# Accelerator Predictive Maintenance (PdM) Using Statistical Process Control Techniques

Research Update

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**Our team believes the analysis of digital data available within the accelerator system is sufficient to:**

- **reduce downtime**
- **reduce maintenance cost (labor, inventory, etc.)**
- **increase constancy of operation thereby increasing quality of treatment delivery**

# HOW?

## Predictive Maintenance (PdM)

"Those activities involving continuous or periodic monitoring and diagnosis in order to forecast component degradation so that as-needed, planned maintenance can be performed prior to equipment failure."

# HOW?

## Statistical Process Control (SPC)

- W. A. Shewhart, Bell Labs, 1924
  - Application of probability and statistics to quality control of mass production
  - Introduced the control chart (or process behavior chart)
- Uses operational or performance data from a process or device
- Information in the variation of the data is important to understanding how the process is performing

# Statistical Process Control (SPC)

**There are three basic evaluation and charting techniques for continuous data:**

- **Xbar/R Charts - provides an evaluation of subgroups (n>1) using the mean (Xbar) and range (R) control charts.**

- **Xbar/S Charts - provides an evaluation of subgroups (n>1) using the mean (Xbar) and standard deviation (S) control charts.**

- **X/MR Charts - provides an evaluation of subgroups (n=1) using the individual value (X) and moving range (MR) control charts.**

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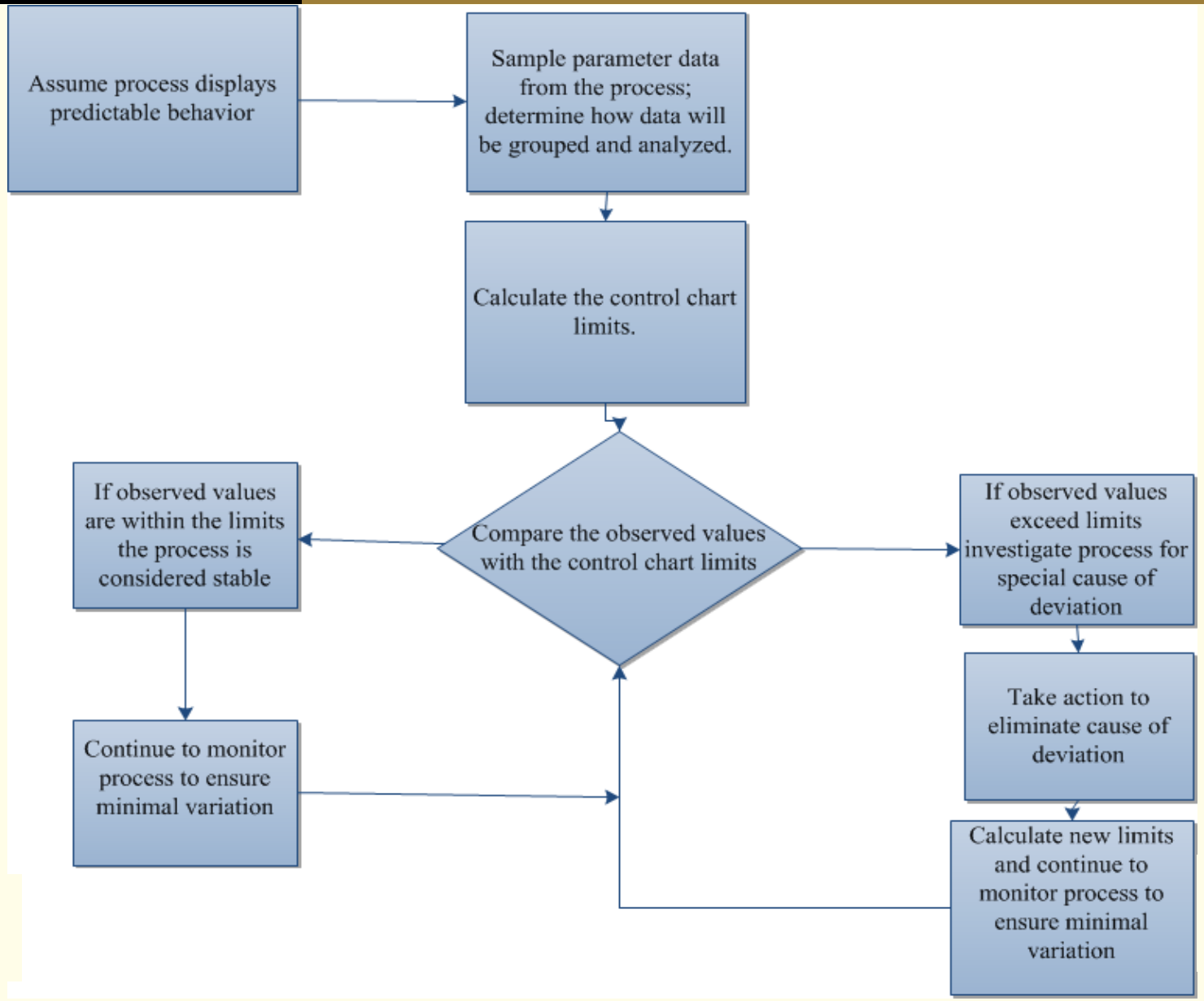
# Statistical Process Control (SPC)



# Statistical Process Control (SPC)

**SPC methodology is used to detect exceptional variation in a process or device using performance data or operational parameters.**

**SPC is widely used the following industries:**

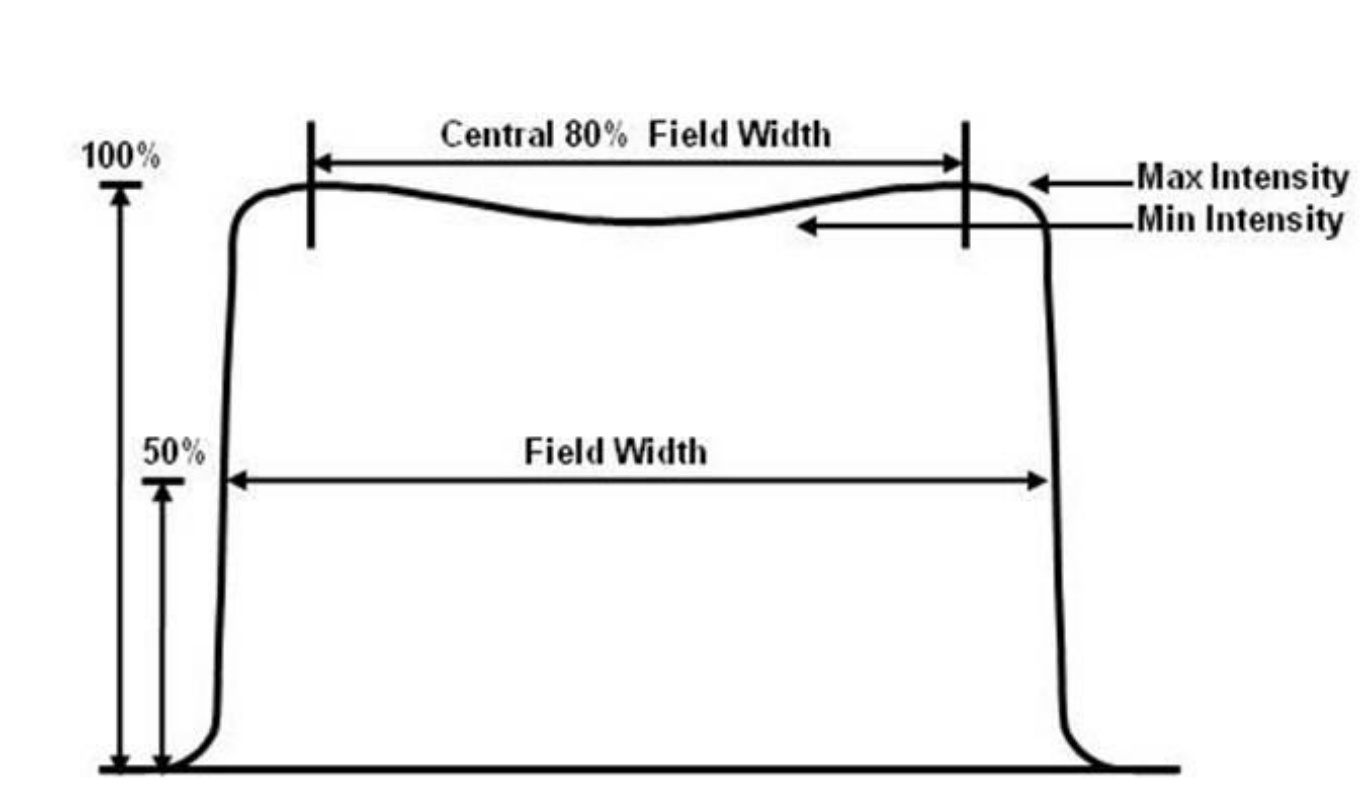
- **Manufacturing of integrated circuits**
- **Automobile manufacturing**
- **Oil refineries and chemical production**

# Project Focus

**To detect deviation from normal operating parameters in two accelerator characteristics critical to the delivery of high quality treatment:**

- **Beam Uniformity (flatness and symmetry)**
  - **Steering Coil Currents (SCC)**
- **MLC leaf speed and positional fidelity**

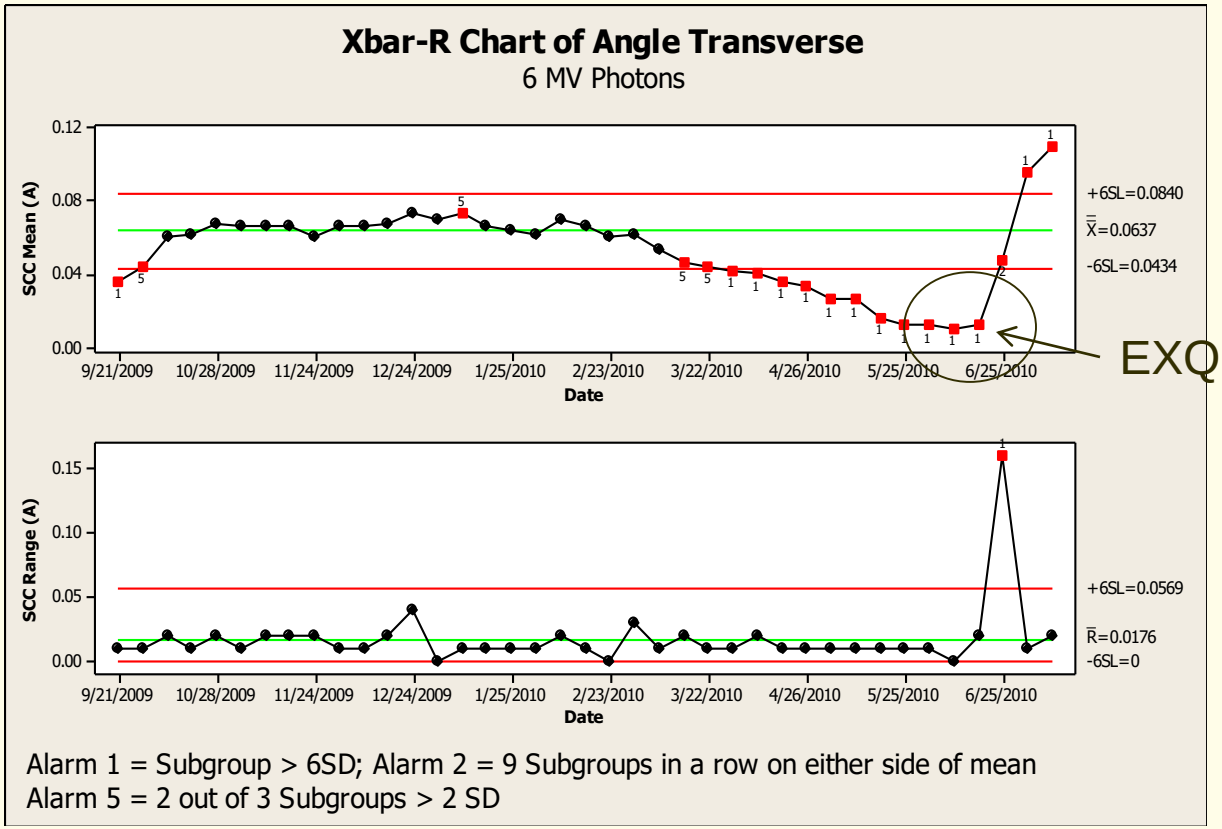
# PdM: Beam Uniformity




2 types of steering coils in each plane: angle and position

Transverse angle & position steering coil
Radial angle and position steering coil

# PdM: Beam Uniformity



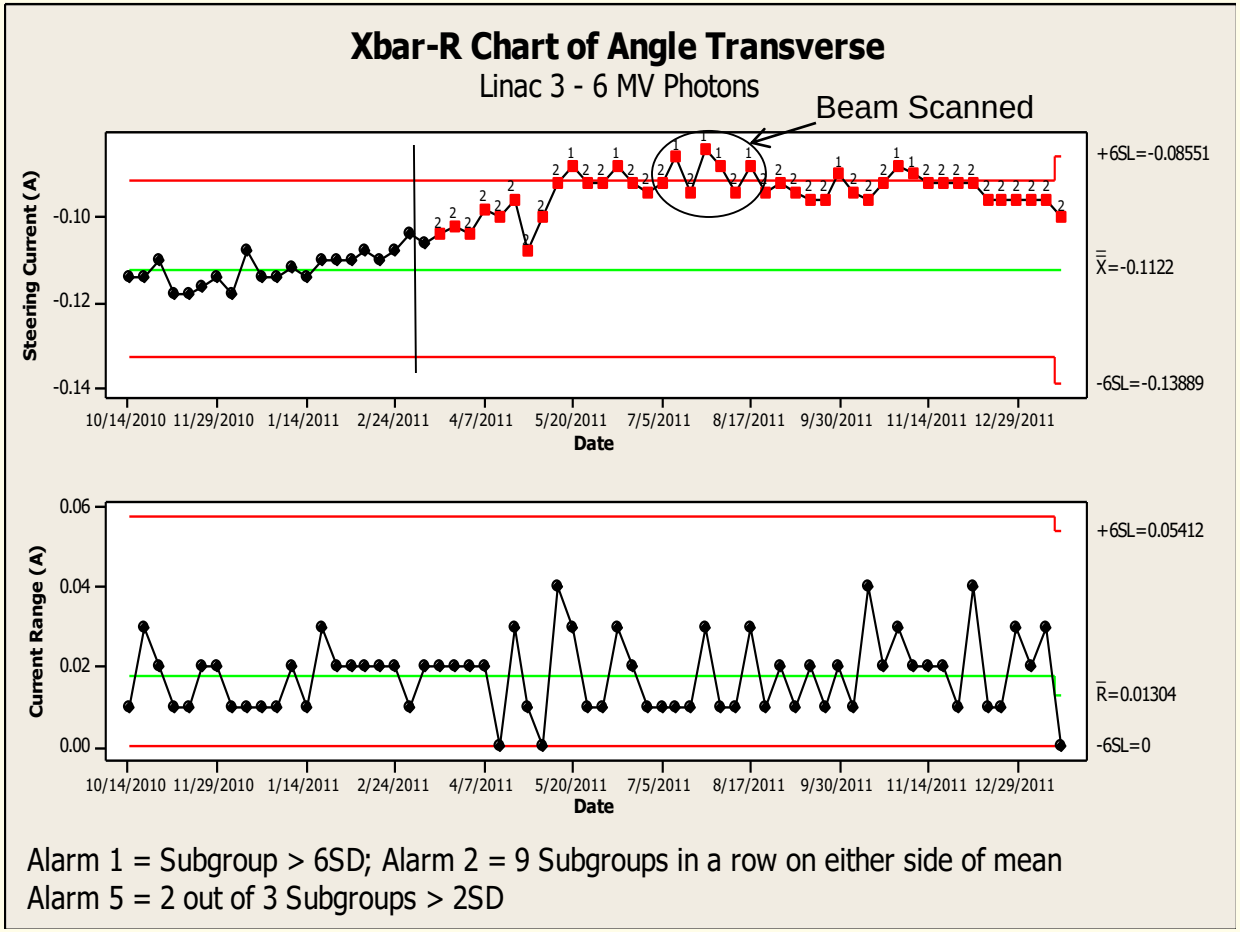

EXQ2 Fault

SPC evaluation of steering coil currents (SCC) suggest changes in beam uniformity may have been detected prior to system interlock being actuated.

## Predictive Maintenance (PdM) Theory

- **Tracking the SCC using Statistical Process Control charts will identify a change in beam uniformity and allow service to intervene prior to the actuation of an system interlock.**
- **Beam uniformity can be maintained at a level required by TG-142 (i.e. less than or equal to 1% constancy)**

# PdM: Beam Uniformity




- First 20 data points used to calculate control limits
- Beam scanned after SCC exceeded upper control limit
- No measureable change in beam uniformity
- Overall, mixed results when a single SCC exceeds control limits

## Alarm validation via beam scanning

- **Results varied substantially. Over 4 linacs and 6 energies we saw alarms that resulted in:**
  - **No change in beam uniformity measured**
  - **Beam uniformity changes measured at <0.5% and**
  - **Beam uniformity changes measured at > 1.0%.**

- **A controlled experiment is necessary to evaluate the magnitude of SCC change required to change beam uniformity >1%.**

# PdM: Beam Uniformity

## Controlled Experiment:

- **Change each steering coil current (SCC) to create non-uniformity of at least 1% from baseline.**
- **Each individual SCC was changed while holding the others constant**
- **Compare the change in SCC to the value of the magnitude of the 6SD control limit**

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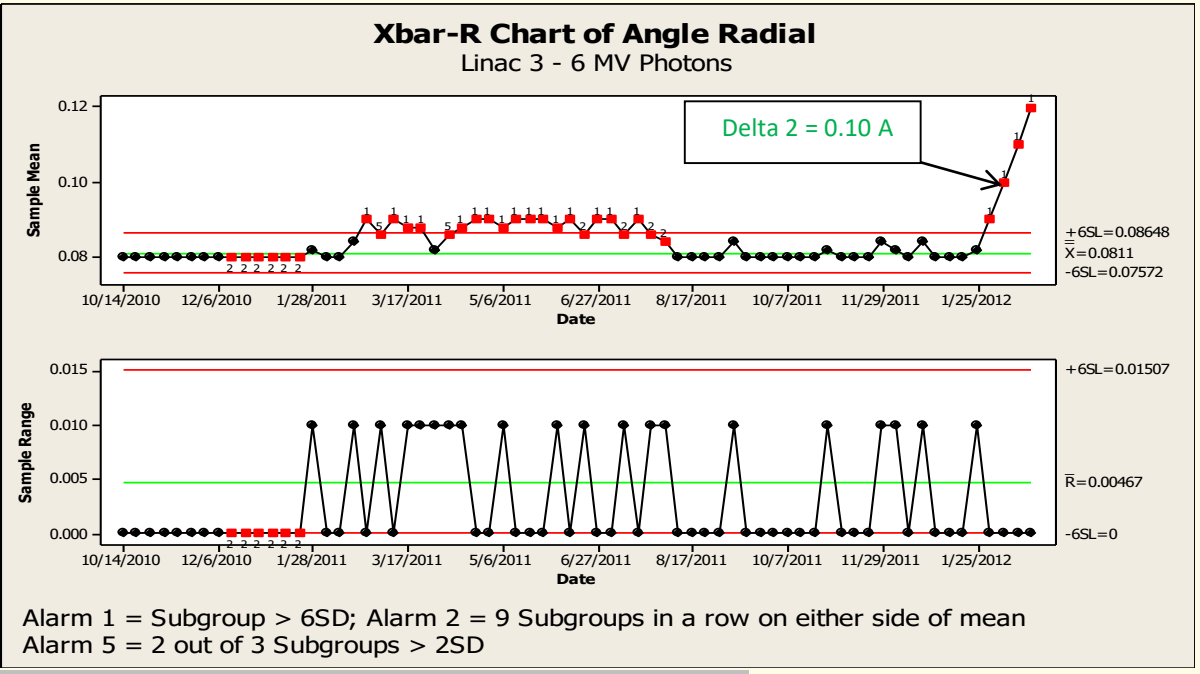
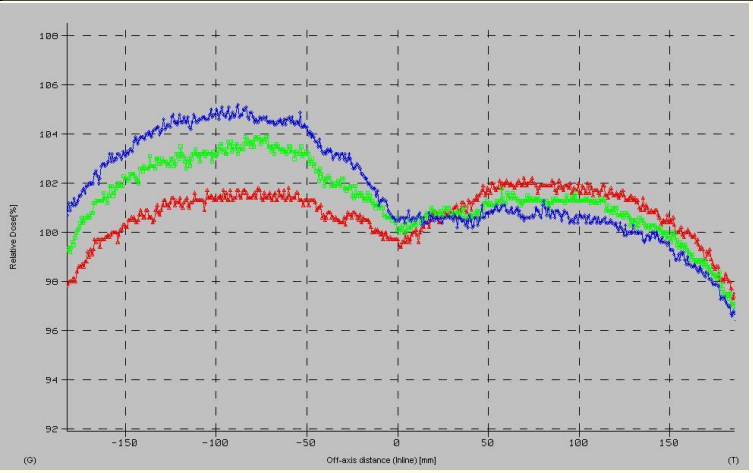
# Controlled Experiment: Single SCC change vs Beam Uniformity




- Change in Radial Angle SCC required for >1% change in Beam Uniformity is ~3 times the upper control limit




Angle Radial

| | Baseline | Delta 1 | Delta 2 | Delta 3 |
|---|---|---|---|---|
| Symmetry | 1.00% | 1.10% | 2.80% | 4.80% |
| Flatness | 1.90% | 2.00% | 2.90% | 3.70% |
| SCC | 0.08A | 0.09A | 0.10A | 0.12A |
| SCC Delta | 0.00A | 0.01A | 0.02A | 0.04A |
| Multiple of Control Limit | | 1.5 | 3.17 | 6.5 |

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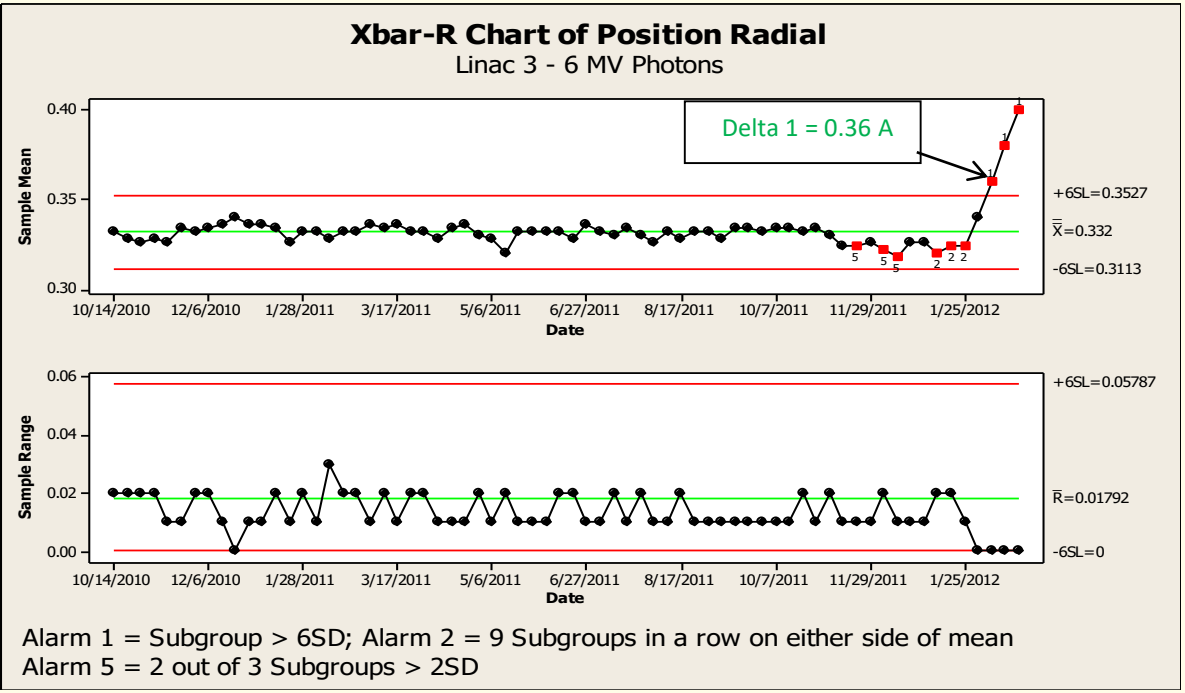
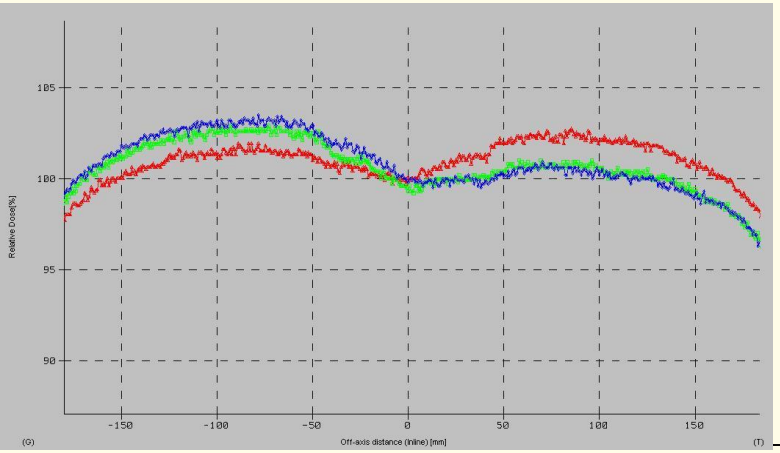
# Controlled Experiment: Single SCC change vs Beam Uniformity




- Change in Radial Position SCC required for >1% change in Beam Uniformity is ~2 times the upper control limit




Position Radial

| | Baseline | Delta 1 | Delta 2 | Delta 3 |
|---|---|---|---|---|
| Symmetry | 1.30% | 2.60% | 2.80% | 3.10% |
| Flatness | 2.20% | 2.80% | 2.90% | 3.10% |
| SCC | 0.32A | 0.36A | 0.38A | 0.40A |
| SCC Delta | 0.00A | 0.04A | 0.06A | 0.08A |
| Multiple of Control Limit | | 1.90 | 2.86 | 3.81 |

# Controlled Experiment: Single SCC change vs Beam Uniformity

## Results From Controlled Experiment

- Individual steering coil alarms (6SD) will result in unwarranted service intervention
- A combination of alarms may be a more appropriate trigger for intervention relative to the TG-142 constancy criteria
- Tracking daily SCC simultaneously with daily beam uniformity may help us better understand the effect of SCC changes.

## Track Beam Uniformity Simultaneous to SCC

- **Use daily symmetry measurements as a surrogate for beam uniformity**
- **Determine if there is a definitive correlation between changes in daily symmetry and daily SCC**

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# Beam Uniformity Tracked Simultaneous to SCC

## Pearson Correlation Coefficient

| | 6MV Photons | | | |
|---|---|---|---|---|
| | Daily Transverse Symmetry | | Daily Radial Symmetry | |
| Steering Coil Current | Coeffcient (r) | p-value | Coefficient (r) | p-value |
| Transverse Position | -0.540 | 0.000 | 0.376 | 0.000 |
| Transverse Angle | 0.735 | 0.000 | -0.707 | 0.000 |
| Radial Position | -0.208 | 0.000 | 0.283 | 0.000 |
| Radial Angle | 0.662 | 0.000 | -0.531 | 0.000 |

| | 15MV Photons | | | |
|---|---|---|---|---|
| | Daily Transverse Symmetry | | Daily Radial Symmetry | |
| Steering Coil Current | Coefficient (r) | p-value | Coeffcient (r) | p-value |
| Transverse Position | -0.051 | 0.356 | 0.240 | 0.000 |
| Transverse Angle | 0.842 | 0.000 | -0.806 | 0.000 |
| Radial Position | 0.155 | 0.005 | 0.148 | 0.007 |
| Radial Angle | 0.604 | 0.000 | -0.588 | 0.000 |

changes in angle SCC showed moderate or high correlation to changes in beam uniformity

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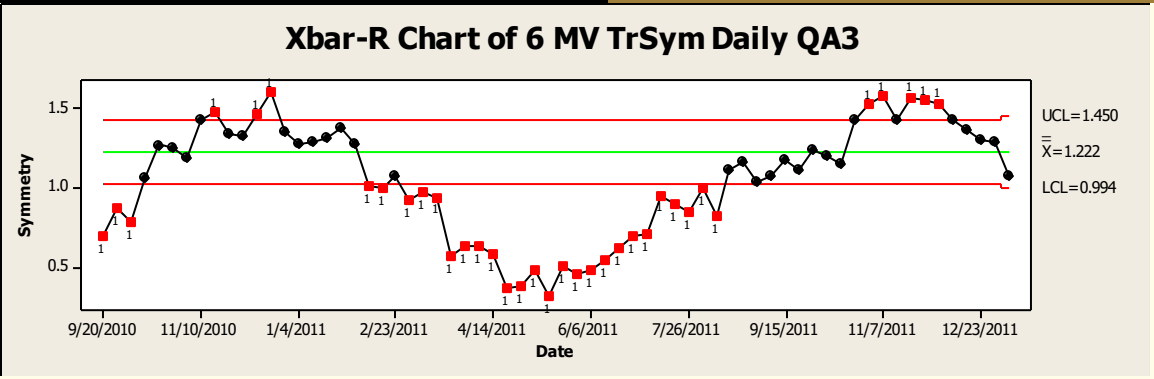
# Beam Uniformity Tracked Simultaneous to SCC



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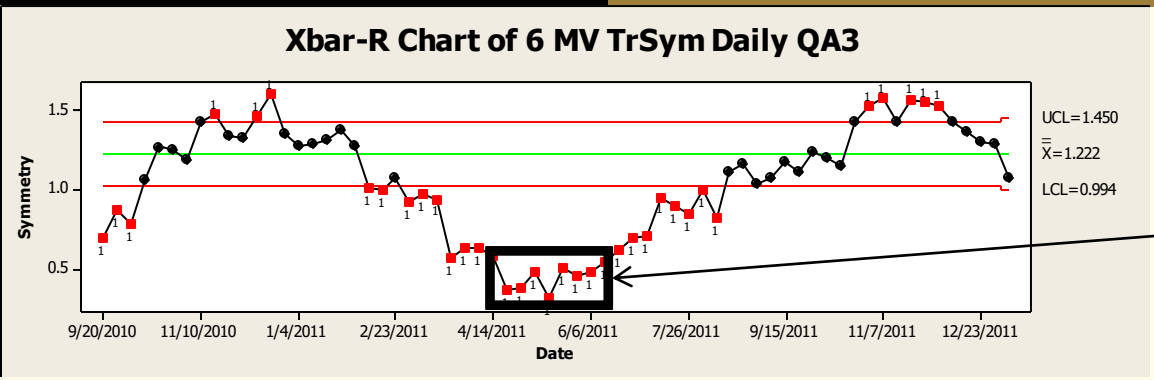


A change in transverse symmetry greater than1% occurred

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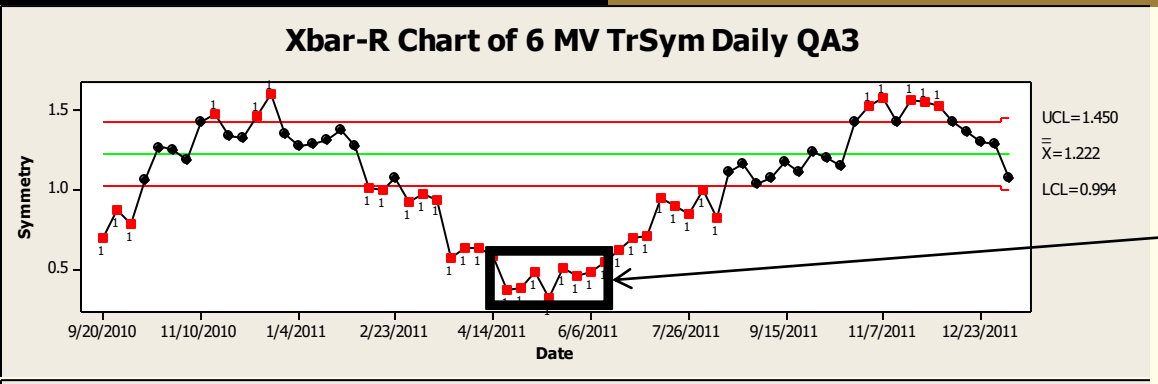


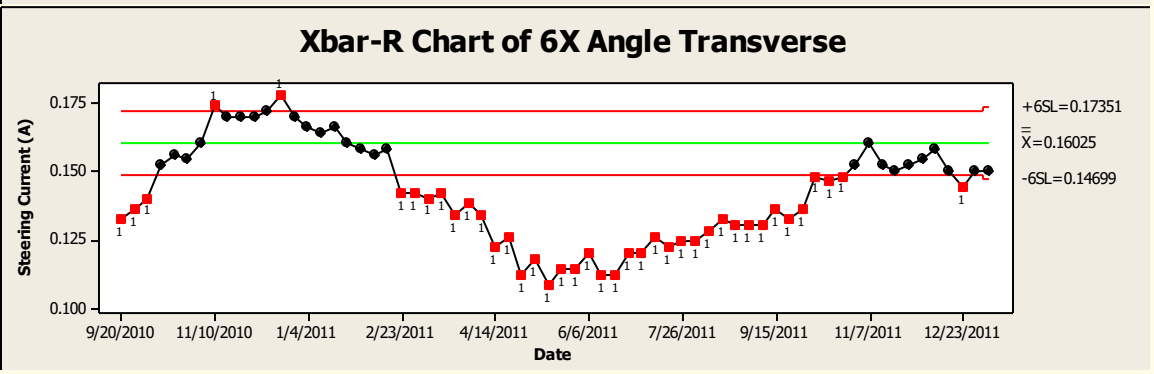


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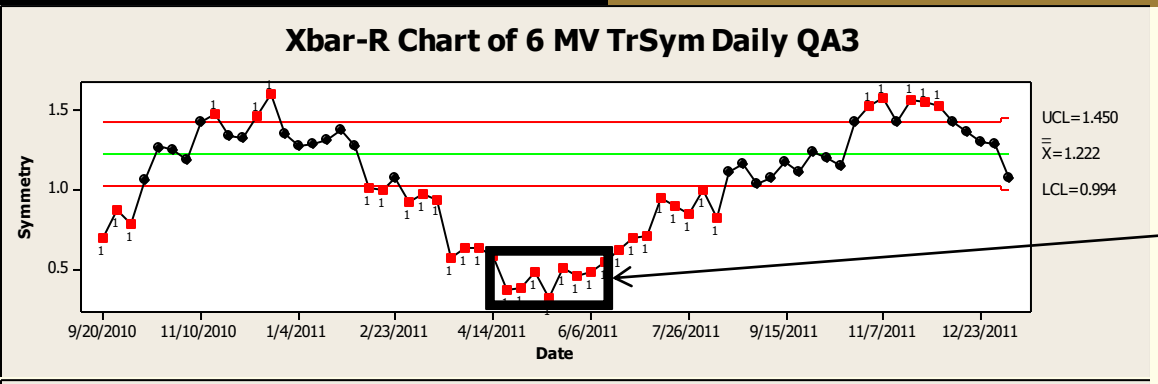


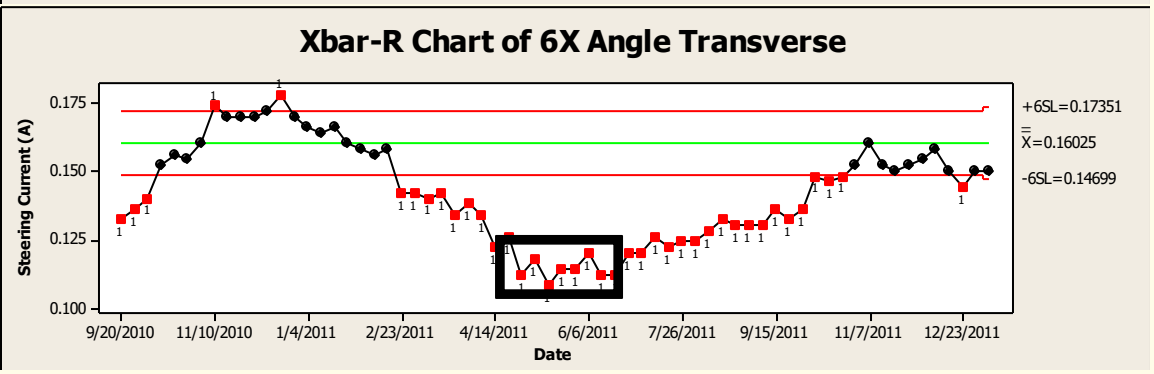


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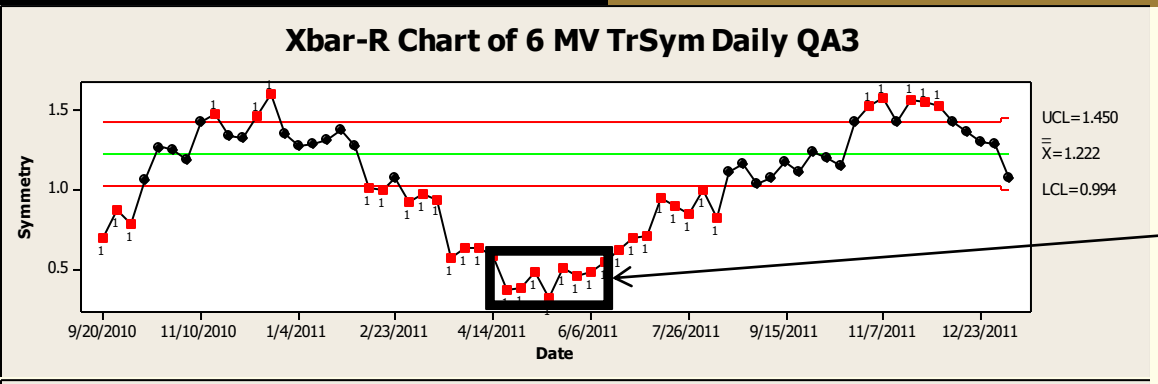


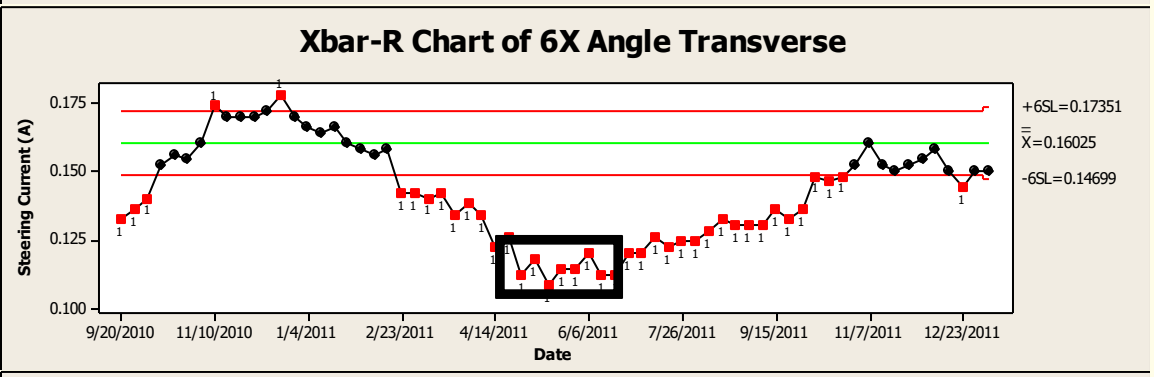


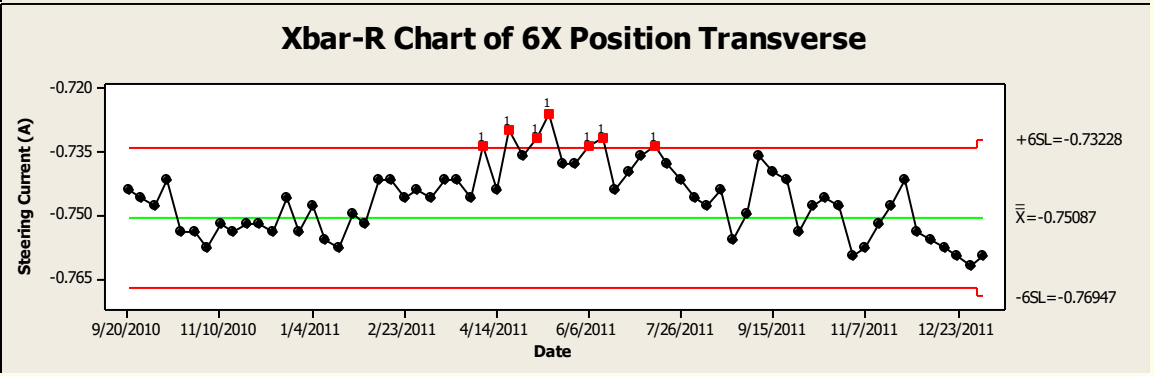


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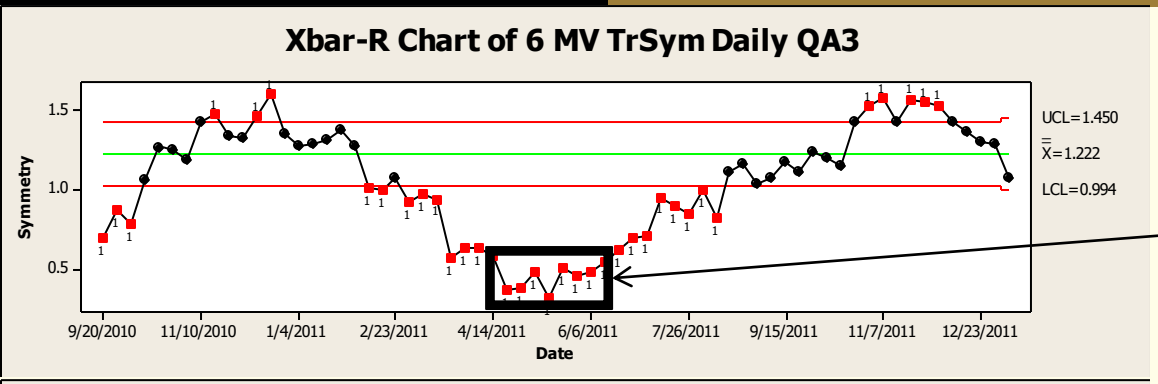


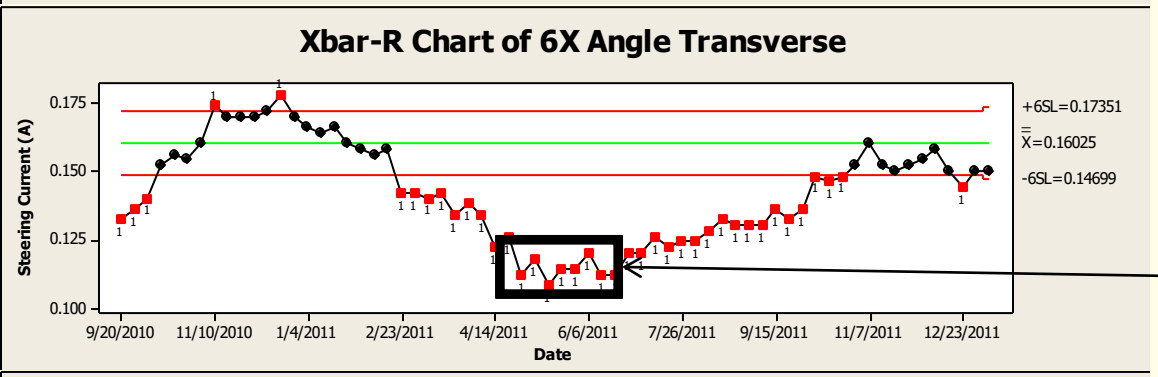


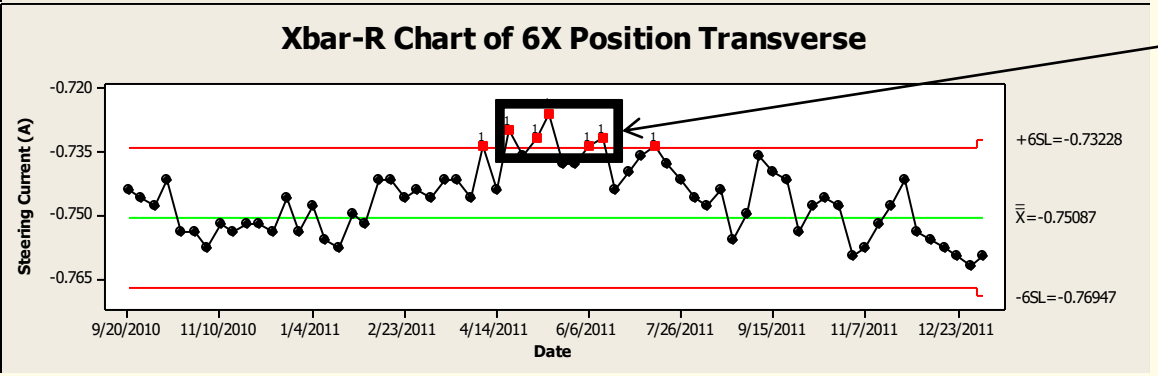


A change in transverse symmetry greater than1% occurred

Two SCC had exceeded the control limits.

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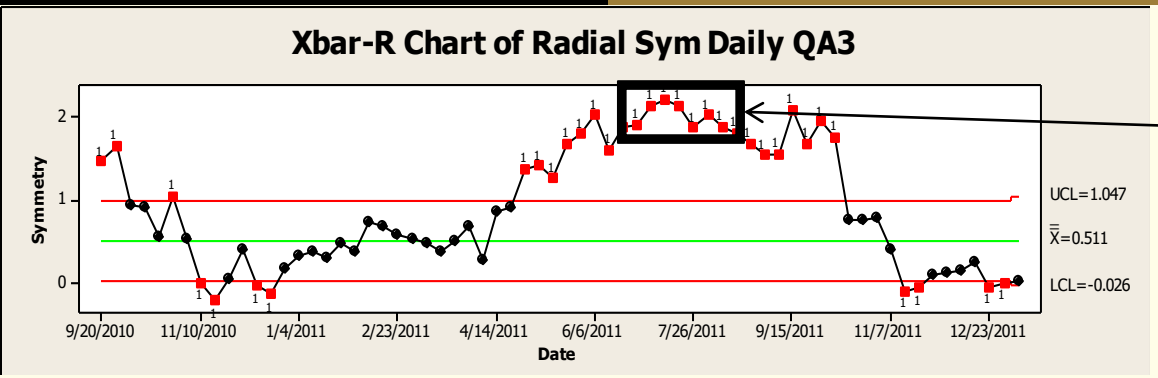
# Beam Uniformity Tracked Simultaneous to SCC




A change in radial symmetry greater than1% occurred

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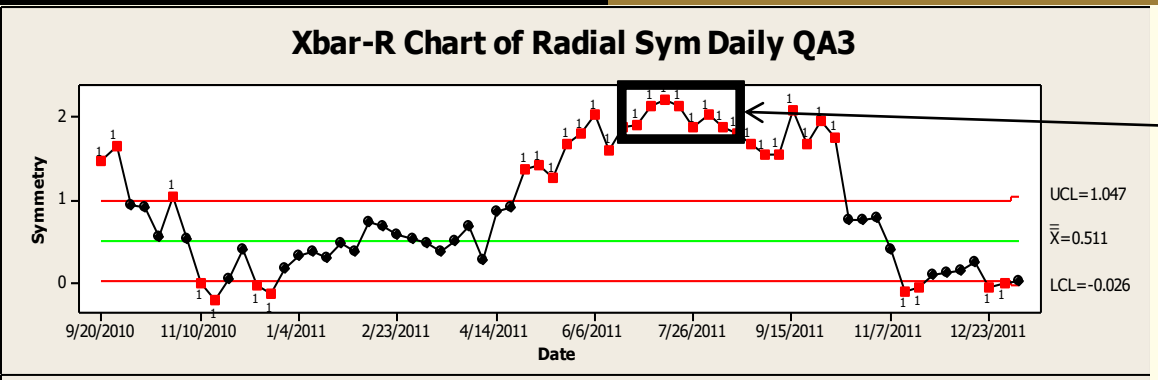
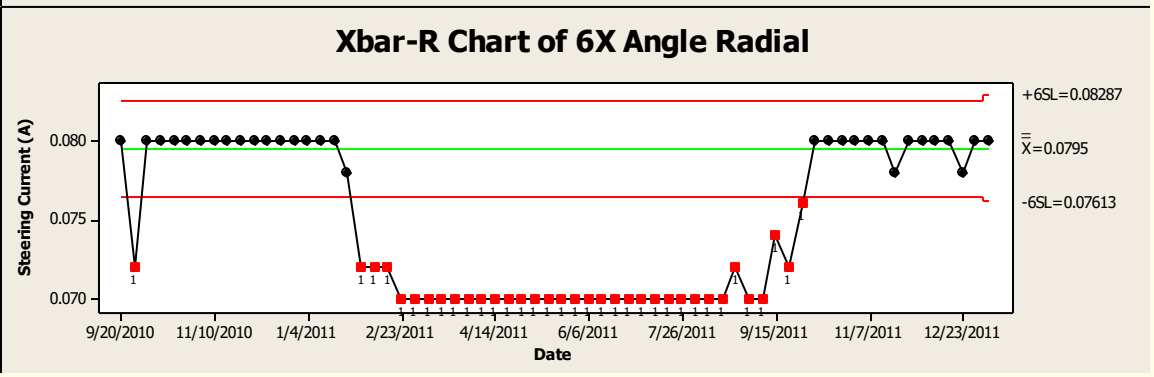
# Beam Uniformity Tracked Simultaneous to SCC




A change in radial symmetry greater than1% occurred

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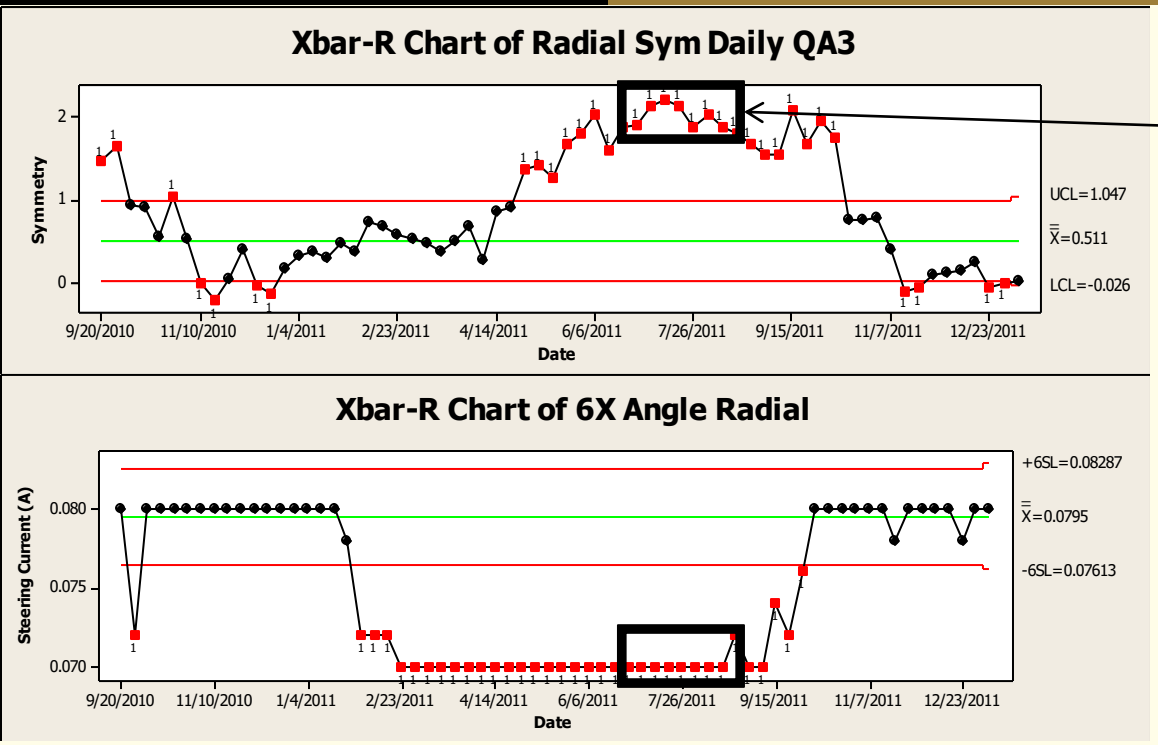
# Beam Uniformity Tracked Simultaneous to SCC




A change in radial symmetry greater than1% occurred

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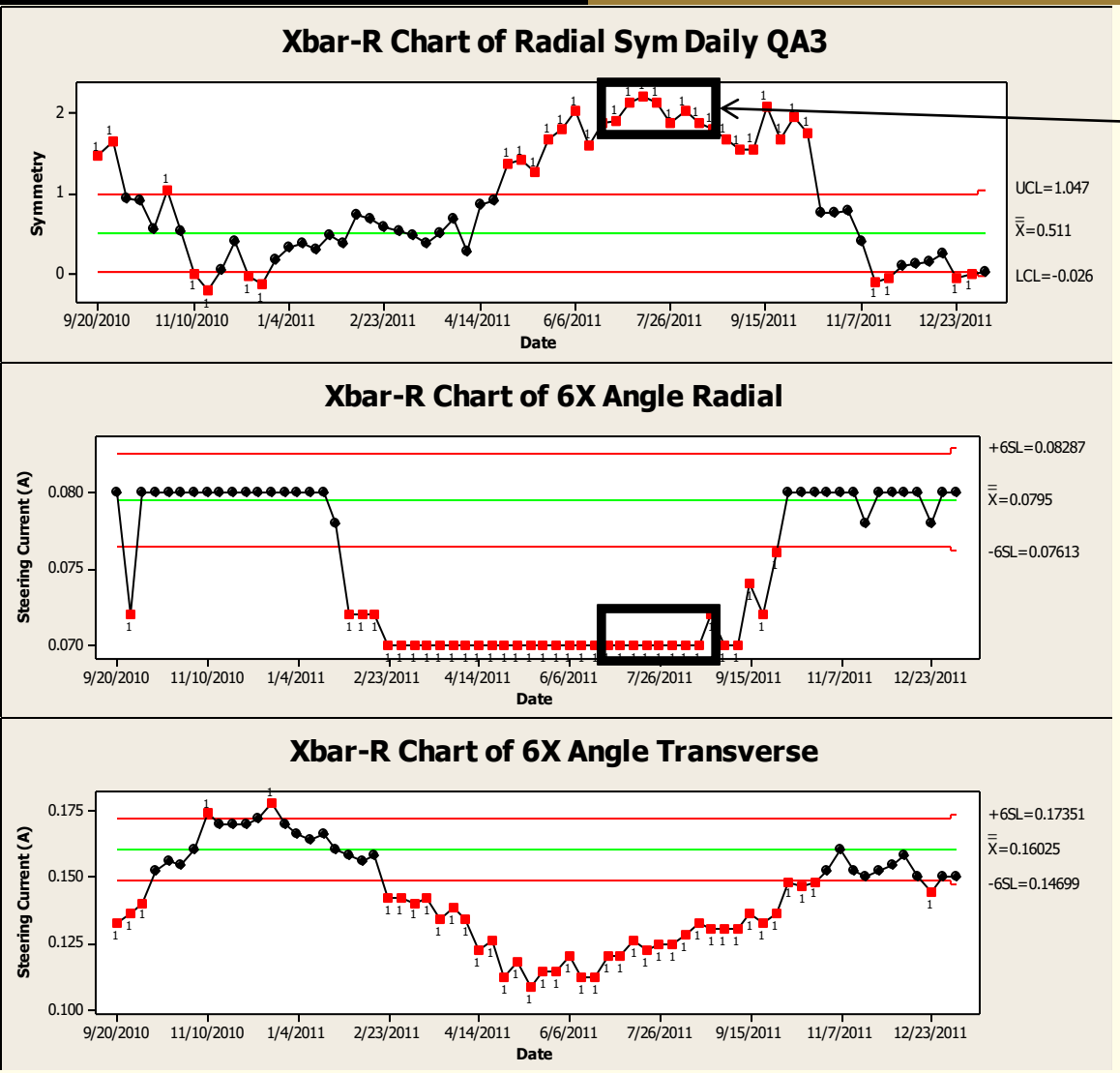


A change in radial symmetry greater than1% occurred

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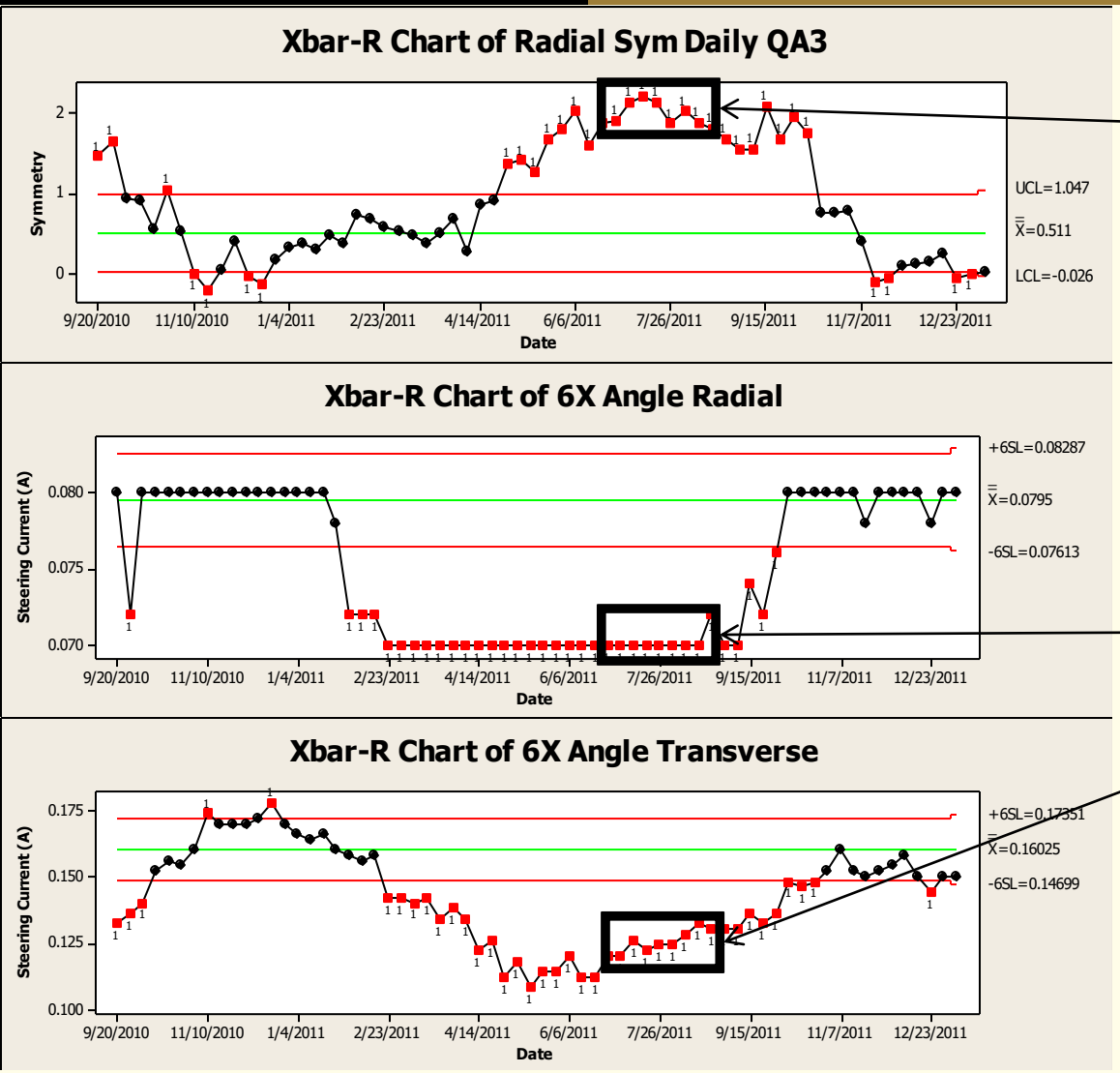



A change in radial symmetry greater than1% occurred

Two SCC had exceeded the control limits.

# PdM: Beam Uniformity Summary

## Findings to date……

- SPC analysis is extremely sensitive to changes in beam steering
- Individual steering coil alarms (6SD) will result in unwarranted service intervention
- A combination of alarms may be a more appropriate trigger for intervention relative to the TG-142 constancy criteria

# PdM: Beam Uniformity Summary

## Further work……

- Coil currents may need to be grouped differently to effectively detect clinically relevant changes in beam uniformity
- SPC analysis could function as a building block to a robust beam uniformity monitoring system
- More data from different accelerators is needed to develop a complete picture of how SPC may best be used predict when service intervention is required

## How Can Varian Help?

1. **Provide engineering knowledge of how individual steering coils effect beam uniformity in each plane.**

2. **Provide engineering input to efficiently gather and monitor beam steering parameters.**

3. **Provide beam steering data from multiple linear accelerators other than our own.**

# MLC Predictive Maintenance

**Our current plan is to analyze two MLC parameters to determine if SPC can be an effective predictor of MLC performance status.**

1. **MLC velocity**
2. **MLC Pulse Width Modulation (PWM)**

## MLC Leaf Velocity Data

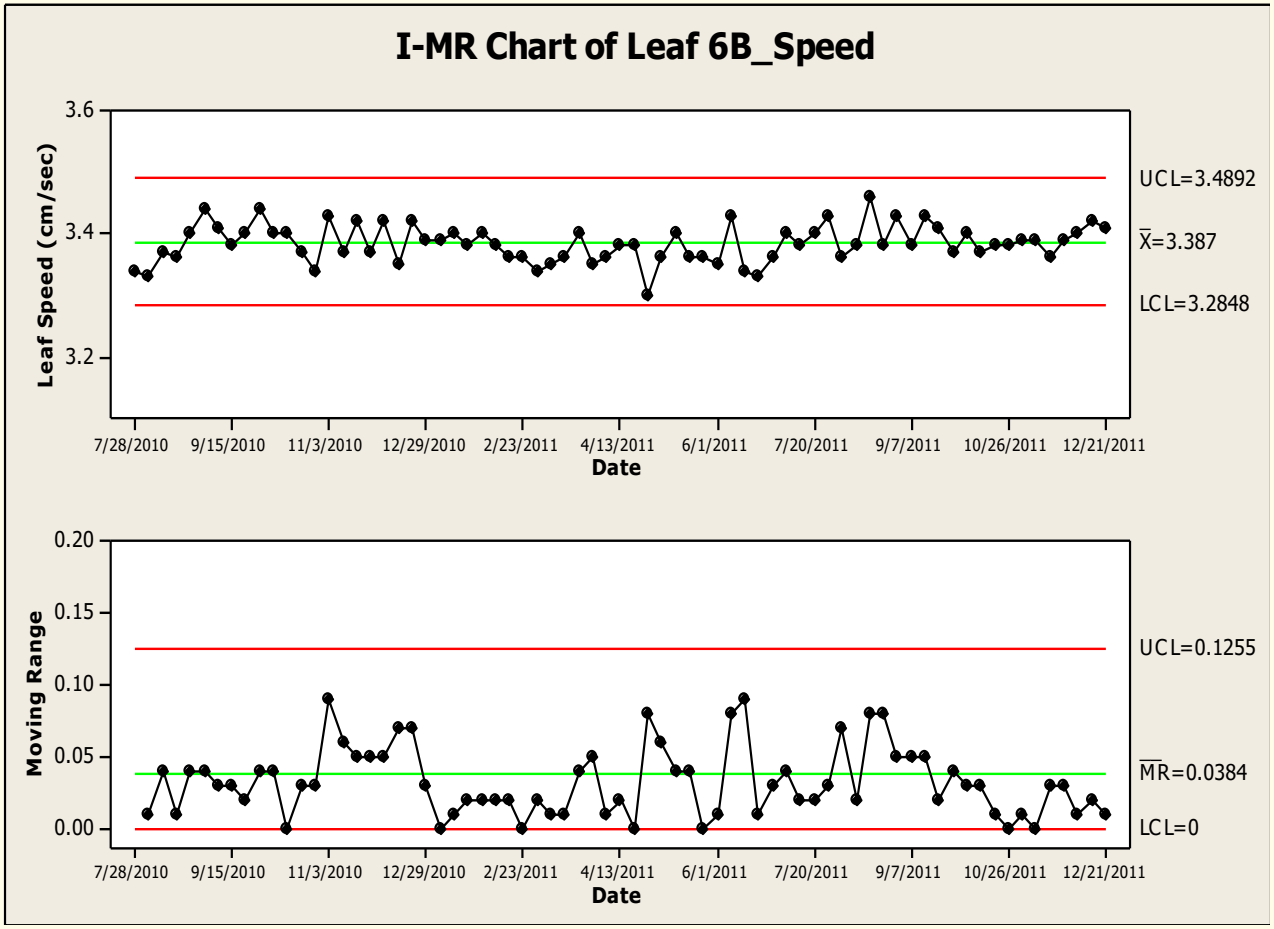
- A MLC velocity test is performed weekly on all leaves during morning QA.
- The leaves sweep 15 cm across the radiation field with the gantry pointing down.

## MLC Leaf Velocity Data

- **The leaf speed is analyzed from the generated dynalog file using Argus QA software.**

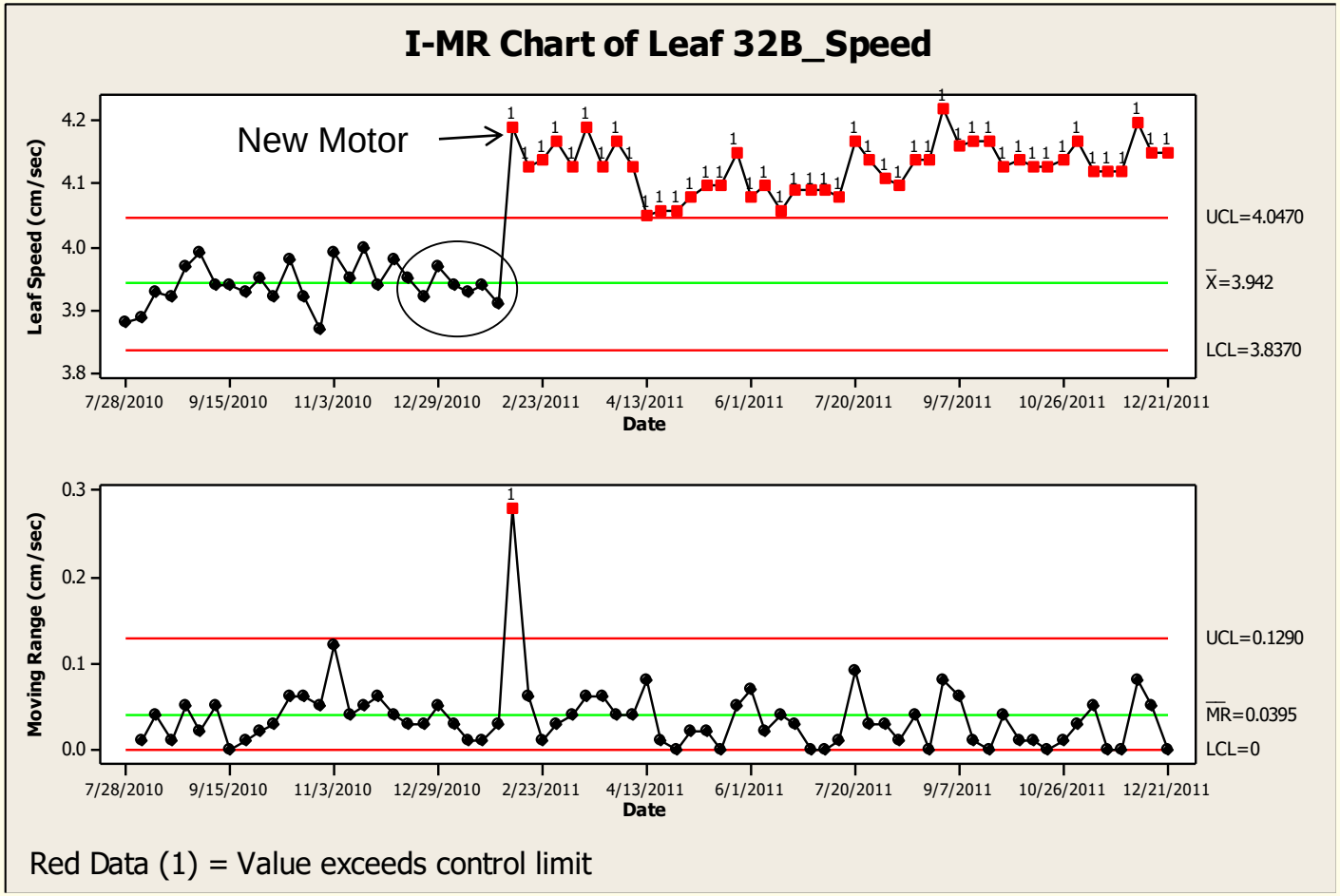
- **MLC leaf speeds in which a known motor failure occurred (8) and those in which no motor replacement was performed (12) were retrospectively evaluated for a 71 week period.**

# MLC Predictive Maintenance



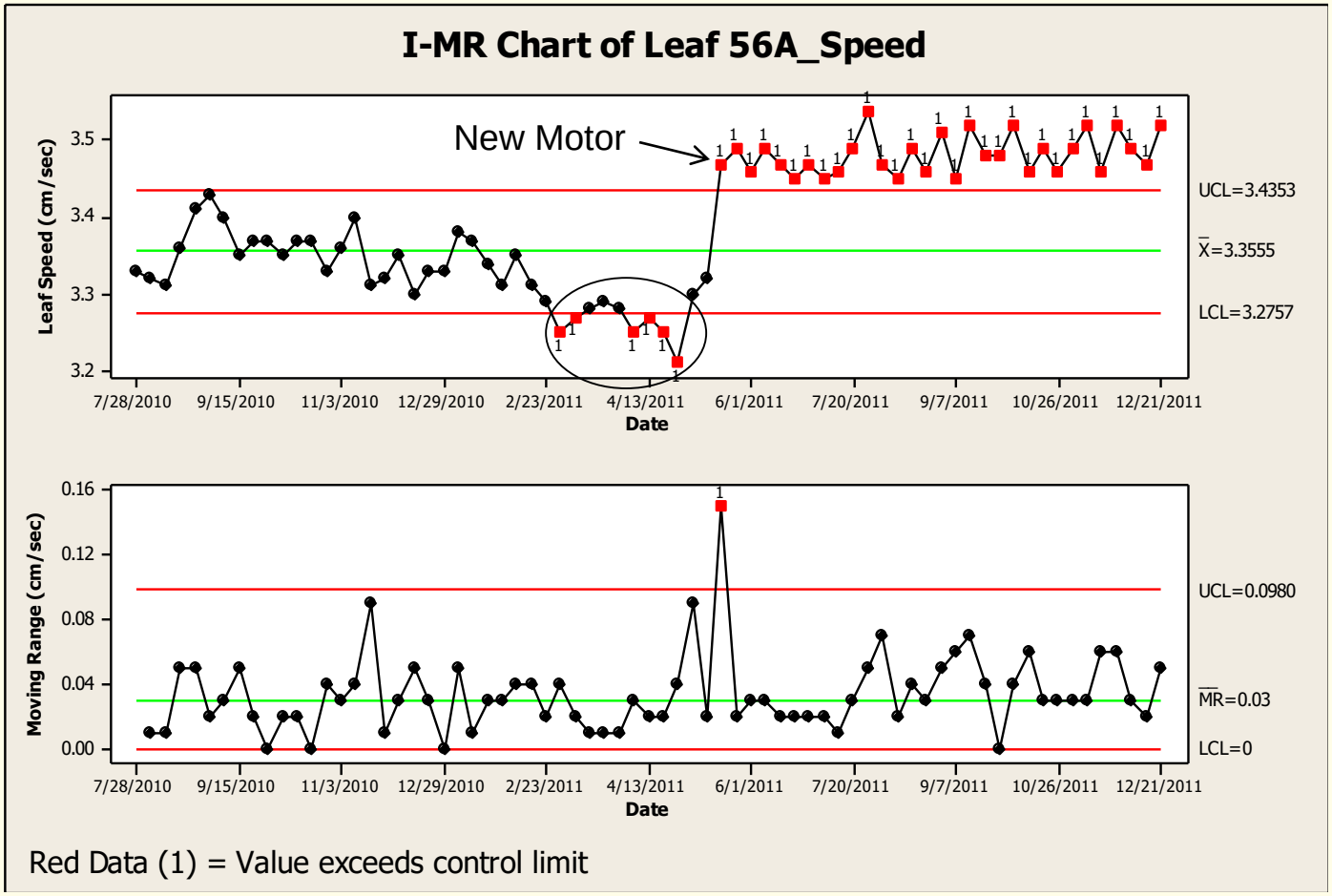

Control charts of leaves with no motor replacement were well behaved and consistently within +/- 1 mm per sec limits

# MLC Predictive Maintenance




Some leaves required a motor replacement but showed no prior indication of performance degradation (catastrophic failure?).

# MLC Predictive Maintenance




Some leaves requiring a motor replacement showed signs of performance degradation several weeks prior to failure.

# MLC Predictive Maintenance - Summary

- **SPC can detect special causes of variation in leaf velocity at the level of 1mm/sec.**
- **Daily velocity testing may increase the reliability of SPC to detect impending leaf motor failure.**
- **More access to leaf performance and operating parameters is necessary to fully explore the use of SPC for MLC predictive maintenance.**

# MLC Predictive Maintenance - Summary

## How can Varian Help?

1. **Provide access to existing software for EX and True Beam accelerators.**

2. **Provide historical data for MLCs currently operating clinically.**

3. **Provide engineering support in understanding the pulse width modulation data that is available.**

# Future Directions: Predictive Maintenance

## PdM of additional Critical Accelerator Subsystems

- Mine digital data of the True Beam accelerator system for processes that may be conducive to SPC Predictive Maintenance monitoring
  - new install May 2012
  - Varian's guidance needed to access data
- Gantry Rotation (Velocity)
- Imaging Source (KV)
- Imaging Detectors (KV and MV)

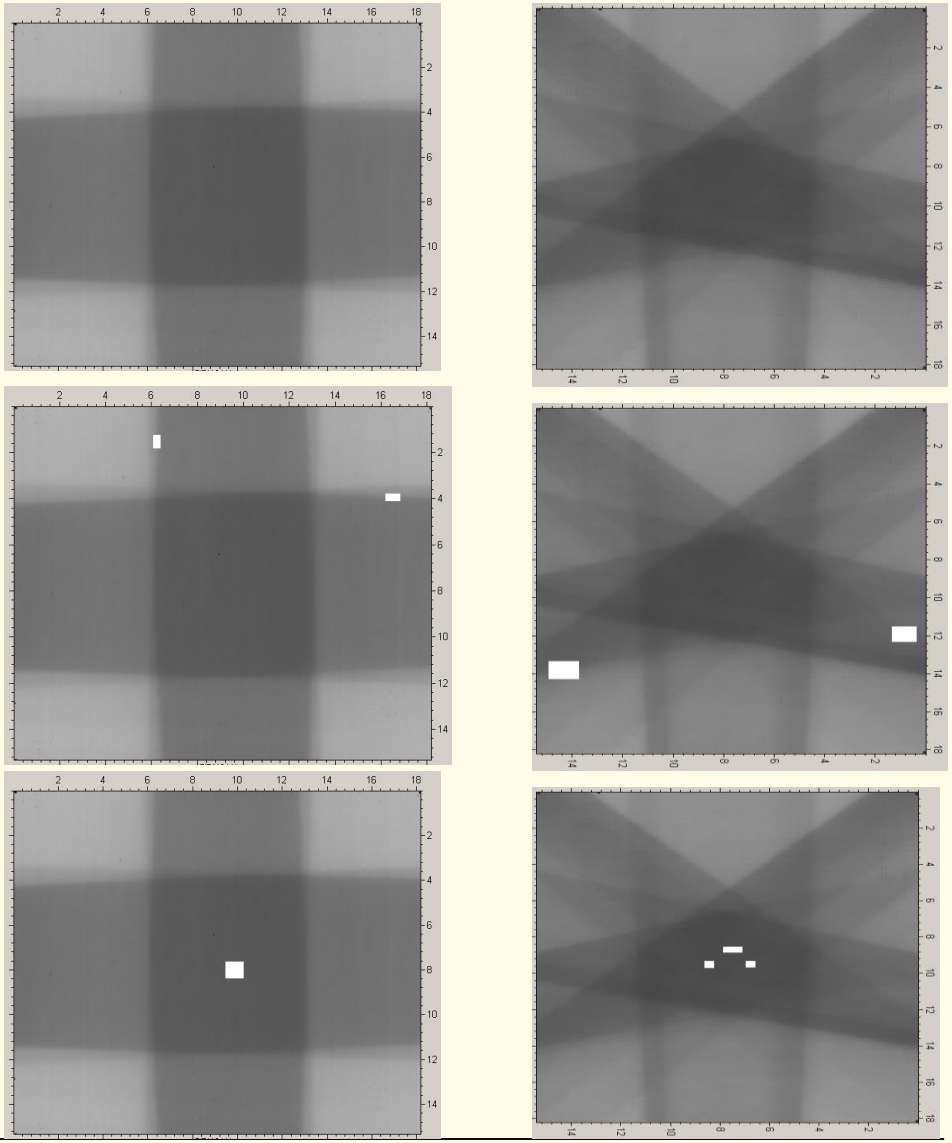
  Positioning accuracy and mechanical stability

# Future Directions: Quality Control

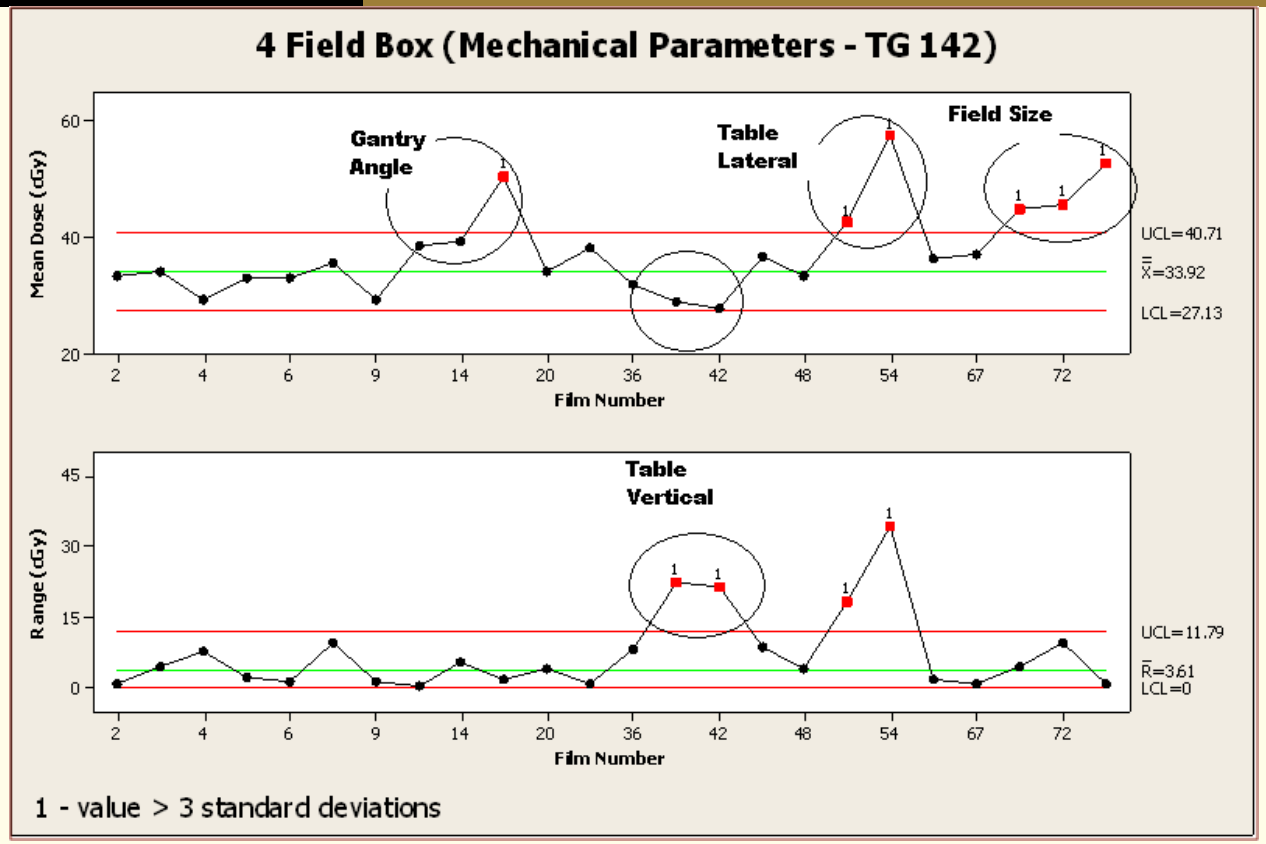
## QC of Linear Accelerator Treatment Delivery

- Can sampling a clinical dose distribution satisfy the requirements of TG-142?

- If so, automated sampling and evaluation can help to more efficiently deploy physics resources.



# Future Directions: Quality Control




- SPC sampling of clinical dose distributions for TG-142/TG-40 mechanical and dosimetric evaluation has shown promise

- Future work will use EPID Imaging to replace GafChromic film

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Thank You for your interest in and support of the

Wake Forest Predictive Maintenance Team