A Random Walk in HV & Pulsed HV with Resonant Circuits and Business Comments

North Star HV

R.J. Adler
North Star High Voltage
At Pulsed Power,
June, 2025, Berlin

Richard Adler - Background

North Star HV

- BSc Physics – University of Alberta 1976
- PhD EE Cornell University 1980 (John Nation Advisor)
- Mission Research Scientist/Group Leader 1980-1985
- Pulse Sciences Inc (LA) Scientist 1985-1987
- Founded North Star Research 1987-2004
  - Founded with Bob Richter-Sand and Karen Adler
- Scientist at Ionatron/Applied Energetics 2004-2012
- Scientist at e2V 2013
- Operated North Star High Voltage 2013-Today
- Erwin Marx Award 2025

Subjects

North Star HV

- Microwaves and electron sources at MRC, PSI
- Systems built at North Star Research
  - More focused on commercial business than most others – We wanted to build hardware
- Design and evolution of resonant driven systems
  - Including Nested Generators
- Evolution of HV probes
- How to make a small fortune in pulsed power?
- Business aspects of building pulsers and systems commercially

Topics from Cornell, Mission Research and Pulse Sciences

North Star HV

- Collective Acceleration of ions with intense Ebeams at Cornell
- First cloth velvet electron emitter (w/Don Voss at MRC)
  - (CL electron emission with v<1 cm/μs – Jesse Neri used for ions)
  - • Desperation and velvet got our 60 kV vircator working
  - • Quickly adopted by AFWL/AFRL and dozens of others
  - • Published in Review of Scientific Instruments, May 1985
- Invented and produced microwaves with the first MILO (Magnetically Insulated Line Oscillator) with Don Voss, 1983
  - Partly inspired by J. Nation's BWOs and partly by the theoretical work of Ott and Lovelace
- Pulsed Immersion Ion Implant (w/ T. Picraux of Sandia)
  - Metal arc ions, implanted directly; Patent 4,587,430
- At PSI we simplified and reduced the cost of the induction accelerator

Metal Ion Implantation

- Sandia surface physics group required a Titanium Ion Source
  - Conventional DC Implanters Metal ion sources had low currents (1981)
- Built at MRC (1983) based on 1981 SBIR work
- Successful Sandia Implantation
- Small thyratron for the ion source
- Medium thyratron PFN for power
- At about the same time Ian Brown of LBL had a similar invention and more funding “MEVVA”
- Such sources are still widely used in TiN coating (yellow drill coating)

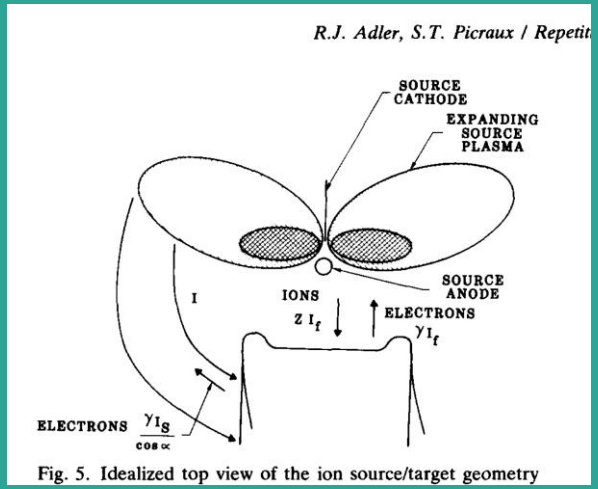


Fig. 5. Idealized top view of the ion source/target geometry

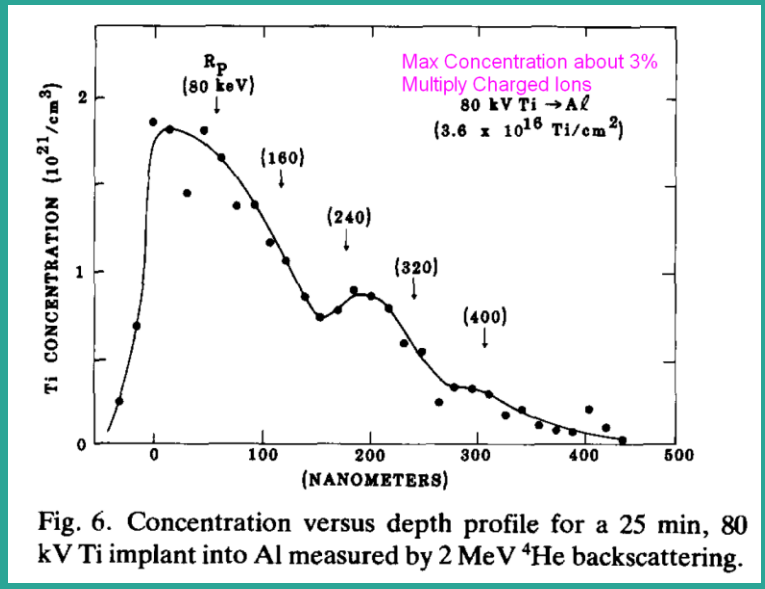
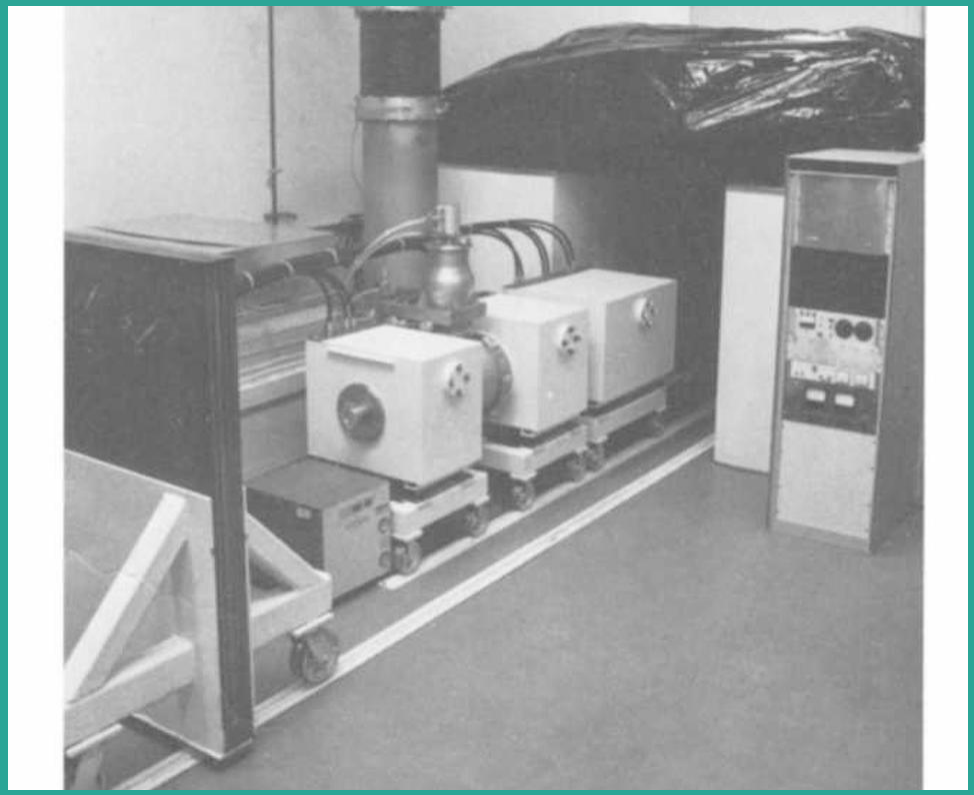


Fig. 6. Concentration versus depth profile for a 25 min, 80 kV Ti implant into Al measured by 2 MeV ^{4}He backscattering.

Pulse Sciences Reduced Cost Induction Accelerator

- 1.6 MV, 2kA
- No Stainless Steel
- Simple steel tanks with simple buswork
- Ferrite Cores
- Steel tanks filled with sand for shielding
- Built for Klystron Tests
- Removable beamline
- Built with John Bayless and Craig Burkhart

North Star HV



First NSRC Projects

NSRC Operated 1987, Sold to Ionatron 2004

North Star HV

- Pulsed Power Formulary inspired by the NRL Plasma Formulary
  - Pulsed power has the advantage of having a limited number of equations
- Thanks to Bruce Smith of the Air Force Office of Scientific Research (AFOSR) for funding the effort!
  - Thanks to Ian Smith, Carl Noggle, and Gerry Kiuttu for helping with formulae
- Virtual Cathode Phase Lock with Kyle Hendricks
  - Dual Blumlein from one Marx
  - Facilitated phase locking of two virtual cathode oscillators

Post 1996 20-30 people

North Star HV

Hardware Topics from NSRC

- Nested Generator/Solid insulation *North Star HV*
- Nested Generator and Resonant Circuits
  - Resonant solid state pulsed
  - Resonant solid state DC
- Built compact air core resonant power supplies
- Type A PFN Marxes in gas
- Plasma Implantation and Diamond Implant/Coat
- Custom pulse power of all kinds
- 200 delivered pulse generators/accelerators built in 14 years

Applications Topics
North Star Research Corp

North Star HV

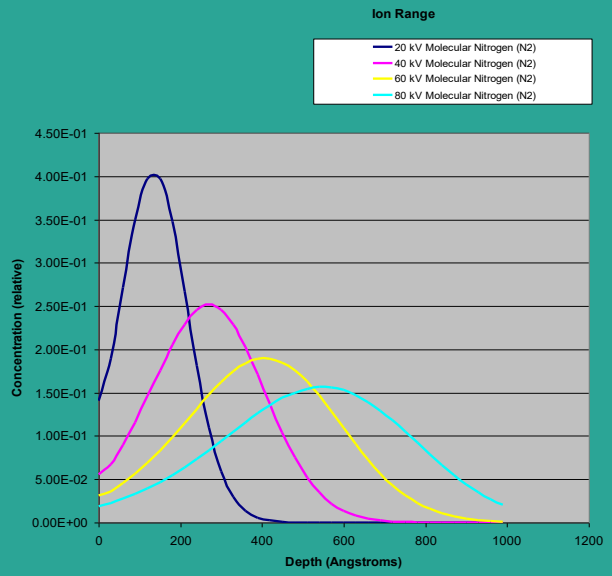
- NHVG Applied to Cargo scanning for security applications
  - Moving beam scanners
- Ebeams for crosslinking/polymerization
- Ebeams for medical products' sterilization
- Ion Beams for High Energy (>500 kV) Ion Implantation

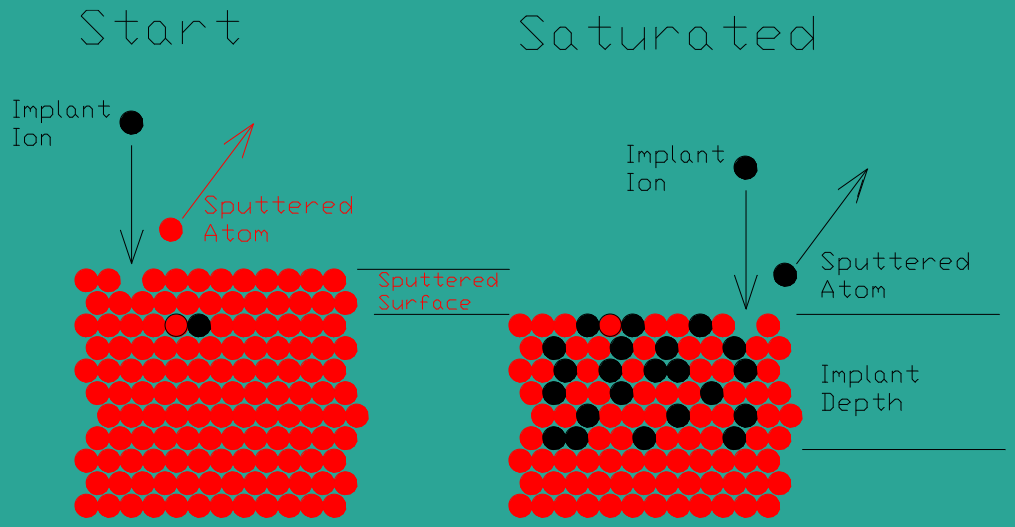
- Non-NHVG
- PFN Marx Generators
- PBII (Plasma Based Ion Implantation) for surface properties' improvement
- SOX/NOX reduction on ships/vehicles with resonant HV
- Resonant air core power supplies

Ion Implantation for Wear and Corrosion

North Star HV

- Implantation and plasma implantation inject ions into a surface to enhance mechanical properties
- Limited by Range
- Initially used accelerators but immersion is more conformal

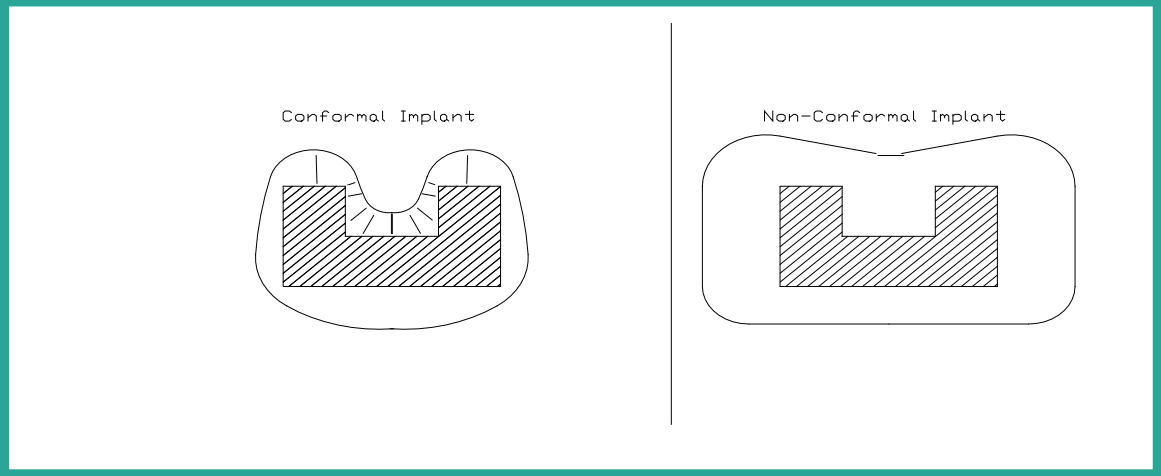




Conformal Ion Implantation

- Plasma is Close to Implanted Part
  - Measure of Conformal Taken is gap at end of Pulse
  - Gap = Distance From Plasma to Part
- Dense plasma and high current were required – therefore pulsed
- Similar to Sandia System

Conformal ***Non-Conformal***

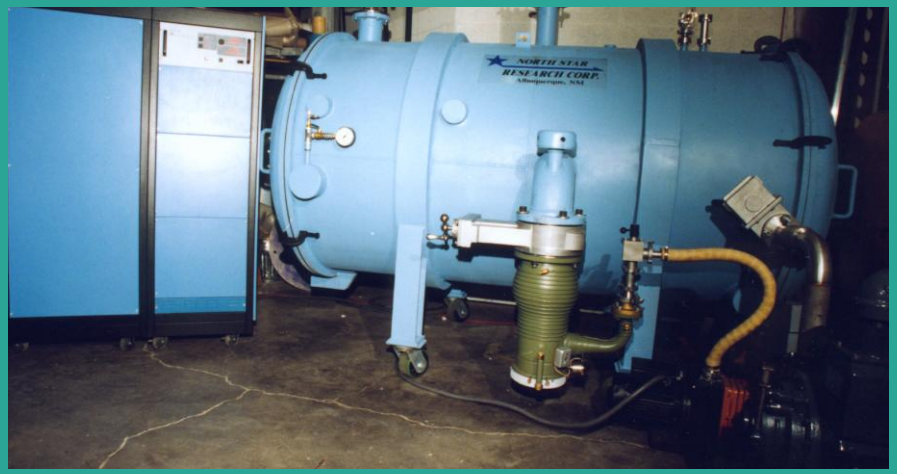


Joint Commercial Plasma Implantation Facility

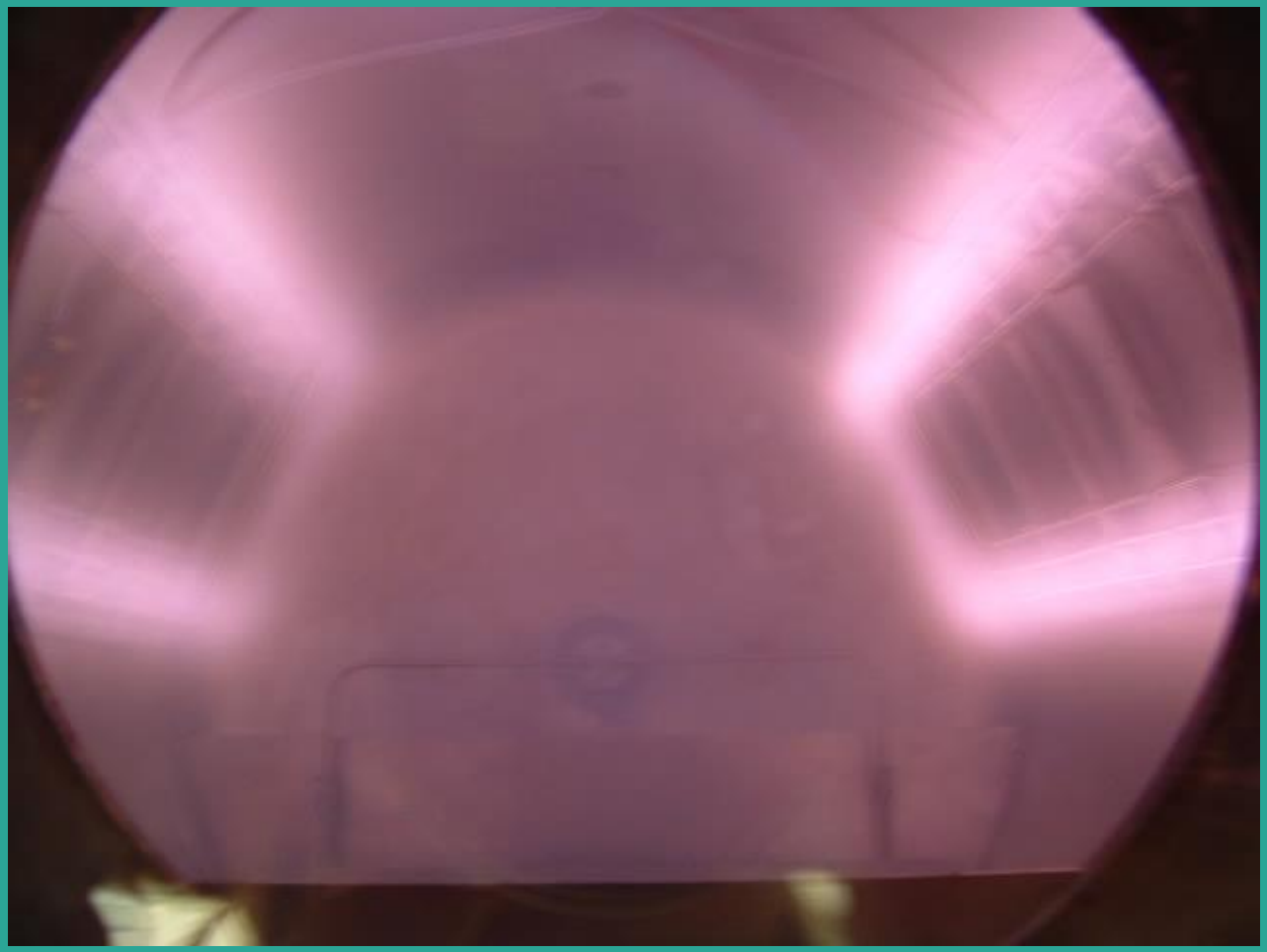
- Located at Empire Hard Chrome plating facility (south side of Chicago)
- >500 Batches in 2 years (single shift)
- >1 batch/day Including Setup Times
- Customers were Primarily Large Companies
- Jay Scheur (LANL) set up the facility and initially supervised operations
-

Empire Implantation System

- 10 usec, 2000 cm^2, 50 kV, 300 A peak
  - => d = 4 - 5 cm. In most conformal case
- Typical Day to Day Implants - 5 – 7
- Facility was profitable

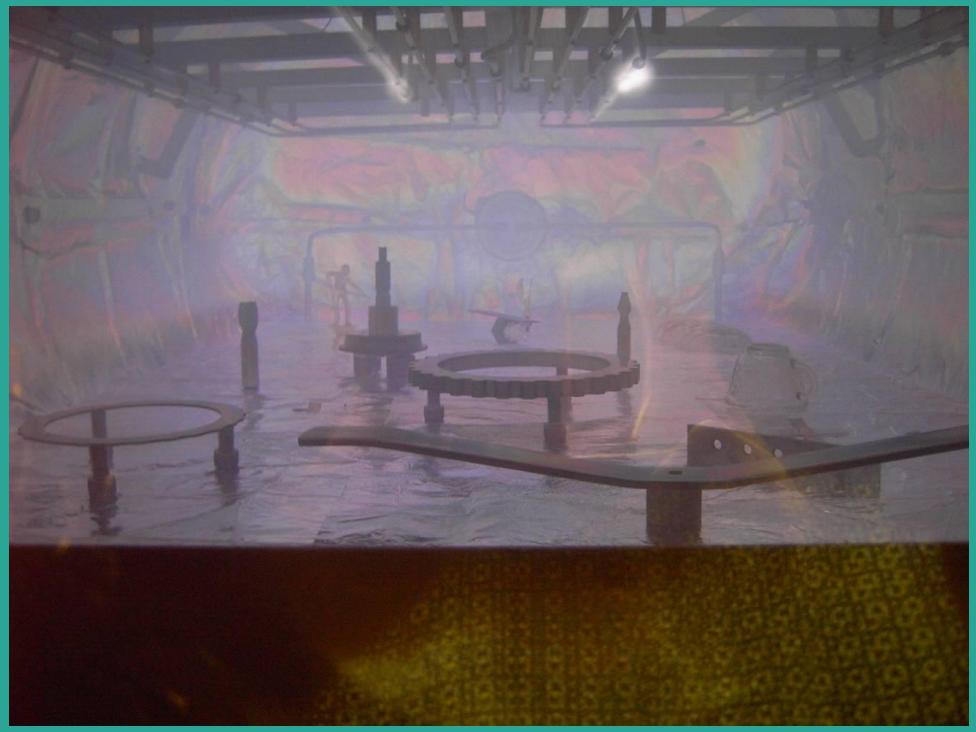


High Density Pulsed RF Source
~ 6e-4 Torr



Conformal deposition developed using PBII Techniques

- PBII techniques were also used to create conformal DLC (Diamond Like Carbon)
- This work continues in successful facilities notably in Germany and Japan
- North Star equipment is still in use in some of these facilities

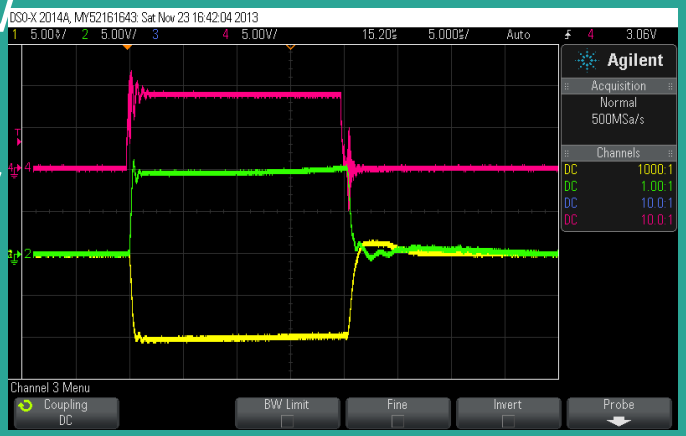


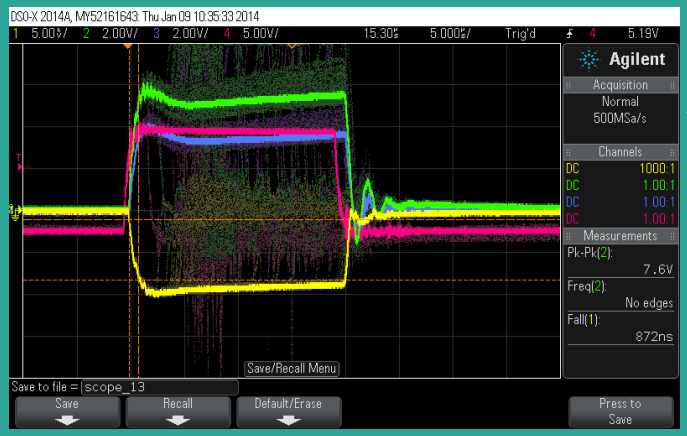
Later Pulsers for Plasma Implantation and Deposition

- Previously we used snubbers but recovering energy into main energy store is better and more reliable

V=Yellow
I=Green

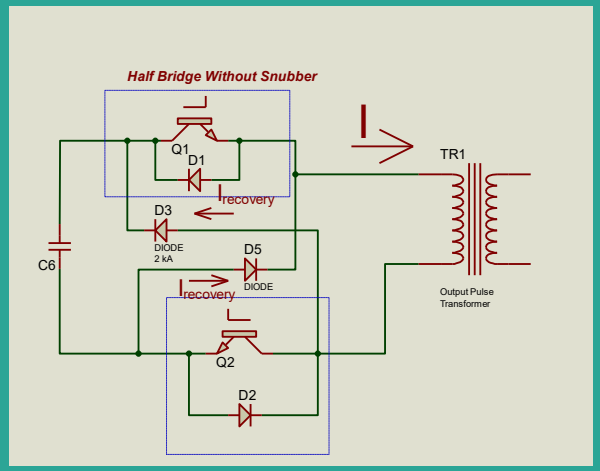
Resistor Load Nice!





Survival w/Plasma Shorts 100Hz Essential!

Plasma Load Nicer!!

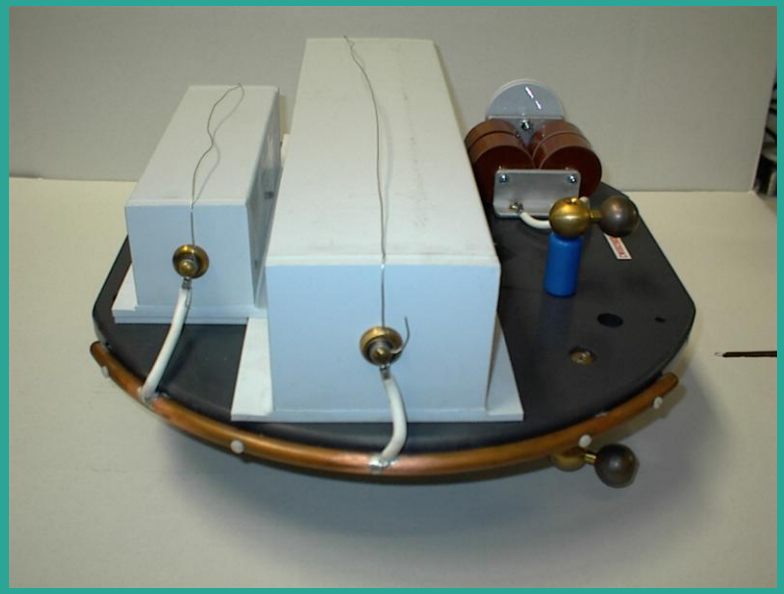


Overcurrent Shutdown Circuit is the MOST IMPORTANT

Wide Variety of Components can be Treated in a Single Batch

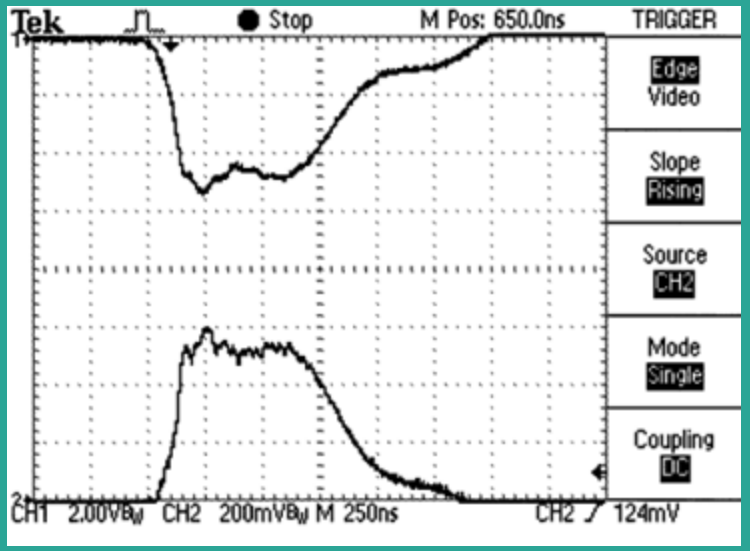
NSRC Prior Gas Marx Systems Cont'd

- Lyre – 1 AFRL
  - 500 kV
  - 150 nsec Pulse Width
  - 4 kA
  - U = 300 Joules
  - PRR 20 Hz
  - Collaborated with Jane Lehr



Stacked Type A PFNs

>400kV Output



Stacked Marx/PFN

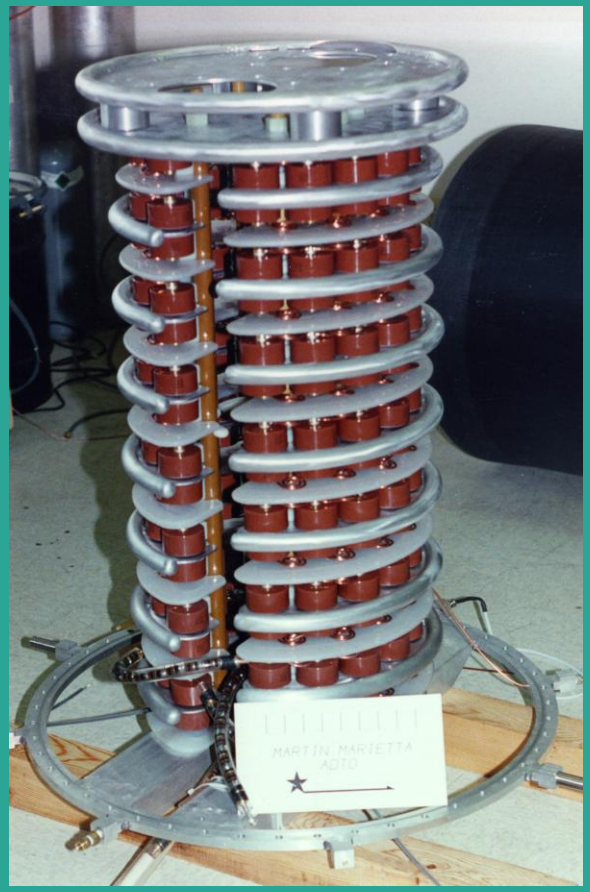
100 ns 1.3 MV Unit

Gas Insulated

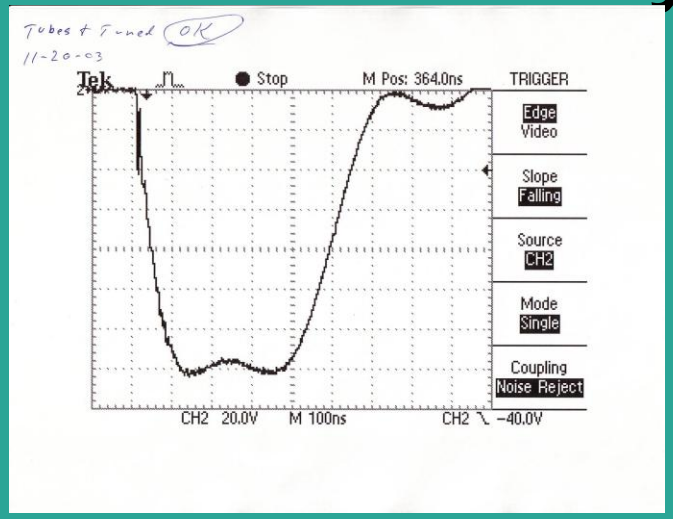
Basis for HPM Pulse

Basis for EMP Generators

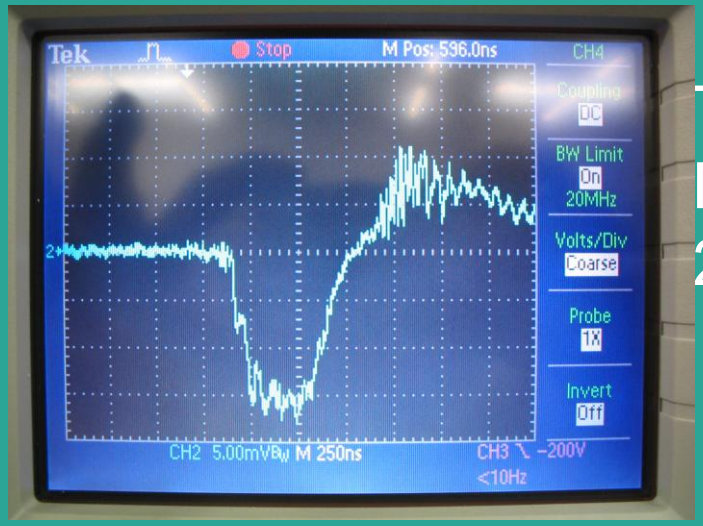
EMP Requires Peaking Sw.



Stacked Type A PFNs (Tuning



Single
Tuned
Platter
100ns/d

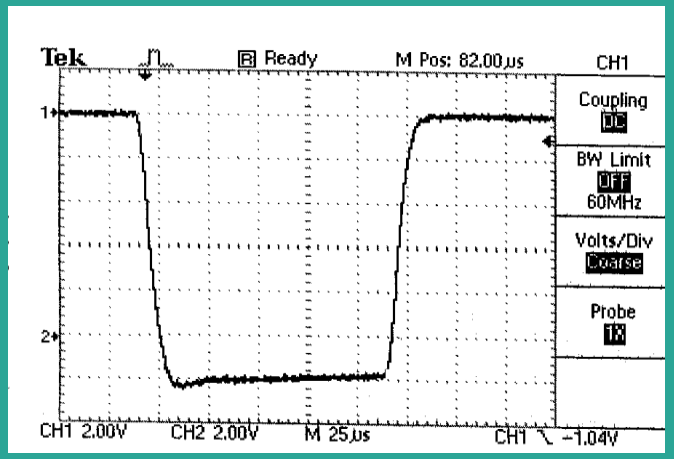


Total
Marx
250ns/d

Solid State/Pulse Transformer Generators

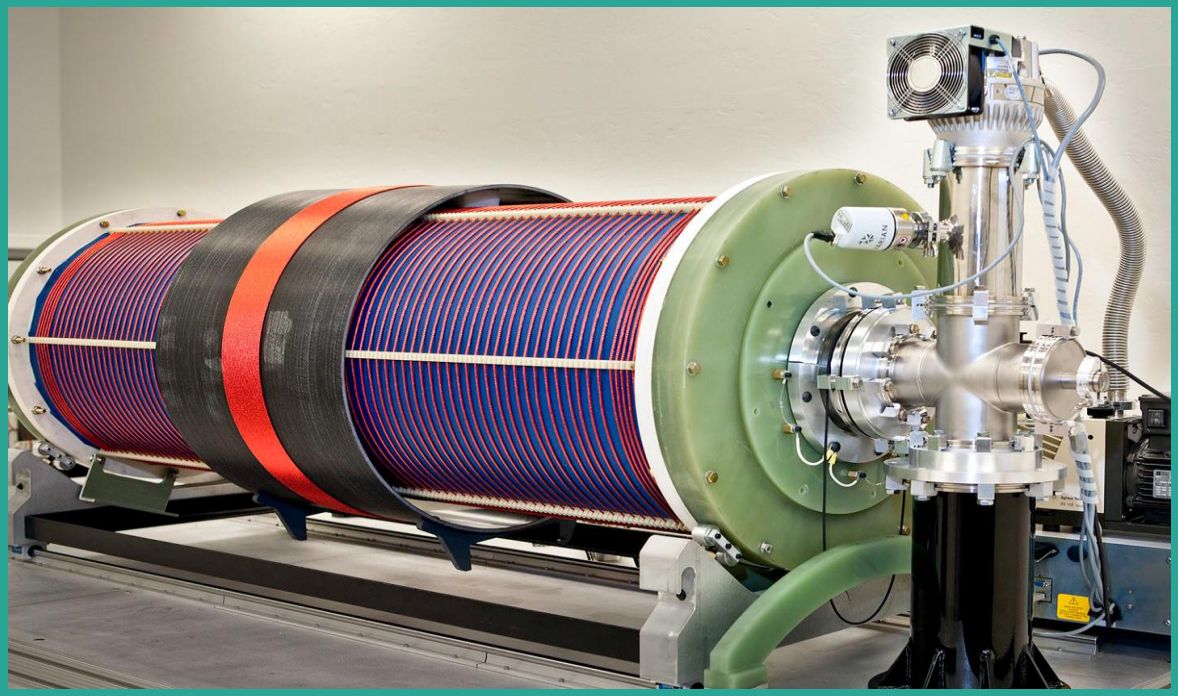
North Star HV

- North Star Research built >30 solid state/pulse transformer generators between 1997 and 2004
- Applications Plasma Implantation, TWT drive, Klystron drive, High Power Microwaves etc
- Long Pulse Klystron Example with IGBTs



Solid State High Power Accelerators

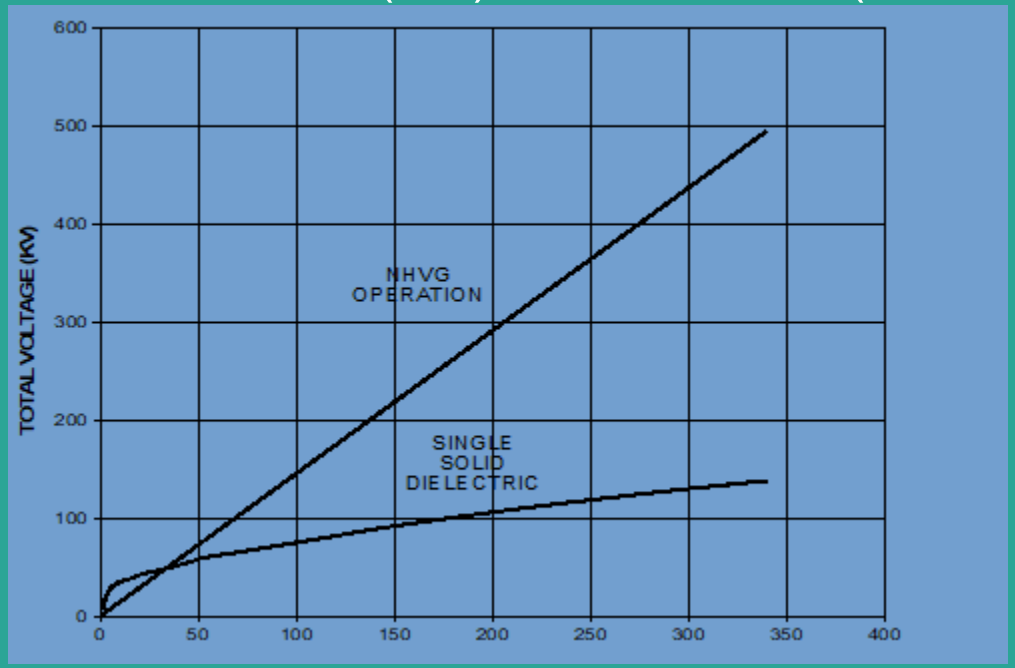
North Star HV

- Nested HV Generators to 1.2 MV are DC machines at high power with excellent fault resistance
- 
- R.J. Adler
- US Patent
- 5,124,658

Nested Solid Insulation Reduces DC Machine Size

North Star HV

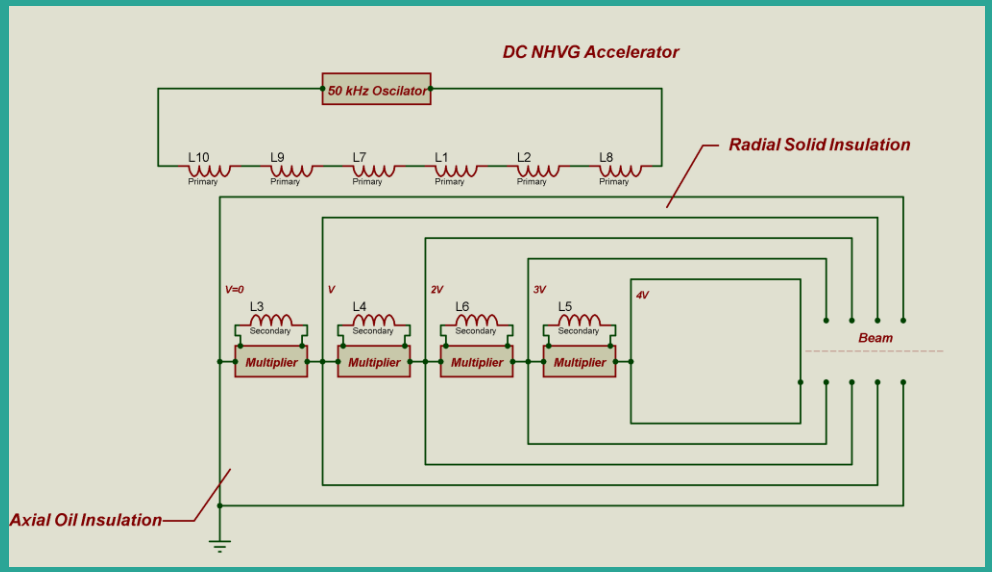
- Typical solid insulation gradient is 0.5 - 1.0 MV/inch
- Solids have been limited by total voltage effect
- Oil hasn't been used (DC) Above 800 kV (Chalk River)



Nested Faraday Cage Allows Solid Insulation Use

North Star HV

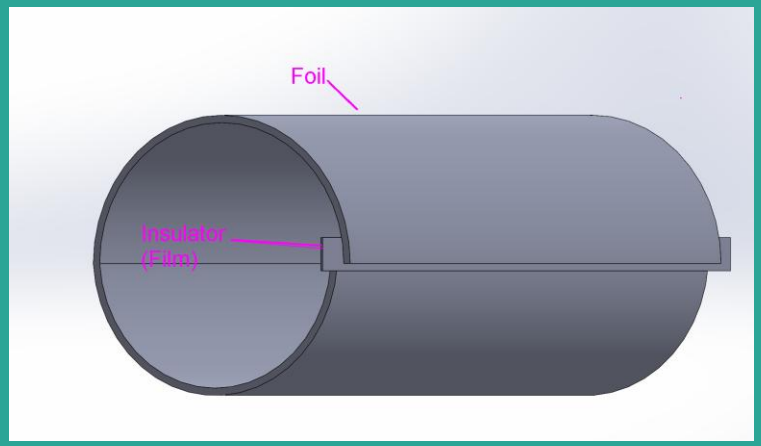
- Faraday cages isolate voltage within stage
- Voltages don't build up during fault
- Fault energy is isolated in a eliminating "Total Voltage Effect"
- Resistors coupling to column damp V-reversal

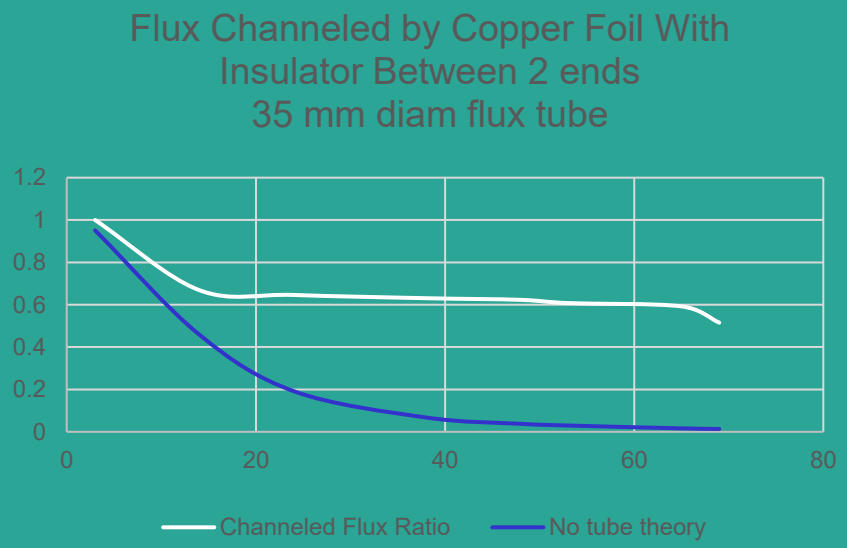


Nested Generator Basic Power Ideas

North Star HV

- Air core flux coupling to main acceleration and to cathode (at a different frequency)
- All metal foils were azimuthally interrupted to allow axial flux penetration





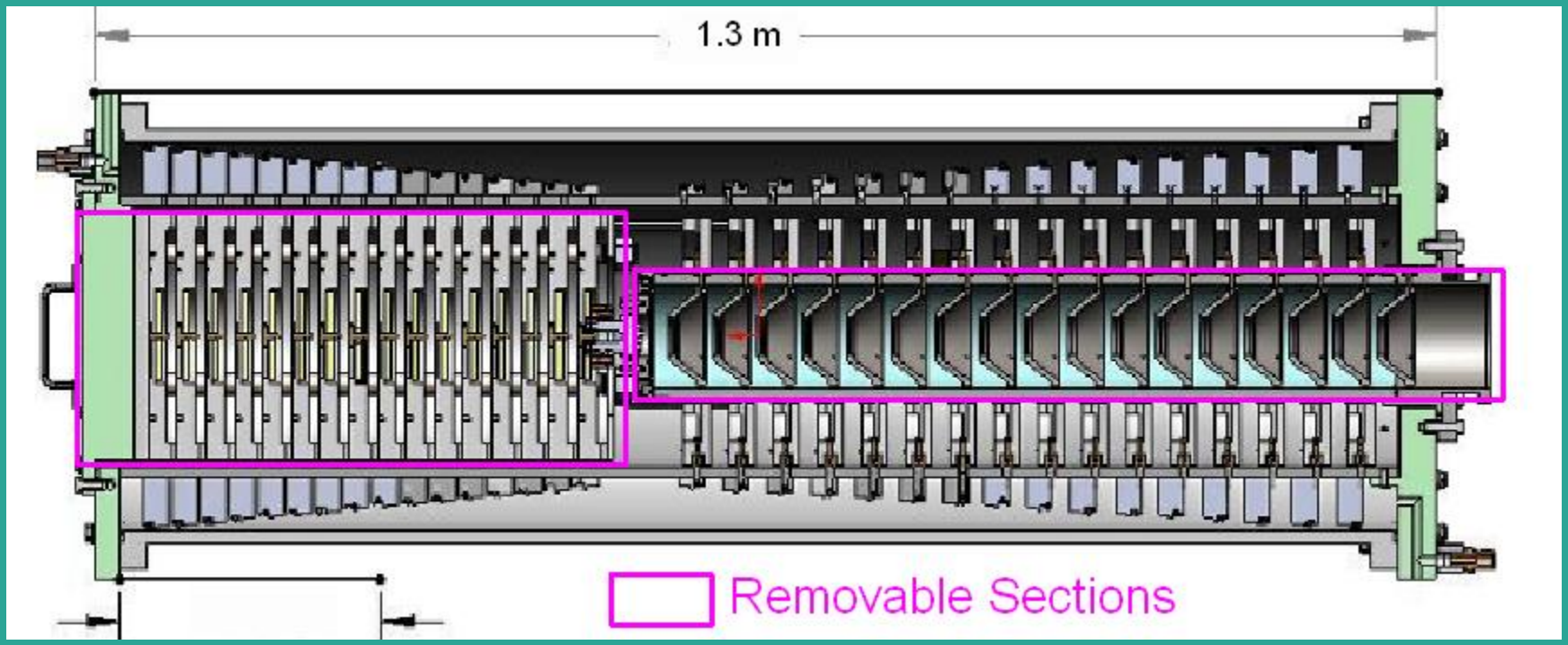
Winding

North Star HV

Overcame Maintainability Issues

Ultimately easy to maintain

North Star HV



Tom Montoya developed many of the techniques which made these units easily maintainable

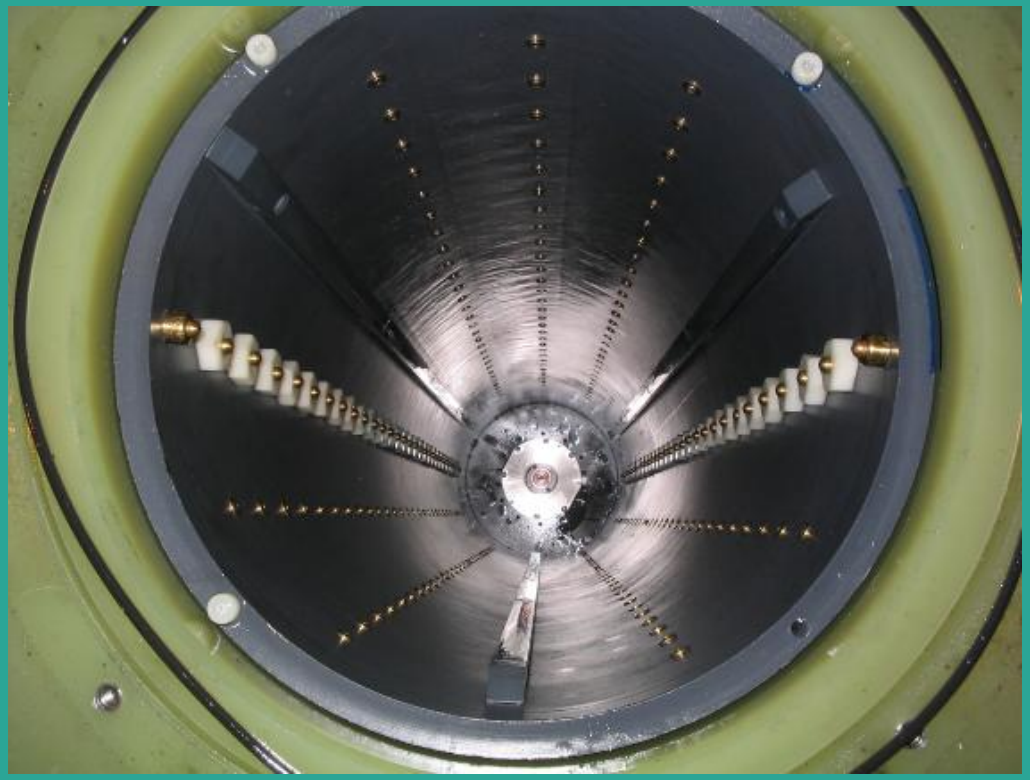
Views of Removable Beamline and Multipliers

North Star HV

Vacuum accelerator column
With some electron discoloration

Looking through the inside

North Star HV



Accelerators Delivered and Used Industrially

North Star HV

- "Big Blue" 400 – 500 kV demonstration unit for Positron Emission Tomography (PET) used as demo facility
- 1 MV electron accelerator For X-Ray Scanning – (operated at 1.15 MeV)
- 0.7 MeV, 1 mA Accelerator for in-Line Sterilization – successful technology demonstration Baxter Healthcare
- 500 kV Ion Implanter Delivered to INER Taiwan 2002
- 600 kV Semiconductor Ion Implanter in Production Innovion (Used for more than 12 years 24/7
- 3M 300 kV unit with advanced fast scanning
- A second 600 kV Unit for Innovion (built at North Star Power Engineering)

Production NHVG

North Star HV

- Medical product irradiation NHVG Under Test

Controls

Accelerator

Other NHVG

North Star HV

- Plastics (3NM)->
- Semiconductor below

Powering the NHVG -Pulsing Increases Efficiency

North Star HV

- Powering the NHVG evolved from pulsed tubes to pulsed and CW RF systems
- Why pulsed?
  - Exactly as for RF accelerators
  - E ~ (PT)^.5 or V~(PT)^.5
    - P = pk power, T = energy store time
    - High Pk Power, Medium Avg Power
    - Duty = (Avg Power/Pk Power)
- Originally used power tubes

Powering the NHVG -Resonance

North Star HV

- Resonant circuits allow multiple “re-use” of energy with reduced loss
- Pulsed resonance made NHVG efficient
- After NHVG we found useful applications in many other areas
  - Multi-stage Pulse Generator power
  - Power supplies
  - Counter-IED technology

What Learned in Practice About Air Core Resonant Circuits

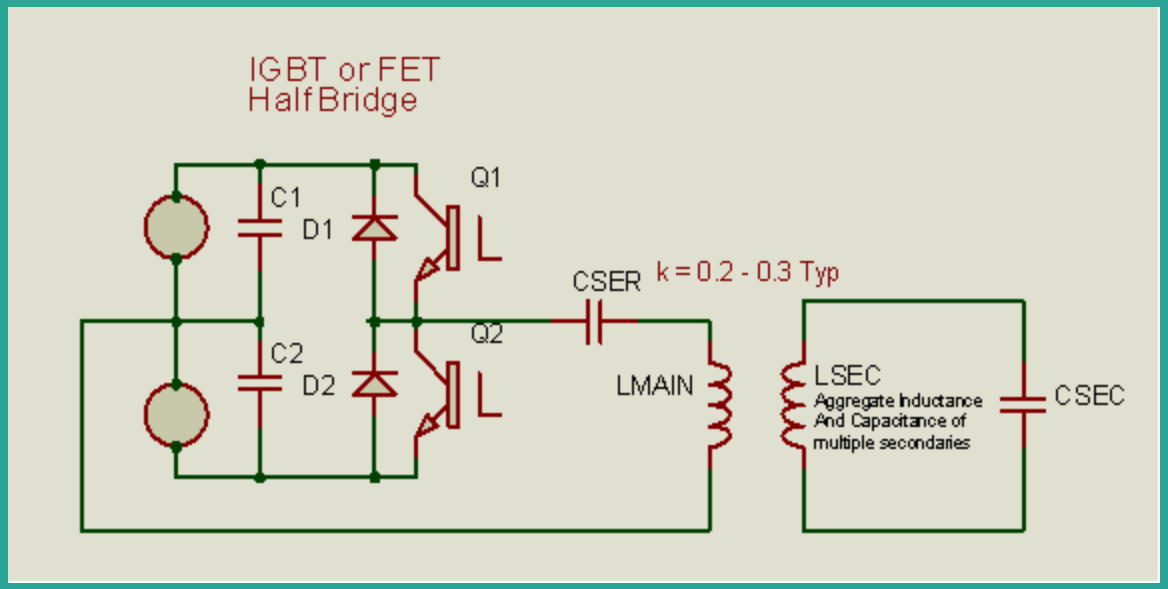
North Star HV

- Series resonant circuits worked better in most applications
- The circuits were series primary dual-resonant, multi-cycle
  - May be similar to some russian DC accelerators
- Solid state was more convenient and much cheaper than tubes

The NHVG Circuit With Series Resonance

North Star HV

- Strong coupling is not critical
  - k=0.2 is fine
- 1.2 kV devices can drive 10 kV primaries reliably

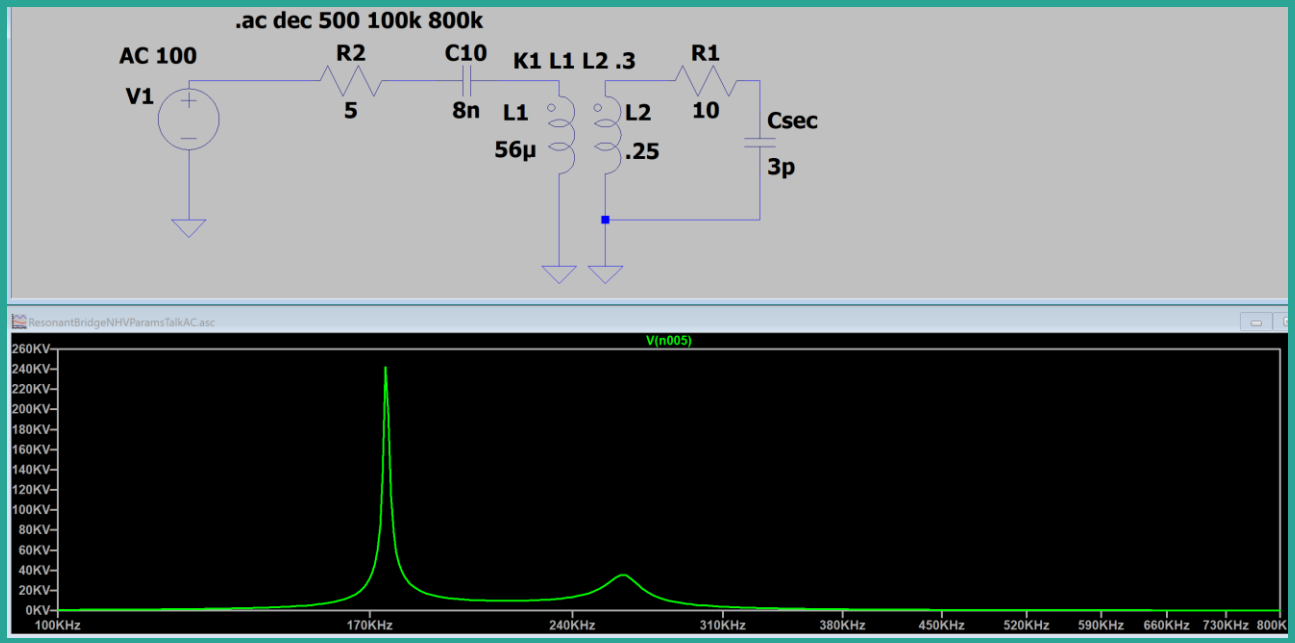


Start with the Simple Circuit in the Frequency Domain

- Easy to Simulate

North Star HV

  - k=0 Prim res = 238kHz, Sec = 178kHz in this example
  - Example: k- 0.3 Roots ~ 232k, 262k



Time Domain Simulation

- Secondary has 20X sections (multiply X 20)

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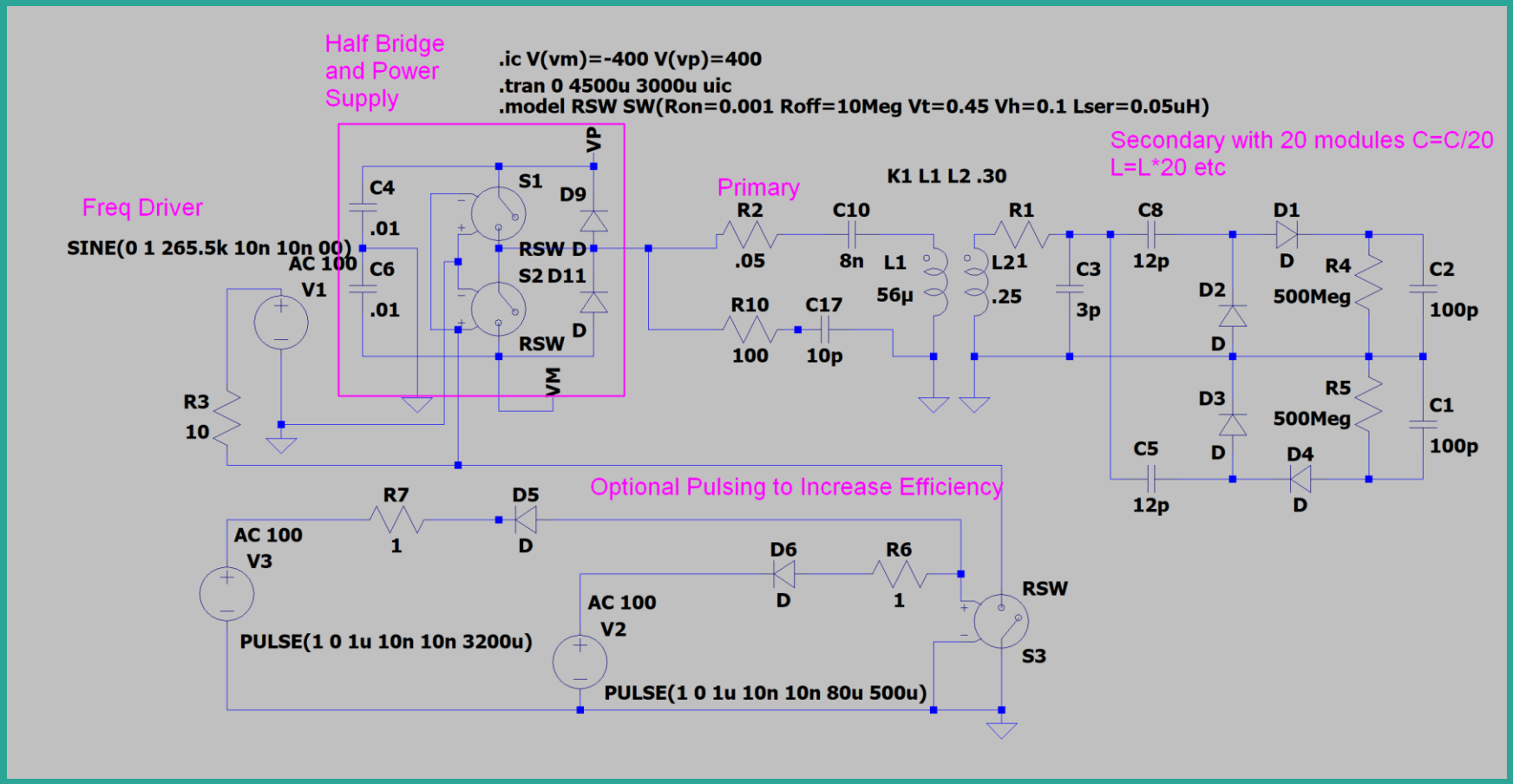
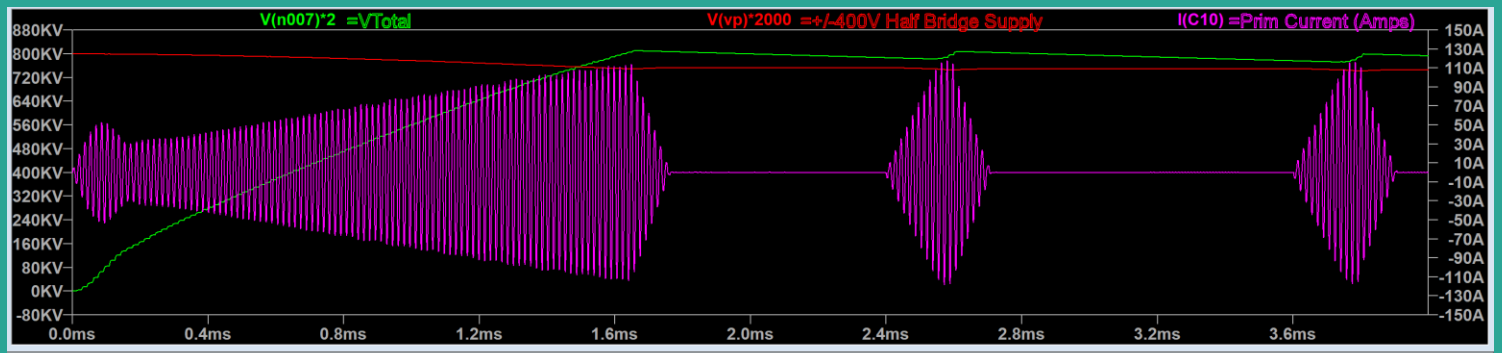
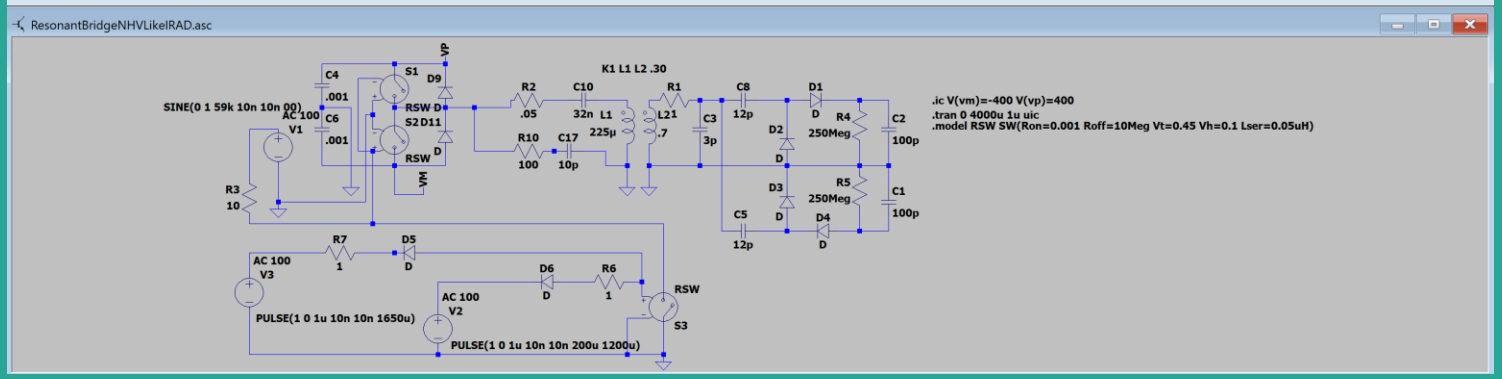


Simulation of 2010 Machine

North Star HV

- Machine built at Applied Energetics designed with Josh Gilbrech
- Customer qualified it for cable irradiation (cross linking)
- Sold to a Semiconductor facility with the machine used extensively for Ion Implantation (4 years)





What the Simulation Tells Us

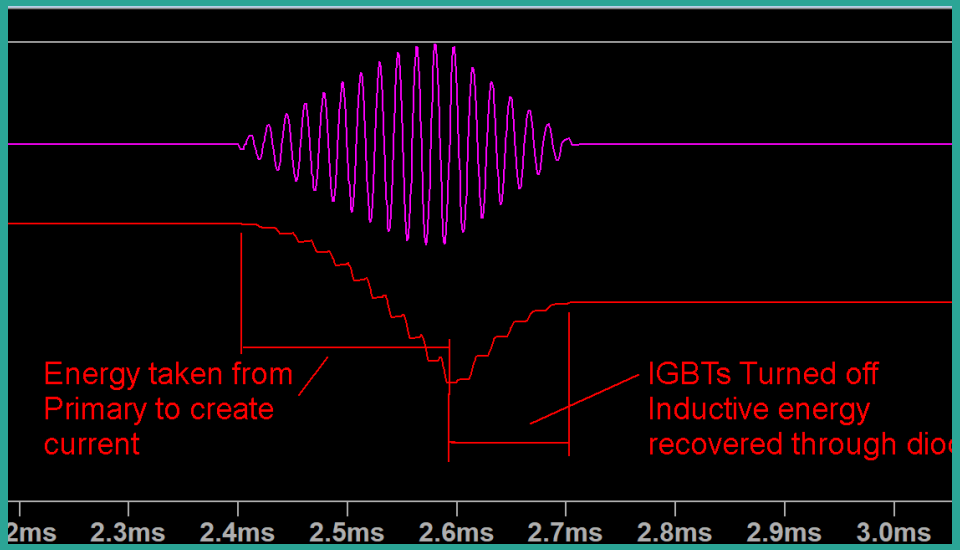
North Star HV

- Excellent voltage gain available (Vout is interrupted in simulation long before saturation)
  - Could run at 1.6 MV subject to insulation and HV Insulator limits
- The NHVG primary current shown is only needs to run 10% of time at that current
- Efficiency is about 65% running intermittent drive as shown
- IGBT drive worked well – no problems
  - IGBTs pk current is cheaper than FETs

Unexpected Benefit of Solid State Drive

North Star HV

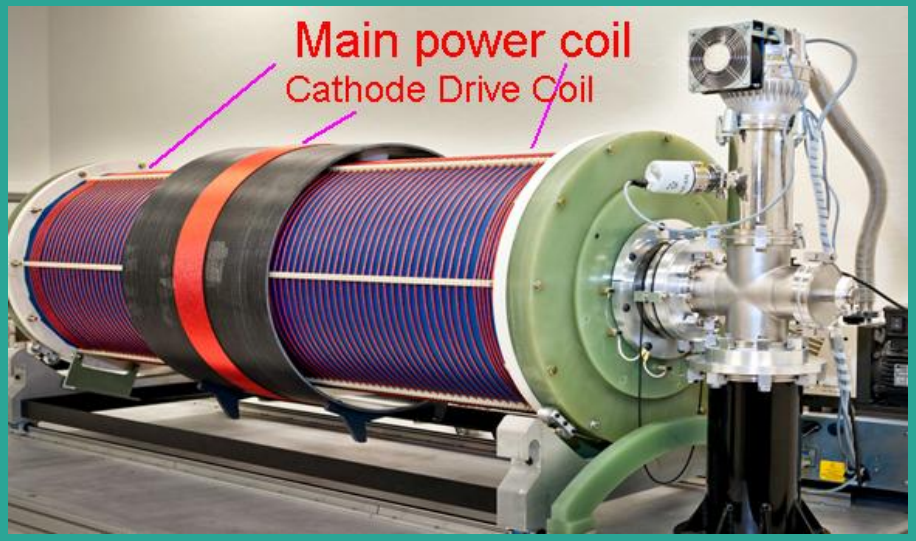
- Note shape of current and 800V energy store
- The NHVG primary current shown is only needs to run 10% of time at that current
- Simulation efficiency predicted (never measured it) is about 65% running pulsed drive as shown



Using 2 Independent Drive Circuits

North Star HV

- Separate power for HV and particle beam source is often required (separate control of V and I)
- Use of 2 air core circuits at distinct frequencies has been a successful method of providing this control
- Source frequency usually 10 kHz with low pass filter



Cable irradiator built in Collaboration with Josh Gilbrech

Later converted to Ion Implatation for Implant Center

X-ray Imaging

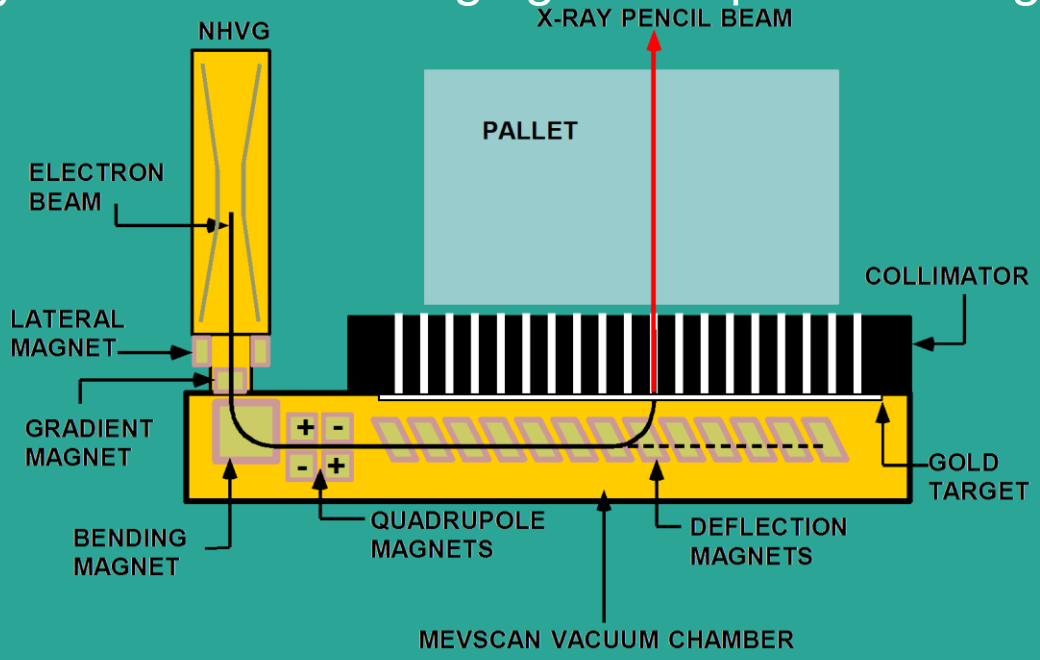
North Star HV

- 1998 X-ray imaging for border control funded (with Martin Annis of AnnisTech) for drug interdiction and security applications
- Unique method of creating images (Adler and Annis US Patent 6,009,146)
- Stereoscopic views for locating contraband position in the pallet
- Backscatter imaging for surfaces of pallet
- Lead to 3D scanning technology
- Fits Niche between Linacs and DC X-ray tubes

Linear Scan

North Star HV

- Linear Scan 4.0 meters long has been built and operated at 1.1 MeV
- 1 MeV scanner is only 27 cm deep
- Beam optics technique was critical (Stan Humphries designed a critical beam optics upgrade)
- X-ray detection and imaging technique knowledge was critical



1.2 MeV System to Create Backscatter and Transmission Images

North Star HV

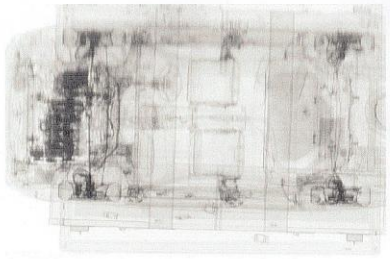
- Invention of Rx technology for high energies was demonstrated by NSHV, using “pencil beams”(1998)
- Cargo System with 2 views + Backscatter was built, demonstrated, and installed at Huntsville airport
- **NSRC developed 1.2 MeV Source, Data acquisition, Image Display (Complete System)**

Some of the Test Cargo

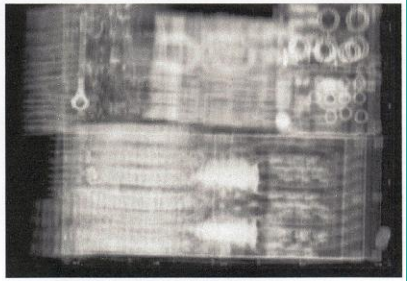
North Star/AnnisTech
Cargo Pallet System at the Huntsville Airport

T. Montoya, R. J. Adler, M. Annis G. Vellasco, T. Hart, K. Rowland, J. Leyba

8 ft X 12 ft X 10 ft high cargo inspection - 10 cu. ft/second at 60 microRem



Automobile with Logarithmic Image



Cargo Pallet with Bearing Races - Reverse Logarithmic

1.15 MV Pallet X-ray

North Star HV

- Pallet X-ray System Using NSRC Accelerator, Electronics, and Scanning Technologies

Images After Installation

North Star HV

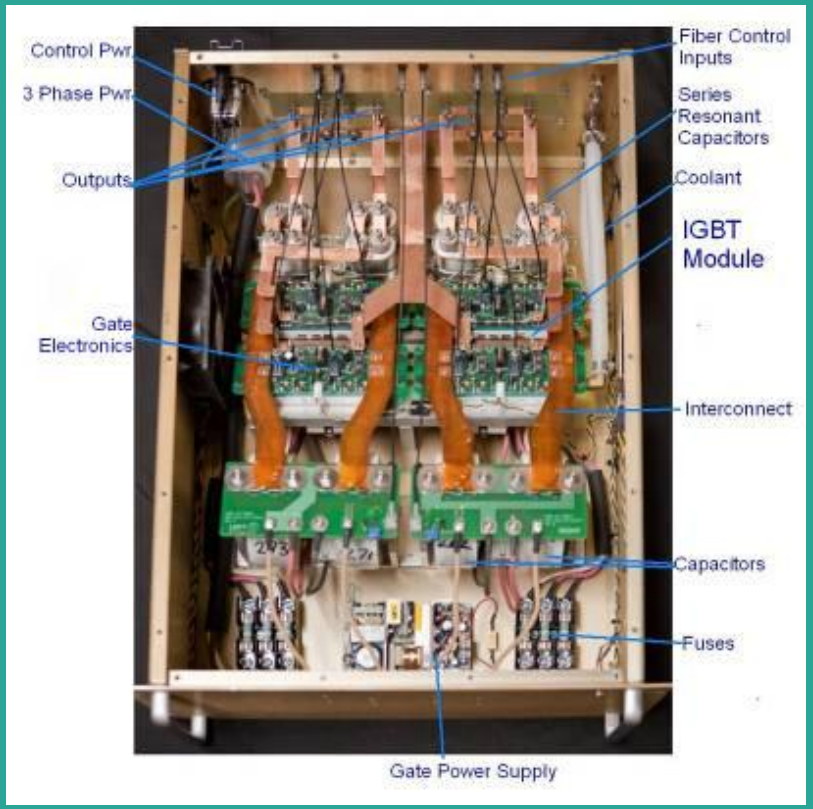
- Standard Sized Ford Rental Car
- True shape display
- 60 uRem is Dose
- Irradiation of Car With Passenger is Legal at 10 uRem
- Pencil Beam system can inspect cars with people inside

- Technical requirement discovered – all clocks in system must be synchronized

H-Bridge Drives

- Source H-bridge drive is minimal power and complexity
- HV H-bridge drives use more devices but they are fundamentally simple devices

North Star HV



Air Core Resonant Circuits Provided Us With a Tool for Many Designs

North Star HV

- Air core resonant circuits were used to power stacked solid state Marxes up to 220 units
- Air core resonant circuits were used to build power supplies up to 90% efficient in small packages
- Air core resonant circuits were used for Corona treatment of exhaust gases
- All of this was possible because the resonators = H-bridge plus coil are easy to build

Power Supply Experience

North Star HV

- Bob Richter-Sand designed many of these units
- NSWC 100 kV 20 kW ~ 1 cu ft
- 100 kV 8 kW, ~ 4 liter volume
- Variety of HV DC Power Supplies included in pulse generator systems
- Advantage of Air core resonant – smaller transformer than with core!

NSWC Power Supply

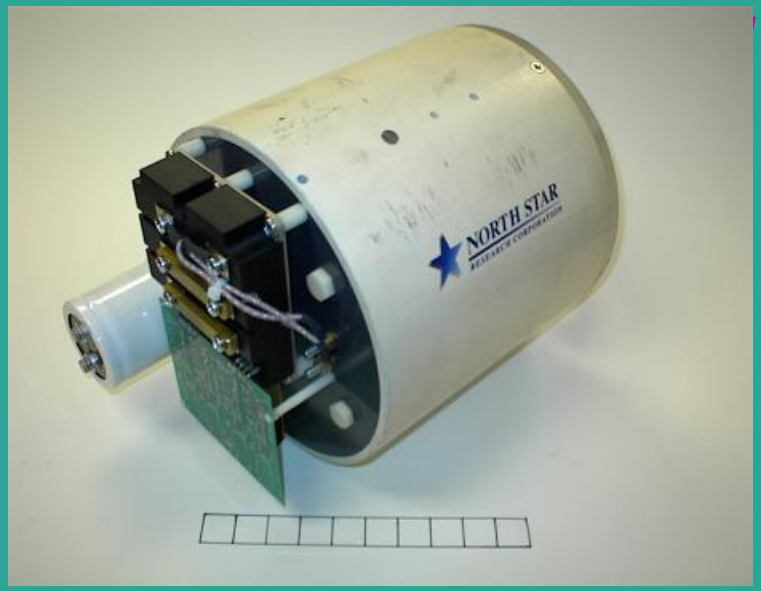
North Star HV

- 20 kJ/sec 100 kV for NSWC Dahlgren - 2002

NORTH STAR 100 KV, 20 kJ/sec DC-DCHV POWER SUPPLY

HV DC Power Supplies

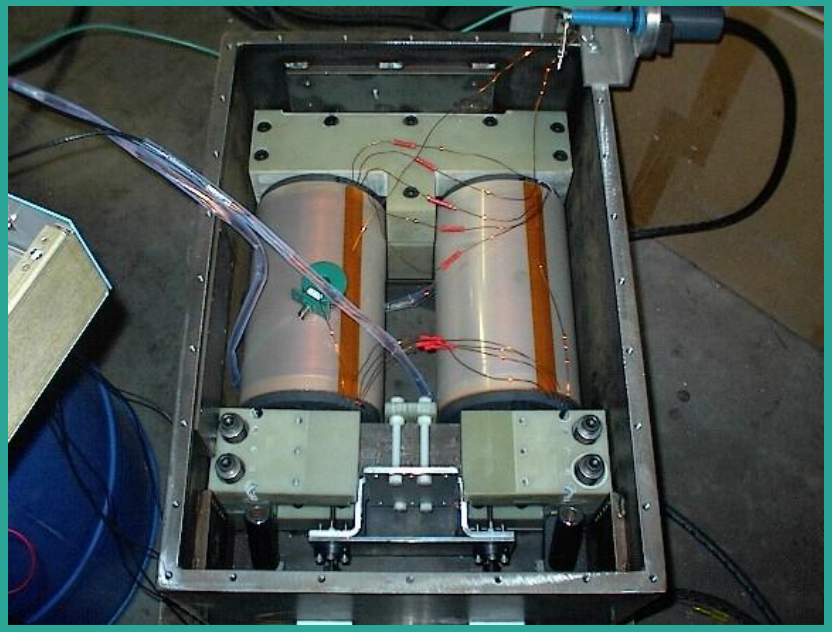
- 8 kJ/sec units
- Up to 40 kV/40 kW for Spark gap system charging



- Additional Opportunity
  - Built HVPS into Marx Feedthrough
  - Primary, secondary side by side – plastic insulator between
  - No contact except magnetic flux – Galvanic isolation

Corona Discharge driver 30 kV

- Variable resonant frequency created by variable air gap
- Operated 3 months on a Royal Navy Ship (SOx, NOx reduction)



North Star HV

700 kV Arbitrary Waveform Generator

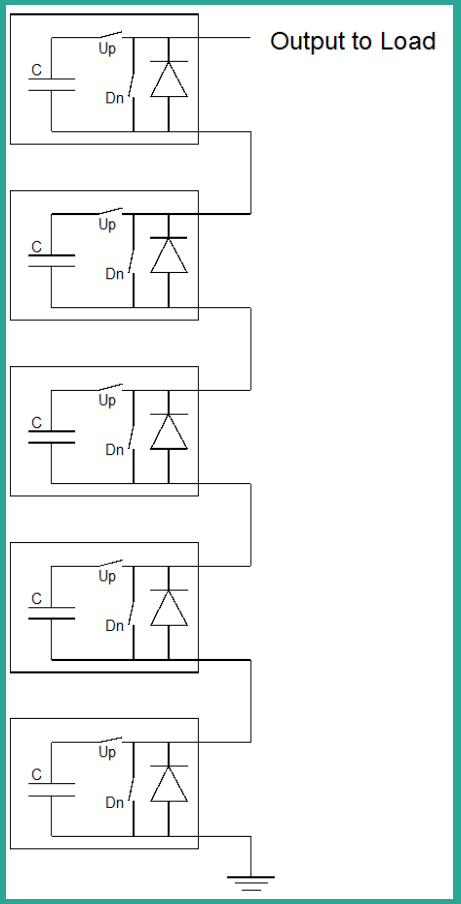
North Star HV

- Built to understand Laser Guided Energy (LGE) Applications at Applied Energetics
- 100 % solid state
- Built in 2006 – 2007
  - Built in 9 months
  - Tested in 2 months
  - Fault tolerant (load shorts were frequent)

AWG Topology Design

- Unit in the class of “Marx switched Solid State”
  - Devices date back to 1980s Harris corp/Swanson
- D/A Converter design with 1-bit ~ 3.5 kV
  - Turn-on 50 stages => 175 kV, 100 stages = 350 kV, 200 stages = 700 kV, etc
    - Control in groups
- 700 kV produced with 220 stages
- Wide voltage range is produced with fixed charge so the same magnetic flux was used for gate controls and HV charge

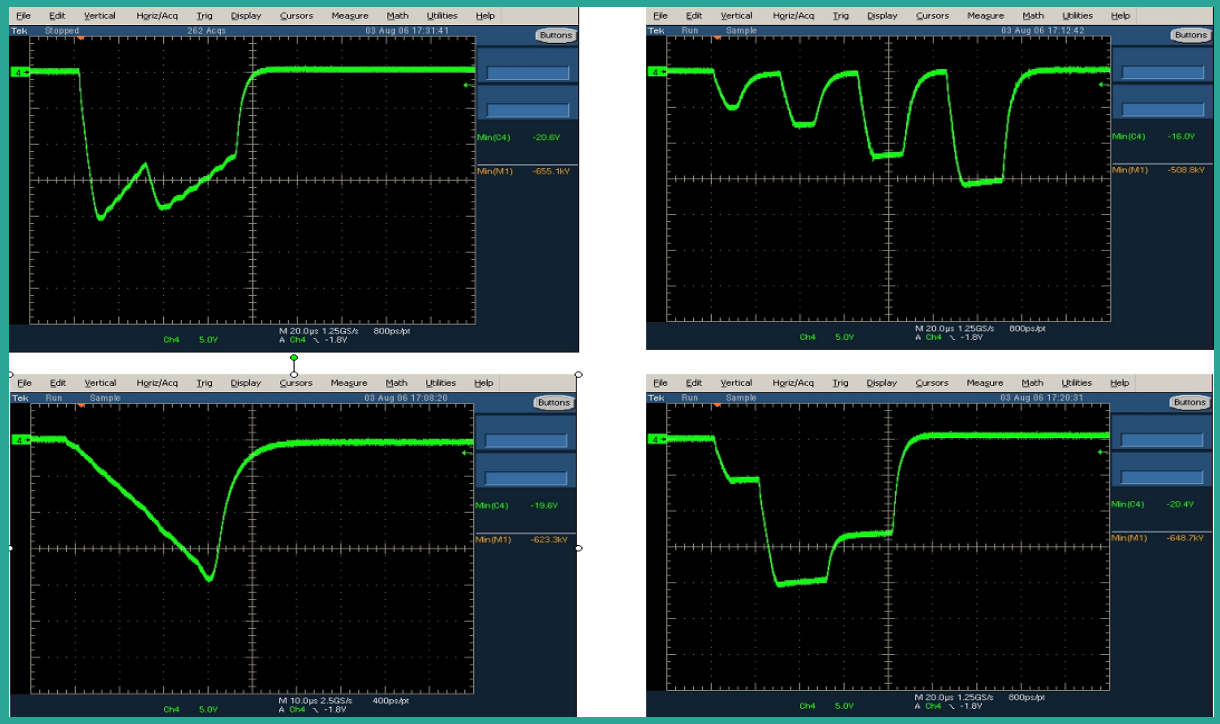
North Star HV



Waveforms

- Waveforms below were programmed and produced in 20 minutes
- Typical voltage 650 kV, 5 usec risetime

Now In Star HV



700 kV AWG with Electrode

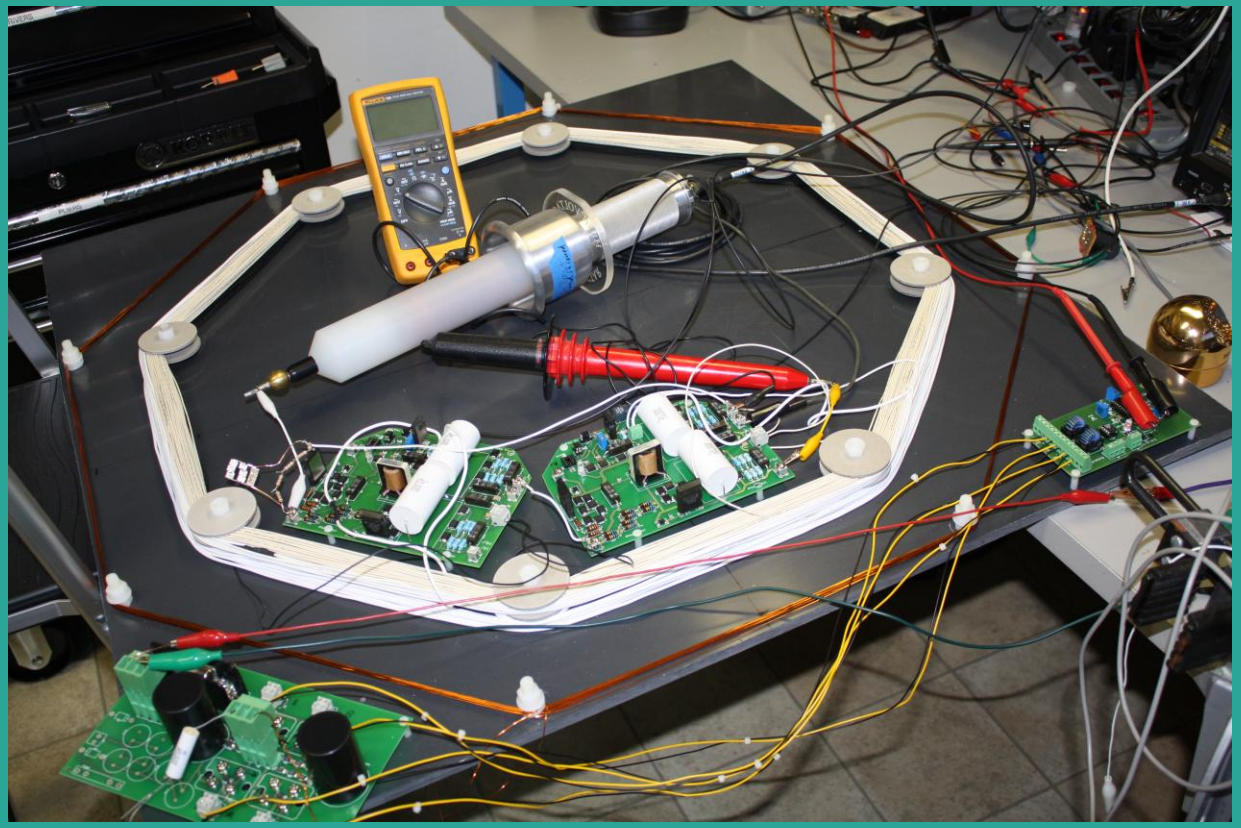
- Purpose was to evaluate waveforms for best use with Laser for Laser Guided Energy
- This was dramatically successful in improving our understanding
- Based on the physics learned, we built a 1MV pulse generator for use with LGE

North Star HV

Units Were Built in Platters

North Star HV

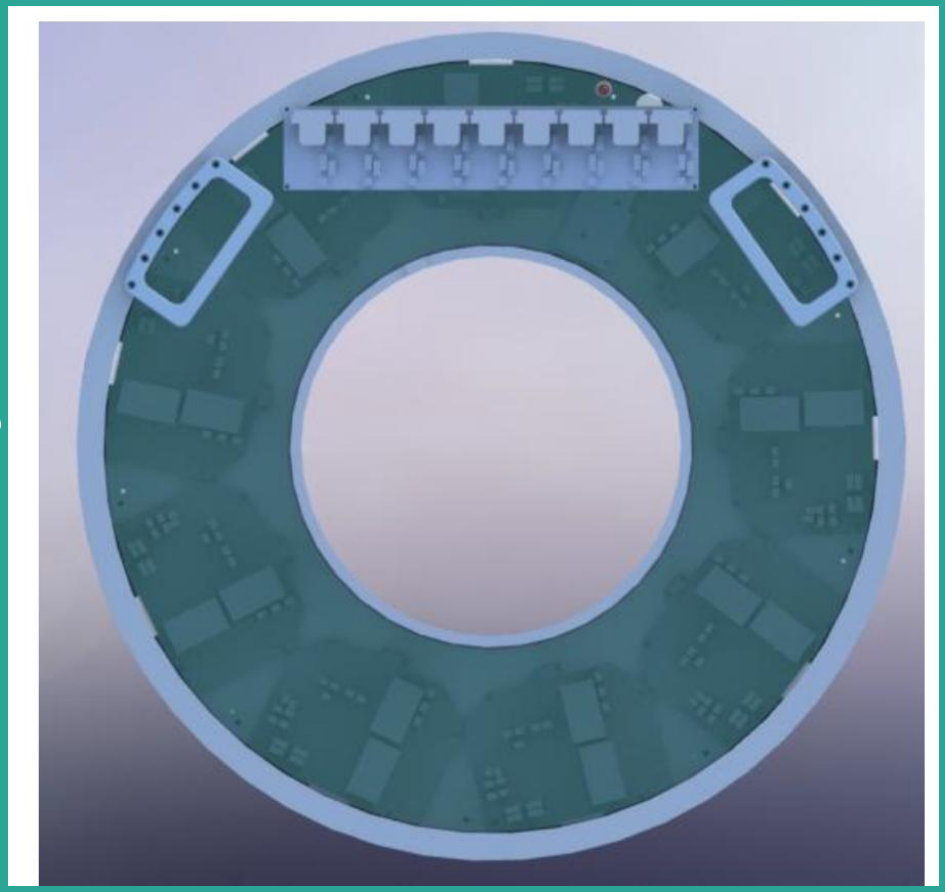
- Testing a Pseudoplatter



Platters

- Charging is done with primary coil magnetic flux
- Platter shown has 9 stages, 18 secondaries 3.5 kV/stage
- Can be built up quite quickly

North Star HV



Flux coupled Solid State Marx Can Drive DC & Pulsed

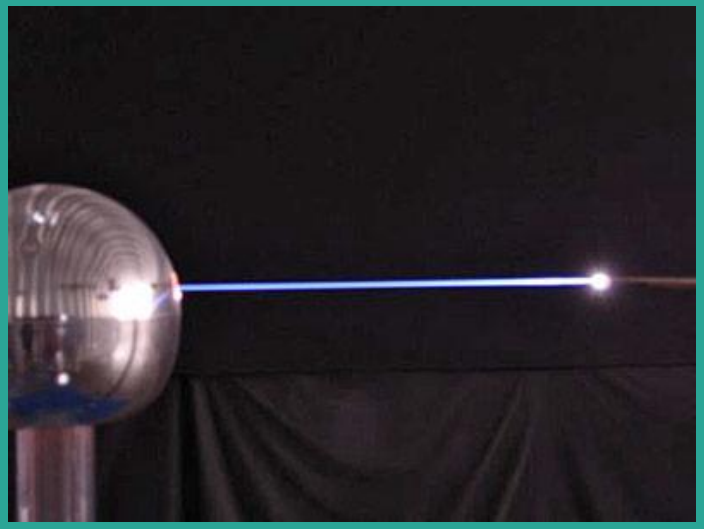
North Star HV

- Charging is done with primary coil magnetic flux
- There is no reliance on pulsed isolation components
  - Stages can remain charged without any additional isolation
  - 1 field coil driven by an H-bridge driving multiple secondaries is actually easy to build

Laser Guided Energy (LGE)

North Star HV

- LGE (Laser Guided Energy) is an electrical discharge guided by a femtosecond laser
- Arbitrary Waveform Generator was Essential to understanding electrical requirements



Another Resonant Circuit Application

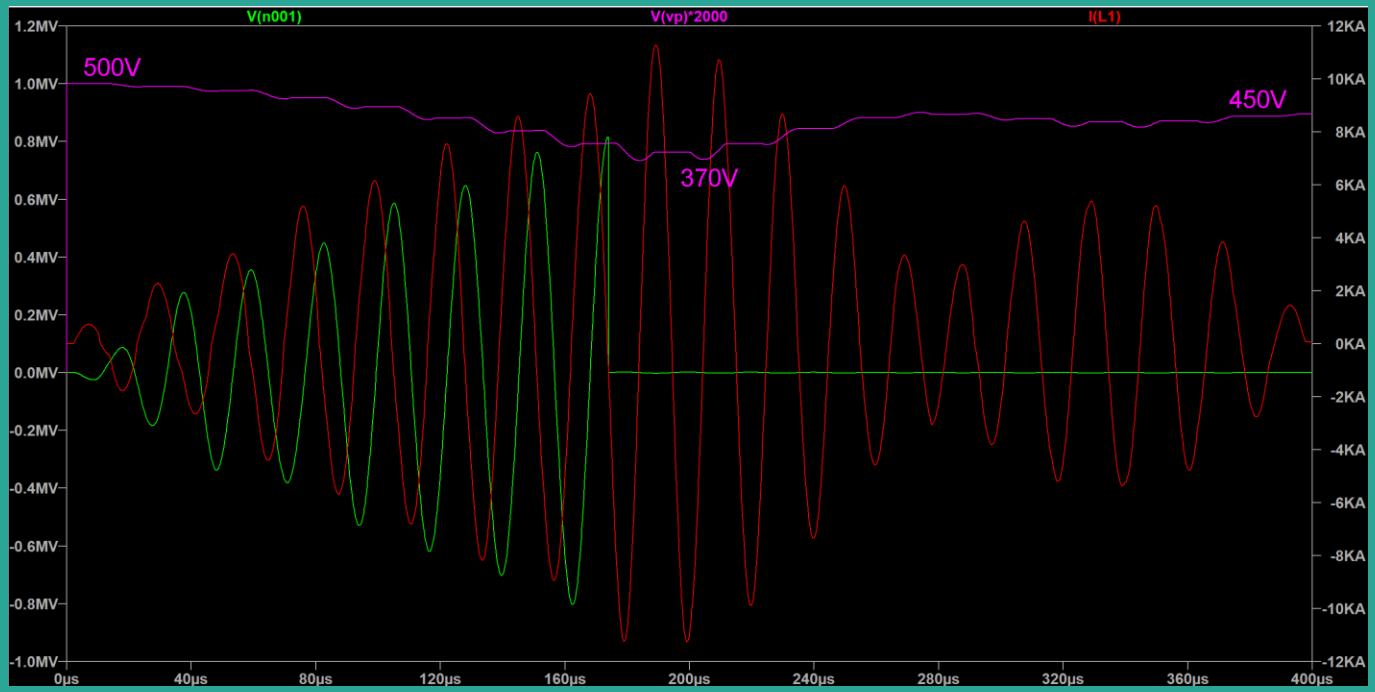
North Star HV

- ~ 1MV “Banshee” Counter IED system used in Afghanistan 2009
- Quote from Leatherneck Magazine (Marine Corps Magazine)
  - “The Banshee supported more than 200 combat logistics patrols while in theater. In more than 15,000 miles, no vehicle that remained in the path cleared by the Banshee was struck by an IED.” Maj. Lash USMC, Leatherneck Magazine, Sept 2011

1 MV, 20 kW High Rep Coil

North Star HV

- Multiple IGBT H-bridges in primary
- Green is electrode voltage
- Energy recovery was observed and important



Long Channels

North Star HV

- At high rep rate with a strong wind, the arc could go 20 meters
  - Similar to lightning
  - Not something customers wanted to see
- Channel buoyancy lifted the arc over the vehicle under strong wind/motion conditions
- This effect was controlled before deployment
- There may still be videos of this device on Youtube

What Happened Later?

North Star HV

- Understanding physics of process increased effectiveness 4X in 6 months before deployment
- Banshees were reliable, but the logistical burden and cost of this technique were significant
- Other much cheaper techniques were ultimately used
- Dogs were cheaper and quite effective at detecting IEDs
- Just because you can do something with pulsed power doesn’t mean you should

HV Probes

North Star HV

VD-400(kV) Sintef

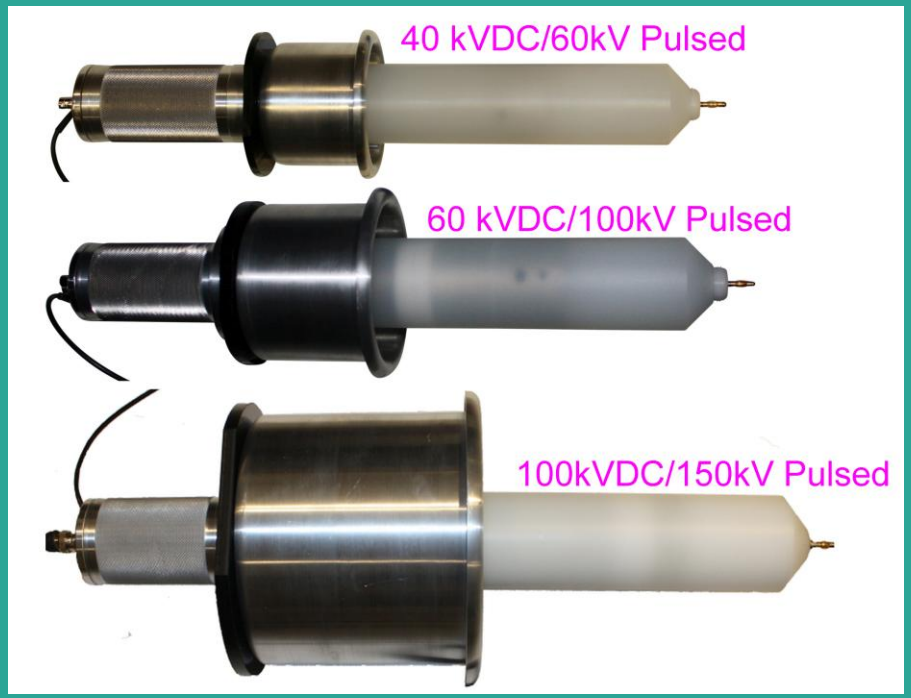
VD-150(kV) SLAC

HV Probes

North Star HV

VD floor mounted

PVM more portable



HV Probes

North Star HV

Finally building more than 1ea

Built 100s for LMJ

PVM-2 for DC Grid projects

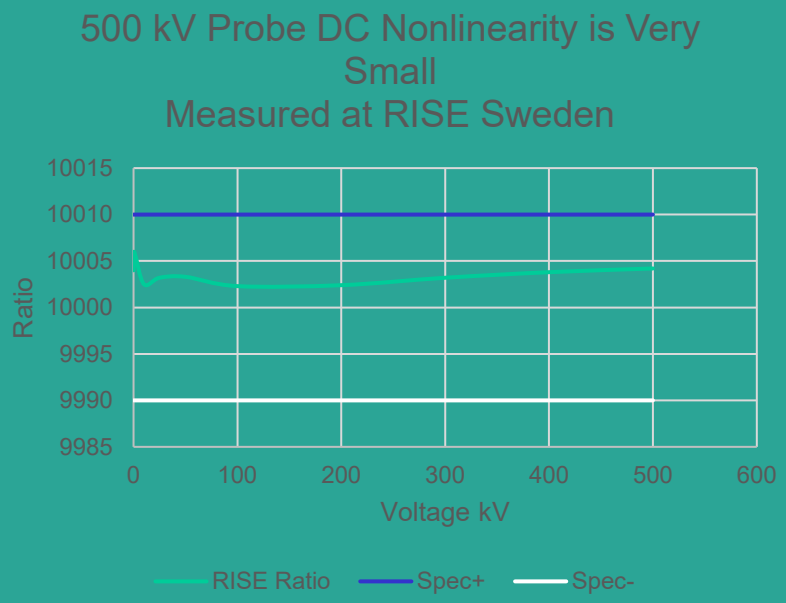
HV Probe Technical Goals

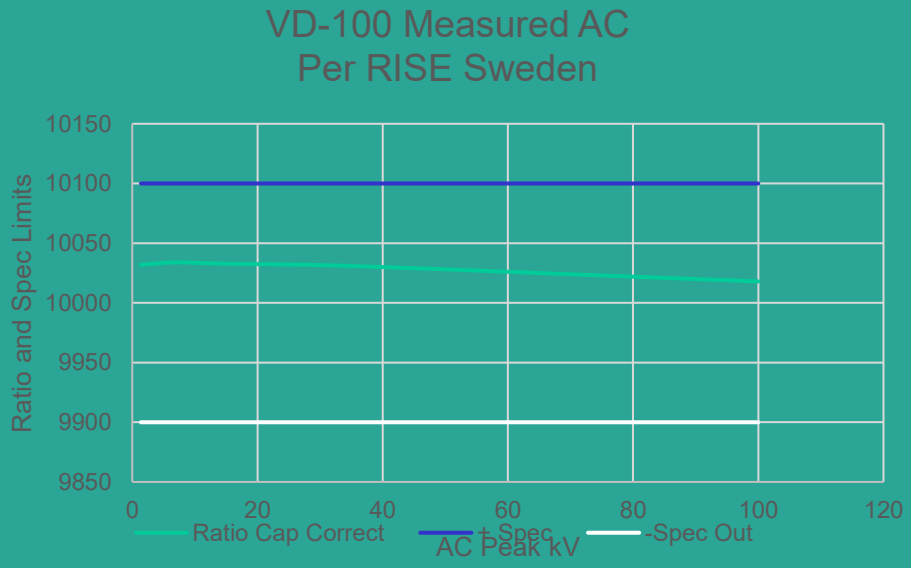
- 0th requirement was HV durability *North Star HV*
- 1st requirement was minimal “proximity effect” (Stray C effect on probe response)
  - Reduced proximity effect by higher capacitance and by RC compensation of the systematic errors
- 2nd requirement was maximize bandwidth
  - Contradicts1st requirement so must compromise
  - Minimize cable effects, allow many cable lengths
- 3rd requirement DC accuracy (0.15%), flat AC/Pulse accuracy, minimal nonlinearity
- 4th requirement - No customer adjustment needed
- I wanted a probe I would want to use.

DC And AC Linearity

North Star HV

- DC and AC Linearity are well within specifications per RISE and many other Independent tests





Ground, HV Notes

North Star HV

- The usual high voltage spacings apply
  - Short pulses <100 ns can sometimes have shorter spacings
- There must always be a ground
  - Low Current <5kA: ***connect probe ground to grounded signal source***
  - High Currents>20kA: High pulsed magnetic fields lead to A*dB/dt, High currents on cables mean that ***the probe must be grounded through the scope***
  - Floating scopes are a dangerous device with knobs saying “touch me!”

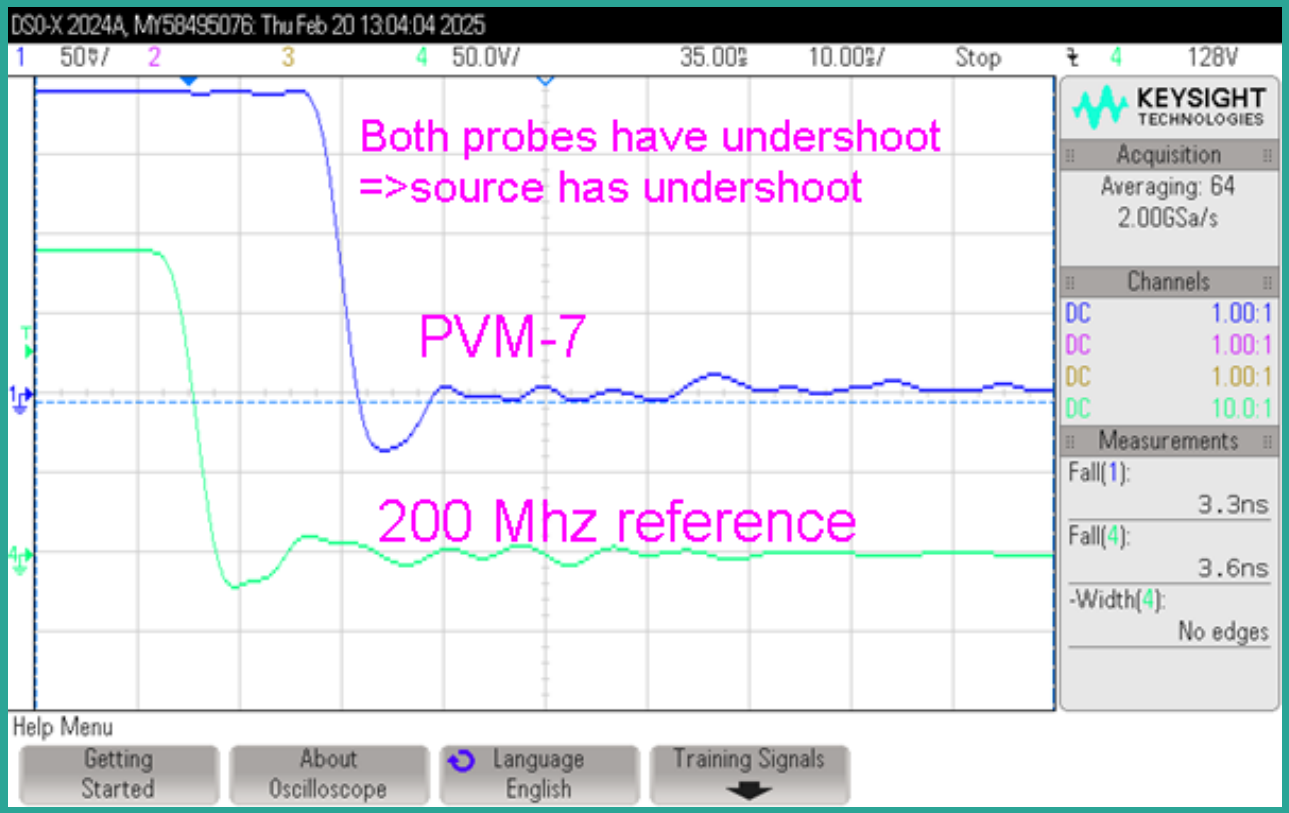
Fast Measurement Considerations

North Star HV

- Probes have 3-12 pf measurement capacitance to reduce proximity
- Connections must be short to reduce inductance
  - Longer connection = distorted result or result with ringing
- Added ground connections further reduce inductance
- Damping resistor built into PVM probes to reduce resonance and loading
  - Resonant frequency above = 125 Mhz
- Additional Element is 50-120 ohm resistor

Examples

- Calibration sheet examples *North Star HV*
- PVM-7 is same as 200 Mhz reference
  - => transition source has overshoot(undershoot)

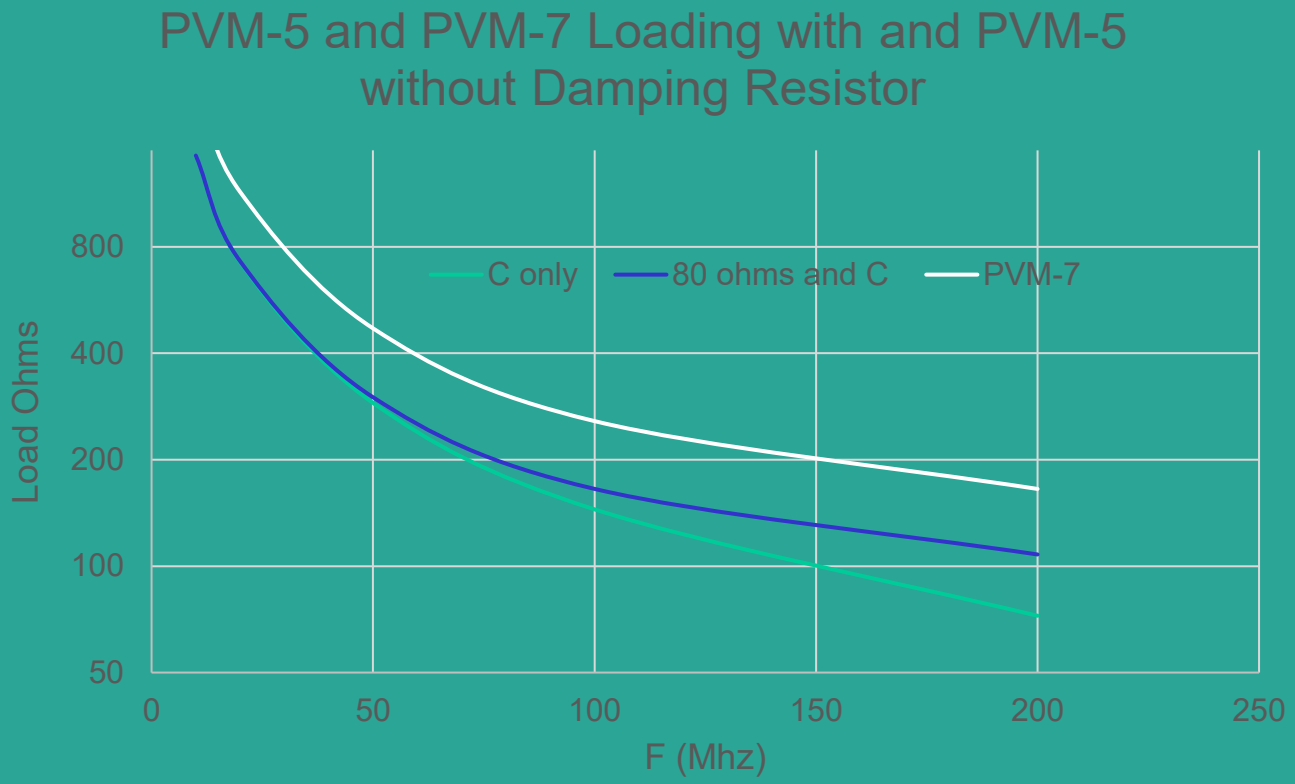


Probe rise = (Measured^2-Reference^2)^.5

Capacitive Loading

- Higher C increases accuracy
- Higher C increases loading
- PVM-4(40/60 kV), PVM-7(60/100 kV) reduce C

North Star HV



Capacitive Only Probe Under Development

- 3-4 pf
- Lower Inductance
- 200-300 Mhz bandwidth TBD
- Max Voltage TBD – 40-50 kV at 100ns?

North Star HV

Important Financial Considerations that Mattered

- Demand is uneven
  - Labor cannot match demand unless you can afford to continually layoff and retrain
- Payments always lag deliveries (cash flow)
  - Payments strongly lag work
  - Financing for cash flow is required

North Star HV

- Financing from a bank usually requires a full personal guarantee of payment! (rarely discussed)
- Cash Flow has two polarities with a dangerous negative possibility sign!!!
- Money has it's own language – Learn it

Mundane Lessons Learned More Technical

North Star HV

- All delivered equipment must be able to survive unlimited short circuits
- Don’t apply too much pressure or allow too much pressure to be applied to the staff
  - Pressure to produce causes accidents
- Working very late often destroys hardware without producing results
- Just because you CAN do something with pulsed power or HV doesn’t mean that you SHOULD do it
- You haven’t built something worthwhile until the customer can operate it reliably

How to Make a Small Fortune in Pulsed Power?

North Star HV

- How to make a large fortune in Pulsed Power?

- Start with a large fortune!

Thank you for listening

North Star HV

- It's been an honor to be part of the pulsed power community since 1976

- We should value and nurture our international collaborations despite (or because of) the problems that have recently arisen