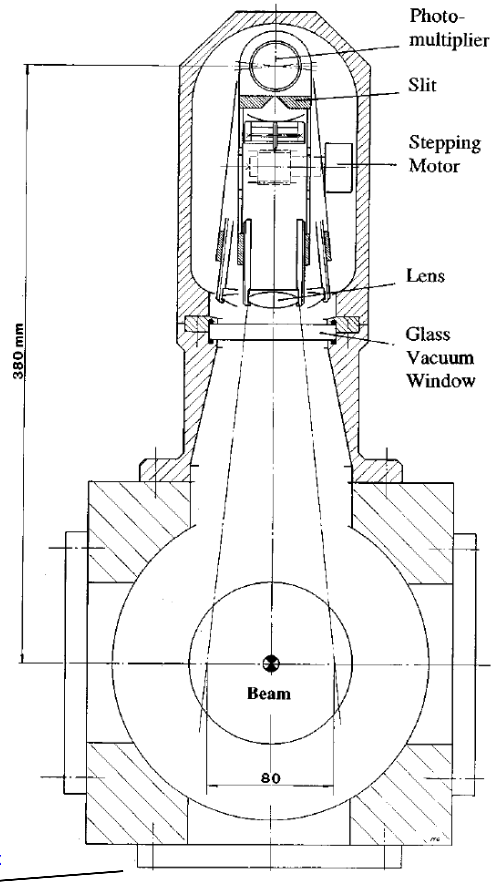
in residual gas: distance earth – moon (i. e. non-destructive)

very faint glow

beam induced fluorescence



picture from
Forck, JUAS2009



- detectors

  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

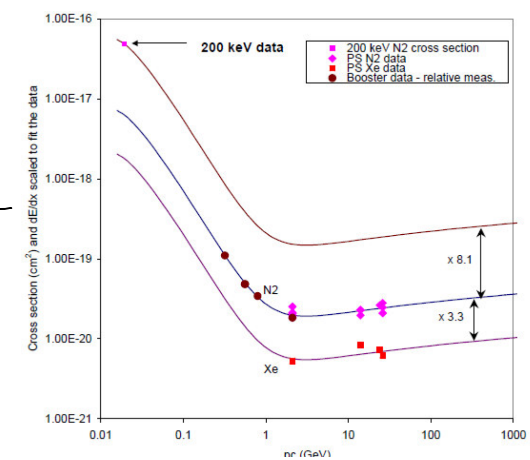
  multichannel PMT — Plum et al., LHC Emittance Workshop (2000), see below
  Dietrich et al., EPAC08, http://accelconf.web.cern.ch/AccelConf/e08/papers/tupc022.p

  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

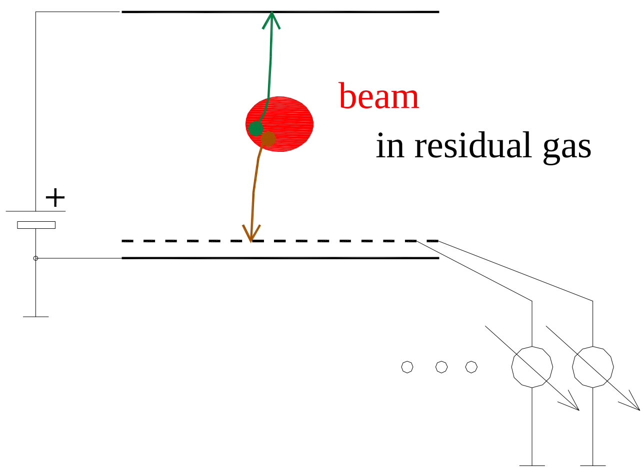


- spectral components — Becker et al., DIPAC09, http://accelconf.web.cern.ch/AccelConf/d09/papers/tupb02.pdf
  Ausset et al. EPAC02, http://accelconf.web.cern.ch/AccelConf/e02/PAPERS/THPRI066.pdf

- distortion & limited dynamic range by

  background radiation, delayed deexcitation (in helium gas) & reflections

residual gas ions (with external fields)



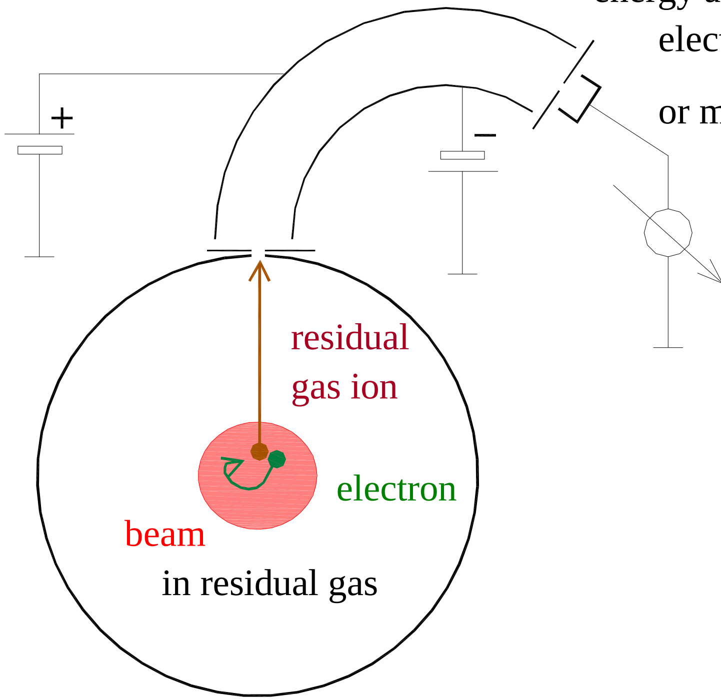
1D-detector for residual gas ions
(strip pattern & current measurement
or MCP + CCD or ...)

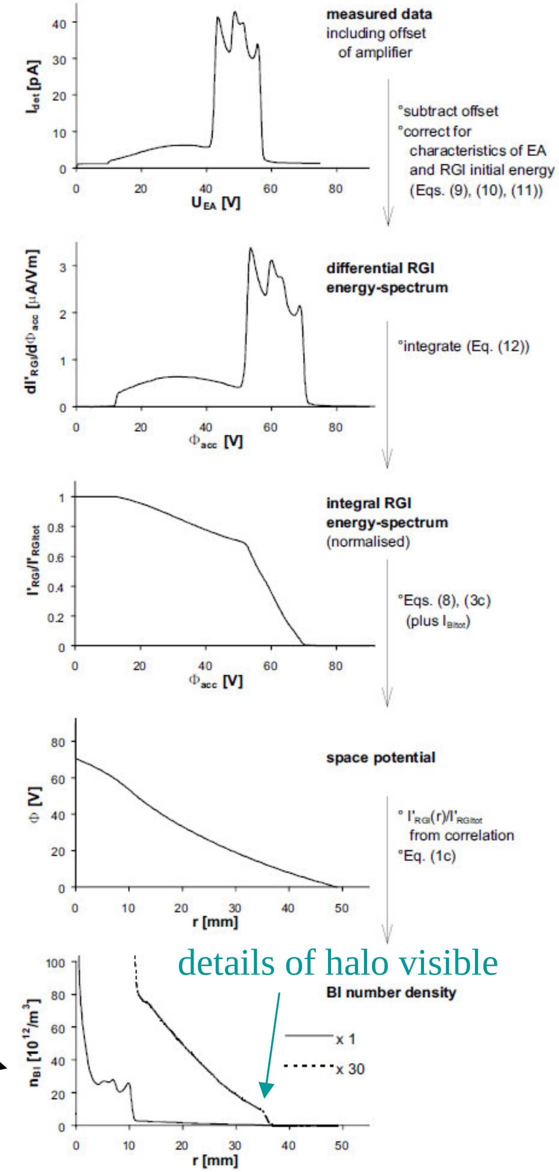
- profile broadened by beam space charge (improved by vertical magnetic field & detecting electrons)
- non-destructive but eventual beam space charge neutralisation disturbed by external electric field
- sensitive

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

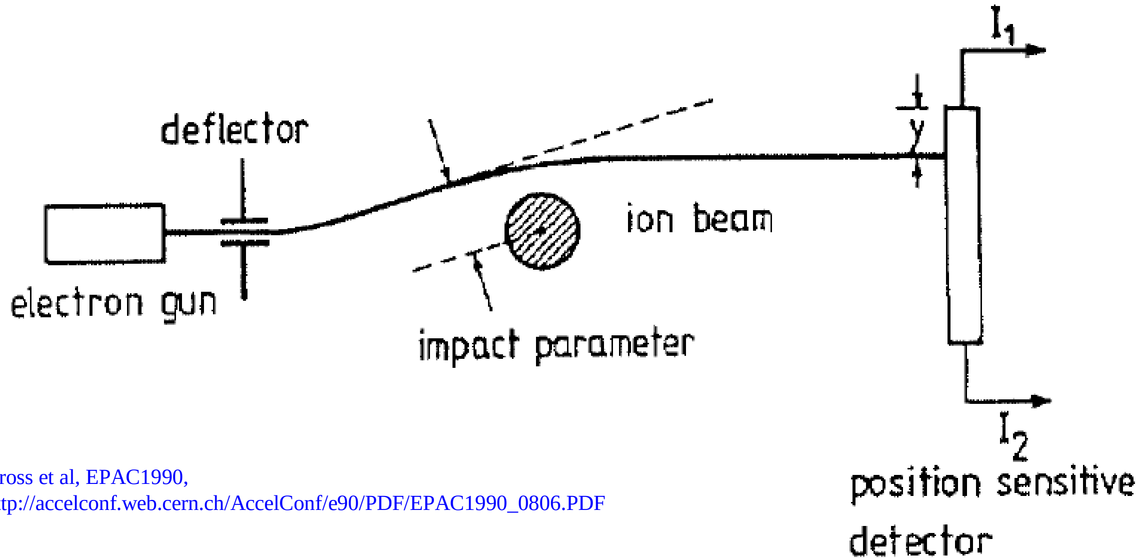




- beam ion distribution creates residual gas ions & accelerating potential
- a positive beam potential depth of at least a few V is required
- analytical solution for charge density distribution of round non-neutralized beams
- non-destructive
- distortion of signal by charging of surfaces & stray magnetic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

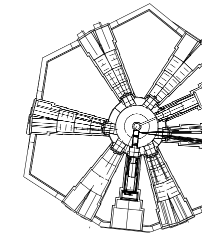
classification

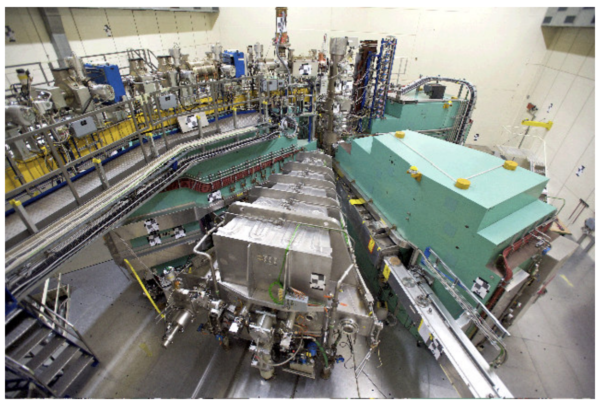
configuration	effects usable for profile (or rough position) measurement in a cyclotron or its injection line	used A) for machine safety B) permanently C) for tuning D) at setup E) for error search F) only at commiss.	destructive	beam current range (assumed DC beam at 70 MeV, 10 mm diameter, to be determined more precisely)
	heating of introduced solid matter			
in full beam	probe finger: direct temperature measurement	D E	yes	nA … uA
beam edge	collimator: -"-	B C D	"no"	nA … mA
wire	vibration resonance shift	C D E	~no	pA … uA
wire	wire: resistance	C D E	~no	uA … mA
in full beam	metal foil: thermal light emission/thermionic emission	A B F	~yes	uA
wire	wire: -"-	C D E	~no	-
	direct beam current			
in full beam	probe finger: current of stopped beam fraction	D E	yes	nA … uA
beam edge	collimator: -"-	A B C D	"no"	pA … mA
wire	wire: -"-	C D E	~no	-
	secondary particles from introduced solid matter			
wire	wire: secondary emission current, direct measurement	C D E	~no	pA … mA
beam edge	foil: -"-	A B C D E	"no"	pA … uA
in full beam	foil: secondary emission current, 2D-measurement	A B C D E	~no	pA … uA
wire	wire + detection of scattered or secondary particles	C D E	~no	nA … mA
in full beam	scintillating screens	C D E	yes	pA … uA
"wire"	scintillating fibres + PMT	C D E	~no	<pA … nA
	changes to introduced solid matter			
in full beam	paper/Kapton darkening	F	yes	nA … uA
in full beam	radiochromic film	F	yes	<pA … nA
in full beam	foil activation analysis	F	yes	pA … uA
	secondary particles from introduced dense gases			
in full beam	ionisation chamber	(B) C D E	~yes	<pA … uA
in full beam	proportional chamber	C D E	~yes	<<pA … nA
in full beam	GEM	C D E	yes	<<pA … nA
	secondary particles from residual gas			
residual gas	beam induced fluorescence	A B C D E	no	mA … >A
residual gas	residual gas ions (with external fields)	A B C D E	~no	uA … A
residual gas	residual gas ions (with beam space charge field)	?	no	mA … >A
	beam space charge field			
"wire"	electron beam probe	B C D E	no	mA … >A

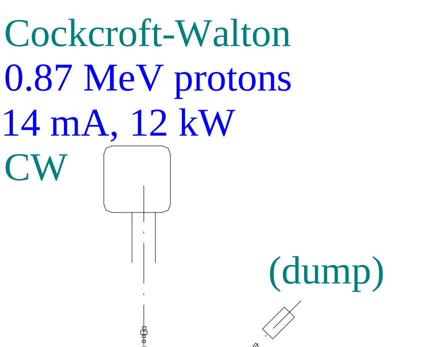
diagnostics along the beam path

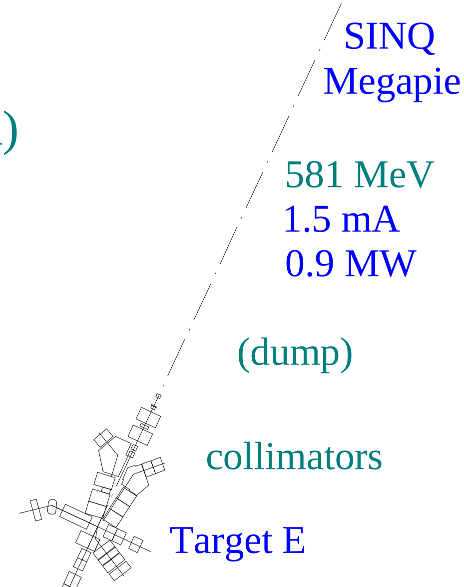
most examples from Inj. 2 cyclotron of PSI's high power proton facility

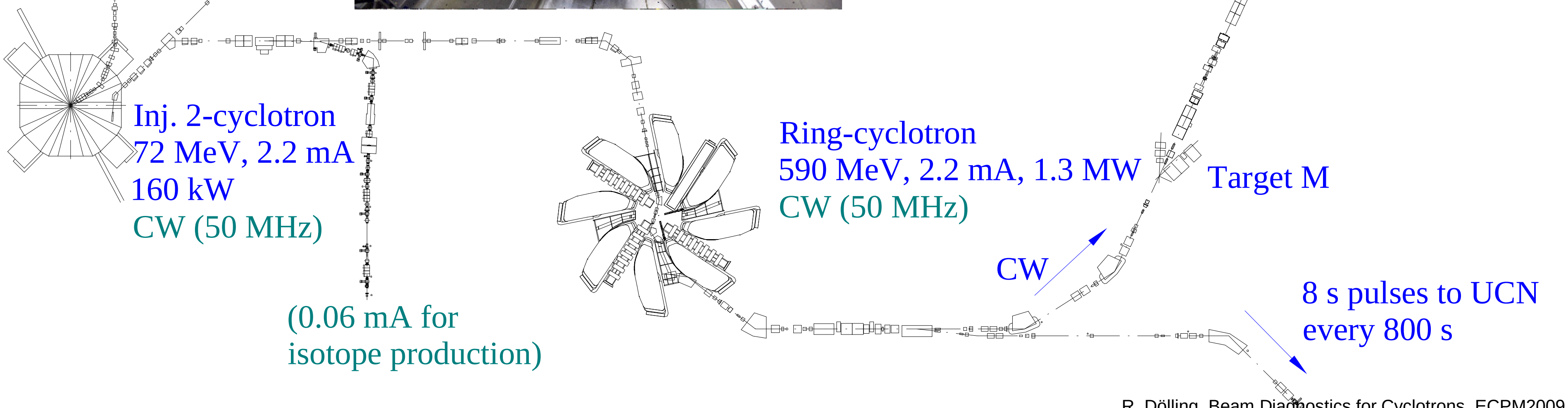
- part of "user lab" ~400 users/a
- targets M, E for meson production (graphite)
- spallation neutron source SINQ since 1998 (solid stainless steel + Pb target)
- test with liquid Pb-Bi target Megapie in 2006
- ultra cold neutron source UCN in 2010 (solid zircaloy + Pb target)
- operates 4800 h/a ≈ 240 d/a ≈ 9000 mAh/a
- ring cyclotron in operation since 1974 (100 µA design goal --> 2.2 mA)







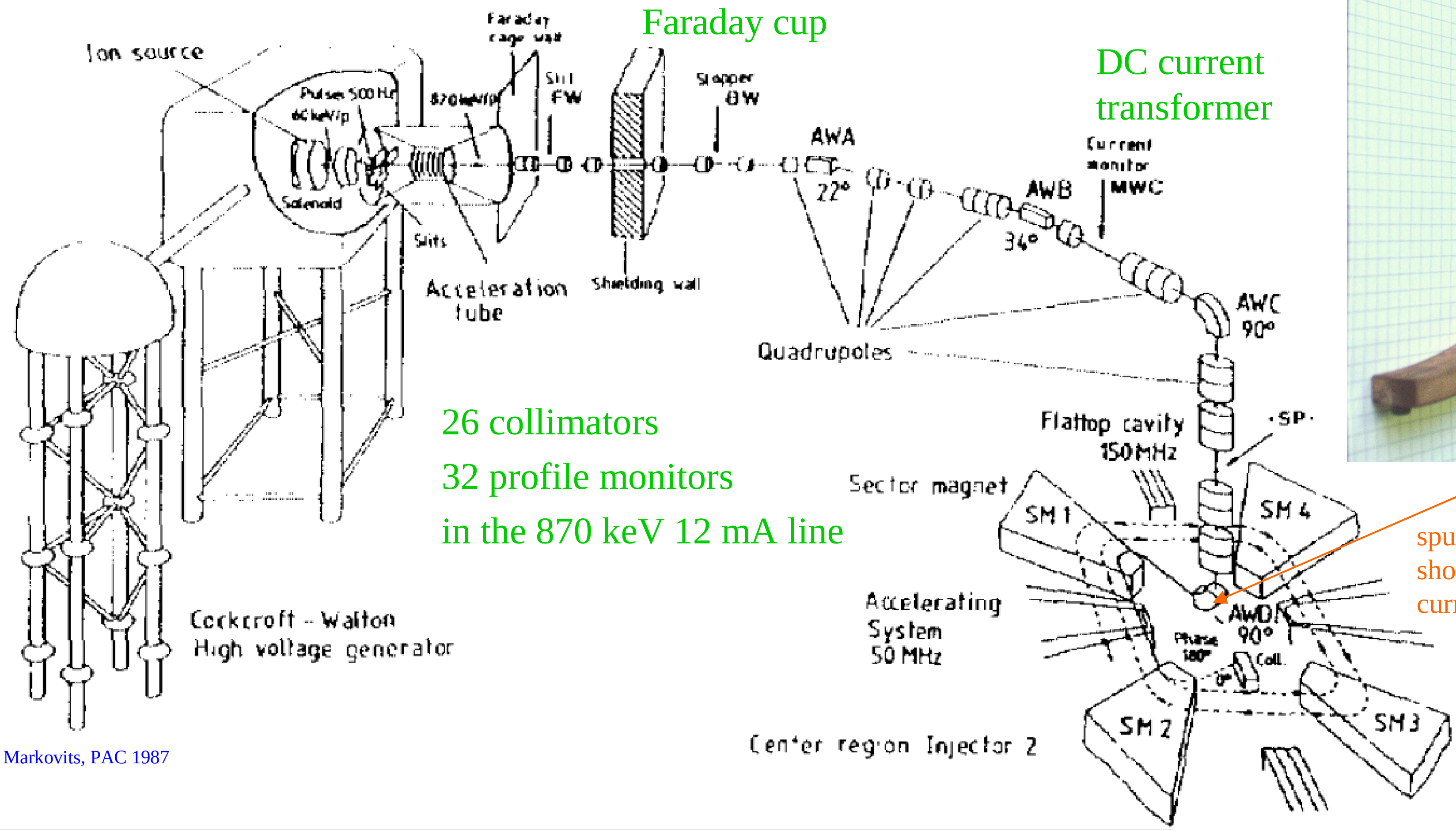




- high beam power
- separated sectors
  → some space for diagnostics

injection line: matching the beam core to the cyclotron acceptance

- collimator current readout and interlock generation protects the machine
- beam positions and widths are needed for a proper alignment of the beam used at routine machine set-up (or for online centering)
- beam profiles give hints in case of problems
- needs reproducible but not very detailed results (preferably at low & full beam current)



Faraday cup

DC current transformer

26 collimators

32 profile monitors

in the 870 keV 12 mA line

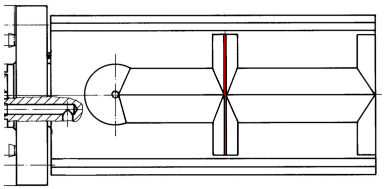
Markovits, PAC 1987

sputtered material
short-cutted
current measurement
→ melts in ~1 s

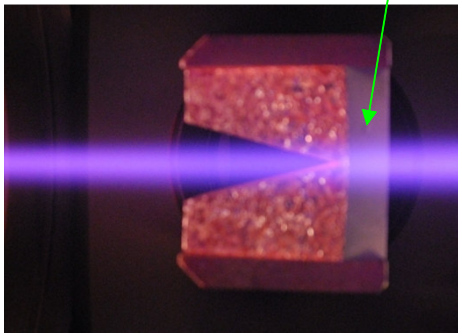
profile monitors

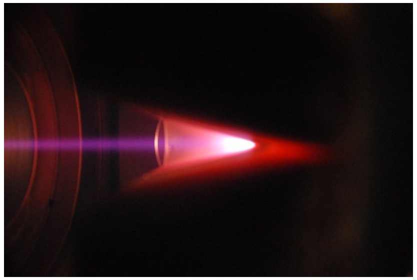
- thermal slit scanner
  (at 60 keV)
  destructive

Olivo, ICCA1987 p. 519-22



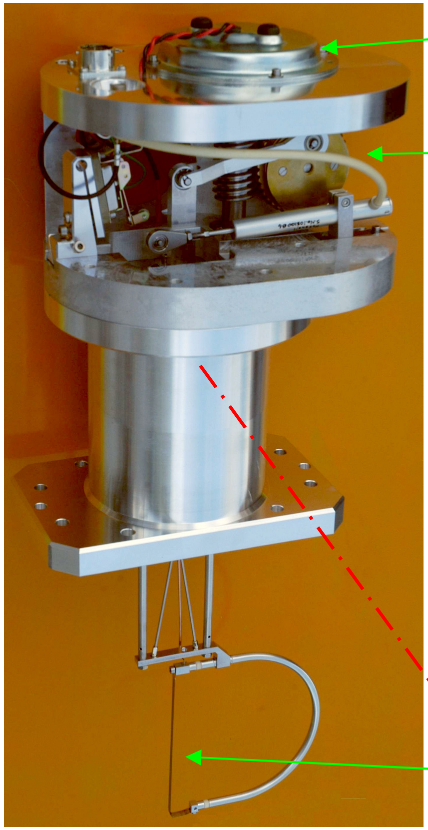
- internal cooled copper block
  behind vertical slit
- measurement of
  water in-/outlet
  temperatures





wire scanner
(870 keV 12 mA
up to 15% DC)

Rezzonico, ICCA1987 p. 457-60



motor

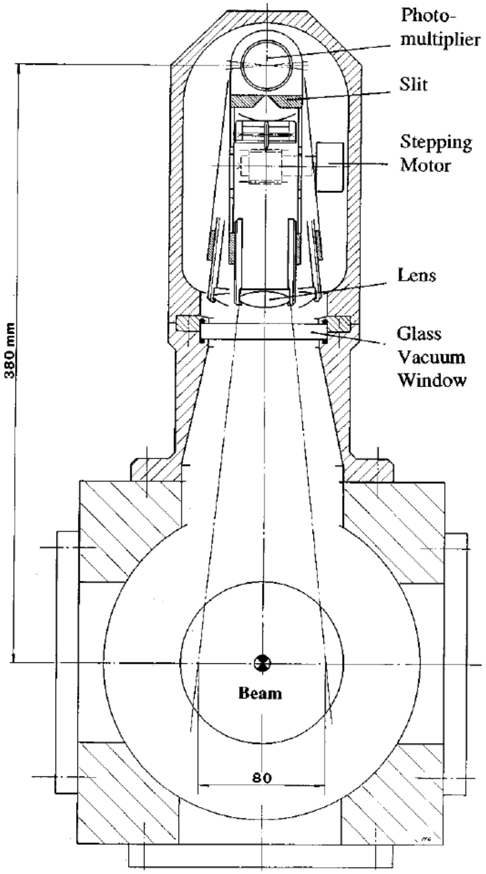
worm gear
crank
con-rod

pendulum axis

wire or foil
(isolated)

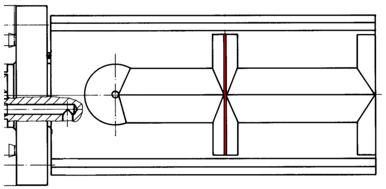
-beam induced
fluorescence monitor
(870 keV full beam)

PMT + Lens scanned
non-destructive

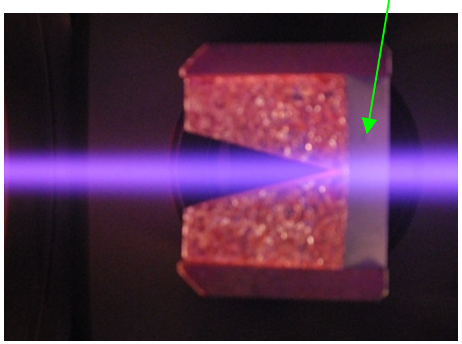


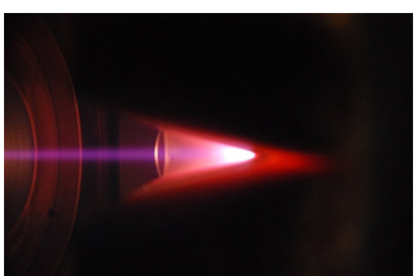
- thermal slit scanner
  (at 60 keV)
  destructive

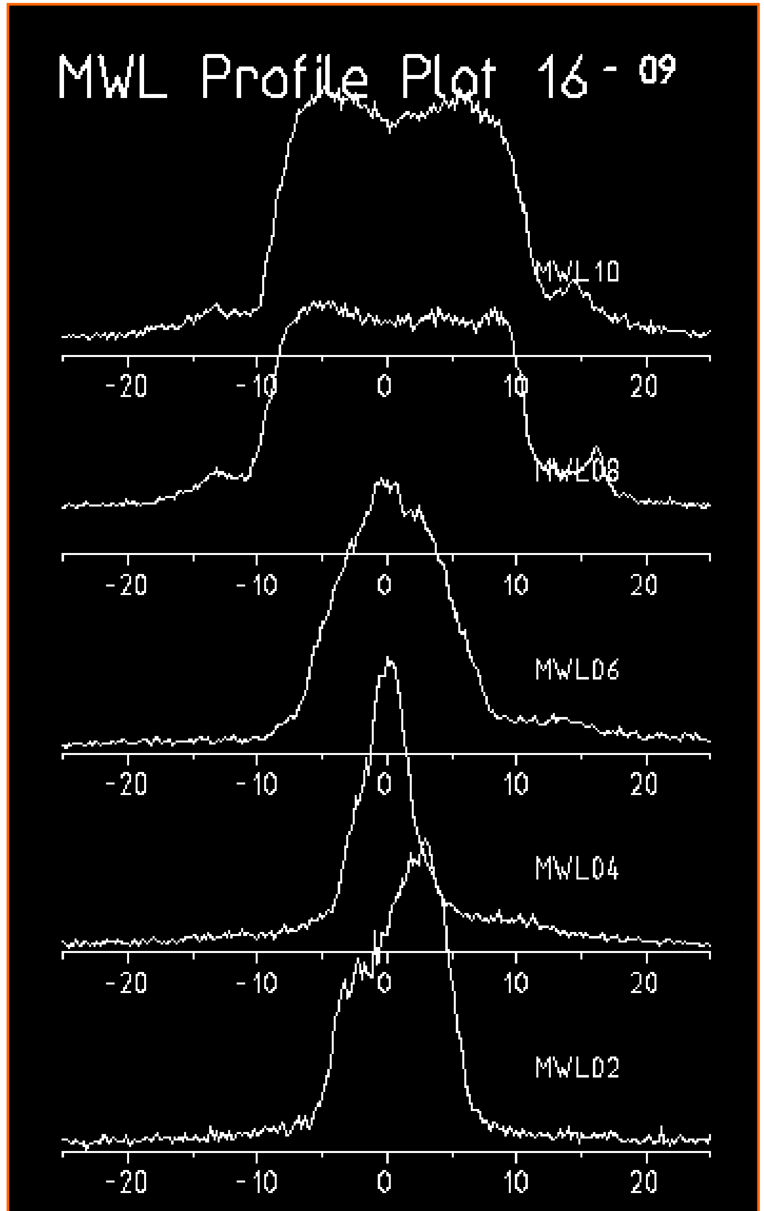
Olivo, ICCA1987 p. 519-22



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



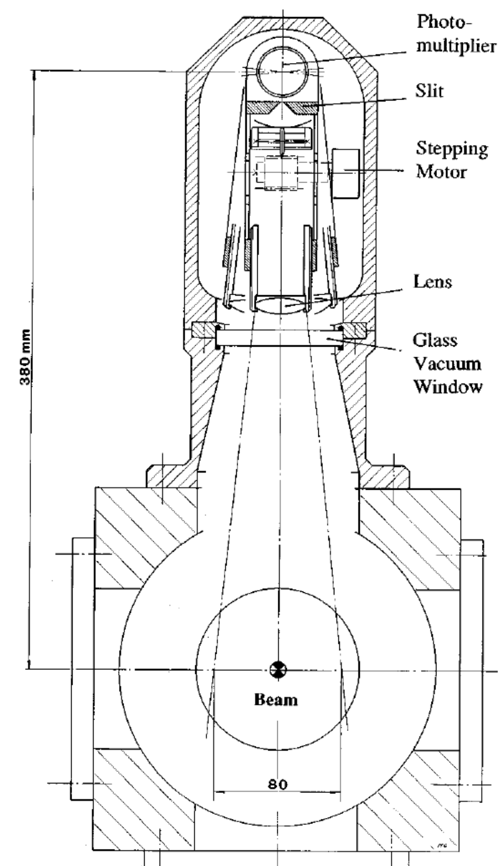




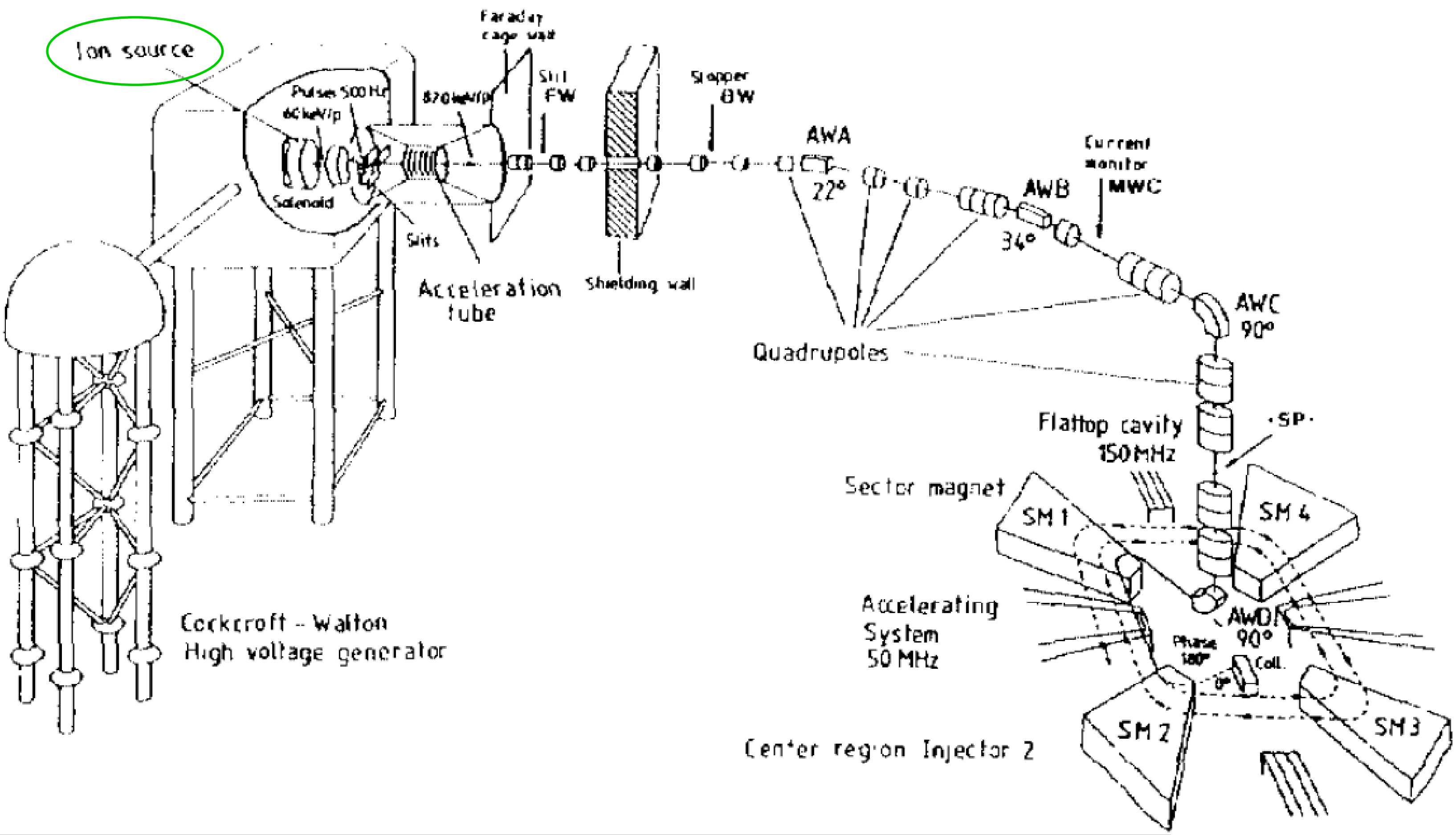
-beam induced fluorescence monitor (870 keV full beam)

PMT + Lens scanned

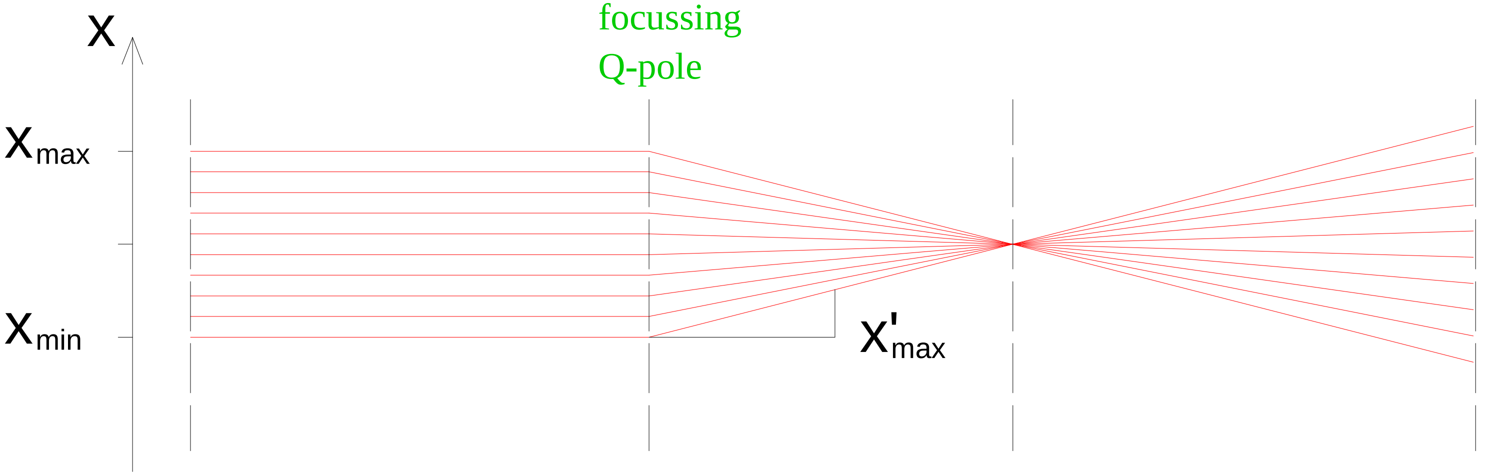
non-destructive

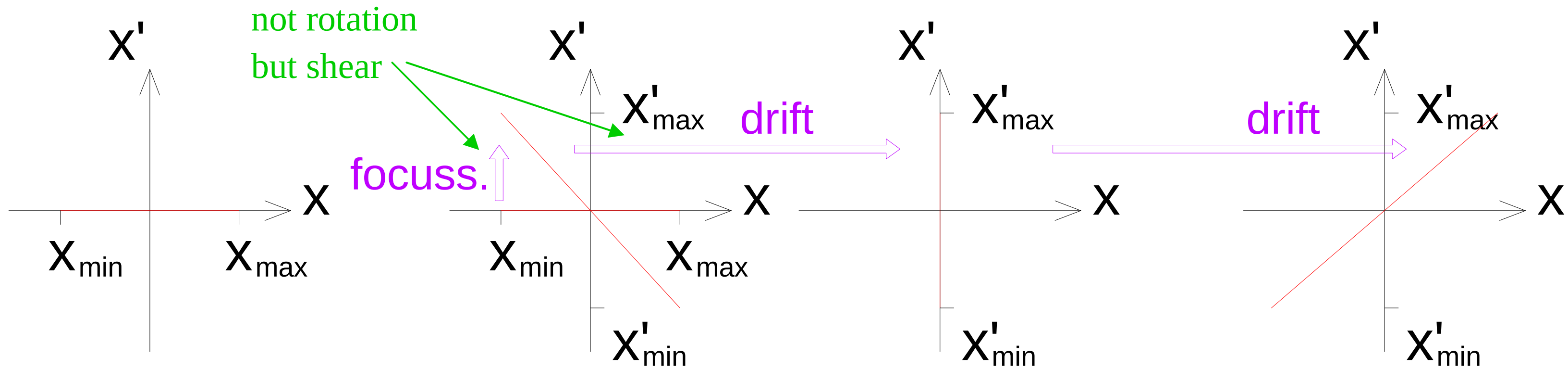


- numerical simulations support the design of the machine and later modifications to it (this layout is based on a „simple“ envelope fit with linear space charge)
- the emittance of the ion source is needed in the design phase as input for a transport code

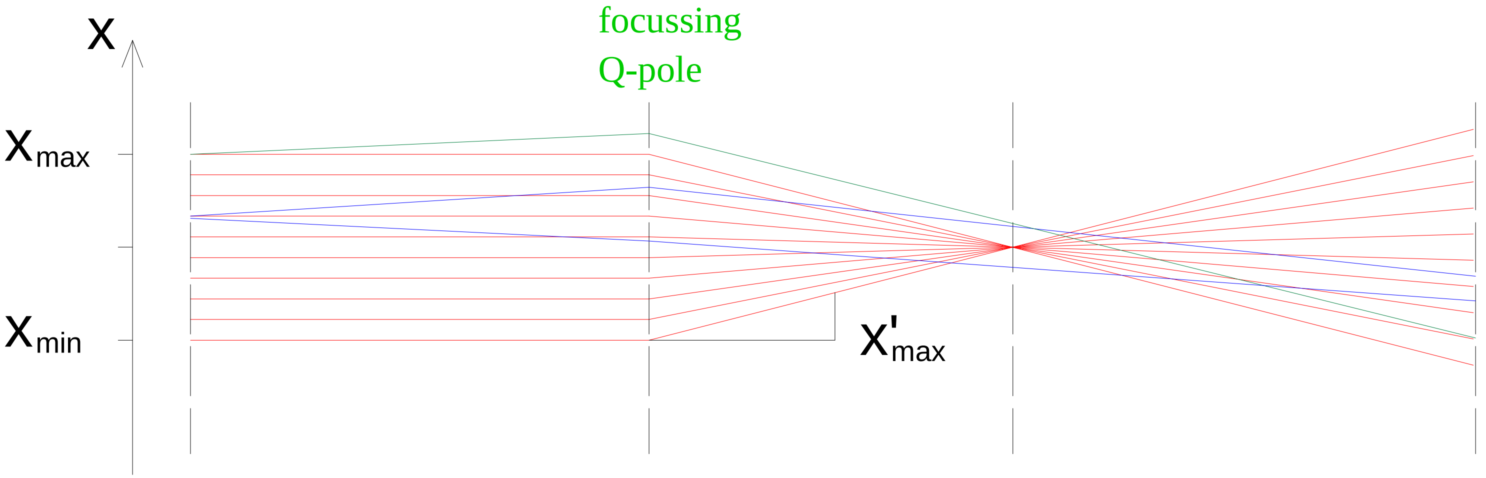


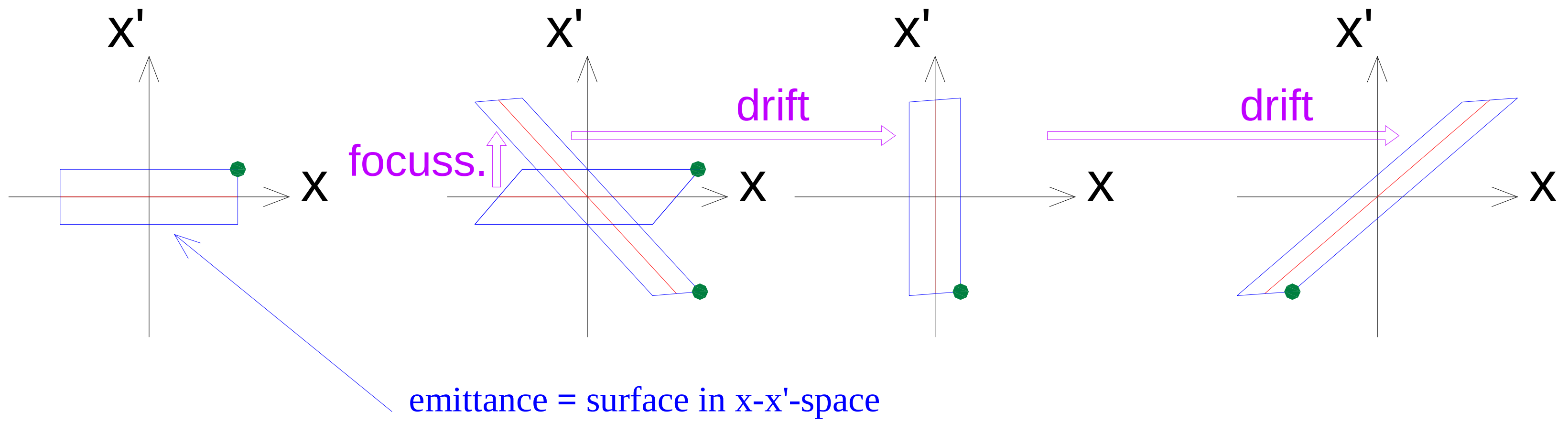
beam with emittance = 0
(and no space charge)
→ no unordered moving particles → sharp focus





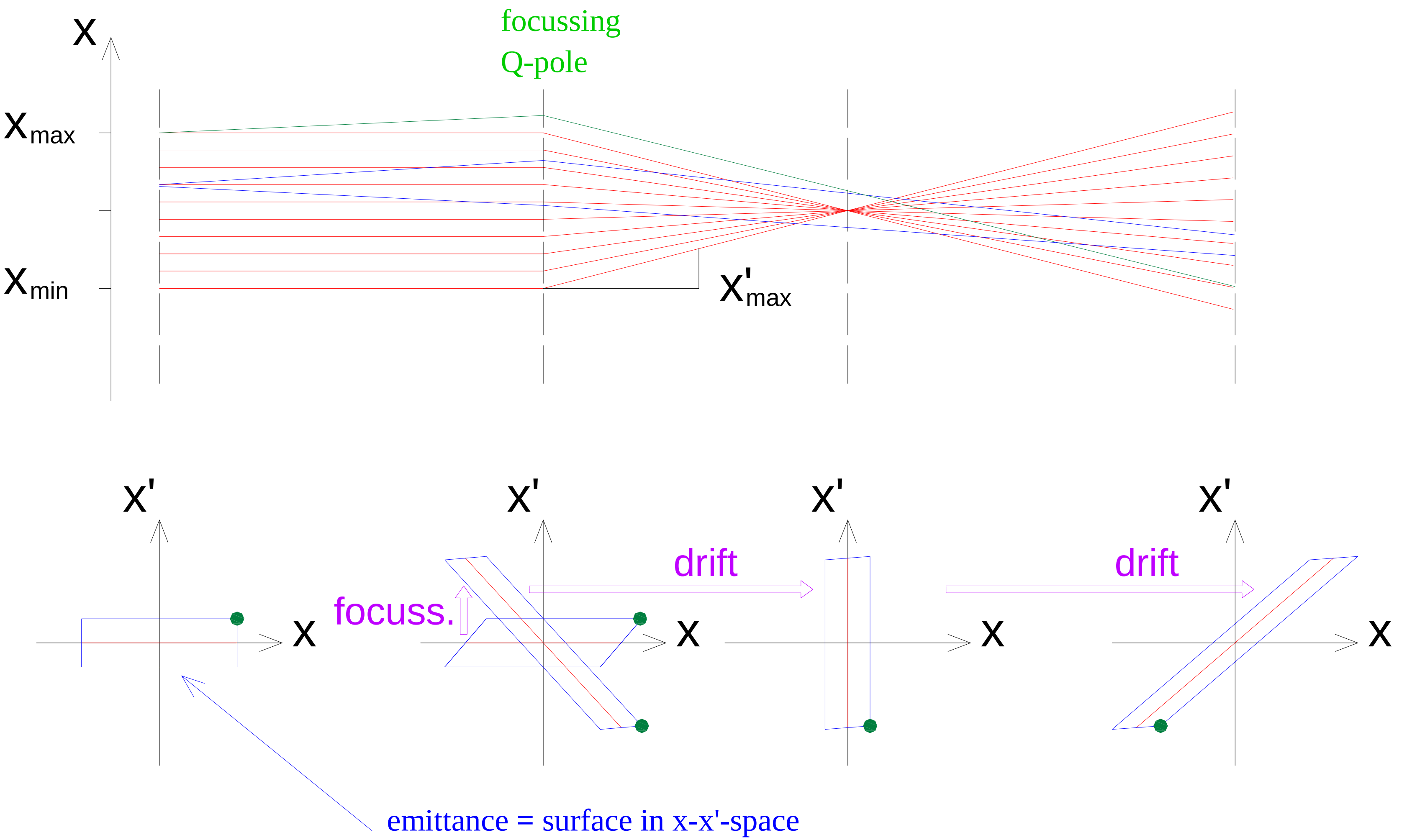
beam with emittance > 0
(and no space charge)
→ unordered particles directions → beam broadens, no sharp focus





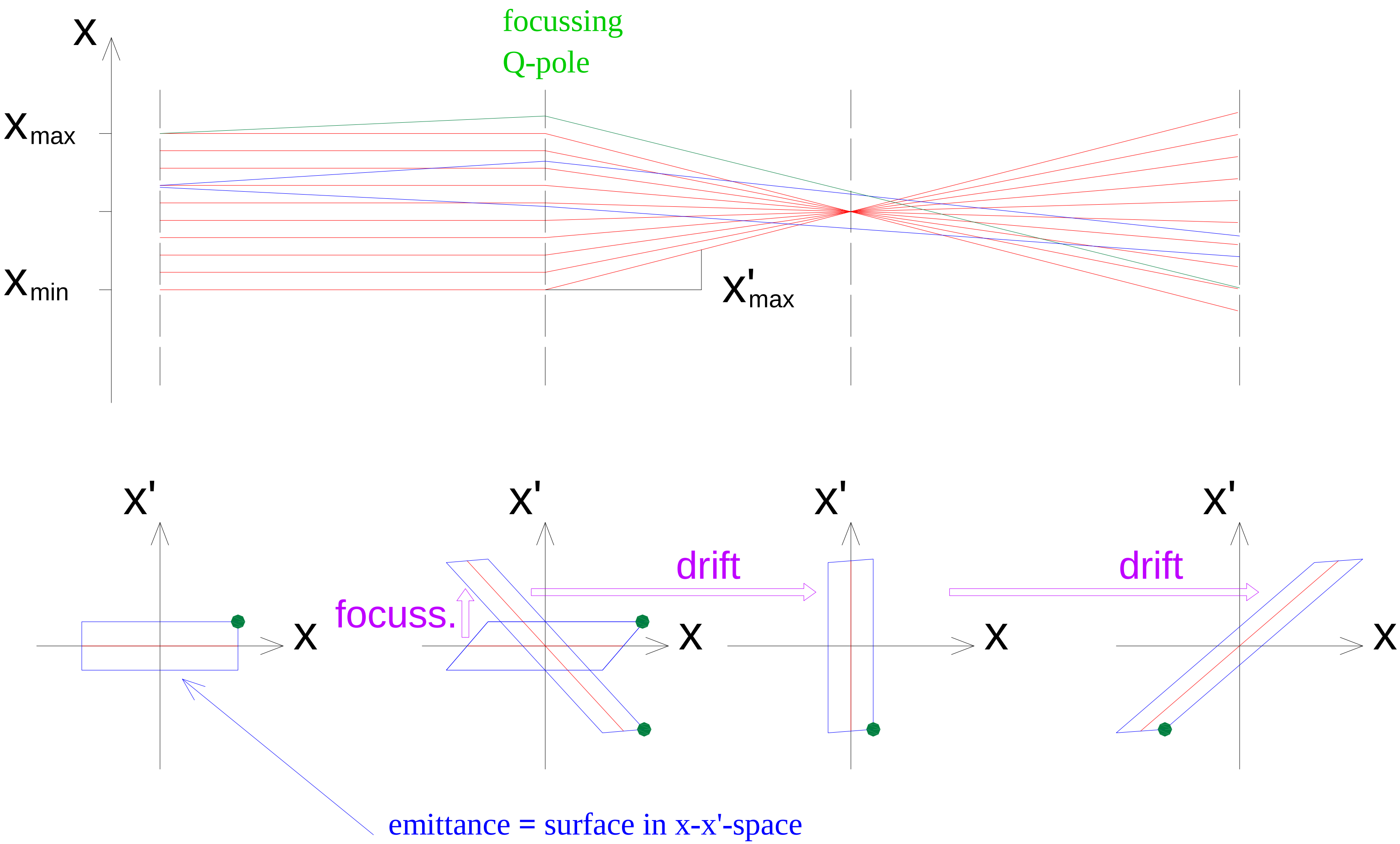
emittance = surface in x-x'-space

beam emittance determines if the beam can be focused through the beam pipe (with the available focussing elements and not taking space charge into account)



emittance = surface in x-x'-space

emittance measurement is the measurement of the unordered particle directions or of the distribution in x-x‘-space



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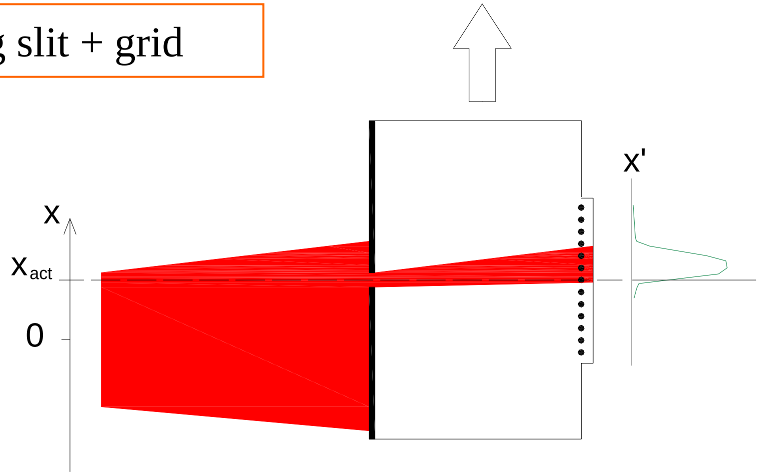
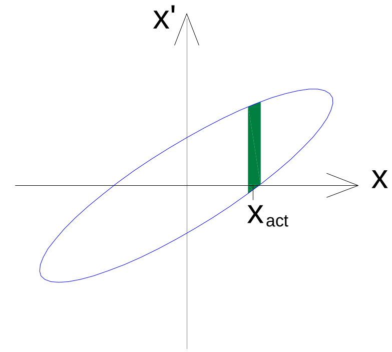
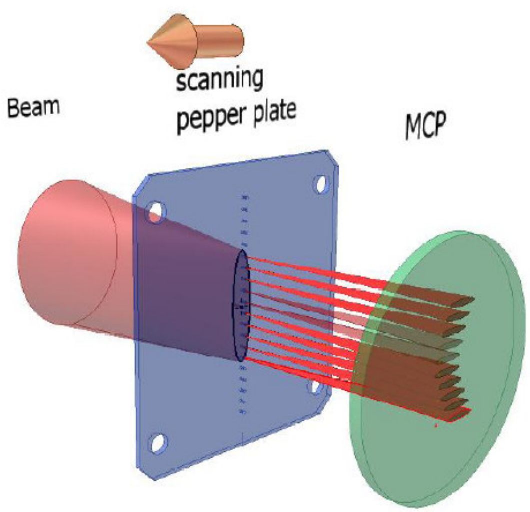
moving slit + grid



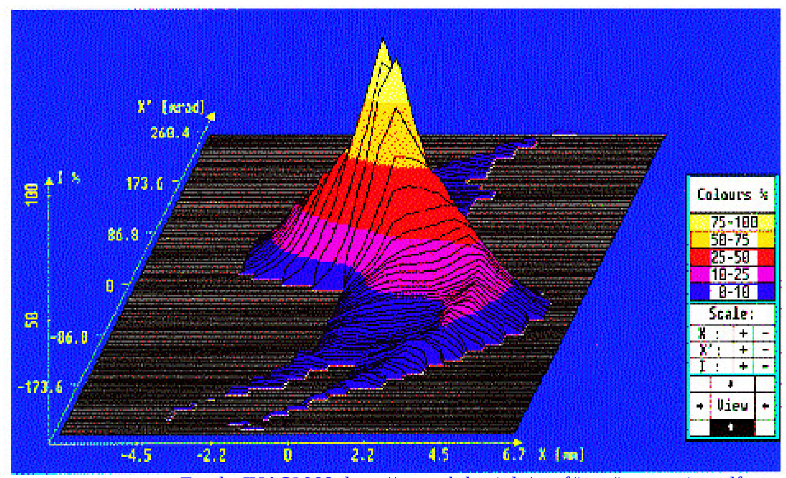


moving line of holes + screen



Kremers et al., ECRIS08, http://accelconf.web.cern.ch/AccelConf/ecris08/papers/thco-a02.pdf

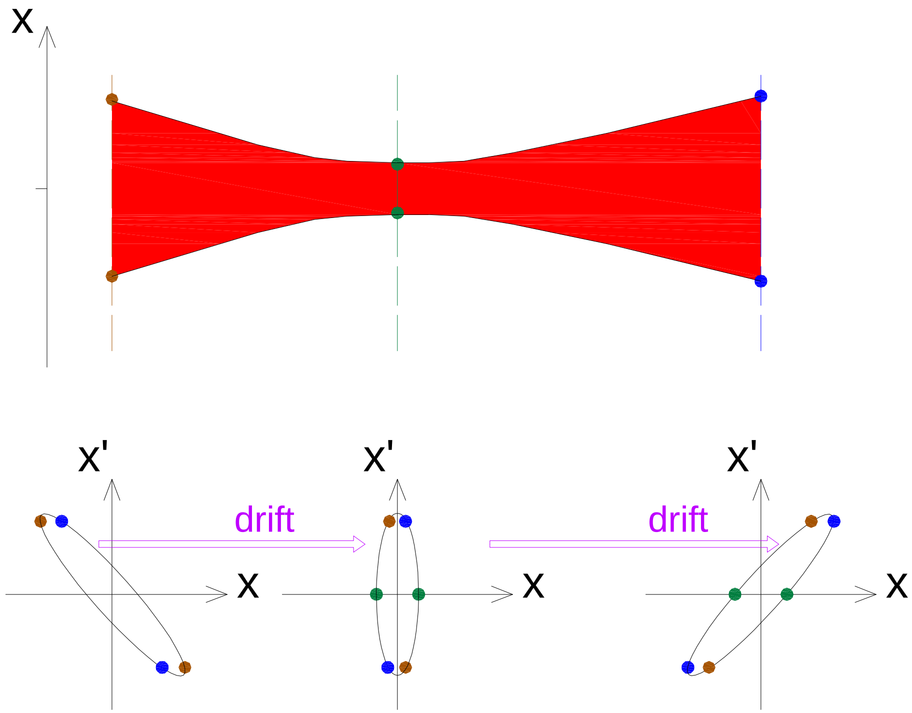
more information than slit + grid



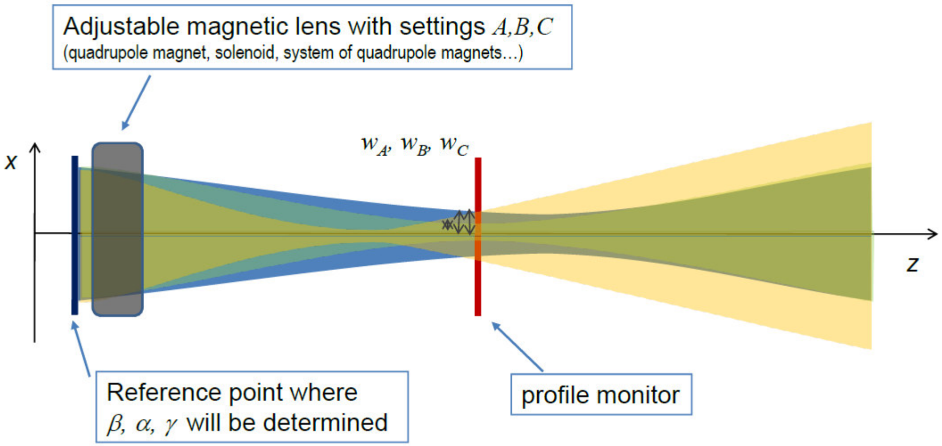
Forck, JUAS2009, http://www-bd.gsi.de/conf/juas/juas_script.pdf

many other configurations (pepperpot, Allison scanner, ...)

3 profile method



Q-pole variation method



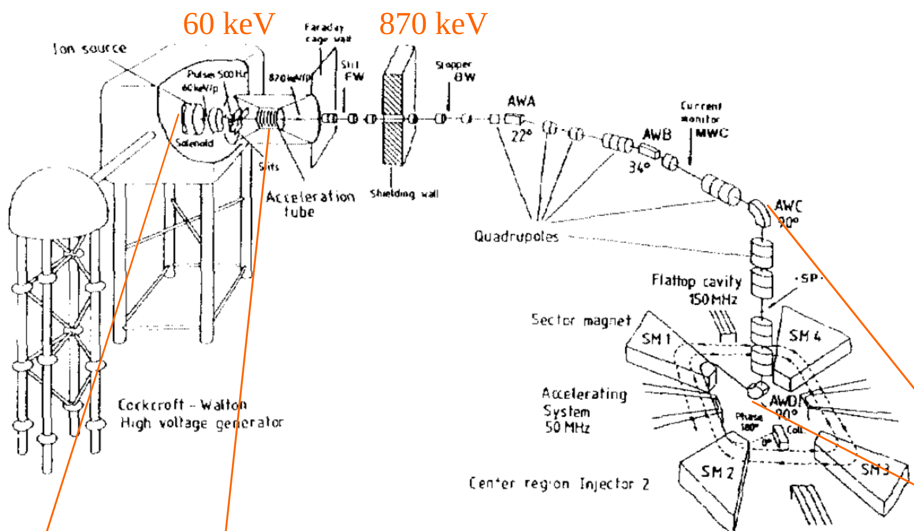
Braun, CAS2008, http://cas.web.cern.ch/cas/France-2008/Lectures/Braun-Emittance.pdf

- „moving the beam instead of moving the monitor“
- more difficult to exercise with high power beams

information input is only 3 beam widths
→ less information than direct measurements

emittance measurement by all the monitors in the beam line (with quadrupoles & dipoles in between

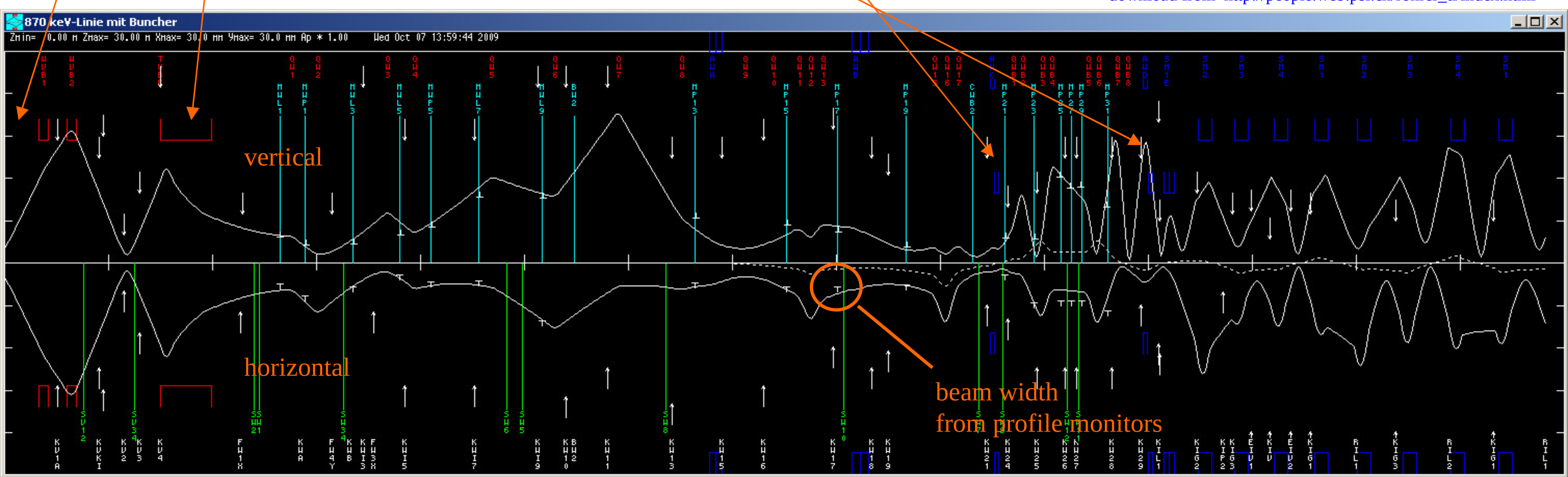
- input: magnet currents & beam width from profile monitors
- enveloppe fit (over-determined) by „simple“ transport calculation (matrices) including linear space charge → emittance



- needs reproducible but not very detailed results (preferably at full beam current)
- useful for machines which accelerate different particles and need frequently adapted beam optics

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



injection, central region: current set & beam shaping, betatron oscillation alignment

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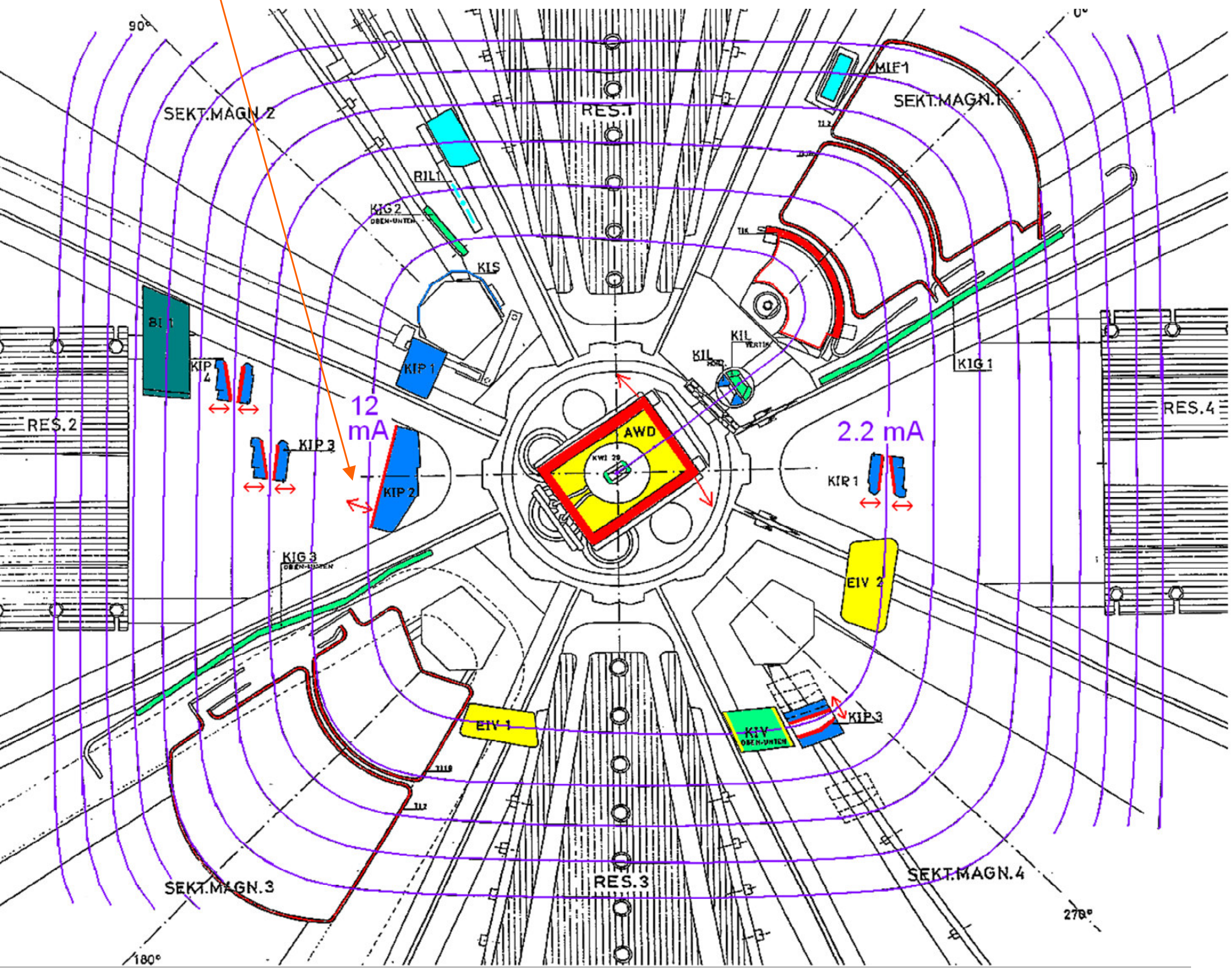
- current set with collimator
- beam shaped with collimators (collimators cooled, no activation below 2 MeV)
- machine protection by collimator readings



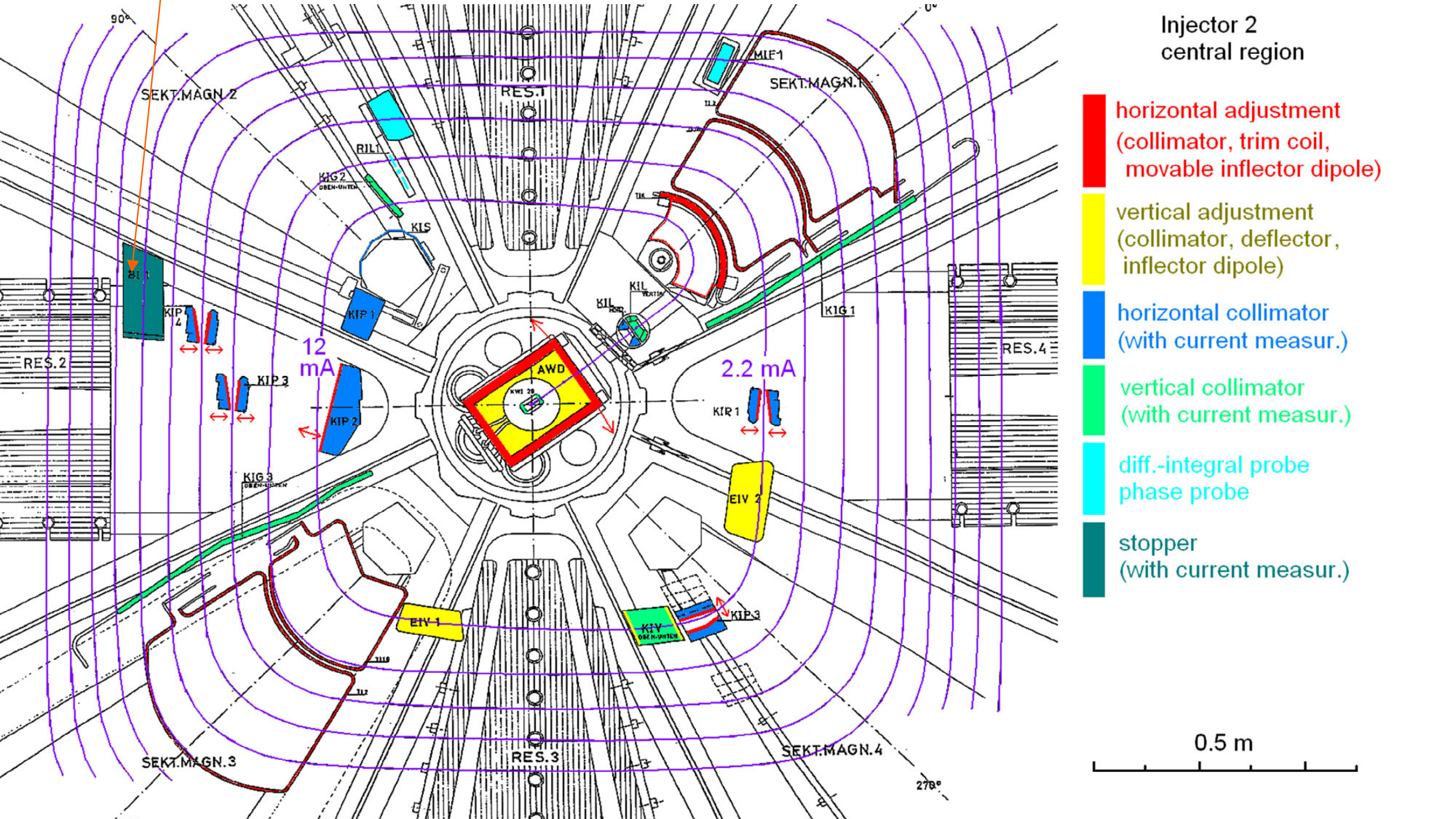
Injector 2
central region

- horizontal adjustment (collimator, trim coil, movable inflector dipole)
- vertical adjustment (collimator, deflector, inflector dipole)
- horizontal collimator (with current measur.)
- vertical collimator (with current measur.)
- diff.-integral probe phase probe
- stopper (with current measur.)

0.5 m

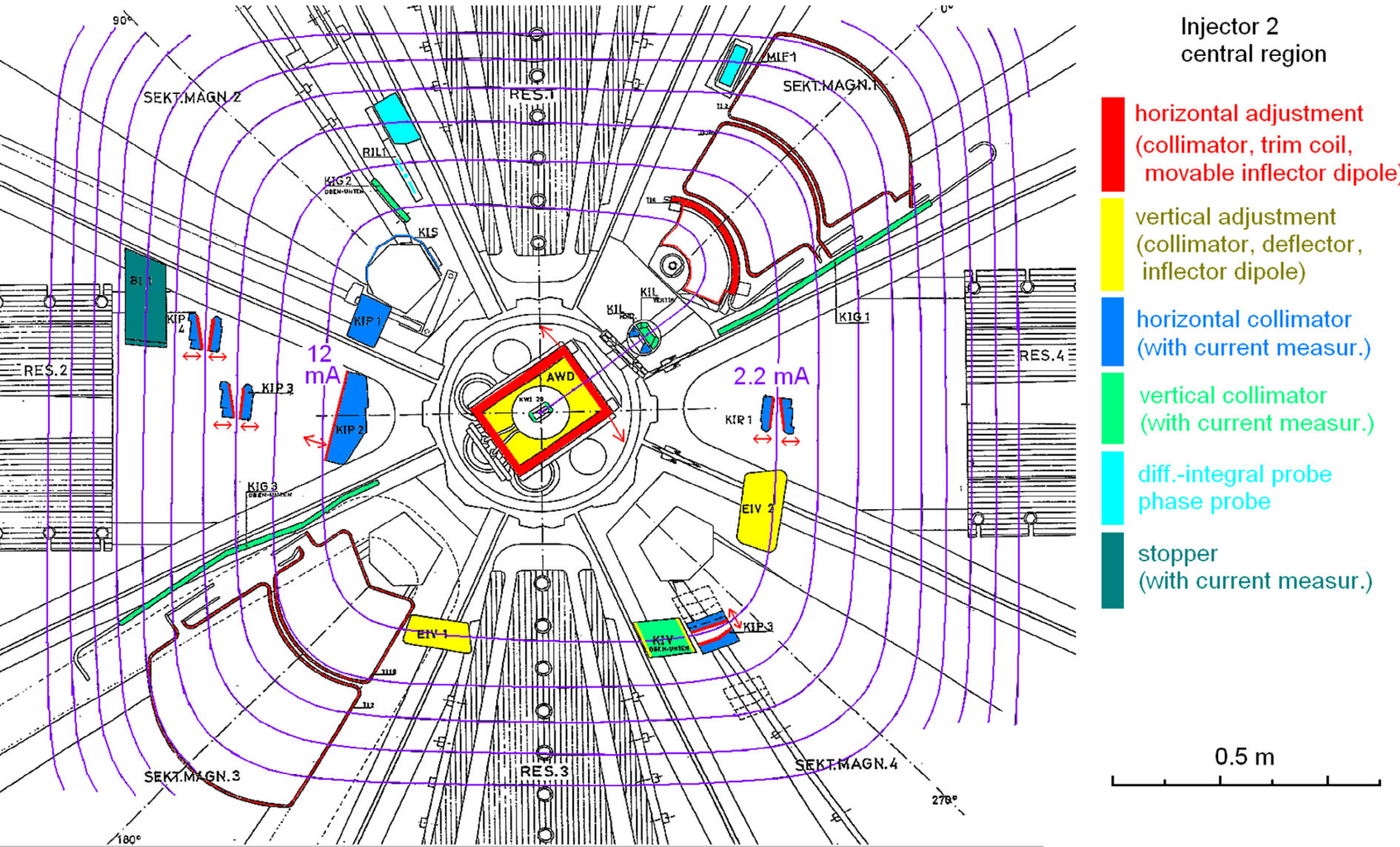
injection, central region: current set & beam shaping, betatron oscillation alignment

- current measured with stopper
- injection efficiency from comparison with Faraday cup or DCCT in injection line
  (less critical in this case: enough beam, no activation below 2 MeV)



injection, central region: current set & beam shaping, betatron oscillation alignment

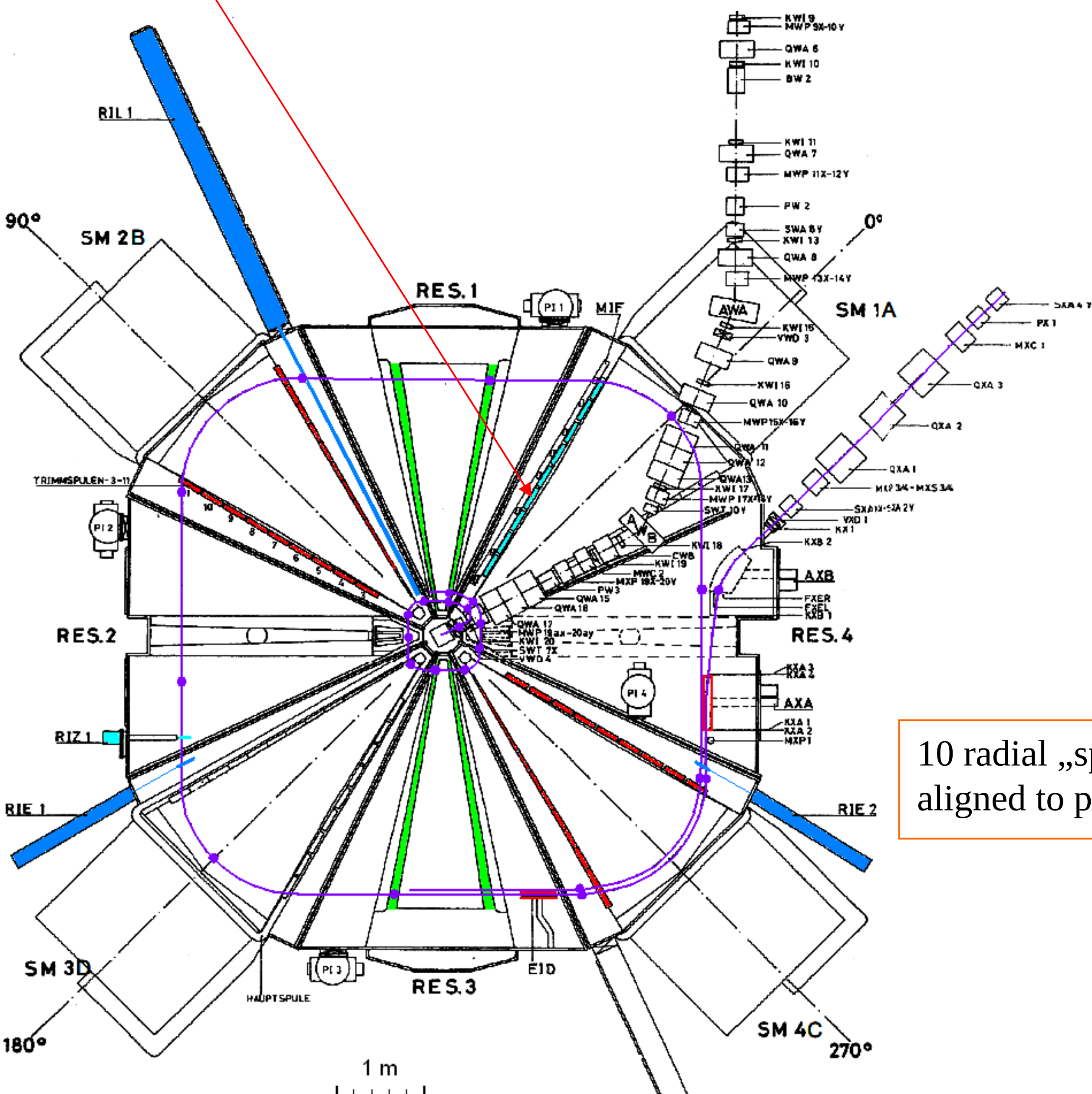
- beam „positions“ at full current: only from collimator currents, at low current: from radial probe
- vertical centering with vertical adjustments
- horizontal betatron oscillations around the centered path adjusted with horizontal adjustments



acceleration: adjustment of magnetic field and RF fields

phase probes

full beam
(2300 uA)



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

accelerating gaps

phase probes,
time structure probe

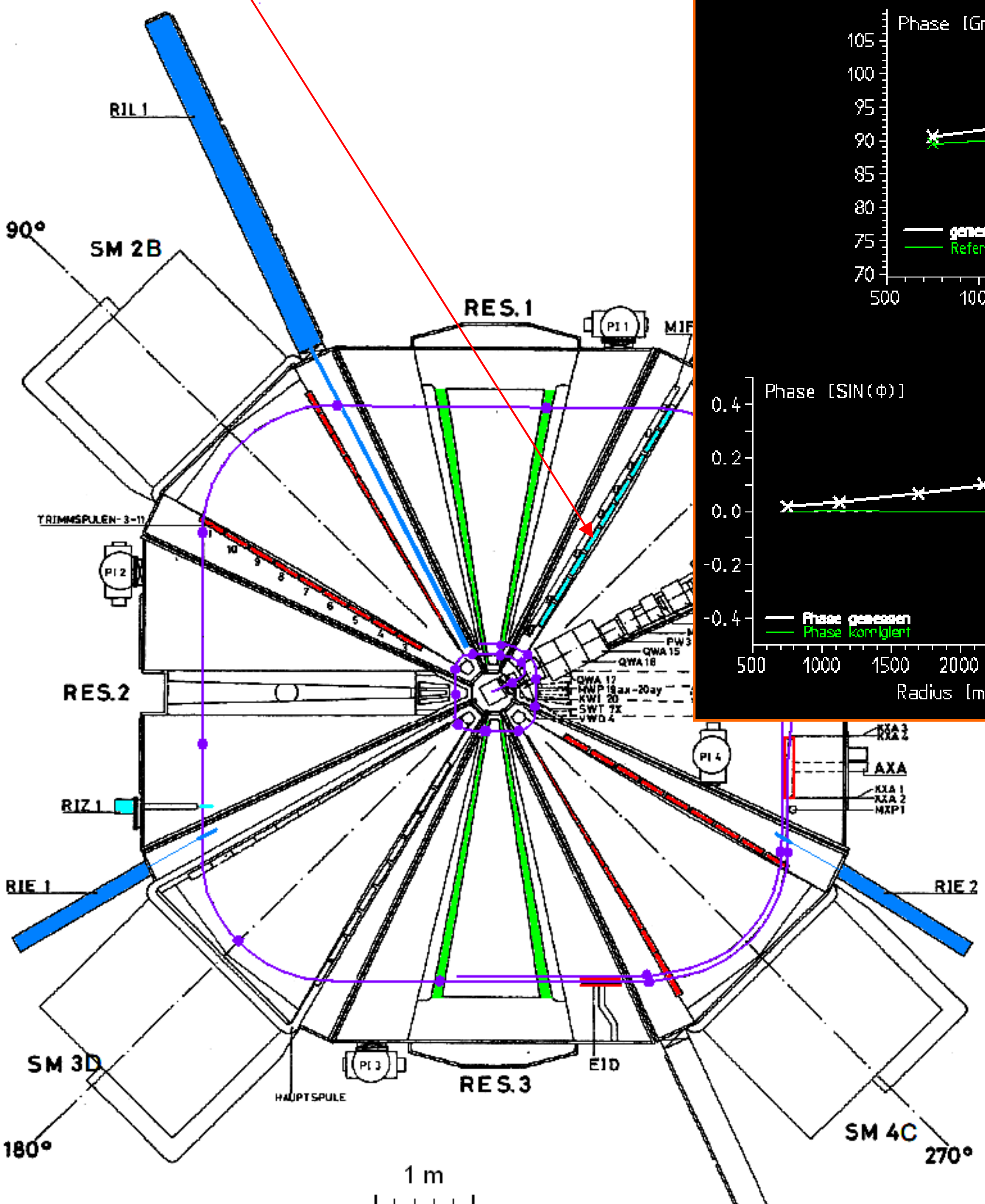
radial probes

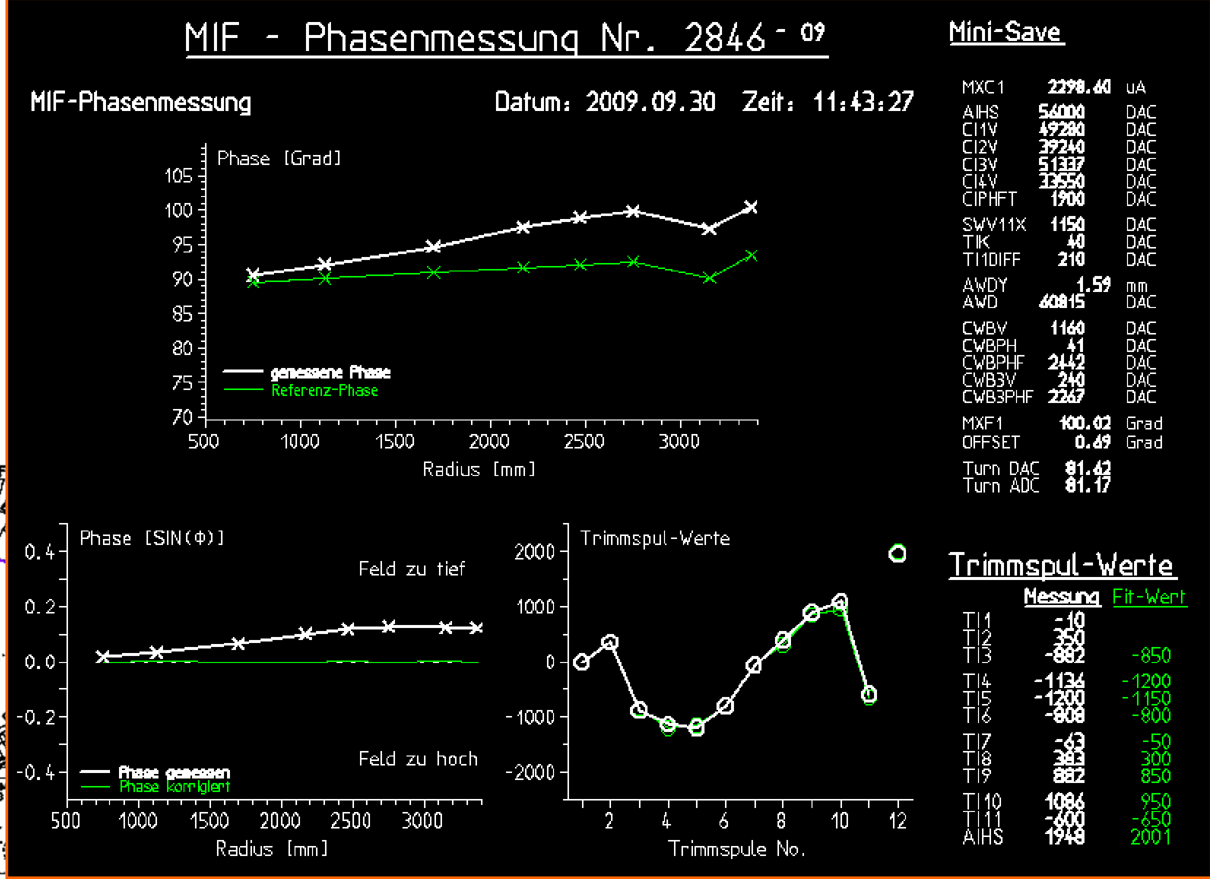
10 radial „spokes“ of bunches
aligned to pass acceleration gaps synchronously

acceleration: adjustment of magnetic field and RF fields

phase probes

full beam
(2300 uA)





M. Humbel, PSI

„isochronism“: 10 radial „spokes“ of bunches aligned to pass acceleration gaps synchronously

from phase probes

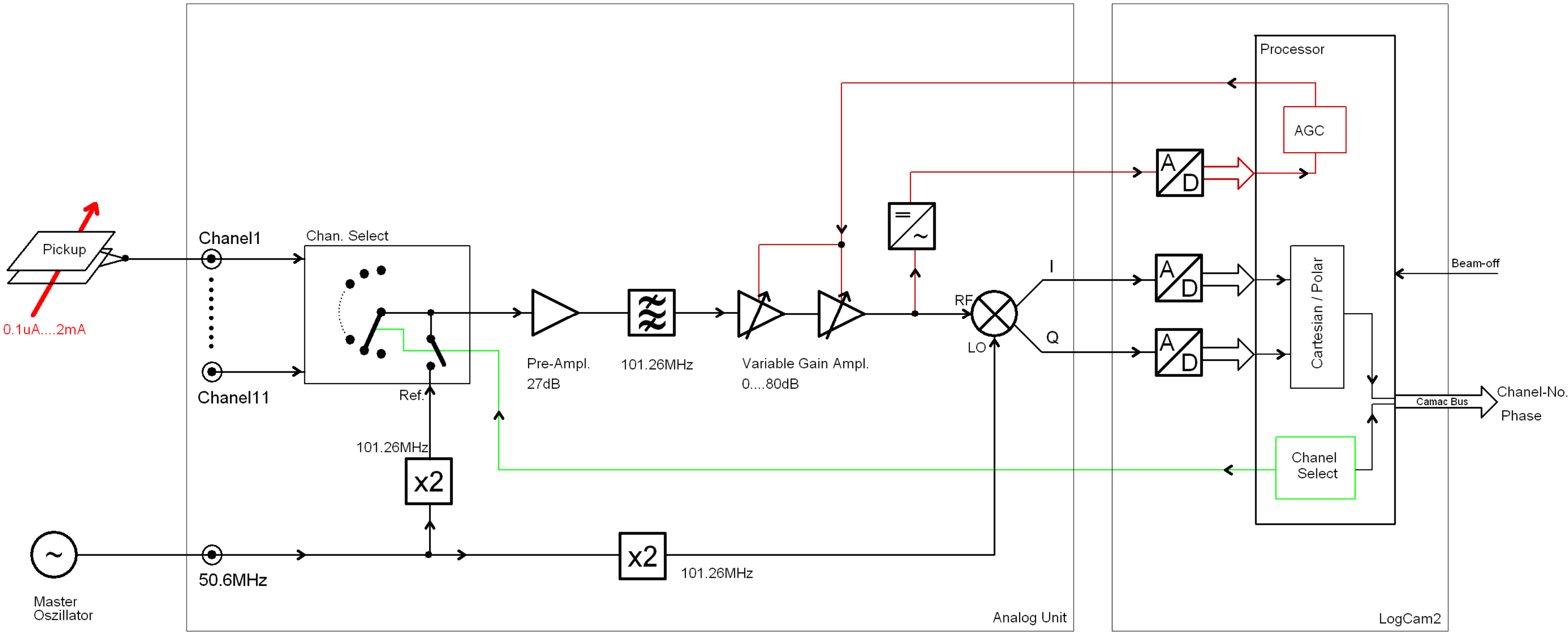
→ correction of (drifting) main field (recommended in this example)

→ recommendation of better trim coil settings

„frequent tuning procedure“

- 9 pick-ups in Injector 2 cyclotron and 13 pick-ups in ring cyclotron
- uses the second harmonic (101MHz), phase measurement with an I-Q down converter
- RF contribution by "beam-off" measurement subtracted
- beam current 0.1 µA ... 2 mA
- precision ±0.5° (over the whole dynamic range of 80 dB), phase range ±90°
- bandwidth 5 Hz … 500 Hz dependent on beam current

U. Müller, PSI



- variant: improved sensitivity by intensity modulation of the beam

Brandenburg et al., DIPAC03, http://accelconf.web.cern.ch/AccelConf/d03/papers/PT12.pdf

long radial probe

- only for few uA beam
- finding the beam and „pulling“ it to greater radii
  at commissioning or „error search“

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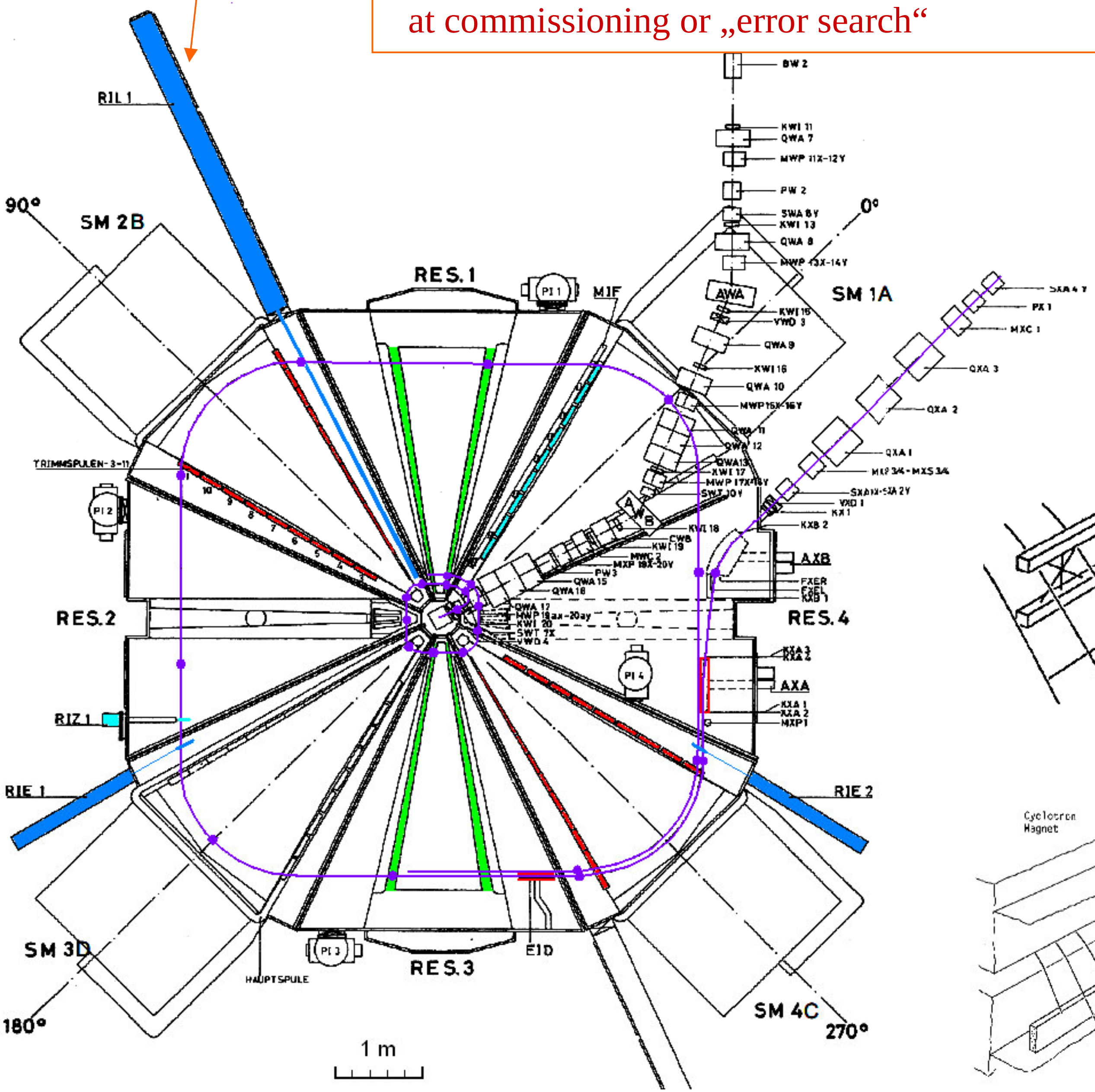
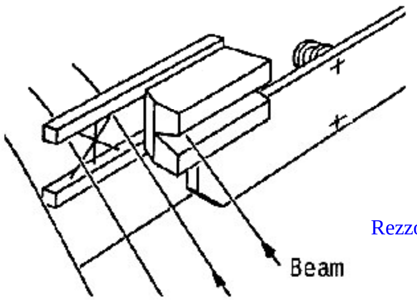
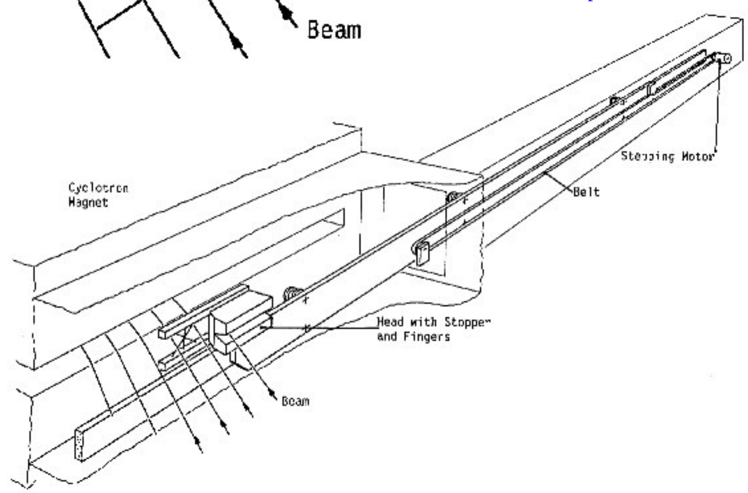


- horizontal adjustment (trim coils, electrostatic septum, septum magnet)
- accelerating gaps
- phase probes, time structure probe
- radial probes



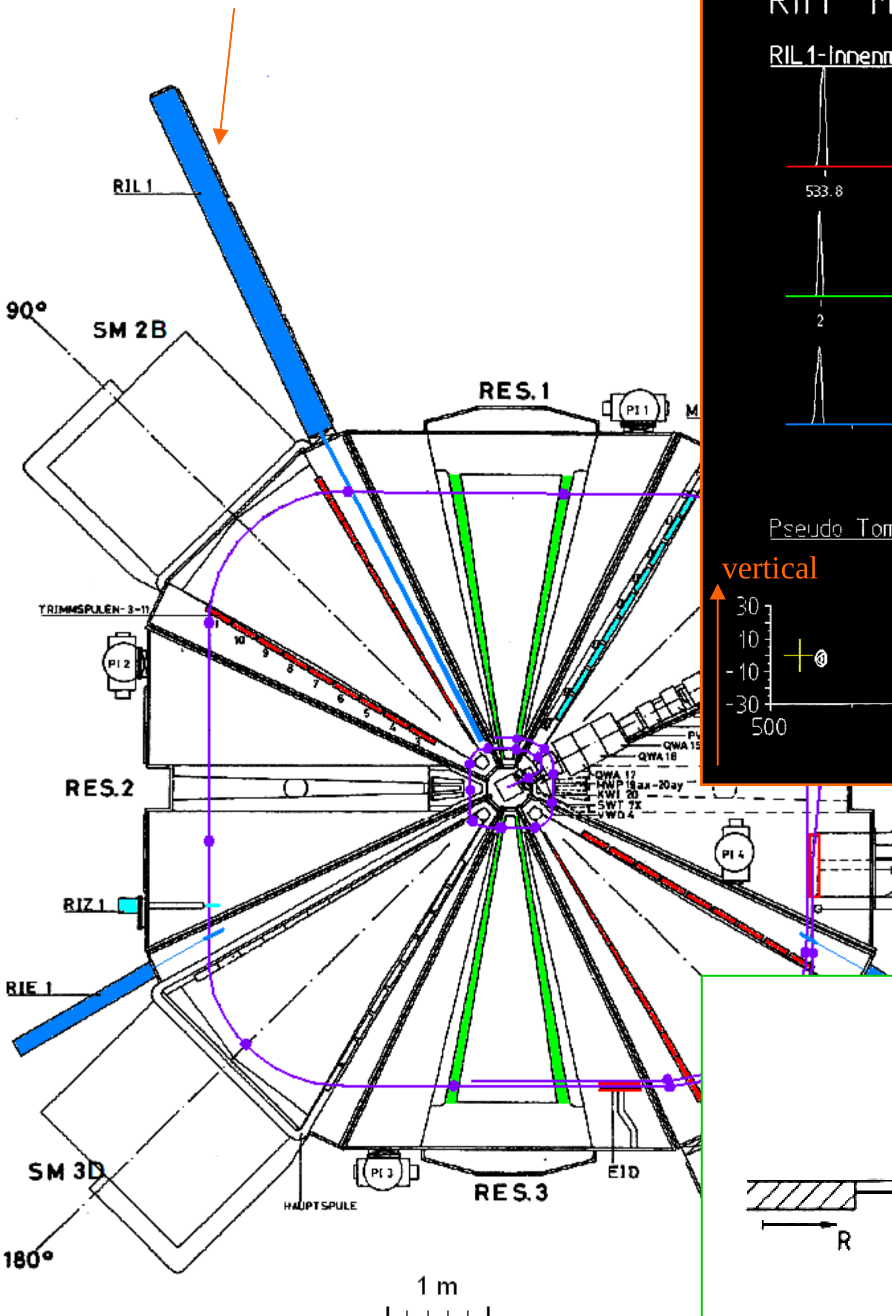
Rezzonico, ICCA1987 p. 457-60

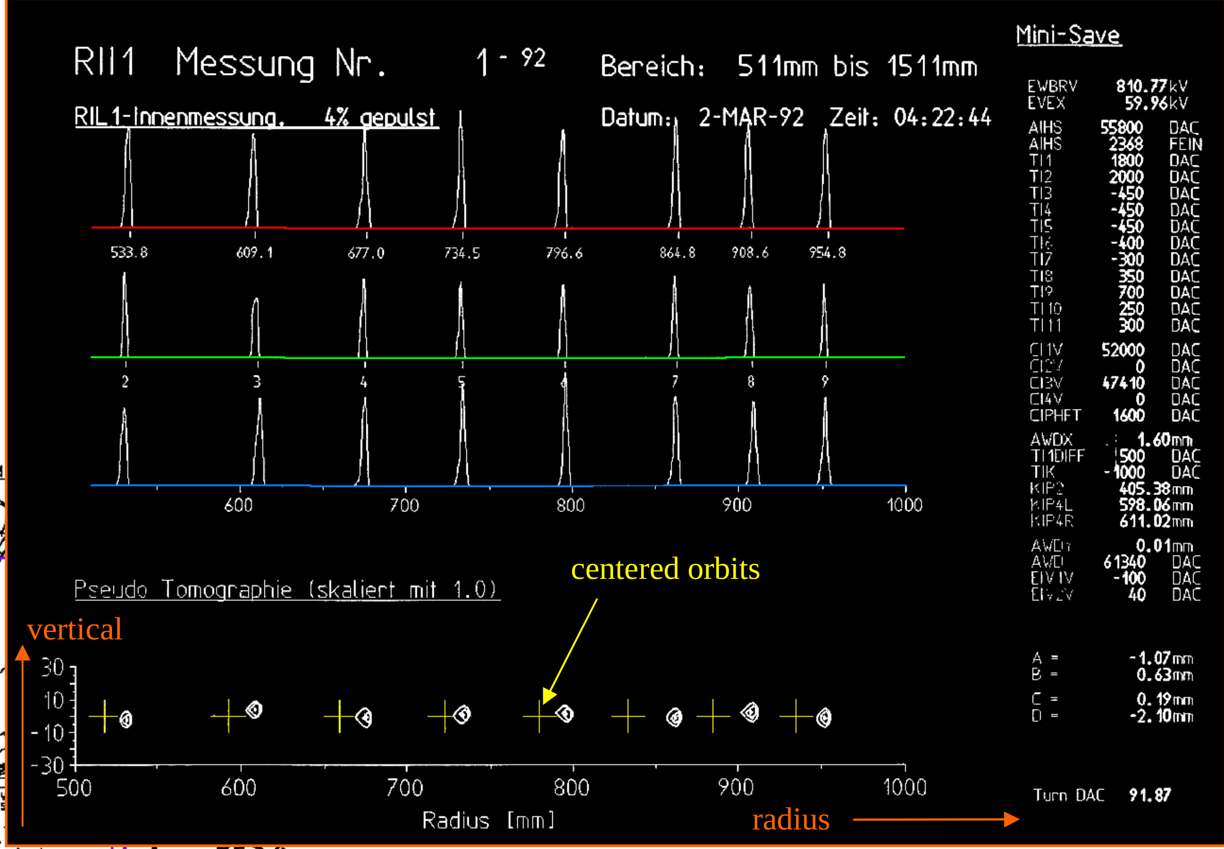


acceleration: adjustment of magnetic field and RF fields

long radial probe

only 1 uA beam



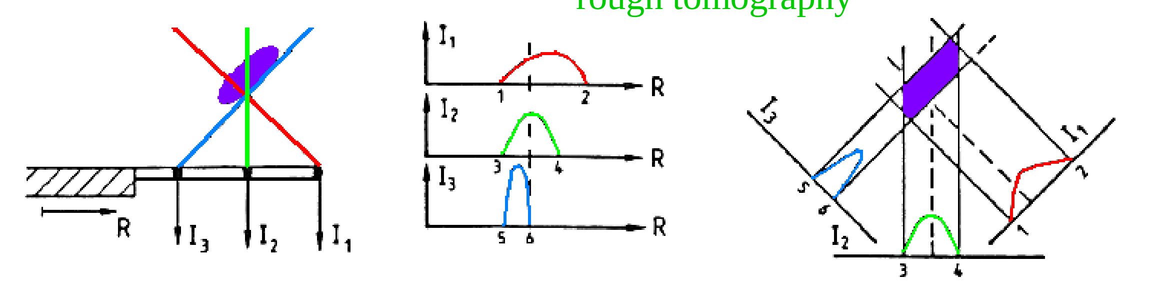


M. Humbel, PSI

control of vertical centering & horizontal betatron oscillation

(here now only at commissioning or error search)

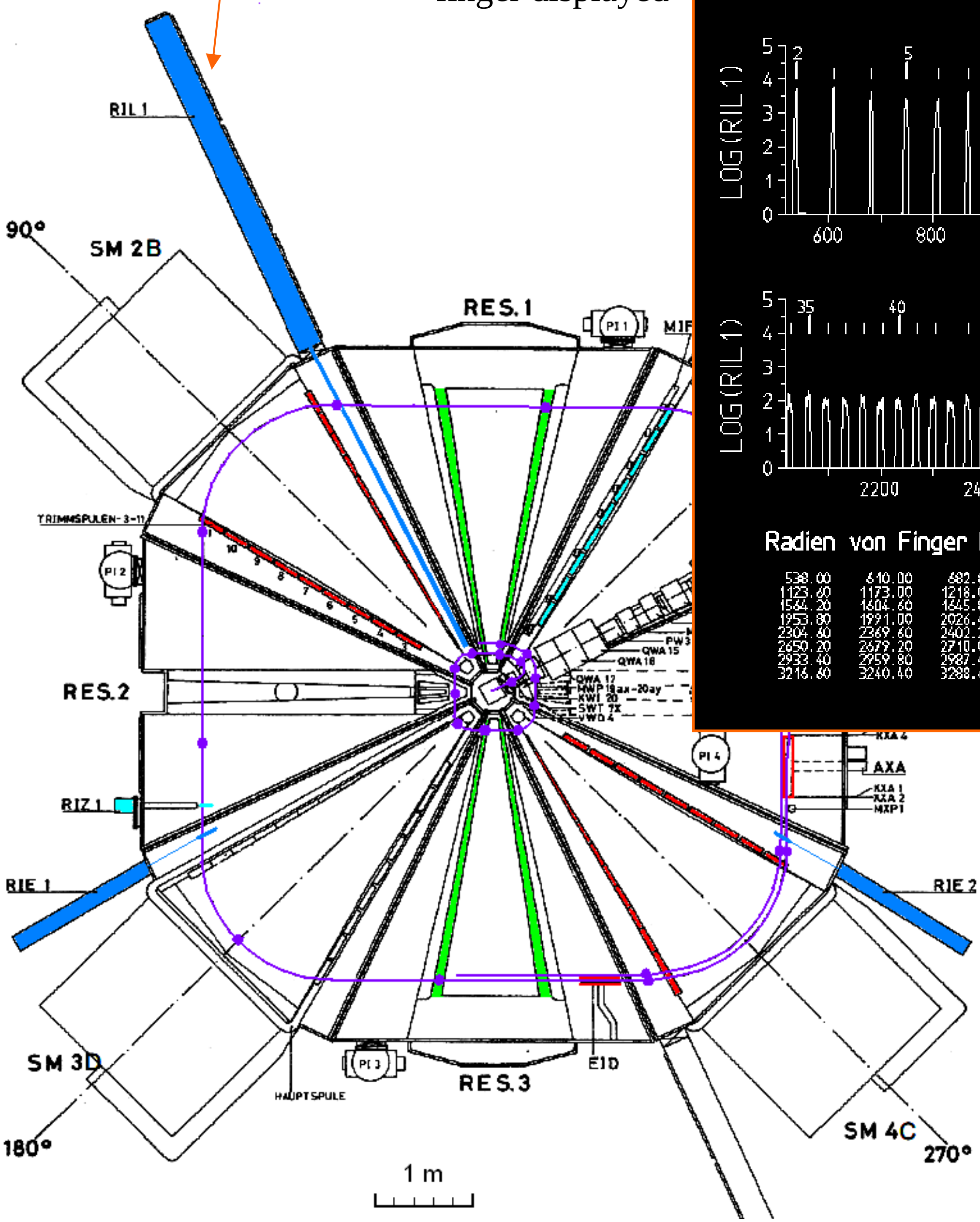
rough tomography

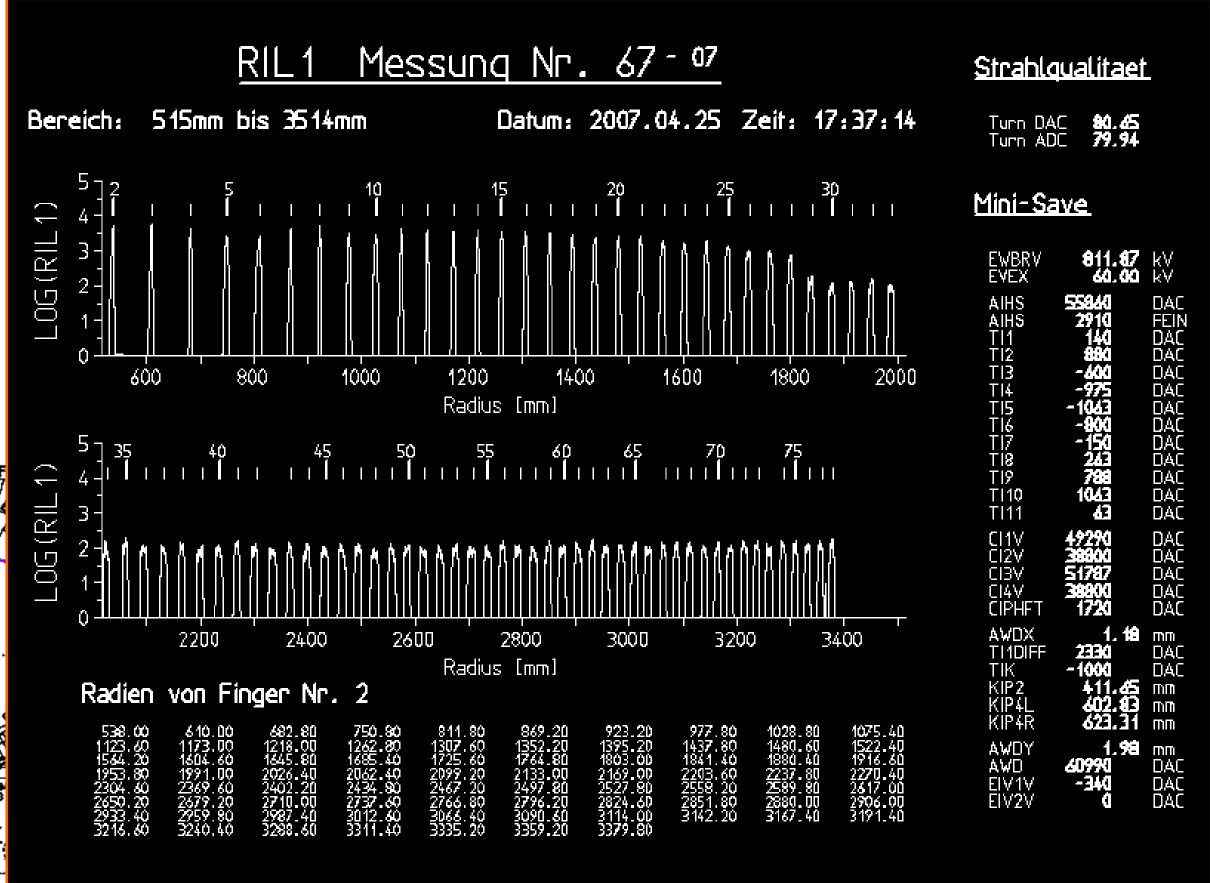


acceleration: adjustment of magnetic field and RF fields

long radial probe

only 1 uA beam
only vertical
finger displayed





M. Humbel, PSI

counting the turns
at beam development

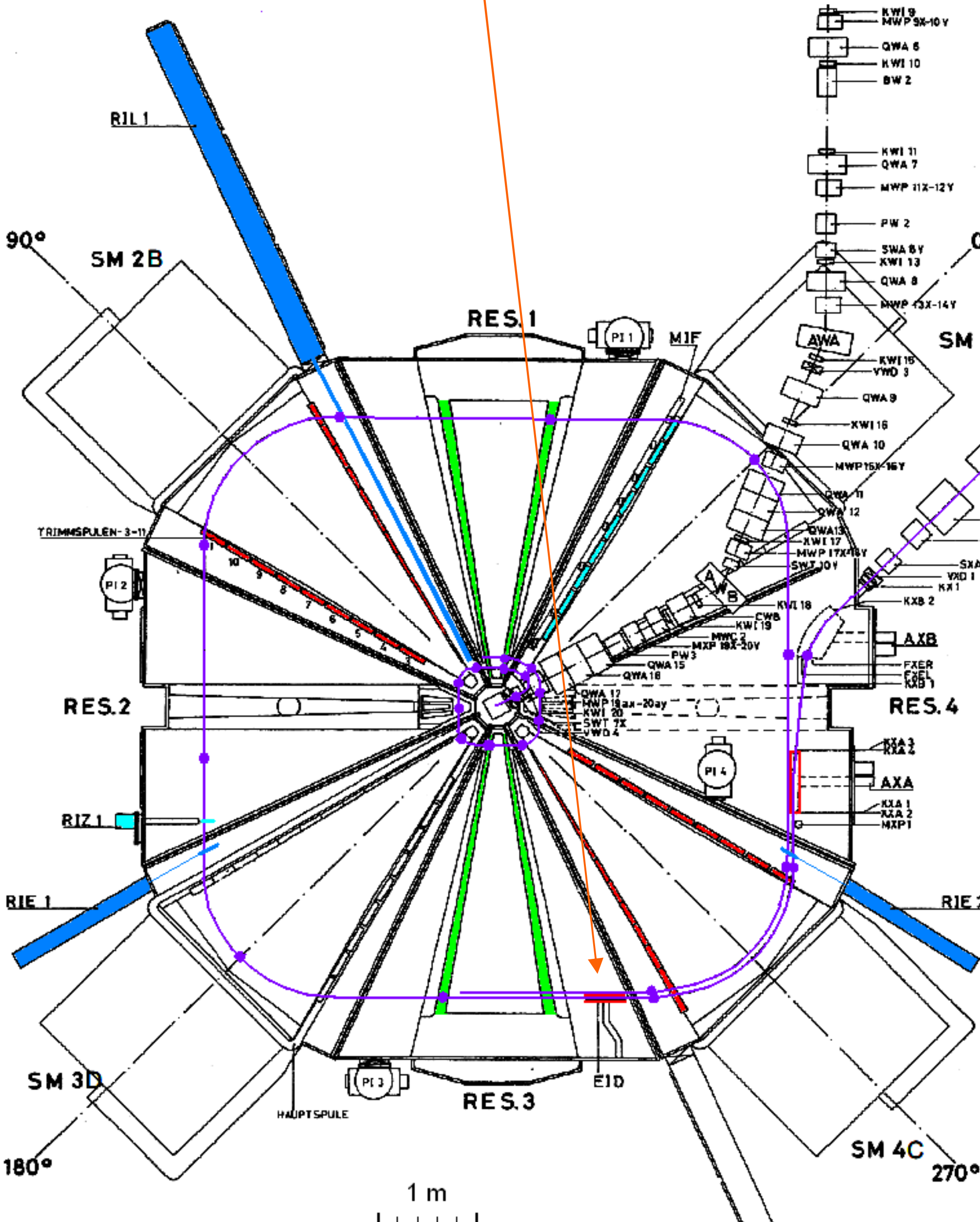
alternative for not separated turns:
- measurement of beam noise (from ion source) before and after the cyclotron
- cross correlation → time of flight

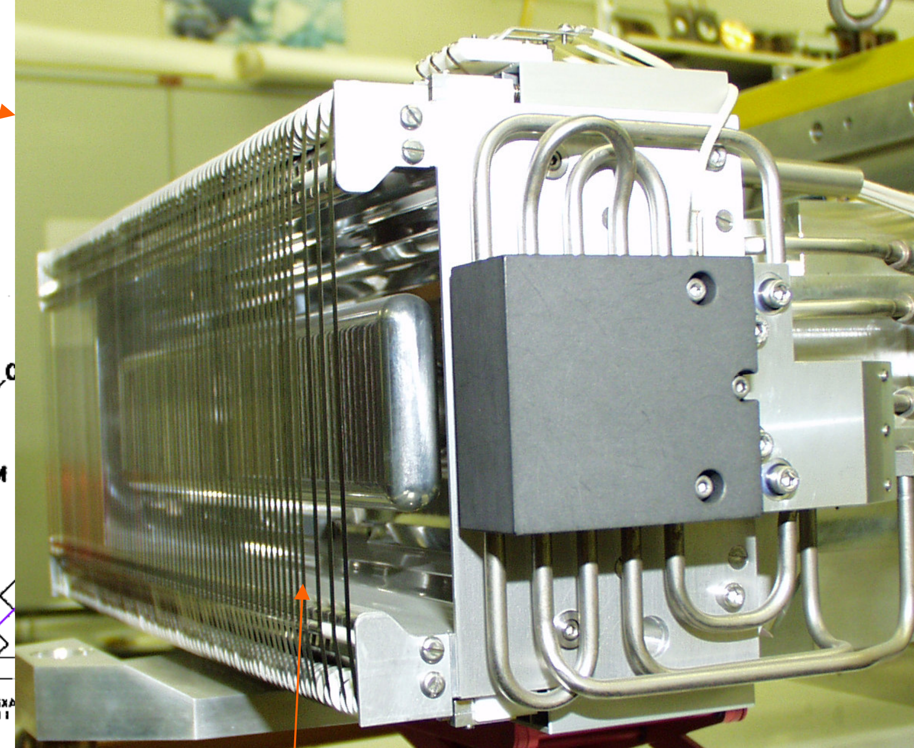
Loyer et al., PAC1985,
http://accelconf.web.cern.ch/AccelConf/p85/PDF/PAC1985_1938.PDF

acceleration: adjustment of magnetic field and RF fields

extraction: efficiency, beam parameters, stability

electrostatic septum for extraction





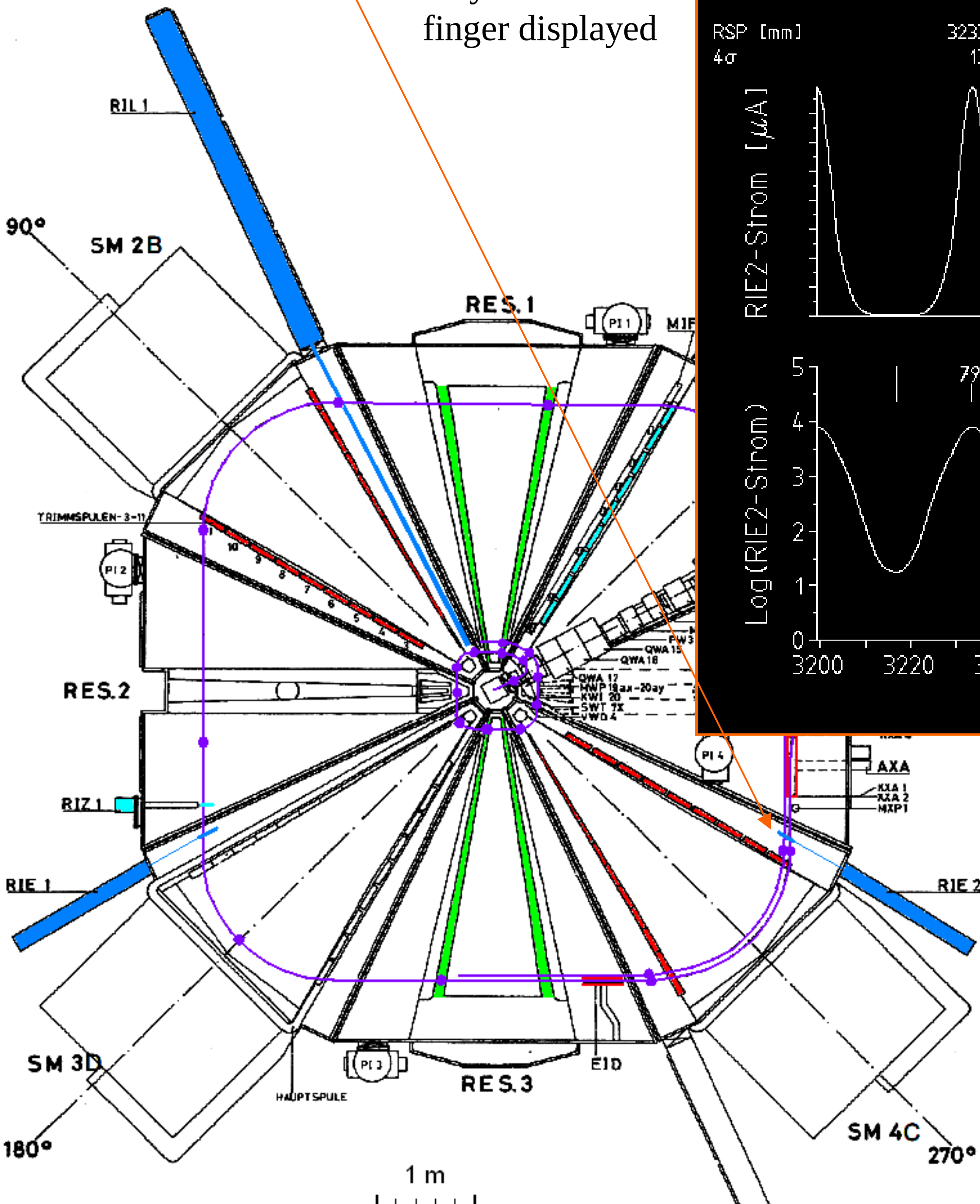
D. Götz, PSI

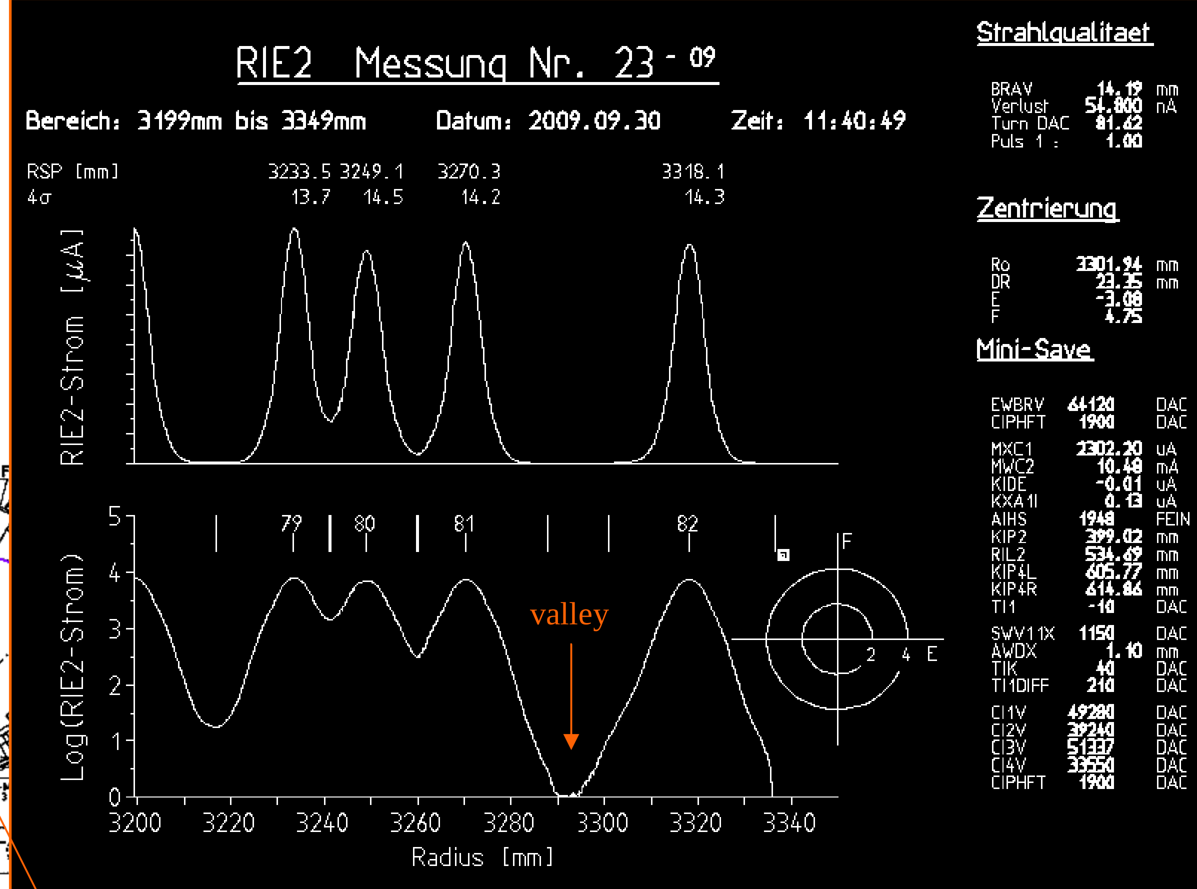
septum foils between the last 2 turns

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

extraction probe 2

full beam
(2300 uA)
only vertical
finger displayed





Rezzonico et al., BIW1994, AIP Conf. Proc. 333 p. 398-404

horizontal betatron oscillation tuned for

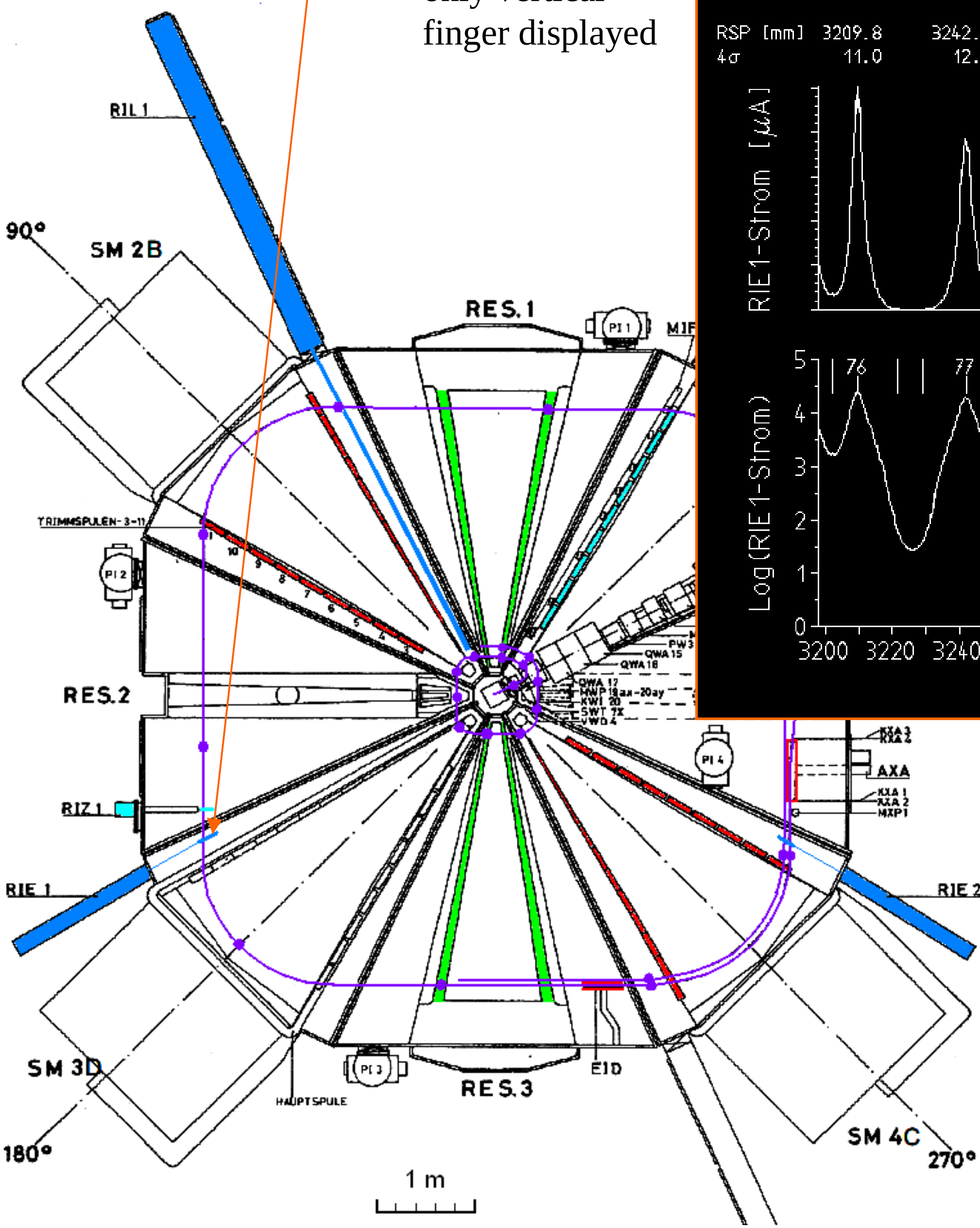
→ large separation of last turn at extraction elements

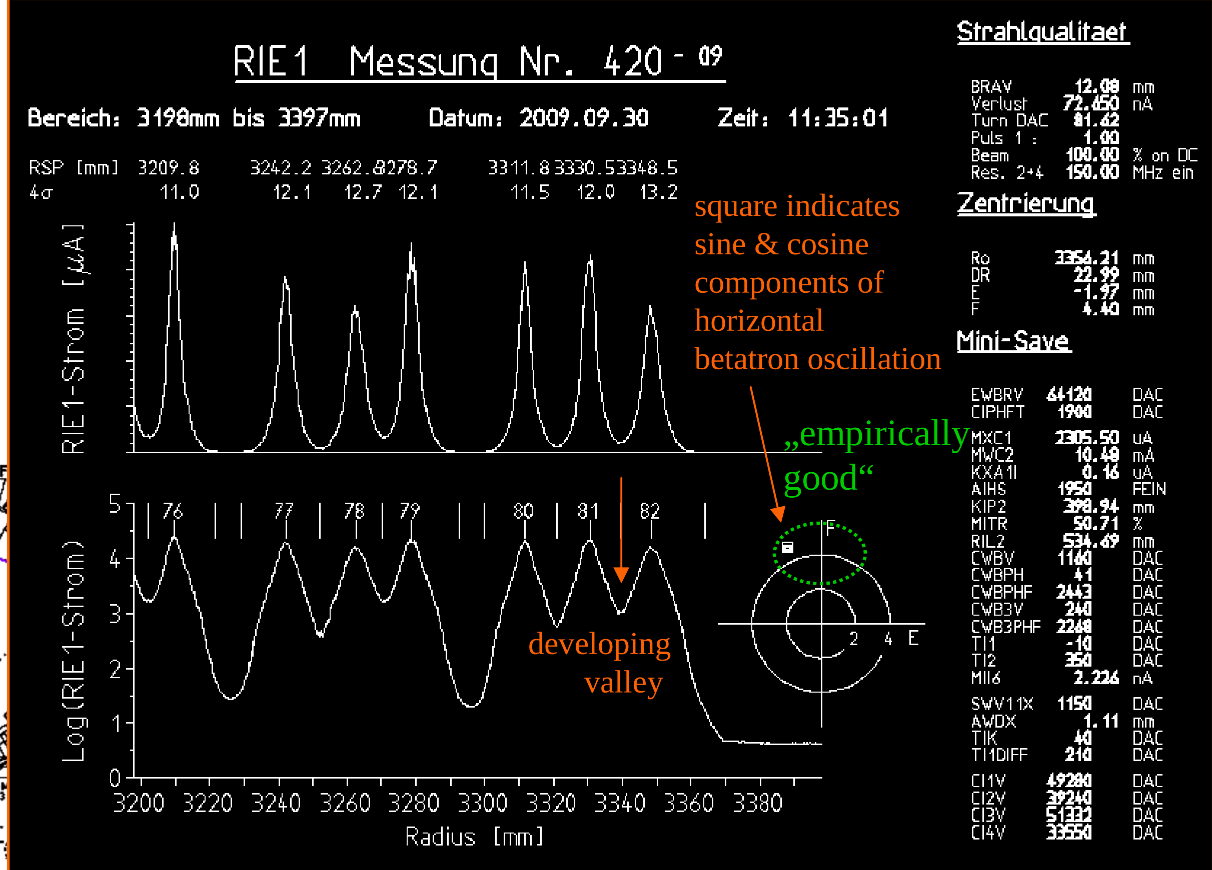
→ nearly 100% extraction efficiency = low losses

„set-up & beam development procedure“

extraction probe 1

full beam
(2300 uA)
only vertical
finger displayed





Rezzonico et al., BIW1994, AIP Conf. Proc. 333 p. 398-404

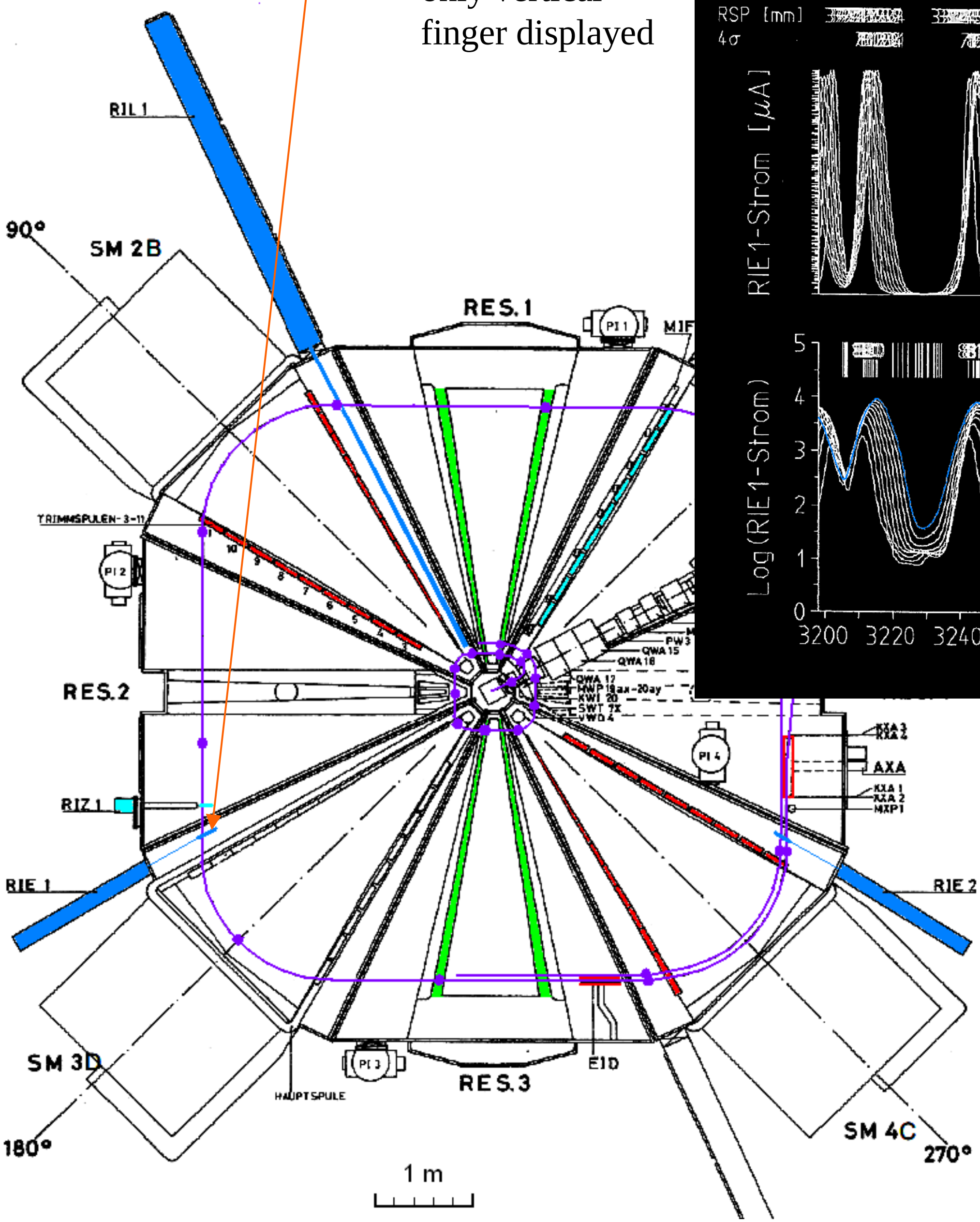
practically done by adjusting sine & cosine at the other extraction probe

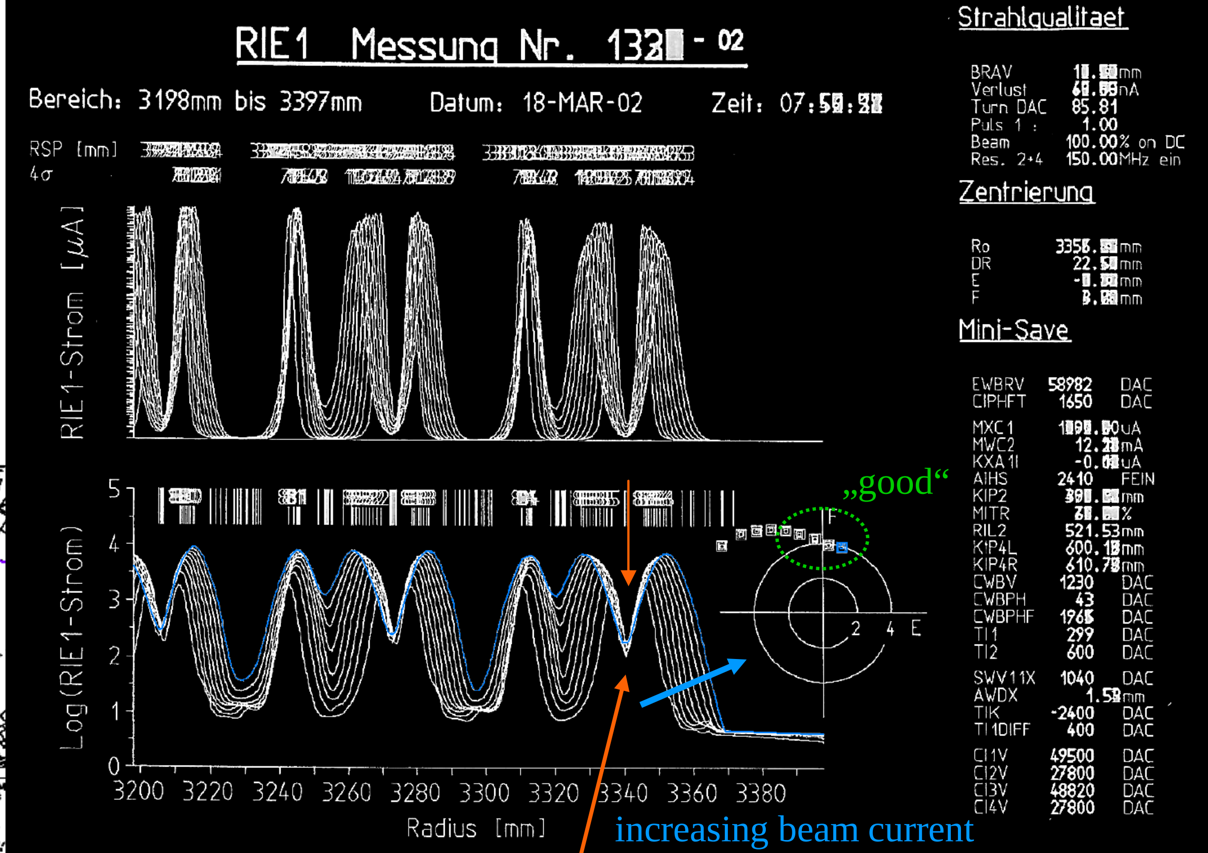
(→ groups of three turns form
→ number of turns should be changed only by n times 3)

„tuning, set-up & beam development procedure“

extraction probe 1

only vertical finger displayed





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

time structure probes

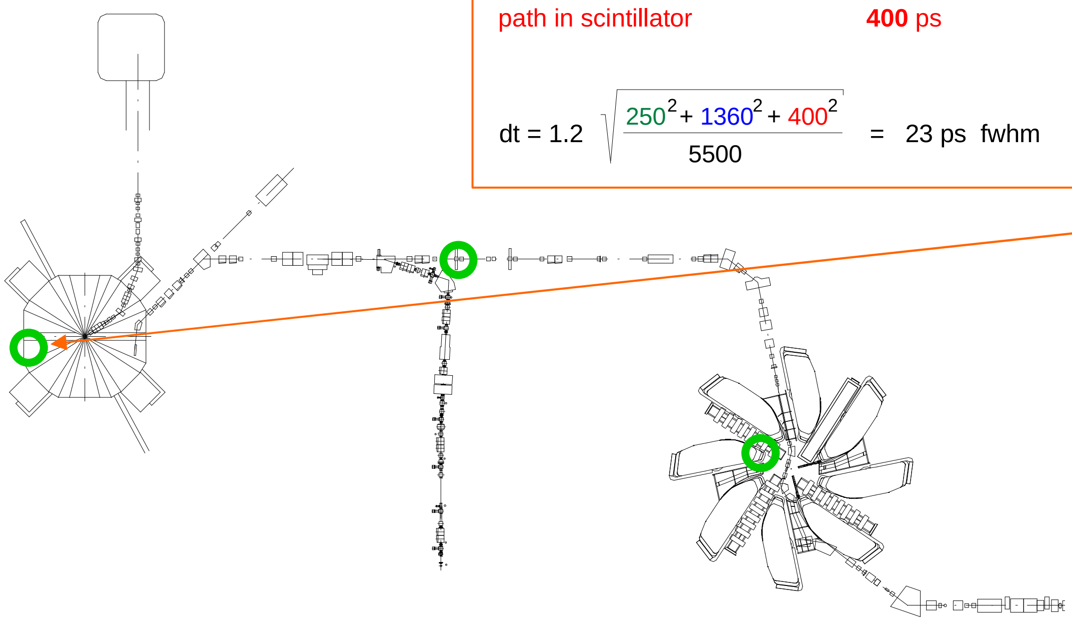
- measure longitudinal and radial density distributions of the beam bunches (averaging over many bunches)
- arrival time of scattered protons compared to RF reference (discriminator & Time-to-Ampl. Converter & Multi-Channel-Analyzer)
- resolution incl. electronics ~31 ps fwhm (determined from correlation between detectors A, B)
- variant: scintillator in radial probe head
  Chautard et al., ICCA2001, http://accelconf.web.cern.ch/AccelConf/c01/cyc2001/paper/P4-17.pdf

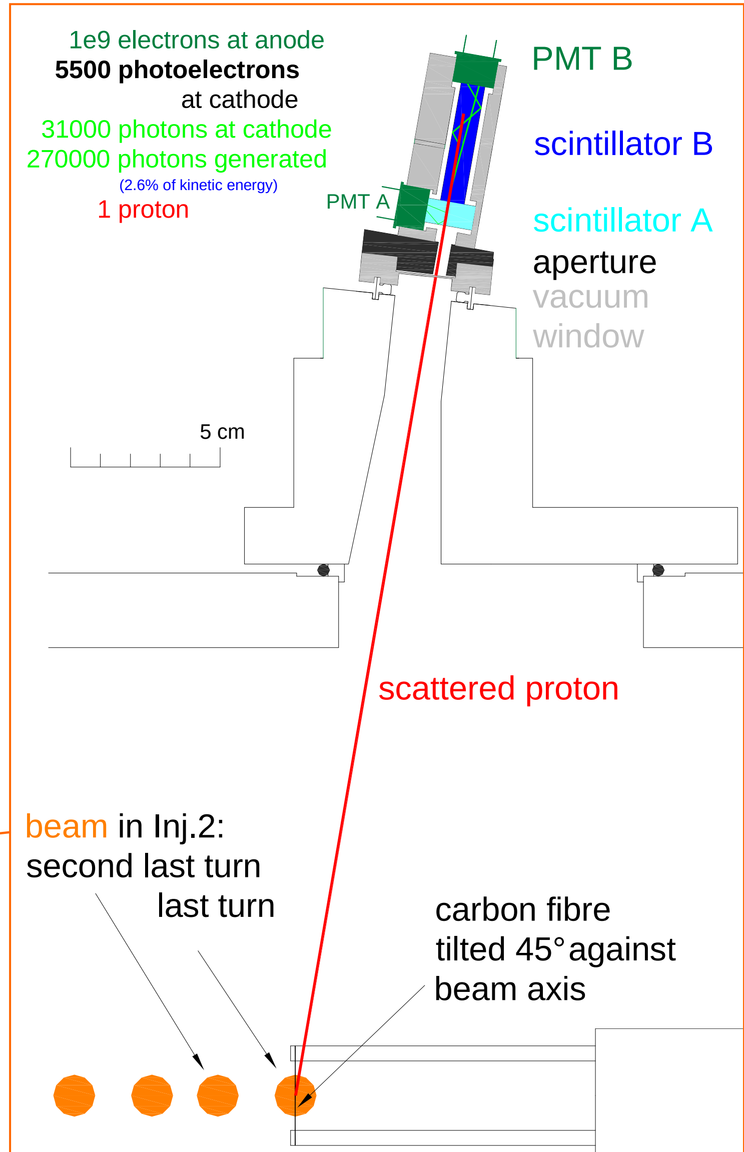
data used for layout of buncher between cyclotrons

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, DIPAC2001, http://accelconf.web.cern.ch/AccelConf/d01/papers/PS05.pdf

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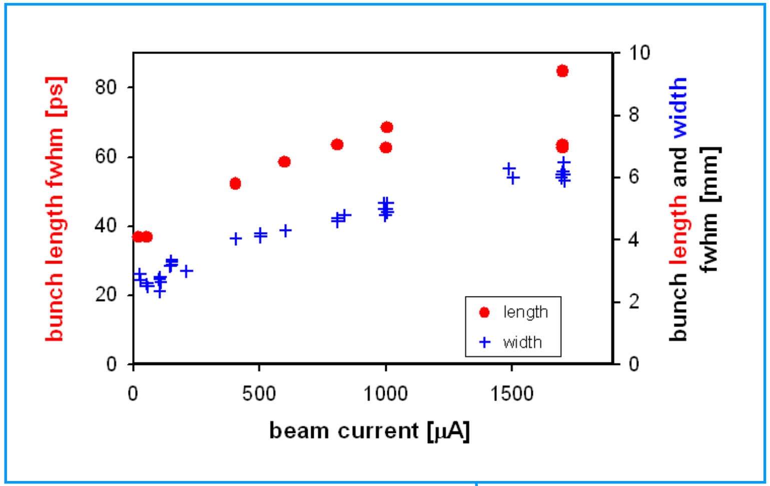
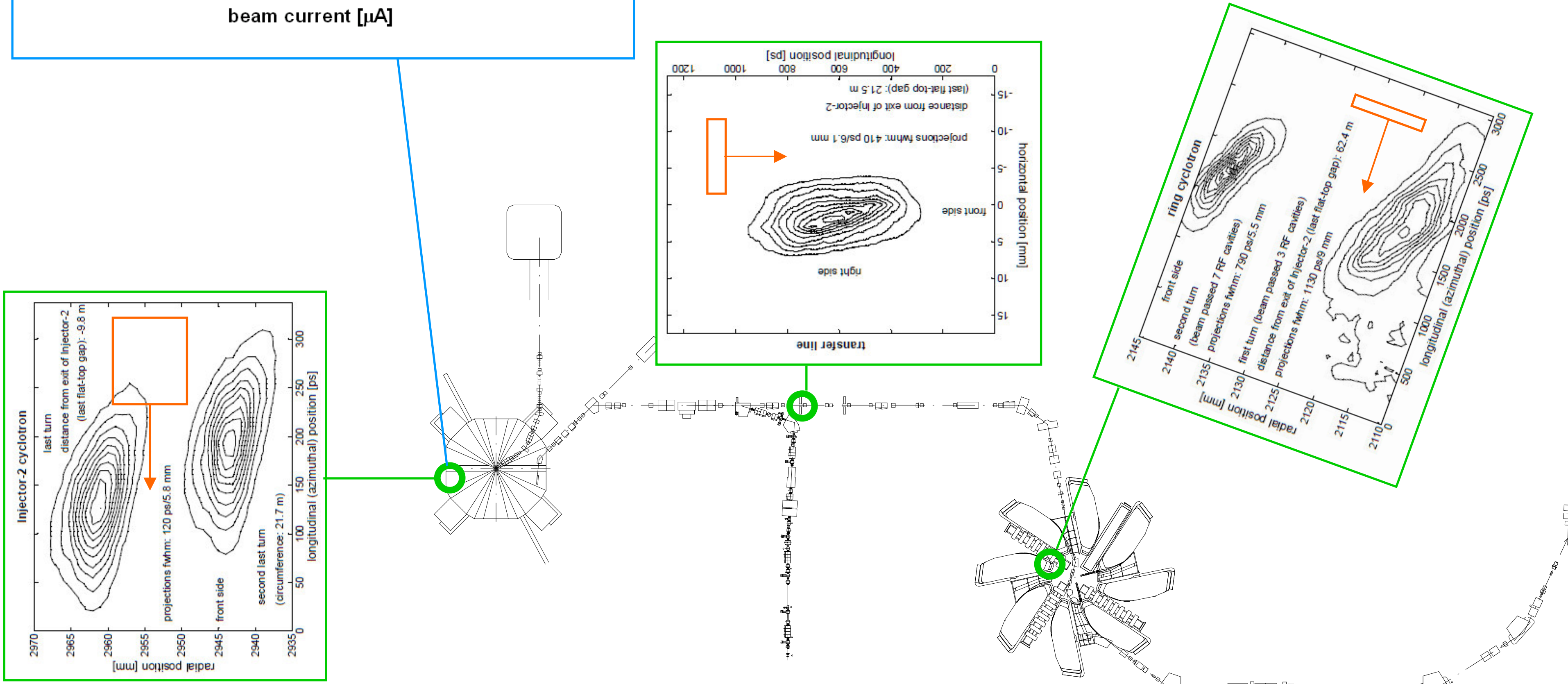


moving bunches as seen from above

(comoving sqare 10x10 mm
10 mm = 90 ps = 1.6° RF)



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

extraction: efficiency, beam parameters, stability at cyclotrons with high extraction efficiency (mostly high power machines):

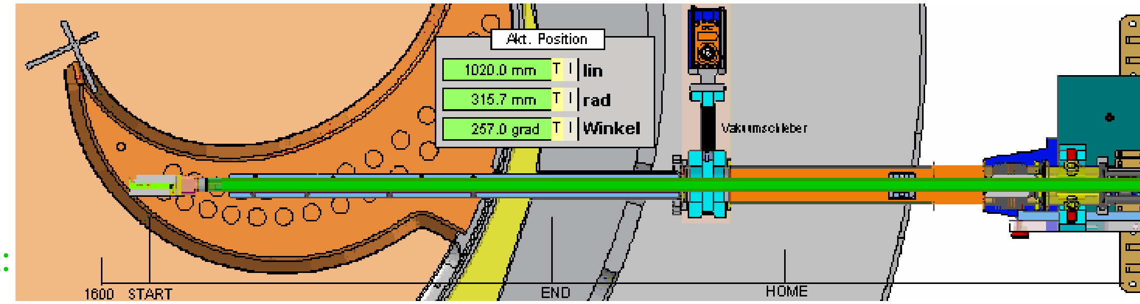
- a direct measurement of the small current difference is difficult
- loss monitors are calibrated with a deliberately lost small known beam current (which is measured beforehand with a stopper in the following beam line)
  → loss monitor readings at normal operation can be converted to lost beam current
- extraction efficiency = 1 – lost beam current / measured beam current
- here this number is only of academical interest: the measured loss itself is important

at cyclotrons with extraction efficiency significantly <1
(and usually no turn-separation at extraction):

Accel / Varian, Geisler et al., ICCA2007, http://accelconf.web.cern.ch/AccelConf/c07/PAPERS/9.PDF

- measurement of the beam current at the machine center and after extraction e. g. with a long radial probe "integral probe"

example: radial probe of PSIs medical cyclotron:



at low & high energies: full beam stopped

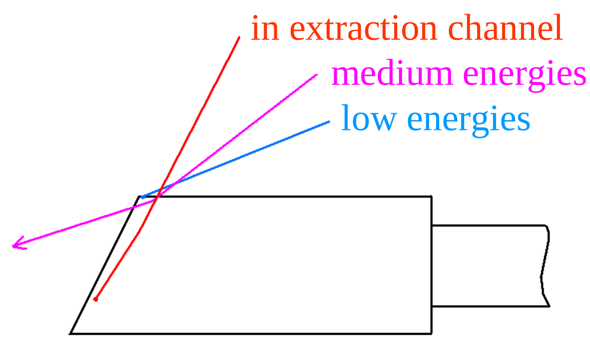
→ extraction efficiency = I_{highE} / I_{lowE}

at medium energies: part of the beam scattered & lost (due to probe geometry)

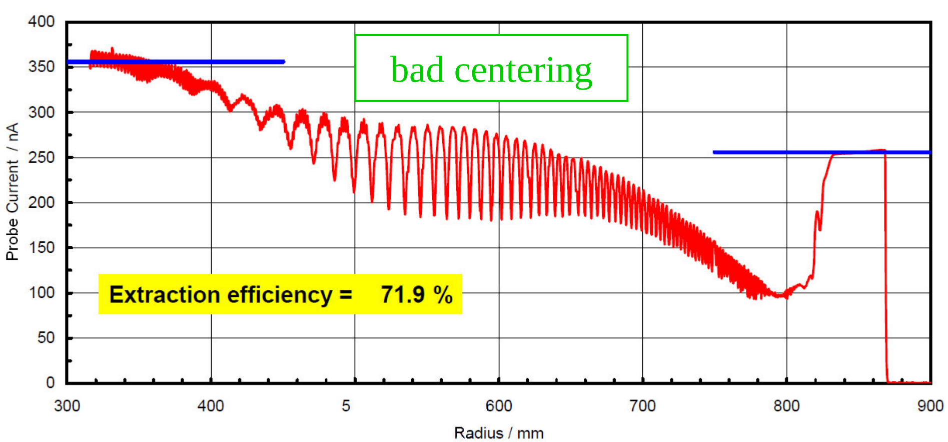
→ probe measures turn density

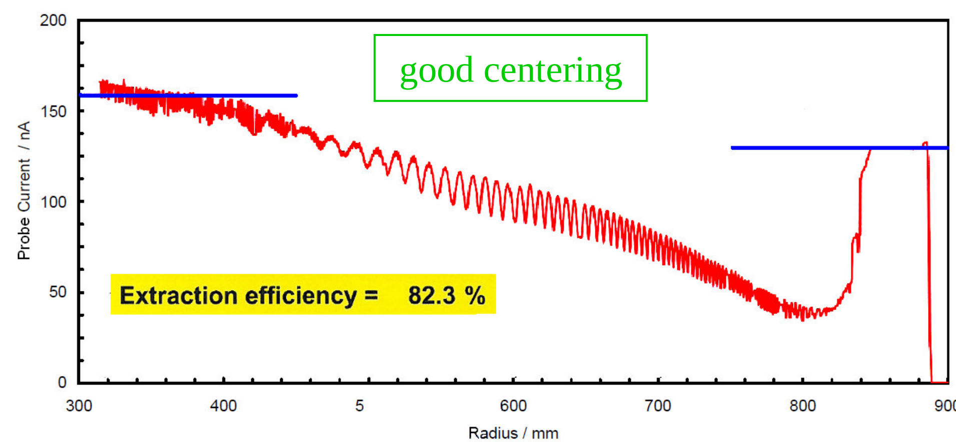
→ radial betatron oscillations visible

→ information on horizontal beam centering



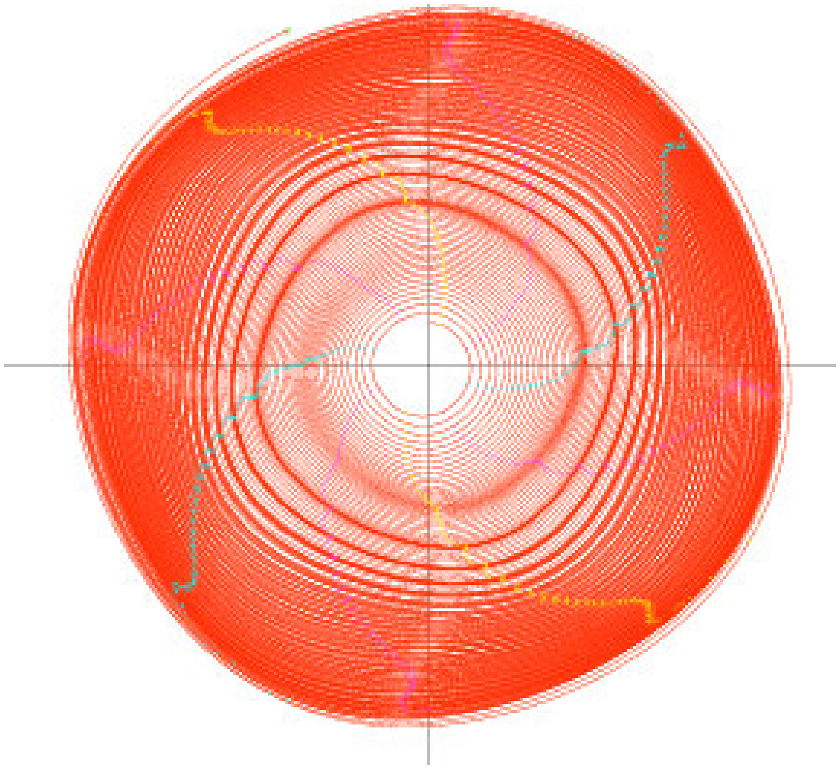
"integral probe head"

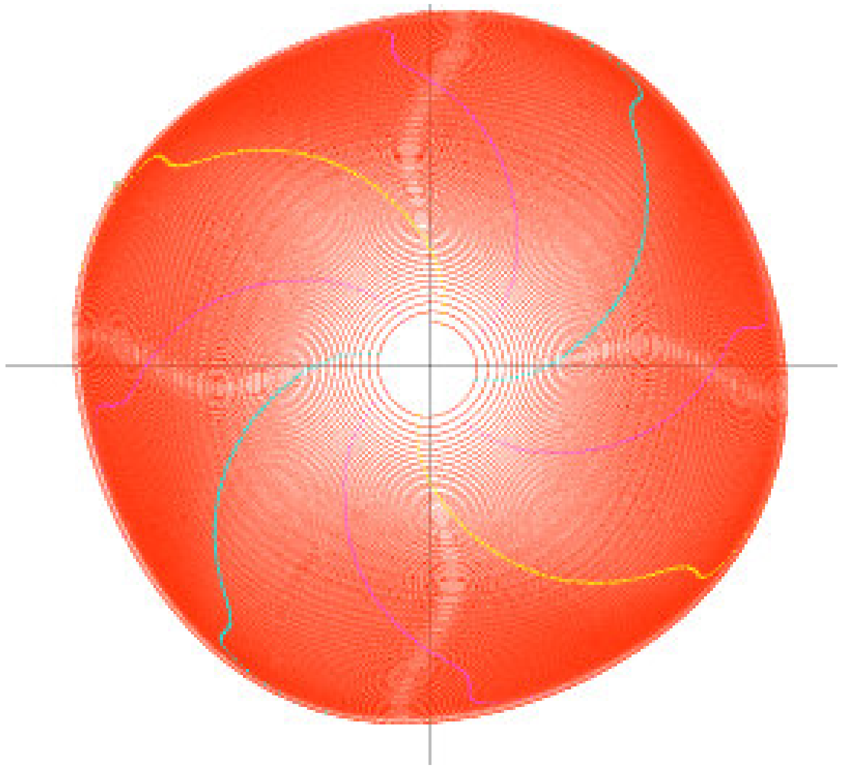


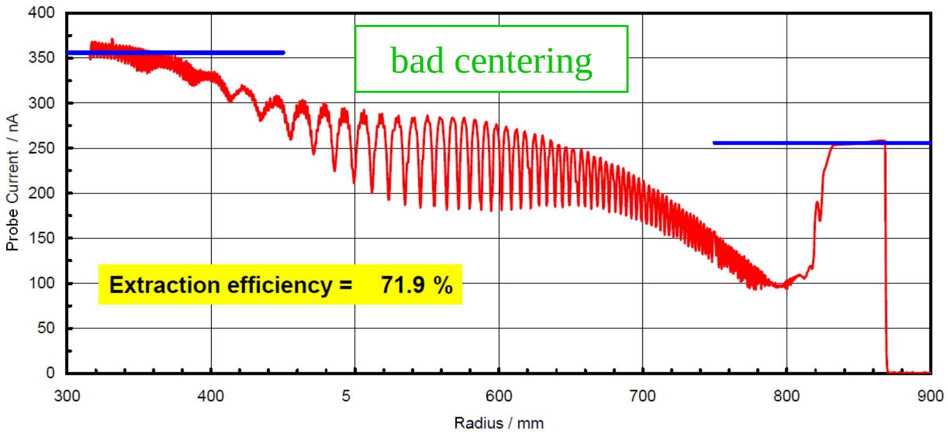


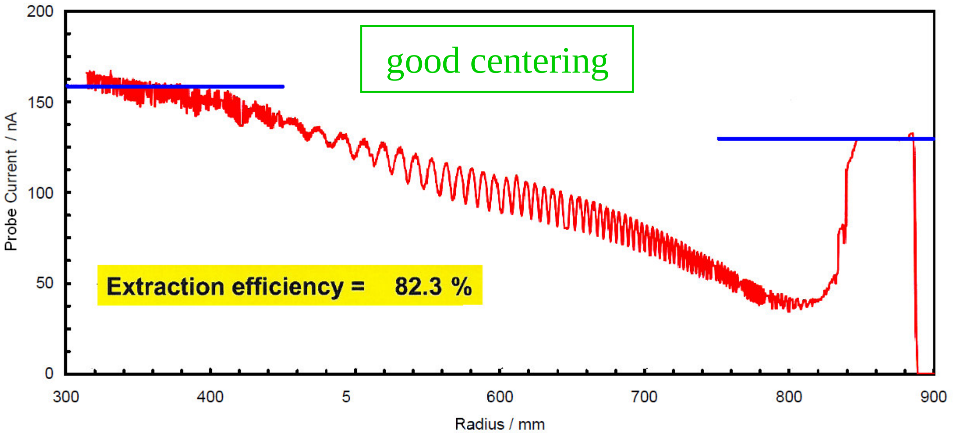
[horizontal betatron oscillations] decreased to zero since anyway no turn separation at extraction

comparison to simulation: Schippers et al. ICCA2004, http://accelconf.web.cern.ch/AccelConf/c04/data/CYC2004_papers/21A3.pdf









[*insertion:* acceleration: adjustment of magnetic field and RF fields]

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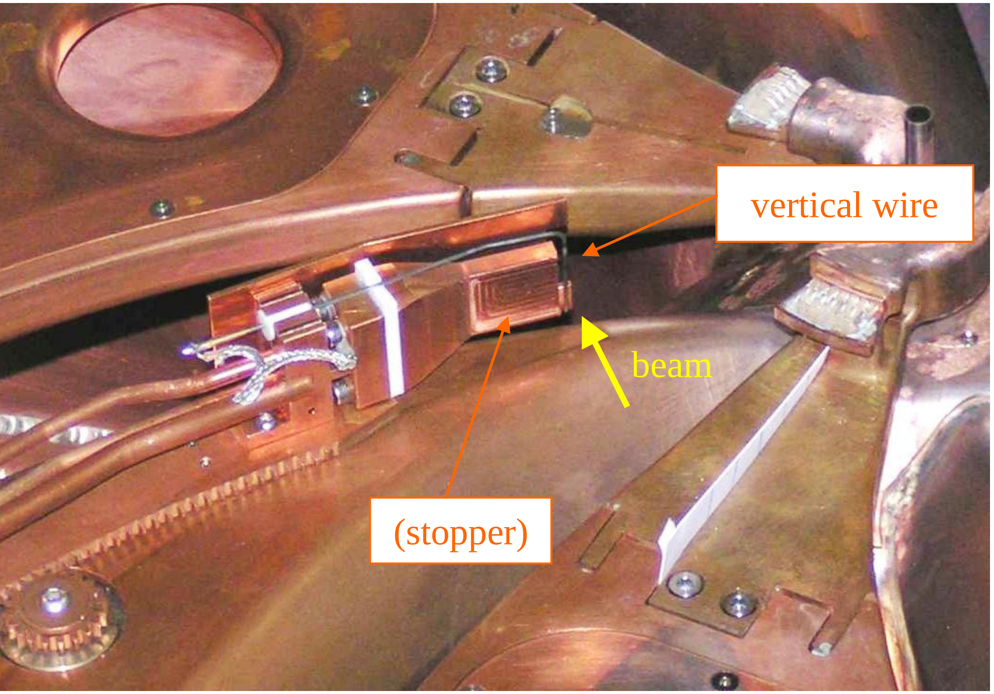
differential probe head

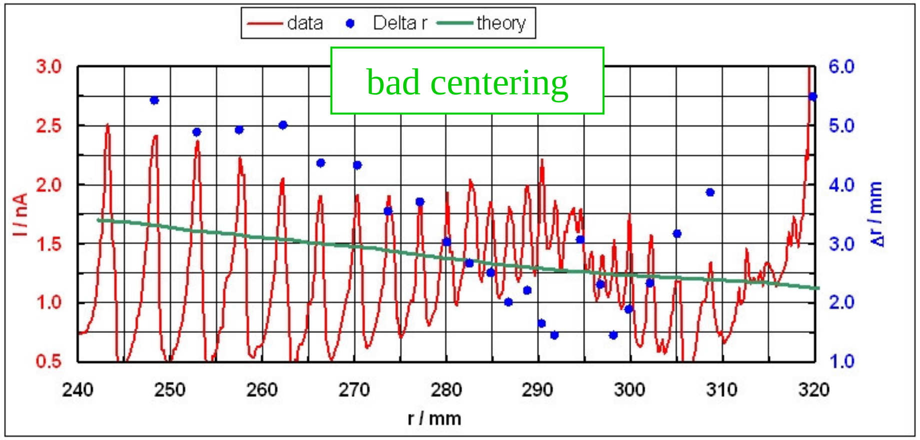


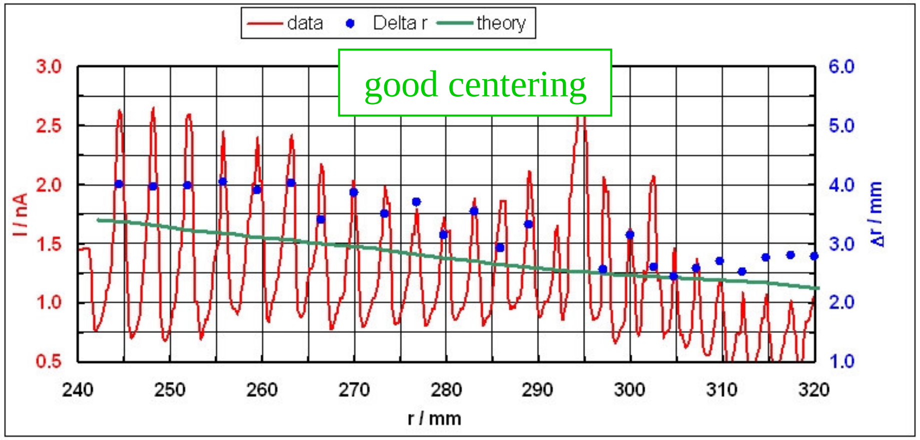
commissioning radial probe of PSIs medical cyclotron

Accel/Varian, Timmer et al., ICAP2006, http://bel.gsi.de/icap2006/PAPERS/TUPPP01.PDF

- beam measured on vertical wire
  (and stopped at latest on stopper block)
- probe measures radial turn profile (red)
  (turns in center region still separated)
- B-field trimmed until turn separation (blue points)
  varies gently (as theoretical prediction: green line)

Accel / PSI





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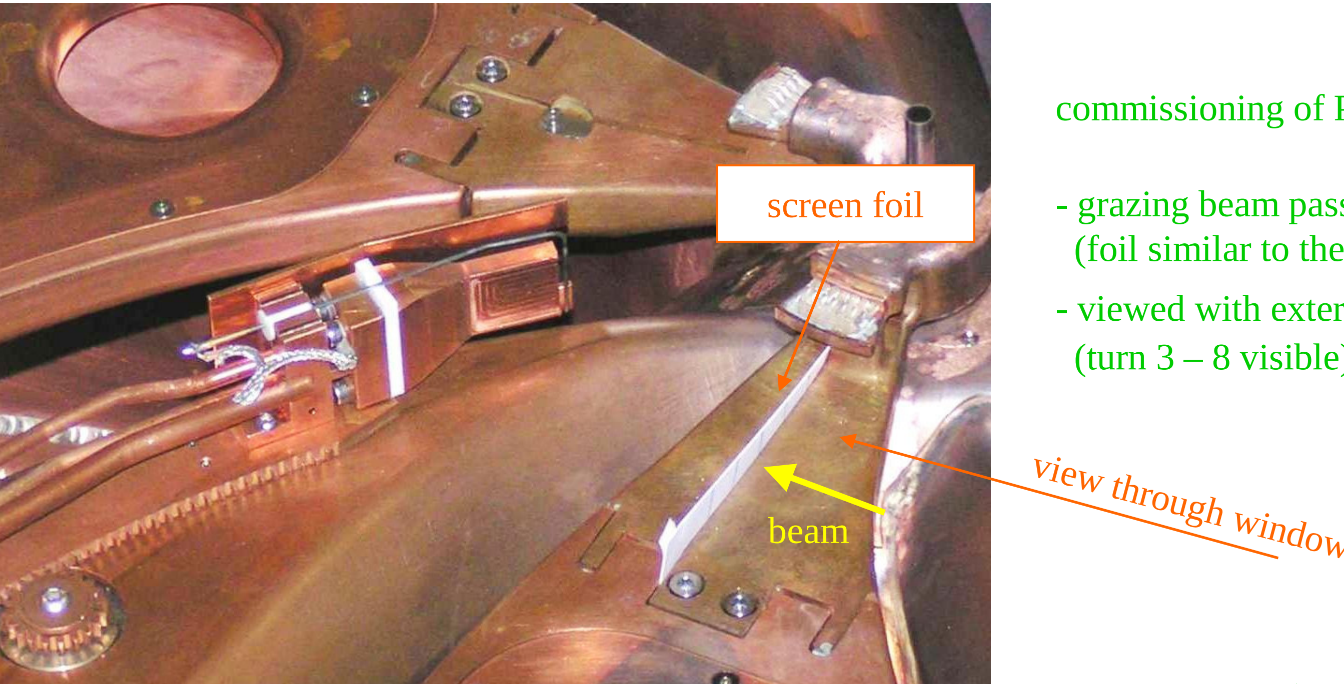
screen foil

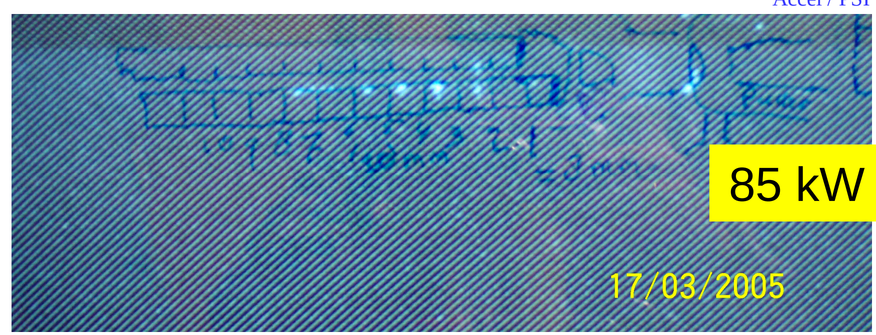


commissioning of PSIs medical cyclotron

- grazing beam pass over screen foil
  (foil similar to the one shown here)
- viewed with external CCD camera through window
  (turn 3 – 8 visible)

(turn 3 – 8 visible)

Accel / PSI



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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:

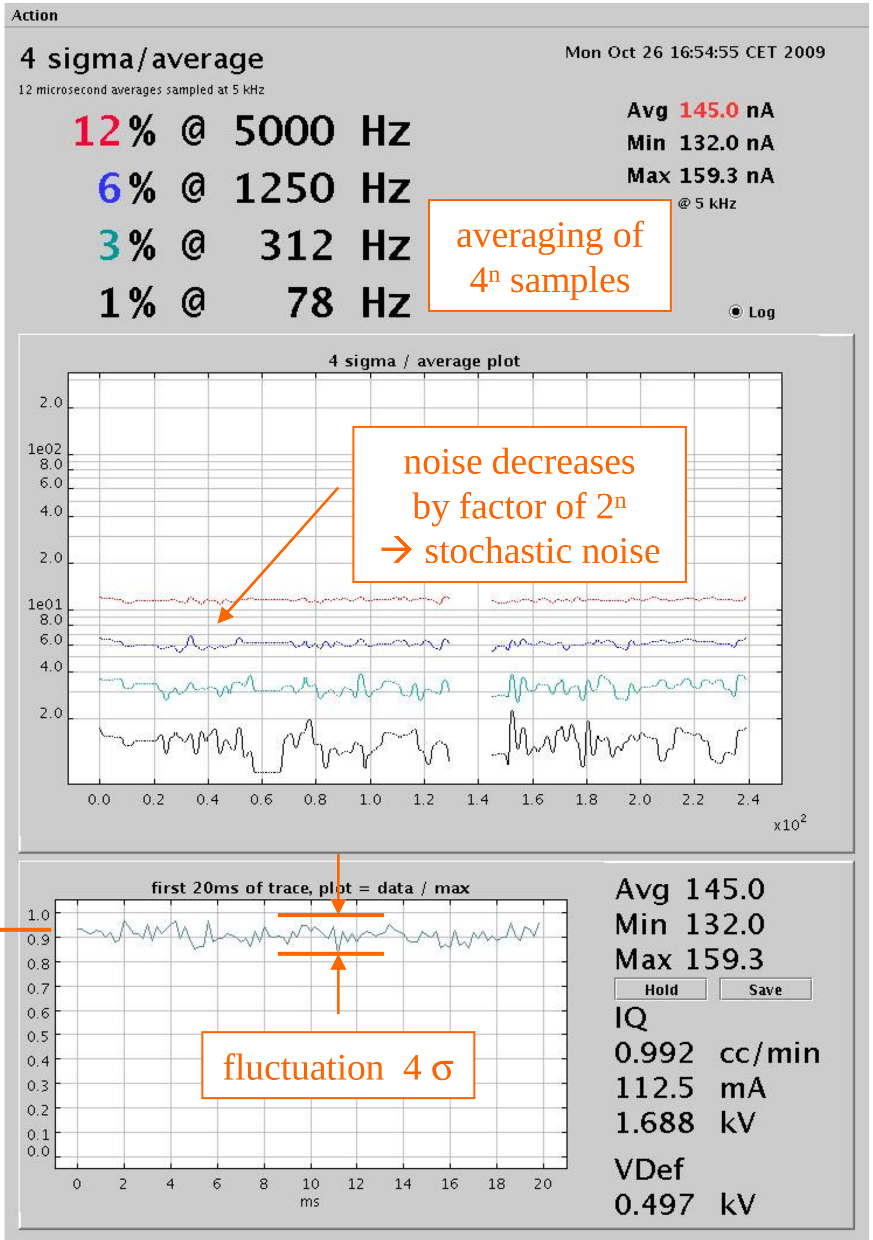
ionisation chamber behind PSIs medical cyclotron

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

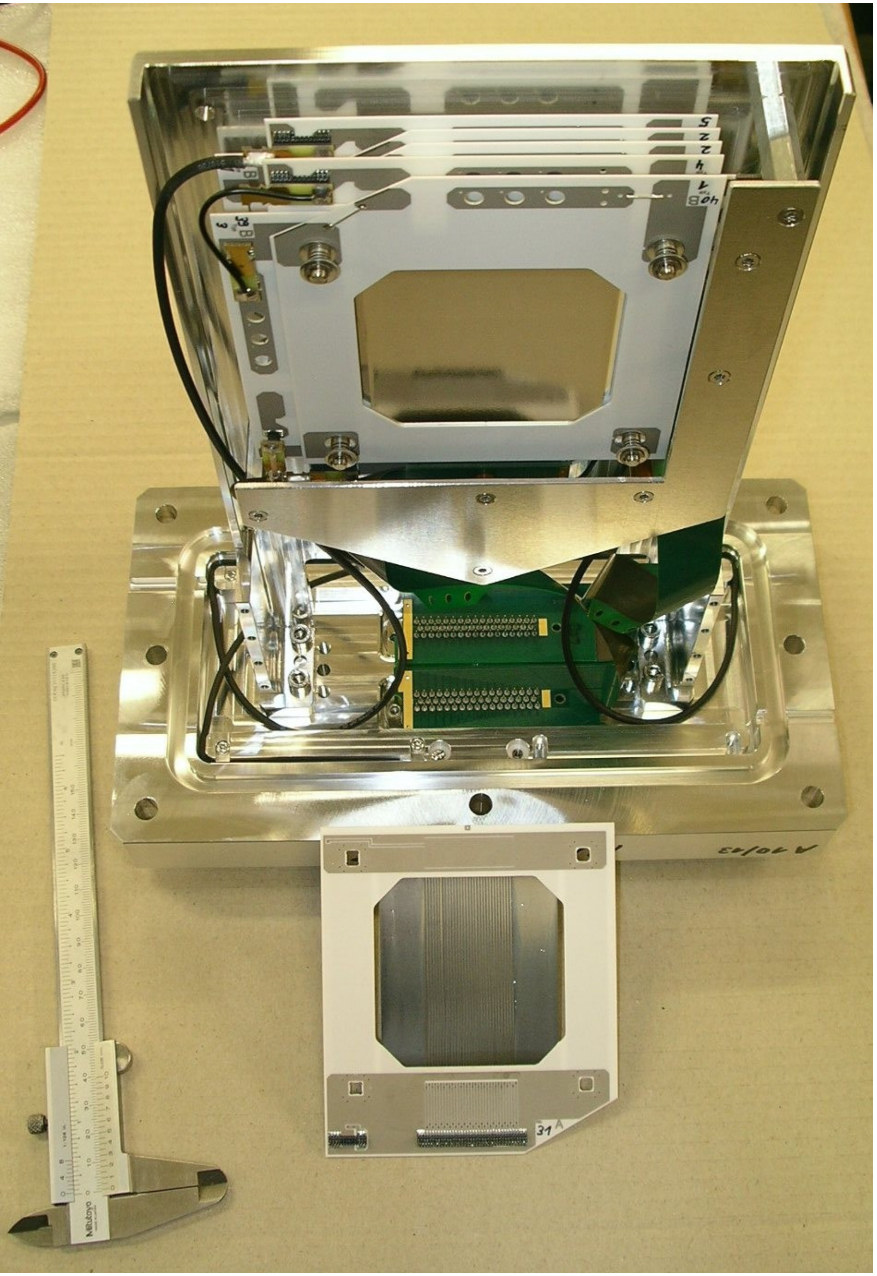
measures current fluctuations from the internal ion source

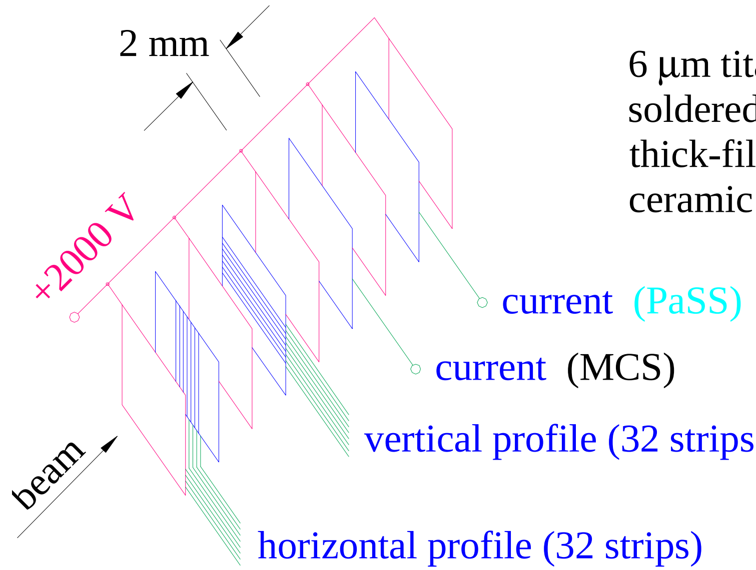
Schippers et al., ICCA2007, http://accelconf.web.cern.ch/AccelConf/c07/PAPERS/300.PDF

average beam current



beam current & its noise





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

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

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

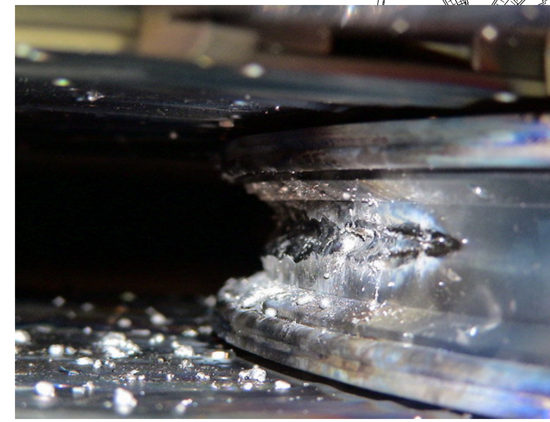
SEM: in vacuum
signal „amplified" by 0.053
microphonics

machine protection & control of activation

(an issue for high current / continuously operating machines)

machine protection from high power beams

- melting of beam line/cyclotron components by missteered beam
  → 2...300 days shut down for replacement/repair/remanufacturing
  (no spare parts for many components, many parts difficult to reach
  sometimes lack of documentation/drawings/exact dimensions)
- time t_{melt} depending on beam diameter/energy
- fast interlock generation needed (<1 ms)



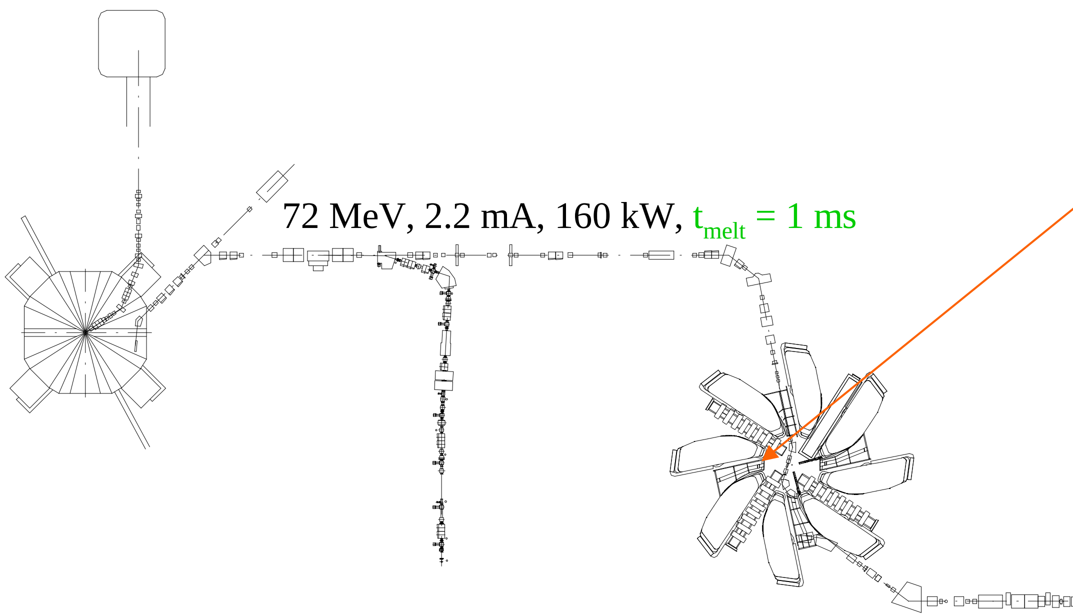
injection into Ring cyclotron:

collimator and coil support destroyed

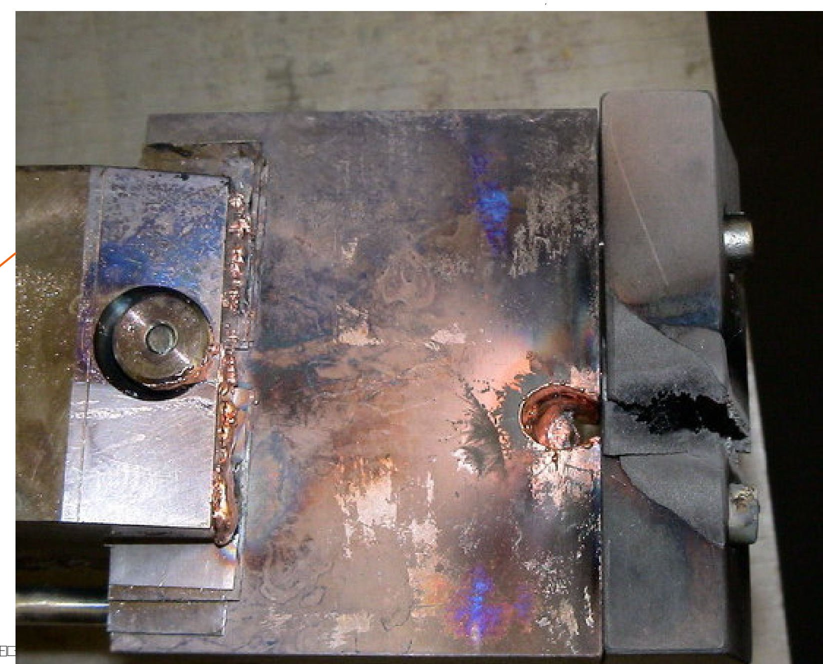
(defect of high level interlock module)

collimators

- with current readout



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

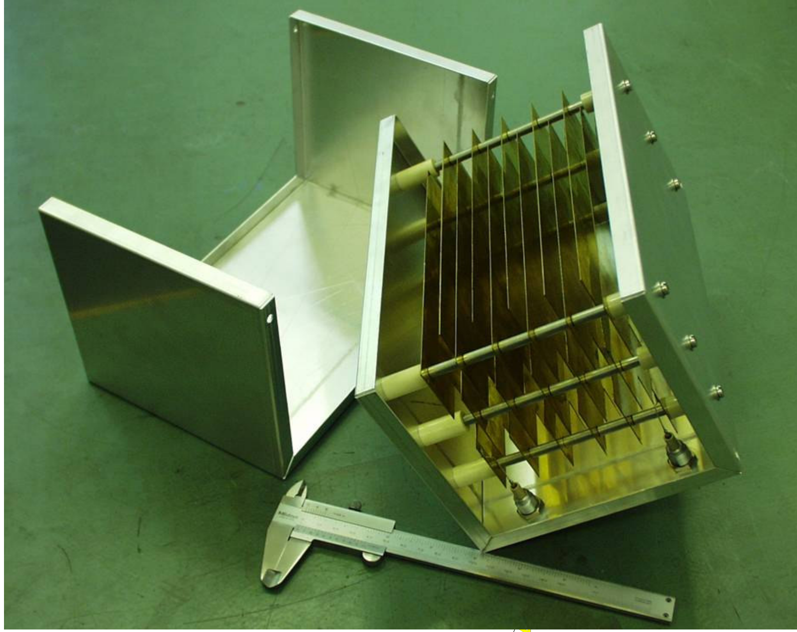


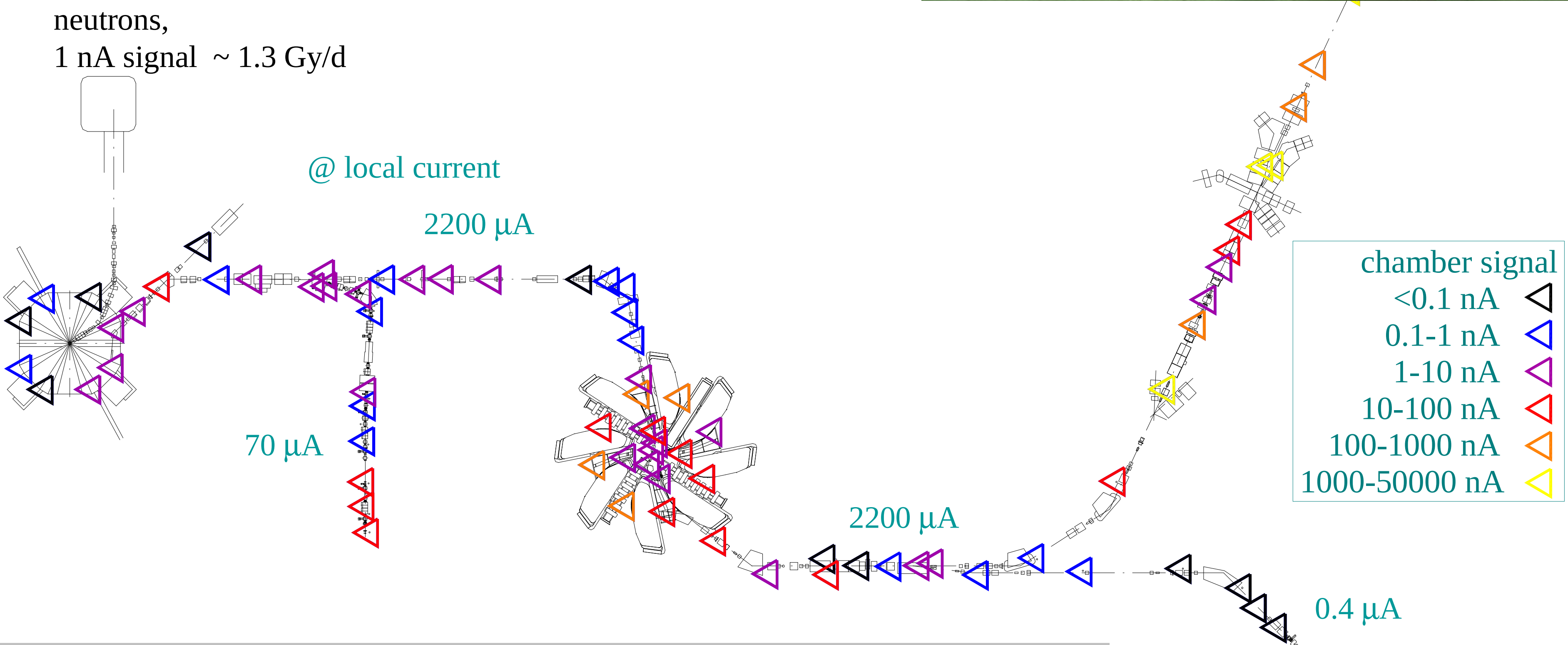
590 MeV, 2.2 mA, 1.3 MW, t_{melt} = 10 ms

[loss monitors]

here: ionisation chambers

- chamber signal linear in used range
- placed ~0.1...1 m from beam, fixed position for reproducibility
- useful at beam energies >40 MeV → proton range in steel > 3 mm
- ambient air filled, 300 V, gap = 1 cm, 2 litres
- also circular type around beam tube/cylindrical in shielding
- simple and reliable, radiation hard
- to consider for dose estimates:
  scattering in forward direction,
  shielding by components (!),
  neutrons,
  1 nA signal ~ 1.3 Gy/d





see also Wittenburg, CAS2008, http://cas.web.cern.ch/cas/France-2008/Lectures/Wittenburg-BLM.pdf

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- 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·ρ·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 ≈ πr²·L·ρ·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·d·ρ·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
  ≈ πr² · 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

Radiation damage problematic!

Flexible gain → linearity and calibration 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

linear in used range, very radiation hard

linear even at very high dose rate, very radiation hard

very sensitive

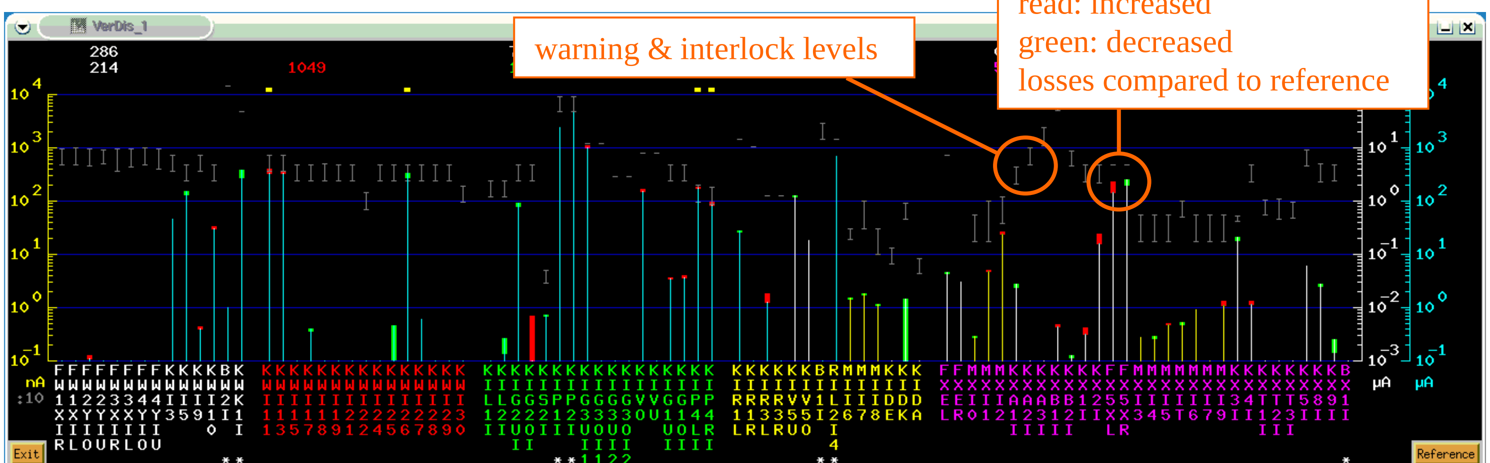
only for relativistic particles (β>0.68)

control of machine activation

- activation of beam line/cyclotron components by beam losses
- leads to personal dose at maintenance

for high power machines with long-term continuous operation this is critical:
- achievable beam current can be limited by the effect of loss-generated activation level on maintenance
- losses are monitored by collimator current and loss monitor readings
  and interlock levels can be set to keep losses down (in the machine control system)
- with a proper design and tuning of the machine losses are decreased

for these machines this has an impact on the role of diagnostics in the past-commissioning era:
- loss minimisation is „most important“
- hence collimators & loss monitors are the main diagnostics for protection and tuning
  (also current monitors for protection and BPMs for centering)
- profile monitors are seldom used for setup and „empirical“ tuning
  (but for error search)



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

A. Mezger, PSI

but profile monitors can contribute to improvements of design of an already running machine:

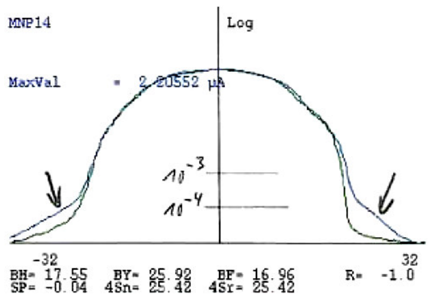
- if detailed numerical simulations
  (including beam halo, scattering at collimators, 3D-poisson solver, space charge neutralisation)
  lead to a better understanding of the losses

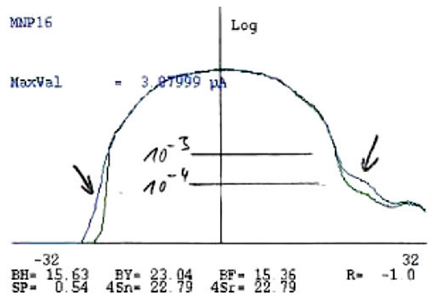
- then detailed proposals can be made for
  an improved machine layout and beam shaping by collimators
  (in the environment of a production machine such changes are nearly impossible on a trial & error basis)

- such simulations need a realistic input on the beam phase space distribution

- this input can be generated (as part of the simulation) from
  the detailed information from profile monitors with high dynamic range

- the simulations can also be calibrated
  by introducing additional beam scattering with wire scanners
  and observing the downstream profiles and loss monitor readings





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%)