BEAM SCANNING WITH AN OUT-OF-FIELD REFERENCE DETECTOR

Practical Advantages and Workflow Considerations

SUN NUCLEAR corporation

Background

The use of a reference detector in beam scanning is widely used and strongly recommended by AAPM TG106 in order to “remove the instantaneous fluctuations or drifts in the incident beam output.”

The traditional approach is to place the reference detector in the corner of the incident beam to maximize the signal but minimize the interference with the field detector. It is well understood that the reference detector should not shadow the field detector or attenuate the beam. If either occur, errant data may be acquired. This is particularly challenging for small field dosimetry where there is little room in the field to fit both the field and reference detector in the beam.

Several techniques exist to address this challenge:

1. Remove the reference detector from the scan entirely and use time-integration or the average of multiple scans to reduce the instantaneous fluctuations. This method is well accepted, but can dramatically increase the time needed to acquire scans.
2. Place the reference detector inside the linac head where it can be in the primary beam but above the collimators. This eliminates the shadowing effect while maintaining a strong signal. However, this requires removing the linac covers (often with the help of the service engineer) and very careful placement of the detector so as not to damage the detector with jaw movements.
3. Utilize transmission type detectors as a reference. This can produce a strong signal for normalization, but can have limitations with field size. Transmission detectors also cause shadowing and attenuation over the field. This attenuation has the potential to change the beam characteristics and must be scrutinized by the physicist for acceptability.
4. Place the detector outside, but near, the treatment field. This completely eliminates the possibility of altering or attenuating the primary beam, but, historically the challenge with this approach has been achieving an appropriate signal-to-noise ratio.

To overcome many of these traditional challenges, Sun Nuclear has successfully developed an out-of-field reference detector, offering ease of use, consistent signal-to-noise ratio, no beam attenuation, and no detector shadowing interference for the very small fields required for SRS type data acquisition.

Selected Approach

Out-of-Field Detector

The Sun Nuclear out-of-field reference detector approach utilizes linac head leakage for its signal, and corresponding scan measurement normalization.

Linac head leakage refers to the scattered photon radiation that transmits through the shielding of the linac head. Due to exponential attenuation, there will always be photons that escape the shielded head. Safety standards limit leakage to less than 0.1% of the primary beam at 100 cm from the target.

- Given the leakage radiation intensity is significantly less than the primary field, it is reasonable to measure this leakage radiation with an ionization chamber proportionately more sensitive than the small volume reference detector in the primary beam, thereby achieving a similar signal-to-noise ratio from the head leakage.
- It is then reasonable to expect that a temporal change in linac primary output will also result in a proportional change in leakage radiation, providing a measurable means of monitoring the linac output performance.

This process is described in full detail in Sun Nuclear Corporation's patent submission (US 9561388 B2, Feb 2017).

Physics of Backscatter Leakage Radiation and Detection

High energy electrons strike the target, producing high energy x rays in the forward direction and lower energy x rays in the plane of the reverse "backscatter" direction (~600 keV or less). The backscattered x rays are emitted from the top of the linac head, with an intensity distribution dependent on the 'line of sight' distance between the source of backscatter and the location on the head.

Sources of scatter and head leakage include:

- Target
- Primary collimator
- Flattening filter (FF)
- Beam shaping collimator
- Room environment
  - Scatter from the room environment (walls, couch, phantom, etc.) interacting with the primary beam

The ideal location for leakage measurement is on the head surface opposite the collimator opening and located toward the gantry away from the beam axis. This location minimizes any field size dependence by reducing the contribution from room scatter.

Sun Nuclear Reference Detector Physical Characteristics

There are several factors that influence the design characteristics.

- Geometry
  - Parallel plate and electrode gap
    The Sun Nuclear 3D SCANNER electrometer (3DE) synchronizes charge measurement updates to linac pulse radiation. Pulse detection relies on ion transit time to be less than the minimum time between linac pulses. Therefore, to achieve optimum ion mobility, the electrodes should be parallel with a gap dimension that allows all positive ion collection.

    The volume of the Sun Nuclear Reference Detector is 39cc and has a geometry optimized to reduce capacitance and increase size to a volume that would produce a signal-to-noise ratio nominally equivalent to an SNC125c ion chamber when used as a reference detector in the field.
- Material and Construction
  - Buildup: The spectrum of the backscatter radiation leaking from the linac head is nominally less than 600 keV; therefore, buildup for charge equilibrium is not a factor.
  - RF: Operating in the linac environment with high impedance electrometers requires shielding against microwave radiation (RF). The Reference Detector has a stainless steel housing to provide this shielding — effectively creating a Faraday cage.
  - Venting: The Sun Nuclear Reference Detector is a vented ionization chamber in order to assure the chamber response is in equilibrium during significant weather events. If sealed, there may be a slow drift in air density in such events.

Discussion

The key operation of the Sun Nuclear Reference Detector is to provide a response proportional only to the accelerator output. The aspects of the detector and its environment above the accelerator head that can affect signal are as follows:

Output Proportionality

As discussed in the previous section, all sources of transmitted scatter can be traced back to interactions originating at the target and flattening filter (when applicable), which are the same interactions that produce the primary beam. While each accelerator model can have unique leakage characteristics (location, strength, etc.), the proportionality will remain consistent.

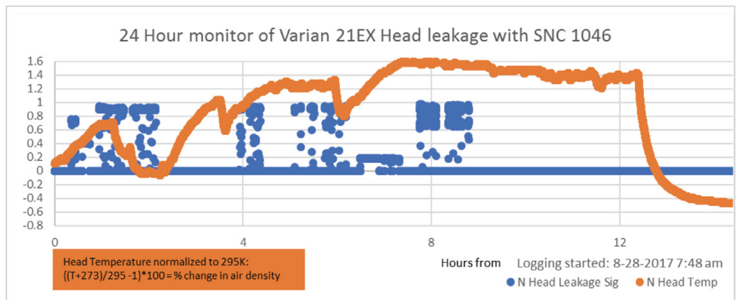


Figure 1: Air-density (head temperature) and beam on (head leakage) – both normalized for significance

Thermal Effects

With a scan event, defined as a continuous data acquisition of field and reference that creates a single profile or depth dose measurement, a significant temperature change during a single scan event would affect the measurement when using a reference detector for normalization.

If the head were to heat appreciably during a scan event, the detector sensitivity would change with temperature. Knowing this and given that there is a significant heat load with the linac, an investigation of head heating was conducted.

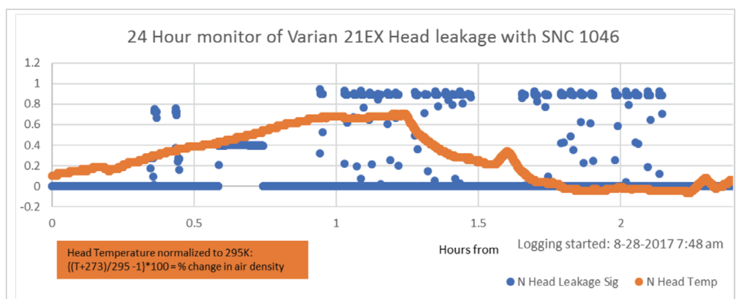


Figure 2: Zoomed on 1st four hours of Figure 1. Head leakage stretch of 0.4 hr starting ~0.6 hr is 18MV, 5000MU

Figures 1-3 illustrate no significant correlation between beam on and chamber gas temperature. There are temperature changes during linac warmup and during the course of the day due to Heating Ventilation and Air Conditioning (HVAC) cycling. However, temperature change is independent of beam on and therefore does not uniquely impact the out-of-field approach. The temperature changes due to HVAC cycling and machine warmup occur over a period of time, which does not significantly impact any single scan event and is equivalent to the effects experienced with an in-field reference detector.

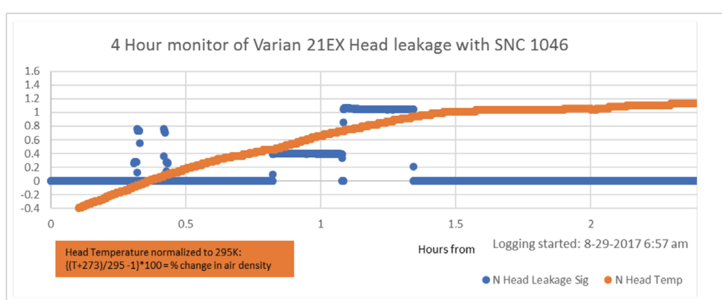


Figure 3: Zoomed on another day which shows 18 MV (10,000 MU) followed by 6 MV (10,000 MU) but no slope change in head temperature

Signal to Noise

The signal-to-noise ratio of head leakage measurements will be lower than an in-field detector. With a volume of 39cc, the Sun Nuclear Reference Detector will measure approximately 360 times more primary events in a given area than a conventional scanning detector. This allows the detector to be placed in a location of maximal head leakage and still measure signal comparable to a field detector.

There are two primary sources of increased noise from the conditions of use of the Sun Nuclear Reference Detector measuring head leakage.

1. Noise from primary events – stochastic

   Signal from radiation detectors is produced by secondary ionization produced by high energy electrons emitted from the chamber wall, which are the primary events from the X-ray interaction with the detector. The statistics of the signal measurement is determined by the number of primary events. A larger wall area will produce less noise.

2. Noise from capacitive coupling HV ripple – systematic (Deterministic)

   Any small change in voltage bias (ripple) will appear as a charge change at the electrometer input, mimicking ionization charge. As a real example, given a chamber with a capacitance of 6 pF, a 300 V bias with 1 mV ripple will induce 6 fC of charge, easily detectable by the 3DE. A larger wall area will produce more capacitance and hence increase noise.

Examples of both are illustrated in Figure 5, stochastic noise being the “static” or “small spikes” on the flat portion of the profile, and systematic (Deterministic) noise being the “large spikes” at measurement points +2 cm and -10 cm which is in the penumbra. Both are larger than that of a conventional in-field reference detector, but are managed through an advanced processing function (i.e., Dynamic Fitting Function) as described in the next section.

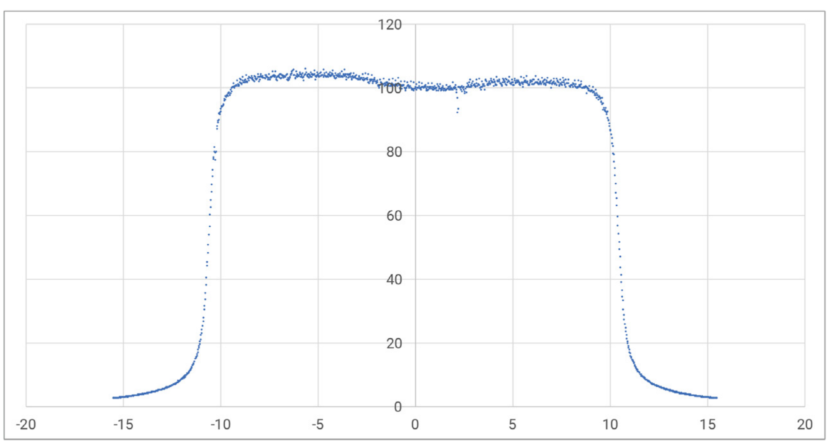


Figure 5: Raw profile with Sun Nuclear solution as normalizing reference detector, illustrates stochastic and deterministic noise events

Dynamic Fitting Function – Noise Management

Sun Nuclear has implemented a Dynamic Fitting Function (DFF) in SNC Dosimetry software to manage and de-noise scans such that the out-of-field Sun Nuclear Reference Detector offers similar signal-to-noise performance as an in-field reference detector. The DFF is a de-noising algorithm consisting of three phases:

Phase 1 manages major noise spikes that meet a criteria based upon standard deviation of normalized local slope at a point. There is no restriction with respect to region such as in a penumbra (high dose gradient).

Phase 2 manages minor spikes that meet criteria based upon the point's difference with respect to a local average. Application is restricted to low slope regions.

Phase 3 manages fitting the point to a quadratic function whose range of surrounding points is determined by three criteria at the measurement point:

a) The ratio difference error between neighbor DFF ranges

b) The ratio difference error between a given DFF range and the nominal residual raw value following Phase 2 for 3 measurement points

1) At the point of focus

2) At two points on either side of the focus point (skipping neighbor points) which effectively avoids the start of penumbra

3) The data density limit which excludes large DFF range applications

Figures 6 and 7 illustrate overlay views of raw data and DFF processed data. Figure 6 illustrates the penumbra preservation. Figure 7 illustrates the top portion of the profile with 0.5% scale divisions and a residual noise post DFF of < 0.2%.

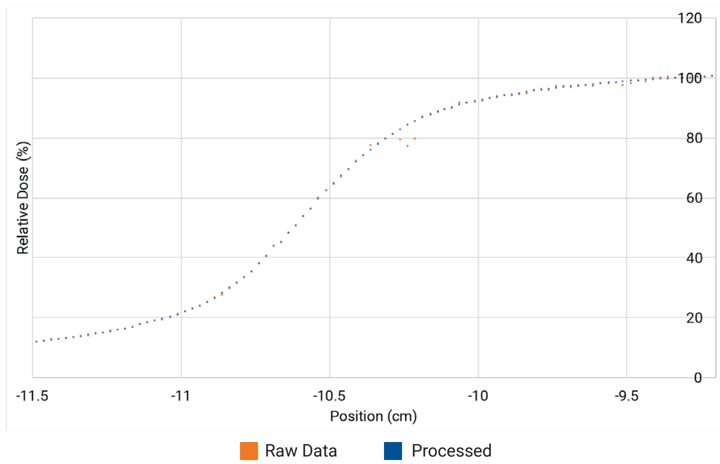


Figure 6: Noise removal in penumbra. Orange points are raw data, before Phase 1, Blue points are post DFF, penumbra preserved

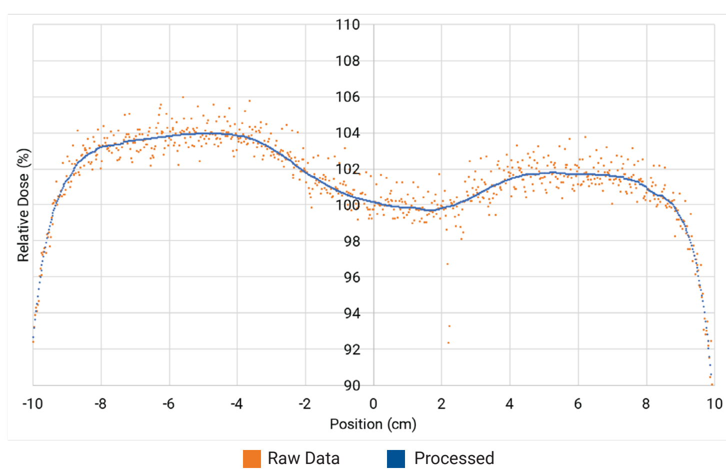
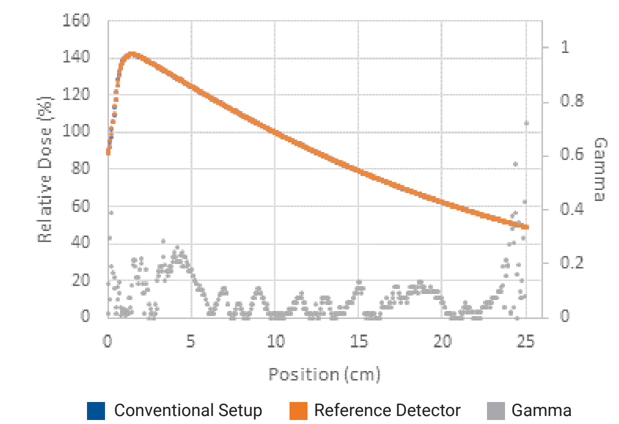


Figure 7: A 6x magnification of the in-beam features of Figure 5 to highlight both the stochastic and systematic noise reduction associated with the DFF.

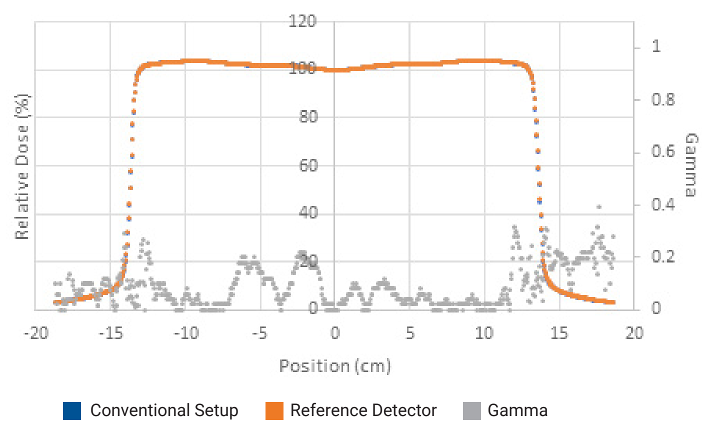
Results and Validation

This section presents figures showing a direct comparison between scans measured with the out-of-field Sun Nuclear Reference Detector and with a conventional in-field setup on various accelerator types. Profiles and depth scans were measured with a Sun Nuclear 3D SCANNER and processed in SNC Dosimetry software with the DFF and normalized to either beam center or D10, as appropriate. Difference plots are presented in terms of percentage of the normalization point of the conventional scan. A 1D gamma value as determined with a 0.5%/0.5 mm criteria is also reported for each scan comparison. The data indicates comparable results between the Sun Nuclear Reference Detector and conventional in-field measurements to within 0.5%.

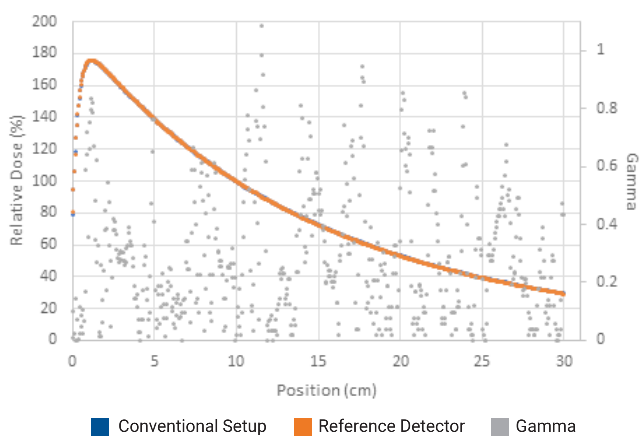
6MV 30x30 PDD (SNC125c)



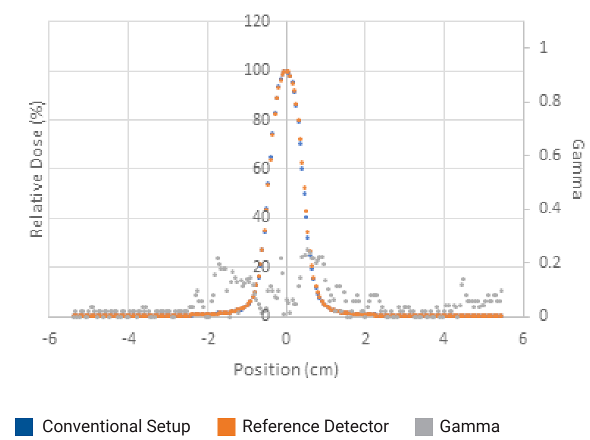
6MV 30x30 Inline Dmax (SNC125c)



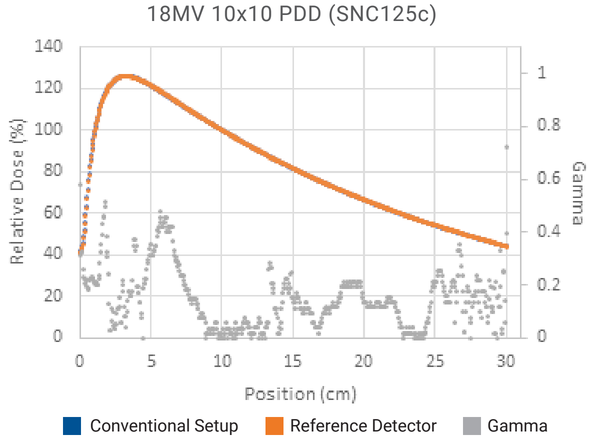
6MV 1x1 PDD (EDGE Detector)



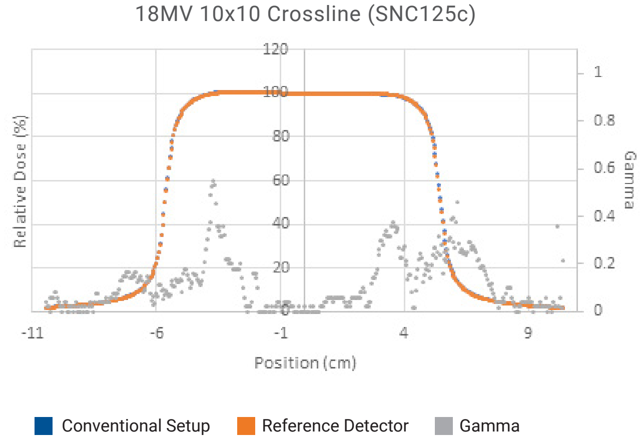
6MV 1x1 Dmax Crossline (EDGE Detector)



18MV 10x10 PDD (SNC125c)



18MV 10x10 Crossline (SNC125c)



Recommendations and Workflow

With proper setup and use with the SNC Dosimetry software using the DFF algorithm, the Sun Nuclear Reference Detector may be used for all photon beam scanning applications. Setup and workflow involves:

1. Mounting the Reference Detector
   a. Using the provided removeable mounting materials, mount Reference Detector on top of the linac head, placed between CAX and 50 cm toward the gantry. This has been validated on several linac models, including Varian Clinac, TrueBEAM and Elekta Versa and Synergy.
2. Voltage settings
   a. Set voltage to +/- 400V polarity as needed for Field detector. Lower voltages should be avoided as they will result in increased noise due to ion transit time encroaching on pulse separation.
3. Scan parameters

   Increased data density, i.e., increased measurement points per unit scan length, improves the DFF algorithm outcomes. Data density is controlled by the 3D SCANNER update rate and scan speed.

   a. Set the 3D SCANNER mode to continuous scan mode.
      i. For fields smaller than 4x4 and/or measured with small volume field chambers or solid-state detectors, continuous scanning at 0.1cm/sec is recommended.
      ii. For fields larger than 4x4 and/or measured with conventional volume scanning chambers (such as the SNC125c), continuous scanning at 0.5cm/sec is recommended.
   b. We recommend using the Sun Nuclear Reference Detector while scanning in either the "SG Fitting" or "No Averaging" mode to maximize the data density used for the FDD de-noising algorithm. This mode is selected in SNC Dosimetry under the Detector Properties of the Reference Detector.

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