AGE RELATED FAILURE OF THE K1200 CYCLOTRON

Jon Paul Bonofiglio
National Superconducting Cyclotron Laboratory
Michigan State University
640 S. Shaw Lane
East Lansing, MI  48824

1-517-908-7308
bonofigl@nscl.msu.edu

Accelerator Reliability Workshop 2017
ORAL PRESENTATION
Cyclotrons & Beam Lines

K500 Cyclotron

Coupling Line

A1900 Fragment Separator

K1200 Cyclotron

Design & Construction started in 1987
K1200 Radio Frequency System

Consists of identical sub-systems (A, B & C)
- Transmitter (Outside the beam chamber)
- Transmission Line (Outside the beam chamber)
- Coupler (Outside & Inside the beam chamber)
- Dee (Inside the beam Chamber)
- Resonator (Outside & Inside the beam chamber)

Operates at 140KV in the 18Mhz to 25Mhz range
Block Diagram of the K1200 RF Transmitter Chain

Power monitoring at Transmitter, Transmission Line and Resonator
Failure Presentation

Maintenance Shutdown

- RF would turn on, but would only run normally for 15 minutes
- Chart recorder plots showed repeatable dropouts starting ~15 after RF turn on
- Dropouts were different from normal “sparking”

Waveform Analysis of Signals

- Normal Mode
- Failure Mode
Failure Presentation

Chart Recorder showing regular dropouts of C RF

Occurred above 110kV

Issue worse at higher frequency
Failure Presentation

Waveform Analysis of a normal turn-off signals
Failure Presentation

Waveform Analysis of failure turn-off signals
Failure Presentation

Waveform Analysis of Turn-Off Signals
Troubleshooting

Diagnostic
Predefined diagnostics used to pinpoint a failure
Not available in old equipment

Binary Chop
Divide the system in half continuously, until the failure is found
More efficient in a large, linear chain of devices

Shotgun
Swap out many parts at the same time
Troublesome if swapping out parts is difficult, costly, or there are many parts

Process of Elimination
Eliminate potential failures one at a time
Order of elimination is not important………. but you MUST eliminate them all
Troubleshooting

There are only two types of failures in the world……..

“A” and “The”
Troubleshooting the K1200 RF

We tried many things…….. for 8 weeks, we tried things

- Adding additional cooling to individual circuits
- Flushed cooling circuits with citric acid
- Swap input coupler
- Transmitted into dummy load
- Swap transmitter tube
- Remove & inspect DFT
- Adjust positions of extraction & injection elements
- Check for localized heating with FLIR camera
- Force asymmetry in upper/lower half of the dees
- Swapped two of the dees
Troubleshooting the K1200 RF

and found and repaired many failures

- Under compressed indium seals
- Damaged RF fingers
- Crack in copper skin of dee
- Loose screws (in the hardware, not the employees)

but they were all “A” failures

Then we found “The” failure
K1200 Dee

Configuration

Each dee is made up of an upper and lower half (symmetric about the median plane)

Each upper/lower half consists of a “dee” and a “shoe”
K1200 Dee
K1200 Dee

“The” Failure
Dee Construction

Original Construction

Copper skin over aluminum sub-structure

Rivets holding copper to aluminum sub-structure

Cross section very similar to C-C
Dee Construction

Aluminum Sub-Structure

Copper Rivets

Copper Skin 0.09” (2.3mm)
Dee Construction

Original Construction

Copper skin over aluminum sub-structure
Dee Construction

Original Construction

Copper skin over aluminum sub-structure
Dee Repair

Where to cut?

A unique and very sophisticated set of tools

1:1 mechanical drawing
Aluminum plate
Felt tip markers
Tape measure
Bread knife
Play-Doh®

Mold was pressed into damaged area
Dee Repair

Access to damaged area from below

- Dee taken to Machine Shop for repair
- Controlled Contamination Area setup
- Radiation specific vacuum cleaner used to collect debris
- Radiation Work Permit (RWP) required
Dee Repair

How to cut?

- Cut larger hole through aluminum
- Cut small hole through copper
- First cut was reasonably accurate
- Cracks in copper were still visible
- A 2nd cut would be needed

What the first cut reveled, was frightening........
Dee Repair

The “Face of Failure”
Dee Repair

Original Cut Needed To Be Larger
Dee Repair

Sub-Structure Prepared
Dee Repair

Copper Skin w/Support Manufactured

Support to prevent future skin failure
Dee Repair

New Copper Skin
Brazed from below
Dee Repair

New Aluminum Sub-Structure Installed

- Sub-structure support installed
- Copper skin mechanically stabilized
Dee Repair

Before

After
Maintaining Future Reliability

Two choices for maintaining future reliability

Repair the device when another failure occurs
- Process is well defined and the risks are known
- Failure time is unpredictable
- Monetary cost is low
- Down-time cost is high

Design a new device and replace before failure occurs
- Process is not well defined and some of the risks are unknown
- Failure predictability issue is removed
- Monetary cost is high
- Down-time cost is low
Maintaining Future Reliability

K1200 Dee Original Construction

- Constructed in 1987
- Hammer formed, machined, brazed, riveted & screwed together
- 52 Copper rivets
- 21 Stainless screws
- 14 Copper skin pieces
- 8 Stainless steel pins
- 3 Aluminum sub-structure parts
- 98 individual parts (not including waterlines)
Maintaining Future Reliability

K1200 Dee Original Construction

Hammer-forms no longer available
Employees retired
Skills lost to time
Maintaining Future Reliability

K1200 Dee New Construction

- Machining new parts from 3 solid blocks of copper
- Electroforming one part
- Braze parts together
- Test machining techniques on aluminum dee
- Test fit aluminum dee into cyclotron
- Manufacture new dee from copper
- Made from less than 10 parts
Maintaining Future Reliability

K1200 Dee New Construction

Machining will be done on new Mazak VTC805G
32”-y 118”-x 33”-z (81cm-y 300cm-x 84cm-z)
Repair Process

Diagnose
- System
  - Transmitter
  - Transmission Line
  - Coupler
  - Dee
  - Resonator
- Troubleshoot
  - Diagnostic
  - Binary Chop
  - Elimination
  - Shotgun

Repair
- Item
  - Dee
- Troubleshoot
  - Diagnostic
  - Binary Chop
  - Elimination
  - Shotgun
- Repair
- Test

Prevent
- Repair
- -or-
- Redesign

Iteration time increases as complexity increases
Repair Process

Over 30 people involved in the repair

24/7 operator shift rotation during the repair process (16 hours of repairs & 8 hours of testing)

17 Repair Team meetings

12 hours of meetings

9 cap raising/lowering/pump/vent cycles (12 hours each)

6 departments

2 retirees
Lessons Learned

The older the device, the more “A” failures will be found…… but there is ever only one “The” failure

The more complex the device, the more unique the failures will be

Combination of troubleshooting techniques are needed

Think outside the box

The processes, people and skills to remake old parts will be lost to time……..be prepared to rethink your entire strategy

Be bold & creative…….. crowbars, hammers and Play-Doh may be necessary

Copper can be brazed from the back side

Don’t be afraid to look failure in the eyes………… It is not as scary as it seams
Lessons Learned

....... or is it?