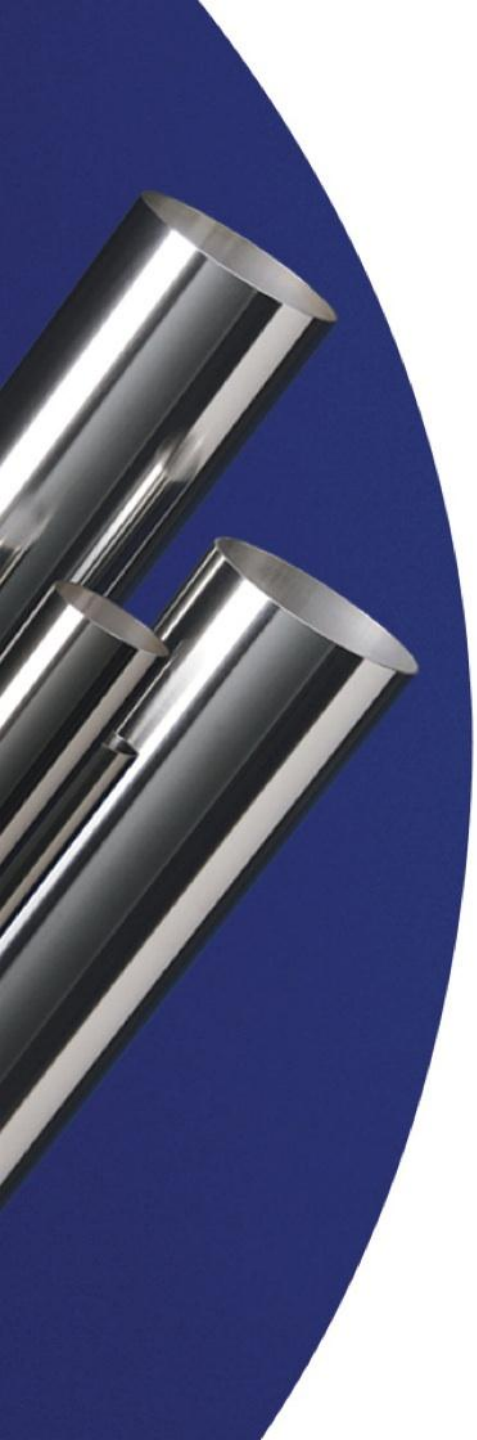
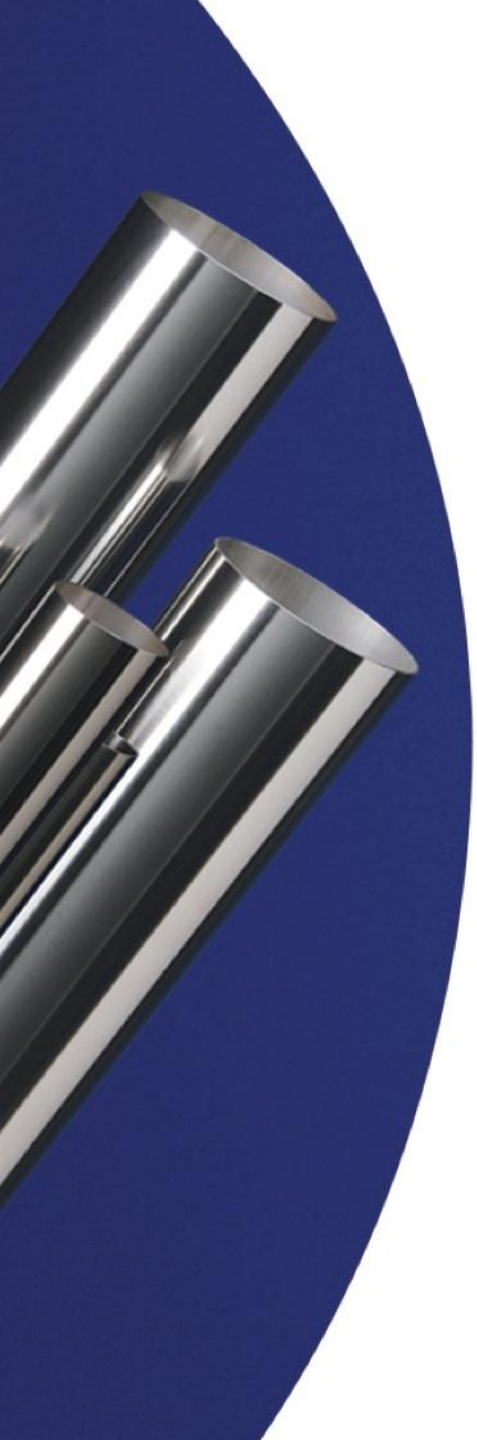


Laser Welded Beam Tube: Testing & Application

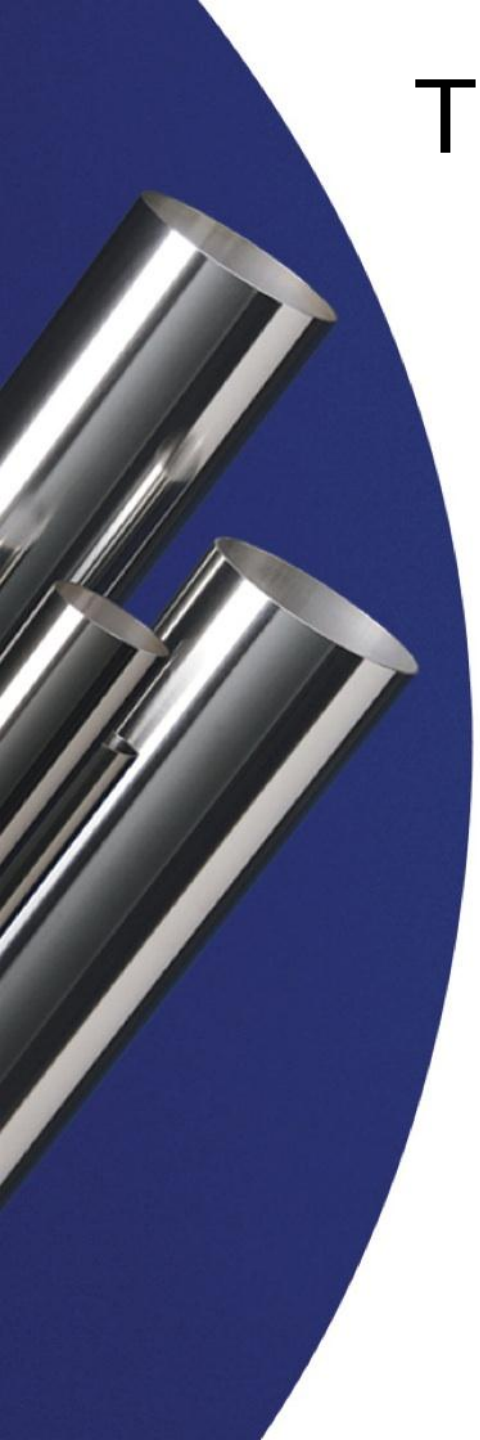
J. DiMarco, R. Schultz, L. Valerio

February 25, 2014



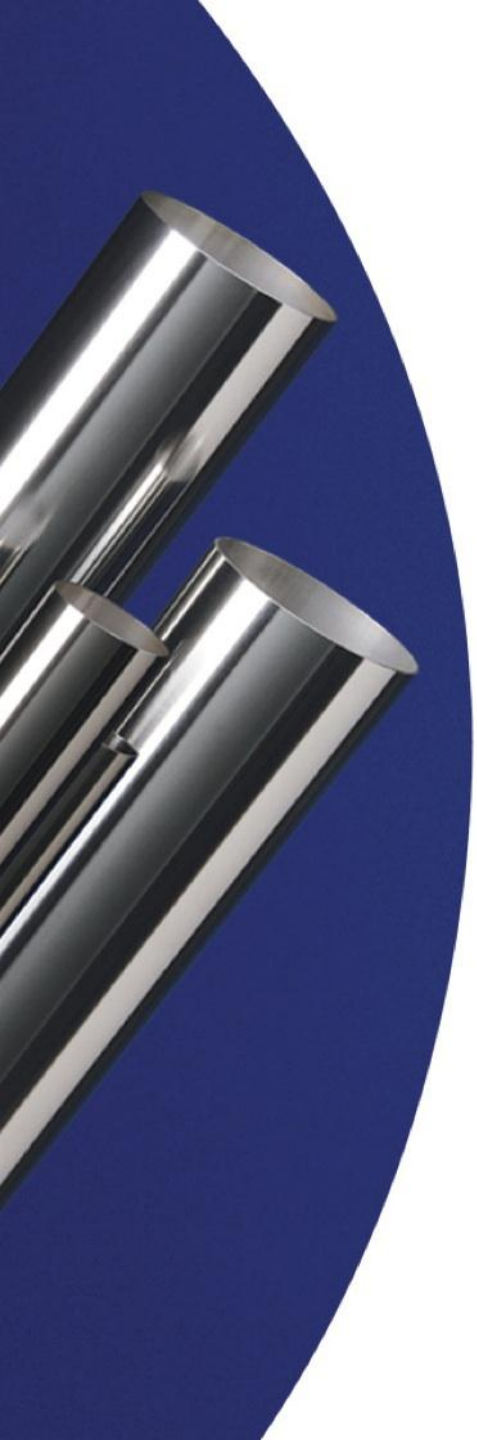
Overview

- Introduction, History, and Recent Difficulties with Seamless Tube
  - Linda Valerio
- Material Properties and Forming Processes
  - Ryan Schultz
- Measurements, Testing, & Conclusions
  - Joe DiMarco



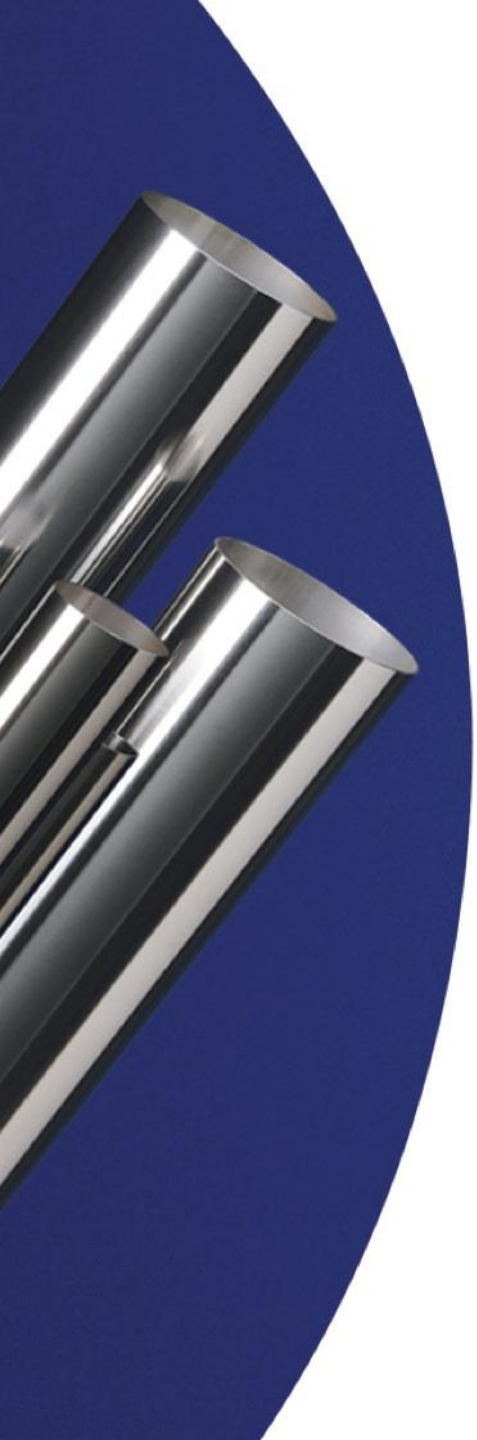
Three Ways to Manufacture Stainless Steel Tubing

- Seamless
  - no welds to interfere with magnetic fields
  - eccentric, wall thickness variation
  - higher cost
- Welded ⟵ **New laser-welded option**
  - ovality, weld bead
- Welded and Drawn (TIG)
  - compromise



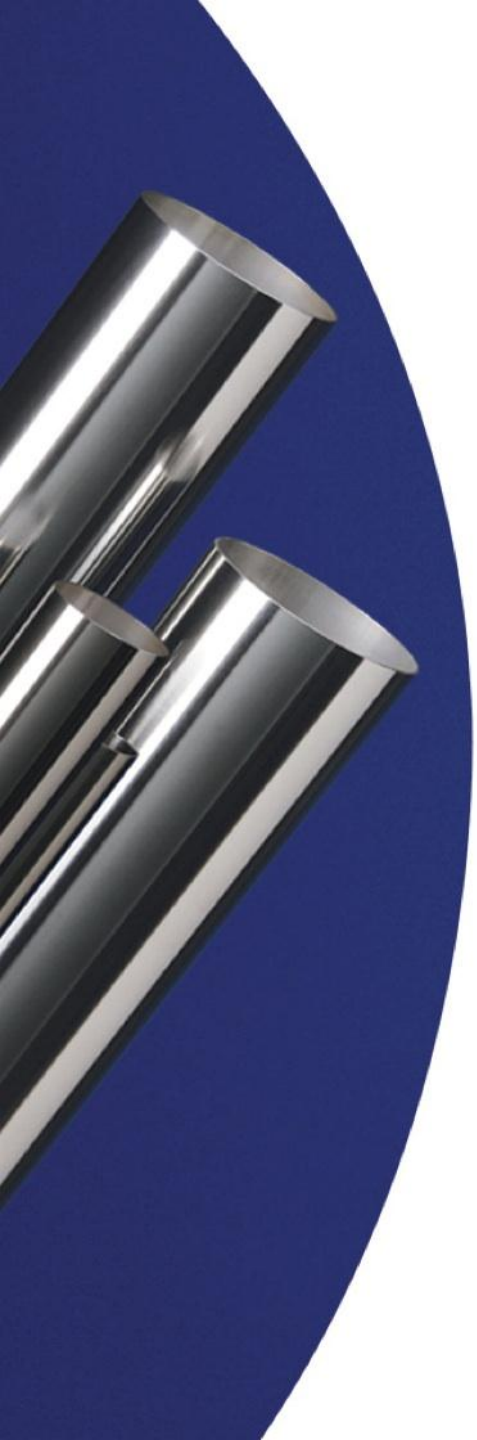
Beam Tube Options

- Seamless tubing
  - The beam tube standard for decades
  - Increasingly difficult to obtain
- TIG-welded tubing (welded & drawn)
  - Not acceptable in most applications due to the magnetic permeability at the seam
  - Annealing the weld causes other problems
- Laser-welded tubing (welded)
  - Newer technology
  - May be a suitable alternative based on material properties, price, and availability



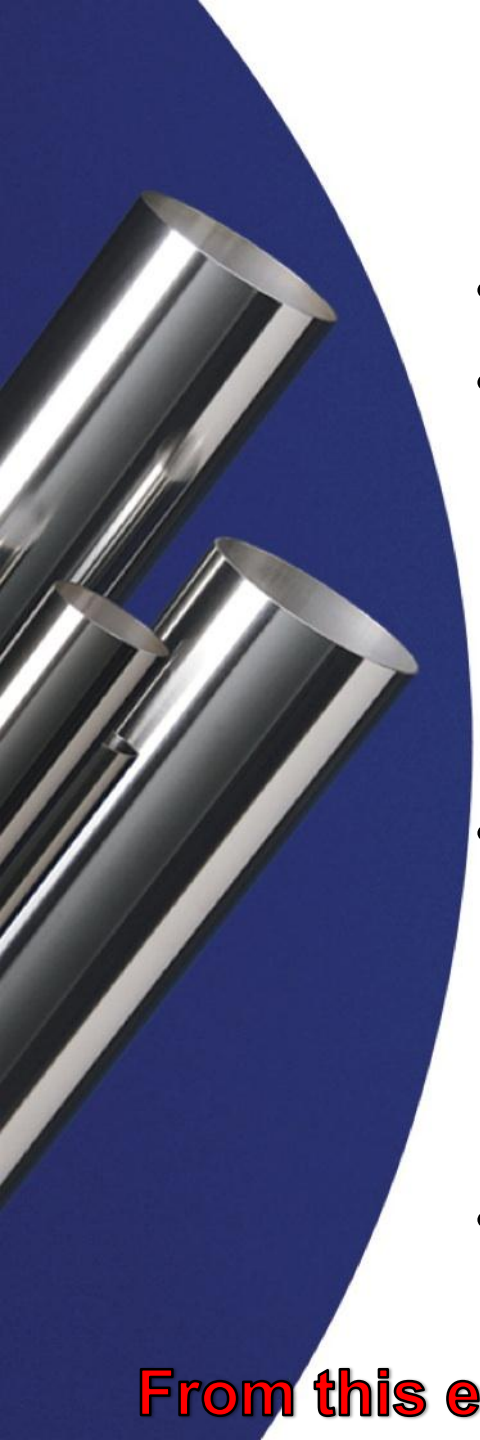
Beam Tube History for Circulating Beamlines

- Seamless 316L with minimal wall thickness
  - low, uniform magnetic permeability ($\mu \leq 1.01$ specified since 1995)
- Welded & drawn 316L allowed for elliptical tube, with weld placed at 45 degrees for minimal effect
- Procurement was simple for round tubes
- Tube for Recycler and other UHV systems required additional treatments
  - electropolishing
  - hydrogen degassing



Recent Difficulties

- Acquiring 600 feet of *standard* 4” OD x 0.065” wall seamless tube for the NOvA/ANU project caused unprecedented cost, labor, and schedule overrun in 2012.
  - Cost and expected ease of availability based on procurements as recent as 2009.
  - Price per foot was approximately twice what was expected.
  - Significant effort spent, and used one calendar year.

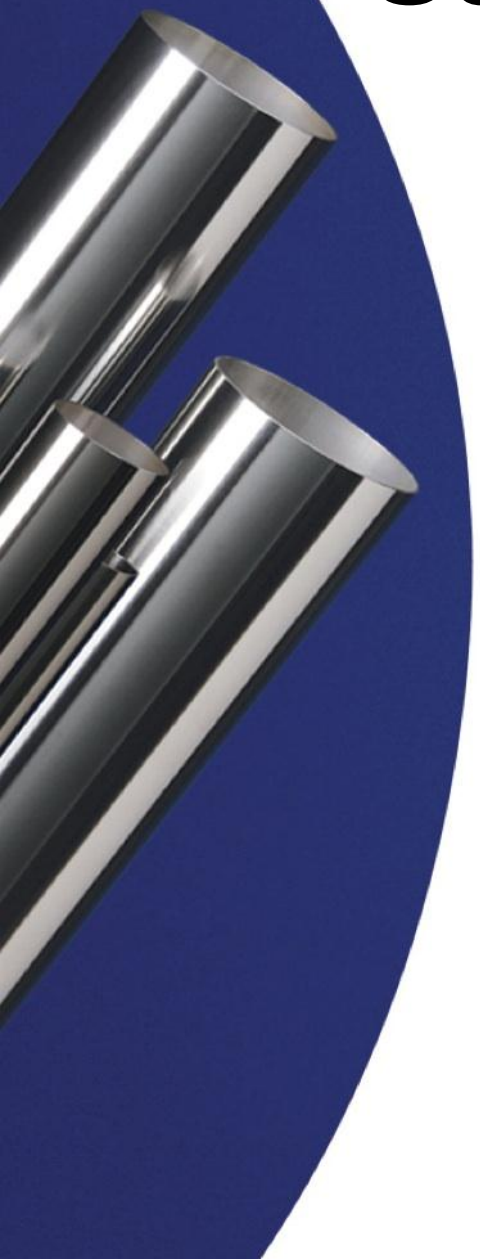


Causes of Difficulties

- Suddenly no seamless available with US origin.
- After exhaustive search, only one vendor able to quote size requested.
  - Not enough stock - had to purchase two different wall thicknesses (.065” and .083”).
  - Premium price ($75/ft) and had to purchase additional 100 ft due to lot sizes.
- Inner surface not acceptable, so tubes sent for mechanical polishing (honing).
  - Added time and cost ($6K).
  - Process reduced wall thickness and was oily process to clean.
- Once cleaned, ready for electropolishing and degassing.

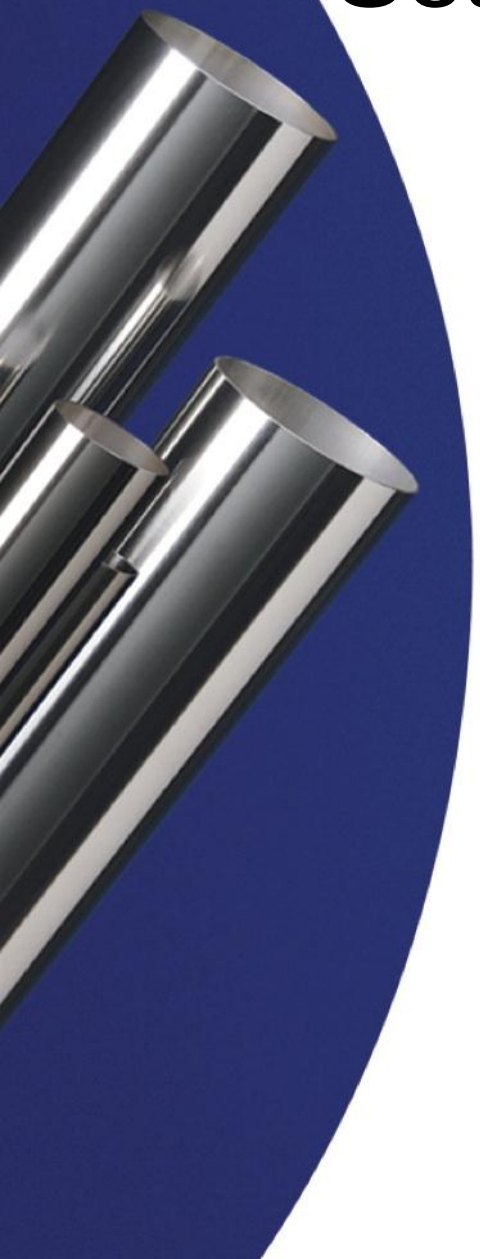
From this experience, definitely time to find alternatives!

Seamless Tubing Formation



- Billets are formed by hot rolling at the steel mill then are peeled, cut, bored, radiused, ground and cleaned
- Billets are heated, lubricated with glass and hot extruded
- Pickling
- Cold drawn or cold-pilgered to final size
- Grit blast ID
- Heat treatment
- Straighten
- Test
- Cut to length

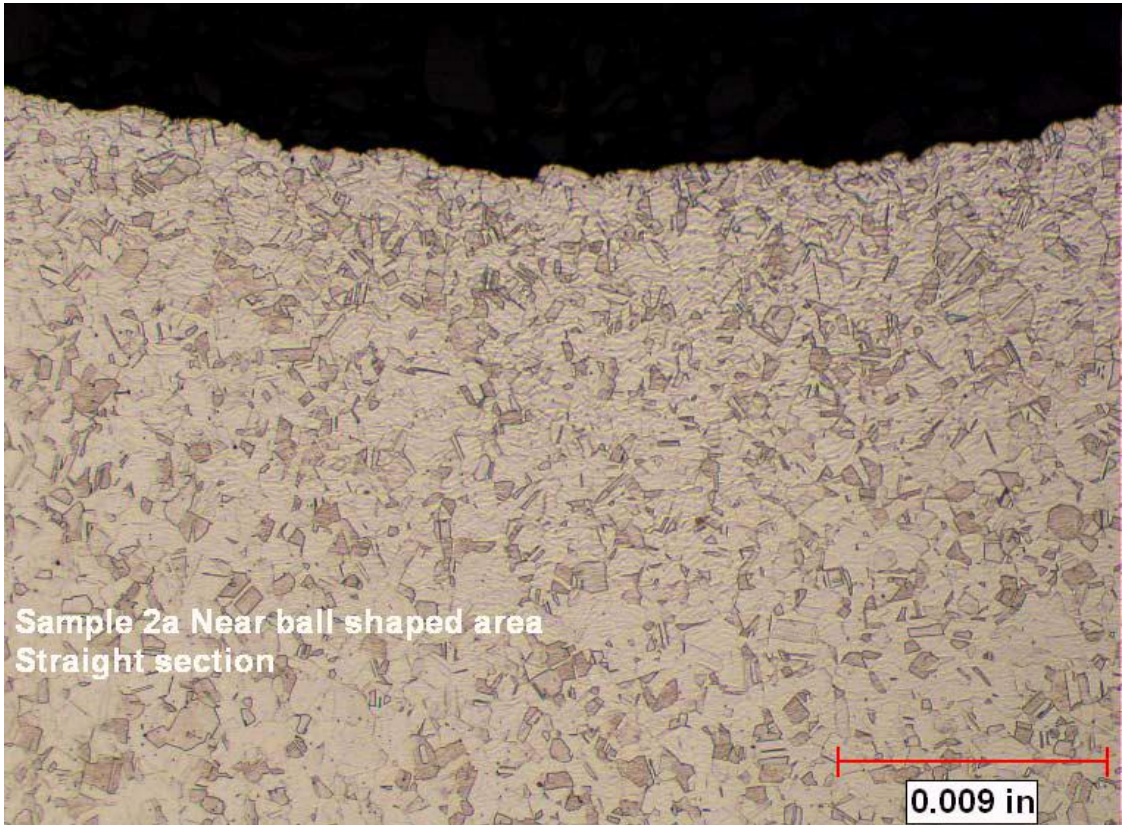
Seamless Tubing Characteristics

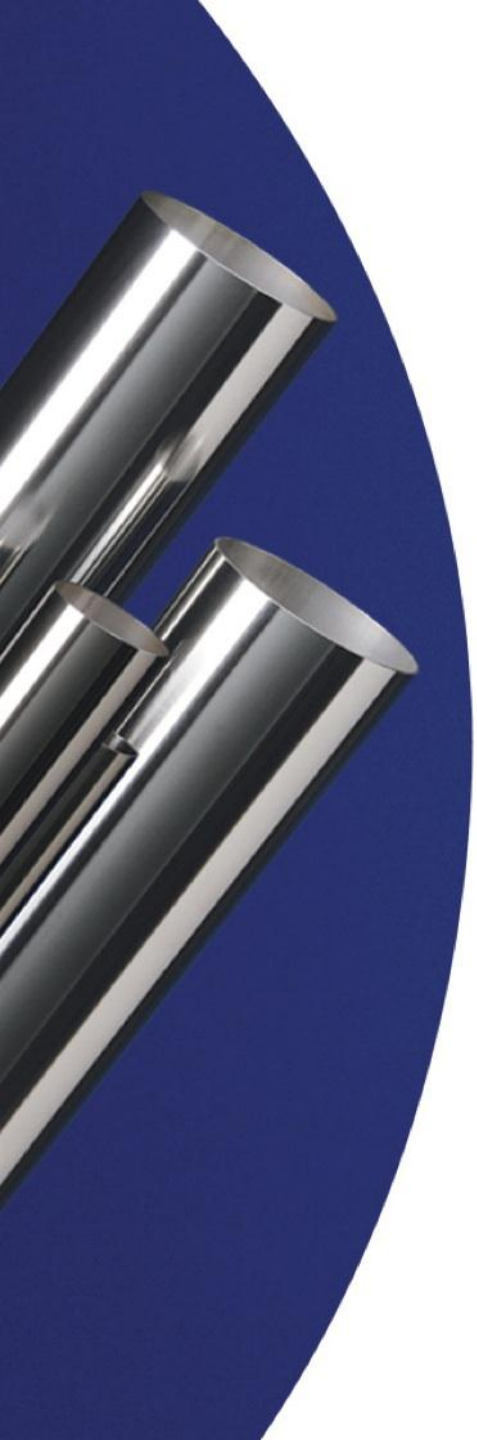


- Wall thickness needs to be increased to compensate for eccentricity
- ID can be eccentric to OD by ± 10% of wall thickness
- ID may be rough due to the large amount of cold reduction
- Typically reduced 90% in cold-pilger process
- Product cost may be 40% to 100% more expensive than welded and drawn tube
- Limited suppliers may result in longer deliveries

Seamless Tubing

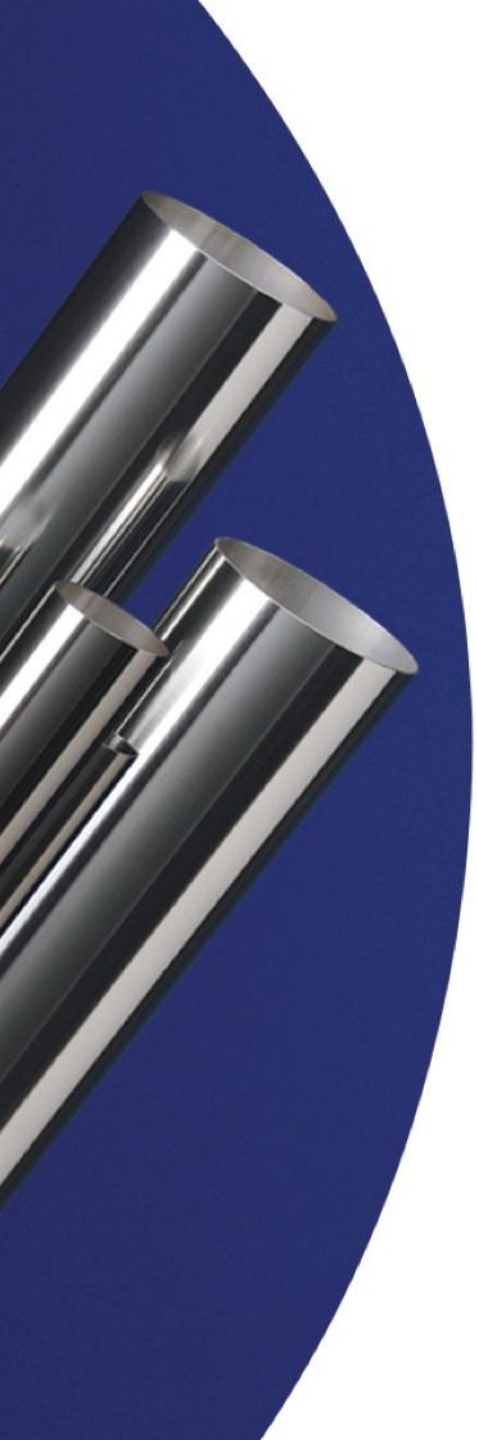
Seamless hollow, cold pilgered and bright annealed





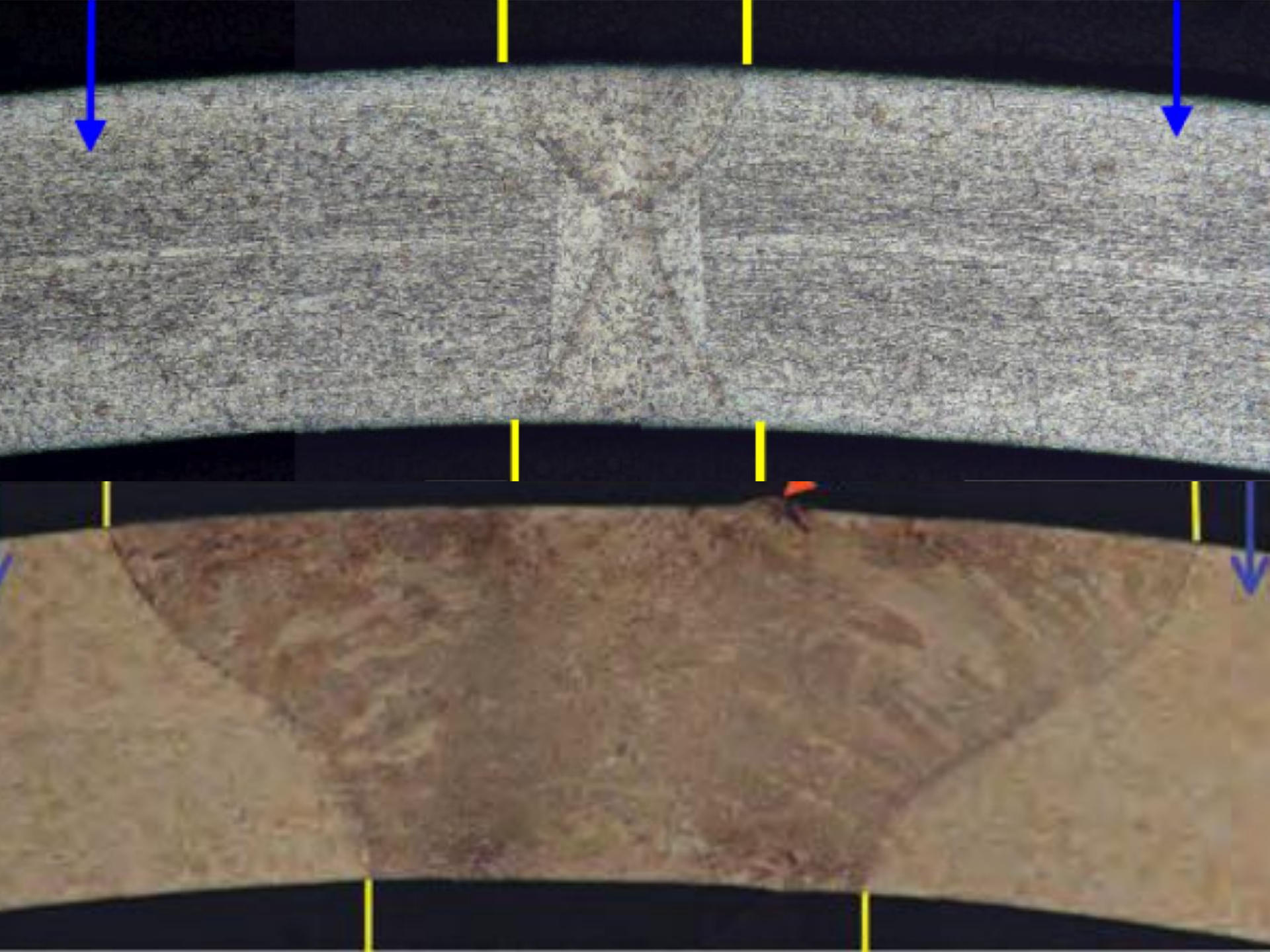
Welded and Drawn

- Welded to a larger diameter than final size
- Heat Treated
- Diameter and Wall are cross-sectionally reduced on a draw bench
  - then additional heat treatment
- Cost is midpoint between seamless and welded
- Similar OD and Wall control to Welded (better than seamless)



Laser Welded Tubing

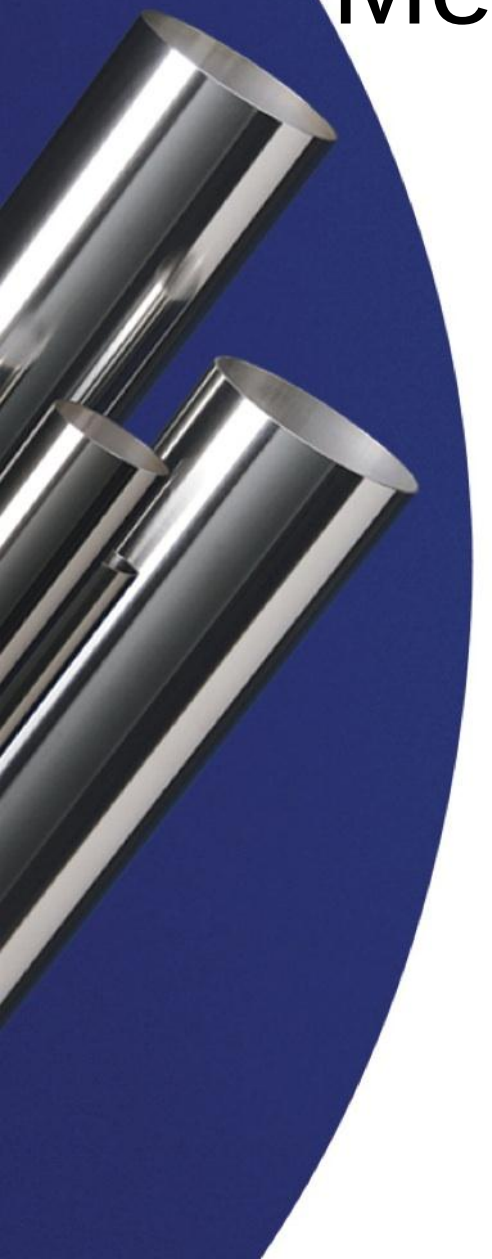
- No filler material
  - Properties virtually identical
    - Chemical
    - Physical
    - Mechanical
- Fuses parent material at weld zone
  - Minimum HAZ
  - Narrow weld seam



Metallurgy of a TIG Weld

- Stainless 304/316 is austenitic
  - Austenite has low solubility for S and P
    - S & P cause cracking during solidification
  - Ferrite
    - Ferrite has high solubility for S & P
    - improves resistance to hot cracking during welding and solidification
    - is also magnetic

Metallurgy of a LASER Weld



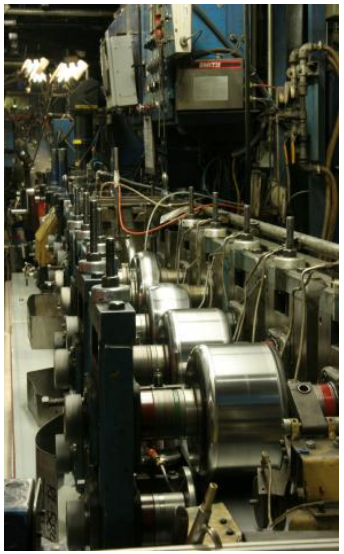
- No filler rod
- Ferrite formation still happens
  - though much smaller than TIG weld
- Post weld solution heat treatment
  - ASTM A 249
  - lowers ferrite levels
  - reduces ferromagnetism of tube
- Volume of HAZ is much less

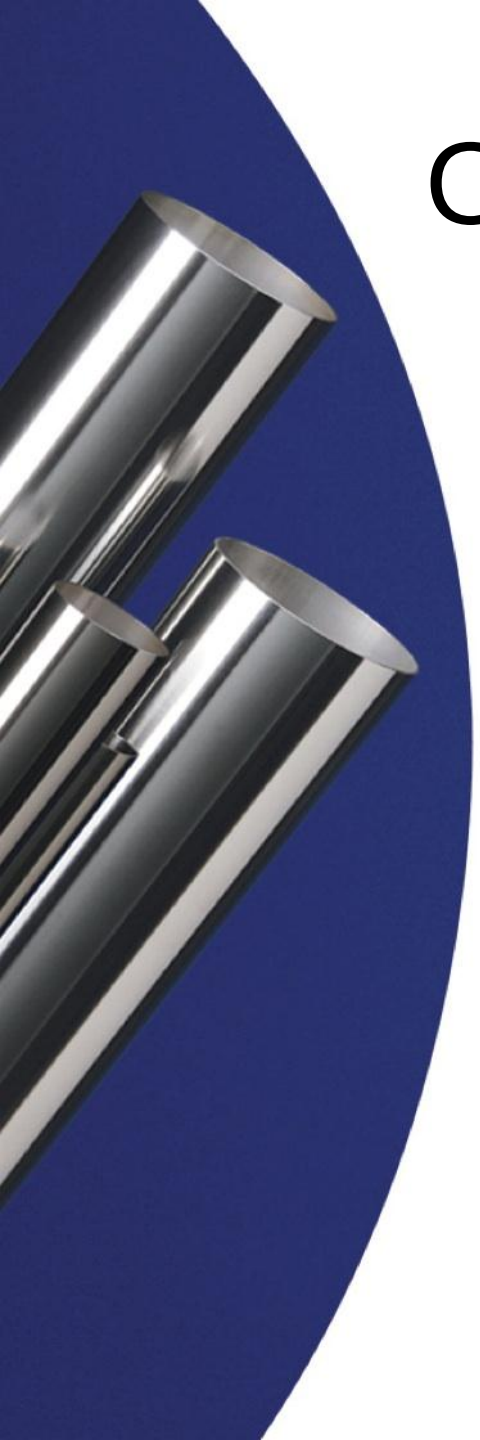
Characteristics of Laser Welded Tubing

- Uniform wall thickness
- OD is concentric to ID
- Smooth OD and ID surface finish
- Homogeneous grain structure
- Mechanical properties are the same as parent material
- Corrosion resistance is not compromised by welding
- Product cost is substantially lower than seamless (less than half)
- Product is more readily available than seamless

United Industries Capabilities

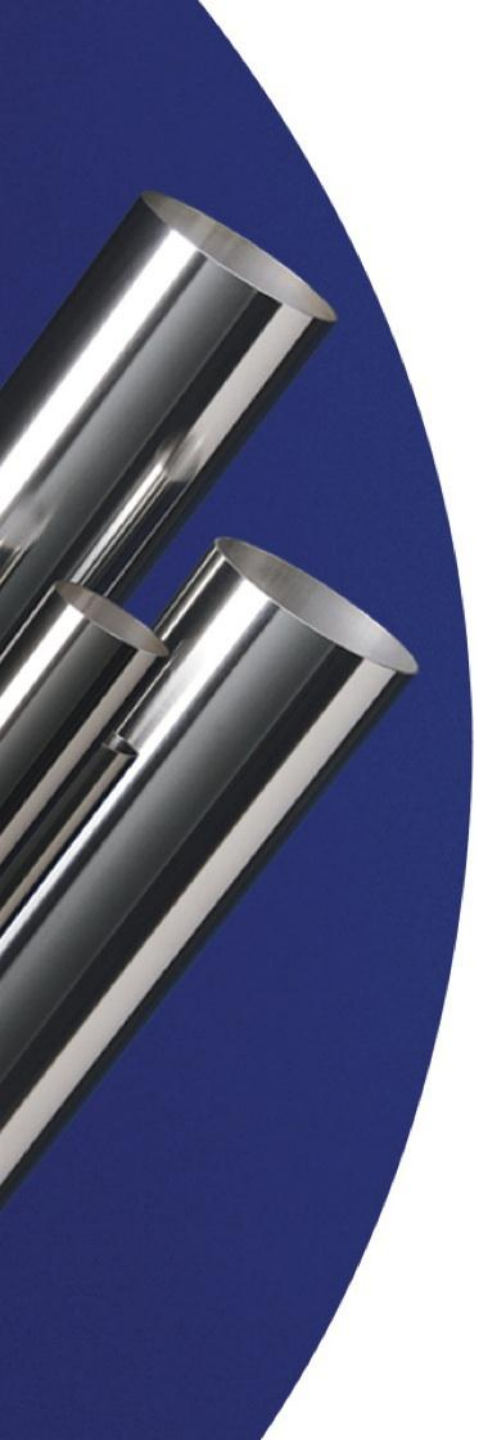
- 100% Laser welding
- 1”-8” diameter
- .020-.120 thickness
- Cut Lengths to 60’
- Metallurgical testing
- HBA, Polished ID/OD, Electro-Polish
- Laser Cut-Off for Custom Lengths and Shapes





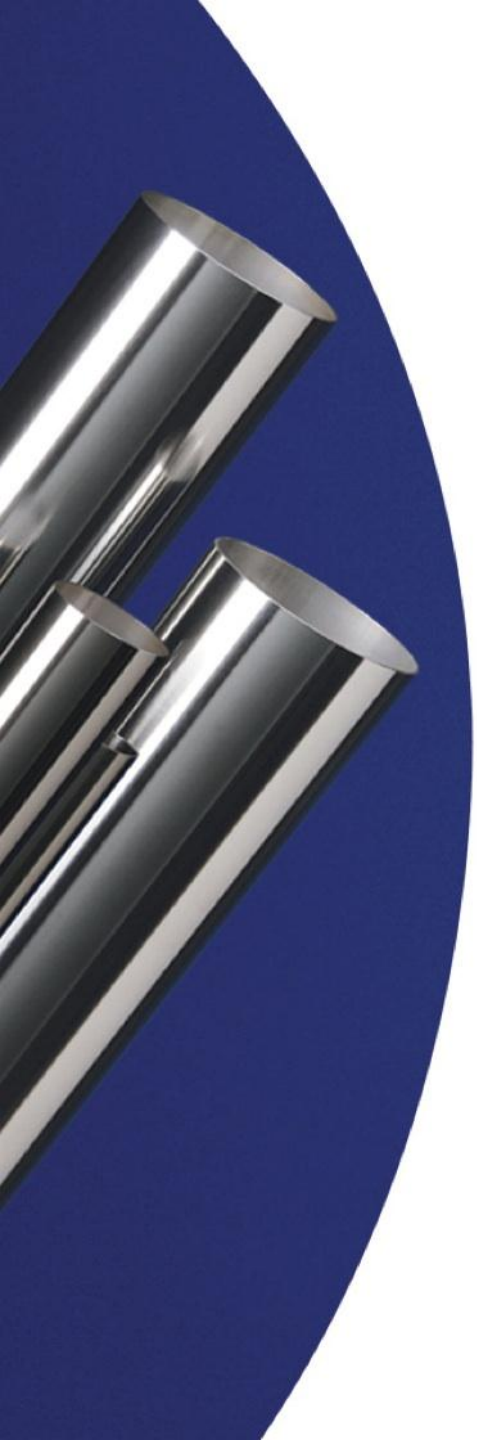
Optional Capabilities

- “Odd-size” OD
- 2000’ minimum runs
- Special Alloys
  - 2205, AL6XN, A611, C-22, others
- Passivation/Pickle
- Electro-polish
- O2 Clean ID



Price Comparison

Mat	Type	Dia	Wall	$/ft	$/lb
304	TIG	4”	0.065	$6.43	$2.05
304	TIG	6”	0.083	$16.18	$2.79
304	Seamless	3”	0.120	$25.76	$5.83
304	Seamless	4”	0.120	$28.14	$4.92
304	Laser	3”	0.065	$9.66	$3.97
304	Laser	4”	0.065	$14.39	$4.59
304	Laser	4”	0.083	$18.33	$4.59
316	Laser	3”	0.065	$13.79	$5.67
316	Laser	4”	0.083	$23.73	$5.95



Investigative Testing

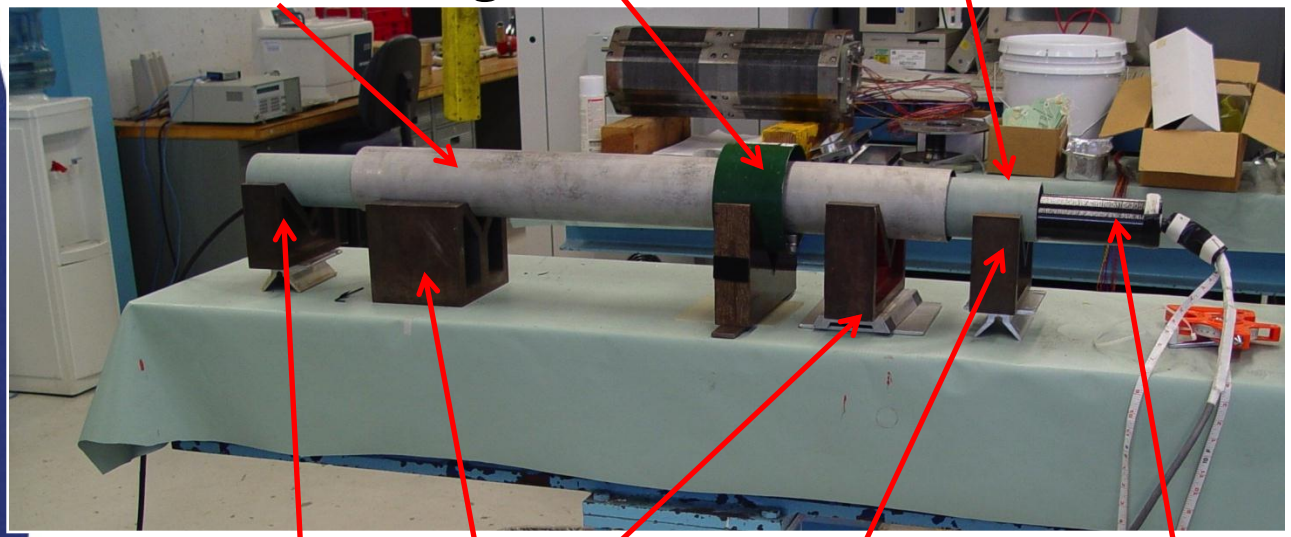
We tried to observe magnetization effects caused by welds by placing the tube in proximity to strong permanent magnets and comparing the measurements obtained with the weld-seams in different orientations with respect to the magnets.

Measurement Set-up

Beam tube under test

‘Coffee can’ Magnet

G10 Probe support tube

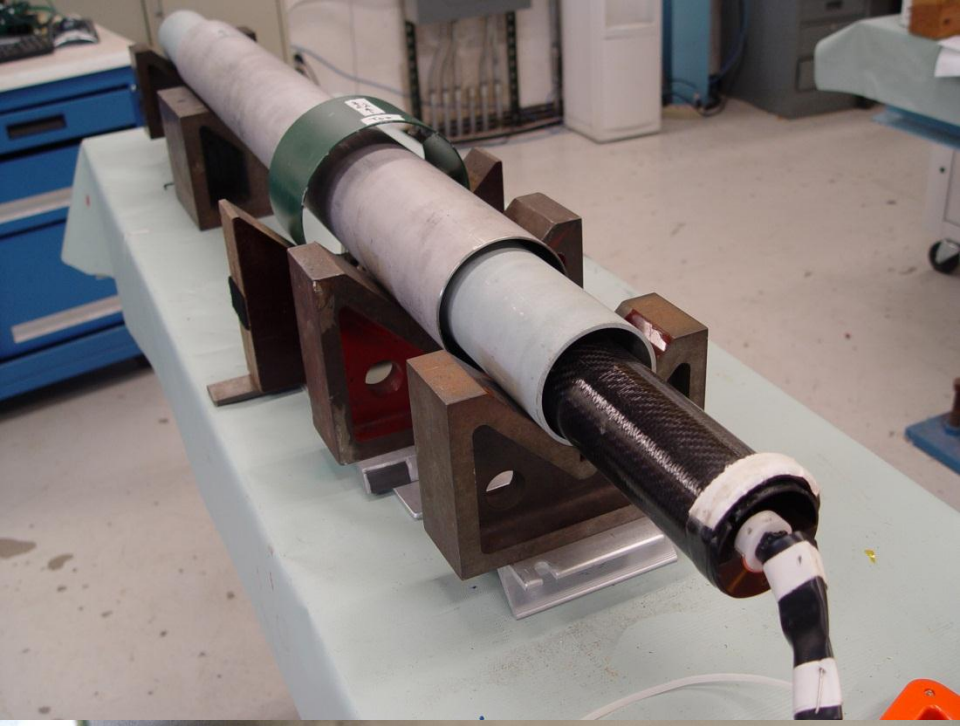


Support blocks for beam tube

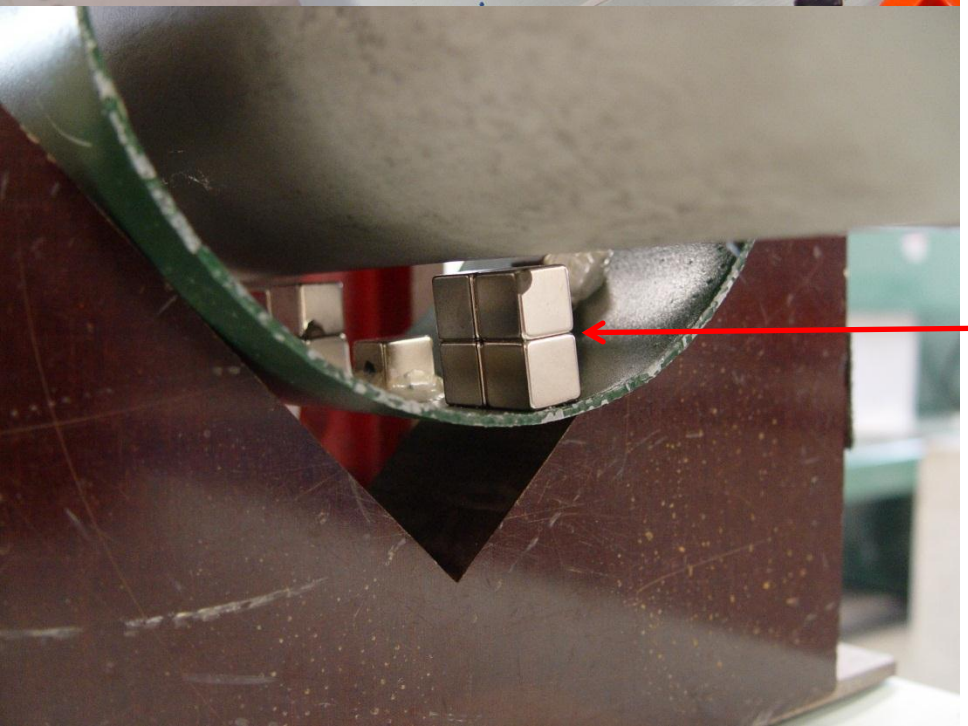
Support blocks for probe tube

Rotating coil probe (‘ferret’)

Beam tube can be rotated on its supports without any disturbance to the magnet or probe

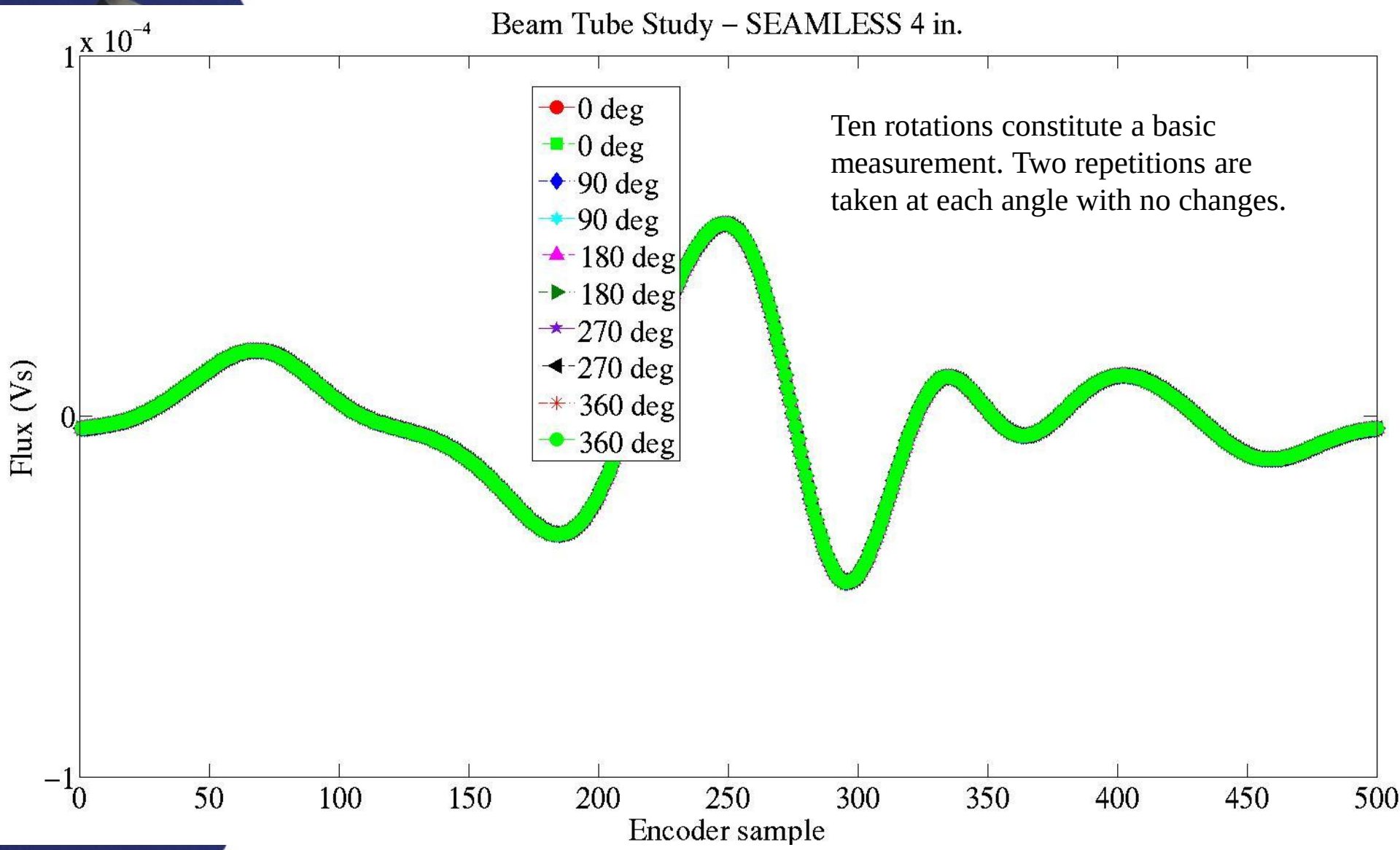


View of nested structure which allows free rotation of tube

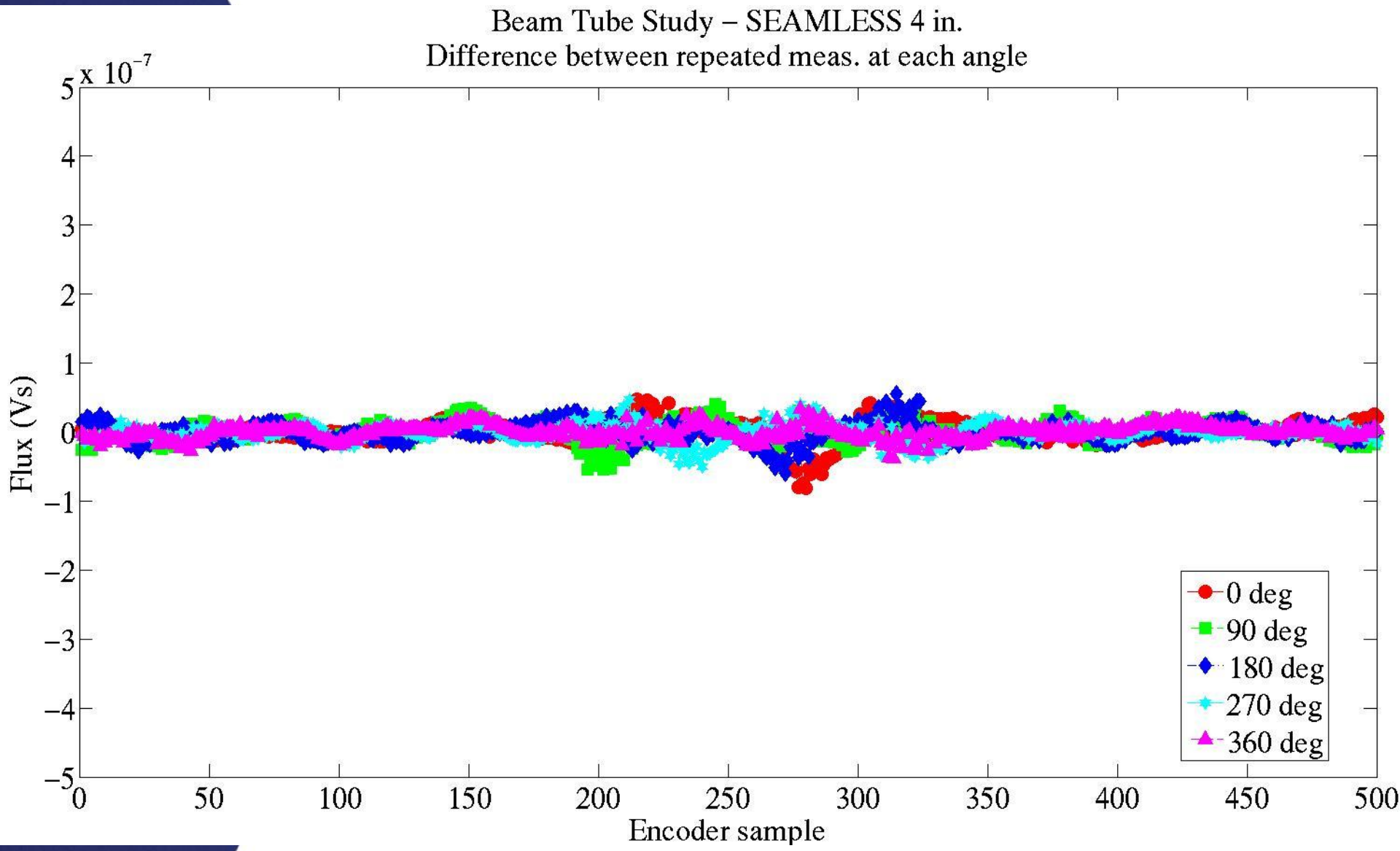


Strong permanent magnets are placed on bottom coffee can inner rim – ‘180˚ position’ - as close to tube as possible without contact. When the seam is at this position, it sees its largest magnetization effects

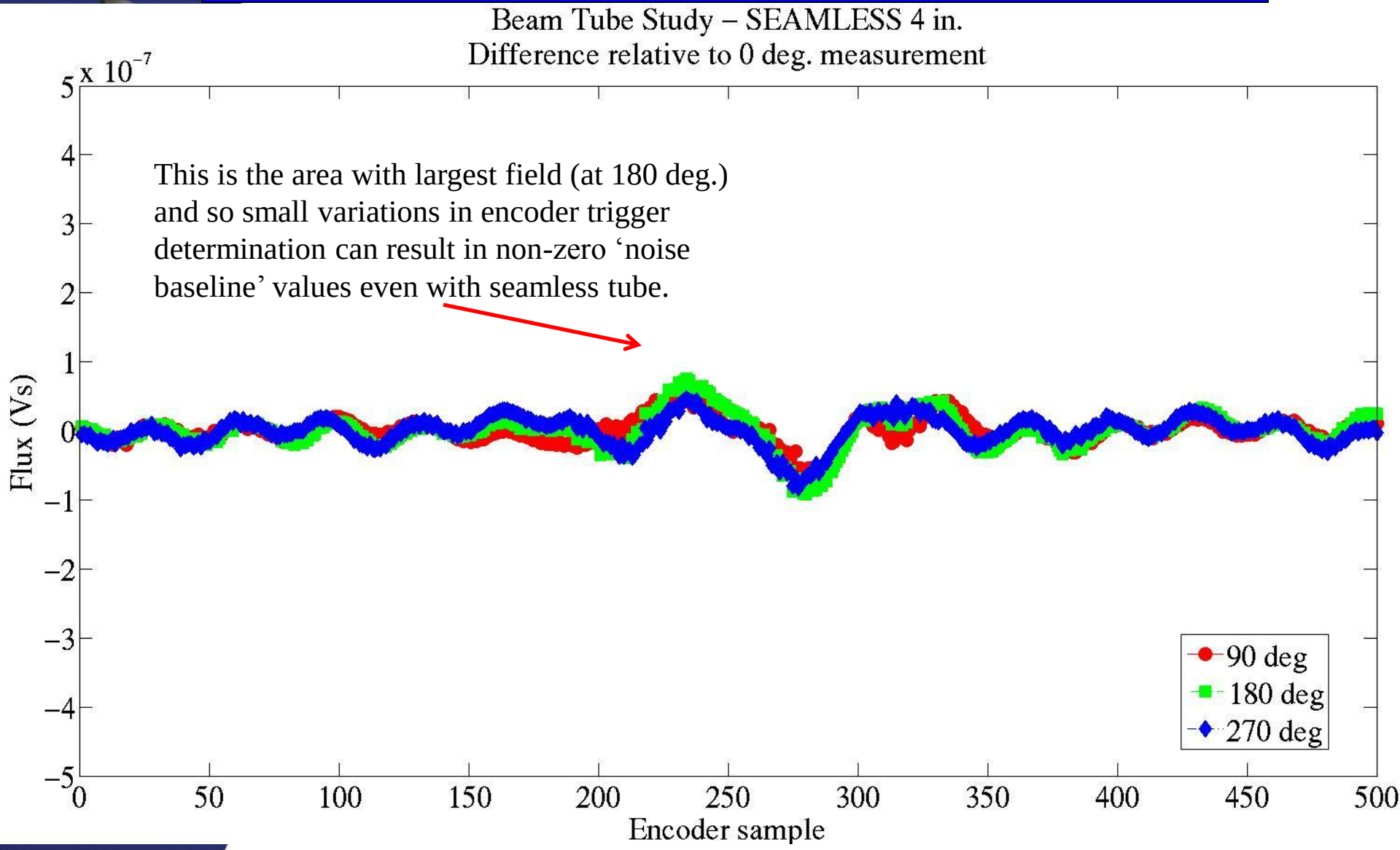
Seamless tube – raw flux output : Flux vs Beam Tube Angle



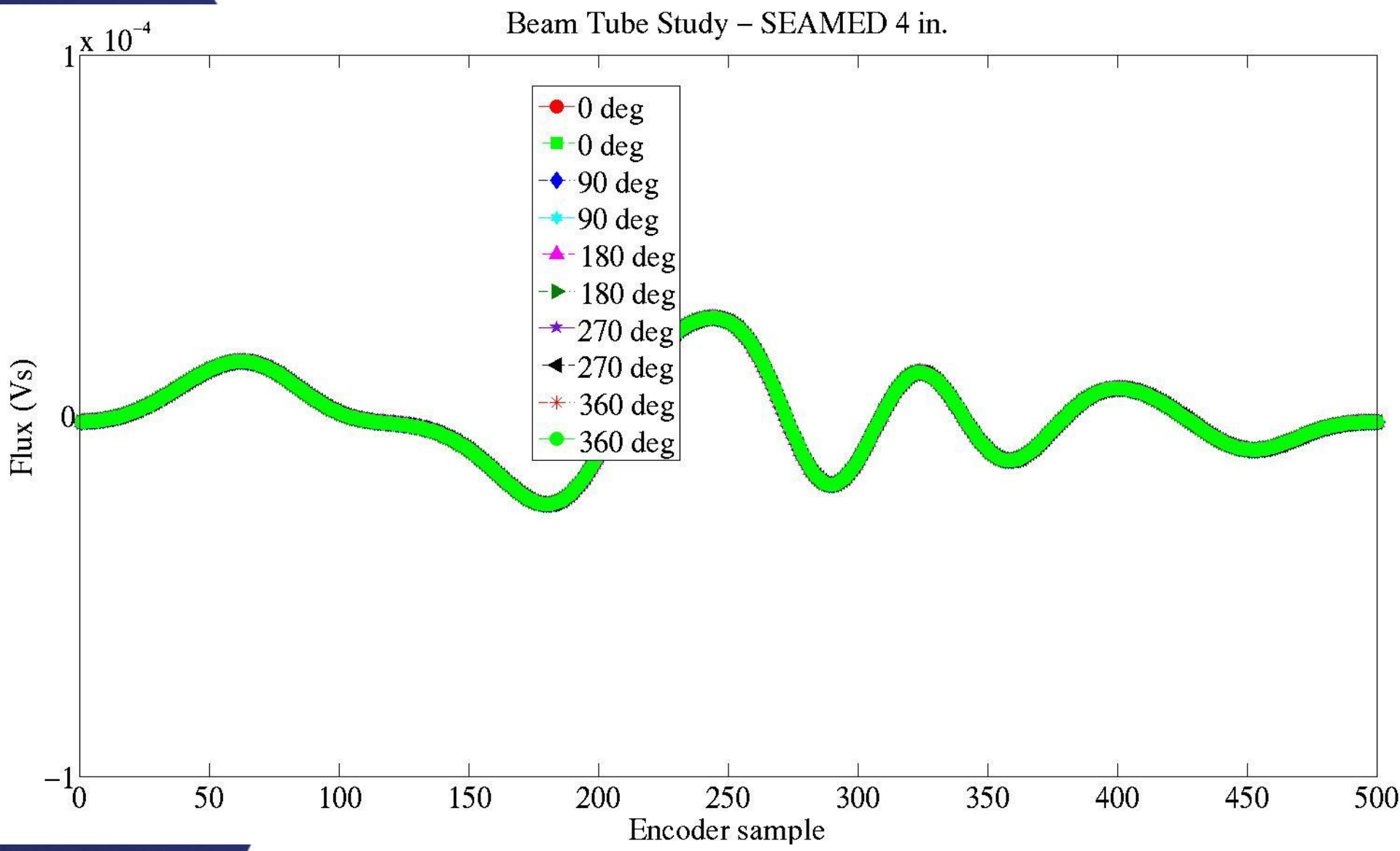
Reproducibility check for Seamless tube



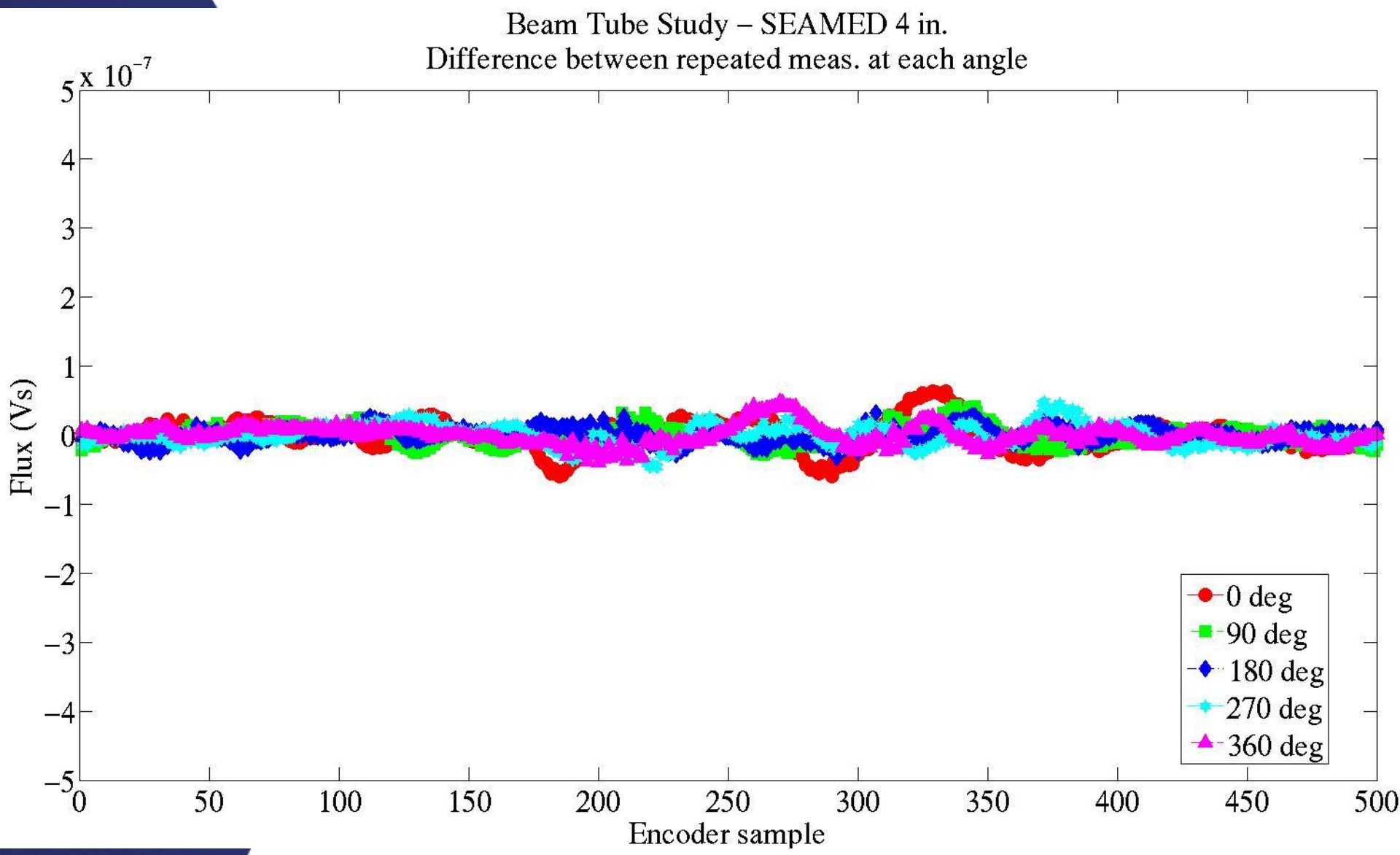
Difference between flux with beam tube at various angles vs. flux at angle zero



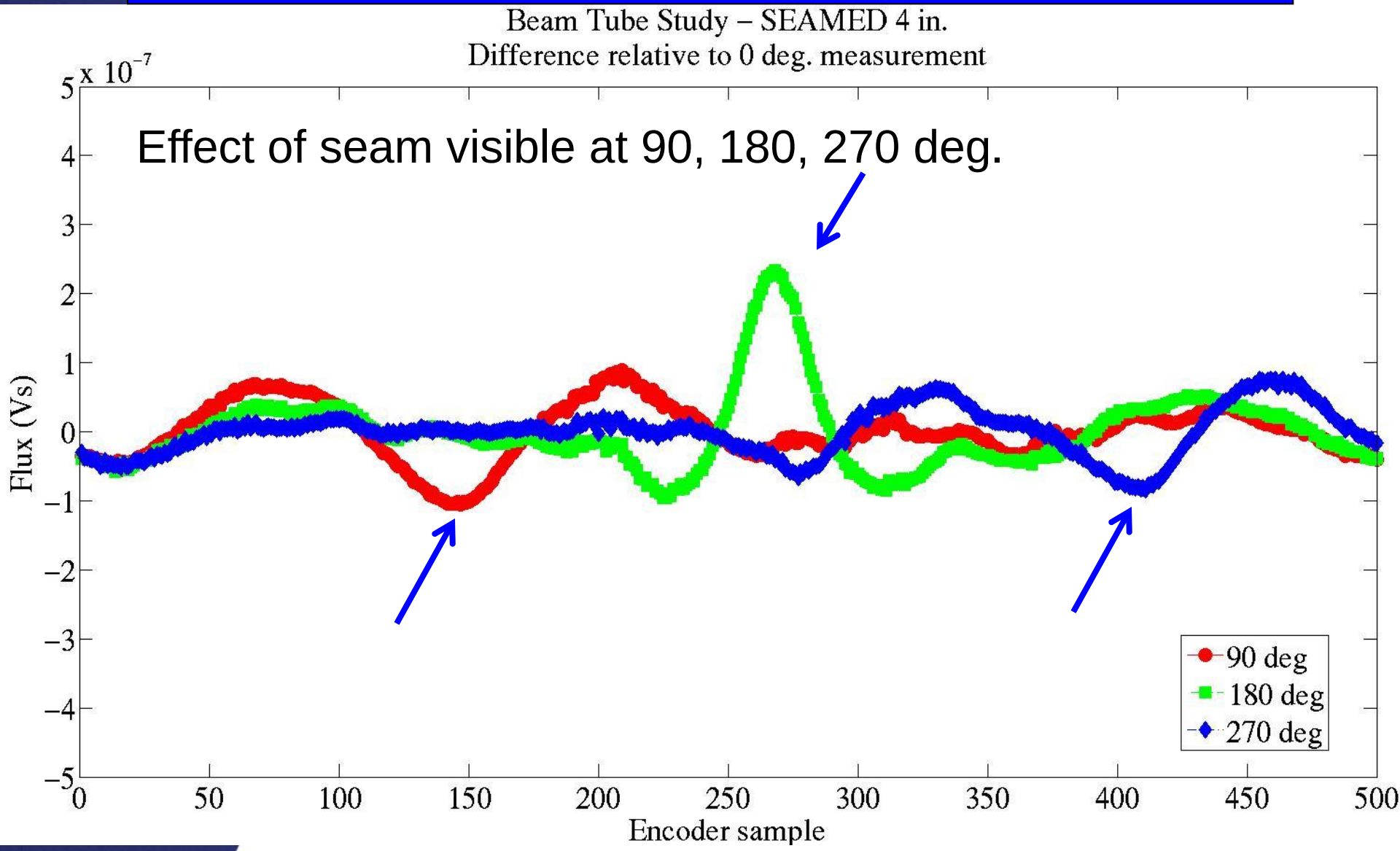
SEAMED tube – raw flux output : Flux vs Beam Tube Angle



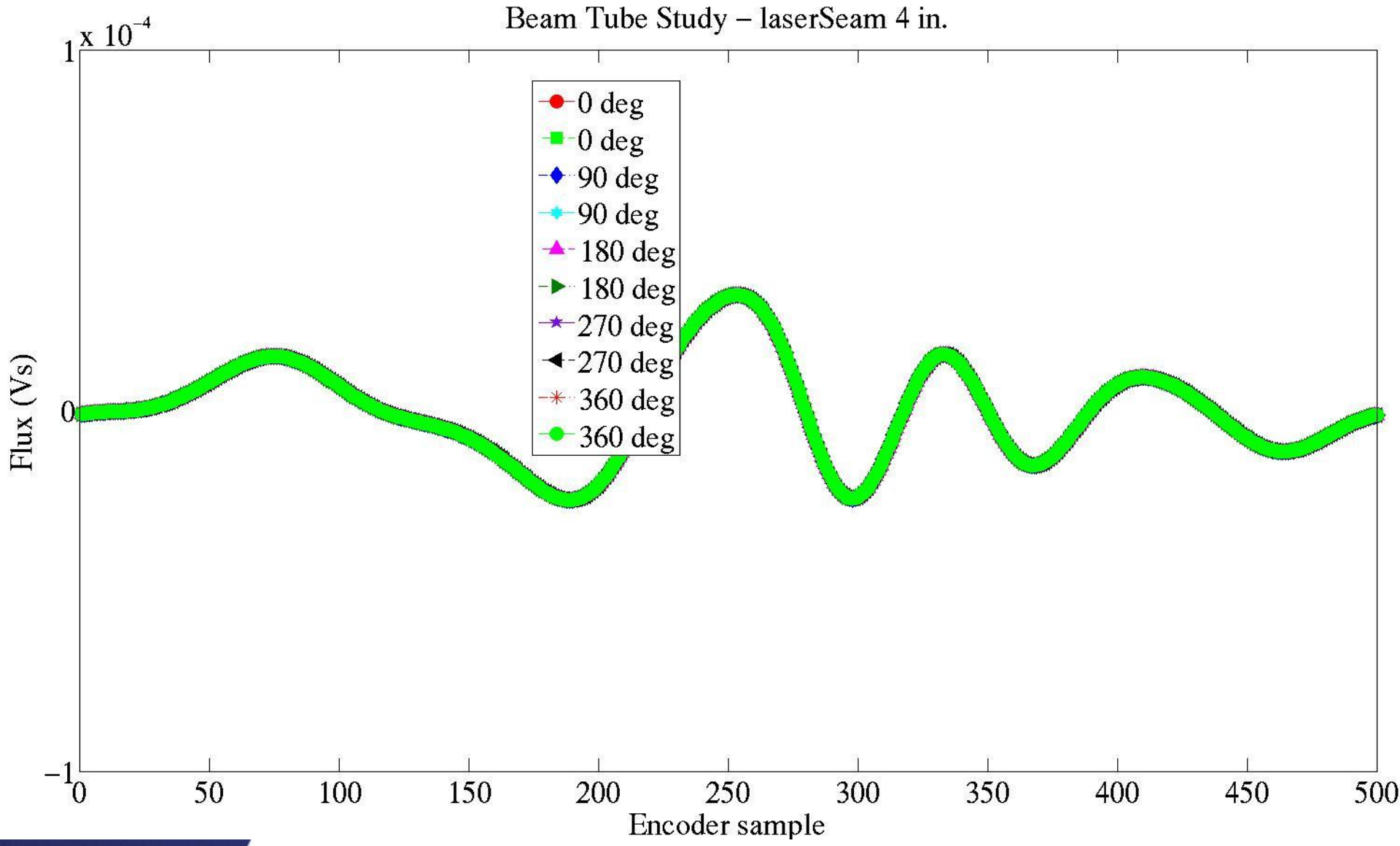
Reproducibility check for Seamed tube



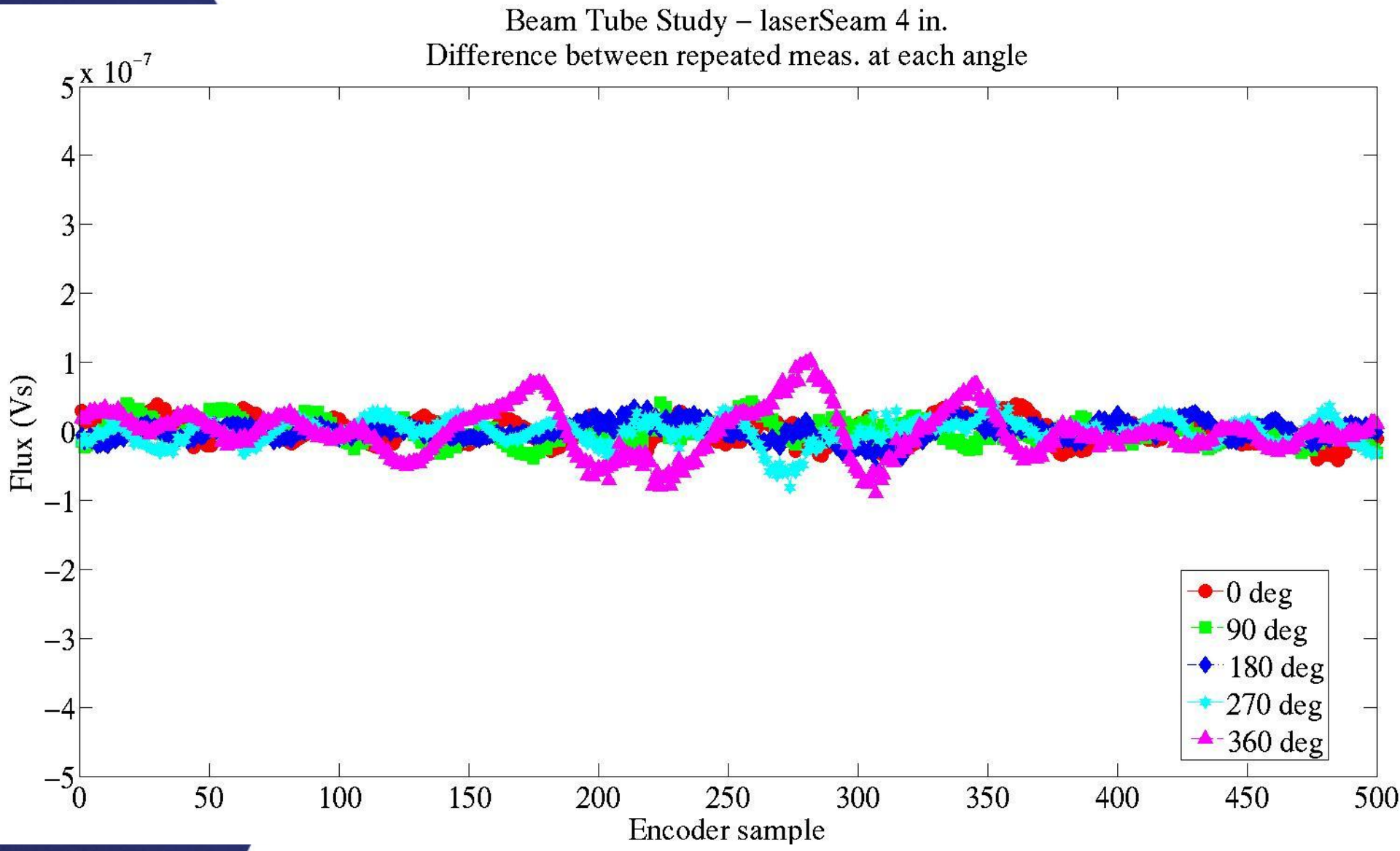
Difference between flux with beam tube at various angles vs. flux at angle zero



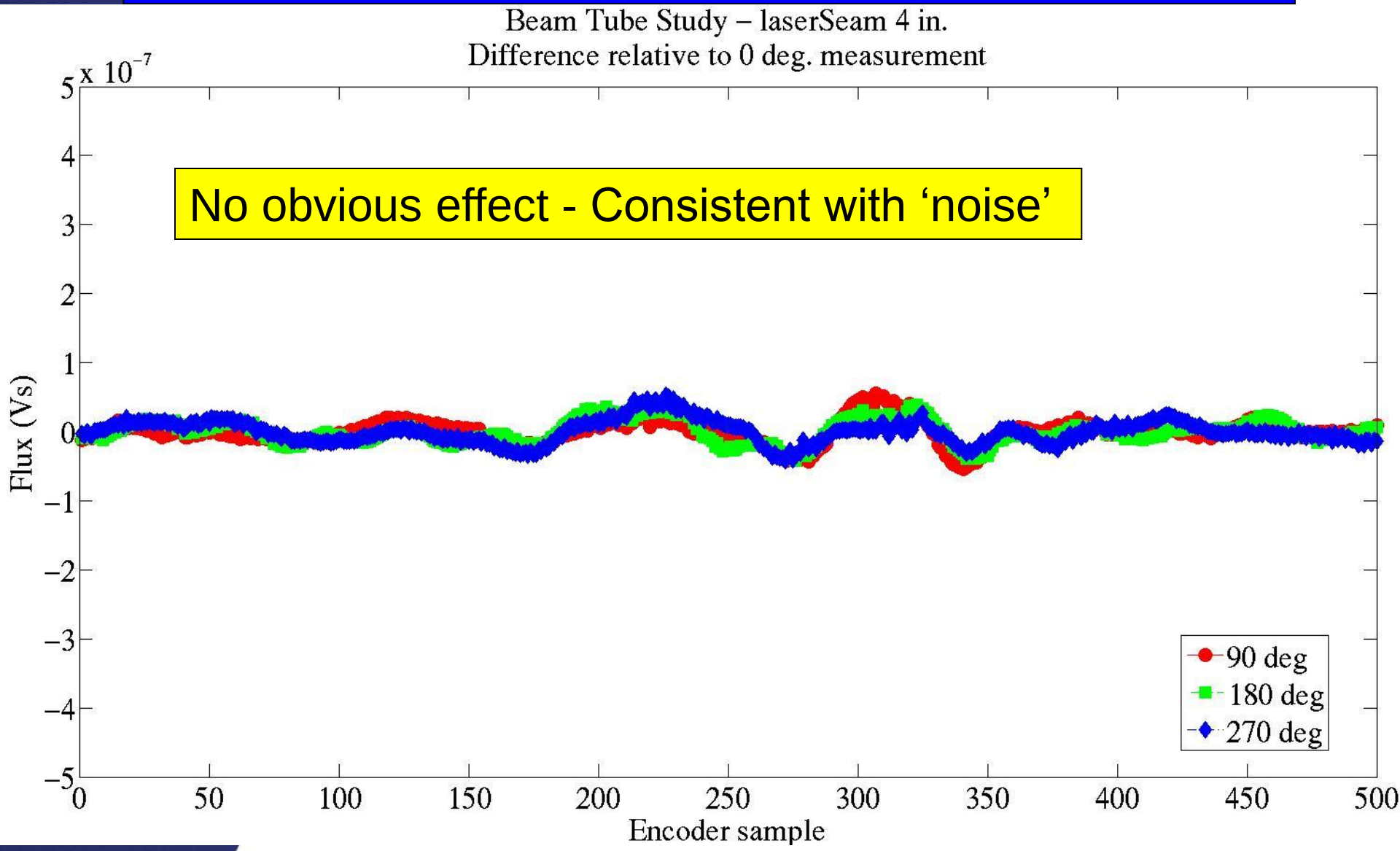
Laser seamed tube – raw flux output : Flux vs Beam Tube Angle



Reproducibility check for Laser seamed tube



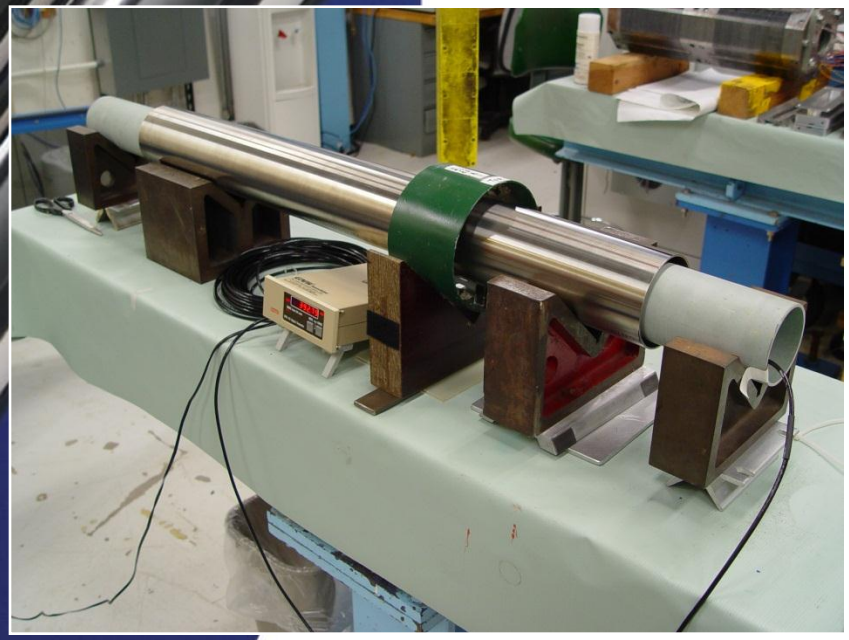
Difference between flux with beam tube at various angles vs. flux at angle zero

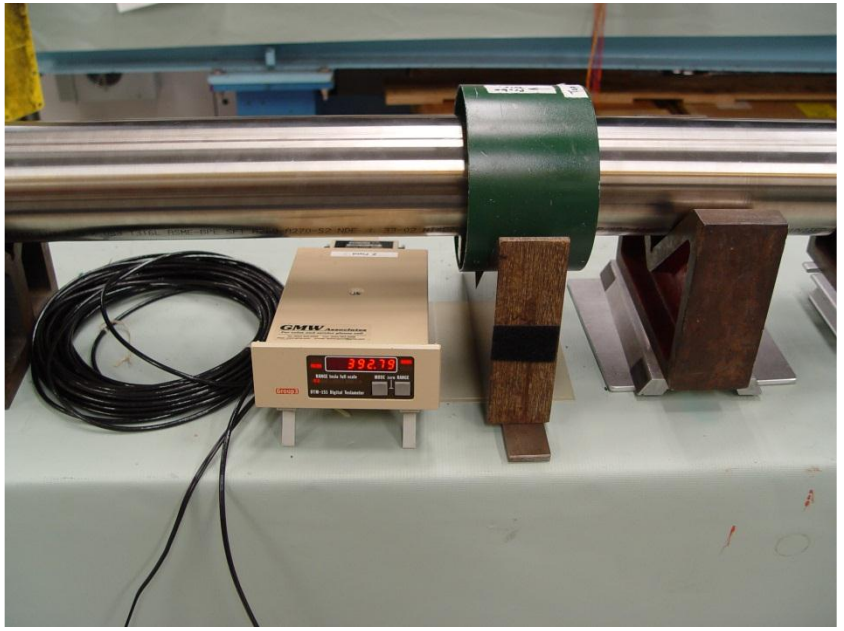


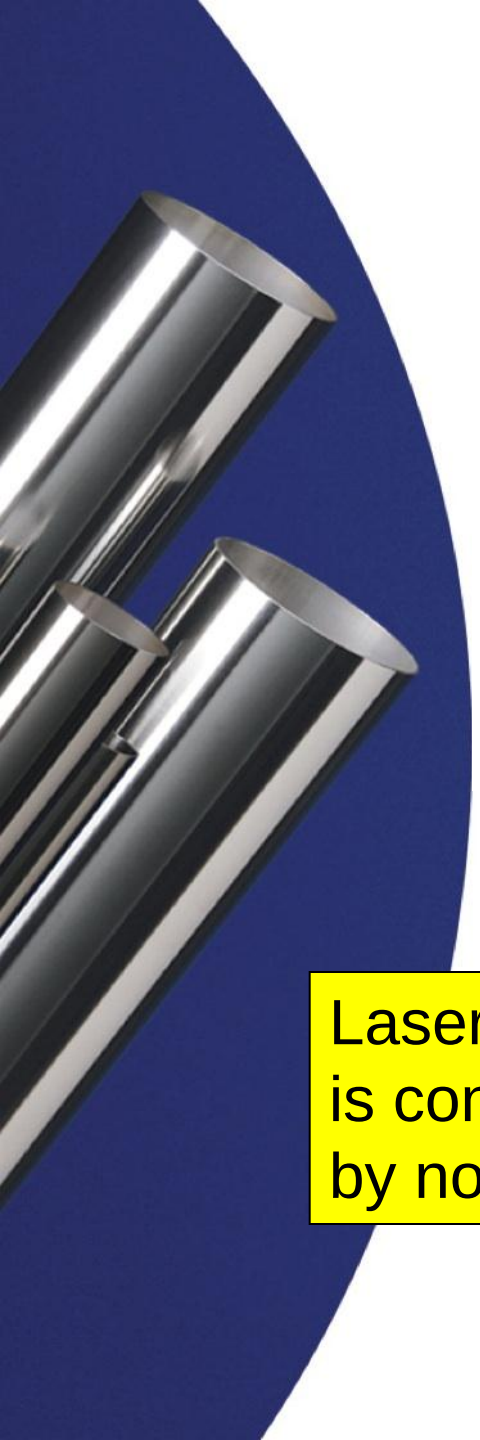
No obvious effect - Consistent with ‘noise’

Hall Probe Cross-check

Instead of the ferret probe, a Hall probe was mounted inside the G10 tube at 180 deg. position. Data was taken with the tubes rotated to different angles while monitoring the measured field. Nominal measured field was about 400 G.





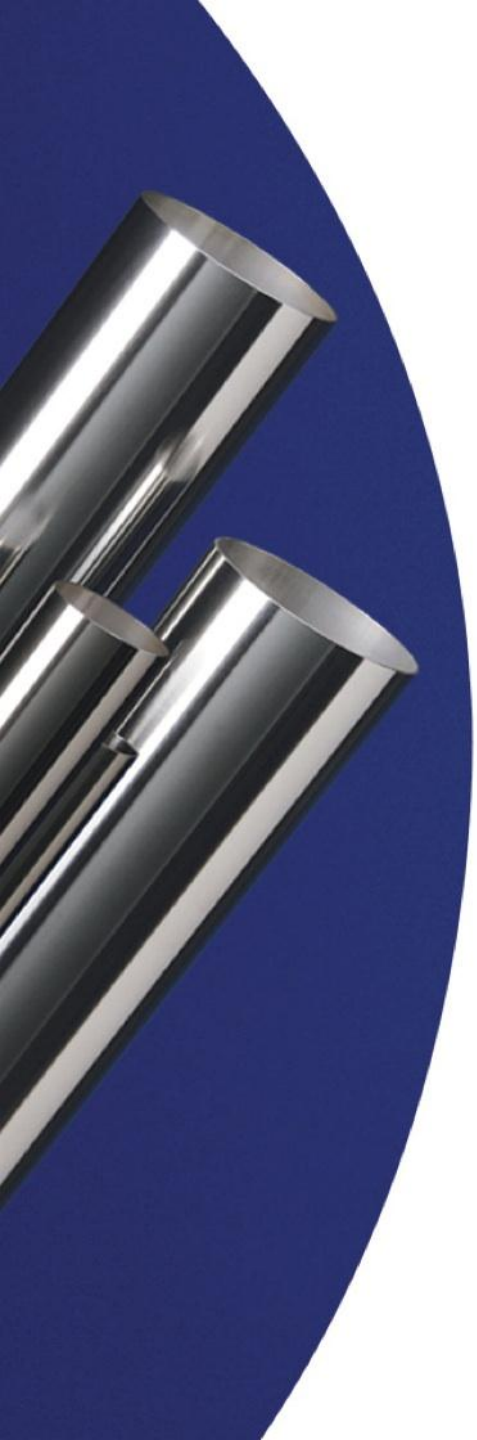


Hall Probe Results

Difference between beam tube at angle 0 and angle 180:

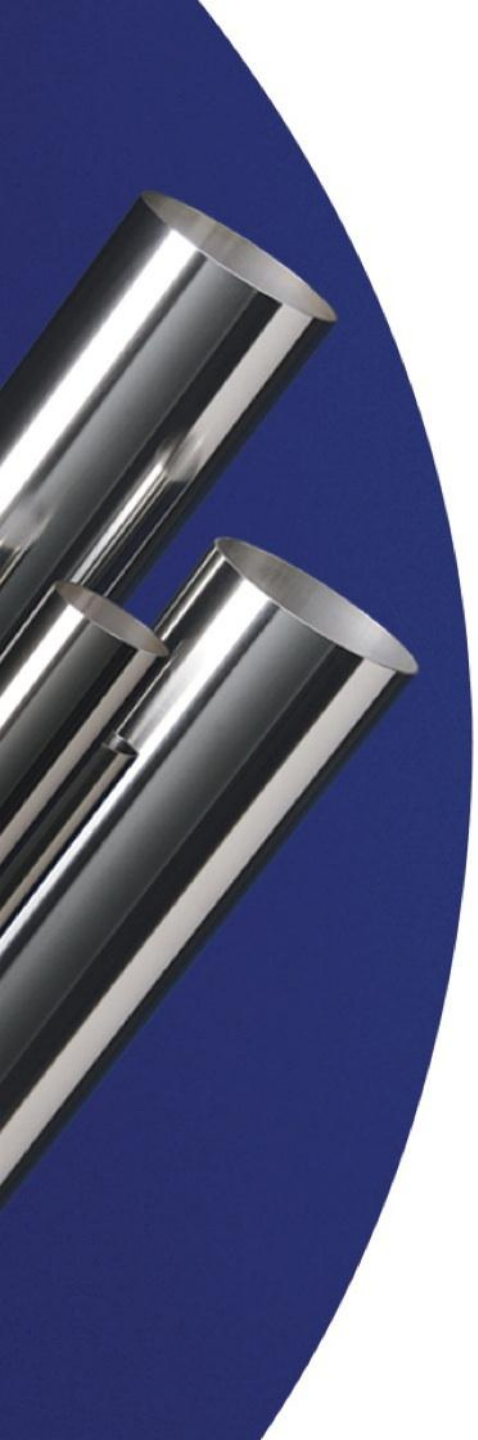
Seamless: ~0 (consistent with noise/drift)
Seamed: ~ 0.5 G
Laser Seam: ~ 0.04 G (± 0.02)

Laser seam ~10x smaller effect than standard seam is consistent with ferret results (which were limited by noise at that level).



Test Summary

- An attempt was made to measure the magnetization effects caused by the welded seam on stainless steel beam tubes by placing the tube in proximity to strong magnets and measuring magnetization changes.
- Rotating coil (ferret) and Hall probes were used to measure the magnetic field strength with the tube seam rotated to various orientations wrt the field.
- The effect from the seam from a standard welded tube was about 0.1% (~0.5 G out of ~400 G).
  With the laser-welded seam the effect dropped to about 0.01% (~ 0.04G).
- The factor of ~10 improvement from standard seam to laser-welded seam was consistent between the two types of measurements performed.



Summary & Outlook

- Recent difficulties acquiring seamless tube were the catalyst to search for alternative solutions.
- Laser welded tube seems promising so far.
  - Magnetization effects are one tenth of TIG welded tube effects and within 0.01% of seamless tube
  - At least half the cost of seamless
  - Magnetic permeability of base material may exceed previous $\mu \leq 1.01$ requirement and needs further consideration
- Additional measurements can be repeated for other conditions of interest (higher fields, AC, etc.) if needed.