Power Electron Tubes as an Enabling Technology for the Grid

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ADVANCED FUSION SYSTEMS

Overview

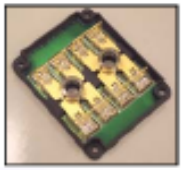
- Advanced Fusion Systems LLC (AFS) is developing a series of products for the power electronics market to replace semiconductor devices.
- Semiconductor devices have a number of well-known deficiencies which limit their utility in power electronics applications.
- AFS is currently constructing a 250,000 square foot facility to manufacture power electronics electron tubes and systems in large quantities.
- Initial power industry product offerings will include:
  - Pulsatron™ - replacement for Thyristor Press-Packs & GTO devices
  - Bi-tron™ - replacement for IGBT
  - *Faultron*™ Combination Fault Current & Over-voltage Limiter
  - Bulkhead Mount Transient Suppressors (E1 rated)
  - HVDC to 3Φ HVAC Inverters (Voltage Source Converters)
  - EMP & GIC Protective Devices
- The AFS facility has an onsite testing capability for High Voltage (AC & DC), Fault Current. EMP, GIC, Flashover and numerous other tests common to the utility industry requirements.

ADVANCED FUSION SYSTEMS

- End of Semi-conductors reign due to superiority of electron tubes in every way
- Can be used in direct replacement for Thyristors, IGBT's – New Circuit Topologies not previously possible
- Multitude of New Applications can be imagined
- Advanced Fusion has tremendous capability to supply market demand
- Testing and Demonstration capability as well. 25 Year Warranty, High Robustness & Reliability, 100% Inspection, Zero defects...

ADVANCED FUSION SYSTEMS

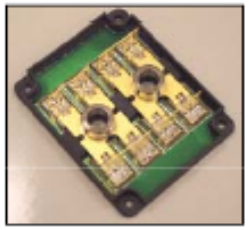
Advanced Power Electronics



Addresses fundamental research required for advances in PE materials

Silicon

- Widely available
- Low cost



Super GTO Switch
2007 R&D 100 Award

Silicon Carbide

- High operating temperature
- Lower switching losses

Silicon Carbide + Gallium Nitride

- Higher Temperature
- Higher Voltage
- Optical switching

New power electronics materials enable newer applications and benefits

EPRI ELECTRIC POWER RESEARCH INSTITUTE

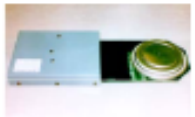
ADVANCED FUSION SYSTEMS

Technical Innovations – *Power Electronics*

Thyristor

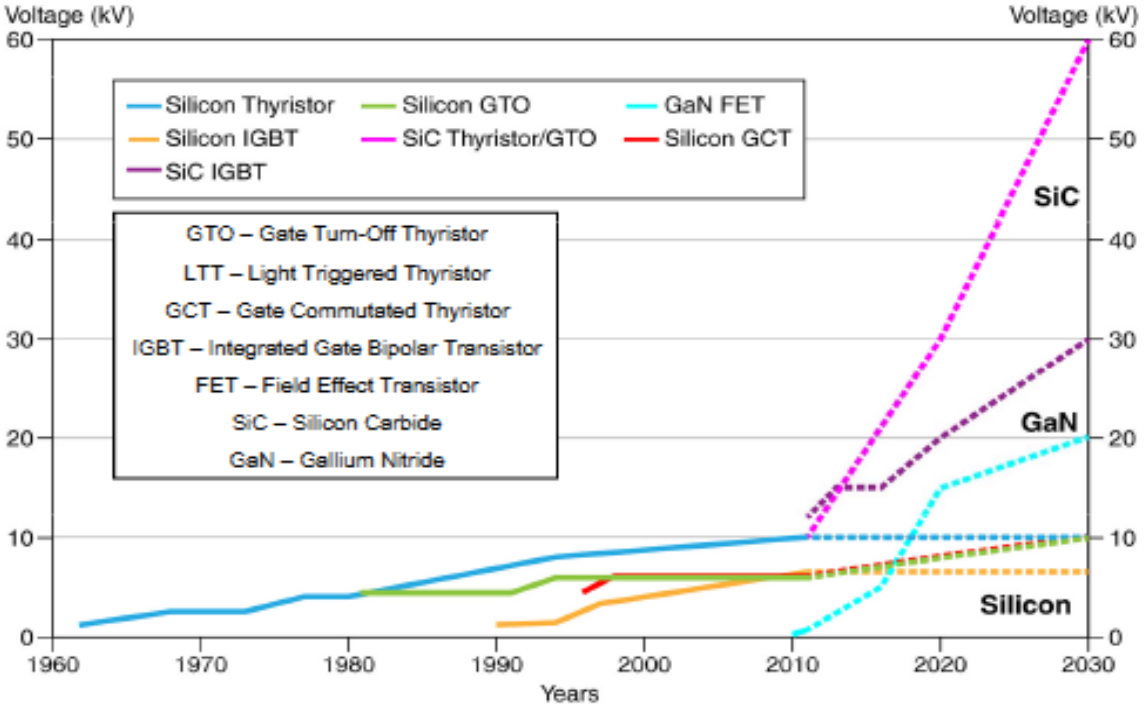
GTO

LTT



GCT

IGBT



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COMPARISON OF SEMICONDUCTORS AND ELECTRON TUBES IN POWER ELECTRONICS APPLICATIONS

Electron Tubes vs. Semiconductors

- AFS electron tubes use technology originally developed for military EMP simulation & high-power microwave applications. They are designed for repeated operation in this extreme transient environment.
- The robustness of electron tubes in the EMP & transient environment is well documented.
- Solid-state devices are subject to failures arising from:
  - Piezo-electric induced over-stress .
  - Single arc failure
  - Thermally-induced overload.
- AFS electron tubes are significantly faster than the fastest power semiconductor devices allowing circuit topologies previously not considered.
- These tubes are not subject to dV/dt or dI/dt constraints as semiconductors. Typical AFS device slew rates are well in excess of megavolts per microsecond.

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Semiconductors vs Electron Tubes

Failure Mode	Semiconductor Devices	Electron Tubes
Arcing	Fail after first arc event	Highly arc resistant
Thermal Sensitivity	Requires elaborate cooling	Can operate up to **1000° F** without cooling
Voltage Handling	Individual devices limited to 20 KV	Individual devices can handle up to **1.2 MV**
Current Handling	Individual devices can handle 8 KA	Individual Devices can handle **>1 MA**
Circuit Complexity	Very complex circuits required	Very simple circuits
Customization	?	Readily Able to Customize Ratings, Features, etc.
Warranty	?	**25 Year Unconditional Warranty**

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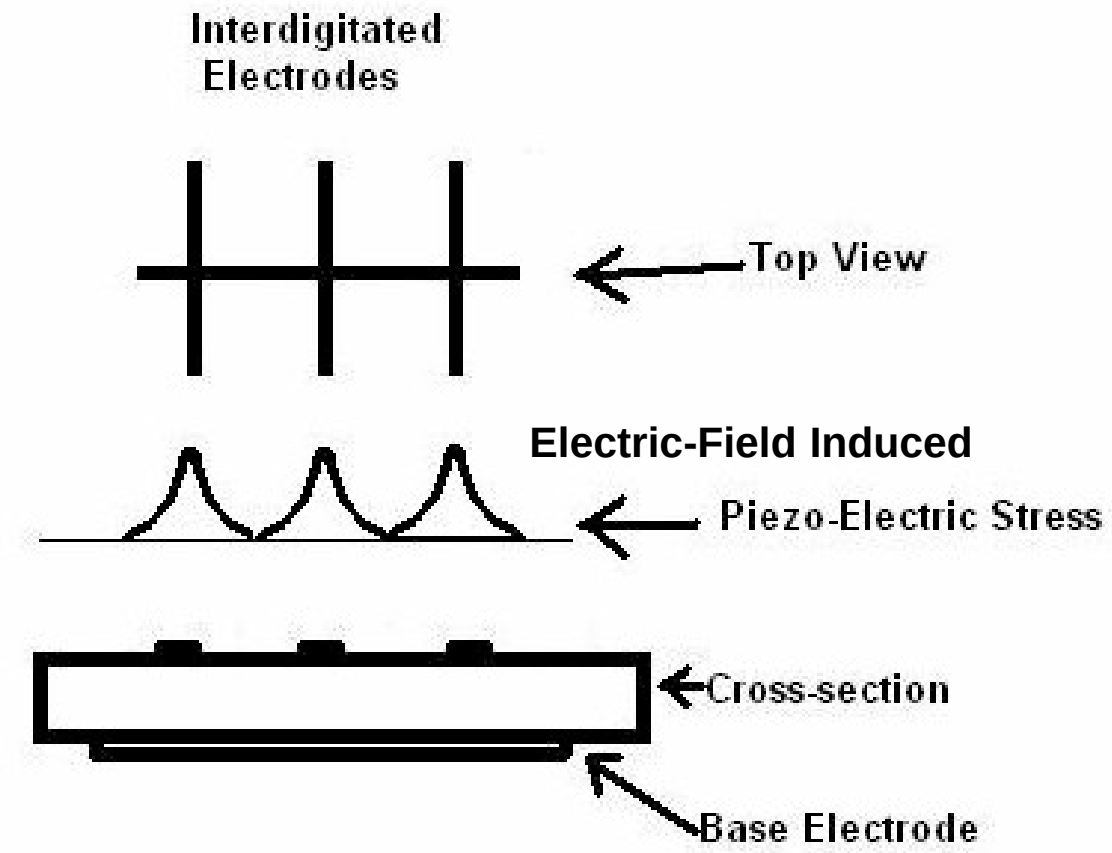
Piezo-electric failure mode of semiconductor devices



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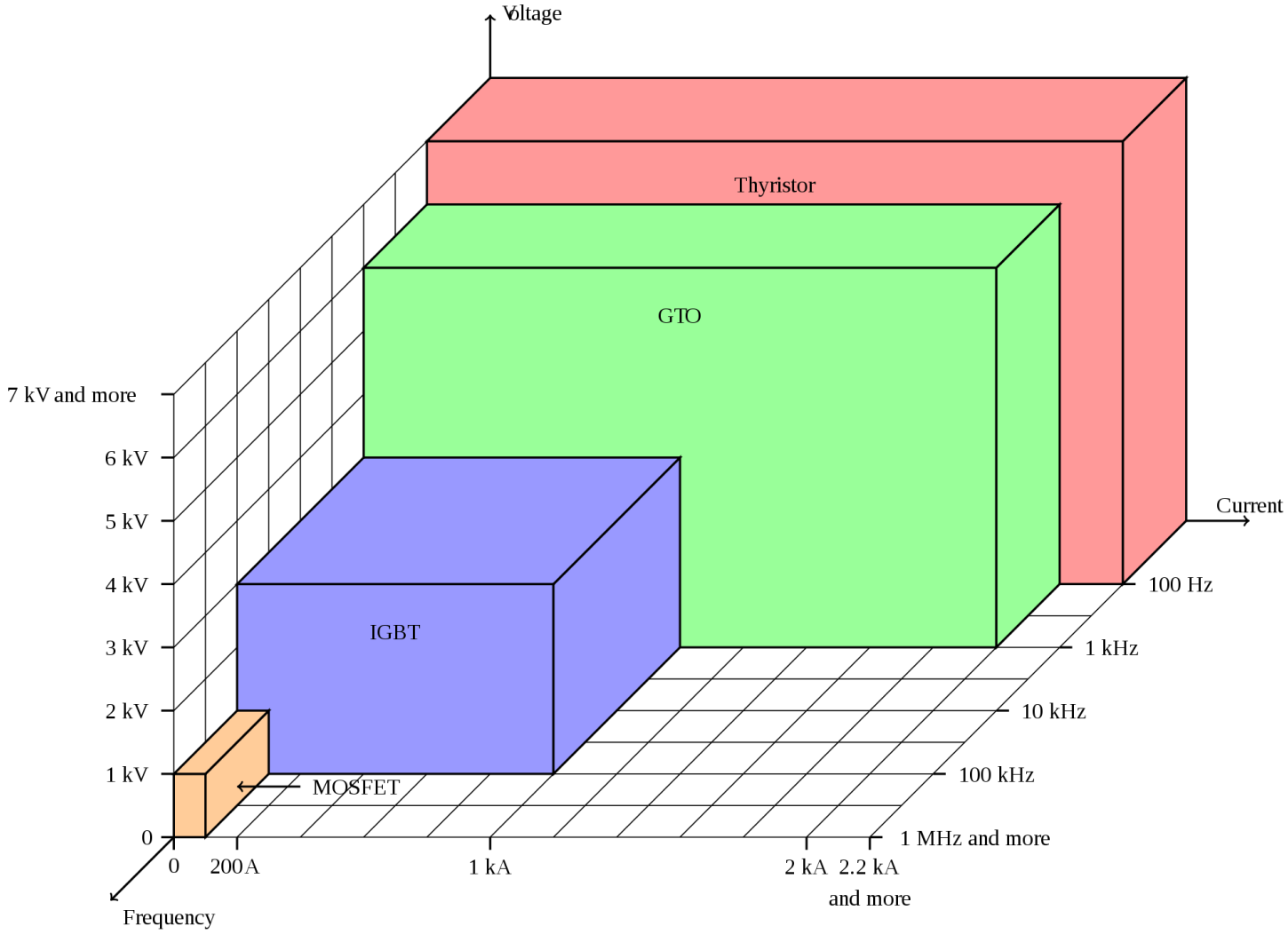
Semiconductors vs Electron Tubes (2)

Parameter	Power Semiconductor Devices	Electron Tubes
Voltage	<20 KV	> 1.2 MV.
Current	<20 KA	>> 1 MA
Max Frequency	KHz	**GHz**
Max Temp.	25ª C (Si); 200ª C (SiC)	**500ª** C
Arc Resistance	None	Highly
Energy Capacity	10's of KiloJoules	10's of MegaJoules
Losses	Typically 0.5 > 0.7 V/junction	~5 eV per device (1 eV = 1.6×10^{-19} J)

The Electron Tube compared to Semi-Conductor Devices

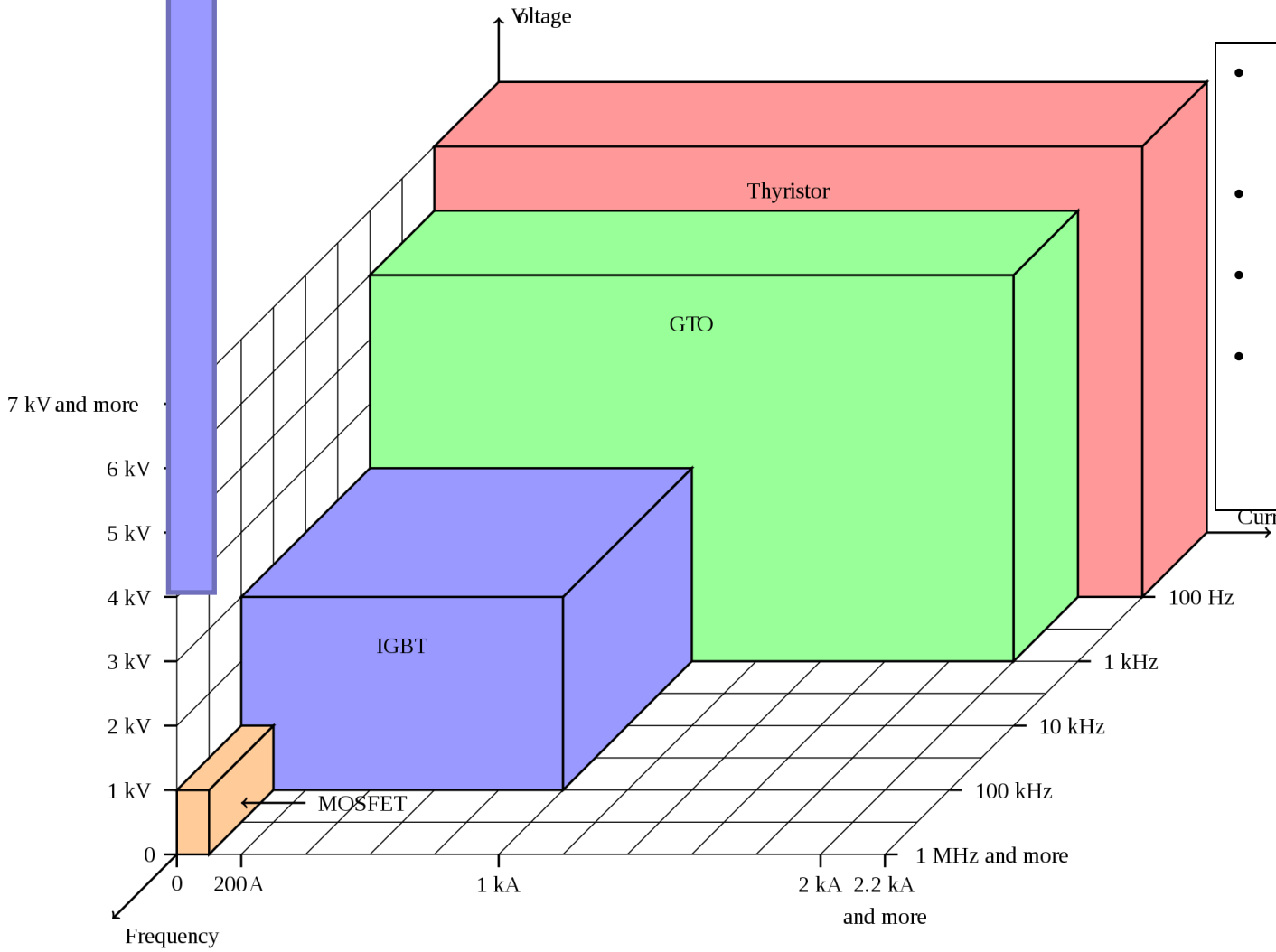
Current/Voltage/switching frequency domains of the main "Semi-Conductor" based power electronics switches

(note some ratings for select devices could be higher than represented in these graphs)



The Electron Tube compared to Semi-Conductor Devices

Voltage Ratings can Span from 4kV to 1000kV per device

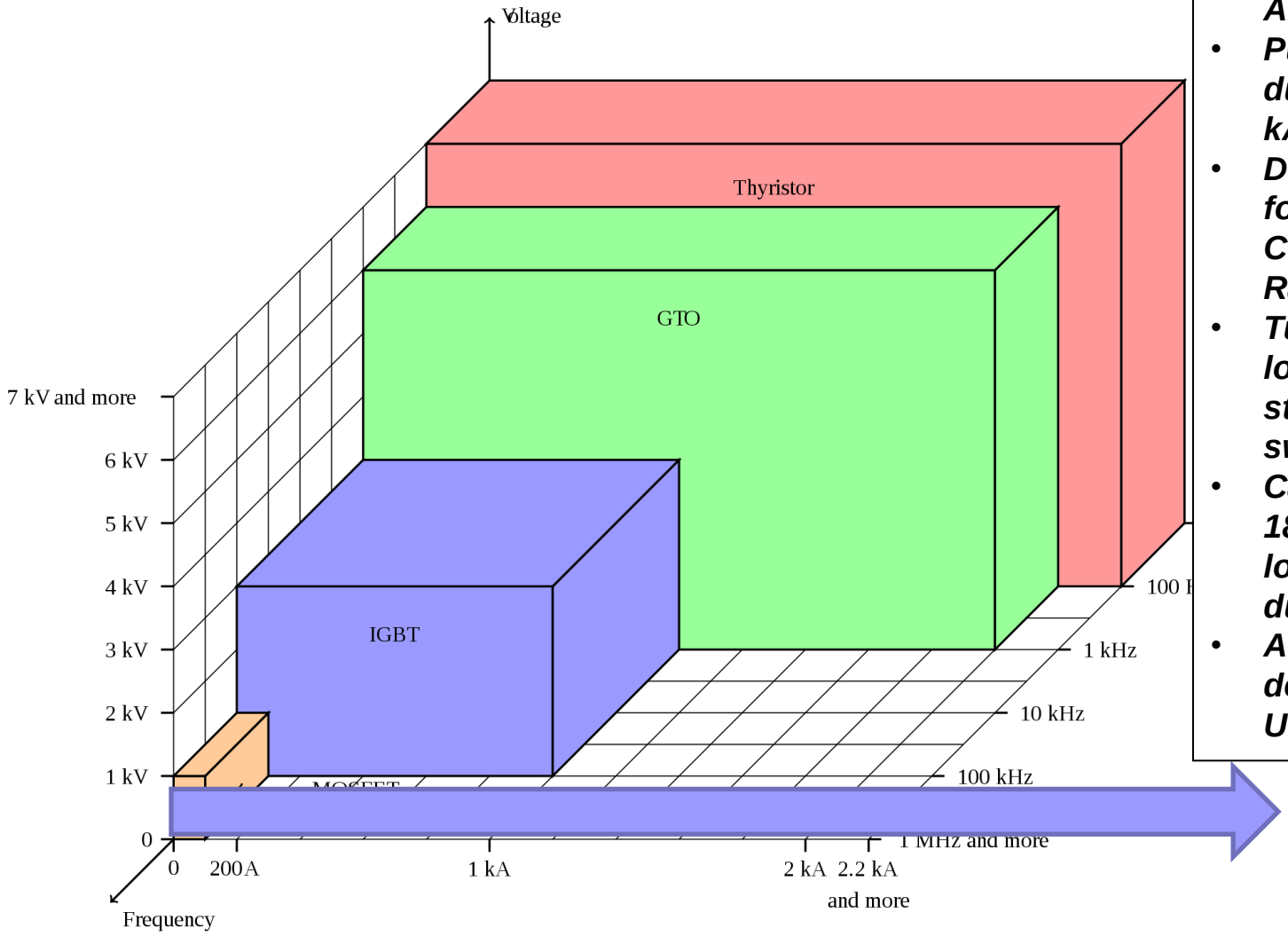


- *Cathode dimensions determine allowable voltage ratings*
- *Cathodes can be very large (>2000cm^2)*
- *Cathodes can be quite small (<1mm^2)*
- *Can be custom sized to meet requirements for Voltage and Current Ratings*

The Electron Tube compared to Semi-Conductor Devices

Current Ratings can Span beyond 100kA

ADVANCED FUSION SYSTEMS

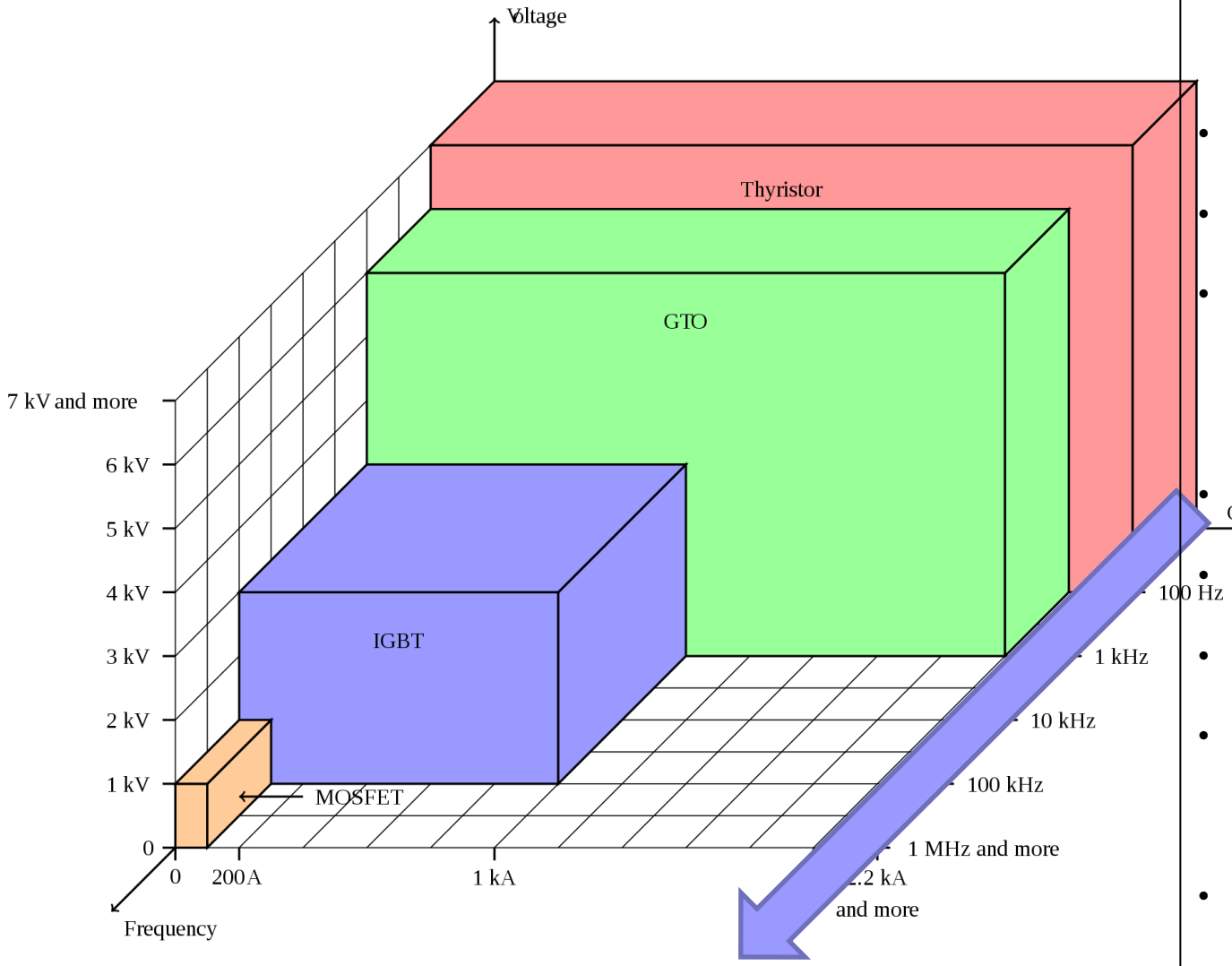


- *Continuous current ratings of 500 Amps/cm²*
- *Pulse Mode or short duration ratings of 81 kA/cm²*
- *Design flexibility allows for Tube Devices with Continuous Current Ratings of >>10kA*
- *Tubes have very low losses (150 micro-ohms steady state), also low switching loss*
- *Cathodes as large as 1800cm² have exhibited long life under extreme duties*
- *Advanced Fusion backs device with 25 Year Unconditional Warranty*

The Electron Tube compared to Semi-Conductor Devices

Frequency Ratings can Span from DC to 3GHz

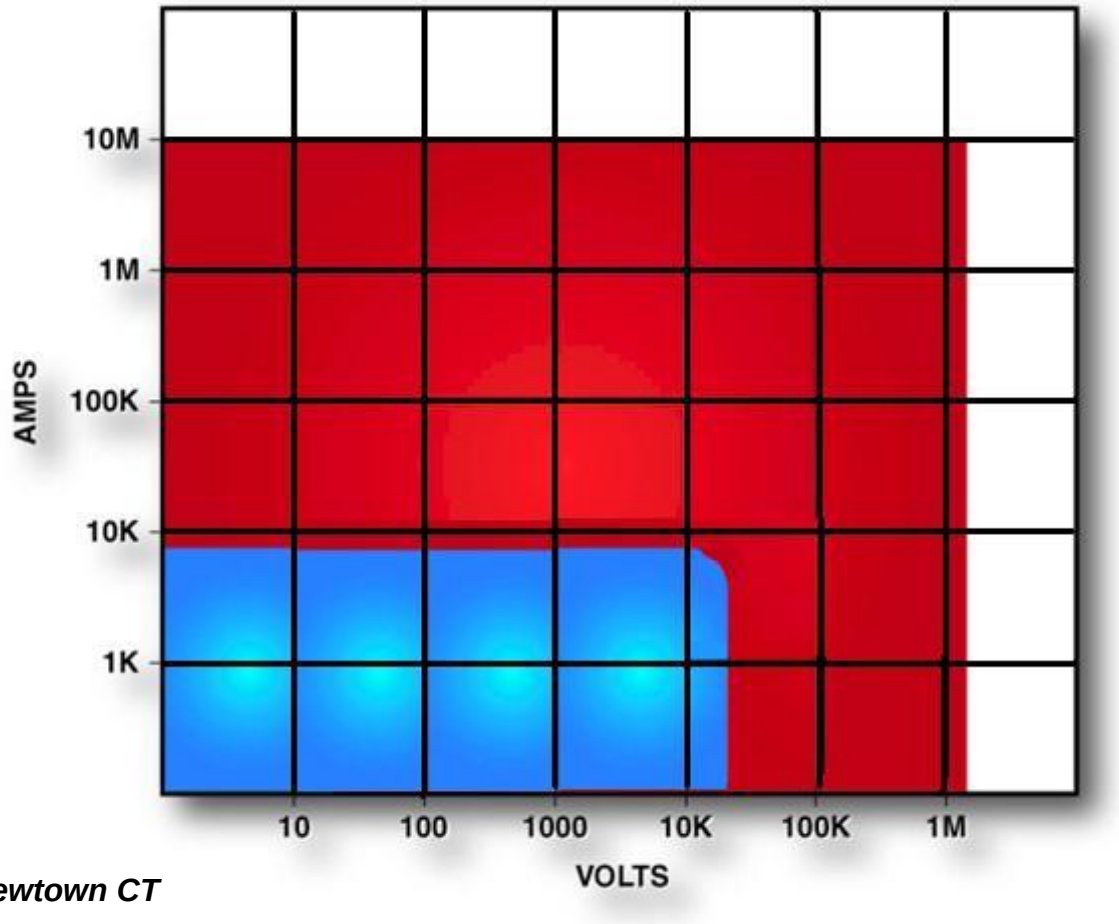
ADVANCED FUSION SYSTEMS



- *Can be switched on, switched off and all CW & Pulse operating modes*
- *Can switch with 100 picosec risetime*
- *10 microsec pulse width*
- *Tube Device does not have di/dt or dv/dt design limitations common in semiconductor devices*
- *Does not need snubber auxilaries*
- *Can operate to temperatures of 1000º*
- *No need for cooling systems*
- *Can also tolerate arc over without failure (unlike semiconductor devices)*
- *Withstand 300G shock forces*

ADVANCED FUSION SYSTEMS

Electron Tubes (Red) vs. Semiconductors (Blue): Single Device Voltage vs. Current Continuous Capacity

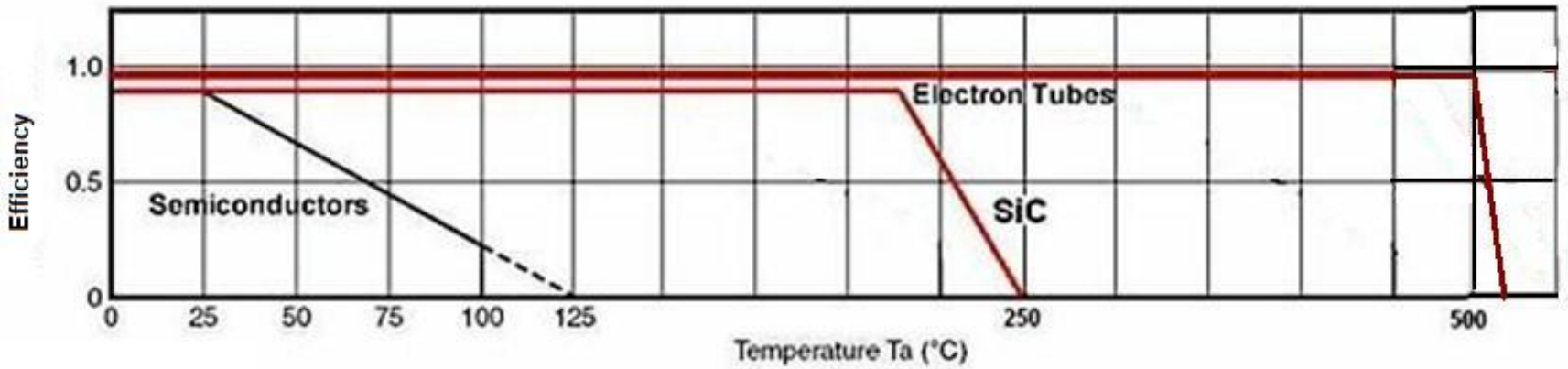


Semiconductors vs Electron Tubes (3)

- AFS electron tubes can replace semiconductors in virtually every circuit configuration.
- These tubes have turn-on, turn-off, and modulation modes.
- AFS electron tubes require very little cooling due to their high operating temperature rating due to higher efficiency and refractory construction.
  - Cooling not required below 1000# F operating temperature.
  - No fall off in performance below maximum operating temperature
- These tubes have orders of higher energy handling capacity due to their refractory construction.
- Voltage and Current Limiter configurations available in all voltages and currents, AC & DC.

ADVANCED FUSION SYSTEMS

Thermal efficiency of power devices

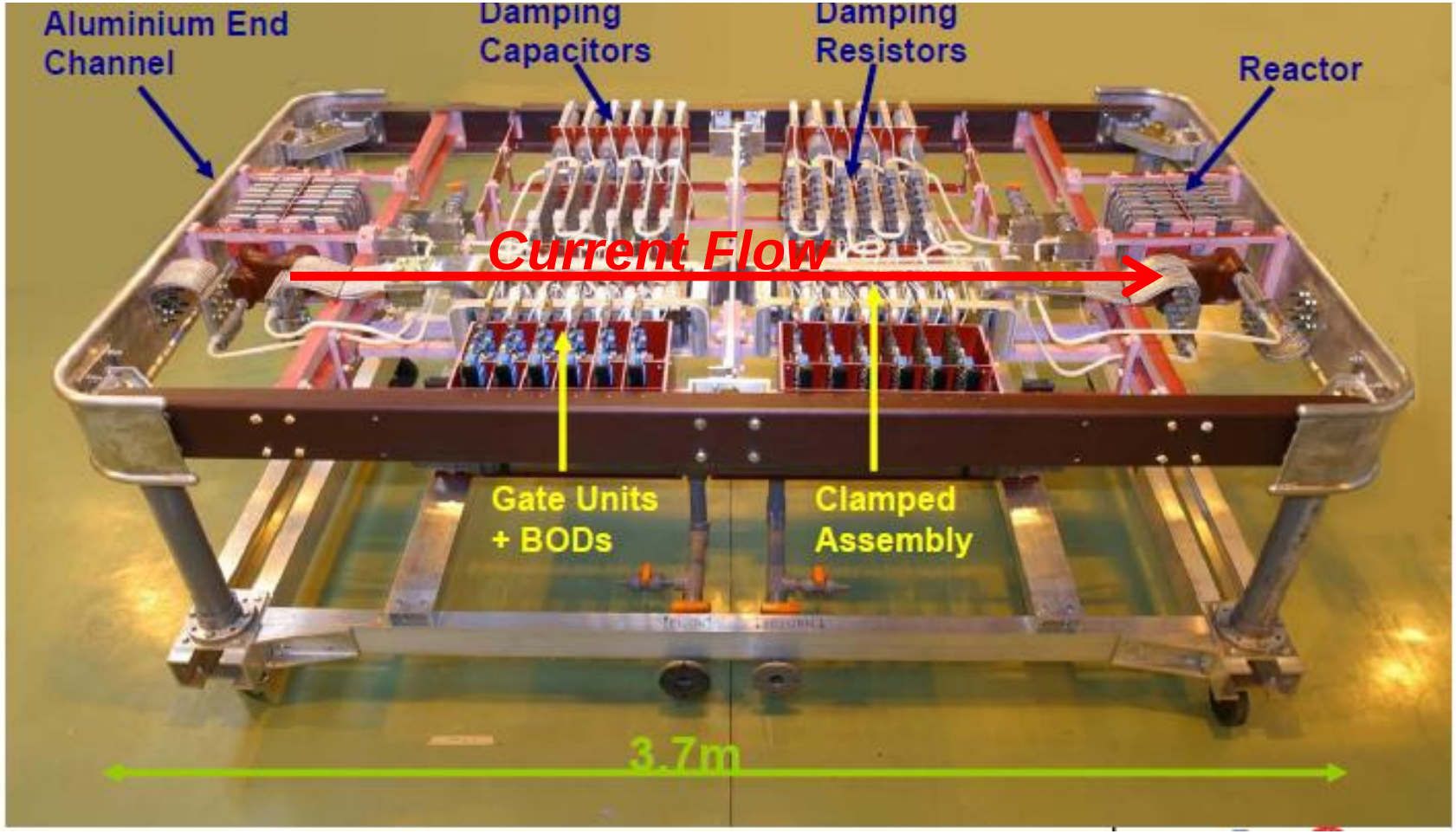


Example 660kV Thyristor Valve

ADVANCED FUSION

Example Thyristor Valve Section

- *Enormous amount of auxiliaries for control, snubbers and cooling and indoor environment housing which*
- *Add costs, complexity, losses, reduces reliability and have lead to catastrophic failures*



ELECTRON TUBE DEVICES

PULSATRON™

3275 Pulsatron™

- The *Pulsatron*™ is a high vacuum, cold-cathode triode electron tube. It is designed for high-speed, high-power operation
- Specifications:
  - DC to 3 GHz
  - 500 KV Max
  - 250 KA Max
  - <100 picosecond risetime
  - 10 µSec pulse width
  - > 500 KHz pulse mode
  - CW Mode
- Compact: 5” 12”, 5lbs

^ Pulsatrons (Block 3)

< High Speed Class A Amp

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Bi-tron™ *pat pending*

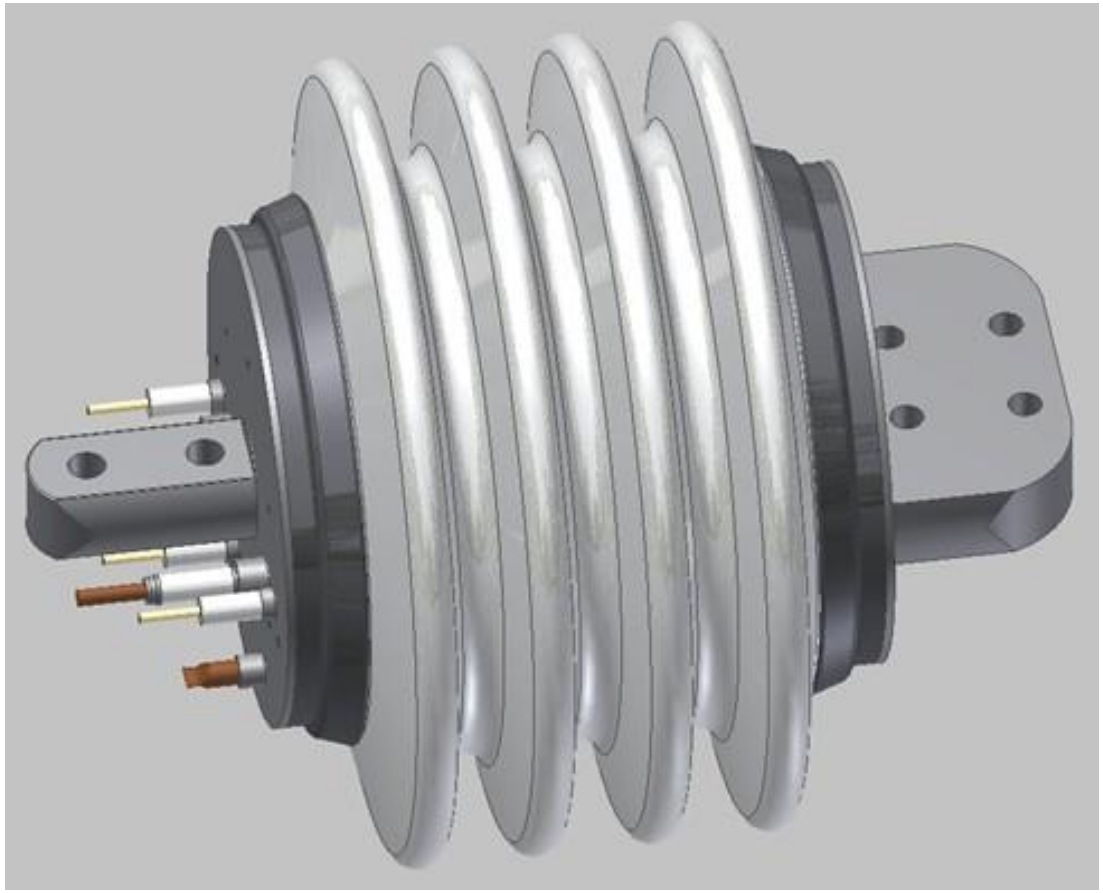
ADVANCED FUSION SYSTEMS

4275 Bi-tron™

- The *Bi-tron*™ is a high vacuum, cold-cathode tetrode electron tube. It is designed for bipolar high-speed, high-power **shunt** operation, and is physically similar to the 3275 except for the extra grid terminal.
- Specifications:
  - 1200 KVAC Max
  - 750 KA Max
  - <100 pSec risetime
- Size varies with voltage. Units below 35 KVAC are 8 - 12 inches in diameter and 12 - 18" long. Units for 1250 KVAC operation are approximately 6 feet in diameter.
- Units under 2 feet in diameter have external control circuits. Larger units have the control circuitry mounted internally.
- All systems have dual vacuum pumping systems.
- All systems provide an external control signal to trip external protective systems.
- All systems are self-resetting and are capable of withstanding and protecting multiple events in rapid succession.
- These devices also protect against lightning of all voltages.

ADVANCED FUSION SYSTEMS

4275 Bi-tron™



35 KV

100 KA

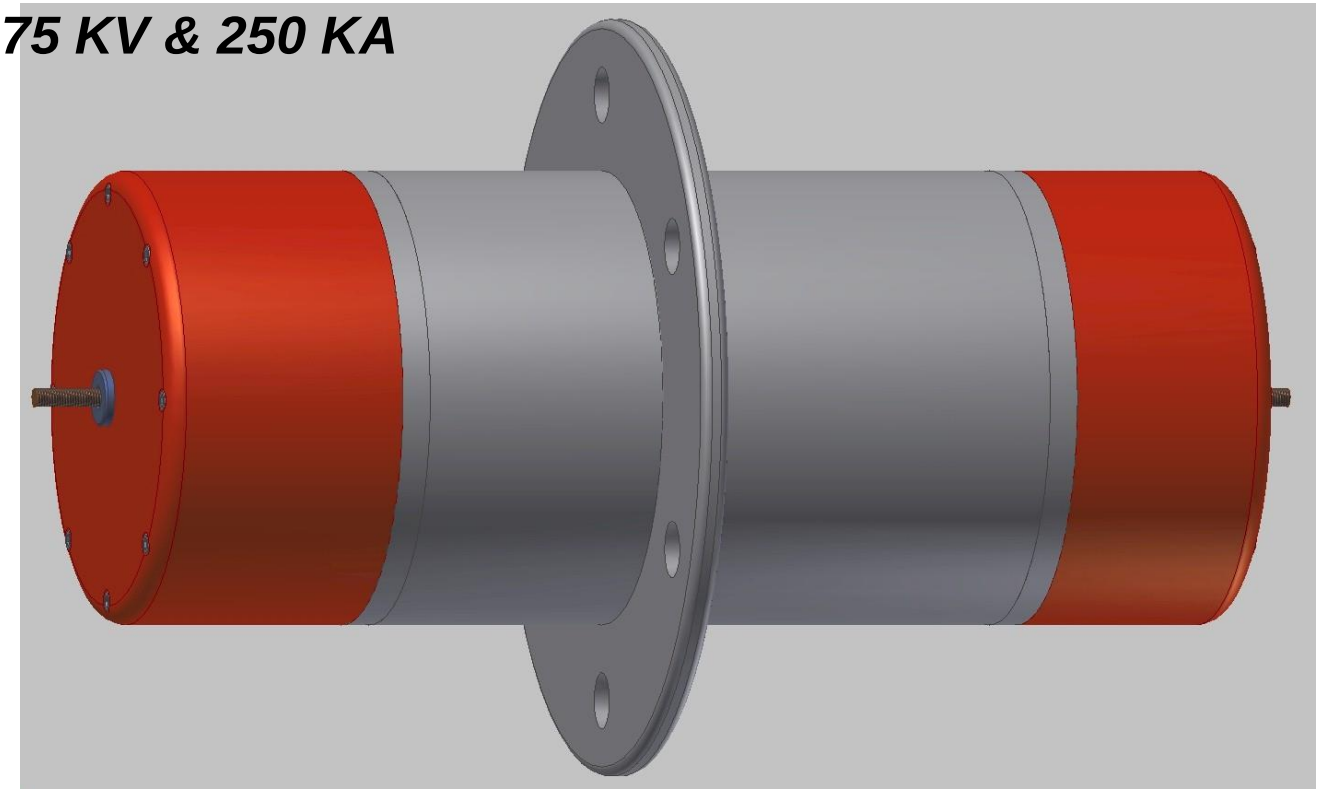
4138 Bi-tron™

- The 4138 is a patent-pending bulkhead mounted version of the Bi-tron designed for **series** insertion in transient suppressor applications.
- It retains the electrical characteristics of the 4275, but is packaged in a housing optimized for bulkhead mounting as a shielded protective feedthrough.
- The design substantially exceeds the Mil188-125 specification.
- Available to 75 KV and 250 KA.
- This tube is designed for transient suppressor & E1 EMP protection.

ADVANCED FUSION SYSTEMS

4138 Bulkhead Mount
Transient Suppressor & EMP Protector

Substantially exceeds MIL-188-125
Available to 75 KV & 250 KA



ADVANCED FUSION SYSTEMS

APPLICATIONS

ADVANCED FUSION SYSTEMS

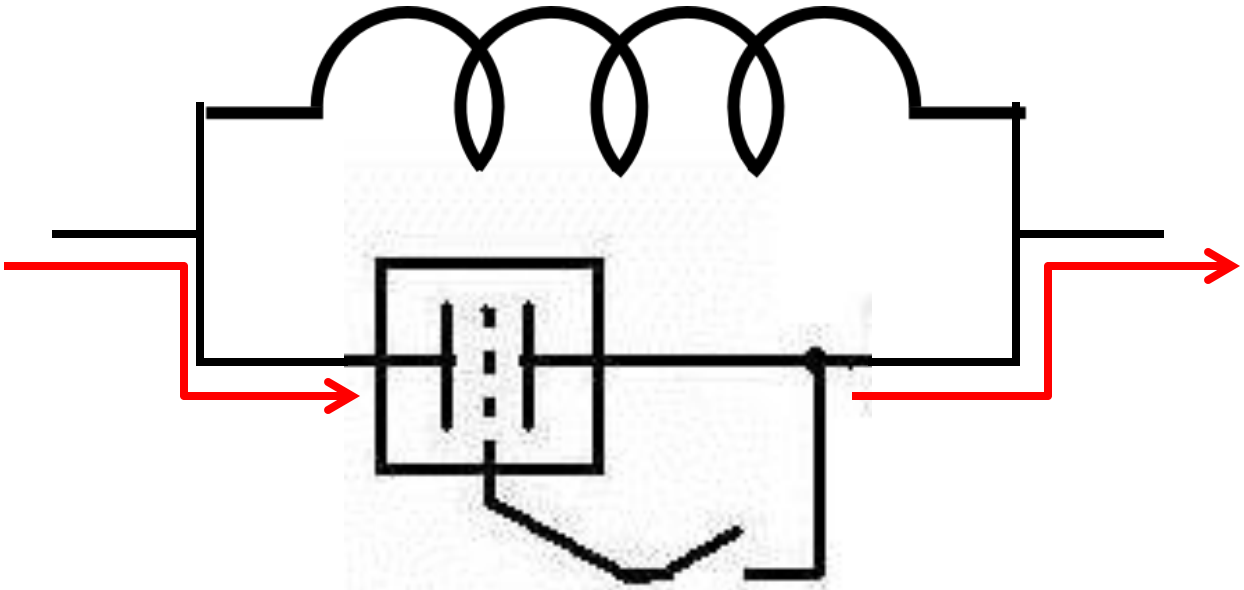
Current Regulation

Fault Current Reduction (Distribution to EHV)

Transmission Voltage Power Flow Regulation

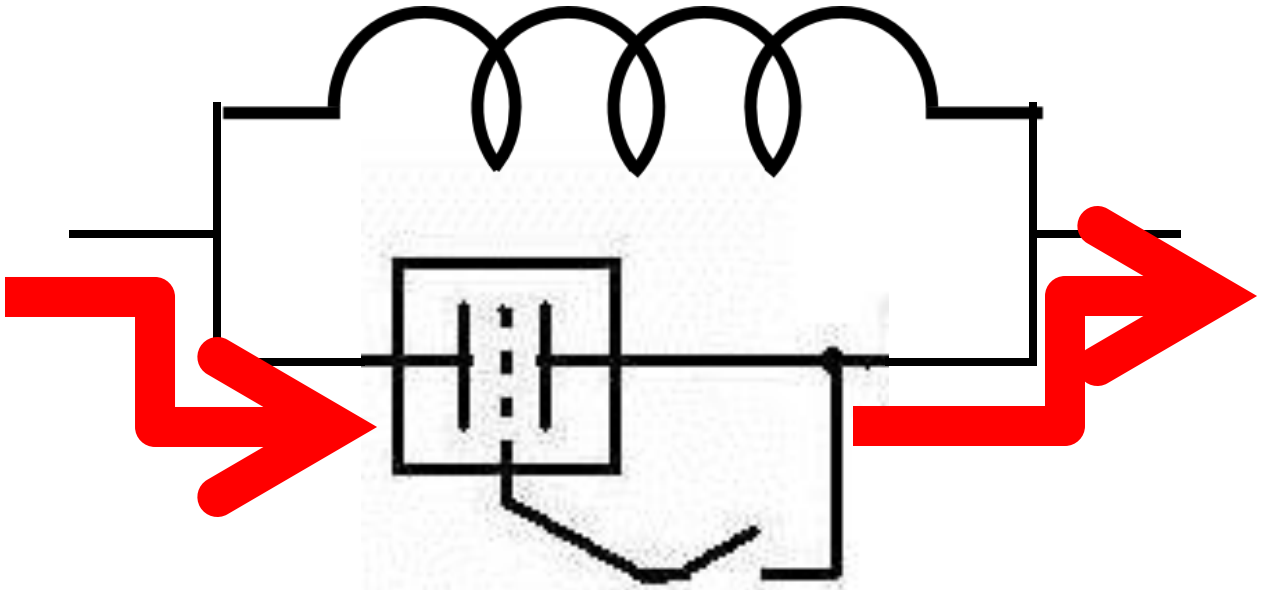
ADVANCED FUSION SYSTEMS

Fault Current Reduction (Distribution to EHV)



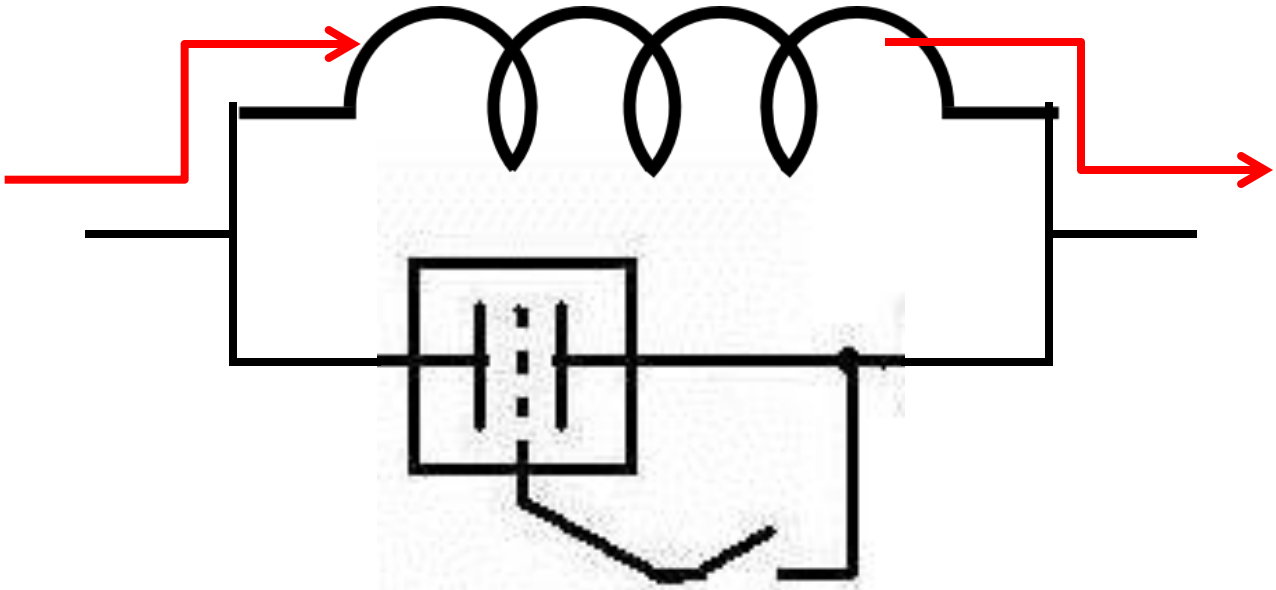
Normal AC Current Flow Through BiTron

ADVANCED FUSION SYSTEMS



Beginning of Hi AC Fault Current Flow Through BiTron

ADVANCED FUSION SYSTEMS



AC Current Flow Diverted to Reactor When BiTron Rapidly shuts off

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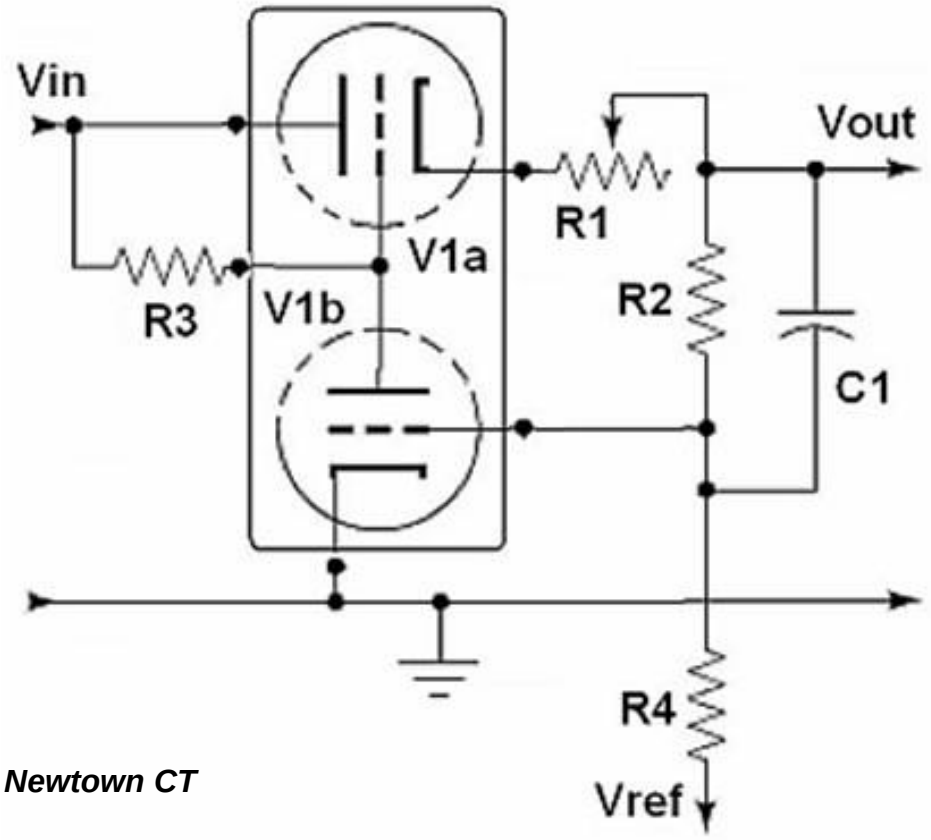
DC Current Regulator[pat pend]



ADVANCED FUSION SYSTEMS

FAULTRON™ PAT. PEN.

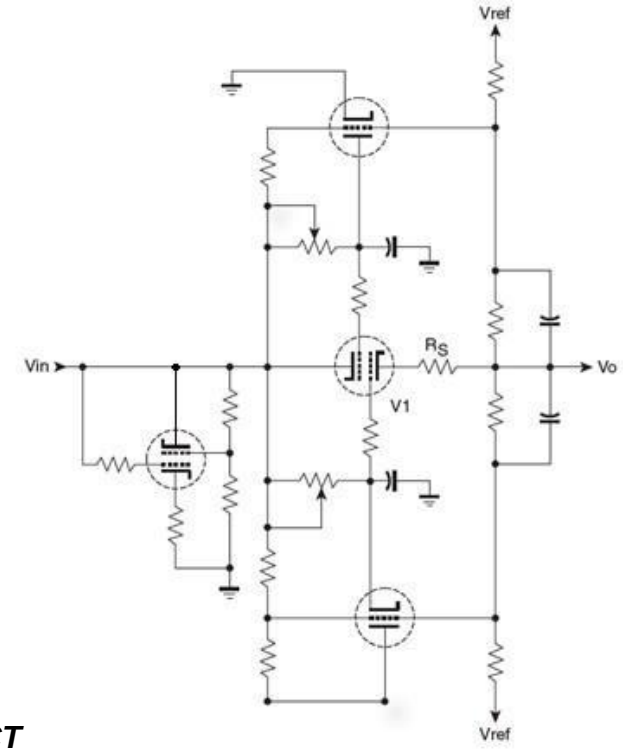
Combined Over-voltage & Over-current Limiter

- Integrated fault-current and overvoltage protection device.
- Available in all voltages from 4160 V to 1.2 MV
- Current ratings to 100’s of thousands of Amps
- Robust stainless steel enclosure
- Arc-resistant technology
- Operating temperature to 1000^{o} F before cooling

ADVANCED FUSION SYSTEMS

FAULTRON™ PAT. PEN.

Combined Over-voltage & Over-current Limiter



ADVANCED FUSION SYSTEMS

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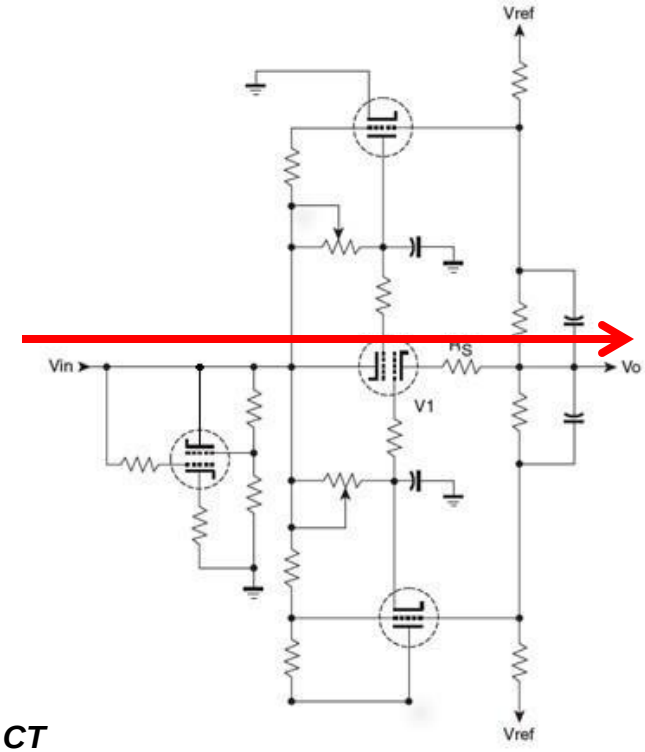
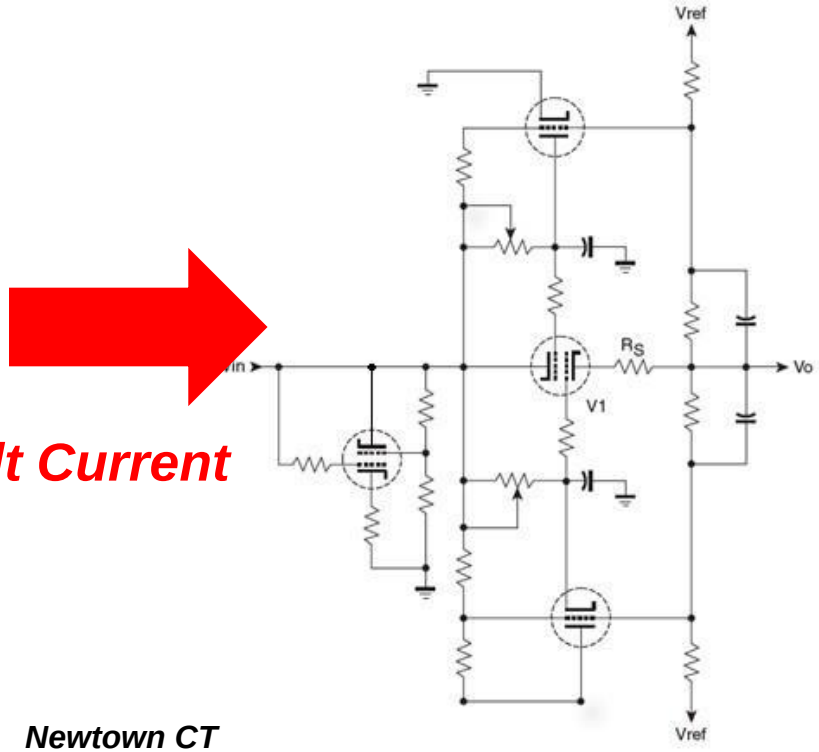


Normal AC Current Flow Through BiTron

ADVANCED FUSION SYSTEMS

FAULTRON™ PAT. PEN.

Combined Over-voltage & Over-current Limiter

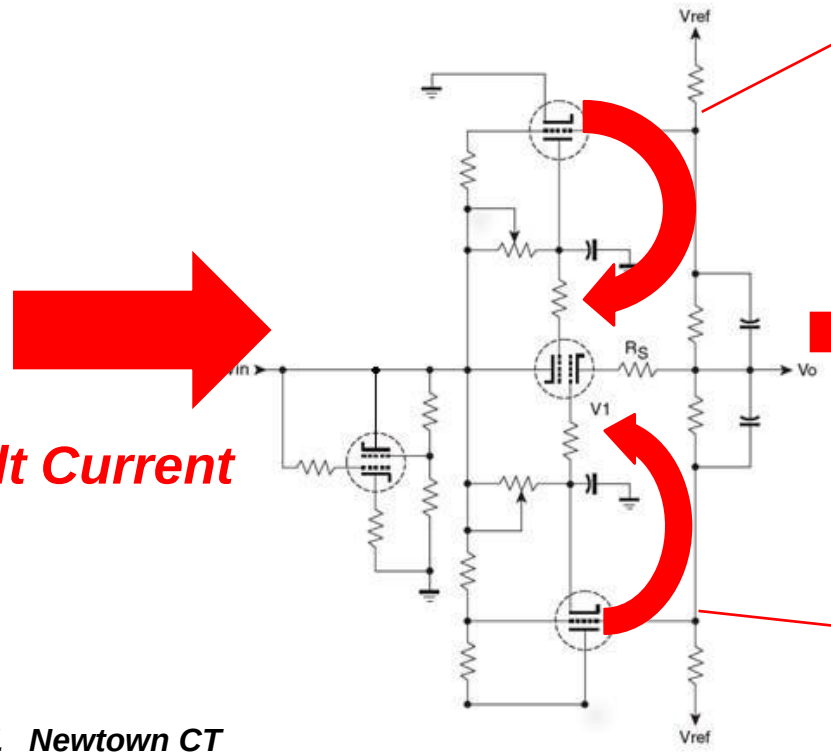


Large AC Fault Current

ADVANCED FUSION SYSTEMS

FAULTRON™ PAT. PEN.

Combined Over-voltage & Over-current Limiter



Regulating Current to reduce Fault Current (1/2 of AC Cycle)

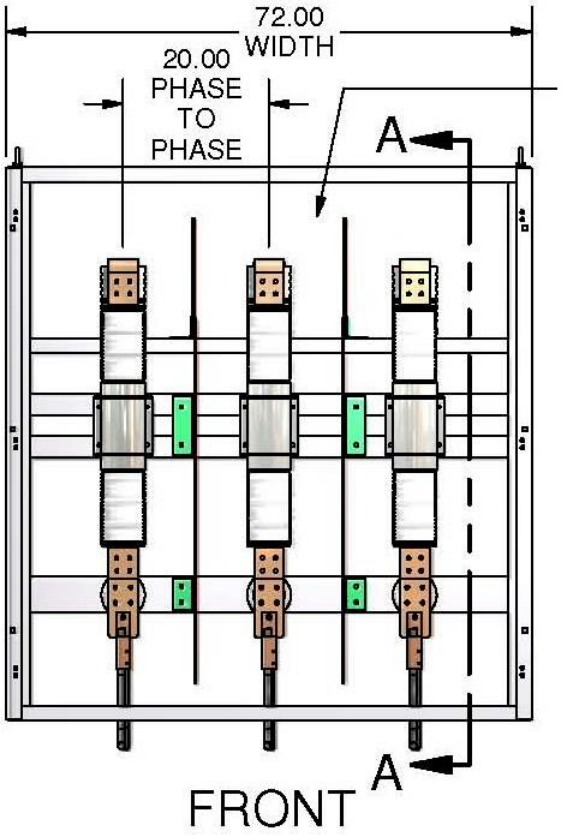
Large AC Fault Current

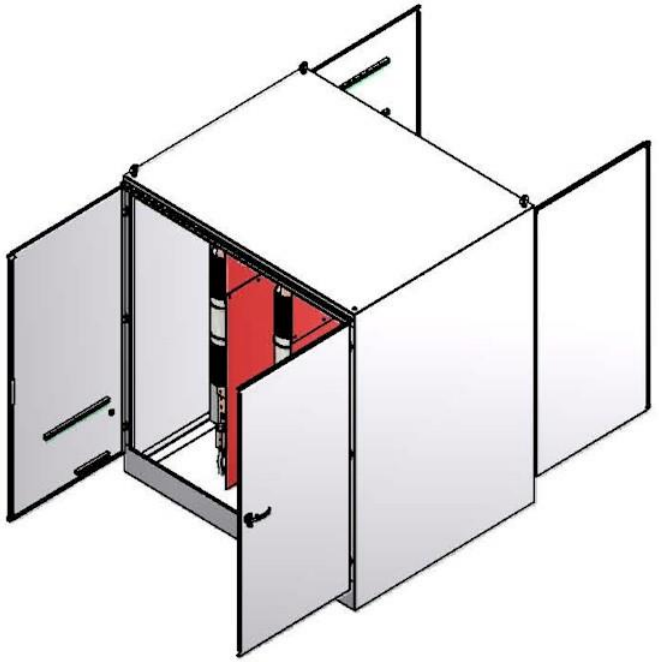
Limited Fault Current Output

Regulating Current to reduce Fault Current (Other Half of AC Cycle)

ADVANCED FUSION SYSTEMS

FCL Integration
13.8 KV, 1000 A





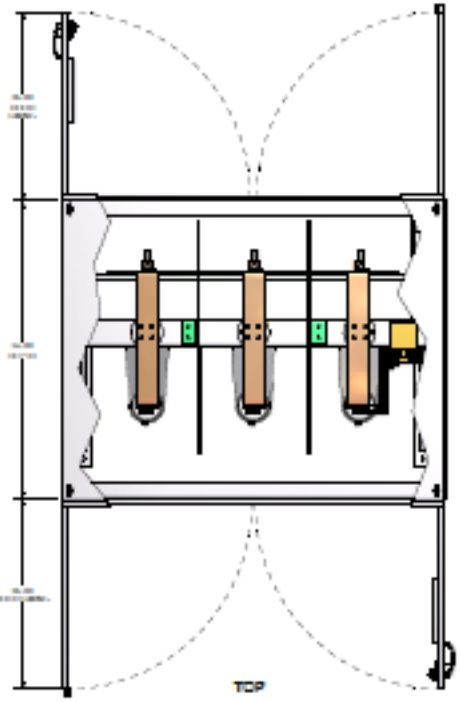
ADVANCED FU

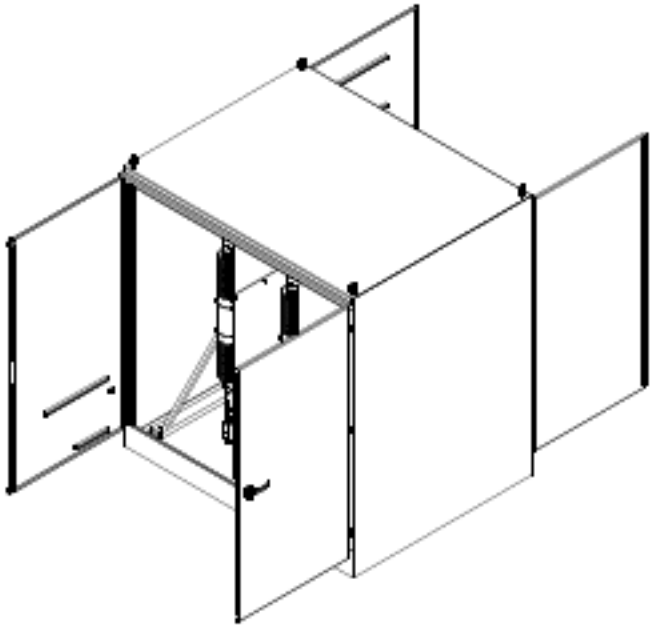
Capture™

Fault Current Limiter

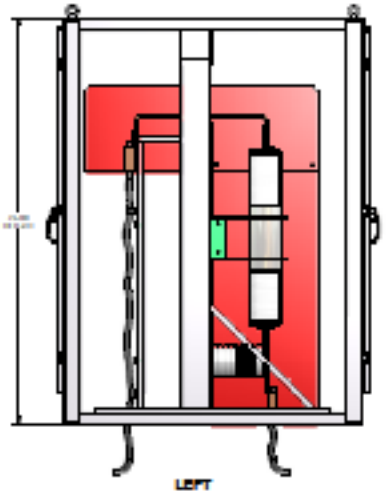
- Introducing a different concept – Faultron™ electron tube technology
- Passively Dynamic operation
- No fuses or parts to replace
- No breakers to reset
- Integrated monitoring control system
- 24/7 sentinel protection
- Keeps your power system functional and reliable

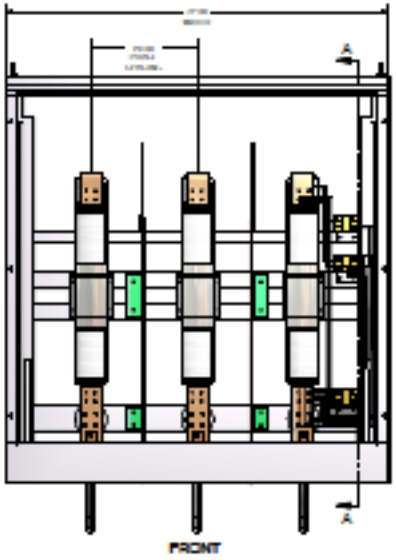
PEC
Phoenix Electric Corporation

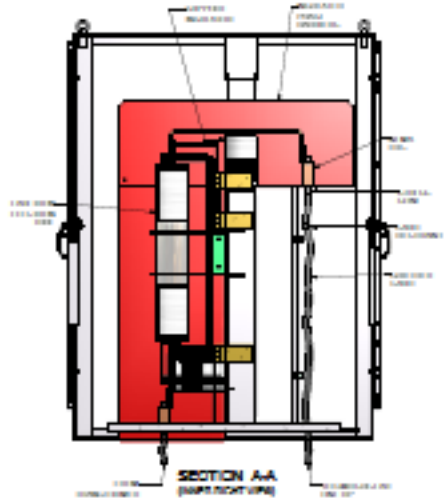


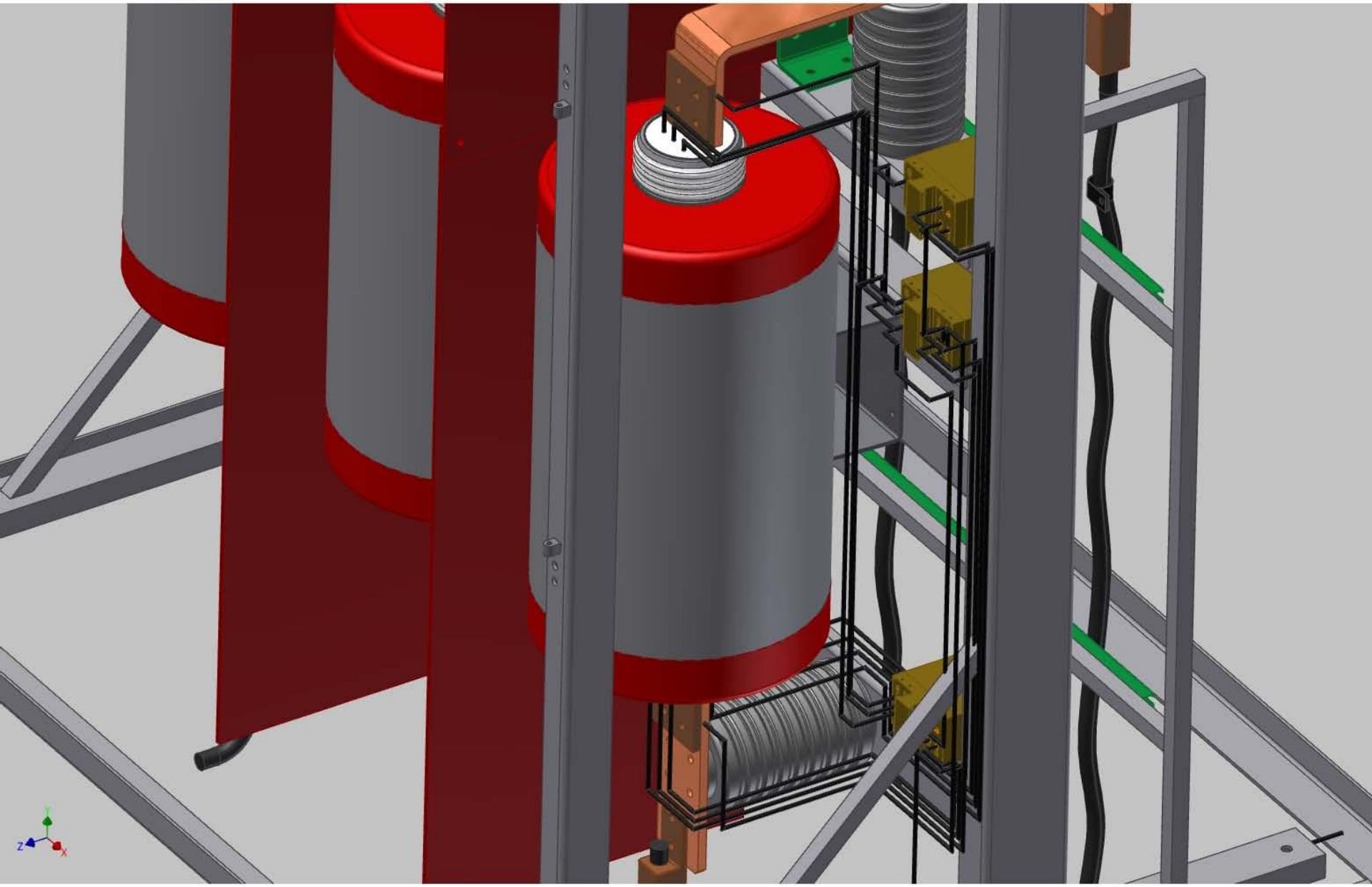


PRELIMINARY









ADVANCED FUSION SYSTEMS

SUPER MOV REPLACEMENT

ADVANCED FUSION SYSTEMS

Super MOV Replacement (3-Phase; Artist Concept)

HVDC Inverter

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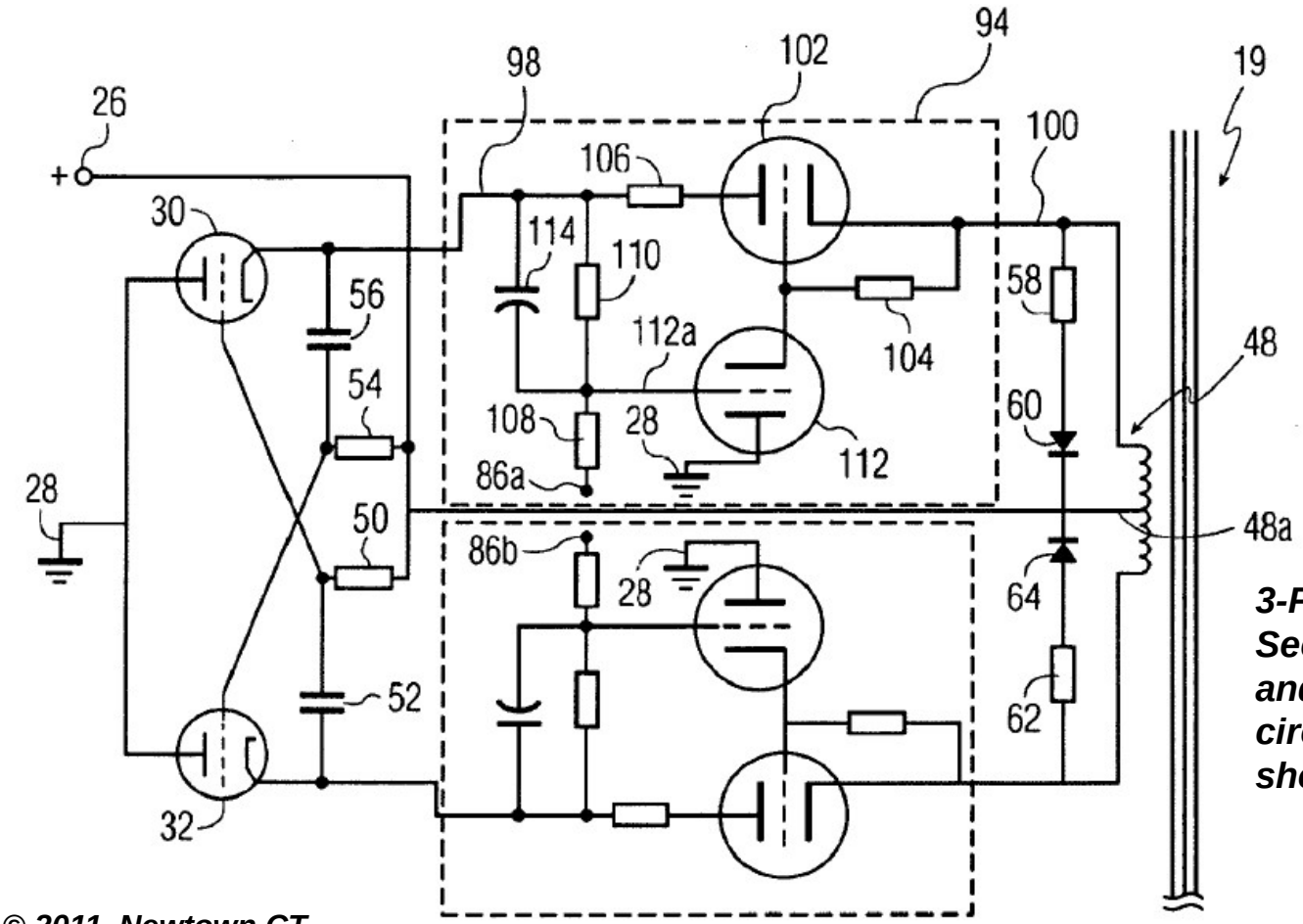
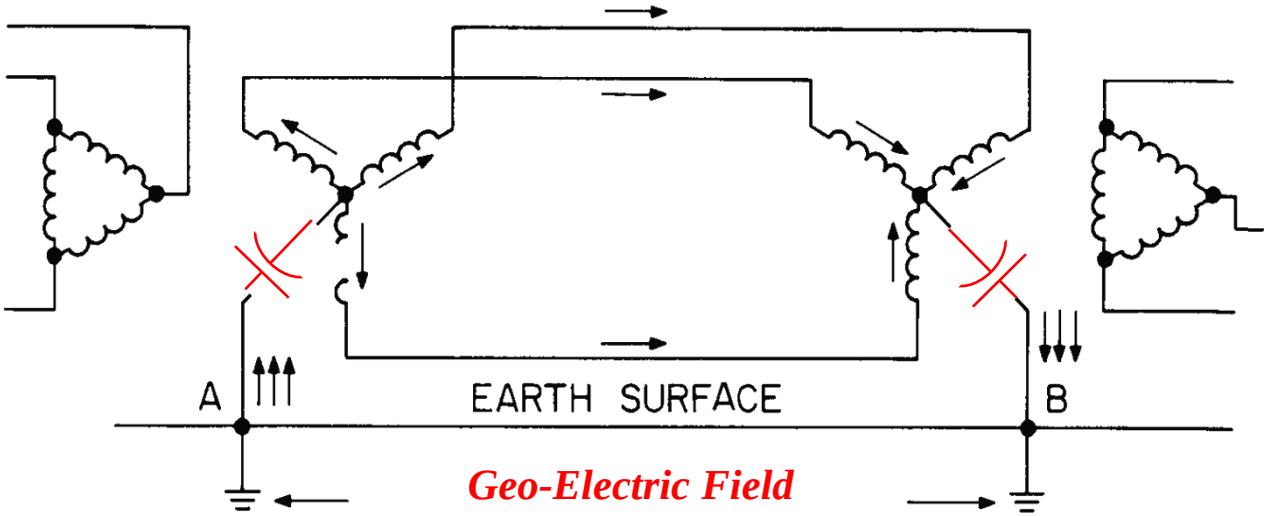
AFS HVDC VSC *pat pend*



3-Phase Secondaries and control circuits not shown

Hardening – GIC Reduction in Power Grids
Transformer Neutral Capacitor Devices

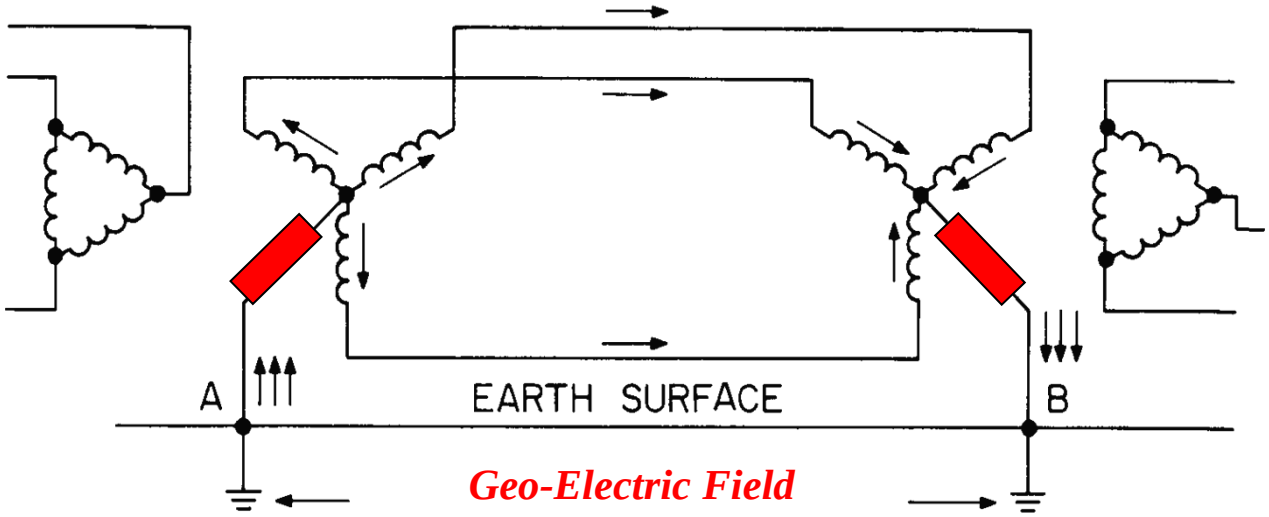


A single low-voltage capacitor in the transformer neutral ground connection at each transformer will also block the GIC flow in the transmission line and each transformer.

- *Capacitor needs added circuitry and sophistication for rapid AC Bypass*
- *This Strategy will produce the greatest overall GIC reductions in the network*

Hardening – GIC Reduction in Power Grids

Transformer Neutral Resistor



A low-ohmic resistor (2.5 to 7.5 ohms) in the transformer neutral ground connection at each transformer will act to significantly reduce but not totally block the GIC flow in the transmission line and each transformer.

NBBD Device Functional Requirements

- *Block the flow of DC current to design DC Voltage Threat Level, while conducting low-level AC current*
- *Must offer high reliability and not call for more maintenance than the transformers to which they are connected.*
- *Must be able to operate autonomously and not require intervention to put them into operation under the threat circumstances they are designed to mitigate*

- *Should not interfere with any existing protections or controls, produce new operating constraints, generate harmful interactions on the transmission system such as ferroresonance, overvoltages*

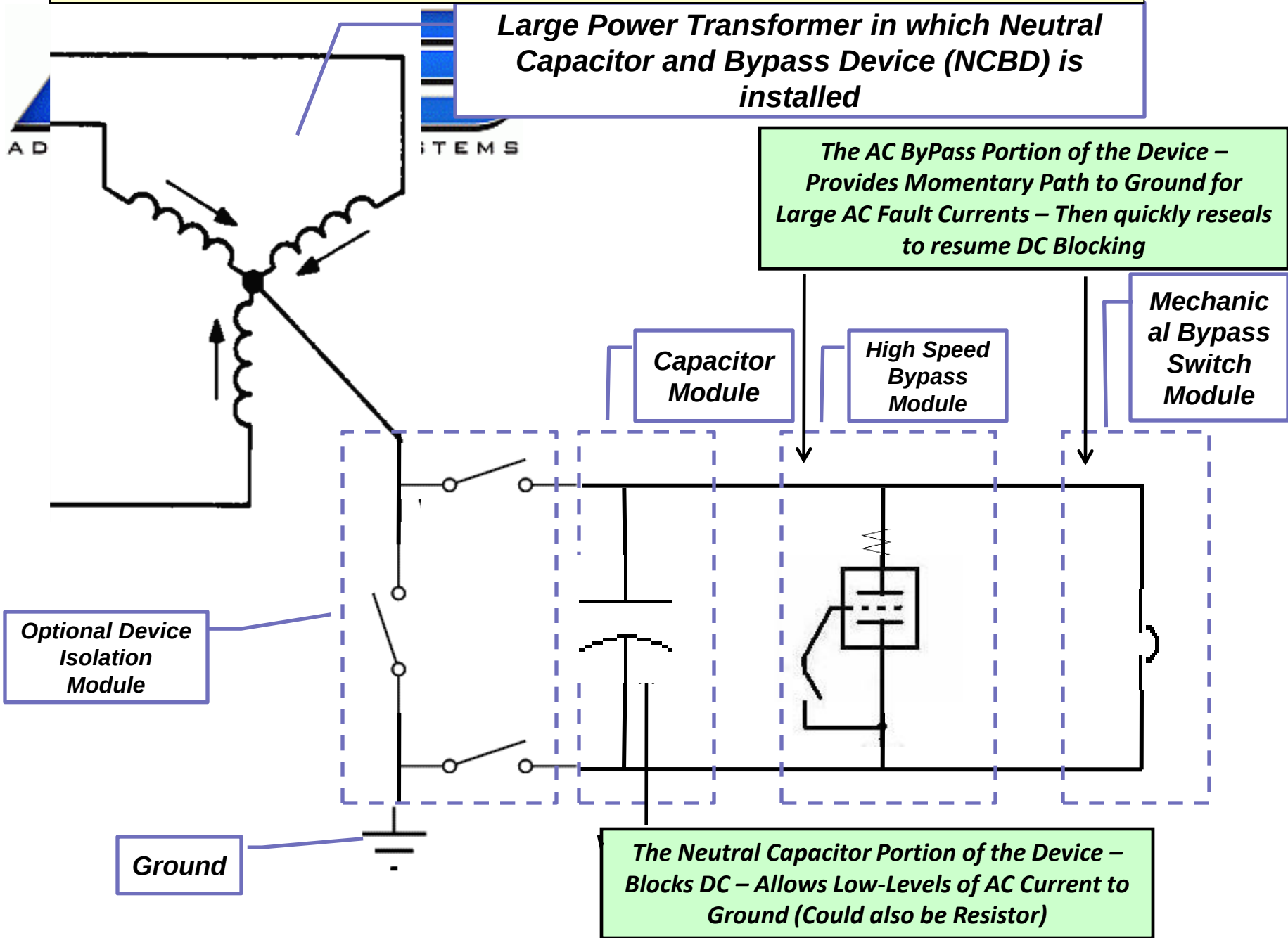
- *Have AC fault current ratings . . .*
  Adequately sized to the available fault current of the system

- *Provide solid neutral grounding for the AC system to maintain the effectively grounded transmission system and limit the transformer neutral to less than ~20 kV peak voltage rise*

The Last Three Requirements are Technically the Most Difficult, but are readily available as Commercial Off-the-Shelf Hardware/Component Solution

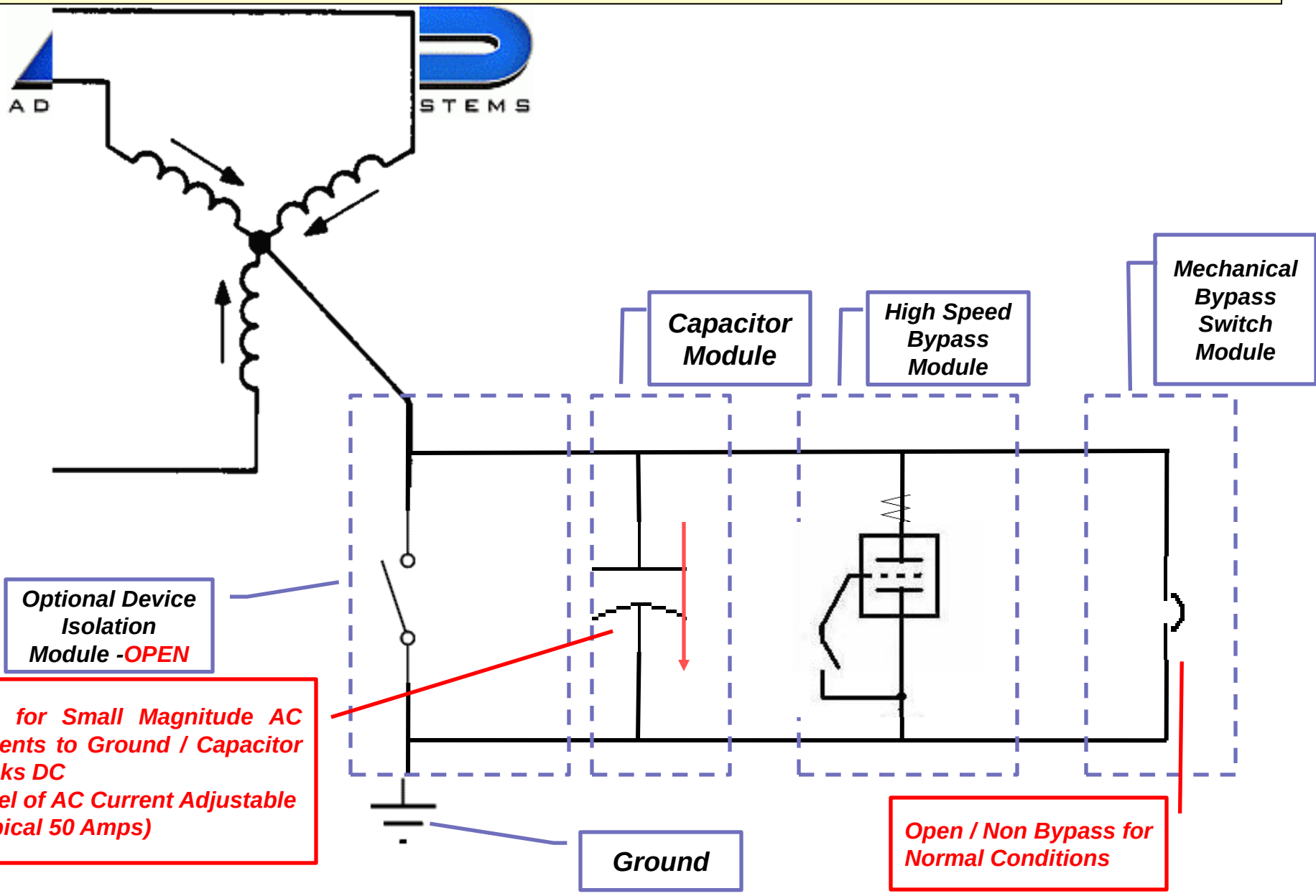
Determining the DC Threat Level Requires Sophisticated Network Analysis, so that Device can be Engineered for Appropriate Withstand Levels

NCBD Device Design Specifics



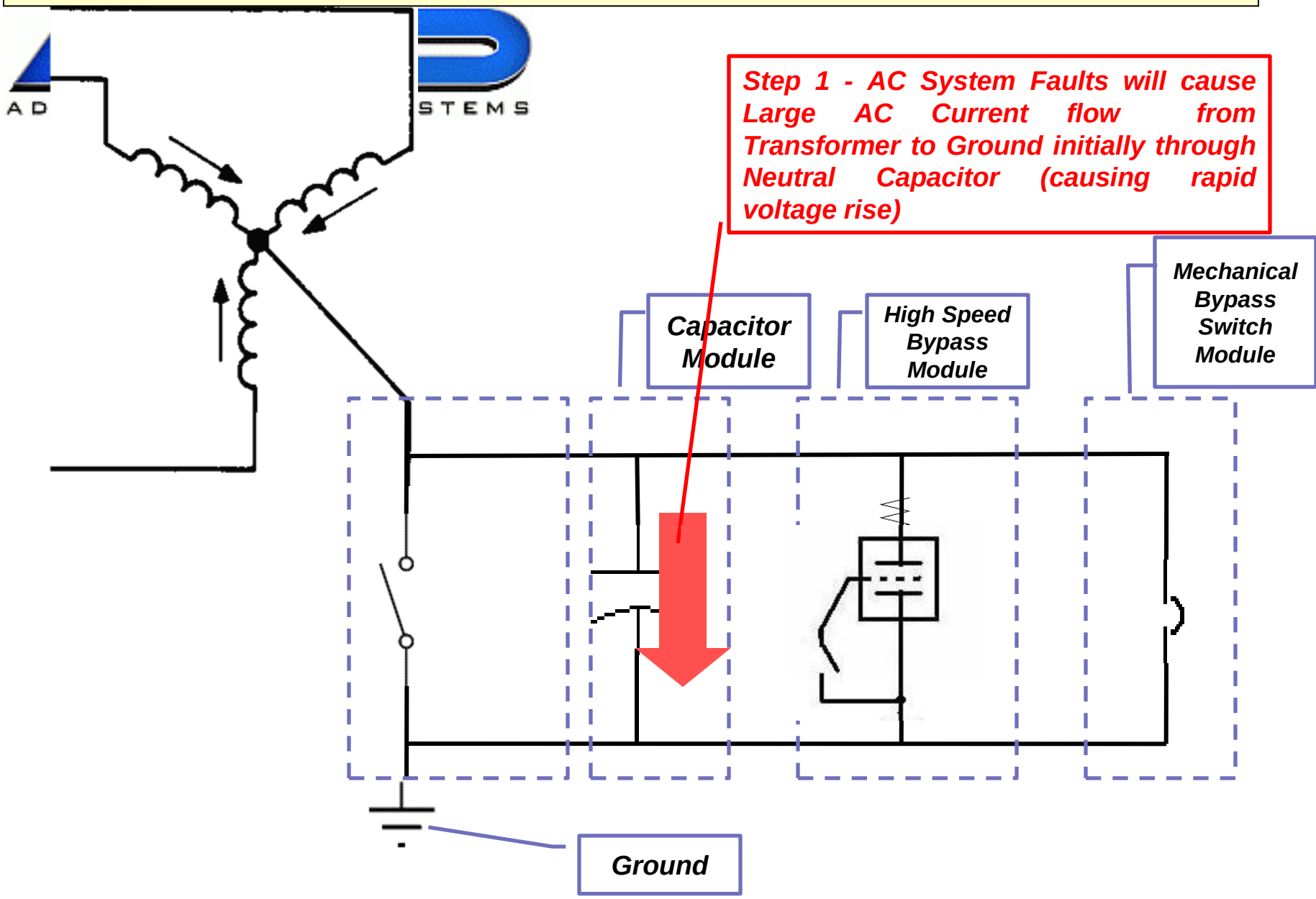
NCBD Device Operation Specifics

Normal Operation in GIC Blocking Mode



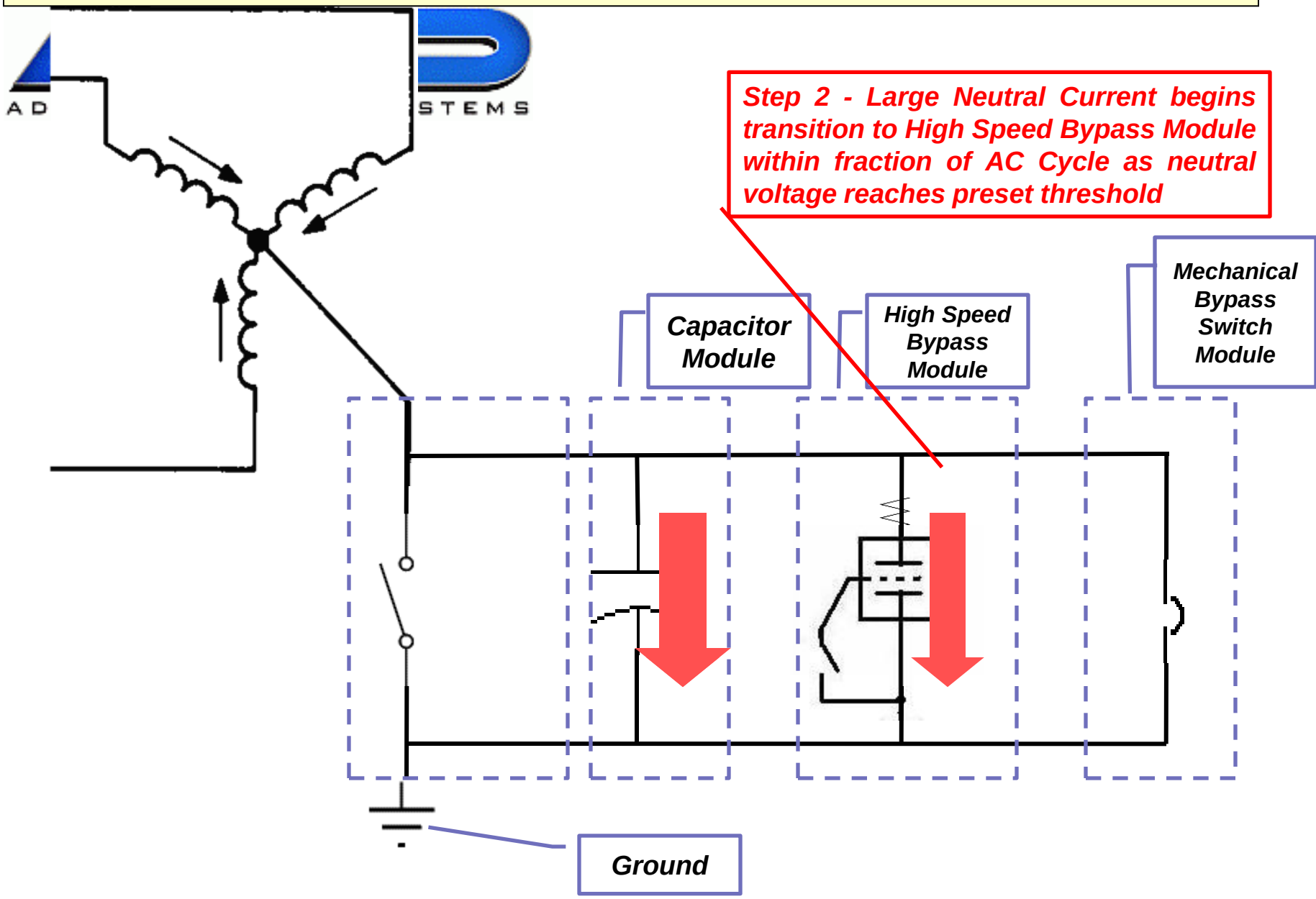
NCBD Device Operation Specifics

AC Fault Conditions – Operation in AC Bypass Mode



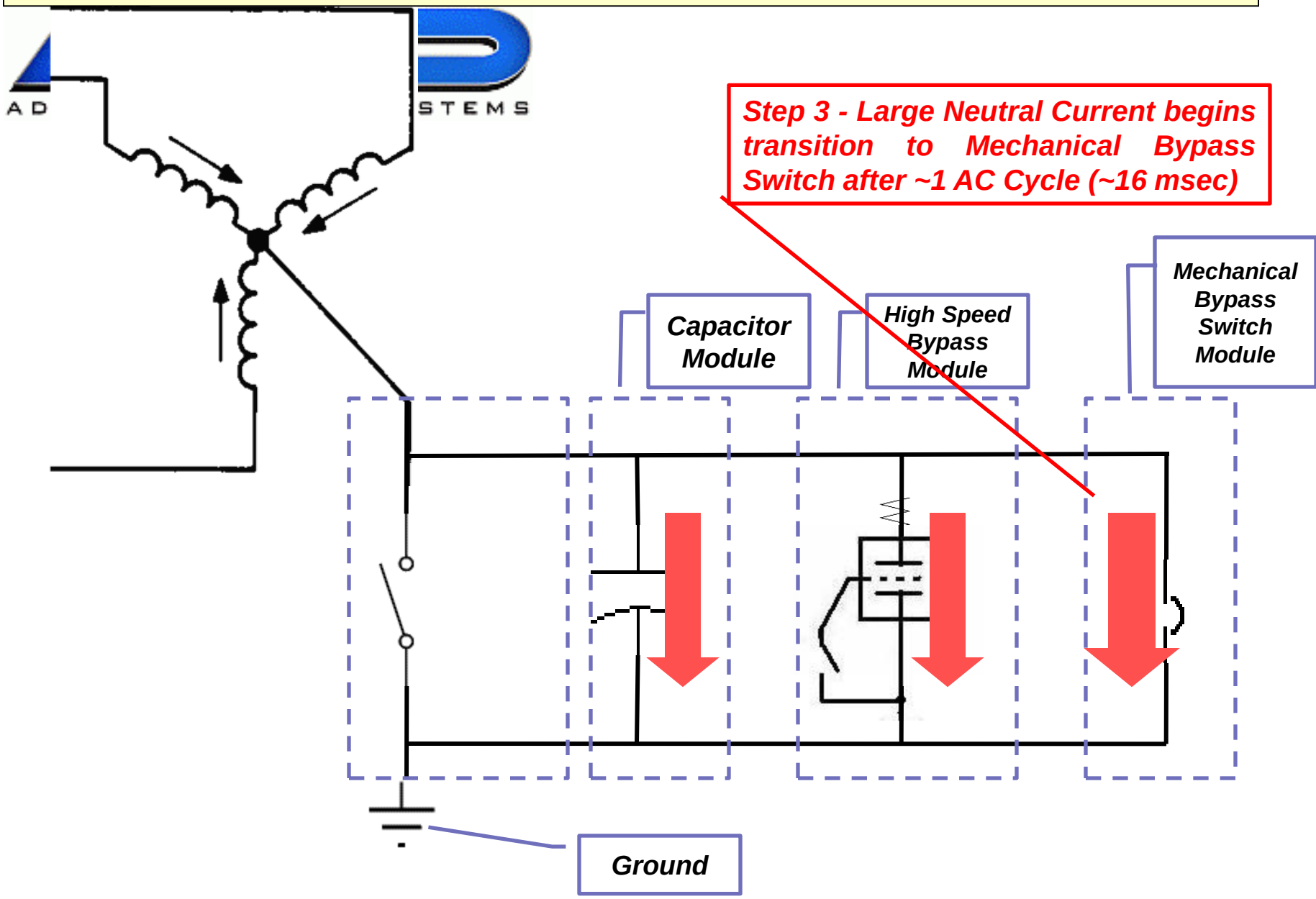
NCBD Device Operation Specifics

AC Fault Conditions – Operation in AC Bypass Mode



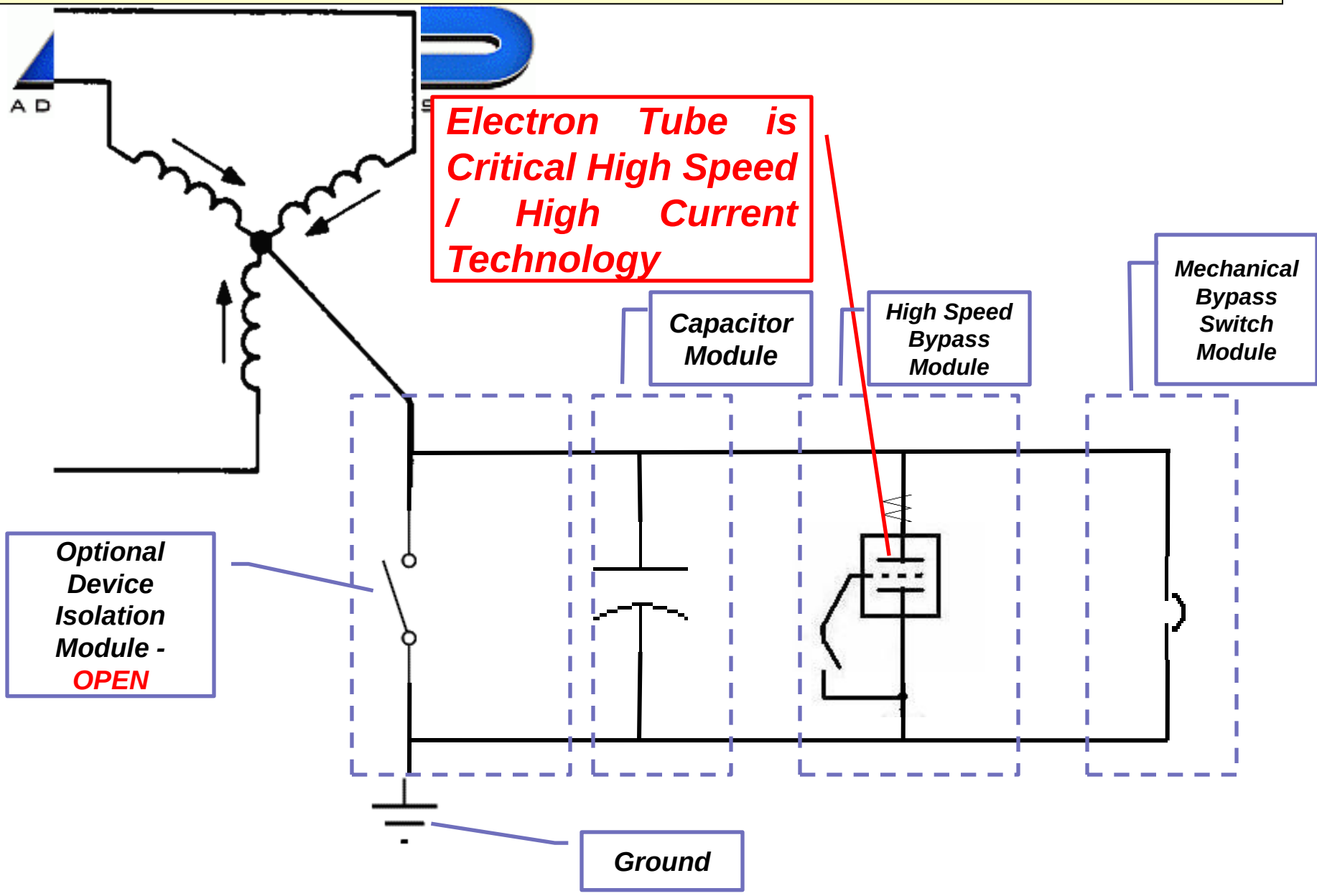
NCBD Device Operation Specifics

AC Fault Conditions – Operation in AC Bypass Mode



NCBD Device Operation Specifics

Normal Operation in GIC Blocking Mode



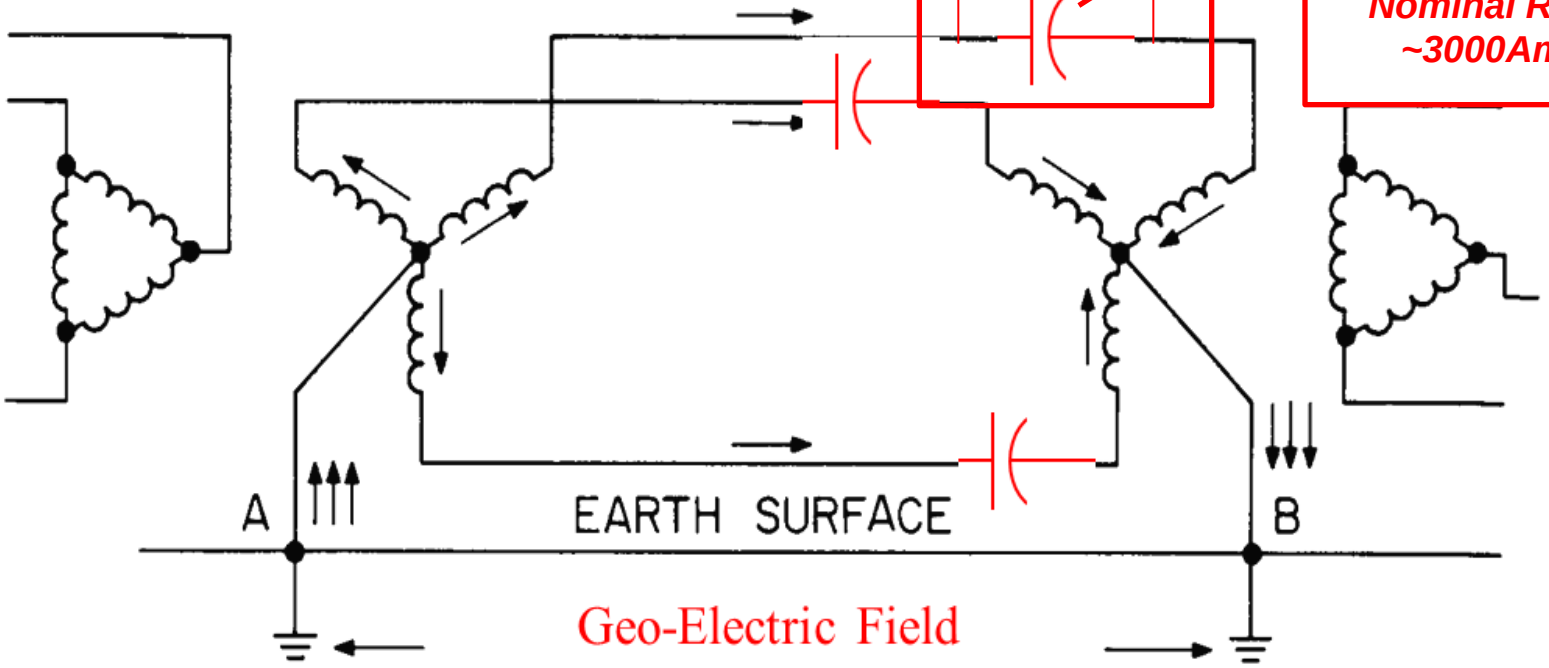
Inexpensive, Compact and Fully Autonomous Transmission Line Series Capacitor Bi-Tron Bypass and Vacuum Capacitor

Entire Assembly Very Compact /Lightweight (55 gallon Drum-size) can be mounted in Bus-Section

Low Cost - ~$1miilion per 3 Phase Assembly

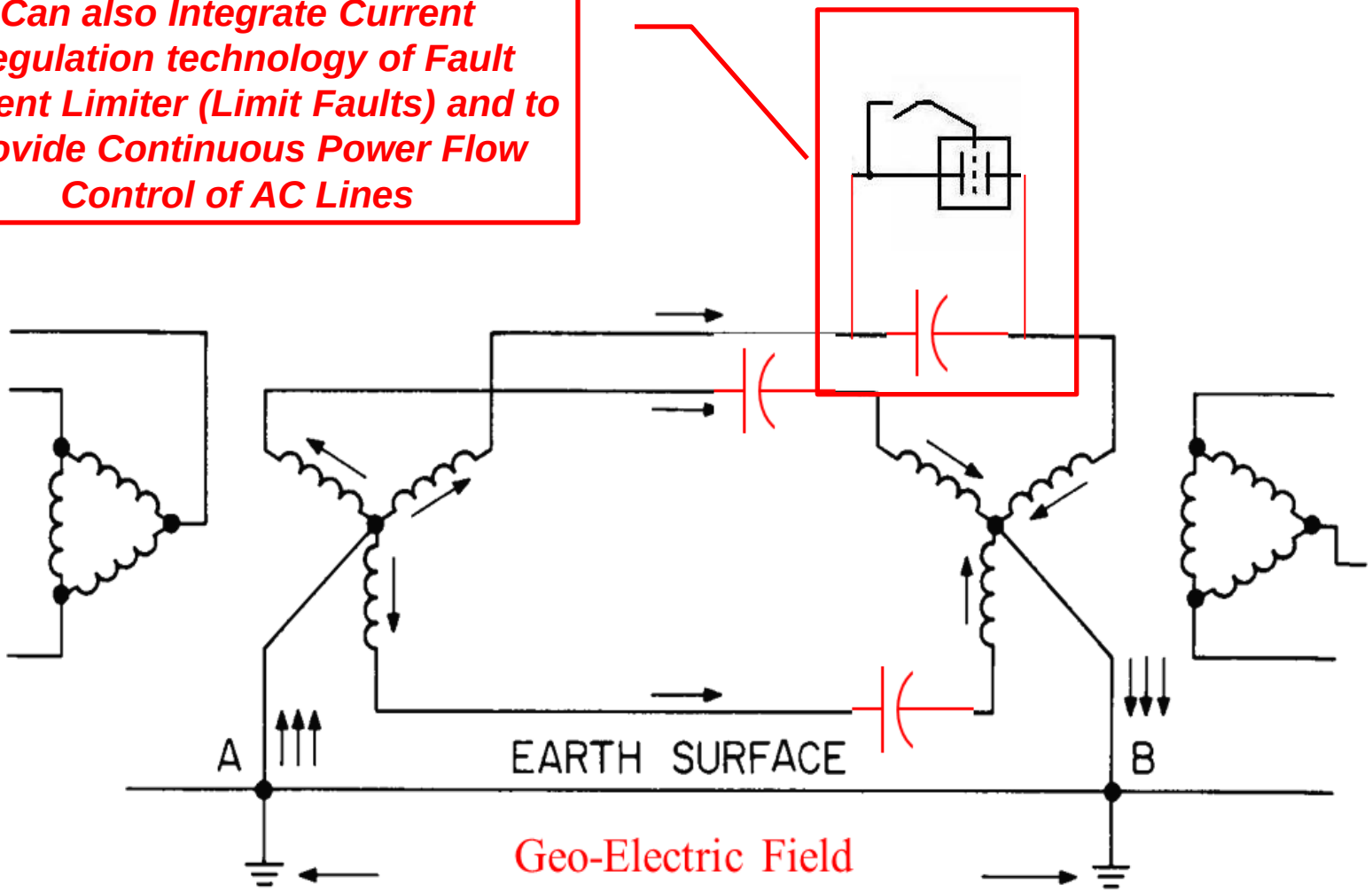
Bi-Tron for Rapid autonomous bypass No Auxiliaries needed

Vacuum Capacitor – Fail-Proof Dielectric Nominal Rating ~3000Amps



Inexpensive, Compact and Fully Autonomous Transmission Line Series Capacitor Bi-Tron Bypass and Vacuum Capacitor

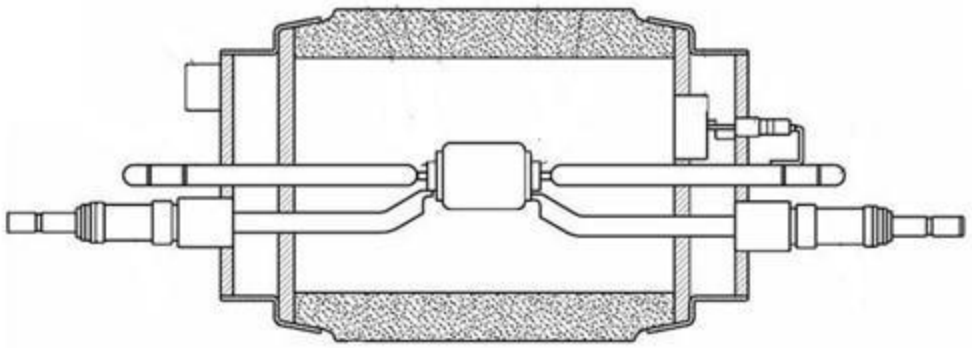
Can also Integrate Current Regulation technology of Fault Current Limiter (Limit Faults) and to Provide Continuous Power Flow Control of AC Lines

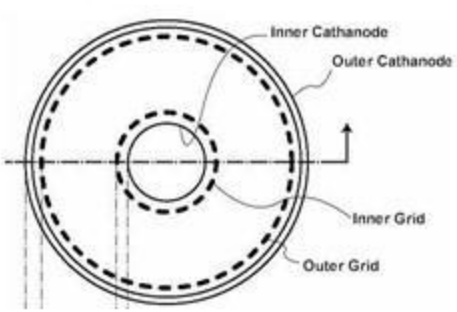


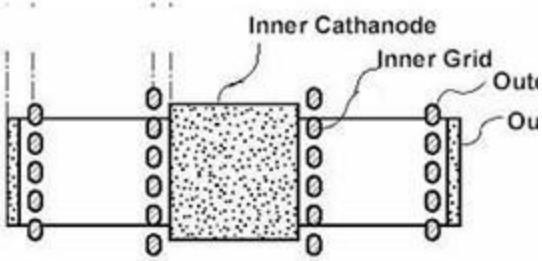
Example 4275 Bi-tron Tube

ADVANCED FUSION SYSTEMS

4275 Bi-tron™







Some structures omitt

Ratings
30kV
75kA
•Significantly faster than semiconductor
•Bi-directional operation
•Nominal size of 12” L, 5” dia
•Scalable to larger KA and KV
Ratings and sizes

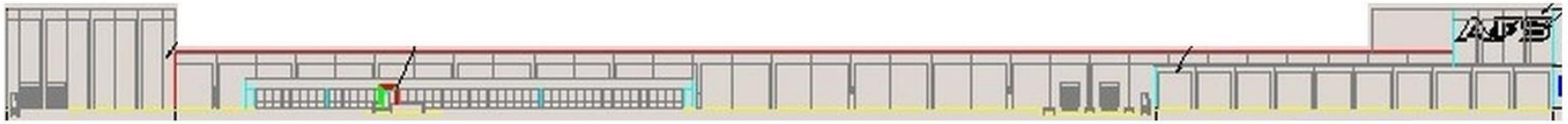
ABOUT
ADVANCED FUSION SYSTEMS LLC

AFS Overview

- Advanced Fusion Systems LLC (AFS) was formed in 2008 to develop and exploit patent-pending and proprietary technologies to produce a series of related products:
  - *Faultron™ Fault Current & Over-Voltage Limiters*
  - *FXI Environmental Remediation Systems*
  - *Electromagnetic Pulse (EMP) Protection systems*
  - *GIC Protection Systems*
  - *Pulse Power-Based Systems*
  - *Advanced Electron Tubes*
- *All technologies are US and International Patents-Pending.*
- *AFS has acquired the assets of Hudson Research Inc which is now a subsidiary.*
- *AFS has acquired the assets of Thryonics Inc which is now a subsidiary.*
- *AFS has acquired and is modifying a 250,000 sq. foot facility in Connecticut .*
- *AFS is a privately-held Delaware limited liability corporation.*

ADVANCED FUSION SYSTEMS

AFS New Facility



Expanded facility ↑↑

Satellite view of << existing facility

- *(4) FCL Test to 345 KV*
- *(2) EMP Test to 1.2 MV AC/DC @ 250 KV/M*
- *Radiation Lab 1 MeV & EMP*
- *EMP & RF Anechoic*

11 Edmond Rd, Newtown, CT. 250,000 ft^2 ***(including expansions)***

ADVANCED FUSION SYSTEMS

Under Construction

>35,000' of 5" conduit; >10,000 cubic yards of concrete

Specialized Test Facilities

- 20 MW power feed to fully shielded test facility
  - (scheduled expansion to 40 MW)
- Fault Current Test Cells: 4160 V – 345 KV
  - On-site 10 MW Generator
  - Armored & Shielded FCL Test Cells
- Radiation Lab: 1 MeV; 100'L x 34'W x 20'H;
  - 3 foot thick concrete walls
  - Full EMP Shielding (Electric & Magnetic)
- EMP Test Cells: Electric & Magnetic Shielding; 250 KV/M sources)
  - (2) @ 135' x 50' x 50';
  - (1) @ 80' x 40' x 22' (also RF anechoic)
- Site Safety includes:
  - Interior and exterior E & H Field monitoring
  - Interior and exterior X-ray monitoring

ADVANCED FUSION SYSTEMS

FCL Test Facilities

- This facility will support Fault Current testing from 4160V to >345KV.
- FCL Test Cell 1: 4160 & 13.8 KV @ 1 MW
- FCL Test Cell 2: 13.8 KV & 25 KV @ 10 MW
- FCL Test Cell 3: 33 KV – 69 KV @ 10 MW
- HV Lab: 115 KV – 345 KV @ 10 MW
- Future Expansion: 500 KV – 1.2 MV @ >10MW
- All FCL test cells use custom-designed transformers.
- Testing to IEC specs where available.

EMP/GIC Test Facility

- It is essential that all devices be tested under realistic conditions, but there are no EMP test facilities capable of on-load testing devices up to 1 million volts (that we are aware of).
- As part of our commitment to the EMP protection arena, AFS is constructing a world-class EMP test facility.
- This facility will be capable of testing devices at line voltages up to 1.2 million VAC or VDC, under load conditions of up to 10 MW, and in a sub-100 picosecond risetime pulsed electric field environment of >250 KV/m.
- This facility will test in excess of the Mil-188-125 standard so as to provide realistic IEMP conditions.
- This facility can successfully create SGEMP environment.
- This facility also does fault-current testing, flashover, and other tests..

ADVANCED FUSION SYSTEMS

Advanced Manufacturing Capabilities

Advanced Manufacturing Capabilities

- CNC Machining: 7-axis, 5-axis, & 4-axis systems (micron tolerances)
- Electron Tube Processing
- Electrochemical Processing
- Vacuum-grade Reinforced Ceramics
- Cathode Fabrication
- Glass Fabrication
- Ultra-High-Speed Electronics
- Optical Fabrication
- Thin-Film Processing; Reactive Ion Plating
- Plasma Processing
- Welding, Brazing, Silver Soldering
- Electronics fabrication
- Precision Assembly
- Vacuum System & Device Fabrication

ADVANCED FUSION SYSTEMS

Advanced Manufacturing

- This is a photo of our large CNC machine.
- It is a fully computerized 7-axis machining center.
- Machining tolerance is 0.00005” over 25 feet.
- It can handle parts up to 7 feet in diameter, up to 25 feet long, weighing over 35 tons.
- This machine itself is 65 feet long and weighs 85,000 pounds.
- A sister machine has been acquired for deep boring to 25 foot depth.
- A very large milling machine, 6’ x 14’ x 10’.

Electron Tube Manufacturing

- AFS and its subsidiaries have the most advanced electron tube processing capability in the US.
- The machine shown at right is a processing station capable of processing five Pulsatron-size triodes simultaneously.
- Our ability to custom build processing equipment coupled with our extraordinary machining and chemical processing technology allows us to build electron tubes of virtually any size, a capability that no other company in the US has.
- AFS is the only manufacturer of direct electrically driven X-ray lasers.
  - A 100 KeV 50 KJ (x-ray output) unit is under design and will be built and tested during 2012.

Advanced Manufacturing (2)

- All critical components are manufactured in-house.
- This manufacturing is supported by a world-class Quality Assurance systems to ensure “Zero-Defects.”
- We use 100% inspection and test for all products.
- **All AFS protection devices are tested in our test facility and certified under realistic load conditions to guarantee operability. Customers are welcome to witness this certification procedure**.
- Each unit comes with performance documentation.

ADVANCED FUSION SYSTEMS

Thin Film Coating

Contact

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Newtown CT, 06470

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cbirnbach@advfusion.com