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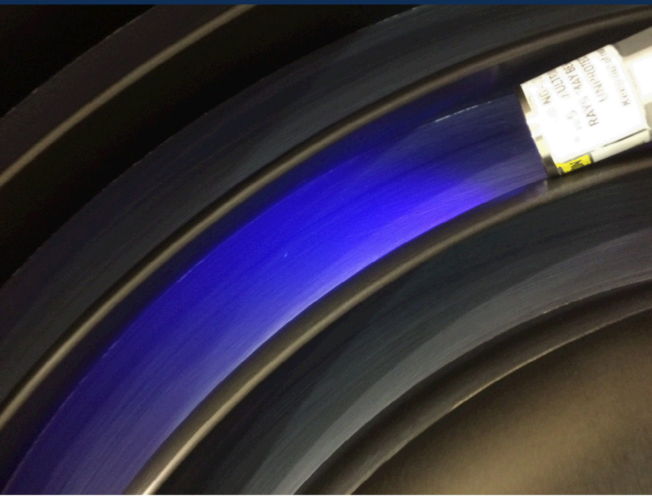

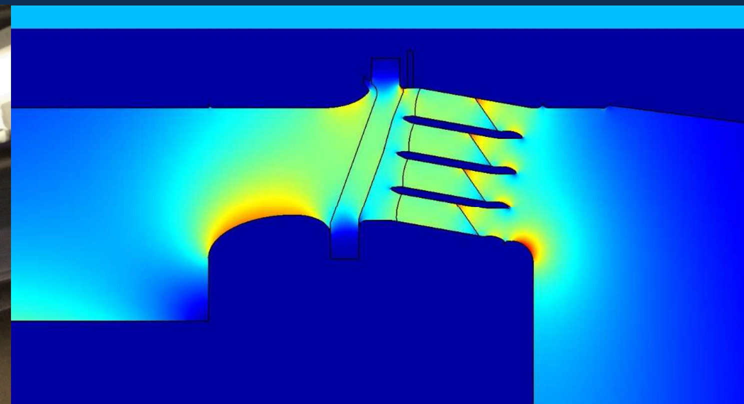

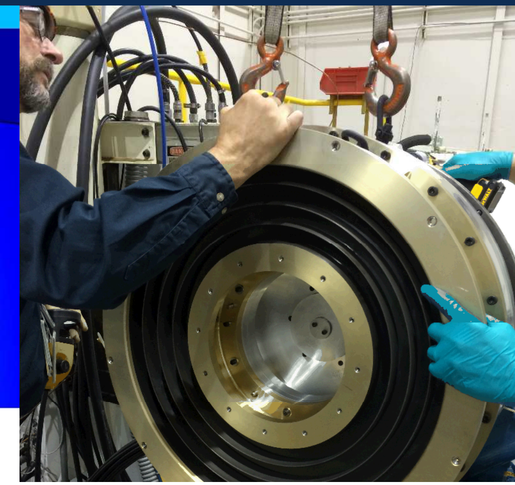

Performance of a radial insulator stack

M. E. Savage, B.S. Stoltzfus, K.N. Austin, P.A. Jones, W.A. Stygar, N.R. Joseph, J.K. Moore

Pulsed Power Sciences

Sandia National Laboratories

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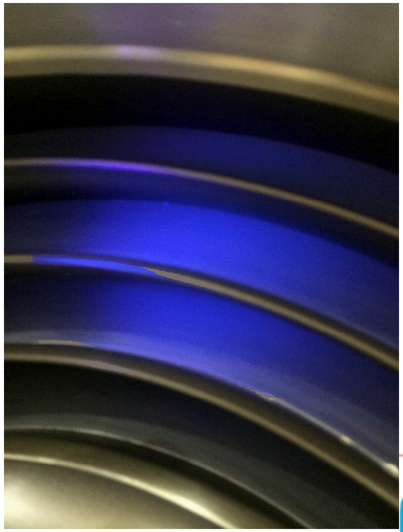
Outline

- Vacuum insulators
- Radial vacuum insulators
- Conical insulator design
- Test results



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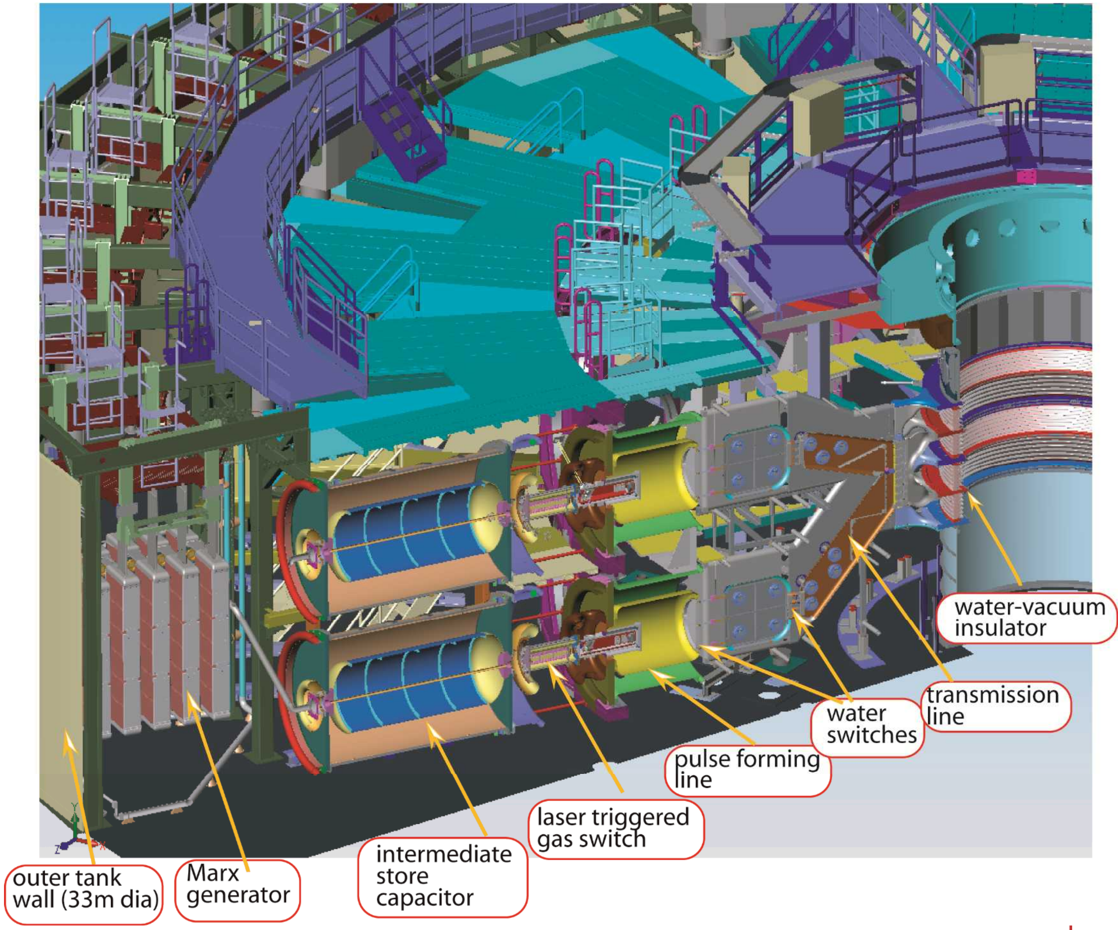
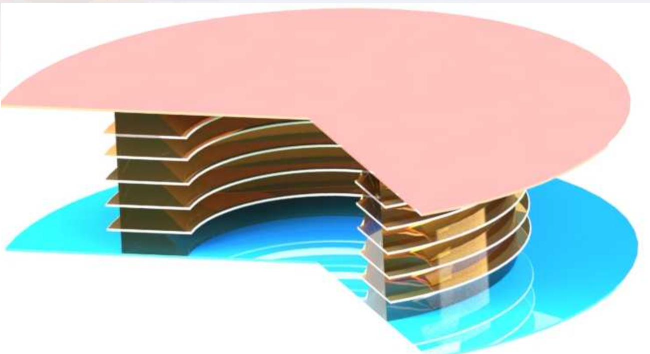
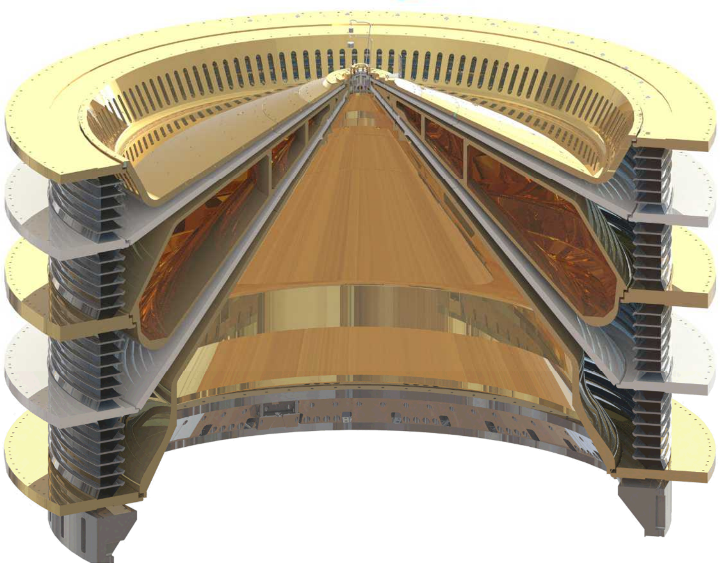
Vacuum insulators

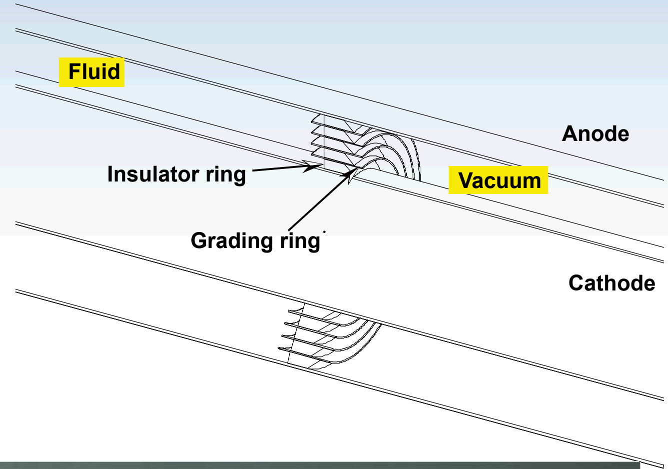
- **The vacuum insulator separates the vacuum-insulated load region from the fluid-insulated pulsed power system**
  - **The solid-vacuum interface can be problematic because insulators in vacuum can "flash" quickly and carry almost arbitrarily large current**
- **The ability of the vacuum interface to withstand voltage often affects the size of the entire system**

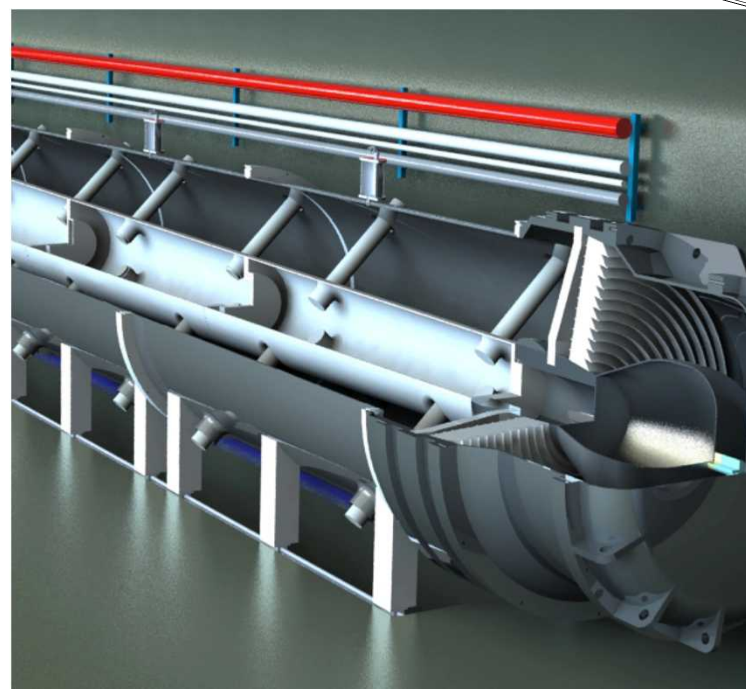


Vacuum insulator topology









***Axial vacuum insulators*: power flows towards the insulator axis**

***Radial vacuum insulators*: power flows along the insulator axis**

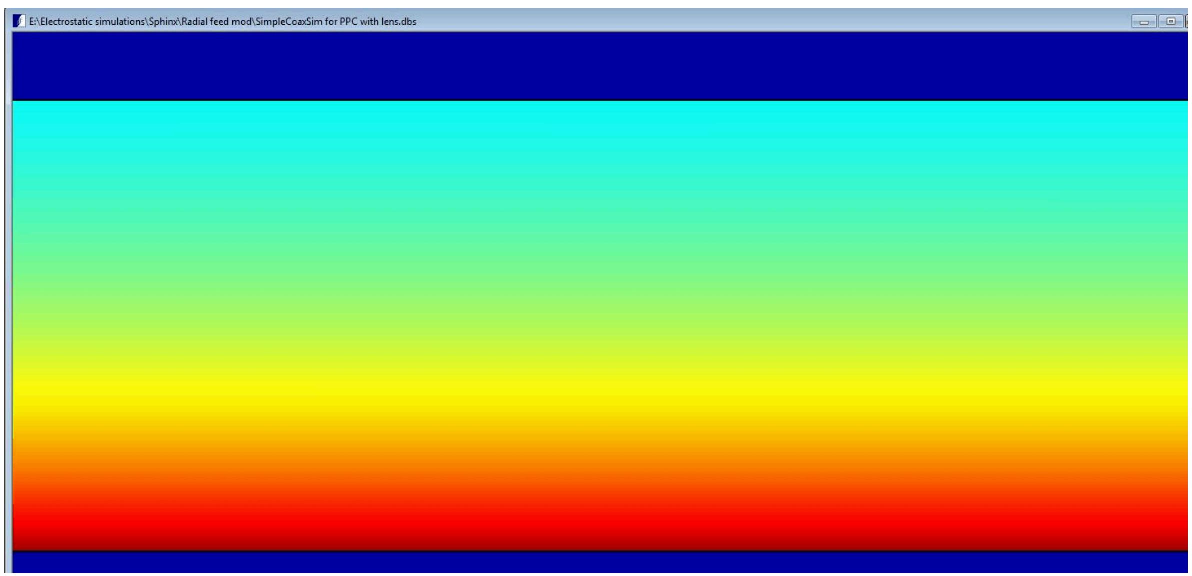
Radial vacuum insulators have additional issues

- **Non-uniform electric field in a coaxial transmission line**

$$E_r = \frac{V}{r}\frac{60}{Z_0\sqrt{\varepsilon_r}}$$

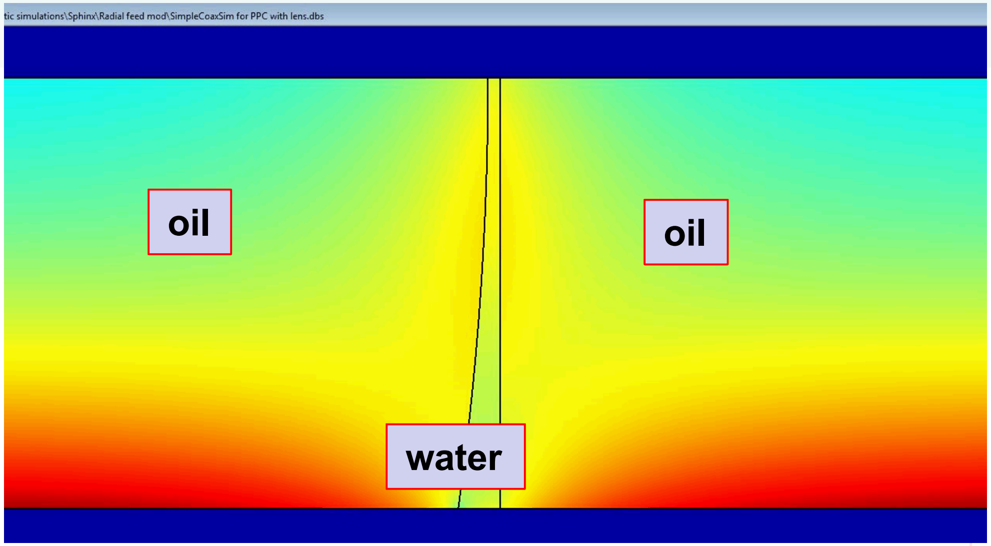
If uncorrected, the field is *higher* on the center conductor by a factor

$$\frac{E_{inner}}{E_{outer}} = \exp\left[\frac{Z_0\sqrt{\varepsilon_r}}{60}\right] = \frac{r_{outer}}{r_{inner}}$$

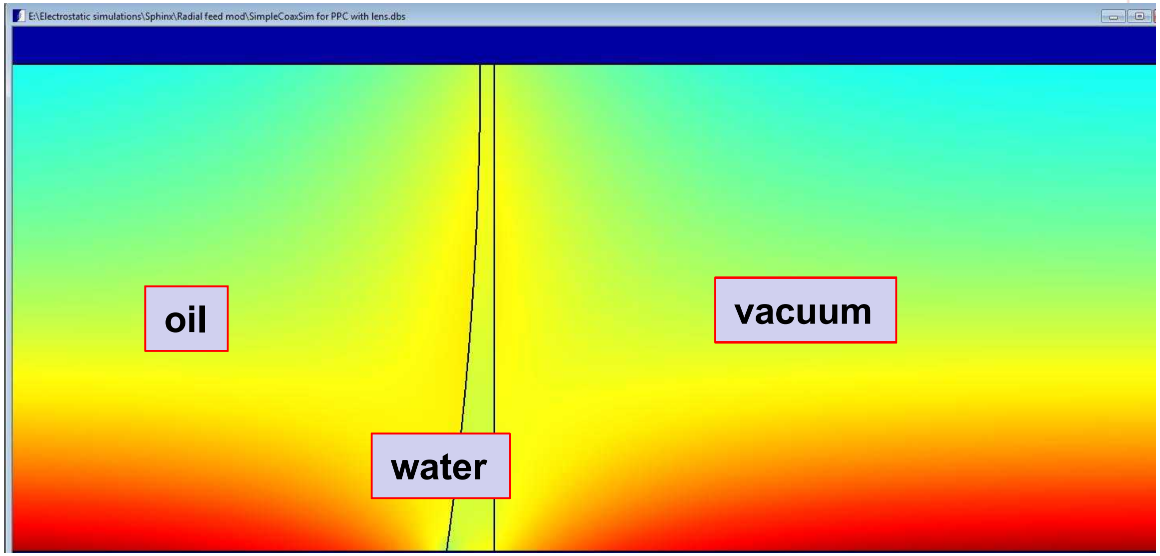


Field magnitude plot

A dielectric wedge with differing permittivity can improve field grading



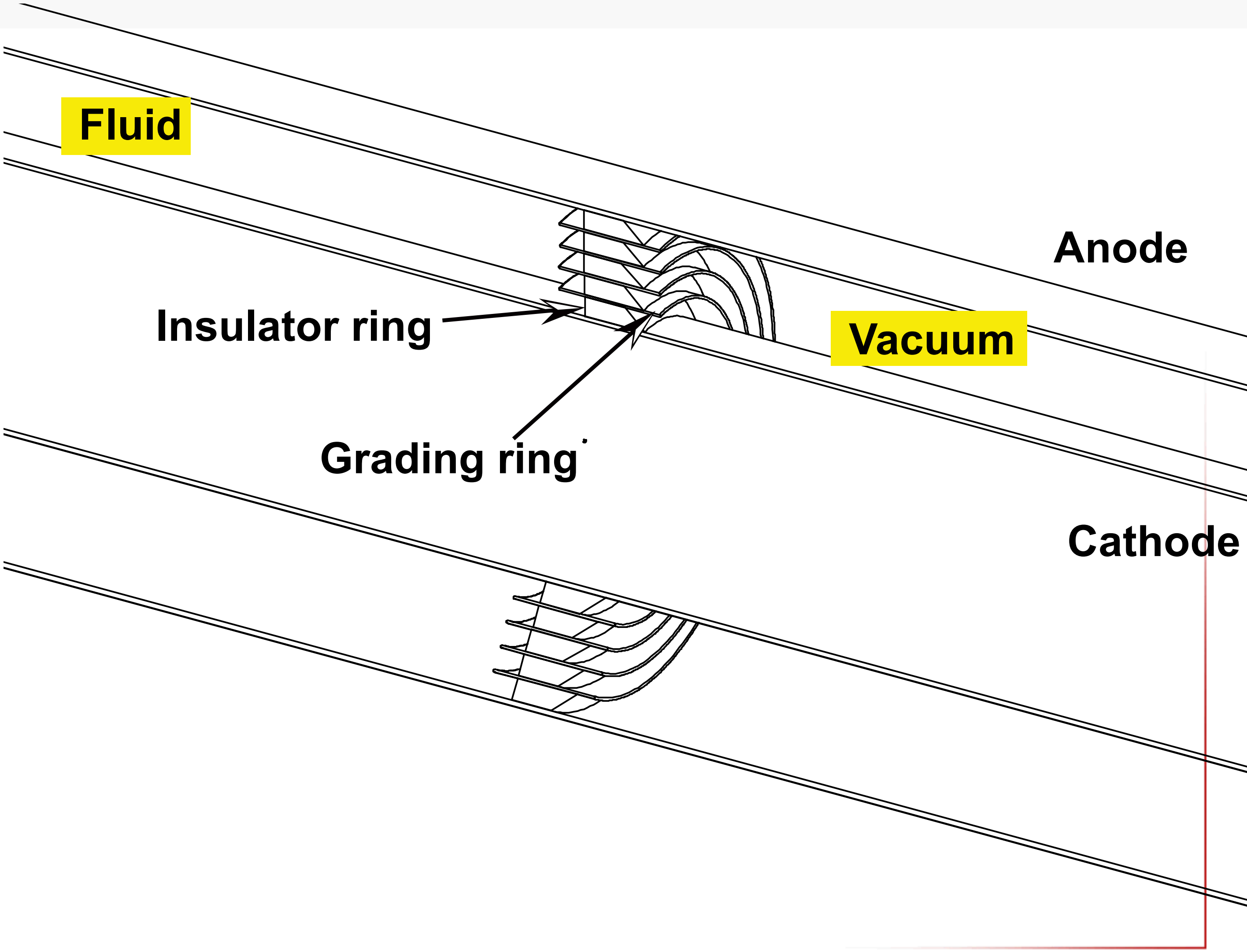
In an oil-insulated system, water is a convenient wedge material



The water increases capacitance in relation to its width
But- the total electrostatic energy in oil is lower with uniform field

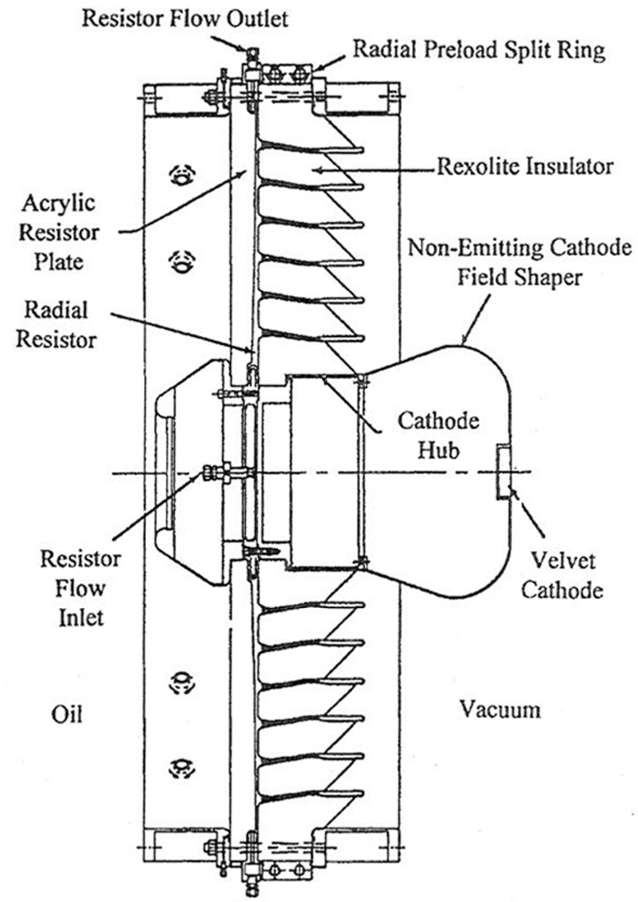
Mechanical stress in a radial insulator can be significant

- A 60 cm diameter insulator has 30 kN total force due to atmospheric pressure
- An insulator built from separate pieces is preferable for fabrication



A graded, wedged radial vacuum insulator has been used successfully on Airix

Adding the 10° angle increases the insulator length slightly, and reduces mechanical stress in the plastic



1.8 m diameter Airix interface

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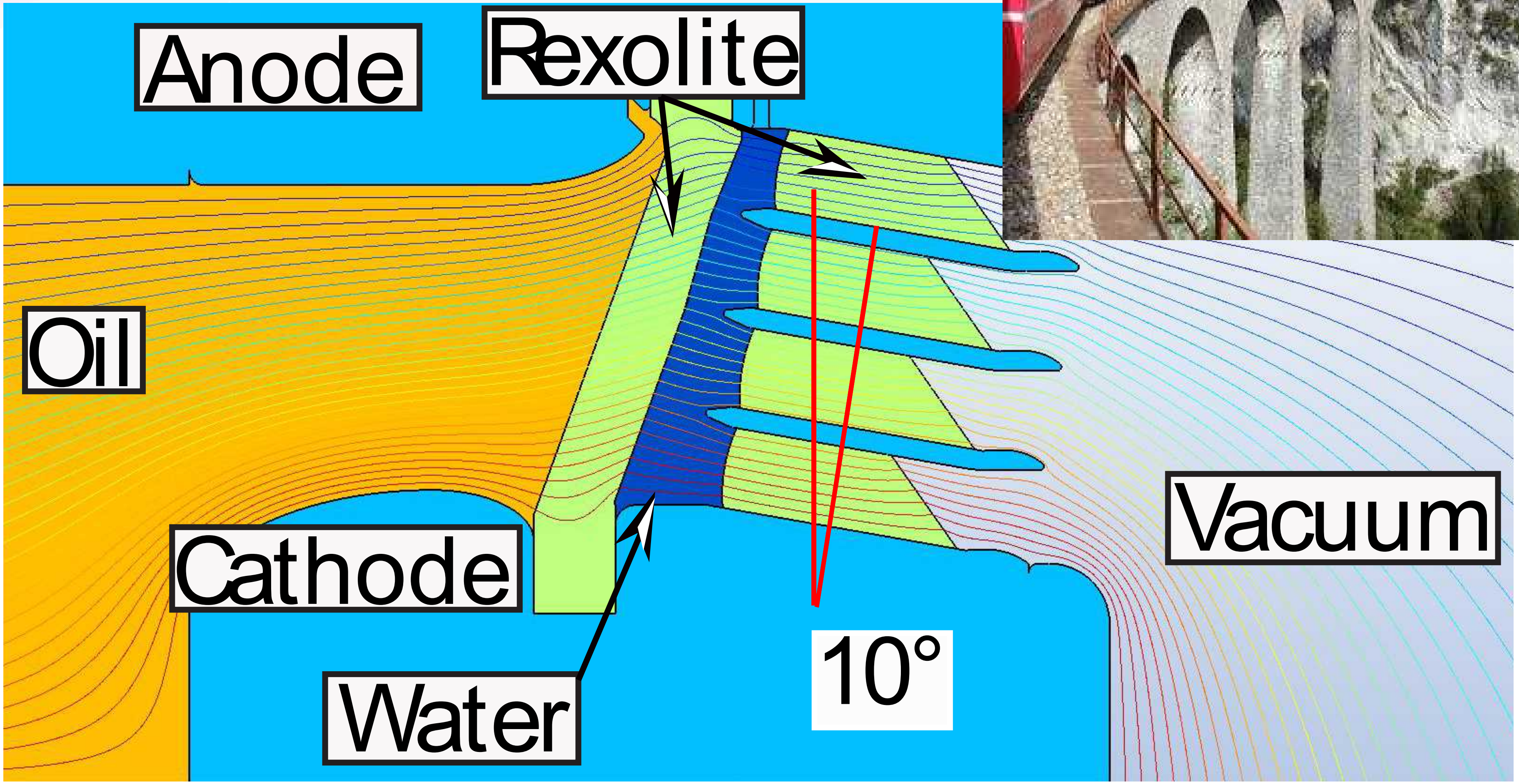
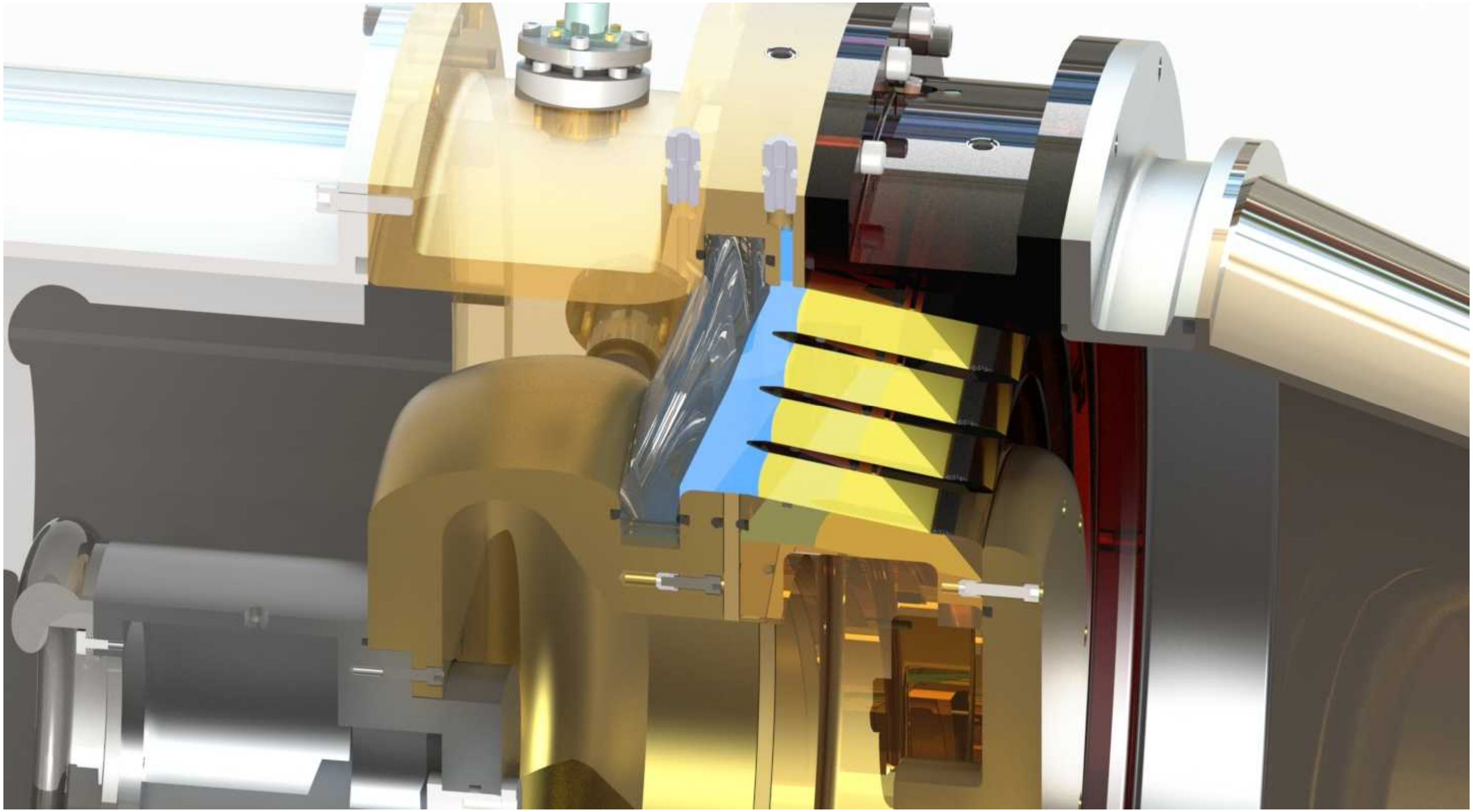
Another solution is to use an arched or conical insulator stack



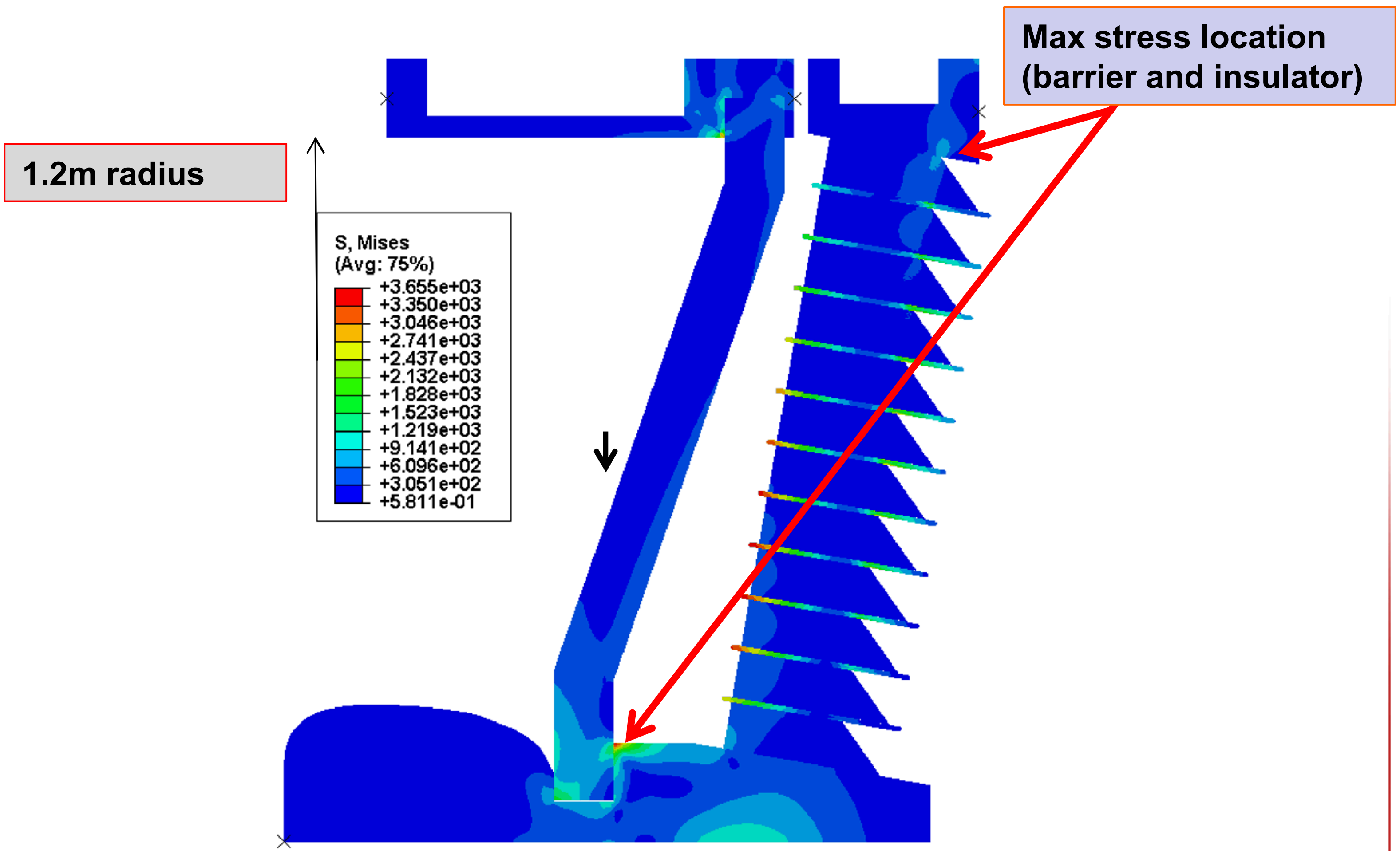
An axial preload force comparable to the vacuum load keeps the assembly stable

The final design uses a 10° cone for strength and a water wedge for grading



Mechanical stress level for a larger assembly is acceptable

Our goal of testing an insulator that can be scaled mechanically to larger sizes is met

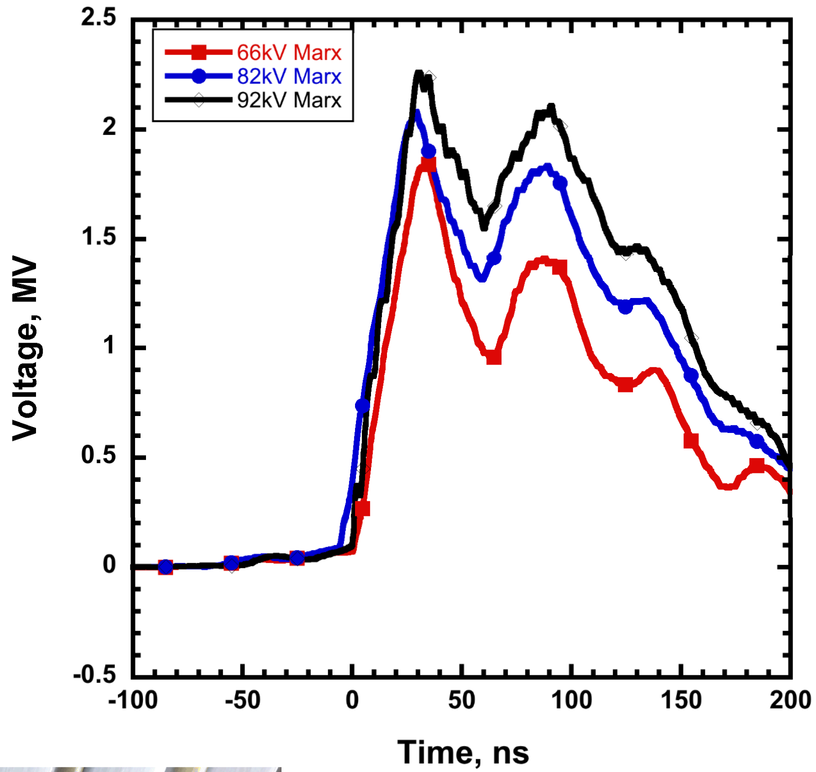


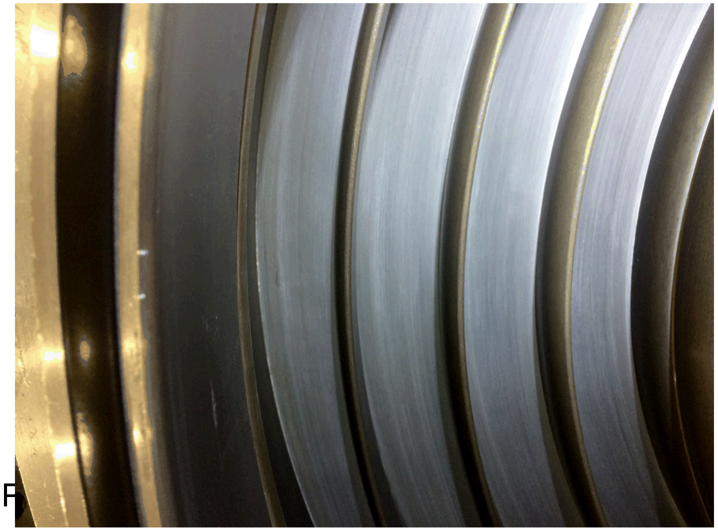
Barrier σ_{max}: 1,676 psi, FOS = 7.2

Insulator σ_{max}: 1,306 psi, FOS = 9.2

Testing of the insulator is done with a high impedance driver and no magnetic field

- No UV is present on the insulator
- No electrons except for emission from stressed surfaces
- Insulator is sanded, and wiped before pump-down and test
  - No conditioning
- No oil applied to the insulator surfaces

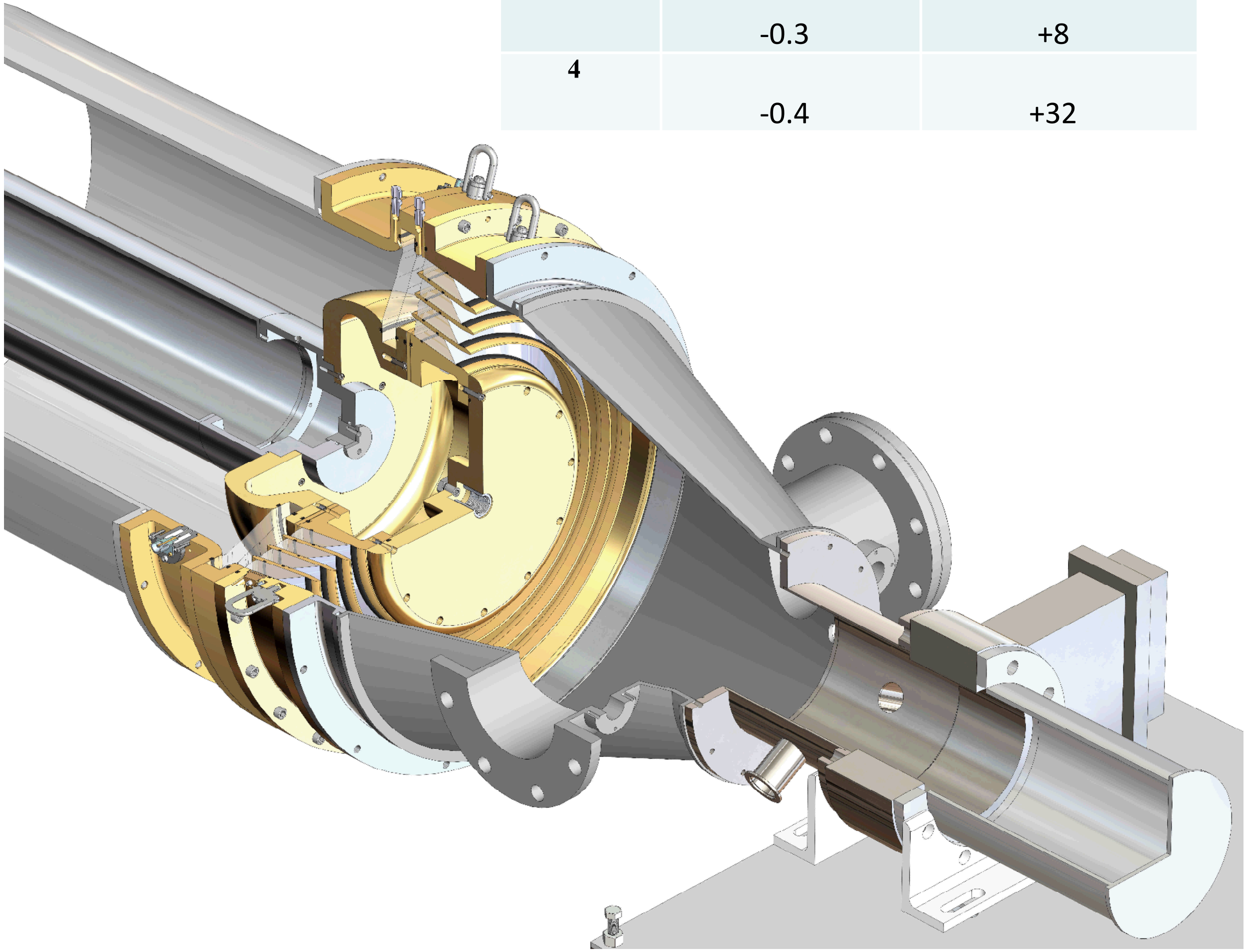




Testing shows that electrical performance of a well-graded radial insulator is no worse than an axial insulator

Insulator number	Voltage deviation, %, (water lens)	Voltage deviation, %, (no lens)
1	+0.2	-28
2	+0.6	-12
3	-0.3	+8
4	-0.4	+32

- **First series:**
  - **184±4 kV/cm: 50 shots, no partial or complete flash**
- **Second series (different stack build):**
  - **204±4 kV/cm: 50 shots, no partial or complete flash**
- **Third series (interrupted):**
  - **220±4 kV/cm: 4 shots, no partial or complete flash**



Large numbers of shots allows additional analysis

- We observed a flashover rate less than 2% at 204 kV/cm
- Flashover calculations consider the stressed area and the stress duration
- Typical flashover models used:
  - JCM: Used for decades, many working systems designed using JCM
  - Statistical model: more recent analysis, more underlying data

We assume that models developed for axial insulators are valid for radial insulators

Simplified JCM analysis
Flashover probability

$$p = 0.5\left[F t^{1/6} A^{1/10} / 175 \right]^{10}$$

This predicts a high (~100%) chance of flashing at 204 kV/cm

Simplified statistical model analysis

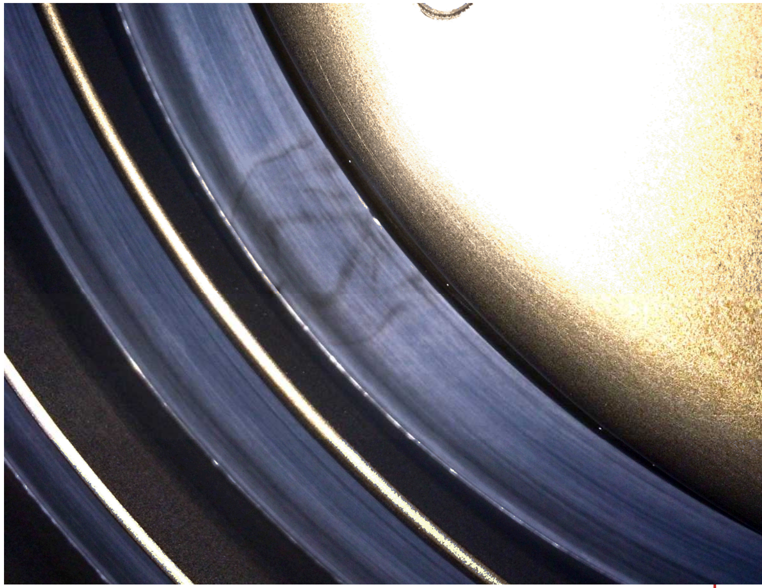
$$p = 1 - \exp\left[\left(\frac{F}{260}\right)^{10} t \frac{C \ln 2}{\left(\exp\left[\frac{.24}{d}\right]\right)^{10}} \right]$$

Predicts 11% chance of flashing at 204 kV/cm

The present experiments are 2300 cm^2 and .014 μs effective time

Agreement with the statistical model is good; the JCM model is conservative

- **Flashover models cannot consider all possible insulator conditions**
- **We believe the present experiment has better than average conditions of the insulator**
  - **Pre-shot cleaning consists of sanding entire insulator surface with 280 grit, then 400 grit, then 1000 grit silicon carbide sandpaper**
  - **The surface is wiped with lint-free cloths dampened with 190-proof ethanol**
  - **The entire surface is blown with synthetic air and inspected with a UV light**
  - **The chamber is pumped to 5×10^{-6} Torr or below with a cryo-pump**
  - **The surface is not oiled**
  - **Condition is critical: we have observed flashing initiated by mm-sized chips on the cathode triple point**



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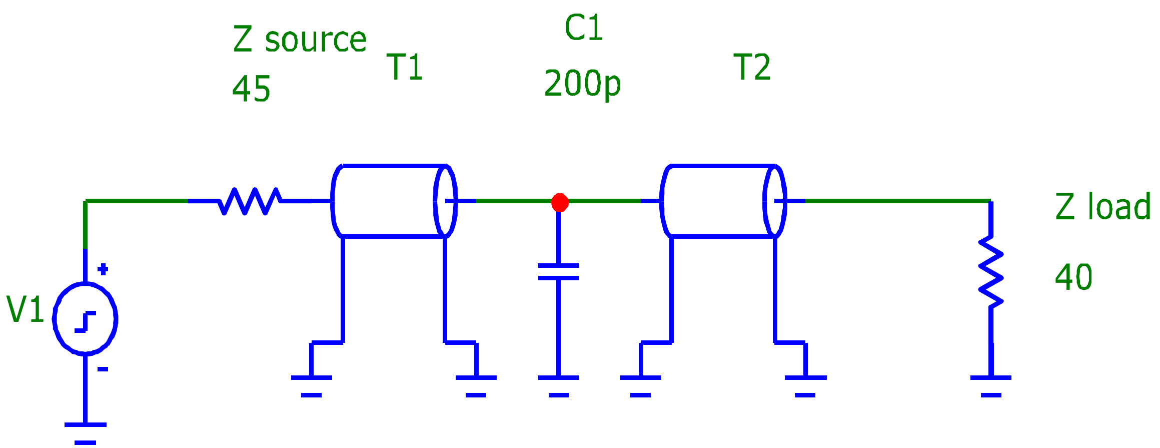
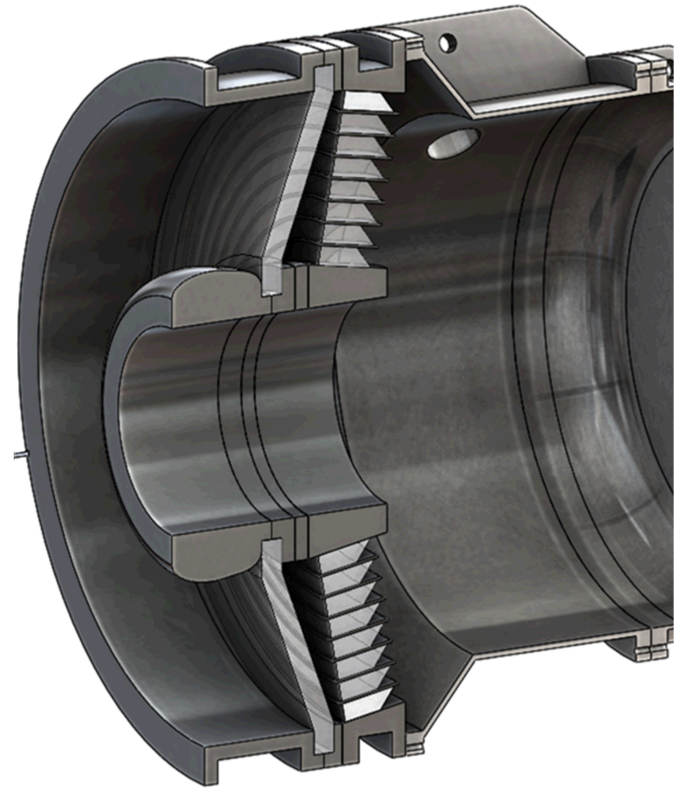
Conclusions

- We have tested a radial insulator design that is scalable to larger systems
- We have done considerable electrical testing in a realistic environment for a large system: venting, inspecting, and cleaning before every shot
- The dielectric lens distributes potential so that grading is nearly ideal
- Large numbers of tests at fields of 204 kV/cm and above without flashover

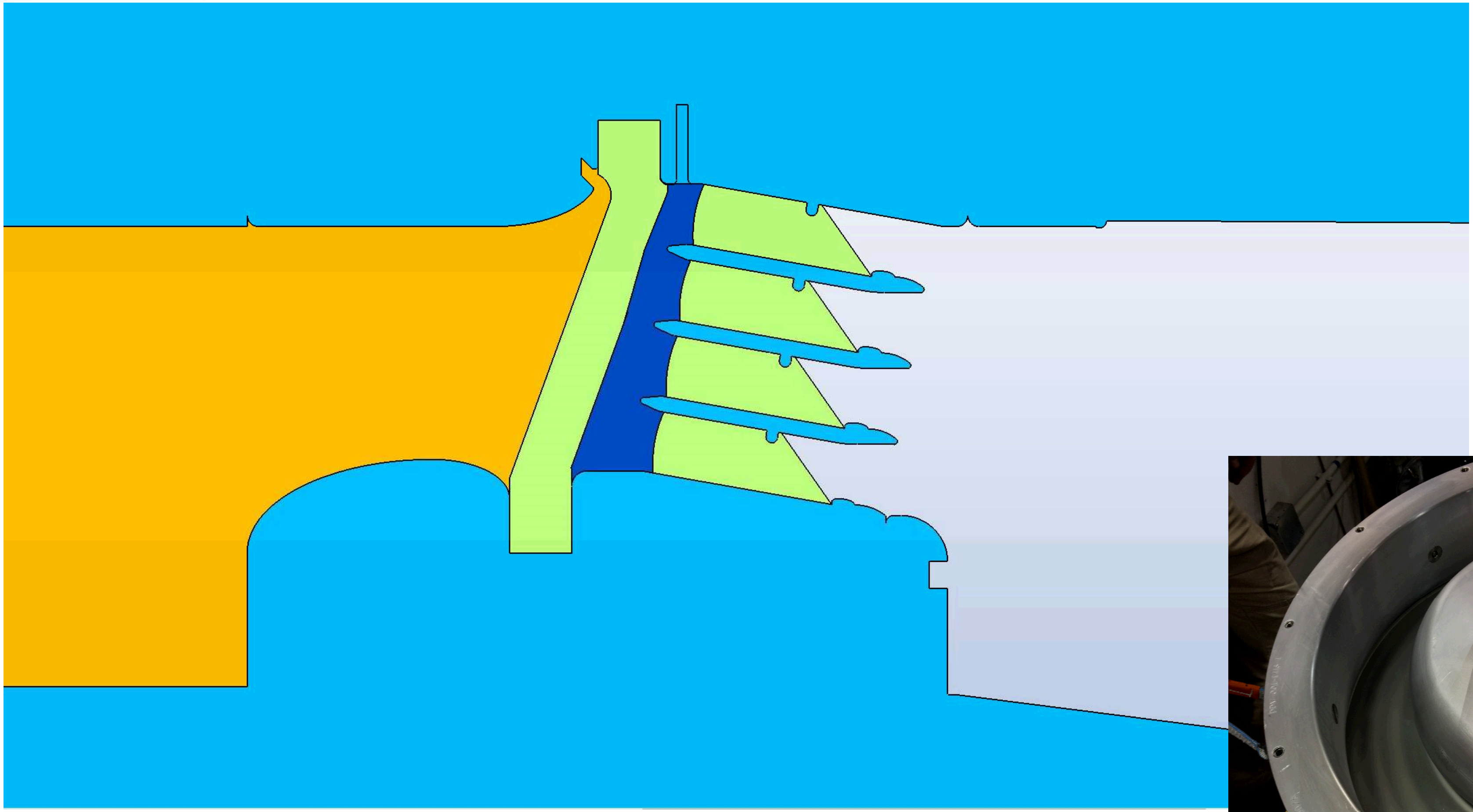
Shunt capacity of the lens could affect the pulse rise time

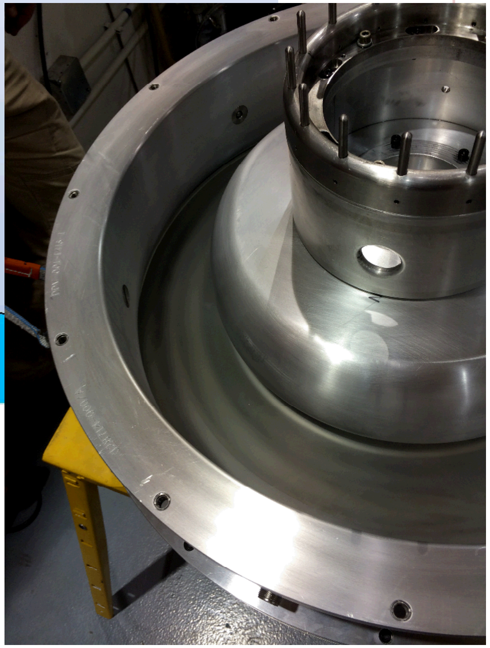
- **RC time adds in quadrature with driver pulse rise time**
  - **Present value of 6 ns is acceptable**
  - **Resistive grading to reduce RC, and pulse compensation can be used if needed**





The insulator uses a water lens to improve the voltage distribution





We can compare the flashover model to ZR data

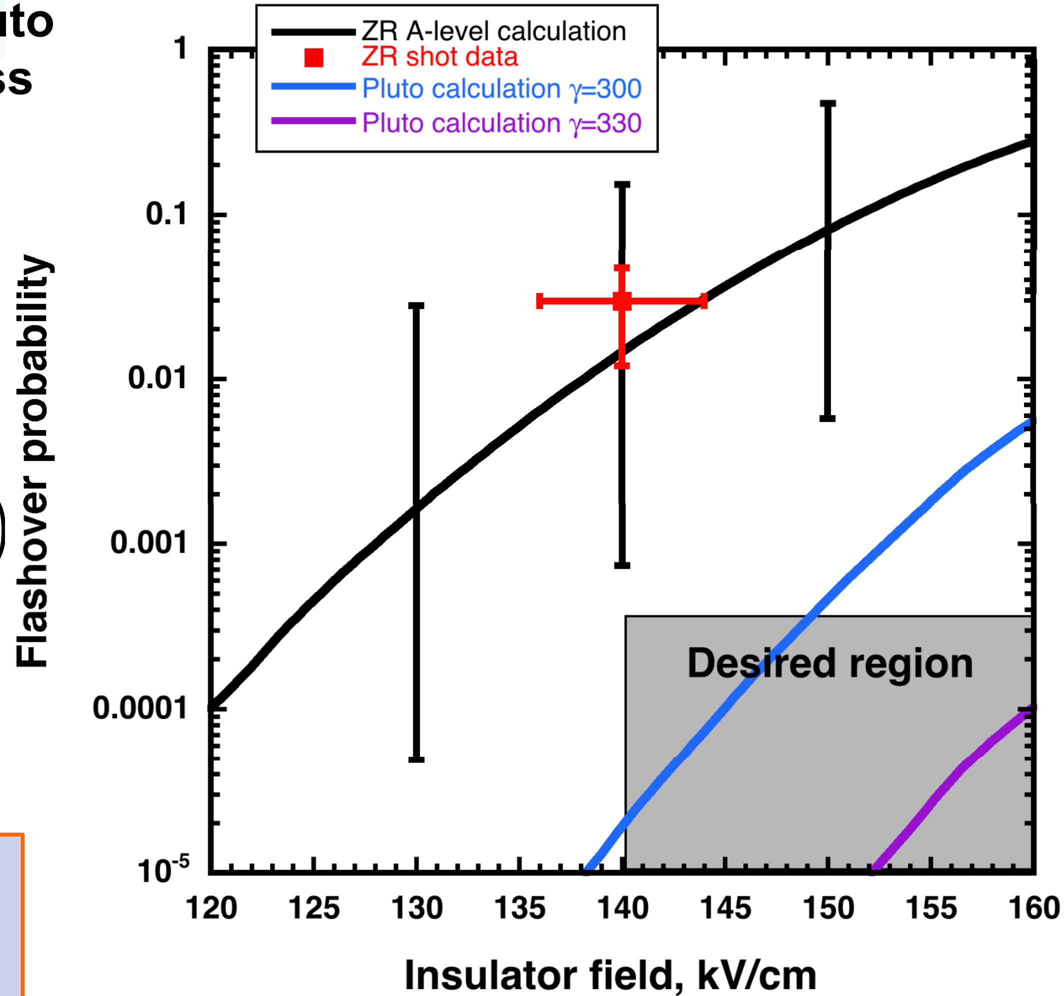
- **ZR A-level is comparable to Pluto in area, effective time and stress**

$$F(t) = n! \int_0^t \cdots \int_{t_{n-2}}^t \int_{t_{n-1}}^t \left(\prod_{i=1}^n \frac{\partial f_i}{\partial t_i} \right) dt_n dt_{n-1} \cdots dt_1,$$

where

$$f_i(t_1, t_2, \ldots t_i) \equiv 1 - \exp\left(-\frac{C}{k^\beta} \sum_{j=1}^i \left\{ \left[\int_{t_{j-1}}^{t_j} [g_j E(\tau)]^\beta d\tau \right] \right\} \right)$$

$$g_j \equiv \frac{n}{n+1-j},$$



We have considerable experience with the large Z vacuum insulator at 140 kV/cm

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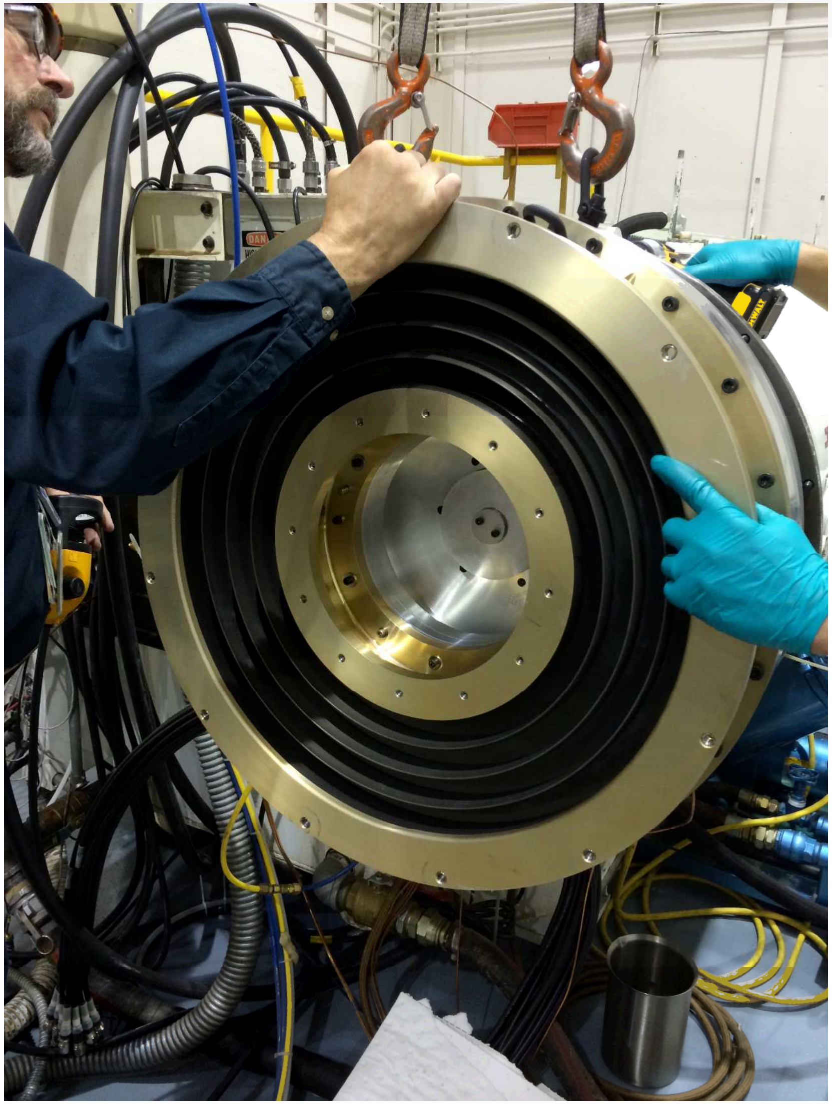
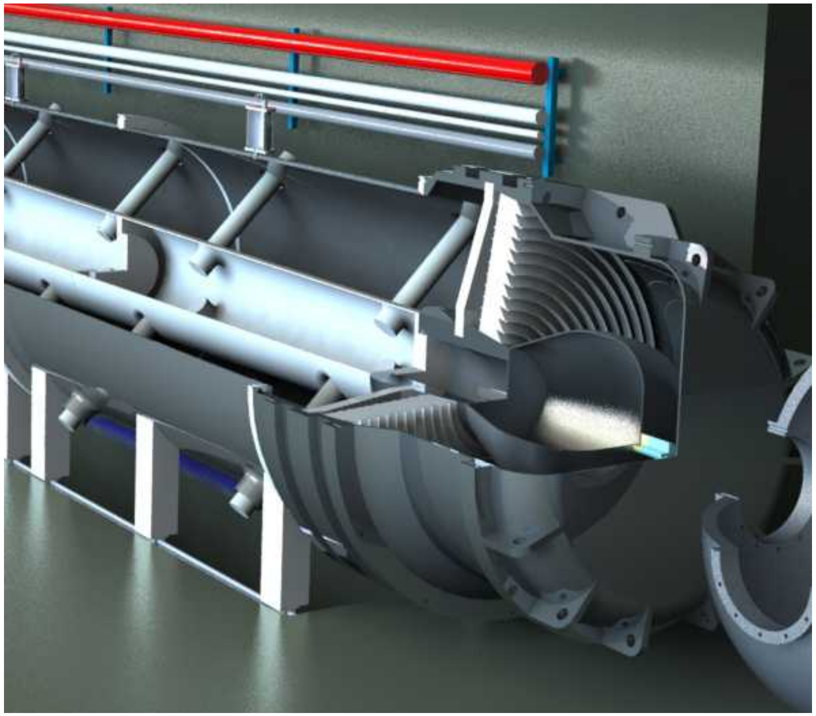
Radial oil-vacuum interface: Mechanical design

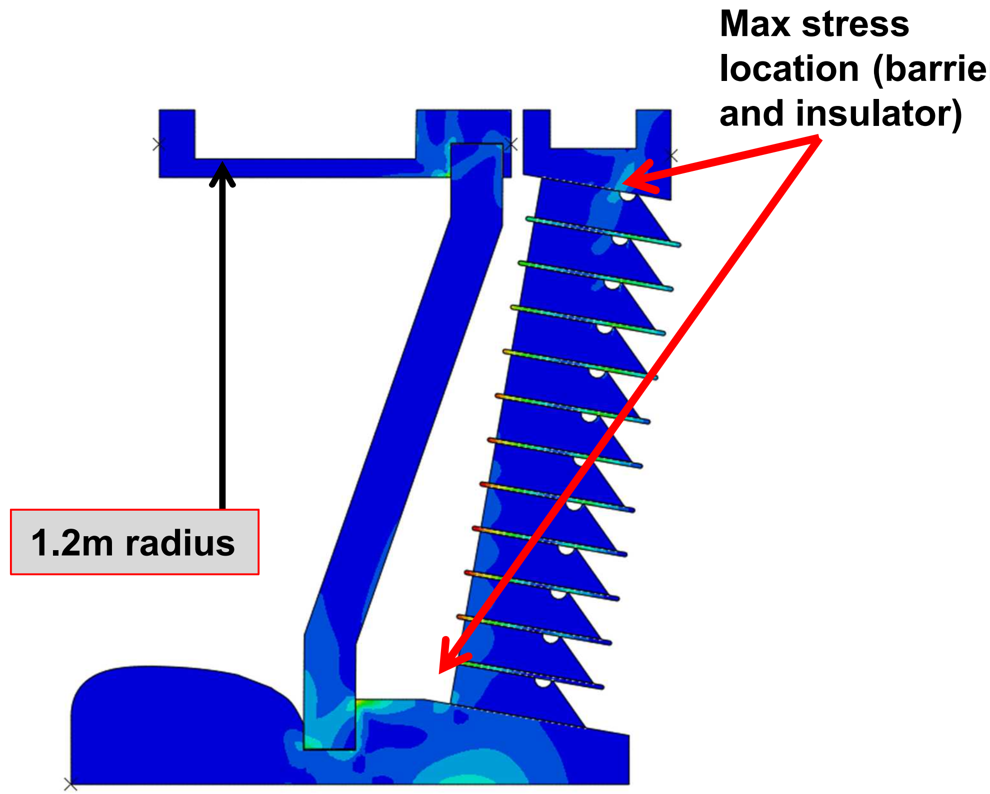
- The oil vacuum interface design is based on prior work
  - Sphinx original design (ca. 1984)
  - DARHT-1 vacuum interface
  - Airix vacuum interface
  - Sphinx scaled design (2014)



Quarter-scale radial insulator testing combined with Z data will enable an accurate assessment of the vacuum interface

Mechanical stress in the plastic is acceptable





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Operational issues

Operations and maintenance for transmission line and vacuum interface

- **Transmission line**
  - **Water: continuous resin bed deionizing and de-aerating. 1MΛ-cm adequate.**
    - **No routine drains**
  - **Oil: continual filtration and de-aeration**
    - **No routine drains**

Fluid processing is routine on Z, and could be automated

- **Vacuum interface and vacuum feed**
  - **Interface: Post-shot wet-sand and wipe**
  - **Vacuum feed: deposited metal removal, re-coat with emission inhibitor**

The insulator area is comparable to one level of the Z interface- two people, ~one hour

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