Research on a Phonon-Driven Solid-State X-Ray Laser

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This discharge driven X-ray laser would offer unique features

The technology:

A deuterium discharge-excited phonon-driven Solid-state plasma laser, which

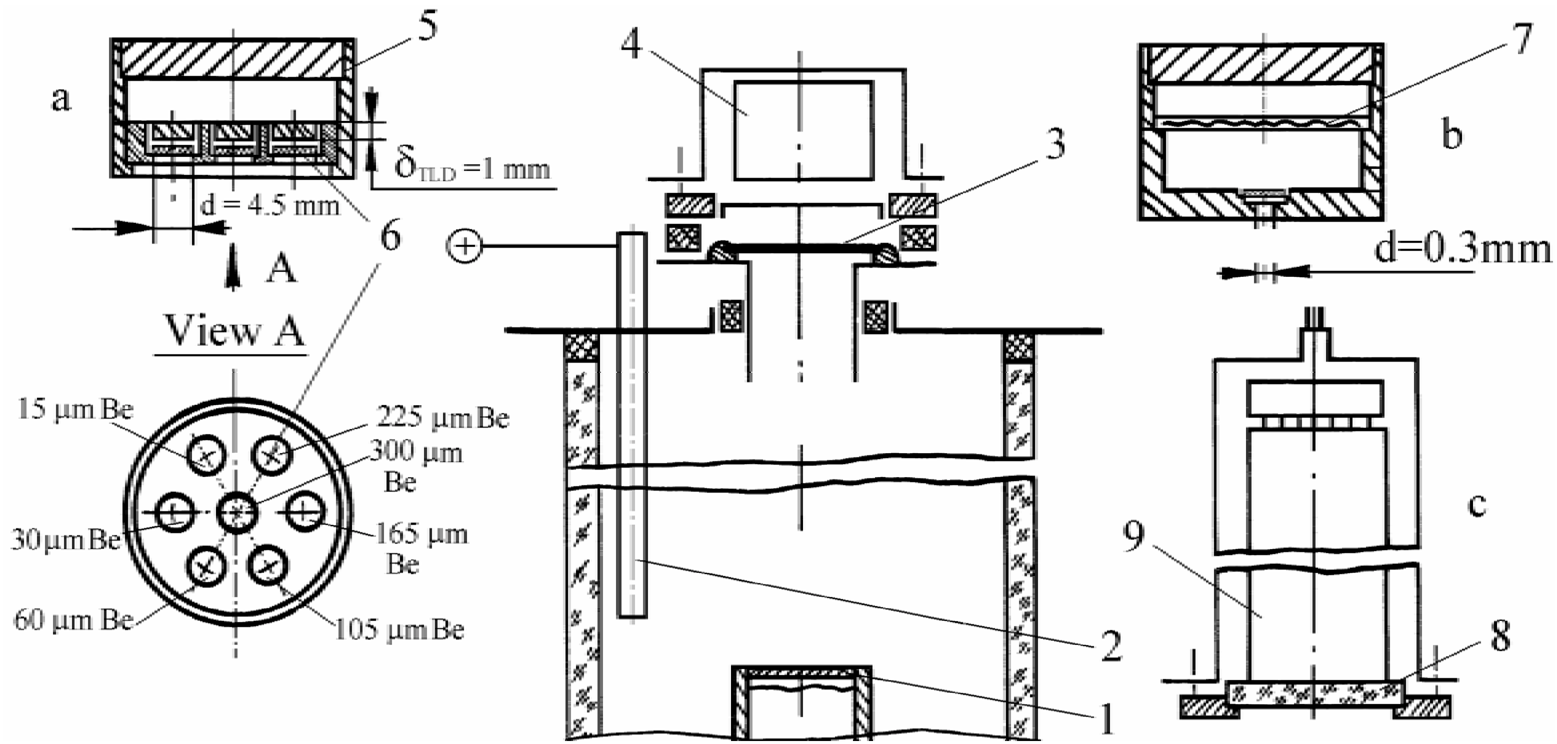
- emits shortwave (1-keV photon) X-ray
- possesses high efficiency (~0.1%, compared with prior "table-top" devices)
- is compact
- high energy output

Background

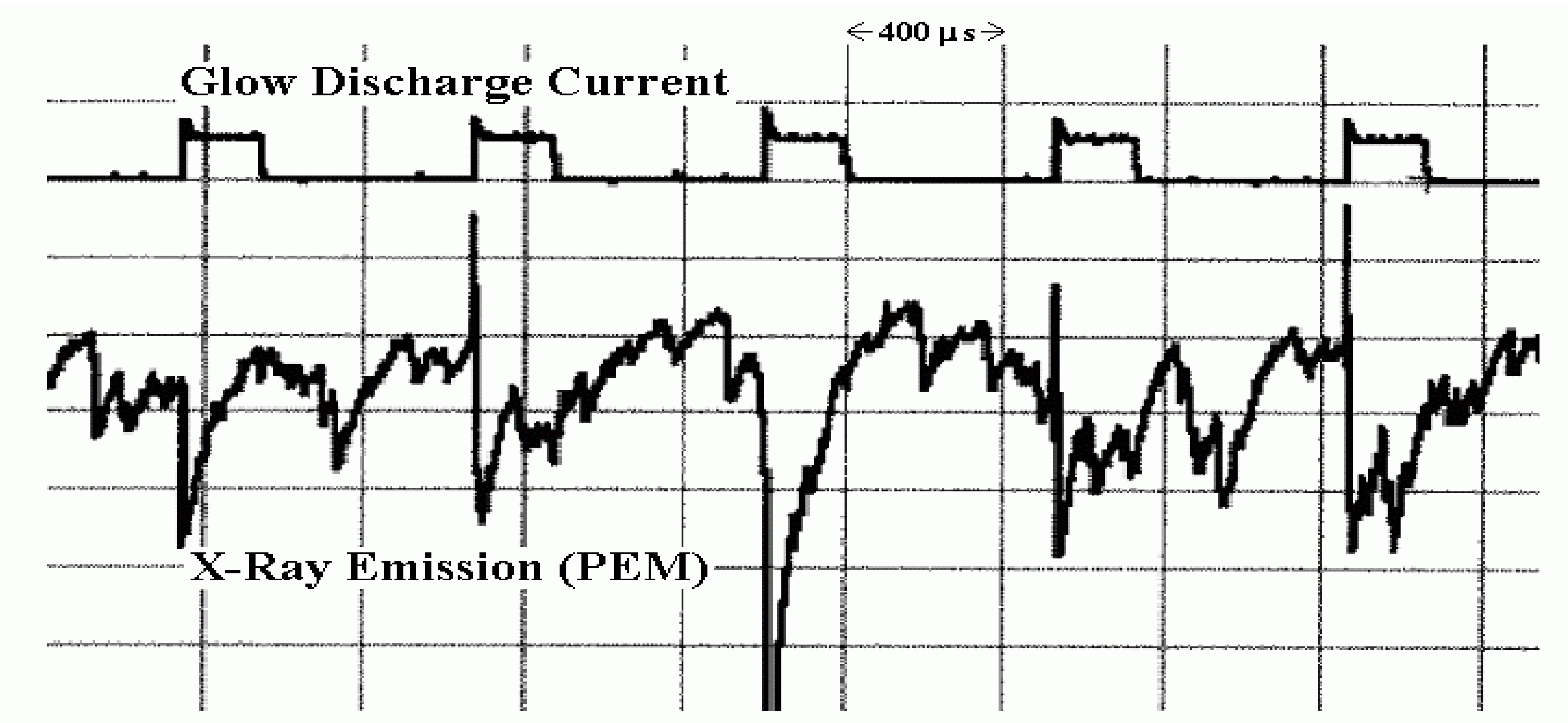
- Concept initiated by report of xray laser by A. Karabut, Lutch, Russia.
- UIUC experiment was designed to verify his results, but use a more flexible experimental unit to allow future extnsions and diagnostics.

Karabut's experimental setup used a cylindrical design. *a –TLD detectors and Be filters of various thickness, b – pin-hole camera, c – PEM-Scintillator system. 1 – cathode; 2 – anode; 3 –Be foil screens; 4 – TLD detectors; 5 – cassette to hold the detectors, 6 – absorbing Be foil screens with thicknesses 15μm - 300μm; 7 – X-ray film; 8 – scintillator; 9 – PEM.*

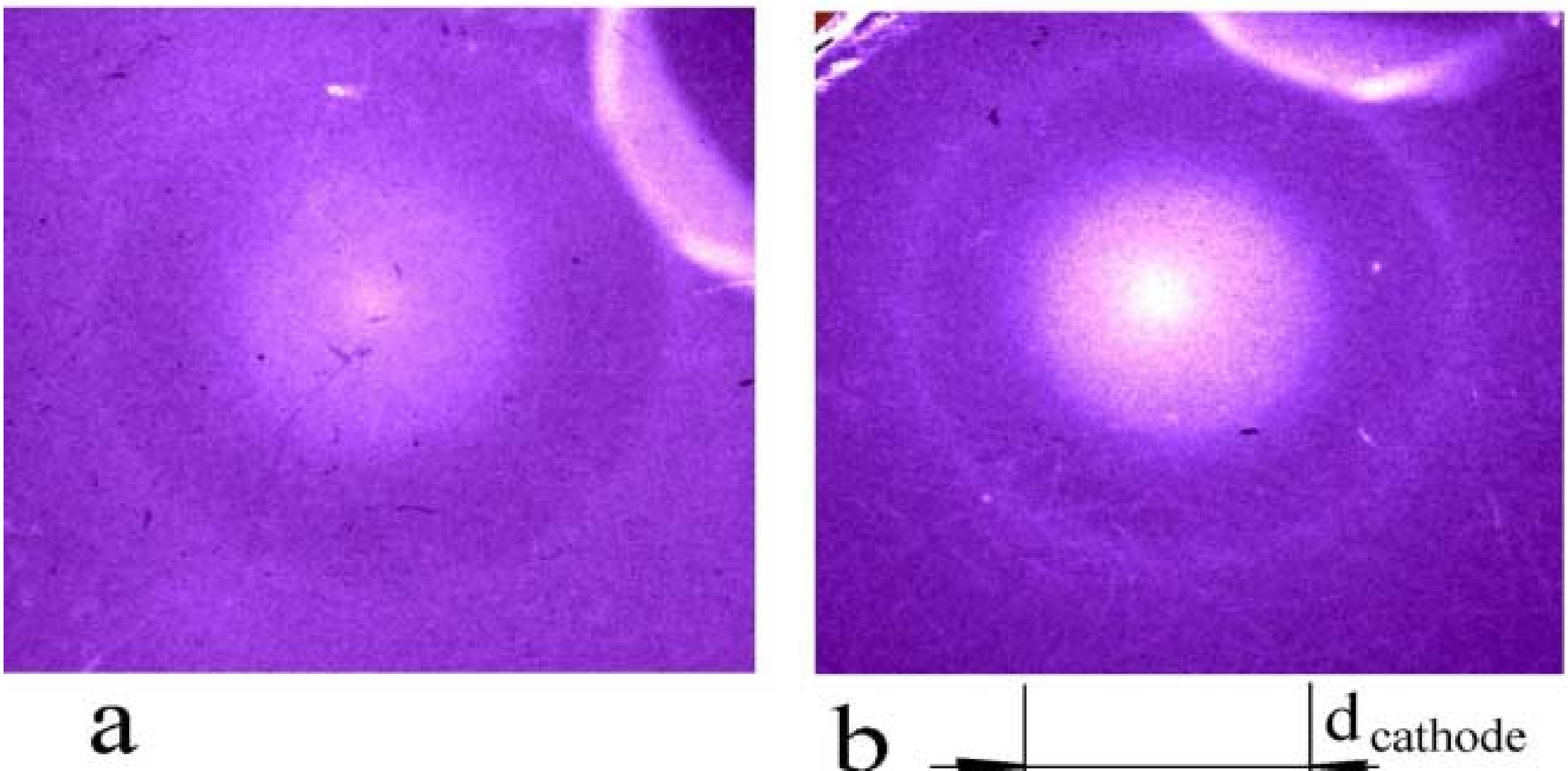
We elected to build a somewhat different design to allow more flexible diagnostics/experiments (plus, originally Karabut was to ship us his unit)



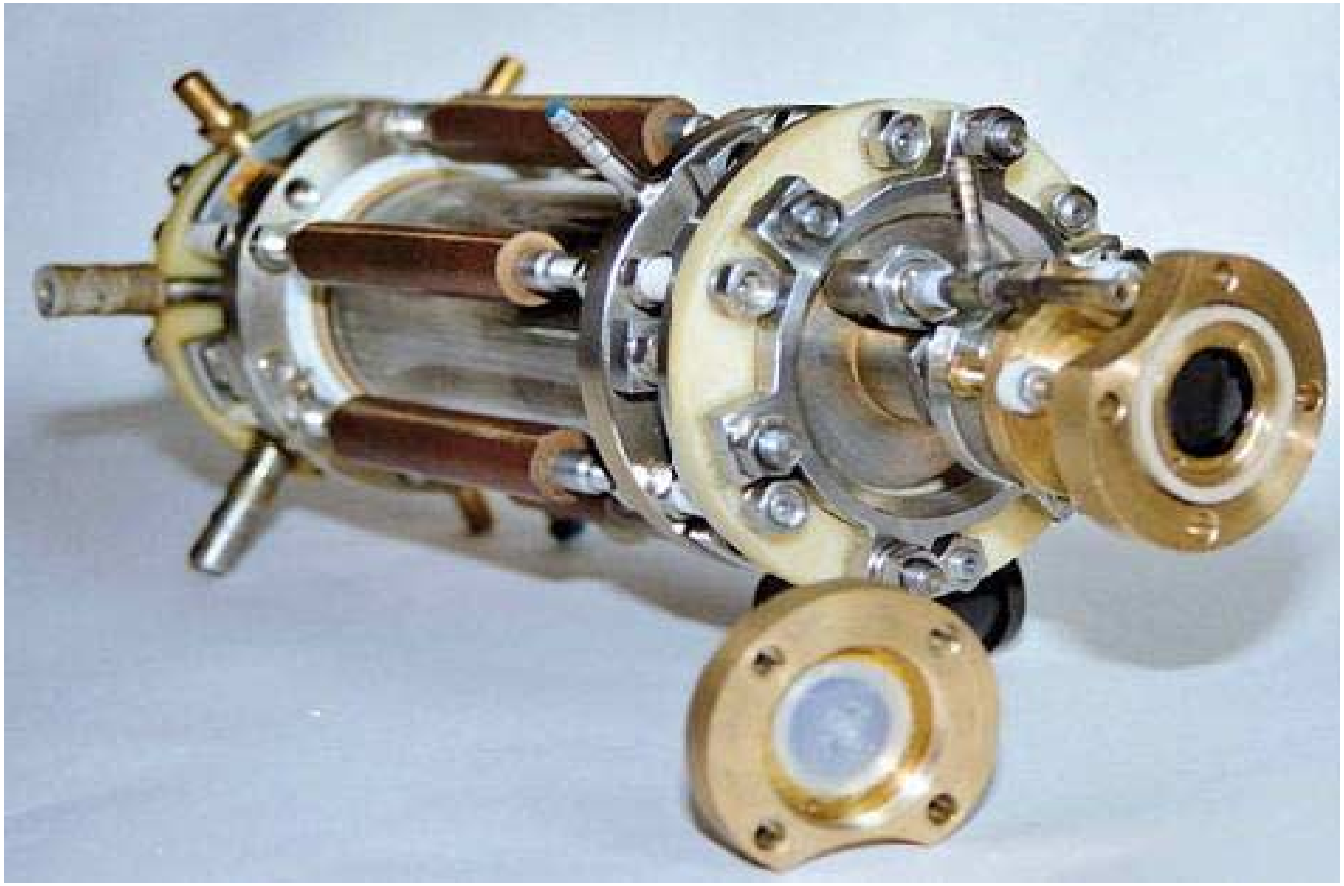
Example of xray output reported by Karabut: Near Threshold X-ray emission recorded by a PEM. Incipient laser pulses appear between the input current pulses while strong incoherent emission occurs during the current pulse. The laser pulses rapidly grow in amplitude above threshold. Year 1 studies have focused on repoducing the non-coherent sub-threshold xrays.



Karabut's Images of x-ray emission using a pinhole camera. The objective of 0.3-mm diameter is narrowed by a 15-μm Be filter in front of the camera. (discharge current – 10 to 150mA, the exposure time – 1000s) Fig. a – the diffusive X-ray emission below threshold, Fig. b – The laser beam near threshold.



Background - Karabut’s deuterium discharge X-ray laser causes damage in plastic target up front



Close-up on the damaged plastic target

Study of this unique new type of laser poses new science and technology challenges

The challenge in technology:

- Verify the lasing operation/phenomenon
- Study the operation parameters
- Scale up the energy/power output
- Adapt for future tactical/strategical application

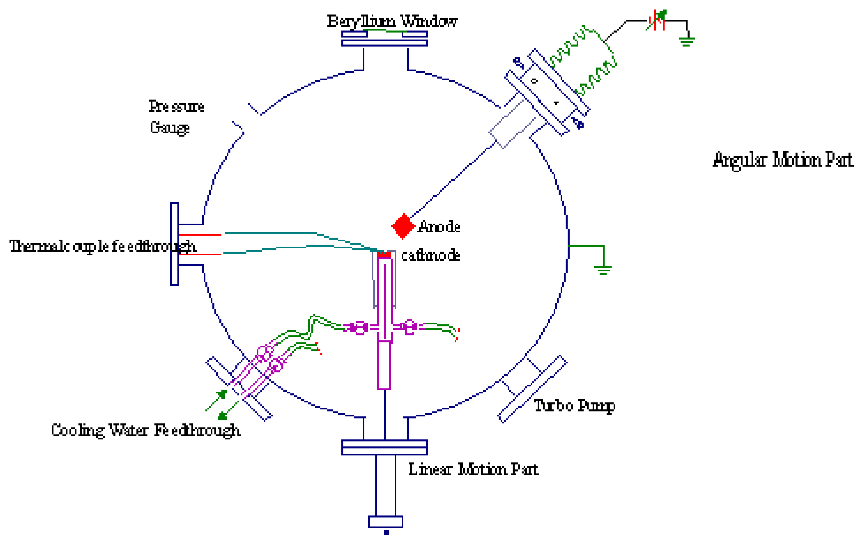
The challenge in science:

- Diagnose the xray coherence properties
- Understand the lasing mechanism
- Diagnose the plasma (solid/gaseous state)
- Study beam propagation and quality

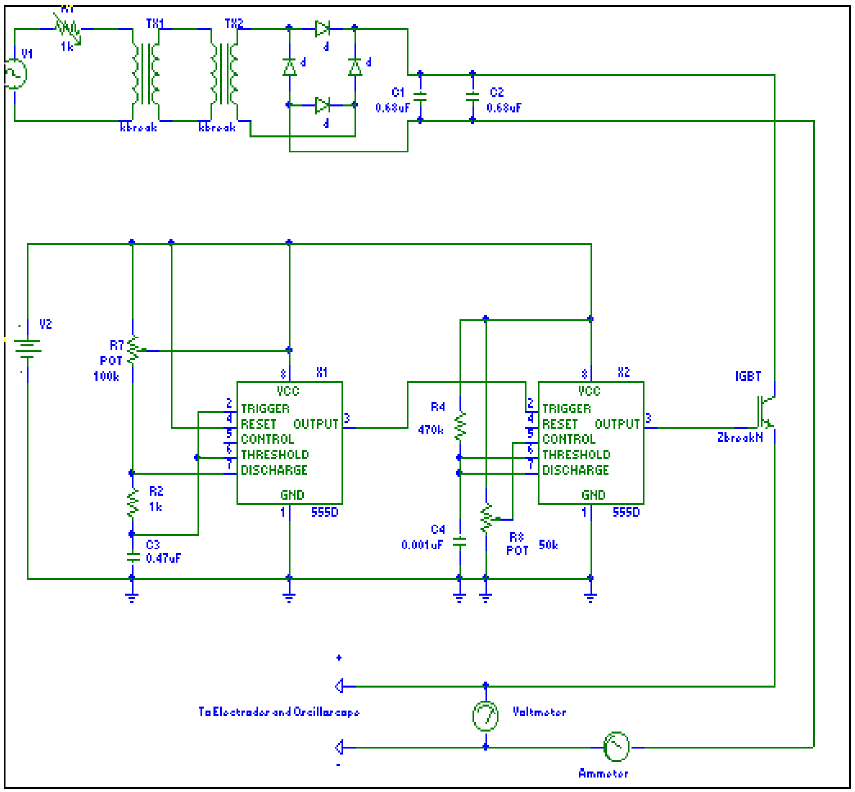
UIUC Progress

- Designed and set up flexible large volume discharge device for study
- Built, with NMT assistant, unique pulsed power supply that closely duplicates and extends Karabut’s
- Set up film and solid-state detector array
- Carried out initial experiments demonstrating operation and anomalous x-ray emission.
- Obtained additional collaborating x-ray data from Russia via collaboration with A. Lipson’s lab using a GD device.

The large volume UIUC chamber gives room for internal diagnostics. Also the anode cathode separation is easily adjusted. Grounded cathode-chamber arrangement suppresses stray chg. pt. beams. A photo of the discharge is also shown.



Circuit and characteristics of special pulsed power supply constructed for experiments



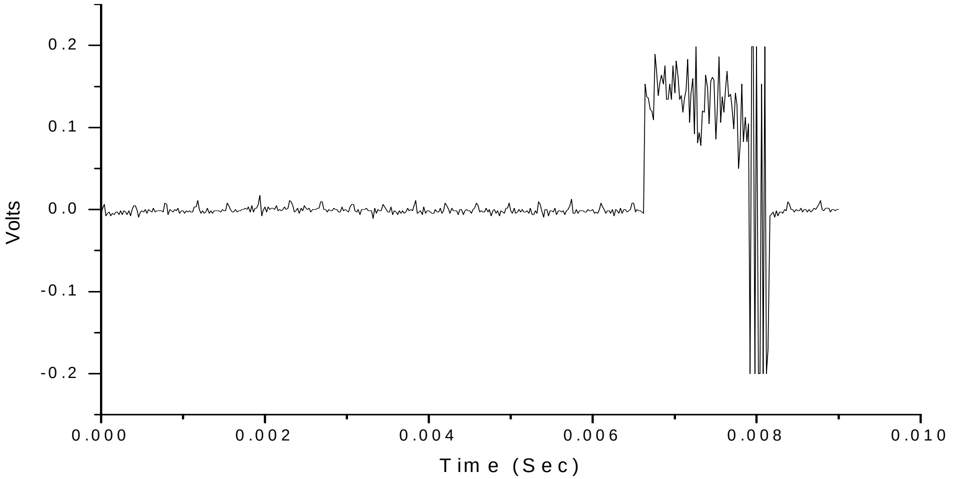
- 220 V input
- 2 kV output
- 555 timers to control frequency and PWM
- 100 Hz - 1 kHz (300 kHz maximum)
- Sharp rise and cutoff

The 2.2 kVA power supply is shown below. The circuit board controlling the frequency works well from 100 Hz to 1800 Hz and the pulse width modulation provides duty cycles of 5% to 95%.

Initial experiments confirm large xray yields during pulsed discharge operation.

- At operating voltages < 2 keV, very small xray yields would be expected
  - The detector views the cathode where ion, not electron bombardment dominates.
  - Ion bombardment-induced Bremsstrahlung (xrays) yields at these energies are virtually negligible.
- These results are essentially in agreement with Karabut’s sub-threshold xray measurements, providing confidence that coherence studies can be achieved in Phase II

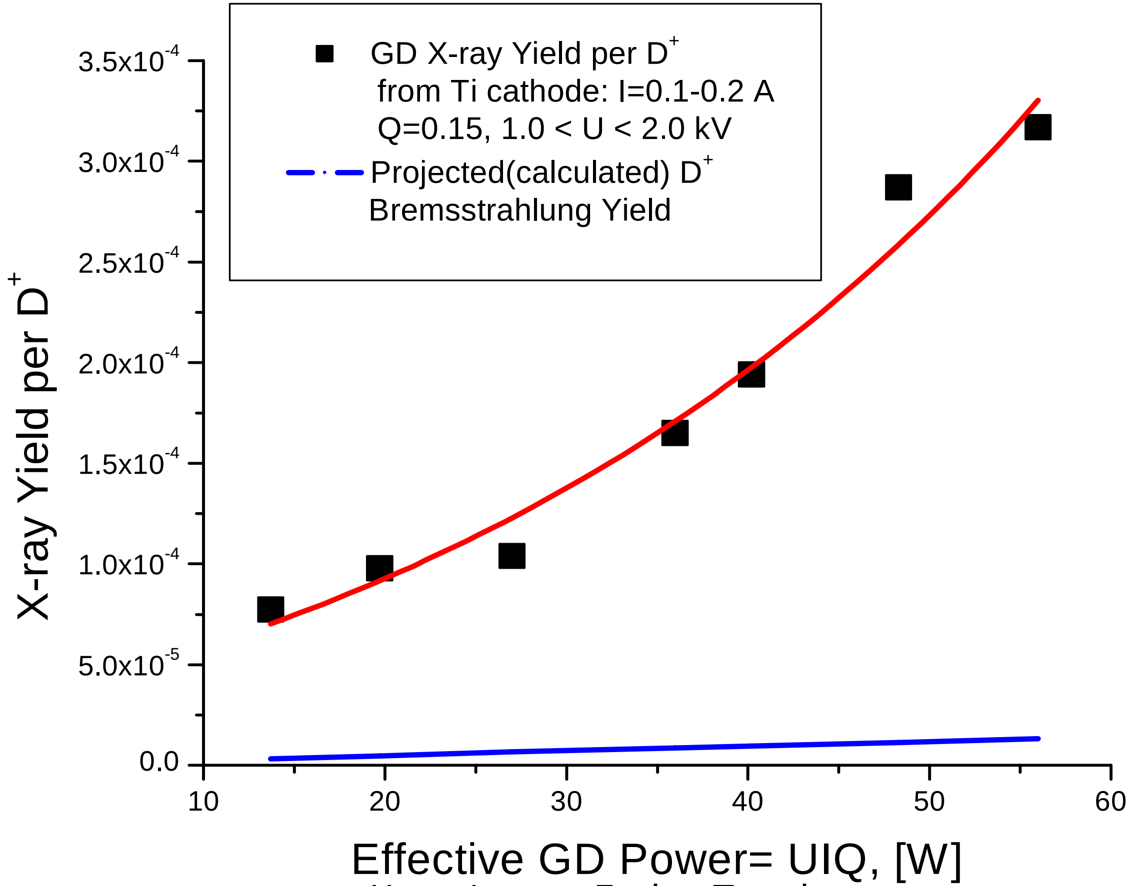
X ray Emission recorded with filtered solid state detector indicates peak emission around p=610 mTorr V=750V I=4A for a Ni cathode. A typical trace is shown. The signal has an optimum amplitude in this pressure range, decreasing with either higher or lower pressure. It also depends on the cathode material.



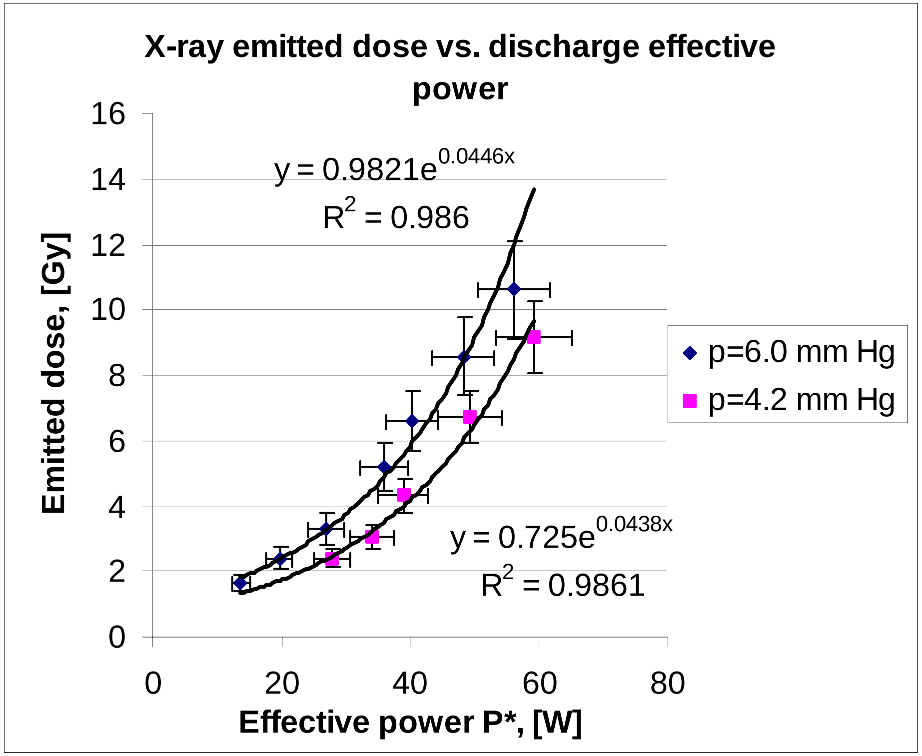
Issues considered in xray signal identification

- Electronic noise – blocked front of detector to identify rf noise component.
- Light interference – special order thin silvered Mylar filter used to discriminate
- Electron beam – suppression by grounded detector-cathode screen arrangement
- Auxiliary TLD measurement of x-rays consistent with solid state detector.

The measured X-ray yield/deuteron (points) vs. effective discharge power greatly exceeds the yield calculated for ion-induced Bremsstrahlung at the cathode. (Blue curve) .



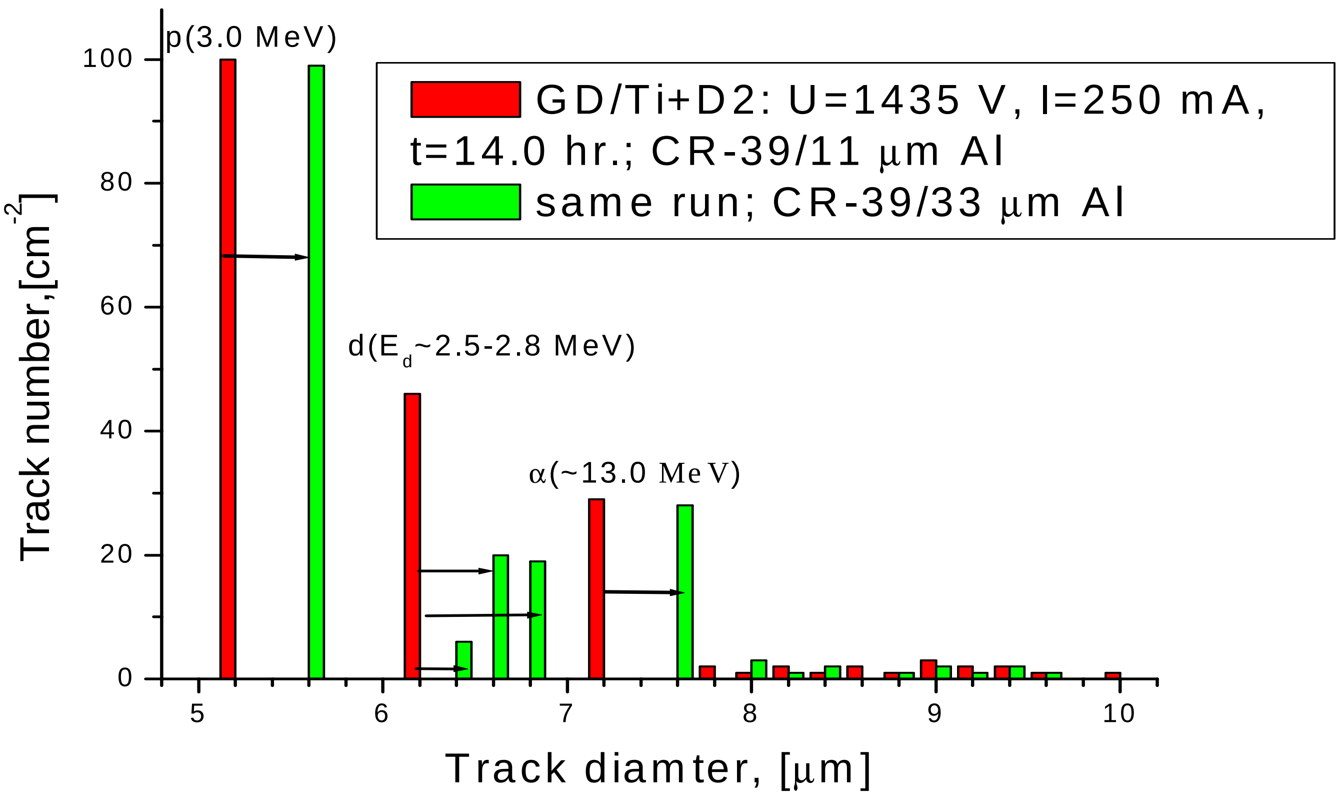
The X-ray dose (in Gy, obtained with TLDs) vs. power at constant pressure follows: Ix = I0 exp[(ε/kTm)P*x/P*0]
where I0 is the X-ray dose: I0 = 0.98 Gy for p=6.0 mm Hg and I0=0.725 Gy for p=4.2 mm Hg.
This behavior again agrees in trend with Karabut's earlier results, providing independent confirmation of a key part of his work.



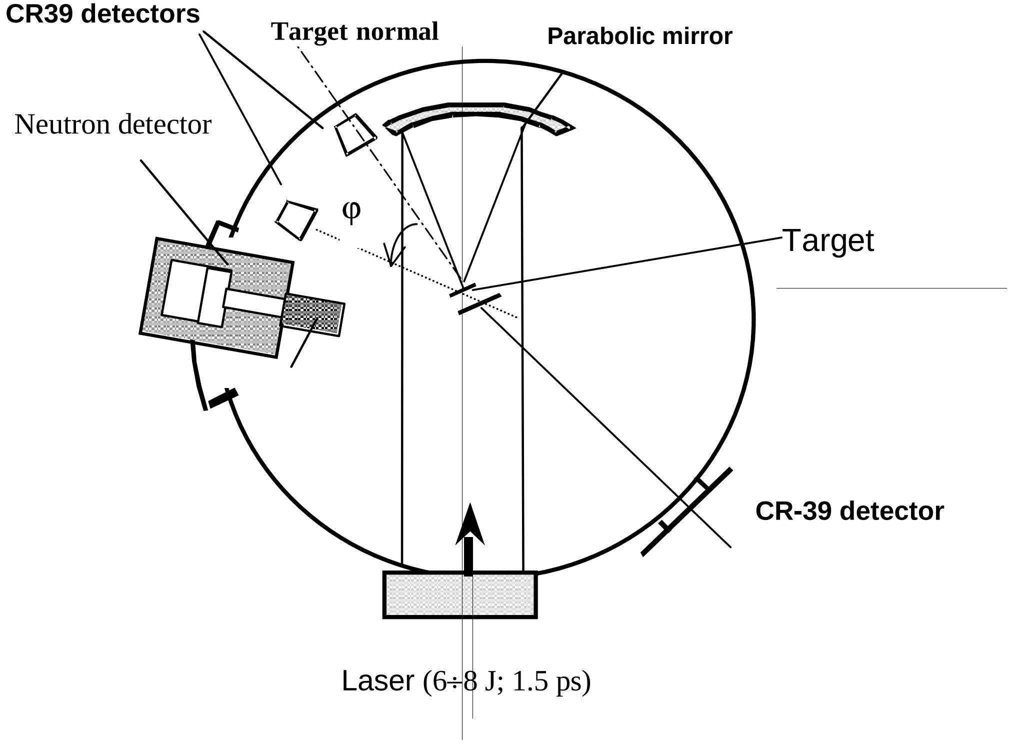
MeV-Alpha Measurements Performed in Russia (Lipson collaboration) add insight into xray laser mechanism.

- MeV alphas measured from cathode during glow discharge using CR-39 foils
- Similar alpha spectrum obtained from fast ps laser irradiation of target
- Similarity suggests theoretical model of focused energy flow in glow discharge driven X-ray laser is plausible

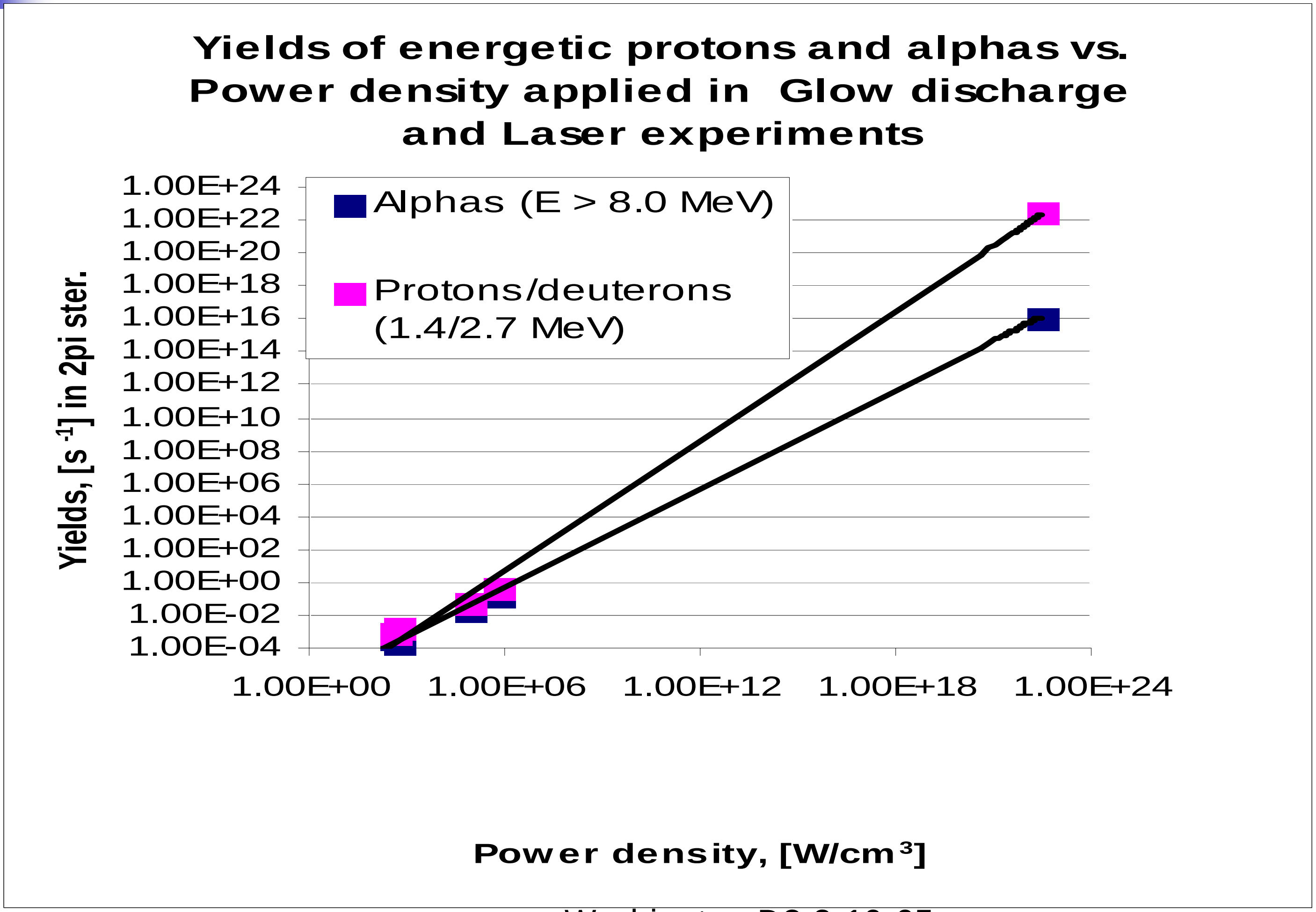
Charged particle (alpha/proton) spectrum from Ti cathode in GD.
Measured by CR-39. Note emission of 2 bands of MeV alpha particles (vs. 1.44 kV applied).
This suggests the input power is focused internally. To test this theory, companion experiments were done with a high power, ps laser focused on a similar Ti target.



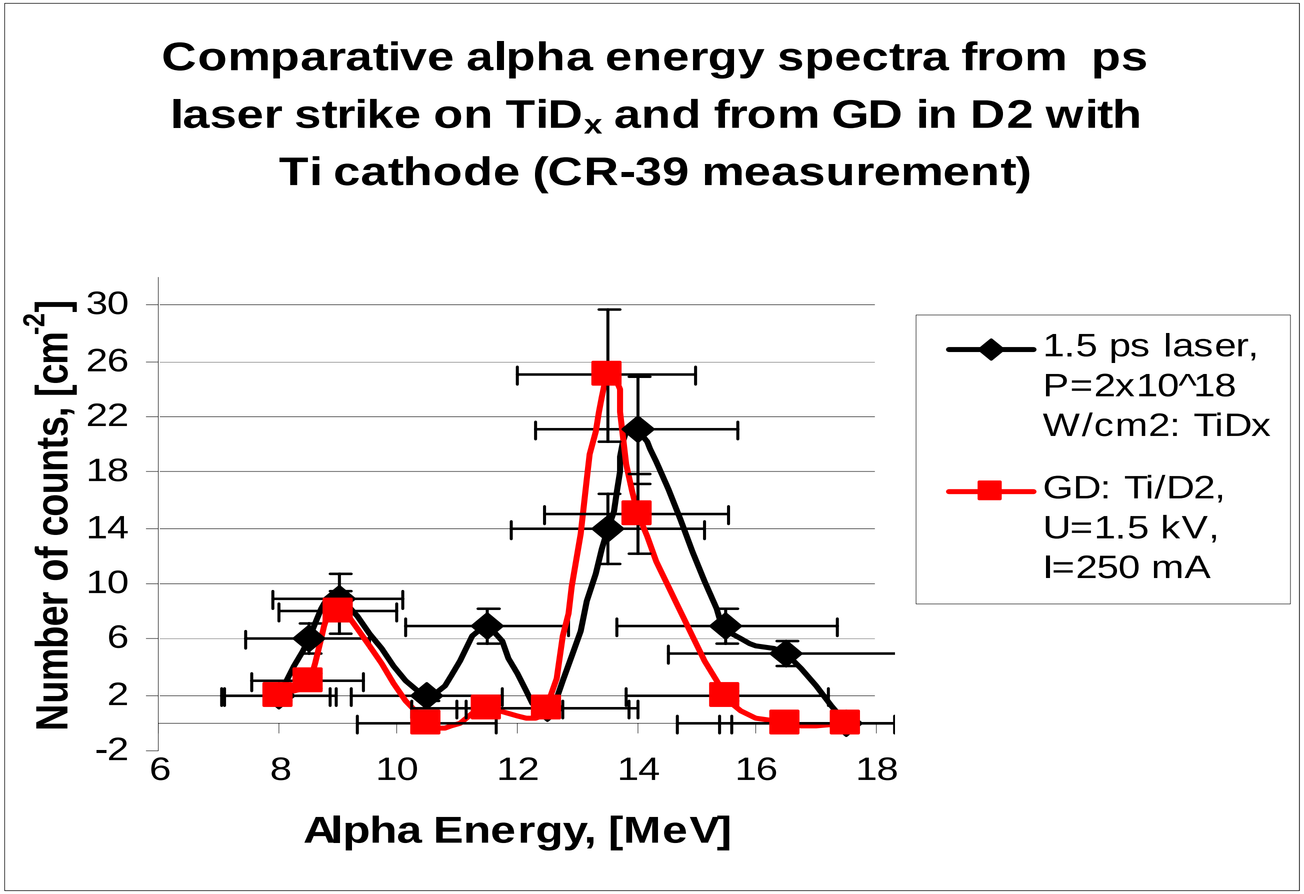
Arrangement of the 1.5 ps P=2x10[18] W/cm[2] laser and TiD_x target used to test the focused energy theory.



The energetic particle yield is proportional to power density applied – thus, as expected, laser yields are orders of magnitude higher than the glow discharge. However, the key point is the energy spectrum shown next.



The alpha spectrum from the glow discharge measurement agrees surprisingly well with the high power PS laser result, supporting the focused energy theory.



Glow Discharge Lasing Theory has been modified to be consistent with alpha emission studies. Key point - dislocation center loading provides effective energy flow focus equivalent to focused laser.

1. **Formation TiD_4 (n_d = $2x10^{23}$ cm^{-3})** over stopping range layer in Ti cathode (at U~ 2.0 keV, **R_s ~ 15 nm**). At I > 100 mA it takes ~ 1us.	2. **Desorption of D+ flux from Ti-surface** at T=1940K (ti melting point), <Ed> = 0.17 eV, v_d = $4x10_5$ cm/s: $\Phi_d = 1/3\ n_d v_d = 10^{29}$ cm^{-2} x s^{-1}, moving coherently
3. Exothermic D+ desorption from Ti-surface **induces shock waves** in opposite direction. Shock waves create dislocations in the R_s layer, N_d ~ 10^8-10^{10} cm^{-2}	4. The **shock waves** produce a high order harmonic generation (similar to powerful IR laser X-ray coherent excitation) and **send electrons out of inner shell of Ti-metal host**

Analogy to PS Laser Theory (Cont'd)

5. Assuming D+ would escape through the active sites at the Ti-surface (dislocation cores), the power density: $P_{eff} = \Phi_d x E_d / S_{eff} \sim 10^{14} - 10^{16}$ W/cm^2 at $S_{eff} \sim 10^{-6}$-10^{-5} of S(Ti). S_{eff} = S(dis)xN_d.	6. Energy of coherent X-ray quanta: $h\nu = U_e + 3.2\ W_p \sim 1.5$ keV(U_e – is a LII Ti ionization potential, W_p – ponderomotive potential). At U_e =460 eV, $W_p \sim$ 300 eV, corresponds to $P_{eff} \sim 10^{15}$ W/cm^2.
7. 2.0 keV D+ bombardment suppresses X-beam de-phasing effects, creating a strong electric field and penetration of Ti LII shell	8. Expected duration of X-ray pulses from the Ti-cathode : $\tau = R_s/v_d \sim 4x10^{-12}$ s

Conclusion from MeV alpha measurements

- Due to localized loading in dislocation cores, and target ablation, very high focused energy release is possible
- This is consistent with the proposition that xray laser inversion could occur in the target despite the seemingly low input power densities.
- Two features, the localized beamlets implied and short burst character, appear consistent with observations previously noted, but not understood, by Karabut. (for example, note localized beamlet-like damage shown in earlier slide of Karabut's plastic target. His detection method can not measure laser pulse lenths, but implies they are < ps.)

Conclusion –results have provided a sound basis for laser studies

- Discharge chamber designed and built
- Pulsed power unit designed and operational
- Diagnostic techniques developed
- Sub-threshold xray measurements confirm anomalous emission similar to Karabut's
  - Strong emission from cathode despite low voltage
  - Higher energy xrays than expected from ion bombardment.
  - Non-linear yield power behavior
- Theory is consistent with alpha emission (and also with high power ps laser-driven xray laser– see appendix C).

Thank You

- For further information contact

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Appendix A. UIUC Hollow Discharge is planned for next step laser.

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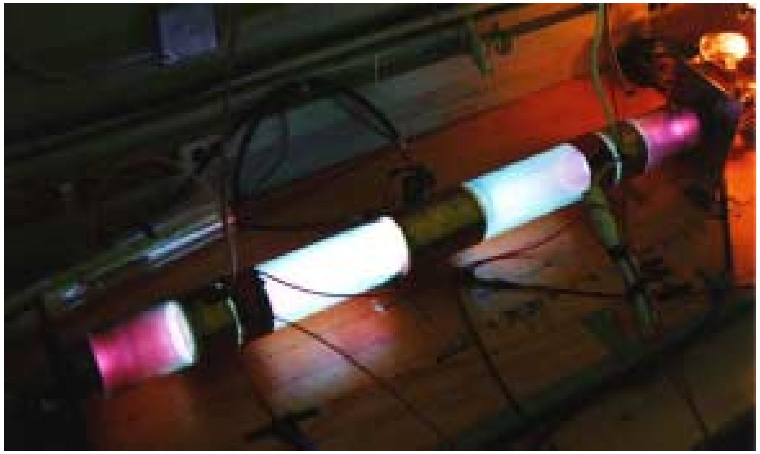


Hollow cathode discharge
plasma tube (C-Device)
working
In FSL lab

Appendix B: Electron Screening(Cont'd)

Comparison of Energy Level and Screening Potentials for GD vs. accelerator bombardment (screening potential = approx. energy level ion can approach; i.e. higher is better)

	Accelerator Exp.	GD Exp.
Target/T, K	Ti/T=186K	Ti/T>1000K
E_d, keV	10.0-2.5	2.45-0.80
U_s[eV], (estimated)	65±15	620±140
Shell	M_I	L_{II}
E (level), eV	58.3	461

Appendix B: Electron Screening(Cont'd)

- Electron screening effects in deuterated metals
- a) The Kasagi experiment: H. Yuki, J.Kasagi, A.G.Lipson, T.Ohtsuki, T.Baba, T.Noda, B.F.Lyakhov, N.Asami, JETP Lett. 68 ,823, (1998)
- b) The Ruhr-Universität Bochum astrophysics team and the LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration, with fruitful and very convincing results. For details, see Appendix B

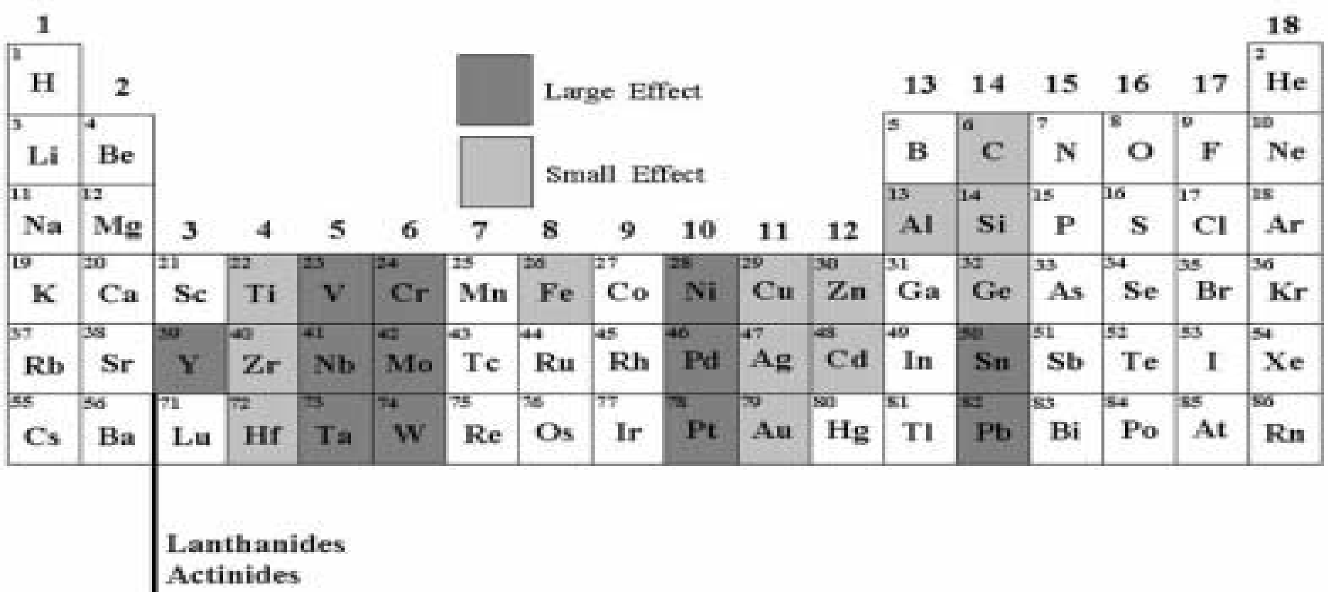
The LUNA collaboration logo. Courtesy of LUNA

Appendix B: Electron Screening (Cont’d) Recent worldwide progress in low energy screening studies

- Selected results from the Ruhr-Luna team

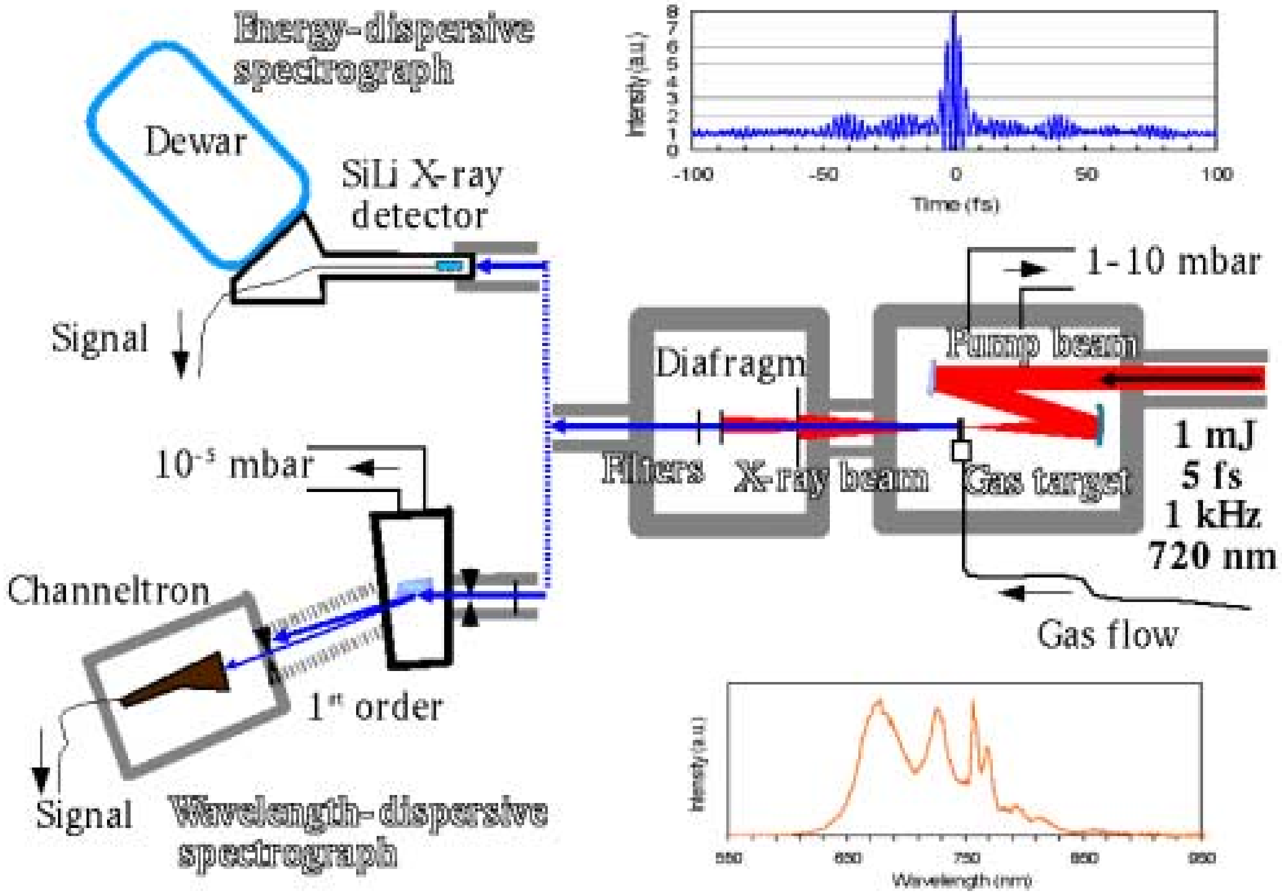
More to be found at

http://nucleus.ep3.ruhr-uni-bochum.de/astro/electron_screening/electron_screening.htm

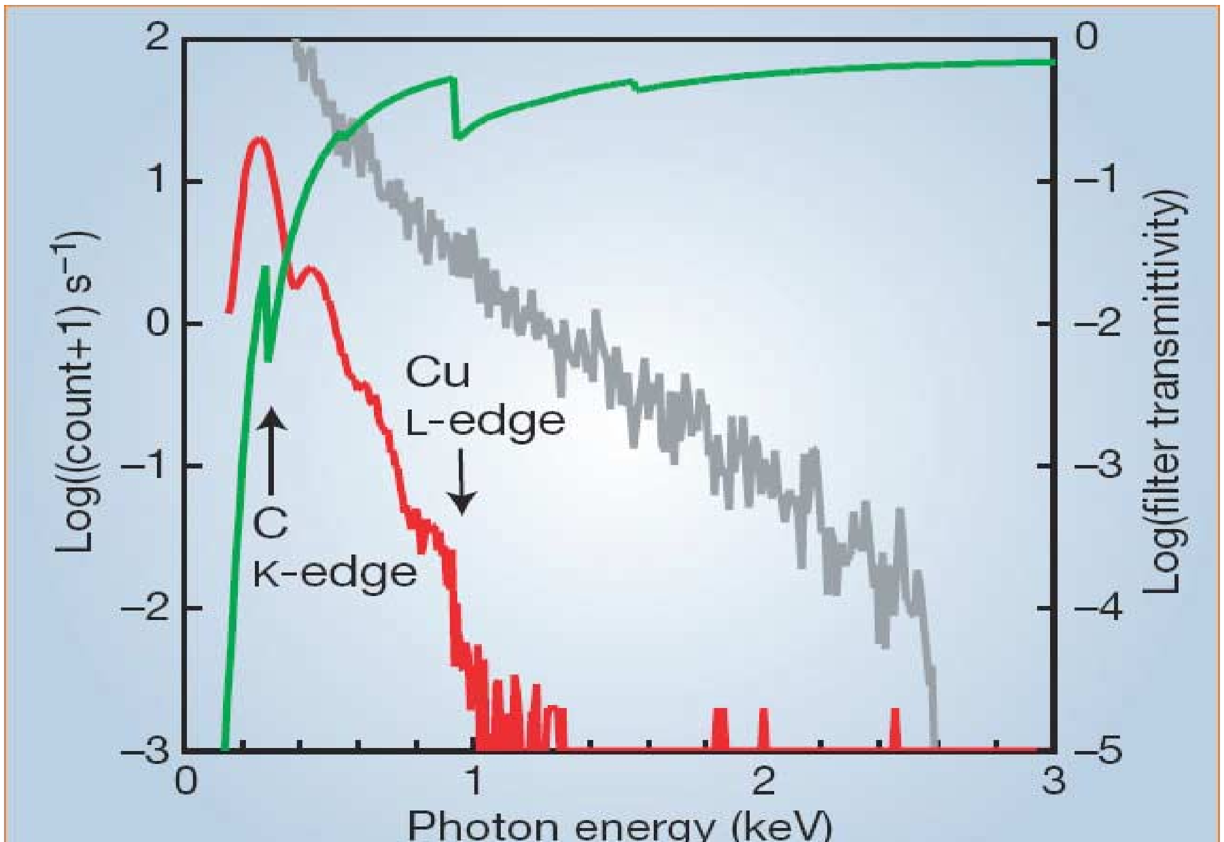


The elements studied showing high electron screening for low energy D-D reactions

APPENDIX C: Present work is also related to new results of 1.3 keV X-ray lasing induced by powerful fs IR-laser hitting He-jet target (J. SERES et al., *Nature* 433, 596 (10 February 2005);



APPENDIX C: In their experiment xray emission is broad in energy.- t**he soft X-ray beam is filtered by 100-cm helium (3 millibar), 100-nm Cu and 100-nm Al filters and a 300-nm AP1.3 window. Green line, overall transmittivity of these filters; grey line, calculated spectrum of radiation emitted by individual He atoms exposed to 5-fs pulses with a peak intensity of 1.4x10^{16}W- cm^{-2}.**
(X-ray laser intensity ~ 10^2-10^3 –quanta/s)



APPENDIX C: Relation of Model for lasing in GD pulsed discharge to fs laser-induced x-ray laser.

- At high surface temperature T=1940 K, E_d = 0.17 eV, v_d = 4x10^5 cm/s;
- Deuterium flux toward the surface in the deuteron sopping range layer (E_d ~ 2 keV, R_s ~ 15 nm): Φ_d = $1/3 n_d v_d$ ~ 10^{29} cm^{-2}-s^{-1} at n_d ~ 2x10^{23} cm^{-3};
- D-diffusion is a coherent process similar to driving IR powerful laser beam in X-ray lasing induced by short IR pulses. High order harmonic generation.
- Deuteron flux effective Power density at the active sites over the Ti surface : $P_{eff} \approx 10^{14}$ W/cm^2.

APPENDIX C: Relation to fs-Laser exp. (Cont'd)

- Feasible energy of X-ray laser quanta would be $h\nu = U_e + 3.2\ W_p \sim 1.4$ keV, where $U_e = 462$ eV is the ionization potential of inner shell (TiLII); $W_p = 250$ eV – is the ponderomotive potential induced by interaction between a coherently moving deuterium flux and bombarding deuterons at $P_{eff} \approx 10^{14}$ W/cm^2.
- D^+ penetration into LII Ti- shell provide a strong electric field suppressing induced X-ray beam de-phasing effects
- Expected duration of X-ray pulses from the Ti-cathode : $\tau = R_s/v_d \sim 4\times10^{-12}$ s

APPENDIX C: Relation to fs-Laser exp. (Cont'd)

- As in case of MeV alpha-emission studies, the recent fs-induced xray lasing is consistent with the present theoretical understanding for the GD-driven xray laser under study.