Performance Report on the 20kV/25A Anode Power Supply System Built for the KEK/ANL/ISIS Low output Impedance Collaboration

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The KEK/ANL/ISIS Low Output Impedance Collaboration

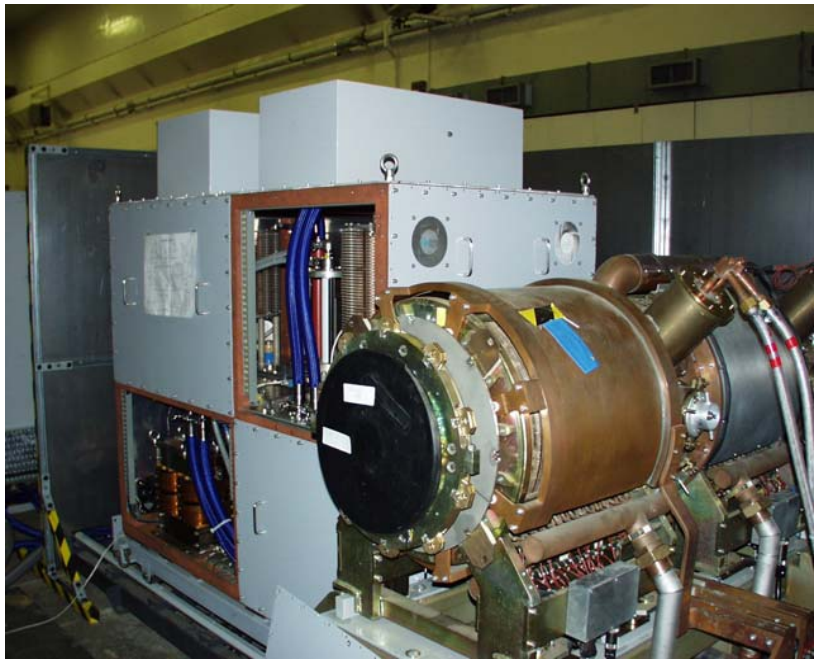
- Initiated in 1996 to develop a prototype 2nd harmonic low-impedance rf amplifier system to drive a swept-tuned ferrite-loaded cavity
- KEK developed the rf amplifier system
- ANL (Argonne) developed the final rf amplifier anode power supply in collaboration with Diversified Technologies funded under SBIR
- ISIS (Rutherford-Appleton Laboratory) provided an ISIS cavity for testing the rf amplifier and is arranging for testing of the entire rf system with ISIS beam

The KEK/ANL/ISIS Low Output Impedance Collaboration

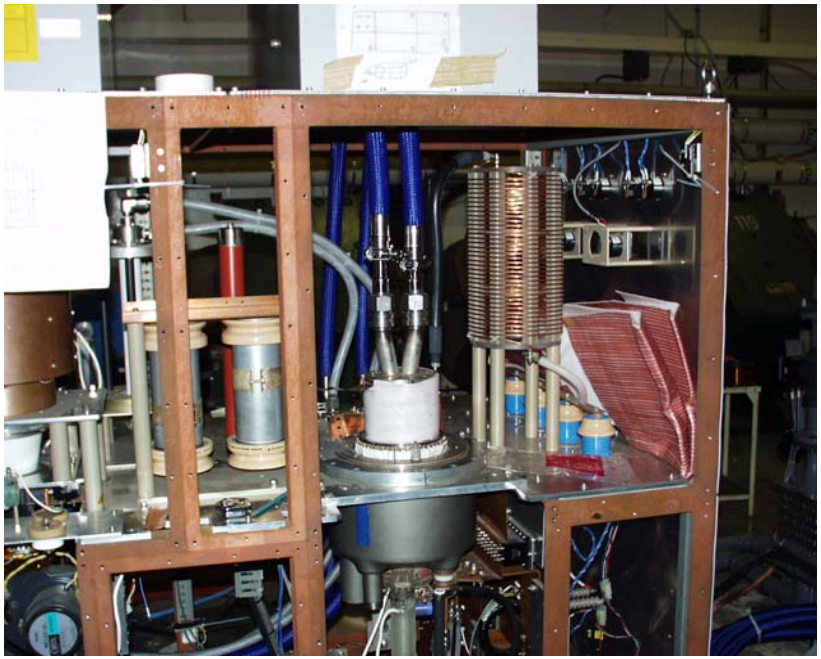
Collaboration Activity Timeline:

- **1998-2000** – Anode power supply development, construction, and low-power testing at ANL
- **October 2000** – Assembly and installation of power supply system at KEK
- **March 2001** – First high-power dc test of anode power supply into final rf amplifier triode as a load
- **July-August 2001** – First run of entire rf into cavity
- **July-August 2002** – Continued testing of entire rf system into cavity
- **Feb-March 2003** – Ship entire rf system to ISIS
- **Nov-Dec 2004** – Install and test anode power supply system at ISIS
- **August 2005** – Operation of rf system at full power into cavity

RF Amplifier and Cavity Test Stand at ISIS



RF amplifier
connected to cavity



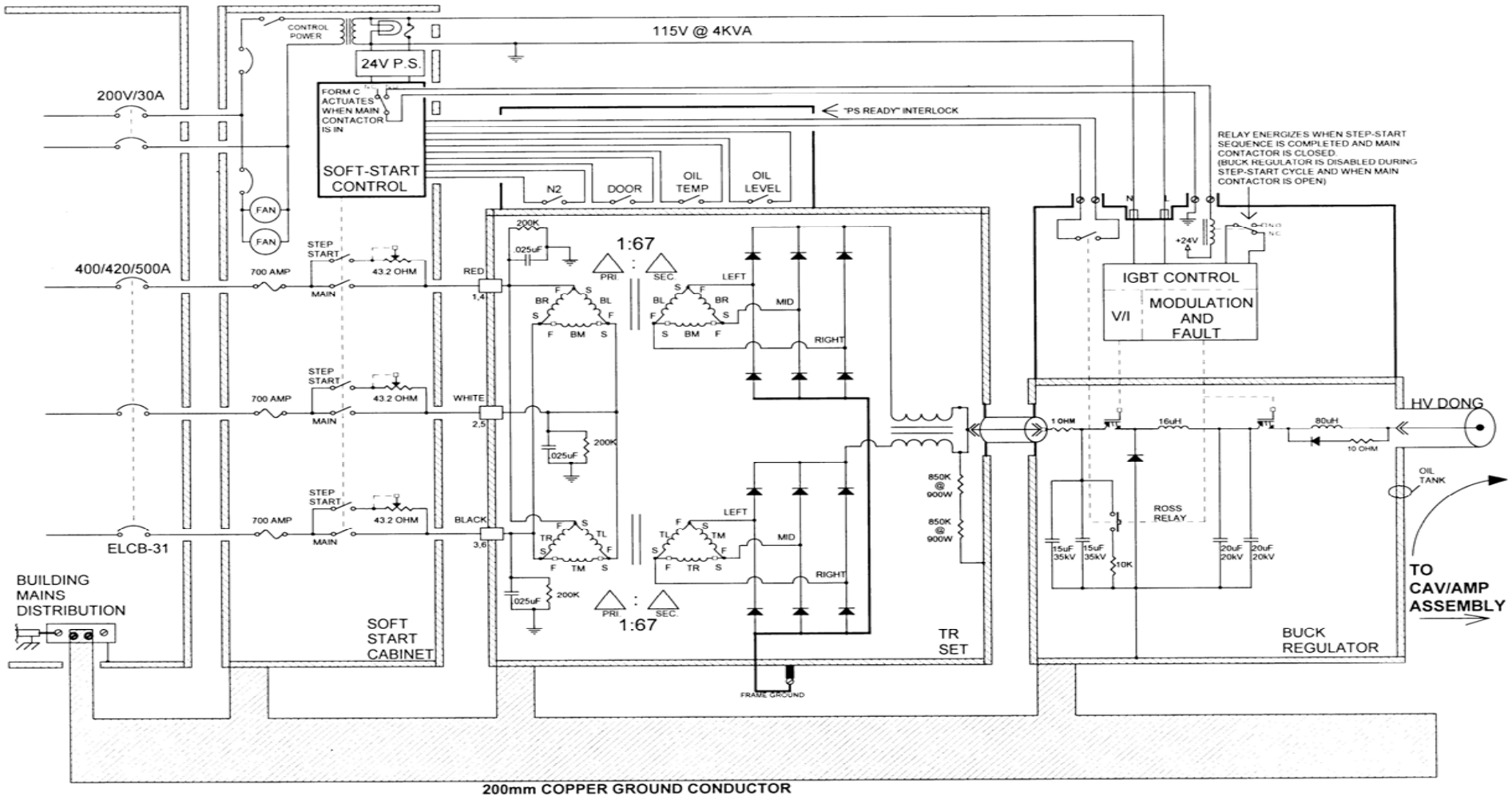
RF amplifier output triode

Anode Power Supply

The Anode Power Supply consists of the following sub-systems:

- Conventional Transformer-Rectifier Set reconfigured with parallel secondary windings using a twin-choke interphase transformer to achieve 32kV@20A output (*re-used from old ANL rf test stand)*
- Conventional resistor step-start for T-R set 400vac primary
- Diversified Technologies 0-20kV@25A buck regulator with fast HV series IGBT output switch for fault protection

Anode Power Supply System Diagram



Initial Operation of the Anode Power Supply at KEK

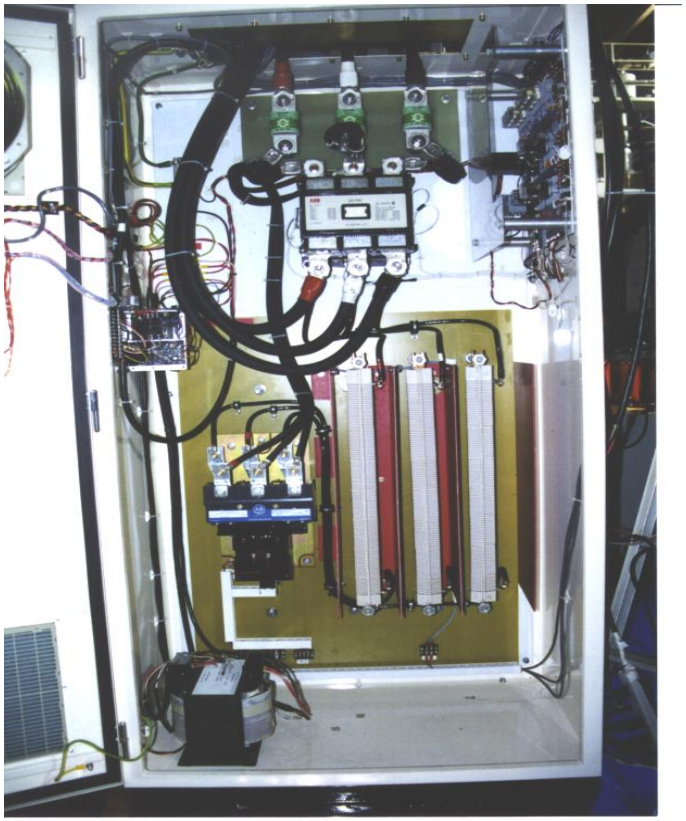
- **Plate dissipation limit on rf output triode required pulsed operation**

  → Fast IGBT output switch provided pulsed operation, *but not at required full power output…….. output cable charging currents tripped overcurrent fault in DTI system*

- It was decided that grid pulsing of the rf output triode would be utilized to limit plate dissipation…….*the buck regulator would then be operated at constant output voltage*

Anode Power Supply Installation at ISIS

T-R set (blue) and Buck Regulator/Fast Switch tank



Resistive step-start for T-R set primary input

Anode Power Supply Installation at ISIS

- T-R set interior was visually inspected for any sign of transport damage before being filled with oil *(memories of earlier failure in Japan!)*

- Photo shows T-R set supported by specially-made inspection stand →

  -- white coils comprise the twin-choke interphase transformer used to connect the floating secondary windings in parallel

Anode Power Supply Installation at ISIS

Interphase transformer mounts were checked for tightness

400v primary connections were checked for tightness and evidence of overheating

Anode Power Supply Installation at ISIS

- Only one problem found during the T-R set inspection:

  → *Cold solder joint on rectifier stack*

We did not want to go back into the oil for any reason that could be avoided!

Anode Power Supply Installation at ISIS

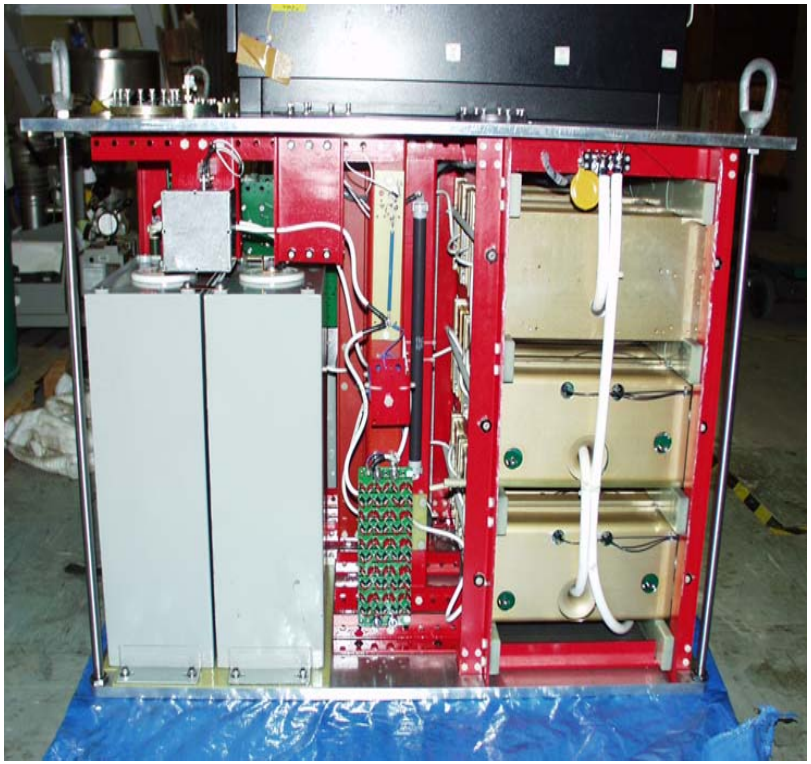
- The T-R set was filled with Midel oil (high-flash point), and the oil level was verified as correct on the HV output connector

Another lesson learned
from a previous failure in Japan:

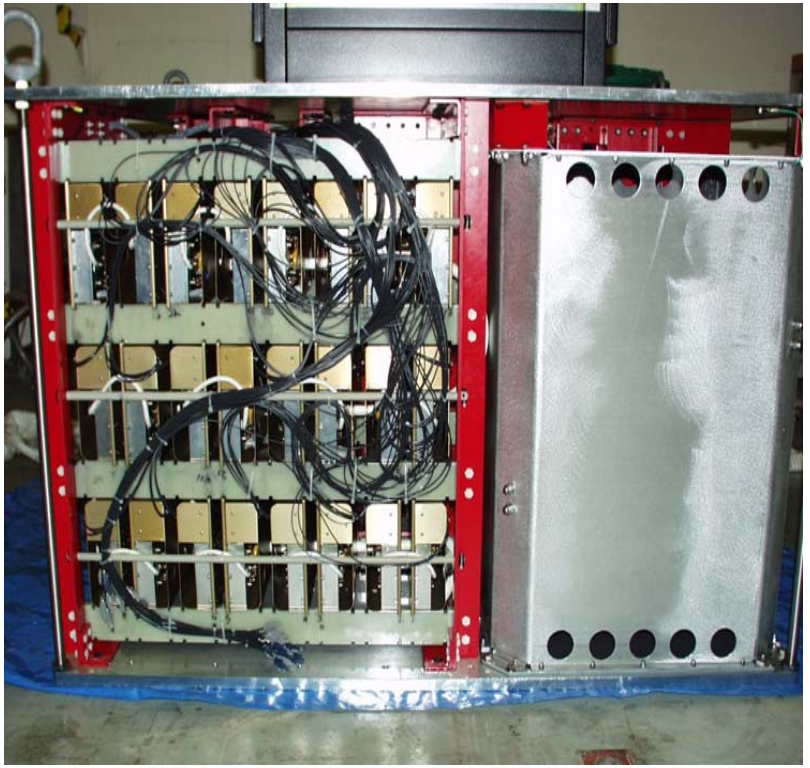
The oil level gauge on the T-R set was not calibrated for correct level when the tank was modified with a different HV output connector……this caused the connector to arc, resulting in damage to the 400VAC power distribution system at KEK

Anode Power Supply Installation at ISIS

Visual Inspection of the Buck Regulator/Fast Switch



Output capacitors and damping diode



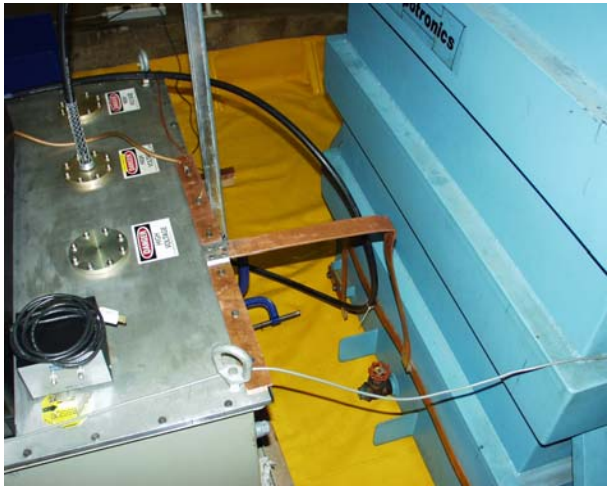
Optical connections to fast series HV output switch modules and output inductor shield

Anode Power Supply Installation at ISIS

After internal inspections, final system assembly was completed

Filling Buck Regulator/Fast Switch tank with Midel oil

Installation of step-start in T-R set primary power feed



Installation of adequate bonding conductors between sub-systems

Anode Power Supply Operation at ISIS

- **Initial testing was low power into a small resistive load with a shorting relay to verify overcurrent fault operation**
  - → *HV fault protection very effective due to <1μs response time of the series output switch to a load overcurrent fault*

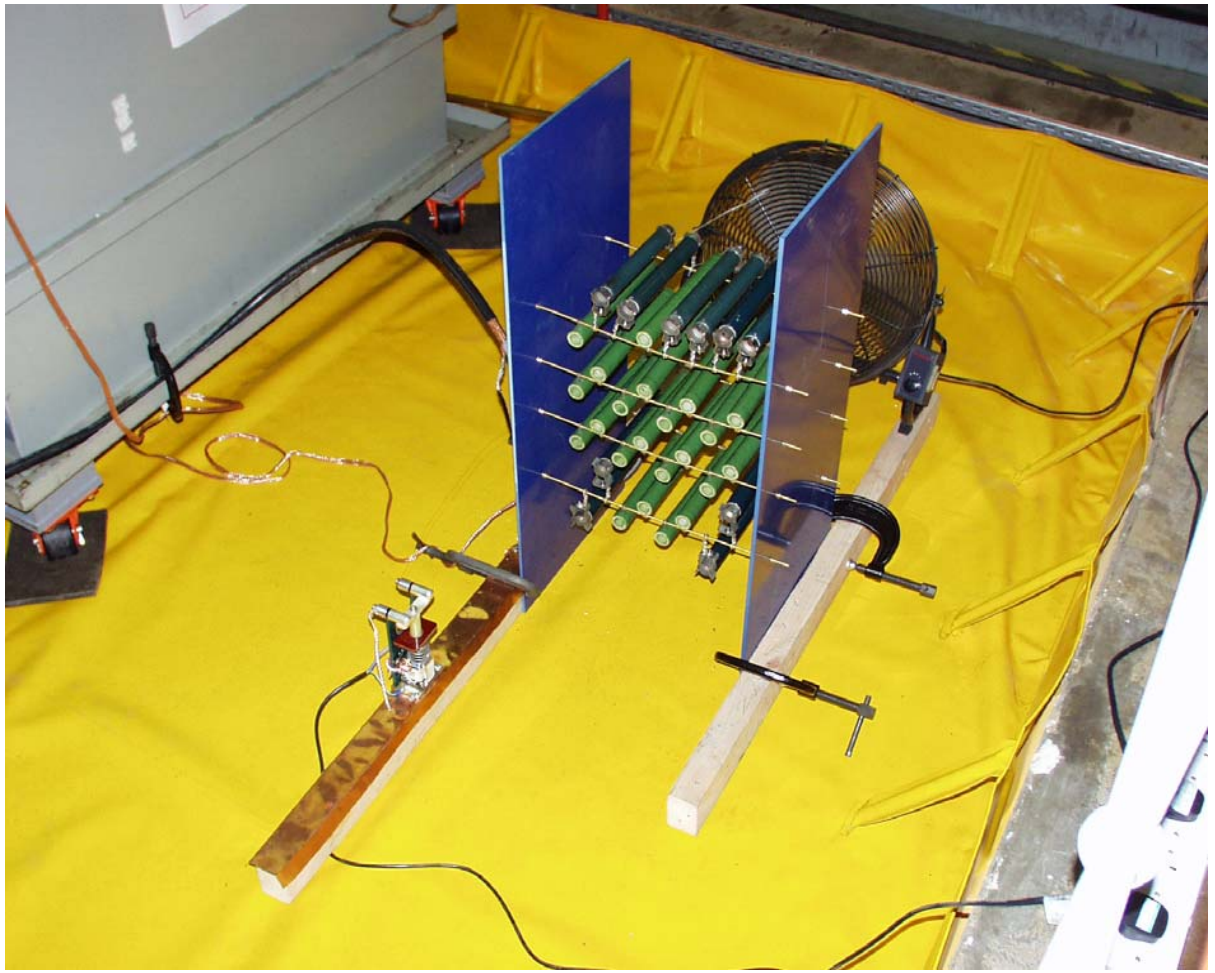
- **After fault test, the anode power supply was operated at high power during rf system operation into the cavity <u>in pulsed mode</u>**

- **The grid bias of the rf output triode was pulsed in and out of cutoff to limit plate dissipation during no-rf periods of the rf voltage function**
  - → *ANL-designed IGBT grid switcher used for this purpose*

- **Performance met rf cavity peak voltage specifications**
  - → 16kV, peak current 35A@54% duty factor (average current ~ 12.4A)

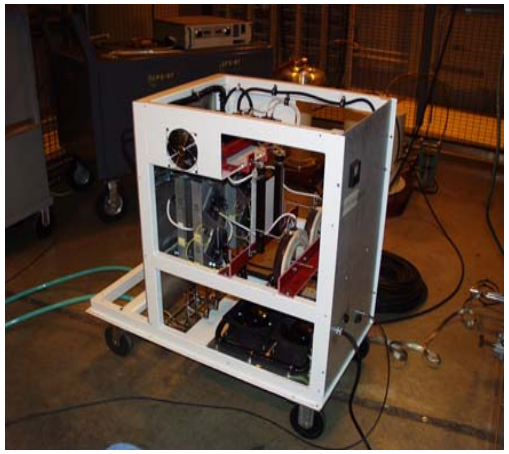
Anode Power Supply Operation at ISIS

- Low-power resistive load for initial tests of anode power supply
- Included hv relay to test operation of overcurrent interlock at ~ 5kV
- The series IGBT switch opening speed was effective, almost totally eliminating sparking when hv shorting relay was closed with voltage applied – *very impressive*

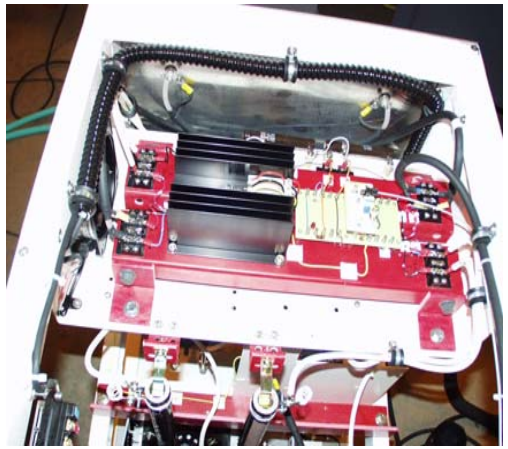


Anode Power Supply Operation at ISIS

The ANL-designed grid switcher was used to achieve pulsed operation of the rf amplifier triode

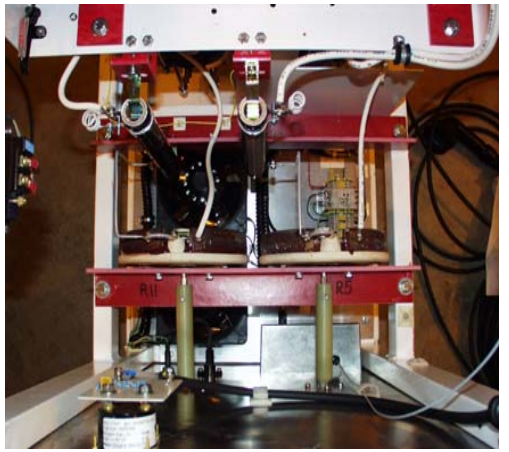


Water-cooled → resistors



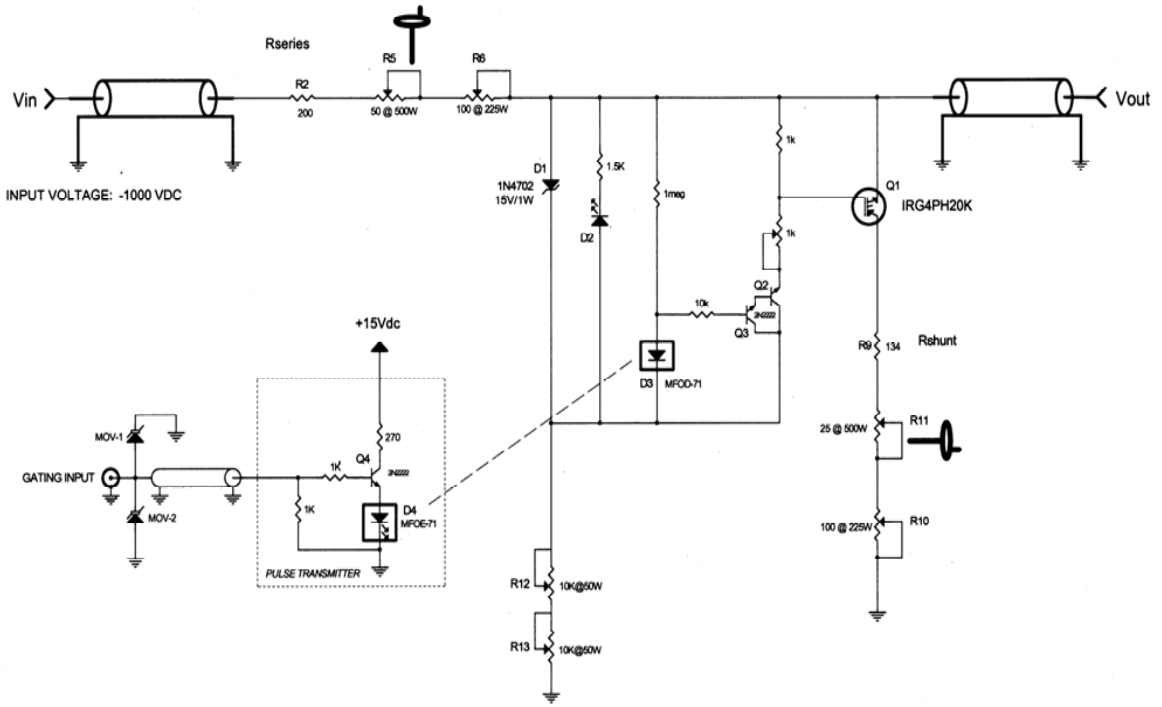
← Single IGBT switched voltage divider

Rheostats for field adjustment →



Details of ANL Grid Switcher

- "Brute-force" design to reduce unknown effects of triode grid current
- Entire IGBT and gating circuit runs only on grid bias voltage supplied by external bias power supply
- Pulsing command optically coupled to IGBT switch
- Rheostats provide field adjustment of bias output ratio

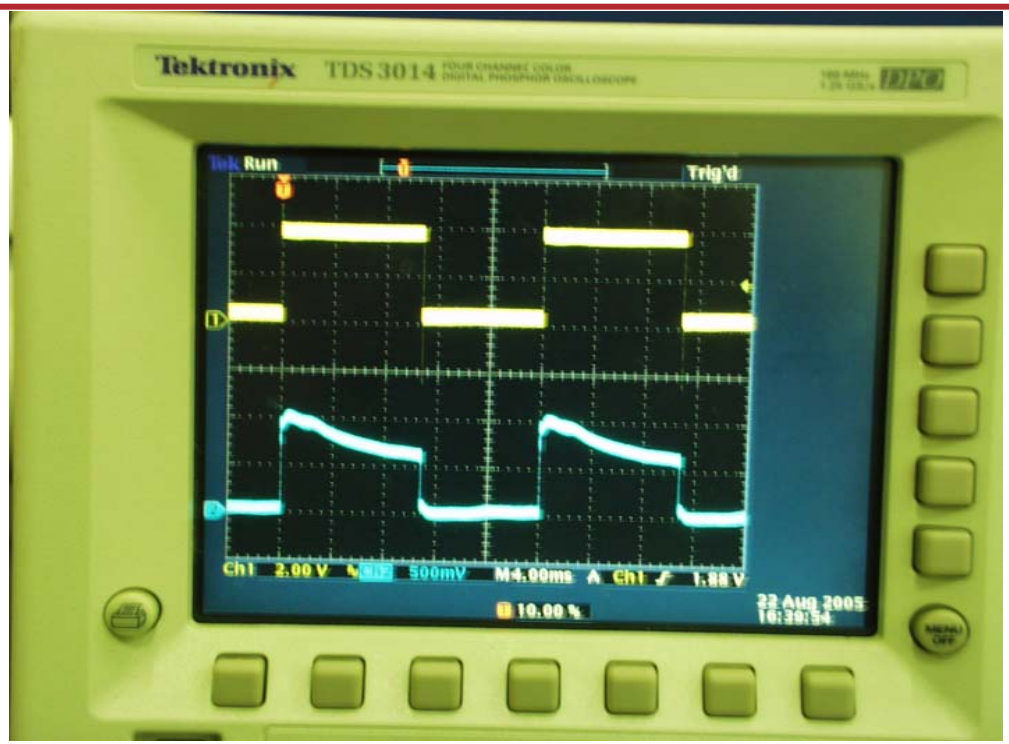


Anode Power Supply Operation at ISIS

- Waveforms show performance of the ANL anode power supply with the rf system developing the rated 11kV p-p rf voltage across the rf cavity gap

  → top trace is grid switcher gating pulse

  → bottom trace is resulting triode rf output stage plate current, ~ 35A peak at 16kV output voltage



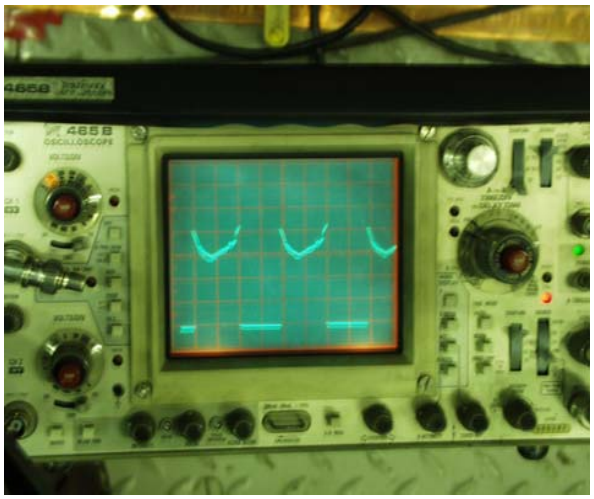
Droop in plate current pulse is due to a 50Hz modulation of rf drive to the triode possibly caused by vibrating filament wires in the Burle 4648 tetrode used to drive the output triode…….
a problem previously noted during system testing in Japan

Anode Power Supply Operation at ISIS

Other Operational Data Taken at Full Power

Buck regulator output current meter indicating ~ 13.5A average current at 16kV output (~ 216kW output power)

T-R Set 400V ac input current ~ 360A/phase



50Hz modulation seen on 4648V1 tetrode driver plate current

vibrating filament wires suspected!

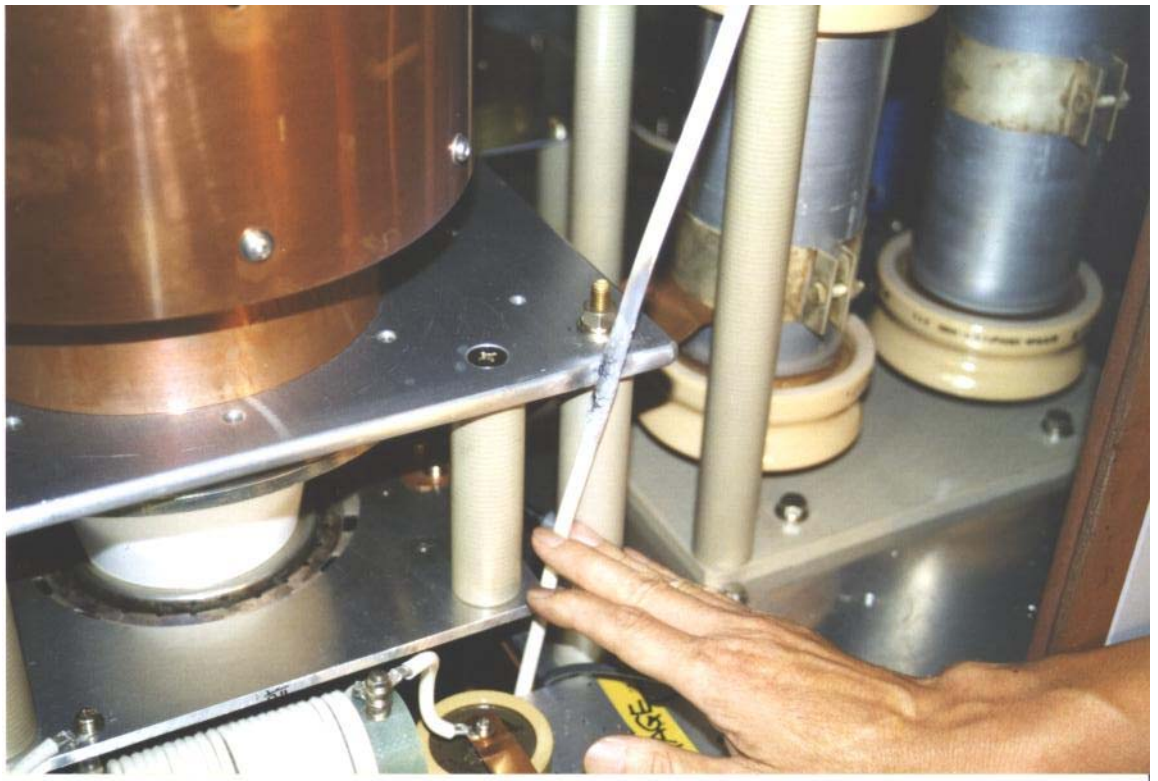
Comments on Anode Power Supply Performance

IGBT HV Series Output Switch is Very Fast!

- Very effective for limiting energy input to faults!

HV wire insulation failure in rf amplifier chassis during early tests →

It made a loud bang, but caused no significant damage!



Comments on Anode Power Supply Performance

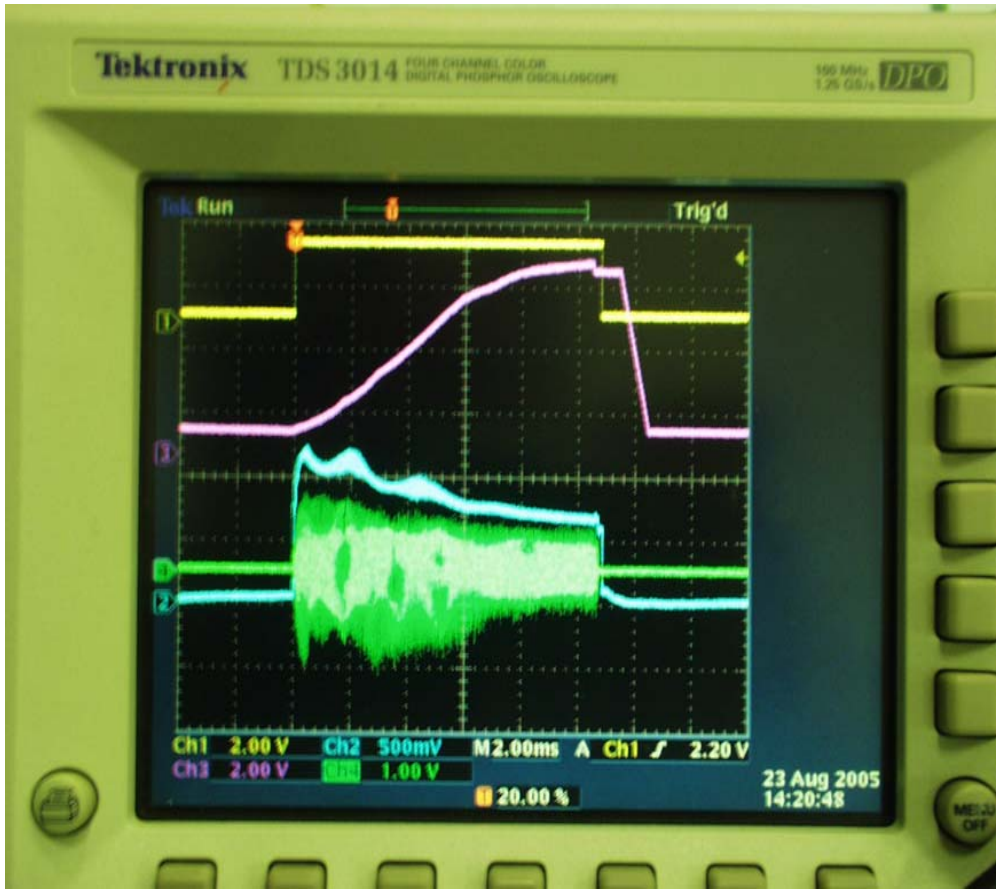
- The amount of 10kHz buck regulator switching noise in the power supply output does not appear to be a significant issue in the performance of the LOI rf system

Top wvfm: Grid Switcher gating pulse →

Second wvfm: rf cavity bias current →

Third wvfm: RF amplifier triode plate current →

Fourth wvfm: rf cavity gap voltage →

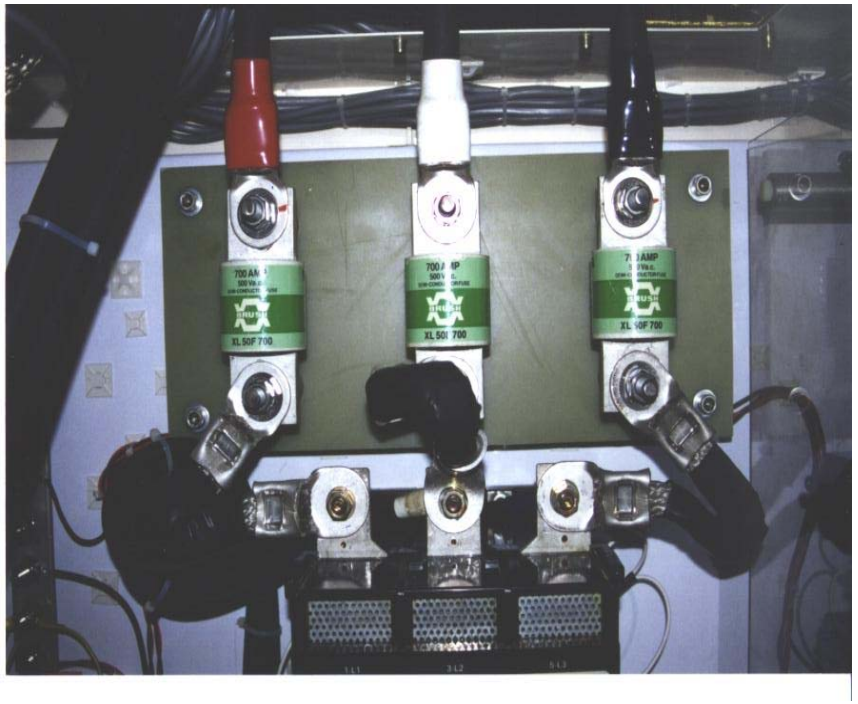


Lessons Learned

- ALWAYS INCLUDE FUSES ON THE MAINS POWER INPUT IN ANY POWER SUPPLY DESIGN!

  → *DO NOT assume that facility ac power distribution equipment can interrupt the fault current it can deliver!*

Fuses added to step-start cabinet after the hv connector fault that resulted in destroyed 400V circuit breakers at KEK →



Lessons Learned

Do not undersize the oil tank for a high-power buck regulator!

- To reduce costs, the buck regulator was designed to fit into a surplus oil tank that was available……..

  But this forced components close together, increasing stray capacitance that increased the coupling of 10kHz buck regulator switching noise in the power supply output than normal

  In spite of this, 10kHz noise does not appear to be a problem at this time

Conclusion

Plans are being developed at this time to:

- Relocate the LOI anode power supply to a different technical area at ISIS in preparation for rf system tests with the ISIS beam
- Install the LOI rf amplifier and cavity in the ISIS ring
- Perform second-harmonic rf experiments using the LOI system with the ISIS beam

At the conclusion of the ISIS tests, the anode power supply will be dismantled and shipped back to ANL

We will use it for future projects!