Beam
Research Program

Lawrence Livermore National Laboratory

High Gradient Induction Accelerator*

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Particle Accelerator Conference
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* Patents Pending. This work was supported under the auspices of the US Department of Energy, the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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New pulsed power technology for high current accelerators

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- **A new type of compact induction accelerator promises to increase accelerating gradients by at least an order of magnitude over that of existing machines**
- **The accelerator is based on the use of high gradient vacuum insulators, advanced dielectric materials and switches and grew out of work to develop a compact flash x-ray radiography source**
- **Research describing an extreme variant of this technology aimed at proton therapy for cancer will be presented**

Outline

- Dielectric Wall Accelerator (DWA) for flash x-ray radiography
- Critical technologies for the DWA
  - High gradient insulator technology
  - Blumlein development
  - Solid-state switch development
  - Dielectric materials
- Proton therapy concept
- Summary

DWA technology originated with a desire for more compact flash x-ray sources

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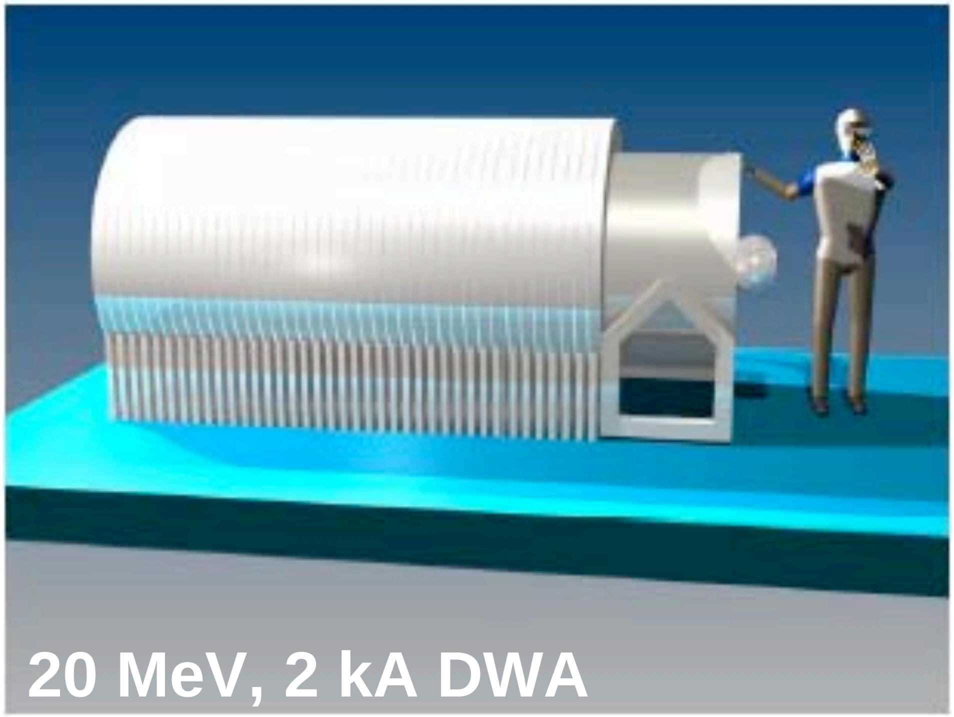
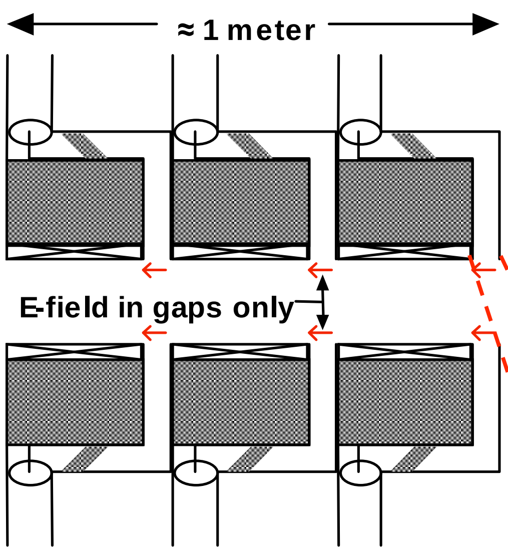


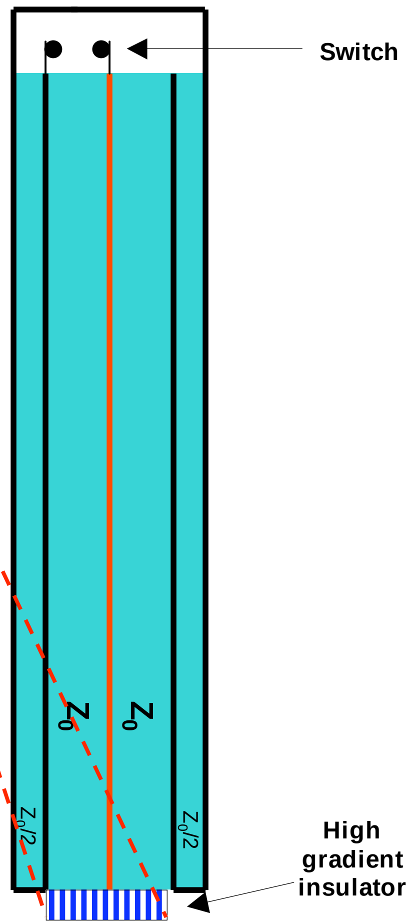
- **existing LIA sources have gradients < 0.5 MV/m**

Dielectric Wall Accelerator (DWA) incorporates pulse forming lines into a high gradient cell with an insulating wall

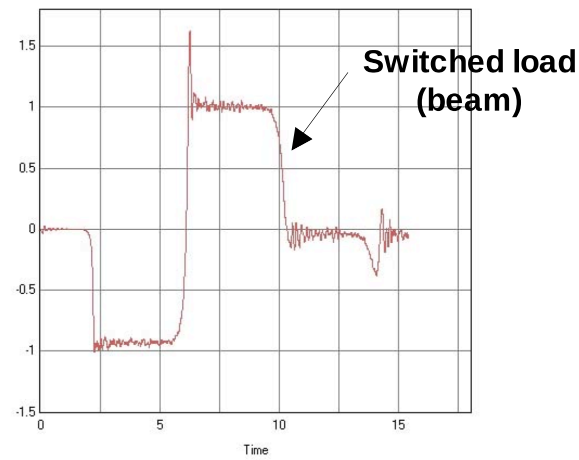


State of the Art Electron Induction Accelerator
≈ 0.3 - 0.5 MV/meter Gradient

* Patent Pending



Novel Zero Integral Pulse (ZIP) Forming Line with potential for > 10 MV/m*



Important elements for the DWA

- High gradient insulators
- PFL architecture
- Switches
- Large size dielectrics with high dielectric constant and high bulk breakdown strength

High gradient insulators (HGIs) perform 2 - 5 x better than conventional insulators*

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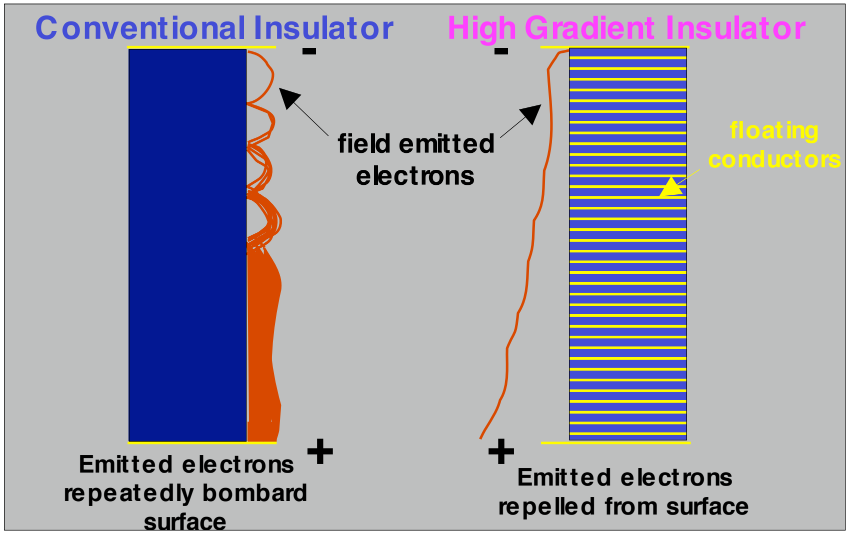
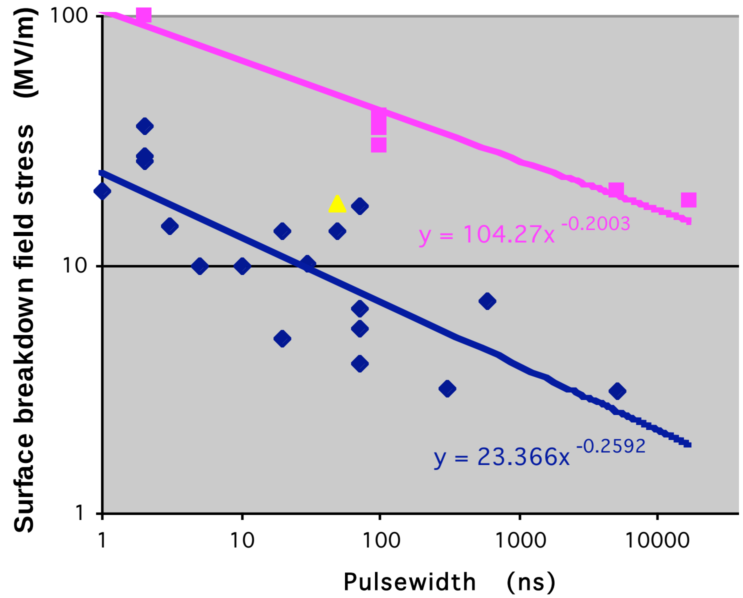
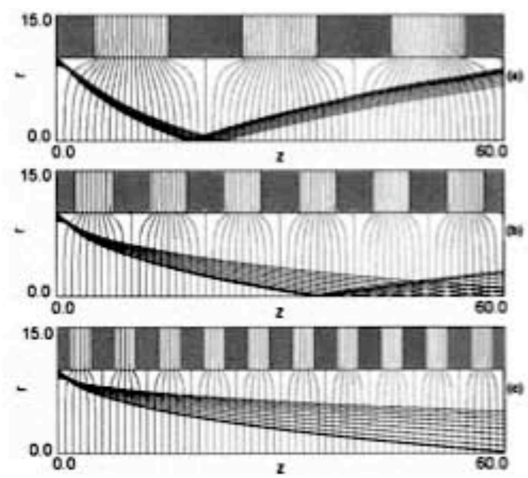




Closely spaced conductors inhibit the breakdown process

HGI structure forms a periodic electrostatic focusing system for low energy electrons

Leopold, et. al., IEEE Trans. Diel. and Elec. Ins. 12, (3) pg. 530 (2005)



* U. S. Patent No. 6,331,194

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HGIs have withstood extreme conditions

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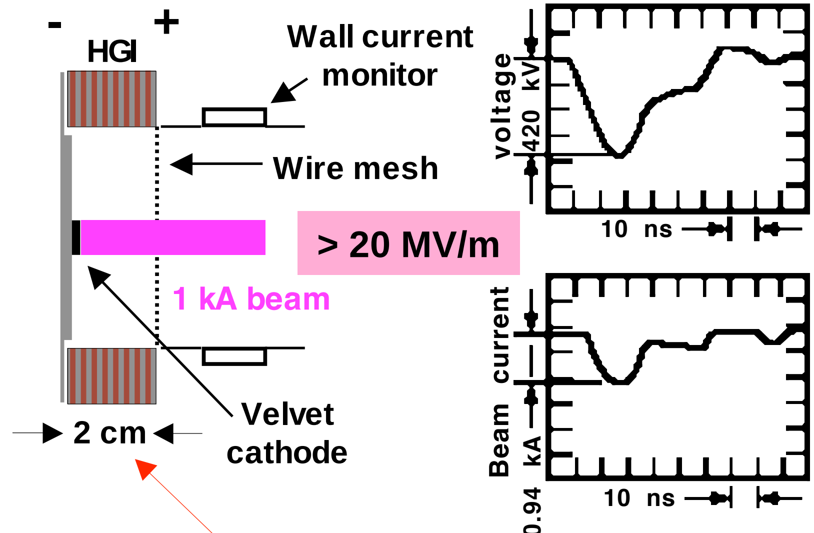
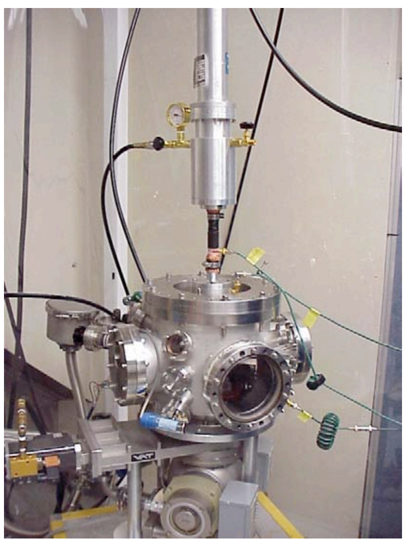
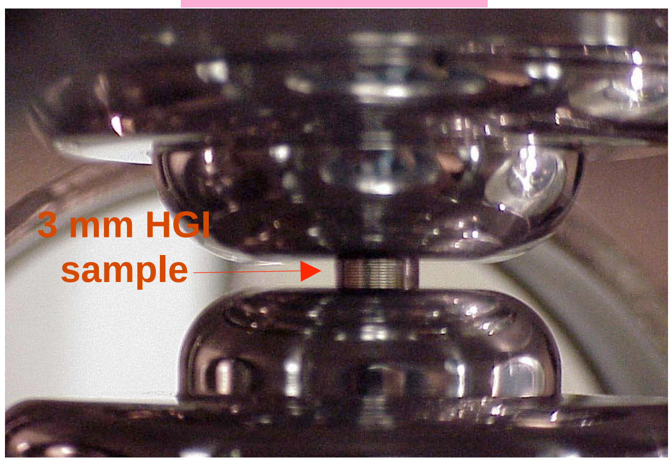
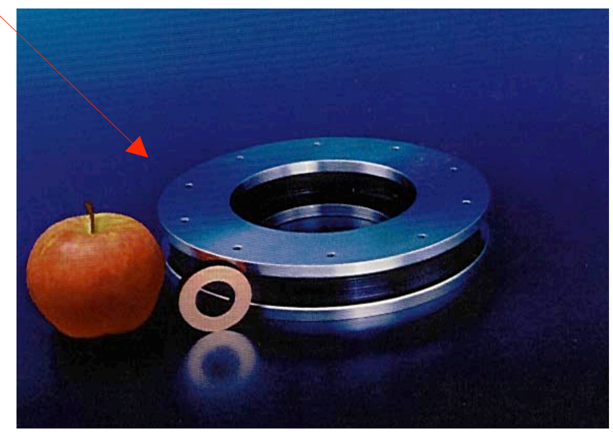
- On ETA-II (5.3 MeV, 2 kA, 50 ns pulses)
- 17 MV/m insulator gradient
- Beam dump in vicinity of insulator
- Line of sight to beam





100 MV/m, 3 ns





Oil switch/Polypropylene Blumlein has achieved 100 MV/m stress in transmission lines for 5 ns pulses

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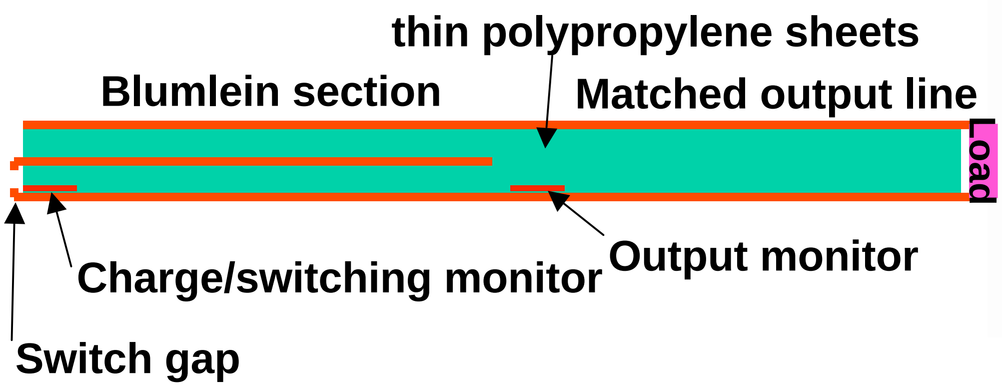
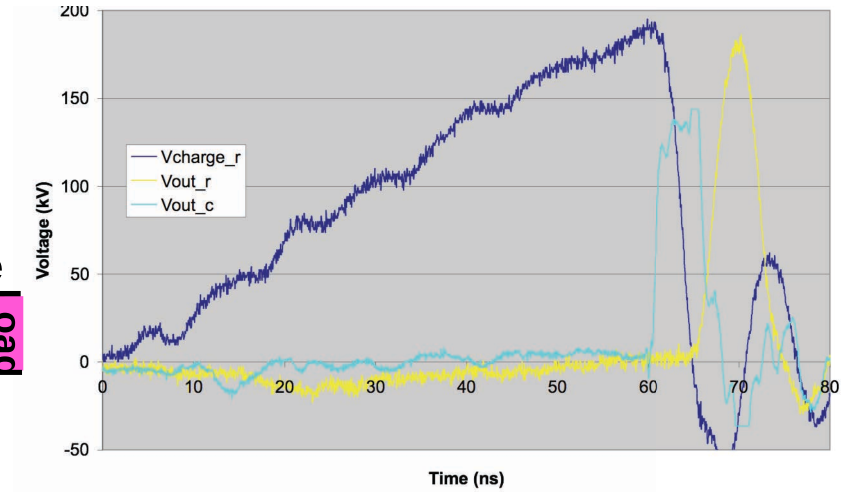
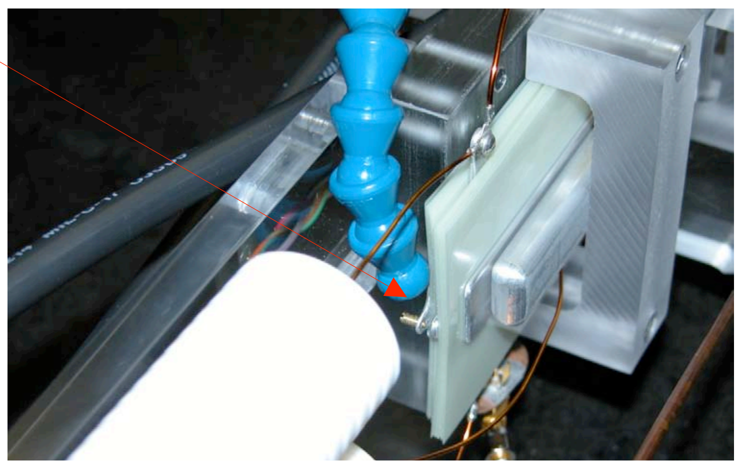
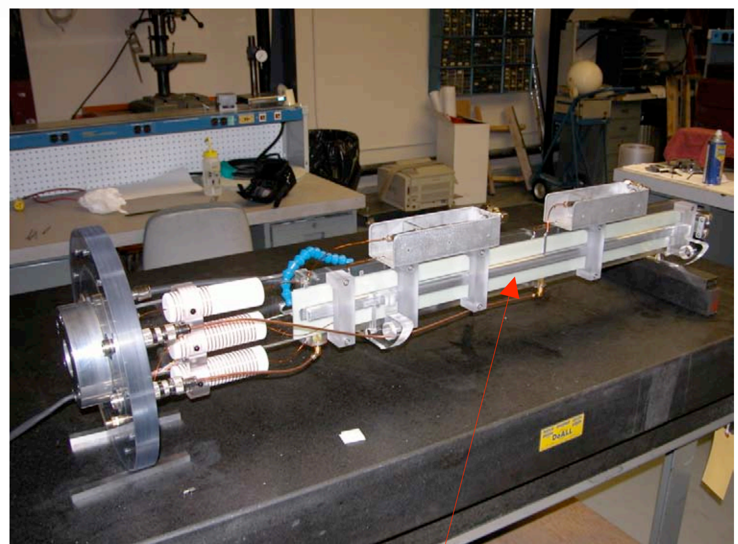
Entire assembly immersed in oil under vacuum









Blumlein

SiC photoconductive switches offer unique advantages*

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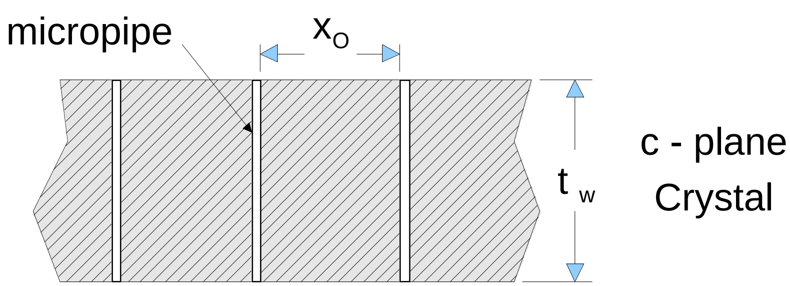

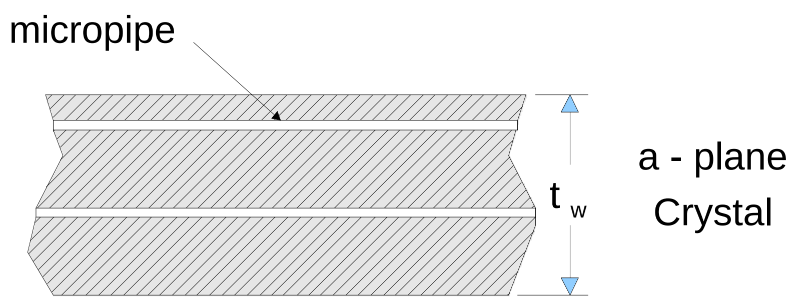

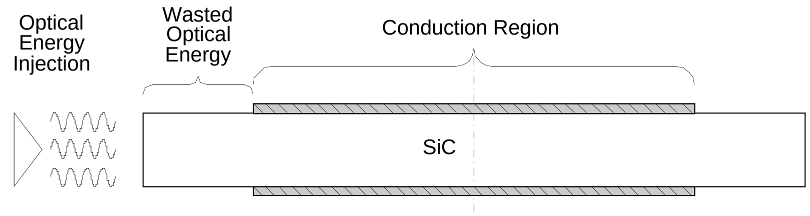

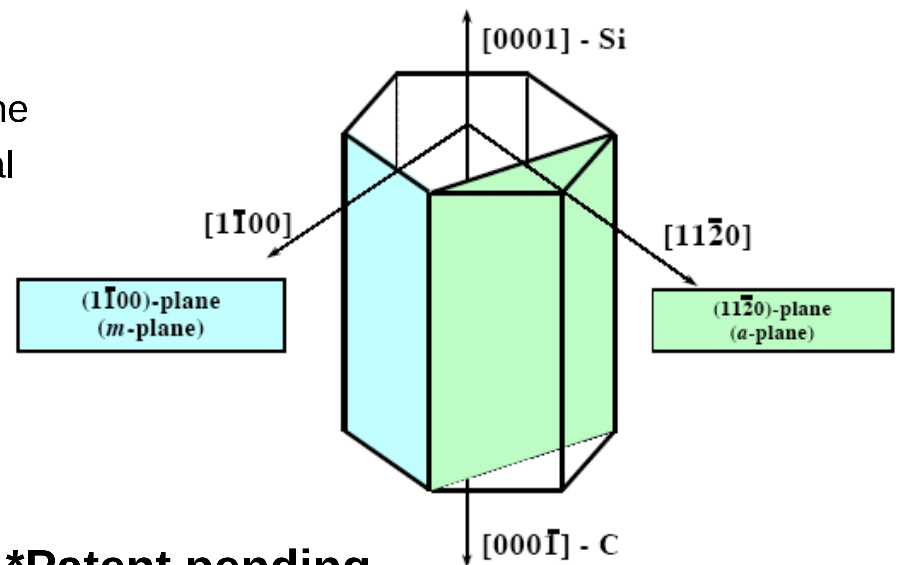

SiC offers the possibility of high voltage, high current operation at elevated temperature with long lifetime and low jitter

***Patent pending**

SiC switch demonstrates fast operation*

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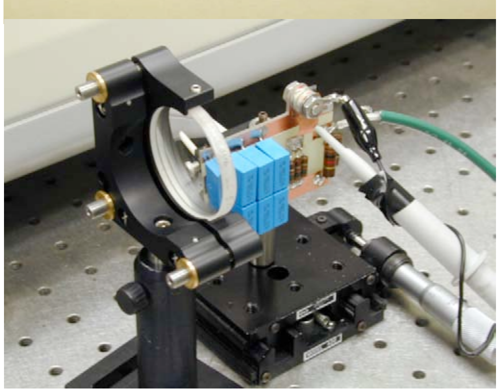
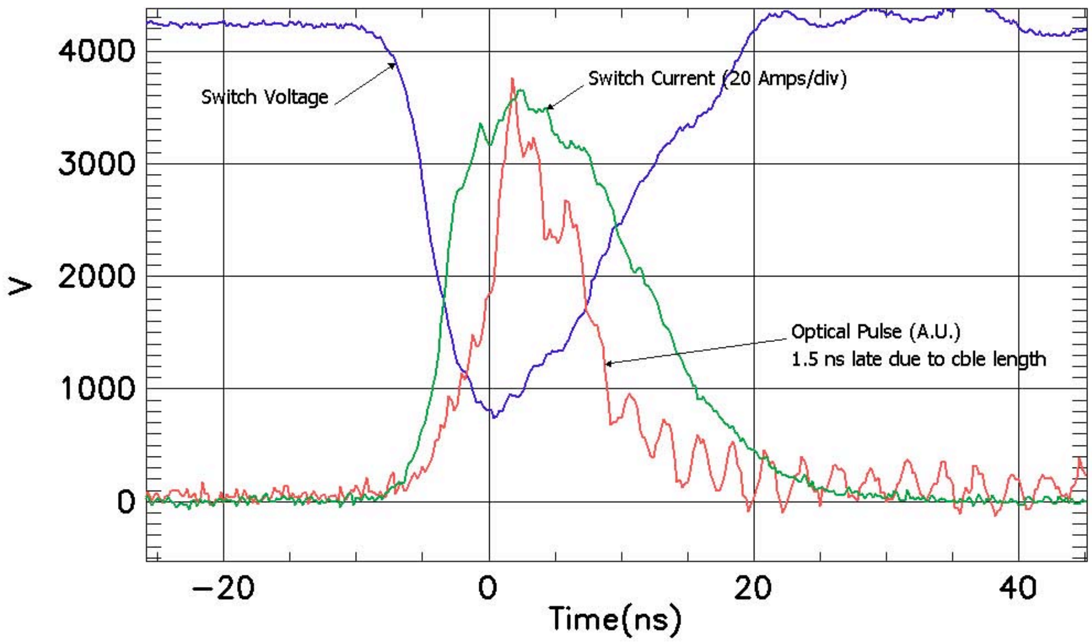
- **SiC photoconductive switch that closes AND opens promptly has been demonstrated at 27.5 MV/m gradient**

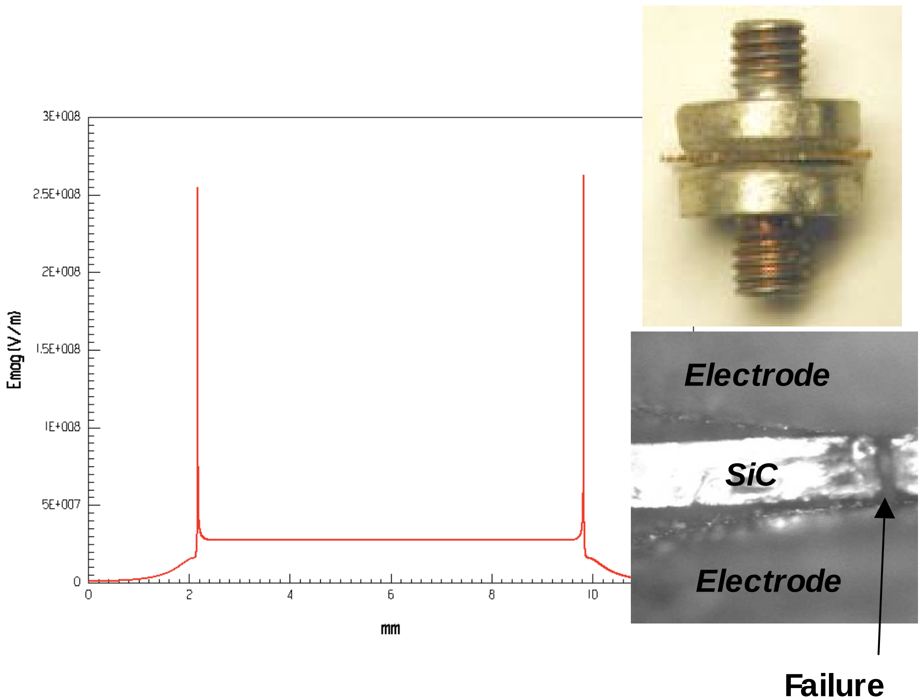




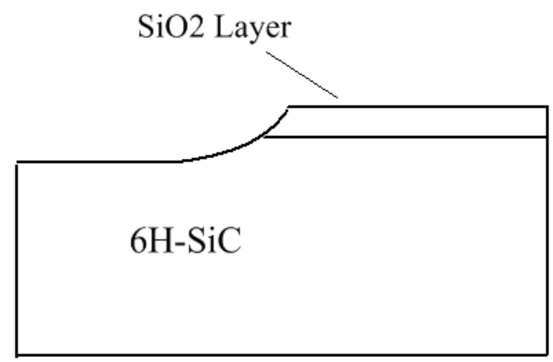
*** Patent pending**

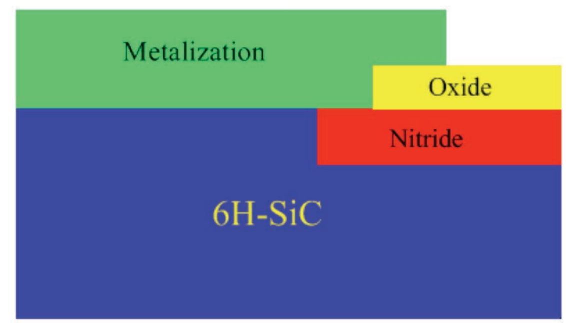
Beyond 27 MV/m, field enhancements must be managed at triple junction interface

Large enhancements are present at electrode interface



Modified electrode geometries are being pursued for increased gradients*





*** Patents pending**

A new castable dielectric is one of the possible materials for a DWA*

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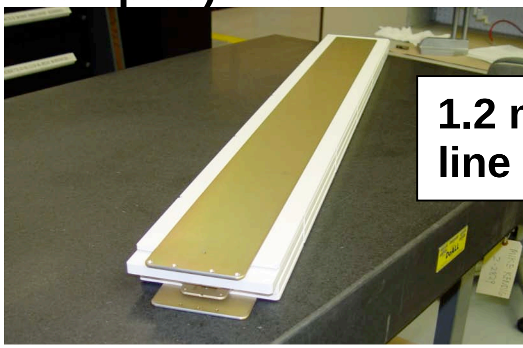
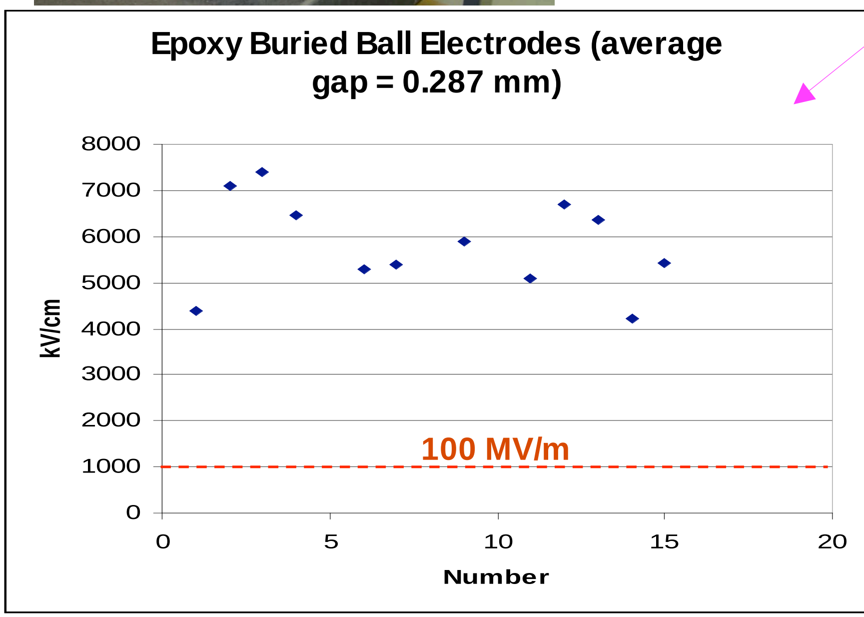
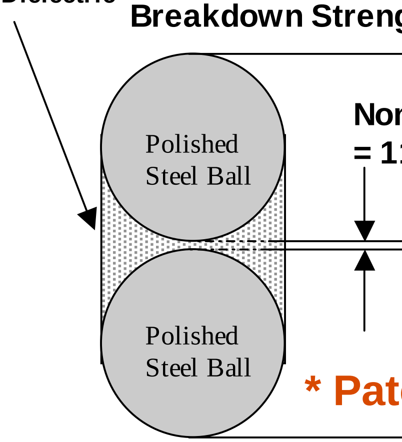
Cast dielectric has high bulk breakdown strength > 400 MV/m (small samples) and can have epsilons from ≈ 3 up to ≈ 50 for transmission lines



1.2 meter cast line (ε_r=10)





*** Patent pending**

Embedded electrodes can withstand 100 MV/m

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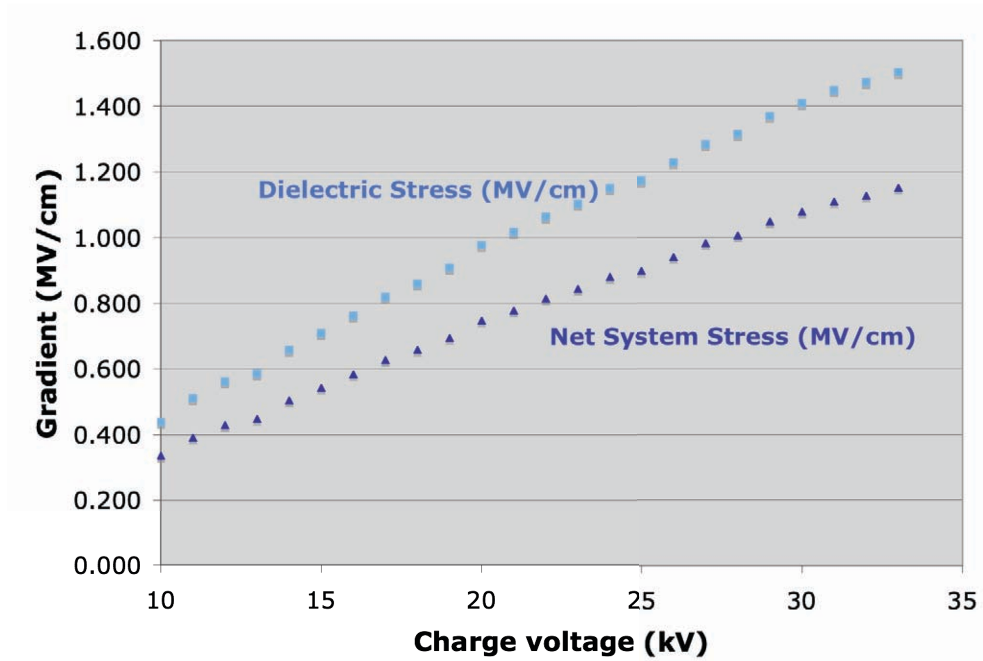

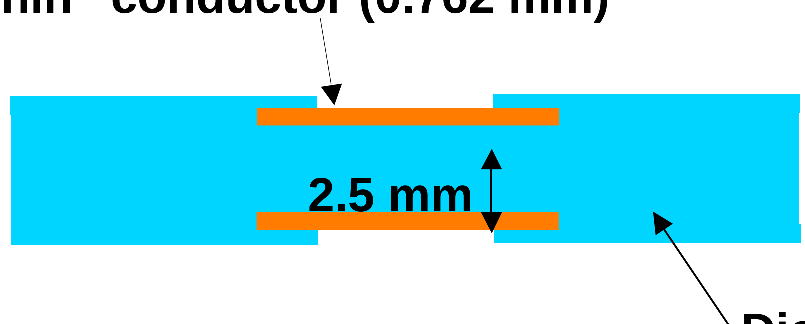

- **System gradient > 100 MV/m (counting electrode thickness)**
- ***Performance for a thinner (SiC) configuration should be better***

Novel ZIP line stack will form the heart of a high gradient cell

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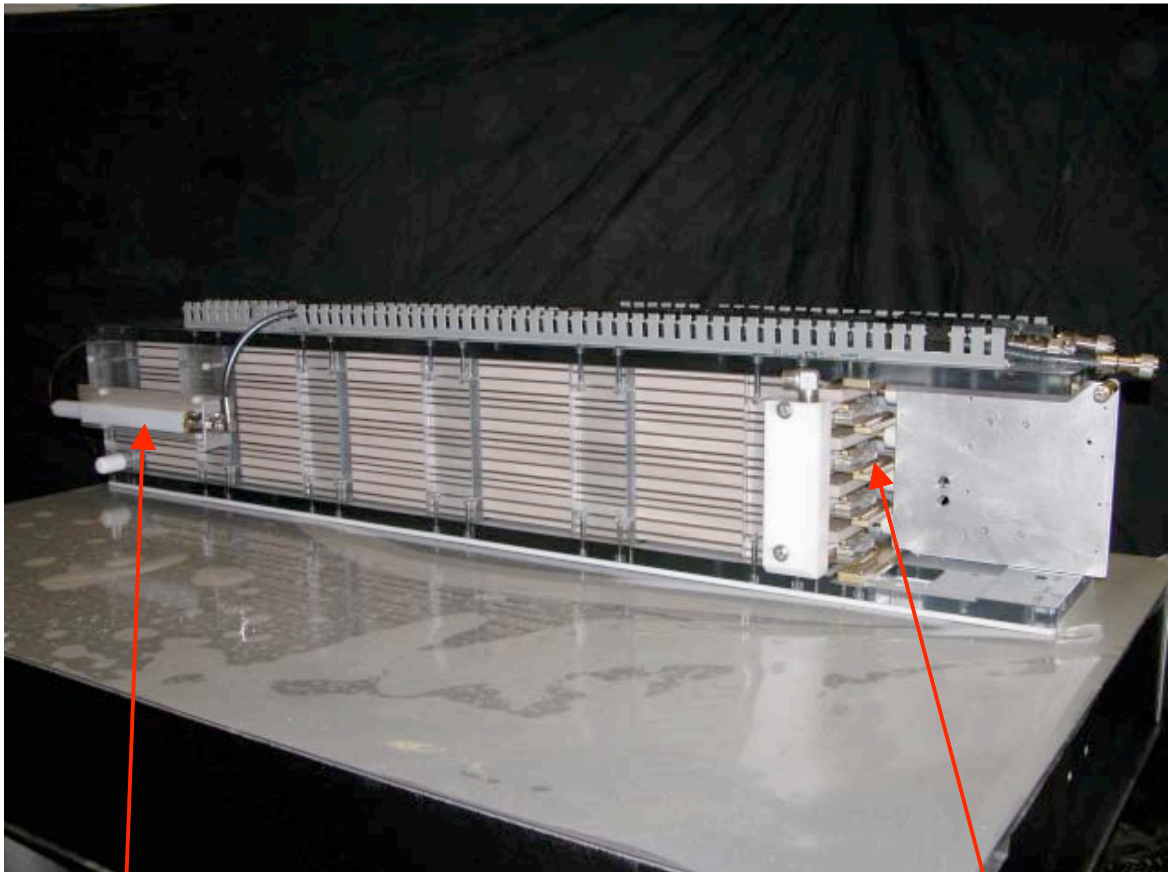
Duroid stack used for initial tests



Output Monitor **Oil Spark-gap Switches**

- **4 ZIP lines (300 kV each)**
- **RT Duroid ε_r=10 (1st stack < 200 kV each)**
- **cast dielectric ε_r=10 (2nd stack for cell)**
- **oil switches**
- **25 ns pulsewidth**
- **1.2 meters long**
- **0.2 meters high**
- **0.1 meters wide**

- **1.2 MV total, 10 kA into a matched load (power delivered to a matched load = 12 GW, energy delivered = 300 J)**

All four Duroid ZIP lines are switching within the required interval

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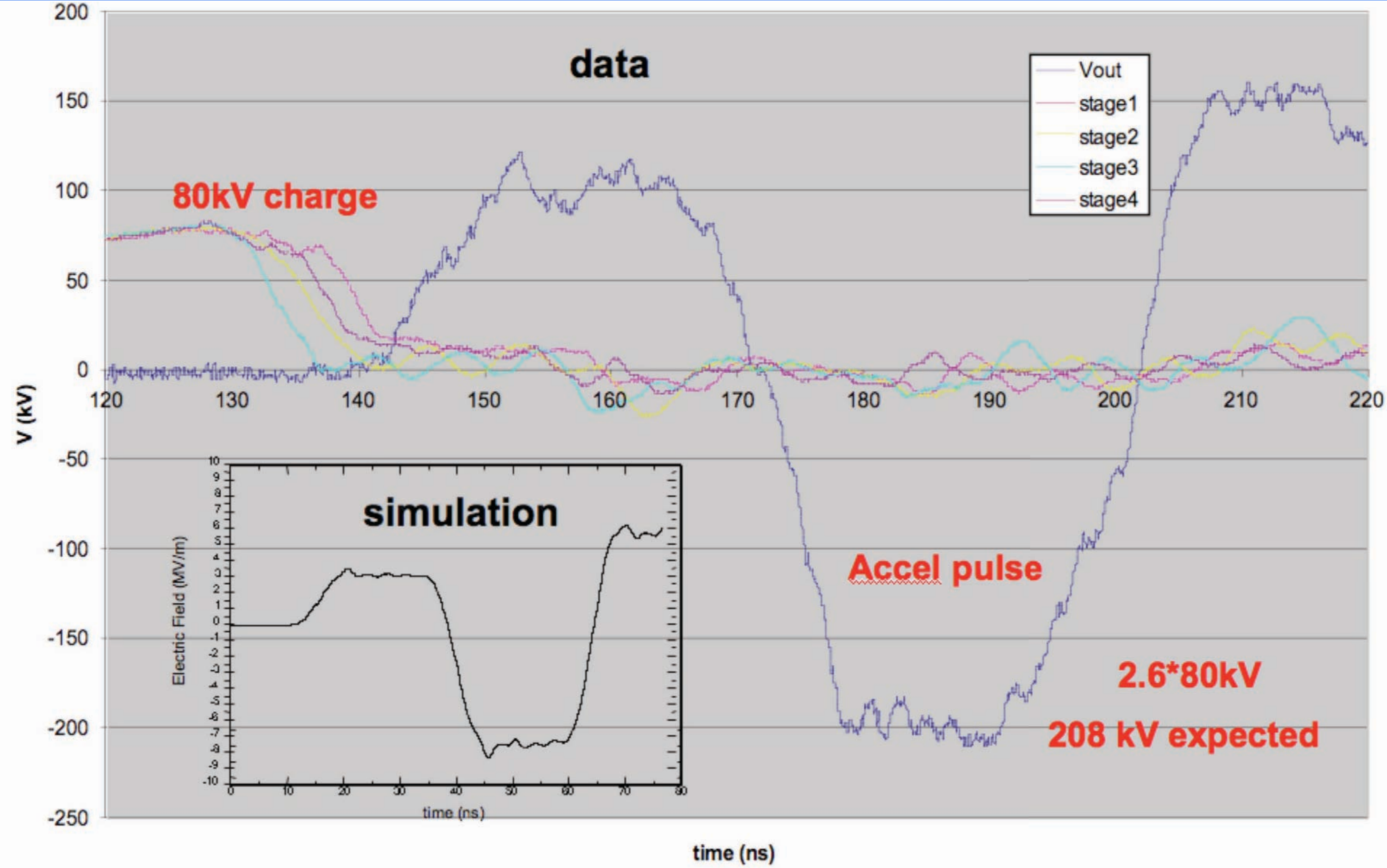

Stack of 4 cast ZIP lines will be used for beam tests on ETA-II

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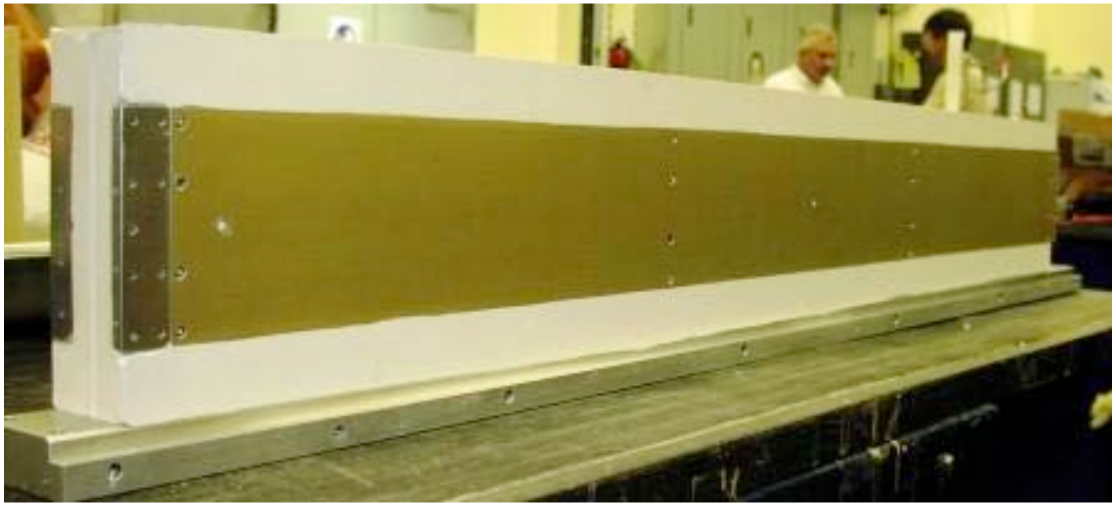
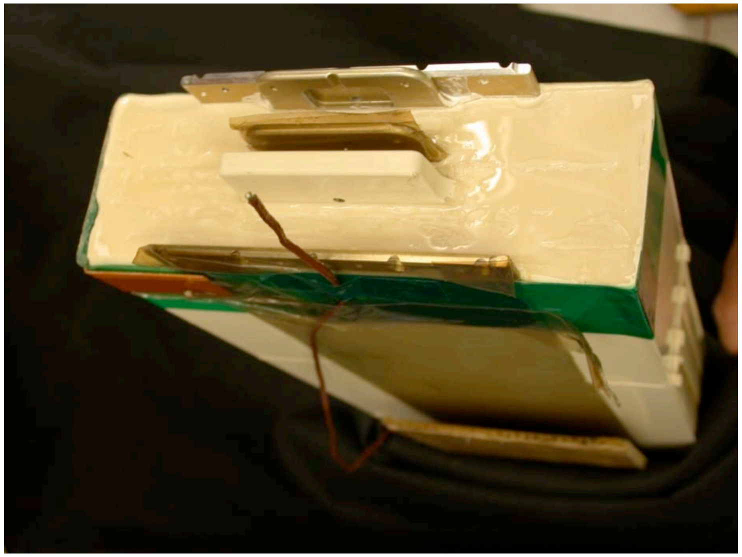
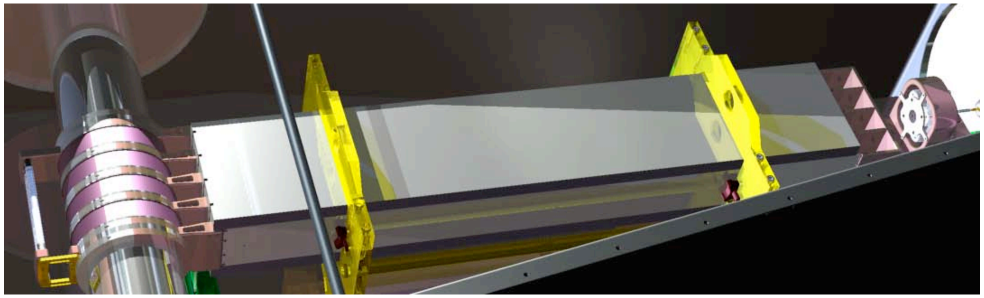


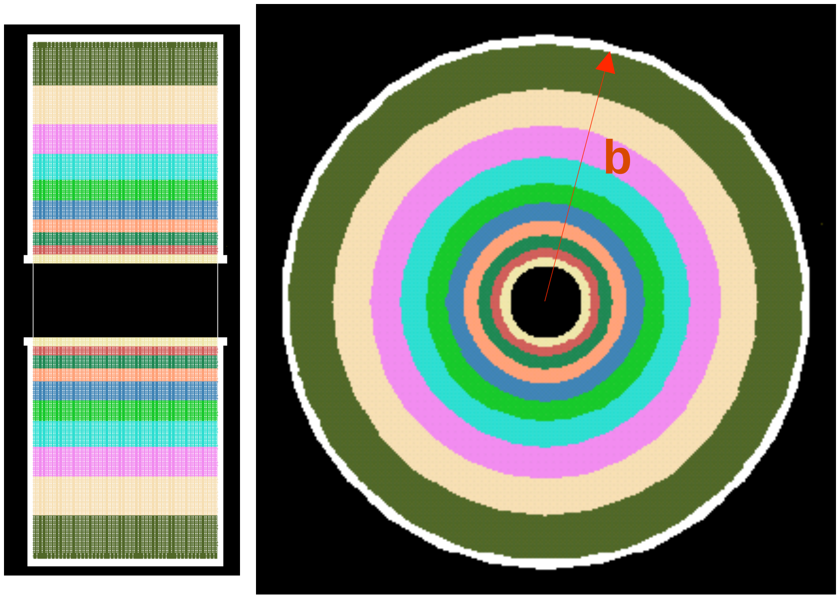
- First cast dielectric ZIP line (ε_r = 10), 25 ns pulse
- Design charge voltage = 300 kV
- Passed qualification test at 165 kV charge





CAD Image of 1.2 MV cell for ETA-II Testing
Beam load will be 2 kA

Cast dielectric opens up new possibilities for cell architectures*

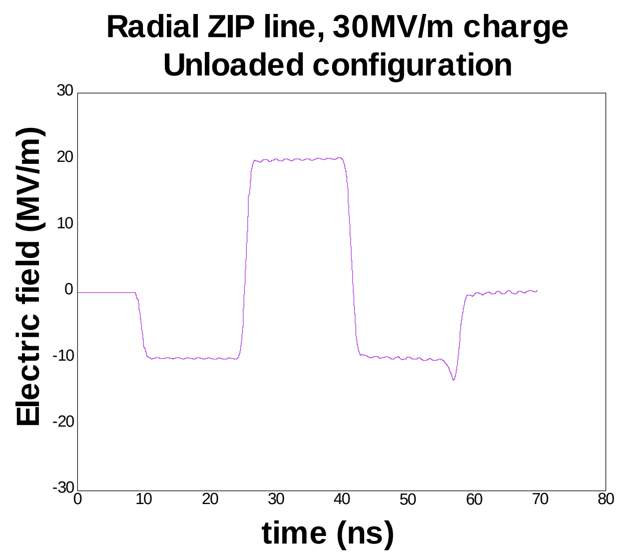


Constant impedance radial ZIP line

$$Z(r) = \frac{60w(r)}{r}\sqrt{\frac{\mu(r)}{\varepsilon(r)}}$$

example: vary relative ε only or relative μ only

$$\varepsilon(r) = \varepsilon_{\min}\left(\frac{b}{r}\right)^2 \qquad \mu(r) = \mu_{\max}\left(\frac{r}{b}\right)^2$$



- varying ε, μ and width of lines with radius such that Z(r) is constant results in distortionless transmission

* Patents pending

We have been investigating the potential application of the DWA to cancer therapy

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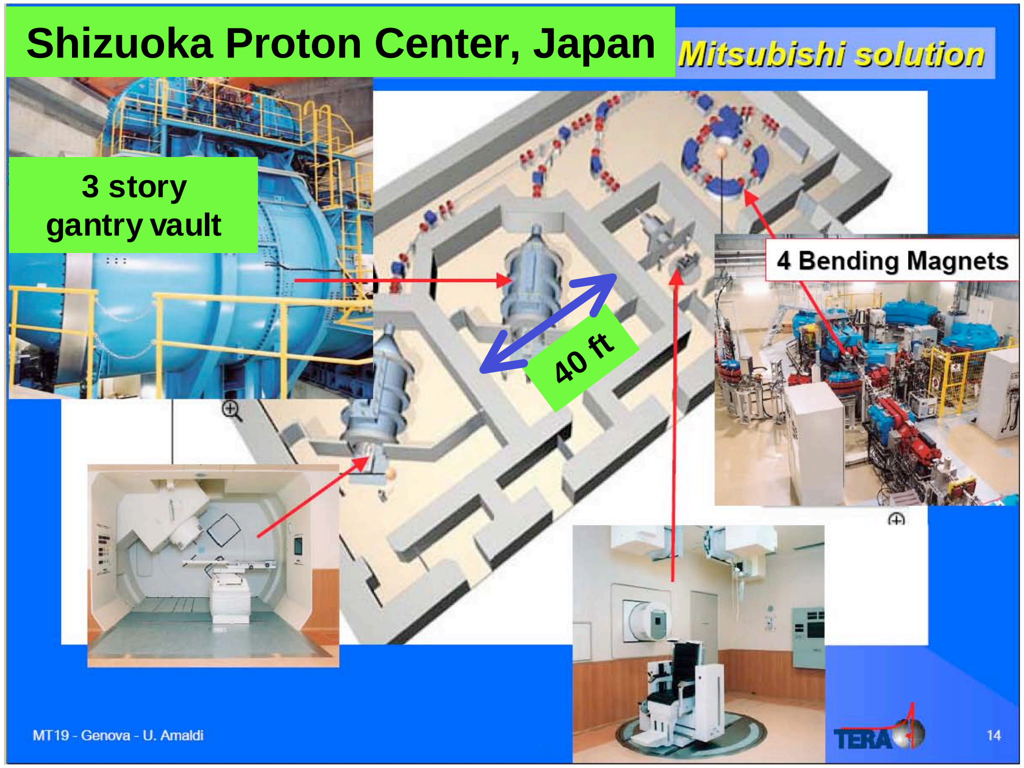
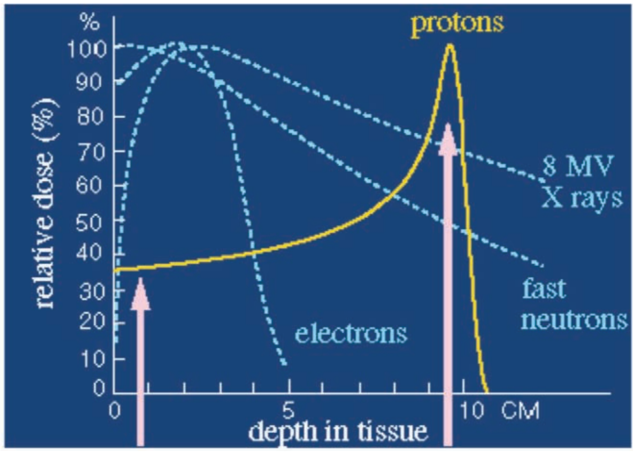
- **Bragg peak minimizes damage to normal tissue**
  - **Requires 70 - 250 MeV at ≈ ten nanoamperes average current**
- **Current space requirements preclude use in most hospital facilities; large capital investment required**





X-ray treatment machines fit in a single room - <u>this is our goal for a compact proton machine</u>

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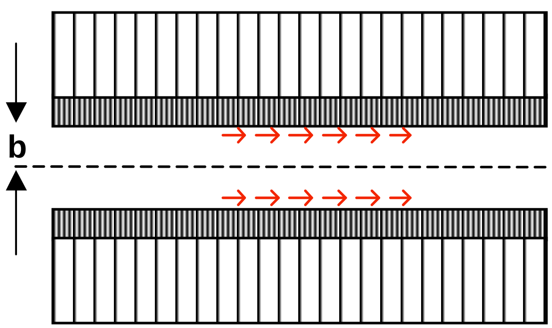
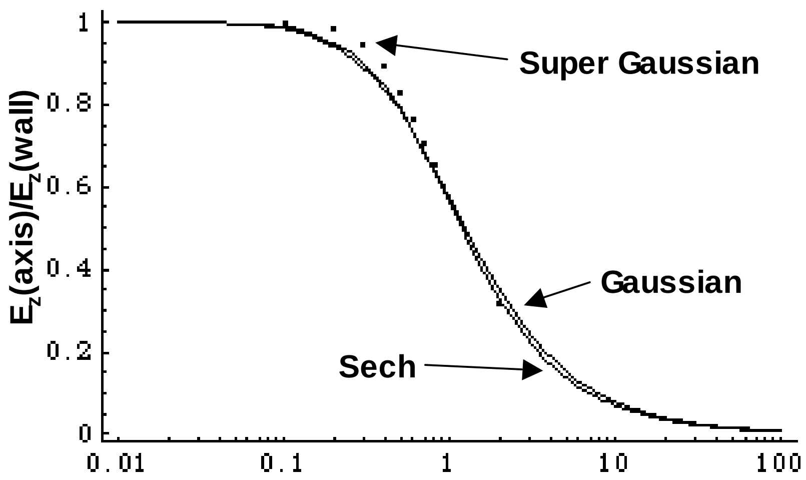
DWA can be used in the single pulse traveling wave mode*

HGI characteristics imply that the highest gradients will be attained for the shortest pulses

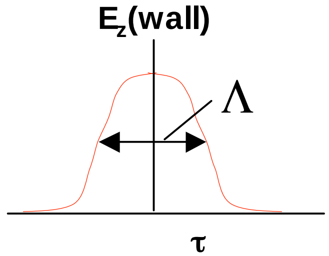
Along the wall $E_z(r,t,z) = E_z(r,\tau)$

$$\tau \equiv t - z/u$$





$$\theta \equiv \frac{b}{\gamma u \Lambda}$$



Λ = full width at half maximum
u = speed of wall excitation
γ = Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - u^2/c^2}}$$

A high on-axis gradient is maintained as long as θ ≤ 0.3
This implies pulses in the range of a fraction to several ns

***patent pending**

There are several viable accelerator architectures*

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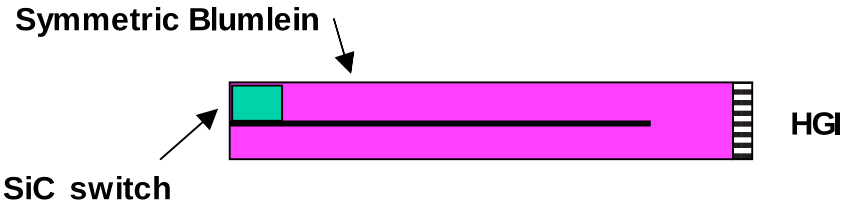

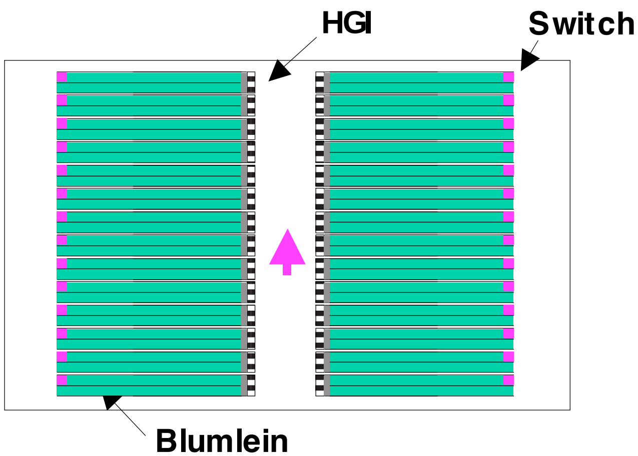

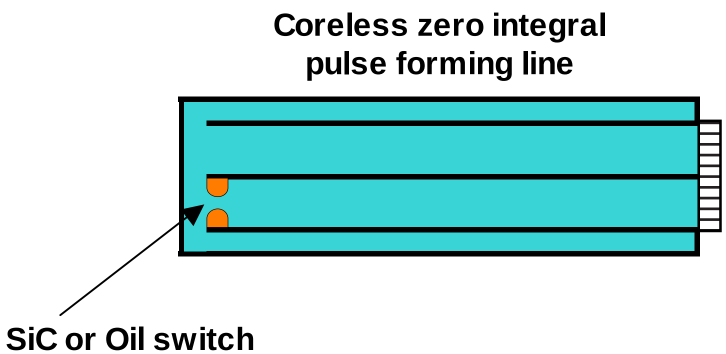

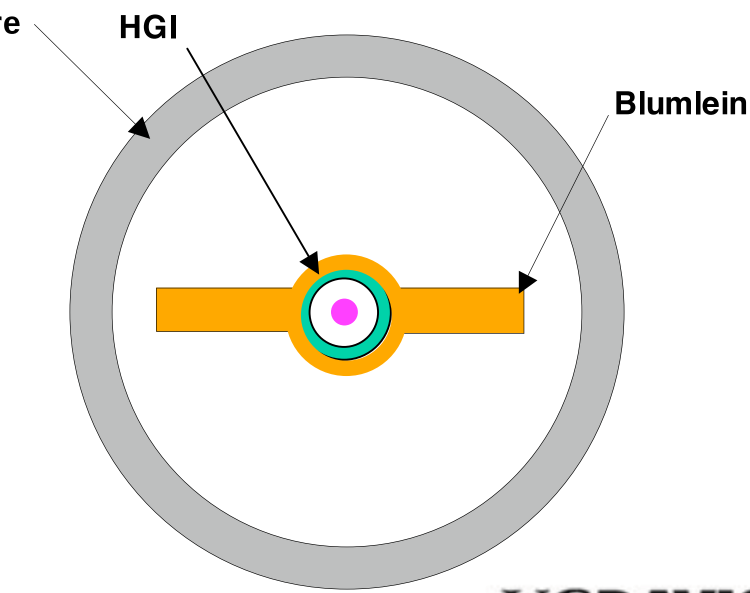

* Patents pending

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DWA can be used in the single pulse traveling wave mode*

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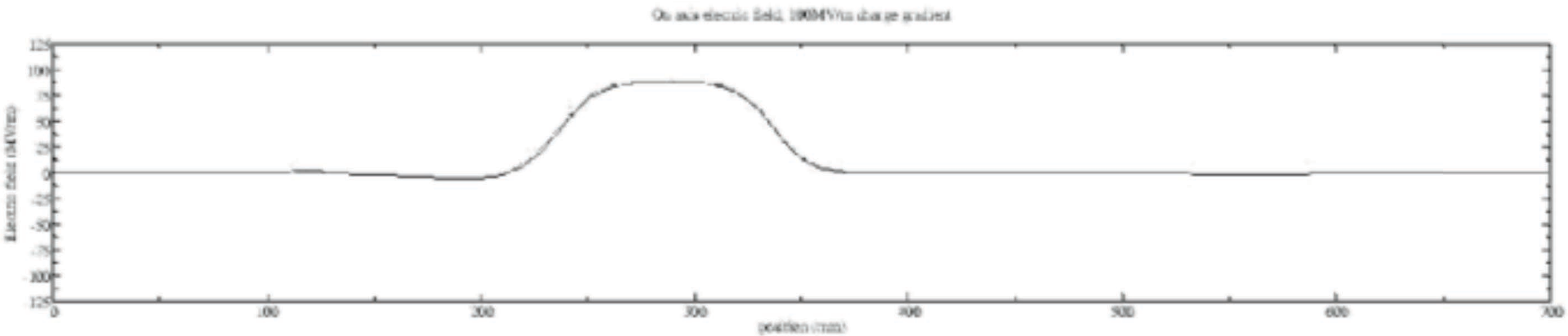
Longitudinal Electric Field Plot



***patent pending**

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Novel source and electrode system provides great flexibility*

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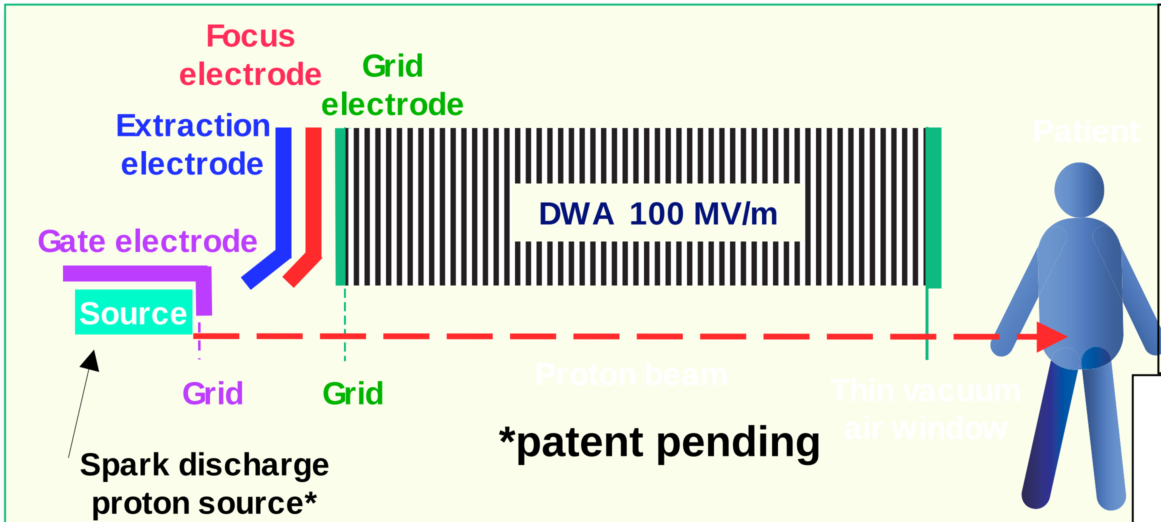

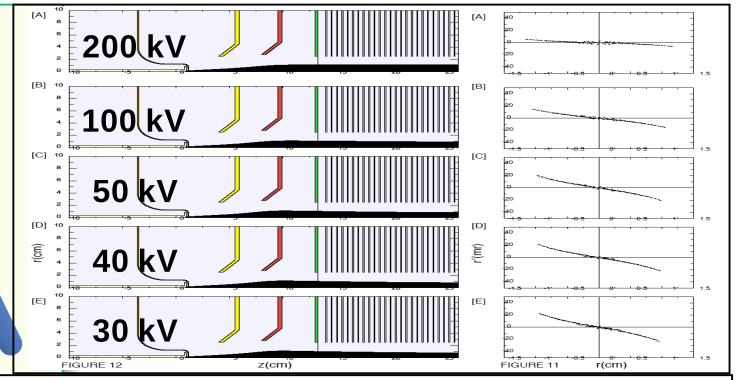

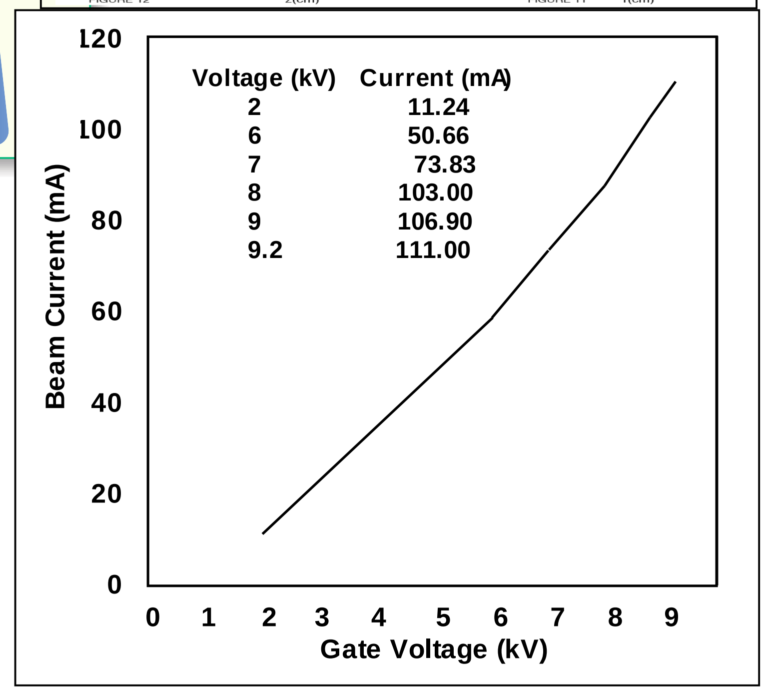

- **The DWA proton accelerator uses only electric focusing fields for transporting the beam and focusing on the patient**
  - — **Wide range of spot sizes (2 mm - 2 cm diameter) can be obtained for 70 - 250 MeV proton energy - varied on each pulse**
  - — **Variable beam current on each pulse**
  - — **Variable beam energy on each pulse**

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Compact proton radiotherapy system concept*

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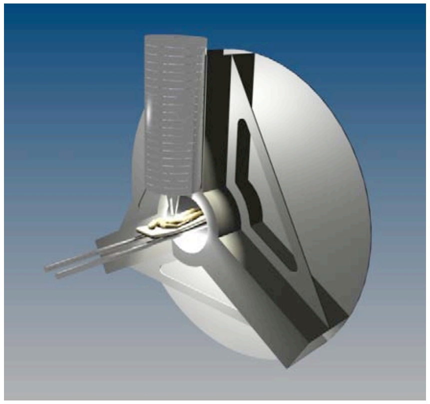
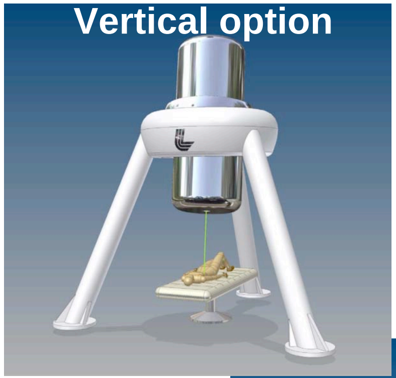
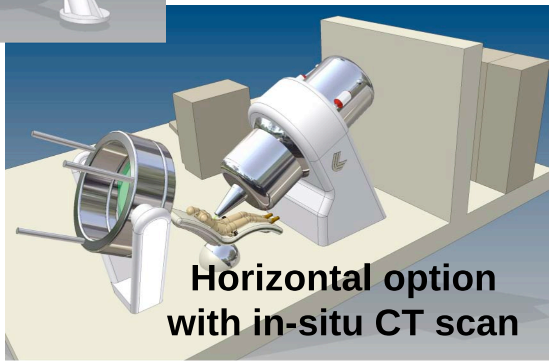
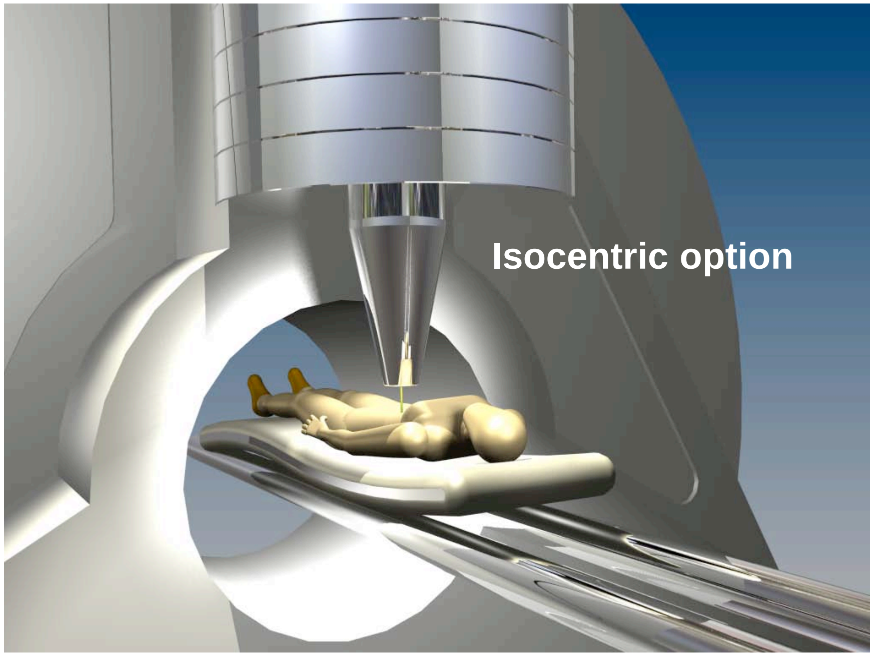
- Pencil beam can be *mechanically* scanned in x and y
- Flexible dose delivery via pulse-to-pulse variable energy and intensity
  - Energy range 70 - 250 MeV
- Multiple patient delivery configurations possible to accommodate available space









* Patent pending

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We are working with Tomotherapy, Incorporated to develop a compact proton DWA

TomoTherapy™ INCORPORATED

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- System will provide CT-guided rotational IMPT
- Goal is to fit machine in a standard linac radiation vault
- The beam intensity, spot size and energy can be varied from pulse to pulse without the use of any beam intercepting methods
  - No range shifting wedges or scattering masks
- Tomotherapy has licensed the DWA technology from the Lawrence Livermore National Laboratory and has a Cooperative Research and Development Agreement (CRADA) with LLNL

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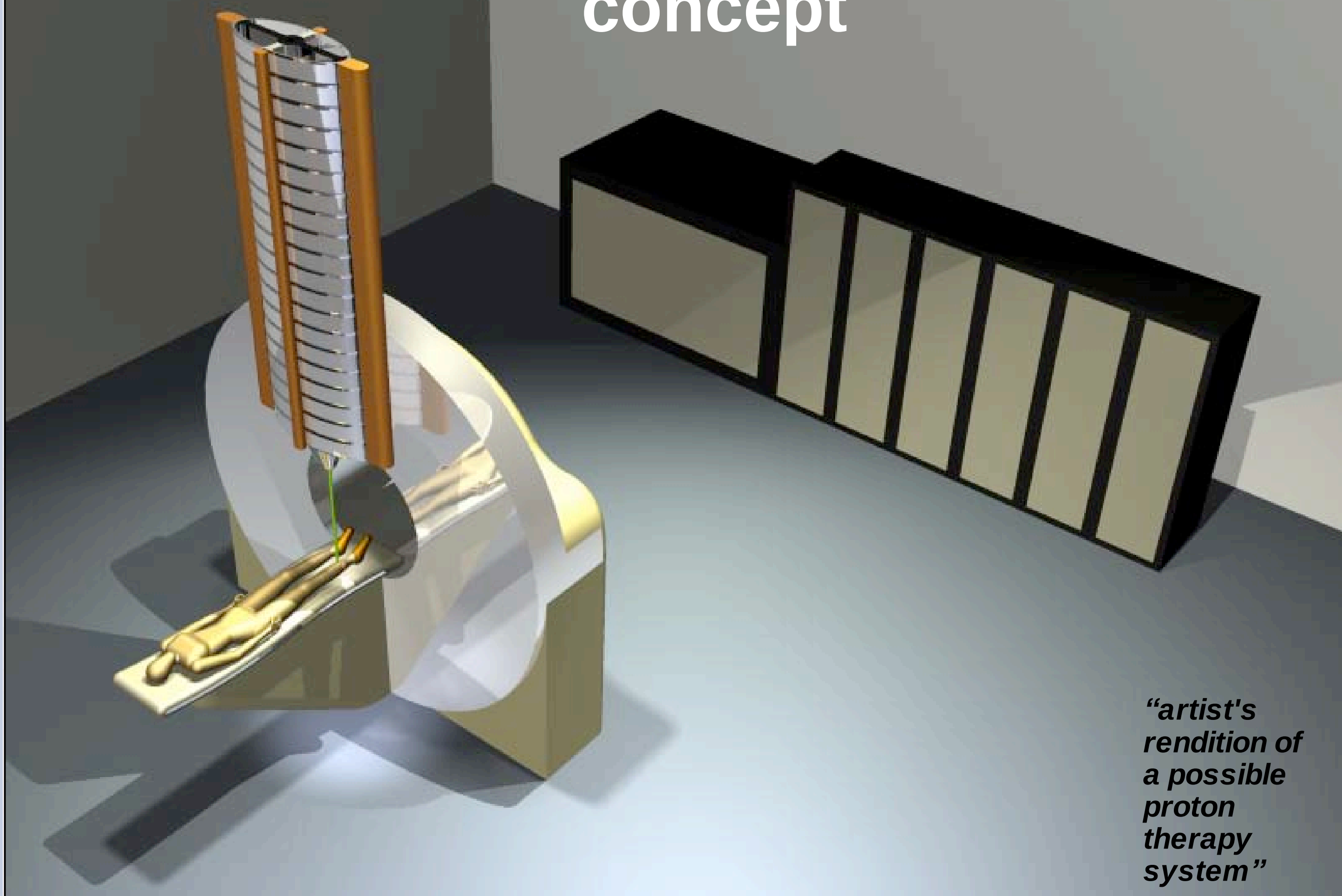
Compact proton radiotherapy system concept



Near term plans for proton accelerator development

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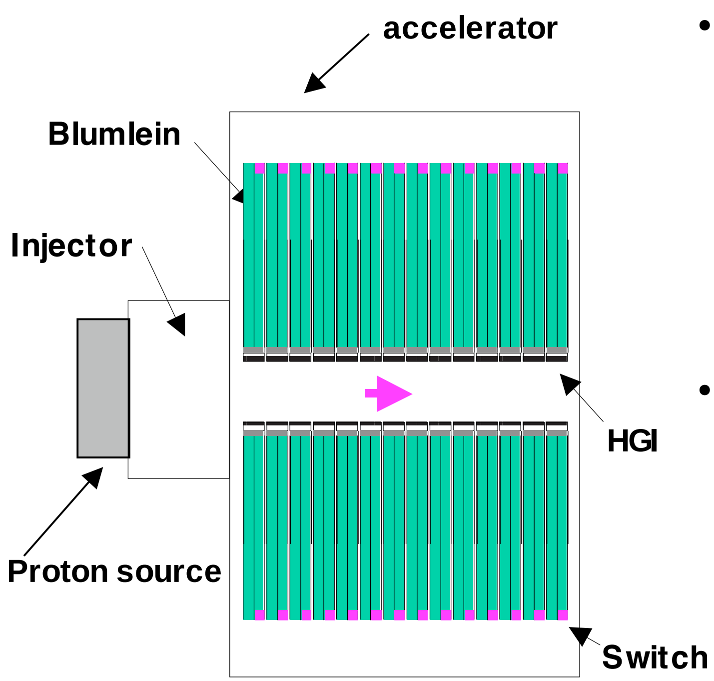
- We are working towards development of a subscale prototype over the next 18 months
  - A small length of accelerator sufficient to verify the accelerator architecture and HGI performance with SiC switches



- New SiC switches over next 6 months
  - Optimized dopant levels to lower "on" resistance and improve quantum efficiency
  - High voltage packaging
- Subscale prototype
  - Integrate components into a proof-of-principle device
  - Electron demonstration in 6 months
  - Proton demonstration within 18 months

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Summary

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- DWA promises to dramatically increase the accelerating gradient of high current accelerators
- Good progress is being made on the technologies needed for the DWA
  - Closing switches
    - Oil gaps (> 100 MV/m stress)
    - SiC photoconductive switch (27.5 MV/m stress)
  - Pulse forming line dielectric materials (> 400 MV/m)
  - High gradient vacuum insulators (up to 100 MV/m)
- Compact proton therapy accelerator concept has been described

DWA posters at PAC '07

Beam Research Program
Lawrence Livermore National Laboratory

- D. Blackfield, et al., "Injector Particle Simulation and Beam Transport in a Compact Linear Proton Accelerator", TUAS057
- S. Nelson, et al., "Electromagnetic Simulations of Linear Proton Accelerator Structures using Dielectric Wall Accelerators", TUPAS058
- Y.-J. Chen and A. Paul, "A Compact Accelerator for Proton Therapy", TUPAS059
- B. Poole, et al., "Particle Simulations of a Linear Dielectric Wall Proton Accelerator", TUPAS060
- L. Wang, et al., "Electromagnetic and Thermal Simulations for the Switch Region of a Compact Proton Accelerator", TUPAS061
- J. Harris, et al., "Vacuum Insulator Studies for the Dielectric Wall Accelerator", WEPMS014