# BC-75

## Beam Collector

# User Manual


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# 1 Contents

# 2 Figures

# 3 Safety Information

This unit is designed for compliance with harmonized electrical safety standard EN61010-1:2000. It must be used in accordance with its specifications and operating instructions. Operators of the unit are expected to be qualified personnel who are aware of electrical safety issues. The customer's Responsible Body, as defined in the standard, must ensure that operators are provided with the appropriate equipment and training.

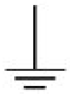
The unit is designed to make measurements in **Measurement Category I** as defined in the standard.

**CAUTION. Radiation**

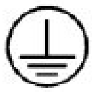
After use in a high-energy particle accelerator beamline, the BC-75 will become activated. Do not work on the device, or move the device from a controlled area until it has been surveyed and declared safe by a qualified radiation supervisor.

Some of the following symbols may be displayed on the unit, and have the indicated meanings.

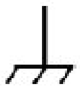
Direct current



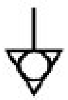
Earth (ground) terminal



Protective conductor terminal



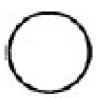
Frame or chassis terminal



Equipotentiality



Supply ON



Supply OFF

CAUTION – RISK OF ELECTRIC SHOCK

CAUTION – RISK OF DANGER – REFER TO MANUAL

CAUTION – ENTRAPMENT HAZARD

# 4 Models

| | |
|---|---|
| BC-75 | Beam collector for proton therapy, 75 mm diameter. |
| BC75-SYS-10 | Beam collector system comprising BC-75, IC101 electrometer and 10' (3 m) low-noise coaxial signal cable |

# 5 Scope of Supply

BC-75 model as specified in your order.

USB memory stick containing:
- BC-75 Data sheet
- BC-75 User manual
- Test data

Shorting plug for signal connector.

High quality shipping case.

Optional items as specified in your order.

# 6 Optional Items and Consumables

## 6.1 Readout electronics

IC101 Single channel electrometer.

PSU24-40M-1 24 VDC universal power supply for IC101.

## 6.2 Signal cables and cable accessories

### 6.2.1 Individual cables

CAB-BNC-COLN-3-BNC. Low-noise cable BNC-terminated, 3’ (0.9 m).

CAB-BNC-COLN-10-BNC. Low-noise cable BNC-terminated, 10’ (3 m).

CAB-BNC-COLN-20-BNC. Low-noise cable BNC-terminated, 10’ (6 m).

# 7 Intended Use and Key Features

## 7.1 Intended Use

The BC75 is intended to provide direct readout of proton beam current in the energy range 30 to 250 MeV. It is very convenient to use, and provides a useful level of absolute accuracy that is independent of beam energy. Best measurement accuracy for protons is achieved in the 100 MeV to 250 MeV range with a beam dimension of 30 mm full diameter or less, or 10 mm sigma.

Proton energy exceeding 250 MeV should not be delivered because the beam will penetrate the full depth of the collector and emerge from the back. The measurement will not be accurate in this case.

Typical continuous average currents are in the range 0.1 to 50 nA. Higher average currents up to 4 µA can be delivered for short periods, but these currents considerably exceed typical proton therapy levels. If such high currents are measured, the user must assess the power load and level of activation and set a time limit for the beam exposure. The maximum recommended limit is 5 seconds at 250 MeV, 4 µA (a 1 kW beam power), which should be followed by a cooldown period of not less than 100 seconds.

Minimum measurable current will depend on noise levels and the quality of the readout electronics. When used with the IC101 electrometer, beam currents of 10 pA or less can be measured, using appropriate current integration time.

**CAUTION. Radiation**

After use in a high-energy proton accelerator, the BC-75 will become activated. The level of activation will depend on the amount of beam charge that is delivered and the time that has elapsed since the beam was present for the activity to decay. Do not work on the device, or move the device from a controlled area until it has been surveyed and declared safe by a qualified radiation supervisor.

The BC-75 is not recommended for accurate measurement of the current of other hadron beams, such as carbon nuclei. The BC-75 will make a measurement, but there is a gain factor which has to be determined by other means.

## 7.2 Key Features

- Direct measurement of high energy proton beam current.
- Proton energies from 30 to 250 MeV.

- Typical accuracy better than 2%.
- Small dependence on beam energy compared to other sensors.
- Compact, fully-screened design.
- Operates in air – no vacuum system or HV bias required.
- Compatible with IC101, I200, F460 and other readout electronics.
- Bias voltage up to 2 kV.
- Based on a proven concept of Bernard Gottschalk developed and used at the Harvard Cyclotron Laboratory.

# 8 Specification

| | | |
|---|---|---|
| *Beam compatibility* | | |
| | Species | Protons |
| | Energy range | 30 MeV/nucleon to 250 MeV |
| | Beam power handling | Up to 75 W continuous in well-ventilated location, up to 1 kW for 5 seconds with not less than 100 second cooldown. |
| *Sensor* | | |
| | Construction | Pure OFHC copper cylinder 100 mm long and 75 mm diameter with dielectric coatings and electrostatic screens. |
| | Sensitive area | 70.5 mm nominal diameter, suitable for protons beams with Gaussian lateral distribution sigma up to 10 mm. |
| | Materials | Epoxy film, conductive epoxy film, polyimide film, OFHC copper. All beam in the specification energy range stops in the copper. |
| | Leakage current | < 5 pA after stabilisation. < 3 pA typical.<br>Offsets can be compensated by active background subtraction. |
| | Accuracy | The BC-75 provides a direct measurement of beam current that is independent of beam energy to a good approximation in the specified energy range. Better than 4% absolute error typical from 100 MeV to 250 MeV before calibration. |
| *Mechanical* | | |
| | Length | 143 mm (excluding mating signal cable) |
| | Overall size | 143 mm by 127 mm by 97 mm approx including handle (see figures) |
| | Weight | 4.8 kg ( 10.6 lb) . |
| | Operating environment | Clean and dust-free, 0 to 35 C (15 to 25 C recommended , < 70% humidity, non-condensing, vibration < 0.05g all axes (1 to 50 Hz)<br>Signal output cable must not flex or vibrate. |
| | Shipping and storage environment | -10 to 50 C, < 80% humidity, non-condensing, vibration < 2g all axes, 1 to 100 Hz |
| *Readout* | | |
| | Connector | BNC jack.<br>The connector must be shorted if the BC-75 is not connected to |

| | | |
|---|---|---|
| | | an electrometer to prevent charge buildup. A terminator plug is included for this purpose. |
| | Compatible Pyramid electronics | IC101, I200, I404, F460 by direct connection of BNC-terminated coax cable.<br><br>F100, ch0 inputs of I128 or I6400 via cable adaptor. |
| | Recommended cable | Low-noise (anti-triboelectric) RG-58 coax cable recommended. |
| | Software | Pyramid Diagnostic software provided with compatible Pyramid electronics units. |

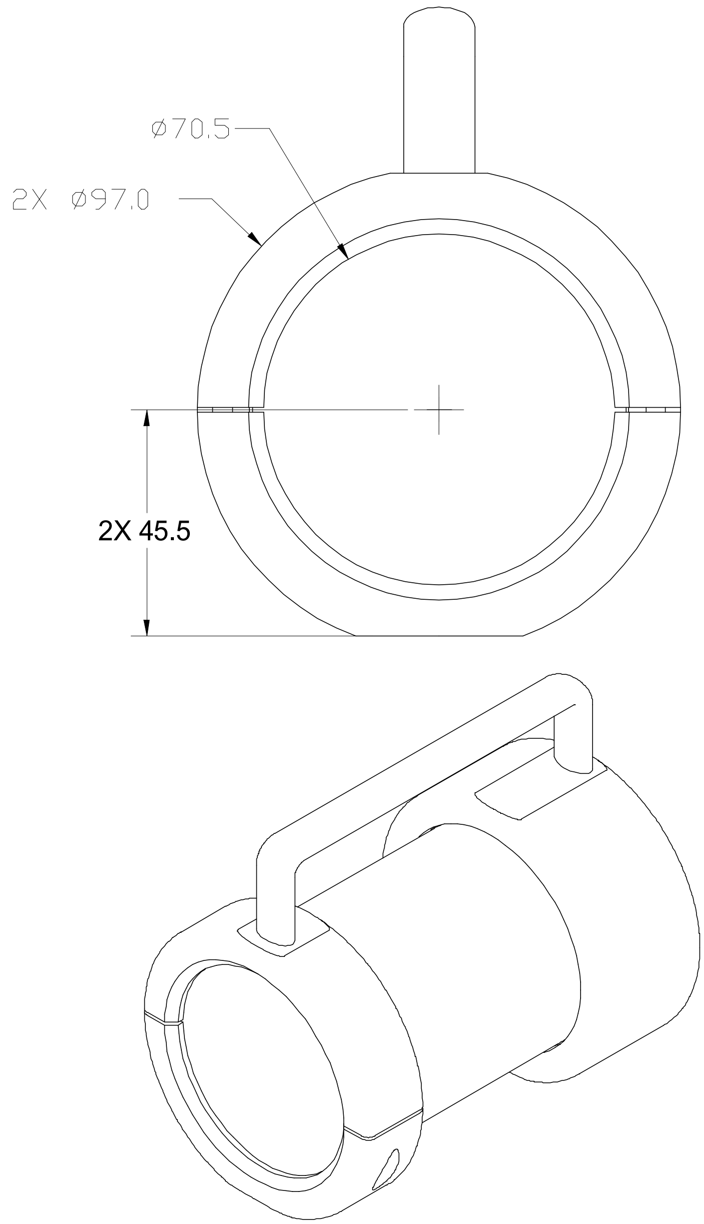



*Figure 1. BC-75 Beam entry face and isometric view from above.*

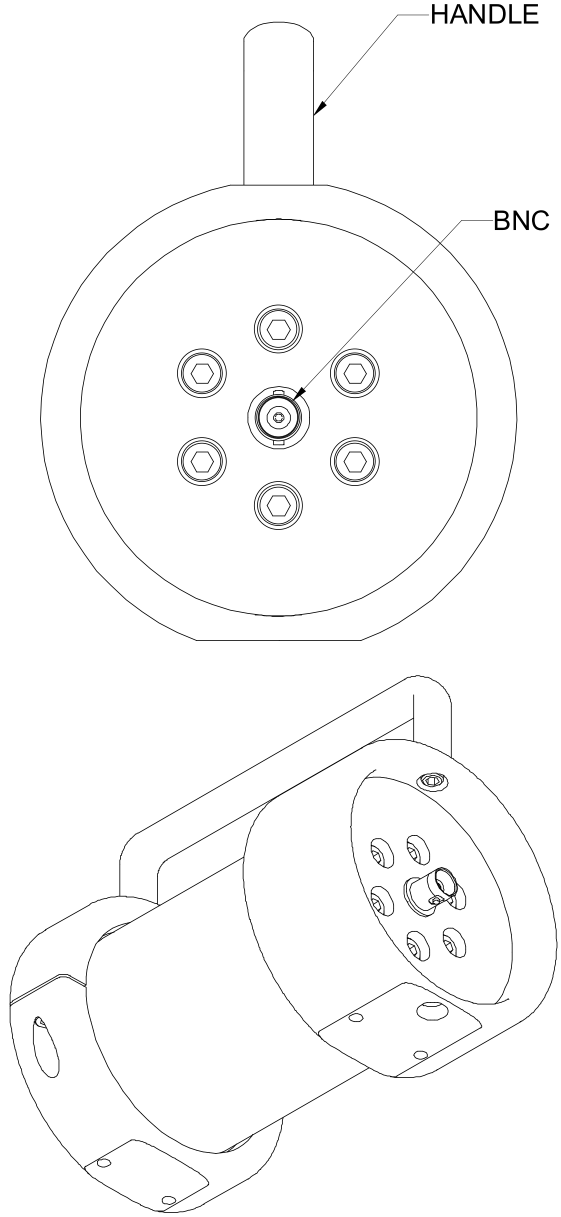



*Figure 2. BC-75 Signal output face and isometric view from below showing mounting features.*

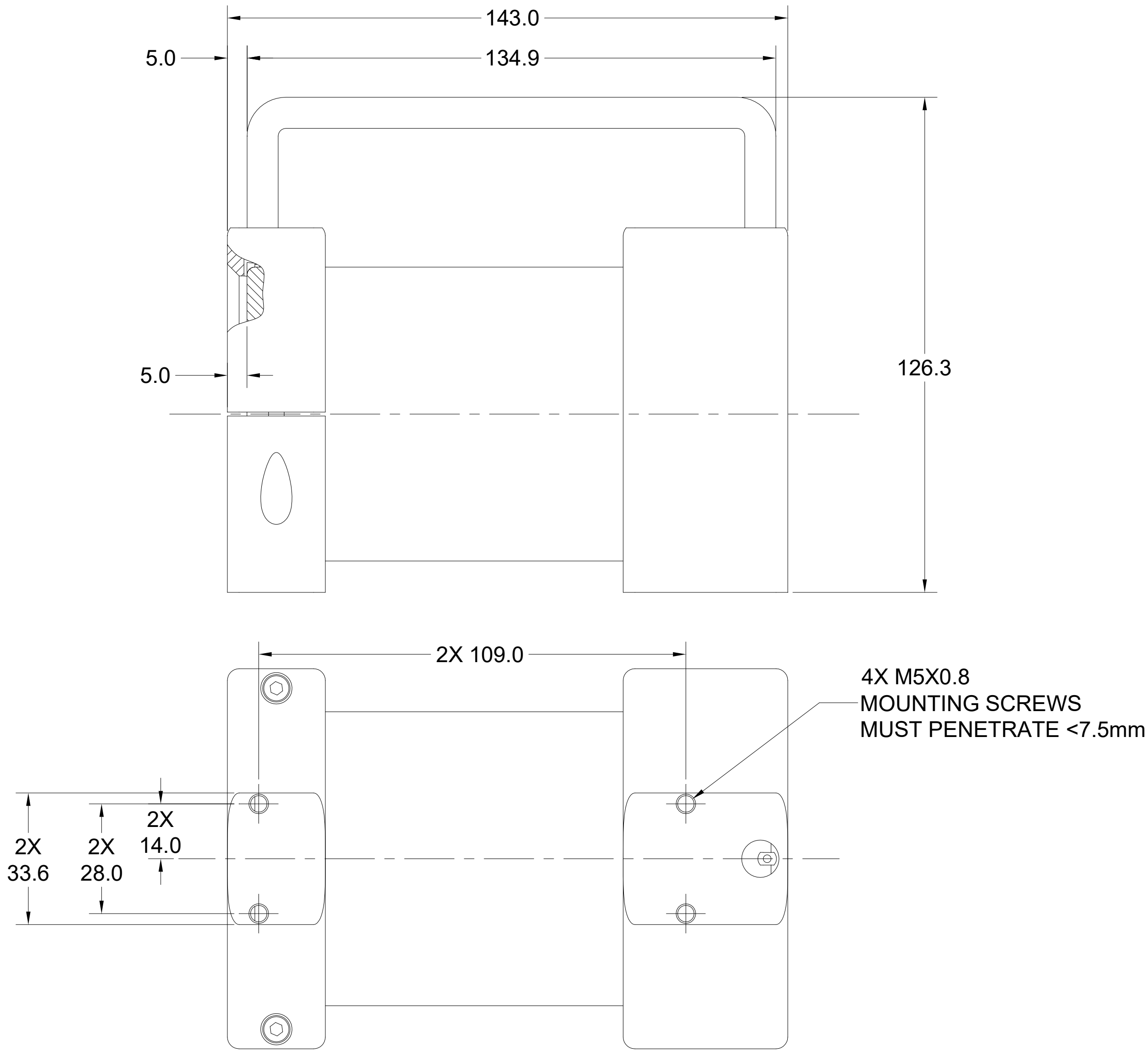



*Figure 3. BC-75 Dimensions and mounting features.*

# 9 Using the BC-75

## 9.1 Principle of operation

The BC-75 is designed to be used in air, and requires no vacuum system or suppression voltage to operate. Protons pass through the thin front window layers, and slow down then stop in the copper body. The charge on the protons is compensated by current from a connected current measurement device, thus giving a measurable signal.

The covering layers provide electrostatic screening and prevent ionization in the surrounding air from affecting the reading. The simulation shown below illustrates how a monoenergetic proton beam (pale blue) stops inside the copper block at a specific range. The right hand view reveals the inside of the copper block. Most electrons from ionization of the air (red) do not reach the copper. Mechanisms that do affect the response can be seen. A very small number of protons may be scattered at large angles close to the surface and be lost. High energy electrons may enter or leave the copper body. Most electrons are low energy and stay in the copper. Interactions in the thin insulating coating layers result in a small amount of trapped charge which is partially measured. The overall result of these mechanisms is a slight under-reading of the beam charge which is minimum at high energy and increases to lower energies. The effects are systematic and can be managed by calibration against a reference current measurement.

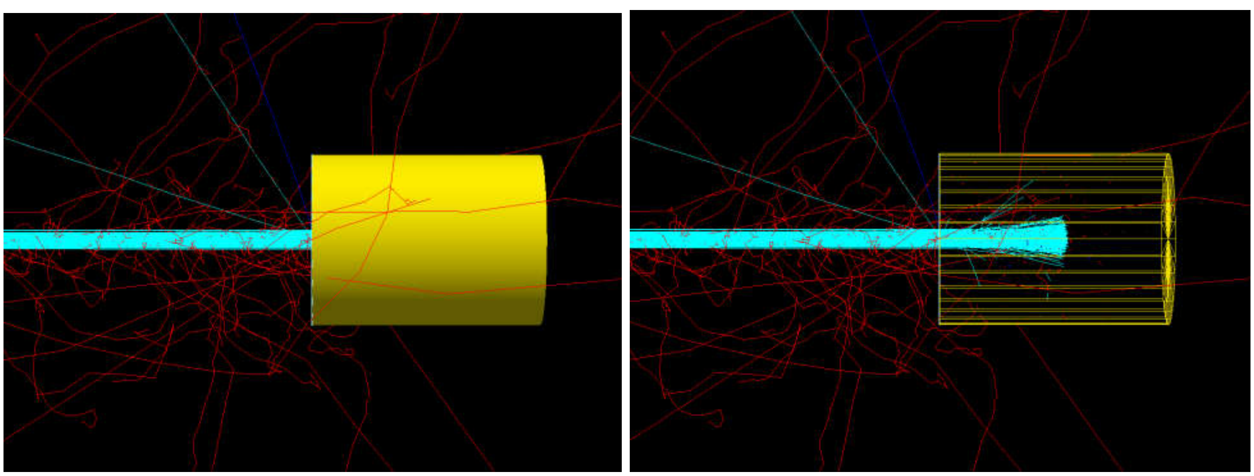


*Figure 4. 230 MeV proton beam stopping in the BC-75*

## 9.2 Preparation and handling

The BC-75 is shipped in a special protective transport case. Use the case to store the device when not in use. Whenever the signal output is not connected to readout electronics, fit the BNC shorting plug to avoid charge build up in the device which can degrade accuracy.

 TAKE CARE WHEN HANDLING

The BC-75 is robust and can be lifted and moved around easily. Nevertheless, take care to avoid damaging the coating as scratches and abrasions that penetrate the outer protective coat will degrade measurement accuracy.

After use, the collector will be radioactive until activation products decay. Allow some time following irradiation by the beam before handling the device, especially its entrance face. Survey the BC-75 and other items than have been exposed to the proton beam with a suitable radiation monitor before handling, and minimize handling time. The plot below shows an average of several measured gamma emission decay curves against time since irradiation, normalized to the dose rate at the entrance face at 30 minutes after the irradiation.

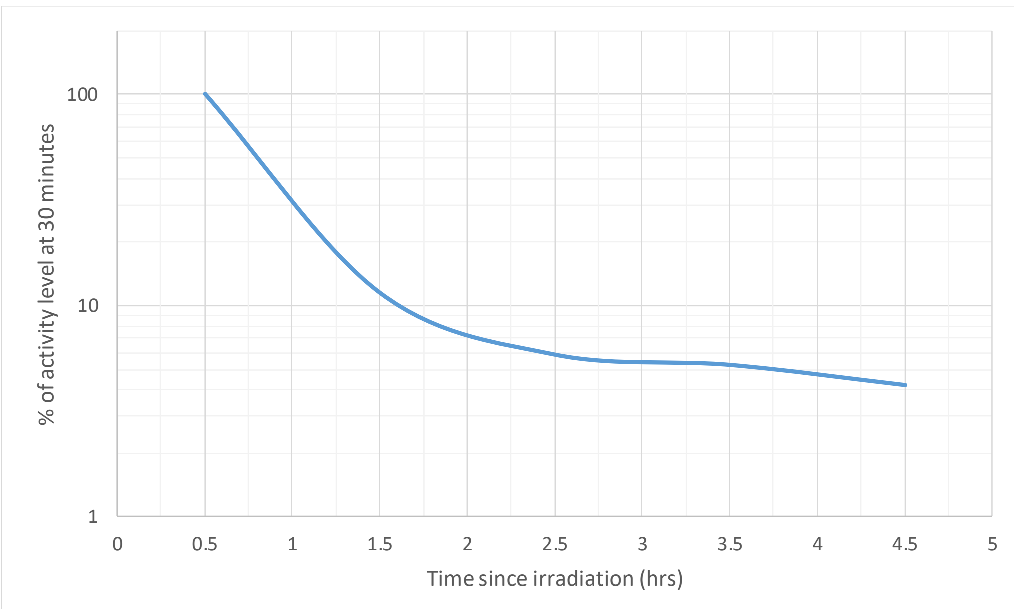



*Figure 5. Typical activation decay rate.*

## 9.3 Making measurements

### 9.3.1 Positioning

The BC-75 can be placed on any convenient surface. Position it so that the proton beam will enter in the centre of the beam entry face at normal incidence.


*Figure 6. Alignment with the beam direction*

The BC-75 can be simply rested on a suitable surface. For a more permanent installation, or allow it to mounted on a rotating platform to follow a proton therapy gantry rotation, use the M5 tapped mounting holes on the base (figure 3). Note that the screws must not run more than 7 mm into the holes, or the insulating and screening layers could be damaged.

To ensure that the beam has not spread too much laterally before it reaches the collector, especially at lower energy, it is best to place it close to where the beam leaves the vacuum or helium transport.

### 9.3.2 Signal readout

The BC-75 measures the beam current directly, with no physical gain. Therefore the readout device must have sufficient sensitivity to measure down to the lowest current level that will be encountered. The Pyramid IC101 is a suitable electrometer for readout, but any precision electrometer able to measure down to picoampere currents would be suitable. The length of the signal cable is a compromise between the need to keep the cable short to minimize noise, and long enough to take the electronics away from the radiation field that surrounds the BC-75 when it is measuring a proton beam. If the cable is coaxial, then a low-noise (anti-triboelectric) cable type should be used. An example is Belden 9223 RG-58 cable.


*Figure 7. Connection to IC101 electrometer*

Many commercial electrometers use triaxial signal connectors. In this case, you should use a triaxial cable and make adaption to a coaxial BNC close to the BC-75. Take care not to apply too much mechanical load to the BNC jack on the device, as this might compromise the internal connections to the copper cylinder and the screening layers.

### 9.3.3 Handling very low currents

When the current being measured is very low (a few 10's pA), then a drift in the background offset may affect accuracy. This can be handled using simple linear background correction, provided only that the source of current can be turned on and off.

The following figure shows how this can be accomplished for the case of a charge integrating electrometer like the IC101. A pulse of beam current arrives in the second of three relatively long equal duration integrations. The background offset is drifting. The second integration is the sum of the beam charge and a background pedestal. The beam charge component can be extracted by assuming linear background drift:

$$q_{bgd2} = (q_{bgd1} + q_{bgd3})/2$$

$$q_{sig} = q_{meas} - q_{bgd2}$$

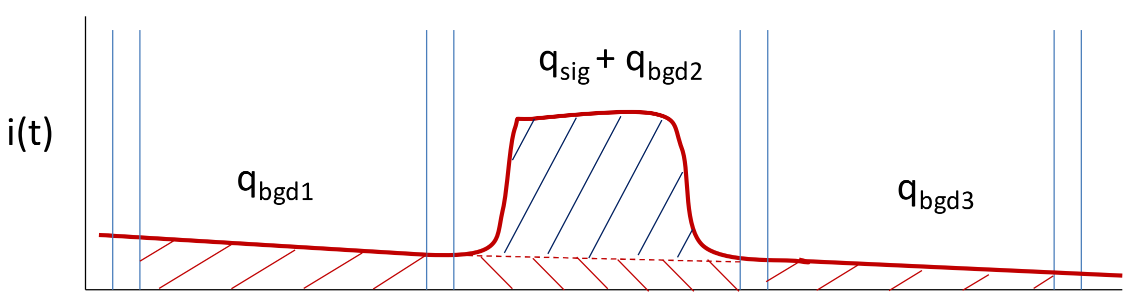



*Figure 8. Interpolating background offset at low beam current*

# 10 Current Measurement Accuracy

The BC-75 is used for the measurement of high-energy proton beam currents in the energy range up to 250 MeV. The BC-75 is robust, stable and very convenient to use. It is well-suited to checking for drift or shifts in the beam current. Different samples of the BC-75 have closely-matched response, to within 0.3%.

Ideally the BC-75 collects all the proton beam current in the copper body. Any other losses or gains of charged particles with the environment lead to errors. The special coating layers of the device prevent collection of ionization from the surrounding air, and prevent low energy particles from entering or leaving. However small losses are inevitable due to high energy scattered particles and protons that stop in the coating layers. These limit the absolute accuracy, and there is a small systematic error that varies with the beam energy. However, if the collector is calibrated over the working energy range against a traceable measure of proton beam current, or dose in water, it will act as a stable secondary standard that requires no compensation for environmental conditions nor support equipment like vacuum systems or high voltage supplies.

## 10.1 Absolute accuracy

Scattered protons are captured by making the device sufficiently large that the whole primary beam stops well within its body. However not all particles can be stopped. The result is that the device has a repeatable gain curve, close to 1.00 but generally somewhat lower (it under-reads by a few percent), and some dependence on proton energy.

The following plots shows some typical energy curves for Pyramid beam collectors. The lower plot is a magnified vertical scale. The measurements were taken at Heidelberg Ion-Beam Therapy Center (HIT) and at the Burr Proton Therapy Center Massachusetts General Hospital (MGH), and are shown with the kind permission of those institutions. Monte Carlo simulations were made using Geant 4. The curves are:

- MC model: Monte Carlo results for monochromatic beam energies, 5 mm sigma
- Measured MGH: average of three BC-75 beam collectors measured at MGH
- Measured HIT: average of five beam collectors measured at HIT

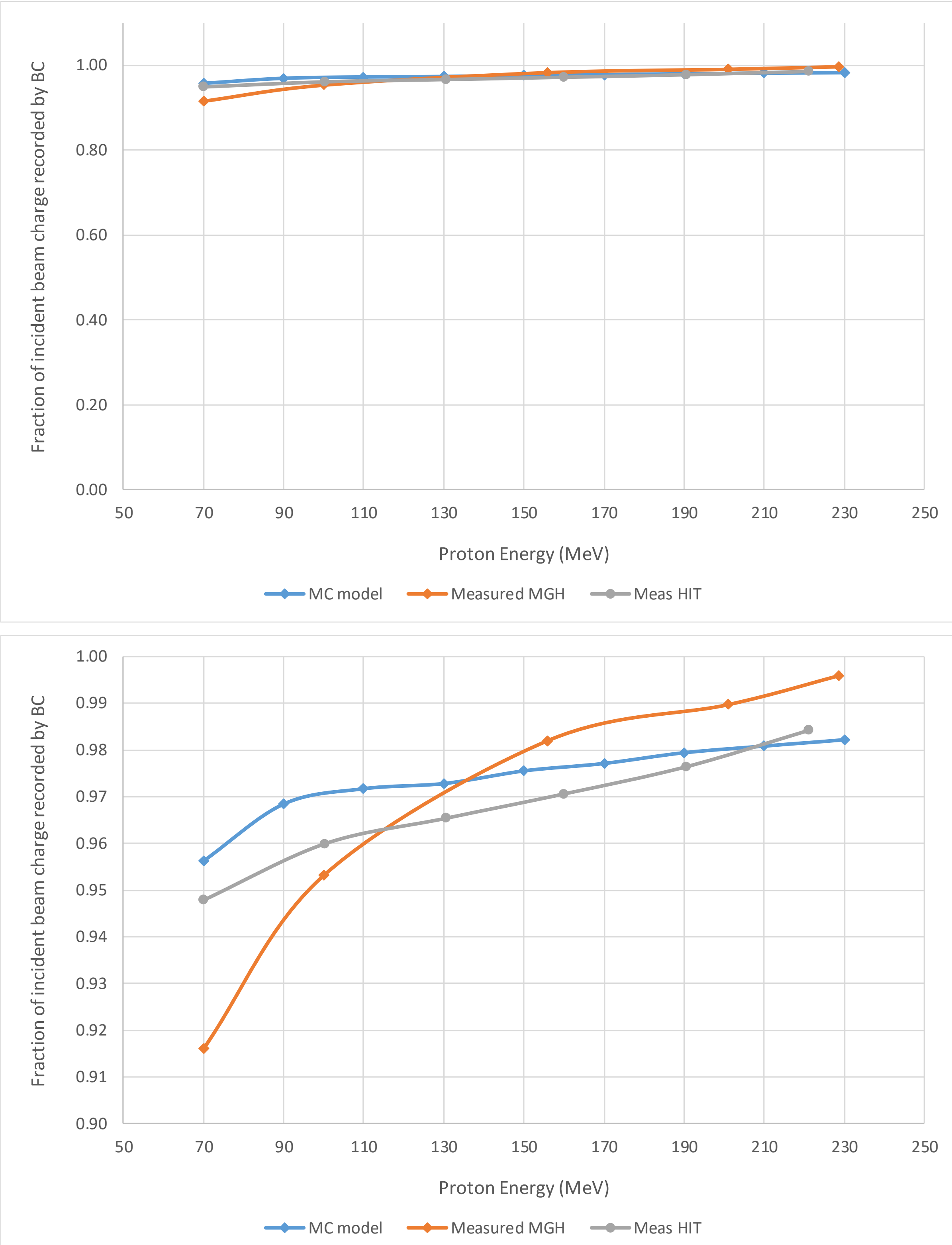



*Figure 9. Gain as a function of proton energy, measurements and simulation.*

In both sets of measurements the beam charges delivered were normalized by the signal from a stable transmission ionization chamber. It is possible that lower energy beams in the data taken at MGH (orange curve) had scattered laterally to become too large for the BC-75, which would produce the observed anomalous fall off. For maximum accuracy, beam dimensions should be limited to 10 mm sigma or less in both axes.

The uncertainty in the results is within +/- 1% in the range of 100-250 MeV. However, this depends on the unknown error in the reference standards. There is no guarantee in the data collected to date that the references were actually more accurate than the beam collector measurements. More data will be collected across multiple sites and operating settings to narrow the error in external accuracy in the future. The consistency between individual BC-75 units means that updates to the gain curve can be applied to all units.

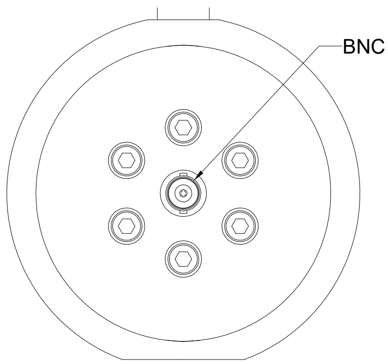
Given the uncertainties in determining absolute accuracy, the following table of gain vs energy showing the Monte-Carlo calculations and fits to the measurements that have been made to date with protons beams is presented for general guidance only. The BC-75 must be cross-calibrated to a traceable dose or beam current reference if it is to be used as an absolute measure.

| Energy | MC model | MGH data | HIT data avg | Meas avg |
|---|---|---|---|---|
| 70 | 0.956 | | | |
| 90 | 0.968 | 0.942 | 0.956 | 0.95 |
| 110 | 0.972 | 0.960 | 0.962 | 0.96 |
| 130 | 0.973 | 0.972 | 0.966 | 0.97 |
| 150 | 0.976 | 0.980 | 0.970 | 0.97 |
| 170 | 0.977 | 0.986 | 0.973 | 0.98 |
| 190 | 0.979 | 0.989 | 0.976 | 0.98 |
| 210 | 0.981 | 0.992 | 0.981 | 0.99 |
| 230 | 0.982 | 0.995 | 0.987 | 0.99 |

# 11 Connectors

## 11.1 Signal output

One BNC jack.




The connector should be shorted if the BC-75 is not being used. The short can be added directly to the BC-75 connector or to the other end of the signal cable. A powered electrometer with relatively low input impedance acts as a short.

# 12 Maintenance

There are no maintenance requirements.

Ensure that the signal connector has the shorting plug fitted if the BC-75 is not in use.

# 13 Fault-finding

The BC-75 is designed to give you trouble-free service. However the following fault-finding is provided to help decide whether the device is faulty, and to guide repairs for customers who do not have a service arrangement.

| *Symptom* | *Possible Cause* | *Confirmation* | *Solution* |
|---|---|---|---|
| Current reading drifts | Dielectric overlayers have accumulated charge. | Check connections carefully. | Ensure signal connector has shorting plug fitted when device not in use.<br>Use background correction in data processing. |
| No signal | BNC connector has no connection to the collector copper body. | Careful inspection. Check BNC connector is not loose. Measure capacitance (the nominal value is 30 - 36 nF) | Call supplier for advice.<br>Avoid using excess torque when making connections. |
| | Overlayers damaged, copper body is shorted to ground. | Check isolation between core and screen of BNC connector (should exceed 1 Gohm) | Call supplier for advice.<br>Avoid using excess torque when making connections.<br>Handle device with care and store in case provided when not in use. |
| Excess noise | Screen overlayer is floating. | Careful inspection. Check BNC connector is not loose. Measure capacitance (the nominal value is 30 - 36 nF) | Call supplier for advice.<br>Avoid using excess torque when making connections. |

# 14 Returns procedure

Damaged or faulty units cannot be returned unless a Returns Material Authorization (RMA) number has been issued by Pyramid Technical Consultants, Inc. If you need to return a unit, contact Pyramid Technical Consultants at support@ptcusa.com, stating

- model
- serial number
- nature of fault

**CAUTION. Radiation.**

The unit cannot be shipped until it is certified to be below legal limits for radiation, and that it is clear of any chemical contamination.

# 15 Support

Manual and other documentation updates are available for download from the Pyramid Technical Consultants website at **www.ptcusa.com**. Technical support is available by email from support@ptcusa.com. Please provide the model number and serial number of your unit, plus relevant details of your application.

# 16 Disposal

We hope that the BC-75 gives you long and reliable service.  BC-75 is manufactured to be compliance with the European Union RoHS Directive 2002/95/EC, and as such should not present any health hazard, once any activation has decayed.

**CAUTION.  Radiation.**

The IC must not be released from a radiation controlled area until it has been surveyed and declared safe by a qualified Radiation Supervisor.

When your BC-75 has reached the end of its working life, you must dispose of it in accordance with local regulations in force.  If you are disposing of the product in the European Union, this includes compliance with the Waste Electrical and Electronic Equipment Directive (WEEE) 2002/96/EC.  Please contact Pyramid Technical Consultants, Inc. for instructions when you wish to dispose of the device.

# 17 Revision History

The release date of a Pyramid Technical Consultants, Inc. user manual can be determined from the document file name, where it is encoded yymmdd.  For example, B10_UM_080105 would be a B10 manual released on 5 January 2008.

| ***Version*** | ***Changes*** |
|---|---|
| BC75_UM_180118 | First general release |
| | |
| | |