# Sub-mm accuracy of accelerators: How manufacturers achieve it, how physicists verify it

Presented by Ivan A. Brezovich, PhD, at the
2015 Annual meeting of the SEAAPM,
Raleigh, NC, April 24, 2015

# Purpose

- To show that with modern accelerators
  - sub-mm accuracy can be readily achieved by manufacturers
  - sub-mm accuracy can be reliably maintained
- That digital systems enhance accuracy
- To suggest methods for physicists to verify accuracy
- Future improvements

# What do we mean by precision?

**The accelerator must accurately reproduce all parameters shown in the treatment plan**

- Gantry angle, collimator angle, position of x-ray jaws, position of all 120 collimator leaves, position of treatment couch; dosimetric beam properties
- MV treatment beams match kV imaging beam
- Beam delivers planned dose

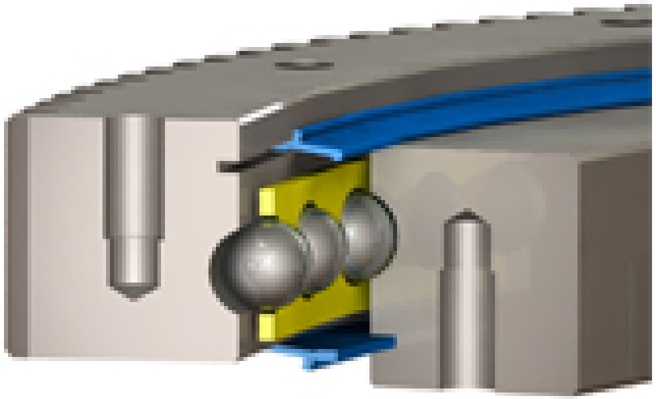
# How to make an accelerator precise?

- Use precise mechanical parts
  - ball bearings for rotation (gantry, collimator, couch)
  - Rack and pinion drives (couch linear motions)
  - Screw drives (MLC carriage motions)
- Eliminate backlash
- Use precise electronic parts
- Use software corrections to compensate for mechanical inaccuracies

# Even large ball bearings can be made with micron precision

Standard ball bearing

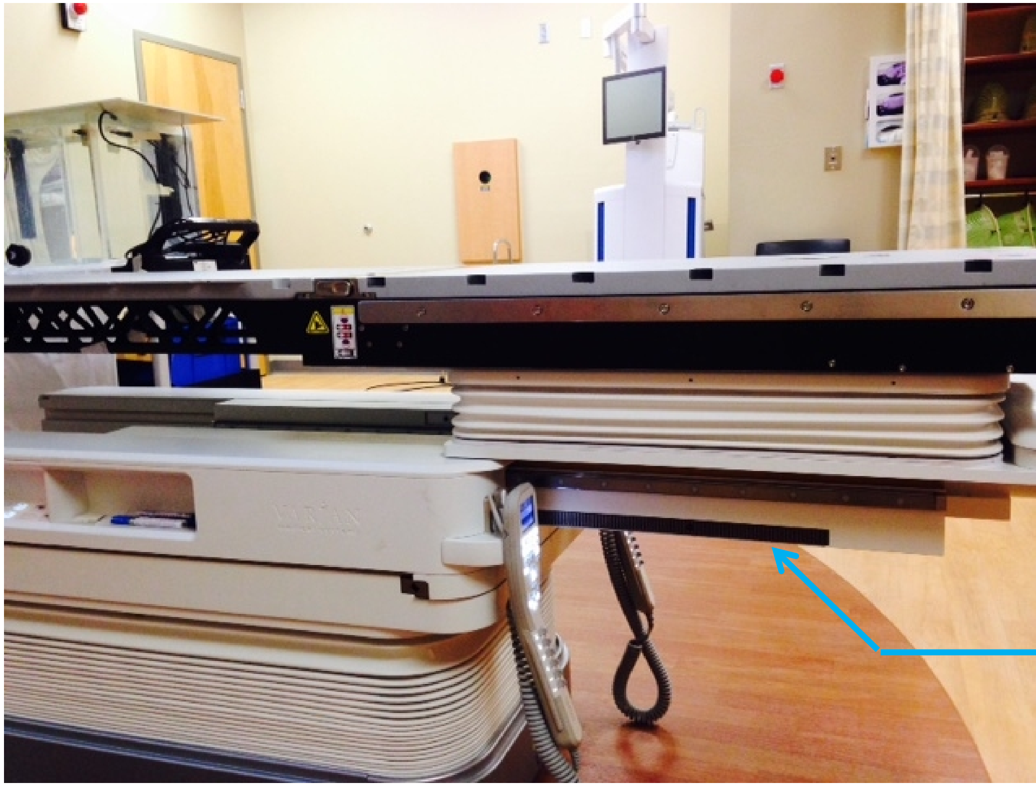
**Slew bearing** as used for gantry rotation **50 micron** accuracy, > 5,000 life expectancy



**Design features** **(from manufacturer's website)**
The internal configuration is a deep groove gothic arch raceway, which provides four points of contact with the balls, enabling it to carry radial, moment, and thrust loads individually or simultaneously. The use of internal diametral preload provides for greater stiffness, which combined with tightly controlled radial and axial runouts, delivers accurate repeatability. The axial **runouts are 0.001 inches** TIR and the radial runouts for locating **diameters are 0.002 inches** TIR. A separator is used to maintain consistent ball spacing interval, keep friction to a minimum, and minimize noise. Integral face riding seals are provided to assist in the exclusion of contaminants. [*TIR = total indicated runout*]

http://www.kaydonbearings.com/KH_turntable_bearings.htm accessed 4-20-2015

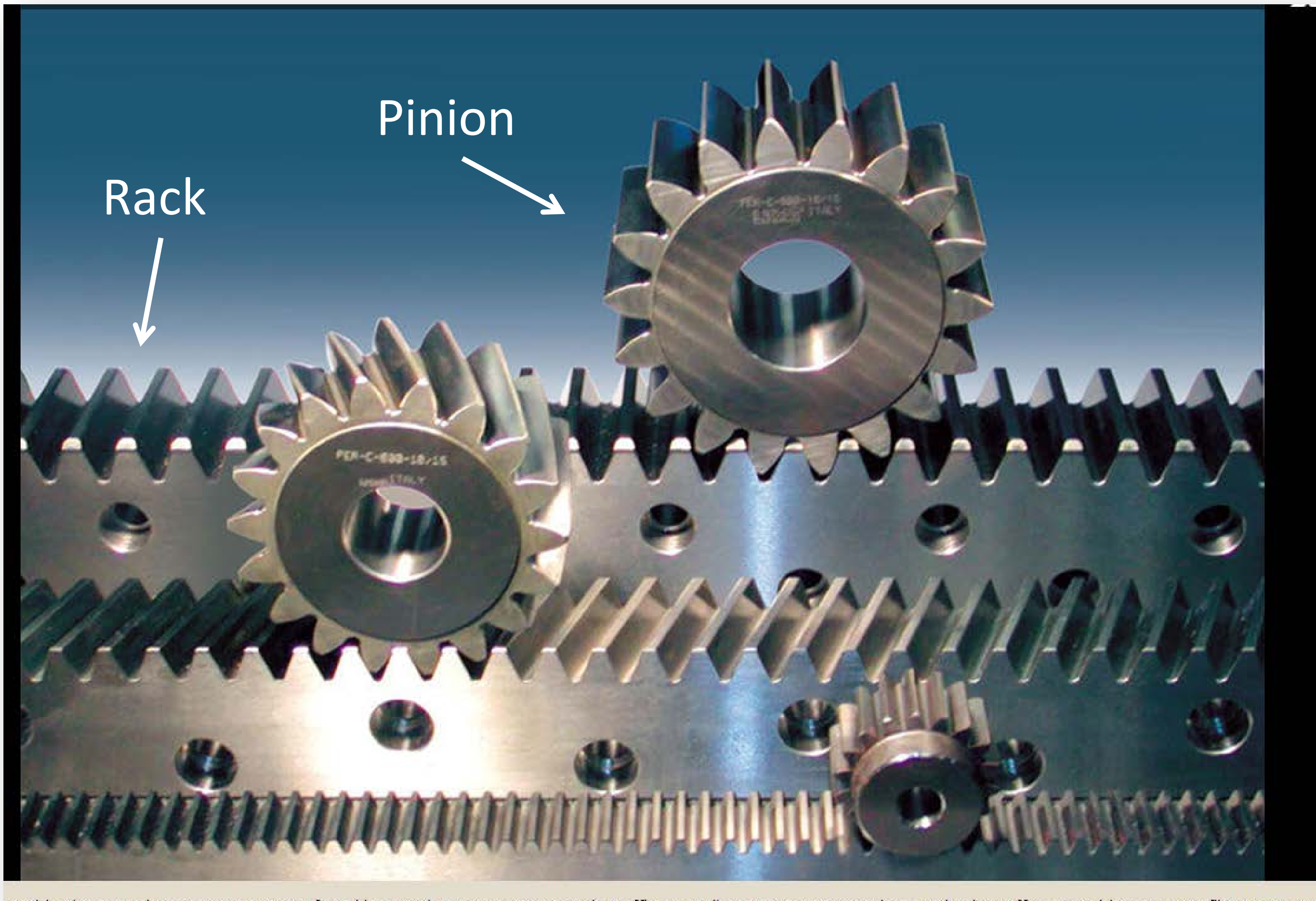
Longitudinal motion control of couch using rack and pinion drive



Rack

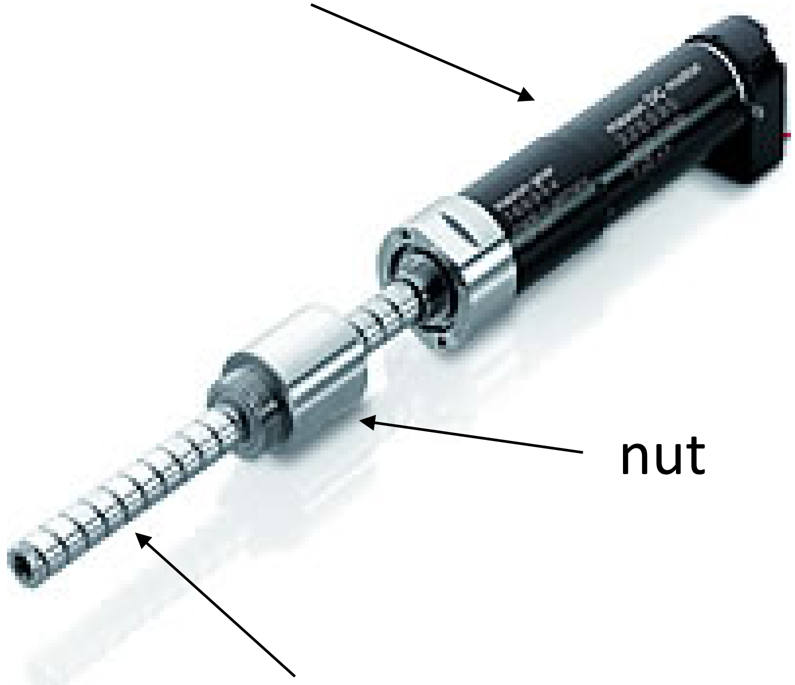
# Rack accuracy:  36 micron per m

## In-out and lateral motion of couch



# Spindle (screw) drive (used for jaw motions)

Geared motor with position readout in back



nut

Rotating spindle

# Precision tools for manufacturers: Accurate to ~ I micron ($10^{-3}$ mm)

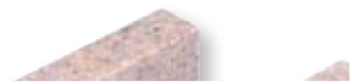
## Five-Face Master Squares

Five-Face Granite Master Squares are popular for accurately checking the X-Y-Z axes on CNC machine tools and coordinate measuring machines.

Lying in the horizontal position, the X and Y axes can be checked for 90° squareness. With the square in the vertical position, tracing along the vertical edge of the square can check the perpendicularity of the Z axis. By tracing along the top edge of the square while in the vertical position, it will check parallelism of the table in the X and Y axes to the spindle.

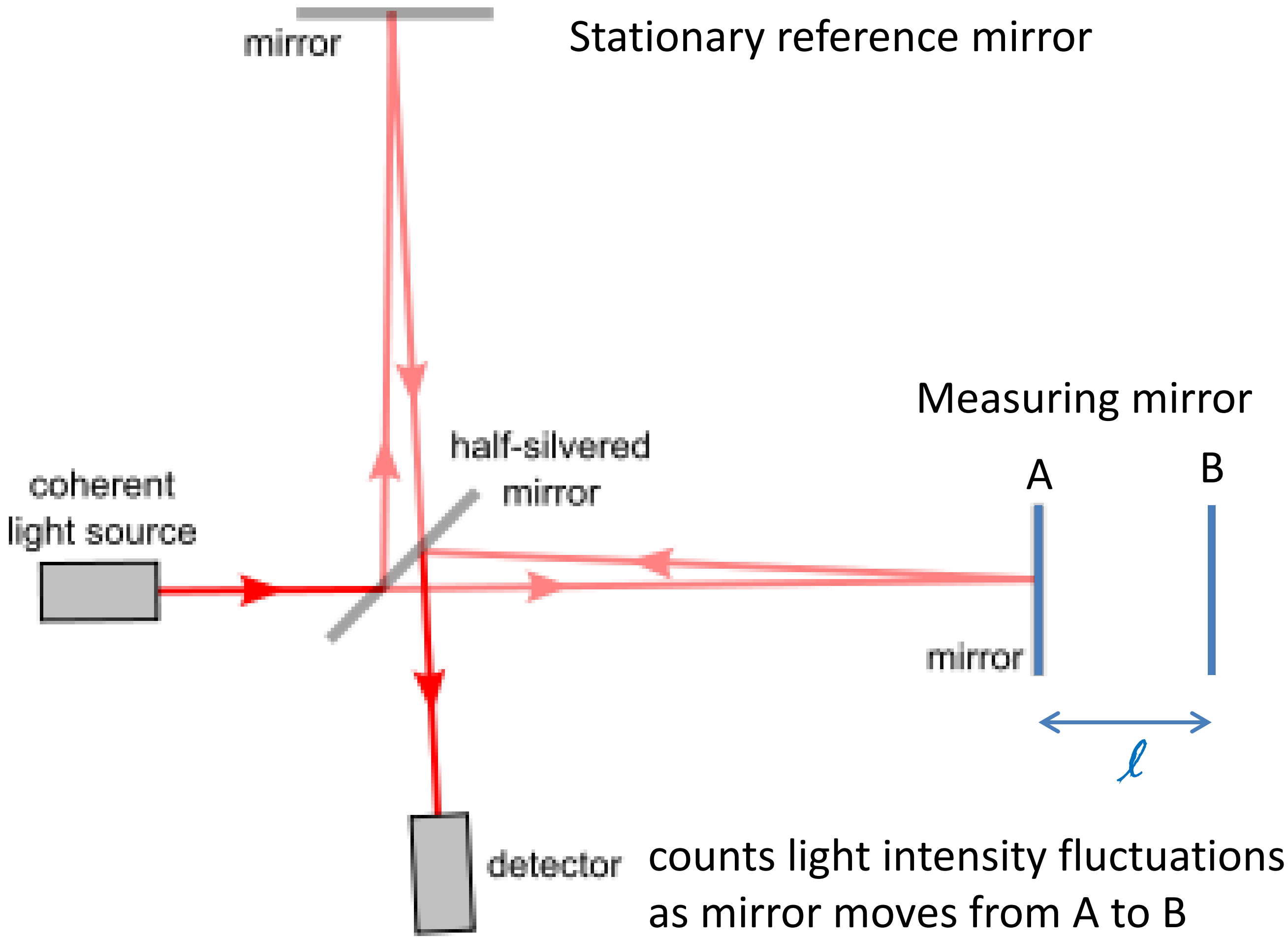
Five-face master squares may also be used on any work that requires the checking of squareness or parallelism.


| Five-Face Master Squares | | | | | |
|---|---|---|---|---|---|
| Dimensions Length x Height x Thickness | | Weight | | Accuracy Grade – EDP | |
| | | | | AA Laboratory .000025"/6" TIR (0.0006/150mm) | A Inspection .000050"/6" TIR (0.0012/150mm) |
| Inch | mm | Lb. | kg | | |
| 12 x 12 x 3 | 300 x 300 x 75 | 41 | 19 | 81919 | 81920 |
| 14 x 14 x 3 | 350 x 350 x 75 | 56 | 25 | 81922 | 81923 |
| 16 x 16 x 4 | 400 x 400 x 100 | 98 | 44 | 81925 | 81926 |
| 24 x 24 x 4 | 600 x 600 x 100 | 220 | 100 | 81931 | 81932 |
| 36 x 36 x 6 | 900 x 900 x 150 | 855 | 388 | 81933 | 81934 |



From Starrett website, accessed April 3, 2015

# Interferometer for accurate length measurements < 1 micron




From Wikipedia, accessed April 3, 2015

# Eliminate backlash by a second, circumferentially offset cogwheel

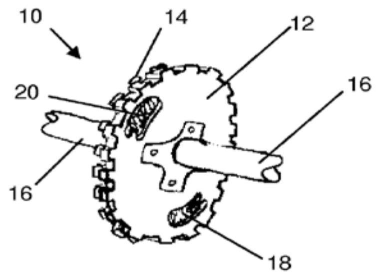



FIG. 1

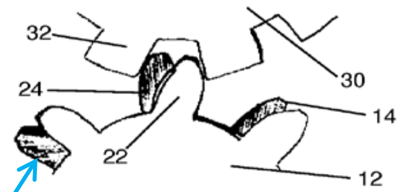



FIG. 2

Offset cogwheel on same shaft

Spring for preloading second cogwheel

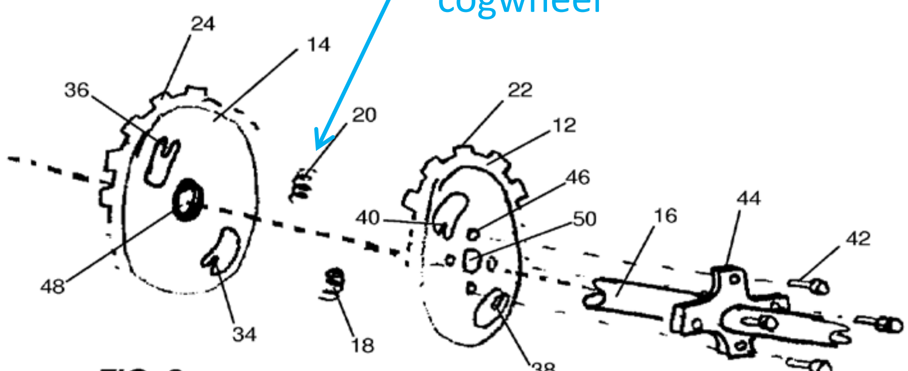
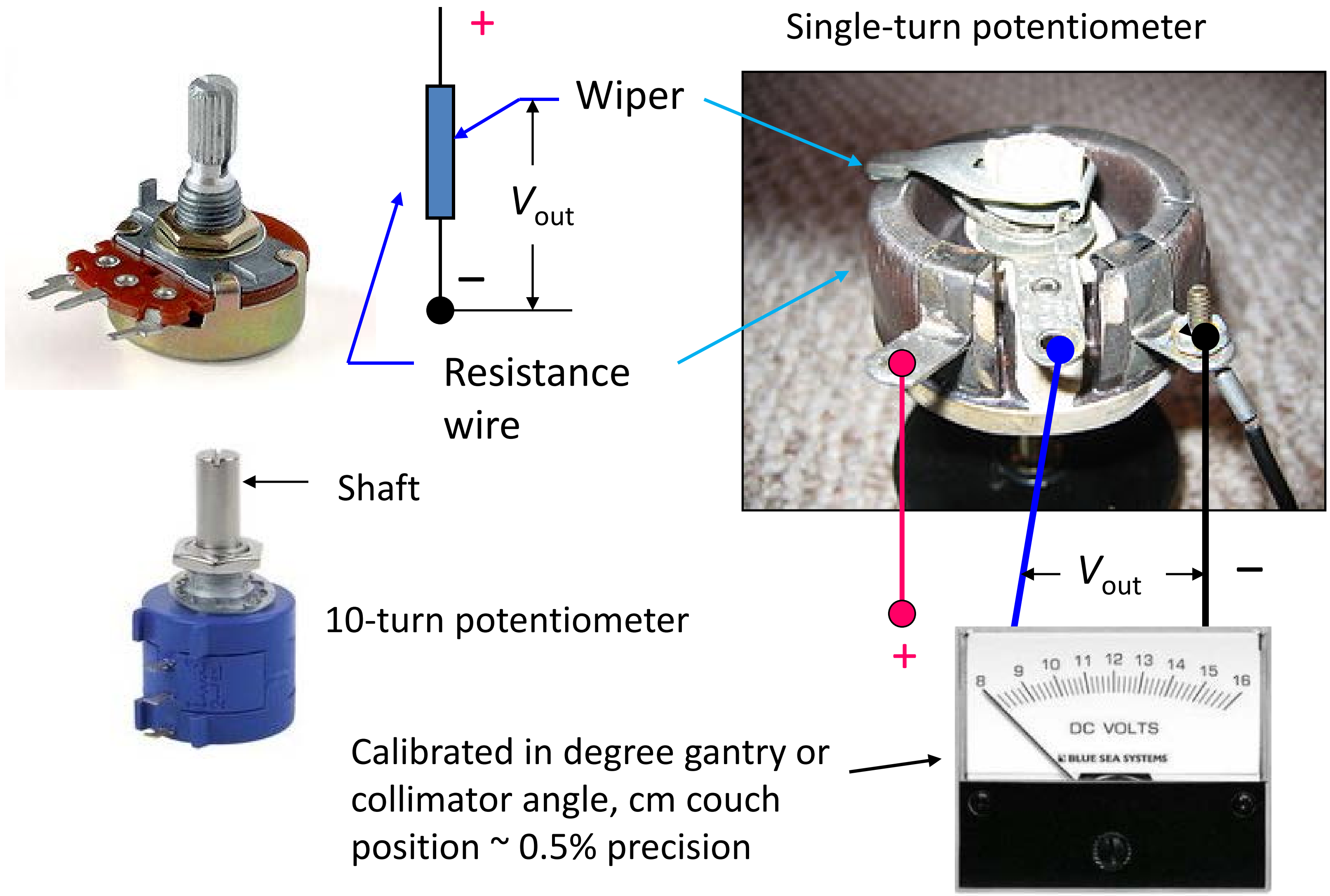



FIG. 3

From US Patent Office website, 2008/0023998

# Avoid potentiometers and analogue readouts: not accurate for gantry angle, couch position



# Limitations of analogue electronic devices:

Accuracy of potentiometers: linearity ± 0.1% when new

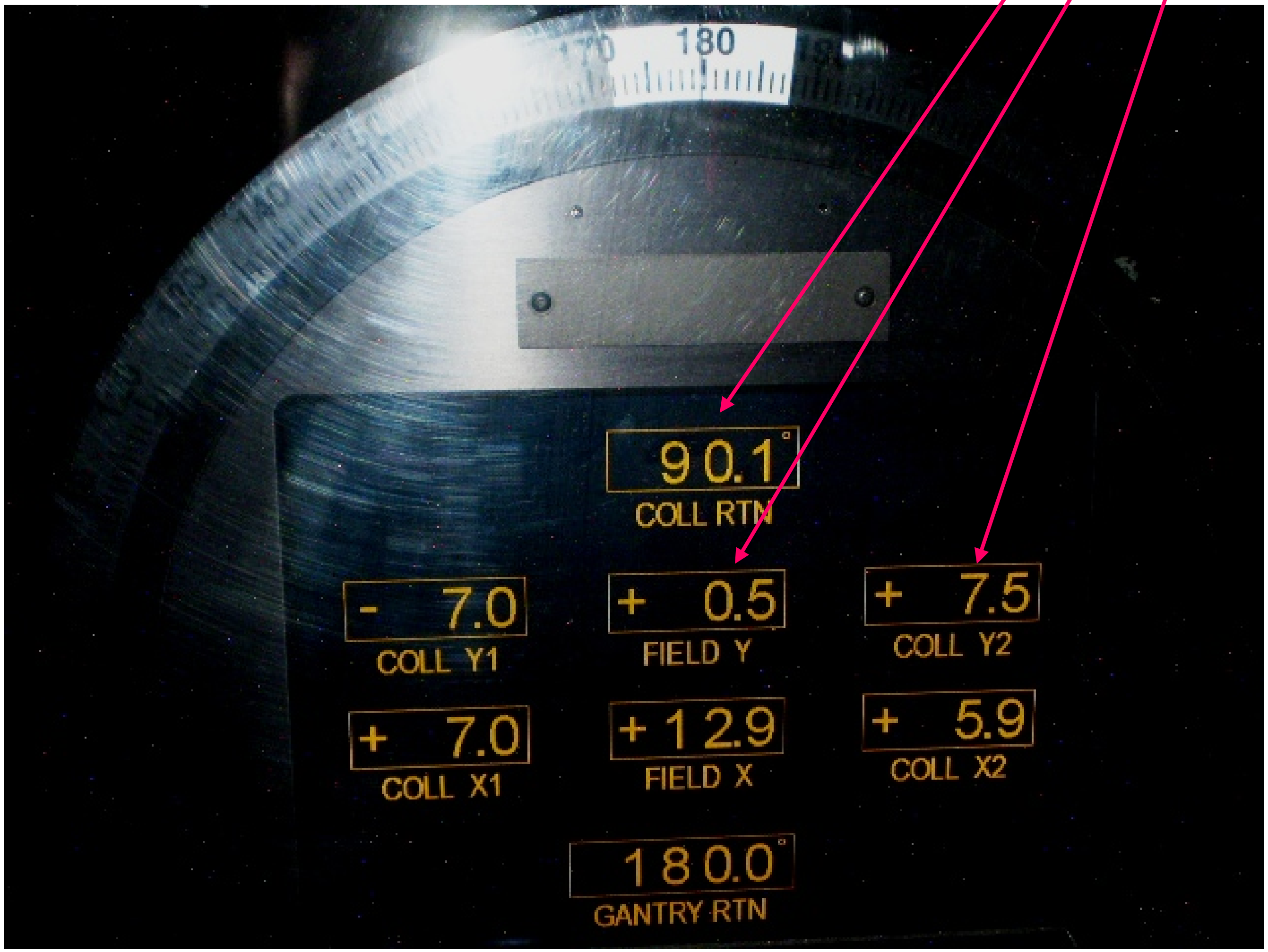
- ~ 1 mm error per m error in linear motion
- ~ 0.36° error in rotations of collimator or gantry

Work-around: Geared potentiometers (one for cm readout, another for sub-mm readout)

Limited lifetime of potentiometers due to scraping of wiper (frequent replacements necessary)

Analogue voltmeters difficult to read (~ 0.5%)

# Analogue transducers (potentiometers), digital readouts

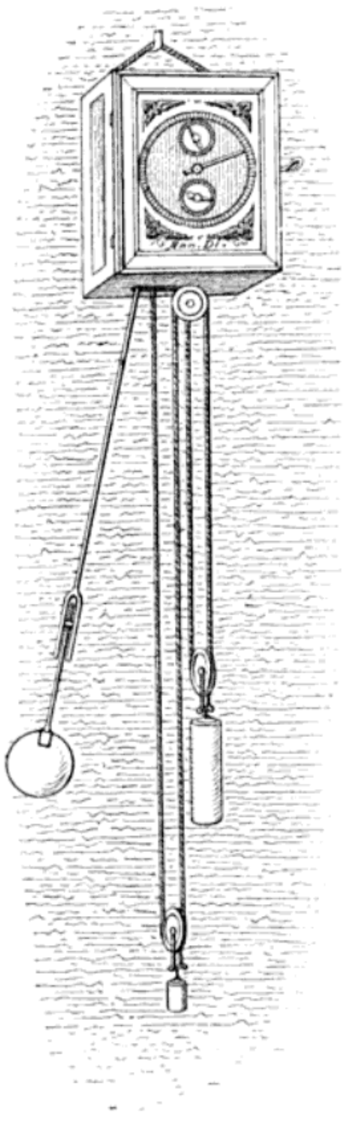


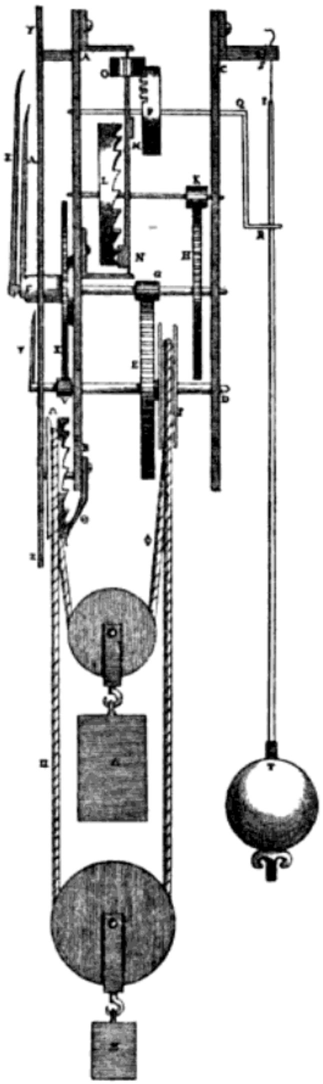
# Avoid analogue devices – not very accurate

## Analogue clocks

From Wikipedia, accessed April 3, 2015

# Go Digital! "Digital" transducer with analogue display





Pendulum clock invented by Christiaan Huygens, 1656

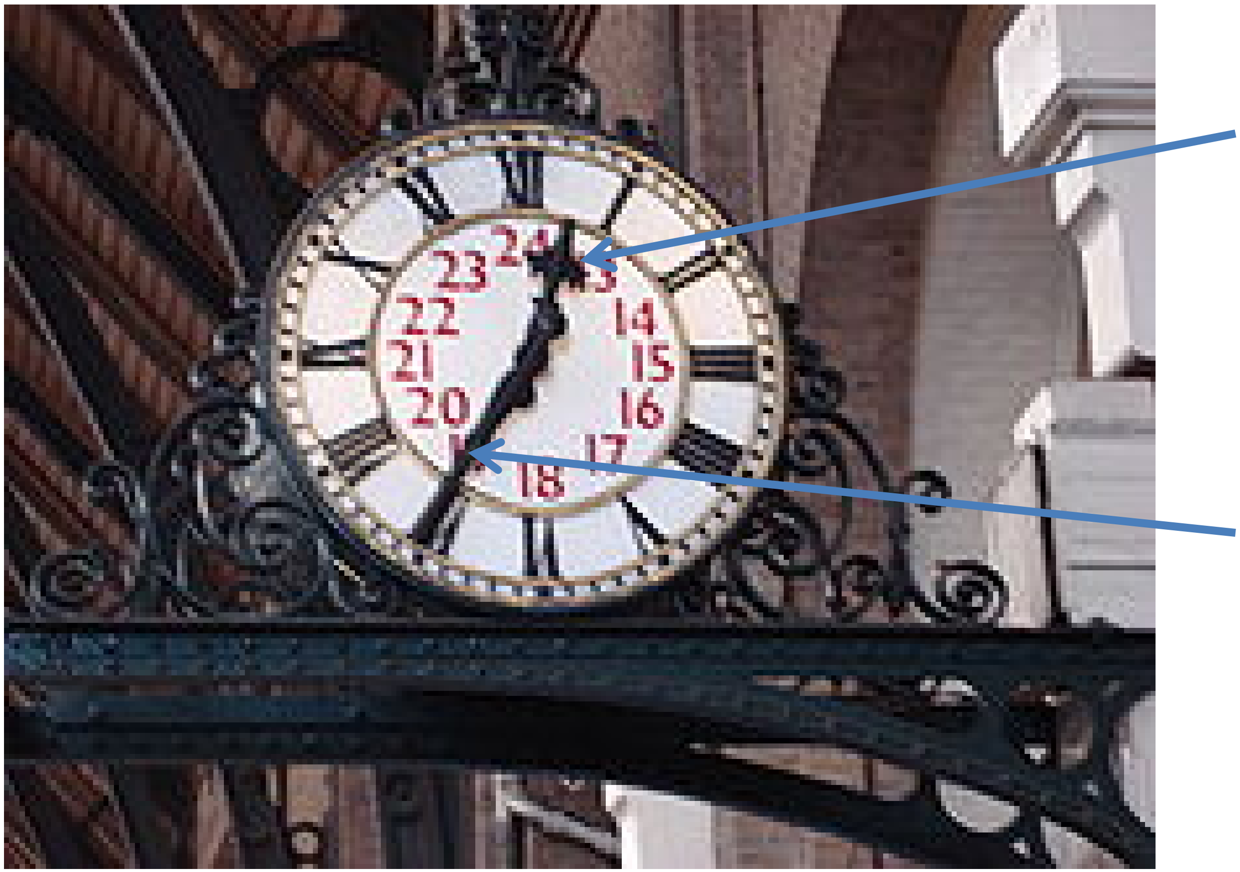
From Wikipedia, accessed April 3, 2015

# Single-hand clock: Digital transducer, analogue display

Reading accuracy about 6 minutes ~ 1%

# Two-hand clock: Digital transducer, hybrid display

## Reading accuracy ½ min (0.1%)




King’s Cross railway station, London

# Go Digital! Digital encoders replace potentiometers

13-bit shaft encoder

shaft

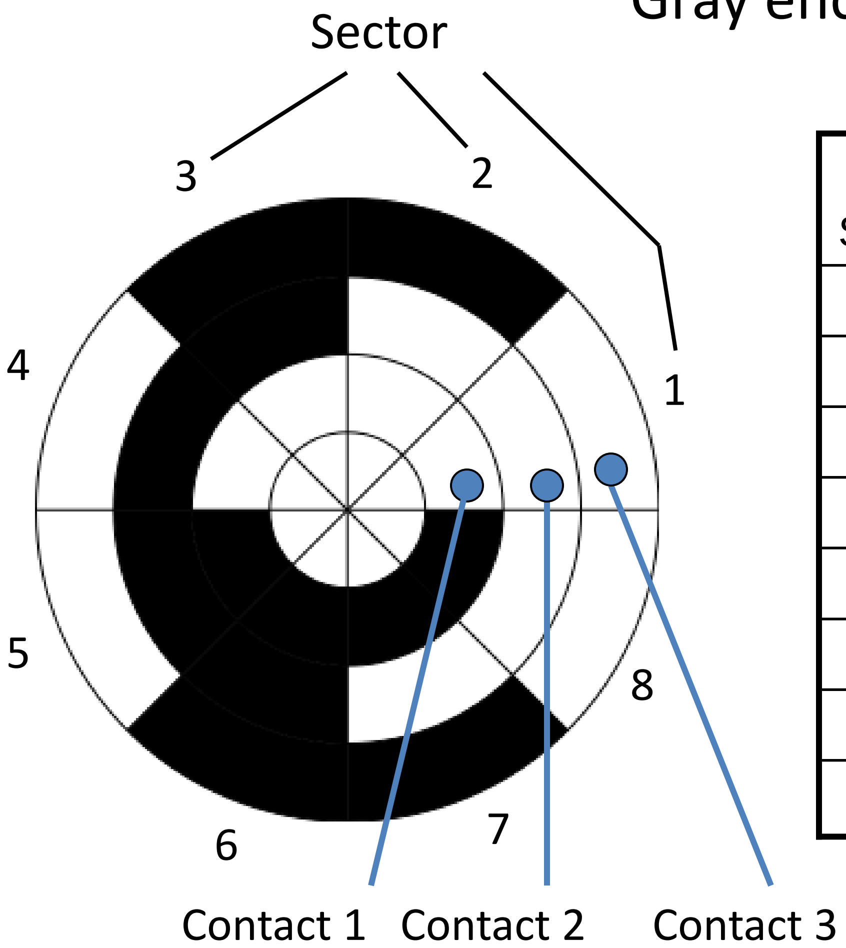

Precision = 1 rev/$2^{13}$
$\approx$ 1/8192 rev
$\approx$ 0.04°

Digital output

From Heidenhain website, accessed April 3, 2015

# 3-bit shaft encoder

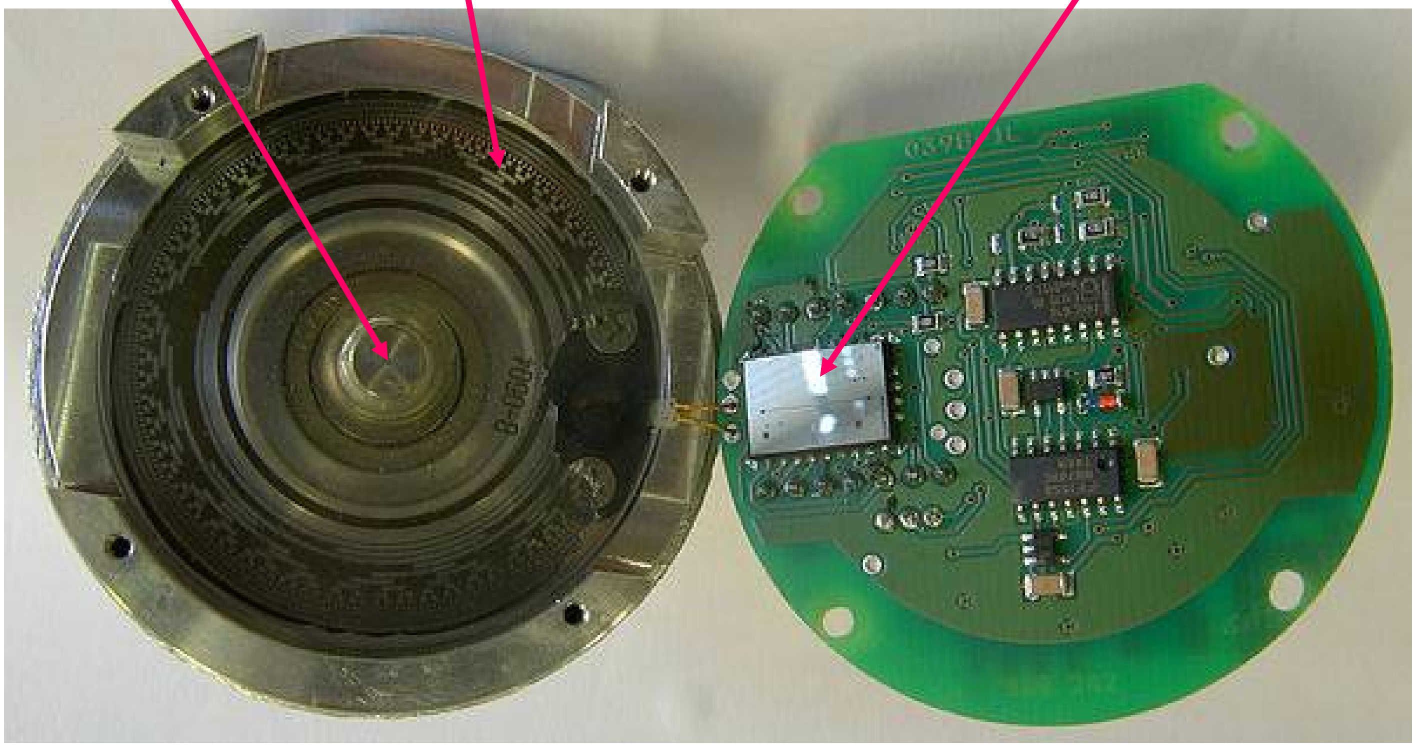
## Gray encoding




| Sector | Con-tact 1 | Con-tact 2 | Con-tact 3 | Angle |
|---|---|---|---|---|
| 1 | off | off | off | 0° - 45° |
| 2 | off | off | ON | 45° - 90° |
| 3 | off | ON | ON | 90° - 135° |
| 4 | off | ON | off | 135° - 180° |
| 5 | ON | ON | off | 180° - 225° |
| 6 | ON | ON | ON | 225° - 270° |
| 7 | ON | off | ON | 270° - 315° |
| 8 | ON | off | off | 315° - 360° |

# 13-bit shaft encoder (absolute encoder)

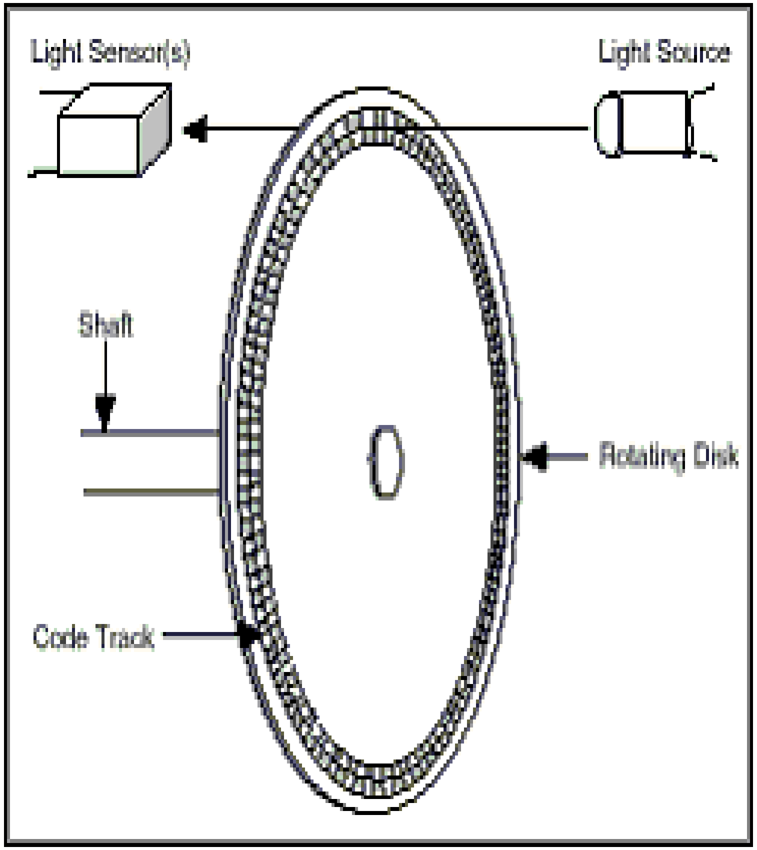
Limitations: Sensitive to radiation

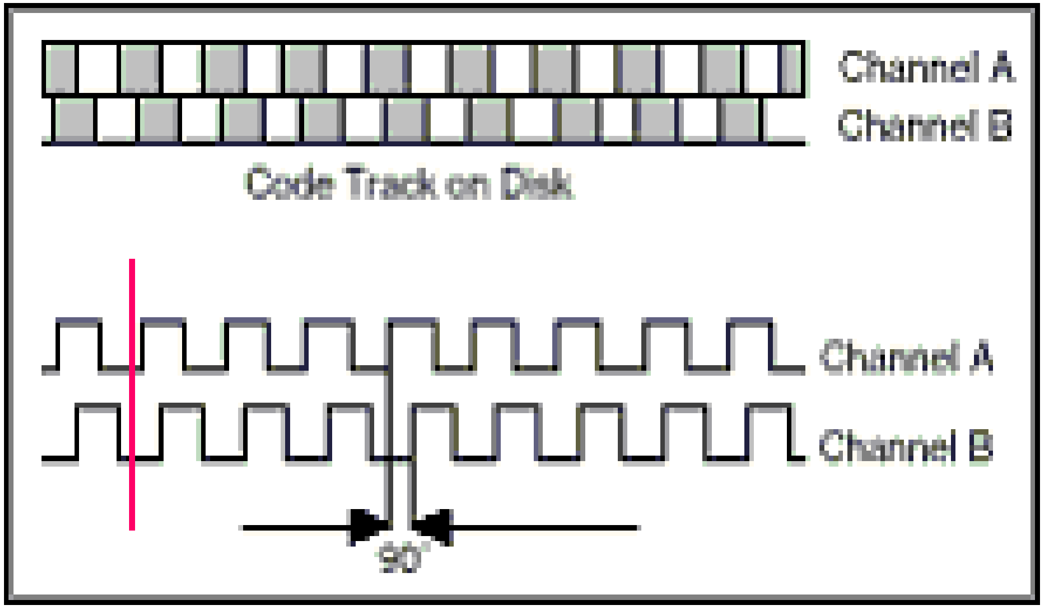


# Incremental encoders count pulses

simpler than absolute encoder, less sensitive to radiation

must be initialized

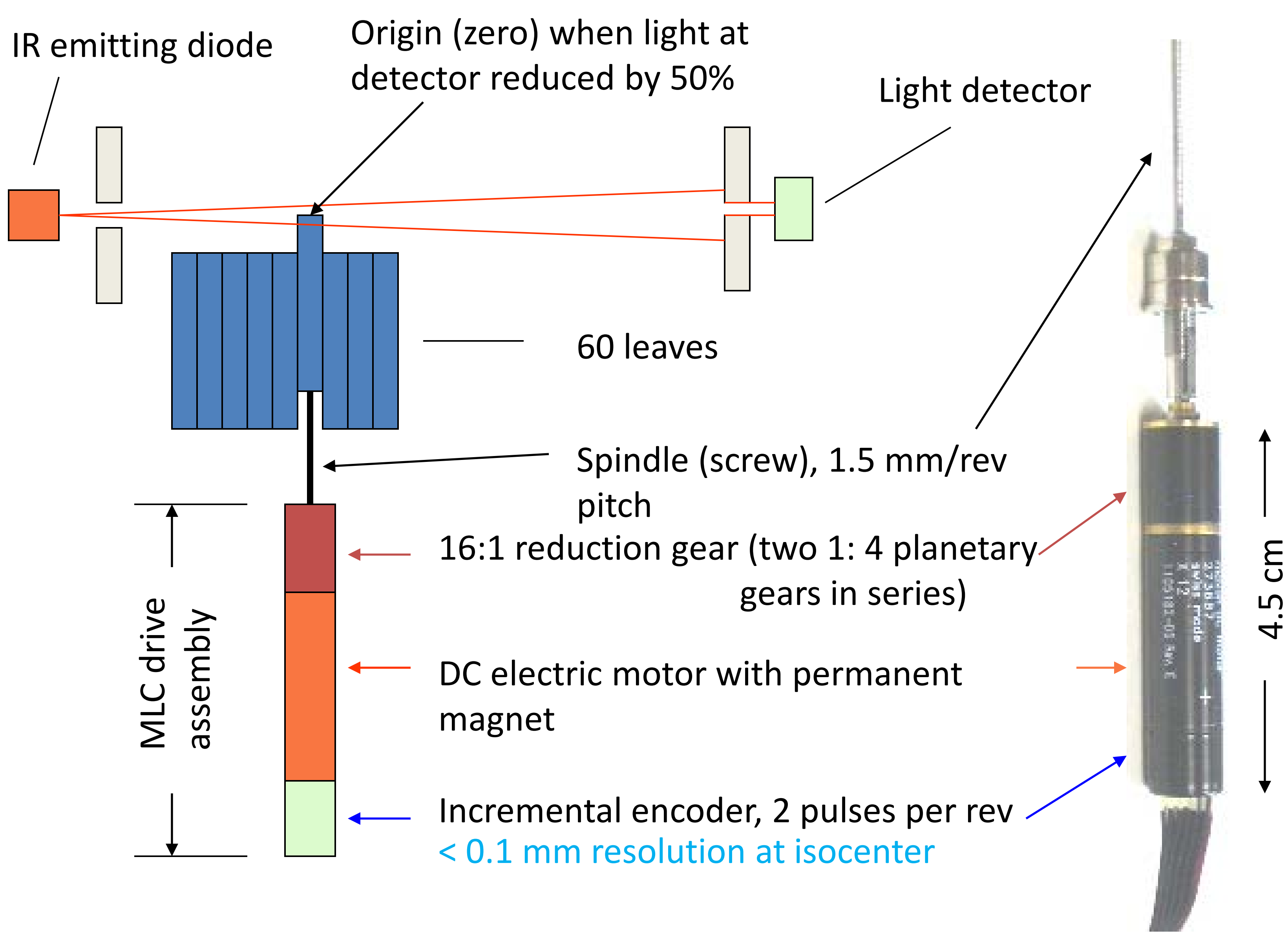


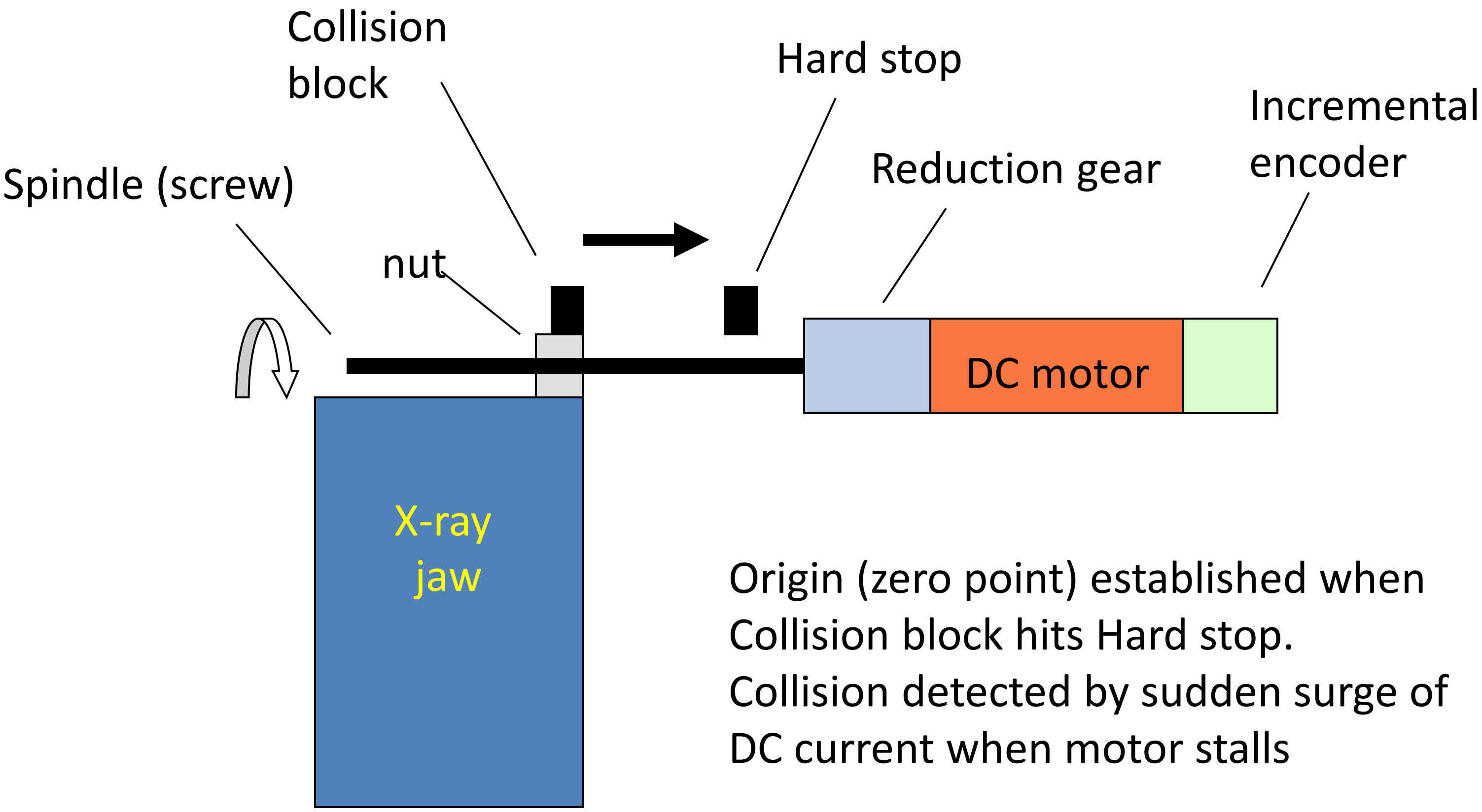

Cannel A leads … clockwise rotation

Cannel B leads … ccw rotation

# Initialization of Varian MLC



# Initialization of Varian x-ray jaws




Origin (zero point) established when Collision block hits Hard stop. Collision detected by sudden surge of DC current when motor stalls

# “Software” correction for mechanical imprecision of imaging system. Goal: treatment beam accurately matches images

## IsoCal calibration

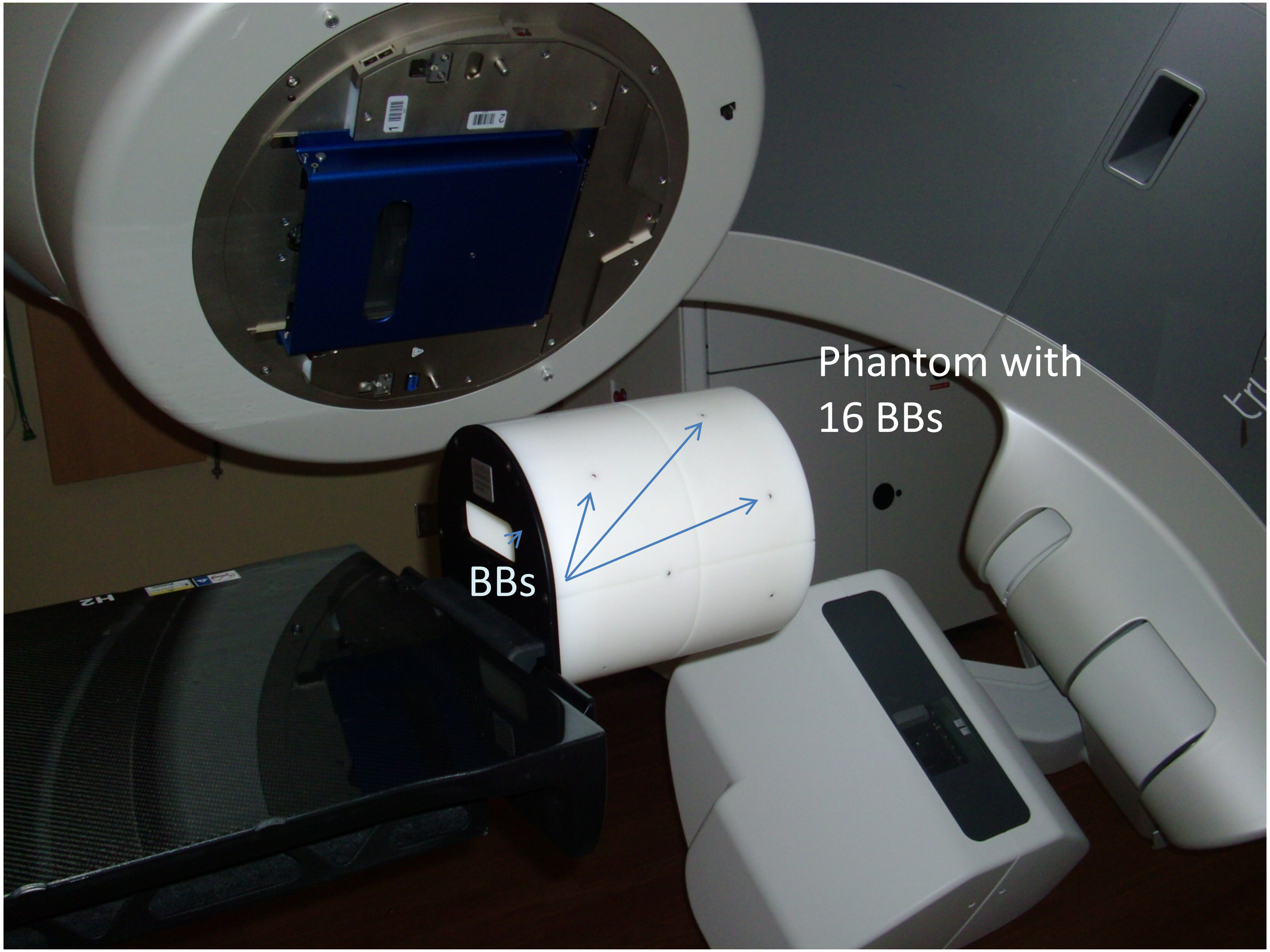
- Collimator rotates while MV views are taken. Computer finds collimator axis from projections of marker in transmission plate mounted in wedge tray
- Gantry rotates 360°, takes 400 kV and MV views of phantom with 16 BBs at precisely known locations
- Computer finds kV and MV isocenters

Computer mechanically shifts kV and MV imaging panels to correct for flex of imaging system

Every x-ray passing through the kV isocenter strikes the kV imager at its center

Every MV-ray passing through the MV isocenter strikes the kV imager at its center

# IsoCal procedure for finding kV and MV imaging isocenters

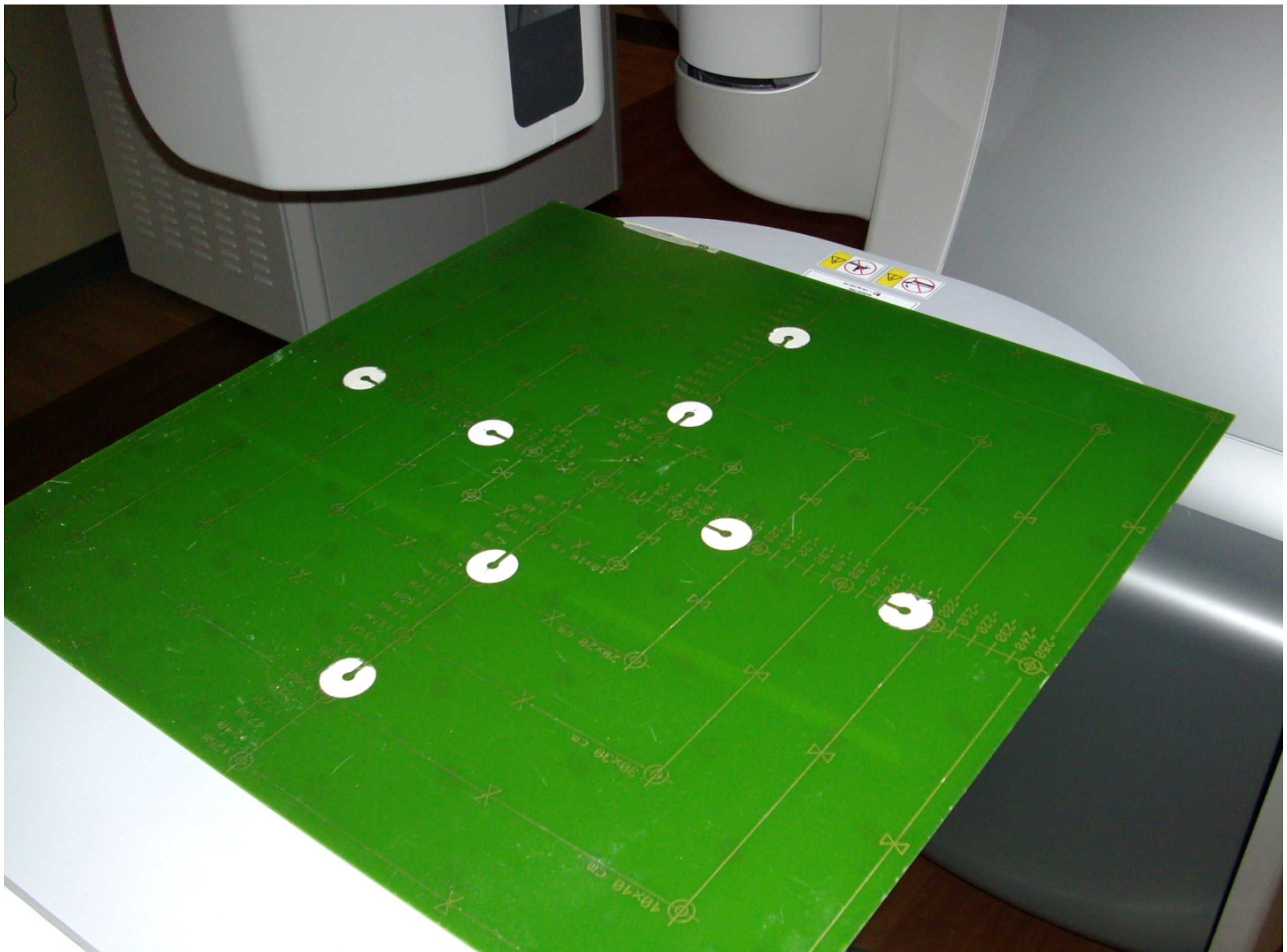


Don’t take precision for granted:

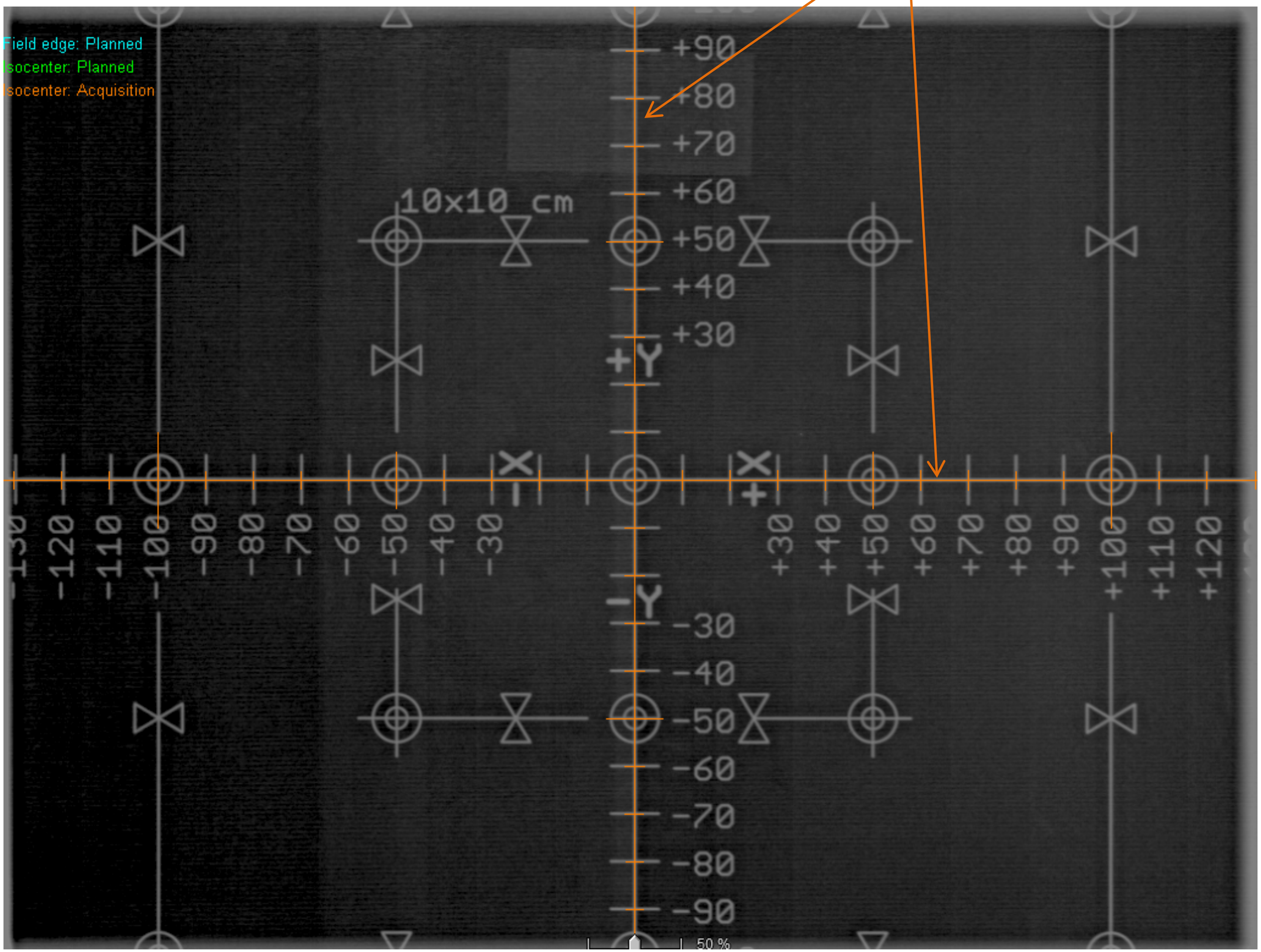
# Trust, but verify

Доверя́й, но проверя́й

# Manufacturer-supplied phantom for planar kV imager QA tests



Manufacturer-supplied phantom for planar kV imager QA tests
Cannot be used for CBCT QA



# Manufacturer-supplied phantom contains one BB at center

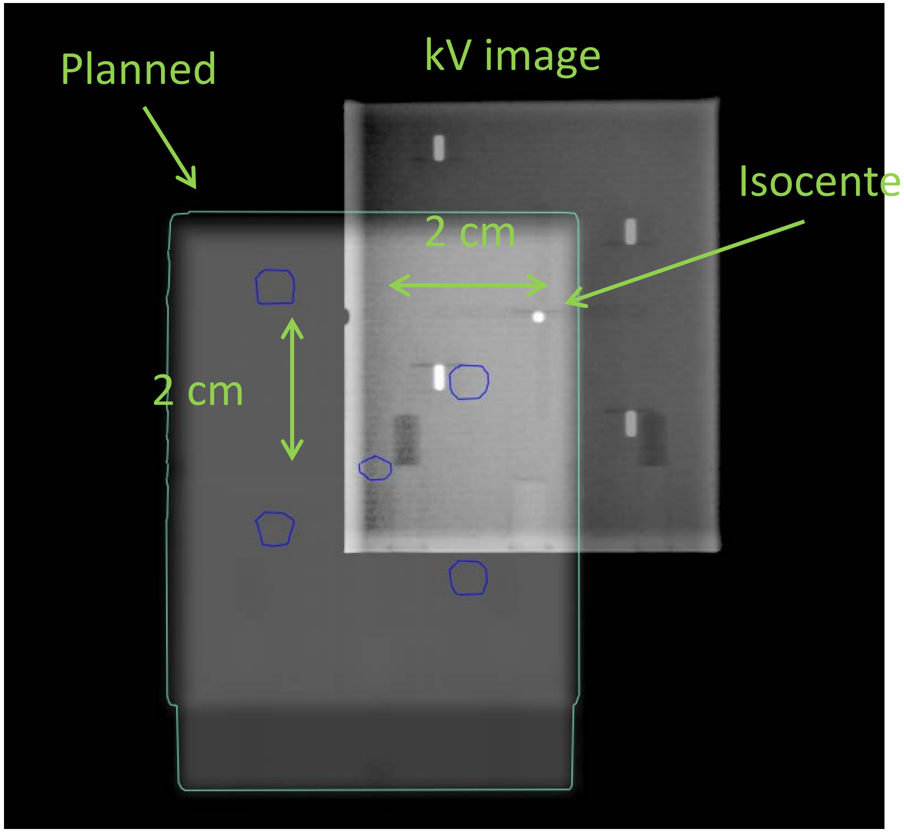
# Manufacturer-supplied QA block for CBCT and MV tests

1 central BB, 1/16” dia, 4 rods 1/16” dia, 1/8” long

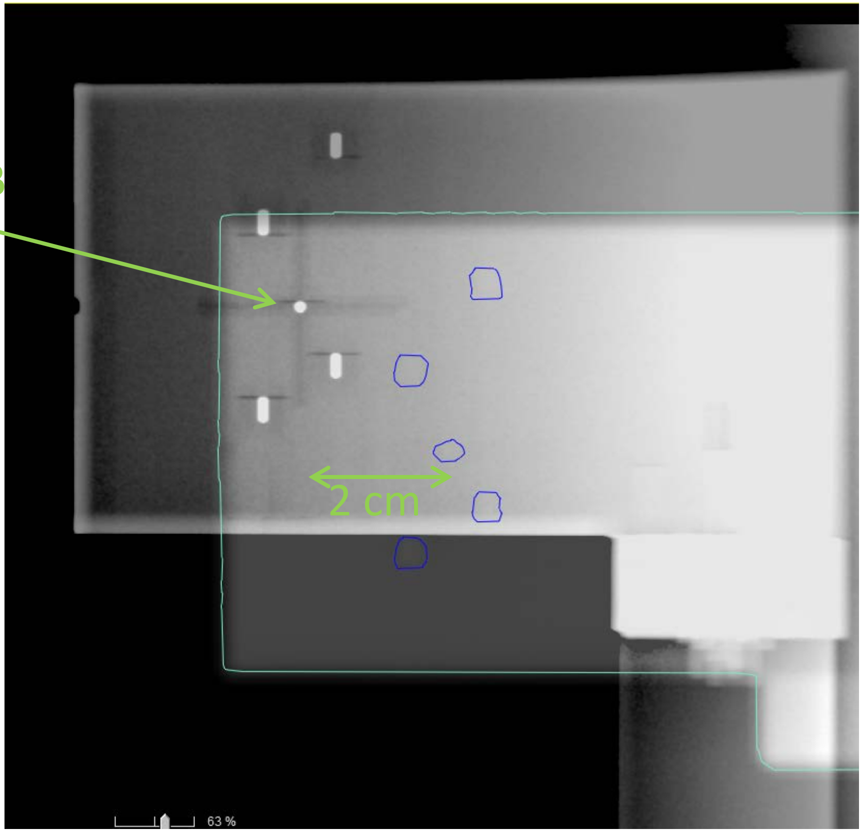
Offset ink marks for initial setup

# kV images of block, purposely offset by 2 cm in each direction

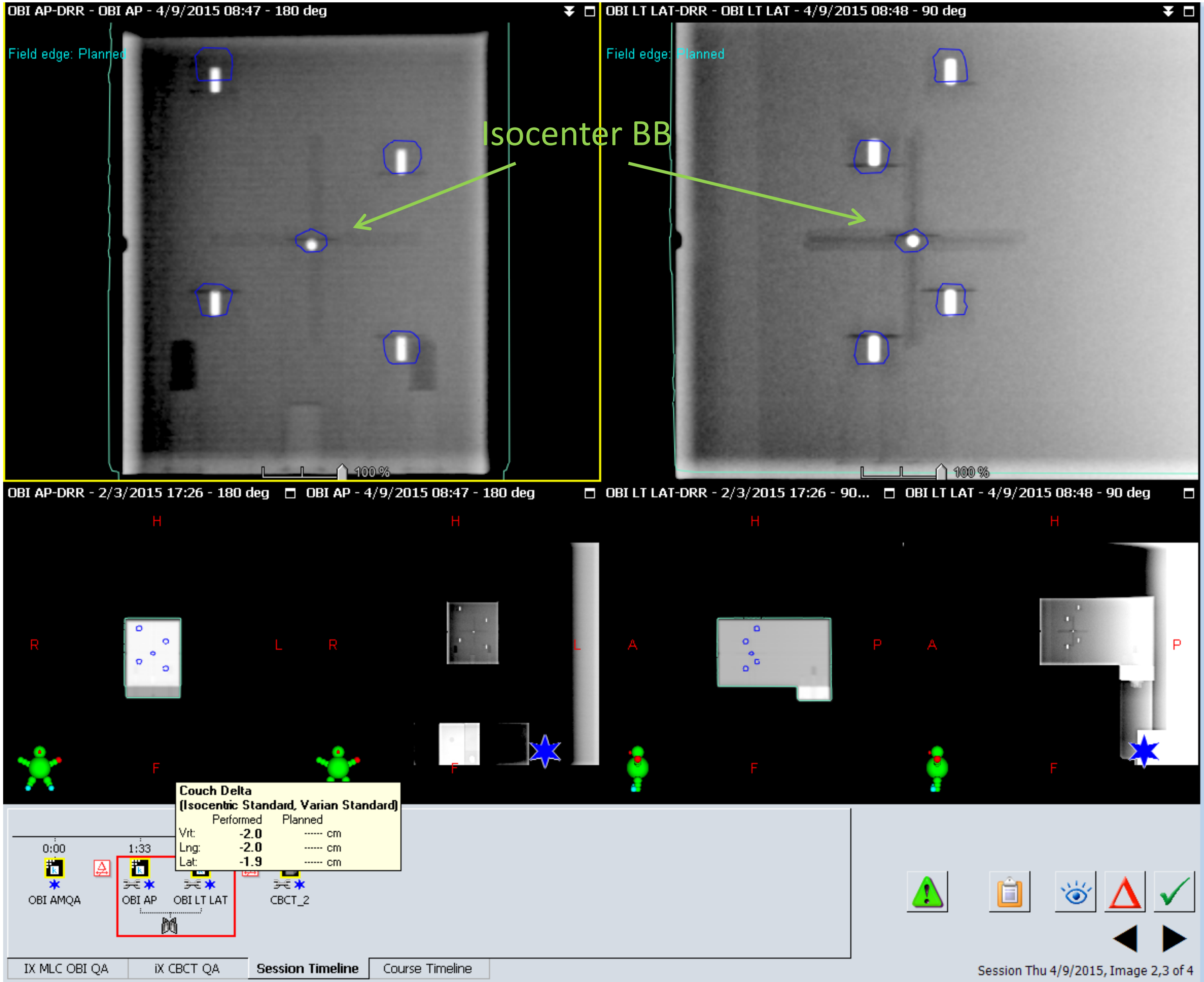
AP planar kV image



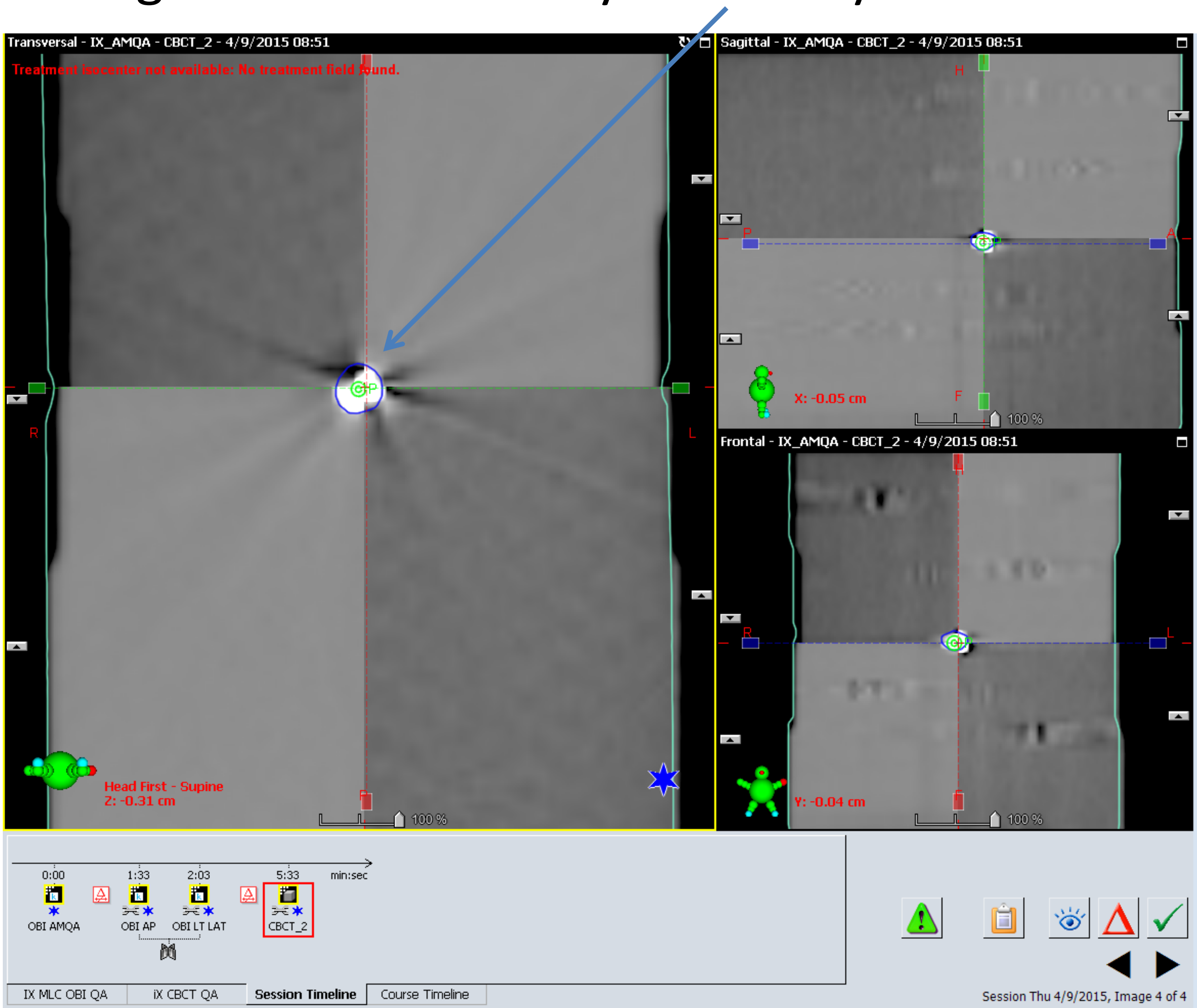

LAT planar kV image



# Registration shows offset distances (should be 2.0 cm)



# CBCT registration:  Accuracy limited by artifacts of BB

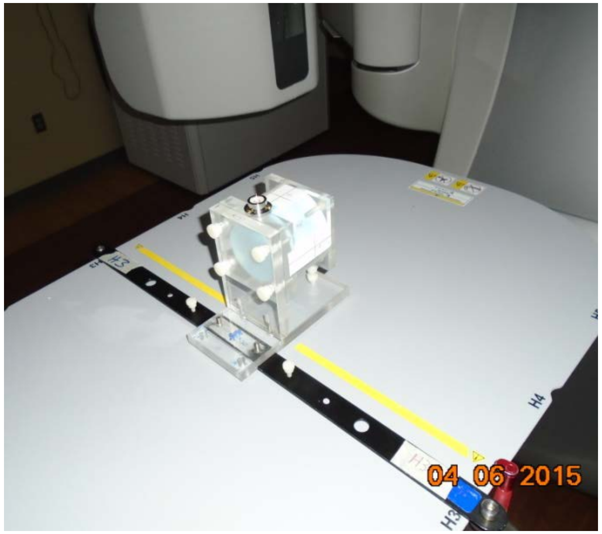


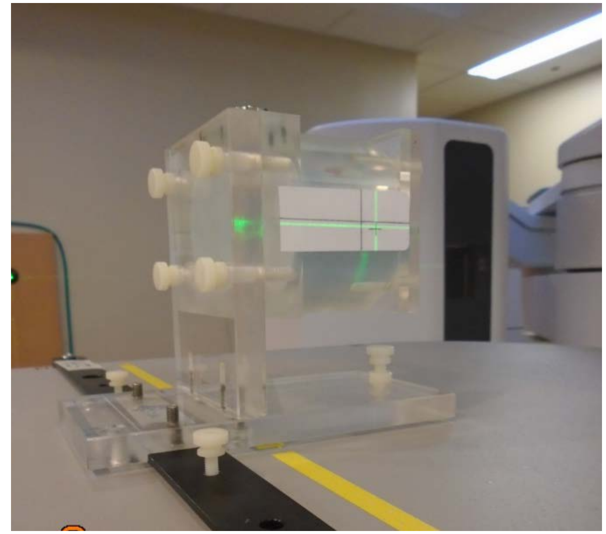
# Results from test:

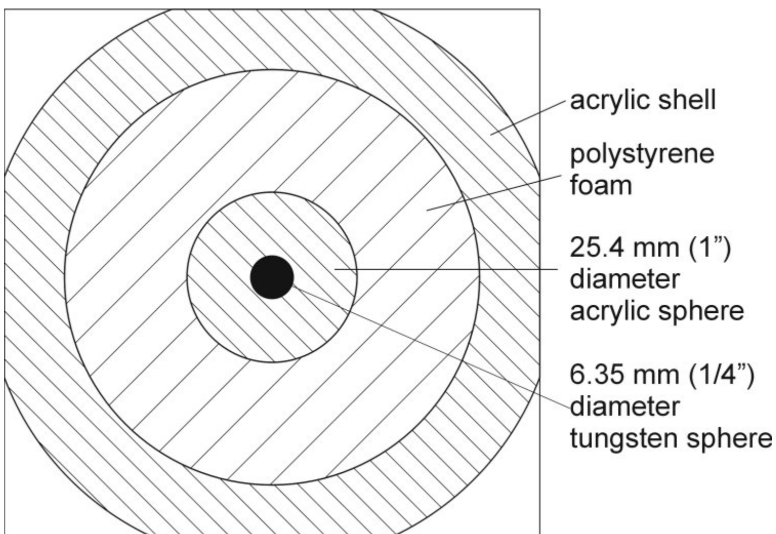
- Lasers are accurately aligned
- kV isocenter matches TPS isocenter
- CBCT isocenter matches planar kV and TPS isocenter
- Couch moves in proper direction
- Couch moves at the proper distance (as directed from console)

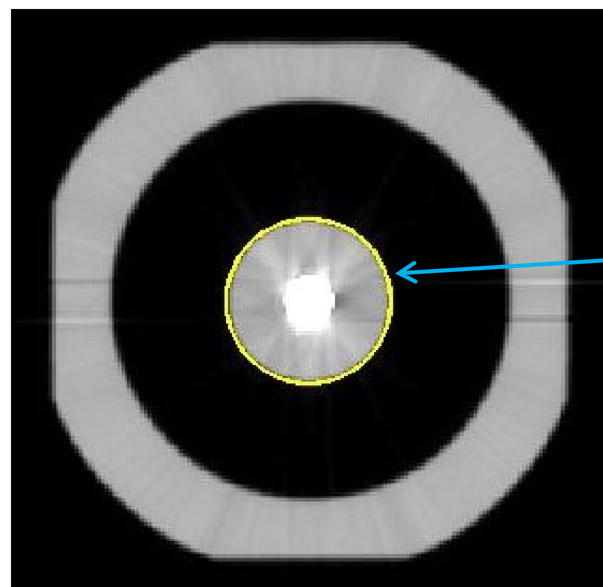
Limitation:  mm accuracy (not sub-mm accuracy) of CBCT isocenter due to artifacts of BBs in CT

# Universal Alignment Ball (UAB) set up for morning QA



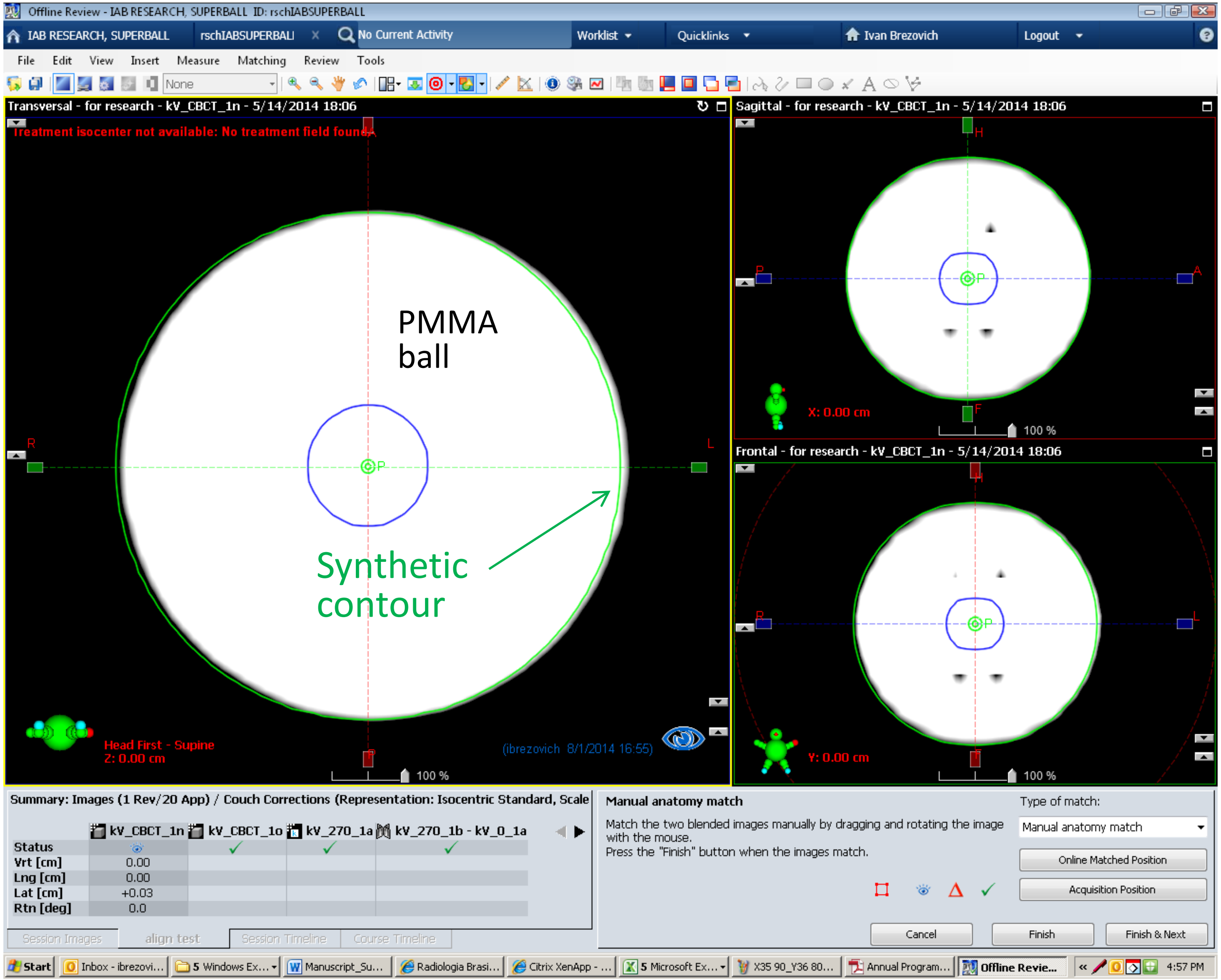





CT artifacts do not reach PMMA sphere surface

# Registration of image of 25.4 mm PMMA ball with synthetic contour
# Mismatch of < 0.1 mm readily discernible

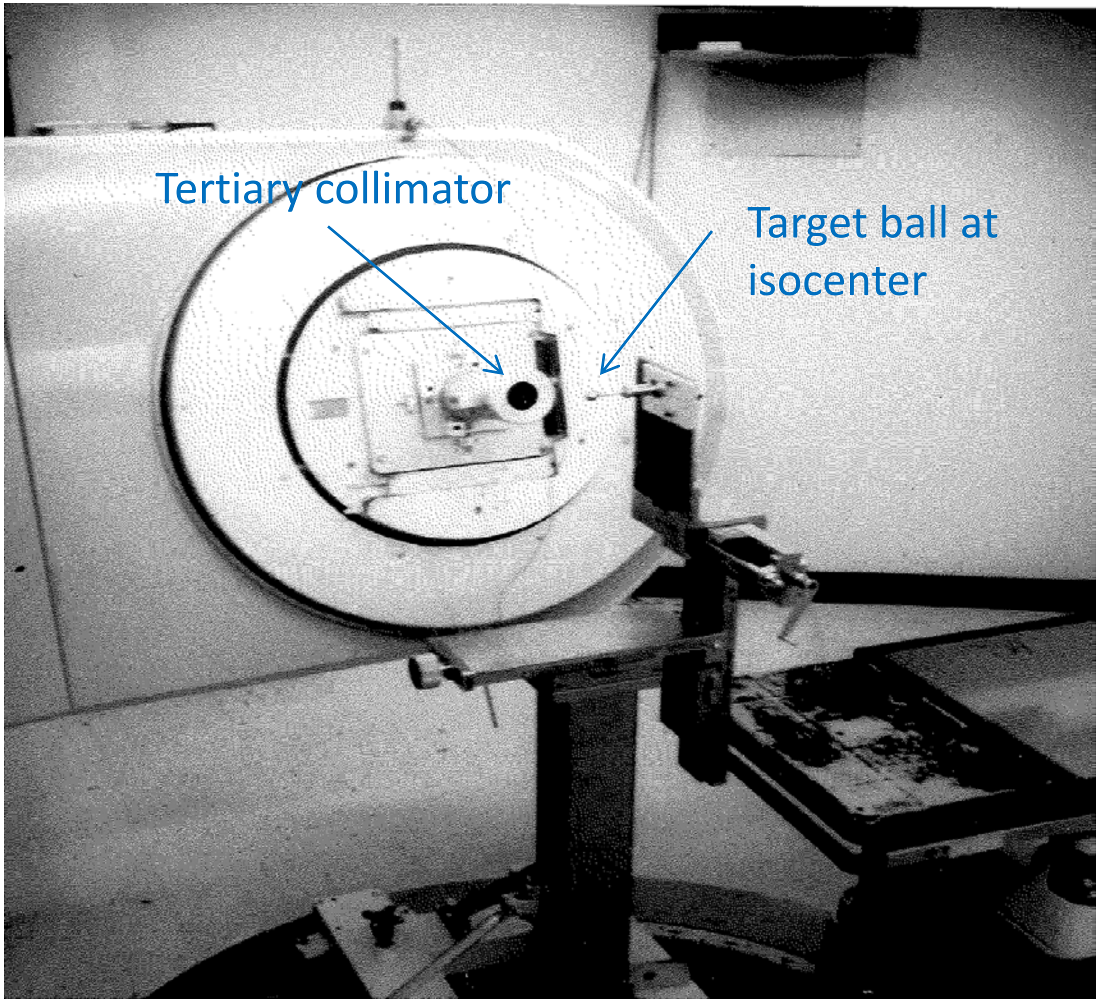


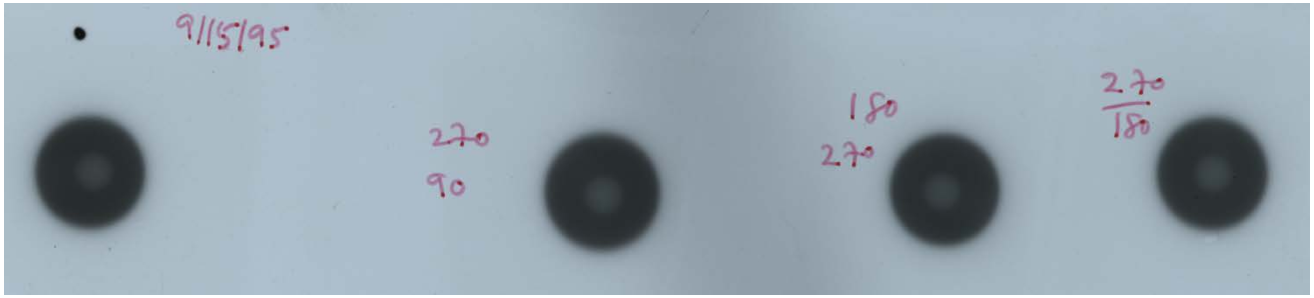
# Precision of UAB phantom: 0.1 mm CBCT isocenter

Measurement errors and standard deviations (in mm) committed by 6 experimenters in determining shift distances of the UAB based on cone beam CT images. Data are averages over 14 shifts.

| exp | *ΔVrt* | *ΔLng* | *ΔLat* | *v* | $v_{max}$ |
|---|---|---|---|---|---|
| 1 | 0.000 ± 0.068 | 0.000 ± 0.048 | 0.000 ± 0.079 | 0.102 ± 0.044 | 0.158 |
| 2 | 0.000 ± 0.056 | -0.007 ± 0.098 | 0.000 ± 0.059 | 0.121 ± 0.042 | 0.185 |
| 3 | 0.000 ± 0.066 | 0.000 ± 0.068 | -0.007 ± 0.068 | 0.098 ± 0.052 | 0.192 |
| 4 | 0.000 ± 0.056 | 0.000 ± 0.079 | -0.007 ± 0.073 | 0.105 ± 0.046 | 0.175 |
| 5 | -0.007 ± 0.040 | -0.007 ± 0.052 | 0.000 ± 0.062 | 0.079 ± 0.033 | 0.136 |
| 6 | 0.000 ± 0.074 | 0.000 ± 0.064 | 0.000 ± 0.076 | 0.100 ± 0.052 | 0.192 |
| all | -0.001 ± 0.057 | -0.002 ± 0.068 | -0.002 ± 0.069 | 0.102 ± 0460 | 0.192 |

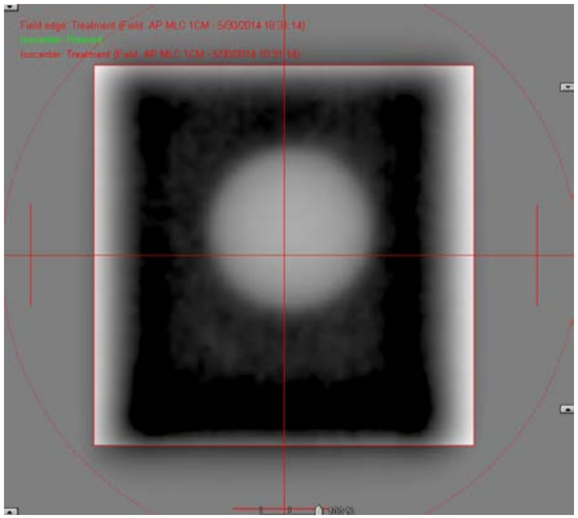
# Winston-Lutz test



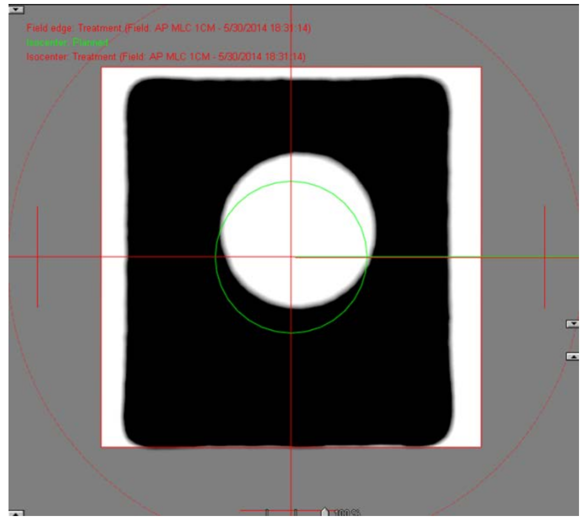



# Daily Winston-Lutz test of MLC field 15x15 mm$^2$ using ¼” tungsten ball

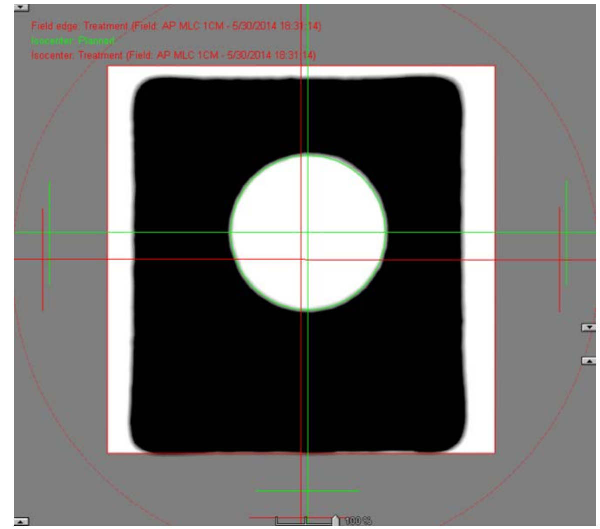
1. Take MV image of ball at CBCT isocenter



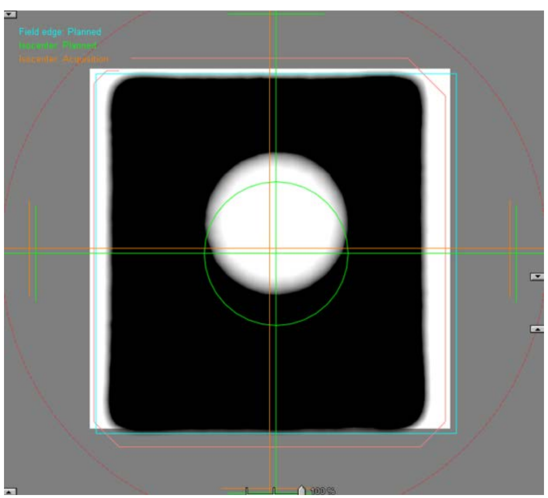
2. Adjust contrast to get sharp outline of ball



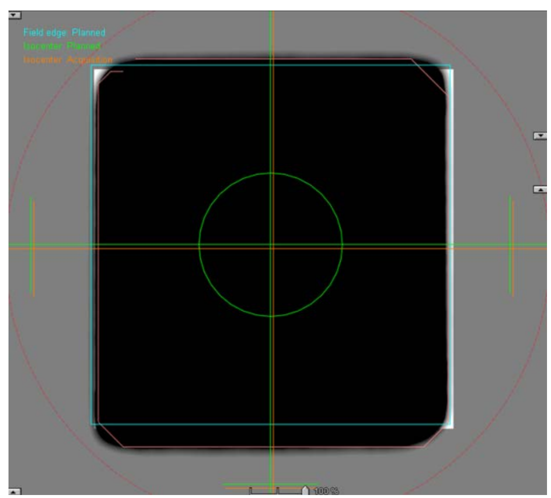
3. Shift contour to match ball. Record shift distance



4. Adjust contrast to get sharp outline of sup and inf field edges. Match edges, record shift distance



5. Adjust contrast to get sharp outline of lateral field edges Match edges, record shift distance



Aperture-Isocenter misalignment =
(shift vector of aperture) –
(shift vector of ball)

# Results of daily Winston-Lutz tests (average over 44 treatment days)

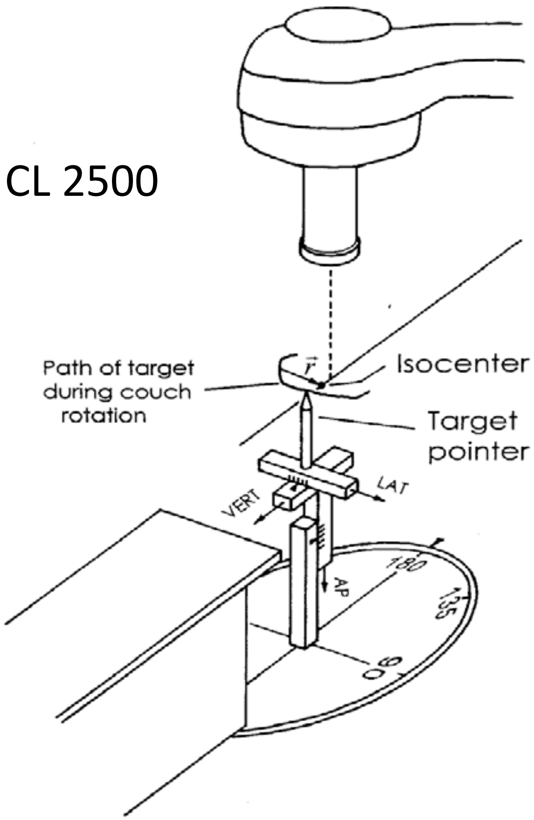
MV beam alignment measurements (in mm) taken by therapists during routine morning QA tests, averaged over 44 treatment days. Second column: Distances between the center of the tungsten ball and the MV synthetic graticule. Third column: Distances between images of MLC-defined central ray and the MV synthetic graticule. Last column: Misalignment between MLC-defined central ray and cone beam CT isocenter.

| Direction | Shift distance ball (mm) | Shift distance aperture (mm) | (Shift dist aperture) – (Shift dist ball) (mm) |
|---|---|---|---|
| **Vrt (Lat image)** | 0.080 ± 0.081 | 0.107 ± 0.065 | 0.027 ± 0.090 |
| **Lng (AP image)** | 0.204 ± 0.175 | 0.133 ± 0.117 | - 0.071 ± 0.165 |
| **Lng (Lat image)** | 0.178 ± 0.182 | 0.349 ± 0.164 | 0.171 ± 0.165 |
| **Lat (AP image)** | 0.011 ± 0.080 | -0.091 ± 0.072 | - 0.102 ± 0.106 |

# Future developments: Automatic couch shifts to correct for inaccurate couch axis alignment?

Manually applied couch shifts keep target at isocenter, achieved targeting error of 0.47 ± 0.23 mm despite 2.7 mm couch wobble

CL 2500



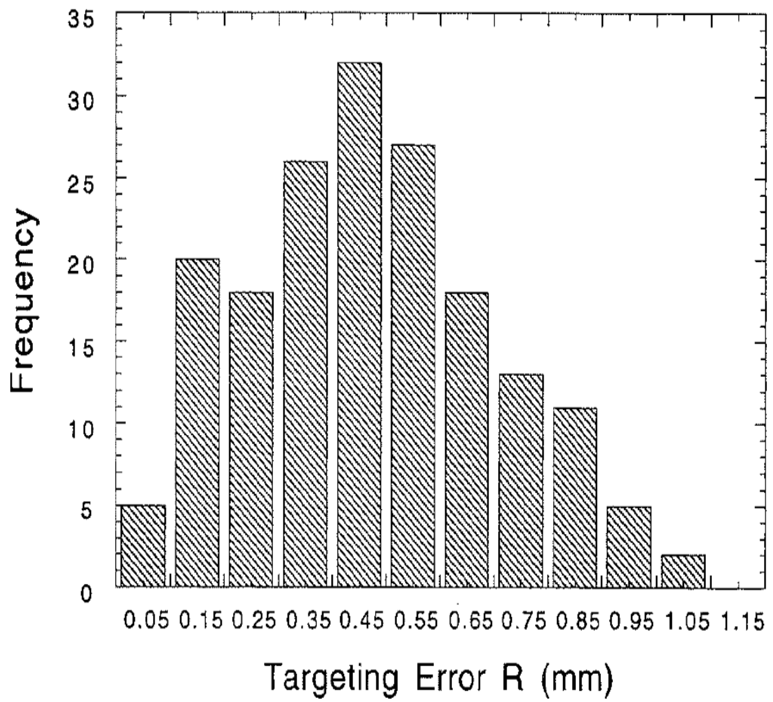




Fig. 10. Frequency distribution of targeting error R in 177 check films. R is defined as the distance between the center of the target simulator ball and the center of the circular radiation beam.

Brezovich, I.A., Pareek, P.N., Plott, W.E., Jennelle, L.S.: "Quality assurance system to correct for errors arising from couch rotation in Linac-based stereotactic radiosurgery." Int J Radiat Onc Biol Physics, 38: 883-890, 1997.

# Future developments: Automatic couch shifts to correct for gantry flex?

Suggested in literature: Move collimator (or MLC) to stay aimed at isocenter
Suggested by presenter: Move couch so that target stays at isocenter

CL 2500

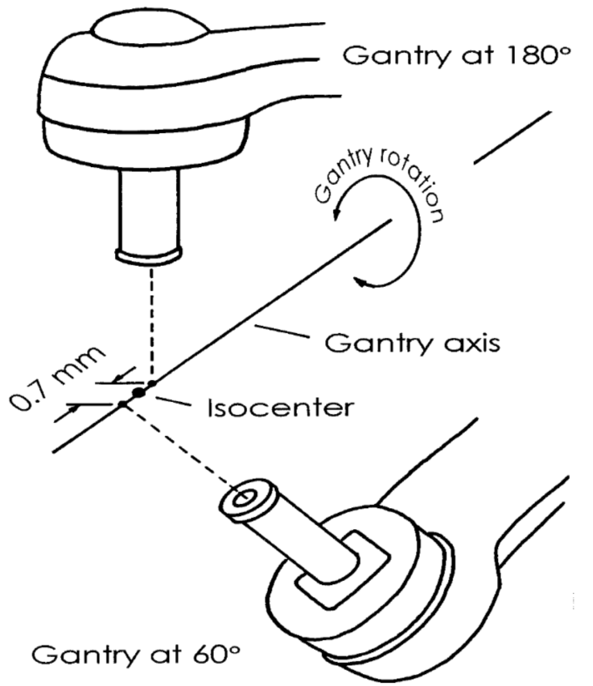



Fig. 2. Due to gantry flex the beam axis shifts as the gantry is rotated.

Brezovich, I.A., Pareek, P.N., Plott, W.E., Jennelle, L.S.: "Quality assurance system to correct for errors arising from couch rotation in Linac-based stereotactic radiosurgery." Int J Radiat Onc Biol Physics, 38: 883-890, 1997.

# ISO Cube Phantom


| | |
|---|---|
| **Dimensions** | 12 cm x 12 cm x 12 cm (4.75" x 4.75" x 4.75") |
| **Phantom Weight** | 1.7 kg (3.9 lb) |
| **Material** | Plastic Water® |
| **Fiducials** | Qty: 4<br>Material: Ceramic<br>Diameter: 6.35 mm |
| **OBI Auto-Registration Target** | Qty: 1<br>Material: Aluminum |
| **Model 023 Includes** | ISO Cube Daily QA Phantom |

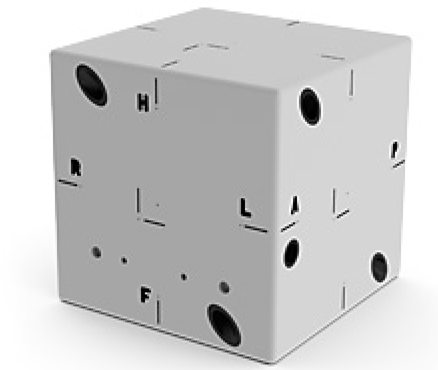
CIRS website, accessed April 18, 2015

# CIRS: STE2EV phantom

**STE2EV Stereotactic End-to-End Verification Phantom Patient**

CIRS website, accessed April 18, 2015

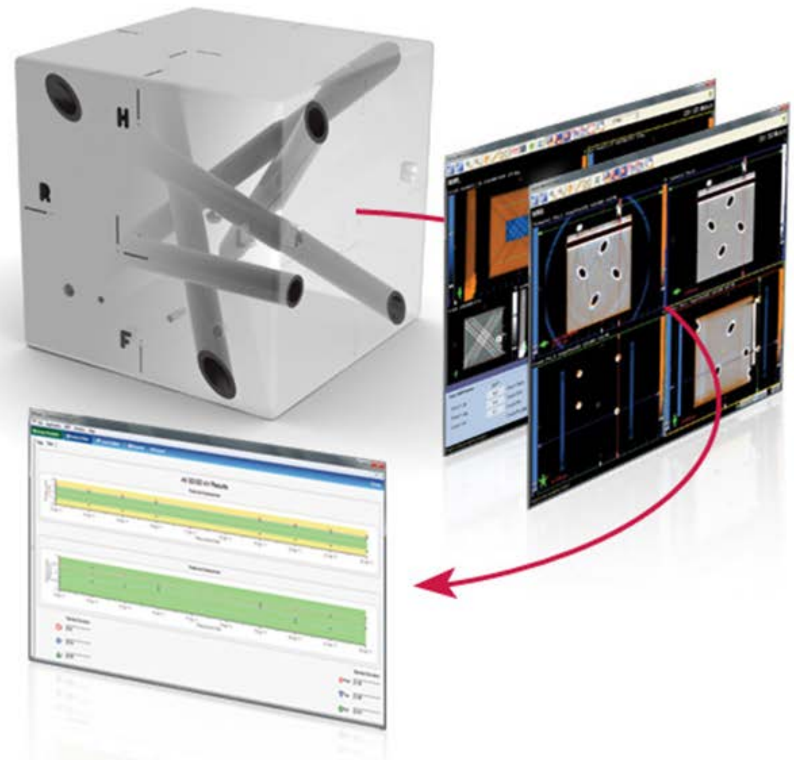
# Standard imaging: MIMI Phantom




OVERVIEW   SPECIFICATIONS   RELATED PRODUCTS   SUPPORT & FAQ

## Easy Alignment, Automatic Registration

Five bone equivalent rods intersect at 90 degree angles. These rods are visible in any image or slice for automatic registration of 2D/2D and 3D/3D matching and verification of isocenter position.




### Fast, Accurate Alignment Checks

- Establish mechanical stability of an image guidance system by verifying isocenter within 1 mm.
- A 6.4 mm sphere at the center of the phantom assists with virtual and physical graticule alignment checks.

### Test Integrated System Accuracy of:

- 3D Cone Beam registration (CBCT, OBI, XVI) systems
- MV/kV Isocentricity

Standard Imaging website, accessed  Jan 29, 2015

# Standard Imaging: Lucy Phantom

**End-to-End Stereotactic QA**

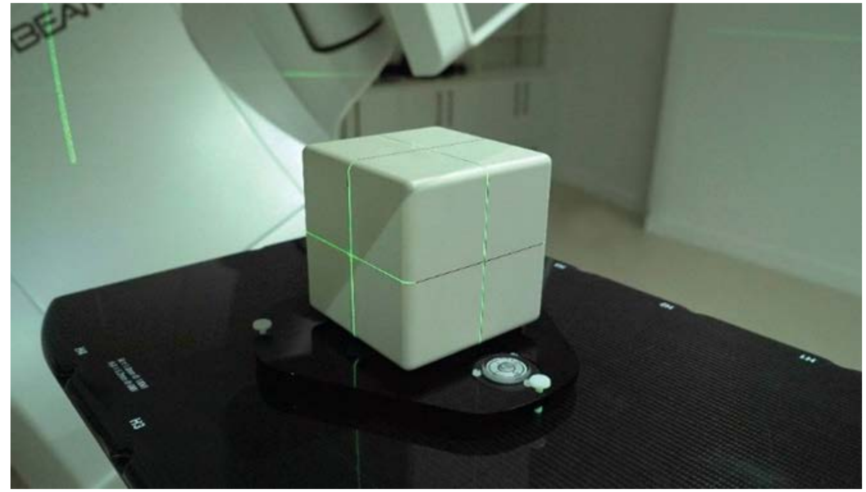
**Precise QA Throughout the Imaging Chain**

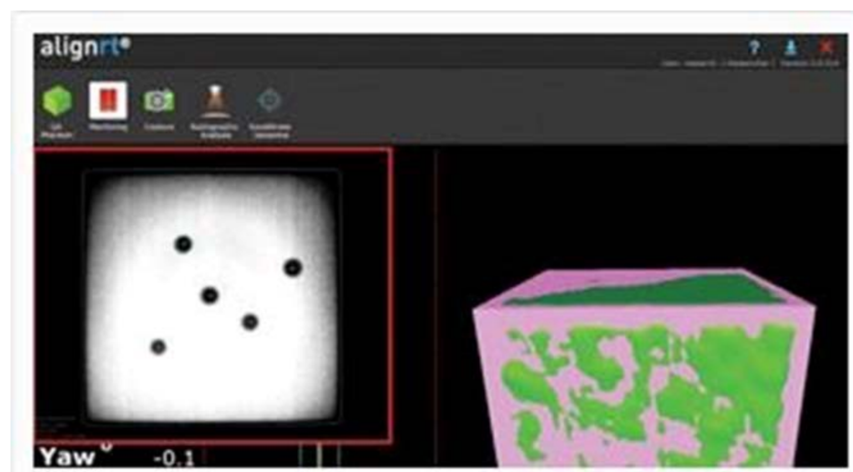
Quantifies variances by measuring cumulative uncertainties, from imaging to dose delivery, within 0.1mm

Standard Imaging website, accessed Jan 29, 2015

# VisionRT: Calibration Phantom

- Verified coincidence of MV, kV and VRT isocenters
- Internal spheres: isocenter calibration software automatically corrects for VRT and MV isocenter mismatches
- Allows high accuracy tracking of surface at all couch rotations (*frameless SRS*)






VisionRT website, accessed Jan 29, 2015

# Modus Medical Devices: QUESAR Penta-Guide Phantom

Perform true spatial alignment and coincidence tests on IGRT systems

The **QUASAR™ Penta-Guide Phantom** is used for the commissioning and daily testing of Image-Guided Radiotherapy (IGRT) systems. The **QUASAR™ Penta-Guide Phantom** ensures the accuracy of linac-mounted image guidance systems, including cone beam CT (CBCT), x-ray volumetric imaging (XVI) and on-board imaging (OBI).


Minimize imaging artifacts by making use of the Penta-Guide's **low-density objects** to allow for rapid and easy daily testing of:
- 3D cone beam registration
- kV and MV system coincidence
- kV and MV projection images
- Laser and light field coincidence
- Remote table adjustments

Modus website, accessed April 20, 2015

# Mobius Medical Systems: DoseLab WL$^3$ Phantom

Made from Plastic Water® and easy to align, the WL3 phantom is designed for DoseLab's Winston-Lutz analysis. The WL3 phantom contains a hidden 5mm **ceramic** sphere at the center, which is easily revealed during MV and kV imaging. Off-set alignment markers are also incorporated, making the WL3 phantom ideal for checking IGRT coincidence accuracy.

Mobius website, accessed April 18, 2015

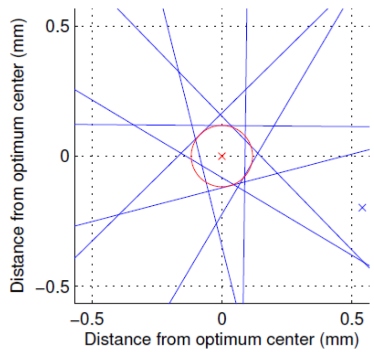
# Mobius Medical Systems: DoseLab QA software

**DoseLab Starshot Results**
Summary: All tests passed

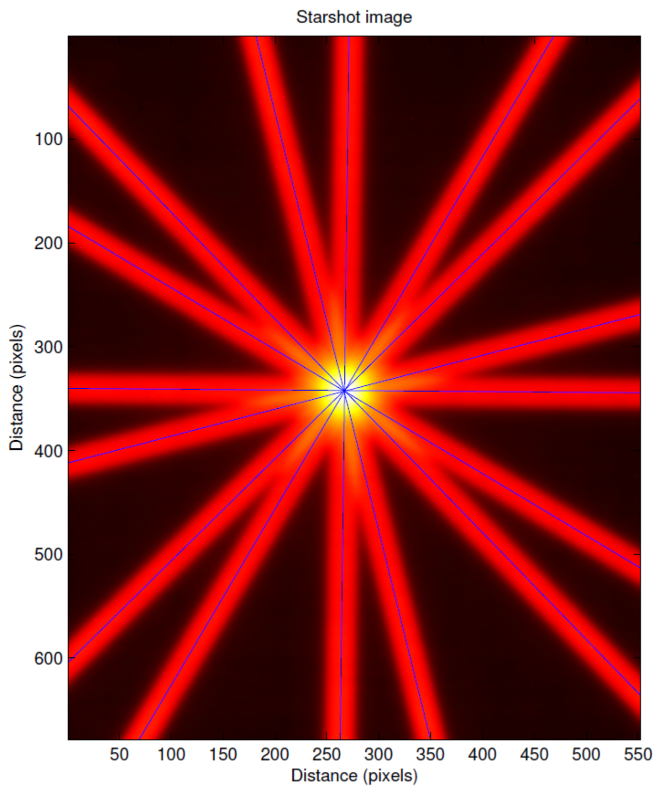
DoseLab version: 6.60
Date: July 07, 2014
Machine: Demo Only, Not Clinical
File: "Starshot, Easy collimator–OD.tif"
Starshot type: Not specified
Performed by: Test User
Tolerance set: Default

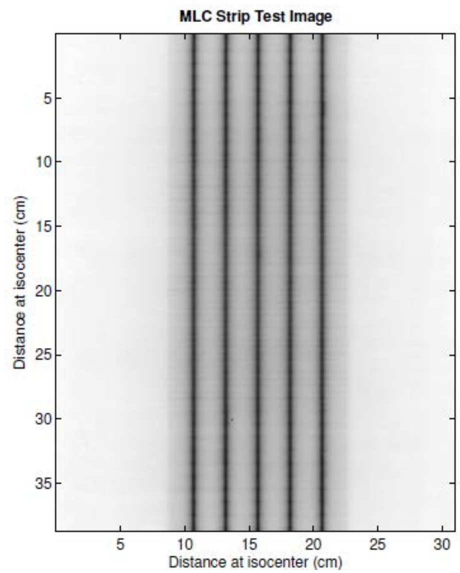
Diameter: 0.24 mm (Pass)
Isocenter offset: 0.57 mm (Pass)

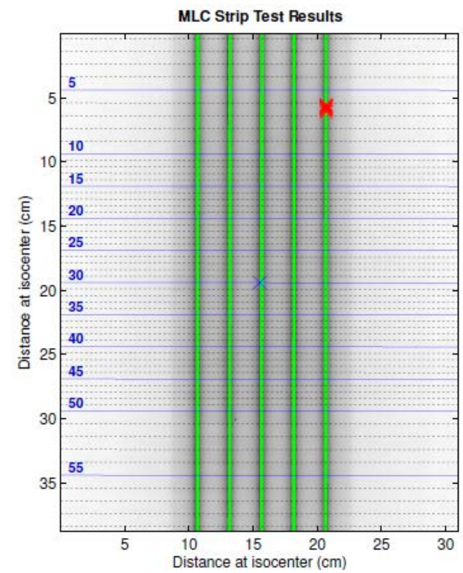
**Note:**
For Test Purposes Only




MLC picket fence test evaluation

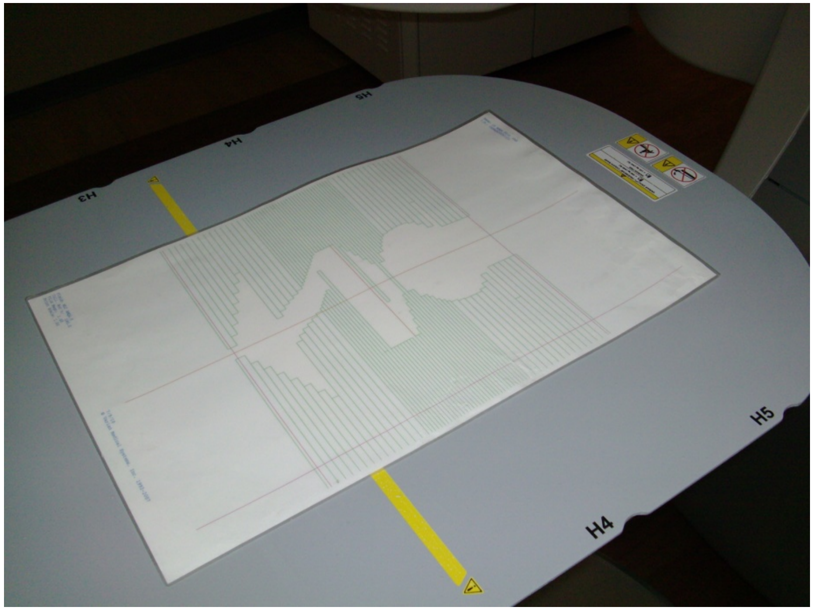


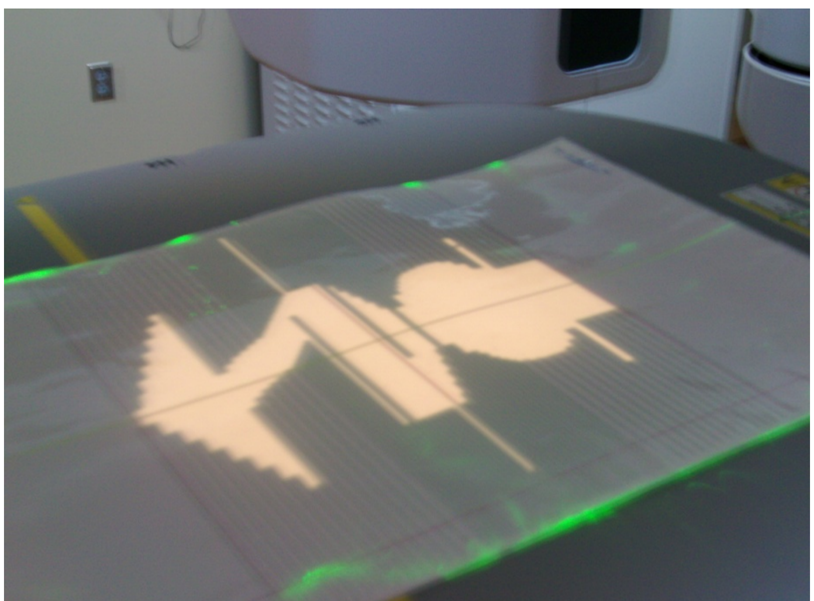




Mobius website, accessed April 18, 2015

# Daily MLC test for entire field at UAB




Irregular MLC field checked with template and light field



1 mm MLC discrepancies readily discernible

# Conclusions

Off-the-shelf components make it possible to **achieve** sub-mm precision and to **maintain** it almost indefinitely

Medical physicists must remain vigilant to consistently verify precision