# Beam diagnostics

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Lowry Conradie

# Overview of the lecture

1. Demand for Beam diagnostics
2. Measurement of beam current Faraday Cups
3. Beam profile measurement
   - Secondary emission monitors
   - Wire scanner
   - Screens
4. Energy measurement and energy spread measurement with dipole magnet

# Demand for Beam diagnostics

Beam diagnostics is an essential part of any accelerator facility. Without beam diagnostics it will be extremely difficult to operate accelerators and their associated beam lines.

There are a number of physical effects that can be used for beam monitoring, namely:

- Electromagnetic influence
- Coulomb interaction of charge particles with material
- Emission of photons by accelerated particles
- Nuclear or elementary particle interactions

# Electromagnetic influence

A charged particle induces electromagnetic fields around itself. With electrodes placed in close proximity of the beam these fields can be measured, which gives information regarding the beam. Typically voltage or current is measured from low to high frequencies. Examples are capacitive pick-ups and beam transformers.

# Coulomb interactions of charge particles with material

The energy loss of the charged particles in the Coulomb-field of the atoms in the target material results in producing various secondary products, like secondary electrons, positive ions, fluorescent light and Bremsstrahlung photons. They can be detected by appropriate devices and can provide data of the interacting particle beam. Examples are beam viewers, secondary emission grids and residual gas monitors.

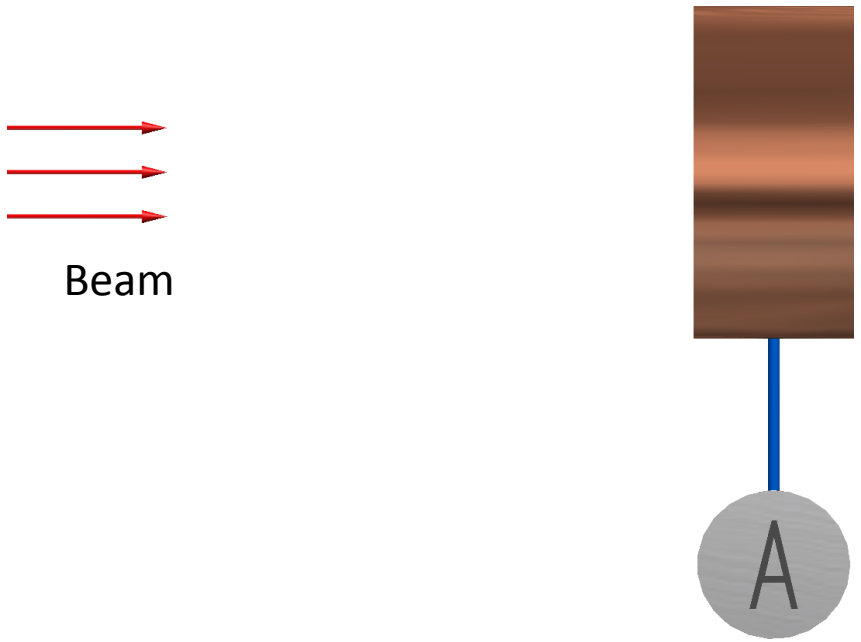
# Emission of photons by accelerated particles

This kind of diagnostics can only be applied for relativistic particles, i.e. mainly for electron beams or very high-energy proton beams. The emitted photons are in the visible range up to the X-ray region. Optical methods can be used. Examples are synchrotron radiation monitors.

# Nuclear or elementary particle interaction

The beam quantity is determined from the known cross-section and the measured reaction products. Mainly particle detectors are used. Examples are polarimeters or luminosity measurements.

# Beam intensity measurement with a Faraday cup




| | Stopping range (mm) | | |
|---|---|---|---|
| Proton Energy | Copper | Aluminium | Tantalum |
| 1 MeV | 6.7 µm | 14.4 µm | 6.25 µm |
| 6 MeV | 104 µm | 257 µm | 86.8 µm |
| 10 MeV | 243 µm | 622.7 µm | 195.1 µm |
| 50 MeV | 3.93 mm | 10.75 mm | 2.86 mm |
| 100 MeV | 13.21 mm | 36.8 mm | 9.37 mm |
| 200 MeV | 43,5 mm | 122.6 mm | 30.21 mm |

The operating principle: The beam particles are captured by conducting material such as copper (beam-stopper) which is isolated. The charge that flows from the beam-stopper to ground can be measured with an ampere meter.

- It is important that al the particles must be captured by the beam-stopper.
- The thickness of the beam-stopper must be larger than the stopping range of the beam-stopper material.

# Faraday cup – methods to prevent the escaping of secondary electrons

The incident particles on the beam-stopper can result in the emission of secondary electrons from the surface of the stopper. If these electrons escape from the beam-stopper one will not get a true reading of the current. The escape of the secondary electrons must be prevented.

**applied methods:**

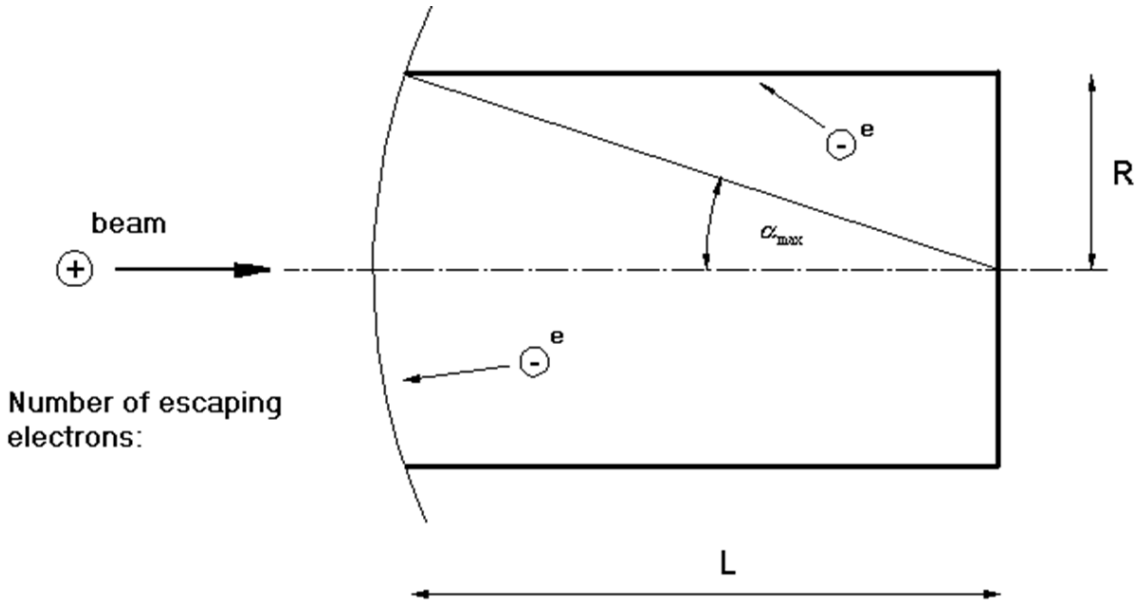
- Geometrical solution
- Electrostatic suppression
- Magnetic suppression

# Geometrical solution to reduce escaping of secondary electrons

For the shape of the beam-stopper (or Faraday cup) a cup geometry is normally used instead of a just a flat plate. The cup geometry limits the solid angle from which the secondary electrons can escape. The number of escaping electrons is given by:

$$n = N\,sin^2\,\alpha_{max} = N\frac{R^2}{R^2 + L^2}$$

$n = number\ of\ escaping\ secondary\ electrons$
$N = total\ number\ of\ secondary\ electrons$



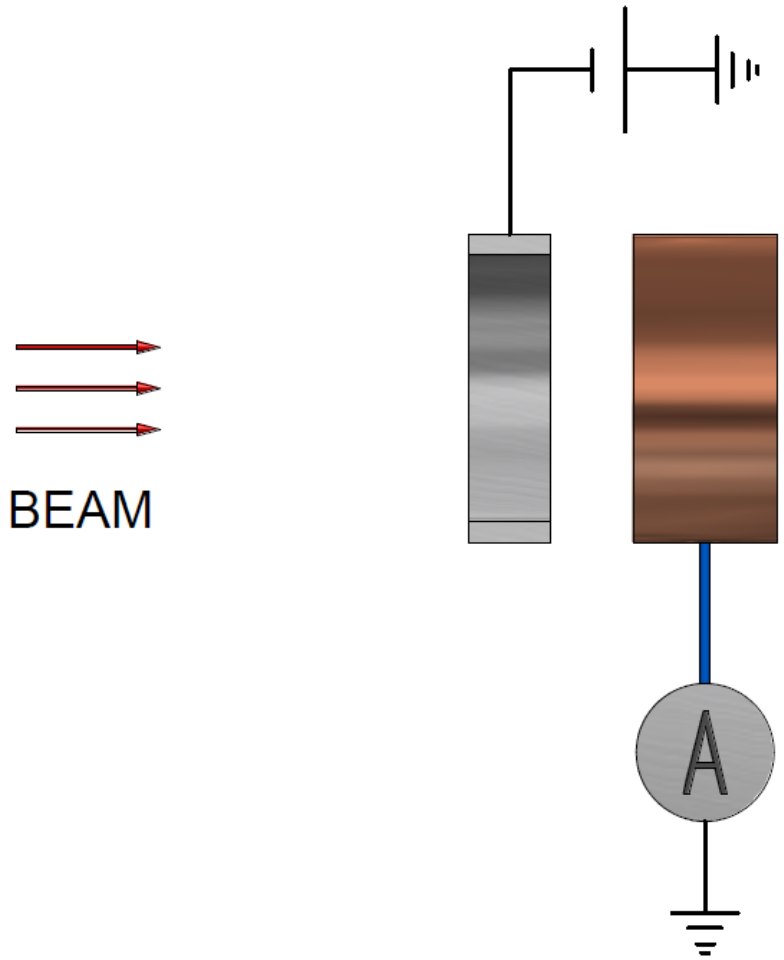

Smaller diameter and longer cup gives higher measurement accuracy

- The length of the cup is determined by the available space on the beam line
- The diameter off the cup is determined by the size of the beam at the position of the Faraday cup

# Electrostatic suppression to reduce escaping of secondary electrons

The average energy of the secondary electrons is in the region of 10 eV and only a few of these electrons have energies up to several hundred of eV. Therefore most of the secondary electrons can be repelled by applying a relatively low electrostatic voltage on a ring type electrode mounted in front of the cup. At iThemba LABS we use voltages of no more than 900 V to stop secondary electrons from proton beams with energies up to 200 MeV

iThemba LABS uses variable voltage power supplies for supplying the voltage on the ring electrode in front of the Faraday cup.



# Magnetic suppression to reduce escaping of secondary electrons

The kinetic energy of the secondary electrons is small and the rest mass of the electron is also small, thus the radius of the Larmour procession of the secondary electrons in a magnetic field can be kept small with relative low magnetic fields:

$$\frac{mv^2}{R} = evB$$

$$R = mv/eB = \frac{\sqrt{2mT}}{eB} \approx 3.37\frac{\sqrt{T(eV)}}{B(mT)}(mm)$$

$m = mass\ of\ electron$

$v = velosity\ of\ electron$

$B = magnetic\ field$

$R = radius\ of\ electron$

$T = kinetic\ energy\ of\ secondary\ electron$

- small rest mass ($m_e$)
- low kinetic energy (T)

small value of Larmour-radius even in weak magnetic fields (B)

Permanent magnets can give a magnetic field of 100 mT over an aperture of 75 mm. For an electron with a kinetic energy of 1000 eV the radius will be 1.07 mm. The radius of the secondary electrons is small compared to the size of the Faraday cup.

# Power dissipation

Since the beam is stopped by the Faraday it must dissipate the total energy of the beam. For a Faraday cup installed in a vacuum chamber there are only two ways to get rid of the heat, namely:

- Heat radiation
- Thermal conductivity

## - radiation:

The radiation power per unit area is given by the Stefan-Boltzman law:

$$P_{radiation} = \varepsilon \sigma T^4$$

$\varepsilon = emissivity\ of\ the\ material\ relative\ to\ a\ complete\ black\ body$ $\sigma = 5.67 \times 10^{-8}\ \mathrm{W}/m^2K^4$

Cooling as a result of radiation is only effective at high temperatures and can only be used with materials with high melting point, e.g. tungsten (W) and tantalum (Ta)

## - conductivity:

forced cooling (typically water)
copper can be used as collector material
cone-like geometry for increasing the effective area

# Beam power calculation

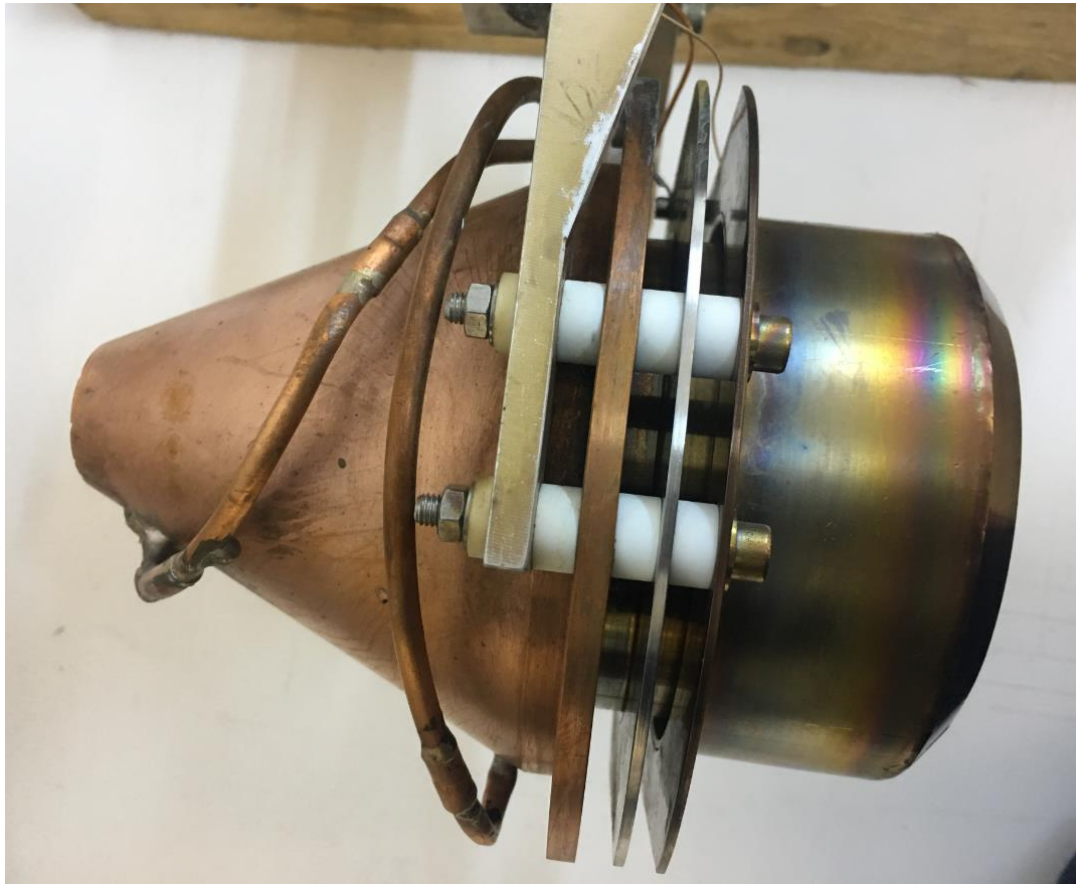
For a beam current of 200 micro ampere of 66 MeV protons the energy that the cup has to dissipate is

Power = Current x Voltage

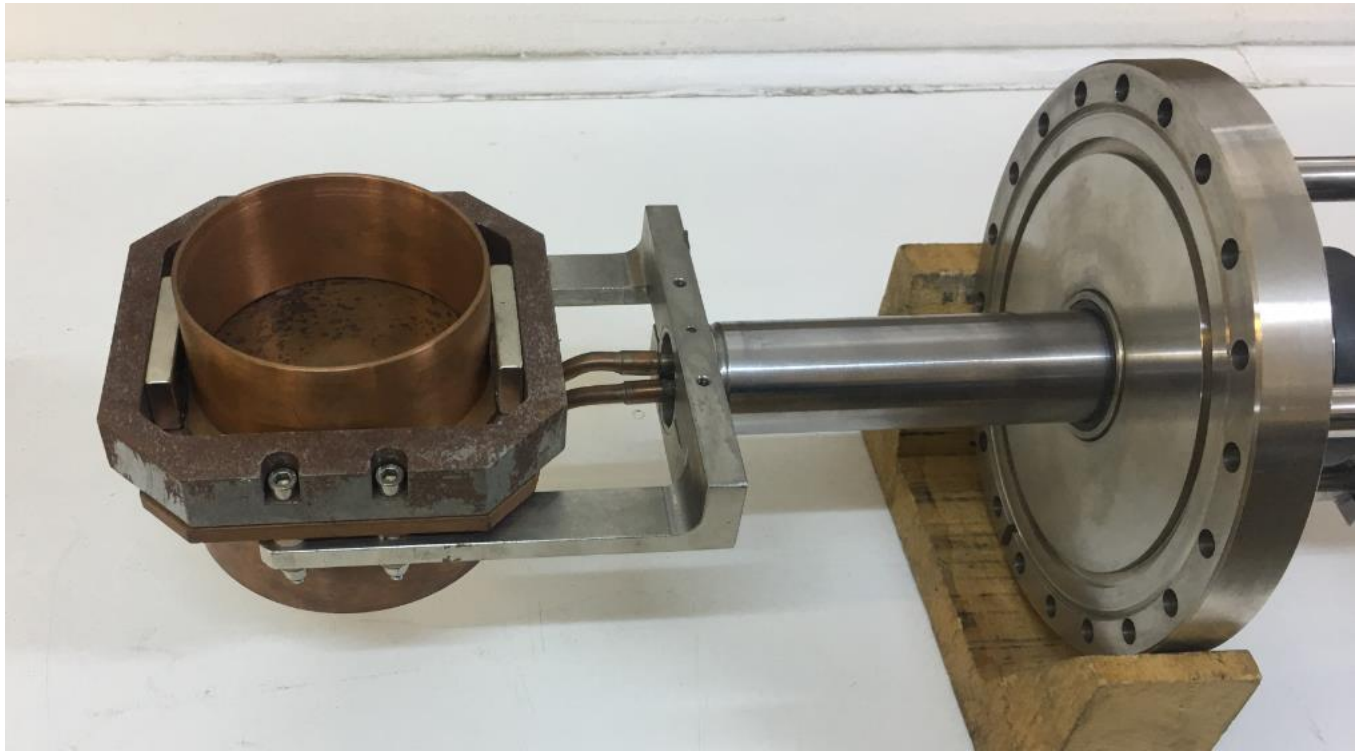
$$Power = 200 \times 10^{-6} \times 66 \times 10^{6} = 13200\ W$$

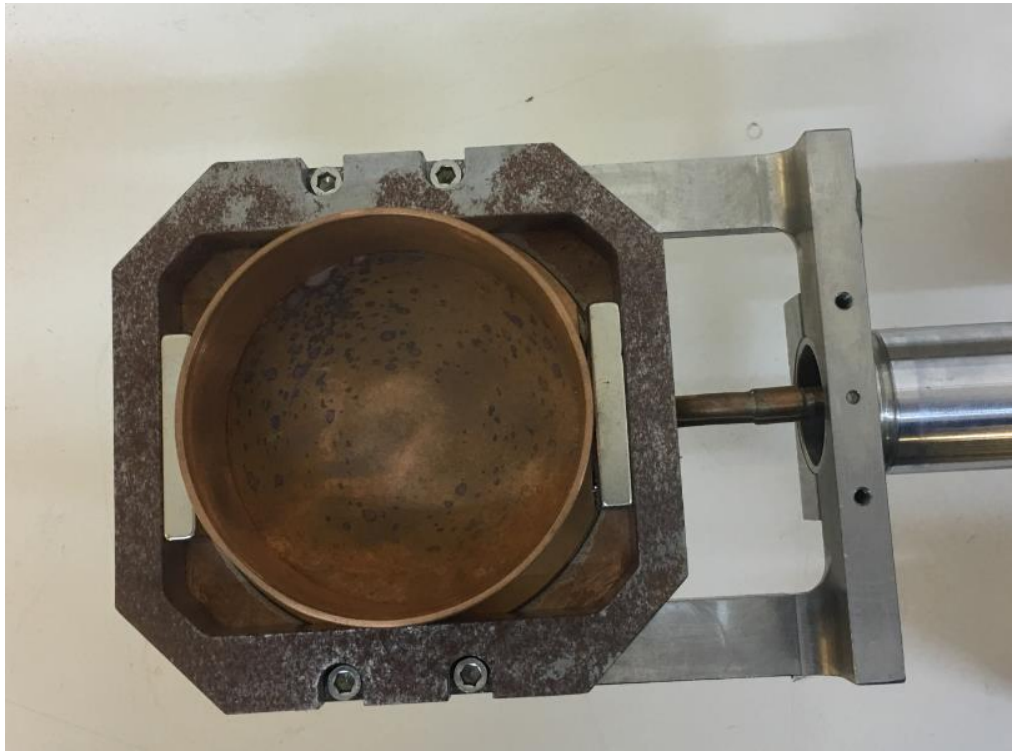
Faraday cups are normally manufacture from copper because copper is relatively cheap, easy to manufacture and one of the best heat conductors.

# Water cooled Faraday cup showing the copper cup, electron suppression electrode and protection screen.

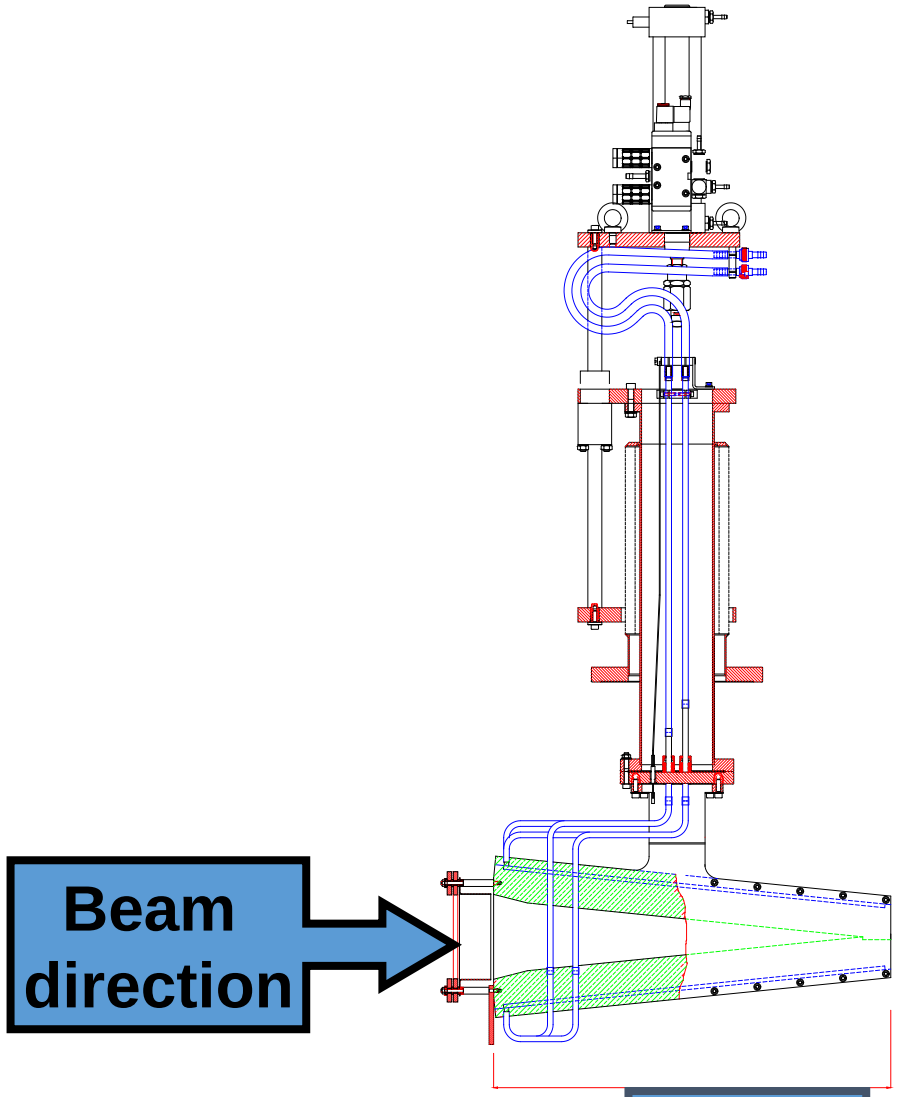


# Water cooled Faraday cup showing the magnets for electron suppression



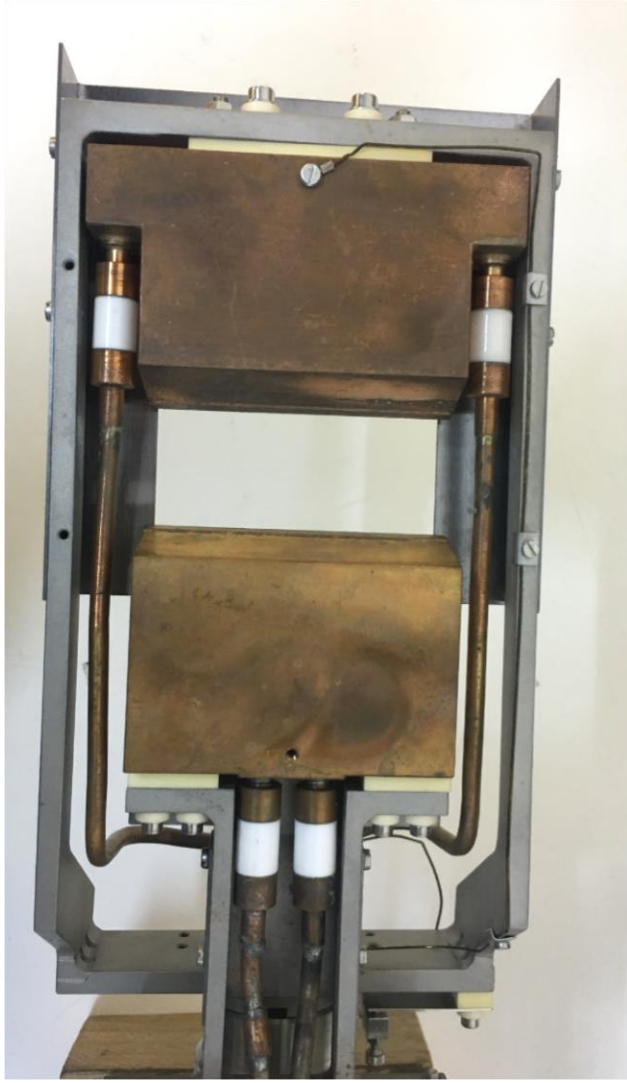


# 50 kW high-intensity beam stop at iThemba LABS

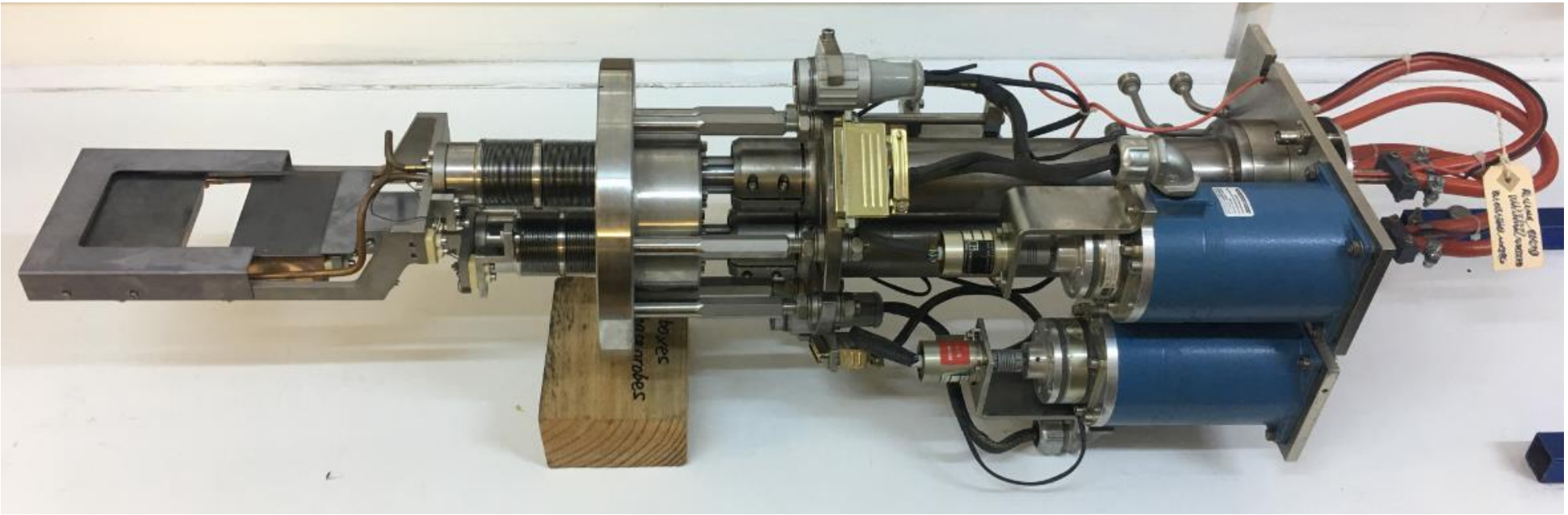


# 50kW beam stop (faraday cup) at iThemba LABS

# Slits to define the beam to a specific size at a specific position in the beam line



# Water cooled slit showing jaws, bellows and stepper motors



# Beam profile measurement

**Grids and scanners**

Beam profile viewers can give an accurate measurement of the beam transverse profile. We will discuss two types, secondary emission grids and scanners:

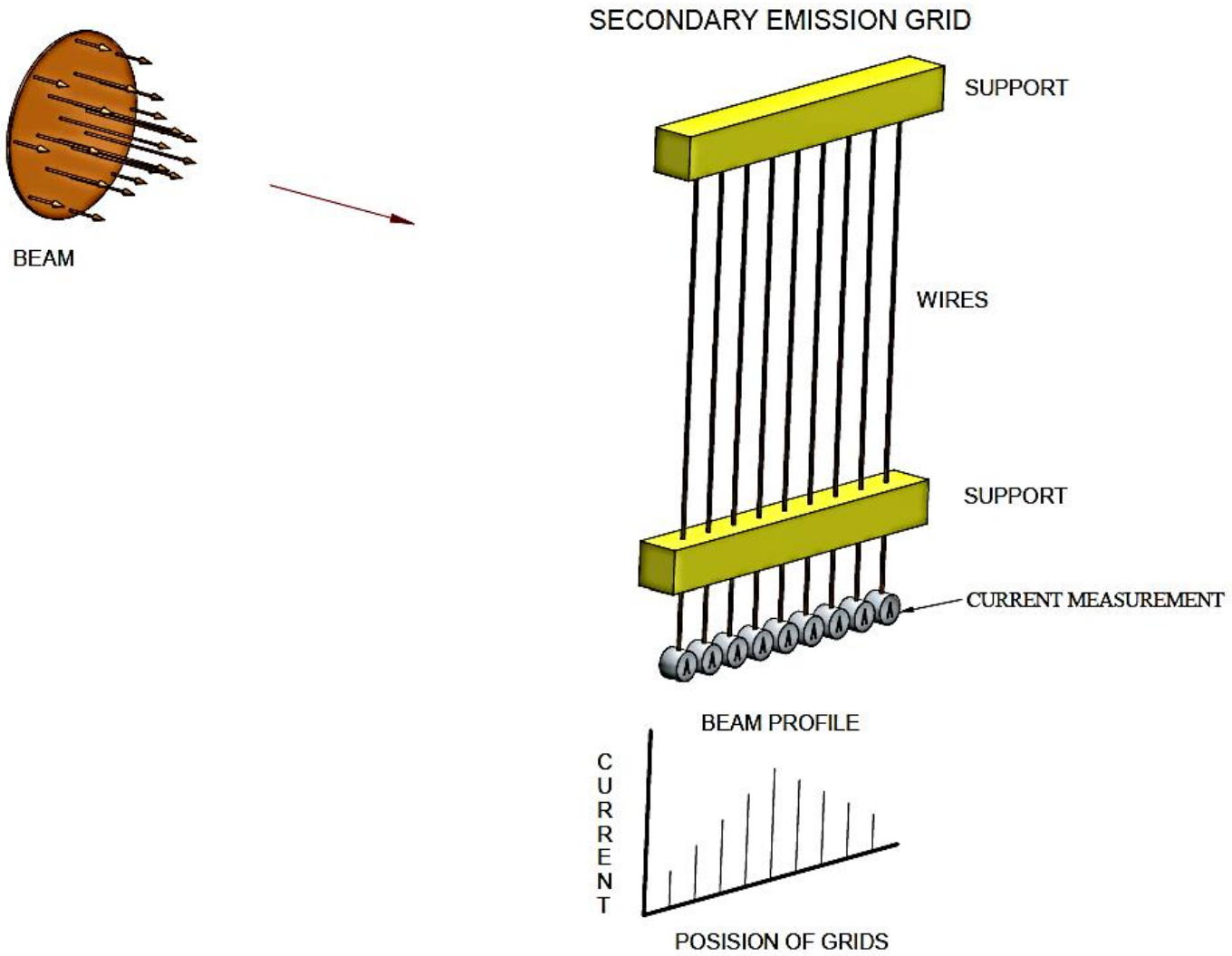
**Secondary emission grids (Harps)**

With the secondary emission grids the beam intensity distribution in one transverse plane can be measured (for example horizontal or vertical). The grids exist of a number of wires parallel to each other over an area that cover the beam width. When the beam hits the grid wires, secondary electrons are emitted from the surface of the wires. The electron current can be measured in each wire.

- A electric field can also be applied to remove the emitted secondary electrons from the vicinity of the grid wires.
- Titanium wires are often used at iThemba LABS.

# Secondary-emission grids “Harps”

This type of beam monitor is capable of measuring the intensity distribution of the beam, the beam profile, along one transverse coordinate. The device consists of a number of metal wires placed parallel to each other and covering the total area of the beam aperture. When particles hit the wire material, secondary electrons are liberated from its surface. The current in the individual wires are measured.

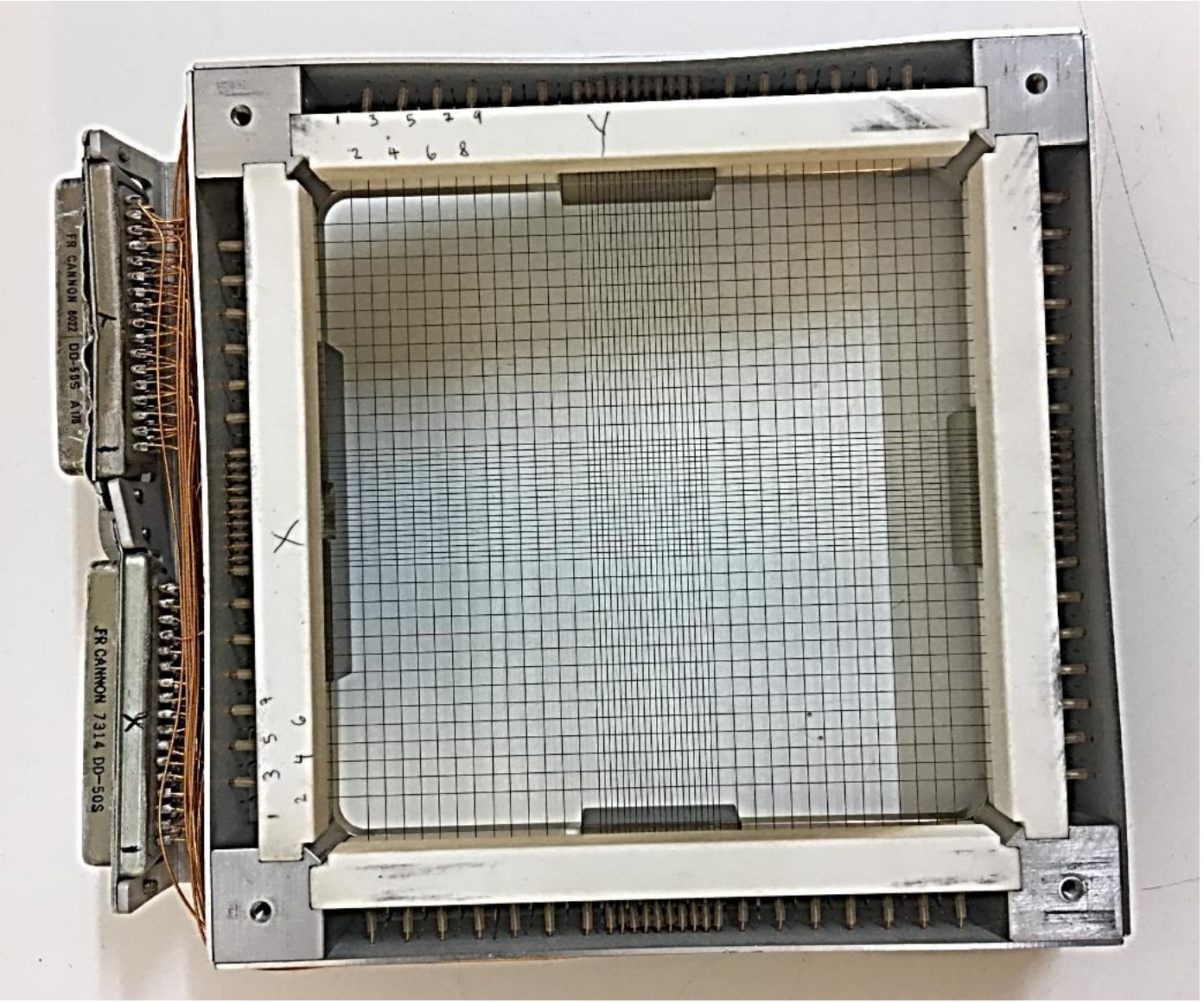


# Properties of secondary emission grids

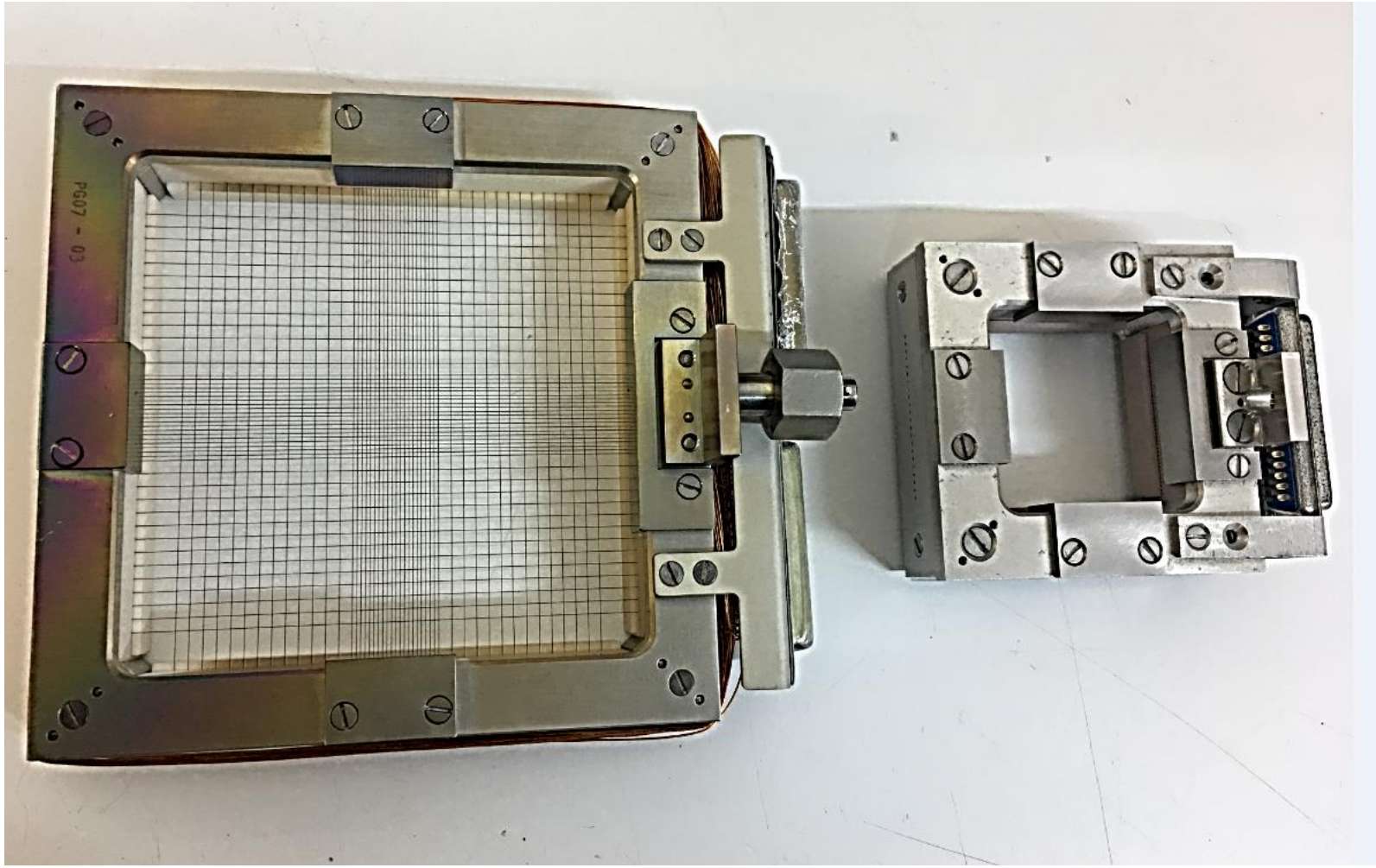
The grids has a much higher dynamic range than viewing screens. To measure the beam profile in both horizontal and vertical place require 2 grids.

- The position and profile information is very accurate since the wires are fixed in defined positions.
- Since the wire spacing is limited to about 1mm, the resolution of the measurement is not optimum for some specific applications.
- An advantage of the grid is that the beam intensity is sampled at the same time in all the wires thus giving an instantaneous snap shot of the beam profile at a specific time.
- Grids require relatively expensive electronics and also expensive cabling to bring the signals from the grids to the electronics, which can be outside the vaults that house the grids to protect the electronics from radiation damage.
- Due to the small diameter of the wires the electron current is small and a pre-amplifiers is needed for each wire.
- At iThemba LABS the read out speed of the harps depend on the beam current and thus the amplification factor of the electronics. The read out time varies from 0.1 sec (few nano-ampere of beam current) to 50 ms for higher intensity beams.

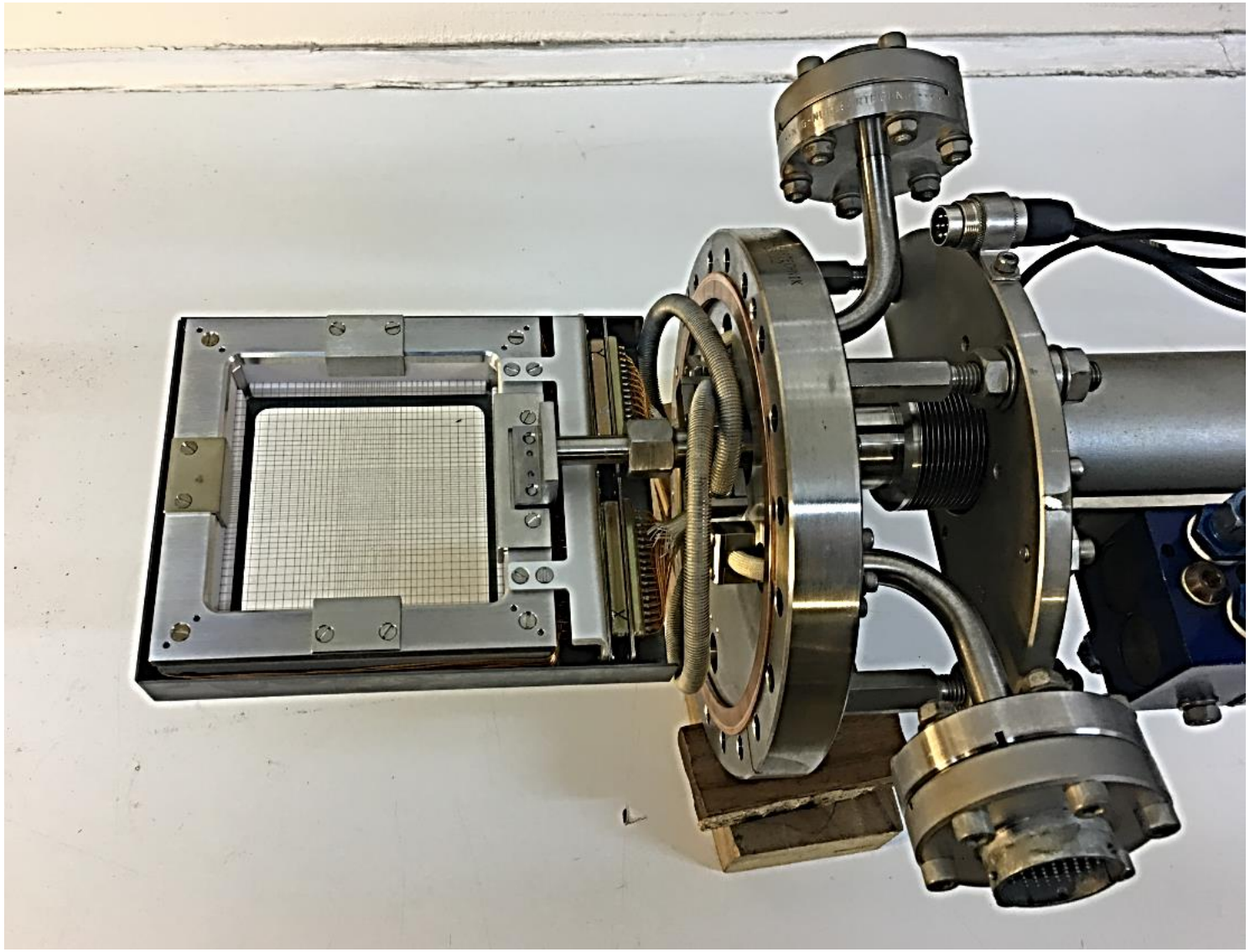
# Secondary emission grid at iThemba LABS



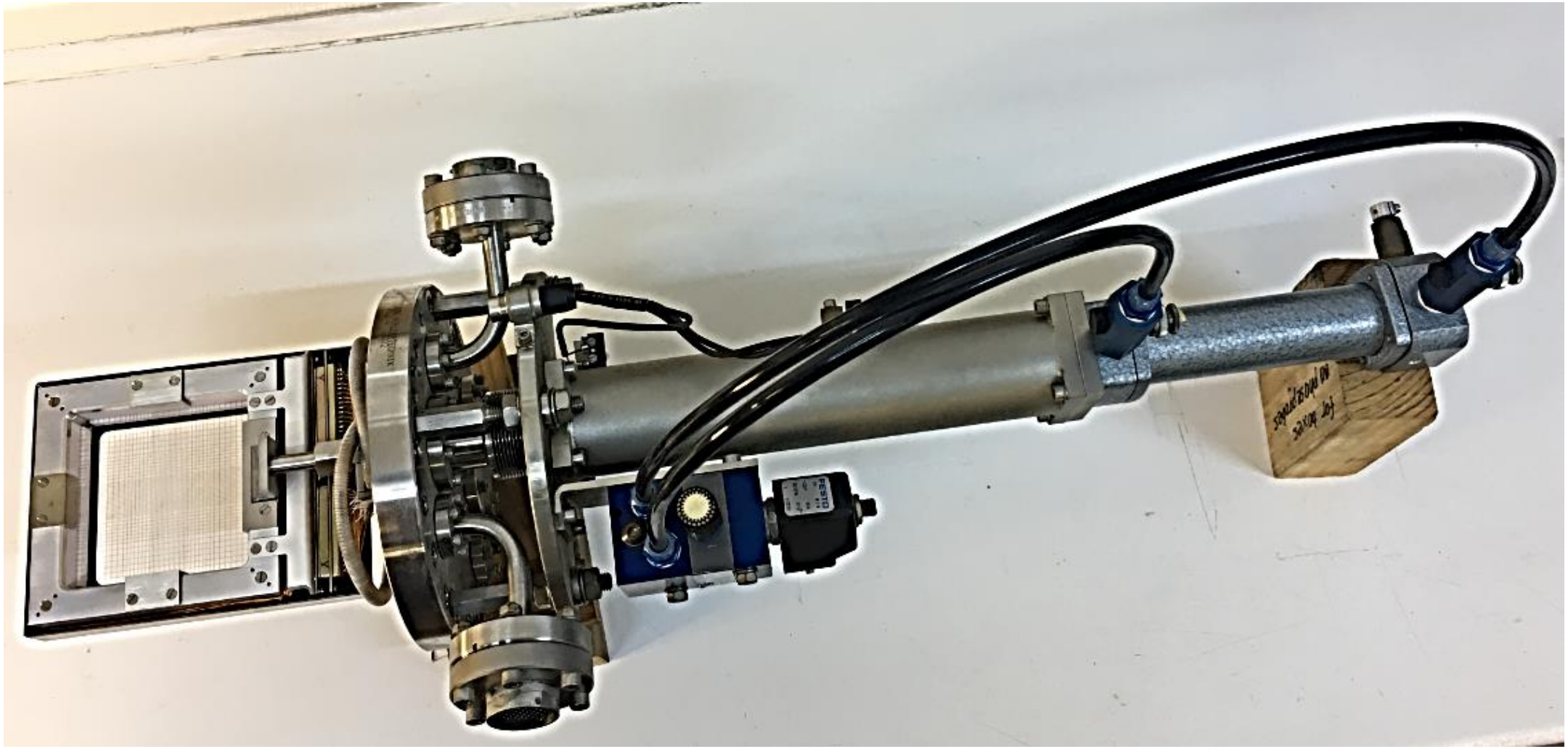
# Different shapes of Harps at iThemba LABS



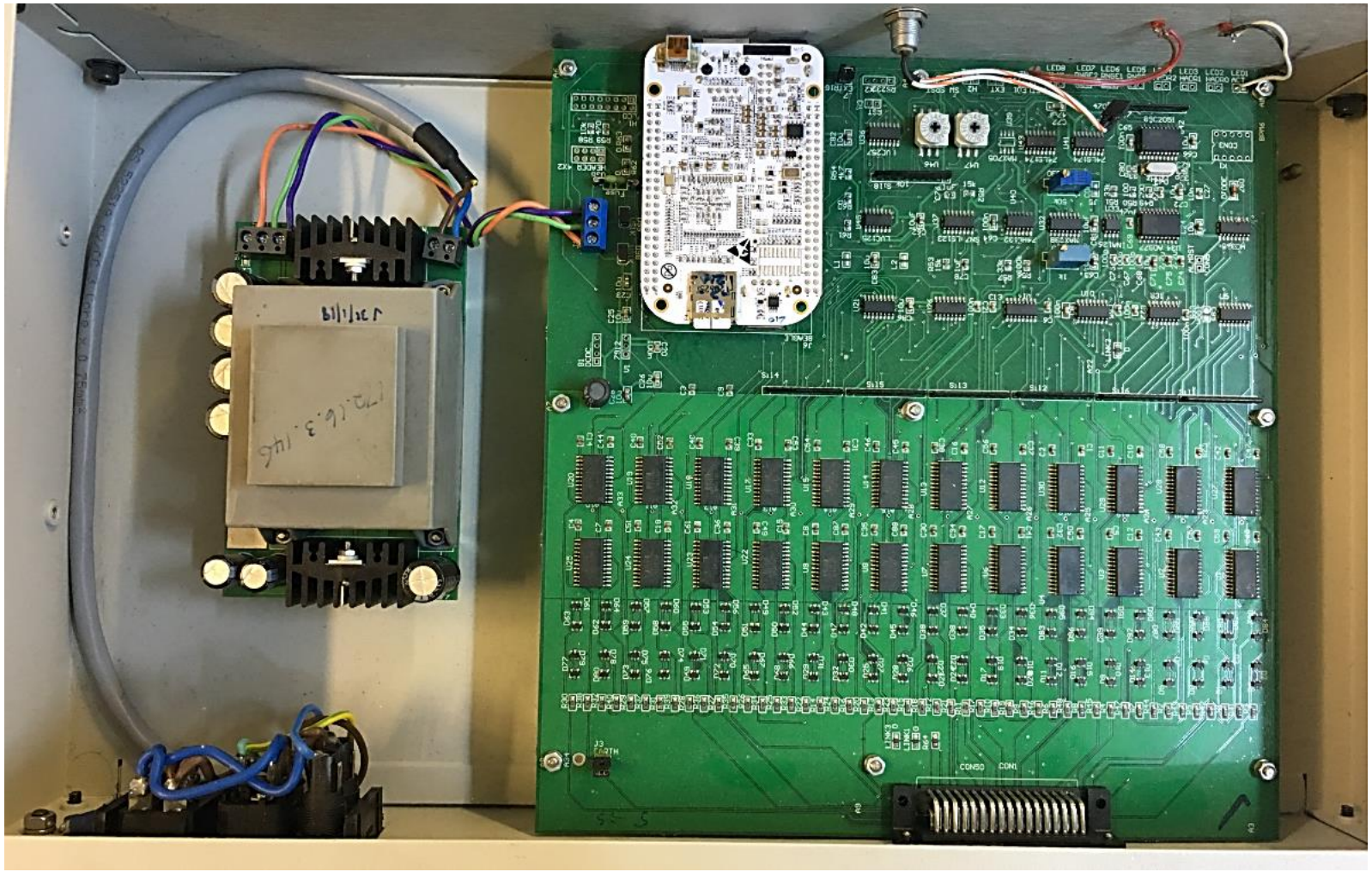
# Feedthroughs and connectors and bellows



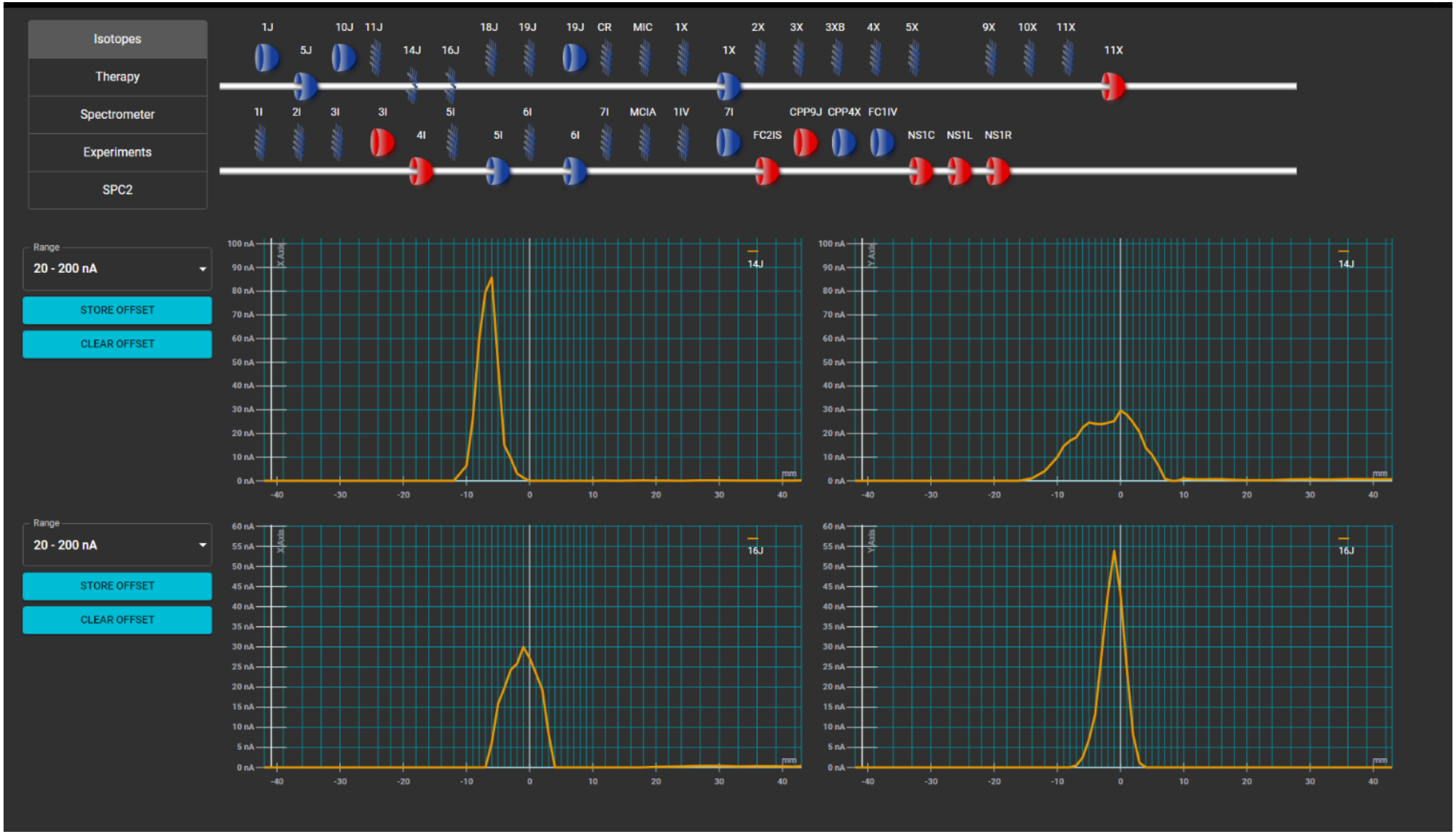
# Complete harp with its actuator



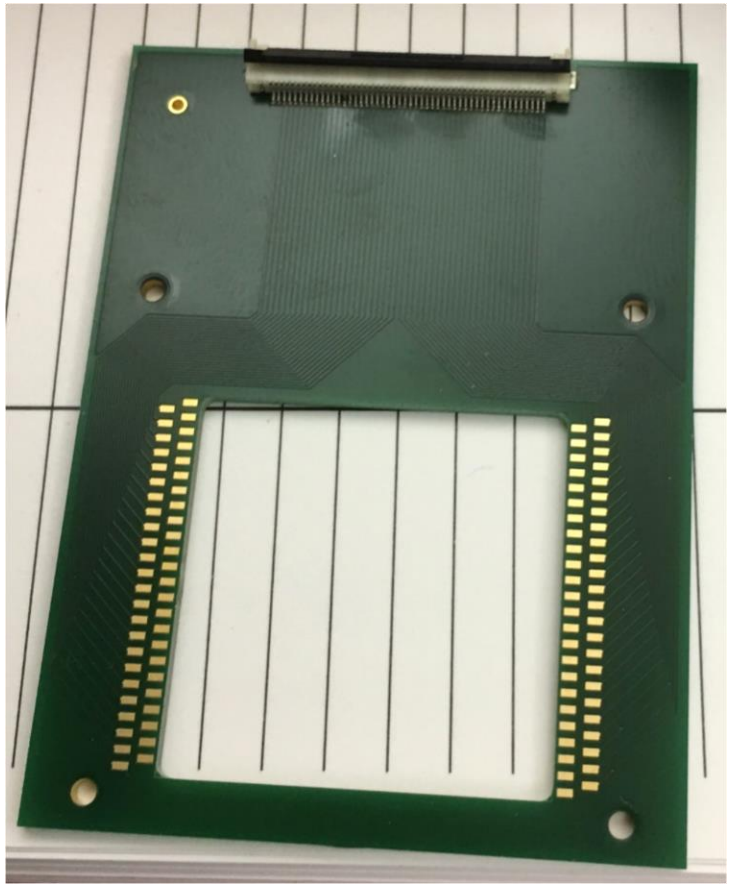
# Electronics to read the current from the Harp wires (48 channel)

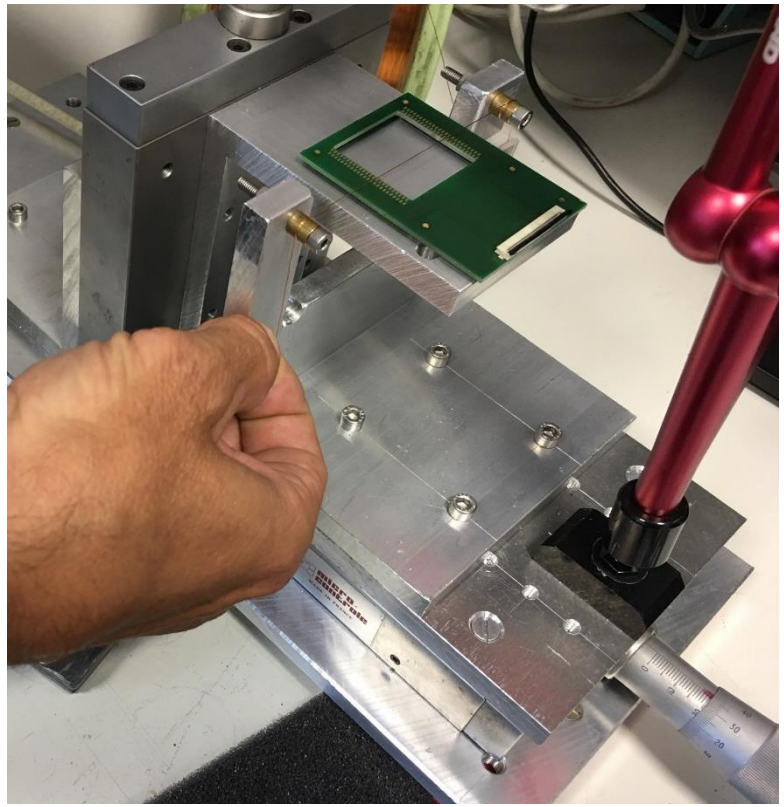


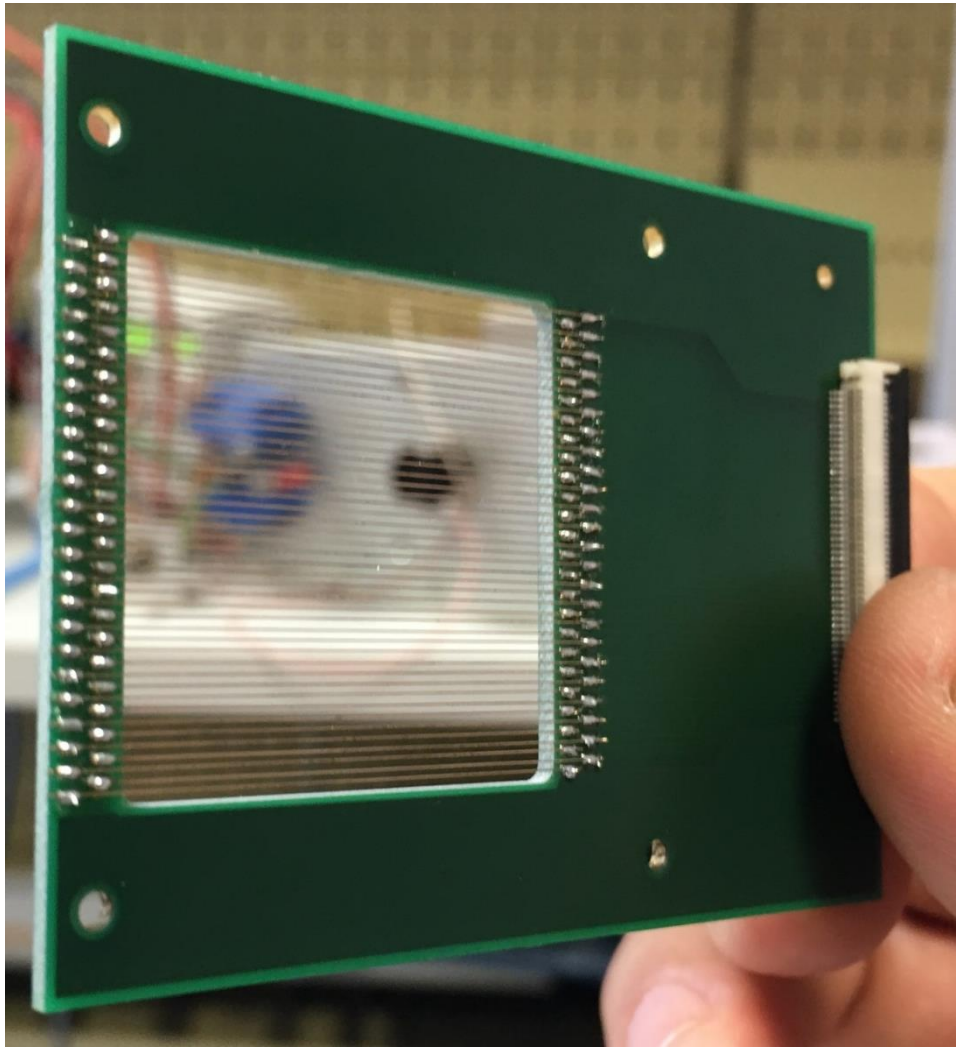
# User interface for display the beam profile measured on the Harps



# Different approach of manufacturing Harp diagnostics (Helmholtz centre Berlin)







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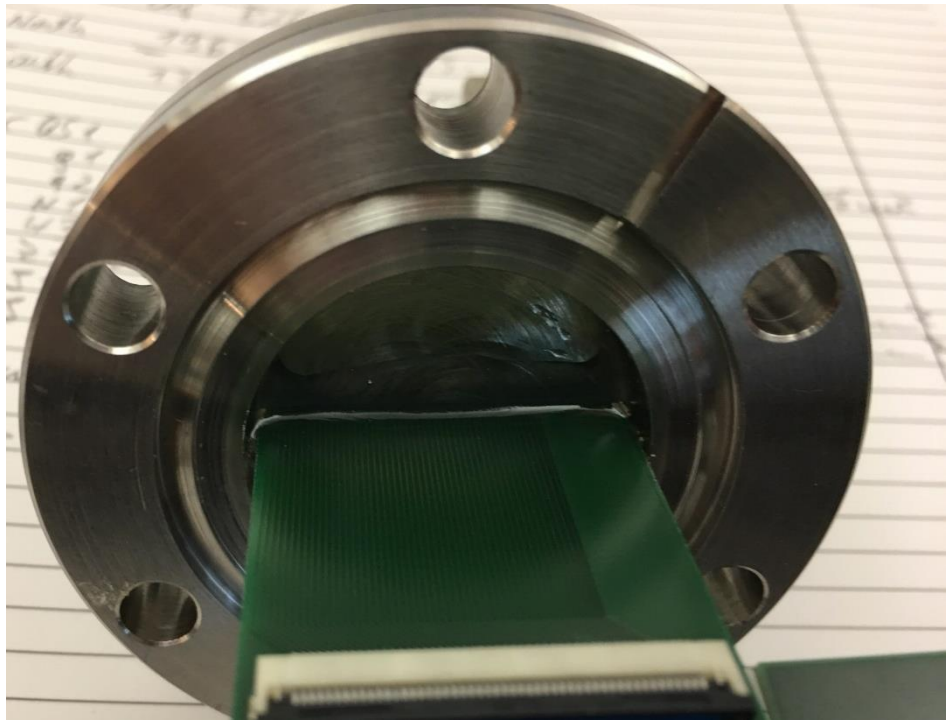
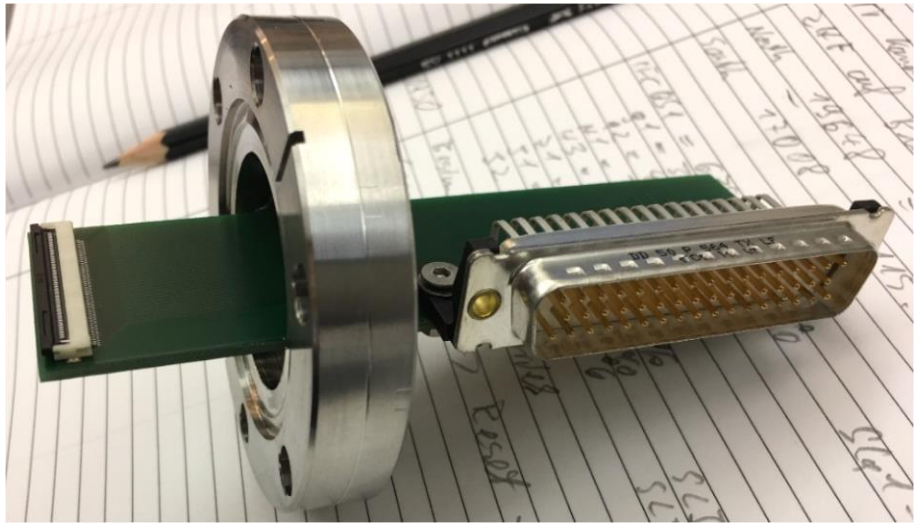
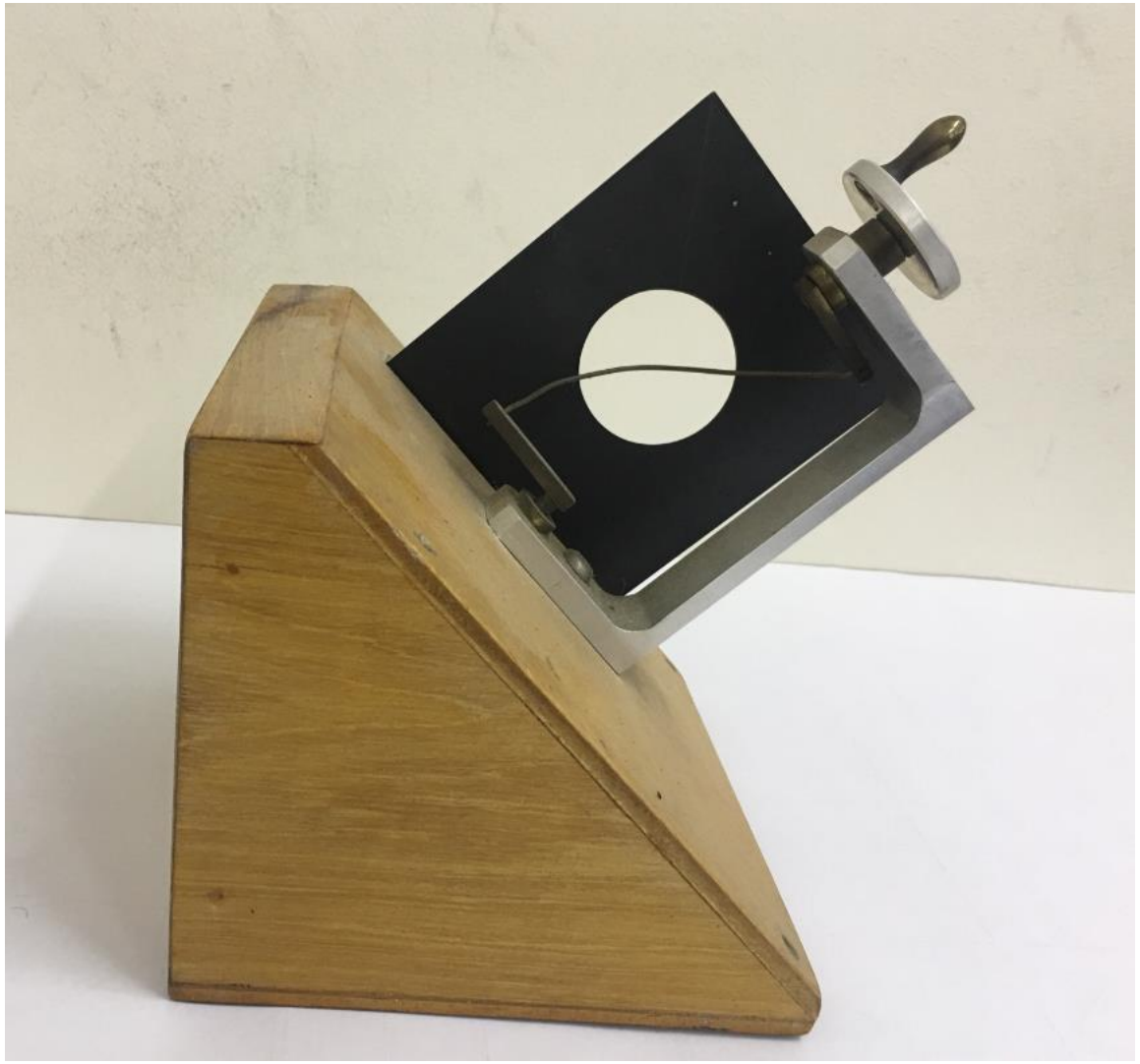




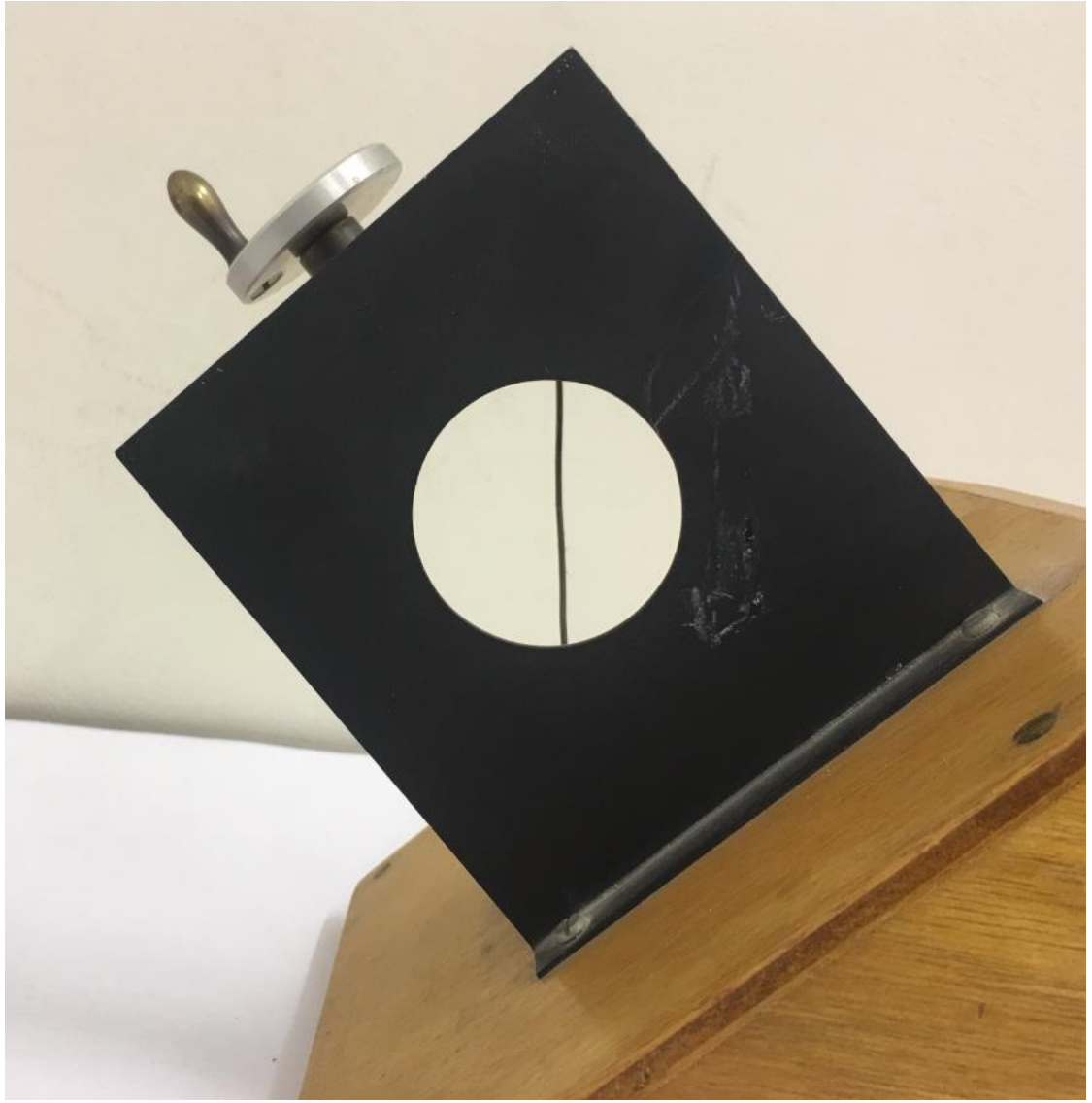
# Wire scanners

- Two perpendicular wires in one plane moving linearly back and forth through the beam can give both transverse profiles
- Also a helical shape wire rotated around it axes and mounted at 45 degrees to the horizontal plane can also give both transverse profiles of the beam
- Wire scanners with there single channel signal processing electronics are considerably cheaper than grid profile monitors
- The wire of the wire scanner can lost it shape due to the movement and heat generated by the beam and thus lost beam position and profile accuracy
- Depending on the energy and particle type of the beam the beam particles that stopped in the wire and secondary electrons emitted from the wire can be measured. To measure the secondary electrons a collector electrode is also needed.
- If a single straight wire is used as a wire scanner, two units are required to get the beam profile in both transverse plains.
- Both transverse profiles of the beam can be obtained with a single wire with a more complex geometry

# Demonstrate the principle of a Helix beam profile scanner

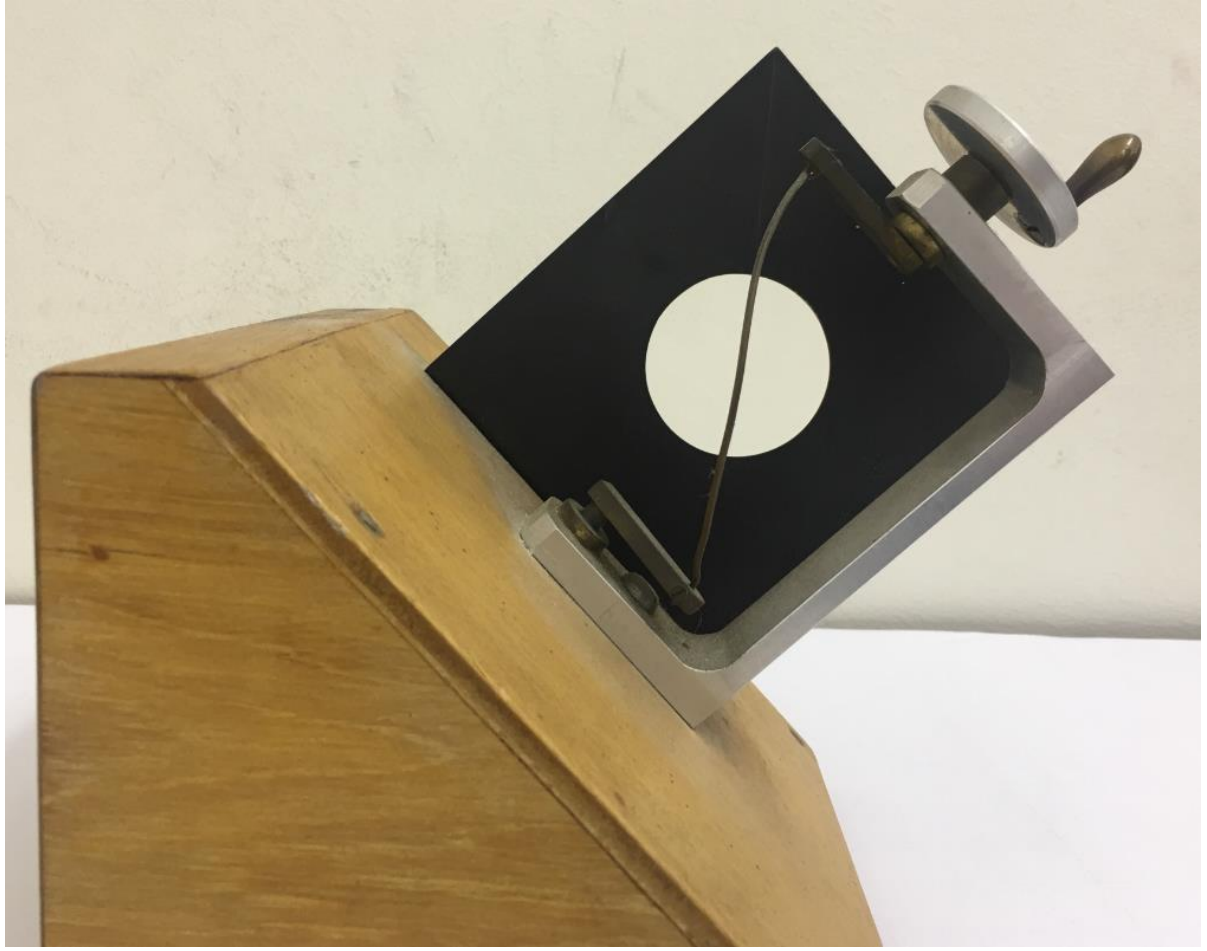


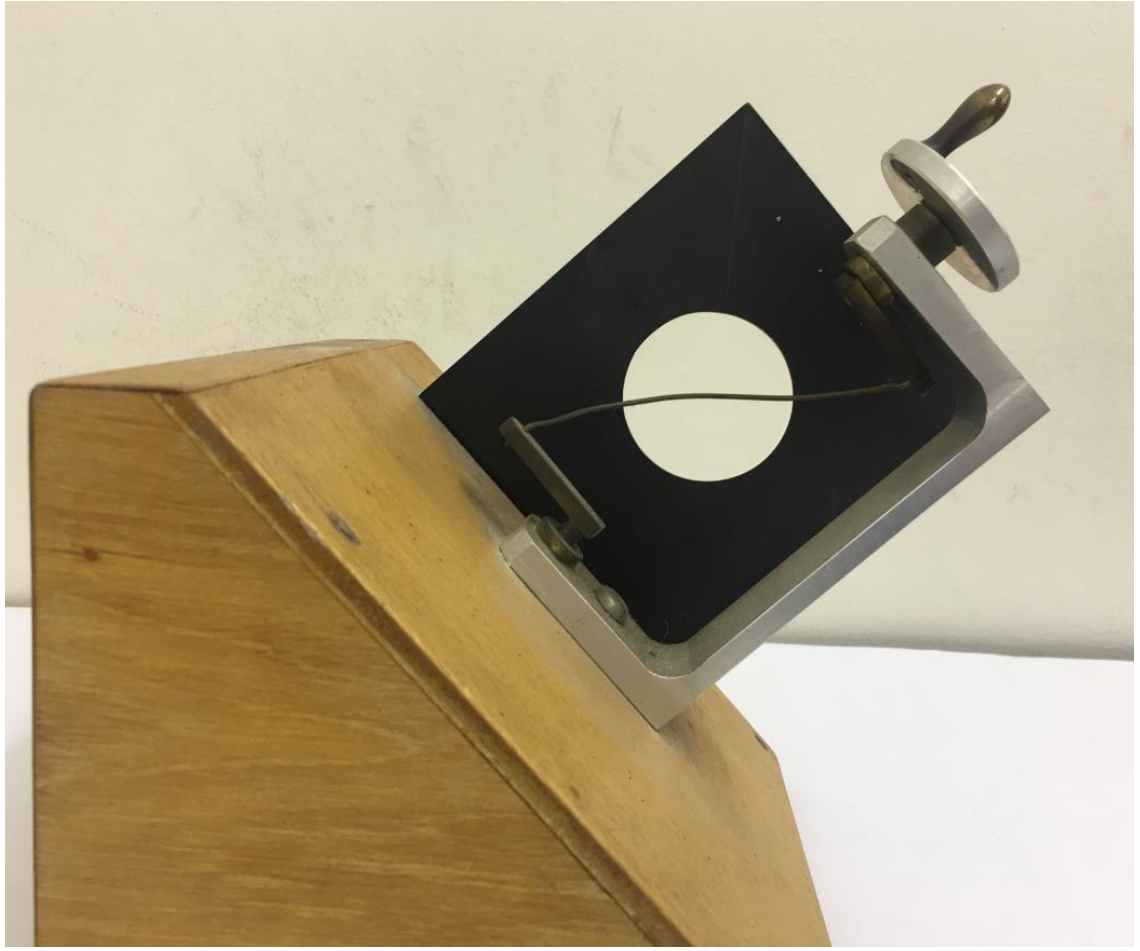
Beam scanner measuring in the horizontal plane



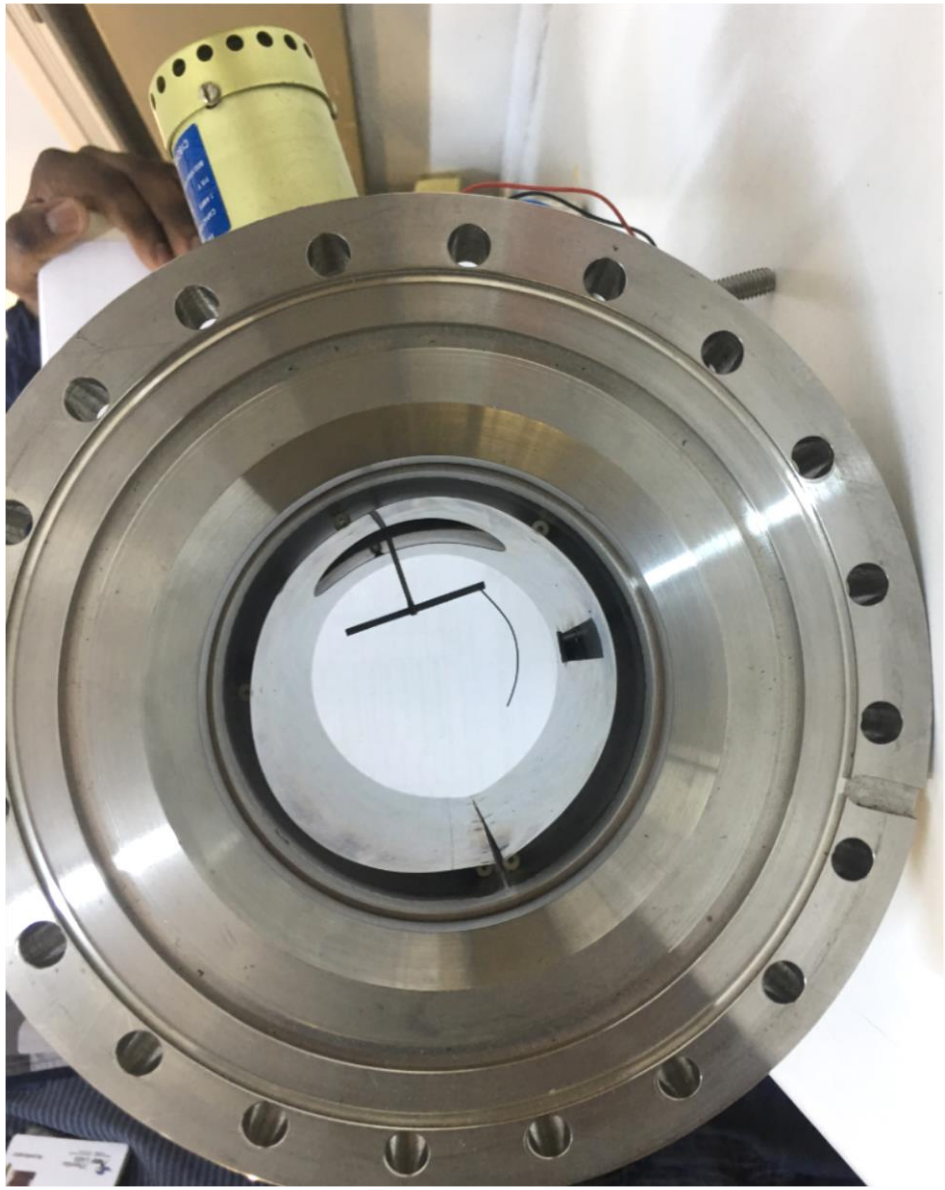
Beam scanner measuring in the Vertical plane

# The horizontal and vertical profile are measured at a small distance apart from each other along the beam line

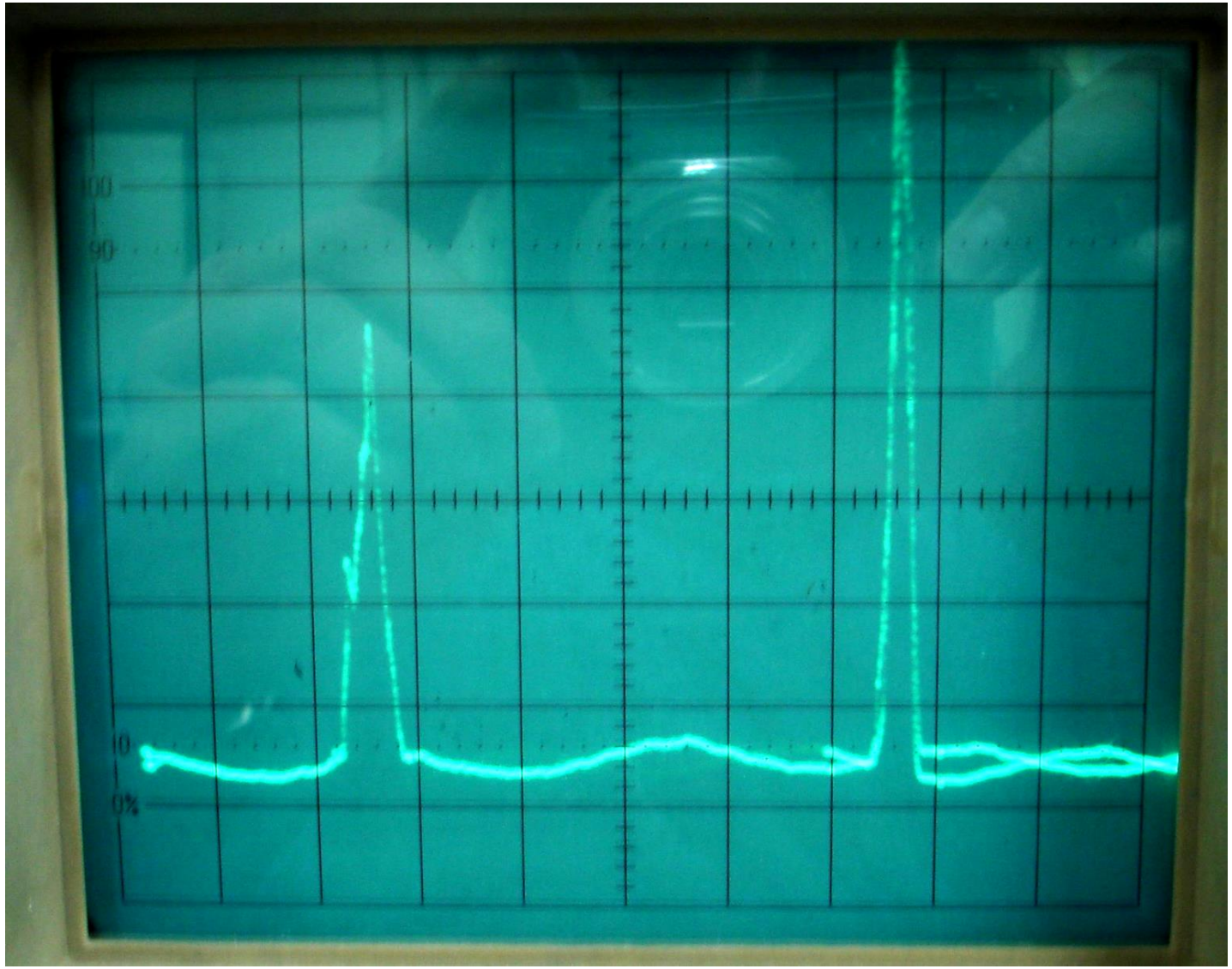




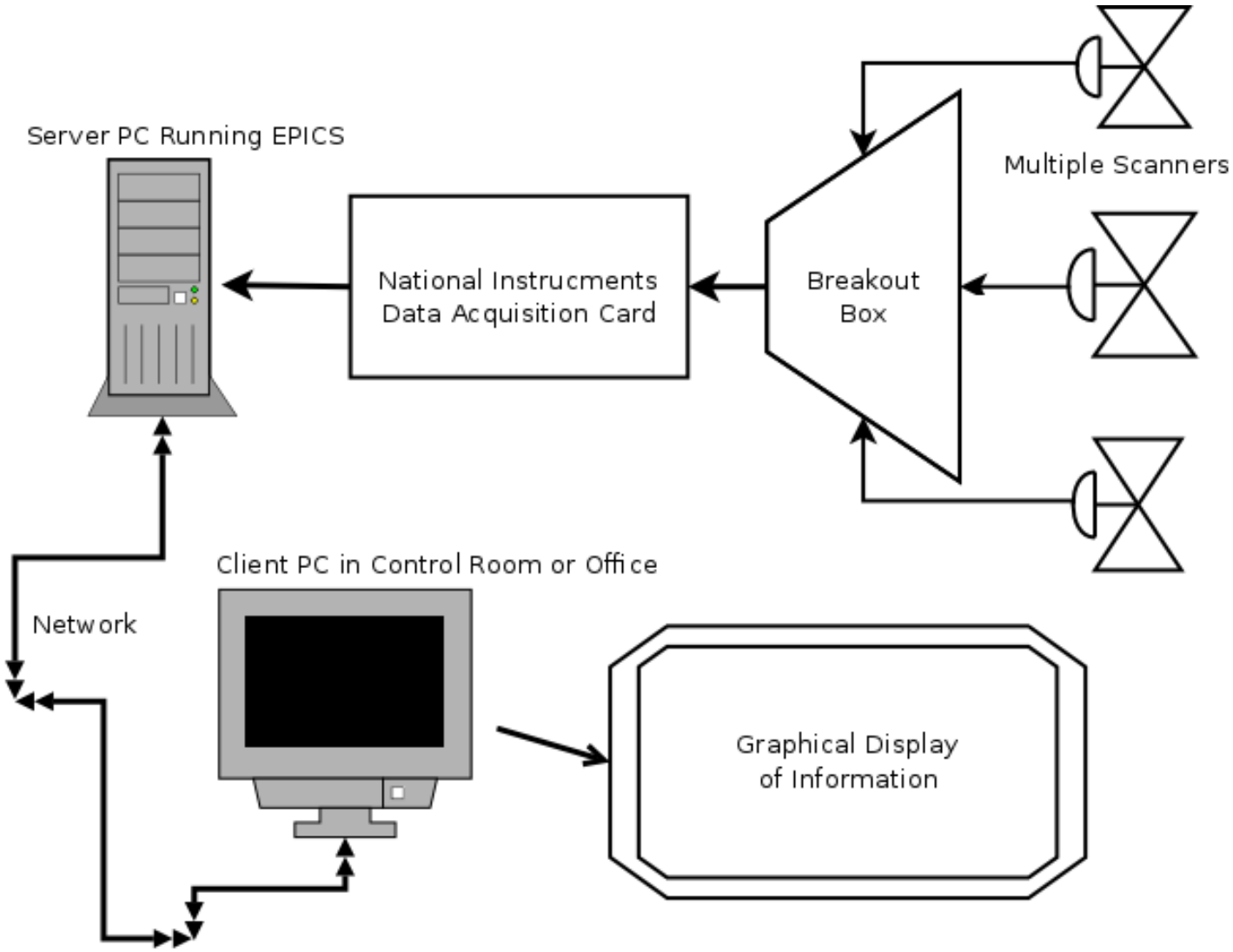
# Beam scanner used at iThemba LABS

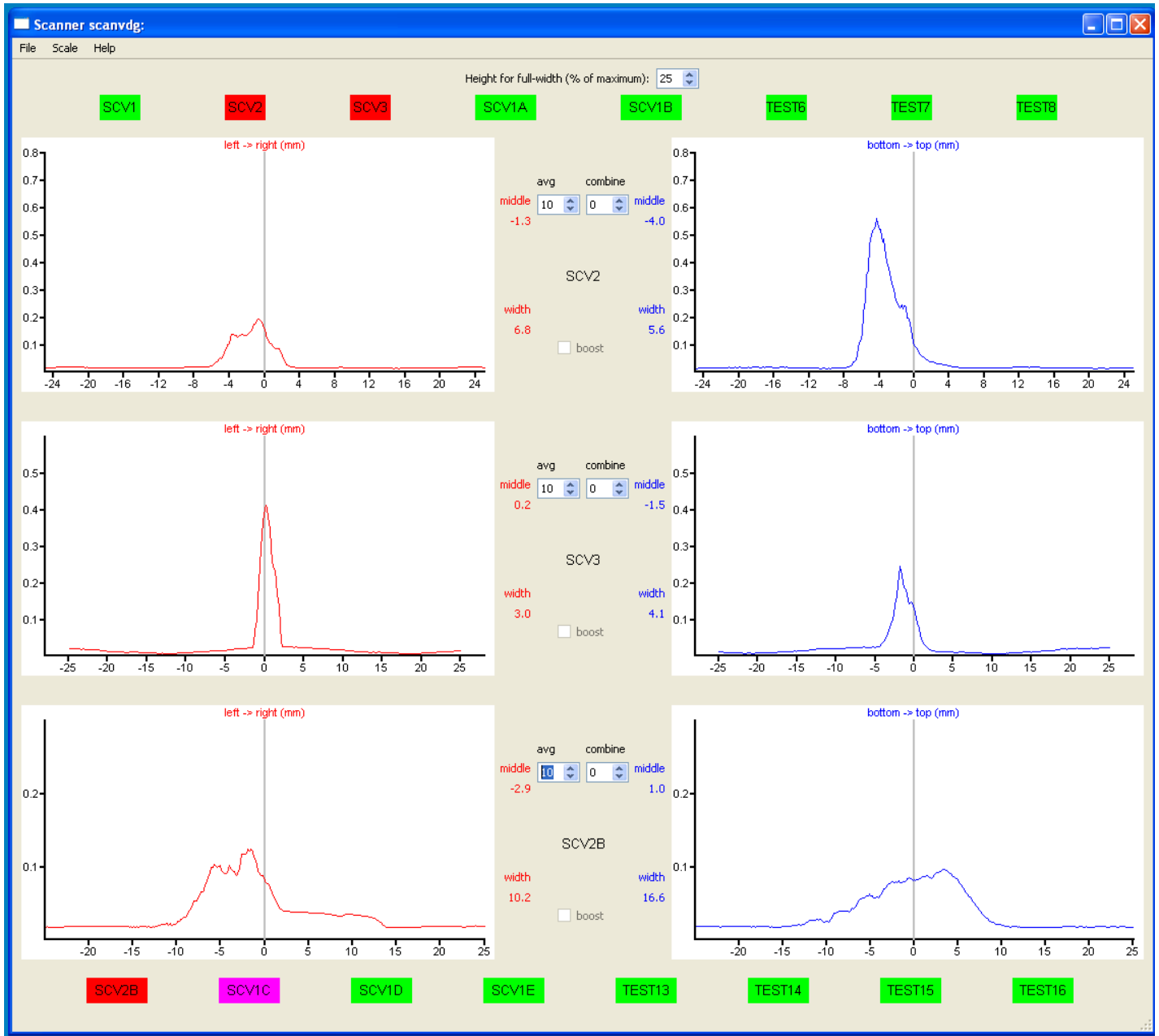
# Oscilloscope picture of the beam profile measured on the a scanner



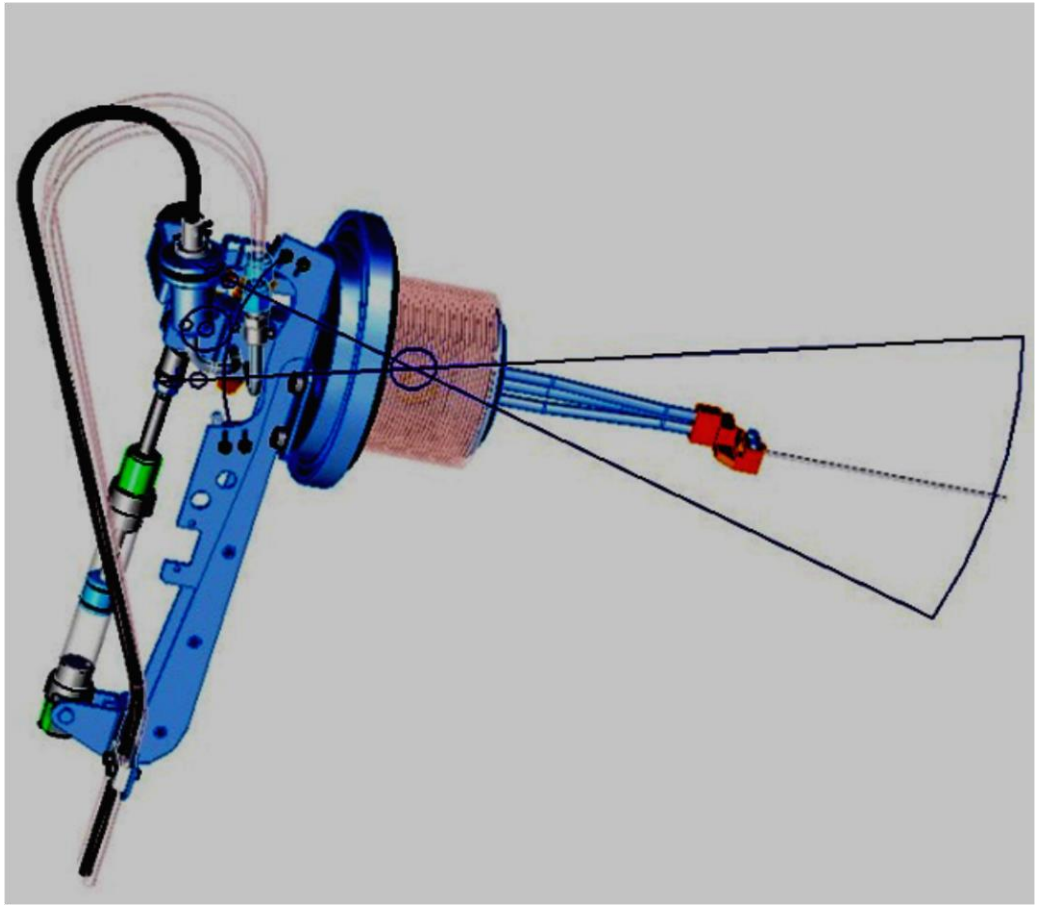
# Scanner system for iThemba LABS Gauteng and MRG

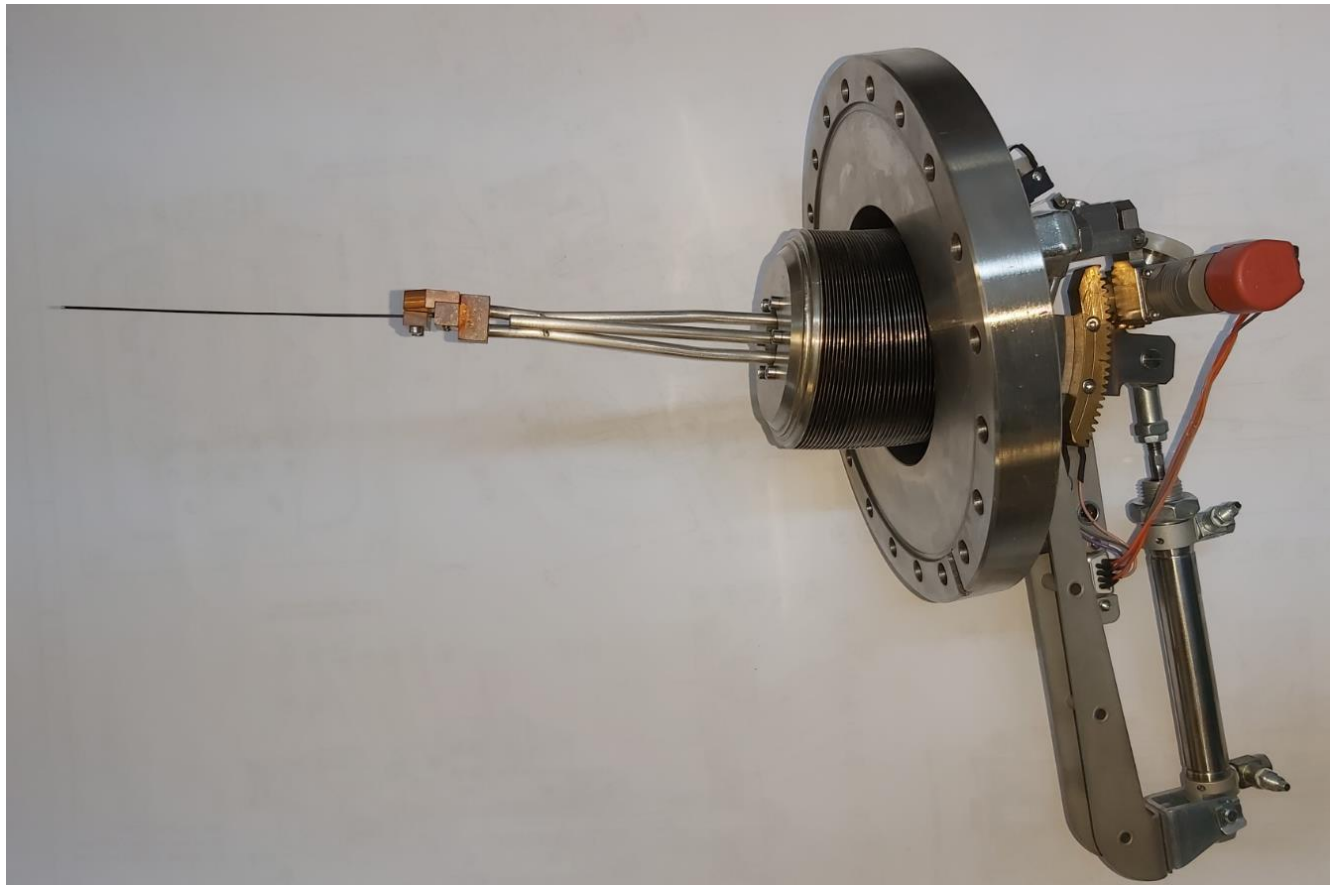


# EPICS scanner control system



# Beam profile scanner developed at iThemba LABS for high intensity beams





# Relation between the Energy, Charge and Mass of beam particle to the secondary electrons create in stopping material

From the Bethe formula for the rate at which a beam particle loses energy in a stopping material, the rate of energy loss is proportional to:

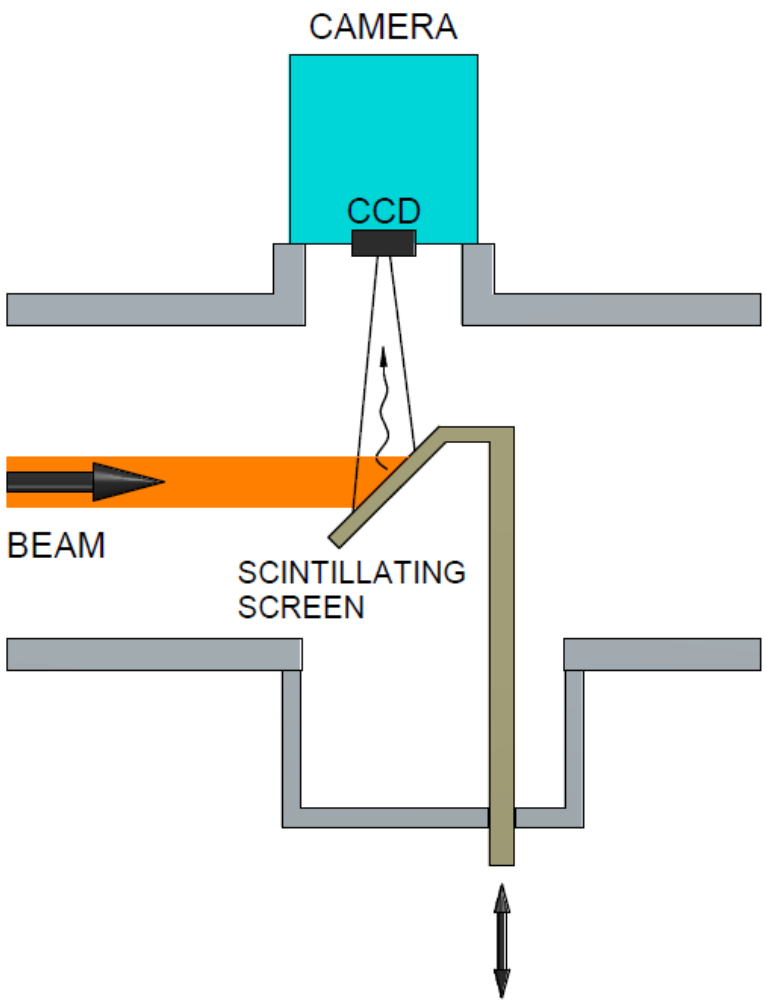
$$\frac{dE}{ds} \propto \frac{z_{projectile}^2}{v^2}$$

$$\propto \frac{z_{projectile}^2 m_{projectile}}{E}$$

This shows that a projectile ion with charge z (in unit of electron charge) and mass m will produce secondary electrons proportional to $z^2$ and m of the ion.

# Scintillation beam viewers

The most direct way of observing a particle beam profile of is by observing the emitted light from a scintillation screen hit by the beam. Although scintillator screens are very simple devices and were the first devices to monitor the profile of particle beams it is still used in many places. It is cheap and easy to setup.



# Scintillator Viewer

The beam energy loss in the coulomb field of the atoms of the viewer can be transformed to fluorescent light when the beam penetrates the viewer.

## Important properties of the scintillator material:

- Requires high light output that match the wavelength of the optical measuring system.
- Fast decay time is important to monitor variation of beam size as a function of time.
- High dynamic range is required between the beam intensity and the emitted light. Saturation of light can not give a true refection of the beam spot size.
- Must have good mechanical properties for easy manufacturing of viewers of different sizes and shapes.
- Radiation hard to prevent permanent damage to the viewer.

# Drawbacks of scintillator viewers

- In the low- to medium energy region the beam will be completely stopped. It not only makes it impossible to perform beam spot size measurements simultaneously at different positions downstream, but also limits the allowed beam current.

- The intensity range that can be covered is rather limited.

- In the combination screen/video camera there is no signal available for computer-aided signal analysis.

# Scintillators available on the market

| Type | Material | Thickness (mm) | λmax (nm) | Suppliers |
|---|---|---|---|---|
| Single crystals | CsI:Tl | 0.8 | 560 | Saint-Gobain Crystals Crytur Ltd |
| | YAG:Ce ($Y_3Al_5O_{12}$:Ce) | 1.08 | 550 | |
| | YAG:Ce | 0.25 | 550 | |
| | | | | |
| Glass | Quartz:Ce(M382) | 1 | 400 | Heraeus Quarz Glas |
| | Quartz (Herasil 102) | 1 | 400 | |
| | | | | |
| Ceramics | $Al_2O_3$ | 0.8 | 350 | BCE Special Ceramics |
| | Al2O3:Cr | 0.8 | 694 | |
| | $ZrO_2$:Mg (Z507) | 1 | 500 | |
| | $ZrO_2$:Y (Z700) | 1 | 440 | |
| | | | | |
| Powder screens | P43($Gd_2O_2S$:Tb) | 0.05 | 544 | Proxitronic Crytur Ltd |
| | P46 ($Y_3Al_5O_{12}$:Ce) | 0.1 | 530 | |

YAG(Ce) — Yttrium Aluminum Garnet doped with Cerium
P43 Gadolinium oxygen sulphur dope in Terbium

**"Scintillation Screen Materials for Beam Profile Measurements of High Energy Ion Beams. "**
Genehmigte Dissertation von M.Sc. Renuka Krishnakumar aus Indien Tag der Einreichung: 08.12.2014
Tag der Prüfung: 26.04.2016

# Optical properties of scintillation materials

- The materials P43, P46, Al2O3:Cr, Al2O3 reproduce image width within a difference of plus minus 4 %, from lower to higher beam intensities.

- Scintillation screen material chromium doped Al2O3, gives the best behaviour both in linearity test and stability test. However, the light output is a factor of 2 less compared to P43. Measurements at higher particle intensity can be performed using Al2O3:Cr screens.

- The materials P43 and P46 show little radiation damage.

**“Scintillation Screen Materials for Beam Profile Measurements of High Energy Ion Beams. “**
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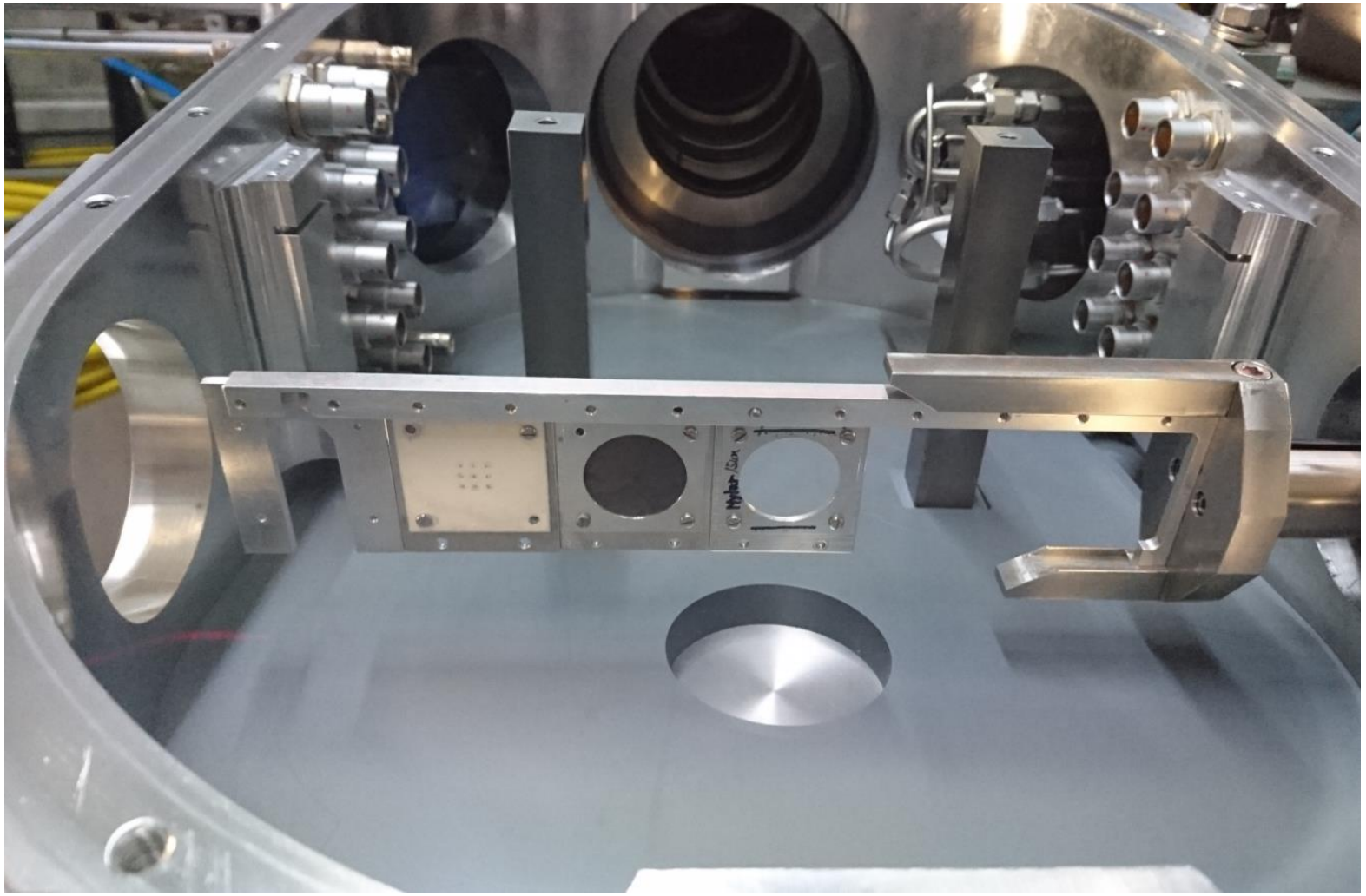
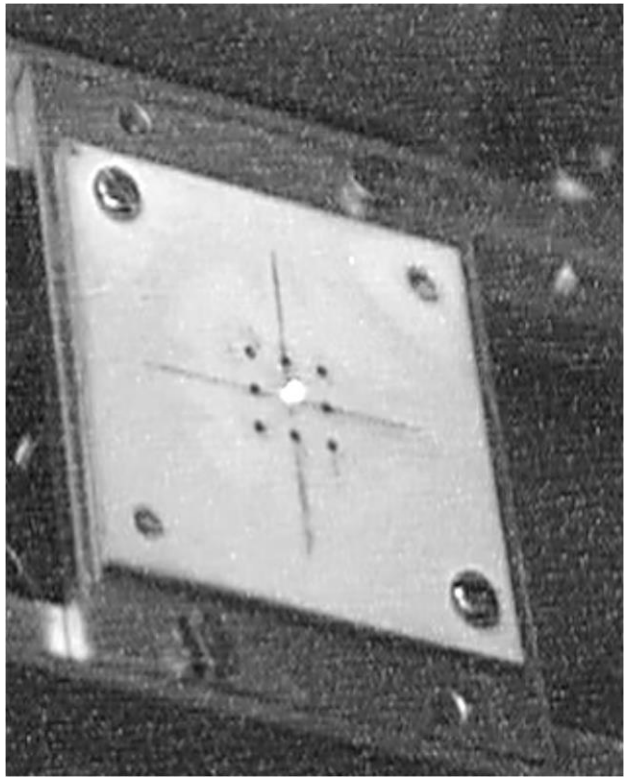
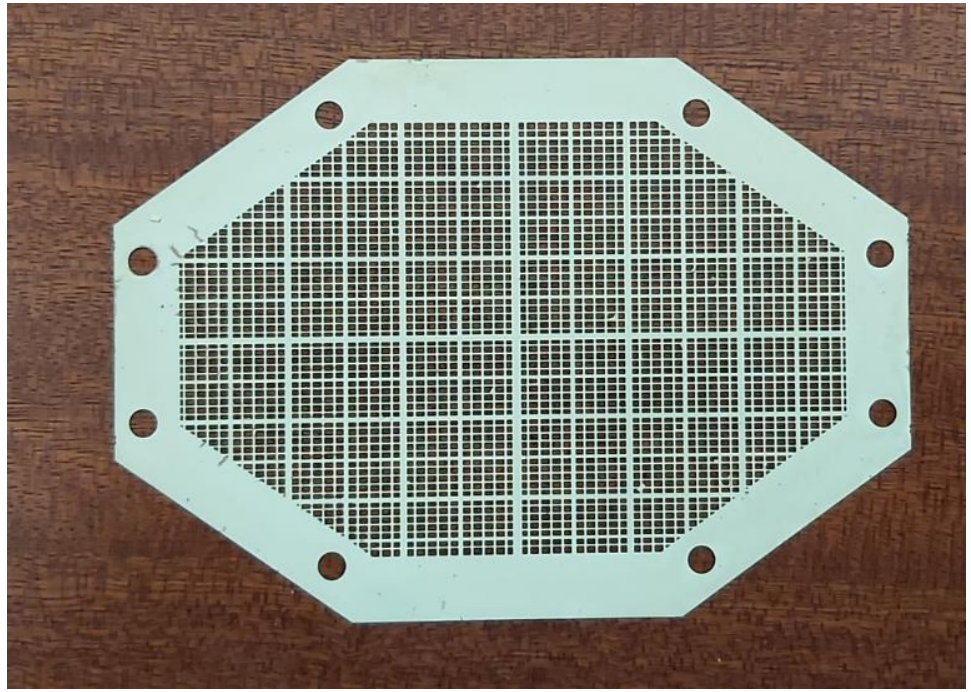
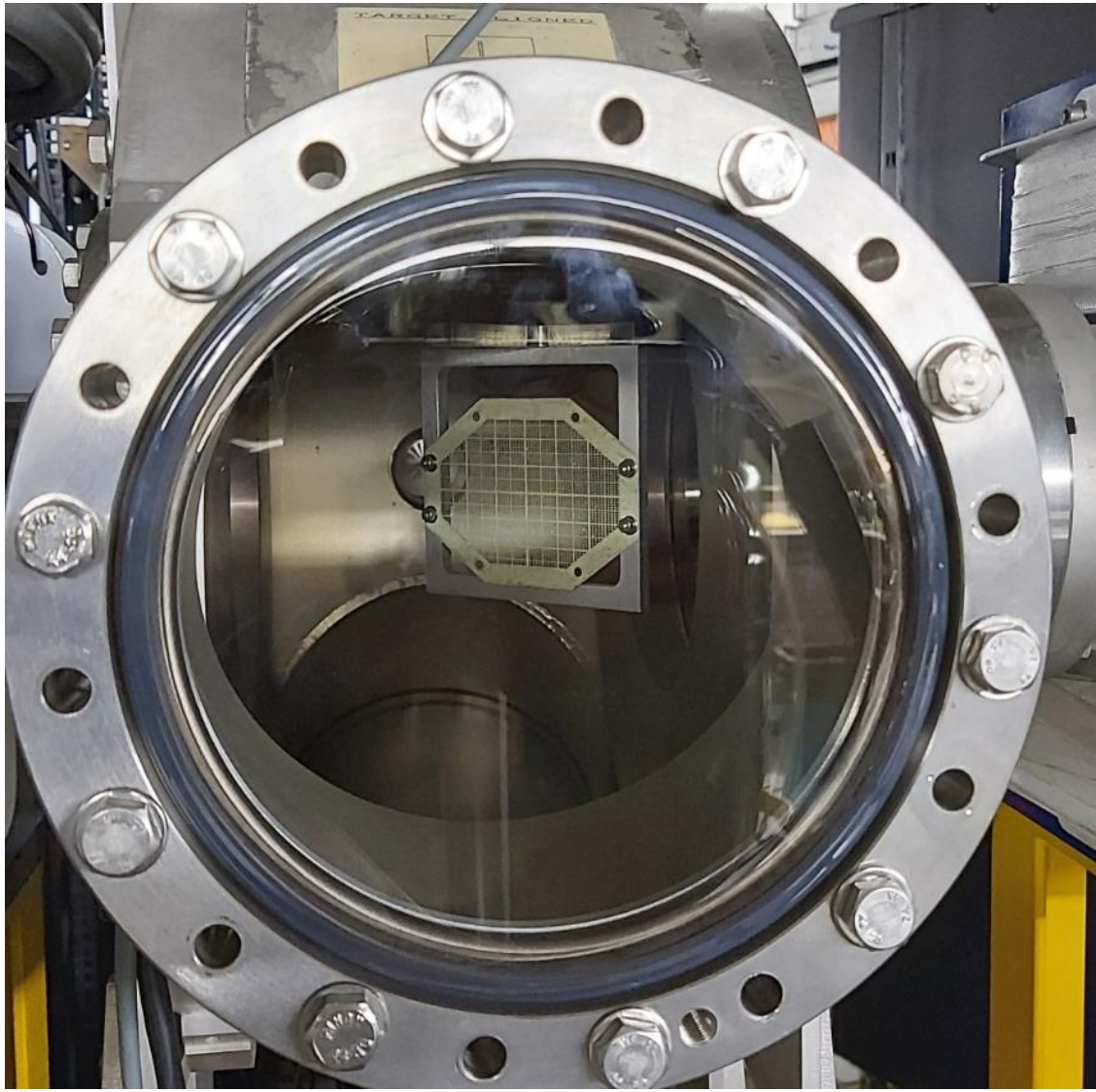
# Scintillator beam monitor at the spectrometer target station at iThemba LABS



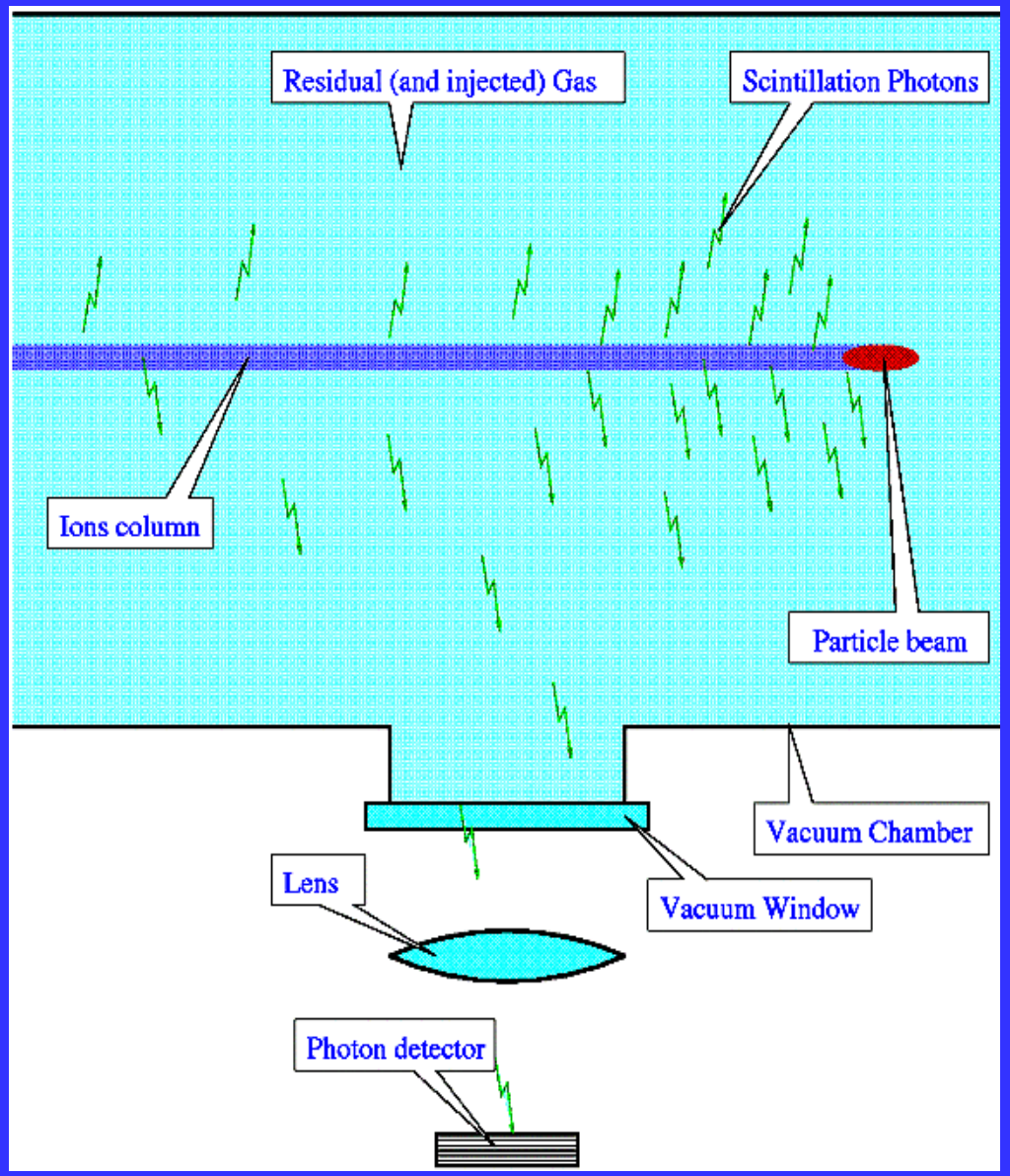


# Scintillator Viewer at iThemba LABS



# Residual gas fluorescence monitor



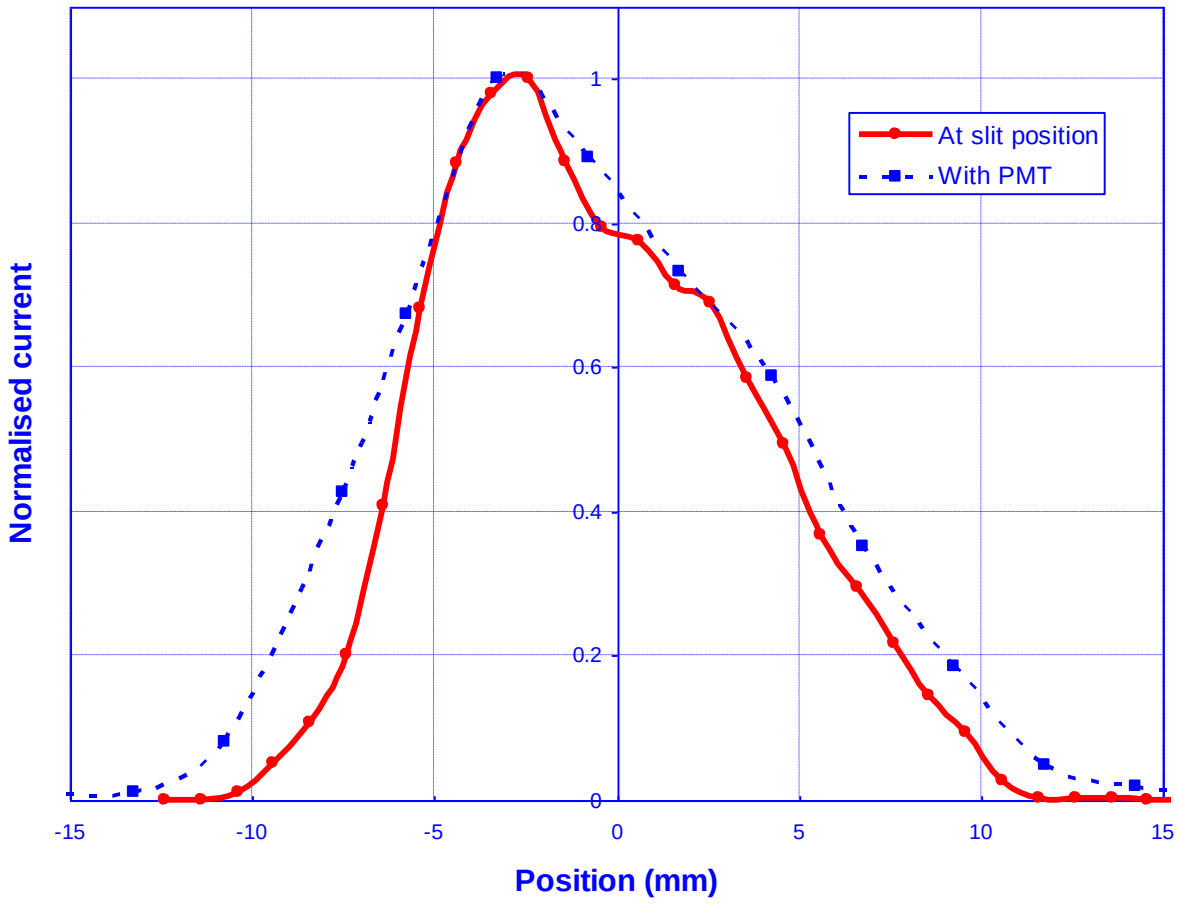

Gas molecules in the beam pipe,from either residual or injected gas, interact with the passing particle beam.

Electrons are promoted to excited states.

When the electrons fall to lower energy orbitals, photons are emitted.

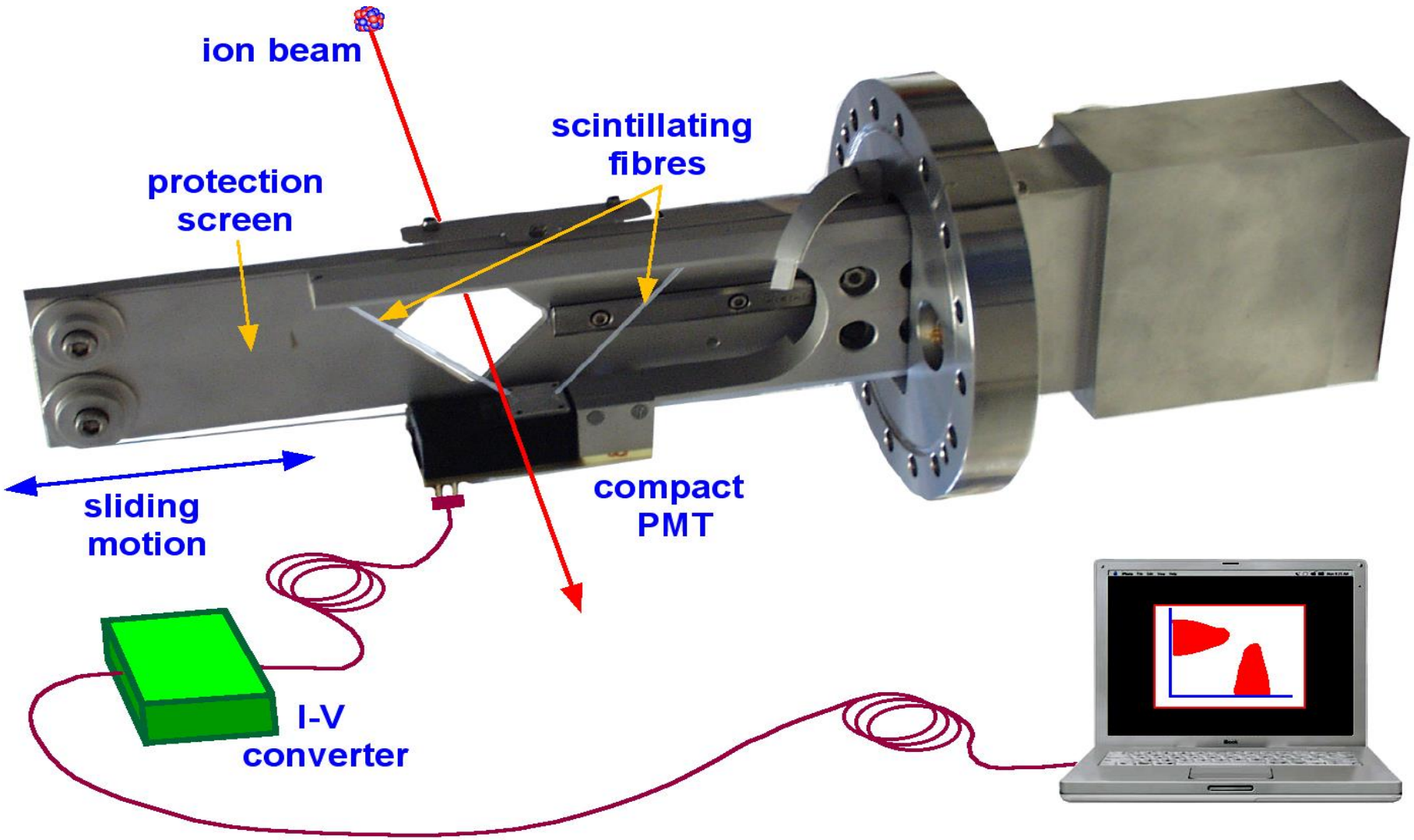
Photons are collected to measure the profile.

M.Plum, BIW2004, Knoxville




**There is good agreement between the beam profiles measured with a 420 µA, 3.14 MeV proton beam at the PMT (broken line) and slit positions (solid line) that are 257 mm apart**

# Scintillating profile monitor used at LNS in Catania Italy



# Beam energy measurement with a magnetic analyzer

- basic equations of movement of charged particles in a magnetic field:

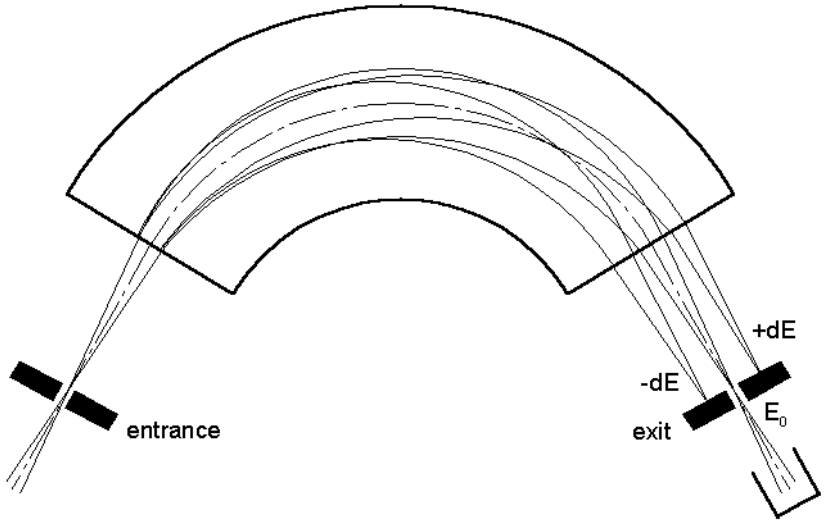
$$F = qv \times B$$ Lorentz-force

$$F = \frac{mv^2}{r}$$ Centripetal force

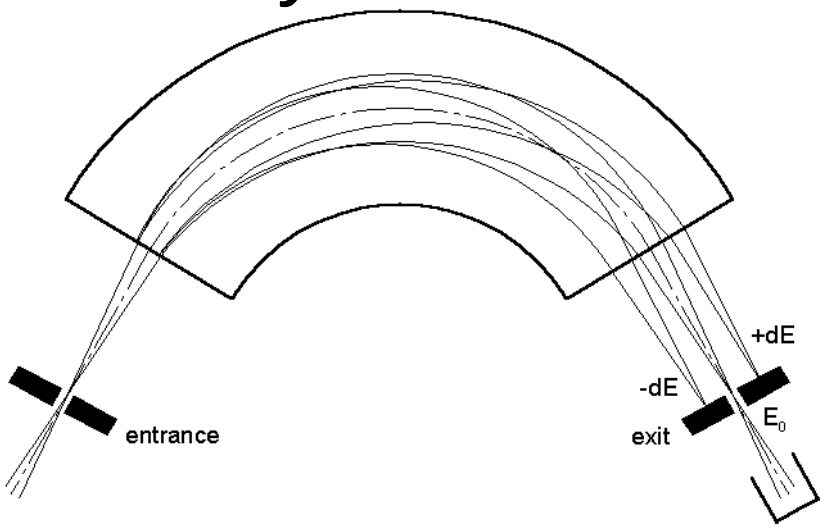
$$qvB = \frac{mv^2}{r}$$

$$r = \frac{p}{qB}$$ dispersion effect

- particles with different momentum move on paths with different radii
- => the dispersion effect can be used to separate particles of different energies
- scheme of a



# Beam energy measurement with a magnetic analyzer continue




- dispersion: *$D \sim 1-\cos\alpha$ => increasing with growing $\alpha$ up to 180*
- geometric limitations in a beam transport system

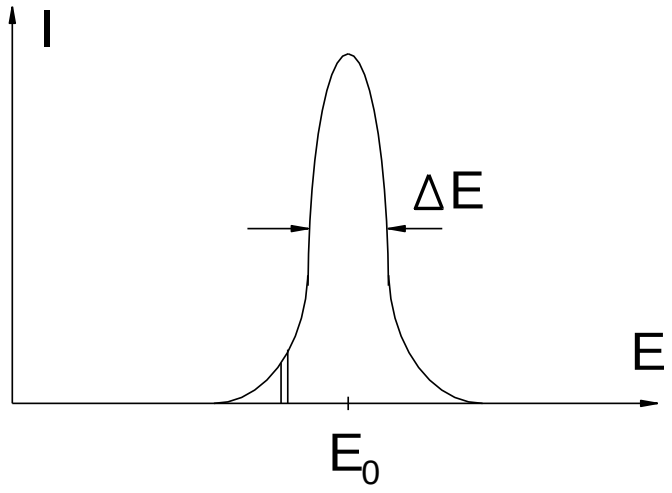
- special requirements on the design of a magnetic analyzer:

  - bending radius has to be known with high precision
  - magnetic field along the bending path has to be known with high precision
  - magnetic field has to have excellent time stability => power supplies!

- typical implementations:
  - highly homogenous magnetic field with an H-type yoke, pole shimming and edge clamps
- special feedback in the power supply with an NMR-probe for the field measurement
- narrow entrance and exit slits
- optical imaging in the plane of deflection

# Energy spread measurement:

- the same system can be used to measure (and also decrease) the energy spread of the beam
- particles with higher and lower energies are captured by the slit plates
- => measured beam intensity is proportional to the number of particles with a given kinetic energy



# Thank you