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Recent Advances in Radiographic X-ray Source Development at Sandia*

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Xian, China
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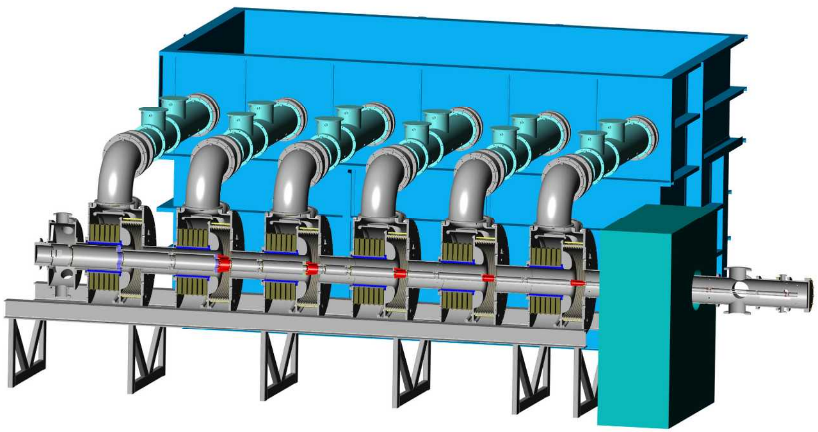

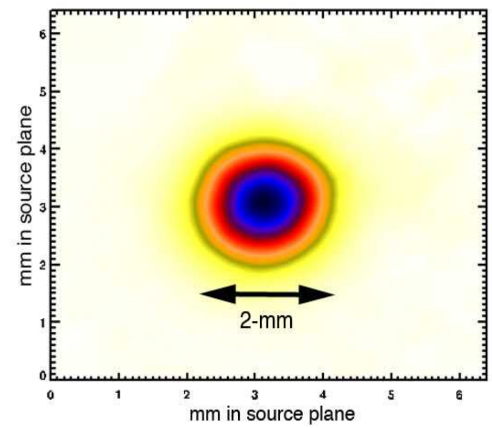

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Sandia National Laboratories

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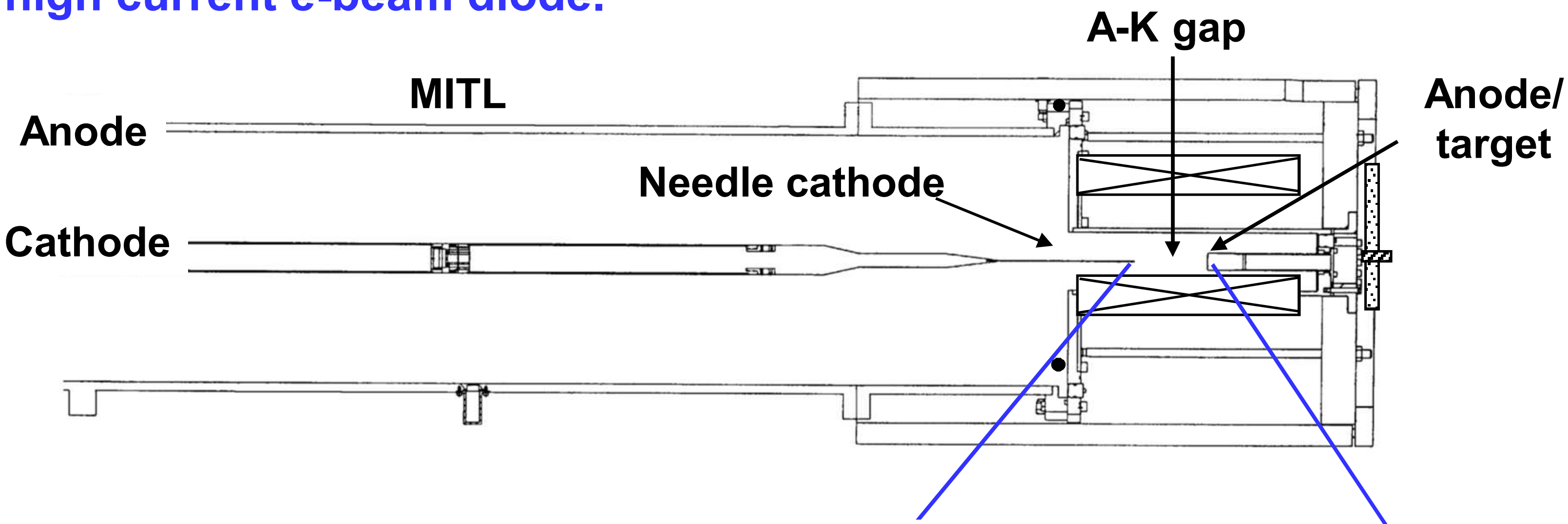
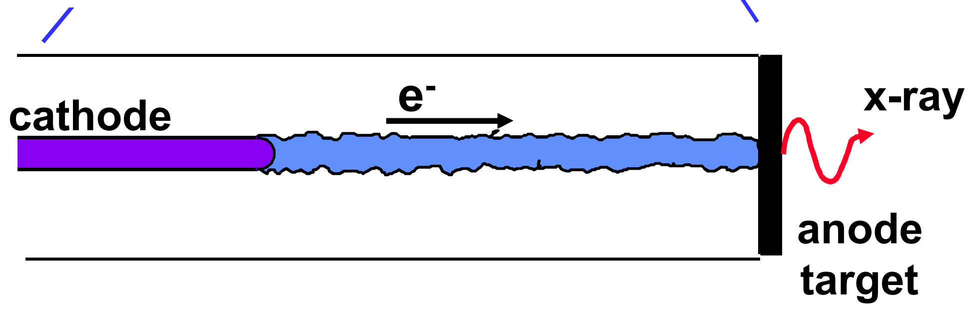
D. Rose (Voss)
D. Welch (Voss)
N. Bruner (Voss)
I. Smith (L-3)
D. Johnson (L-3)
V. Bailey (L-3)
P. Corcoran (L-3)

Inductive Voltage Adder (IVA) based e-beam driven radiography

The electron beam is created in the accelerating gap of a high current e-beam diode.



Bremmstrahlung x-rays are created when the e-beam is stopped in a high atomic number converter.

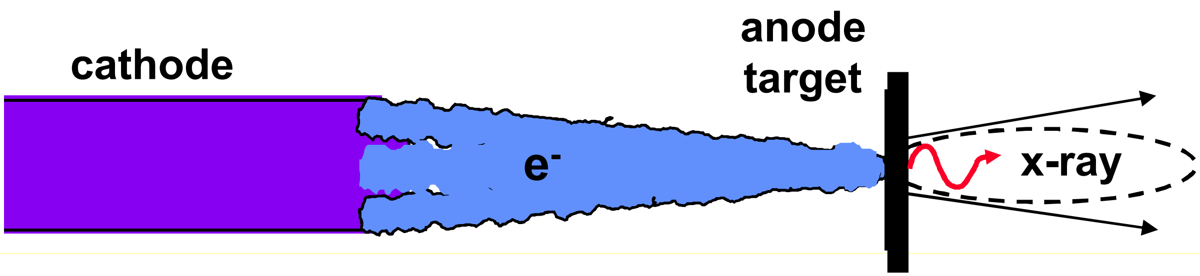


Energy = 2-10 MeV, Current = 20-150 kA, Pulse length = 50-100ns

Some General Beam/Radiation Principles

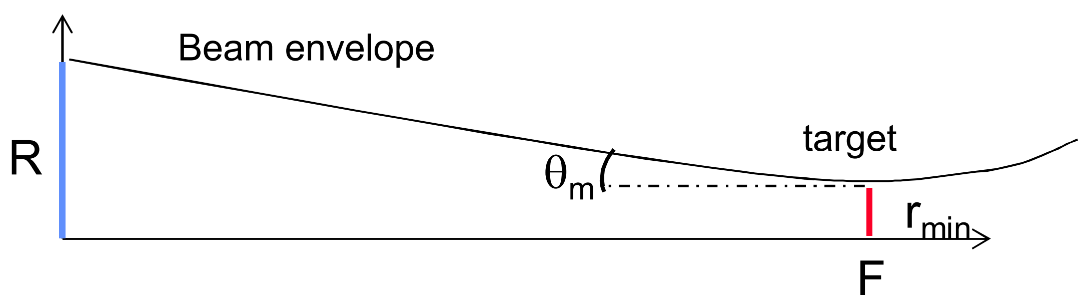
Radiation dose/flux: $\propto \int dt\ I_b\ V^{\alpha}, \quad 1 < \alpha < 3$

related to the beam current I and voltage V.



x-rays are forward directed within an angle $\propto 1/\gamma$. α is dependent on beam angles of incidence and temperature.

Radiation spot size: equivalent to the beam spot on target.



$$r_{min} \cong \theta_{\mu} F, \qquad \theta_m \cong R / F$$

$$\theta_{\mu} = \frac{1}{\sqrt{\pi}} \frac{\varepsilon}{R}$$

Spots are limited by beam emittance/micro-divergence

Optimization of radiographic performance

A figure of merit (FOM) for the diode radiographic utility is quantified by the photon intensity, defined as:

$$\text{FOM} = \text{Dose}/\text{spot}^2 \quad \text{rads@m}/\text{mm}^2$$

To increase the FOM one must either decrease spot, increase dose or both.

Smaller spots are achieved by:

- -increasing beam macro-angle θ_m at target
- -decreasing beam emittance/micro-divergence ε, θ_μ

Larger dose is achieved by:

- -decreasing beam macro-angle θ_m at target
- -increasing beam energy and or current (V, I)

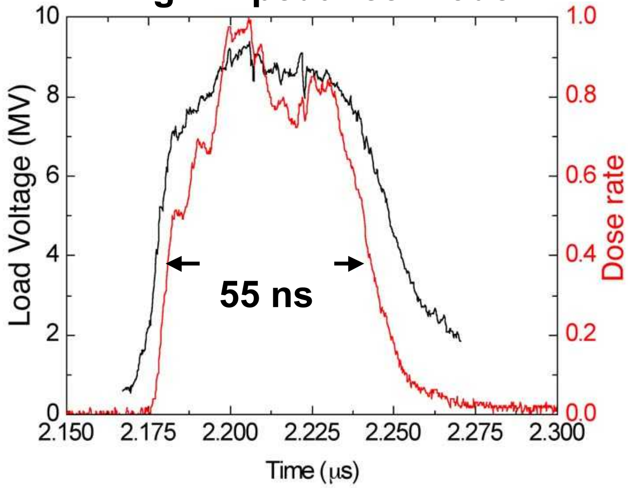
Conflicting requirements

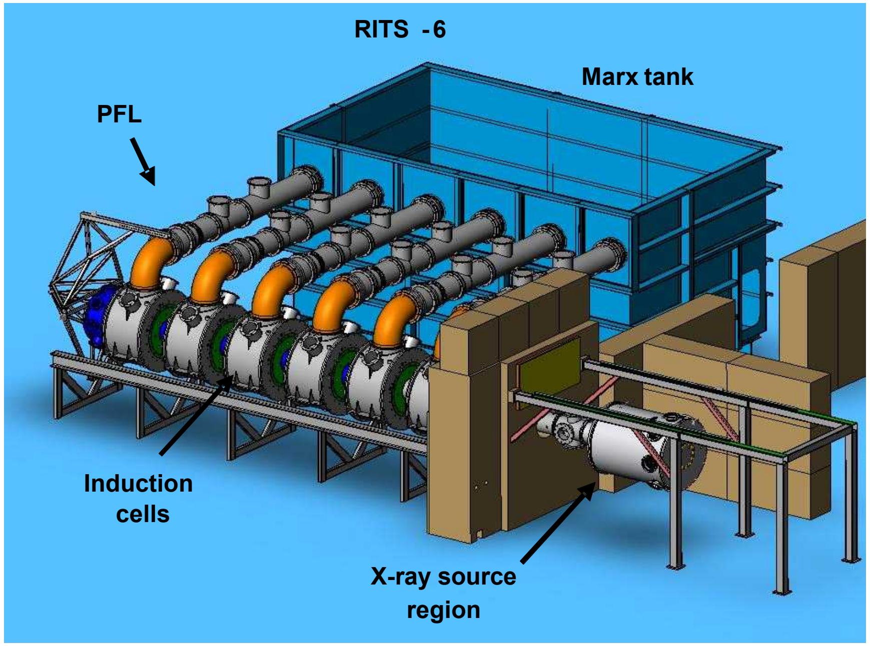
Experiments are fielded on the Radiographic Integrated Test Stand RITS-6

E-beam driven x-ray radiography test stand based on Induction Voltage Adder (IVA) technology

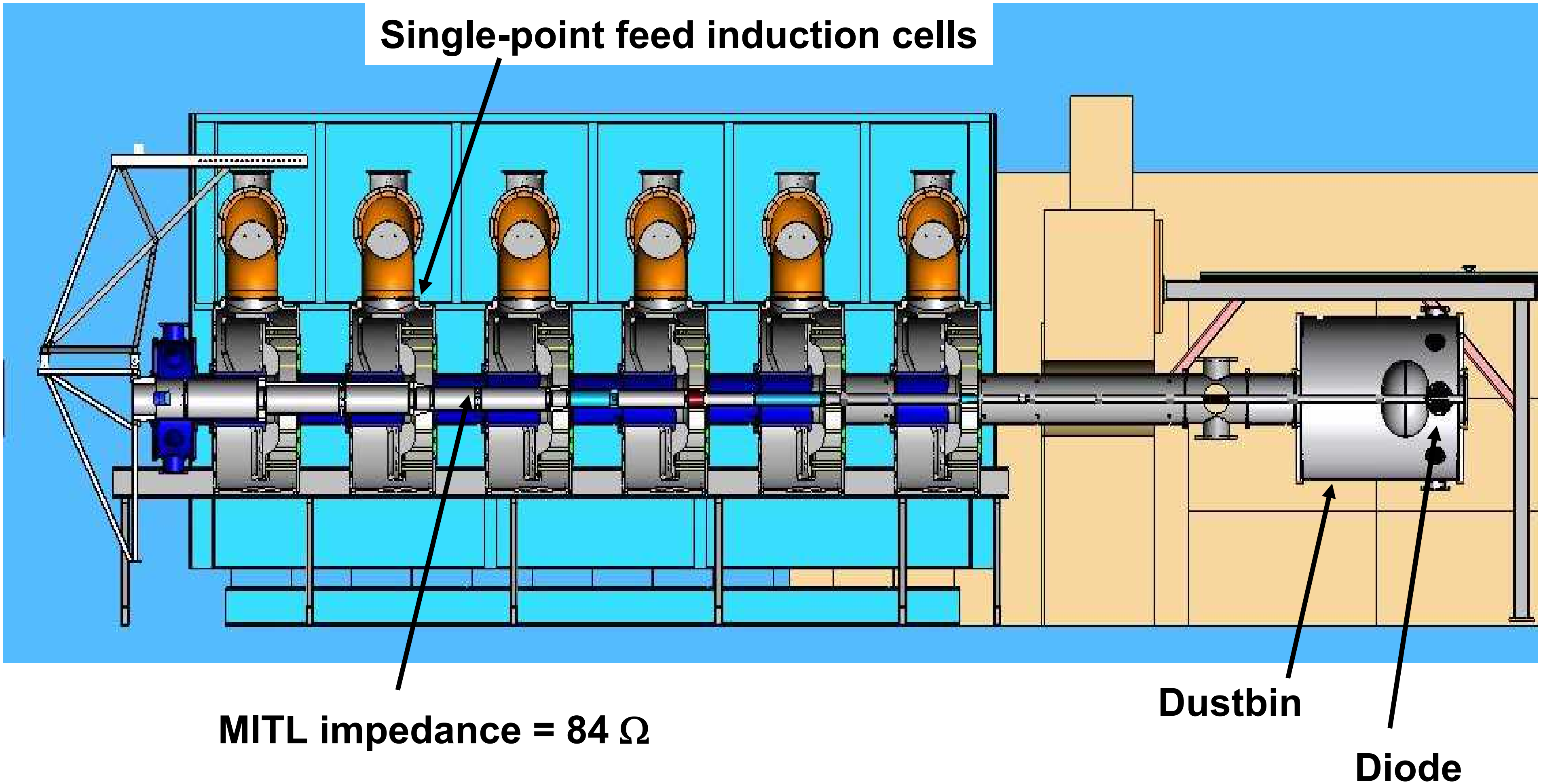
Flexible accelerator producing:
4.5-11 MV, 125-190 kA, 70 ns pulse.

Voltage and Radiation Dose Rate
High impedance mode



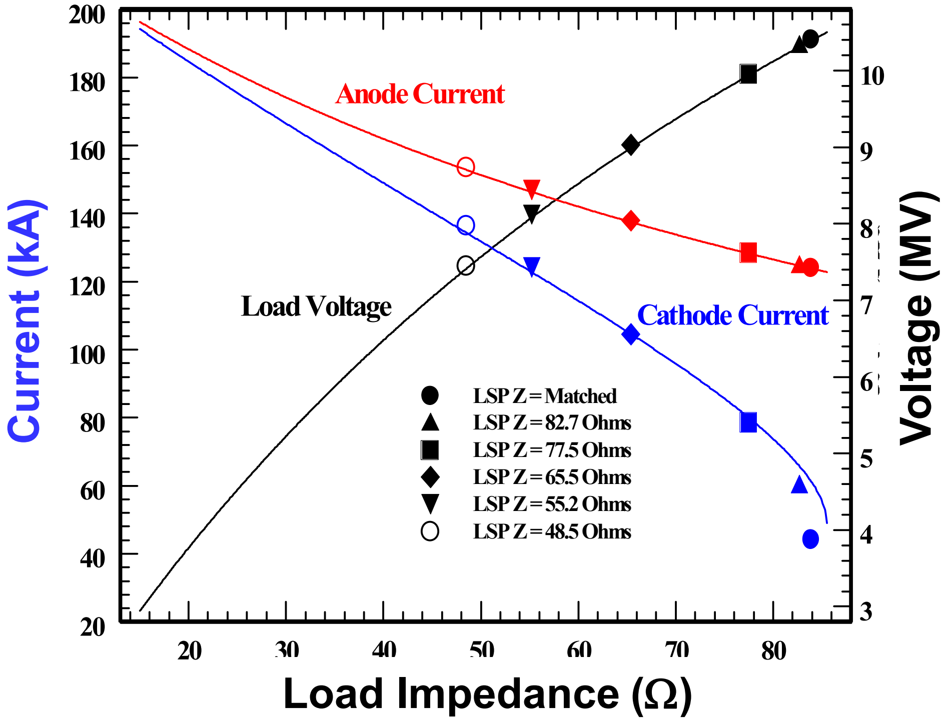


RITS-6 Cross-section and MITL



RITS-6 is a flexible accelerator architecture for driving high voltage sources.

RITS-6 MITL Operating Points



MITL Load impedance $Z_L = V/I_A$

Diode impedance $Z_D = V/I_C$

Dose ~ IV$^\alpha$, $1<\alpha<3$: we can increase dose by either increasing current, voltage or both

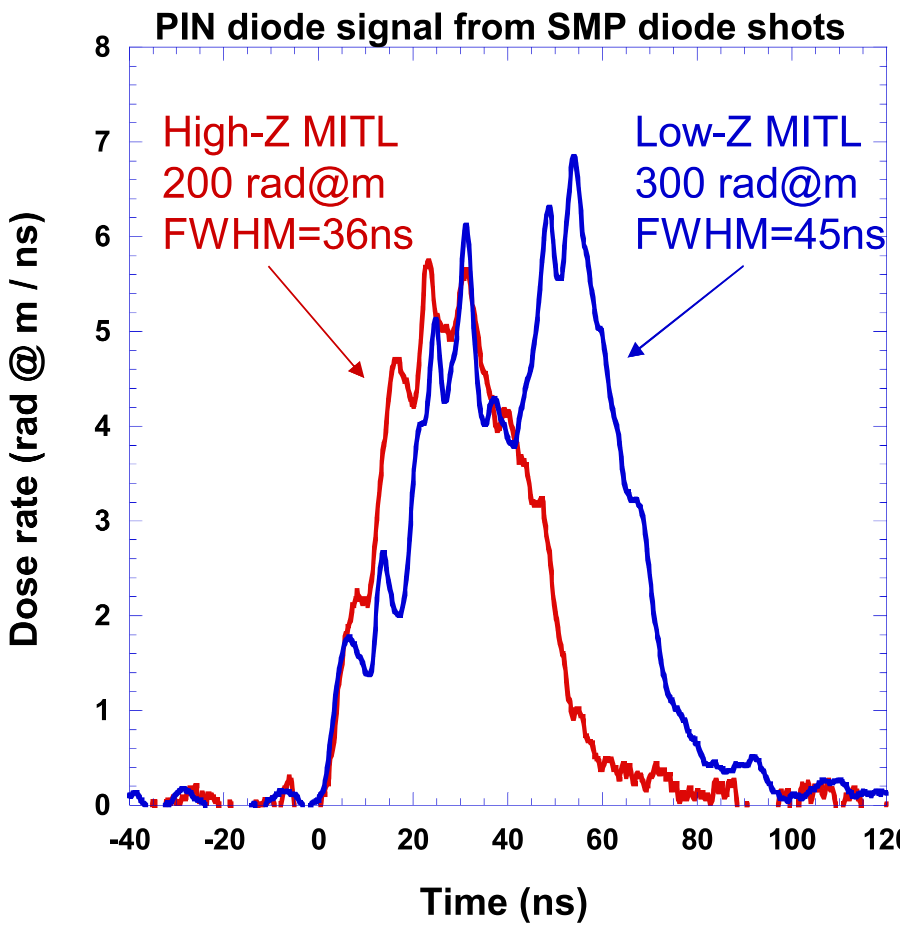
Non-linear MITL impedance V=IZ(V) enables efficient drive for a variety of diode impedances. Can obtain 300% increase in diode current for only 30% decrease in voltage!

We can also use different MITL's to enhance power coupling

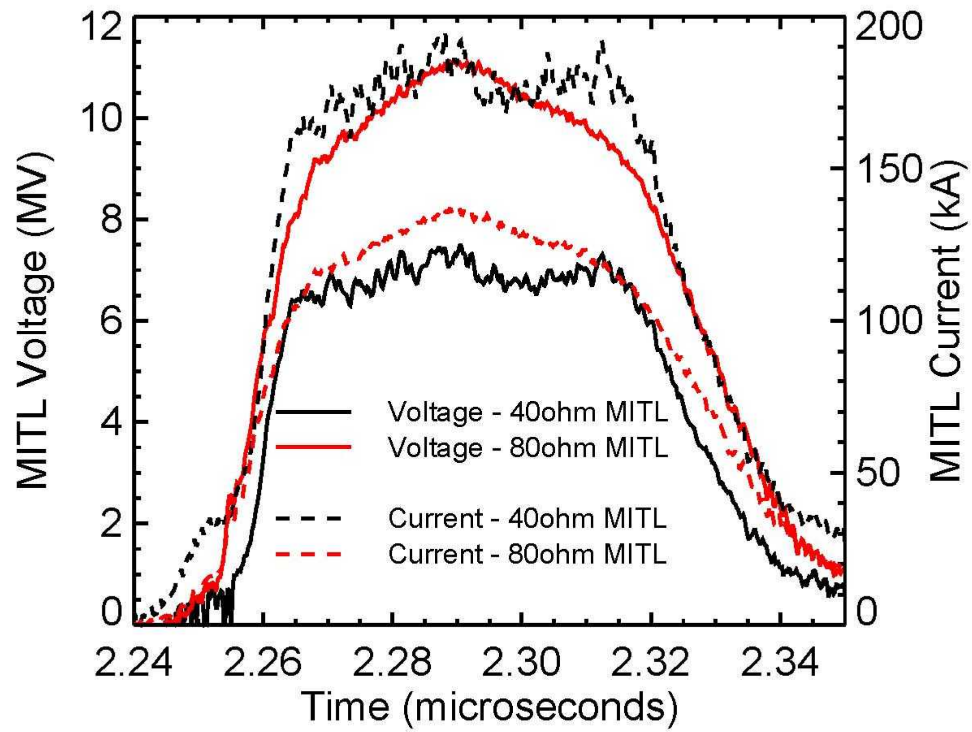
1. V. Bailey et al., proc. 14th Intl. PPC, 2003

Minor changes to accelerator architecture increase power coupling to source

Designed a 42 Ohm MITL (vs. 82 Ohm) to thread the center of accelerator



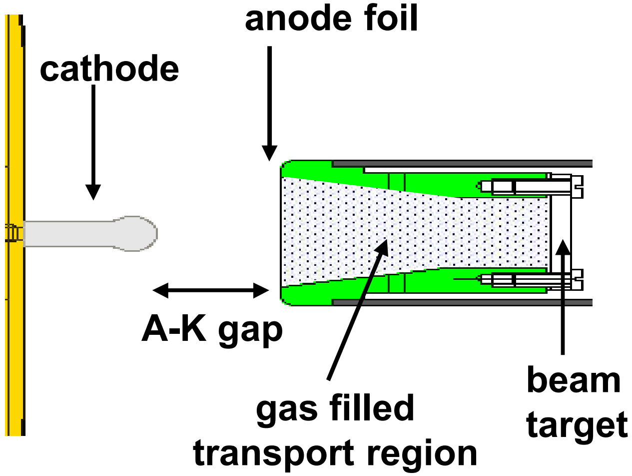
Low impedance MITL used to couple power to low impedance sources



High Impedance Diodes (~200+ Ohms)
Dose $\propto IV^{2.65}$

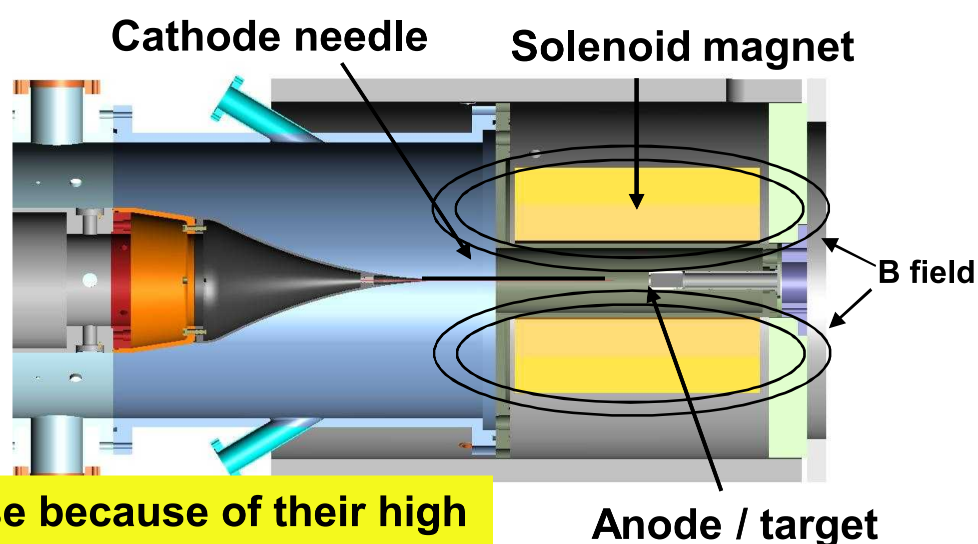
Paraxial Diode:

e-beam accelerated in vacuum A-K gap and transported to the target in gas.



Immersed B_z:

e-beam accelerated in vacuum and transported directly to anode/target. Beam is confined by strong 40T B_z magnetic field.

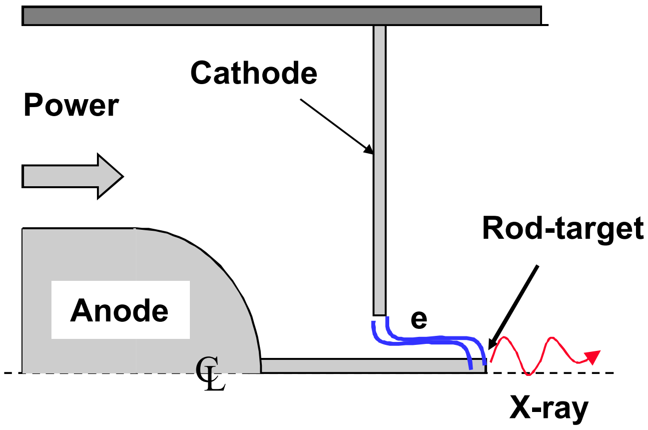


These diodes produce high radiation dose because of their high operating voltage and ~ normal incidence on target!

Low Impedance Diodes (~ 50 Ohms)
Dose $\propto IV^{1.2-2}$

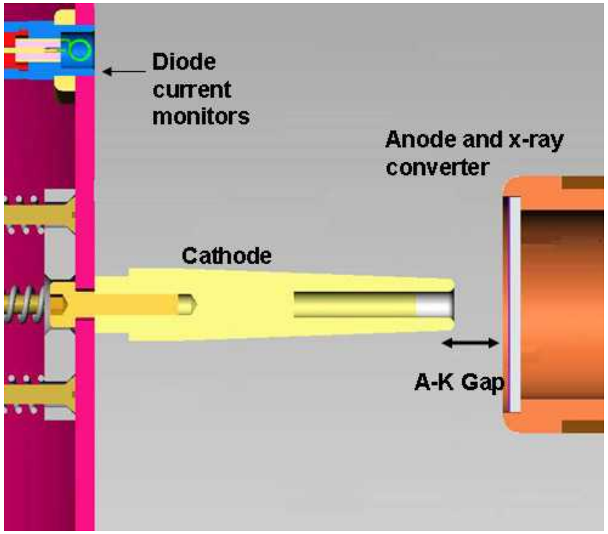
Rod-Pinch:

Bi-polar diode (e+ions). e-beam is self-field insulated and propagates to tip of anode rod/target.



Self-Magnetic Pinch:

Bi-polar diode (e+ions). e-beam is pinched onto anode/target by self-magnetic B_θ field.



These diodes produce small spots but less radiation dose because of their high average angle of incidence on target!

Paraxial diode: beam propagation in overdense gas $n_b/n_g \ll 1$. Gas-cell acts as a ¼ betatron focusing lens[1]

Gas breakdown sufficient for complete charge neutralization but incomplete current neutralization.

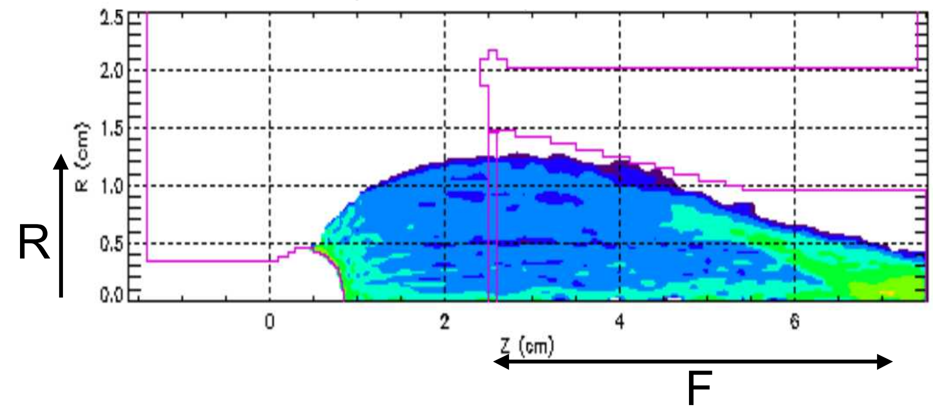
$$\frac{d^2 r_b}{dz^2} \cong -\frac{1}{r_b}\frac{2I_{net}}{I_A} + \frac{\varepsilon^2}{r_b^3}, \qquad I_{net} = I_b + I_{plasma}$$

For $\varepsilon^2 \ll 2R^2 I_{net}/I_A$

$$F \cong \frac{R}{2}\sqrt{\frac{\pi I_A}{I_{net}}}, \qquad I_A = 17\gamma\beta\ (\mathrm{kA})$$

$$\propto \sqrt{\frac{\gamma}{I_{net}}}$$

Beam density contours from Lsp simulations

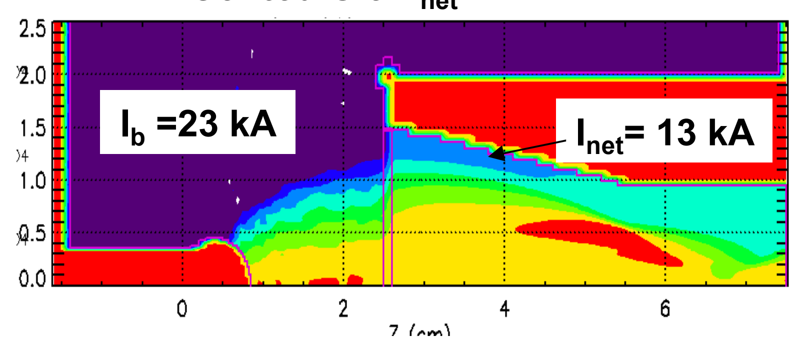


Net current (beam + plasma) $I_{net} = crB_\theta/2$

$$\frac{\partial B}{\partial t} = -\nabla\times\frac{c}{4\pi e n_e}\left(\nabla\times B - \frac{4\pi}{c}j_b\right)\times B + \nabla\times\frac{c^2}{4\pi\sigma}\left(\nabla\times B - \frac{4\pi}{c}j_b\right)$$

Hall current advection — Resistive diffusion

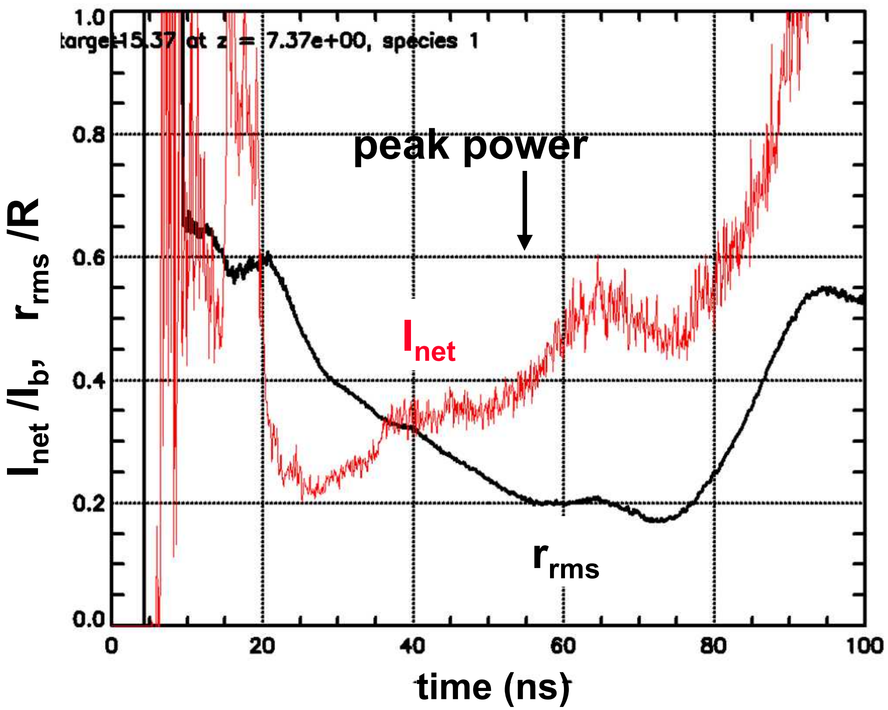
Contours of I_{net}



1. B.V. Oliver, D. Short, G. Cooper and J. McLean, IEEE Trans. on Plasma Science **33**, 704 (2005).

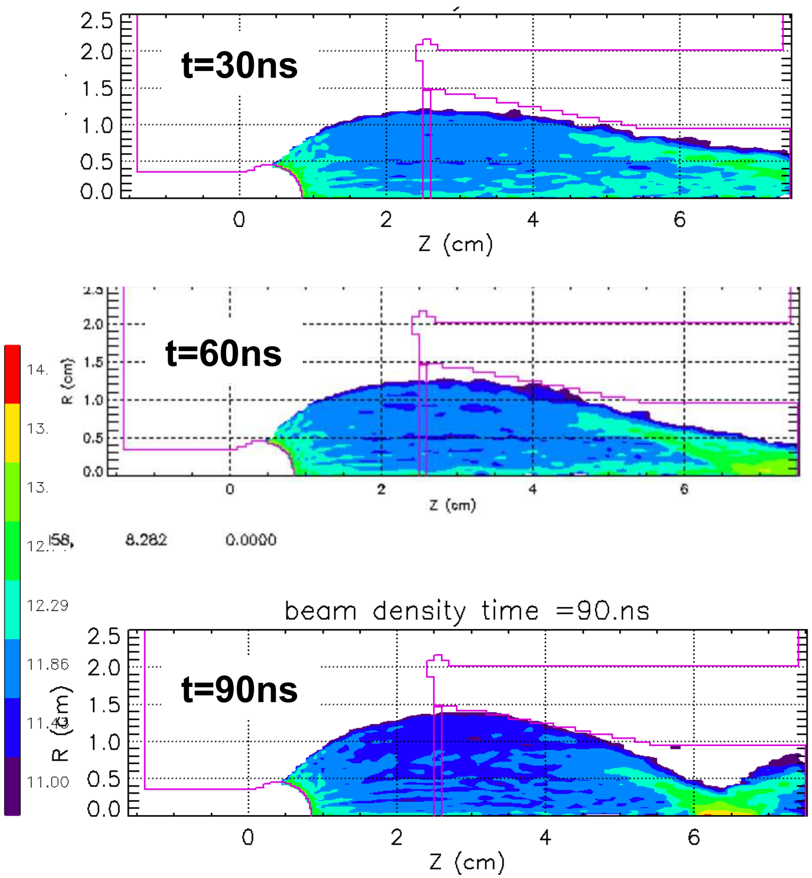
Time dependence of I_{net} causes a sweeping focus!

$$F(t) \cong \frac{R}{2}\sqrt{\frac{\pi I_A}{I_{net}(t)}}$$



Beam rms radius and I_{net} vs time. At peak power, I_{net}= 9 kA, r_{rms}= 0.2 cm

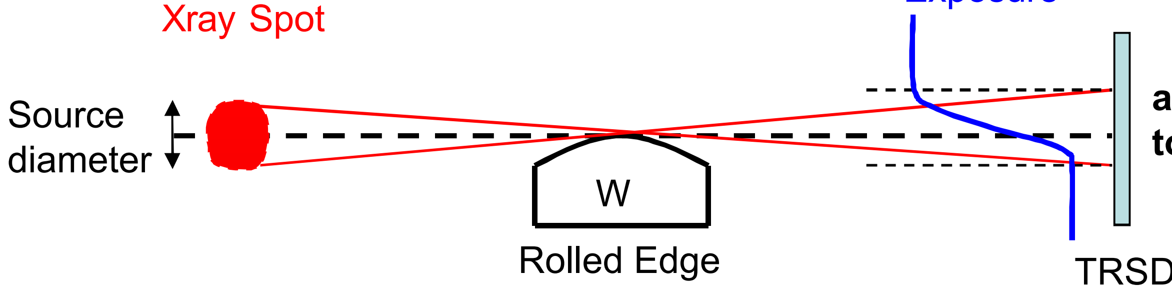
Contours of beam density



Focal sweeping is a primary contributor to larger than desired time integrated spots.

Time-resolved x-ray spot diagnostic measures beam sweep on paraxial diodes

Diagnostic layout

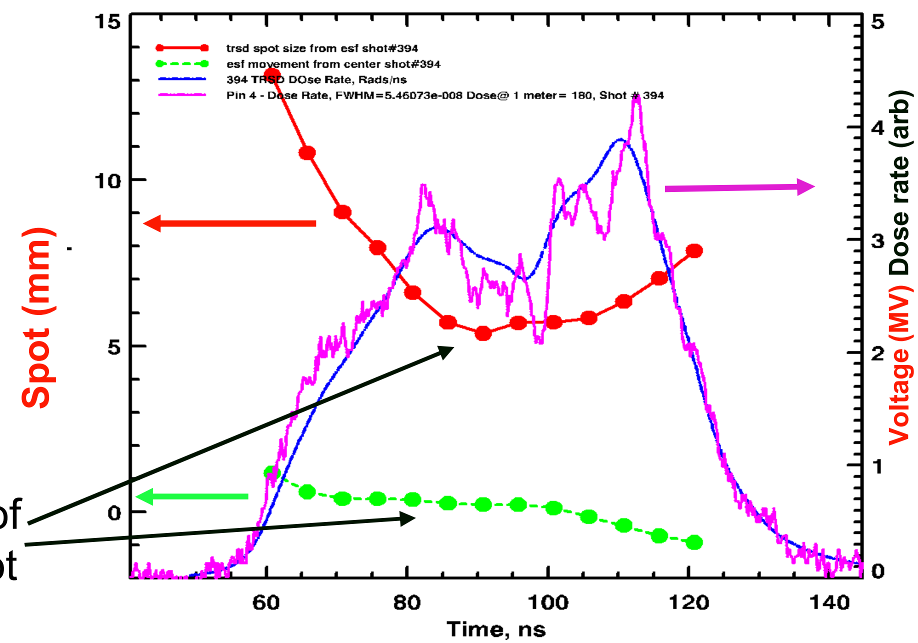


array of scintillation fibers coupled to a streak camera.

The baseline AWE x-ray source is being improved
Hybrid 3D simulations
Time resolved spot diagnostic
Spectroscopy for plasma diagnostics
Expect to decrease the spot by a factor 2.

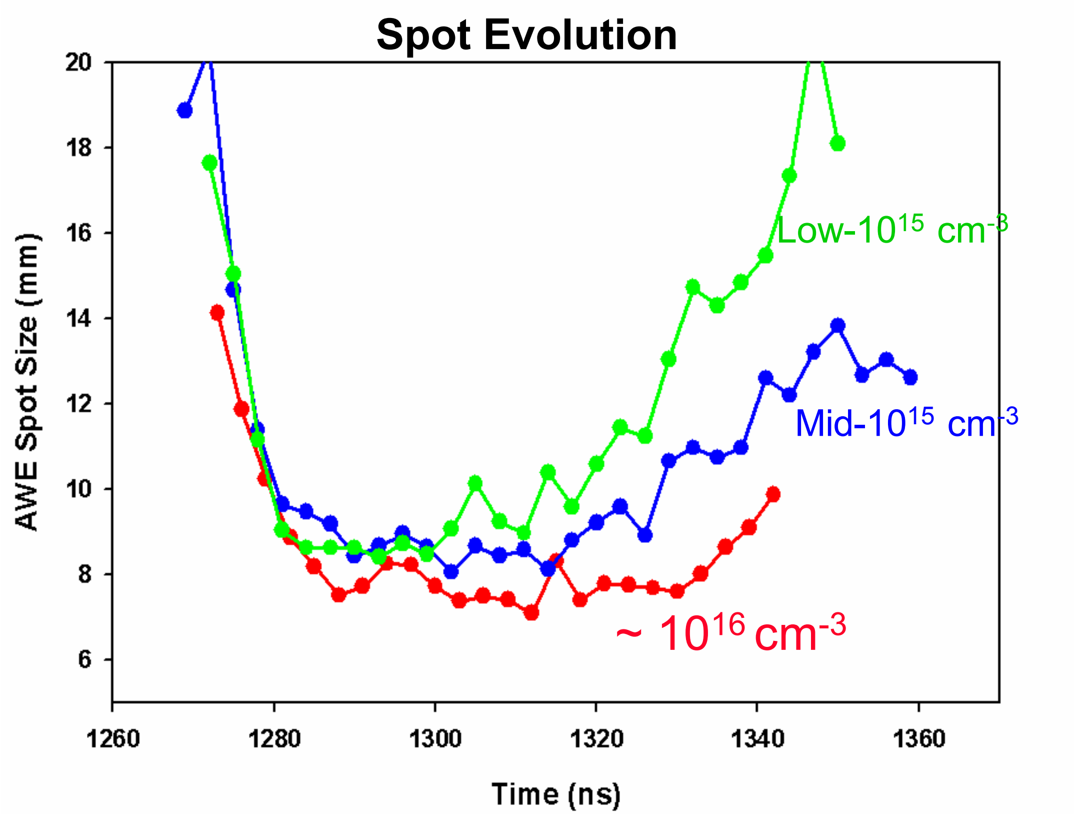
11 MeV Paraxial source on RITS
500 rads @ 1m from a
7.0 mm (0-100% AWE) spot

First measurements of beam sweep and spot wander



Demonstrated Plasma-filled focusing cell controls time dependent spot growth

Theory and simulations[1] suggest replacing gas-filled transport cell with a highly pre-ionized plasma limits beam sweep. Confirmed on RITS Accelerator



see K. Hahn[2] et al. poster

1. D. Welch, D.V. Rose, B.V. Oliver et al, Phys. Plasmas, **11**, 2004
2. K. Hahn, PhD thesis, Univ. of New Mexico, 2006

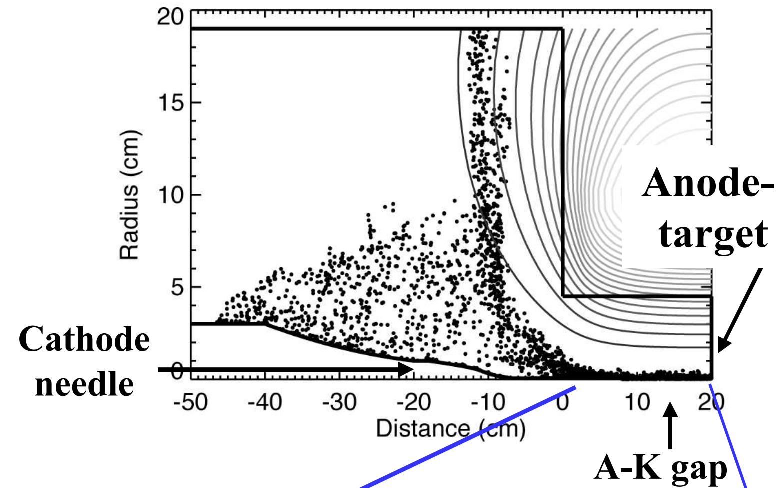
see D. Short et al. 10-I-02

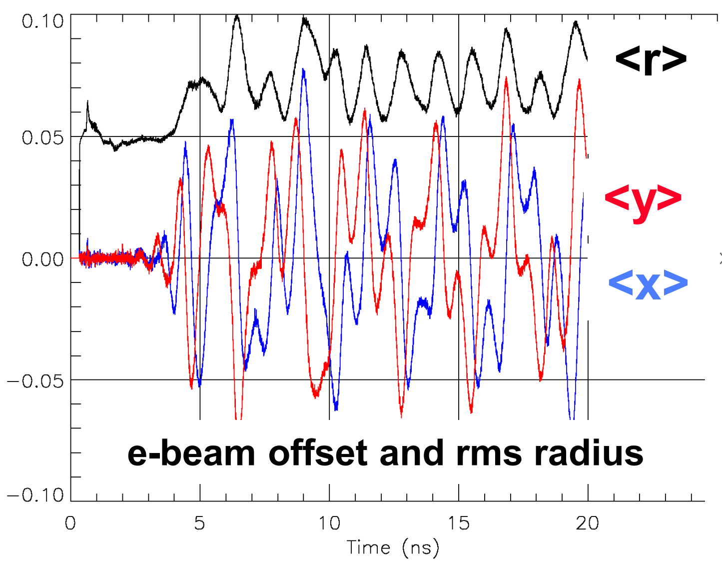
The ion-hose instability limits spot-size in immersed-B_z diodes

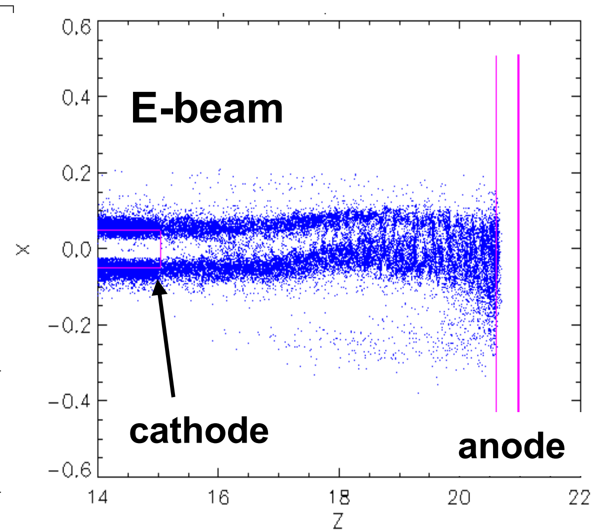
Immersed-B[1]**:** High dose production because beam incidence angle θ_m~0

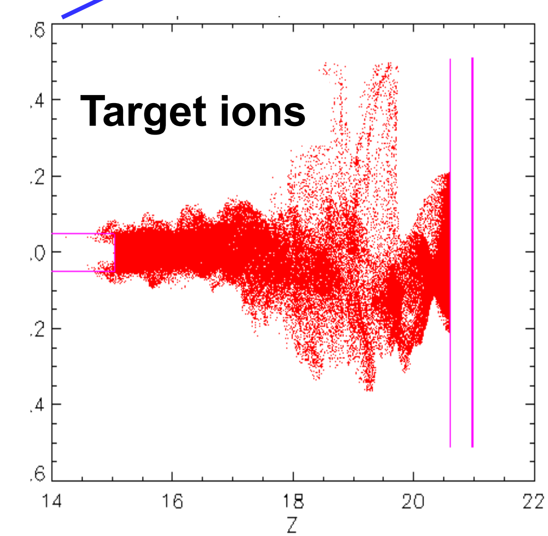
spot: spot is determined by ion-hose saturation amplitude

$$< r_{sat} > \approx \frac{c}{\Omega_e}\sqrt{2\gamma\frac{I_b}{I_A}}$$









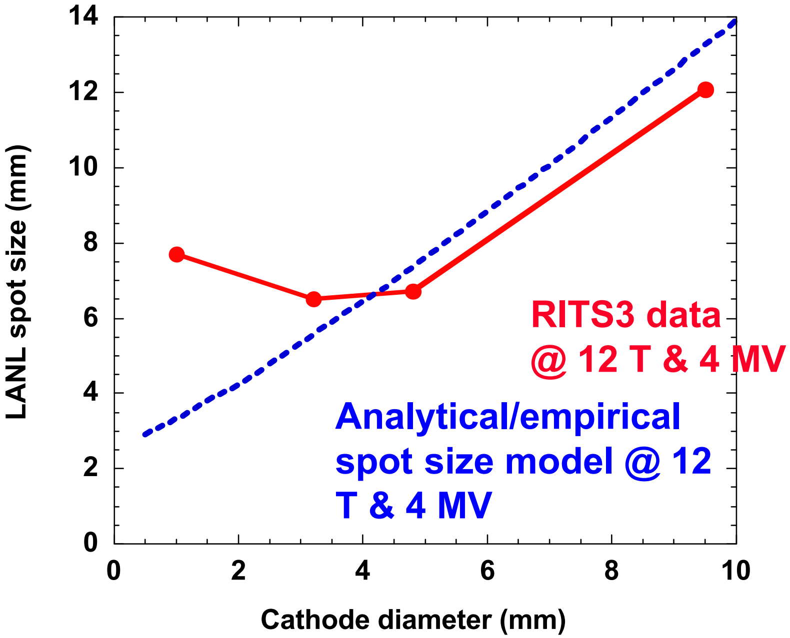
3-D PIC simulations of immersed-B diode electron and ion dynamics

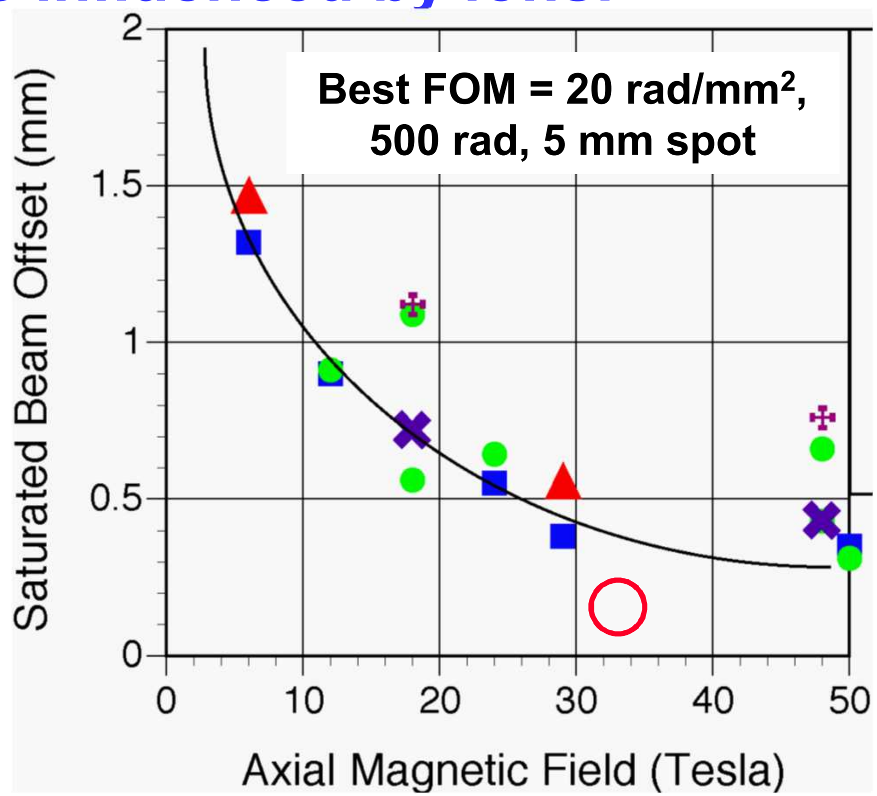
1. M.G. Mazarakis et al. Appl. Phys. Lett **70**, 832 (1997)

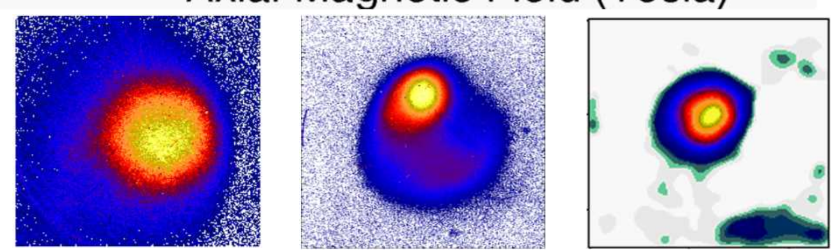
Nonlinear saturation of ion-hose ∝ $1/B_z$. But small spots influenced by ions.

Radiographic spot size decreases as ~ 1/B!..........up to some critical spot size![1]. Time of flight suggests ion interactions not plasma interactions.

Scaling is not reproduced for small spots!







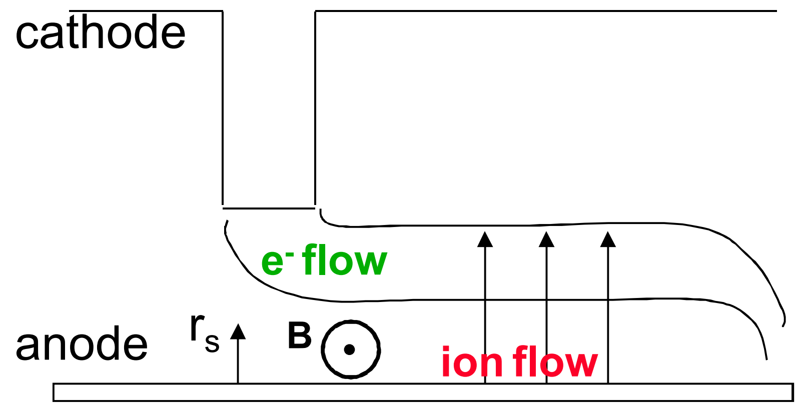
6 Tesla 29 Tesla 50 Tesla

Spot data courtesy of J. Maenchen[2]

1. D.C. Rovang et al., Phys. Plasmas **14**, 113107 (2007)
2. J. Maenchen, et al. Proc. IEEE Trans. **92**, 1021, (2004)

The Rod-Pinch is a self-magnetically insulated diode that provides small spots

rod-pinch diode



Operation is described by self-insulated flow theory with the inclusion of ions[1,2].

Spot determined by rod diameter

Diode current well modeled by critical current formulation:

$$I = \alpha I_{crit}, \qquad 2.0 < \alpha < 2.6$$

$$I_{crit} = 8.5 \frac{\sqrt{\gamma^2 - 1}}{\ln\left(r_c / r_a\right)} \quad \text{kA}, \qquad \gamma = 1 + eV/mc^2$$

Normal Rod pinch diode

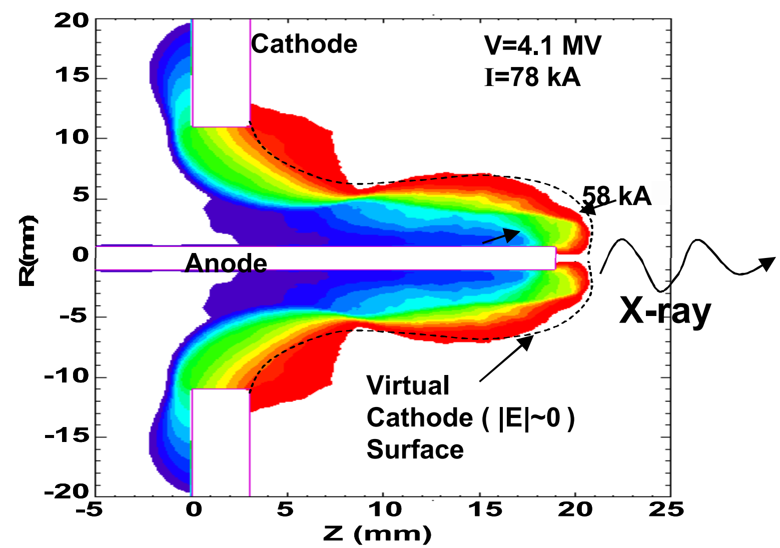
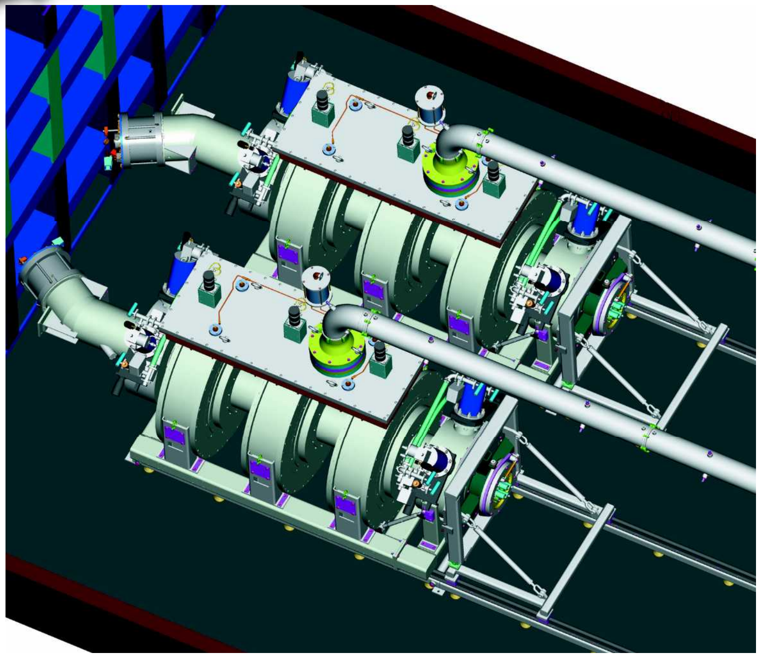
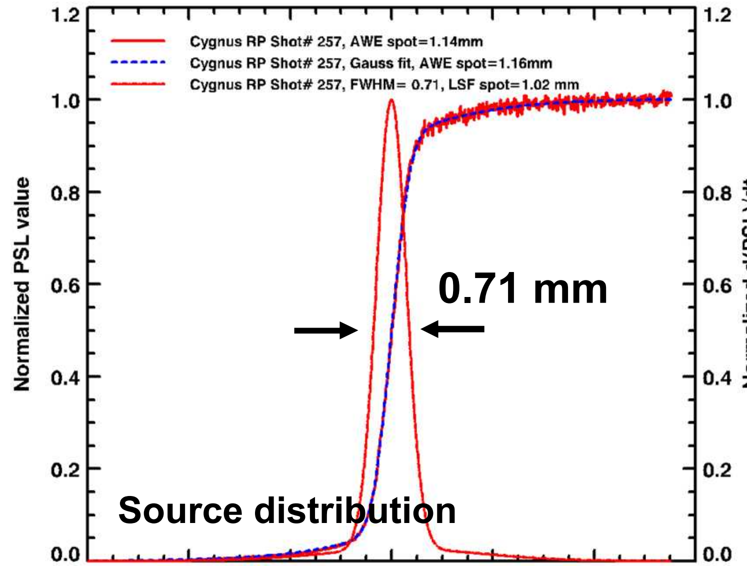


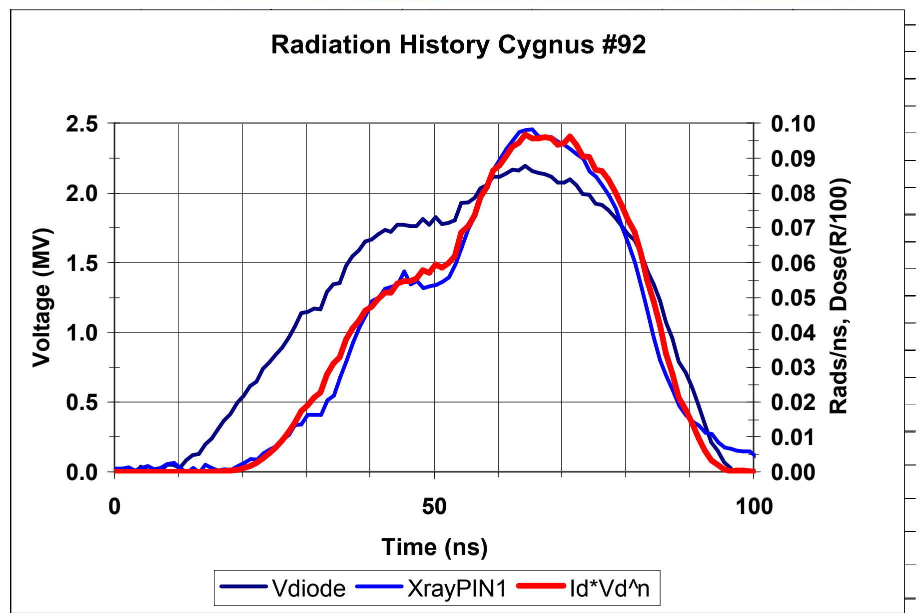
Fig. courtesy of S. Swanekamp, NRL

1. G. Cooperstein et al. Phys. Plasmas, **8**, 4618 (2001)
2. B.V. Oliver et al. Phys. Plasmas, **11**, (2004);

Cygnus is a dual axis IVA-driven high resolution radiographic system







- Provides dual axis radiographs at NTS
- Each 2.2 MV axis produces a > 4 rad@m, 1.1mm spot from a rod-pinch x-ray source.

National Security Technologies LLC Vision • Service • Partnership

Los Alamos NATIONAL LABORATORY

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Alternative source development for the future: Negative Polarity Rod-Pinch

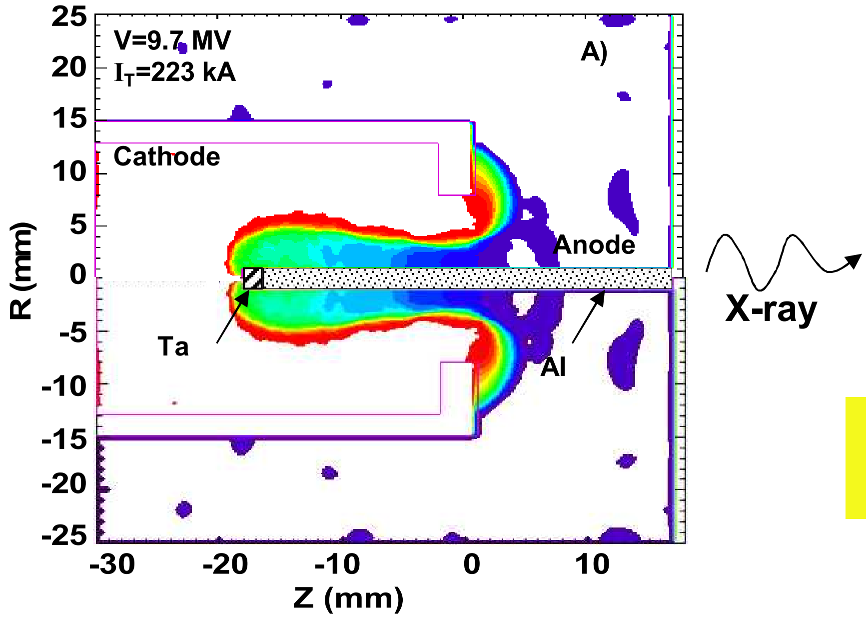
Dose at 0^0 scales weakly with voltage[1]!

$$D\ (\mathrm{rad}) \propto \int I_e V^{1.25}\, dt$$

Dose at 180^0 in backwards direction is maximized[2]

$$D\ (\mathrm{rad}) \propto \int I_e V^{2.22}\, dt$$

Reentrant Rod pinch diode



Dose rate dependence on angle

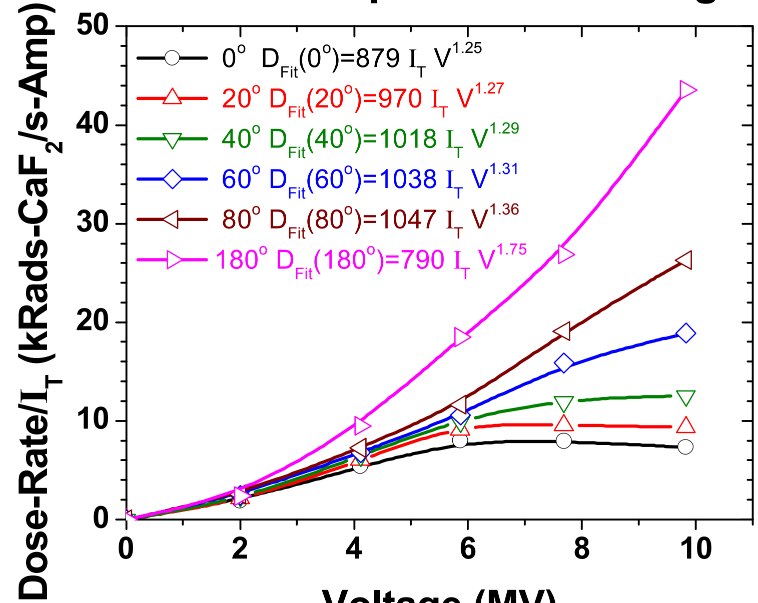


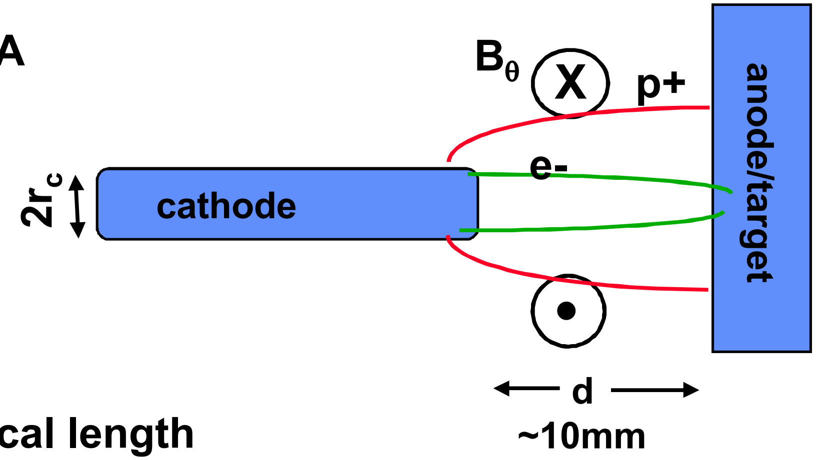
Fig. courtesy of S. Swanekamp, NRL

Should be capable of producing > 150 rad with < 2mm spots, FOM > 35 rad/mm²

1. D.V. Rose et al. JAP,**91**,3328 (2002)
2. S.B Swanekamp, G. Cooperstein, J.W Schumer et al. IEEE Trans. Plasma Sci. **32**, 2004 (2004)

Self-Magnetic pinch diode acts similar to a ¼ betatron focusing cell, but in vacuum!

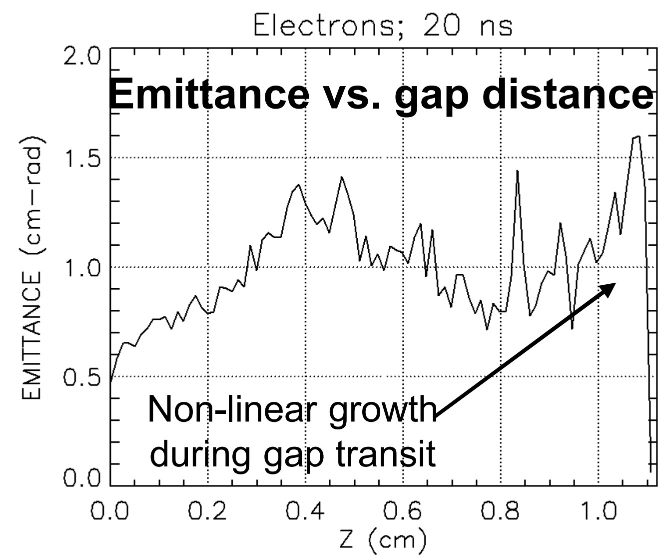
Relativistic Bi-polar diode. High current I_b~150 kA



Self-magnetic B_θ pinches the beam on target. Focal length function of total current. Spot determined by emittance which is driven by non-linear field structure

$$F \cong \frac{r_c}{2}\sqrt{\frac{\pi I_A}{I_b}}, \qquad \sim 14 \text{ mm}$$

$$\text{spot} \cong 2.4 \frac{1}{\sqrt{\pi}} \frac{\varepsilon}{r_c} F \qquad \text{~}2.5 \text{ mm}$$

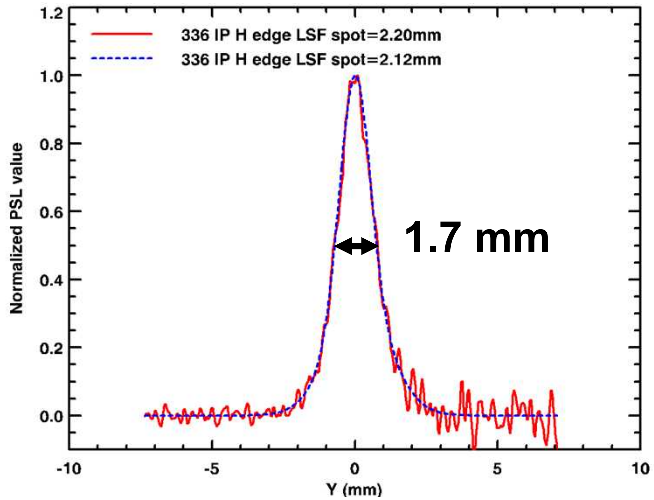


It is not influenced by ion-hose instability because the A-K gap is too small for growth.

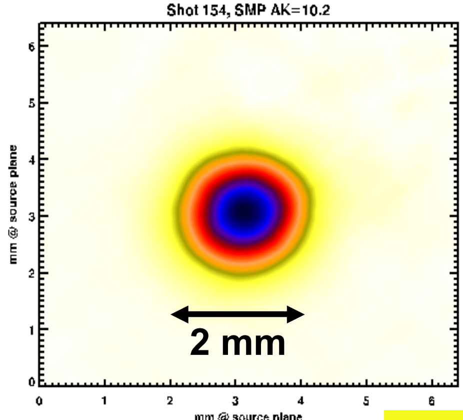
Self-pinch diode is one of our brightest sources!

SNL, AWE, NRL team have demonstrated 350+ rads from a 1.7-mm FWHM source distribution on RITS-6 Accelerator with 6.5 MeV endpoint energy.

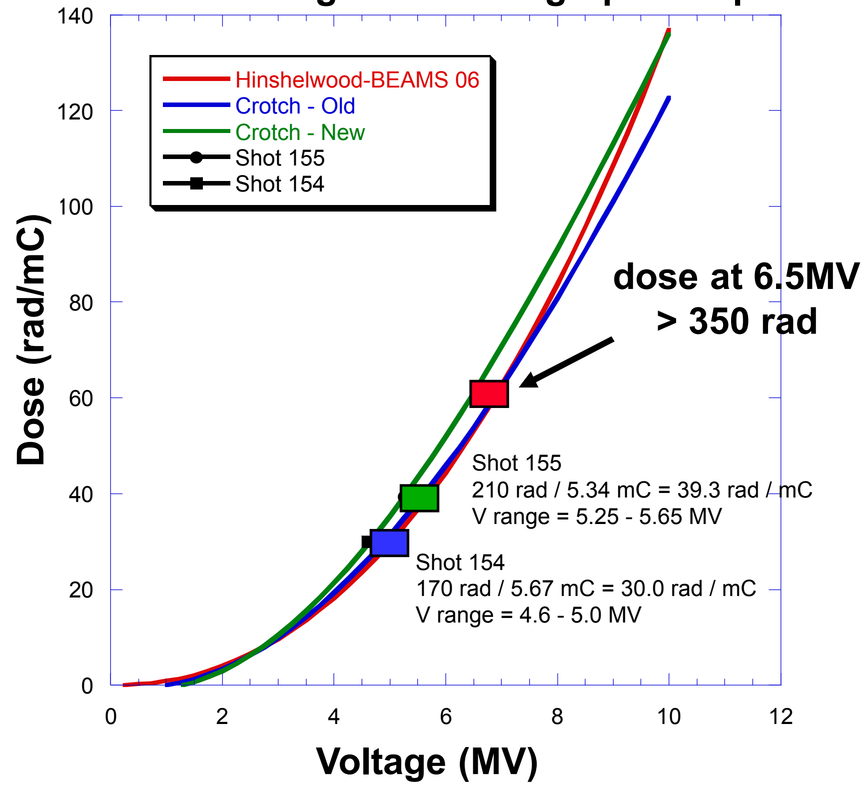
Measured x-ray source spot



Shot 154, SMP AK=10.2



Dose scaling from Radiographer Eqns.



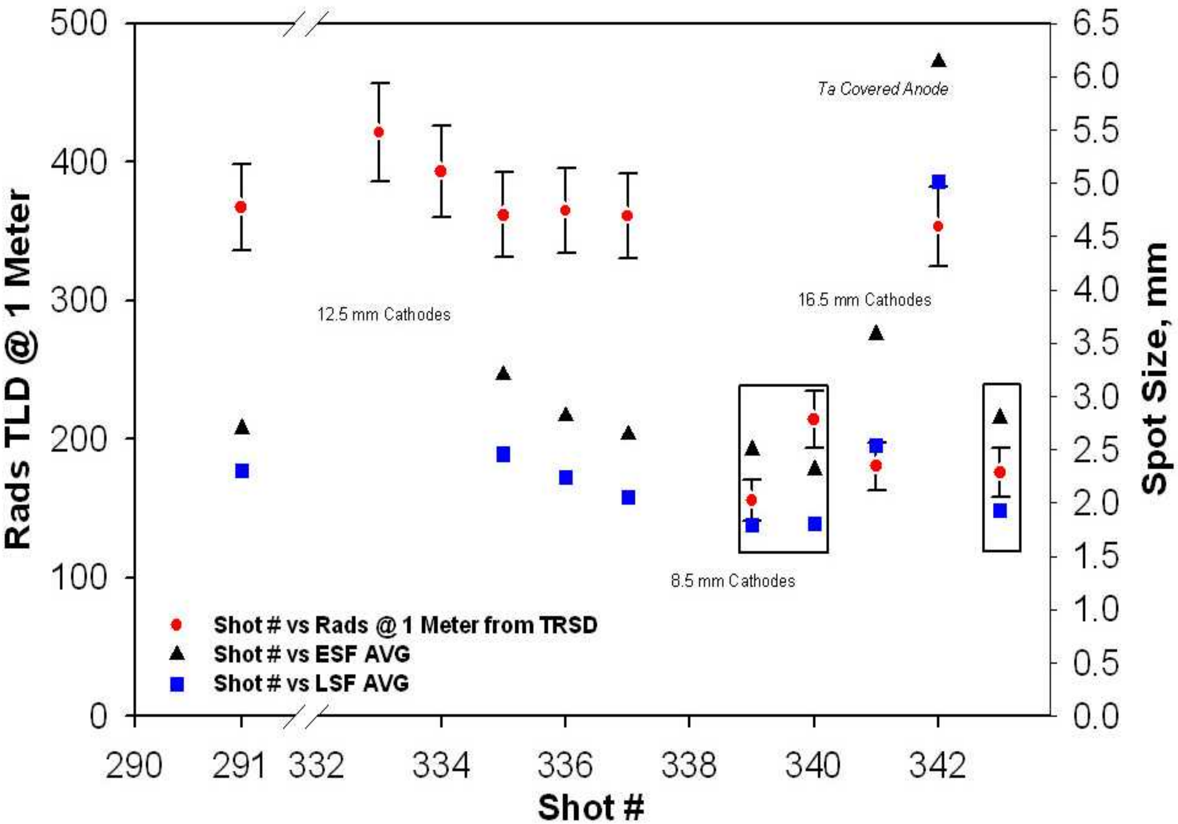
PIC/Monte-Carlo rad transport calculations

Demonstrated brightness > 50 rad/mm^2

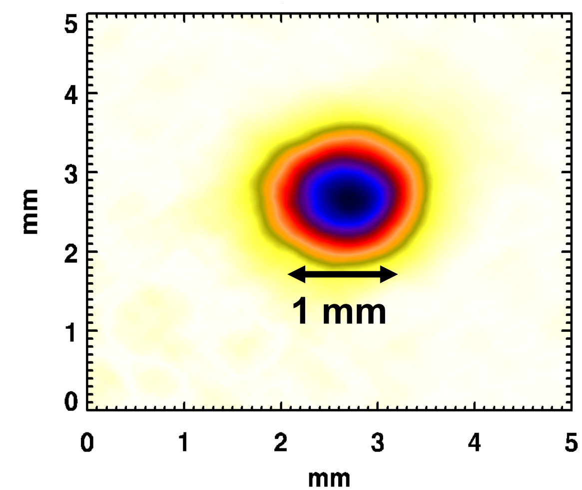
Self-pinched diode geometric changes can produce smaller spot at reduced dose.

AWE definition spot = 2.3 mm ± 0.2 mm
A LLNL definition (1.44x fwhm LSF) = 1.75 ± 0.1 mm
Implies a peaked core (non Gaussian) spot.

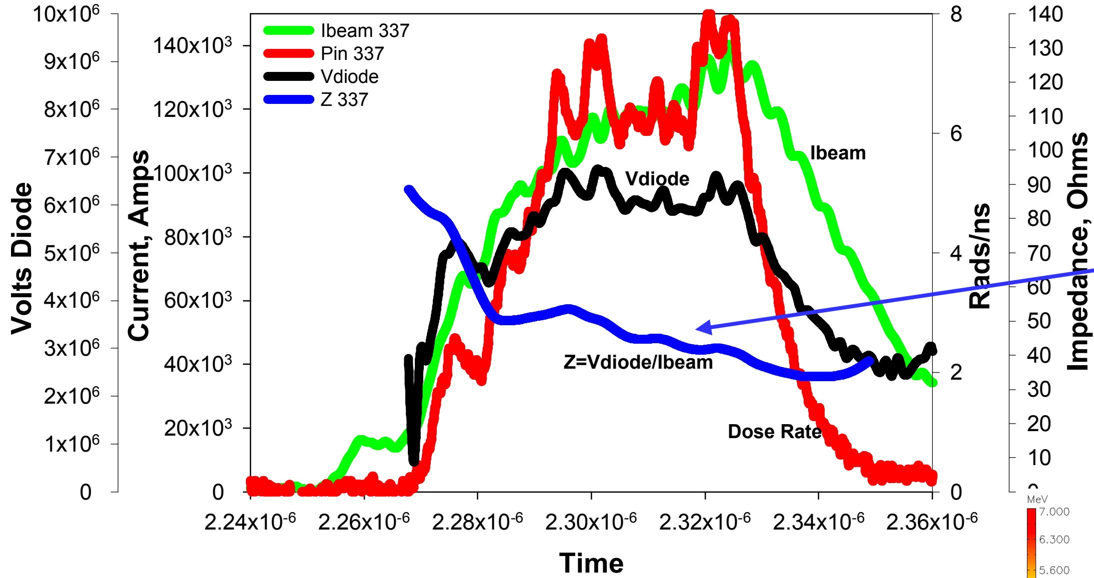
Spot and dose



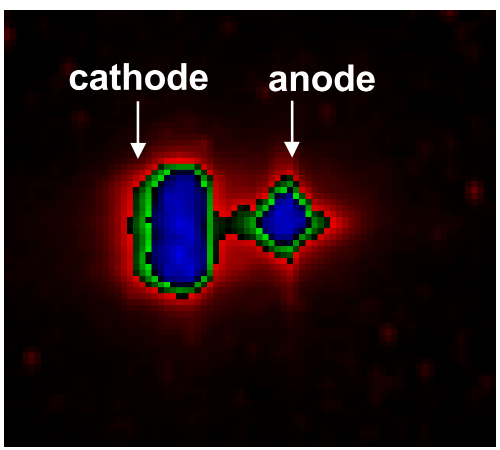
Small cathode produces 150 rad@m, 1.85mm spot



Plasma gap closure must be controlled for brighter performance on the SMP

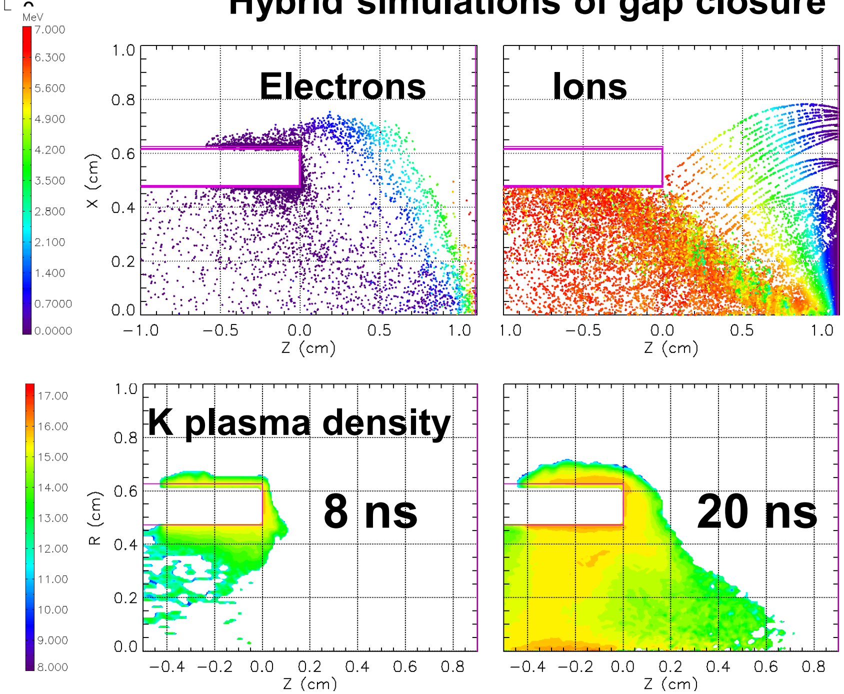


Diode impedance decreases during pulse



Light emission in A-K gap

Hybrid simulations of gap closure



Future driver architectures:1-MV Radiographic system based on LTD's

A 1-MV, 140 kA radiographic Linear Transformer Driver (LTD) has been assembled and tested in Russia and now at Sandia

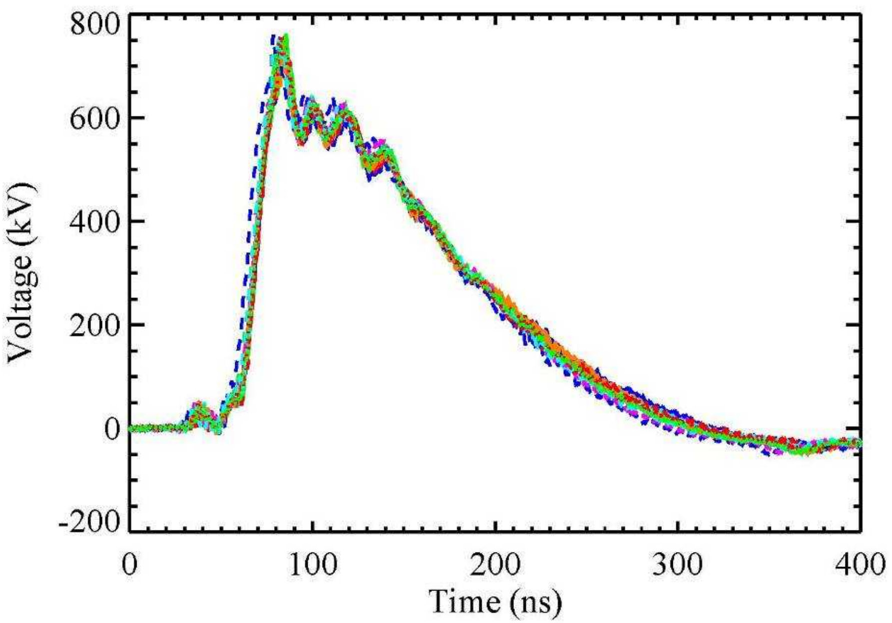
Voltage adds along coaxial Magnetically insulated transmission line, like an IVA

Successfully tested with electron-beam diode load for more than 300 shots

<u>Advantages</u>: lower cost and smaller foot-print:

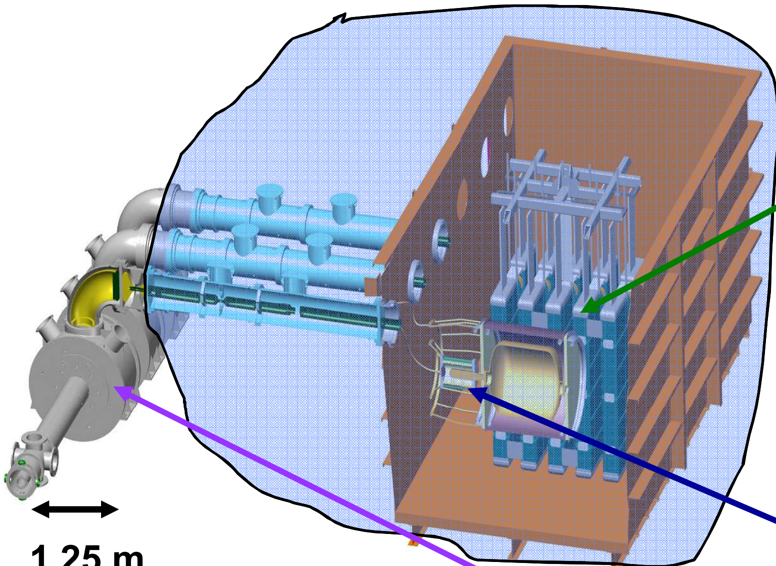
<u>Status</u>: Demonstrated both single and stacked-cavity performance to 1 MV.

<u>Collaborators:</u> designed and built in collaboration with Institute of High Current Electronics in Tomsk, Russia and CEA and ITHPP in France.



The LTD is much more compact than conventional IVAs

Inductive Voltage Adder (IVA)

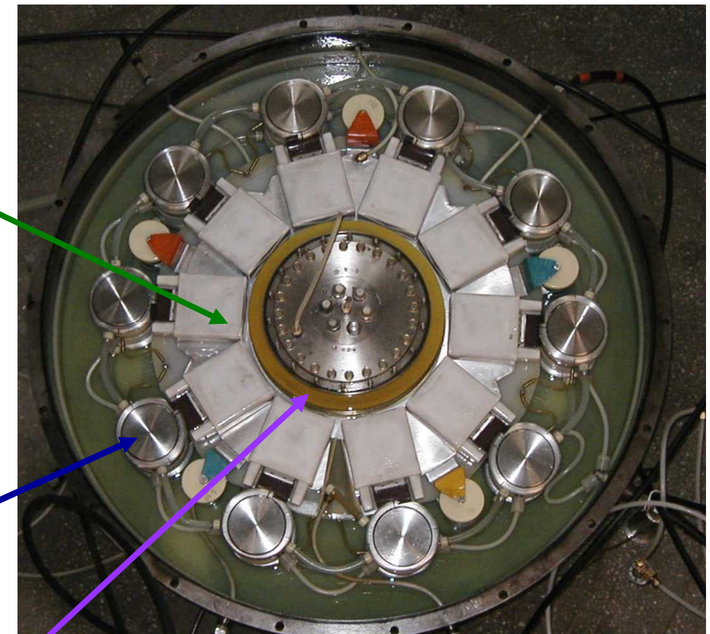


1.25 m

Remove pulse formation and compression hardware

10 m

Linear Transformer Driver (LTD)



1.25 m

Capacitors

switches

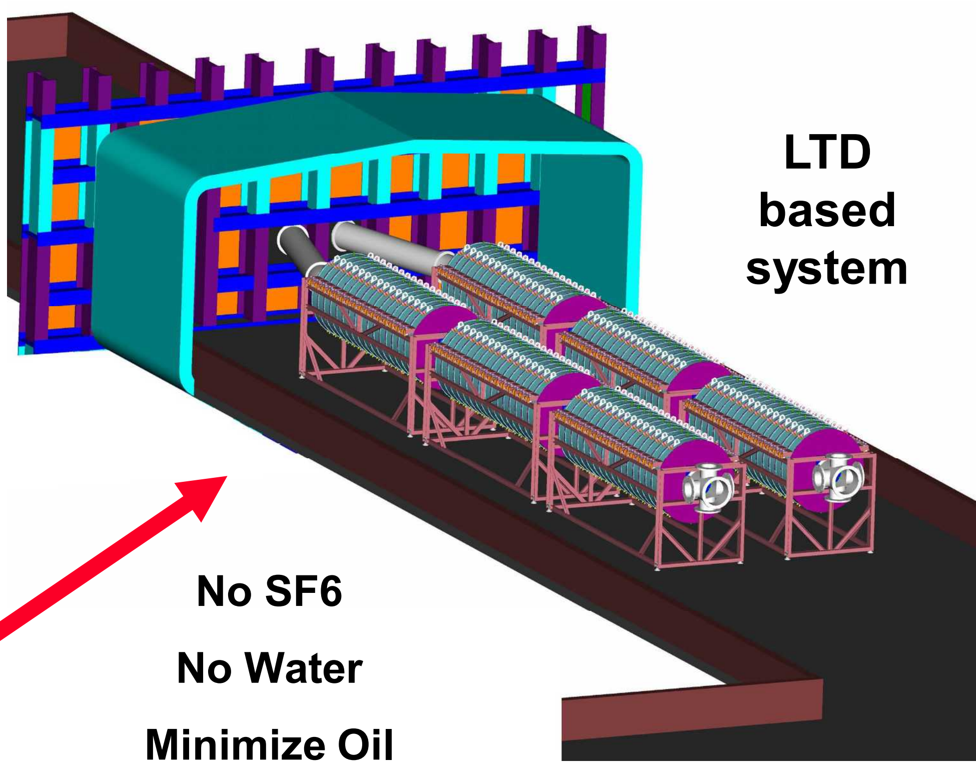
Inductive isolation

A 2-axis LTD can provide 6.5 MV, 250 rad@m, 2.5mm spot in same foot print as Cygnus system

12' wide x 50' long x 6' high

Can replicate existing Cygnus capability

As well as provide increased capability in steps up to 250 rad@m, 2.5-mm spot



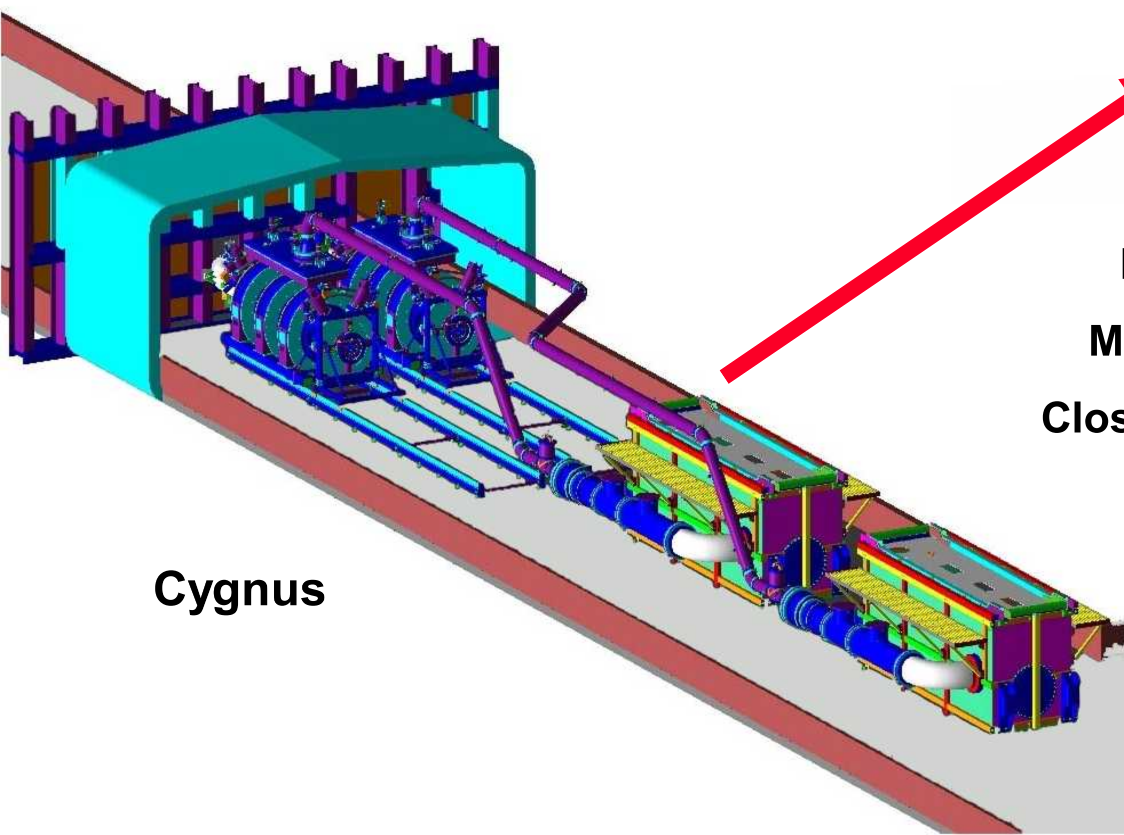
LTD based system

No SF6

No Water

Minimize Oil

Closed geometry



Cygnus

Use either an SMP or negative polarity Rod-pinch diode at ~ 50 Ohms to drive 6.5 MeV, 130 kA diode.