Beam Instrumentation for SEEIIST facility

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Outlook

- Introduction
- Sources of information: HIT and MedAustron
- Measured beam parameters, types of devices
  - Beam intensity
  - Beam position, beam size/emittance
  - Transverse beam motion
- Cost estimation
- Developments, FLASH therapy
- Conclusions

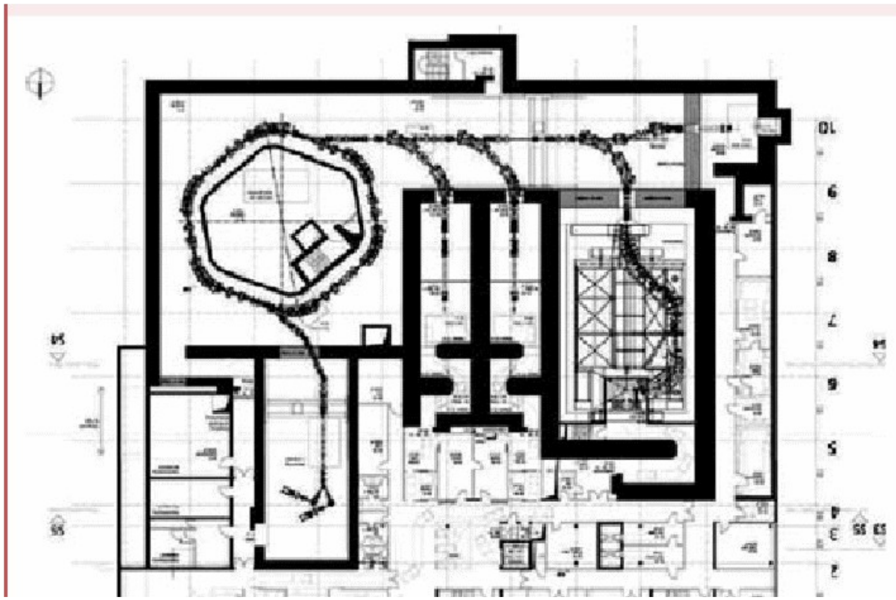
Introduction

- Beam Instrumentation in medical machine is not different than in research
- Sometimes cost-saving considerations play important role
- Research machine often exceed their design parameters, medical machines do not, but SEEIIST is – to some extent - both
- The dose delivery system is the main difference; it is based on special medically certified beam instruments placed in the Irradiation Room
- Ion Sources + LEBT + Linac (Injector), MEBT, Synchrotron (SYNC), High Energy Beam Transfer (HEBT)
- Operational phases: Commissioning - CO, Quality Assurance - QA, Operation (with patients or for experiments) - OP
- Experiments may require more sophisticated instrumentation (eg. higher dynamic range)
- Some devices are multipurpose, eg. slits: instrumentation but also beam production, or they are often assigned to instrumentation eg. RF-kicker

Sources of information

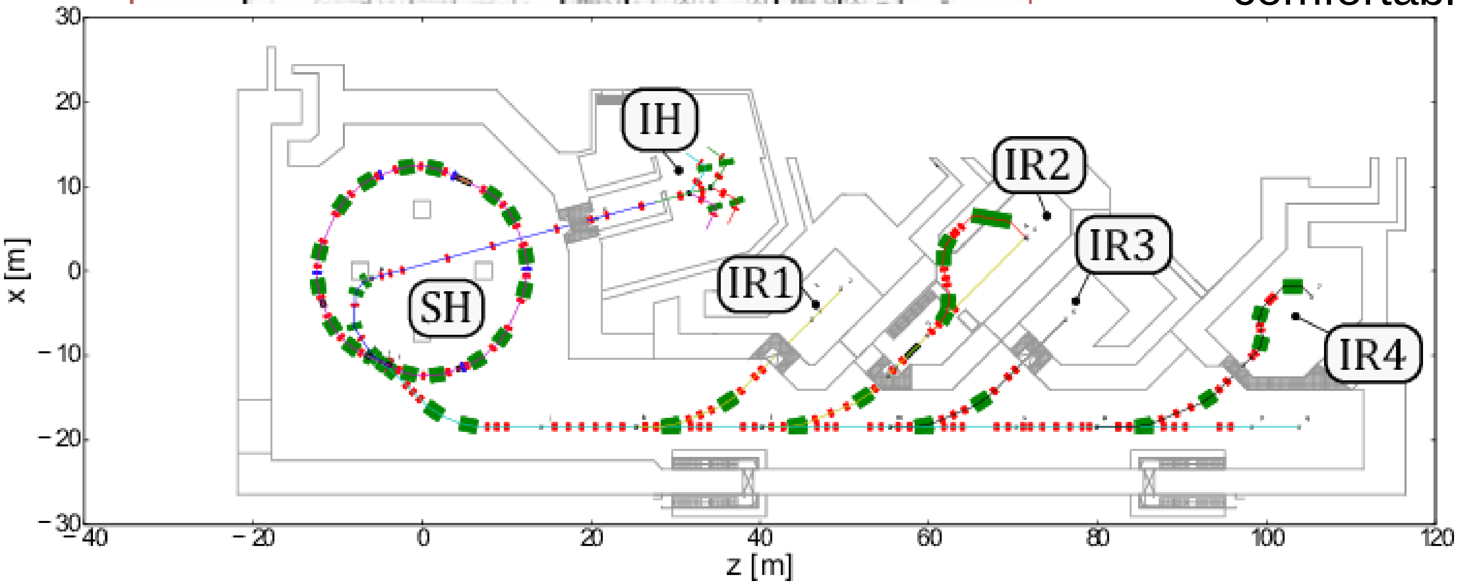
- **Andreas Peters** and Peter Forck, ,,Beam Diagnostics for the Heavy Ion Cancer Therapy Facility'' in Proceeding of Beam Instrumentation Workshop BIW 2000, Boston, USA
- i-tech (**Katarina Roskar**)
- MedAustron: **Dale Prokopovich** and **Claus Schmitzer**
- GSI colleagues: **Andreas Reiter, Plamen Boutachkov, Beata Wałasek-Hoechne**
- MIT (Marburg) not included yet because they are commercial facility with rather poor instrumentation to reduce costs,
- (But it maybe interesting to see commercial approach)
- CNAO will be included in the report

Layouts



Heigelberg Ion Therapy:
- precursor facility (R&D),
- build by GSI,
- with strong space constraints

MedAustron:
- most recent facility (commercial),
- build with help of CERN,
- generously using the space (more comfortable beam envelope)



Cost breakdown

1) Vacuum chamber - can host multiple instruments, can have multiple flanges and feedthroughts – typical cost 10-30 kEUR
2) The instrument itself (could be expensive, eg. MWPC), sometimes it is difficult to asses the price, eg. Faraday cup with cooling costs x2
3) Readout electronics – commercialization
4) Pneumatic drive or stepper motor with its control system, etc.
5) Front-end software – done by control system, sometimes in-house
6) Control room GUI (usually with functionality like curve fitting, etc)
7) (Sometimes there is just a scope showing the signal from a pickup, replacing 3-6)
8) Only some devices are commercial, other obtained via collaboration with CERN or GSI or via **in-house developments**
9) DDS devices, slits, scrapers, kickers, degraders, stripping foil, RF phase probes, RF-kickers not included here

Beam current

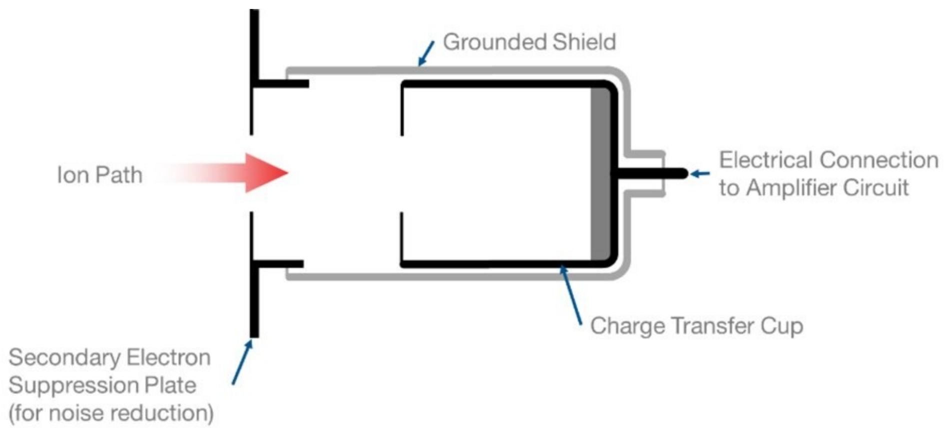
- Beam current is typically expressed in uA at low energies and in number of particles circulating or per second at higher energies

$$I_{beam} = \frac{qeN}{t} = \frac{qeN}{l} \cdot \beta c$$

- Beam current has a structure: micropulses, pulses, bunches
- Typical number is carbon therapy machine: 200-1000 uA (ion source), 10^8-10^{10} ions (circulating current), 10^8 ions/second (extracted beam)
- Devices to measure beam current:
  - Faraday cups
  - Beam current monitors

Faraday cup

- Faraday cups perform destructive measurement
- They are simple, robust and very precise and sensitive
- They work well at low energies (sources), but there are special multi-layer Faraday cups which could be used even at extraction



- Sensitivity: nA
- Resolution: 1 nA
- Price:
  - 5-10 kEUR (device)
  - 10 kEUR (pneumatic drive)
  - 10 kEUR – electronics,
  - Total 40 kEUR (inc vac. chamber)

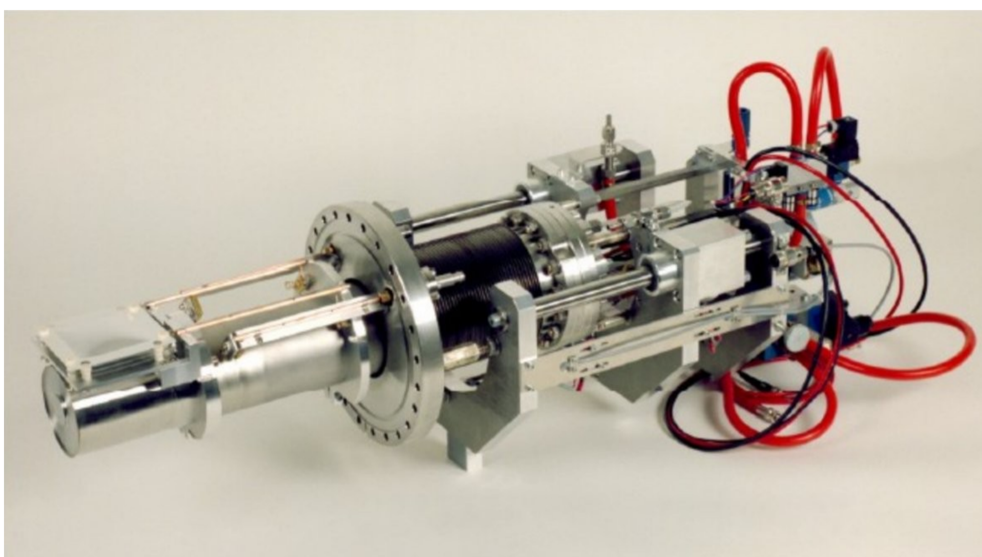
Beam current monitor (BCT)

- There are two main types of BCTs:
  - Fast - ACCT
  - DC current (for coasting beam) - DCCT
- They both measure field induced by the beam – nondestructive measurement

- Sensitivity: 0.1 uA – 10 uA
- Resolution: 0.5 uA/f$^{1/2}$
- Price:
  - Torus in flange: 15-30 kEUR
  - Electronics: 25 kEUR (?)
  - Total: 40-50 kEUR

Particle counters
(PDC – Particle Detector Combination)

- Devices insertable to the beam path
- Usually containing 2-3 detectors for various beam intensities
- SEM plate, Ionization chamber (IC) and scintillator
- Heidelberg uses PDC, MedAustron uses scintillating fibers
- No commercial supplier, PDCs are made in GSI detector lab
- DDS uses IC to measure number of particles delivered to patient



- Sensitivity: 100 – 10^{11} particles
- Precision: 100 particles
- Price:
  - Detectors: 6+ kEUR
  - Pneumatic drive: 15 kEUR
  - Readout electronics: 5 kEUR
  - Total: ~45 kEUR

Beam current measurements

Zone	Device type	Oerational phase	No of devices(cost [kEUR])		
			Heidelberg	MedAustron	SEEIIST
Injector	Faraday cup	CO, QA	7 (280)	7 (280)	7 (280)
	DCT	CO, OP	3 (150)	0 (0)	3 (150)
	ACT	CO, OP	1 (40)	1 (40)	1 (40)
MEBT	Faraday cup	CO, QA	2 (80)	4 (160)	2 (80)
	ACT	CO, OP	2 (80)	2 (80)	2 (80)
SYNC	DCT	CO, OP, QA	1 (50)	1 (50)	1 (50)
	ACT	CO, OP, QA	1 (40)	1 (40) FCT	1 (40)
HEBT	PDC	CO, QA	11IC+4SC (675)	0	15 (700)
	Scint. fibers/ counters	CO, QA	0/1 (6)	1/0 (30?)	0?
Total:			32 (1,401)	17 (680)	32 (1,420)

Beam position and size

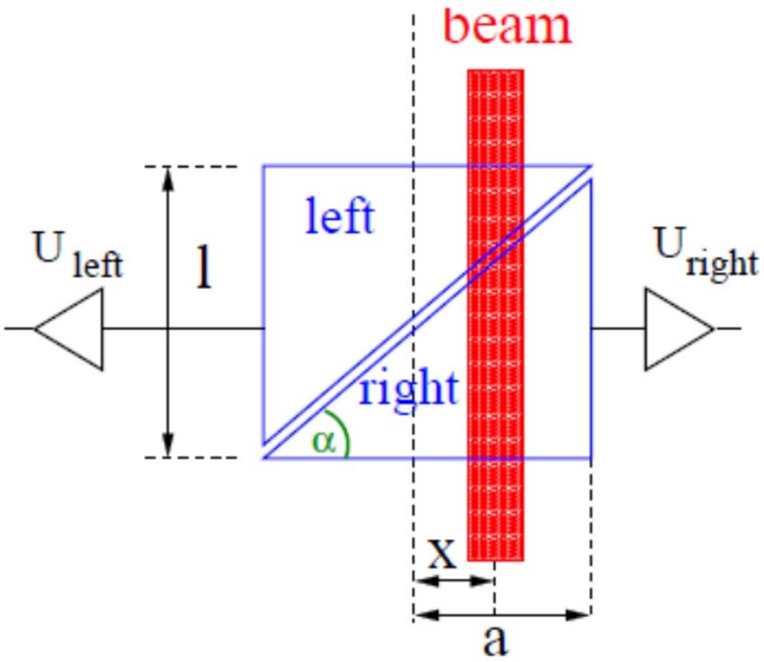
- Beam position is measured in mm of deviation from the reference orbit
- Devices to measure beam current:
  - Pick-ups (BPMs):
    - Button type for linac and MEBT
    - Shoe-box type for synchrotron
  - Profile grids (SEM grids) or wire scanners
  - Multi-Wire Proportional Chambers (MWPC)
  - Scintillating screens
  - Scintillating fiber hodoscopes

Beam position only

Beam size and also position

Pick-ups

- Measure position of bunched beam, so Linac, Synchrotron but not HEBT (unless for fast extraction)
- Shoe-box pickups used in both: HIT and MedAustron (and SEEIIST): good linearity, work well with bunches longer than BPM size
- For superconducting synchrotron: they are quite large, around 20 cm/plane

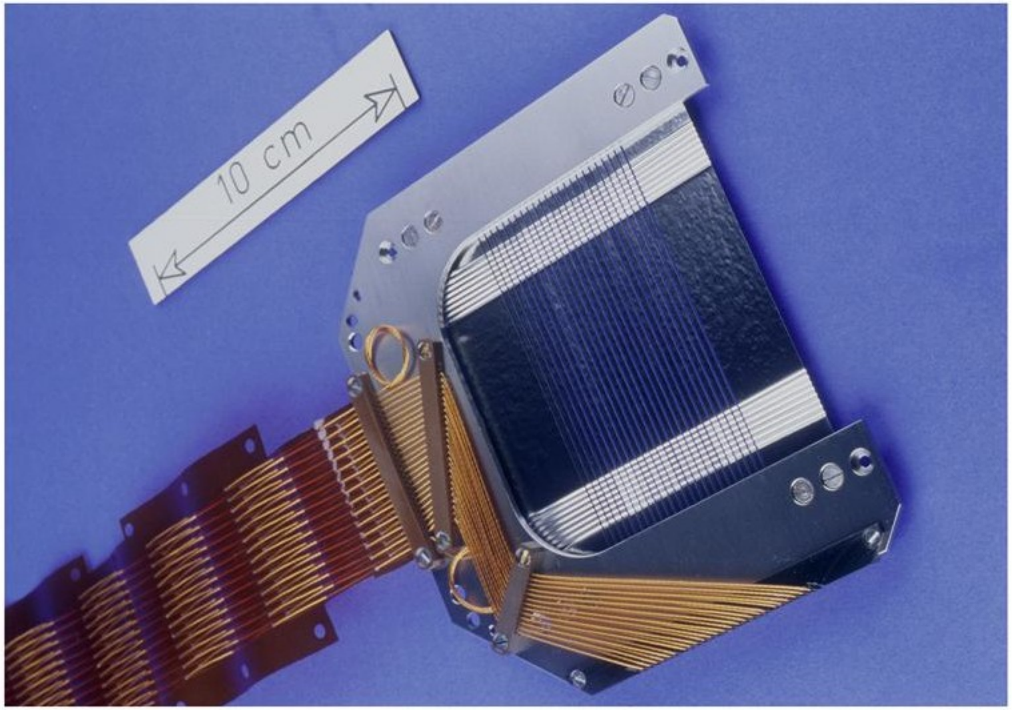


- Precision: 0.1 mm
- Price:
  - Detectors and vacuum chambers: 20 kEUR (cold 25 kEUR)
  - Electronics: 10-13 kEUR
  - Total: 30-40 kEUR

- Linac/MEBT pickups – buttons, different electronics (phase measurement) cost about: 15 kEUR (detector)+7kEUR (electronics)

SEM Wire Scanners or Grids

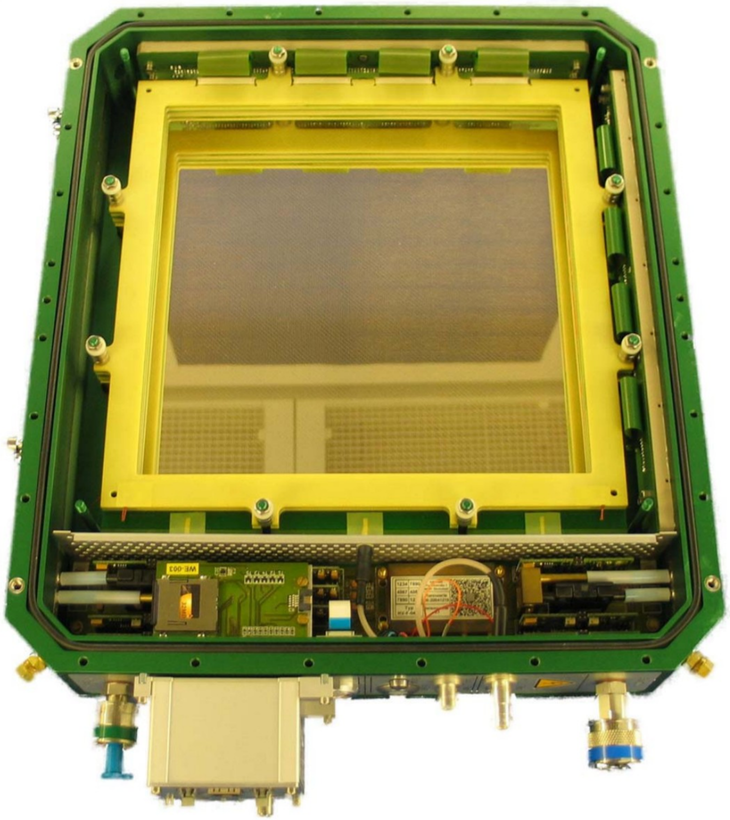
- Based on phenomena of secondary electron emission from metallic foil or wire crossed by the charged particle beam
- Wire scanners move the wire through the beam while measuring the outgoing electron current; wire grids use a grid of wires.
- Together with two slits, the wire or grid are used to measure beam emittance at LEBT



- Precision: 0.1-0.5 mm
- Price:
  - Wire scanner: 15 kEUR
  - SEM grid and pneumatic drive: 25 kEUR
  - Slits for emittance: 15 kEUR
  - Vacuum chamber shared with eg. Faraday cup

Multi-Wire Proportional Chambers MWPC

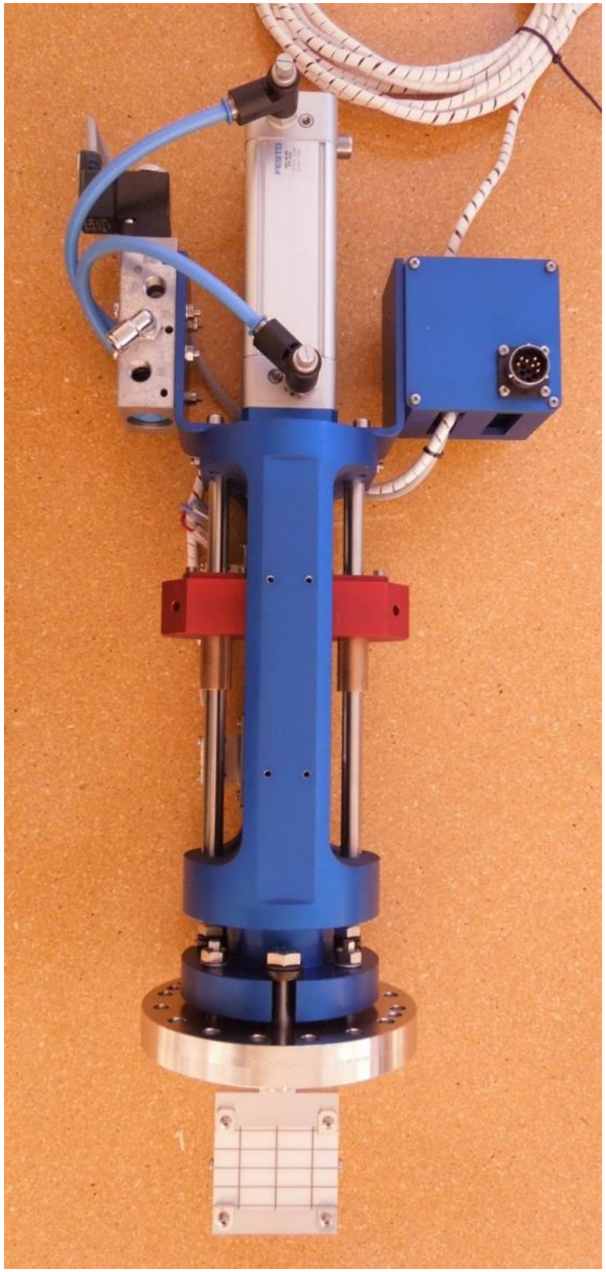
- Take a SEM-grid and put it in thin metallic envelope with gas,
- Electric field is high, so detector works in proportional mode (eg. intensity measurement is not very precise)
- Devices with medical certification used in nozzle in front of patient
- Radiation hard, requires gas distribution system



- Precision: 0.1-0.5 mm
- Price:
  - 100 kEUR (medical, Siemens)
  - 65 kEUR (diagnostics, including pneumatic drive)

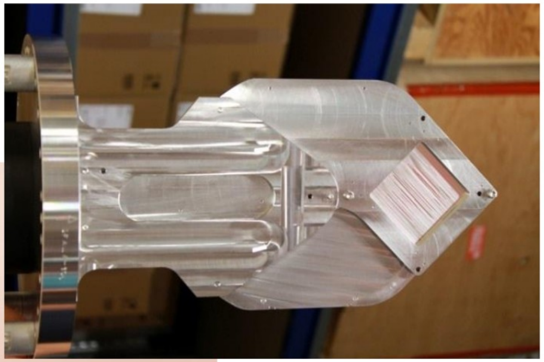
Scintillating screens

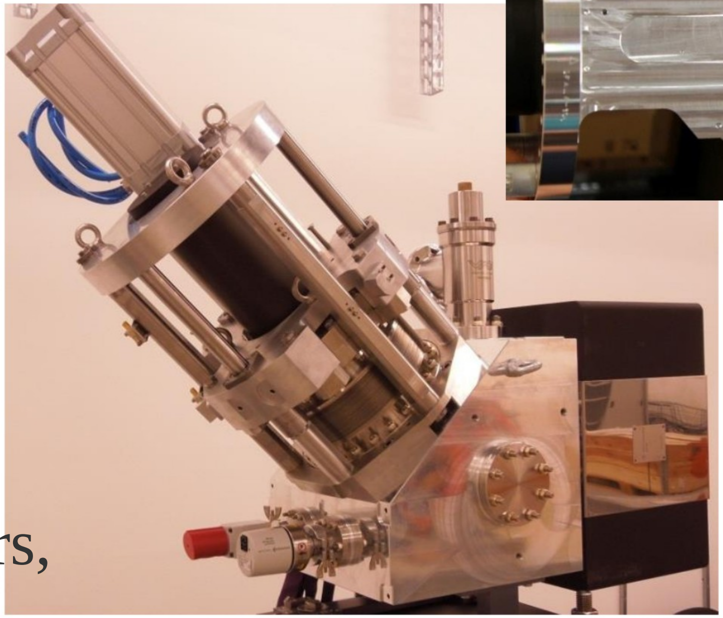
- Beam hits a scintillating plate, generates light registered by a camera
- Cameras have much better resolution than MWPC, but sensitivity and dynamic range is much smaller
- They are used for first-turn diagnostic in synchrotron (all centers) and in HEBT (only in Heidelberg)
- Sensitivity: depends
- Resolution: < 0.1 mm
- Price:
  - Pneumatic drive: 8 kEUR
  - Scintillator, camera: 7 kEUR
  - Total: 30 kEUR (including vacuum chamber)



Scintillating fiber hodoscopes

- Position resolution obtained by scintillating fibers (typical size 0.25 mm)
- Problems:
  - Radiation damage: need to recalibrate regularly
  - Camera readout is slow, the main advantage of scintillation is not used
  - More material than MWPC
- Used in MedAustron and CNAO; MedAustron plans to replace them with scintillating screens (better resolution, cheaper)
- I would not use them in SEEIIST unless…
- New development proposed for HIT (2018), based on LHCb fibers, readout out by PMT array





Beam position and size

Zone	Device type	Operational phase	No of devices (cost [kEUR])		
			Heidelberg	MedAustron	SEEIIST
IS+LINAC	pick-ups	CO, OP, QA	1 (22)	1 (22)	1 (22)
	wire scanners	CO, QA	0	22 (330)	6 (90)
	grid	CO, QA	7 (210)	1 (30)	4 (120)
MEBT	pick-ups	CO, OP, QA	3 (66)	1 (22)	3 (66)
	grid	CO, QA	4 (100)	7 (280)	4 (100)
SYNC	pick-ups	CO, OP, QA	12 (360)	20 (700)	20 (700)
	Scint. screen	CO, OP, QA	2 (60)	2 (60)	2 (60)
HEBT	MWPC	CO, QA	13 (845)	0	7 (455)
	Scint. fibers	CO, QA	0	30 (900?)	0 ?
	Scint screen	CO, QA	5 (150)	0	20 (600)
total			47 (1,813)	84 (2,344)	67 (2,213)

Tune, chromaticity (transverse beam motion)

- Tune is usually measured using a single BPM turn-by-turn signal in response to a fast kick
- So one horizontal and one vertical BPMs are dedictated to tune measurement and connected to tune-processing electronics (or a scope!)
- Signal is converted to frequency domain (FFT), tune peak detection is sometimes a problem
- Improvements: Direct Diode Detection electronics (BBQ system) – allows for much smaller excitation (CERN development, used in MedAustron)
- Standard way of chromaticity measurement: slightly change beam momentum and measure the tune again, repeat
- BBQ electronics system cost: several kEUR
- Vertical and horizontal tune kickers: (is that part of BI cost?)
- Shottky pick-up: allow for dp/p, slow tune measurements, cost: 50 kEUR/plane

Other points

- Beam-Induced Fluorescence monitor in linac:
  - could be useful for online emittance measurement during high-intensity operation
- Cryogenic Current Comparator (CCC):
  - could be useful for online spill intensity measurement for slow extraction; very expensive (500 kEUR)
- Beam halo monitors - present in HIT, not in MedAustron
- Standardization is crucial for small facility, eg. have one pneumatic drive for all instertable devices
- Machine data archiving – important for understanding long term stability, predicitive maintenance, application of ML

Overall price, number of channels

- Around 100-150 devices spread around the facility (after adding *other devices*)
- The cost, after including other devices, integration, cabling, is probably ~2-3 MEUR
- The other devices are:
  - Slits
  - Halo monitors
  - Stipper
  - Degrader
  - Tune kickers
  - RF kicker

Measured parameter	No of devices (cost [kEUR])		
	Heidelberg	MedAustron	SEEIIST
Beam current	32 (1,401)	17 (680)	32 (1,420)
Beam position + size	47 (1,813)	84 (2,344)	67 (2,213)
Transverse beam motion	2 (150)	2 (150)	2 (150)
Beam Losses	5 (50)	1 (10)	5 (50)
total	86 (3,004)	104 (3,184)	106 (3,833)

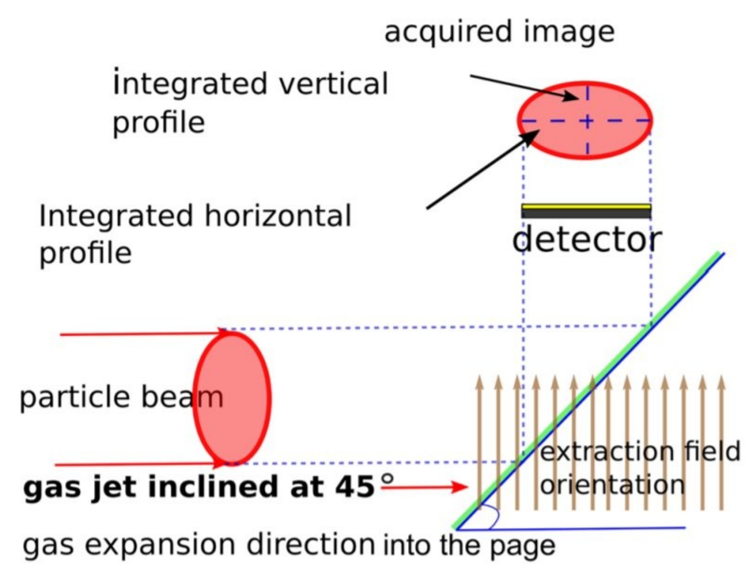
Future developments

- Current instrumentation is enough for standard mode of operations, but what about FLASH therapy where feedback from dose delivery system is too slow?
- One of the options is to perfectly understand the machine and relay on its repeatability; for this to work multiple online measurements must be done to know the state of the machine (and eventually correct it – feed forward)
- Example: online beam width measurement – not done up to now – could help to know the state of the machine before FLASH extraction
- (BTW currently the emmitance in synchrotron is measured by scrapping the beam intensity)
- Digital Ionization Profile Monitor combined with gas jet technique allows for turn-by-turn profile measurement in synchrotron and in HEBT

Gas jet and digital IPM

- IPM measures beam profile through rest gas ionization; signal rate is very slow because vacuum is very good
- Local pressure bump takes lots of space and is large
- Supersonic gas jet makes thin curtain, does not lead to pressure increase
- Together with fast detector of ionization products based on semiconductor pixel detector it can provide turn-by-turn emittance
- V. Tzoganis, H. D. Zhang, A. Jeff, Ca. Welsch

  Phys. Rev. Accel. Beams 20, 062801
- S. Levasseur et al., Time-resolved Transverse Beam Profile Measurements with a Rest Gas Ionisation Profile Monitor Based on Hybrid Pixel Detectors, Proceeding of IPAC 2018, WEPAL075



Conclusions

- SEEIIST as general purpose machine should be rich in instrumentation
- SEEIIST will profit from better electronics, which can really make a difference (eg. BPM single turn orbit measurement)
- Foresee budget for upgrades: electronics develops fast, sensors slower
- Differences in existing facilities mainly in HEBT: larger machines require more measurement locations and use cheaper technologies
- Cost of instrumentation: ~6-7 MEUR, ~150 channels
- Standardization and data archiving are important
- Some in-house development capability is important
- FLASH therapy may require feed-forward capabilities based on precise and reliable online measurement of the beam
- New capabilities may become important, eg. online beam emittance monitoring in the ring; they are also expansive (eg. IPM, gas jet) and may require R&D