Technical Note

TN0019
Selecting a transmission ionization chamber for proton therapy dosimetry

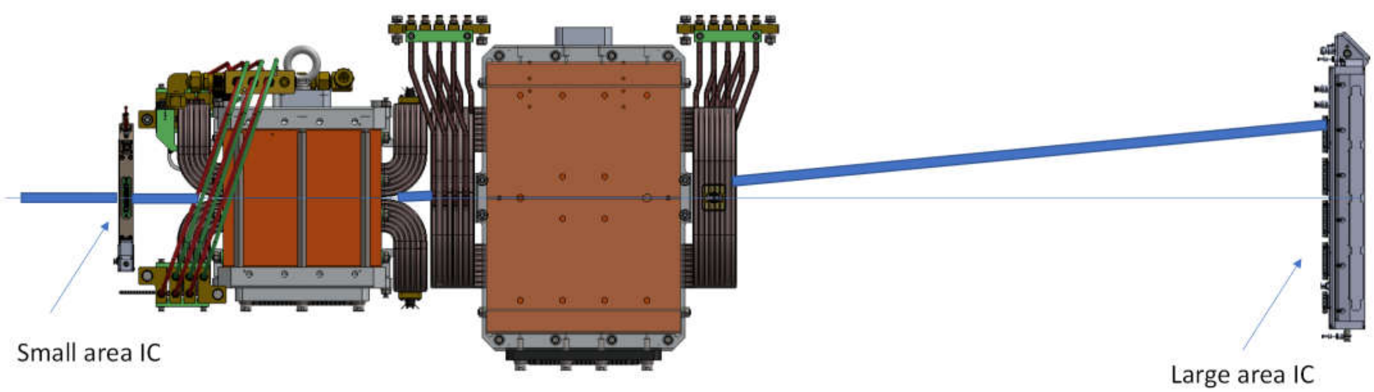
Types of ionization chamber and their use for proton therapy

Ionization chambers are well-established radiation detection devices that are reliable, radiation-hard, simple to use, have good linearity and can be constructed in a wide variety of sizes and configurations. In the case of a proton therapy system, ionization chambers are invariably used in the dose delivery nozzle. They can also be used for beam diagnostics in a transfer line and for quality assurance in the treatment room. This note focuses on parallel plate transmission chambers that are integrated into medical radiation therapy devices that deliver beams of charged particles such as protons. The important design features of Pyramid ionization chamber products designed for dose delivery control are summarized.

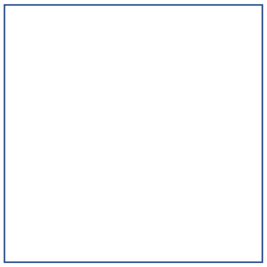
Dose delivery control in proton therapy

The following considerations apply to ionization chambers used a dose delivery nozzle:

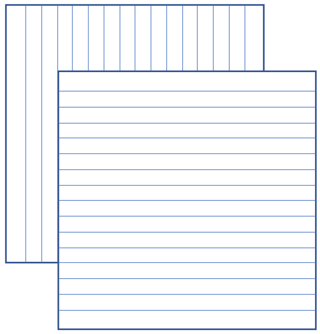
- Sensitive area. This distinguishes chambers which are located downstream of scanning magnets or lateral scattering systems, which need area sufficient for the maximum deflection or useful limits of the beam. Chambers used upstream of scanning or scattering, or which are used for specific research purposes, can have smaller area.



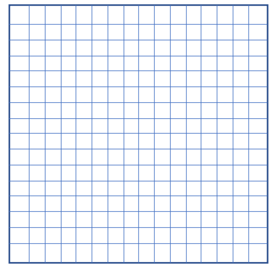
- ***Electrode patterning***. For a measurement of the current of whole beam, the readout electrode can be a continuous plane, called an integral plane or dose plane. If information about the position and shape of the beam is required, the electrode must be patterned. The most common patterns are an array of strips, pixels or a quadrant pattern, although any pattern is possible in principle. Patterned electrodes can also provide integral information by summing all the channels in software, but this generally results loss of signal to noise performance compared to a single electronics channel reading out an integral electrode.



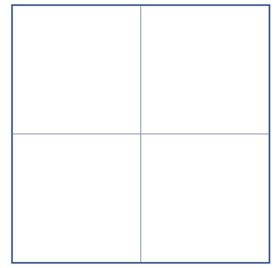
Integral (no pattern)



Strip pattern (orthogonal pair of electrodes)



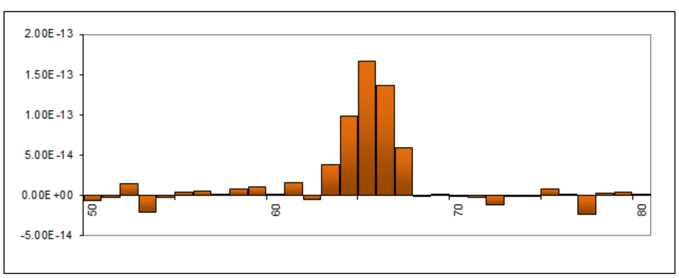
Pixel pattern

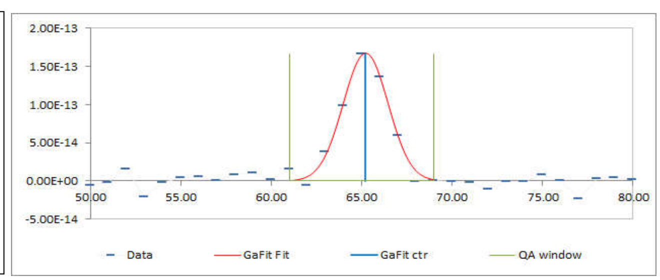


Quadrant pattern

A quadrant pattern is excellent for beam centering control in both axes but does not provide direct information about the amount the beam is offset or its shape. An array of strips provides a one-dimensional projection of the beam profile, so two arrays are needed to measure both axes transverse to the beam direction. Since the transport of the beam in a vacuum transfer line is usually independent in the two transverse axes, a one-dimensional projection is sufficient. A pixel array provides true two-dimensional visualization, allowing anomalous beam shapes such as rotated beams to be seen. It requires a much greater number of readout channels for given resolution, which impacts electronics cost.

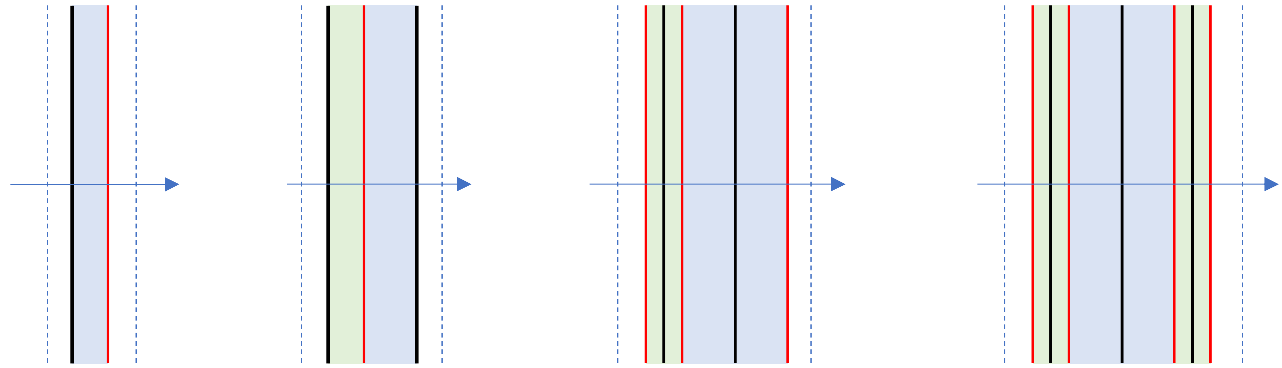
- Position resolution. The resolution of beam spot peak centroid and width is dependent on the strip or pixel pitch. The pitch should be sufficient that there is useful signal from the smallest beam spot in three or more strips. It is then possible to fit a curve to the data. The resolution of the fitted curve is typically one tenth of the strip pitch or better. The figures illustrate fitting a peak with a Gaussian sigma of one strip pitch.





- Number of active volumes. The minimum possible number of active volumes in a parallel plate ionization chamber assembly is one, defined by the gap between a readout electrode and a bias voltage electrode. The gap is uniform to produce a uniform electric field over the active area. It is highly desirable for reliability and stability to operate in a well-controlled gas volume and the whole should be in an electrically screened enclosure. Thin beam entry and exit windows allow the beam to pass through.

More than one active gap can be included in the enclosure which permits multiple functions in the minimum space. The following sketch illustrates some gap configurations from the Pyramid product range.



Single gap position (PX3)	Two gaps dose & position (IC64-13)	Four gaps One dual-gap dose & two position (IC128-25LC)	Six gaps Two dual-gap dose & two position (IC128-25LC-2I)

Although all the electrodes and gaps are in a single enclosure, they can be made completely electrically independent as necessary to provide redundant readings for safety-critical applications like medical therapy.

A dual gap integral configuration connects the signal from two gaps to a single readout to provide twice the signal without losing the benefit of small gaps.

- Gain. The gain of a transmission parallel plate chamber is proportional to the electrode gap size, other things being equal. Larger gaps are therefore appropriate for low current beams. However at higher beam currents, particularly the levels used in flash therapy or the peak currents which occur in pulsed beam accelerators, the signal becomes non-linear due to electric field suppression and charge carrier recombination losses in the gas. This can be mitigated very effectively by reducing the gaps and maintaining a high bias voltage. Pyramid chambers models that are optimized for higher beam currents use gaps as small as 1 mm.

- Water equivalent thickness. As far as practicable the ionization chambers in a dose delivery nozzle should have minimal effect on the beam, which otherwise loses energy and scatters laterally. In Pyramid chambers the materials in the beampath are very thin films of tensioned Kapton® with fine coatings of gold or aluminium. The total effect on the beam is represented as the water equivalent thickness (WET), which is the depth of water which has the same effect. All Pyramid chambers designed for dosimetry have very low WET values from 255 µm down to below 100 µm.

- ***Gas filling***. Air filling is typical for proton therapy applications. Atmospheric air is convenient and has stable composition. It is important to exclude water vapour which can affect the gain and degrade electrical connections over time. The temperature and pressure of the fill gas must be known to correct the signal for the density of the gas. Most Pyramid chambers include desiccant to dry the air and built-in sensors that measure the temperature, pressure and humidity inside the chamber housing.

Other fill gases such as nitrogen and Ar/CO_2 can be beneficial in specific applications such as high beam current measurement. All Pyramid dosimetry chambers have ports for gas flow and return to allow the use of any compatible chamber fill gas.

- External dimensions. Space is usually at a premium in a dose delivery nozzle, particularly in the z axis along the beampath. Pyramid chambers are designed to occupy the minimum practical space, and many models include multiple active gaps in the same housing to reduce the number chambers required.

Summary of dose delivery ionization chamber models

The Pyramid ionization chambers cover a sensing area range from 25 by 25 cm down to 1.9 cm diameter, and a range of electrode gaps from 10 mm down to 1 mm. Nearly all models have gold coated Kapton® readout electrodes, environmental sensors for the fill gas, desiccant to maintain low humidity and loopback of the bias voltage. New configurations are added regularly to meet customer needs.

IC128-25LC A widely-used chamber for dose and position measurement downstream of scan magnets in cyclotron and synchrotron systems. Dual gap integral dose section, orthogonal strip readout. Generally used in a pair to provide redundant dose and redundant position data.

IC128-25VH The same geometry as the IC128-25LC, but with alternative signal connectors and reduced foil thicknesses for lower WET.

IC128-25LC-2I A version of the IC128-25LC with a second completely independent integral dose section. This allows a single ionization chamber assembly to meet the dose redundancy requirements of IEC 6061-2-64.

IC64-16SG A medium-sized chamber with small gaps, suitable for the higher beam currents used in flash therapy.

IC64-13 A medium-sized chamber with integral dose section and one axis of position readout. Used in a pair to provide redundant dose information and orthogonal position readout.

IC64-13SG A version of the IC64-13 with a small gap integral dose section, suitable for the higher beam currents used in flash therapy.

IC64-6 A small chamber with very small gaps and fine pitch position readout specifically developed for flash therapy research.

IC32-6 A small chamber for position readout upstream of scan magnets and general research work.

IC16-5 A general-purpose low cost chamber for position readout using aluminized electrode coating.

PX3-3.8 A small pixelated chamber for 2D position readout upstream of scan magnets.

PX3-2.5 A PX3 version with reduced pixel size for improved position resolution.

QIC-2S A miniature ionization chamber with aluminized quadrant readout electrode for use with narrow pencil beams in confined locations.

QIC-6E A small chamber with very low scattering developed for use in ophthalmic treatments. Useful for low energy proton beams below 70 MeV.

Comparative data for these models is provided in the following section.

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Key parameters of Pyramid ionization chamber models used in proton therapy dose delivery systems

The gain and WET values are from Monte-Carlo simulations for monoenergetic beams in an air filling at STP. These values allow the chambers to be compared but are not intended to replace calibrated results against traceable detectors in water phantoms with particular accelerator beams.

Features: Au – gold electrode coatings; BVL – bias voltage loopback; Env – built in sensors for temperature pressure, humidity; Des – built in desiccant

Signal connectors: 0B.304  BNC:  00.250  HD44:  VHDCI68: 

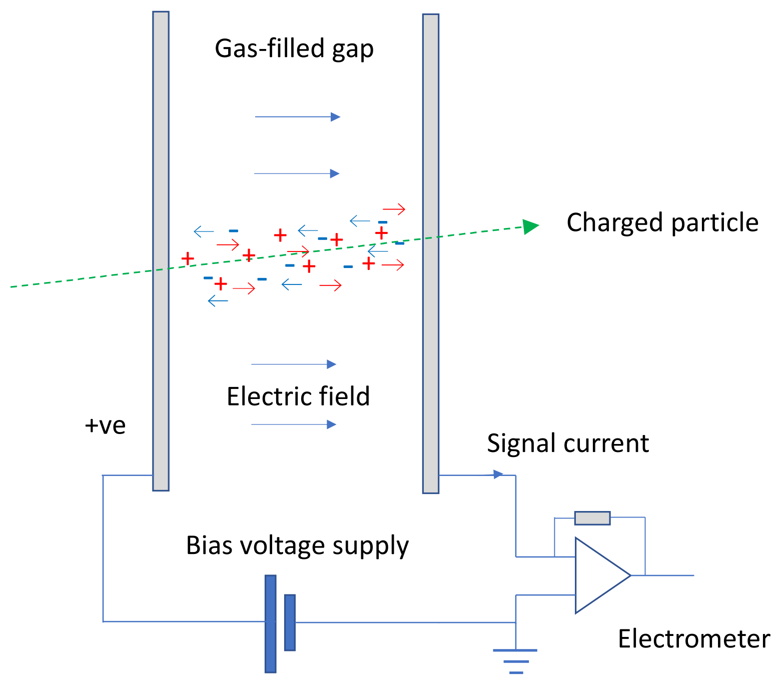
All high voltage connectors are SHV.

Model	***Area cm***	***Configuration Pattern pitch mm***	***Gaps mm***	***Gain 70/150/230 MeV p+ air filling***	***WET µm***	***Ins. Length mm***	***Features / signal connectors***
IC128-25LC	25 x 25	Dual gap integral 128 X strips 2.0 128 Y strips 2.0	5.0 / 5.0 7.0 7.0	294 / 162 / 122 210 / 115 / 88 “	195	50.7	Au, 2x BVL, 2x Env, Des 0B.304, 8x HD44
IC128-25VH	25 x 25	Dual gap integral 128 X strips 2.0 128 Y strips 2.0	5.0 / 5.0 7.0 7.0	294 / 162 / 121 210 / 115 / 88 “	170	50.7	Au, BVL, 2x Env, Des BNC, 4x VHDCI68
IC128-25LC-2I	25 x 25	Dual gap integral 128 X strips 2.0 128 Y strips 2.0 Dual gap integral	5.0 / 5.0 7.0 7.0 5.0 / 5.0	298 / 167 / 126 211 / 118 / 89 “ 298 / 167 / 126	255	55.7	Au, 2x BVL, 2x Env, Des 2x 0B.304, 8x HD44
IC64-16SG	16 x 16	Dual gap integral 64 X strips 2.5 64 Y strips 2.5	1.0 / 1.0 3.0 3.0	57 / 31 / 24 87 / 49 / 36 “	130	50.7	Au, BVL, 2x Env, Des BNC, 2x VHDCI68
IC64-13	12.8 x 12.8	Integral 64 W strips 2.0	3.8 3.8	111 / 61 / 47 113 / 62 / 47	140	28.4	Au, BVL, 2x Env, Des 0B.304, 2x HD44
IC64-13SG	12.8 x 12.8	Integral 64 W strips 2.0	1.0 6.6	29/ 16 / 12 197 / 108 / 80	140	28.4	Au, SG, BVL, 2x Env, Des 0B.304, 2x HD44

IC64-6	6.4 x 6.4	Integral 64 X strips 1.0 64 Y strips 1.0	1.0 3.0 3.0	29 / 16 / 12 90 / 51 / 37 “	200	37.0	Au, SG, BVL, Env, Des 0B.304, 2x VHDCI68
IC32-6	6.4 x 6.4	32 X strips 2.0 32 Y strips 2.0	3.0 3.0	88 / 49 / 36 “	150	37.0	Au, BVL, Env, Des 0B.304, 2x HD44
IC16-5	4.8 x 4.8	16 X strips 3.0 16 Y strips 3.0	3.0 3.0	88 / 49 / 37	150	37.0	Env, Des 2x D25
PX3-3.8	4.2 dia	120 pixels 3.8 sq	5.0	145 / 81 / 60	105	14.6	Au, BVL, Env, Des 2x VHDCI68
PX3-2.5	2.8 dia	120 pixels 2.5 sq	5.0	145 / 81 / 60	105	14.6	Au, BVL, Env, Des 2x VHDCI68
QIC-2S	1.9 dia	Quadrant	3.2	93 / 51 / 38	70	7.6	Des 0B.304
QIC-6E	6.0 dia	Quadrant	3.6	104 / 57 / 44	65	31.4	Au, BVL, Env, Des 4x Lemo00.250

Appendix: Parallel plate ionization chamber principle of operation

A pair of electrically conductive planar electrodes relatively transparent to the radiation beam are biased to create a uniform electric field in a gas filling between them. This voltage is called the bias or polarization voltage. A beam of ionizing radiation passing across the gap ionizes the gas to create pairs of positive ions and negative electrons. The electrons may be captured by gas molecules to form negative ions. The electric field causes the positive and negative ionization products to drift through the gas in opposite directions. This movement of charged particles is an electric current which can be measured by sensitive electronics connected to the electrodes. It is typical to apply the bias voltage to one electrode and measure the current on the other, although some miniature ionization chambers used for quality assurance bias and measure the current on the same electrode.



Because the average energy to form one ion/electron pair, W, is well-known for a particular gas and is independent of the flux of ionizing radiation over a significant dynamic range (W = 34 eV for air, for example), the measured current is a linear function of the beam flux. In the case of charged particle beams, we can define a gain for the ionization chamber which is the measured current from the ionization chamber divided by the beam current. On average this can be also stated as the number of ion-electron pairs that created per ionizing particle incident on the detector, which permits a gain to defined also for photons.

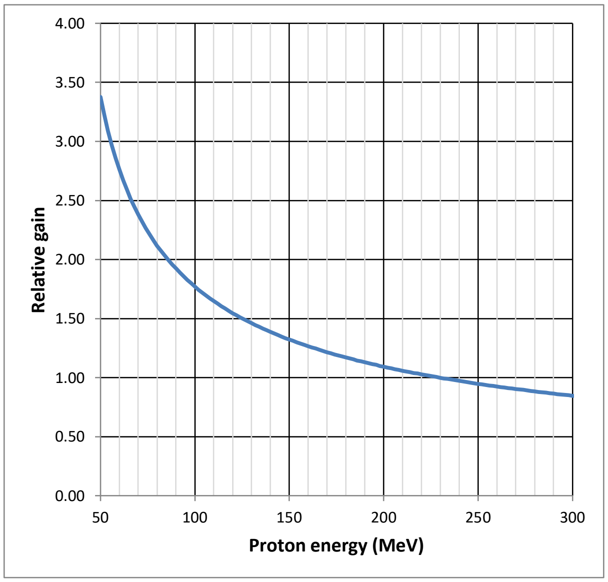
In practice the gain is affected by various factors that may affect precision and accuracy and the useful dynamic range.

- The amount of ionization is a function of the number density of the gas molecules, which is in turn a function of the temperature and pressure of the gas.

- The amount of ionization is a function of the length of the path in the sensitive volume, and thus the spacing of the electrodes and the crossing angle.

- The amount of ionization is a function of the gas species present. Different species have different W values.

- The amount of ionization is a function of the energy of the incident radiation. In the case of proton beams the gain of the chamber reduces as particle energy increases. The plot below shows typical gain variation with energy for protons, relative to 230 MeV.

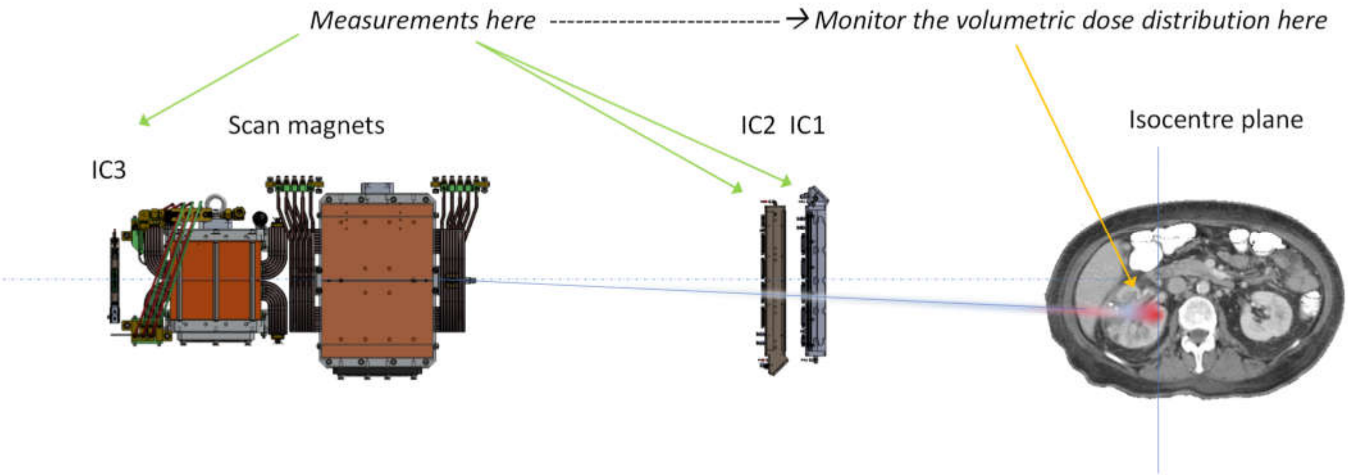


- Not all ionization created by the incident beam contributes to the measured signal. Some mutual neutralization of oppositely charged species occurs, called recombination. The proportion of the signal lost to recombination depends on the density of the ionization and thus the flux of the beam. It also depends on the speed that the positive and negative products of ionization are transported to the electrodes. The faster they move, the lower is the chance of recombination. High electric fields and lower gas density increase the drift velocities of charged species.

- Deficient design or construction can result in localized high electric fields, at sharp edges for example. This may lead to electron avalanching and thus spurious signal. This effect is used in a controlled way in proportional detectors but must be avoided in ionization chambers.

Appendix: Using ionization chambers for dosimetry

Proton therapy therapeutic beam delivery is defined on an isocentre plane that lies within the patient. The majority of treatments are delivered using the spot scanning method. Quality assurance runs can be performed with diagnostic detectors at this plane in a water or water-equivalent phantom, but of course this is not possible during patient treatment. Instead measurements of charge and position on ionization chambers in the nozzle plus knowledge of the beam energy are used as a proxy for measurements of dose distribution in the patient.



The relationship between the measured parameters and the dose distribution in the patient is computed by the treatment planning software, based on measurements of dose distributions in water phantoms. The relationship is confirmed as necessary by quality assurance runs on dose delivery maps with expected dose distributions in water.

The requirements for ionization chambers in the application are:

- Stable and linear performance over the expected range of beam currents
- Sensitive area that allows the chamber to be placed in the required location and still capture all of the beam in all relevant settings
- Low WET to ensure small beam spots can be delivered,
- Position resolution suitable for the smallest beam spots
- Gain that provides a suitable compromise between good signal to noise ratio over the expected dynamic range of current verses excess recombination losses
- Radiation hardness
- General reliability
- Compact packaging