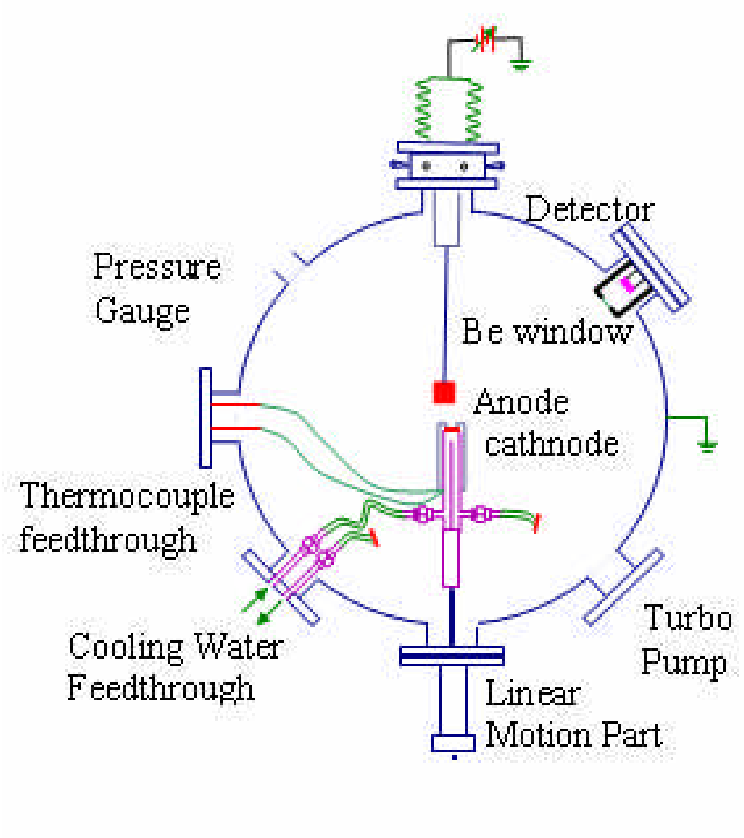
Abstract

A high-current discharge apparatus with a unique pulsed power supply was successfully constructed to demonstrate intense "anomalous" (exceeding direct charged-particle Bremsstrahlung) x-ray emission in the 1-2 keV range. Anomalous x-ray emission is attributed to ion implantation rather than normal electron Bremsstrahlung x-ray emission. A striking characteristic is that the x-ray energy can be several times the energy of the bombarding ions, suggesting a strong non-linear mechanism. Such emission was observed during glow discharge operation in the pressure range 0.1 – 5.0 torr with a cathode/anode separation of ~ 4.0 mm. This discharge operates at a voltage of 1-2 kV with high pulsed current up to 2 A. The current pulses have "square" time shape with 0.2-2.0 ms duration and a rise time of 0.1 μs.

Pulsed GD

- Pulsed high flux bombardment loading builds up D density and creates dislocations
- D diffuses to dislocations building up high density localized state
- High velocity deloading of localized states produces shock high harmonic generation, disassembly of states, and x-ray emission.

Experimental GD Setup at UIUC



- A positive voltage is applied at the anode. Cathode and vessel are grounded.
- A plasma is produced between this and the water-cooled cathode.
- Cathode on movable mount to vary electrode spacing.
- The GD plasma is covered by glass cylinder.
- The photodiode uses a a thin Beryllium filter to block light and set threshold x-ray energy.

The large volume UIUC chamber gives room for internal diagnostics and easily adjustable anode-cathode separation. A photo of the discharge is also shown.

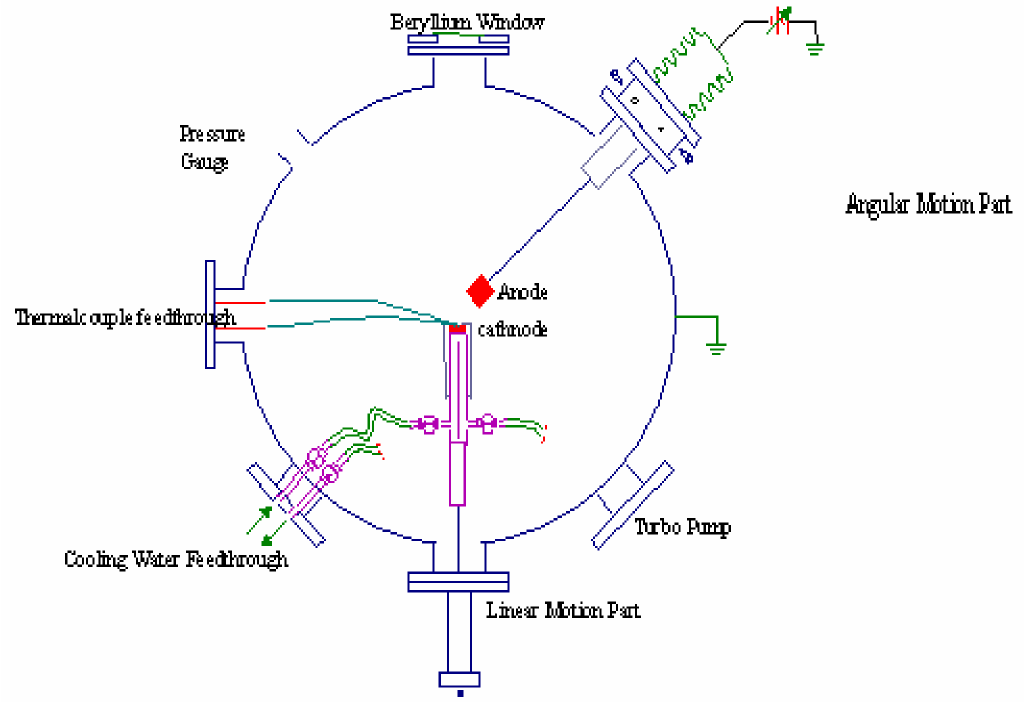


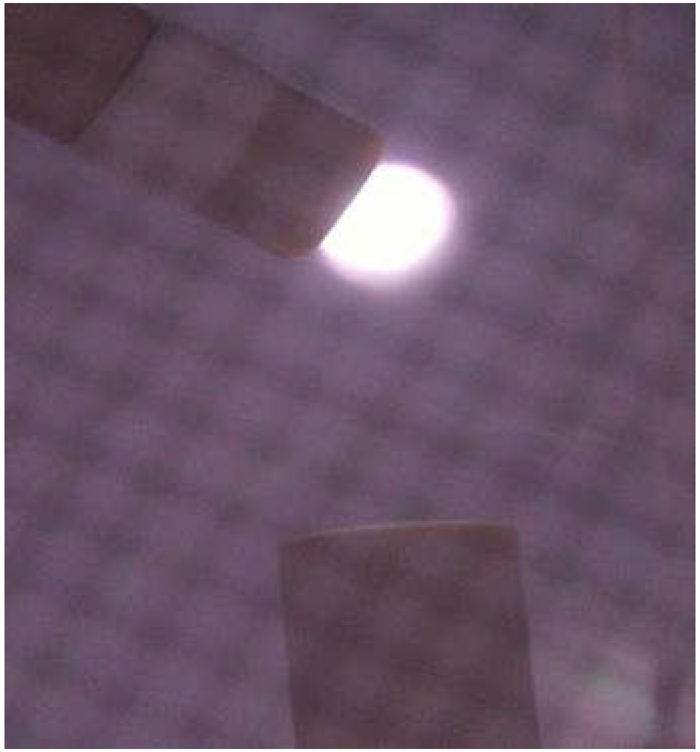
Photo of Experimental Setup

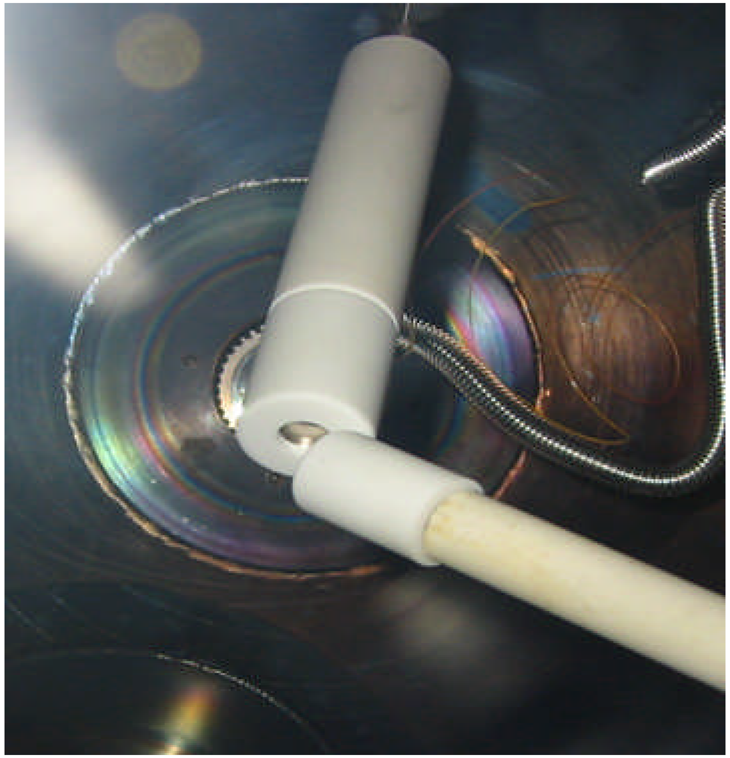
- The experiment is housed in a spherical vacuum chamber
- 10 smaller ports
  - Measurements and inputs
- 4 larger ports
  - Pumping and view ports

Electrodes Have Flexible Design:

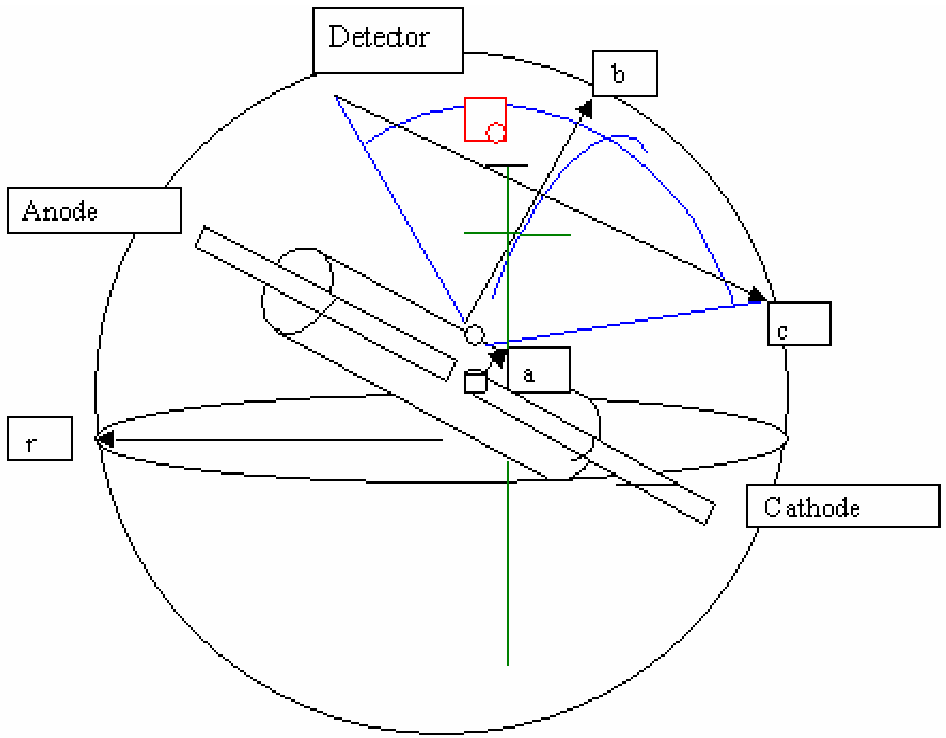
Water-cooling cathode (Target can be mounted easily, capable of linear motion).
Stainless steel anode (Capable of angular motion).
K type thermocouple embedded between the target and the water-cooling jacket.

Discharge with angular orientation





Detector Arrangement – AXUV detector, film and TLD foils – key point – detectors face cathode where D bombardment occurs, not anode with electron bombardment, i.e. x-rays not simple electron Bremsstrahlung



•The **cathode and anode** enclosed by the **glass tube**. The blue projected surface is the solid angle extending out of the opening in the glass tube.

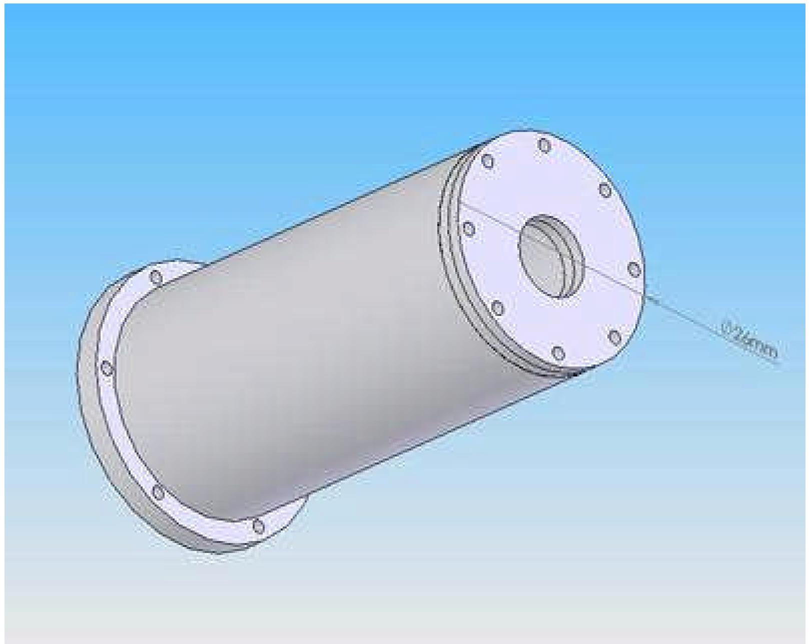
•The calibration measurement described is indicated by the arrows on the diagram given by: r = 275 mm, a = 26 mm, b = 225 mm, and c = 400 mm.

•The crossed green lines are the **wire hanger for** inserting x-ray detection **film** or **TLD detectors**. It is separated from the tube a distance of 150 mm.

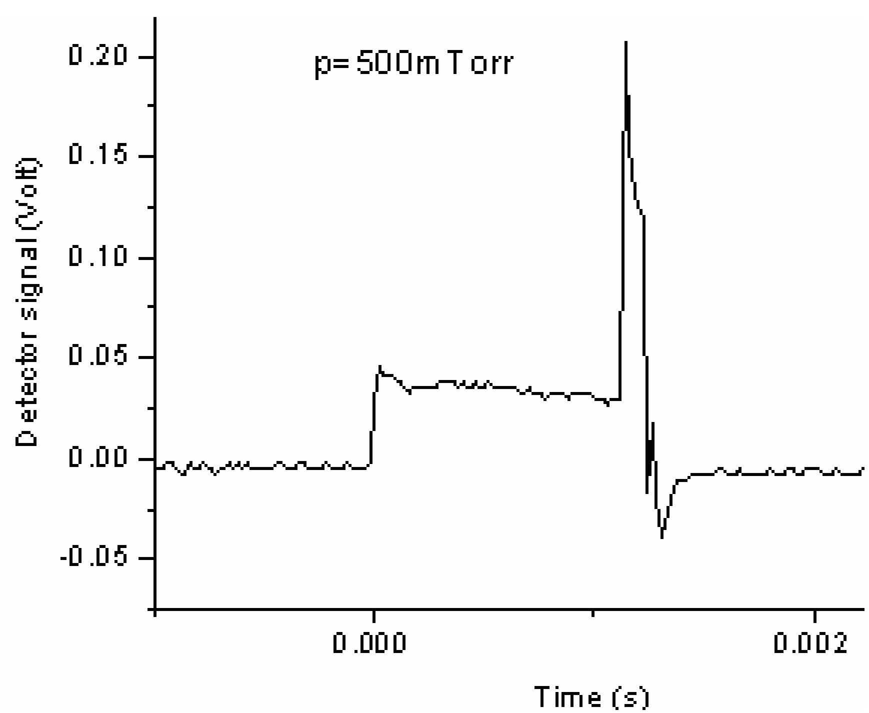
•The red box - circle show the approximate placement of the **AXUV detector.**

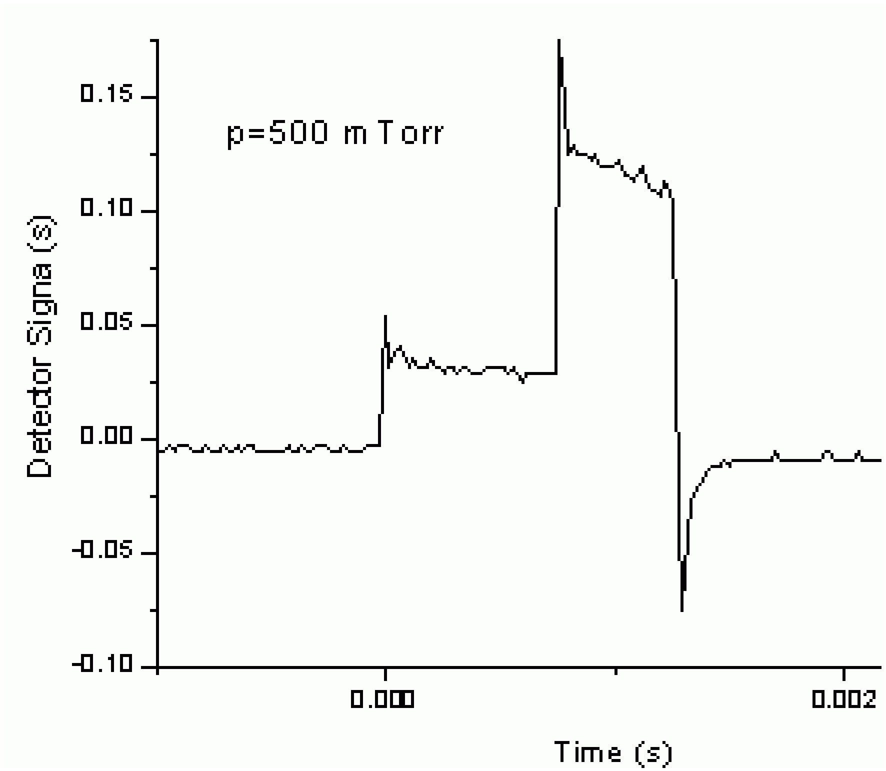
AXUV and Beryllium Window SS Housing

Housing was designed so that it would outgas minimally as well as facilitate frequent modification of detection setup



Typical Result -- filtered AXUV detector indicates peak p=500 mTorr V=250V I=2A for a Pd cathode. The delay time of ~ msec before onset of x-raysis associate with D diffusion time. X-rays are > 600 eV with 250 V discharge! Blank experiment - a cu foil in front of the Be causes the trailing spike (xrays) to disappear as expected,





Comments

- X-ray energy > discharge voltage can not be explained classically
- Delay time before onset consistent with D diffusion into localized sites and time for heat wave to initiate expulsion of excited state from loops.
- While only qualitative proof, results are consistent with excited 2e-D-D theory.

Estimates of Intensity and Efficiency

- Calculated x-ray intensity/efficiency (averaged for 3 measurements):
  - X-ray power out/pulse = 13.4 mW
  - Intensity ~ 13.4 mW/cm^2 (1 cm^2 Pd target)
  - X-ray pulse duration ~ 0.26 ms
  - Energy per pulse ~ 3.3 μJ/cm^2
  - Efficiency = 10^{-3} % wall plug. Much higher if non pumping losses not included as in an optimized case.

Noid-Miley Theory for State Formation in a Cavity

• Due to the fluctuations in the vector potential in the nano-cavity, the instantaneous dipole moment of the e-D system is modulated. This increases or decreases the separation between the electron and D.

• When the separation decreases, the tunneling probability between that pair and another D increases exponentially and when the separation increases the tunneling probability is exponentially suppressed.

• However, because of the asymmetry in the exponential decay function, the tunneling probability function slope normally increases with decreasing separation. Thus, the overall contribution to the tunneling probability from the modulation in dipole moment is positive.

D desorption from small diameter dislocation loops in Pd target results in very large local power flux

- Discharge loading of Pd target occurs at about 2 kW/cm*2
- At high surface temperature T=1940 K, D escape velocity is ~ E_d = 0.17 eV, v_d = $4x10^5$ cm/s;
- Deuterium flux toward the surface in the deuteron stopping range layer (E_d ~ 2 keV, R_s ~ 15 nm): $\Phi_d = 1/3 n_d v_d \sim 10^{29}$ cm^{-2}-s^{-1} at $n_d \sim 2x10^{23}$ cm^{-3};
- Assuming D+ escapes through the active sites at the Pd-surface (dislocation cores), the local power density is: S_{eff} = S(dis)xN_d. $S_{eff} \sim 10^{-6}$-10^{-5} ,then
- Then associated localized power: $\boldsymbol{P_{eff} = \Phi_d x E_d / S_{eff} \sim 10^{14} - 10^{16}\ W/cm^2}$
- **Estimated x-ray quanta: hν = U_e + 3.2 W_p ~ 1.5 keV**

  (Here U_e – is a LII ionization potential, W_p – ponderomotive potential. At U_e =460 eV, W_p ~ 300 eV, corresponding to D escape at $P_{eff} \sim 10^{15}$ W/cm^2.)
- Expected duration of individual x-ray pulses from the Pd-cathode : $\tau = R_s/v_d \sim 4x10^{-12}$ s.

Conclusions

- Strong evidence has been obtained to support the earlier theory that an excited state of 2e-D-D can be formed in dislocation loops in hydrides.
- This discovery can potentially lead to a whole new class of soft x-ray sources.
- Much work remains to pin down details and find if this new type of laser can be used in practical situations as has been predicted.
- If successful, this new class of x-ray sources would provide a materials interaction capability not accessible with present sources.

- Insignificant x-ray yields would be expected due to classical Bremsstrahlung.
  - Detector views cathode where ion, not electron bombardment dominates.
  - Ion bombardment induced bremsstrahlung (x-rays) yields at these energies are virtually negligible.
- Yes, quite significant (> 10 mW/cm^2) x-ray yields are observed.
- Most striking: > 600 eV x-rays obtained with only a 300 V discharge. This can not be explained by a classical mechanism such as Bremsstrahlung, suggesting a nonlinear collective phenomenon.